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Contents

Table of Contents

1 Introduction
   1.1 Meta notation ................................................. 13

2 Lexical elements
   2.1 Whitespace and comments ................................. 14
   2.2 Identifiers and keywords ................................. 14
   2.3 Integer literals ............................................ 14
      2.3.1 Type conversion of integer literals ................. 15
   2.4 Real literals ................................................ 16
      2.4.1 Type conversion of real literals .................... 16
   2.5 String literals ............................................. 16
      2.5.1 Type conversion of string literals ................. 17
   2.6 Don’t-care values ........................................... 17
   2.7 Compiler directives ....................................... 17
      2.7.1 File inclusion: ‘include and ‘line ................. 18
      2.7.2 Macro definition and substitution: ‘define and related directives ............... 18
      2.7.3 Conditional compilation: ‘ifdef and related directives ....................... 19

3 Packages and the outermost structure of a BSV design .......................... 20
   3.1 Scopes, name clashes and qualified identifiers ............ 21
   3.2 The Standard Prelude package ............................ 22
   3.3 AzureIP™ Foundation Libraries ............................ 22

4 Types ........................................................................... 22
   4.1 Polymorphism .................................................. 24
   4.2 Provisos (brief intro) ........................................ 24
      4.2.1 The pseudo-function valueof (or valueOf) .................. 26
   4.3 A brief introduction to deriving clauses .................. 26

5 Modules and interfaces, and their instances .................................... 27
   5.1 Explicit state via module instantiation, not variables ........ 27
   5.2 Interface declaration ....................................... 28
      5.2.1 Subinterfaces ............................................ 30
   5.3 Module definition ............................................ 31
   5.4 Module and interface instantiation .......................... 33
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4.1 Short form instantiation</td>
<td>33</td>
</tr>
<tr>
<td>5.4.2 Long form instantiation</td>
<td>34</td>
</tr>
<tr>
<td>5.5 Interface definition (definition of methods)</td>
<td>35</td>
</tr>
<tr>
<td>5.5.1 Shorthands for Action and ActionValue method definitions</td>
<td>37</td>
</tr>
<tr>
<td>5.5.2 Definition of subinterfaces</td>
<td>37</td>
</tr>
<tr>
<td>5.5.3 Definition of methods and subinterfaces by assignment</td>
<td>38</td>
</tr>
<tr>
<td>5.6 Rules in module definitions</td>
<td>39</td>
</tr>
<tr>
<td>5.7 Examples</td>
<td>40</td>
</tr>
<tr>
<td>5.8 Synthesizing Modules</td>
<td>42</td>
</tr>
<tr>
<td>5.8.1 Type Polymorphism</td>
<td>43</td>
</tr>
<tr>
<td>5.8.2 Module Interfaces and Arguments</td>
<td>44</td>
</tr>
<tr>
<td>6 Static and dynamic semantics</td>
<td>44</td>
</tr>
<tr>
<td>6.1 Static semantics</td>
<td>45</td>
</tr>
<tr>
<td>6.1.1 Type checking</td>
<td>45</td>
</tr>
<tr>
<td>6.1.2 Proviso checking and bit-width constraints</td>
<td>45</td>
</tr>
<tr>
<td>6.1.3 Static elaboration</td>
<td>45</td>
</tr>
<tr>
<td>6.2 Dynamic semantics</td>
<td>46</td>
</tr>
<tr>
<td>6.2.1 Reference semantics</td>
<td>46</td>
</tr>
<tr>
<td>6.2.2 Mapping into efficient parallel clocked synchronous hardware</td>
<td>47</td>
</tr>
<tr>
<td>6.2.3 How rules are chosen to fire</td>
<td>48</td>
</tr>
<tr>
<td>6.2.4 Mapping specific hardware models</td>
<td>49</td>
</tr>
<tr>
<td>7 User-defined types (type definitions)</td>
<td>50</td>
</tr>
<tr>
<td>7.1 Type synonyms</td>
<td>50</td>
</tr>
<tr>
<td>7.2 Enumerations</td>
<td>51</td>
</tr>
<tr>
<td>7.3 Structs and tagged unions</td>
<td>53</td>
</tr>
<tr>
<td>8 Variable declarations and statements</td>
<td>55</td>
</tr>
<tr>
<td>8.1 Variable and array declaration and initialization</td>
<td>56</td>
</tr>
<tr>
<td>8.2 Variable assignment</td>
<td>57</td>
</tr>
<tr>
<td>8.3 Implicit declaration and initialization</td>
<td>58</td>
</tr>
<tr>
<td>8.4 Register reads and writes</td>
<td>59</td>
</tr>
<tr>
<td>8.4.1 Registers and square-bracket notation</td>
<td>59</td>
</tr>
<tr>
<td>8.4.2 Registers and range notation</td>
<td>60</td>
</tr>
<tr>
<td>8.4.3 Registers and struct member selection</td>
<td>61</td>
</tr>
<tr>
<td>8.5 Begin-end statements</td>
<td>61</td>
</tr>
<tr>
<td>8.6 Conditional statements</td>
<td>62</td>
</tr>
</tbody>
</table>
8.7 Loop statements ....................................................... 63
  8.7.1 While loops .................................................. 64
  8.7.2 For loops .................................................... 64
8.8 Function definitions .............................................. 65
  8.8.1 Definition of functions by assignment .................. 66
  8.8.2 Function types .............................................. 66
9 Expressions .......................................................... 67
  9.1 Don't-care expressions .......................................... 67
  9.2 Conditional expressions ....................................... 68
  9.3 Unary and binary operators ................................... 68
  9.4 Bit concatenation and selection ............................. 69
  9.5 Begin-end expressions ........................................ 70
  9.6 Actions and action blocks ..................................... 71
  9.7 Actionvalue blocks ............................................ 72
  9.8 Function calls ................................................ 74
  9.9 Method calls .................................................. 74
  9.10 Static type assertions ......................................... 75
  9.11 Struct and union expressions ............................... 76
    9.11.1 Struct expressions ...................................... 76
    9.11.2 Struct member selection ................................. 76
    9.11.3 Tagged union expressions ............................... 77
    9.11.4 Tagged union member selection ......................... 77
  9.12 Interface expressions ......................................... 78
    9.12.1 Differences between interfaces and structs .......... 79
  9.13 Rule expressions ............................................. 80
10 Pattern matching .................................................. 81
  10.1 Case statements with pattern matching .................... 83
  10.2 Case expressions with pattern matching .................... 84
  10.3 Pattern matching in if statements and other contexts .... 85
  10.4 Pattern matching assignment statements .................... 86
11 Finite state machines ............................................ 87
12 Important primitives

12.1 The types bit and Bit ................................. 87
   12.1.1 Bit-width compatibility ......................... 88
12.2 UInt, Int, int and Integer .......................... 88
12.3 String and Char .................................... 88
12.4 Tuples .............................................. 89
12.5 Registers .......................................... 89
12.6 FIFOs .............................................. 90
12.7 FIFOFs .............................................. 91
12.8 System tasks and functions ............................ 91
   12.8.1 Displaying information ............................ 91
   12.8.2 $format ....................................... 93
   12.8.3 Opening and closing file operations .......... 93
   12.8.4 Writing to a file ................................ 94
   12.8.5 Formatting output to a string .................. 95
   12.8.6 Reading from a file ............................... 96
   12.8.7 Flushing output .................................. 96
   12.8.8 Stopping simulation ............................... 96
   12.8.9 VCD dumping .................................... 97
   12.8.10 Time functions .................................. 97
   12.8.11 Real functions .................................. 97
   12.8.12 Testing command line input ...................... 97

13 Guiding the compiler with attributes .......................... 98

13.1 Verilog module generation attributes .................... 98
   13.1.1 synthesize ..................................... 98
   13.1.2 noinline ........................................ 99
13.2 Interface attributes .................................. 99
   13.2.1 Renaming attributes .............................. 100
   13.2.2 Port protocol attributes ........................ 101
   13.2.3 Interface attributes example .................... 101
13.3 Scheduling attributes .................................. 102
   13.3.1 fire_when_enabled ................................ 102
   13.3.2 noImplicit_conditions ............................ 103
   13.3.3 descending_urgency ............................... 105
   13.3.4 execution_order .................................. 107
   13.3.5 mutually_exclusive ............................... 107
15 Embedding RTL in a BSV design

15.1 Parameter ................................................................. 133
15.2 Method ................................................................. 134
15.3 Port ................................................................. 135
15.4 Input clock ............................................................ 135
15.5 Default clock .......................................................... 136
15.6 Output clock ........................................................... 138
15.7 Input reset ............................................................. 138
15.8 Default reset ........................................................... 139
15.9 Output reset ............................................................ 141
15.10 Ancestor, same family ............................................... 141
15.11 Schedule .............................................................. 142
15.12 Path ................................................................. 143
15.13 Interface .............................................................. 144
15.14 Inout ................................................................. 144

16 Embedding C in a BSV Design ......................................... 145

16.1 Argument Types ....................................................... 146
16.2 Return types ........................................................... 147
16.3 Implicit pack/unpack .................................................. 148
16.4 Other examples ....................................................... 148

A Keywords .................................................................. 150

B The Standard Prelude package ........................................ 154

B.1 Type classes ............................................................ 154
  B.1.1 Bits ................................................................. 154
  B.1.2 Eq ................................................................. 155
  B.1.3 Literal ............................................................. 156
  B.1.4 RealLiteral ......................................................... 156
  B.1.5 SizedLiteral ........................................................ 157
  B.1.6 Arith ............................................................... 157
  B.1.7 Ord ................................................................. 159
  B.1.8 Bounded ............................................................ 161
  B.1.9 Bitwise ............................................................. 162
  B.1.10 BitReduction ....................................................... 163
  B.1.11 BitExtend .......................................................... 165
  B.1.12 SaturatingArith .................................................. 166
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.1.13 Alias and NumAlias</td>
<td>167</td>
</tr>
<tr>
<td>B.1.14 FShow</td>
<td>167</td>
</tr>
<tr>
<td>B.1.15 StringLiteral</td>
<td>169</td>
</tr>
<tr>
<td>B.2 Data Types</td>
<td>169</td>
</tr>
<tr>
<td>B.2.1 Bit</td>
<td>169</td>
</tr>
<tr>
<td>B.2.2 UInt</td>
<td>171</td>
</tr>
<tr>
<td>B.2.3 Int</td>
<td>171</td>
</tr>
<tr>
<td>B.2.4 Integer</td>
<td>171</td>
</tr>
<tr>
<td>B.2.5 Bool</td>
<td>172</td>
</tr>
<tr>
<td>B.2.6 Real</td>
<td>173</td>
</tr>
<tr>
<td>B.2.7 String</td>
<td>174</td>
</tr>
<tr>
<td>B.2.8 Char</td>
<td>176</td>
</tr>
<tr>
<td>B.2.9 Fmt</td>
<td>178</td>
</tr>
<tr>
<td>B.2.10 Void</td>
<td>179</td>
</tr>
<tr>
<td>B.2.11 Maybe</td>
<td>179</td>
</tr>
<tr>
<td>B.2.12 Tuples</td>
<td>180</td>
</tr>
<tr>
<td>B.2.13 Array</td>
<td>182</td>
</tr>
<tr>
<td>B.2.14 Ordering</td>
<td>183</td>
</tr>
<tr>
<td>B.2.15 File</td>
<td>183</td>
</tr>
<tr>
<td>B.2.16 Clock</td>
<td>184</td>
</tr>
<tr>
<td>B.2.17 Reset</td>
<td>184</td>
</tr>
<tr>
<td>B.2.18 Inout</td>
<td>184</td>
</tr>
<tr>
<td>B.2.19 Action/ActionValue</td>
<td>186</td>
</tr>
<tr>
<td>B.2.20 Rules</td>
<td>187</td>
</tr>
<tr>
<td>B.3 Operations on Numeric Types</td>
<td>188</td>
</tr>
<tr>
<td>B.3.1 Size Relationship/Provisos</td>
<td>188</td>
</tr>
<tr>
<td>B.3.2 Size Relationship Type Functions</td>
<td>189</td>
</tr>
<tr>
<td>B.3.3 valueOf and SizeOf pseudo-functions</td>
<td>189</td>
</tr>
<tr>
<td>B.4 Registers and Wires</td>
<td>190</td>
</tr>
<tr>
<td>B.4.1 Reg</td>
<td>190</td>
</tr>
<tr>
<td>B.4.2 CReg</td>
<td>192</td>
</tr>
<tr>
<td>B.4.3 RWire</td>
<td>195</td>
</tr>
<tr>
<td>B.4.4 Wire</td>
<td>196</td>
</tr>
<tr>
<td>B.4.5 BypassWire</td>
<td>198</td>
</tr>
<tr>
<td>B.4.6 DWire</td>
<td>198</td>
</tr>
<tr>
<td>B.4.7 PulseWire</td>
<td>199</td>
</tr>
<tr>
<td>B.4.8 ReadOnly</td>
<td>201</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
</tr>
<tr>
<td>---------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>B.4.9</td>
<td>WriteOnly</td>
</tr>
<tr>
<td>B.5</td>
<td>Miscellaneous Functions</td>
</tr>
<tr>
<td>B.5.1</td>
<td>Compile-time Messages</td>
</tr>
<tr>
<td>B.5.2</td>
<td>Arithmetic Functions</td>
</tr>
<tr>
<td>B.5.3</td>
<td>Operations on Functions</td>
</tr>
<tr>
<td>B.5.4</td>
<td>Bit Functions</td>
</tr>
<tr>
<td>B.5.5</td>
<td>Integer Functions</td>
</tr>
<tr>
<td>B.5.6</td>
<td>Control Flow Function</td>
</tr>
<tr>
<td>B.6</td>
<td>Environment Values</td>
</tr>
<tr>
<td>B.7</td>
<td>Compile-time IO</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>AzureIP Foundation Libraries</td>
<td>213</td>
</tr>
<tr>
<td>C.1</td>
<td>Storage Structures</td>
<td></td>
</tr>
<tr>
<td>C.1.1</td>
<td>Register File</td>
<td>213</td>
</tr>
<tr>
<td>C.1.2</td>
<td>ConfigReg</td>
<td>216</td>
</tr>
<tr>
<td>C.1.3</td>
<td>DReg</td>
<td>217</td>
</tr>
<tr>
<td>C.1.4</td>
<td>RevertingVirtualReg</td>
<td>218</td>
</tr>
<tr>
<td>C.1.5</td>
<td>BRAM</td>
<td>219</td>
</tr>
<tr>
<td>C.1.6</td>
<td>BRAMCore</td>
<td>226</td>
</tr>
<tr>
<td>C.2</td>
<td>FIFOs</td>
<td></td>
</tr>
<tr>
<td>C.2.1</td>
<td>FIFO Overview</td>
<td>231</td>
</tr>
<tr>
<td>C.2.2</td>
<td>FIFO and FIFOF packages</td>
<td>231</td>
</tr>
<tr>
<td>C.2.3</td>
<td>FIFOLevel</td>
<td>239</td>
</tr>
<tr>
<td>C.2.4</td>
<td>BRAMFIFO</td>
<td>246</td>
</tr>
<tr>
<td>C.2.5</td>
<td>SpecialFIFOs</td>
<td>248</td>
</tr>
<tr>
<td>C.2.6</td>
<td>AlignedFIFOs</td>
<td>250</td>
</tr>
<tr>
<td>C.2.7</td>
<td>Gearbox</td>
<td>254</td>
</tr>
<tr>
<td>C.2.8</td>
<td>MIMO</td>
<td>256</td>
</tr>
<tr>
<td>C.3</td>
<td>Aggregation: Vectors</td>
<td></td>
</tr>
<tr>
<td>C.3.1</td>
<td>Creating and Generating Vectors</td>
<td>258</td>
</tr>
<tr>
<td>C.3.2</td>
<td>Extracting Elements and Sub-Vectors</td>
<td>260</td>
</tr>
<tr>
<td>C.3.3</td>
<td>Vector to Vector Functions</td>
<td>262</td>
</tr>
<tr>
<td>C.3.4</td>
<td>Tests on Vectors</td>
<td>265</td>
</tr>
<tr>
<td>C.3.5</td>
<td>Bit-Vector Functions</td>
<td>268</td>
</tr>
<tr>
<td>C.3.6</td>
<td>Functions on Vectors of Registers</td>
<td>270</td>
</tr>
<tr>
<td>C.3.7</td>
<td>Combining Vectors with Zip</td>
<td>271</td>
</tr>
<tr>
<td>C.3.8</td>
<td>Mapping Functions over Vectors</td>
<td>272</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>C.3.9</td>
<td>ZipWith Functions</td>
<td>273</td>
</tr>
<tr>
<td>C.3.10</td>
<td>Fold Functions</td>
<td>274</td>
</tr>
<tr>
<td>C.3.11</td>
<td>Scan Functions</td>
<td>277</td>
</tr>
<tr>
<td>C.3.12</td>
<td>Monadic Operations</td>
<td>279</td>
</tr>
<tr>
<td>C.3.13</td>
<td>Converting to and from Vectors</td>
<td>282</td>
</tr>
<tr>
<td>C.3.14</td>
<td>ListN</td>
<td>283</td>
</tr>
<tr>
<td>C.4</td>
<td>Aggregation: Lists</td>
<td>283</td>
</tr>
<tr>
<td>C.4.1</td>
<td>Creating and Generating Lists</td>
<td>284</td>
</tr>
<tr>
<td>C.4.2</td>
<td>Extracting Elements and Sub-Lists</td>
<td>285</td>
</tr>
<tr>
<td>C.4.3</td>
<td>List to List Functions</td>
<td>289</td>
</tr>
<tr>
<td>C.4.4</td>
<td>Tests on Lists</td>
<td>291</td>
</tr>
<tr>
<td>C.4.5</td>
<td>Combining Lists with Zip Functions</td>
<td>293</td>
</tr>
<tr>
<td>C.4.6</td>
<td>Mapping Functions over Lists</td>
<td>294</td>
</tr>
<tr>
<td>C.4.7</td>
<td>ZipWith Functions</td>
<td>294</td>
</tr>
<tr>
<td>C.4.8</td>
<td>Fold Functions</td>
<td>295</td>
</tr>
<tr>
<td>C.4.9</td>
<td>Scan Functions</td>
<td>298</td>
</tr>
<tr>
<td>C.4.10</td>
<td>Monadic Operations</td>
<td>300</td>
</tr>
<tr>
<td>C.5</td>
<td>Math</td>
<td>301</td>
</tr>
<tr>
<td>C.5.1</td>
<td>Real</td>
<td>301</td>
</tr>
<tr>
<td>C.5.2</td>
<td>OInt</td>
<td>305</td>
</tr>
<tr>
<td>C.5.3</td>
<td>Complex</td>
<td>306</td>
</tr>
<tr>
<td>C.5.4</td>
<td>FixedPoint</td>
<td>309</td>
</tr>
<tr>
<td>C.5.5</td>
<td>NumberTypes</td>
<td>316</td>
</tr>
<tr>
<td>C.6</td>
<td>FSM</td>
<td>318</td>
</tr>
<tr>
<td>C.6.1</td>
<td>StmtFSM</td>
<td>318</td>
</tr>
<tr>
<td>C.7</td>
<td>Connectivity</td>
<td>328</td>
</tr>
<tr>
<td>C.7.1</td>
<td>GetPut</td>
<td>328</td>
</tr>
<tr>
<td>C.7.2</td>
<td>Connectable</td>
<td>334</td>
</tr>
<tr>
<td>C.7.3</td>
<td>ClientServer</td>
<td>335</td>
</tr>
<tr>
<td>C.7.4</td>
<td>Memory</td>
<td>337</td>
</tr>
<tr>
<td>C.7.5</td>
<td>CGetPut</td>
<td>339</td>
</tr>
<tr>
<td>C.7.6</td>
<td>CommitIfc</td>
<td>341</td>
</tr>
<tr>
<td>C.8</td>
<td>Utilities</td>
<td>345</td>
</tr>
<tr>
<td>C.8.1</td>
<td>LFSR</td>
<td>345</td>
</tr>
<tr>
<td>C.8.2</td>
<td>Randomizable</td>
<td>347</td>
</tr>
<tr>
<td>C.8.3</td>
<td>Arbiter</td>
<td>349</td>
</tr>
<tr>
<td>C.8.4</td>
<td>Cntrs</td>
<td>351</td>
</tr>
</tbody>
</table>
Packages provided as BSV source code  460

Typeclasses  461
1 Introduction

Bluespec SystemVerilog (BSV) is aimed at hardware designers who are using or expect to use Verilog [IEE05], VHDL [IEE02], SystemVerilog [IEE13], or SystemC [IEE12] to design ASICs or FPGAs. It is also aimed at people creating synthesizable models, transactors, and verification components to run on FPGA emulation platforms. BSV substantially extends the design subset of SystemVerilog, including SystemVerilog types, modules, module instantiation, interfaces, interface instantiation, parameterization, static elaboration, and “generate” elaboration. BSV can significantly improve the hardware designer’s productivity with some key innovations:

- It expresses synthesizable behavior with Rules instead of synchronous always blocks. Rules are powerful concepts for achieving correct concurrency and eliminating race conditions. Each rule can be viewed as a declarative assertion expressing a potential atomic state transition. Although rules are expressed in a modular fashion, a rule may span multiple modules, i.e., it can test and affect the state in multiple modules. Rules need not be disjoint, i.e., two rules can read and write common state elements. The BSV compiler produces efficient RTL code that manages all the potential interactions between rules by inserting appropriate arbitration and scheduling logic, logic that would otherwise have to be designed and coded manually. The atomicity of rules gives a scalable way to avoid unwanted concurrency (races) in large designs.

- It enables more powerful generate-like elaboration. This is made possible because in BSV, actions, rules, modules, interfaces and functions are all first-class objects. BSV also has more general type parameterization (polymorphism). These enable the designer to “compute with design fragments,” i.e., to reuse designs and to glue them together in much more flexible ways. This leads to much greater succinctness and correctness.

- It provides formal semantics, enabling formal verification and formal design-by-refinement. BSV rules are based on Term Rewriting Systems, a clean formalism supported by decades of theoretical research in the computer science community [Ter03]. This, together with a judicious choice of a design subset of SystemVerilog, makes programs in BSV amenable to formal reasoning.

This manual is meant to be a stand-alone reference for BSV, i.e., it fully describes the subset of Verilog and SystemVerilog used in BSV. It is not intended to be a tutorial for the beginner. A reader with a working knowledge of Verilog 1995 or Verilog 2001 should be able to read this manual easily. Prior knowledge of SystemVerilog is not required.

1.1 Meta notation

The grammar in this document is given using an extended BNF (Backus-Naur Form). Grammar alternatives are separated by a vertical bar (“|”). Items enclosed in square brackets (“[ ]”) are optional. Items enclosed in curly braces (“{ }”) can be repeated zero or more times.

Another BNF extension is parameterization. For example, a moduleStmt can be a moduleIf, and an actionStmt can be an actionIf. A moduleIf and an actionIf are almost identical; the only difference is that the former can contain (recursively) moduleStmts whereas the latter can contain actionStmts. Instead of tediously repeating the grammar for moduleIf and actionIf, we parameterize it by giving a single grammar for <ctxt> If, where <ctxt> is either module or action. In the productions for <ctxt> If, we call for <ctxt> Stmt which, therefore, either represents a moduleStmt or an actionStmt, depending on the context in which it is used.
2 Lexical elements

BSV has the same basic lexical elements as Verilog.

2.1 Whitespace and comments

Spaces, tabs, newlines, formfeeds, and carriage returns all constitute whitespace. They may be used freely between all lexical tokens.

A comment is treated as whitespace (it can only occur between, and never within, any lexical token). A one-line comment starts with // and ends with a newline. A block comment begins with /* and ends with */ and may span any number of lines.

Comments do not nest. In a one-line comment, the character sequences //, /* and */ have no special significance. In a block comment, the character sequences // and /* have no special significance.

2.2 Identifiers and keywords

An identifier in BSV consists of any sequence of letters, digits, dollar signs $ and underscore characters (_). Identifiers are case-sensitive: glurph, GluRph and Glurph are three distinct identifiers. The first character cannot be a digit.

BSV currently requires a certain capitalization convention for the first letter in an identifier. Identifiers used for package names, type names, enumeration labels, union members and type classes must begin with a capital letter. In the syntax, we use the non-terminal Identifier to refer to these. Other identifiers (including names of variables, modules, interfaces, etc.) must begin with a lowercase letter and, in the syntax, we use the non-terminal identifier to refer to these.

As in Verilog, identifiers whose first character is $ are reserved for so-called system tasks and functions (see Section 12.8).

If the first character of an instance name is an underscore, (_), the compiler will not generate this instance in the Verilog hierarchy name. This can be useful for removing submodules from the hierarchical naming.

There are a number of keywords that are essentially reserved identifiers, i.e., they cannot be used by the programmer as identifiers. Keywords generally do not use uppercase letters (the only exception is the keyword valueOf). BSV includes all keywords in SystemVerilog. All keywords are listed in Appendix A.

The types Action and ActionValue are special, and cannot be redefined.

2.3 Integer literals

Integer literals are written with the usual Verilog and C notations:

\[
\begin{align*}
\text{intLiteral} &::= \ '0 '1 \\
&\quad| \text{sizedIntLiteral} \\
&\quad| \text{unsizedIntLiteral} \\
\text{sizedIntLiteral} &::= \text{bitWidth baseLiteral} \\
\text{unsizedIntLiteral} &::= [ \text{sign} ] \text{baseLiteral} \\
&\quad| [ \text{sign} ] \text{decNum} \\
\text{baseLiteral} &::= ( \text{'d} \text{'D} ) \text{decDigitsUnderscore} \\
&\quad| ( \text{'h} \text{'H} ) \text{hexDigitsUnderscore}
\end{align*}
\]
| (’o | ’0) octDigitsUnderscore  |
| (’b | ’B) binDigitsUnderscore  |

\[ \text{decNum} ::= \text{decDigits} \ [\text{decDigitsUnderscore}] \]

\[ \text{bitWidth} ::= \text{decDigits} \]

\[ \text{sign} ::= + | - \]

\[ \text{decDigits} ::= \{ 0...9 \} \]

\[ \text{decDigitsUnderscore} ::= \{ 0...9, _ \} \]

\[ \text{hexDigitsUnderscore} ::= \{ 0...9, a...f, A...F, _ \} \]

\[ \text{octDigitsUnderscore} ::= \{ 0...7, _ \} \]

\[ \text{binDigitsUnderscore} ::= \{ 0,1, _ \} \]

An integer literal is a sized integer literal if a specific `bitWidth` is given (e.g., `8’o255`). There is no leading `sign` (+ or -) in the syntax for sized integer literals; instead we provide unary prefix + or - operators that can be used in front of any integer expression, including literals (see Section 9). An optional sign (+ or -) is part of the syntax for unsized literals so that it is possible to construct negative constants whose negation is not in the range of the type being constructed (e.g. `Int#(4)` x = -8; since 8 is not a valid `Int#(4)`, but -8 is).

Examples:

125
-16
’h48454a
32’h48454a
8’o255
12’b101010
32’h_FF_FF_FF_FF

2.3.1 Type conversion of integer literals

Integer literals can be used to specify values for various integer types and even for user-defined types. BSV uses its systematic overloading resolution mechanism to perform these type conversions. Overloading resolution is described in more detail in Section 14.1.

An integer literal is a sized literal if a specific `bitWidth` is given (e.g., `8’o255`), in which case the literal is assumed to have type `bit [w-1:0]`. The compiler implicitly applies the function `fromSizedInteger` to the literal to convert it to the type required by the context. Thus, sized literals can be used for any type on which the overloaded function `fromSizedInteger` is defined, i.e., for the types `Bit`, `UInt` and `Int`. The function `fromSizedInteger` is part of the `SizedLiteral` typeclass, defined in Section B.1.5.

If the literal is an unsized integer literal (a specific `bitWidth` is not given), the literal is assumed to have type `Integer`. The compiler implicitly applies the overloaded function `fromInteger` to the literal to convert it to the type required by the context. Thus, unsized literals can be used for any type on which the overloaded function `fromInteger` is defined. The function `fromInteger` is part of the `Literal` typeclass, defined in Section B.1.3.

The literal ’0 just stands for 0. The literal ’1 stands for a value in which all bits are 1 (the width depends on the context).
2.4 Real literals

Real number literals are written with the usual Verilog notation:

```
realLiteral ::= decNum [. decDigitsUnderscore | exp [ sign ] decDigitsUnderscore |
               decNum . decDigitsUnderscore

sign ::= + | -
exp ::= e | E
decNum ::= decDigits [ decDigitsUnderscore ]
decDigits ::= { 0...9 }
decDigitsUnderscore ::= { 0...9, _ }
```

There is no leading sign (+ or -) in the syntax for real literals. Instead, we provide the unary prefix `+` and `-` operators that can be used in front of any expression, including real literals (Section 9).

If the real literal contains a decimal point, there must be digits following the decimal point. An exponent can start with either an `E` or an `e`, followed by an optional sign (+ or -), followed by digits. There cannot be an exponent or a sign without any digits. Any of the numeric components may include an underscore, but an underscore cannot be the first digit of the real literal.

Unlike integer literals, real literals are of limited precision. They are represented as IEEE floating point numbers of 64 bit length, as defined by the IEEE standard.

Examples:

```
1.2
0.6
2.4E10 // exponent can be e or E
5e-3
325.761_452_e-10 // underscores are ignored
9.2e+4
```

2.4.1 Type conversion of real literals

Real literals can be used to specify values for real types. By default, real literals are assumed to have the type `Real`. BSV uses its systematic overloading resolution mechanism to perform these type conversions. Overloading resolution is described in more detail in Section 14.1. There are additional functions defined for `Real` types, provided in the `Real` package (Section C.5.1).

The function `fromReal` (Section B.1.4) converts a value of type `Real` into a value of another datatype. Whenever you write a real literal in BSV (such as 3.14), there is an implied `fromReal` applied to it, which turns the real into the specified type. By defining an instance of `RealLiteral` for a datatype, you can create values of that type from real literals.

The type `FixedPoint`, defined in the `FixedPoint` package, defines a type for representing fixed point numbers. The `FixedPoint` type has an instance of `RealLiteral` defined for it and contains functions for operating on fixed-point real numbers.

2.5 String literals

String literals are written enclosed in double quotes "..." and must be contained on a single source line.

```
stringLiteral ::= " ... string characters ... ">
```

Special characters may be inserted in string literals with the following backslash escape sequences:
\n newline
\t tab
\\ backslash
\" double quote
\v vertical tab
\f form feed
\a bell
\OOO exactly 3 octal digits (8-bit character code)
\xHH exactly 2 hexadecimal digits (8-bit character code)

Example - printing characters using form feed.

```verilog
module mkPrinter (Empty);
  String display_value;

  display_value = "a\nb\nc"; //prints a
      // b
      // c repeatedly

  rule every;
    $display(display_value);
  endrule
endmodule
```

### 2.5.1 Type conversion of string literals

String literals are used to specify values for string types. BSV uses its systematic overloading resolution mechanism to perform these type conversions. Overloading resolution is described in more detail in Section 14.1.

Whenever you write a string literal in BSV there is an implicit `fromString` applied to it, which defaults to type `String`.

### 2.6 Don’t-care values

A lone question mark `?` is treated as a special don’t-care value. For example, one may return `?` from an arm of a case statement that is known to be unreachable.

Example - Using `?` as a don’t-care value

```verilog
module mkExample (Empty);
  Reg#(Bit#(8)) r <- mkReg(?); // don’t-care is used for the
  rule every; // reset value of the Reg
    $display("value is %h", r); // the value of r is displayed
  endrule
endmodule
```

### 2.7 Compiler directives

The following compiler directives permit file inclusion, macro definition and substitution, and conditional compilation. They follow the specifications given in the Verilog 2001 LRM plus the extensions given in the SystemVerilog 3.1a LRM.

In general, these compiler directives can appear anywhere in the source text. In particular, they do not need to be on lines by themselves, and they need not begin in the first column. Of course, they should not be inside strings or comments, where the text remains uninterpreted.
2.7.1 File inclusion: ‘include and ‘line

\[
\text{compilerDirective ::= ‘include "filename"}
| ‘include <filename>
| ‘include macroInvocation
\]

In an ‘include directive, the contents of the named file are inserted in place of this line. The included files may themselves contain compiler directives. Currently there is no difference between the "..." and <...> forms. A macroInvocation should expand to one of the other two forms. The file name may be absolute, or relative to the current directory.

\[
\text{compilerDirective ::= ‘line lineNumber "filename" level}
\]

\[
\text{lineNumber ::= decLiteral}
\]

\[
\text{level ::= 0 | 1 | 2}
\]

A ‘line directive is terminated by a newline, i.e., it cannot have any other source text after the level. The compiler automatically keeps track of the source file name and line number for every line of source text (including from included source files), so that error messages can be properly correlated to the source. This directive effectively overrides the compiler’s internal tracking mechanism, forcing it to regard the next line onwards as coming from the given source file and line number. It is generally not necessary to use this directive explicitly; it is mainly intended to be generated by other preprocessors that may themselves need to alter the source files before passing them through the BSV compiler; this mechanism allows proper references to the original source.

The level specifier is either 0, 1 or 2:

- 1 indicates that an include file has just been entered
- 2 indicates that an include file has just been exited
- 0 is used in all other cases

2.7.2 Macro definition and substitution: ‘define and related directives

\[
\text{compilerDirective ::= ‘define macroName | ( macroFormals ) | macroText}
\]

\[
\text{macroName ::= identifier}
\]

\[
\text{macroFormals ::= identifier , identifier}
\]

The ‘define directive is terminated by a bare newline. A backslash (\) just before a newline continues the directive into the next line. When the macro text is substituted, each such continuation backslash-newline is replaced by a newline.

The macroName is an identifier and may be followed by formal arguments, which are a list of comma-separated identifiers in parentheses. For both the macro name and the formals, lower and upper case are acceptable (but case is distinguished). The macroName cannot be any of the compiler directives (such as include, define, ...).

The scope of the formal arguments extends to the end of the macroText.

The macroText represents almost arbitrary text that is to be substituted in place of invocations of this macro. The macroText can be empty.

One-line comments (i.e., beginning with //) may appear in the macroText; these are not considered part of the substitutable text and are removed during substitution. A one-line comment that is not on the last line of a ‘define directive is terminated by a backslash-newline instead of a newline.

A block comment (/\*...*/\) is removed during substitution and replaced by a single space.

The macroText can also contain the following special escape sequences:
• " Indicates that a double-quote (") should be placed in the expanded text.
• " Indicates that a backslash and a double-quote (\") should be placed in the expanded text.
• " Indicates that there should be no whitespace between the preceding and following text. This allows construction of identifiers from the macro arguments.

A minimal amount of lexical analysis of macroText is done to identify comments, string literals, identifiers representing macro formals, and macro invocations. As described earlier, one-line comments are removed. The text inside string literals is not interpreted except for the usual string escape sequences described in Section 2.5.

There are two define macros in the define environment initially: ‘bluespec’ and ‘BLUESPEC’.

Once defined, a macro can be invoked anywhere in the source text (including within other macro definitions) using the following syntax.

```
compilerDirective ::= macroInvocation

macroInvocation ::= ‘macroName’ [ ( macroActuals ) ]

macroActuals ::= substText { , substText }
```

The macroName must refer to a macro definition available at expansion time. The macroActuals, if present, consist of substitution text substText that is arbitrary text, possibly spread over multiple lines, excluding commas. A minimal amount of parsing of this substitution text is done, so that commas that are not at the top level are not interpreted as the commas separating macroActuals. Examples of such “inner” uninterpreted commas are those within strings and within comments.

```
compilerDirective ::= ‘undef macroName
| ‘resetall
```

The ‘undef directive’s effect is that the specified macro (with or without formal arguments) is no longer defined for the subsequent source text. Of course, it can be defined again with ‘define in the subsequent text. The ‘resetall directive has the effect of undefining all currently defined macros, i.e., there are no macros defined in the subsequent source text.

### 2.7.3 Conditional compilation: ‘ifdef and related directives

```
compilerDirective ::= ‘ifdef macroName
| ‘ifndef macroName
| ‘elsif macroName
| ‘else
| ‘endif
```

These directives are used together in either an ‘ifdef-endif sequence or an ifndef-endif sequence. In either case, the sequence can contain zero or more elseif directives followed by zero or one else directives. These sequences can be nested, i.e., each ‘ifdef or ifndef introduces a new, nested sequence until a corresponding endif.

In an ‘ifdef sequence, if the macroName is currently defined, the subsequent text is processed until the next corresponding elseif, else or endif. All text from that next corresponding elseif or else is ignored until the endif.

If the macroName is currently not defined, the subsequent text is ignored until the next corresponding ‘elseif, ‘else or ‘endif. If the next corresponding directive is an ‘elseif, it is treated just as if it were an ‘ifdef at that point.

If the ‘ifdef and all its corresponding ‘elsifs fail (macros were not defined), and there is an ‘else present, then the text between the ‘else and ‘endif is processed.
An ‘ifndef sequence is just like an ‘ifdef sequence, except that the sense of the first test is inverted, i.e., its following text is processes if the macroName is not defined, and its ‘elsif and ‘else arms are considered only if the macro is defined.

Example using ‘ifdef to determine the size of a register:

```verilog
ifdef USE_16_BITS
    Reg#(Bit#(16)) a_reg <- mkReg(0);
else
    Reg#(Bit#(8)) a_reg <- mkReg(0);
endif
```

3 Packages and the outermost structure of a BSV design

A BSV program consists of one or more outermost constructs called packages. All BSV code is assumed to be inside a package. Further, the BSV compiler and other tools assume that there is one package per file, and they use the package name to derive the file name. For example, a package called Foo is assumed to be located in a file Foo.bsv.

A BSV package is purely a linguistic namespace-management mechanism and is particularly useful for programming in the large, so that the author of a package can choose identifiers for the package components freely without worrying about choices made by authors of other packages. Package structure is usually uncorrelated with hardware structure, which is specified by the module construct.

A package contains a collection of top-level statements that include specifications of what it imports from other packages, what it exports to other packages, and its definitions of types, interfaces, functions, variables, and modules. BSV tools ensure that when a package is compiled, all the packages that it imports have already been compiled.

```
package ::= package packageIde ;
    { exportDecl }
    { importDecl }
    { packageStmt }
endpackage [ : packageIde ]

exportDecl ::= export exportItem ;

exportItem ::= identifier [(..)]
             | Identifier [(..)]
             | packageIde :: *

importDecl ::= import importItem ;

importItem ::= packageIde :: *

packageStmt ::= moduleDef
               | interfaceDecl
               | typedef
               | varDecl | varAssign
               | functionDef
               | typeclassDef
               | typeclassInstanceDef
               | externModuleImport

packageIde ::= Identifier
```

The name of the package is the identifier following the package keyword. This name can optionally be repeated after the endpackage keyword (and a colon). We recommend using an uppercase first letter in package names. In fact, the package and endpackage lines are optional: if they are absent, BSV derives the assumed package name from the filename.
An export item can specify an identifier defined elsewhere within the package, making the identifier accessible outside the package. An export item can also specify an identifier from an imported package. In that case, the imported identifier is re-exported from this package, so that it is accessible by importing this package (without requiring the import of its source package). It is also possible to re-export all of the identifiers from an imported package by using the following syntax: `export packageId::*`. If there are any export statements in a package, then only those items are exported. If there are no export statements, by default all identifiers defined in this package (and no identifiers from any imported packages) are exported.

If the exported identifier is the name of a struct (structure) or union type definition, then the members of that type will be visible only if `(..)` is used. By omitting the `(..)` suffix, only the type, but not its members, are visible outside the package. This is a way to define abstract data types, i.e., types whose internal structure is hidden. When the exported identifier is not a structure or union type definition, the `(..)` has no effect on the exported identifier.

Each import item specifies a package from which to import identifiers, i.e., to make them visible locally within this package. For each imported package, all identifiers exported from that package are made locally visible.

Example:

```verbatim
package Foo;
export x;
export y;

import Bar::*;

... top level definition ...
... top level definition ...
... top level definition ...
endpackage: Foo
```

Here, `Foo` is the name of this package. The identifiers `x` and `y`, which must be defined by the top-level definitions in this package are names exported from this package. From package `Bar` we import all its definitions. To export all identifiers from packages `Foo` and `Bar`, add the statement: `export Foo::*`

### 3.1 Scopes, name clashes and qualified identifiers

BSV uses standard static scoping (also known as lexical scoping). Many constructs introduce new scopes nested inside their surrounding scopes. Identifiers can be declared inside nested scopes. Any use of an identifier refers to its declaration in the nearest textually surrounding scope. Thus, an identifier `x` declared in a nested scope "shadows", or hides, any declaration of `x` in surrounding scopes. We recommend, however, that the programmer avoids such shadowing, because it often makes code more difficult to read.

Packages form the outermost scopes. Examples of nested scopes include modules, interfaces, functions, methods, rules, action and actionvalue blocks, begin-end statements and expressions, bodies of for and while loops, and seq and par blocks.

When used in any scope, an identifier must have an unambiguous meaning. If there is name clash for an identifier `x` because it is defined in the current package and/or it is available from one or more imported packages, then the ambiguity can be resolved by using a qualified name of the form `P::* x` to refer to the version of `x` contained in package `P`. 
3.2 The Standard Prelude package

The Standard Prelude is a predefined package that is imported implicitly into every BSV package, i.e., it does not need an explicit `import` statement. It contains a number of useful predefined entities (types, values, functions, modules, etc.). The Standard Prelude package is described in more detail in appendix B. Reusing the name of Prelude entity when defining other entities, which would require the entity’s name to be qualified with the package name, is strongly discouraged.

3.3 AzureIP™ Foundation Libraries

Section C describes the collection of AzureIP Foundation library packages. To use any of the constructs or components of these packages you must explicitly import the library package using an `import` clause. Many common constructs, such as FIFOs and Vectors are provided in the library.

4 Types

Bluespec provides a strong, static type-checking environment; every variable and every expression in BSV has a type. Variables must be assigned values which have compatible types. Type checking, which occurs before program elaboration or execution, ensures that object types are compatible and applied functions are valid for the context and type.

Data types in BSV are case sensitive. The first character of a type is almost always uppercase, the only exceptions being the types `int` and `bit` for compatibility with Verilog.

The syntax of types (type expressions) is given below:

```
type ::= typePrimary  
      | typePrimary ( type { , type } )  

function type

typePrimary ::= typeIde [ # ( type { , type } ) ]
      | typeNat
      | bit [ typeNat : typeNat ]

typeIde ::= Identifier

typeNat ::= decDigits
```

The Prelude package defines many common datatypes (Section B.2). Other types are defined in the Foundation library packages (Section C) and users can define new types (Section 7). The following tables list some of the more commonly used types. Refer to the Prelude and Foundation library packages for additional types.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit#(n)</td>
<td>Polymorphic data type containing n bits</td>
<td>B.2.1</td>
</tr>
<tr>
<td>UInt#(n)</td>
<td>Unsigned fixed-width representation of an integer value of n bits</td>
<td>B.2.2</td>
</tr>
<tr>
<td>Int#(n)</td>
<td>Signed fixed-width representation of an integer value of n bits</td>
<td>B.2.3</td>
</tr>
<tr>
<td>Bool</td>
<td>Type which can have two values, True or False</td>
<td>B.2.5</td>
</tr>
<tr>
<td>Maybe</td>
<td>Used to tag values as Valid or Invalid, where valid values contain data</td>
<td>B.2.11</td>
</tr>
<tr>
<td>Tuples</td>
<td>Predefined structures which group a small number of values together</td>
<td>B.2.12</td>
</tr>
</tbody>
</table>
### Common Non-Bit Types Defined in Prelude(B.2)

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integer</td>
<td>Non-synthesizable data type used for integer values and functions</td>
<td>B.2.4</td>
</tr>
<tr>
<td>Real</td>
<td>Non-synthesizable data type which can represent numbers with a fractional component</td>
<td>B.2.6, C.5.1</td>
</tr>
<tr>
<td>String, Char</td>
<td>Data type representing string literals</td>
<td>B.2.7</td>
</tr>
<tr>
<td>Fmt</td>
<td>Representation of arguments to the $display family of tasks</td>
<td>B.2.9</td>
</tr>
</tbody>
</table>

### Common Interface Types Defined in Prelude and Foundation Library Packages

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reg</td>
<td>Register interface</td>
<td>B.4.1</td>
</tr>
<tr>
<td>FIFO</td>
<td>FIFO interfaces</td>
<td>C.2.2</td>
</tr>
<tr>
<td>Clock</td>
<td>Abstract type with a oscillator and a gate</td>
<td>B.2.16, C.9</td>
</tr>
<tr>
<td>Reset</td>
<td>Abstract type for a reset</td>
<td>B.2.17, C.9</td>
</tr>
<tr>
<td>Inout</td>
<td>Type used to pass Verilog inouts through a BSV module</td>
<td>B.2.18</td>
</tr>
</tbody>
</table>

### Types Used by the Compiler

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action</td>
<td>An expression intended to act on the state of the circuit</td>
<td>B.2.19</td>
</tr>
<tr>
<td>ActionValue</td>
<td>An expression intended to act on the state of the circuit</td>
<td>B.2.19</td>
</tr>
<tr>
<td>Rules</td>
<td>Used to represent one or more rules as a first class type</td>
<td>B.2.20</td>
</tr>
</tbody>
</table>

Examples of simple types:

- `Integer` // Unbounded signed integers, for static elaboration only
- `int` // 32-bit signed integers
- `Bool`
- `String`
- `Action`

Type expressions of the form \(X\#(t_1, \ldots, t_N)\) are called *parameterized* types. \(X\) is called a *type constructor* and the types \(t_1, \ldots, t_N\) are the parameters of \(X\). Examples:

- `Tuple2#(int,Bool)` // pair of items, an int and a Bool
- `Tuple3#(int,Bool,String)` // triple of items, an int, a Bool and a String
- `List#(Bool)` // list containing booleans
- `List#(List#(Bool))` // list containing lists of booleans
- `RegFile#(Integer, String)` // a register file (array) indexed by integers, containing strings

Type parameters can be natural numbers (also known as *numeric* types). These usually indicate some aspect of the size of the type, such as a bit-width or a table capacity. Examples:

- `Bit#(16)` // 16-bit wide bit-vector (16 is a numeric type)
- `bit [15:0]` // synonym for `Bit#(16)`
- `UInt#(32)` // unsigned integers, 32 bits wide
- `Int#(29)` // signed integers, 29 bits wide
- `Vector#(16,Int#(29))` // Vector of size 16 containing Int#(29)’s
Currently the second index \( n \) in a \( \text{bit}[m:n] \) type must be 0. The type \( \text{bit}[m:0] \) represents the type of bit vectors, with bits indexed from \( m \) (msb/left) down through 0 (lsb/right), for \( m \geq 0 \).

### 4.1 Polymorphism

A type can be *polymorphic*. This is indicated by using type variables as parameters. Examples:

\[
\begin{align*}
\text{List#}(a) & \quad // \text{lists containing items of some type } a \\
\text{List#}(\text{List#}(b)) & \quad // \text{lists containing lists of items of some type } b \\
\text{RegFile#}(i, \text{List#}(x)) & \quad // \text{arrays indexed by some type } i, \text{ containing} \\
& \quad // \quad \text{lists that contain items of some type } x
\end{align*}
\]

The type variables represent unknown (but specific) types. In other words, \( \text{List#}(a) \) represents the type of a list containing items all of which have some type \( a \). It does not mean that different elements of a list can have different types.

### 4.2 Provisos (brief intro)

Provisos are described in detail in Section 14.1.1, and the general facility of type classes (overloading groups), of which provisos form a part, is described in Section 14.1. Here we provide a brief description, which is adequate for most uses and for continuity in a serial reading of this manual.

A proviso is a static condition attached to certain constructs, to impose certain restrictions on the types involved in the construct. The restrictions are of two kinds:

- Require instance of a type class (overloading group): this kind of proviso states that certain types must be instances of certain type classes, i.e., that certain overloaded functions are defined on this type.
- Require size relationships: this kind of proviso expresses certain constraints between the sizes of certain types.

The most common overloading provisos are:

\[
\begin{align*}
\text{Bits#}(t,n) & \quad // \text{Type class (overloading group) Bits} \\
& \quad // \text{Meaning: overloaded operators pack/unpack are defined} \\
& \quad // \quad \text{on type } t \text{ to convert to/from Bit#}(n) \\
\text{Eq#}(t) & \quad // \text{Type class (overloading group) Eq} \\
& \quad // \text{Meaning: overloaded operators } == \text{ and } != \text{ are defined on type } t \\
\text{Literal#}(t) & \quad // \text{Type class (overloading group) Literal} \\
& \quad // \text{Meaning: Overloaded function } \text{fromInteger()} \text{ defined on type } t \\
& \quad // \quad \text{to convert an integer literal to type } t \text{. Also overloaded} \\
& \quad // \quad \text{function } \text{inLiteralRange} \text{ to determine if an Integer} \\
& \quad // \quad \text{is in the range of the target type } t. \\
\text{Ord#}(t) & \quad // \text{Type class (overloading group) Ord} \\
& \quad // \text{Meaning: Overloaded order-comparison operators } <, <=, \\
& \quad // \quad > \text{ and } >= \text{ are defined on type } t \\
\text{Bounded#}(t) & \quad // \text{Type class (overloading group) Bounded} \\
& \quad // \text{Meaning: Overloaded identifiers } \text{minBound} \text{ and } \text{maxBound}
\end{align*}
\]
// are defined for type t
Bitwise#(t) // Type class (overloading group) Bitwise
// Meaning: Overloaded operators &, |, ^, ~^, ~^~, ^~, << and >>
// and overloaded function invert are defined on type t

BitReduction#(t) // Type class (overloading group) BitReduction
// Meaning: Overloaded prefix operators &, |, ^,
// ~&, ~|, ~^, and ^~ are defined on type t

BitExtend#(t) // Type class (overloading group) BitExtend
// Meaning: Overloaded functions extend, zeroExtend, signExtend
// and truncate are defined on type t

Arith#(t) // Type class (overloading group) Arith
// Meaning: Overloaded operators +, -, and *, and overloaded
// prefix operator - (same as function negate), and
// overloaded function negate are defined on type t

The size relationship provisos are:

Add#(n1,n2,n3) // Meaning: assert n1 + n2 = n3
Mul#(n1,n2,n3) // Meaning: assert n1 * n2 = n3
Div#(n1,n2,n3) // Meaning: assert ceiling n1 / n2 = n3
Max#(n1,n2,n3) // Meaning: assert max(n1,n2) = n3
Log#(n1,n2) // Meaning: assert ceiling(log(n1)) = n2
// The logarithm is base 2

Example:

module mkExample (ProvideCurrent#(a))
provisos(Bits#(a, sa), Arith#(a));

Reg#(a) value_reg <- mkReg(?); // requires that type "a" be in the Bits typeclass.
rule every;
    value_reg <= value_reg + 1; // requires that type "a" be in the Arith typeclass.
endrule

Example:

function Bit#(m) pad0101 (Bit#(n) x)
    provisos (Add#(n,4,m)); // m is 4 bits longer than n
    pad0101 = { x, 0b0101 }; // m is 4 bits longer than n
endfunction: pad0101

This defines a function pad0101 that takes a bit vector x and pads it to the right with the four bits “0101” using the standard bit-concatenation notation. The types and proviso express the idea that the function takes a bit vector of length n and returns a bit vector of length m, where n + 4 = m. These provisos permit the BSV compiler to statically verify that entities (values, variables, registers, memories, FIFOs, and so on) have the correct bit-width.
4.2.1 The pseudo-function valueof (or valueOf)

To get the value that corresponds to a size type, there is a special pseudo-function, valueof, that takes a size type and gives the corresponding Integer value. The pseudo-function is also sometimes written as valueOf; both are considered correct.

\[ \text{exprPrimary} \quad ::= \quad \text{valueOf} \ (\text{type}) \]

In other words, it converts from a numeric type expression into an ordinary value. These mechanisms can be used to do arithmetic to derive dependent sizes. Example:

```verilog
definition ... foo (Vector#(n, int) xs) provisos (Log#(n, k));
  Integer maxindex = valueof(n) - 1;
  Int#(k) index;
  index = fromInteger(maxindex);
  ...
endfunction
```

This function takes a vector of length \( n \) as an argument. The proviso fixes \( k \) to be the (ceiling of the) logarithm of \( n \). The variable \( \text{index} \) has bit-width \( k \), which will be adequate to hold an index into the list. The variable is initialized to the maximum index.

Note that the function \( \text{foo} \) may be invoked in multiple contexts, each with a different vector length. The compiler will statically verify that each use is correct (e.g., the index has the correct width).

The pseudo-function valueof, which converts a numeric type to a value, should not be confused with the pseudo-function SizeOf, described in Section 14.1.5, which converts a type to a numeric type.

4.3 A brief introduction to deriving clauses

The deriving clause is a part of the general facility of type classes (overloading groups), which is described in detail in Section 14.1. Here we provide a brief description, which is adequate for most uses and for continuity in a serial reading of this manual.

It is possible to attach a deriving clause to a type definition (Section 7), thereby directing the compiler to define automatically certain overloaded functions for that type. The most common forms of these clauses are:

- `deriving(Eq)` // Meaning: automatically define == and !=
  // for equality and inequality comparisons

- `deriving(Bits)` // Meaning: automatically define pack and unpack
  // for converting to/from bits

- `deriving(FShow)` // Meaning: automatically define fshow to convert
  // to a Fmt representation for $display functions

- `deriving(Bounded)` // Meaning: automatically define minBound and maxBound

Example:

```verilog
typedef enum {LOW, NORMAL, URGENT} Severity deriving(Eq, Bits);
// == and != are defined for variables of type Severity
```
Reference Guide

5 Modules and interfaces, and their instances

Modules and interfaces form the heart of BSV. Modules and interfaces turn into actual hardware. An interface for a module $m$ mediates between $m$ and other, external modules that use the facilities of $m$. We often refer to these other modules as clients of $m$.

In SystemVerilog and BSV we separate the declaration of an interface from module definitions. There was no such separation in Verilog 1995 and Verilog 2001, where a module’s interface was represented by its port list, which was part of the module definition itself. By separating the interface declaration, we can express the idea of a common interface that may be offered by several modules, without having to repeat that declaration in each of the implementation modules.

As in Verilog and SystemVerilog, it is important to distinguish between a module definition and a module instantiation. A module definition can be regarded as specifying a scheme that can be instantiated multiple times. For example, we may have a single module definition for a FIFO, and a particular design may instantiate it multiple times for all the FIFOs it contains.

Similarly, we also distinguish interface declarations and instances, i.e., a design will contain interface declarations, and each of these may have multiple instances. For example an interface declaration $I$ may have one instance $i_1$ for communication between module instances $a_1$ and $b_1$, and another instance $i_2$ for communication between module instances $a_2$ and $b_2$.

Module instances form a pure hierarchy. Inside a module definition $mkM$, one can specify instantiations of other modules. When $mkM$ is used to instantiate a module $m$, it creates the specified inner module instances. Thus, every module instance other than the top of the hierarchy unambiguously has a single parent module instance. We refer to the top of the hierarchy as the root module. Every module instance has a unique set, possibly empty, of child module instances. If there are no children, we refer to it as a leaf module.

A module consists of three things: state, rules that operate on that state, and the module’s interface to the outside world (surrounding hierarchy). The state conceptually consists of all state in the subhierarchy headed by this module; ultimately, it consists of all the lower leaf module instances (see next section on state and module instantiation). Rules are the fundamental means to express behavior in BSV (instead of the always blocks used in traditional Verilog). In BSV, an interface consists of methods that encapsulate the possible transactions that clients can perform, i.e., the micro-protocols with which clients interact with the module. When compiled into RTL, an interface becomes a collection of wires.

5.1 Explicit state via module instantiation, not variables

In Verilog and SystemVerilog RTL, one simply declares variables, and a synthesis tool “infers” how these variables actually map into state elements in hardware using, for example, their lifetimes
relative to events. A variable may map into a bus, a latch, a flip-flop, or even nothing at all. This ambiguity is acknowledged in the Verilog 2001 and SystemVerilog LRMs.\(^1\)

BSV removes this ambiguity and places control over state instantiation explicitly in the hands of the designer. From the smallest state elements (such as registers) to the largest (such as memories), all state instances are specified explicitly using module instantiation.

Conversely, an ordinary declared variable in BSV never implies state, i.e., it never holds a value over time. Ordinary declared variables are always just convenient names for intermediate values in a computation. Ordinary declared variables include variables declared in blocks, formal parameters, pattern variables, loop iterators, and so on. Another way to think about this is that ordinary variables play a role only in static elaboration, not in the dynamic semantics. This is one of the aspects of BSV style that may initially appear unusual to the Verilog or SystemVerilog programmer.

Example:

```verilog
class module mkExample (Empty);

// Hardware registers are created here
Reg#(Bit#(8)) value_reg <- mkReg(0);
FIFO#(Bit#(8)) fifo <- mkFIFO;

rule pop;
  let value = fifo.first(); // value is a ordinary declared variable
  value_reg <= fifo.first(); // value_reg is state variable
  fifo.deq();
endrule

eendmodule
```

### 5.2 Interface declaration

In BSV an interface contains members that are called methods (an interface may also contain subinterfaces, which are described in Section 5.2.1). To first order, a method can be regarded exactly like a function, i.e., it is a procedure that takes zero or more arguments and returns a result. Thus, method declarations inside interface declarations look just like function prototypes, the only difference being the use of the keyword method instead of the keyword function. Each method represents one kind of transaction between a module and its clients. When translated into RTL, each method becomes a bundle of wires.

The fundamental difference between a method and a function is that a method also carries with it a so-called implicit condition. These will be described later along with method definitions and rules.

An interface declaration also looks similar to a struct declaration. One can think of an interface declaration as declaring a new type similar to a struct type (Section 7), where the members all happen to be method prototypes. A method prototype is essentially the header of a method definition (Section 5.5).

```verilog
interfaceDecl ::= [ attributeInstances ]
  interface typeDefType ;
  { interfaceMemberDecl }
endinterface [ : typeIde ]
```

\(^1\)In the Verilog 2001 LRM, Section 3.2.2, Variable declarations, says: “A variable is an abstraction of a data storage element. ... NOTE In previous versions of the Verilog standard, the term register was used to encompass both the reg, integer, time, real and realtime types; but that term is no longer used as a Verilog data type.”

In the SystemVerilog LRM, Section 5.1 says: “Since the keyword reg no longer describes the user’s intent in many cases, SystemVerilog 2001 has already deprecated the use of the term register in favor of variable.”
Example: a stack of integers:

```haskell
interface IntStack;
    method Action push (int x);
    method Action pop;
    method int top;
endinterface: IntStack
```

This describes an interface to a circuit that implements a stack (LIFO) of integers. The `push` method takes an `int` argument, the item to be pushed onto the stack. Its output type is `Action`, namely it returns an `enable` wire which, when asserted, will carry out the pushing action.\(^2\) The `pop` method takes no arguments, and simply returns an `enable` wire which, when asserted, will discard the element from the top of the stack. The `top` method takes no arguments, and returns a value of type `int`, i.e., the element at the top of the stack.

What if the stack is empty? In that state, it should be illegal to use the `pop` and `top` methods. This is exactly where the difference between methods and functions arises. Each method has an implicit `ready` wire, which governs when it is legal to use it, and these wires for the `pop` and `top` methods will presumably be de-asserted if the stack is empty. Exactly how this is accomplished is an internal detail of the module, and is therefore not visible as part of the interface declaration. (We can similarly discuss the case where the stack has a fixed, finite depth; in this situation, it should be illegal to use the `push` method when the stack is full.)

One of the major advantages of BSV is that the compiler automatically generates all the control circuitry needed to ensure that a method (transaction) is only used when it is legal to use it.

Interface types can be polymorphic, i.e., parameterized by other types. For example, the following declaration describes an interface for a stack containing an arbitrary but fixed type:

```haskell
interface Stack#(type a);
    method Action push (a x);
    method Action pop;
    method a top;
endinterface: Stack
```

We have replaced the previous specific type `int` with a type variable `a`. By “arbitrary but fixed” we mean that a particular stack will specify a particular type for `a`, and all items in that stack will have that type. It does not mean that a particular stack can contain items of different types.

For example, using this more general definition, we can also define the `IntStack` type as follows:

```haskell
typedef Stack#(int) IntStack;
```

\(^2\) The type `Action` is discussed in more detail in Section 9.6.
i.e., we simply specialize the more general type with the particular type int. All items in a stack of this type will have the int type.

Usually there is information within the interface declaration which indicates whether a polymorphic interface type is numeric or nonnumeric. The optional numeric is required before the type when the interface type is polymorphic and must be numeric but there is no information in the interface declaration which would indicate that the type is numeric.

For example, in the following polymorphic interface, count_size must be numeric because it is defined as a parameter to Bit#().

```verilog
interface Counter#(type count_size);
    method Action increment();
    method Bit#(count_size) read();
endinterface
```

From this use, it can be deduced that Counter’s parameter count_size must be numeric. However, sometimes you might want to encode a size in an interface type which isn’t visible in the methods, but is used by the module implementing the interface. For instance:

```verilog
interface SizedBuffer#(numeric type buffer_size, type element_type);
    method Action enq(element_type e);
    method ActionValue#(element_type) deq();
endinterface
```

In this interface, the depth of the buffer is encoded in the type. For instance, `SizedBuffer#(8, Bool)` would be a buffer of depth 8 with elements of type Bool. The depth is not visible in the interface, but is used by the module to know how much storage to instantiate.

Because the parameter is not mentioned anywhere else in the interface, there is no information to determine whether the parameter is a numeric type or a non-numeric type. In this situation, the default is to assume that the parameter is non-numeric. The user can override this default by specifying numeric in the interface declaration.

The Standard Prelude defines a standard interface called Empty which contains no methods, i.e., its definition is:

```verilog
interface Empty;
endinterface
```

This is often used for top-level modules that integrate a testbench and a design-under-test, and for modules like mkConnection(C.7.2) that just take interface arguments and do not themselves offer any interesting interface.

### 5.2.1 Subinterfaces

Note: this is an advanced topic that may be skipped on first reading.

Interfaces can also be declared hierarchically, using subinterfaces.

```verilog
subinterfaceDecl ::= [ attributeInstances ]
    interface typeDefType;
```

where typeDefType is another interface type available in the current scope. Example:
interface ILookup;
  interface Server#( RequestType, ResponseType ) mif;
  interface RAMclient#( AddrType, DataType ) ram;
  method Bool initialized;
endinterface: ILookup

This declares an interface ILookup module that consists of three members: a Server subinterface called mif, a RAMClient subinterface called ram, and a boolean method called initialized (the Server and RAMClient interface types are defined in the libraries, see Appendix C). Methods of subinterfaces are accessed using dot notation to select the desired component, e.g.,

  ilookup.mif.request.put(...);

Since Clock and Reset are both interface types, they can be used in interface declarations. Example:

interface ClockTickIfc;
  method Action tick();
  interface Clock new_clk;
endinterface

5.3 Module definition

A module definition begins with a module header containing the module keyword, the module name, parameters, arguments, interface type and provisos. The header is followed by zero or more module statements. Finally we have the closing endmodule keyword, optionally labelled again with the module name.

\[
\text{moduleDef} ::= [ \text{attributeInstances} ]
\text{moduleProto} \\
\{ \text{moduleStmt} \} \\
\text{endmodule} | : \text{identifier} |
\]

\[
\text{moduleProto} ::= \text{module} [ [ \text{type} ] \text{identifier} ]
\{ [ \text{moduleFormalParams} ] ( [ \text{moduleFormalArgs} ] ) [ \text{provisos} ];
\]

\[
\text{moduleFormalParams} ::= \# ( \text{moduleFormalParam} \{ , \text{moduleFormalParam} \})
\]

\[
\text{moduleFormalParam} ::= [ \text{attributeInstances} ] [ \text{parameter} ] \text{type} \text{identifier}
\]

\[
\text{moduleFormalArgs} ::= [ \text{attributeInstances} ] \text{type}
\{ [ \text{attributeInstances} ] \text{type} \text{identifier}
\}
\]

As a stylistic convention, many BSV examples use module names like mkFoo, i.e., beginning with the letters mk, suggesting the word make. This serves as a reminder that a module definition is not a module instance. When the module is instantiated, one invokes mkFoo to actually create a module instance.

The optional moduleFormalParams are exactly as in Verilog and SystemVerilog, i.e., they represent module parameters that must be supplied at each instantiation of this module, and are resolved at elaboration time. The optional keyword parameter specifies a Verilog parameter is to be generated; without the keyword a Verilog port is generated. A Verilog parameter requires that the value is a constant at elaboration. When the module is instantiated, the actual expression provided for the parameter must be something that can be computed using normal Verilog elaboration rules. The bluespec compiler will check for this. The parameter keyword is only relevant when the module is marked with the synthesize attribute.
Inside the module, the `parameter` keyword can be used for a parameter `n` that is used, for example, for constants in expressions, register initialization values, and so on. However, `n` cannot be used for structural variations in the module, such as declaring an array of `n` registers. Such structural decisions (generate decisions) are taken by the Bluespec compiler, and cannot currently be postponed into the Verilog.

The optional `moduleFormalArgs` represent the interfaces used by the module, such as clocks or wires. The final argument is a single interface provided by the module instead of Verilog’s port list. The interpretation is that this module will define and offer an interface of that type to its clients. If the only argument is the interface, only the interface type is required. If there are other arguments, both a type and an identifier must be specified for consistency, but the final interface name will not be used in the body. Omitting the interface type completely is equivalent to using the pre-defined `Empty` interface type, which is a trivial interface containing no methods.

The arguments and parameters may be enclosed in a single set of parentheses, in which case the `#` would be omitted.

Provisos, which are optional, come next. These are part of an advanced feature called type classes (overloading groups), and are discussed in more detail in Section 14.1.

Examples

A module with parameters and an interface.

```verilog
module mkFifo#(Int#(8) a) (Fifo);
...
endmodule
```

A module with arguments and an interface, but no parameters

```verilog
module mkSyncPulse (Clock sClkIn, Reset sRstIn,
                    Clock dClkIn,
                    SyncPulseIfc ifc);
...
endmodule
```

A module definition with parameters, arguments, and provisos

```verilog
module mkSyncReg#(a_type initValue)
                   (Clock sClkIn, Reset sRstIn,
                    Clock dClkIn,
                    Reg#(a_type) ifc)
                   provisos (Bits#(a_type, sa));
...
endmodule
```

The above module definition may also be written with the arguments and parameters combined in a single set of parentheses.

```verilog
module mkSyncReg (a_type initValue,
                   Clock sClkIn, Reset sRstIn,
                   Clock dClkIn,
                   Reg#(a_type) ifc)
                   provisos (Bits#(a_type, sa));
...
endmodule
The body of the module consists of a sequence of moduleStmts:

\[
\text{moduleStmt} ::= \text{moduleInst} \\
| \text{methodDef} \\
| \text{subinterfaceDef} \\
| \text{rule} \\
| \text{varDo} | \text{varDeclDo} \\
| \text{functionCall} \\
| \text{systemTaskStmt} \\
| (\text{expression}) \\
| \text{returnStmt} \\
| \text{varDecl} | \text{varAssign} \\
| \text{functionDef} \\
| \text{moduleDef} \\
| <\text{module}>\text{BeginEndStmt} \\
| <\text{module}>\text{If} | <\text{module}>\text{Case} \\
| <\text{module}>\text{For} | <\text{module}>\text{While}
\]

Most of these are discussed elsewhere since they can also occur in other contexts (e.g., in packages, function bodies, and method bodies). Below, we focus solely on those statements that are found only in module bodies or are treated specially in module bodies.

### 5.4 Module and interface instantiation

Module instances form a hierarchy. A module definition can contain specifications for instantiating other modules, and in the process, instantiating their interfaces. A single module definition may be instantiated multiple times within a module.

#### 5.4.1 Short form instantiation

There is a one-line shorthand for instantiating a module and its interfaces.

\[
\text{moduleInst} ::= \text{[attributeInstances]} \\
| \text{type identifier <- moduleApp} ;
\]

\[
\text{moduleApp} ::= \text{identifier} \\
| (\text{[moduleActualParamArg} \{, \text{moduleActualParamArg}\}])
\]

\[
\text{moduleActualParamArg} ::= \text{expression} \\
| \text{clocked_by expression} \\
| \text{reset_by expression}
\]

The statement first declares an identifier with an interface type. After the <- symbol, we have a module application, consisting of a module identifier optionally followed by a list of parameters and arguments, if the module is defined to have parameters and arguments. Note that the parameters and the arguments are within a single set of parentheses, the parameters listed first, and there is no # before the list.

Each module has an implicit clock and reset. These defaults can be changed by explicitly specifying a clocked_by or reset_by argument in the module instantiation.

An optional documentation attribute (Section 13.7) placed before the module instantiation will place a comment in the generated Verilog file.

The following skeleton illustrates the structure and relationships between interface and module definition and instantiation.
interface ArithIO#(type a); //interface type called ArithIO
    method Action input (a x, a y); //parameterized by type a
    method a output; //contains 2 methods, input and output
endinterface: ArithIO

module mkGCD#(int n) (ArithIO#(bit [31:0]));
    ... //module definition for mkGCD
    ... //one parameter, an integer n
endmodule: mkGCD //presents interface of type ArithIO#(bit[31:0])

//declare the interface instance gcdIFC, instantiate the module mkGCD, set n=5
module mkTest ();
    ...
    ArithIO#(bit [31:0]) gcdIfc <- mkGCD (5, clocked_by dClkIn);
    ...
endmodule: mkTest

The following example shows an module instantiation using a clocked_by statement.

interface Design_IFC;
    method Action start(Bit#(3) in_data1, Bit#(3) in_data2, Bool select);
    interface Clock clk_out;
    method Bit#(4) out_data();
endinterface: Design_IFC

module mkDesign(Clock prim_clk, Clock sec_clk, Design_IFC ifc);
    ...
    RWire#(Bool) select <- mkRWire (select, clocked_by sec_clk);
    ...
endmodule: mkDesign

5.4.2 Long form instantiation

A module instantiation can also be written in its full form on two consecutive lines, as typical in SystemVerilog. The full form specifies names for both the interface instance and the module instance. In the shorthand described above, there is no name provided for the module instance and the compiler infers one based on the interface name. This is often acceptable because module instance names are only used occasionally in debugging and in hierarchical names.

An optional documentation attribute (Section 13.7) placed before the module instantiation will place a comment in the generated Verilog file.

moduleInst ::= [ attributeInstances ]
              type identifier () ;
              moduleApp2 identifier ( [ moduleActualArgs ] ) ;
moduleApp2 ::= identifier [ # ( moduleActualParam { , moduleActualParam } ) ]
moduleActualParam ::= expression
moduleActualArgs ::= moduleActualArg { , moduleActualArg }
moduleActualArg ::= expression
                  | clocked_by expression
                  | reset_by expression
The first line of the long form instantiation declares an identifier with an interface type. The second line actually instantiates the module and defines the interface. The moduleApp2 is the module (definition) identifier, and it must be applied to actual parameters (in #(...)) if it had been defined to have parameters. After the moduleApp, the first identifier names the new module instance. This may be followed by one or more moduleActualArg which define the arguments being used by the module. The last identifier (in parentheses) of the moduleActualArg must be the same as the interface identifier declared immediately above. It may be followed by a clocked_by or reset_by statement.

The following examples show the complete form of the module instantiations of the examples shown above.

```verilog
module mkTest (); //declares a module mkTest
  ...
  //
  ArithIO#(bit [31:0]) gcdIfc(); //declares the interface instance
  mkGCD#(5) a_GCD (gcdIfc); //instantiates module mkGCD
  ...
  //sets N=5, names module instance a_GCD
endmodule: mkTest //and interface instance gcdIfc

module mkDesign(Clock prim_clk, Clock sec_clk, Design_IFC ifc);
  ...
  RWire#(Bool) select();
  mkRWire t_select(select, clocked_by sec_clk);
  ...
endmodule: mkDesign
```

### 5.5 Interface definition (definition of methods)

A module definition contains a definition of its interface. Typically this takes the form of a collection of definitions, one for each method in its interface. Each method definition begins with the keyword method, followed optionally by the return-type of the method, then the method name, its formal parameters, and an optional implicit condition. After this comes the method body which is exactly like a function body. It ends with the keyword endmethod, optionally labelled again with the method name.

```verilog
moduleStmt ::= methodDef
methodDef ::= method [ type ] identifier ( methodFormals ) [ implicitCond ] ;
  functionBody
  endmethod [ : identifier ]
methodFormals ::= methodFormal { , methodFormal }
methodFormal ::= [ type ] identifier
implicitCond ::= if ( condPredicate )
condPredicate ::= exprOrCondPattern { &&& exprOrCondPattern }
exprOrCondPattern ::= expression
  | expression matches pattern
```

The method name must be one of the methods in the interface whose type is specified in the module header. Each of the module’s interface methods must be defined exactly once in the module body. The compiler will issue a warning if a method is not defined within the body of the module.

The return type of the method and the types of its formal arguments are optional, and are present for readability and documentation purposes only. The compiler knows these types from the method
prototypes in the interface declaration. If specified here, they must exactly match the corresponding types in the method prototype.

The implicit condition, if present, may be a boolean expression, or it may be a pattern-match (pattern matching is described in Section 10). Expressions in the implicit condition can use any of the variables in scope surrounding the method definition, i.e., visible in the module body, but they cannot use the formal parameters of the method itself. If the implicit condition is a pattern-match, any variables bound in the pattern are available in the method body. Omitting the implicit condition is equivalent to saying if (True). The semantics of implicit conditions are discussed in Section 9.13, on rules.

Every method is ultimately invoked from a rule (a method \( m_1 \) may be invoked from another method \( m_2 \) which, in turn, may be invoked from another method \( m_3 \), and so on, but if you follow the chain, it will end in a method invocation inside a rule). A method’s implicit condition controls whether the invoking rule is enabled. Using implicit conditions, it is possible to write client code that is not cluttered with conditionals that test whether the method is applicable. For example, a client of a FIFO module can just call the enqueue or the dequeue method without having explicitly to test whether the FIFO is full or empty, respectively; those predicates are usually specified as implicit conditions attached to the FIFO methods.

Please note carefully that the implicit condition precedes the semicolon that terminates the method definition header. There is a very big semantic difference between the following:

```verilog
method ... foo (...) if (expr);
...
endmethod
```

and

```verilog
method ... foo (...) ; if (expr)
...
endmethod
```

The only syntactic difference is the position of the semicolon. In the first case, if (expr) is an implicit condition on the method. In the second case the method has no implicit condition, and if (expr) starts a conditional statement inside the method. In the first case, if the expression is false, any rule that invokes this method cannot fire, i.e., no action in the rule or the rest of this method is performed. In the second case, the method does not prevent an invoking rule from firing, and if the rule does fire, the conditional statement is not executed but other actions in the rule and the method may be performed.

The method body is exactly like a function body, which is discussed in Section 8.8 on function definitions.

See also Section 9.12 for the more general concepts of interface expressions and expressions as first-class objects.

Example:

```verilog
interface GrabAndGive; // interface is declared
  method Action grab(Bit#(8) value); // method grab is declared
  method Bit#(8) give(); // method give is declared
endinterface

module mkExample (GrabAndGive);
  Reg#(Bit#(8)) value_reg <- mkReg(?);
  Reg#(Bool) not_yet <- mkReg(True);
```

37
// method grab is defined
method Action grab(Bit#(8) value) if (not_yet);
    value_reg <= value;
    not_yet <= False;
endmethod

// method give is defined
method Bit#(8) give() if (!not_yet);
    return value_reg;
endmethod
endmodule

5.5.1 Shorthands for Action and ActionValue method definitions

If a method has type Action, then the following shorthand syntax may be used. Section 9.6 describes action blocks in more detail.

```
methodDef ::= method Action identifier ( methodFormals ) [ implicitCond ] ;
{ actionStmt }
endmethod [ : identifier ]
```

i.e., if the type Action is used after the method keyword, then the method body can directly contain a sequence of actionStmts without the enclosing action and endaction keywords.

Similarly, if a method has type ActionValue(t) (Section 9.7), the following shorthand syntax may be used:

```
methodDef ::= method ActionValue #( type ) identifier ( methodFormals )
[ implicitCond ; ]
{ actionValueStmt }
endmethod [ : identifier ]
```

i.e., if the type ActionValue(t) is used after the method keyword, then the method body can directly contain a sequence of actionStmts without the enclosing actionvalue and endactionvalue keywords.

Example: The long form definition of an Action method:

```
method grab(Bit#(8) value);
    action
        last_value <= value;
    endaction
endmethod
```

can be replaced by the following shorthand definition:

```
method Action grab(Bit#(8) value);
    last_value <= value;
endmethod
```

5.5.2 Definition of subinterfaces

Declaration of subinterfaces (hierarchical interfaces) was described in Section 5.2.1. A subinterface member of an interface can be defined using the following syntax.

```
moduleStmt ::= subinterfaceDef
```
The subinterface member is defined within `interface-endinterface` brackets. The first `Identifier` must be the name of the subinterface member’s type (an interface type), without any parameters. The second `identifier` (and the optional `identifier` following the `endinterface`) must be the subinterface member name. The `interfaceStmts` then define the methods or further nested subinterfaces of this member. Example (please refer to the `ILookup` interface defined in Section 5.2.1):

```verbatim
module ...
...
interface Server mif;
  interface Put request;
    method put(...);
    ...
  endmethod: put
  endinterface: request

  interface Get response;
    method get();
    ...
  endmethod: get
  endinterface: response

endinterface: mif
...
endmodule
```

### 5.5.3 Definition of methods and subinterfaces by assignment

Note: this is an advanced topic and can be skipped on first reading.

A method can also be defined using the following syntax.

```verbatim
methodDef ::= method [ type ] identifier ( methodFormals ) [ implicitCond ] = expression ;
```

The part up to and including the `implicitCond` is the same as the standard syntax shown in Section 5.5. Then, instead of a semicolon, we have an assignment to an expression that represents the method body. The expression can of course use the method’s formal arguments, and it must have the same type as the return type of the method. See Sections 9.6 and 9.7 for how to construct expressions of `Action` type and `ActionValue` type, respectively.
A subinterface member can also be defined using the following syntax.

\[
\text{subinterfaceDef} ::= \text{interface} [\text{type}] \text{identifier} = \text{expression} ;
\]

The `identifier` is just the subinterface member name. The `expression` is an interface expression (described in Section 9.12) of the appropriate interface type.

For example, in the following module the subinterface `Put` is defined by assignment.

```
// in this module, there is an instantiated FIFO, and the Put interface
// of the "mkSameInterface" module is the same interface as the fifo's:

interface IFC1;
  interface Put#(int) in0;
endinterface

(*synthesize*)
module mkSameInterface (IFC1);
  FIFO#(int) myFifo <- mkFIFO;
  interface Put in0 = fifoToPut(myFifo);
endmodule
```

### 5.6 Rules in module definitions

The internal behavior of a module is described using zero or more rules.

**moduleStmt** ::= rule

```
rule ::= [ attributeInstances ]
  rule identifier [ ruleCond ] ;
  ruleBody
endrule [ : identifier ]
```

**ruleCond** ::= ( condPredicate )

**condPredicate** ::= exprOrCondPattern { &&& exprOrCondPattern } | expression matches pattern

**exprOrCondPattern** ::= expression

```
ruleBody ::= { actionStmt }
```

A rule is optionally preceded by an `attributeInstances`; these are described in Section 13.3. Every rule must have a name (the `identifier`). If the closing `endrule` is labelled with an identifier, it must be the same name. Rule names must be unique within a module.

The `ruleCond`, if present, may be a boolean expression, or it may be a pattern-match (pattern matching is described in Section 10). It can use any identifiers from the scope surrounding the rule, i.e., visible in the module body. If it is a pattern-match, any variables bound in the pattern are available in the rule body.

The `ruleBody` must be of type `Action`, using a sequence of zero or more `actionStmts`. We discuss `actionStmts` in Section 9.6, but here we make a key observation. Actions include updates to state elements (including register writes). There are no restrictions on different rules updating the same state elements. The BSV compiler will generate all the control logic necessary for such shared update, including multiplexing, arbitration, and resource control. The generated control logic will ensure rule atomicity, discussed briefly in the next paragraphs.

A more detailed discussion of rule semantics is given in Section 6.2, Dynamic Semantics, but we outline the key point briefly here. The `ruleCond` is called the *explicit condition* of the rule. Within the `ruleCond` and `ruleBody`, there may be calls to various methods of various interfaces. Each such
method call has an associated implicit condition. The rule is enabled when its explicit condition and all its implicit conditions are true. A rule can fire, i.e., execute the actions in its ruleBody, when the rule is enabled and when the actions cannot “interfere” with the actions in the bodies of other rules. Non-interference is described more precisely in Section 6.2 but, roughly speaking, it means that the rule execution can be viewed as an atomic state transition, i.e., there cannot be any race conditions between this rule and other rules.

This atomicity and the automatic generation of control logic to guarantee atomicity is a key benefit of BSV. Note that because of method calls in the rule and, transitively, method calls in those methods, a rule can touch (read/write) state that is distributed in several modules. Thus, a rule can express a major state change in the design. The fact that it has atomic semantics guarantees the absence of a whole class of race conditions that might otherwise bedevil the designer. Further, changes in the design, whether in this module or in other modules, cannot introduce races, because the compiler will verify atomicity.

See also Section 9.13 for a discussion of the more general concepts of rule expressions and rules as first-class objects.

5.7 Examples

A register is primitive module with the following predefined interface:

```verilog
interface Reg#(type a);
    method Action _write (a x1);
    method a _read ();
endinterface: Reg
```

It is polymorphic, i.e., it can contain values of any type a. It has two methods. The _write() method takes an argument x1 of type a and returns an Action, i.e., an enable-wire that, when asserted, will deposit the value into the register. The _read() method takes no arguments and returns the value that is in the register.

The principal predefined module definition for a register has the following header:

```verilog
// takes an initial value for the register
module mkReg#(a v) (Reg#(a)) provisos (Bits#(a, sa));
```

The module parameter v of type a is specified when instantiating the module (creating the register), and represents the initial value of the register. The module defines an interface of type Reg #(a). The proviso specifies that the type a must be convertible into an sa-bit value. Provisos are discussed in more detail in Sections 4.2 and 14.1.

Here is a module to compute the GCD (greatest common divisor) of two numbers using Euclid’s algorithm.

```verilog
interface ArithIO#(type a);
    method Action start (a x, a y);
    method a result;
endinterface: ArithIO

module mkGCD(ArithIO#(Bit#(size_t)));
    Reg#(Bit#(size_t)) x(); // x is the interface to the register
    mkRegU reg_1(x);        // reg_1 is the register instance
```
Reg #(Bit#(size_t)) y();  // y is the interface to the register
mkRegU reg_2(y);  // reg_2 is the register instance

rule flip (x > y && y != 0);
  x <= y;
  y <= x;
endrule

rule sub (x <= y && y != 0);
  y <= y - x;
endrule

method Action start(Bit#(size_t) num1, Bit#(size_t) num2) if (y == 0);
  action
    x <= num1;
    y <= num2;
  endaction
endmethod: start

method Bit#(size_t) result() if (y == 0);
  result = x;
endmethod: result

endmodule: mkGCD

The interface type is called ArithIO because it expresses the interactions of modules that do any kind of two-input, one-output arithmetic. Computing the GCD is just one example of such arithmetic. We could define other modules with the same interface that do other kinds of arithmetic.

The module contains two rules, flip and sub, which implement Euclid’s algorithm. In other words, assuming the registers x and y have been initialized with the input values, the rules repeatedly update the registers with transformed values, terminating when the register y contains zero. At that point, the rules stop firing, and the GCD result is in register x. Rule flip uses standard Verilog non-blocking assignments to express an exchange of values between the two registers. As in Verilog, the symbol <= is used both for non-blocking assignment as well as for the less-than-or-equal operator (e.g., in rule sub’s explicit condition), and as usual these are disambiguated by context.

The start method takes two arguments num1 and num2 representing the numbers whose GCD is sought, and loads them into the registers x and y, respectively. The result method returns the result value from the x register. Both methods have an implicit condition (y == 0) that prevents them from being used while the module is busy computing a GCD result.

A test bench for this module might look like this:

module mkTest ();
  ArithIO#(Bit#(32)) gcd();  // declare ArithIO interface gcd
  mkGCD the_gcd (gcd);  // instantiate gcd module the_gcd

  rule getInputs;
    ... read next num1 and num2 from file ...
    the_gcd.start (num1, num2);  // start the GCD computation
  endrule

  rule putOutput;
    $display("Output is %d", the_gcd.result());  // print result
endrule
endmodule: mkTest

The first two lines instantiate a GCD module. The getInputs rule gets the next two inputs from a file, and then initiates the GCD computation by calling the start method. The putOutput rule prints the result. Note that because of the semantics of implicit conditions and enabling of rules, the getInputs rule will not fire until the GCD module is ready to accept input. Similarly, the putOutput rule will not fire until the output method is ready to deliver a result.\(^3\)

The mkGCD module is trivial in that the rule conditions ((x > y) and (x <= y)) are mutually exclusive, so they can never fire together. Nevertheless, since they both write to register y, the compiler will insert the appropriate multiplexers and multiplexer control logic.

Similarly, the rule getInputs, which calls the start method, can never fire together with the mkGCD rules because the implicit condition of getInputs, i.e., (y == 0) is mutually exclusive with the explicit condition (y != 0) in flip and sub. Nevertheless, since getInputs writes into the gcd's registers via the start method, the compiler will insert the appropriate multiplexers and multiplexer control logic.

In general, many rules may be enabled simultaneously, and subsets of rules that are simultaneously enabled may both read and write common state. The BSV compiler will insert appropriate scheduling, datapath multiplexing, and control to ensure that when rules fire in parallel, the net state change is consistent with the atomic semantics of rules.

### 5.8 Synthesizing Modules

In order to generate code for a BSV design (for either Verilog or Bluesim), it is necessary to indicate to the compiler which module(s) are to be synthesized. A BSV module that is marked for code generation is said to be a synthesized module.

In order to be synthesizable, a module must meet the following characteristics:

- The module must be of type Module and not of any other module type that can be defined with ModuleCollect;
- Its interface must be fully specified; there can be no polymorphic types in the interface;
- Its interface is a type whose methods and subinterfaces are all convertible to wires (see Section 5.8.2);
- All other inputs to the module must be convertible to Bits (see Section 5.8.2).

A module can be marked for synthesis in one of two ways.

1. A module can be annotated with the synthesize attribute (see section 13.1.1). The appropriate syntax is shown below.

```vhdl
(* synthesize *)
module mkFoo (FooIfc);
...
endmodule
```

\(^3\)The astute reader will recognize that in this small example, since the result method is initially ready, the test bench will first output a result of 0 before initiating the first computation. Let us overlook this by imagining that Euclid is clearing his throat before launching into his discourse.
2. Alternatively, the \texttt{-g} compiler flag can be used on the \texttt{bsc} command line to indicate which module is to be synthesized. In order to have the same effect as the attribute syntax shown above, the flag would be used with the format \texttt{-g mkFoo} (the appropriate module name follows the \texttt{-g} flag).

Note that multiple modules may be selected for code generation (by using multiple \texttt{synthesize} attributes, multiple \texttt{-g} compiler flags, or a combination of the two).

Separate synthesis of a module can affect scheduling. This is because input wires to the module, such as method arguments, now become a fixed resource that must be shared, whereas without separate synthesis, module inlining allows them to be bypassed (effectively replicated). Consider a module representing a register file containing 32 registers, with a method \texttt{read(j)} that reads the value of the j\textsuperscript{th} register. Inside the module, this just indexes an array of registers. When separately synthesized, the argument \( j \) becomes a 5-bit wide input port, which can only be driven with one value in any given clock. Thus, two rules that invoke \texttt{read(3)} and \texttt{read(11)}, for example, will conflict and then they cannot fire in the same clock. If, however, the module is not separately synthesized, the module and the \texttt{read()} method are inlined, and then each rule can directly read its target register, so the rules can fire together in the same clock. Thus, in general, the addition of a synthesis boundary can restrict behaviors.

5.8.1 Type Polymorphism

As discussed in section 4.1, BSV supports polymorphic types, including interfaces (which are themselves types). Thus, a single BSV module definition, which provides a polymorphic interface, in effect defines a family of different modules with different characteristics based on the specific parameter(s) of the polymorphic interface. Consider the module definition presented in section 5.7.

\begin{verbatim}
module mkGCD (ArithIO#(Bit#(size_t)));
...
endmodule
\end{verbatim}

Based on the specific type parameter given to the \texttt{ArithIO} interface, the code required to implement \texttt{mkGCD} will differ. Since the Bluespec compiler does not create “parameterized” Verilog, in order for a module to be synthesizable, the associated interface must be fully specified (i.e not polymorphic). If the \texttt{mkGCD} module is annotated for code generation \textit{as is}

\begin{verbatim}
(* synthesize *)
module mkGCD (ArithIO#(Bit#(size_t)));
...
endmodule
\end{verbatim}

and we then run the compiler, we get the following error message.

\textbf{Error: “GCD.bsv”, line 7, column 8: (T0043) “Cannot synthesize ‘mkGCD’: Its interface is polymorphic”}

If however we instead re-write the definition of \texttt{mkGCD} such that all the references to the type parameter \texttt{size_t} are replaced by a specific value, in other words if we write something like,

\begin{verbatim}
(* synthesize *)
module mkGCD32 (ArithIO#(Bit#(32)));
\end{verbatim}
Reg#(Bit#(32)) x(); // x is the interface to the register
mkRegU reg_1(x);  // reg_1 is the register instance

... 
endmodule

then the compiler will complete successfully and provide code for a 32-bit version of the module (called mkGCD32). Equivalently, we can leave the code for mkGCD unchanged and instantiate it inside another synthesized module which fully specifies the provided interface.

(* synthesize *)
module mkGCD32(ArithIO#(Bit#(32)));
let ifc();
mkGCD _temp(ifc);
return (ifc);
endmodule

5.8.2 Module Interfaces and Arguments

As mentioned above, a module is synthesizable if its interface is convertible to wires.

- An interface is convertible to wires if all methods and subinterfaces are convertible to wires.
- A method is convertible to wires if
  - all arguments are convertible to bits;
  - it is an Action method or it is an ActionValue or value method where the return value is convertible to bits.
- Clock, Reset, and Inout subinterfaces are convertible to wires.
- A Vector interface can be synthesized as long as the type inside the Vector is of type Clock, Reset, Inout or a type which is convertible to bits.

To be convertible to bits, a type must be in the Bits typeclass.

For a module to be synthesizable its arguments must be of type Clock, Reset, Inout, or a type convertible to bits. Vectors of the preceding types are also synthesizable. If a module has one or more arguments which are not one of the above types, the module is not synthesizable. For example, if an argument is a datatype, such as Integer, which is not in the Bits typeclass, then the module cannot be separately synthesized.

6 Static and dynamic semantics

What is a legal BSV source text, and what are its legal behaviors? These questions are addressed by the static and dynamic semantics of BSV. The BSV compiler checks that the design is legal according to the static semantics, and produces RTL hardware that exhibits legal behaviors according to the dynamic semantics.

Conceptually, there are three phases in processing a BSV design, just like in Verilog and SystemVerilog:
- **Static checking:** this includes syntactic correctness, type checking and proviso checking.
- **Static elaboration:** actual instantiation of the design and propagation of parameters, producing the module instance hierarchy.
- **Execution:** execution of the design, either in a simulator or as real hardware.

We refer to the first two as the static phase (i.e., pre-execution), and to the third as the dynamic phase. Dynamic semantics are about the temporal behavior of the statically elaborated design, that is, they describe the dynamic execution of rules and methods and their mapping into clocked synchronous hardware.

A BSV program can also contain assertions; assertion checking can occur in all three phases, depending on the kind of assertion.

### 6.1 Static semantics

The static semantics of BSV are about syntactic correctness, type checking, proviso checking, static elaboration and static assertion checking. Syntactic correctness of a BSV design is checked by the parser in the BSV compiler, according to the grammar described throughout this document.

#### 6.1.1 Type checking

BSV is statically typed, just like Verilog, SystemVerilog, C, C++, and Java. This means the usual things: every variable and every expression has a type; variables must be assigned values that have compatible types; actual and formal parameters/arguments must have compatible types, etc. All this checking is done on the original source code, before any elaboration or execution.

BSV uses SystemVerilog’s new tagged union mechanism instead of the older ordinary unions, thereby closing off a certain kind of type loophole. BSV also allows more type parameterization (polymorphism), without compromising full static type checking.

#### 6.1.2 Proviso checking and bit-width constraints

In BSV, overloading constraints and bit-width constraints are expressed using provisos (Sections 4.2 and 14.1.1). Overloading constraints provide an extensible mechanism for overloading.

BSV is stricter about bit-width constraints than Verilog and SystemVerilog in that it avoids implicit zero-extension, sign-extension and truncation of bit-vectors. These operations must be performed consciously by the designer, using library functions, thereby avoiding another source of potential errors.

#### 6.1.3 Static elaboration

As in Verilog and SystemVerilog, static elaboration is the phase in which the design is instantiated, starting with a top-level module instance, instantiating its immediate children, instantiating their children, and so on to produce the complete instance hierarchy.

BSV has powerful generate-like facilities for succinctly expressing regular structures in designs. For example, the structure of a linear pipeline may be expressed using a loop, and the structure of a tree-structured reduction circuit may be expressed using a recursive function. All these are also unfolded and instantiated during static elaboration. In fact, the BSV compiler unfolds all structural loops and functions during static elaboration.

A fully elaborated BSV design consists of no more than the following components:
• A module instance hierarchy. There is a single top-level module instance, and each module instance contains zero or more module instances as children.

• An interface instance. Each module instance presents an interface to its clients, and may itself be a client of zero or more interfaces of other module instances.

• Method definitions. Each interface instance consists of zero or more method definitions. A method’s body may contain zero or more invocations of methods in other interfaces. Every method has an implicit condition, which can be regarded as a single output wire that is asserted only when the method is ready to be invoked. The implicit condition may directly test state internal to its module, and may indirectly test state of other modules by invoking their interface methods.

• Rules. Each module instance contains zero or more rules, each of which contains a condition and an action. The condition is a boolean expression. Both the condition and the action may contain invocations of interface methods of other modules. Since those interface methods can themselves contain invocations of other interface methods, the conditions and actions of a rule may span many modules.

6.2 Dynamic semantics

The dynamic semantics of BSV specify the temporal behavior of rules and methods and their mapping into clocked synchronous hardware.

Every rule has a syntactically explicit condition and action. Both of these may contain invocations of interface methods, each of which has an implicit condition. A rule’s composite condition consists of its syntactically explicit condition ANDed with the implicit conditions of all the methods invoked in the rule. A rule is said to be enabled if its composite condition is true.

6.2.1 Reference semantics

The simplest way to understand the dynamic semantics is through a reference semantics, which is completely sequential. However, please do not equate this with slow execution; the execution steps described below are not the same as clocks; we will see in the next section that many steps can be mapped into each clock. The execution of any BSV program can be understood using the following very simple procedure:

Repeat forever:
Step: Pick any one enabled rule, and perform its action.
(We say that the rule is fired or executed.)

Note that after each step, a different set of rules may be enabled, since the current rule’s action will typically update some state elements in the system which, in turn, may change the value of rule conditions and implicit conditions.

Also note that this sequential, reference semantics does not specify how to choose which rule to execute at each step. Thus, it specifies a set of legal behaviors, not just a single unique behavior. The principles that determine which rules in a BSV program will be chosen to fire (and, hence, more precisely constrain its behavior) are described in section 6.2.3.

Nevertheless, this simple reference semantics makes it very easy for the designer to reason about invariants (correctness conditions). Since only one rule is executed in each step, we only have to look at the actions of each rule in isolation to check how it maintains or transforms invariants. In particular, we do not have to consider interactions with other rules executing simultaneously.
Another way of saying this is: each rule execution can be viewed as an atomic state transition.\textsuperscript{4} Race conditions, the bane of the hardware designer, can generally be explained as an atomicity violation; BSV’s rules are a powerful way to avoid most races.

The reference semantics is based on Term Rewriting Systems (TRSs), a formalism supported by decades of research in the computer science community [Ter03]. For this reason, we also refer to the reference semantics as “the TRS semantics of BSV.”

6.2.2 Mapping into efficient parallel clocked synchronous hardware

A BSV design is mapped by the BSV compiler into efficient parallel clocked synchronous hardware. In particular, the mapping permits multiple rules to be executed in each clock cycle. This is done in a manner that is consistent with the reference TRS semantics, so that any correctness properties ascertained using the TRS semantics continue to hold in the hardware.

Standard clocked synchronous hardware imposes the following restrictions:

- Persistent state is updated only once per clock cycle, at a clock edge. During a clock cycle, values read from persistent state elements are the ones that were registered in the last cycle.
- Clock-speed requirements place a limit on the amount of combinational computation that can be performed between state elements, because of propagation delay.

The composite condition of each rule is mapped into a combinational circuit whose inputs, possibly many, sense the current state and whose 1-bit output specifies whether this rule is enabled or not.

The action of each rule is mapped into a combinational circuit that represents the state transition function of the action. It can have multiple inputs and multiple outputs, the latter being the computed next-state values.

\begin{figure}[h]
    \centering
    \includegraphics[width=\textwidth]{figure1.png}
    \caption{A general scheme for mapping an N-rule system into clocked synchronous hardware.}
    \label{fig:1}
\end{figure}

Figure \ref{fig:1} illustrates a general scheme to compose rule components when mapping the design to clocked synchronous hardware. The State box lumps together all the state elements in the BSV design (as described earlier, state elements are explicitly specified in BSV). The BSV compiler produces a rule-control circuit which conceptually takes all the enable (cond) signals and all the data (action) outputs and controls which of the data outputs are actually captured at the next clock in the state.

\textsuperscript{4} We use the term \textit{atomic} as it is used in concurrency theory (and in operating systems and databases), i.e., to mean\textit{ indivisible}.  

48
elements. The enable signals feed a *scheduler* circuit that decides which of the rules will actually fire. The scheduler, in turn, controls data multiplexers that select which data outputs reach the data inputs of state elements, and controls which state elements are enabled to capture the new data values. Firing a rule simply means that the scheduler selects its data output and clocks it into the next state.

At each clock, the scheduler selects a subset of rules to fire. Not all subsets are legal. A subset is legal if and only if the rules in the subset can be ordered with the following properties:

- A hypothetical sequential execution of the ordered subset of rules is legal at this point, according to the TRS semantics. In particular, the first rule in the ordered subset is currently enabled, and each subsequent rule would indeed be enabled when execution reaches it in the hypothetical sequence.

  A special case is where all rules in the subset are already currently enabled, and no rule would be disabled by execution of prior rules in the order.

- The hardware execution produces the same net effect on the state as the hypothetical sequential execution, even though the hardware execution performs reads and writes in a different order from the hypothetical sequential execution.

The BSV compiler performs a very sophisticated analysis of the rules in a design and synthesizes an efficient hardware scheduler that controls execution in this manner.

Note that the scheme in Figure 1 is for illustrative purposes only. First, it lumps together all the state, shows a single rule-control box, etc., whereas in the real hardware generated by the BSV compiler these are distributed, localized and modular. Second, it is not the only way to map the design into clocked synchronous hardware. For example, any two enabled rules can also be executed in a single clock by feeding the action outputs of the first rule into the action inputs of the second rule, or by synthesizing hardware for a composite circuit that computes the same function as the composition of the two actions, and so on. In general, these alternative schemes may be more complex to analyze, or may increase total propagation delay, but the compiler may use them in special circumstances.

In summary, the BSV compiler performs a detailed and sophisticated analysis of rules and their interactions, and maps the design into very efficient, highly parallel, clocked synchronous hardware including a dynamic scheduler that allows many rules to fire in parallel in each clock, but always in a manner that is consistent with the reference TRS semantics. The designer can use the simple reference semantics to reason about correctness properties and be confident that the synthesized parallel hardware will preserve those properties. (See Section 13.3 for the “scheduling attributes” mechanism using which the designer can guide the compiler in implementing the mapping.)

When coding in other HDLs, the designer must maintain atomicity manually. He must recognize potential race conditions, and design the appropriate data paths, control and synchronization to avoid them. Reasoning about race conditions can cross module boundaries, and can be introduced late in the design cycle as the problem specification evolves. The BSV compiler automates all of this and, further, is capable of producing RTL that is competitive with hand-coded RTL.

### 6.2.3 How rules are chosen to fire

The previous section described how an efficient circuit can be built whose behavior will be consistent with sequential TRS semantics of BSV. However, as noted previously, the sequential reference semantics can be consistent with a range of different behaviors. There are two rule scheduling principles that guide the BSV compiler in choosing which rules to schedule in a clock cycle (and help a designer build circuits with predictable behavior). Except when overridden by an explicit user command or annotation, the BSV compiler schedules rules according to the following two principles:
1. Every rule enabled during a clock cycle will either be fired as part of that clock cycle or a warning will be issued during compilation.

2. A rule will fire at most one time during a particular clock cycle.

The first principle comes into play when two (or more) rules conflict - either because they are competing for a limited resource or because the result of their simultaneous execution is not consistent with any sequential rule execution. In the absence of a user annotation, the compiler will arbitrarily choose which rule to prioritize, but must also issue a warning. This guarantees the designer is aware of the ambiguity in the design and can correct it. It might be corrected by changing the rules themselves (rearranging their predicates so they are never simultaneously applicable, for example) or by adding an urgency annotation which tells the compiler which rule to prefer (see section 13.3.3). When there are no scheduling warnings, it is guaranteed that the compiler is making no arbitrary choices about which rules to execute.

The second principle ensures that continuously enabled rules (like a counter increment rule) will not be executed an unpredictable number of times during a clock cycle. According to the first rule scheduling principle, a rule that is always enabled will be executed at least once during a clock cycle. However, since the rule remains enabled it theoretically could execute multiple times in a clock cycle (since that behavior would be consistent with a sequential semantics). Since rules (even simple things like a counter increment) consume limited resources (like register write ports) it is pragmatically useful to restrict them to executing only once in a cycle (in the absence of specific user instructions to the contrary). Executing a continuously enabled rule only once in a cycle is also the more straightforward and intuitive behavior.

Together, these two principles allow a designer to completely determine the rules that will be chosen to fire by the schedule (and, hence, the behavior of the resulting circuit).

6.2.4 Mapping specific hardware models

Annotations on the methods of a module are used by the BSV compiler to model the hardware behavior into TRS semantics. For example, all reads from a register must be scheduled before any writes to the same register. That is to say, any rule which reads from a register must be scheduled earlier than any other rule which writes to it. More generally, there exist scheduling constraints for specific hardware modules which describe how methods interact within the schedule. The scheduling annotations describe the constraints enforced by the BSV compiler.

The meanings of the scheduling annotations are:

- **C** conflicts
- **CF** conflict-free
- **SB** sequence before
- **SBR** sequence before restricted (cannot be in the same rule)
- **SA** sequence after
- **SAR** sequence after restricted (cannot be in the same rule)

The annotations **SA** and **SAR** are provided for documentation purposes only; they are not supported in the BSV language.

Below is an example of the scheduling annotations for a register:

---

5The compiler’s choice, while arbitrary, is deterministic. Given the same source and compiler version, the same schedule (and, hence, the same hardware) will be produced. However, because it is an arbitrary choice, it can be sensitive to otherwise irrelevant details of the program and is not guaranteed to remain the same if the source or compiler version changes.
The table describes the following scheduling constraints:

- Two read methods would be conflict-free (CF), that is, you could have multiple methods that read from the same register in the same rule, sequenced in any order.
- A write is sequenced after (SA) a read.
- A read is sequenced before (SB) a write.
- And finally, if you have two write methods, one must be sequenced before the other, and they cannot be in the same rule, as indicated by the annotation SBR.

The scheduling annotations are specific to the TRS model desired and a single hardware component can have multiple TRS models. For example, a register may be implemented using a mkReg module or a mkConfigReg module, which are identical except for their scheduling annotations.

7 User-defined types (type definitions)

User-defined types must be defined at the top level of a package.

```
typeDef ::= typedefSynonym
          | typedefEnum
          | typedefStruct
          | typedefTaggedUnion
```

As a matter of style, BSV requires that all enumerations, structs and unions be declared only via typedef, i.e., it is not possible directly to declare a variable, formal parameter or formal argument as an enum, struct or union without first giving that type a name using a typedef.

Each typedef of an enum, struct or union introduces a new type that is different from all other types. For example, even if two typedefs give names to struct types with exactly the same corresponding member names and types, they define two distinct types.

Other typedefs, i.e., not involving an enum, struct or union, merely introduce type synonyms for existing types.

7.1 Type synonyms

Type synonyms are just for convenience and readability, allowing one to define shorter or more meaningful names for existing types. The new type and the original type can be used interchangeably anywhere.

```
typedefSynonym ::= typedef type typeDefType ;
typeDefType ::= typeIde [ typeFormals ]
typeFormals ::= # ( typeFormal { , typeFormal } )
typeFormal ::= [ numeric ] type typeIde
```

Examples. Defining names for bit vectors of certain lengths:
typedef bit [7:0] Byte;
typedef bit [31:0] Word;
typedef bit [63:0] LongWord;

Examples. Defining names for polymorphic data types.

typedef Tuple3#(a, a, a) Triple#(type a);
typedef Int#(n) MyInt#(type n);

The above example could also be written as:

typedef Int#(n) MyInt#(numeric type n);

The numeric is not required because the parameter to Int will always be numeric. numeric is only required when the compiler can’t determine whether the parameter is a numeric or non-numeric type. It will then default to assuming it is non-numeric. The user can override this default by specifying numeric in the typedef statement.

A typedef statement can be used to define a synonym for an already defined synonym. Example:

typedef Triple#(Longword) TLW;

Since an Interface is a type, we can have nested types:

typedef Reg#(Vector#(8, UInt#(8))) ListReg;
typedef List#(List#(Bit#(4))) ArrayOf4Bits;

The typedef statement must always be at the top level of a package, not within a module. To introduce a local name within a module, use Alias or NumAlias (B.1.13). Since these introduce new names which are type variables as opposed to types, the new names must begin with lower case letters. NumAlias is used to give new names to numeric types, while Alias is used for types which can be the types of variables. Example:

module mkMod(Ifc)
  provisos (Alias#(Bit#(crc_size), crc));

module mkRAM(RAMIfc)
  provisos (NumAlias#(addr_size, TLog#(buff_size)));

7.2 Enumerations

typedefEnum ::= typedef enum { typedefEnumElements } Identifier [ derives ] ;
typedefEnumElements ::= typedefEnumElement { , typedefEnumElement };
typedefEnumElement ::= Identifier [ = intLiteral ]
| Identifier[intLiteral] [ = intLiteral ]
| Identifier[intLiteral:intLiteral] [ = intLiteral ]

Enumerations (enums) provide a way to define a set of unique symbolic constants, also called labels or member names. Each enum definition creates a new type different from all other types. Enum labels may be repeated in different enum definitions. Enumeration labels must begin with an uppercase letter.
The optional *derives* clause is discussed in more detail in Sections 4.3 and 14.1. One common form is *deriving*(Bits), which tells the compiler to generate a bit-representation for this enum. Another common form of the clause is *deriving*(Eq), which tells the compiler to pick a default equality operation for these labels, so they can also be tested for equality and inequality. A third common form is *deriving*(Bounded), which tells the compiler to define constants minBound and maxBound for this type, equal in value to the first and last labels in the enumeration. Also defined in *deriving*(FShow), which defines a Fmt type for the labels for use with $Display functions. These specifications can be combined, e.g., *deriving*(Bits, Eq, Bounded, FShow). All these default choices for representation, equality and bounds can be overridden (see Section 14.1).

The declaration may specify the encoding used by *deriving*(Bits) by assigning numbers to tags. When an assignment is omitted, the tag receives an encoding of the previous tag incremented by one; when the encoding for the initial tag is omitted, it defaults to zero. Specifying the same encoding for more than one tag results in an error.

Multiple tags may be declared by using the index (*Tag*[ntags]) or range (*Tag*[start:end]) notation. In the former case, ntags tags will be generated, from *Tag*0 to *Tag*n-1; in the latter case, |end − start| + 1 tags, from *Tag*start to *Tag*end.

Example. The boolean type can be defined in the language itself:

```verilog
typedef enum { False, True } Bool deriving (Bits, Eq);
```

The compiler will pick a one-bit representation, with 1'b0 and 1'b1 as the representations for False and True, respectively. It will define the == and != operators to also work on Bool values.

Example. Excerpts from the specification of a processor:

```verilog
typedef enum { R0, R1, ..., R31 } RegName deriving (Bits);
typedef RegName Rdest;
typedef RegName Rsrc;
```

The first line defines an enum type with 32 register names. The second and third lines define type synonyms for RegName that may be more informative in certain contexts (“destination” and “source” registers). Because of the *deriving* clause, the compiler will pick a five-bit representation, with values 5'h00 through 5'h1F for R0 through R31.

Example. Tag encoding when *deriving*(Bits) can be specified manually:

```verilog
typedef enum {
    Add = 5,
    Sub = 0,
    Not,
    Xor = 3,
    ...
} OpCode deriving (Bits);
```

The Add tag will be encoded to five, Sub to zero, Not to one, and Xor to three.

Example. A range of tags may be declared in a single clause:

```verilog
typedef enum {
    Foo[2],
    Bar[5:7],
    Quux[3:2]
} Glurph;
```
This is equivalent to the declaration

```systemverilog
typedef enum {
    Foo0,
    Foo1,
    Bar5,
    Bar6,
    Bar7,
    Quux3,
    Quux2
} Glurph;
```

### 7.3 Structs and tagged unions

A struct definition introduces a new record type.

SystemVerilog has ordinary unions as well as tagged unions, but in BSV we only use tagged unions, for several reasons. The principal benefit is safety (verification). Ordinary unions open a serious type-checking loophole, whereas tagged unions are completely type-safe. Other reasons are that, in conjunction with pattern matching (Section 10), tagged unions yield much more succinct and readable code, which also improves correctness. In the text below, we may simply say “union” for brevity, but it always means “tagged union.”

```systemverilog
typedef Struct ::= typedef struct {
    { structMember }
} typedefType [ derives ];
typedefTaggedUnion ::= typedef union tagged {
    { unionMember }
} typedefType [ derives ];
structMember ::= type identifier ;
| subUnion identifier ;
unionMember ::= type Identifier ;
| subStruct Identifier ;
| subUnion Identifier ;
| void Identifier ;
subStruct ::= struct {
    { structMember }
}
subUnion ::= union tagged {
    { unionMember }
}
typeDefType ::= typeIde [ typeFormals ]
typeFormals ::= # ( typeFormal { , typeFormal } )
typeFormal ::= | numeric | type typeIde
```

All types can of course be mutually nested if mediated by typedefs, but unions can also be mutually nested directly, as described in the syntax above. Structs and unions contain members. A union member (but not a struct member) can have the special `void` type (see the types `MaybeInt` and `Maybe` in the examples below for uses of `void`). All the member names in a particular struct or union must be unique, but the same names can be used in other structs and members; the compiler will try to disambiguate based on type.
A struct value contains the first member and the second member and the third member, and so on. A union value contains just the first member or just the second member or just the third member, and so on. Struct member names must begin with a lowercase letter, whereas union member names must begin with an uppercase letter.

In a tagged union, the member names are also called tags. Tags play a very important safety role. Suppose we had the following:

```markdown
typedef union tagged { int Tagi; OneHot Tagoh; } U deriving (Bits);
U x;
```

The variable x not only contains the bits corresponding to one of its member types int or OneHot, but also some extra bits (in this case just one bit) that remember the tag, 0 for Tagi and 1 for Tagoh. When the tag is Tagi, it is impossible to read it as a OneHot member, and when the tag is Tagoh it is impossible to read it as an int member, i.e., the syntax and type checking ensure this. Thus, it is impossible accidentally to misread what is in a union value.

The optional derives clause is discussed in more detail in Section 14.1. One common form is deriving (Bits), which tells the compiler to pick a default bit-representation for the struct or union. For structs it is simply a concatenation of the representations of the members. For unions, the representation consists of \( t + m \) bits, where \( t \) is the minimum number of bits to code for the tags in this union and \( m \) is the number of bits for the largest member. Every union value has a code in the \( t \)-bit field that identifies the tag, concatenated with the bits of the corresponding member, right-justified in the \( m \)-bit field. If the member needs fewer than \( m \) bits, the remaining bits (between the tag and the member bits) are undefined.

Struct and union typedefs can define new, polymorphic types, signalled by the presence of type parameters in #(...). Polymorphic types are discussed in section 4.1.

Section 9.11 on struct and union expressions describes how to construct struct and union values and to access and update members. Section 10 on pattern-matching describes a more high-level way to access members from structs and unions and to test union tags.

Example. Ordinary, traditional record structures:

```markdown
typedef struct { int x; int y; } Coord;
typedef struct { Addr pc; RegFile rf; Memory mem; } Proc;
```

Example. Encoding instruction operands in a processor:

```markdown
typedef union tagged {
  bit [4:0] Register;
  bit [21:0] Literal;
  struct {
    bit [4:0] regAddr;
    bit [4:0] regIndex;
  } Indexed;
} InstrOperand;
```

An instruction operand is either a 5-bit register specifier, a 22-bit literal value, or an indexed memory specifier, consisting of two 5-bit register specifiers.

Example. Encoding instructions in a processor:

```markdown
typedef union tagged {
  struct {
```
An `Instruction` is either an `Immediate` or a `Jump`. In the former case, it contains a field, `op`, containing a value of type `Op`; a field, `rs`, containing a value of type `Reg`; a field, `rt`, containing a value of type `CPUReg`; and a field, `imm`, containing a value of type `UInt16`. In the latter case, it contains a field, `op`, containing a value of type `Op`, and a field, `target`, containing a value of type `UInt26`.

Example. Optional integers (an integer together with a valid bit):

```verbatim
typedef union tagged {
  void Invalid;
  int Valid;
} MaybeInt
  deriving (Bits);
```

A `MaybeInt` is either invalid, or it contains an integer (Valid tag). The representation of this type will be 33 bits—one bit to represent `Invalid` or `Valid` tag, plus 32 bits for an `int`. When it carries an invalid value, the remaining 32 bits are undefined. It will be impossible to read/interpret those 32 bits when the tag bit says it is `Invalid`.

This `MaybeInt` type is very useful, and not just for integers. We generalize it to a polymorphic type:

```verbatim
typedef union tagged {
  void Invalid;
  a Valid;
} Maybe#(type a)
  deriving (Bits);
```

This `Maybe` type can be used with any type `a`. Consider a function that, given a key, looks up a table and returns some value associated with that key. Such a function can return either an invalid result (`Invalid`), if the table does not contain an entry for the given key, or a valid result `Valid v` if `v` is associated with the key in the table. The type is polymorphic (type parameter `a`) because it may be used with lookup functions for integer tables, string tables, IP address tables, etc. In other words, we do not over-specify the type of the value `v` at which it may be used.

See Section 12.4 for an important, predefined set of struct types called `Tuples` for adhoc structs of between two and eight members.

## 8 Variable declarations and statements

Statements can occur in various contexts: in packages, modules, function bodies, rule bodies, action blocks and actionvalue blocks. Some kinds of statements have been described earlier because they were specific to certain contexts: module definitions (`moduleDef`) and instantiation (`moduleInst`), interface declarations (`interfaceDecl`), type definitions (`TypeDef`), method definitions (`methodDef`) inside modules, rules (`rule`) inside modules, and action blocks (`actionBlock`) inside modules.

Here we describe variable declarations, register assignments, variable assignments, loops, and function definitions. These can be used in all statement contexts.
8.1 Variable and array declaration and initialization

Variables in BSV are used to name intermediate values. Unlike Verilog and SystemVerilog, variables never represent state, i.e., they do not hold values over time. Every variable’s type must be declared, after which it can be bound to a value one or more times.

One or more variables can be declared by giving the type followed by a comma-separated list of identifiers with optional initializations:

\[
\text{varDecl} ::= \text{type} \ varInit \{ \ , \ varInit \} ;
\]

\[
\text{varInit} ::= \text{identifier} \ [ \ \text{arrayDims} \ ] \ [ \ = \ \text{expression} \ ]
\]

\[
\text{arrayDims} ::= [ \ \text{expression} \ ] \{ [ \ \text{expression} \ ] \}
\]

The declared identifier can be an array (when \text{arrayDims} is present). The \text{expressions} in \text{arrayDims} represent the array dimensions, and must be constant expressions (i.e., computable during static elaboration). The array can be multidimensional.

Note that array variables are distinct from the \text{RegFile} (section C.1.1) and \text{Vector} (section C.3) data types. Array variables are just a structuring mechanism for values, whereas the \text{RegFile} type represents a particular hardware module, like a register file, with a limited number of read and write ports. In many programs, array variables are used purely for static elaboration, e.g., an array of registers is just a convenient way to refer to a collection of registers with a numeric index.

The type of array variables is generally expressed anonymously, using the bracket syntax. It is equivalent to the \text{Array} type (section B.2.13), which can be used when an explicit type name is needed.

Each declared variable can optionally have an initialization.

Example. Declare two \text{Integer} variables and initialize them:

\[
\text{Integer} \ x = 16, \ y = 32;
\]

Example. Declare two array identifiers \text{a} and \text{b} containing \text{int} values at each index:

\[
\text{int} \ a[20], \ b[40];
\]

Example. Declare an array of 3 \text{Int#(5)} values and initialize them:

\[
\text{Int#(5)} \ xs[3] = \{14, 12, 9\};
\]

Example. Declare an array of 3 arrays of 4 \text{Int#(5)} values and initialize them:

\[
\text{Int#(5)} \ xs[3][4] = \{(1,2,3,4),
\{5,6,7,8\},
\{9,10,11,12\}\};
\]

Example. The array values can be polymorphic, but they must defined during elaboration:

\[
\text{Get } #(a) \ gs[3] = \{g0,g2, g2\};
\]
8.2 Variable assignment

A variable can be bound to a value using assignment:

\[
\text{varAssign} ::= \text{lValue} = \text{expression} ;
\]

\[
\text{lValue} ::= \text{identifier} \\
| \text{lValue} . \text{identifier} \\
| \text{lValue} [ \text{expression} ] \\
| \text{lValue} [ \text{expression} : \text{expression} ]
\]

The left-hand side (lValue) in its simplest form is a simple variable (identifier).

Example. Declare a variable \texttt{wordSize} to have type \texttt{Integer} and assign it the value 16:

\begin{verbatim}
Integer wordSize;
wordSize = 16;
\end{verbatim}

Multiple assignments to the same variable are just a shorthand for a cascaded computation. Example:

\begin{verbatim}
int x;
x = 23;
// Here, x represents the value 23
x = ifc.meth (34);
// Here, x represents the value returned by the method call
x = x + 1;
// Here, x represents the value returned by the method call, plus 1
\end{verbatim}

Note that these assignments are ordinary, zero-time assignments, i.e., they never represent a dynamic assignment of a value to a register. These assignments only represent the convenient naming of an intermediate value in some zero-time computation. Dynamic assignments are always written using the non-blocking assignment operator <=, and are described in Section 8.4.

In general, the left-hand side (lValue) in an assignment statement can be a series of index- and field-selections from an identifier representing a nesting of arrays, structs and unions. The array-indexing expressions must be computable during static elaboration.

For bit vectors, the left-hand side (lValue) may also be a range between two indices. The indices must be computable during static elaboration, and, if the indices are not literal constants, the right-hand side of the assignment should have a defined bit width. The size of the updated range (determined by the two literal indices or by the size of the right-hand side) must be less than or equal to the size of the target bit vector.

Example. Update an array variable \texttt{b}:

\begin{verbatim}
b[15] = foo.bar(x);
\end{verbatim}

Example. Update bits 15 to 8 (inclusive) of a bit vector \texttt{b}:

\begin{verbatim}
b[15:8] = foo.bar(x);
\end{verbatim}

Example. Update a struct variable (using the processor example from Section 7.3):

\begin{verbatim}
cpu.pc = cpu.pc + 4;
\end{verbatim}

Semantically, this can be seen as an abbreviation for:
cpu = Proc { pc: cpu.pc + 4, rf: cpu.rf, mem: cpu.mem }; 

i.e., it reassigns the struct variable to contain a new struct value in which all members other than the updated member have their old values. The right-hand side is a struct expression; these are described in Section 9.11.

Update of tagged union variables is done using normal assignment notation, i.e., one replaces the current value in a tagged union variable by an entirely new tagged union value. In a struct it makes sense to update a single member and leave the others unchanged, but in a union, one member replaces another. Example (extending the previous processor example):

typedef union tagged {
  bit [4:0] Register;
  bit [21:0] Literal;
  struct {
    bit [4:0] regAddr;
    bit [4:0] regIndex;
  } Indexed;
} InstrOperand;
...
InstrOperand orand;
...
orand = tagged Indexed { regAddr:3, regIndex:4 };
...
orand = tagged Register 23;

The right-hand sides of the assignments are tagged union expressions; these are described in Section 9.11.

8.3 Implicit declaration and initialization

The let statement is a shorthand way to declare and initialize a variable in a single statement. A variable which has not been declared can be assigned an initial value and the compiler will infer the type of the variable from the expression on the right hand side of the statement:

\[\text{varDecl} \quad ::= \quad \text{let identifier} = \text{expression} ;\]

Example:

let n = valueof(BuffSize);

The pseudo-function valueof returns an Integer value, which will be assigned to n at compile time. Thus the variable n is assumed to have the type of Integer.

If the expression is the value returned by an actionvalue method, the notation will be:

\[\text{varAssign} \quad ::= \quad \text{let identifier} \leftarrow \text{expression} ;\]

Note the difference between this statement:

let m1 = m1displayfifo.first;

and this statement:

let z1 \leftarrow \text{rndm.get};

In the first example, m1displayfifo.first is a value method; m1 is assigned the value and type returned by the value method. In the latter, \text{rndm.get} is an actionvalue method; z1 is assigned the value and type returned by the actionvalue method.
8.4 Register reads and writes

Register writes occur primarily inside rules and methods.

\[
\text{regWrite} \quad ::= \quad l\text{Value} \Leftarrow \text{expression} \\
\quad | \quad (\text{expression}) \Leftarrow \text{expression}
\]

The left-hand side must contain a writeable interface type, such as \texttt{Reg#(t)} (for some type \texttt{t} that has a representation in bits). It is either an \texttt{lValue} or a parenthesized expression (e.g., the register interface could be selected from an array of register interfaces or returned from a function). The right-hand side must have the same type as the left-hand side would have if it were typechecked as an expression (including read desugaring, as described below). BSV allows only the so-called non-blocking assignments of Verilog, i.e., the statement specifies that the register gets the new value at the end of the current cycle, and is only available in the next cycle.

Following BSV’s principle that all state elements (including registers) are module instances, and all interaction with a module happens through its interface, a simple register assignment \texttt{r<=e} is just a convenient alternative notation for a method call:

\[r\_\text{write}(e)\]

Similarly, if \texttt{r} is an expression of type \texttt{Reg#(t)}, then mentioning \texttt{r} in an expression is just a convenient alternative notation for different method call:

\[r\_\text{read}()\]

The implicit addition of the \texttt{._read} method call to variables of type \texttt{Reg#(t)} is the simplest example of read desugaring.

Example. Instantiating a register interface and a register, and using it:

\begin{verbatim}
Reg#(int) r(); // create a register interface
mkReg#(0) the_r (r); // create a register the_r with interface r
... 
... 
rule ...
  r <= r + 1; // Convenient notation for: r._write (r._read() + 1)
endrule
\end{verbatim}

8.4.1 Registers and square-bracket notation

Register writes can be combined with the square-bracket notation.

\[
\text{regWrite} \quad ::= \quad l\text{Value arrayIndexes} \Leftarrow \text{expression} \\
\text{arrayIndexes} \quad ::= \quad [ \text{expression} ] \{ [ \text{expression} ] \}
\]

There are two different ways to interpret this combination. First, it can mean to select a register out of a collection of registers and write it.

Example. Updating a register in an array of registers:

\begin{verbatim}
List#(Reg#(int)) regs;
... 
\end{verbatim}
Note that when the square-bracket notation is used on the right-hand side, read desugaring is also applied. This allows the expression `regs[3]` to be interpreted as a register read without unnecessary clutter.

The indexed register assignment notation can also be used for partial register updates, when the register contains an array of elements of some type `t` (in a particular case, this could be an array of bits). This interpretation is just a shorthand for a whole register update where only the selected element is updated. In other words,

\[
x[j] <= v;
\]

can be a shorthand for:

\[
x <= replace (x, j, v);
\]

where `replace` is a pure function that takes the whole value from register `x` and produces a whole new value with the `j`'th element replaced by `v`. The statement then assigns this new value to the register `x`.

It is important to understand the tool infers the appropriate meaning for an indexed register write based on the types available and the context:

```verilog
Reg#(Bit#(32)) x;
x[3] <= e;
List#(Reg#(a)) x;
y[3] <= e;
```

In the former case, `x` is a register containing an array of items (in this example a bit vector), so the statement updates the third item in this array (a single bit) and stores the updated bit vector in the register. In the latter case, `y` is an array of registers, so register at position 3 in the array is updated. In the former case, multiple writes to different indices in a single rule with non-exclusive conditions are forbidden (because they would be multiple conflicting writes to the same register), writing the final result back to the register. In the latter case, multiple writes to different indices will be allowed, because they are writes to different registers (though multiple writes to the same index, under non-exclusive conditions would not be allowed, of course).

It also is possible to mix these notations, i.e., writing a single statement to perform a partial update of a register in an array of registers.

Example: Mixing types of square-bracket notation in a register write

```verilog
List#(Reg#(bit[3:0])) ys;
...
y[4][3] <= e;       // Update bit 3 of the register at position 4
```

### 8.4.2 Registers and range notation

Just as there is a range notation for bit extraction and variable assignments, there is also a range notation for register writes.

\[
\text{regWrite} \quad ::= \quad lValue [ expression : expression ] <= expression
\]

\[^{6}\text{To suppress read desugaring use \texttt{asReg} or \texttt{asIfc}}\]

\[^{7}\text{If multiple partial register writes are desired the best thing to do is to assign the register's value to a variable and then do cascaded variable assignments (as described in section 8.2)}\]
The index expressions in the range notation follow the same rules as the corresponding expressions in variable assignment range updates (they must be static expressions and if they are not literal constants the right-hand side should have a defined bit width). Just as the indexed, partial register writes described in the previous subsection, multiple range-notation register writes cannot be mixed in the same rule.

Example: A range-notation register write

```verilog
Reg#(Bit#(32)) r;

r[23:12] <= e; // Update a 12-bit range in the middle of r
```

### 8.4.3 Registers and struct member selection

```
regWrite ::= lValue . identifier <= expression
```

As with the square-bracket notation, a register update involving a field selection can mean one of two things. First, for a register containing a structure, it means update the particular field of the register value and write the result back to the register.

Example: Updating a register containing a structure

```verilog
typedef struct { Bit#(32) a; Bit#(16) b; } Foo deriving(Bits);
...
Reg#(Foo) r;
...
r.a <= 17;
```

Second, it can mean to select the named field out of a compile-time structure that contains a register and write that register.

Example: Writing a register contained in a structure

```verilog
typedef struct { Reg#(Bit#(32)) c; Reg#(Bit#(16)) d; } Baz;
...
Baz b;
...
b.a <= 23;
```

In both cases, the same notation is used and the compiler infers which interpretation is appropriate. As with square-bracket selection, struct member selection implies read desugaring, unless inhibited by asReg or asIfc.

### 8.5 Begin-end statements

A begin-end statement is a block that allows one to collect multiple statements into a single statement, which can then be used in any context where a statement is required.

```verilog
<ctxt>BeginEndStmt ::= begin [ : identifier ] 
{ <ctxt>Stmt }
end [ : identifier ]
```

The optional identifier labels are currently used for documentation purposes only; in the future they may be used for hierarchical references. The statements contained in the block can contain local variable declarations and all the other kinds of statements. Example:

---

8As described in the preceding footnote, using variable assignment is the best way to achieve this effect, if desired.
module mkBeginEnd#(Bit#(2) sel) ();
    Reg#(Bit#(4)) a <- mkReg(0);
    Reg#(Bool) done <- mkReg(False);

    rule decode (!done);
        case (sel)
            2'b00: a <= 0;
            2'b01: a <= 1;
            2'b10: a <= 2;
            default: begin
                a <= 3; // in the 2'b11 case we don't want more than
                done <= True; // one action done, therefore we add begin/end
            end
        endcase
    endrule
endmodule

8.6 Conditional statements

Conditional statements include if statements and case statements. An if statement contains a
predicate, a statement representing the true arm and, optionally, the keyword else followed by a
statement representing the false arm.

\[
\text{If} ::= \text{if (condPredicate) [else Stmt]} \\
\text{condPredicate} ::= \text{exprOrCondPattern} \{ &&& \text{exprOrCondPattern} \} \\
\text{exprOrCondPattern} ::= \text{expression} \mid \text{expression matches pattern}
\]

If-statements have the usual semantics — the predicate is evaluated, and if true, the true arm is exe-
cuted, otherwise the false arm (if present) is executed. The predicate can be any boolean expression.
More generally, the predicate can include pattern matching, and this is described in Section 10, on
pattern matching.

There are two kinds of case statements: ordinary case statements and pattern-matching case state-
ments. Ordinary case statements have the following grammar:

\[
\text{Case} ::= \text{case (expression) } \\
\{ \text{CaseItem} \} \mid \text{DefaultItem} \}
\]

\[
\text{CaseItem} ::= \text{expression} \{ , \text{expression} \} : \text{Stmt} \\
\text{DefaultItem} ::= \text{default} [ : ] \text{Stmt}
\]

Each case item contains a left-hand side and a right-hand side, separated by a colon. The left-
hand side contains a series of expressions, separated by commas. The case items may optionally be
followed, finally, by a default item (the colon after the default keyword is optional).

Case statements are equivalent to an expansion into a series of nested if-then-else statements. For
example:

case (e1)
    e2, e3 : s2;
e4 : s4;
e5, e6, e7: s5;
default : s6;
endcase

is equivalent to:

x1 = e1; // where x1 is a new variable:
if (x1 == e2) s2;
else if (x1 == e3) s2;
else if (x1 == e4) s4;
else if (x1 == e5) s5;
else if (x1 == e6) s5;
else if (x1 == e7) s5;
else s6;

The case expression (e1) is evaluated once, and tested for equality in sequence against the value of each of the left-hand side expressions. If any test succeeds, then the corresponding right-hand side statement is executed. If no test succeeds, and there is a default item, then the default item’s right-hand side is executed. If no test succeeds, and there is no default item, then no right-hand side is executed.

Example:

module mkConditional#(Bit#(2) sel) ();
    Reg#(Bit#(4)) a <- mkReg(0);
    Reg#(Bool) done <- mkReg(False);

    rule decode;
        case (sel)
            2'b00: a <= 0;
            2'b01: a <= 1;
            2'b10: a <= 2;
            2'b11: a <= 3;
        endcase
    endrule

    rule finish;
        if (a == 3)
            done <= True;
        else
            done <= False;
    endrule
endmodule

Pattern-matching case statements are described in Section 10.

8.7 Loop statements

BSV has for loops and while loops.

It is important to note that this use of loops does not express time-based behavior. Instead, they are used purely as a means to express zero-time iterative computations, i.e., they are statically unrolled and express the concatenation of multiple instances of the loop body statements. In particular, the
loop condition must be evaluable during static elaboration. For example, the loop condition can never depend on a value in a register, or a value returned in a method call, which are only known during execution and not during static elaboration.

See Section 11 on FSMs for an alternative use of loops to express time-based (temporal) behavior.

### 8.7.1 While loops

\[
\text{While} ::= \text{while ( expression ) Stmt}
\]

While loops have the usual semantics. The predicate \( \text{expression} \) is evaluated and, if true, the loop body statement is executed, and then the while loop is repeated. Note that if the predicate initially evaluates false, the loop body is not executed at all.

Example. Sum the values in an array:

```verilog
type a[32];
type x = 0;
type j = 0;
...
while (j < 32)
    x = x + a[j];
```

### 8.7.2 For loops

\[
\text{For} ::= \text{for ( forInit ; forTest ; forIncr ) Stmt}
\]

The \( \text{forInit} \) phrase can either initialize previously declared variables (\( \text{forOldInit} \)), or it can declare and initialize new variables whose scope is just this loop (\( \text{forNewInit} \)). They differ in whether or not the first thing after the open parenthesis is a type.

In \( \text{forOldInit} \), the initializer is just a comma-separated list of variable assignments.

In \( \text{forNewInit} \), the initializer is a comma-separated list of variable declarations and initializations. After the first one, not every initializer in the list needs a type; if missing, the type is the nearest type earlier in the list. The scope of each variable declared extends to subsequent initializers, the rest of the for-loop header, and the loop body statement.

Example. Copy values from one array to another:

```verilog
int a[32], b[32];
...
...
for (int i = 0, j = i+offset; i < 32-offset; i = i+1, j = j+1)
    a[i] = b[j];
```
8.8 Function definitions

A function definition is introduced by the `function` keyword. This is followed by the type of the function return-value, the name of the function being defined, the formal arguments, and optional provisos (provisos are discussed in more detail in Section 14.1). After this is the function body and, finally, the `endfunction` keyword that is optionally labelled again with the function name. Each formal argument declares an identifier and its type.

```
functionDef ::= [ attributeInstances ]
    functionProto
    functionBody
    endfunction [ : identifier ]

functionProto ::= function type identifier ( [ functionFormals ] ) [ provisos ] ;

functionFormals ::= functionFormal { , functionFormal }

functionFormal ::= type identifier
```

The function body can contain the usual repertoire of statements:

```
functionBody ::= actionBlock
    | actionValueBlock
    | { functionBodyStmt }

functionBodyStmt ::= returnStmt
    | varDecl | varAssign
    | functionDef
    | moduleDef
    | <functionBody>BeginEndStmt
    | <functionBody> If | <functionBody> Case
    | <functionBody> For | <functionBody> While

returnStmt ::= return expression ;
```

A value can be returned from a function in two ways, as in SystemVerilog. The first method is to assign a value to the function name used as an ordinary variable. This “variable” can be assigned multiple times in the function body, including in different arms of conditionals, in loop bodies, and so on. The function body is viewed as a traditional sequential program, and value in the special variable at the end of the body is the value returned. However, the “variable” cannot be used in an expression (e.g., on the right-hand side of an assignment) because of ambiguity with recursive function calls.

Alternatively, one can use a `return` statement anywhere in the function body to return a value immediately without any further computation. If the value is not explicitly returned nor bound, the returned value is undefined.

Example. The boolean negation function:

```verilog
function Bool notFn (Bool x);
    if (x) notFn = False;
    else notFn = True;
endfunction: notFn
```

Example. The boolean negation function, but using `return` instead:

```verilog
function Bool notFn (Bool x);
    if (x) return False;
    else return True;
endfunction: notFn
```
Example. The factorial function, using a loop:

```verilog
function int factorial (int n);
    int f = 1, j = 0;
    while (j < n)
        begin
            f = f * j;
            j = j + 1;
        end
    factorial = f;
endfunction: factorial
```

Example. The factorial function, using recursion:

```verilog
function int factorial (int n);
    if (n <= 1) return (1);
    else return (n * factorial (n - 1));
endfunction: factorial
```

8.8.1 Definition of functions by assignment

A function can also be defined using the following syntax.

```
functionProto ::= function type identifier ( [ functionFormals ] ) [ provisos ] = expression ;
```

The part up to and including the `provisos` is the same as the standard syntax shown in Section 8.8. Then, instead of a semicolon, we have an assignment to an expression that represents the function body. The expression can of course use the function’s formal arguments, and it must have the same type as the return type of the function.

Example 1. The factorial function, using recursion (from above:)

```
function int factorial (int n) = (n<=1 ? 1 : n * factorial(n-1));
```

Example 2. Turning a method into a function. The following function definition:

```
function int f1 (FIFO#(int) i);
    return i.first();
endfunction
```

could be rewritten as:

```
function int f2(FIFO#(int) i) = i.first();
```

8.8.2 Function types

The function type is required for functions defined at the top level of a package and for recursive functions (such as the factorial examples above). You may choose to leave out the types within a function definition at lower levels for non-recursive functions,

If not at the top level of a package, Example 2 from the previous section could be rewritten as:
function f1(i);
    return i.first();
endfunction

or, if defining the function by assignment:

function f1 (i) = i.first();

Note that currently incomplete type information will be ignored. If, in the above example, partial type information were provided, it would be the same as no type information being provided. This may cause a type-checking error to be reported by the compiler.

function int f1(i) = i.first();  // The function type int is specified
                                       // The argument type is not specified

9 Expressions

Expressions occur on the right-hand sides of variable assignments, on the left-hand and right-hand side of register assignments, as actual parameters and arguments in module instantiation, function calls, method calls, array indexing, and so on.

There are many kinds of primary expressions. Complex expressions are built using the conditional expressions and unary and binary operators.

expression ::= condExpr
             | operatorExpr
             | exprPrimary

exprPrimary ::= identifier
             | intLiteral
             | realLiteral
             | stringLiteral
             | systemFunctionCall
             | ( expression )
             | ··· see other productions ···

9.1 Don’t-care expressions

When the value of an expression does not matter, a don’t-care expression can be used. It is written with just a question mark and can be used at any type. The compiler will pick a suitable value.

exprPrimary ::= ?

A don’t-care expression is similar, but not identical to, the x value in Verilog, which represents an unknown value. A don’t-care expression is unknown to the programmer, but represents a particular fixed value chosen statically by the compiler.

The programmer is encouraged to use don’t-care values where possible, both because it is useful documentation and because the compiler can often choose values that lead to better circuits.

Example:

module mkDontCare();

// instantiating registers where the initial value is "Dontcare"


```plaintext
Reg#(Bit#(4)) a <- mkReg(?);
Reg#(Bit#(4)) b <- mkReg(?);

Bool done = (a==b);
// defining a Variable with an initial value of "Dontcare"
Bool mybool = ?;
endmodule

9.2 Conditional expressions

Conditional expressions include the conditional operator and case expressions. The conditional operator has the usual syntax:

\[
\text{condExpr} ::= \text{condPredicate} \? \text{expression} : \text{expression}
\]

\[
\text{condPredicate} ::= \text{exprOrCondPattern} \&\& \text{exprOrCondPattern}
\]

\[
\text{exprOrCondPattern} ::= \text{expression} \mid \text{expression matches pattern}
\]

Conditional expressions have the usual semantics. In an expression $e_1?e_2:e_3$, $e_1$ can be a boolean expression. If it evaluates to True, then the value of $e_2$ is returned; otherwise the value of $e_3$ is returned. More generally, $e_1$ can include pattern matching, and this is described in Section 10, on pattern matching.

Example.

module mkCondExp ();

// instantiating registers
Reg#(Bit#(4)) a <- mkReg(0);
Reg#(Bit#(4)) b <- mkReg(0);

rule dostuff;
a <= (b>4) ? 2 : 10;
endrule
endmodule

Case expressions are described in Section 10, on pattern matching.

9.3 Unary and binary operators

\[
\text{operatorExpr} ::= \text{unop expression} \mid \text{expression binop expression}
\]

Binary operator expressions are built using the \textit{unop} and \textit{binop} operators listed in the following table, which are a subset of the operators in SystemVerilog. The operators are listed here in order of decreasing precedence.

69
Unary and Binary Operators in order of Precedence

<table>
<thead>
<tr>
<th>Operator</th>
<th>Associativity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ - ! ~</td>
<td>n/a</td>
<td>Unary: plus, minus, logical not, bitwise invert</td>
</tr>
<tr>
<td>&amp;</td>
<td>n/a</td>
<td>Unary: and bit reduction</td>
</tr>
<tr>
<td>~&amp;</td>
<td>n/a</td>
<td>Unary: nand bit reduction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>n/a</td>
</tr>
<tr>
<td>~= ~^</td>
<td>n/a</td>
<td>Unary: nor bit reduction</td>
</tr>
<tr>
<td>^</td>
<td>n/a</td>
<td>Unary: xor bit reduction</td>
</tr>
<tr>
<td>~^ ~^</td>
<td>n/a</td>
<td>Unary: xnor bit reduction</td>
</tr>
<tr>
<td>* / %</td>
<td>Left</td>
<td>multiplication, division, modulus</td>
</tr>
<tr>
<td>+ -</td>
<td>Left</td>
<td>addition, subtraction</td>
</tr>
<tr>
<td>&lt;&lt; &gt;&gt;</td>
<td>Left</td>
<td>left and right shift</td>
</tr>
<tr>
<td>&lt;= &gt;= &lt; &gt;</td>
<td>Left</td>
<td>comparison ops</td>
</tr>
<tr>
<td>== !=</td>
<td>Left</td>
<td>equality, inequality</td>
</tr>
<tr>
<td>&amp;</td>
<td>Left</td>
<td>bitwise and</td>
</tr>
<tr>
<td>~</td>
<td>Left</td>
<td>bitwise or</td>
</tr>
<tr>
<td>~~ ~^</td>
<td>Left</td>
<td>bitwise equivalence (xnor)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Constructs that do not have any closing token, such as conditional statements and expressions, have lowest precedence so that, for example,

```verilog
e1 ? e2 : e3 + e4
```

is parsed as follows:

```verilog
e1 ? e2 : (e3 + e4)
```

and not as follows:

```verilog
(e1 ? e2 : e3) + e4
```

### 9.4 Bit concatenation and selection

Bit concatenation and selection are expressed in the usual Verilog notation:

```verilog
eexprPrimary ::= bitConcat | bitSelect

bitConcat ::= { expression , expression }

bitSelect ::= eexprPrimary [ expression : expression ]
```

In a bit concatenation, each component must have the type `bit[m:0]` (`m ≥ 0`, width `m + 1`). The result has type `bit[n:0]` where `n + 1` is the sum of the individual bit-widths (`n ≥ 0`).

In a bit or part selection, the `exprPrimary` must have type `bit[m:0]` (`m ≥ 0`), and the index `expressions` must have an acceptable index type (e.g. `Integer`, `Bit#(n)`, `Int#(n)`, or `UInt#(n)`). With a single index ([`e`]), a single bit is selected, and the output is of type `bit[1:0]`. With two indexes ([`e1:e2`]), `e1` must be ≥ `e2`, and the indexes are inclusive, i.e., the bits selected go from the low index to the high index, inclusively. The selection has type `bit[k:0]` where `k + 1` is the width of the selection and `bit[0]` is the least significant bit. Since the index expressions can in general be dynamic values (e.g., read out of a register), the type-checker may not be able to figure out this...
type, in which case it may be necessary to use a type assertion to tell the compiler the desired result type (see Section 9.10). The type specified by the type assertion need not agree with width specified by the indexes— the system will truncate from the left (most-significant bits) or pad with zeros to the left as necessary.

Example:

```verilog
d宗ile mkBitConcatSelect ();
  Bit#(3) a = 3’b010; // a = 010
  Bit#(7) b = 7’h5e; // b = 1011110
  Bit#(10) abconcat = {a,b}; // = 0101011110
  Bit#(4) bselect = b[6:3]; // = 1011
endmodule
```

In BSV programs one will sometimes encounter the `Bit#(0)` type. One common idiomatic example is the type `Maybe#(Bit#(0))` (see the `Maybe#()` type in Section 7.3). Here, the type `Bit#(0)` is just used as a place holder, when all the information is being carried by the `Maybe` structure.

### 9.5 Begin-end expressions

A begin-end expression is like an “inline” function, i.e., it allows one to express a computation using local variables and multiple variable assignments and then finally to return a value. A begin-end expression is analogous to a “let block” commonly found in functional programming languages. It can be used in any context where an expression is required.

```
exprPrimary ::= beginEndExpr
beginEndExpr ::= begin [ : identifier ]
   expressionStmt
   expression
  end [ : identifier ]
```

Optional identifier labels are currently used for documentation purposes only. The statements contained in the block can contain local variable declarations and all the other kinds of statements.

```
expressionStmt ::= varDecl | varAssign |
   functionDef |
   moduleDef |
   <expression>BeginEndStmt |
   <expression>If | <expression>Case |
   <expression>For | <expression>While
```

Example:

```verilog
int z;
z = (begin
  int x2 = x * x; // x2 is local, x from surrounding scope
  int y2 = y * y; // y2 is local, y from surrounding scope
  (x2 + y2); // returned value (sum of squares)
end);
```
9.6 Actions and action blocks

Any expression that is intended to act on the state of the circuit (at circuit execution time) is called an action and has type Action. The type Action is special, and cannot be redefined.

Primitive actions are provided as methods in interfaces to predefined objects (such as registers or arrays). For example, the predefined interface for registers includes a _write() method of type Action:

```verbatim
interface Reg#(type a);
    method Action _write (a x);
    method a _read ();
endinterface: Reg
```

Section 8.4 describes special syntax for register reads and writes using non-blocking assignment so that most of the time one never needs to mention these methods explicitly.

The programmer can create new actions only by building on these primitives, or by using Verilog modules. Actions are combined by using action blocks:

```verbatim
exprPrimary ::= actionBlock

actionBlock ::= action [ : identifier ]
{ actionStmt }
endaction [ : identifier ]

actionStmt ::= regWrite
| varDo | varDeclDo
| functionCall
| systemTaskStmt
| ( expression )
| actionBlock
| varDecl | varAssign
| functionDef
| moduleDef
| <action> BeginEndStmt
| <action> If | <action> Case
| <action> For | <action> While
```

The action block can be labelled with an identifier, and the endaction keyword can optionally be labelled again with this identifier. Currently this is just for documentation purposes.

Example:

```verbatim
Action a;
a = (action
    x <= x+1;
y <= z;
endaction);
```

The Standard Prelude package defines the trivial action that does nothing:

```verbatim
Action noAction;
```

which is equivalent to the expression:

```verbatim
action
endaction
```
The **Action** type is actually a special case of the more general type **ActionValue**, described in the next section:

```plaintext
typedef ActionValue#(void) Action;
```

### 9.7 Actionvalue blocks

Note: this is an advanced topic and can be skipped on first reading.

Actionvalue blocks express the concept of performing an action and simultaneously returning a value. For example, the **pop()** method of a stack interface may both pop a value from a stack (the action) and return what was at the top of the stack (the value). **ActionValue** is a predefined abstract type:

```plaintext
ActionValue#(a)
```

The type parameter **a** represents the type of the returned value. The type **ActionValue** is special, and cannot be redefined.

Actionvalues are created using actionvalue blocks. The statements in the block contain the actions to be performed, and a **return** statement specifies the value to be returned.

```plaintext
exprPrimary ::= actionValueBlock

actionValueBlock ::= actionvalue [ : identifier ]
{ actionValueStmt }
endactionvalue [ : identifier ]

actionValueStmt ::= regWrite |
varDo | varDeclDo |
functionCall |
systemTaskStmt |
( expression ) |
returnStmt |
varDecl | varAssign |
functionDef |
moduleDef |
<actionValue> BeginEndStmt |
<actionValue> If | <actionValue> Case |
<actionValue> For | <actionValue> While
```

Given an actionvalue **av**, we use a special notation to perform the action and yield the value:

```plaintext
varDeclDo ::= type identifier <- expression ;
varDo ::= identifier <- expression ;
```

The first rule above declares the identifier, performs the actionvalue represented by the expression, and assigns the returned value to the identifier. The second rule is similar and just assumes the identifier has previously been declared.

Example. A stack:

```plaintext
interface IntStack;
    method Action push (int x);
    method ActionValue#(int) pop();
endinterface: IntStack

...
IntStack s1;
...
IntStack s2;
...

action
    int x <- s1.pop; -- A
    s2.push (x+1); -- B
endaction

In line A, we perform a pop action on stack s1, and the returned value is bound to x. If we wanted to discard the returned value, we could have omitted the “x <-” part. In line B, we perform a push action on s2.

Note the difference between this statement:

   x <- s1.pop;

and this statement:

   z = s1.pop;

In the former, x must be of type int; the statement performs the pop action and x is bound to the returned value. In the latter, z must be a method of type (ActionValue#(int)) and z is simply bound to the method s1.pop. Later, we could say:

   x <- z;

to perform the action and assign the returned value to x. Thus, the = notation simply assigns the left-hand side to the right-hand side. The <- notation, which is only used with actionvalue right-hand sides, performs the action and assigns the returned value to the left-hand side.

Example: Using an actionvalue block to define a pop in a FIFO.

import FIFO :: *

// Interface FifoWithPop combines first with deq
interface FifoWithPop#(type t);
    method Action enq(t data);
    method Action clear;
    method ActionValue#(t) pop;
endinterface

// Data is an alias of Bit#(8)
typedef Bit#(8) Data;

// The next function makes a deq and first from a fifo and returns an actionvalue block
function ActionValue#(t) fifoPop(FIFO#(t) f) provisos(Bits#(t, st));
    return(
        actionvalue
        f.deq;
        return f.first;
        endactionvalue
    );
endfunction
// Module mkFifoWithPop
(* synthesize, always_ready = "clear" *)
module mkFifoWithPop(FifoWithPop#(Data));

// A fifo of depth 2
FIFO#(Data) fifo <- mkFIFO;

// methods
method enq = fifo.enq;
method clear = fifo.clear;
method pop = fifoPop(fifo);
endmodule

9.8 Function calls

Function calls are expressed in the usual notation, i.e., a function applied to its arguments, listed in parentheses. If a function does not have any arguments, the parentheses are optional.

\begin{align*}
exprPrimary & ::= \text{functionCall} \\
functionCall & ::= exprPrimary \ [ \ ( \ [ \ expression \ { , \ expression } \ ] \ ) \ ]
\end{align*}

A function which has a result type of \text{Action} can be used as a statement when in the appropriate context.

\textbf{Note} that the function position is specified as \text{exprPrimary}, of which \text{identifier} is just one special case. This is because in BSV functions are first-class objects, and so the function position can be an expression that evaluates to a function value. Function values and higher-order functions are described in Section 14.2.

Example:

module mkFunctionCalls ();

function Bit#(4) everyOtherBit(Bit#(8) a);
    let result = {a[7], a[5], a[3], a[1]};
    return result;
endfunction

function Bool isEven(Bit#(8) b);
    return (b[0] == 0);
endfunction

Reg#(Bit#(8)) a <- mkReg(0);
Reg#(Bit#(4)) b <- mkReg(0);

rule doSomething (isEven(a)); // calling "isEven" in predicate: fire if a is an even number
    b <= everyOtherBit(a); // calling a function in the rule body
endrule
endmodule

9.9 Method calls

Method calls are expressed by selecting a method from an interface using dot notation, and then applying it to arguments, if any, listed in parentheses. If the method does not have any arguments the parentheses are optional.
The `exprPrimary` is any expression that represents an interface, of which `identifier` is just one special case. This is because in BSV interfaces are first-class objects. The `identifier` must be a method in the supplied interface. Example:

```verilog
// consider the following stack interface

interface StackIFC #(type data_t);
    method Action push(data_t data); // an Action method with an argument
    method ActionValue#(data_t) pop(); // an actionvalue method
    method data_t first; // a value method
endinterface

// when instantiated in a top module
module mkTop ();
    StackIFC#(int) stack <- mkStack; // instantiating a stack module
    Reg#(int) counter <- mkReg(0); // a counter register
    Reg#(int) result <- mkReg(0); // a result register

    rule pushdata;
        stack.push(counter); // calling an Action method
    endrule

    rule popdata;
        let x <- stack.pop; // calling an ActionValue method
        result <= x;
    endrule

    rule readValue;
        let temp_val = stack.first; // calling a value method
    endrule

    rule inc_counter;
        counter <= counter +1;
    endrule
endmodule
```

### 9.10 Static type assertions

We can assert that an expression must have a given type by using Verilog’s “type cast” notation:

```verilog
exprPrimary ::= typeAssertion

typeAssertion ::= type ' bitConcat
                | type ' ( expression )

bitConcat ::= { expression { , expression } }
```

In most cases type assertions are used optionally just for documentation purposes. Type assertions are necessary in a few places where the compiler cannot work out the type of the expression (an example is a bit-selection with run-time indexes).
In BSV although type assertions use Verilog’s type cast notation, they are never used to change an expression’s type. They are used either to supply a type that the compiler is unable to determine by itself, or for documentation (to make the type of an expression apparent to the reader of the source code).

9.11 Struct and union expressions

Section 7.3 describes how to define struct and union types. Section 8.1 describes how to declare variables of such types. Section 8.2 describes how to update variables of such types.

9.11.1 Struct expressions

To create a struct value, e.g., to assign it to a struct variable or to pass it an actual argument for a struct formal argument, we use the following notation:

```
exprPrimary ::= structExpr
structExpr ::= Identifier { memberBind { , memberBind } }
memberBind ::= identifier : expression
```

The leading `Identifier` is the type name to which the struct type was typedefed. Each `memberBind` specifies a member name (identifier) and the value (expression) it should be bound to. The members need not be listed in the same order as in the original typedef. If any member name is missing, that member’s value is undefined.

Semantically, a `structExpr` creates a struct value, which can then be bound to a variable, passed as an argument, stored in a register, etc.

Example (using the processor example from Section 7.3):

```plaintext
typedef struct { Addr pc; RegFile rf; Memory mem; } Proc;
...
Proc cpu;

cpu = Proc { pc : 0, rf : ... };
```

In this example, the `mem` field is undefined since it is omitted from the struct expression.

9.11.2 Struct member selection

A member of a struct value can be selected with dot notation.

```
exprPrimary ::= exprPrimary . identifier
```

Example (using the processor example from Section 7.3):

```plaintext
cpu.pc
```

Since the same member name can occur in multiple types, the compiler uses type information to resolve which member name you mean when you do a member selection. Occasionally, you may need to add a type assertion to help the compiler resolve this.

Update of struct variables is described in Section 8.2.
9.11.3 Tagged union expressions

To create a tagged union value, e.g., to assign it to a tagged union variable or to pass it an actual argument for a tagged union formal argument, we use the following notation:

\[
\begin{align*}
\text{exprPrimary} & \quad ::= \quad \text{taggedUnionExpr} \\
\text{taggedUnionExpr} & \quad ::= \quad \text{tagged Identifier \{ memberBind \{ , memberBind \} \}} \\
& \quad \mid \quad \text{tagged Identifier exprPrimary} \\
\text{memberBind} & \quad ::= \quad \text{identifier : expression}
\end{align*}
\]

The leading Identifier is a member name of a union type, i.e., it specifies which variant of the union is being constructed.

The first form of taggedUnionExpr can be used when the corresponding member type is a struct. In this case, one directly lists the struct member bindings, enclosed in braces. Each memberBind specifies a member name (identifier) and the value (expression) it should be bound to. The members do not need to be listed in the same order as in the original struct definition. If any member name is missing, that member’s value is undefined.

Otherwise, one can use the second form of taggedUnionExpr, which is the more general notation, where exprPrimary is directly an expression of the required member type.

Semantically, a taggedUnionExpr creates a tagged union value, which can then be bound to a variable, passed as an argument, stored in a register, etc.

Example (extending the previous one-hot example):

```verilog
typedef union tagged { int Tagi; OneHot Tagoh; } U deriving (Bits);
...
U x; // these lines are (e.g.) in a module body.
x = tagged Tagi 23;
...
x = tagged Tagoh (encodeOneHot (23));
```

Example (extending the previous processor example):

```verilog
typedef union tagged {
    bit [4:0] Register;
    bit [21:0] Literal;
    struct {
        bit [4:0] regAddr;
        bit [4:0] regIndex;
    } Indexed;
} InstrOperand;
...
InstrOperand orand;
...
orand = tagged Indexed { regAddr:3, regIndex:4 };
```

9.11.4 Tagged union member selection

A tagged union member can be selected with the usual dot notation. If the tagged union value does not have the tag corresponding to the member selection, the value is undefined. Example:

```verilog
InstrOperand orand;
...
... orand.Indexed.regAddr ...
```
In this expression, if `orand` does not have the `Indexed` tag, the value is undefined. Otherwise, the `regAddr` field of the contained struct is returned.

Selection of tagged union members is more often done with pattern matching, which is discussed in Section 10.

Update of tagged union variables is described in Section 8.2.

### 9.12 Interface expressions

Note: this is an advanced topic that may be skipped on first reading.

Section 5.2 described top-level interface declarations. Section 5.5 described definition of the interface offered by a module, by defining each of the methods in the interface, using `methodDef`s. That is the most common way of defining interfaces, but it is actually just a convenient alternative notation for the more general mechanism described in this section. In particular, method definitions in a module are a convenient alternative notation for a `return` statement that returns an interface value specified by an interface expression.

```markdown
moduleStmt ::= returnStmt

returnStmt ::= return expression ;

expression ::= · · · see other productions · · ·
             | exprPrimary

exprPrimary ::= interfaceExpr

interfaceExpr ::= interface Identifier ;
                { interfaceStmt ; }
                endinterface [ : Identifier ]

interfaceStmt ::= methodDef
                | subinterfaceDef
                | expressionStmt

expressionStmt ::= varDecl | varAssign
                | functionDef
                | moduleDef
                | <expression>BeginEndStmt
                | <expression>If | <expression>Case
                | <expression>For | <expression>While
```

An interface expression defines a value of an interface type. The `Identifier` must be an interface type in an existing interface type definition.

Example. Defining the interface for a stack of depth one (using a register for storage):

```verilog
module mkStack#(type a) (Stack#(a));
    Reg#(Maybe#(a)) r;
    ...
    Stack#(a) stkIfc;
    stkIfc = interface Stack;
    method push (x) if (r matches tagged Invalid);
        r <= tagged Valid x;
    endmethod: push
    method pop if (r matches tagged Valid . *);
        r <= tagged Invalid;
```
endmethod: pop

method top if (r matches tagged Valid .v);
    return v;
endmethod: top
endinterface: Stack

return stkIfc;
endmodule: mkStack

The Maybe type is described in Section 7.3. Note that an interface expression looks similar to an interface declaration (Section 5.2) except that it does not list type parameters and it contains method definitions instead of method prototypes.

Interface values are first-class objects. For example, this makes it possible to write interface transformers that convert one form of interface into another. Example:

interface FIFO#(type a); // define interface type FIFO
    method Action enq (a x);
    method Action deq;
    method a first;
endinterface: FIFO

interface Get#(type a); // define interface type Get
    method ActionValue#(a) get;
endinterface: Get

// Function to transform a FIFO interface into a Get interface

function Get#(a) fifoToGet (FIFO#(a) f);
    return (interface Get
        method get();
        actionvalue
            f.deq();
        return f.first();
        endactionvalue
        endmethod: get
        endinterface);
endfunction: fifoToGet

9.12.1 Differences between interfaces and structs

Interfaces are similar to structs in the sense that both contain a set of named items—members in structs, methods in interfaces. Both are first-class values—structs are created with struct expressions, and interfaces are created with interface expressions. A named item is selected from both using the same notation—struct.member or interface.method.

However, they are different in the following ways:

- Structs cannot contain methods; interfaces can contain nothing but methods (and subinterfaces).
- Struct members can be updated; interface methods cannot.
- Struct members can be selected; interface methods cannot be selected, they can only be invoked (inside rules or other interface methods).
- Structs can be used in pattern matching; interfaces cannot.
9.13 Rule expressions

Note: This is an advanced topic that may be skipped on first reading.

Section 5.6 described definition of rules in a module. That is the most common way to define rules, but it is actually just a convenient alternative notation for the more general mechanism described in this section. In particular, rule definitions in a module are a convenient alternative notation for a call to the built-in addRules() function passing it an argument value of type Rules. Such a value is in general created using a rule expression. A rule expression has type Rules and consists of a collection of individual rule constructs.

A rule expression is optionally preceded by an attributeInstances; these are described in Section 13.3. A rule expression is a block, bracketed by rules and endrules keywords, and optionally labelled with an identifier. Currently the identifier is used only for documentation. The individual rule construct is described in Section 5.6.

Example. Executing a processor instruction:

```graphviz
rules
    Word instr = mem[pc];

    rule instrExec;
      case (instr) matches
        tagged Add { .r1, .r2, .r3 }:
          begin
            pc <= pc+1;
            rf[r1] <= rf[r2] + rf[r3];
          end;
        tagged Jz { .r1, .r2 }:
          if (r1 == 0)
            begin
              pc <= r2;
            end;
    endcase
  endrule
endrules
```

Example. Defining a counter:

```verbatim
// IfcCounter with read method
interface IfcCounter#(type t);
  method t readCounter;
endinterface
```
// Definition of CounterType
typedef Bit#(16) CounterType;

// The next function returns the rule addOne
function Rules incReg(Reg#(CounterType) a);
    return( rules
        rule addOne;
            a <= a + 1;
        endrule
    endrules);
endfunction

// Module counter using IfcCounter interface
(* synthesize,
    reset_prefix = "reset_b",
    clock_prefix = "counter_clk",
    always_ready, always_enabled *)
module counter (IfcCounter#(CounterType));

// Reg counter gets reset to 1 asynchronously with the RST signal
Reg#(CounterType) counter <- mkRegA(1);

// Add incReg rule to increment the counter
addRules(incReg(asReg(counter)));

// Next rule resets the counter to 1 when it reaches its limit
rule resetCounter (counter == '1);
    action
        counter <= 0;
    endaction
endrule

// Output the counters value
method CounterType readCounter;
    return counter;
endmethod
endmodule

10 Pattern matching

Pattern matching provides a visual and succinct notation to compare a value against structs, tagged unions and constants, and to access members of structs and tagged unions. Pattern matching can be used in case statements, case expressions, if statements, conditional expressions, rule conditions, and method conditions.

\[
\text{pattern} ::= \text{identifier} \\
| .* \\
| \text{constantPattern} \\
| \text{taggedUnionPattern}
\]

Pattern variable

| Wildcard
| Constant
| Tagged union
constantPattern ::= intLiteral 
| realLiteral 
| stringLiteral 
| Identifier 

A pattern is a nesting of tagged union and struct patterns with the leaves consisting of pattern variables, constant expressions, and the wildcard pattern .*. 

In a pattern .x, the variable x is declared at that point as a pattern variable, and is bound to the corresponding component of the value being matched. 

A constant pattern is an integer literal, or an enumeration label (such as True or False). Integer literals can include the wildcard character ? (example: 4'b00??). 

A tagged union pattern consists of the tagged keyword followed by an identifier which is a union member name. If that union member is not a void member, it must be followed by a pattern for that member. 

In a struct pattern, the Identifier following the tagged keyword is the type name of the struct as given in its typedef declaration. Within the braces are listed, recursively, the member name and a pattern for each member of the struct. The members can be listed in any order, and members can be omitted. 

A tuple pattern is enclosed in braces and lists, recursively, a pattern for each member of the tuple (tuples are described in Section 12.4). 

A pattern always occurs in a context of known type because it is matched against an expression of known type. Recursively, its nested patterns also have known type. Thus a pattern can always be statically type-checked. 

Each pattern introduces a new scope; the extent of this scope is described separately for each of the contexts in which pattern matching may be used. Each pattern variable is implicitly declared as a new variable within the pattern's scope. Its type is uniquely determined by its position in the pattern. Pattern variables must be unique in the pattern, i.e., the same pattern variable cannot be used in more than one position in a single pattern. 

In pattern matching, the value V of an expression is matched against a pattern. Note that static type checking ensures that V and the pattern have the same type. The result of a pattern match is: 

- A boolean value, True, if the pattern match succeeds, or False, if the pattern match fails. 
- If the match succeeds, the pattern variables are bound to the corresponding members from V, using ordinary assignment. 

Each pattern is matched using the following simple recursive rule: 

- A pattern variable always succeeds (matches any value), and the variable is bound to that value (using ordinary procedural assignment). 
- The wildcard pattern .* always succeeds.
• A constant pattern succeeds if \( V \) is equal to the value of the constant. Literals, including integer literals, string literals, and real literals, can include the wildcard character \(?\). A literal containing a wildcard will match any constant obtained by replacing each wildcard character by a valid digit. For example, \( ^{\text{h}}12?4 \) will match any constant between \( ^{\text{h}}1204 \) and \( ^{\text{h}}12f4 \) inclusive.

• A tagged union pattern succeeds if the value has the same tag and, recursively, if the nested pattern matches the member value of the tagged union.

• A struct or tuple pattern succeeds if, recursively, each of the nested member patterns matches the corresponding member values in \( V \). In struct patterns with named members, the textual order of members does not matter, and members may be omitted. Omitted members are ignored.

Conceptually, if the value \( V \) is seen as a flattened vector of bits, the pattern specifies the following: which bits to match, what values they should be matched with and, if the match is successful, which bits to extract and bind to the pattern identifiers.

10.1 Case statements with pattern matching

Case statements can occur in various contexts, such as in modules, function bodies, action and actionValue blocks, and so on. Ordinary case statements are described in Section 8.6. Here we describe pattern-matching case statements.

\[
<ctxt>\text{Case} \quad ::= \quad \text{case ( expression ) matches} \\
\quad \{ \quad <ctxt>\text{CasePatItem} \} \\
\quad | \quad <ctxt>\text{DefaultItem} \quad \}
\]

\[
<ctxt>\text{CasePatItem} \quad ::= \quad \text{pattern} \{ \quad &&& \quad \text{expression} \} : <ctxt>\text{Stmt}
\]

\[
<ctxt>\text{DefaultItem} \quad ::= \quad \text{default} \quad [ \quad : \quad ] <ctxt>\text{Stmt}
\]

The keyword \text{matches} after the main expression (following the \text{case} keyword) signals that this is a pattern-matching case statement instead of an ordinary case statement.

Each case item contains a left-hand side and a right-hand side, separated by a colon. The left-hand side contains a pattern and an optional filter (\text{&&&} followed by a boolean expression). The right-hand side is a statement. The pattern variables in a pattern may be used in the corresponding filter and right-hand side. The case items may optionally be followed, finally, by a default item (the colon after the \text{default} keyword is optional).

The value of the main expression (following the \text{case} keyword) is matched against each case item, in the order given, until an item is selected. A case item is selected if and only if the value matches the pattern and the filter (if present) evaluates to \text{True}. Note that there is a left-to-right sequentiality in each item—the filter is evaluated only if the pattern match succeeds. This is because the filter expression may use pattern variables that are meaningful only if the pattern match succeeds. If none of the case items matches, and a default item is present, then the default item is selected.

If a case item (or the default item) is selected, the right-hand side statement is executed. Note that the right-hand side statement may use pattern variables bound on the left hand side. If none of the case items succeed, and there is no default item, no statement is executed.

Example (uses the \text{Maybe} type definition of Section 7.3):

\[
\text{case (f(a)) matches} \\
\quad \text{tagged Valid .x : return x;} \\
\quad \text{tagged Invalid : return 0;} \\
\text{endcase}
\]
First, the expression $f(a)$ is evaluated. In the first arm, the value is checked to see if it has the form tagged Valid .x, in which case the pattern variable x is assigned the component value. If so, then the case arm succeeds and we execute return x. Otherwise, we fall through to the second case arm, which must match since it is the only other possibility, and we return 0.

Example:

```verilog
typedef union tagged {
    bit [4:0] Register;
    bit [21:0] Literal;
    struct {
        bit [4:0] regAddr;
        bit [4:0] regIndex;
    } Indexed;
} InstrOperand;

InstrOperand orand;

case (orand) matches
    tagged Register .r : x = rf [r];
    tagged Literal .n : x = n;
    tagged Indexed {regAddr: .ra, regIndex: .ri} : x = mem[ra+ri];
endcase
```

Example:

```verilog
Reg#(Bit#(16)) rg <- mkRegU;
rule r;
    case (rg) matches
        'b_0000_000?_0000_0000: $display("1");
        'o_0?_00: $display("2");
        'h_?_0: $display("3");
        default: $display("D");
    endcase
endrule
```

### 10.2 Case expressions with pattern matching

Case expressions with pattern matching are similar to case statements with pattern matching. In fact, the process of selecting a case item is identical, i.e., the main expression is evaluated and matched against each case item in sequence until one is selected. Case expressions can occur in any expression context, and the right-hand side of each case item is an expression. The whole case expression returns a value, which is the value of the right-hand side expression of the selected item. It is an error if no case item is selected and there is no default item.

In contrast, case statements can only occur in statement contexts, and the right-hand side of each case arm is a statement that is executed for side effect. The difference between case statements and case expressions is analogous to the difference between if statements and conditional expressions.
Example. Rules and rule composition for Pipeline FIFO using case statements with pattern matching.

```verilog
package PipelineFIFO;
import FIFO::*;

module mkPipelineFIFO (FIFO#(a))
    provisos (Bits#(a, sa));

    // STATE ----------------
    Reg#(Maybe#(a)) taggedReg <- mkReg (tagged Invalid); // the FIFO
    RWire#(a) rw_enq <- mkRWire; // enq method signal
    RWire#(Bit#(0)) rw_deq <- mkRWire; // deq method signal

    // RULES and RULE COMPOSITION ----------------
    Maybe#(a) taggedReg_post_deq = case (rw_deq.wget) matches
        tagged Invalid : return taggedReg;
        tagged Valid .x : return tagged Invalid;
    endcase;

    Maybe#(a) taggedReg_post_enq = case (rw_enq.wget) matches
        tagged Invalid : return taggedReg_post_deq;
        tagged Valid .v : return tagged Valid v;
    endcase;

    rule update_final (isValid(rw_enq.wget) || isValid(rw_deq.wget));
        taggedReg <= taggedReg_post_enq;
    endrule
```

10.3 Pattern matching in if statements and other contexts

If statements are described in Section 8.6. As the grammar shows, the predicate \((condPredicate)\) can be a series of pattern matches and expressions, separated by `&&&`. Example:

```
if (e_1 matches p_1 &&& e_2 &&& e_3 matches p_3)
    stmt1
else
    stmt2
```

Here, the value of \(e_1\) is matched against the pattern \(p_1\); if it succeeds, the expression \(e_2\) is evaluated; if it is true, the value of \(e_3\) is matched against the pattern \(p_3\); if it succeeds, \(stmt1\) is executed, otherwise \(stmt2\) is executed. The sequential order is important, because \(e_2\) and \(e_3\) may use pattern variables bound in \(p_1\), and \(stmt1\) may use pattern variables bound in \(p_1\) and \(p_3\), and pattern variables are only meaningful if the pattern matches. Of course, \(stmt2\) cannot use any of the pattern variables, because none of them may be meaningful when it is executed.

In general the \(condPredicate\) can be a series of terms, where each term is either a pattern match or a filter expression (they do not have to alternate). These are executed sequentially from left to right, and the \(condPredicate\) succeeds only if all of them do. In each pattern match \(e matches p\), the value of the expression \(e\) is matched against the pattern \(p\) and, if successful, the pattern variables are bound appropriately and are available for the remaining terms. Filter expressions must be boolean.
expressions, and succeed if they evaluate to True. If the whole condPredicate succeeds, the bound pattern variables are available in the corresponding “consequent” arm of the construct.

The following contexts also permit a condPredicate cp with pattern matching:

- Conditional expressions (Section 9.2):
  
  ```
  cp ? e2 : e3
  ```

  The pattern variables from cp are available in e2 but not in e3.

- Conditions of rules (Sections 5.6 and 9.13):
  
  ```
  rule r (cp);
  ...
  endrule
  ```

  The pattern variables from cp are available in the rule body.

- Conditions of methods (Sections 5.5 and 9.12):
  
  ```
  method t f (...) if (cp);
  ...
  endmethod
  ```

  The pattern variables from cp are available in the method body.

Example. Continuing the Pipeline FIFO example from the previous section (10.2).

```
// INTERFACE ----------------

method Action enq(v) if (taggedReg_post_deq matches tagged Invalid);
  rw_enq.wset(v);
endmethod

method Action deq() if (taggedReg matches tagged Valid .v);
  rw_deq.wset(?);
endmethod

method first() if (taggedReg matches tagged Valid .v);
  return v;
endmethod

method Action clear();
  taggedReg <= tagged Invalid;
endmethod

endmodule: mkPipelineFIFO

endpackage: PipelineFIFO
```

10.4 Pattern matching assignment statements

Pattern matching can be used in variable assignments for convenient access to the components of a tuple or struct value.

```
varAssign ::= match pattern = expression ;
```
The pattern variables in the left-hand side pattern are declared at this point and their scope extends to subsequent statements in the same statement sequence. The types of the pattern variables are determined by their position in the pattern.

The left-hand side pattern is matched against the value of the right-hand side expression. On a successful match, the pattern variables are assigned the corresponding components in the value.

Example:

```verilog
Reg#(Bit#(32)) a <- mkReg(0);
Tuple2#(Bit#(32), Bool) data;
rule r1;
    match {.in, .start} = data;
    //using "in" as a local variable
    a <= in;
endrule
```

11  Finite state machines

BSV contains a powerful and convenient notation for expressing finite state machines (FSMs). FSMs are essentially well-structured processes involving sequencing, parallelism, conditions and loops, with a precise compositional model of time. In principle, FSMs can be coded with rules, which are strictly more powerful, but the FSM sublanguage herein provides a succinct notation for FSM structures and automates all the generation and management of the actual FSM state. In fact, the BSV compiler translates all the constructs described here internally into rules. In particular, the primitive statements in these FSMs are standard actions (Section 9.6), obeying all the scheduling semantics of actions (Section 6.2).

First, one uses the Stmt sublanguage, described in Section C.6.1 to compose the actions of an FSM using sequential, parallel, conditional and looping structures. This sublanguage is within the expression syntactic category, i.e., a term in the sublanguage is an expression whose value is of type Stmt. This value can be bound to identifiers, passed as arguments and results of functions, held in static data structures, etc., like any other value. Finally, the FSM can be instantiated into hardware, multiple times if desired, by passing the Stmt value to the module constructor mkFSM. The resulting module interface has type FSM, which has methods to start the FSM and to wait until it completes.

In order to use this sublanguage, it is necessary to import the StmtFSM package, which is described in more detail in Section C.6.1.

12  Important primitives

These primitives are available via the Standard Prelude package and other standard libraries. See also Appendix C more useful libraries.

12.1  The types bit and Bit

The type bit[m:0] and its synonym Bit#(Mplus1) represents bit-vectors of width \( m + 1 \), provided the type Mplus1 has been suitably defined. The lower (lsb) index must be zero. Example:

```verilog
bit [15:0] zero;
zero = 0

typedef bit [50:0] BurroughsWord;
```
Syntax for bit concatenation and selection is described in Section 9.4.

There is also a useful function, `split`, to split a bit-vector into two subvectors:

```haskell
function Tuple2#(Bit#(m), Bit#(n)) split (Bit#(mn) xy)
    provisos (Add#(m,n,mn));
```

It takes a bit-vector of size `mn` and returns a 2-tuple (a pair, see Section 12.4) of bit-vectors of size `m` and `n`, respectively. The proviso expresses the size constraints using the built-in `Add` type class.

The function `split` is polymorphic, i.e, `m` and `n` may be different in different applications of the function, but each use is fully type-checked statically, i.e., the compiler verifies the proviso, performing any calculations necessary to do so.

### 12.1.1 Bit-width compatibility

BSV is currently very strict about bit-width compatibility compared to Verilog and SystemVerilog, in order to reduce the possibility of unintentional errors. In BSV, the types `bit[m:0]` and `bit[n:0]` are compatible only if `m = n`. For example, an attempt to assign from one type to the other, when `m ≠ n`, will be reported by the compiler as a type-checking error—there is no automatic padding or truncation. The Standard Prelude package (see Section B) contains functions such as `extend()` and `truncate()`, which may be used explicitly to extend or truncate to a required bit-width. These functions, being overloaded over all bit widths, are convenient to use, i.e., you do not have to constantly calculate the amount by which to extend or truncate; the type checker will do it for you.

### 12.2 UInt, Int, int and Integer

The types `UInt#(n)` and `Int#(n)`, respectively, represent unsigned and signed integer data types of width `n` bits. These types have all the operations from the type classes (overloading groups) `Bits`, `Literal`, `Eq`, `Arith`, `Ord`, `Bounded`, `Bitwise`, `BitReduction`, and `BitExtend`. (See Appendix B for the specifications of these type classes and their associated operations.)

Note that the types `UInt` and `Int` are not really primitive; they are defined completely in BSV.

The type `int` is just a synonym for `Int#(32)`.

The type `Integer` represents unbounded integers. Because they are unbounded, they are only used to represent static values used during static elaboration. The overloaded function `fromInteger` allows conversion from an `Integer` to various other types.

### 12.3 String and Char

The type `String` is defined in the Standard Prelude package (B.2.7) along with the type `Char`. Strings and chars are mostly used in system tasks (such as `$display`). Strings can be concatenated using the `+` infix operator or, equivalently, the `strConcat` function. Strings can be tested for equality and inequality using the `==` and `!=` operators. String literals, written in double-quotes, are described in Section 2.5.

The `Char` type provides the ability to traverse and modify the characters of a string. The `Char` type can be tested for equality and inequality using the `==` and `!=` operators. The `Char` type can also be compared for ordering through the `Ord` class.
12.4 Tuples

It is frequently necessary to group a small number of values together, e.g., when returning multiple results from a function. Of course, one could define a special struct type for this purpose, but BSV predetermines a number of structs called tuples that are convenient:

```verbatim
typedef struct {a _1; b _2;} Tuple2#(type a, type b) deriving (Bits,Eq,Bounded);
typedef ... Tuple3#(type a, type b, type c) ...;
typedef ... ... ... ...;
typedef ... Tuple8#(type a, ..., type h) ...;
```

Values of these types can be created by applying a predefined family of constructor functions:

```verbatim
tuple2 (e1, e2)
tuple3 (e1, e2, e3)
...
tuple8 (e1, e2, e3, ..., e8)
```

where the expressions \( e_j \) evaluate to the component values of the tuples. The tuple types are defined in the Standard Prelude package (B.2.12).

Components of tuples can be extracted using a predefined family of selector functions:

```verbatim
tpl_1 (e)
tpl_2 (e)
...
tpl_8 (e)
```

where the expression \( e \) evaluates to tuple value. Of course, only the first two are applicable to Tuple2 types, only the first three are applicable to Tuple3 types, and so on.

In using a tuple component selector, it is sometimes necessary to use a static type assertion to help the compiler work out the type of the result. Example:

```verbatim
UInt#(6)’(tpl_2 (e))
```

Tuple components are more conveniently selected using pattern matching. Example:

```verbatim
Tuple2#(int, Bool) xy;
...
case (xy) matches
  { .x, .y } : ... use x and y ...
endcase
```

12.5 Registers

The most elementary module available in BSV is the register (B.4), which has a Reg interface. Registers are instantiated using the mkReg module, whose single parameter is the initial value of the register. Registers can also be instantiated using the mkRegU module, which takes no parameters (don’t-care initial value). The Reg interface type and the module types are shown below.
interface Reg#(type a);
  method Action _write (a x);
  method a _read;
endinterface: Reg

module mkReg#(a initVal) (Reg#(a))
  provisos (Bits#(a, sa));
module mkRegU (Reg#(a))
  provisos (Bits#(a, sa));

Registers are polymorphic, i.e., in principle they can hold a value of any type but, of course, ultimately registers store bits. Thus, the provisos on the modules indicate that the type must be in the Bits type class (overloading group), i.e., the operations pack() and unpack() must be defined on this type to convert into to bits and back.

Section 8.4 describes special notation whereby one rarely uses the _write() and _read methods explicitly. Instead, one more commonly uses the traditional non-blocking assignment notation for writes and, for reads, one just mentions the register interface in an expression.

Since mentioning the register interface in an expression is shorthand for applying the _read method, BSV also provides a notation for overriding this implicit read, producing an expression representing the register interface itself:

    asReg (r)

Since it is also occasionally desired to have automatically read interfaces that are not registers, BSV also provides a notation for more general suppression of read desugaring, producing an expression that always represents an interface itself:

    asIfc(ifc)

12.6 FIFOs

Package FIFO (C.2.2) defines several useful interfaces and modules for FIFOs:

interface FIFO#(type a);
  method Action enq (a x);
  method Action deq;
  method a first;
  method Action clear;
endinterface: FIFO

module mkFIFO#(FIFO#(a))
  provisos (Bits#(a, as));
module mkSizedFIFO#(Integer depth) (FIFO#(a))
  provisos (Bits#(a, as));

The FIFO interface type is polymorphic, i.e., the FIFO contents can be of any type a. However, since FIFOs ultimately store bits, the content type a must be in the Bits type class (overloading group); this is specified in the provisos for the modules.

The module mkFIFO leaves the capacity of the FIFO unspecified (the number of entries in the FIFO before it becomes full).
The module `mkSizedFIFO` takes the desired capacity of the FIFO explicitly as a parameter.

Of course, when compiled, `mkFIFO` will pick a particular capacity, but for formal verification purposes it is useful to leave this undetermined. It is often useful to be able to prove the correctness of a design without relying on the capacity of the FIFO. Then the choice of FIFO depth can only affect circuit performance (speed, area) and cannot affect functional correctness, so it enables one to separate the questions of correctness and “performance tuning.” Thus, it is good design practice initially to use `mkFIFO` and address all functional correctness questions. Then, if performance tuning is necessary, it can be replaced with `mkSizedFIFO`.

### 12.7 FIFOFs

Package `FIFOF` (C.2.2) defines several useful interfaces and modules for FIFOs. The `FIFOF` interface is like `FIFO`, but it also has methods to test whether the FIFO is full or empty:

```verilog
interface FIFOF#(type a);
  method Action enq (a x);
  method Action deq;
  method a first;
  method Action clear;
  method Bool notFull;
  method Bool notEmpty;
endinterface: FIFOF
```

```verilog
module mkFIFOF#(FIFOF#(a))
  provisos (Bits#(a, as));

module mkSizedFIFOF#(Integer depth) (FIFOF#(a))
  provisos (Bits#(a, as));
```

The module `mkFIFO` leaves the capacity of the FIFO unspecified (the number of entries in the FIFO before it becomes full). The module `mkSizedFIFO` takes the desired capacity of the FIFO as an argument.

### 12.8 System tasks and functions

BSV supports a number of Verilog’s system tasks and functions. There are two types of system tasks; statements which are conceptually equivalent to `Action` functions, and calls which are conceptually equivalent to `ActionValue` and `Value` functions. Calls can be used within statements.

```verilog
systemTaskStmt ::= systemTaskCall;
```

#### 12.8.1 Displaying information

```verilog
systemTaskStmt ::= displayTaskName ( [ expression [ , expression ] ]);
```

```verilog
displayTaskName ::= $display | $displayb | $displayo | $displayh
                 | $write | $writeb | $writeo | $writeh
```

These system task statements are conceptually function calls of type `Action`, and can be used in any context where an action is expected.

The only difference between the `$display` family and the `$write` family is that members of the former always output a newline after displaying the arguments, whereas members of the latter do not.
The only difference between the ordinary, b, o and h variants of each family is the format in which numeric expressions are displayed if there is no explicit format specifier. The ordinary $display and $write will output, by default, in decimal format, whereas the b, o and h variants will output in binary, octal and hexadecimal formats, respectively.

There can be any number of argument expressions between the parentheses. The arguments are displayed in the order given. If there are no arguments, $display just outputs a newline, whereas $write outputs nothing.

The argument expressions can be of type String, Char, Bit#(n) (i.e., of type bit[n-1:0]), Integer, or any type that is a member of the overloading group Bits. Values of type Char are treated as a String of one character, by implicitly converting to String. Members of Bits will display their packed representation. The output will be interpreted as a signed number for the types Integer and Int#(n). Arguments can also be literals. Integers and literals are limited to 32 bits.

Arguments of type String and Char are interpreted as they are displayed. The characters in the string are output literally, except for certain special character sequences beginning with a % character, which are interpreted as format-specifiers for subsequent arguments. The following format specifiers are supported:

<table>
<thead>
<tr>
<th>Specifier</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>%d</td>
<td>Output a number in decimal format</td>
</tr>
<tr>
<td>%b</td>
<td>Output a number in binary format</td>
</tr>
<tr>
<td>%o</td>
<td>Output a number in octal format</td>
</tr>
<tr>
<td>%h</td>
<td>Output a number in hexadecimal format</td>
</tr>
<tr>
<td>%c</td>
<td>Output a character with given ASCII code</td>
</tr>
<tr>
<td>%s</td>
<td>Output a string (argument must be a string)</td>
</tr>
<tr>
<td>%t</td>
<td>Output a number in time format</td>
</tr>
<tr>
<td>%m</td>
<td>Output hierarchical name</td>
</tr>
</tbody>
</table>

The values output are sized automatically to the largest possible value, with leading zeros, or in the case of decimal values, leading spaces. The automatic sizing of displayed data can be overridden by inserting a value n indicating the size of the displayed data. If n=0 the output will be sized to minimum needed to display the data without leading zeros or spaces.

ActionValues (see Section 9.7) whose returned type is displayable can also be directly displayed. This is done by performing the associated action (as part of the action invoking $display) and displaying the returned value.

Example:
$display ("%t", $time);

For display statements in different rules, the outputs will appear in the usual logical scheduling order of the rules. For multiple display statements within a single rule, technically there is no defined ordering in which the outputs should appear, since all the display statements are Actions within the rule and technically all Actions happen simultaneously in the atomic transaction. However, as a convenience to the programmer, the compiler will arrange for the display outputs to appear in the normal textual order of the source text, taking into account the usual flow around if-then-elses, statically elaborated loops, and so on. However, for a rule that comprises separately compiled parts (for example, a rule that invokes a method in a separately compiled module), the system cannot guarantee the ordering of display statements across compilation boundaries. Within each separately compiled module, the compiler will arrange for the display outputs to appear in the normal textual order of the source text, taking into account the usual flow around if-then-elses, statically elaborated loops, and so on.

---

\(^9\)Displayed strings are passed through the compiler unchanged, so other format specifiers may be supported by your Verilog simulator. Only the format specifiers above are supported by Bluespec’s C-based simulator.
compiled part, the display outputs will appear in source text order, but these groups may appear in any order. In particular, verification engineers should be careful about these benign (semantically equivalent) reorderings when checking the outputs for correctness.

12.8.2 $format

\[ systemTaskCall ::= $format \left( \begin{array}{ll} \text{expression} & \text{expression} \end{array} \right) \]

Bluespec also supports $format, a display related system task that does not exist in Verilog. $format takes the same arguments as the $display family of system tasks. However, unlike $display (which is a function call of type Action), $format is a value function which returns an object of type Fmt (section B.2.9). Fmt representations of data objects can thus be written hierarchically and applied to polymorphic types. The FShow typeclass is based on this capability.

Example:

typedef struct {OpCommand command;  
    Bit#(8) addr;  
    Bit#(8) data;  
    Bit#(8) length;  
    Bool lock;  
} Header deriving (Eq, Bits, Bounded);

function Fmt fshow (Header value);  
    return ($format("<HEAD ")  
        + fshow(value.command)  
        + $format(" (%0d)", value.length)  
        + $format(" A:%h", value.addr)  
        + $format(" D:%h>", value.data));  
endfunction

12.8.3 Opening and closing file operations

\[ systemTaskCall ::= $fopen \left( \text{fileName} \right) \]
\[ systemTaskStmt ::= $fclose \left( \text{fileIdentifier} \right) ; \]

The $fopen system call is of type ActionValue and can be used anywhere an ActionValue is expected. The argument fileName is of type String. $fopen returns a fileIdentifier of type File. If there is a fileType argument, the fileIdentifier returned is a multi channel descriptor of type FD.

File is a defined type in BSV which is defined as:

\[ typedef \text{union} \tagged{\{ void \text{InvalidFile} ; \} File; } \]

If there is not a fileType argument, the fileIdentifier returned is a multi channel descriptor of type MCD.

One file of type MCD is pre-opened for append, stdout\_mcd (value 1).
Three files of type FD are pre-opened; they are stdin (value 0), stdout (value 1), and stderr (value 2). stdin is pre-opened for reading and stdout and stderr are pre-opened for append.

The **fileType** determines, according to the following table, how other files of type FD are opened:

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;r&quot; or &quot;rb&quot;</td>
<td>open for reading</td>
</tr>
<tr>
<td>&quot;w&quot; or &quot;wb&quot;</td>
<td>truncate to zero length or create for writing</td>
</tr>
<tr>
<td>&quot;a&quot; or &quot;ab&quot;</td>
<td>append; open for writing at end of file, or create for writing</td>
</tr>
<tr>
<td>&quot;r+&quot;, or &quot;r+b&quot;, or &quot;rb+&quot;</td>
<td>open for update (reading and writing)</td>
</tr>
<tr>
<td>&quot;w+&quot;, or &quot;w+b&quot;, or &quot;wb+&quot;</td>
<td>truncate or create for update</td>
</tr>
<tr>
<td>&quot;a+&quot;, or &quot;a+b&quot;, or &quot;ab+&quot;</td>
<td>append; open or create for update at end of file</td>
</tr>
</tbody>
</table>

The **$fclose** system call is of type **Action** and can be used in any context where an action is expected.

### 12.8.4 Writing to a file

```plaintext
systemTaskStmt ::=  fileTaskName ( fileIdentifier , [ expression [ , expression ] ] ) ;

fileTaskName ::=  $fdisplay | $fdisplayb | $fdisplayo | $fdisplayh
                | $fwrite | $fwriteb | $fwriteo | $fwriteh
```

These system task calls are conceptually function calls of type **Action**, and can be used in any context where an action is expected. They correspond to the display tasks (**$display, $write**) but they write to specific files instead of to the standard output. They accept the same arguments (Section 12.8.1) as the tasks they are based on, with the addition of a first parameter **fileIdentifier** which indicates where to direct the file output.

Example:

```plaintext
Reg#(int) cnt <- mkReg(0);
let fh <- mkReg(InvalidFile) ;
let fmcd <- mkReg(InvalidFile) ;

rule open (cnt == 0 ) ;
    // Open the file and check for proper opening
    String dumpFile = "dump_file1.dat" ;
    File lfh <- $fopen( dumpFile, "w" ) ;
    if ( lfh == InvalidFile )
        begin
            $display("cannot open %s", dumpFile);
            $finish(0);
        end
    cnt <= 1 ;
    fh <= lfh ;   // Save the file in a Register
endrule

rule open2 (cnt == 1 ) ;
    // Open the file and check for proper opening
    // Using a multi-channel descriptor.
    String dumpFile = "dump_file2.dat" ;
```

95
File lmcd <- $fopen( dumpFile ) ;
if ( lmcd == InvalidFile )
begin
 $display("cannot open %s", dumpFile );
 $finish(0);
end
lmcd = lmcd | stdout_mcd ; // Bitwise operations with File MCD
cnt <= 2 ;
fmcd <= lmcd ; // Save the file in a Register
endrule

rule dump (cnt > 1 );
$fwrite( fh , "cnt = %d\n", cnt); // Writes to dump_file1.dat
$fwrite( fmcd , "cnt = %d\n", cnt); // Writes to dump_file2.dat
dump_file2.dat // and stdout
cnt <= cnt + 1;
endrule

12.8.5 Formatting output to a string

systemTaskStmt ::= stringTaskName ( ifcIdentifier , [ expression [ , expression ] ] ) ;
stringTaskName ::= $swrite | $swriteb | $swriteo | $swriteh | $sformat

These system task calls are analogous to the $fwrite family of system tasks. They are conceptually function calls of type Action, and accept the same type of arguments as the corresponding $fwrite tasks, except that the first parameter must now be an interface with an _write method that takes an argument of type Bit#(n).

The task $sformat is similar to $swrite, except that the second argument, and only the second argument, is interpreted as a format string. This format argument can be a static string, or it can be a dynamic value whose content is interpreted as the format string. No other arguments in $sformat are interpreted as format strings. $sformat supports all the format specifies supported by $display, as documented in 12.8.1.

The Bluespec compiler de-sugars each of these task calls into a call of an ActionValue version of the same task. For example:

$swrite(foo, "The value is %d", count);

de-sugars to

let x <- $swriteAV("The value is %d", count);
foo <= x;

An ActionValue value version is available for each of these tasks. The associated syntax is given below.

systemTaskCall ::= stringAVTaskName ( [ expression [ , expression ] ] )
stringAVTaskName ::= $swriteAV | $swritebAV | $swriteoAV | $swritehAV | $sformatAV

The ActionValue versions of these tasks can also be called directly by the user.

Use of the system tasks described in this section allows a designer to populate state elements with dynamically generated debugging strings. These values can then be viewed using other display tasks (using the %s format specifier) or output to a VCD file for examination in a waveform viewer.
12.8.6 Reading from a file

systemTaskCall ::= $fgetc ( fileIdentifier )

systemTaskStmt ::= $ungetc ( expression, fileIdentifier ) ;

The $fgetc system call is a function of type ActionValue#(int) which returns an int from the file specified by fileIdentifier.

The $ungetc system statement is a function of type Action which inserts the character specified by expression into the buffer specified by fileIdentifier.

Example:

rule open ( True ) ;
    String readFile = "gettests.dat";
    File lfh <- $fopen(readFile, "r") ;

    int i <- $fgetc( lfh );
    if ( i != -1 )
        begin
            Bit#(8) c = truncate( pack(i) ) ;
        end
    else // an error occurred.
        begin
            $display( "Could not get byte from %s", 
                readFile ) ;
        end

    $fclose ( lfh ) ;
    $finish(0);
endrule

12.8.7 Flushing output

systemTaskStmt ::= $fflush ( [ fileIdentifier ] ) ;

The system call $fflush is a function of type Action and can be used in any context where an action is expected. The $fflush function writes any buffered output to the file(s) specified by the fileIdentifier. If no argument is provided, $fflush writes any buffered output to all open files.

12.8.8 Stopping simulation

systemTaskStmt ::= $finish [ ( expression ) ] ;
    | $stop [ ( expression ) ] ;

These system task calls are conceptually function calls of type Action, and can be used in any context where an action is expected.

The $finish task causes simulation to stop immediately and exit back to the operating system. The $stop task causes simulation to suspend immediately and enter an interactive mode. The optional argument expressions can be 0, 1 or 2, and control the verbosity of the diagnostic messages printed by the simulator. The default (if there is no argument expression) is 1.
12.8.9 VCD dumping

\[ \text{systemTaskStmt} ::= \$dumpvars \mid \$dumpon \mid \$dumpoff ; \]

These system task calls are conceptually function calls of type \texttt{Action}, and can be used in any context where an action is expected.

A call to \$dumpvars starts dumping the changes of all the state elements in the design to the VCD file. BSV’s \$dumpvars does not currently support arguments that control the specific module instances or levels of hierarchy that are dumped.

Subsequently, a call to \$dumpoff stops dumping, and a call to \$dumpon resumes dumping.

12.8.10 Time functions

\[ \text{systemFunctionCall} ::= \$time \mid \$stime \]

These system function calls are conceptually of \texttt{ActionValue} type (see Section 9.7), and can be used anywhere an \texttt{ActionValue} is expected. The time returned is the time when the associated action was performed.

The \$time function returns a 64-bit integer (specifically, of type \texttt{Bit#(64)}) representing time, scaled to the timescale unit of the module that invoked it.

The \$stime function returns a 32-bit integer (specifically, of type \texttt{Bit#(32)}) representing time, scaled to the timescale unit of the module that invoked it. If the actual simulation time does not fit in 32 bits, the lower-order 32 bits are returned.

12.8.11 Real functions

There are two system tasks defined for the \texttt{Real} data type (section B.2.6), used to convert between \texttt{Real} and IEEE standard 64-bit vector representation, \$realtobits and \$bitstoreal. They are identical to the Verilog functions.

\[ \text{systemTaskCall} ::= \$realtobits ( \text{expression} ) \]

\[ \text{systemTaskCall} ::= \$bitstoreal ( \text{expression} ) \]

12.8.12 Testing command line input

Information for use in simulation can be provided on the command line. This information is specified via optional arguments in the command used to invoke the simulator. These arguments are distinguished from other simulator arguments by starting with a plus (+) character and are therefore known as plusargs. Following the plus is a string which can be examined during simulation via system functions.

\[ \text{systemTaskCall} ::= \$test$plusargs ( \text{expression} ) \]

The \$test$plusargs system function call is conceptually of \texttt{ActionValue} type (see Section 9.7), and can be used anywhere an \texttt{ActionValue} is expected. An argument of type \texttt{String} is expected and a boolean value is returned indicating whether the provided string matches the beginning of any plusarg from the command line.
13 Guiding the compiler with attributes

This section describes how to guide the compiler in some of its decisions using BSV’s attribute syntax.

\[ attributeInstances ::= \begin{array}{l}
\text{attributeInstance} \\
\text{\{ attributeInstance \}}
\end{array} \]

\[ attributeInstance ::= \begin{array}{l}
\text{\{ \ast \ attrSpec \{ , attrSpec \} \ \ast \}}
\end{array} \]

\[ attrSpec ::= \begin{array}{l}
\text{attrName} [ \ \text{=} \ expression \ ]
\end{array} \]

\[ attrName ::= \begin{array}{l}
\text{identifier | Identifier}
\end{array} \]

Multiple attributes can be written together on a single line

\((\ast \ \text{synthesize}, \ \text{always\_ready} = \ "\text{read, subifc\_enq}\" \ \ast)\)

Or attributes can be written on multiple lines

\((\ast \ \text{synthesize} \ \ast)\)
\((\ast \ \text{always\_ready} = \ "\text{read, subifc\_enq}\" \ \ast)\)

Attributes can be associated with a number of different language constructs such as module, interface, and function definitions. A given attribute declaration is applied to the first attribute construct that follows the declaration.

13.1 Verilog module generation attributes

In addition to compiler flags on the command line, it is possible to guide the compiler with attributes that are included in the BSV source code.

The attributes \texttt{synthesize} and \texttt{noinline} control code generation for top-level modules and functions, respectively.

<table>
<thead>
<tr>
<th>Attribute name</th>
<th>Section</th>
<th>Top-level module definitions</th>
<th>Top-level function definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>synthesize</td>
<td>13.1.1</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>noinline</td>
<td>13.1.2</td>
<td></td>
<td>√</td>
</tr>
</tbody>
</table>

13.1.1 synthesize

When the compiler is directed to generate Verilog or Bluesim code for a BSV module, by default it tries to integrate all definitions into one big module. The \texttt{synthesize} attribute marks a module for code generation and ensures that, when generated, instantiations of the module are not flattened but instead remain as references to a separate module definition. Modules that are annotated with the \texttt{synthesize} attribute are said to be synthesized modules. The BSV hierarchy boundaries associated with synthesized modules are maintained during code generation. Not all BSV modules can be synthesized modules (i.e., can maintain a module boundary during code generation). Section 5.8 describes in more detail which modules are synthesizable.
13.1.2 noinline

The `noinline` attribute is applied to functions, instructing the compiler to generate a separate module for the function. This module is instantiated as many times as required by its callers. When used in complicated calling situations, the use of the `noinline` attribute can simplify and speed up compilation. The `noinline` attribute can only be applied to functions that are defined at the top level and the inputs and outputs of the function must be in the typeclass `Bits`.

Example:

```vhdl
(* noinline *)
function Bit#(LogK) popCK(Bit#(K) x);
    return (popCountTable(x));
endfunction: popCK
```

13.2 Interface attributes

Interface attributes express protocol and naming requirements for generated Verilog interfaces. They are considered during generation of the Verilog module which uses the interface. These attributes can be applied to synthesized modules, methods, interfaces, and subinterfaces at the top level only. If the module is not synthesized, the attribute is ignored. The following table shows which attributes can be applied to which elements. These attributes cannot be applied to `Clock`, `Reset`, or `Inout` subinterface declarations.

<table>
<thead>
<tr>
<th>Attribute name</th>
<th>Section</th>
<th>Synthesized module definitions</th>
<th>Interface type declarations</th>
<th>Methods of interface type declarations</th>
<th>Subinterfaces of interface type declarations</th>
</tr>
</thead>
<tbody>
<tr>
<td>ready=</td>
<td>13.2.1</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>enable=</td>
<td>13.2.1</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>result=</td>
<td>13.2.1</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>prefix=</td>
<td>13.2.1</td>
<td></td>
<td></td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>port=</td>
<td>13.2.1</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>always_ready=</td>
<td>13.2.2</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>always_enabled=</td>
<td>13.2.2</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>

There is a direct correlation between interfaces in Bluespec and ports in the generated Verilog. These attributes can be applied to interfaces to control the naming and the protocols of the generated Verilog ports.

Bluespec uses a simple Ready-Enable micro-protocol for each method within the module’s interface. Each method contains both a output Ready (RDY) signal and an input Enable (EN) signal in addition to any needed directional data lines. When a method can be safely called it asserts its RDY signal. When an external caller sees the RDY signal it may then call (in the same cycle) the method by asserting the method’s EN signal and providing any required data.

Generated Verilog ports names are based the method name and argument names, with some standard prefixes. In the ActionValue method `method1` shown below

```vhdl
method ActionValue#( type_out ) method1 ( type_in data_in );
```

the following ports are generated:

- `RDY_method1` Output ready signal of the protocol
- `EN_method1` Input signal for Action and Action Value methods
- `method1` Output signal of ActionValue and Value methods
- `method1_data_in` Input signal for method arguments
Interface attributes allow control over the naming and protocols of individual methods or entire interfaces.

### 13.2.1 Renaming attributes

**ready= and enable=** Ready and enable ports use RDY\_ and EN\_ as the default prefix to the method names. The attributes `ready= "string"` and `enable= "string"` replace the prefix annotation and method name with the specified string as the name instead. These attributes may be associated with method declarations (`methodProto`) only (Section 5.2).

In the above example, the following attribute would replace the RDY\_method1 with avMethodIsReady and EN\_method1 with GO.

```plaintext
(* ready = "avMethodIsReady", enable = "GO" *)
```

Note that the `ready=` attribute is ignored if the method or module is annotated as `always_ready` or `always_enabled`, while the `enable=` attribute is ignored for value methods as those are annotated as `always_enabled`.

**result=** By default the output port for value methods and `ActionValue` methods use the method name. The attribute `result= "string"` causes the output to be renamed to the specified string. This is useful when the desired port names must begin with an upper case letter, which is not valid for a method name. These attributes may be associated with method declarations (`methodProto`) only (Section 5.2).

In the above example, the following attribute would replace the method1 port with OUT.

```plaintext
(* result = "OUT" *)
```

Note that the `result=` attribute is ignored if the method is an `Action` method which does not return a result.

**prefix= and port=** By default, the input ports for methods are named by using the name of the method as the prefix and the name of the method argument as the suffix, into `method_argument`. The prefix and/or suffix name can be replaced by the attributes `prefix= "string"` and `port= "string"`. By combining these attributes any desired string can be generated. The `prefix=` attribute replaces the method name and the `port=` attribute replaces the argument name in the generated Verilog port name. The prefix string may be empty, in which case the joining underscore is not added.

The `prefix=` attribute may be associated with method declarations (`methodProto`) or subinterface declarations (`subinterfaceDecl`). The `port=` attribute may be associated with each method prototype argument in the interface declaration (`methodProtoFormal`) (Section 5.2).

In the above example, the following attribute would replace the method1\_data\_in port with IN\_DATA.

```plaintext
(* prefix = "" *)
```

```plaintext
method ActionValue#( type_out )
    method1( (* port="IN_DATA" *) type_in data_in ) ;
```

Note that the `prefix=` attribute is ignored if the method does not have any arguments.

The `prefix=` attribute may also be used on subinterface declarations to aid the renaming of interface hierarchies. By default, interface hierarchies are named by prefixing the subinterface name to names of the methods within that interface (Section 5.2.1.) Using the `prefix` attribute on the subinterface is a way of replacing the subinterface name. This is demonstrated in the example in Section 13.2.3.
13.2.2 Port protocol attributes

The port protocol attributes `always_enabled` and `always_ready` remove unnecessary ports. These attributes are applied to synthesized modules, methods, interfaces, and subinterfaces at the top level only. If the module is not synthesized, the attribute is ignored. The compiler verifies that the attributes are correctly applied.

The attribute `always_enabled` specifies that no enable signal will be generated for the associated interface methods. The methods will be executed on every clock cycle and the compiler verifies that the caller does this.

The attribute `always_ready` specifies that no ready signals will be generated. The compiler verifies that the associated interface methods are permanently ready. `always_enabled` implies `always_ready`.

The `always_ready` and `always_enabled` attributes can be associated with the method declarations (`methodProto`), the subinterface declarations (`subinterfaceDecl`), or the interface declaration (`interfaceDecl`) itself. In these cases, the attribute does not take any arguments. Example:

```verilog
interface Test;
  (* always_enabled *)
  method ActionValue#(Bool) check;
endinterface: Test
```

The attributes can also be associated with a module, in which case the attribute can have as an argument the list of methods to which the attribute is applied. When associated with a module, the attributes are applied when the interface is implemented by a module, not at the declaration of the interface. Example:

```verilog
interface ILookup; //the definition of the interface
  interface Fifo#(int) subifc;
    method Action read ();
  endinterface: ILookup

(* synthesize *)
(* always_ready = "read, subifc.enq" *) //the attribute is applied when the
module mkServer (ILookup); //interface is implemented within
  ... //a module.
endmodule: mkServer
```

In this example, note that only the `enq` method of the `subifc` interface is `always_ready`. Other methods of the interface, such as `deq`, are not `always_ready`.

If every method of the interface is `always_ready` or `always_enabled`, individual methods don’t have to be specified when applying the attribute to a module. Example:

```verilog
(* synthesize *)
(* always_enabled *)
module mkServer (ILookup);
```

13.2.3 Interface attributes example

```verilog
(* always_ready *) // all methods in this and all subinterface // have this property
  // always_enabled is also allowed here
interface ILookup;
```
13.3 Scheduling attributes

<table>
<thead>
<tr>
<th>Attribute name</th>
<th>Section</th>
<th>Module definitions</th>
<th>rule definitions</th>
<th>rules expressions</th>
</tr>
</thead>
<tbody>
<tr>
<td>fire_when_enabled</td>
<td>13.3.1</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>no_implicit_conditions</td>
<td>13.3.2</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>descending_urgency</td>
<td>13.3.3</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>execution_order</td>
<td>13.3.4</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>mutually_exclusive</td>
<td>13.3.5</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>conflict_free</td>
<td>13.3.6</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>preempts</td>
<td>13.3.7</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Scheduling attributes are used to express certain performance requirements. When the compiler maps rules into clocks, as described in Section 6.2.2, scheduling attributes guide or constrain its choices, in order to produce a schedule that will meet performance goals.

Scheduling attributes are most often attached to rules or to rule expressions, but some can also be added to module definitions.

The scheduling attributes are only applied when the module is synthesized.

13.3.1 fire_when_enabled

The fire_when_enabled scheduling attribute immediately precedes a rule (just before the rule keyword) and governs the rule.

It asserts that this rule must fire whenever its predicate and its implicit conditions are true, i.e., when the rule conditions are true, the attribute checks that there are no scheduling conflicts with other rules that will prevent it from firing. This is statically verified by the compiler. If the rule won’t fire, the compiler will report an error.

Example. Using fire_when_enabled to ensure the counter is reset:

```vhdl
// IfcCounter with read method
interface IfcCounter#(type t);
    method t readCounter;
endinterface
```
// Definition of CounterType
typedef Bit#(16) CounterType;

// Module counter using IfcCounter interface. It never contains 0.

(* synthesize,
   reset_prefix = "reset_b",
   clock_prefix = "counter_clk",
   always_ready = "readCounter",
   always_enabled = "readCounter" *)

module counter (IfcCounter#(CounterType));

// Reg counter gets reset to 1 asynchronously with the RST signal
Reg#(CounterType) counter <- mkRegA(1);

// Next rule resets the counter to 1 when it reaches its limit.
// The attribute fire_when_enabled will check that this rule will fire
// if counter == '1
(* fire_when_enabled *)
rule resetCounter (counter == '1);
   counter <= 1;
endrule

// Next rule updates the counter.
rule updateCounter;
   counter <= counter + 1;
endrule

// Method to output the counter's value
method CounterType readCounter;
   return counter;
endmethod
endmodule

Rule resetCounter conflicts with rule updateCounter because both rules try to read and write the counter register when it contains all its bits set to one. If the rule updateCounter is more urgent, only the rule updateCounter will fire. In this case, the assertion fire_when_enabled will be violated and the compiler will produce an error message. Note that without the assertion fire_when_enabled the compilation process will be correct.

13.3.2 no_implicit_conditions

The no_implicit_conditions scheduling attribute immediately precedes a rule (just before the rule keyword) and governs the rule.

It asserts that the implicit conditions of all interface methods called within the rule must always be true; only the explicit rule predicate controls whether the rule can fire or not. This is statically verified by the compiler, and it will report an error if necessary.

Example:

// Import the FIFO package
import FIFO :: *;
// IfcCounter with read method
interface IfcCounter#(type t);
  method t readCounter;
  method Action setReset(t a);
endinterface

// Definition of CounterType
typedef Bit#(16) CounterType;

// Module counter using IfcCounter interface
(* synthesize,
  reset_prefix = "reset_b",
  clock_prefix = "counter_clk",
  always_ready = "readCounter",
  always_enabled = "readCounter" *)
module counter (IfcCounter#(CounterType));

  // Reg counter gets reset to 1 asynchronously with the RST signal
  Reg#(CounterType) counter <- mkRegA(1);

  // The 4 depth valueFifo contains a list of reset values
  FIFO#(CounterType) valueFifo <- mkSizedFIFO(4);

  /* Next rule increases the counter with each counter_clk rising edge
     if the maximum has not been reached */
  (* no_implicit_conditions *)
  rule updateCounter;
    if (counter != '1)
      counter <= counter + 1;
  endrule

  // Next rule resets the counter to a value stored in the valueFifo
  (* no_implicit_conditions *)
  rule resetCounter (counter == '1);
    counter <= valueFifo.first();
    valueFifo.deq();
  endrule

  // Output the counters value
  method CounterType readCounter;
    return counter;
  endmethod

  // Update the valueFifo
  method Action setReset(CounterType a);
    valueFifo.enq(a);
  endmethod
endmodule

The assertion no_implicit_conditions is incorrect for the rule resetCounter, resulting in a compilation error. This rule has the implicit condition in the FIFO module due to the fact that the deq method cannot be invoked if the fifo valueFifo is empty. Note that without the assertion no error will be produced and that the condition if (counter != '1) is not considered an implicit one.
13.3.3 descending_urgency

The compiler maps rules into clocks, as described in Section 6.2.2. In each clock, amongst all the rules that can fire in that clock, the system picks a subset of rules that do not conflict with each other, so that their parallel execution is consistent with the reference TRS semantics. The order in which rules are considered for selection can affect the subset chosen. For example, suppose rules \( r_1 \) and \( r_2 \) conflict, and both their conditions are true so both can execute. If \( r_1 \) is considered first and selected, it may disqualify \( r_2 \) from consideration, and vice versa. Note that the urgency ordering is independent of the TRS ordering of the rules, i.e., the TRS ordering may be \( r_1 \) before \( r_2 \), but either one could be considered first by the compiler.

The designer can specify that one rule is more urgent than another, so that it is always considered for scheduling before the other. The relationship is transitive, i.e., if rule \( r_1 \) is more urgent than rule \( r_2 \), and rule \( r_2 \) is more urgent than rule \( r_3 \), then \( r_1 \) is considered more urgent than \( r_3 \).

Urgency is specified with the `descending_urgency` attribute. Its argument is a string containing a comma-separated list of rule names (see Section 5.6 for rule syntax, including rule names). Example:

```
(* descending_urgency = "r1, r2, r3" *)
```

This example specifies that \( r_1 \) is more urgent than \( r_2 \) which, in turn, is more urgent than \( r_3 \).

If urgency attributes are contradictory, i.e., they specify both that one rule is more urgent than another and its converse, the compiler will report an error. Note that such a contradiction may be a consequence of a collection of urgency attributes, because of transitivity. One attribute may specify \( r_1 \) more urgent than \( r_2 \), another attribute may specify \( r_2 \) more urgent than \( r_3 \), and another attribute may specify \( r_3 \) more urgent than \( r_1 \), leading to a cycle, which is a contradiction.

The `descending_urgency` attribute can be placed in one of three syntactic positions:

- It can be placed just before the `module` keyword in a module definitions (Section 5.3), in which case it can refer directly to any of the rules inside the module.
- It can be placed just before the `rule` keyword in a rule definition, (Section 5.6) in which case it can refer directly to the rule or any other rules at the same level.
- It can be placed just before the `rules` keyword in a rules expression (Section 9.13), in which case it can refer directly to any of the rules in the expression.

In addition, an urgency attribute can refer to any rule in the module hierarchy at or below the current module, using a hierarchical name. For example, suppose we have:

```
module mkFoo ...;
    mkBar the_bar (barInterface);
    /* descending_urgency = "r1, the_bar.r2" */
    rule r1 ...
        ...
    endrule
endmodule: mkFoo
```

The hierarchical name `the_bar.r2` refers to a rule named `r2` inside the module instance `the_bar`. This can be several levels deep, i.e., the scheduling attribute can refer to a rule deep in the module.
hierarchy, not just the submodule immediately below. In general a hierarchical rule name is a sequence of module instance names and finally a rule name, separated by periods.

A reference to a rule in a submodule cannot cross synthesis boundaries. This is because synthesis boundaries are also scheduler boundaries. Each separately synthesized part of the module hierarchy contains its own scheduler, and cannot directly affect other schedulers. Urgency can only apply to rules considered within the same scheduler.

If rule urgency is not specified, and it impacts the choice of schedule, the compiler will print a warning to this effect during compilation.

Example. Using `descending_urgency` to control the scheduling of conflicting rules:

```systemverilog
// IfcCounter with read method
interface IfcCounter#(type t);
  method t readCounter;
endinterface

// Definition of CounterType
typedef Bit#(16) CounterType;

// Module counter using IfcCounter interface. It never contains 0.
(* synthesize,
  reset_prefix = "reset_b",
  clock_prefix = "counter_clk",
  always_ready = "readCounter",
  always_enabled= "readCounter" *)
module counter (IfcCounter#(CounterType));

// Reg counter gets reset to 1 asynchronously with the RST signal
Reg#(CounterType) counter <- mkRegA(1);

/* The descending_urgency attribute will indicate the scheduling
order for the indicated rules. */
(* descending_urgency = "resetCounter, updateCounter" *)

// Next rule resets the counter to 1 when it reaches its limit.
rule resetCounter (counter == '1);
  action
    counter <= 1;
  endaction
endrule

// Next rule updates the counter.
rule updateCounter;
  action
    counter <= counter + 1;
  endaction
endrule

// Method to output the counter’s value
method CounterType readCounter;
  return counter;
endmethod
endmodule
```
Rule `resetCounter` conflicts with rule `updateCounter` because both try to modify the counter register when it contains all its bits set to one. Without any `descending_urgency` attribute, the `updateCounter` rule may obtain more urgency, meaning that if the predicate of `resetCounter` is met, only the rule `updateCounter` will fire. By setting the `descending_urgency` attribute the designer can control the scheduling in the case of conflicting rules.

13.3.4 execution_order

With the `execution_order` attribute, the designer can specify that, when two rules fire in the same cycle, one rule should sequence before the other. This attribute is similar to the `descending_urgency` attribute (section 13.3.3) except that it specifies the execution order instead of the urgency order. The `execution_order` attribute may occur in the same syntactic positions as the `descending_urgency` attribute (Section 13.3.3) and takes a similar argument, a string containing a comma-separated list of rule names. Example:

(* execution_order = "r1, r2, r3" *)

This example specifies that r1 should execute before r2 which, in turn, should execute before r3. If two rules cannot execute in the order specified, because of method calls which must sequence in the opposite order, for example, then the two rules are forced to conflict.

13.3.5 mutually_exclusive

The scheduler always attempts to deduce when two rules are mutually exclusive (based on their predicates). However, this deduction can fail even when two rules are actually exclusive, either because the scheduler effort limit is exceeded or because the mutual exclusion depends on a higher-level invariant that the scheduler does not know about. The `mutually_exclusive` attribute allows the designer to overrule the scheduler’s deduction and forces the generated schedule to treat the annotated rules as exclusive. The `mutually_exclusive` attribute may occur in the same syntactic positions as the `descending_urgency` attribute (Section 13.3.3) and takes a similar argument, a string containing a comma-separated list of rule names. Example:

(* mutually_exclusive = "r1, r2, r3" *)

This example specifies that every pair of rules that are in the annotation (i.e (r1, r2), (r1, r3), and (r2, r3)) is a mutually-exclusive rule pair. Since an asserted mutual exclusion does not come with a proof of this exclusion, the compiler will insert code that will check and generate a runtime error if two rules ever execute during the same clock cycle during simulation. This allows a designer to find out when their use of the `mutually_exclusive` attribute is incorrect.

13.3.6 conflict_free

Like the `mutually_exclusive` rule attribute (section 13.3.5), the `conflict_free` rule attribute is a way to overrule the scheduler’s deduction about the relationship between two rules. However, unlike rules that are annotated `mutually_exclusive`, rules that are `conflict_free` may fire in the same clock cycle. Instead, the `conflict_free` attribute asserts that the annotated rules will not make method calls that are inconsistent with the generated schedule when they execute. The `conflict_free` attribute may occur in the same syntactic positions as the `descending_urgency` attribute (Section 13.3.3) and takes a similar argument, a string containing a comma-separated list of rule names. Example:
This example specifies that every pair of rules that are in the annotation (i.e. (r1, r2), (r1, r3), and (r2, r3)) is a conflict-free rule pair.

For example, two rules may both conditionally enqueue data into a FIFO with a single enqueue port. Ordinarily, the scheduler would conclude that the two rules conflict since they are competing for a single method. However, if they are annotated as `conflict_free` the designer is asserting that when one rule is enqueuing into the FIFO, the other will not be, so the conflict is apparent, not real. With the annotation, the schedule will be generated as if any conflicts do not exist and code will be inserted into the resulting model to check if conflicting methods are actually called by the conflict free rules during simulation.

It is important to know the `conflict_free` attribute’s capabilities and limitations. The attribute works with more than method calls that totally conflict (like the single enqueue port). During simulation, it will check and report any method calls amongst `conflict_free` rules that are inconsistent with the generated schedule (including registers being read after they have been written and wires being written after they are read). On the other hand, the `conflict_free` attribute does not overrule the scheduler’s deductions with respect to resource usage (like uses of a multi-ported register file).

### 13.3.7 preempts

The designer can also prevent a rule from firing whenever another rule (or set of rules) fires. The `preempts` attribute accepts two elements as arguments. Each element may be either a rule name or a list of rule names. A list of rule names must be separated by commas and enclosed in parentheses. In each cycle, if any of the rule names specified in the first list can be executed and are scheduled to fire, then none of the rules specified in the second list will be allowed to fire.

The `preempts` attribute is similar to the `descending_urgency` attribute (section 13.3.3), and may occur in the same syntactic positions. The `preempts` attribute is equivalent to forcing a conflict and adding `descending_urgency`. With `descending_urgency`, if two rules do not conflict, then both would be allowed to fire even if an urgency order had been specified; with `preempts`, if one rule preempts the other, they can never fire together. If r1 preempts r2, then the compiler forces a conflict and gives r1 priority. If r1 is able to fire, but is not scheduled to, then r2 can still fire.

Examples:

```verbatim
(* preempts = "r1, r2" *)
```

If r1 will fire, r2 will not.

```verbatim
(* preempts = "(r1, r2), r3" *)
```

If either r1 or r2 (or both) will fire, r3 will not.

```verbatim
(* preempts = "(the_bar.r1, (r2, r3)" *)
```

If the rule r1 in the submodule `the_bar` will fire, then neither r2 nor r3 will fire.
13.4 Evaluation behavior attributes

13.4.1 split and nosplit

<table>
<thead>
<tr>
<th>Attribute name</th>
<th>Section</th>
<th>Action statements</th>
<th>ActionValue statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>split/nosplit</td>
<td>13.4.1</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>

The split/nosplit attributes are applied to Action and ActionValue statements, but cannot precede certain expressions inside an action/endaction including return, variable declarations, instantiations, and function statements.

When a rule contains an if (or case) statement, the compiler has the option either of splitting the rule into two mutually exclusive rules, or leaving it as one rule for scheduling but using MUXes in the production of the action. Rule splitting can sometimes be desirable because the two split rules are scheduled independently, so non-conflicting branches of otherwise conflicting rules can be scheduled concurrently. Splitting also allows the split fragments to appear in different positions in the logical execution order, providing the effect of condition dependent scheduling.

Splitting is turned off by default for two reasons:

- When a rule contains many if statements, it can lead to an exponential explosion in the number of rules. A rule with 15 if statements might split into \( 2^{15} \) rules, depending on how independent the statements and their branch conditions are. An explosion in the number of rules can dramatically slow down the compiler and cause other problems for later compiler phases, particularly scheduling.

- Splitting propagates the branch condition of each if to the predicates of the split rules. Resources required to compute rule predicates are reserved on every cycle. If a branch condition requires a scarce resource, this can starve other parts of the design that want to use that resource.

The split and nosplit attributes override any compiler flags, either the default or a flag entered on the command line (-split-if).

The split attribute splits all branches in the statement immediately following the attribute statement, which must be an Action statement. A split immediately preceding a binding (e.g. let) statement is not valid. If there are nested if or case statements within the split statement, it will continue splitting recursively through the branches of the statement. The nosplit attribute can be used to disable rule splitting within nested if statements.

Example:

```verilog
module mkConditional#(Bit#(2) sel) ();
    Reg#(Bit#(4)) a <- mkReg(0);
    Reg#(Bool) done <- mkReg(False);

    rule finish ;
    (*split*)
        if (a == 3)
          begin
            done <= True;
          end
    else
        (*nosplit*)
```

110
if (a == 0)
    begin
        done <= False;
        a    <= 1;
    end
else
    begin
        done <= False;
    end
endrule
endmodule

To enable rule splitting for an entire design, use the compiler flag `-split-if` at compile time. See the user guide for more information on compiler flags. You can enable rule splitting for an entire design with the `-split-if` flag and then disable the effect for specific rules, by specifying the `nosplit` attribute before the rules you do not want to split.

### 13.5 Input clock and reset attributes

The following attributes control the definition and naming of clock oscillator, clock gate, and reset ports. The attributes can only be applied to top-level module definitions.

<table>
<thead>
<tr>
<th>Attribute name</th>
<th>Section</th>
<th>Top-level module</th>
</tr>
</thead>
<tbody>
<tr>
<td>clock_prefix=</td>
<td>13.5.1</td>
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</tr>
<tr>
<td>gate_prefix=</td>
<td>13.5.1</td>
<td>✓</td>
</tr>
<tr>
<td>reset_prefix=</td>
<td>13.5.1</td>
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</tr>
<tr>
<td>gate_input_clocks=</td>
<td>13.5.2</td>
<td>✓</td>
</tr>
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<td>gate_all_clocks</td>
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<td>✓</td>
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<td>default_clock_osc=</td>
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<tr>
<td>default_clock_gate=</td>
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<td>default_reset=</td>
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</tr>
<tr>
<td>clock_ancestors=</td>
<td>13.5.4</td>
<td>✓</td>
</tr>
</tbody>
</table>

#### 13.5.1 Clock and reset prefix naming attributes

The generated port renaming attributes `clock_prefix=`, `gate_prefix=`, and `reset_prefix=` rename the ports for the clock oscillators, clock gates, and resets in a module by specifying a prefix string to be added to each port name. The prefix is used only when a name is not provided for the port, (as described in Sections 13.5.3 and 13.6.1), requiring that the port name be created from the prefix and argument name. The attributes are associated with a module and are only applied when the module is synthesized.
### Clock Prefix Naming Attributes

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Default name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>clock_prefix=</td>
<td>CLK</td>
<td>Provides the prefix string to be added to port names for all the clock oscillators in a module.</td>
</tr>
<tr>
<td>gate_prefix=</td>
<td>CLK_GATE</td>
<td>Provides the prefix string to be added to port names for all the clock gates in a module.</td>
</tr>
<tr>
<td>reset_prefix=</td>
<td>RST_N</td>
<td>Provides the prefix string to be added to port names for all the resets in a module.</td>
</tr>
</tbody>
</table>

If a prefix is specified as the empty string, then no prefix will be used when creating the port names; that is the argument name alone will be used as the name.

Example:

```verilog
(* synthesize, clock_prefix = "CK" *)
module mkMod(Clock clk2, ModIfc ifc);
```

generates the following in the Verilog:

```verilog
module mkMod (CK, RST_N, CK_clk2, ...)
```

Where CK is the default clock (using the user-supplied prefix), RST_N is the default reset (using the default prefix), and CK_clk2 is the oscillator for the input clk2 (using the user-supplied prefix).

#### 13.5.2 Gate synthesis attributes

When a module is synthesized, one port, for the oscillator, is created for each clock input (including the default clock). The gate for the clock is defaulted to a logical 1. The attributes `gate_all_clocks` and `gate_input_clocks=` specify that a second port be generated for the gate.

The attribute `gate_all_clocks` will add a gate port to the default clock and to all input clocks. The attribute `gate_input_clocks=` is used to individually specify each input clock which should have a gate supplied by the parent module.

If an input clock is part of a vector of clocks, the gate port will be added to all clocks in the vector. Example:

```verilog
(* gate_input_clock = "clks, c2" *)
module mkM(Vector#(2, Clock) clks, Clock c2);
```

In this example, a gate port will be added to both the clocks in the vector clks and the clock c2. A gate port cannot be added to just one of the clocks in the vector clks.

The `gate_input_clocks=` attribute can be used to add a gate port to the default clock. Example:

```verilog
(* gate_input_clocks = "default_clock" *)
```

Note that by having a gate port, the compiler can no longer assume the gate is always logical 1. This can cause an error if the clock is connected to a submodule which requires the gate to be logical 1.

The gate synthesis attributes are associated with a module and are only applied when the module is synthesized.
13.5.3 Default clock and reset naming attributes

The default clock and reset naming attributes are associated with a module and are only applied when the module is synthesized.

The attributes `default_clock_osc=`, `default_clock_gate=`, and `default_reset=` provide the names for the default clock oscillator, default gate, and default reset ports for a module. When a name for the default clock or reset is provided, any prefix attribute for that port is ignored.

The attributes `default_gate_inhigh` and `default_gate_unused` indicate that a gate port should not be generated for the default clock and whether the gate is always logical 1 or unused. The default is `default_gate_inhigh`. This is only necessary when the attribute `gate_all_clocks` (section 13.5.2) has been used.

The attributes `no_default_clock` and `no_default_reset` are used to remove the ports for the default clock and the default reset.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>default_clock_osc=</code></td>
<td>Provides the name for the default oscillator port.</td>
</tr>
<tr>
<td><code>no_default_clock</code></td>
<td>Removes the port for the default clock.</td>
</tr>
<tr>
<td><code>default_clock_gate=</code></td>
<td>Provides the name for the default gate port.</td>
</tr>
<tr>
<td><code>default_gate_inhigh</code></td>
<td>Removes the gate ports for the module and the gate is always high.</td>
</tr>
<tr>
<td><code>default_gate_unused</code></td>
<td>Removes the gate ports for the module and the gate is unused.</td>
</tr>
<tr>
<td><code>default_reset=</code></td>
<td>Provides the name for the default reset port.</td>
</tr>
<tr>
<td><code>no_default_reset</code></td>
<td>Removes the port for the default reset.</td>
</tr>
</tbody>
</table>

13.5.4 Clock family attributes

The `clock_family` and `clock_ancestors` attributes indicate to the compiler that clocks are in the same domain in situations where the compiler may not recognize the relationship. For example, when clocks split in synthesized modules and are then recombined in a subsequent module, the compiler may not recognize that they have a common ancestor. The `clock_ancestors` and `clock_family` attributes allow the designer to explicitly specify the family relationship between the clocks. These attributes are applied to modules only.

The `clock_ancestors` attribute specifies an ancestry relationship between clocks. A clock is a gated version of its ancestors. In other words, if `clk1` is an ancestor of `clk2` then `clk2` is a gated version of `clk1`, as specified in the following statement:

```
(* clock_ancestors = "clk1 AOF clk2" *)
```

Multiple ancestors as well as multiple independent groups can be listed in a single attribute statement. For example:

```
(* clock_ancestors = "clk1 AOF clk2 AOF clk3, clk1 AOF clk4, clka AOF clkb" *)
```

The above statement specifies that `clk1` is an ancestor of `clk2`, which is itself an ancestor of `clk3`; that `clk1` is also an ancestor of `clk4`; and that `clka` is an ancestor of `clkb`. You can also repeat the attribute statement instead of including all clock ancestors in a single statement. Example:
For clocks which do not have an ancestor relationship, but do share a common ancestor, you can use the `clock_family` attribute. Clocks which are in the same family have the same oscillator with a different gate. To be in the same family, one does not have to be a gated version of the other, instead they may be gated versions of a common ancestor.

(* clock_family = "clk1, clk2, clk3" *)

Note that `clock_ancestors` implies `clock_family`.

### 13.6 Module argument and parameter attributes

The attributes in this section are applied to module arguments and module parameters. The following table shows which type of module argument or parameter each attribute can be applied to. More information on module arguments and module parameters can be found in Section 5.3.

In most instances BSV allows arguments and parameters to be enclosed in a single set of parentheses, in which case the `#` is eliminated. However, the compiler is stricter about where attributes are placed. Only port attributes can be placed in the attribute list `()` and only parameter attributes in the parameter `#()` list.

**Examples:**

(* synthesize *)

```verilog
module mkMod((* osc="ACLK", gate="AGATE" *) Clock clk,
  (* reset="RESET" *) Reset rst,
  ModIfc ifc);
```

```verilog
module mkMod #((* parameter="DATA_WIDTH" *) parameter Int#(8) width)
  ( ModIfc ifc );
```

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Section</th>
<th>Clock/ vector of clock</th>
<th>Reset/ vector of reset</th>
<th>Inout/ vector of inouts</th>
<th>Value argument</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>osc=</td>
<td>13.6.1</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gate=</td>
<td>13.6.1</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gate_inhigh</td>
<td>13.6.1</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gate_unused</td>
<td>13.6.1</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>reset=</td>
<td>13.6.1</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>clocked_by=</td>
<td>13.6.2</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>reset_by=</td>
<td>13.6.3</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>port=</td>
<td>13.6.4</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>parameter=</td>
<td>13.6.5</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>
13.6.1 Argument-level clock and reset naming attributes

The non-default clock and reset inputs to a module will have a port name created using the argument name and any associated prefix for that port type. This name can be overridden on a per-argument basis by supplying argument-level attributes that specify the names for the ports.

These attributes are applied to the clock module arguments, except for \texttt{reset=} which is applied to the reset module arguments.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Applies to</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>osc=</td>
<td>Clock or vector of clocks module arguments</td>
<td>Provides the full name of the oscillator port.</td>
</tr>
<tr>
<td>gate=</td>
<td>Clock or vector of clocks module arguments</td>
<td>Provides the full name of the gate port.</td>
</tr>
<tr>
<td>gate_inhigh</td>
<td>Clock or vector of clocks module arguments</td>
<td>Indicates that the gate port should be omitted and the gate is assumed to be high.</td>
</tr>
<tr>
<td>gate_unused</td>
<td>Clock or vector of clocks module arguments</td>
<td>Indicates that the gate port should be omitted and is never used within the module.</td>
</tr>
<tr>
<td>reset=</td>
<td>Reset or vector of resets module arguments</td>
<td>Provides the full name of the reset port.</td>
</tr>
</tbody>
</table>

Example:

\begin{verbatim}
(* synthesize *)
module mkMod((* osc="ACLK", gate="AGATE" *) Clock clk,
    (* reset="RESET" *) Reset rst,
    ModIfc ifc);
\end{verbatim}

generates the following in the Verilog:

\begin{verbatim}
module mkMod(CLK, RST_N, ACLK, AGATE, RESET, ...)
\end{verbatim}

The attributes can be applied to the base name generated for a vector of clocks, gates or resets.

Example:

\begin{verbatim}
(* synthesize *)
module mkMod((* osc="ACLK", gate="AGATE" *) Vector#(2, Clock) clks,
    (* reset="ARST" *) Vector#(2, Reset) rsts,
    ModIfc ifc);
\end{verbatim}

generates the following in the Verilog:

\begin{verbatim}
module mkMod(CLK, RST_N, ACLK_0, AGATE_0, ACLK_1, AGATE_1, ARST_0, ARST_1, ...)
\end{verbatim}

13.6.2 \texttt{clocked\_by=}  

The attribute \texttt{clocked\_by=} allows the user to assert which clock a reset, inout, or value module argument is associated with, to specify that the argument has \texttt{no\_clock}, or to associate the argument with the \texttt{default\_clock}. If the \texttt{clocked\_by=} attribute is not provided, the default clock will be used for inout and value arguments; the clock associated with a reset argument is derived from where the reset is connected.

Examples:
module mkMod (Clock c2, (* clocked_by="c2" *) Bool b,
   ModIfc ifc);
module mkMod (Clock c2, (* clocked_by="default_clock" *) Bool b,
   ModIfc ifc);
module mkMod (Clock c2, (* clocked_by="c2" *) Reset rstIn,
   (* clocked_by="default_clock" *) Inout q_inout,
   (* clocked_by="c2" *) Bool b,
   ModIfc ifc);

To specify that an argument is not associated with any clock domain, the clock no_clock is used. Example:

module mkMod (Clock c2, (* clocked_by="no_clock" *) Bool b,
   ModIfc ifc);

13.6.3 reset_by=

The attribute reset_by= allows the user to assert which reset an inout or value module argument is associated with, to specify that the argument has no_reset, or to associate the argument with the default_reset. If the reset_by= attribute is not provided, the default reset will be used. Examples:

module mkMod (Reset r2, (* reset_by="r2" *) Bool b,
   ModIfc ifc);
module mkMod (Reset r2, (* reset_by="default_reset" *) Inout q_inout,
   ModIfc ifc);

To specify that the port is not associated with any reset, no_reset is used. Example:

module mkMod (Reset r2, (* reset_by="no_reset" *) Bool b,
   ModIfc ifc);

13.6.4 port=

The attribute port= allows renaming of value module arguments. These are port-like arguments that are not clocks, resets or parameters. It provides the full name of the port generated for the argument. This is the same attribute as the port= attribute in Section 13.2.1, as applied to module arguments instead of interface methods.

module mkMod (a_type initValue, (* port="B" *) Bool b, ModIfc ifc);
module mkMod (((* port="PBUS" *) Inout#(Bit#(32)) pbus, ModIfc ifc);

13.6.5 parameter=

The attribute parameter= allows renaming of parameters in the generated RTL. This is similar to the port= attribute, except that the parameter= attribute can only be used for parameters in the moduleFormalParams list. More detail on module parameters can be found in Section 5.3. The name provided in the parameter= attribute statement is the name generated for the parameter in the RTL.

Example:
module mkMod #(
  (* parameter="DATA_WIDTH" *)
  parameter Int#(8) width)
  (ModIfc ifc);

13.7 Documentation attributes

A BSV design can specify comments to be included in the generated Verilog by use of the doc attribute.

<table>
<thead>
<tr>
<th>Attribute name</th>
<th>Section</th>
<th>Top-level module definitions</th>
<th>Submodule instantiations</th>
<th>rule definitions</th>
<th>rules expressions</th>
</tr>
</thead>
<tbody>
<tr>
<td>doc</td>
<td>13.7</td>
<td>√</td>
<td></td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>

Example:

(* doc = "This is a user-provided comment" *)

To provide a multi-line comment, either include a \n character:

(* doc = "This is one line
And this is another" *)

Or provide several instances of the doc attribute:

(* doc = "This is one line" *)
(* doc = "And this is another" *)

Or:

(* doc = "This is one line",
  doc = "And this is another" *)

Multiple doc attributes will appear together in the order that they are given. doc attributes can be added to modules, module instantiations, and rules, as described in the following sections.

13.7.1 Modules

The Verilog file that is generated for a synthesized BSV module contains a header comment prior to the Verilog module definition. A designer can include additional comments between this header and the module by attaching a doc attribute to the module being synthesized. If the module is not synthesized, the doc attributes are ignored.

Example:

(* synthesize *)
(* doc = "This is important information about the following module" *)
module mkMod (IFC);
...
endmodule
13.7.2 Module instantiation

In generated Verilog, a designer might want to include a comment on submodule instantiations, to document something about that submodule. This can be achieved with a doc attribute on the corresponding BSV module. There are three ways to express instantiation in BSV syntax, and the doc attribute can be attached to all three.

\[
\begin{align*}
(* \text{doc = "This submodule does something" *}) \\
\text{FIFO#(Bool) f();} \\
\text{mkFIFO the_f(f);} \\
\end{align*}
\]

\[
\begin{align*}
(* \text{doc = "This submodule does something else" *}) \\
\text{Server srv <- mkServer;} \\
\text{Client c;} \\
\text{...} \\
(* \text{doc = "This submodule does a third thing" *}) \\
\text{c <- mkClient;} \\
\end{align*}
\]

The syntax also works if the type of the module interface is given with let, a variable, or the current module type. Example:

\[
\begin{align*}
(* \text{doc = "This submodule does something else" *}) \\
\text{let srv <- mkServer;} \\
\end{align*}
\]

If the submodule being instantiated is a separately synthesized module or primitive, then its corresponding Verilog instantiation will be preceded by the comments. Example:

\[
\begin{align*}
// \text{submodule the_f} \\
// \text{This submodule does something} \\
\text{wire the_f$CLR, the_f$DEQ, the_f$ENQ;} \\
\text{FIFO2 #(.width(1)) the_f(...);} \\
\end{align*}
\]

If the submodule is not separately synthesized, then there is no place in the Verilog module to attach the comment. Instead, the comment is included in the header at the beginning of the module. For example, assume that the module the_sub was instantiated inside mkTop with a user-provided comment but was not separately synthesized. The generated Verilog would include these lines:

\[
\begin{align*}
// ... \\
// \text{Comments on the inlined module 'the_sub':} \\
// \text{This is the submodule} \\
// \text{module mkTop(...);} \\
\end{align*}
\]

The doc attribute can be attached to submodule instantiations inside functions and for-loops. If several submodules are inlined and their comments carry to the top-module's header comment, all of their comments are printed. To save space, if the comments on several modules are the same, the comment is only displayed once. This can occur, for instance, with doc attributes on instantiations inside for-loops. For example:

\[
\begin{align*}
// \text{Comments on the inlined modules 'the_sub_1', 'the_sub_2', 'the_sub_3':} \\
// \text{...} \\
\end{align*}
\]

118
If the `doc` attribute is attached to a register instantiation and the register is inlined (as is the default), the Verilog comment is included with the declaration of the register signals. Example:

```verilog
// register the_r
// This is a register
reg the_r;
wire the_r$D_IN, the_r$EN;
```

If the `doc` attribute is attached to an RWire instantiation, and the wire instantiation is inlined (as is the default), then the comment is carried to the top-module’s header comment.

If the `doc` attribute is attached to a probe instantiation, the comment appears in the Verilog above the declaration of the probe signals. Since the probe signals are declared as a group, the comments are listed at the start of the group. Example:

```verilog
// probes
//
// Comments for probe ‘the_r’:
// This is a probe
//
wire the_s$PROBE;
wire the_r$PROBE;
...
```

### 13.7.3 Rules

In generated Verilog, a designer might want to include a comment on rule scheduling signals (such as `CAN_FIRE_` and `WILL_FIRE_` signals), to say something about the actions that are performed when that rule is executed. This can be achieved with a `doc` attribute attached to a BSV rule declaration or rules expression.

The `doc` attribute can be attached to any `rule...endrule` or `rules...endrules` statement. Example:

```verilog
(* doc = "This rule is important" *)
rule do_something (b);
x <= !x;
endrule
```

If any scheduling signals for the rule are explicit in the Verilog output, their definition will be preceded by the comment. Example:

```verilog
// rule RL_do_something
// This rule is important
assign CAN_FIRE_RL_do_something = b;
assign WILL_FIRE_RL_do_something = CAN_FIRE_RL_do_something;
```

If the signals have been inlined or otherwise optimized away and thus do not appear in the Verilog, then there is no place to attach the comments. In that case, the comments are carried to the top module’s header. Example:

```verilog
// ...
// Comments on the inlined rule ‘RL_do_something’:
// This rule is important
//
module mkTop(...);
```
The designer can ensure that the signals will exist in the Verilog by using an appropriate compiler flag, the `-keep-fires` flag which is documented in the Bluespec SystemVerilog User Guide.

The `doc` attribute can be attached to any `rule..endrule` expression, such as inside a function or inside a for-loop.

As with comments on submodules, if the comments on several rules are the same, and those comments are carried to the top-level module header, the comment is only displayed once.

```verilog
// ...  
// Comments on the inlined rules `RL_do_something_2`, `RL_do_something_1`, 
// `RL_do_something`:  
// This rule is important  
//  
module mkTop(...);
```

# 14 Advanced topics

This section can be skipped on first reading.

## 14.1 Type classes (overloading groups) and provisos

Note that for most BSV programming, one just needs to know about a few predefined type classes such as `Bits` and `Eq`, about provisos, and about the automatic mechanism for defining the overloaded functions in those type classes using a `deriving` clause. The brief introduction in Sections 4.2 and 4.3 should suffice.

This section is intended for the advanced programmer who may wish to define new type classes (using a `typeclass` declaration), or explicitly to define overloaded functions using an `instance` declaration.

In programming languages, the term *overloading* refers to the use of a common function name or operator symbol to represent some number (usually finite) of functions with distinct types. For example, it is common to overload the operator symbol `+` to represent integer addition, floating point addition, complex number addition, matrix addition, and so on.

Note that overloading is distinct from *polymorphism*, which is used to describe a single function or operator that can operate at an infinity of types. For example, in many languages, a single polymorphic function `arraySize()` may be used to determine the number of elements in any array, no matter what the type of the contents of the array.

A type class (or overloading group) further recognizes that overloading is often performed with related groups of function names or operators, giving the group of related functions and operators a name. For example, the type class `Ord` contains the overloaded operators for order-comparison: `<`, `<=`, `>`, and `>=`.

If we specify the functions represented by these operator symbols for the types `int`, `Bool`, `bit[m:0]` and so on, we say that those types are instances of the `Ord` type class.

A proviso is a (static) condition attached to some constructs. A proviso requires that certain types involved in the construct must be instances of certain type classes. For example, a generic `sort` function for sorting lists of type `List#(t)` will have a proviso (condition) that `t` must be an instance of the `Ord` type class, because the generic function uses an overloaded comparison operator from that type class, such as the operator `< or >`.

Type classes are created explicitly using a `typeclass` declaration (Section 14.1.2). Further, a type class is explicitly populated with a new instance type `t`, using an `instance` declaration (Section 14.1.3), in which the programmer provides the specifications for the overloaded functions for the type `t`.

120
14.1.1 Provisos

Consider the following function prototype:

\[
\text{function List#(t) sort (List#(t) xs)} \\
\text{\hspace{1em} provisos (Ord#(t))};
\]

This prototype expresses the idea that the sorting function takes an input list \(xs\) of items of type \(t\) (presumably unsorted), and produces an output list of type \(t\) (presumably sorted). In order to perform its function it needs to compare elements of the list against each other using an overloaded comparison operator such as \(<\). This, in turn, requires that the overloaded operator be defined on objects of type \(t\). This is exactly what is expressed in the proviso, i.e., that \(t\) must be an instance of the type class (overloading group) \(\text{Ord}\), which contains the overloaded operator \(<\).

Thus, it is permissible to apply \(\text{sort}\) to lists of \text{Integers} or lists of \text{Bools}, because those types are instances of \(\text{Ord}\), but it is not permissible to apply \(\text{sort}\) to a list of, say, some interface type \(\text{Ifc}\) (assuming \(\text{Ifc}\) is not an instance of the \(\text{Ord}\) type class).

The syntax of provisos is the following:

\[
\begin{align*}
\text{provisos} & \quad ::= \quad \text{provisos ( proviso \{ , proviso \} )} \\
\text{proviso} & \quad ::= \quad \text{Identifier \#(type \{ , type \})}
\end{align*}
\]

In each proviso, the \text{Identifier} is the name of type class (overloading group). In most provisos, the type class name \(T\) is followed by a single type \(t\), and can be read as a simple assertion that \(t\) is an instance of \(T\), i.e., that the overloaded functions of type class \(T\) are defined for the type \(t\). In some provisos the type class name \(T\) may be followed by more than one type \(t_1, \ldots, t_n\) and these express more general relationships. For example, a proviso like this:

\[
\text{provisos (Bits#(macAddress, 48))}
\]

can be read literally as saying that the types \(\text{macAddress}\) and \(48\) are in the \text{Bits} type class, or can be read more generally as saying that values of type \(\text{macAddress}\) can be converted to and from values of the type \text{bit}[47:0] using the \text{pack} and \text{unpack} overloaded functions of type class \text{Bits}.

We sometimes also refer to provisos as contexts, meaning that they constrain the types that may be used within the construct to which the provisos are attached.

Occasionally, if the context is too weak, the compiler may be unable to figure out how to resolve an overloading. Usually the compiler’s error message will be a strong hint about what information is missing. In these situations it may be necessary for the programmer to guide the compiler by adding more type information to the program, in either or both of the following ways:

- Add a static type assertion (Section 9.10) to some expression that narrows down its type.
- Add a proviso to the surrounding construct.

14.1.2 Type class declarations

A new class is declared using the following syntax:

\[
\begin{align*}
\text{typeclassDef} & \quad ::= \quad \text{typeclass typeclassIde typeFormals [ provisos ]} \\
& \hspace{1em} [ typedepends ] ; \\
& \quad \{ \text{overloadedDef} \} \\
& \quad \text{endtypeclass} [ : \text{typeclassIde} ] \\
\text{typeclassIde} & \quad ::= \quad \text{Identifier}
\end{align*}
\]
The `typeclassIde` is the newly declared class name. The `typeFormals` represent the types that will be instances of this class. These `typeFormals` may themselves be constrained by `provisos`, in which case the classes named in `provisos` are called the “super type classes” of this type class. Type dependencies (`typedepends`) are relevant only if there are two or more `type` parameters; the `typedepends` comes after the typeclass’s `provisos` (if any) and before the semicolon. The `overloadedDefs` declare the overloaded variables or function names, and their types.

Example (from the Standard Prelude package):

```plaintext

typeclass Literal#(type a);
    function a fromInteger (Integer x);
    function Bool inLiteralRange(a target, Integer i);
endtypeclass: Literal
```

This defines the type class `Literal`. Any type `a` that is an instance of `Literal` must have an overloaded function called `fromInteger` that converts an `Integer` value into the type `a`. In fact, this is the mechanism that BSV uses to interpret integer literal constants, e.g., to resolve whether a literal like `6847` is to be interpreted as a signed integer, an unsigned integer, a floating point number, a bit value of 10 bits, a bit value of 8 bits, etc. (See Section 2.3.1 for a more detailed description.).

The typeclass also provides a function `inLiteralRange` that takes an argument of type `a` and an `Integer` and returns a `Bool`. In the standard `Literal` typeclass this boolean indicates whether or not the supplied `Integer` is in the range of legal values for the type `a`.

Example (from a predefined type class in BSV):

```plaintext

typeclass Bounded#(type a);
    a minBound;
    a maxBound;
endtypeclass
```

This defines the type class `Bounded`. Any type `a` that is an instance of `Bounded` will have two values called `minBound` and `maxBound` that, respectively, represent the minimum and maximum of all values of this type.

Example (from a predefined type class in BSV):^10

```plaintext

typeclass Arith #(type data_t)
    provisos (Literal#(data_t));
    function data_t "+" (data_t x, data_t y);
    function data_t "-" (data_t x, data_t y);
    function data_t negate (data_t x);
```

---

^10 We are using Verilog’s notation for `escaped identifiers` to treat operator symbols as ordinary identifiers. The notation allows an identifier to be constructed from arbitrary characters beginning with a backslash and ending with a whitespace (the backslash and whitespace are not part of the identifier.)
This defines the type class `Arith` with super type class `Literal`, i.e., the proviso states that in order for a type `data_t` to be an instance of `Arith` it must also be an instance of the type class `Literal`. Further, it has six overloaded functions with the given names and types. Said another way, a type that is an instance of the `Arith` type class must have a way to convert integer literals into that type, and it must have addition, subtraction, negation, multiplication, and division defined on it.

The semantics of a dependency say that once the types on the left of the `determines` keyword are fixed, the types on the right are uniquely determined. The types on either side of the list can be a single type or a list of types, in which case they are enclosed in parentheses.

Example of a typeclass definition specifying type dependencies:

```
typeclass Connectable #(type a, type b)
    dependencies (a determines b, b determines a);
    module mkConnection#(a x1, b x2) (Empty);
endtypeclass
```

For any type `t` we know that `Get#(t)` and `Put#(t)` are connectable because of the following declaration in the `GetPut` package:

```
instance Connectable#(Get#(element_type), Put#(element_type));
```

In the `Connectable` dependency above, it states that `a` determines `b`. Therefore, you know that if `a` is `Get#(t)`, the only possibility for `b` is `Put#(t)`.

Example of a typeclass definition with lists of types in the dependencies:

```
typeclass Extend #(type a, type b, type c)
    dependencies ((a,c) determines b, (b,c) determines a);
endtypeclass
```

An example of a case where the dependencies are not commutative:

```
typeclass Bits#(type a, type sa)
    dependencies (a determines sa);
    function Bit#(sa) pack(a x);
    function a unpack (Bit#(sa) x);
endtypeclass
```

In the above example, if `a` were `UInt#(16)` the dependency would require that `b` had to be 16; but the fact that something occupies 16 bits by no means implies that it has to be a `UInt`.

### 14.1.3 Instance declarations

A type can be declared to be an instance of a class in two ways, with a general mechanism or with a convenient shorthand. The general mechanism of `instance` declarations is the following:

```
typeclassInstanceDef ::= instance typeclassIde # ( type { , type } ) [ provisos ] ;
    { varAssign ; | functionDef | moduleDef }
endinstance | : typeclassIde |
```
This says that the *types* are an instance of type class *typeclassIde* with the given provisos. The *varAssigns*, *functionDefs* and *moduleDefs* specify the implementation of the overloaded identifiers of the type class.

Example, declaring a type as an instance of the Eq typeclass:

```plaintext
typedef enum { Red, Blue, Green } Color;

instance Eq#(Color);
    function Bool \== (Color x, Color y); //must use \== with a trailing
        return True; //space to define custom instances
    endfunction //of the Eq typeclass
endinstance
```

The shorthand mechanism is to attach a *deriving* clause to a typedef of an enum, struct or tagged union and let the compiler do the work. In this case the compiler chooses the "obvious" implementation of the overloaded functions (details in the following sections). The only type classes for which *deriving* can be used for general types are *Bits*, *Eq*, *Bounded*, and *FShow*. Furthermore, *deriving* can be used for any class if the type is a data type that is isomorphic to a type that has an instance for the derived class.

```
derives ::= deriving ( typeclassIde { , typeclassIde } )
```

Example:

```plaintext
typedef enum { Red, Blue, Green } Color deriving (Eq);
```

### 14.1.4 The Bits type class (overloading group)

The type class *Bits* contains the types that are convertible to bit strings of a certain size. Many constructs have membership in the *Bits* class as a proviso, such as putting a value into a register, array, or FIFO.

Example: The *Bits* type class definition (which is actually predefined in BSV) looks something like this:

```plaintext
typeclass Bits#(type a, type n);
    function Bit#(n) pack (a x);
    function a unpack (Bit#(n) y);
endtypeclass
```

Here, *a* represents the type that can be converted to/from bits, and *n* is always instantiated by a size type (Section 4) representing the number of bits needed to represent it. Implementations of modules such as registers and FIFOs use these functions to convert between values of other types and the bit representations that are really stored in those elements.

Example: The most trivial instance declaration states that a bit-vector can be converted to a bit vector, by defining both the *pack* and *unpack* functions to be identity functions:

```plaintext
instance Bits#(Bit#(k), k);
    function Bit#(k) pack (Bit#(k) x);
        return x;
    endfunction: pack

    function Bit#(k) unpack (Bit#(k) x);
        return x;
    endfunction: unpack
endinstance
```

124
Example:

```verilog
typedef enum { Red, Green, Blue } Color deriving (Eq);

instance Bits#(Color, 2);
    function Bit#(2) pack (Color c);
        if (c == Red) return 3;
        else if (c == Green) return 2;
        else return 1; // (c == Blue)
    endfunction: pack

function Color unpack (Bit#(2) x);
    if (x == 3) return Red;
    else if (x == 2) return Green;
    else if (x == 1) return Blue;
    else ? //Illegal opcode; return unspecified value
    endfunction: unpack
endinstance
```

Note that the `deriving (Eq)` phrase permits us to use the equality operator `==` on `Color` types in the `pack` function. `Red`, `Green` and `Blue` are coded as 3, 2 and 1, respectively. If we had used the `deriving(Bits)` shorthand in the `Color` typedef, they would have been coded as 0, 1 and 2, respectively (Section 14.1.6).

### 14.1.5 The `SizeOf` pseudo-function

The pseudo-function `SizeOf#(t)` can be applied to a type `t` to get the numeric type representing its bit size. The type `t` must be in the `Bits` class, i.e., it must already be an instance of `Bits#(t,n)`, either through a `deriving` clause or through an explicit instance declaration. The `SizeOf` function then returns the corresponding bit size `n`. Note that `SizeOf` returns a numeric type, not a numeric value, i.e., the output of `SizeOf` can be used in a type expression, and not in a value expression.

`SizeOf`, which converts a type to a (numeric) type, should not be confused with the pseudo-function `valueOf`, described in Section 4.2.1, which converts a numeric type to a numeric value.

Example:

```verilog
typedef Bit#(8) MyType;
// MyType is an alias of Bit#(8)

typedef SizeOf#(MyType) NumberOfBits;
// NumberOfBits is a numeric type, its value is 8

Integer ordinaryNumber = valueOf(NumberOfBits);
// valueOf converts a numeric type into Integer
```

### 14.1.6 Deriving Bits

When attaching a `deriving(Bits)` clause to a user-defined type, the instance derived for the `Bits` type class can be described as follows:

- For an enum type it is simply an integer code, starting with zero for the first enum constant and incrementing by one for each subsequent enum constant. The number of bits used is the minimum number of bits needed to represent distinct codes for all the enum constants.
• For a struct type it is simply the concatenation of the bits for all the members. The first member is in the leftmost bits (most significant) and the last member is in the rightmost bits (least significant).

• For a tagged union type, all values of the type occupy the same number of bits, regardless of which member it belongs to. The bit representation consists of two parts—a tag on the left (most significant) and a member value on the right (least significant).

The tag part uses the minimum number of bits needed to code for all the member names. The first member name is given code zero, the next member name is given code one, and so on.

The size of the member value part is always the size of the largest member. The member value is stored in this field, right-justified (i.e., flush with the least-significant end). If the member value requires fewer bits than the size of the field, the intermediate bits are don’t-care bits.

Example. Symbolic names for colors:

typedef enum { Red, Green, Blue } Color deriving (Eq, Bits);

This is the same type as in Section 14.1.4 except that Red, Green and Blue are now coded as 0, 1 and 2, instead of 3, 2, and 1, respectively, because the canonical choice made by the compiler is to code consecutive labels incrementing from 0.

Example. The boolean type can be defined in the language itself:

typedef enum { False, True } Bool deriving (Bits);

The type Bool is represented with one bit. False is represented by 0 and True by 1.

Example. A struct type:

typedef struct { Bit#(8) foo; Bit#(16) bar } Glurph deriving (Bits);

The type Glurph is represented in 24 bits, with foo in the upper 8 bits and bar in the lower 16 bits.

Example. Another struct type:

typedef struct { int x; int y } Coord deriving (Bits);

The type Coord is represented in 64 bits, with x in the upper 32 bits and y in the lower 32 bits.

Example. The Maybe type from Section 7.3:

typedef union tagged {
  void Invalid;
  a Valid;
} Maybe#(type a)
  deriving (Bits);

is represented in 1 + n bits, where n bits are needed to represent values of type a. If the leftmost bit is 0 (for Invalid) the remaining n bits are unspecified (don’t-care). If the leftmost bit is 1 (for Valid) then the remaining n bits will contain a value of type a.
14.1.7 Deriving Eq

The Eq type class contains the overloaded operators == (logical equality) and != (logical inequality):

```plaintext
typeclass Eq#(type a);
  function Bool == (a x1, a x2);
  function Bool /= (a x1, a x2);
endtypeclass: Eq
```

When deriving(Eq) is present on a user-defined type definition t, the compiler defines these equality/inequality operators for values of type t. It is the natural recursive definition of these operators, i.e.,

- If t is an enum type, two values of type t are equal if they represent the same enum constant.
- If t is a struct type, two values of type t are equal if the corresponding members are pairwise equal.
- If t is a tagged union type, two values of type t are equal if they have the same tag (member name) and the two corresponding member values are equal.

14.1.8 Deriving Bounded

The predefined type class Bounded contains two overloaded identifiers minBound and maxBound representing the minimum and maximum values of a type a:

```plaintext
typeclass Bounded#(type a);
  a minBound;
  a maxBound;
endtypeclass
```

The clause deriving(Bounded) can be attached to any user-defined enum definition t, and the compiler will define the values minBound and maxBound for values of type t as the first and last enum constants, respectively.

The clause deriving(Bounded) can be attached to any user-defined struct definition t with the proviso that the type of each member is also an instance of Bounded. The compiler-defined minBound (or maxBound) will be the struct with each member having its respective minBound (respectively, maxBound).

14.1.9 Deriving FShow

The intent of the FShow type class is to format values for use with the $display family of functions. When attaching a deriving(FShow) clause to a user-defined type, the instance derived for the FShow type class can be described as follows:

- For an enum type, the output contains the enumerated value.
  Example:

  ```plaintext
typedef enum { Red, Blue, Green } Colors deriving (FShow);
  ...
  $display("Basic enum");
  ```
Colors be0 = Red;
Colors be1 = Blue;
Colors be2 = Green;
$display(fshow(be0));
$display(fshow(be1));
$display(fshow(be2));

Displays:

Basic enum
Red
Blue
Green

• For a struct type, the output contains the struct name, with each value prepended with the name of the field. The values are formatted with FShow according to the data type.

  Struct_name {field1_name: value1, field2_name: value2,...}

Example:

typedef struct {
  Bool   val_bool;
  Bit#(8) val_bit;
  UInt#(16) val_uint;
  Int#(32) val_int;
} BasicS deriving (FShow);
...
$display("Basic struct");
  BasicS bs1 =
    BasicS { val_bool: True, val_bit: 22,
             val_uint: 'hABCD, val_int: -'hABCD };
  $display(fshow(bs1));

Displays:

Basic struct
BasicS { val_bool: True, val_bit: 'h16, val_uint: 43981, val_int: -43981 }

• For a tagged union type, the output contains the name of the tag followed by the value. The values are formatted with FShow according to the data type.

  tagged Tag1 value1
tagged Tag2 value2

Example:

typedef union tagged {
  Bool   Val_bool;
  Bit#(8) Val_bit;
  UInt#(16) Val_uint;
  Int#(32) Val_int;
} BasicU deriving (FShow);
...
```SystemVerilog
$display("Basic tagged union");
BasicU bu0 = tagged Val_bool True;
BasicU bu1 = tagged Val_bit 22;
BasicU bu2 = tagged Val_uint 'hABCD;
BasicU bu3 = tagged Val_int -'hABCD;
$display(fshow(bu0));
$display(fshow(bu1));
$display(fshow(bu2));
$display(fshow(bu3));
```

Displays:

```
Basic tagged union
tagged Val_bool True
ntagged Val_bit 'h16
tagged Val_uint 43981
tagged Val_int -43981
```

### 14.1.10 Deriving type class instances for isomorphic types

Generally speaking, the `deriving(...)` clause can only be used for the predefined type classes `Bits`, `Eq`, `Bounded`, and `FShow`. However there is a special case where it can be used for any type class. When a user-defined type `t` is *isomorphic* to an existing type `t'`, then all the functions on `t'` automatically work on `t`, and so the compiler can trivially derive a function for `t` by just using the corresponding function for `t'`.

There are two situations where a newly defined type is isomorphic to an old type: a struct or tagged union with precisely one member. For example:

```SystemVerilog
typedef struct { t' x; } t deriving (anyClass);
typedef union tagged { t' X; } t deriving (anyClass);
```

One sometimes defines such a type precisely for type-safety reasons because the new type is distinct from the old type although isomorphic to it, so that it is impossible to accidentally use a `t` value in a `t'` context and vice versa. Example:

```SystemVerilog
typedef struct { UInt#(32) x; } Apples deriving (Literal, Arith);
...
Apples five;
...
five = 5; // ok, since RHS applies 'fromInteger()' from Literal // class to Integer 5 to create an Apples value

function Apples eatApple (Apples n);
    return n - 1; // '1' is converted to Apples by fromInteger()
    // '-' is available on Apples from Arith class
endfunction: eatApple
```

The typedef could also have been written with a singleton tagged union instead of a singleton struct:

```SystemVerilog
typedef union tagged { UInt#(32) X; } Apples deriving (Literal, Arith);
```

```SystemVerilog
```
14.1.11 Monad

The Monad typeclass is an abstraction which allows different composition strategies and is useful for combining computations into more complex computations. The definition and use of monads in BSV is the standard definition as used in other programming languages.

The Monad instance for Module and Action are how statements in those blocks are composed, which is why you can use `replicateM` and `mapM` in those blocks. Monad is mostly only needed inside libraries and not something that users will be working with directly, so beyond modules and actions, this is an advanced topic that isn’t commonly used.

14.2 Higher-order functions

In BSV it is possible to write an expression whose value is a function value. These function values can be passed as arguments to other functions, returned as results from functions, and even carried in data structures.

Example - the function `map`, as defined in the package Vector (C.3.8):

```verilog
function Vector#(vsize, b_type) map (function b_type func (a_type x),
        Vector#(vsize, a_type) xvect);
    Vector#(vsize, b_type) yvect = newVector;
    for (Integer j = 0; j < valueof(vsize); j=j+1)
        yvect[j] = func (xvect[j]);
    return yvect;
endfunction: map

function int sqr (int x);
    return x * x;
endfunction: sqr

Vector#(100,int) avect = ...; // initialize vector avect
Vector#(100,int) bvect = map (sqr, avect);
```

The function `map` is polymorphic, i.e., is defined for any size type `vsize` and value types `a_type` and `b_type`. It takes two arguments:

- A function `func` with input of type `a_type` and output of type `b_type`.
- A vector `xvect` of size `vsize` containing values of type `a_type`.

Its result is a new vector `yvect` that is also of size `vsize` and containing values of type `b_type`, such that `yvect[j]=func(xvect[j])`. In the last line of the example, we call `map` passing it the `sqr` function and the vector `avect` to produce a vector `bvect` that contains the squared versions of all the elements of vector `avect`.

Observe that in the last line, the expression `sqr` is a function-valued expression, representing the squaring function. It is not an invocation of the `sqr` function. Similarly, inside `map`, the identifier `func` is a function-valued identifier, and the expression `func (xsize [j])` invokes the function.

The function `map` could be called with a variety of arguments:
// Apply the extend function to each element of avect
Vector#(13, Bit#(5)) avect;
Vector#(13, Bit#(10)) bvect;
...
bvect = map(extend, avect);

or

// test all elements of avect for even-ness
Vector#(100, Bool) bvect = map(isEven, avect);

In other words, map captures, in one definition, the generic idea of applying some function to all elements of a vector and returning all the results in another vector. This is a very powerful idea enabled by treating functions as first-class values. Here is another example, which may be useful in many hardware designs:

interface SearchableFIFO#(type element_type);
    ... usual enq() and deq() methods ...
    method Bool search (element_type key);
endinterface: SearchableFIFO

module mkSearchableFIFO#(function Bool test_func
    (element_type x, element_type key))
    (SearchableFIFO#(element_type));
    ...
    method Bool search (element_type key);
        ... apply test_func(x, key) to each element of the FIFO, ...
        ... return OR of all results ...
    endmethod: search
endmodule: mkSearchableFIFO

The SearchableFIFO interface is like a normal FIFO interface (contains usual enq() and deq() methods), but it has an additional bit of functionality. It has a search() method to which you can pass a search key key, and it searches the FIFO using that key, returning True if the search succeeds.

Inside the mkSearchableFIFO module, the method applies some element test predicate test_func to each element of the FIFO and ORs all the results. The particular element-test function test_func to be used is passed in as a parameter to mkSearchableFIFO. In one instantiation of mkSearchableFIFO we might pass in the equality function for this parameter (“search this FIFO for this particular element”). In another instantiation of mkSearchableFIFO we might pass in the “greater-than” function (“search this FIFO for any element greater than the search key”). Thus, a single FIFO definition captures the general idea of being able to search a FIFO, and can be customized for different applications by passing in different search functions to the module constructor.

A final important point is that all this is perfectly synthesizable in BSV, i.e., the compiler can produce RTL hardware for such descriptions. Since polymorphic modules cannot be synthesized, for synthesis a non-polymorphic version of the module would have to be instantiated.

14.3 Module types

There are many types of modules in BSV. The default BSV module type is Module#(ifc). When instantiated, a Module adds state elements and rules to the accumulation of elements and rules
already in the design. This is the only synthesizable module type, but other types can exist. For instance, the type `ModuleCollect#(t,ifc)`, defined in Section C.10.2, allows items other than states and rules to be collected while elaborating the module structure.

For most applications the modules in the design will be of type `Module` and the type can be inferred. When you write:

```plaintext
module mkMod(Ifc);
...
endmodule
```

the compiler doesn’t force this code to be specific to the basic `Module` type, although it usually will be. BSV allows this syntax to be used for any type of module; what you are declaring here is a polymorphic module. In fact, it is really just a function that returns a module type. But instead of returning back the type `Module`, it returns back any type `m` with the proviso that `m` is a module. That is expressed with the proviso:

```plaintext
IsModule#(m,c)
```

However, if the code for `mkMod` uses a feature that is specific to one type of module, such as trying to add to the collection in a `ModuleCollect` module, then type inference will discover that your module can’t be any module type `m`, but must be a specific type (such as `ModuleCollect` in this example).

In that case, you need to declare that the module `mkMod` works for a specific module type using the bracket syntax:

```plaintext
module [ModuleCollect#(t)] mkMod(Ifc);
```

In some instances, type inference will determine that the module must be the specific type `Module`, and you may get a signature mismatch error stating that where the code said any module type `m`, it really has to be `Module`. This can be fixed by explicitly stating the module type in the module declaration:

```plaintext
module [Module] mkMod(Ifc);
```

15 Embedding RTL in a BSV design

This section describes how to embed existing RTL modules, Verilog or VHDL, in a BSV module. The `import "BVI"` statement is used to utilize existing components, utilize components generated by other tools, or to define a custom set of primitives. One example is the definition of BSV primitives (registers, FIFOs, etc.), which are implemented through import of Verilog modules. The `import "BVI"` statement creates a Bluespec wrapper around the RTL module so that it looks like a BSV module. Instead of ports, the wrapped module has methods and interfaces.

The `import "BVI"` statement can be used to wrap Verilog or VHDL modules. Throughout this section Verilog will be used to refer to either Verilog or VHDL. (One limitation for VHDL is that BSV does not support two dimensional ports.)
The body consists of a sequence of `importBVIStmts`:

```
importBVIStmt ::= parameterBVIStmt
                  | methodBVIStmt
                  | portBVIStmt
                  | inputClockBVIStmt
                  | defaultClockBVIStmt
                  | outputClockBVIStmt
                  | inputResetBVIStmt
                  | defaultResetBVIStmt
                  | noResetBVIStmt
                  | outputResetBVIStmt
                  | ancestorBVIStmt
                  | sameFamilyBVIStmt
                  | scheduleBVIStmt
                  | pathBVIStmt
                  | interfaceBVIStmt
                  | inoutBVIStmt
```

The optional `identifier` immediately following the "BVI" is the name of the Verilog module to be imported. This will usually be found in a Verilog file of the same name (`identifier.v`). If this `identifier` is excluded, it is assumed that the Verilog module name is the same as the BSV name of the module.

The `moduleProto` is the first line in the module definition as described in Section 5.3.

The BSV wrapper returns an interface. All arguments and return values must be in the `Bits` class or be of type `Clock`, `Reset`, `Inout`, or a subinterface which meets these requirements. Note that the BSV module's parameters have no inherent relationship to the Verilog module's parameters. The BSV wrapper is used to connect the Verilog ports to the BSV parameters, performing any data conversion, such as packs or unpacks, as necessary.

Example of the header of a BVI import statement:

```verbatim
import "BVI" RWire =
    module RWire (VRWire#(a))
        provisos (Bits#(a,sa));
...
endmodule: vMkRWire
```

Since the Verilog module’s name matches the BSV name, the header could be also written as:

```verbatim
import "BVI"
    module RWire (VRWire#(a))
        provisos (Bits#(a,sa));
...
endmodule: vMkRWire
```

The module body may contain both `moduleStmts` and `importBVIStmts`. Typically when including a Verilog module, the only module statements would be a few local definitions. However, all module statements, except for method definitions, subinterface definitions, and return statements, are valid, though most are rarely used in this instance. Only the statements specific to `importBVIStmt` bodies are described in this section.

The `importBVIStmts` must occur at the end of the body, after the `moduleStmts`. They may be written in any order.

The following is an example of embedding a Verilog SRAM model in BSV. The Verilog file is shown after the BSV wrapper.
import "BVI" mkVerilog_SRAM_model =
module mkSRAM #(String filename) (SRAM_Ifc #(addr_t, data_t))
provisos(Bits#(addr_t, addr_width),
    Bits#(data_t, data_width));
parameter FILENAME = filename;
parameter ADDRESS_WIDTH = valueOf(addr_width);
parameter DATA_WIDTH = valueOf(data_width);
method request (v_in_address, v_in_data, v_in_write_not_read)
    enable (v_in_enable);
method v_out_data read_response;
default_clock clk(clk, (*unused*) clk_gate);
default_reset no_reset;
schedule (read_response) SB (request);
endmodule

This is the Verilog module being wrapped in the above BVI import statement.

module mkVerilog_SRAM_model (clk,
    v_in_address, v_in_data,
    v_in_write_not_read,
    v_in_enable,
    v_out_data);
parameter FILENAME = "Verilog_SRAM_model.data";
parameter ADDRESS_WIDTH = 10;
parameter DATA_WIDTH = 8;
parameter NWORDS = (1 << ADDRESS_WIDTH);

input clk;
input [ADDRESS_WIDTH-1:0] v_in_address;
input [DATA_WIDTH-1:0] v_in_data;
input v_in_write_not_read;
input v_in_enable;
output [DATA_WIDTH-1:0] v_out_data;
...
endmodule

15.1 Parameter

The parameter statement specifies the parameter values which will be used by the Verilog module.

\[
\text{parameterBVIStmt} ::= \text{parameter}\ identifier = \text{expression} ;
\]

The value of \text{expression} is supplied to the Verilog module as the parameter named \text{identifier}. The \text{expression} must be a compile-time constant. The valid types for parameters are \text{String}, \text{Integer} and \text{Bit#}(n). Example:

import "BVI" ClockGen =
module vAbsoluteClock#(Integer start, Integer period)
    ( ClockGenIfc );
    let halfPeriod = period/2 ;
    parameter initDelay = start; //the parameters start,
    parameter v1Width = halfPeriod ; //halfPeriod and period
    parameter v2Width = period - halfPeriod ; //must be compile-time constants
...
endmodule
15.2 Method

The method statement is used to connect methods in a Bluespec interface to the appropriate Verilog wires. The syntax imitates a function prototype in that it doesn’t define, but only declares. In the case of the method statement, instead of declaring types, it declares ports.

```
methodBVISstmt ::= method [ portId ] identifer [ ([ portId { , portId } ] ) ]
[ enable ( portId ) | ready ( portId ) ]
[ clocked_by ( clockId ) | reset_by ( resetId ) ]
```

The first portId is the output port for the method, and is only used when the method has a return value. The identifier is the method’s name according to the BSV interface definition. The parenthesized list is the input port names corresponding to the method’s arguments, if there are any. There may follow up to four optional clauses (in any order): enable (for the enable input port if the method has an Action component), ready (for the ready output port), clocked_by (to indicate the clock of the method, otherwise the default clock will be assumed) and reset_by (for the associated reset signal, otherwise the default reset will be assumed). If no ready port is given, the constant value 1 is used meaning the method is always ready. The names no_clock and no_reset can be used in clocked_by and reset_by clauses indicating that there is no associated clock and no associated reset, respectively.

If the input port list is empty and none of the optional clauses are specified, the list and its parentheses may be omitted. If any of the optional clauses are specified, the empty list () must be shown. Example:

```
method CLOCKREADY_OUT clockready() clocked_by(clk);
```

If there was no clocked_by statement, the following would be allowed:

```
method CLOCKREADY_OUT clockready;
```

The BSV types of all the method’s arguments and its result (if any) must all be in the Bits typeclass. Any of the port names may have an attribute attached to them. The allowable attributes are reg, const, unused, and inhigh. The attributes are translated into port descriptions. Not all port attributes are allowed on all ports.

For the output ports, the ready port and the method return value, the properties reg and const are allowed. The reg attribute specifies that the value is coming directly from a register with no intermediate logic. The const attribute indicates that the value is hardwired to a constant value.

For the input ports, the input arguments and the enable port, reg and unused are allowed. In this context reg specifies that the value is immediately written to a register without intermediate logic. The attribute unused indicates that the port is not used inside the module; its value is ignored.

Additionally, for the method enable, there is the inhigh property, which indicates that the method is always enabled, as described in Section 13.2.2. Inside the module, the value of the enable is assumed to be 1 and, as a result, the port doesn’t exist. The user still gives a name for the port as a placeholder. Note that only Action or ActionValue methods can have an enable signal.

The following code fragment shows an attribute on a method enable:

```
method load(flopA, flopB) enable((*inhigh*) EN);
```

The output ports may be shared across methods (and ready signals).
15.3 Port

The `port` statement declares an input port, which is not part of a method, along with the value to be passed to the port. While parameters must be compile-time constants, ports can be dynamic. The `port` statements are analogous to arguments to a BSV module, but are rarely needed, since BSV style is to interact and pass arguments through methods.

```plaintext
portBVISstmt ::= port identifier [ clocked_by ( clockId ) ]
[ reset_by ( resetId ) ] = expression ;
```

The `clocked_by` clause is used to specify the clock domain that the port is associated with, named by `clockId`. Any clock in the domain may be used. The values `no_clock` and `default_clock`, as described in Section 15.5, may be used. If the clause is omitted, the associated clock is the default clock.

The `reset_by` clause is used to specify the reset the port is associated with, named by `resetId`. Any reset in the domain may be used. The values `no_reset` and `default_reset`, as described in Section 15.8 may be used. If the clause is omitted, the associated reset is the default reset.

Example - Setting port widths to a specific width:

```plaintext
// Tie off the test ports
Bit#(1) v = 0 ;
port TM = v ; // This ties off the port TM to a 1 bit wide 0
Bit#(w) z = 0 ;
port TD = z ; // This ties off the port TD to w bit wide 0
```

15.4 Input clock

The `input_clock` statement specifies how an incoming clock to a module is connected. Typically, there are two ports, the oscillator and the gate, though the connection may use fewer ports.

```plaintext
inputClockBVISstmt ::= input_clock [ identifier | [ [ portsDef ] ] = expression ;
portsDef ::= portId [ , [ attributeInstances ] portId ]
portId ::= identifier
```

The `clocked_by` clause is used to specify the clock domain that the port is associated with, named by `clockId`. Any clock in the domain may be used. The values `no_clock` and `default_clock`, as described in Sections 15.7 and 15.2. The `portsDef` statement describes the ports that define the clock. The clock value which is being connected is given by `expression`.
If the expression is an identifier being assigned with =, and the user wishes this to be the name of the clock, then the identifier of the clock can be omitted and the expression will be assumed to be the name. The clock name can be omitted in other circumstances, but then no name is associated with the clock. An unnamed clock cannot be referred to elsewhere, such as in a method or reset or other statement. Example:

\[
\text{input\_clock (OSC, GATE) = clk;}
\]

is equivalent to:

\[
\text{input\_clock clk (OSC, GATE) = clk;}
\]

The user may leave off the gate (one port) or the gate and the oscillator (no ports). It is the designer’s responsibility to ensure that not connecting ports does not lead to incorrect behavior. For example, if the Verilog module is purely combinational, there is no requirement to connect a clock, though there may still be a need to associate its methods with a clock to ensure that they are in the correct clock domain. In this case, the portsDef would be omitted. Example of an input clock without any connection to the Verilog ports:

\[
\text{input\_clock ddClk() = dClk;}
\]

If the clock port is specified and the gate port is to be unconnected, an attribute, either unused or inhigh, describing the gate port should be specified. The attribute unused indicates that the submodule doesn’t care what the unconnected gate is, while inhigh specifies the gate is assumed in the module to be logical 1. It is an error if a clock with a gate that is not logical 1 is connected to an input clock with an inhigh attribute. The default when a gate port is not specified is inhigh, though it is recommended style that the designer specify the attribute explicitly.

To add an attribute, the usual attribute syntax, (* attribute_name *) immediately preceding the object of the attribute, is used. For example, if a Verilog module has no internal transitions and responds only to method calls, it might be unnecessary to connect the gating signal, as the implicit condition mechanism will ensure that no method is invoked if its clock is off. So the second portId, for the gate port, would be marked unused.

\[
\text{input\_clock ddClk (OSC, (*unused*) UNUSED) = dClk;}
\]

The options for specifying the clock ports in the portsDef clause are:

\[
( ) \quad \text{ // there are no Verilog ports}
(OSC, GATE) \quad \text{ // both an oscillator port and a gate port are specified}
(OSC, (*unused*)GATE) \quad \text{ // there is no gate port and it’s unused}
(OSC, (*inhigh*)GATE) \quad \text{ // there is no gate port and it’s required to be logical 1}
(OSC) \quad \text{ // same as (OSC, (*inhigh*) GATE)}
\]

In an input_clock statement, it is an error if both the port names and the input clock name are omitted, as the clock is then unusable.

### 15.5 Default clock

In BSV, each module has an implicit clock (the current clock) which is used to clock all instantiated submodules unless otherwise specified with a clocked_by clause. Other clocks to submodules must be explicitly passed as input arguments.
Every BVI import module must declare which input clock (if any) is the default clock. This default clock is the implicit clock provided by the parent module, or explicitly given via a `clocked_by` clause. The default clock is also the clock associated with methods and resets in the BVI import when no `clocked_by` clause is specified.

The simplest definition for the default clock is:

```plaintext
defaultClockBVIStmt ::= default_clock identifier ;
```

where the `identifier` specifies the name of an input clock which is designated as the default clock.

The default clock may be unused or not connected to any ports, but it must still be declared. Example:

```plaintext
default_clock no_clock;
```

This statement indicates the implicit clock from the parent module is ignored (and not connected). Consequently, the default clock for methods and resets becomes `no_clock`, meaning there is no associated clock.

To save typing, you can merge the `default_clock` and `input_clock` statements into a single line:

```plaintext
defaultClockBVIStmt ::= default_clock [ identifier ] [ ( portsDef ) ] [ = expression ] ;
```

The defining operator `=` or `<-` may be used.

This is precisely equivalent to defining an input clock and then declaring that clock to be the default clock. Example:

```plaintext
default_clock clk_src (OSC, GATE) = sClkIn;
```

is equivalent to:

```plaintext
input_clock clk_src (OSC, GATE) = sClkIn;
default_clock clk_src;
```

If omitted, the `= expression` in the `default_clock` statement defaults to `<- exposeCurrentClock`. Example:

```plaintext
default_clock xclk (OSC, GATE);
```

is equivalent to:

```plaintext
default_clock xclk (OSC, GATE) <- exposeCurrentClock;
```

If the portnames are excluded, the names default to `CLK, CLK_GATE`. Example:

```plaintext
default_clock xclk = clk;
```

is equivalent to:

```plaintext
default_clock xclk (CLK, CLK_GATE) = clk;
```

Alternately, if the `expression` is an identifier being assigned with `=`, and the user wishes this to be the name of the default clock, then he can leave off the name of the default clock and `expression` will be assumed to be the name. Example:
default_clock (OSC, GATE) = clk;

is equivalent to:

default_clock clk (OSC, GATE) = clk;

If an expression is provided, both the ports and the name cannot be omitted.
However, omitting the entire statement is equivalent to:

default_clock (CLK, CLK_GATE) <- exposeCurrentClock;

specifying that the current clock is to be associated with all methods which do not specify otherwise.

15.6 Output clock

The output_clock statement gives the port connections for a clock provided in the module’s interface.

outputClockBVIStmt ::= output_clock identifier ( [ portsDef ] ) ;

The identifier defines the name of the output clock, which must match a clock declared in the module’s interface. Example:

interface ClockGenIfc;
  interface Clock gen_clk;
endinterface

import "BVI" ClockGen =
module vMkAbsoluteClock #( Integer start, Integer period ) ( ClockGenIfc );
...
  output_clock gen_clk(CLK_OUT);
endmodule

It is an error for the same identifier to be declared by more than one output_clock statement.

15.7 Input reset

The input_reset statement defines how an incoming reset to the module is connected. Typically there is one port. BSV assumes that the reset is inverted (the reset is asserted with the value 0).

inputResetBVIStmt ::= input_reset [ identifier ] [ ( portId ) ] [ clocked_by ( clockId ) ] = expression ;

portId ::= identifier

clockId ::= identifier

where the = may be replaced by <-.

The reset given by expression is to be connected to the Verilog port specified by portId. The identifier is the name of the reset and may be used elsewhere in the import to associate the reset with methods via a reset_by clause.

The clocked_by clause is used to specify the clock domain that the reset is associated with, named by clockId. Any clock in the domain may be used. If the clause is omitted, the associated clock is the default clock. Example:
input_reset rst(sRST_N) = sRstIn;

is equivalent to:

input_reset rst(sRST_N) clocked_by(clk) = sRstIn;

where clk is the identifier named in the default_clock statement.

If the user doesn't care which clock domain is associated with the reset, no_clock may be used. In this case the compiler will not check that the connected reset is associated with the correct domain. Example

input_reset rst(sRST_N) clocked_by(no_clock) = sRstIn;

If the expression is an identifier being assigned with =, and the user wishes this to be the name of the reset, then he can leave off the identifier of the reset and the expression will be assumed to be the name. The reset name can be left off in other circumstances, but then no name is associated with the reset. An unnamed reset cannot be referred to elsewhere, such as in a method or other statement.

In the cases where a parent module needs to associate a reset with methods, but the reset is not used internally, the statement may contain a name, but not specify a port. In this case, there is no port expected in the Verilog module. Example:

input_reset rst() clocked_by (clk_src) = sRstIn ;

Example of a BVI import statement containing an input_reset statement:

import "BVI" SyncReset =
module vSyncReset#(Integer stages ) ( Reset rstIn, ResetGenIfc rstOut ) ;
    ...
    // we don't care what the clock is of the input reset
    input_reset rst(IN_RST_N) clocked_by (no_clock) = rstIn ;
    ...
endmodule

15.8 Default reset

In BSV, when you define a module, it has an implicit reset (the current reset) which is used to reset all instantiated submodules (unless otherwise specified via a reset_by clause). Other resets to submodules must be explicitly passed as input arguments.

Every BVI import module must declare which reset, if any, is the default reset. The default reset is the implicit reset provided by the parent module (or explicitly given with a reset_by). The default reset is also the reset associated with methods in the BVI import when no reset_by clause is specified.

The simplest definition for the default reset is:

defaultResetBVIStmt ::= default_reset identifier ;

where identifier specifies the name of an input reset which is designated as the default reset.

The reset may be unused or not connected to a port, but it must still be declared. Example:

default_reset no_reset;
The keyword `default_reset` may be omitted when declaring an unused reset. The above statement can thus be written as:

```plaintext
no_reset;       // the default_reset keyword can be omitted
```

This statement declares that the implicit reset from the parent module is ignored (and not connected). In this case, the default reset for methods becomes `no_reset`, meaning there is no associated reset.

To save typing, you can merge the `default_reset` and `input_reset` statements into a single line:

```plaintext
defaultResetBVIStmt ::= default_reset [ identifier ] [ ( portId ) ] [ clocked_by ( clockId ) ] [ = expression ] ;
```

The defining operator `=` or `<-` may be used.

This is precisely equivalent to defining an input reset and then declaring that reset to be the default. Example:

```plaintext
default_reset rst (RST_N) clocked_by (clk) = sRstIn;
```

is equivalent to:

```plaintext
input_reset rst (RST_N) clocked_by (clk) = sRstIn;
default_reset rst;
```

If omitted, `= expression` in the `default_reset` statement defaults to `<- exposeCurrentReset`. Example:

```plaintext
default_reset rst (RST_N);
```

is equivalent to

```plaintext
default_reset rst (RST_N) <- exposeCurrentReset;
```

The `clocked_by` clause is optional; if omitted, the reset is clocked by the default clock. Example:

```plaintext
default_reset rst (sRST_N) = sRstIn;
```

is equivalent to

```plaintext
default_reset rst (sRST_N) clocked_by(clk) = sRstIn;
```

where `clk` is the `default_clock`.

If `no_clock` is specified, the reset is not associated with any clock. Example:

```plaintext
input_reset rst (sRST_N) clocked_by(no_clock) = sRstIn;
```

If the `portId` is excluded, the reset port name defaults to `RST_N`. Example:

```plaintext
default_reset rstIn = rst;
```

is equivalent to:
default_reset rstIn (RST_N) = rst;

Alternatively, if the *expression* is an identifier being assigned with *=*, and the user wishes this to be the name of the default reset, then he can leave off the name of the default reset and *expression* will be assumed to be the name. Example:

```
default_reset (rstIn) = rst;
```

is equivalent to:

```
default_reset rst (rstIn) = rst;
```

Both the ports and the name cannot be omitted.

However, omitting the entire statement is equivalent to:

```
default_reset (RST_N) <- exposeCurrentReset;
```

specifying that the current reset is to be associated with all methods which do not specify otherwise.

### 15.9 Output reset

The **output_reset** statement gives the port connections for a reset provided in the module’s interface.

```
outputResetBVIStmt ::= output_reset identifier [(portId)] [clocked_by (clockId)];
```

The *identifier* defines the name of the output reset, which must match a reset declared in the module’s interface. Example:

```
interface ResetGenIfc;
    interface Reset gen_rst;
endinterface

import "BVI" SyncReset =
module vSyncReset#(Integer stages) (Reset rstIn, ResetGenIfc rstOut);
...
output_reset gen_rst(OUT_RST_N) clocked_by(clk);
endmodule
```

It is an error for the same *identifier* to be declared by more than one **output_reset** statement.

### 15.10 Ancestor, same family

There are two statements for specifying the relationship between clocks: **ancestor** and **same_family**.

```
ancestorBVIStmt ::= ancestor (clockId, clockId);
```

This statement indicates that the second named clock is an **ancestor** of the first named clock. To say that `clock1` is an **ancestor** of `clock2`, means that `clock2` is a gated version of `clock1`. This is written as:

```
ancestor (clock2, clock1);
```
For clocks which do not have an ancestor relationship, but do share a common ancestor, we have:

\[ \text{sameFamilyBVIStmt} ::= \text{same\_family} ( \text{clockId}, \text{clockId} ) ; \]

This statement indicates that the clocks specified by the clockIds are in the same family (same clock domain). When two clocks are in the same family, they have the same oscillator with a different gate. To be in the same family, one does not have to be a gated version of the other, instead they may be gated versions of a common ancestor. Note that ancestor implies same\_family, which then need not be explicitly stated. For example, a module which gates an input clock:

\[
\begin{align*}
\text{input\_clock} & \text{ clk\_in(CLK\_IN, CLK\_GATE\_IN) = clk\_in ;} \\
\text{output\_clock} & \text{ new\_clk(CLK\_OUT, CLK\_GATE\_OUT);} \\
\text{ancestor} & \text{ (new\_clk, clk\_in);} \\
\end{align*}
\]

15.11 Schedule

\[ \text{scheduleBVIStmt} ::= \text{schedule} ( \text{identifier} \{ , \text{identifier} \} ) \text{operatorId} \text{(} \text{identifier} \{ , \text{identifier} \} \text{);} \]

\[ \text{operatorId} ::= \text{CF} | \text{SB} | \text{SBR} | \text{C} \]

The schedule statement specifies the scheduling constraints between methods in an imported module. The operators relate two sets of methods; the specified relation is understood to hold for each pair of an element of the first set and an element of the second set. The order of the methods in the lists is unimportant and the parentheses may be omitted if there is only one name in the set.

The meanings of the operators are:

- \text{CF} \quad \text{conflict-free}
- \text{SB} \quad \text{sequences before}
- \text{SBR} \quad \text{sequences before, with range conflict (that is, not composable in parallel)}
- \text{C} \quad \text{conflicts}

It is an error to specify two relationships for the same pair of methods. It is an error to specify a scheduling annotation other than \text{CF} for methods clocked by unrelated clocks. For such methods, \text{CF} is the default; for methods clocked by related clocks the default is \text{C}. The compiler generates a warning if an annotation between a method pair is missing. Example:

\[
\begin{align*}
\text{import "BVI" FIFO2 =} \\
\text{module vFIFOF2\_MC} \quad ( \text{Clock sClkIn, Reset sRstIn,} \\
\text{Clock dClkIn, Reset dRstIn,} \\
\text{Clock realClock, Reset realReset,} \\
\text{FIFOF\_MC#(a) ifc}) \\
\text{provisos (Bits\#(a,sa));} \\
\text{...} \\
\text{method enq(D\_IN) enable(ENQ) clocked\_by( clk\_src ) reset\_by( srst );} \\
\text{method FULL\_N notFull clocked\_by( clk\_src ) reset\_by( srst );} \\
\text{method deq() enable(DEQ) clocked\_by( clk\_dst ) reset\_by( drst );} \\
\text{method D\_OUT first clocked\_by( clk\_dst ) reset\_by( drst );} \\
\text{method EMPTY\_N notEmpty clocked\_by( clk\_dst ) reset\_by( drst );} \\
\end{align*}
\]
schedule (enq, notFull) CF (deq, first, notEmpty) ;
schedule (first, notEmpty) CF (first, notEmpty) ;
schedule (notFull) CF (notFull) ;
// CF: conflict free – methods in the first list can be scheduled
// in any order or any number of times, with the methods in the
// second list – there is no conflict between the methods.
schedule first SB deq ;
schedule (notEmpty) SB (deq) ;
schedule (notFull) SB (enq) ;
// SB indicates the order in which the methods must be scheduled
// the methods in the first list must occur (be scheduled) before
// the methods in the second list
// SB allows these methods to be called from one rule but the
// SBR relationship does not.
schedule (enq) C (enq) ;
schedule (deq) C (deq) ;
// C: conflicts – methods in the first list conflict with the
// methods in the second – they cannot be called in the same clock cycle.
// if a method conflicts with itself, (enq and deq), it
// cannot be called more than once in a clock cycle
endmodule

15.12 Path

The path statement indicates that there is a combinational path from the first port to the second port.

\[
\text{pathBVIStmt} \quad ::= \quad \text{path} \left( \text{portId}, \text{portId} \right)
\]

It is an error to specify a path between ports that are connected to methods clocked by unrelated clocks. This would be, by definition, an unsafe clock domain crossing. Note that the compiler assumes that there will be a path from a value or ActionValue method’s input parameters to its result, so this need not be specified explicitly.

The paths defined by the path statement are used in scheduling. A path may impact rule urgency by implying an order in how the methods are scheduled. The path is also used in checking for combinational cycles in a design. The compiler will report an error if it detects a cycle in a design. In the following example, there is a path declared between WSET and WHAS, as shown in figure 2.

Figure 2: Path in the RWire0 Verilog module between WSET and WHAS ports

```
import "BVI" RWire0 =
module vMkRWire0 (VRWire0);
...
method wset() enable(WSET) ;
method WHAS whas ;
schedule whas CF whas ;
schedule wset SB whas ;
```
15.13 Interface

\[
\text{interfaceBVIStmt} \ ::= \ \text{interface typeDefsType} ; \\
\quad \{ \ \text{interfaceBVIStmt} \} \\
\quad \text{endinterface} [ : \ \text{typeIde} ]
\]

\[
\text{interfaceBVIStmt} \ ::= \ \text{methodBVIStmt} \\
\quad \text{interfaceBVIStmt} ; \\
\]

An interface statement can contain two types of statements: method statements and subinterface declarations. The interface statement in BVI import is the same as any other interface statement (Section 5.2) with one difference: the method statements within the interface are BVI method statements (methodBVIStmt 15.2).

Example:

import "BVI" BRAM2 =
module vSyncBRAM2#(Integer memSize, Bool hasOutputRegister, 
\quad \text{Clock clkA, Reset rstNA, Clock clkB, Reset rstNB} \\
\quad ) (BRAM_DUAL_PORT#(addr, data)) \\
\quad \text{provisos(Bits#(addr, addr_sz),} \\
\quad \quad \text{Bits#(data, data_sz));} \\
\quad ...

\begin{verbatim}
interface BRAM_PORT a; \\
\text{method put(WEA, (*reg*)ADDRA, (*reg*)DIA) enable(ENA) clocked_by(clkA) reset_by(rstA);} \\
\text{method DOA read() clocked_by(clkA) reset_by(rstA);} \\
\text{endinterface: a}
\end{verbatim}

\begin{verbatim}
interface BRAM_PORT b; \\
\text{method put(WEB, (*reg*)ADDRB, (*reg*)DIB) enable(ENB) clocked_by(clkB) reset_by(rstB);} \\
\text{method DOB read() clocked_by(clkB) reset_by(rstB);} \\
\text{endinterface: b}
\end{verbatim}

endmodule: vSyncBRAM2

Since a BVI wrapper module can only provide a single interface (BRAM_DUAL_PORT in this example), to provide multiple interfaces you have to create an interface hierarchy using interface statements.

The interface hierarchy provided in this example is:

\begin{verbatim}
interface BRAM_DUAL_PORT#: (type addr, type data); \\
\text{interface BRAM_PORT#(addr, data) a;} \\
\text{interface BRAM_PORT#(addr, data) b;} \\
\text{endinterface: BRAM_DUAL_PORT}
\end{verbatim}

where the subinterfaces, a and b, are defined as interface statements in the body of the import "BVI" statement.

15.14 Inout

The following statements describe how to pass an inout port from a wrapped Verilog module through a BSV module. These ports are represented in BSV by the type inout. There are two ways that
an **Inout** can appear in BSV modules: as an argument to the module or as a subinterface of the interface provided by the module. There are, therefore, two ways to declare an **Inout** port in a BVI import: the statement `inout` declares an argument of the current module; and the statement `ifc_inout` declares a subinterface of the provided interface.

**inoutBVIStmt** ::= `inout` portId [clocked_by (clockId)] [reset_by (resetId)] = expression;

The value of `portId` is the Verilog name of the **inout** port and `expression` is the name of an argument from the module.

**inoutBVIStmt** ::= `ifc_inout` identifier (inoutId) [clocked_by (clockId)] [reset_by (resetId)];

Here, the `identifier` is the name of the subinterface of the provided interface and `portId` is, again, the Verilog name of the **inout** port.

The clock and reset associated with the **Inout** are assumed to be the default clock and default reset unless explicitly specified.

Example:

```verilog
interface Q;
    interface Inout#(Bit#(13)) q_inout;
    interface Clock c_clock;
endinterface

import "BVI" Foo = module mkFoo#(Bool b)(Inout#(int) x, Q ifc);
    default_clock ();
    no_reset;

    inout iport = x;

    ifc_inout q_inout(qport);
    output_clock c_clock(clockport);
endmodule
```

The wrapped Verilog module is:

```verilog
module Foo (iport, clockport, qport);
    input cccport;
    inout [31:0] iport;
    inout [12:0] qport;
    ...
endmodule
```

## 16 Embedding C in a BSV Design

This section describes how to declare a BSV function that is provided as a C function. This is used when there are existing C functions which the designer would like to include in a BSV module. Using the `importBDPI` syntax, the user can specify that the implementation of a BSV function is provided as a C function.

**externCImport** ::= `import "BDPI" [ identifier = ] function type identifier ( [ CFuncArgs ] ) [ provisos ];`
\[ \text{CFuncArgs} ::= \text{CFuncArg} \{ \, , \text{CFuncArg} \} \]

\[ \text{CFuncArg} ::= \text{type} \left[ \text{identifier} \right] \]

This defines a function \textit{identifier} in the BSV source code which is implemented by a C function of the same name. A different link name (C name) can be specified immediately after the "BDPI", using an optional \([\text{identifier} = \)]. The link name is not bound by BSV case-restrictions on identifiers and may start with a capital letter.

Example of an import statement where the C name matches the BSV name:

\[
\begin{verbatim}
// the C function and the BSV function are both named checksum
import "BDPI" function Bit#(32) checksum (Bit#(n), Bit#(32));
\end{verbatim}
\]

Example of an import statement where the C name does not match the BSV name:

\[
\begin{verbatim}
// the C function name is checksum
// the BSV function name is checksum_raw
import "BDPI" checksum = function Bit#(32) checksum_raw (Bit#(n), Bit#(32));
\end{verbatim}
\]

The first \textit{type} specifies the return type of the function. The optional \textit{CFuncArgs} specify the arguments of the function, along with an optional identifier to name the arguments.

For instance, in the above checksum example, you might want to name the arguments to indicate that the first argument is the input value and the second argument is the size of the input value.

\[
\begin{verbatim}
import "BDPI" function Bit#(32) checksum (Bit#(n) input_val, Bit#(32) input_size);
\end{verbatim}
\]

### 16.1 Argument Types

The types for the arguments and return value are BSV types. The following table shows the correlation from BSV types to C types.

<table>
<thead>
<tr>
<th>BSV Type</th>
<th>C Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>String</td>
<td>char*</td>
</tr>
<tr>
<td>Bit#(0) - Bit#(8)</td>
<td>unsigned char</td>
</tr>
<tr>
<td>Bit#(9) - Bit#(32)</td>
<td>unsigned int</td>
</tr>
<tr>
<td>Bit#(33) - Bit#(64)</td>
<td>unsigned long long</td>
</tr>
<tr>
<td>Bit#(65) -</td>
<td>unsigned int*</td>
</tr>
<tr>
<td>Bit#(n)</td>
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</table>

The \textit{importBDPI} syntax provides the ability to import simple C functions that the user may already have. A C function with an argument of type \texttt{char} or \texttt{unsigned char} should be imported as a BSV function with an argument of type \texttt{Bit#(8)}. For \texttt{int} or \texttt{unsigned int}, use \texttt{Bit#(32)}. For \texttt{long long} or \texttt{unsigned long long}, use \texttt{Bit#(64)}. While BSV creates unsigned values, they can be passed to a C function which will treat the value as signed. This can be reflected in BSV with \texttt{Int#(8)}, \texttt{Int#(32)}, \texttt{Int#(64)}, etc.

The user may also import new C functions written to match a given BSV function type. For instance, a function on bit-vectors of size 17 (that is, \texttt{Bit#(17)}) would expect to pass this value as the C type \texttt{unsigned int} and the C function should be aware that only the first 17 bits of the value are valid data.
Wide data  Bit vectors of size 65 or greater are passed by reference, as type `unsigned int*`. This is a pointer to an array of 32-bit words, where bit 0 of the BSV vector is bit 0 of the first word in the array, and bit 32 of the BSV vector is bit 0 of the second word, etc. Note that we only pass the pointer; no size value is passed to the C function. This is because the size is fixed and the C function could have the size hardcoded in it. If the function needs the size as an additional parameter, then either a C or BSV wrapper is needed. See the examples below.

Polymorphic data  As the above table shows, bit vectors of variable size are passed by reference, as type `unsigned int*`. As with wide data, this is a pointer to an array of 32-bit words, where bit 0 of the BSV vector is bit 0 of the first word in the array, and bit 32 of the BSV vector is bit 0 of the second word, etc. No size value is passed to the C function, because the import takes no stance on how the size should be communicated. The user will need to handle the communication of the size, typically by adding an additional argument to the import function and using a BSV wrapper to pass the size via that argument, as follows:

```plaintext
// This function computes a checksum for any size bit-vector
// The second argument is the size of the input bit-vector
import "BDPI" checksum = function Bit#(32) checksum_raw (Bit#(n), Bit#(32));

// This wrapper handles the passing of the size
function Bit#(32) checksum (Bit#(n) vec);
    return checksum_raw(vec, fromInteger(valueOf(n)));
endfunction
```

16.2 Return types

Imported functions can be value functions, `Action` functions, or `ActionValue` functions. The acceptable return types are the same as the acceptable argument types, except that `String` is not permitted as a return type.

Imported functions with return values correlate to C functions with return values, except in the cases of wide and polymorphic data. In those cases, where the BSV type correlates to `unsigned int*`, the simulator will allocate space for the return result and pass a pointer to this memory to the C function. The C function will not be responsible for allocating memory. When the C function finishes execution, the simulator copies the result in that memory to the simulator state and frees the memory. By convention, this special argument is the first argument to the C function.

For example, the following BSV import:

```plaintext
import "BDPI" function Bit#(32) f (Bit#(8));
```

would connect to the following C function:

```plaintext
unsigned int f (unsigned char x);
```

While the following BSV import with wide data:

```plaintext
import "BDPI" function Bit#(128) g (Bit#(8));
```

would connect to the following C function:

```plaintext
void g (unsigned int* resultptr, unsigned char x);
```
16.3 Implicit pack/unpack

So far we have only mentioned Bit and String types for arguments and return values. Other types are allowed as arguments and return values, as long as they can be packed into a bit-vector. These types include Int, UInt, Bool, and Maybe, all of which have an instance in the Bits class.

For example, this is a valid import:

    import "BDPI" function Bool my_and (Bool, Bool);

Since a Bool packs to a Bit#(1), it would connect to a C function such as the following:

    unsigned char my_and (unsigned char x, unsigned char y);

In this next example, we have two C functions, signedGT and unsignedGT, both of which implement a greater-than function, returning a Bool indicating whether x is greater than y.

    import "BDPI" function Bool signedGT (Int#(32) x, Int#(32) y);
    import "BDPI" function Bool unsignedGT (UInt#(32) x, UInt#(32) y);

Because the function signedGT assumes that the MSB is a sign bit, we use the type-system to make sure that we only call that function on signed values by specifying that the function only works on Int#(32). Similarly, we can enforce that unsignedGT is only called on unsigned values, by requiring its arguments to be of type UInt#(32).

The C functions would be:

    unsigned char signedGT (unsigned int x, unsigned int y);
    unsigned char unsignedGT (unsigned int x, unsigned int y);

In both cases, the packed value is of type Bit#(32), and so the C function is expected to take the its arguments as unsigned int. The difference is that the signedGT function will then treat the values as signed values while the unsignedGT function will treat them as unsigned values. Both functions return a Bool, which means the C return type is unsigned char.

Argument and return types to imported functions can also be structs, enums, and tagged unions. The C function will receive the data in bit form and must return values in bit form.

16.4 Other examples

Shared resources In some situations, several imported functions may share access to a resource, such as memory or the file system. If these functions wish to share file handles, pointers, or other cookies between each other, they will have to pass the data as a bit-vector, such as unsigned int/Bit#(32).

When to use Action components If an imported function has a side effect or if it matters how many times or in what order the function is called (relative to other calls), then the imported function should have an Action component in its BSV type. That is, the functions should have a return type of Action or ActionValue.
Removing indirection for polymorphism within a range  A polymorphic type will always become `unsigned int*` in the C, even if there is a numeric proviso which restricts the size. Consider the following import:

```verilog
import "BDPI" function Bit#(n) f(Bit#(n), Bit#(8)) provisos (Add#(n,j,32));
```

This is a polymorphic vector, so the conversion rules indicate that it should appear as `unsigned int*` in the C. However, the proviso indicates that the value of `n` can never be greater than 32. To make the import be a specific size and not a pointer, you could use a wrapper, as in the example below.

```verilog
import "BDPI" f = function Bit#(32) f_aux(Bit#(32), Bit#(8));

function Bit#(n) f (Bit#(n) x) provisos (Add#(n,j,32));
    return f_aux(extend(x), fromInteger(valueOf(n)));
endfunction
```

References


A Keywords

In general, keywords do not use uppercase letters (the only exception is the keyword `valueOf`). The following are the keywords in BSV (and so they cannot be used as identifiers).

```
Action
ActionValue
BVI
C
CF
E
SB
SBR
action         endaction
actionvalue    endactionvalue
ancestor
begin
bit
case         endcase
clocked_by
default
default_clock
default_reset
dependencies
deriving
determines
e
else
enable
end
enum
export
for
function     endfunction
if
ifc_inout
import
inout
input_clock
input_reset
instance     endinstance
interface    endinterface
let
match
matches
method     endmethod
module     endmodule
numeric
output_clock
output_reset
package     endpackage
parameter
path
port
```
provisos
reset_by
return
rule
rules
same_family
schedule
struct
tagged
type
typeclass
typedef
union
valueOf
valueof
void
while
The following are keywords in SystemVerilog (which includes all the keywords in Verilog). Although most of them are not used in BSV, for compatibility reasons they are not allowed as identifiers in BSV either.

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</tr>
</tbody>
</table>

153
signed       time       var
small        timeprecision vectored
solve        timeunit     virtual
specify      endspecify  tran  void
specparam    tranif0     wait
static       tranifi1    wait_order
string       tri          wand
strong0      tri0         weak0
strong1      tri1         weak1
struct       triand      while
super        trior       wildcard
supply0      trireg      wire
supply1      type        with
table        endtable    typedef  within
tagged       union       wor
task         endtask     unique   xnor
this          unsigned   xor
throughout   use
B  The Standard Prelude package

This section describes the type classes, data types, interfaces and functions provided by the Prelude package. The standard Prelude package is automatically included in all BSV packages. You do not need to take any special action to use any of the features defined in the Prelude package.

Section C describes BSV’s large collection of AzureIP Foundation libraries. To use any of these libraries in a design you must explicitly import the library package.

B.1 Type classes

A type class groups related functions and operators and allows for instances across the various datatypes which are members of the typeclass. Hence the function names within a type class are overloaded across the various type class members.

A typeclass declaration creates a type class. An instance declaration defines a datatype as belonging to a type class. A datatype may belong to zero or many type classes.

The Prelude package declares the following type classes:

<table>
<thead>
<tr>
<th>Prelude Type Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>Eq</td>
</tr>
<tr>
<td>Literal</td>
</tr>
<tr>
<td>RealLiteral</td>
</tr>
<tr>
<td>Arith</td>
</tr>
<tr>
<td>Ord</td>
</tr>
<tr>
<td>Bounded</td>
</tr>
<tr>
<td>Bitwise</td>
</tr>
<tr>
<td>BitReduction</td>
</tr>
<tr>
<td>BitExtend</td>
</tr>
<tr>
<td>SaturatingArith</td>
</tr>
<tr>
<td>Alias</td>
</tr>
<tr>
<td>NumAlias</td>
</tr>
<tr>
<td>FShow</td>
</tr>
<tr>
<td>StringLiteral</td>
</tr>
</tbody>
</table>

B.1.1 Bits

Bits defines the class of types that can be converted to bit vectors and back. Membership in this class is required for a data type to be stored in a state, such as a Register or a FIFO, or to be used at a synthesized module boundary. Often instance of this class can be automatically derived using the deriving statement.

    typeclass Bits #(type a, numeric type n);
    function Bit#(n) pack(a x);
    function a unpack(Bit#(n) x);
endtypeclass

Note: the numeric keyword is not required

The functions pack and unpack are provided to convert elements to Bit#() and to convert Bit#() elements to another datatype.
Bits Functions

<table>
<thead>
<tr>
<th>pack</th>
<th>Converts element a of datatype data_t to a element of datatype Bit#() of size_a.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Bit#(size_a) pack(data_t a);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>unpack</th>
<th>Converts an element a of datatype Bit#() and size_a into an element with of element type data_t.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function data_t unpack(Bit#(size_a) a);</td>
<td></td>
</tr>
</tbody>
</table>

Examples

```verilog
Reg#(int) cycle <- mkReg (0);
...
rule r;
...
if (pack(cycle)[0] == 0) a = a + 1;
else a = a + 2;
if (pack(cycle)[1:0] == 3) a = a + 3;

Int#(10) src_step = unpack(config6[9:0]);
Bool src_rdy_en = unpack(config6[16]);
```

B.1.2 Eq

Eq defines the class of types whose values can be compared for equality. Instances of the Eq class are often automatically derived using the deriving statement.

```verilog
typeclass Eq #(type data_t);
  function Bool == (data_t x, data_t y);
  function Bool /= (data_t x, data_t y);
endtypeclass
```

The equality functions == and /= are Boolean functions which return a value of True if the equality condition is met. When defining an instance of an Eq typeclass, the == and /= notations must be used. If using or referring to the functions, the standard Verilog operators == and != may be used.

<table>
<thead>
<tr>
<th>Eq Functions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>==</td>
<td>Returns True if x is equal to y.</td>
</tr>
<tr>
<td>function Bool == (data_t x, data_t y);</td>
<td></td>
</tr>
<tr>
<td>/=</td>
<td>Returns True if x is not equal to y.</td>
</tr>
<tr>
<td>function Bool /= (data_t x, data_t y);</td>
<td></td>
</tr>
</tbody>
</table>

Examples

```verilog
return (pack(i) & 3) == 0;
if (a != maxInt)
```

156
B.1.3 Literal

Literal defines the class of types which can be created from integer literals.

```verbatim
typedef class Literal (type data_t);

function data_t fromInteger(Integer x);

function Bool inLiteralRange(data_t target, Integer x);
endtypedef
```

The `fromInteger` function converts an `Integer` into an element of datatype `data_t`. Whenever you write an integer literal in BSV (such as “0” or “1”), there is an implied `fromInteger` applied to it, which turns the literal into the type you are using it as (such as `Int`, `UInt`, `Bit`, etc.). By defining an instance of `Literal` for your own datatypes, you can create values from literals just as for these predefined types.

The typeclass also provides a function `inLiteralRange` that takes an argument of the target type and an `Integer` and returns a `Bool` that indicates whether the `Integer` argument is in the legal range of the target type. For example, assuming `x` has type `Bit#(4)`, `inLiteralRange(x, 15)` would return `True`, but `inLiteralRange(x, 22)` would return `False`.

**Literal Functions**

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>fromInteger</code></td>
<td>Converts an element <code>x</code> of datatype <code>Integer</code> into an element of data type <code>data_t</code></td>
</tr>
<tr>
<td><code>inLiteralRange</code></td>
<td>Tests whether an element <code>x</code> of datatype <code>Integer</code> is in the legal range of data type <code>data_t</code></td>
</tr>
</tbody>
</table>

**Examples**

```verbatim
function foo (Vector#(n,int) xs) provisos (Log#(n,k));
    Integer maxindex = valueof(n) - 1;
    Int#(k) index;
    index = fromInteger(maxindex);
    ...
endfunction

function Bool inLiteralRange(RegAddress a, Integer i);
    return(i >= 0 && i < 83);
endfunction
```

B.1.4 RealLiteral

RealLiteral defines the class of types which can be created from real literals.

```verbatim
typedef class RealLiteral (type data_t);

function data_t fromReal(Real x);
endtypedef
```
The `fromReal` function converts a `Real` into an element of datatype `data_t`. Whenever you write a real literal in BSV (such as “3.14”), there is an implied `fromReal` applied to it, which turns the real into the specified type. By defining an instance of `RealLiteral` for a datatype, you can create values from reals for any type.

<table>
<thead>
<tr>
<th>RealLiteral Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>fromReal</code></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

**Examples**

```
FixedPoint#(is, fs) f = fromReal(n);  // n is a Real number
```

### B.1.5 SizedLiteral

`SizedLiteral` defines the class of types which can be created from integer literals with a specified size.

```plaintext
typeclass SizedLiteral #(type data_t, type size_t)
  dependencies (data_t determines size_t);
  function data_t fromSizedInteger(Bit#(size_t));
endtypeclass
```

The `fromSizedInteger` function converts a literal of type `Bit#(size_t)` into an element of datatype `data_t`. Whenever you write a sized literal like `1'b0`, there is an implied `fromSizedInteger` which turns the literal into the type you are using it as, with the defined size. Instances are defined for the types `Bit`, `UInt`, and `Int`.

<table>
<thead>
<tr>
<th>SizedLiteral Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>fromSizedInteger</code></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

### B.1.6 Arith

`Arith` defines the class of types on which arithmetic operations are defined.

```plaintext
typeclass Arith #(type data_t)
  provisos (Literal#(data_t));
  function data_t `+ (data_t x, data_t y);
  function data_t `- (data_t x, data_t y);
  function data_t negate (data_t x);
  function data_t `* (data_t x, data_t y);
  function data_t `/ (data_t x, data_t y);
  function data_t `% (data_t x, data_t y);
  function data_t abs (data_t x);
  function data_t signum (data_t x);
  function data_t `** (data_t x, data_t y);
```

158
function data_t exp_e (data_t x);
function data_t log (data_t x);
function data_t logb (data_t b, data_t x);
function data_t log2 (data_t x);
function data_t log10 (data_t x);
endtypeclass

The Arith functions provide arithmetic operations. For the arithmetic symbols, when defining an instance of the Arith typeclass, the escaped operator names must be used as shown in the tables below. The negate name may be used instead of the operator for negation. If using or referring to these functions, the standard (non-escaped) Verilog operators can be used.

<table>
<thead>
<tr>
<th>Arith Functions</th>
<th>Description</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Element ( x ) is added to element ( y ).</td>
<td>function data_t + (data_t x, data_t y);</td>
</tr>
<tr>
<td>-</td>
<td>Element ( y ) is subtracted from element ( x ).</td>
<td>function data_t - (data_t x, data_t y);</td>
</tr>
<tr>
<td>negate</td>
<td>Change the sign of the number. When using the function the Verilog negate operator, (-), may be used.</td>
<td>function data_t negate (data_t x);</td>
</tr>
<tr>
<td>*</td>
<td>Element ( x ) is multiplied by ( y ).</td>
<td>function data_t * (data_t x, data_t y);</td>
</tr>
<tr>
<td>/</td>
<td>Element ( x ) is divided by ( y ). The definition depends on the type - many types truncate the remainder. Note: may not be synthesizable with downstream tools.</td>
<td>function data_t / (data_t x, data_t y);</td>
</tr>
<tr>
<td>%</td>
<td>Returns the remainder of ( x/y ). Obeys the identity ((x/y) \times y + (x % y) = x).</td>
<td>function data_t % (data_t x, data_t y);</td>
</tr>
</tbody>
</table>

Note: Division by 0 is undefined. Both \( x/0 \) and \( x \% 0 \) will generate errors at compile-time and run-time for most instances.

<p>| abs             | Returns the absolute value of ( x ).          | function data_t abs (data_t x); |</p>
<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>signum</code></td>
<td>Returns a unit value with the same sign as <code>x</code>, such that <code>abs(x)*signum(x) = x</code>. <code>signum(12)</code> returns 1 and <code>signum(-12)</code> returns -1.</td>
<td><code>function data_t signum (data_t x);</code></td>
</tr>
<tr>
<td><code>**</code></td>
<td>The element <code>x</code> is raised to the <code>y</code> power (<code>x**y = x^y</code>).</td>
<td><code>function data_t ** (data_t x, data_t y);</code></td>
</tr>
<tr>
<td><code>log2</code></td>
<td>Returns the base 2 logarithm of <code>x</code> (<code>log_2 x</code>).</td>
<td><code>function data_t log2(data_t x) ;</code></td>
</tr>
<tr>
<td><code>exp_e</code></td>
<td><code>e</code> is raised to the power of <code>x</code> (<code>e^x</code>).</td>
<td><code>function data_t exp_e (data_t x);</code></td>
</tr>
<tr>
<td><code>log</code></td>
<td>Returns the base <code>e</code> logarithm of <code>x</code> (<code>log_e x</code>).</td>
<td><code>function data_t log (data_t x);</code></td>
</tr>
<tr>
<td><code>logb</code></td>
<td>Returns the base <code>b</code> logarithm of <code>x</code> (<code>log_b x</code>).</td>
<td><code>function data_t logb (data_t b, data_t x);</code></td>
</tr>
<tr>
<td><code>log10</code></td>
<td>Returns the base 10 logarithm of <code>x</code> (<code>log_{10} x</code>).</td>
<td><code>function data_t log10(data_t x) ;</code></td>
</tr>
</tbody>
</table>

### Examples

```plaintext
real u = log(1);
real x = 128.0;
real y = log2(x);
real z = 100.0;
real v = log10(z);
real w = logb(3,9.0);
real a = -x;
real b = abs(x);
```

### B.1.7 Ord

`Ord` defines the class of types for which an `order` is defined, allowing comparison operations. A complete definition of an instance of `Ord` requires defining either `<=` or `compare`. 

160
typedef Ord #(type data_t);
  function Bool < (data_t x, data_t y);
  function Bool <= (data_t x, data_t y);
  function Bool > (data_t x, data_t y);
  function Bool >= (data_t x, data_t y);
  function Ordering compare(data_t x, data_t y);
  function data_t min(data_t x, data_t y);
  function data_t max(data_t x, data_t y);
endtypedef

The functions <, <=, >, and >= are Boolean functions which return a value of True if the comparison condition is met.

<table>
<thead>
<tr>
<th>Ord Functions</th>
<th>Returns True if x is less than y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;</td>
<td>function Bool &lt; (data_t x, data_t y);</td>
</tr>
<tr>
<td>&lt;=</td>
<td>Returns True if x is less than or equal to y.</td>
</tr>
<tr>
<td></td>
<td>function Bool &lt;= (data_t x, data_t y);</td>
</tr>
<tr>
<td>&gt;</td>
<td>Returns True if x is greater than y.</td>
</tr>
<tr>
<td></td>
<td>function Bool &gt; (data_t x, data_t y);</td>
</tr>
<tr>
<td>&gt;=</td>
<td>Returns True if x is greater than or equal to y.</td>
</tr>
<tr>
<td></td>
<td>function Bool &gt;= (data_t x, data_t y);</td>
</tr>
</tbody>
</table>

The function compare returns a value of the Ordering (Section B.2.14) data type (LT, GT, or EQ).

<table>
<thead>
<tr>
<th>compare</th>
<th>Returns the Ordering value describing the relationship of x to y.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>function Ordering compare (data_t x, data_t y);</td>
</tr>
</tbody>
</table>

The functions min and max return a value of datatype data_t which is either the minimum or maximum of the two values, depending on the function.

<table>
<thead>
<tr>
<th>min</th>
<th>Returns the minimum of the values x and y.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>function data_t min (data_t x, data_t y);</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>max</th>
<th>Returns the maximum of the values x and y.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>function data_t max (data_t x, data_t y);</td>
</tr>
</tbody>
</table>
Examples

rule r1 (x <= y);
rule r2 (x > y);

function Ordering onKey(Record r1, Record r2);
  return compare(r1.key,r2.key);
endfunction

List#(Record) sorted_rs = sortBy(onKey,rs);
List#(List#(Record)) grouped_rs = groupBy(equiv,sorted_rs);

let read_count = min(reads_remaining, 16);

B.1.8 Bounded

Bounded defines the class of types with a finite range and provides functions to define the range.

typeclass Bounded #(type data_t);
  data_t minBound;
  data_t maxBound;
endtypeclass

The Bounded functions minBound and maxBound define the minimum and maximum values for the type data_t. Instances of the Bounded class are often automatically derived using the deriving statement.

<table>
<thead>
<tr>
<th>Bounded Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>minBound</td>
</tr>
<tr>
<td>The minimum value the type data_t can have.</td>
</tr>
<tr>
<td>data_t minBound;</td>
</tr>
</tbody>
</table>

| maxBound                           |
| The maximum value the type data_t can have. |
| data_t maxBound;                   |

Examples

module mkGenericRandomizer (Randomize#(a))
  provisos (Bits#(a, sa), Bounded#(a));

typedef struct {
  Bit#(2) red;
  Bit#(1) blue;
} RgbColor deriving (Eq, Bits, Bounded);
### B.1.9 Bitwise

**Bitwise** defines the class of types on which bitwise operations are defined.

```mil
typedef Bitwise #(type data_t);

function data_t & (data_t x1, data_t x2);
function data_t | (data_t x1, data_t x2);
function data_t ^ (data_t x1, data_t x2);
function data_t ~^ (data_t x1, data_t x2);
function data_t ^~ (data_t x1, data_t x2);
function data_t invert (data_t x1);
function data_t << (data_t x1, x2);
function data_t >> (data_t x1, x2);
function Bit#(1) msb (data_t x);
function Bit#(1) lsb (data_t x);
endtypedef
```

The **Bitwise** functions compare two operands bit by bit to calculate a result. That is, the bit in the first operand is compared to its equivalent bit in the second operand to calculate a single bit for the result.

<table>
<thead>
<tr>
<th>Bitwise Functions</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&amp;</td>
<td>Performs an <em>and</em> operation on each bit in x1 and x2 to calculate the result.</td>
</tr>
<tr>
<td>&amp;</td>
<td>function data_t &amp; (data_t x1, data_t x2);</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>|</td>
<td>function data_t | (data_t x1, data_t x2);</td>
</tr>
<tr>
<td>^</td>
<td>Performs an <em>exclusive or</em> operation on each bit in x1 and x2 to calculate the result.</td>
</tr>
<tr>
<td>^</td>
<td>function data_t ^ (data_t x1, data_t x2);</td>
</tr>
<tr>
<td>~^</td>
<td>Performs an <em>exclusive nor</em> operation on each bit in x1 and x2 to calculate the result.</td>
</tr>
</tbody>
</table>
| ^~                | function data_t ~^ (data_t x1, data_t x2);
| ^~                | function data_t ^~ (data_t x1, data_t x2); |
| invert            | Performs a *unary negation* operation on each bit in x1. When using this function, the corresponding Verilog operator, ^, may be used. |
| invert            | function data_t invert (data_t x1); |
The << and >> operators perform left and right shift operations. Whether the shift is an arithmetic shift (Int) or a logical shift (Bit, UInt) is dependent on how the type is defined.

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
<th>Code Snippet</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;&lt;</td>
<td>Performs a left shift operation of x1 by the number of bit positions given by x2. x2 must be of an acceptable index type (Integer, Bit#(n), Int#(n) or UInt#(n)).</td>
<td>function data_t &lt;&lt; (data_t x1, x2);</td>
</tr>
<tr>
<td>&gt;&gt;</td>
<td>Performs a right shift operation of x1 by the number of bit positions given by x2. x2 must be of an acceptable index type (Integer, Bit#(n), Int#(n) or UInt#(n)).</td>
<td>function data_t &gt;&gt; (data_t x1, x2);</td>
</tr>
</tbody>
</table>

The functions msb and lsb operate on a single argument.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code Snippet</th>
</tr>
</thead>
<tbody>
<tr>
<td>msb</td>
<td>Returns the value of the most significant bit of x. Returns 0 if width of data_t is 0.</td>
<td>function Bit#(1) msb (data_t x);</td>
</tr>
<tr>
<td>lsb</td>
<td>Returns the value of the least significant bit of x. Returns 0 if width of data_t is 0.</td>
<td>function Bit#(1) lsb (data_t x);</td>
</tr>
</tbody>
</table>

Examples

```verilog
class Value computeOp(AOp aop, Value v1, Value v2) {
    case (aop) matches
        Aand : return v1 & v2;
        Anor : return invert(v1 | v2);
        Aor  : return v1 | v2;
        Axor : return v1 ^ v2;
        Asll : return v1 << vToNat(v2);
        Asrl : return v1 >> vToNat(v2);
    endcase
}
class BitReduction

BitReduction defines the class of types on which the Verilog bit reduction operations are defined.
```
typeclass BitReduction #(type x, numeric type n)
    function x#(1) reduceAnd (x#(n) d);
    function x#(1) reduceOr (x#(n) d);
    function x#(1) reduceXor (x#(n) d);
    function x#(1) reduceNand (x#(n) d);
    function x#(1) reduceNor (x#(n) d);
endtypeclass

Note: the numeric keyword is not required

The BitReduction functions take a sized type and reduce it to one element. The most common example is to operate on a Bit#() to produce a single bit result. The first step of the operation applies the operator between the first bit of the operand and the second bit of the operand to produce a result. The function then applies the operator between the result and the next bit of the operand, until the final bit is processed.

Typically the bit reduction operators will be accessed through their Verilog operators. When defining a new instance of the BitReduction type class the BSV names must be used. The table below lists both values. For example, the BSV bit reduction and operator is reduceAnd and the corresponding Verilog operator is &.

<table>
<thead>
<tr>
<th>BitReduction Functions</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>reduceAnd</td>
<td>Performs an and bit reduction operation between the elements of d to calculate the result.</td>
</tr>
<tr>
<td>&amp;</td>
<td>function x#(1) reduceAnd (x#(n) d);</td>
</tr>
<tr>
<td>reduceOr</td>
<td>Performs an or bit reduction operation between the elements of d to calculate the result.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>reduceXor</td>
<td>Performs an xor bit reduction operation between the elements of d to calculate the result.</td>
</tr>
<tr>
<td>^</td>
<td>function x#(1) reduceXor (x#(n) d);</td>
</tr>
<tr>
<td>reduceNand</td>
<td>Performs an nand bit reduction operation between the elements of d to calculate the result.</td>
</tr>
<tr>
<td>^&amp;</td>
<td>function x#(1) reduceNand (x#(n) d);</td>
</tr>
<tr>
<td>reduceNor</td>
<td>Performs an nor bit reduction operation between the elements of d to calculate the result.</td>
</tr>
<tr>
<td>^</td>
<td></td>
</tr>
</tbody>
</table>
### reduceXnor

Performs an \textit{xnor} bit reduction operation between the elements of \( d \) to calculate the result.

\[
\text{function } x\#(1) \ \text{reduceXnor} \ (x\#(n) \ d);
\]

#### B.1.11 BitExtend

**BitExtend** defines types on which bit extension operations are defined.

\[
\text{typeclass BitExtend } #\text{(numeric type m, numeric type n, type x);} \quad // \ n > m \\
\quad \text{function } x\#(n) \ \text{extend} \ (x\#(m) \ d); \\
\quad \text{function } x\#(n) \ \text{zeroExtend} \ (x\#(m) \ d); \\
\quad \text{function } x\#(n) \ \text{signExtend} \ (x\#(m) \ d); \\
\quad \text{function } x\#(m) \ \text{truncate} \ (x\#(n) \ d); \\
\text{endtypeclass}
\]

The **BitExtend** operations take as input of one size and changes it to an input of another size, as described in the tables below. It is recommended that \textit{extend} be used in place of \textit{zeroExtend} or \textit{signExtend}, as it will automatically perform the correct operation based on the data type of the argument.

<table>
<thead>
<tr>
<th><strong>BitExtend Functions</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>extend</strong></td>
</tr>
<tr>
<td>Performs either a zeroExtend or a signExtend as appropriate, depending on the data type of the argument (zeroExtend for an unsigned argument, signExtend for a signed argument).</td>
</tr>
<tr>
<td>function ( x#(n) \ \text{extend} \ (x#(m) \ d) )</td>
</tr>
<tr>
<td>provisos (Add#(k, m, n));</td>
</tr>
</tbody>
</table>

| **zeroExtend**          |
| Use of \textit{extend} instead is recommended. Adds extra zero bits to the MSB of argument \( d \) of size \( m \) to make the datatype size \( n \). |
| function \( x\#(n) \ \text{zeroExtend} \ (x\#(m) \ d) \) |
| provisos (Add\#(k, m, n)); |

| **signExtend**          |
| Use of \textit{extend} instead is recommended. Adds extra sign bits to the MSB of argument \( d \) of size \( m \) to make the datatype size \( n \) by replicating the sign bit. |
| function \( x\#(n) \ \text{signExtend} \ (x\#(m) \ d) \) |
| provisos (Add\#(k, m, n)); |

| **truncate**            |
| Removes bits from the MSB of argument \( d \) of size \( n \) to make the datatype size \( m \). |
| function \( x\#(m) \ \text{truncate} \ (x\#(n) \ d) \) |
| provisos (Add\#(k, n, m)); |
Examples

\[
\begin{align*}
\text{UInt}(T\text{Add}(1, T\text{Log}(n))) \; \text{zz} &= \text{extend}(xx) + \text{extend}(yy); \\
\text{Bit}(n) \; v1 &= \text{zeroExtend}(v); \\
\text{Int}(4) \; i\_\text{index} &= \text{signExtend}(i) + 4; \\
\text{Bit}(32) \; \text{upp} &= \text{truncate}(\text{din}); \\
r \;\leq \text{zeroExtend}(c + \text{truncate}(r))
\end{align*}
\]

B.1.12 SaturatingArith

The SaturatingArith typeclass contains modified addition and subtraction functions which saturate to the values defined by maxBound or minBound when the operation would otherwise overflow or wrap-around.

There are 4 types of saturation modes which determine how an overflow or underflow should be handled, as defined by the SaturationMode type.

<table>
<thead>
<tr>
<th>Saturation Modes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sat_Wrap</td>
<td>Ignore overflow and underflow, just wrap around</td>
</tr>
<tr>
<td>Sat_Bound</td>
<td>On overflow or underflow result becomes maxBound or minBound</td>
</tr>
<tr>
<td>Sat_Zero</td>
<td>On overflow or underflow result becomes 0</td>
</tr>
<tr>
<td>Sat_Symmetric</td>
<td>On overflow or underflow result becomes maxBound or (minBound+1)</td>
</tr>
</tbody>
</table>

typedef enum { Sat_Wrap, Sat_Bound, Sat_Zero, Sat_Symmetric } SaturationMode deriving (Bits, Eq);

typeclass SaturatingArith#( type t);
  function t satPlus (SaturationMode mode, t x, t y);
  function t satMinus (SaturationMode mode, t x, t y);
  function t boundedPlus (t x, t y) = satPlus (Sat_Bound, x, y);
  function t boundedMinus (t x, t y) = satMinus(Sat_Bound, x, y);
endtypeclass

Instances of the SaturatingArith class are defined for Int, UInt, Complex, and FixedPoint.

<table>
<thead>
<tr>
<th>satPlus</th>
<th>Modified plus function which saturates when the operation would otherwise overflow or wrap-around. The saturation value (maxBound, wrap, or 0) is determined by the value of mode, the SaturationMode.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>function t satPlus (SaturationMode mode, t x, t y);</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>satMinus</th>
<th>Modified minus function which saturates when the operation would otherwise overflow or wrap-around. The saturation value (minBound, wrap, minBound +1, or 0) is determined by the value of mode, the SaturationMode.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>function t satMinus (SaturationMode mode, t x, t y);</td>
</tr>
</tbody>
</table>
**boundedPlus**

Modified plus function which saturates to maxBound when the operation would otherwise overflow or wrap-around. The function is the same as satPlus where the SaturationMode is Sat_Bound.

```
function t boundedPlus (t x, t y) = satPlus (Sat_Bound, x, y);
```

**boundedMinus**

Modified minus function which saturates to minBound when the operation would otherwise overflow or wrap-around. The function is the same as satMinus where the SaturationMode is Sat_Bound.

```
function t boundedMinus (t x, t y) = satMinus(Sat_Bound, x, y);
```

### Examples

```
Reg#(SaturationMode) smode <- mkReg(Sat_Wrap);

rule okdata (isOk);
    tstCount <= boundedPlus (tstCount, 1);
endrule
```

### B.1.13 Alias and NumAlias

**Alias** specifies that two types can be used interchangeably, providing a way to introduce local names for types within a module. They are used in Provisos. See Section 7.1 for more information.

```
typeclass Alias#(type a, type b)
    dependencies (a determines b, b determines a);
endtypeclass
```

**NumAlias** is used to give a new name to a numeric type.

```
typeclass NumAlias#(numeric type a, numeric type b)
    dependencies (a determines b, b determines a);
endtypeclass
```

### Examples

```
Alias#(fp, FixedPoint#(i,f));
NumAlias#(TLog#(a,b), logab);
```

### B.1.14 FShow

The FShow typeclass defines the types to which the function fshow can be applied. The function converts a value to an associated Fmt representation for use with the $display family of system tasks. Instances of the FShow class can often be automatically derived using the deriving statement.
typeclass FShow#(type t);
    function Fmt fshow(t value);
endtypeclass

<table>
<thead>
<tr>
<th>FShow function</th>
</tr>
</thead>
<tbody>
<tr>
<td>fshow</td>
</tr>
<tr>
<td>Returns a Fmt representation when applied to a value</td>
</tr>
<tr>
<td>function Fmt fshow(t value);</td>
</tr>
</tbody>
</table>

Instances of FShow for Prelude data types are defined in the Prelude package. Instances for non-Prelude types are documented in the type package. If an instance of FShow is not already defined for a type you can create your own instance. You can also redefine existing instances as required for your design.

<table>
<thead>
<tr>
<th>FShow Instances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>String, Char</td>
</tr>
<tr>
<td>Bool</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>int#(n)</td>
</tr>
<tr>
<td>uint#(n)</td>
</tr>
<tr>
<td>Bit#(n)</td>
</tr>
<tr>
<td>Maybe#(a)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Tuple2#(a,b)</td>
</tr>
<tr>
<td>Tuple3#(a,b,c)</td>
</tr>
<tr>
<td>Tuple4#(a,b,c,d)</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>Tuple8#(a,b,c,d,e,f,g,h)</td>
</tr>
</tbody>
</table>

Example

typedef enum {READ, WRITE, UNKNOWN} OpCommand deriving(Bounded,Bits, Eq, FShow);

typedef struct {OpCommand command;
    Bit#(8) addr;
    Bit#(8) data;
    Bit#(8) length;
    Bool    lock;
} Header deriving (Eq, Bits, Bounded);

typedef union tagged {Header Descriptor;
    Bit#(8) Data;
} Request deriving(Eq, Bits, Bounded);

// Define FShow instances where definition is different
// than the derived values

instance FShow#(Header);
    function Fmt fshow (Header value);
    return ($format("<HEAD "))
+ fshow(value.command)
+ $\text{format}(" (\%0d)\", \text{value.length})
+ $\text{format}(" A:\%h\", \text{value.addr})
+ $\text{format}(" D:\%h>\", \text{value.data});
endfunction
endinstance

instance FShow#(Request);
 function Fmt fshow (Request request);
 case (request) matches
 tagged Descriptor .a:
 return fshow(a);
 tagged Data .a:
 return $\text{format}("<DATA \%h>\", a);
 endcase
 endfunction
endinstance

B.1.15 StringLiteral

StringLiteral defines the class of types which can be created from strings.

typeclass StringLiteral #(type data_t);
 function data_t fromString(String x);
endtypeclass

<table>
<thead>
<tr>
<th>StringLiteral Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>fromString</td>
</tr>
<tr>
<td>Converts an element x of datatype String into an element of data type data_t</td>
</tr>
<tr>
<td>function data_t fromString(String x);</td>
</tr>
</tbody>
</table>

B.2 Data Types

Every variable and every expression in BSV has a type. Prelude defines the data types which are always available. An instance declaration defines a data type as belonging to a type class. Each data type may belong to one or more type classes; all functions, modules, and operators declared for the type class are then defined for the data type. A data type does not have to belong to any type classes.

Data type identifiers must always begin with a capital letter. There are three exceptions; bit, int, and real, which are predefined for backwards compatibility.

B.2.1 Bit

To define a value of type Bit:

Bit#(type n);
The data type `bit` is defined as a single bit. This is a special case of `Bit`.

typedef Bit#(1) bit;

**Examples**

Bit#(32) a; // like 'reg [31:] a'
Bit#(1) b; // like 'reg a'
bit c; // same as Bit#(1) c

The `Bit` data type provides functions to concatenate and split bit-vectors.

**Bit Functions**

- `{x,y}`: Concatenate two bit vectors, x of size n and y of size m returning a bit vector of size k. The Verilog operator `{ }` is used.
  
  ```verilog
  function Bit#(k) bitconcat(Bit#(n) x, Bit#(m) y)
  provisos (Add#(n, m, k));
  ```

- `split`: Split a bit vector into two bit vectors (higher-order bits (n), lower-order bits (m)).

  ```verilog
  function Tuple2 #(Bit#(n), Bit#(m)) split(Bit#(mn) xy)
  provisos (Add#(n, m, mn));
  ```

**Examples**

```
module mkBitConcatSelect();
  Bit#(3) a = 3'b010; // a = 010
  Bit#(7) b = 7'h5e; // b = 1011110
  Bit#(10) abconcat = {a,b}; // = 0101011110
  Bit#(4) bselect = b[6:3]; // = 1011
endmodule

function Tuple2#(Bit#(m), Bit#(n)) split (Bit#(mn) xy)
  provisos (Add#(m, n, mn));
```
B.2.2 UInt

The UInt type is an unsigned fixed width representation of an integer value.

<table>
<thead>
<tr>
<th>Type Classes for UInt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>UInt</td>
</tr>
</tbody>
</table>

Examples

```
UInt#(8) a = 'h80;
UInt#(12) b = zeroExtend(a); // b => 'h080
UInt#(8) c = truncate(b); // c => 'h80
```

B.2.3 Int

The Int type is a signed fixed width representation of an integer value.

<table>
<thead>
<tr>
<th>Type Classes for Int</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Int</td>
</tr>
</tbody>
</table>

Examples

```
Int#(8) a = 'h80;
Int#(12) b = signExtend(a); // b => 'hF80
Int#(8) c = truncate(d); // c => 'h80
```

Int type aliases

```
int The data type int is defined as a 32-bit signed integer. This is a special case of Int.
typedef Int#(32) int;
```

B.2.4 Integer

The Integer type is a data type used for integer values and functions. Because Integer is not part of the Bits typeclass, the Integer type is used for static elaboration only; all values must be resolved at compile time.

<table>
<thead>
<tr>
<th>Type Classes for Integer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Integer</td>
</tr>
</tbody>
</table>

172
### Integer Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code snippet</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>div</code></td>
<td>Element (x) is divided by element (y) and the result is rounded toward negative infinity. Division by 0 is undefined.</td>
<td><code>function Integer div(Integer x, Integer y);</code></td>
</tr>
<tr>
<td><code>mod</code></td>
<td>Element (x) is divided by element (y) using the <code>div</code> function and the remainder is returned as an <code>Integer</code> value. <code>div</code> and <code>mod</code> satisfy the identity ((\text{div}(x, y) \times y) + \text{mod}(x, y) == x). Division by 0 is undefined.</td>
<td><code>function Integer mod(Integer x, Integer y);</code></td>
</tr>
<tr>
<td><code>quot</code></td>
<td>Element (x) is divided by element (y) and the result is truncated (rounded towards 0). Division by 0 is undefined.</td>
<td><code>function Integer quot(Integer x, Integer y);</code></td>
</tr>
<tr>
<td><code>rem</code></td>
<td>Element (x) is divided by element (y) using the <code>quot</code> function and the remainder is returned as an <code>Integer</code> value. <code>quot</code> and <code>rem</code> satisfy the identity ((\text{quot}(x, y) \times y) + \text{rem}(x, y) == x). Division by 0 is undefined.</td>
<td><code>function Integer rem(Integer x, Integer y);</code></td>
</tr>
</tbody>
</table>

The `fromInteger` function, defined in Section B.1.3, can be used to convert an `Integer` into any type in the `Literal` typeclass.

**Examples**

```verilog
Int#(32) arr2[16];
for (Integer i=0; i<16; i=i+1)
    arr2[i] = fromInteger(i);

Integer foo = 10;
foo = foo + 1;
foo = foo * 5;
Bit#(16) var1 = fromInteger( foo );
```

### Bool

The `Bool` type is defined to have two values, True and False.

```verilog
typedef enum {False, True} Bool;
```

<table>
<thead>
<tr>
<th>Type Classes for Bool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>Bool</td>
</tr>
</tbody>
</table>

The `Bool` functions return either a value of `True` or `False`. 
Reference Guide

### Bool Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>not</code> !</td>
<td>Returns True if x is false, returns False if x is true.</td>
<td><code>function Bool not (Bool x);</code></td>
</tr>
<tr>
<td><code>&amp;&amp;</code></td>
<td>Returns True if x and y are true, else it returns False.</td>
<td><code>function Bool &amp;&amp; (Bool x, Bool y);</code></td>
</tr>
<tr>
<td>`</td>
<td></td>
<td>`</td>
</tr>
</tbody>
</table>

### Examples

```verilog
Bool a // A variable named a with a type of Bool
Reg#(Bool) done // A register named done with a type of Bool
Vector#(5, Bool) // A vector of 5 Boolean values

Bool a = 0; // ERROR! You cannot do this
Bool a = True; // correct
if (a) // correct
    ....
if (a == 0) // ERROR!
    ....

Bool b1 = True;
Bool b2 = True;
Bool b3 = b1 && b2;
```

### B.2.6 Real

The **Real** type is a data type used for real values and functions.

Real numbers are of the form:

$$\text{Real} ::= \text{decNum}[.\text{decDigitsUnderscore}] | \text{exp} [\text{sign}] \text{decDigitsUnderscore}$$

- **decNum**: $0...9$
- **decDigitsUnderscore**: $0...9, _$
- **sign**: $+ | -$
- **exp**: $e | E$

If there is a decimal point, there must be digits following the decimal point. An exponent can start with either an E or an e, followed by an optional sign (+ or -), followed by digits. There cannot be an exponent or a sign without any digits. Any of the numeric components may include an underscore, but an underscore cannot be the first digit of the real number.
Unlike integer numbers, real numbers are of limited precision. They are represented as IEEE floating point numbers of 64 bit length, as defined by the IEEE standard.

Because the type `Real` is not part of the `Bits` typeclass, the `Real` type is used for static elaboration only; all values must be resolved at compile time.

There are many functions defined for `Real` types, provided in the `Real` package (Section C.5.1). To use these functions, the `Real` package must be imported.

### Type Classes for `Real`

<table>
<thead>
<tr>
<th>Bits</th>
<th>Eq</th>
<th>Literal</th>
<th>Real Literal</th>
<th>Arith</th>
<th>Ord</th>
<th>Bounded</th>
<th>Bitwise</th>
<th>Bit Reduction</th>
<th>Bit Extend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### `Real` type aliases

```
typedef Real real;
```

There are two system tasks defined for the `Real` data type, used to convert between `Real` and IEEE standard 64-bit vector representation (`Bit#(64)`).

#### `Real` system tasks

<table>
<thead>
<tr>
<th><code>$realtobits</code></th>
<th>Converts from a <code>Real</code> to the IEEE 64-bit vector representation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Bit#(64) $realtobits (Real x) ;</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><code>$bitstoreal</code></th>
<th>Converts from a 64-bit vector representation to a <code>Real</code>.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Real $bitstoreal (Bit#(64) x) ;</td>
<td></td>
</tr>
</tbody>
</table>

### Examples

```
Bit#(1) sign1 = 0;
Bit#(52) mantissa1 = 0;
Bit#(11) exp1 = 1024;
Real r1 = $bitstoreal([sign1, exp1, mantissa1]); // r1 = 2.0

Real x = pi;
let m = realToString(x)); // m = 3.141592653589793
```

#### B.2.7 String

Strings are mostly used in system tasks (such as `$display`). The `String` type belongs to the `Eq` type class; strings can be tested for equality and inequality using the `==` and `!=` operators. The `String` type is also part of the `Arith` class, but only the addition (+) operator is defined. All other `Arith` operators will produce an error message.
### Type Classes for String

<table>
<thead>
<tr>
<th></th>
<th>Bits</th>
<th>Eq</th>
<th>Literal</th>
<th>Arith</th>
<th>Ord</th>
<th>Bounded</th>
<th>Bitwise</th>
<th>String Literal</th>
<th>FShow</th>
</tr>
</thead>
<tbody>
<tr>
<td>String</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

### String Functions

**strConcat**

Concatenates two strings (same as the + operator)

```hs
function String strConcat(String s1, String s2);
```

**stringLength**

Returns the number of characters in a string

```hs
function Integer stringLength (String s);
```

**stringSplit**

If the string is empty, returns `Invalid`; otherwise it returns `Valid` with the `Tuple` containing the first character as the head and the rest of the string as the tail.

```hs
function Maybe#(Tuple#2(Char, String)) stringSplit(String s);
```

**stringHead**

Extracts the first character of a string; reports an error if the string is empty.

```hs
function Char stringHead(String s);
```

**stringTail**

Extracts all the characters of a string after the first; reports an error if the string is empty.

```hs
function String stringTail(String s);
```

**stringCons**

Adds a character to the front of a string. This function is the complement of `stringSplit`.

```hs
function String stringCons(Char c, String s);
```

**stringToCharList**

Converts a `String` to a `List` of characters

```hs
function List#(Char) stringToCharList (String s);
```

**charListToString**

Converts a `List` of characters to a `String`

```hs
function String charListToString (List#(Char) cs);
```

**quote**

Add single quotes around a string: `'str'`

```hs
function String quote (String s);
```
**doubleQuote**

Add double quotes around a string: "str"

```verilog
function String doubleQuote (String s);
```

### Examples

```verilog
String s1 = "This is a test";
$display("first string = ", s1);

// we can use + to concatenate
String s2 = s1 + " of concatenation"
$display("Second string = ", s2);
```

**B.2.8 Char**

The Char data type is used mostly in system tasks (such as $display). The Char type provides the ability to traverse the characters of a string. The Char type belongs to the Eq type class; chars can be tested for equality and inequality using the == and != operators.

The Char type belongs to the Ord type class.

<table>
<thead>
<tr>
<th>Type Classes for Char</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>Char</td>
</tr>
</tbody>
</table>

#### Char Functions

**charToString**

Convert a single character to a string

```verilog
function String charToString (Char c);
```

**charToInteger**

Convert a character to its ASCII numeric value

```verilog
function Integer charToInteger (Char c);
```

**integerToChar**

Convert an ASCII value to its character equivalent, returns an error if the number is out of range

```verilog
function Char integerToChar (Integer n);
```

**isSpace**

Determine if a character is whitespace (space, tab \t, vertical tab \v, newline \n, carriage return \r, linefeed \f)

```verilog
function Bool isSpace (Char c);
```

**isLower**

Determine if a character is a lowercase ASCII character (a - z)

```verilog
function Bool isLower (Char c);
```
<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>isUpper</code></td>
<td>Determine if a character is an uppercase ASCII character (A - Z)</td>
</tr>
<tr>
<td><code>function Bool isUpper (Char c);</code></td>
<td></td>
</tr>
<tr>
<td><code>isAlpha</code></td>
<td>Determine if a character is an ASCII letter, either upper or lowercase</td>
</tr>
<tr>
<td><code>function Bool isAlpha (Char c);</code></td>
<td></td>
</tr>
<tr>
<td><code>isDigit</code></td>
<td>Determine if a character is an ASCII decimal digit (0 - 9)</td>
</tr>
<tr>
<td><code>function Bool isDigit (Char c);</code></td>
<td></td>
</tr>
<tr>
<td><code>isAlphaNum</code></td>
<td>Determine if a character is an ASCII letter or decimal digit</td>
</tr>
<tr>
<td><code>function Bool isAlphaNum (Char c);</code></td>
<td></td>
</tr>
<tr>
<td><code>isOctDigit</code></td>
<td>Determine if a character is an ASCII octal digit (0 - 7)</td>
</tr>
<tr>
<td><code>function Bool isOctDigit (Char c);</code></td>
<td></td>
</tr>
<tr>
<td><code>isHexDigit</code></td>
<td>Determine if a character is an ASCII hexadecimal digit (0 - 9, a - f, or A - F)</td>
</tr>
<tr>
<td><code>function Bool isHexDigit (Char c);</code></td>
<td></td>
</tr>
<tr>
<td><code>toUpper</code></td>
<td>Convert an ASCII lowercase letter to uppercase; other characters are unchanged</td>
</tr>
<tr>
<td><code>function Char toUpper (Char c);</code></td>
<td></td>
</tr>
<tr>
<td><code>toLower</code></td>
<td>Convert an ASCII uppercase letter to lowercase; other characters are unchanged</td>
</tr>
<tr>
<td><code>function Char toLower (Char c);</code></td>
<td></td>
</tr>
<tr>
<td><code>digitToInteger</code></td>
<td>Convert an ASCII decimal digit to its numeric value (0 to 0, unlike <code>charToInteger</code> which would return the ASCII code 48); returns an error if the character is not a digit.</td>
</tr>
<tr>
<td><code>function Integer digitToInteger (Char c);</code></td>
<td></td>
</tr>
<tr>
<td><code>digitToBits</code></td>
<td>Convert an ASCII decimal digit to its numeric value; returns an error if the character is not a digit. Same as <code>digitToInteger</code>, but returns the value as a bit vector; the vector can be any size, but the user will get an error if the size is too small to represent the value</td>
</tr>
<tr>
<td><code>function Bit#(n) digitToBits (Char c);</code></td>
<td></td>
</tr>
<tr>
<td>Function</td>
<td>Description</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>integerToDigit</td>
<td>Convert a decimal digit value (0 to 9) to the ASCII character for that digit; returns an error if the value is out of range. This function is the complement of digitToInteger.</td>
</tr>
<tr>
<td>bitsToDigit</td>
<td>Convert a Bit type digit value to the ASCII character for that digit; returns an error if the value is out of range. This is the same as integerToDigit but for values that are Bit types.</td>
</tr>
<tr>
<td>hexDigitToInteger</td>
<td>Convert an ASCII decimal digit to its numeric, including hex characters a-f and A-F</td>
</tr>
<tr>
<td>hexDigitToBits</td>
<td>Convert an ASCII decimal digit to its numeric, including hex characters a-f and A-F returning the value as a bit vector. The vector can be any size, but an error will be returned if the size is too small to represent the value.</td>
</tr>
<tr>
<td>integerToHexDigit</td>
<td>Convert a hexadecimal digit value (0 to 15) to the ASCII character for that digit; returns an error if the value is out of range. This function is the complement of hexDigitToInteger. The function returns lowercase for the letters a to f; apply the function toUpper to get uppercase.</td>
</tr>
<tr>
<td>bitsToHexDigit</td>
<td>Convert a Bit type hexadecimal digit value to the ASCII character for that digit, returns an error if the value is out of range. The function returns lowercase for the letters a to f; apply the function toUpper to get uppercase.</td>
</tr>
</tbody>
</table>

**B.2.9 Fmt**

The Fmt primitive type provides a representation of arguments to the $display family of system tasks (Section 12.8.1) that can be manipulated in BSV code. Fmt representations of data objects can be written hierarchically and applied to polymorphic types.

Objects of type Fmt can be supplied directly as arguments to system tasks in the $display family. An object of type Fmt is returned by the $format (Section 12.8.2) system task.

The Fmt type is part of the Arith class, but only the addition (+) operator is defined. All other Arith operators will produce an error message.
### Type Classes for `Fmt`

<table>
<thead>
<tr>
<th></th>
<th>Bits</th>
<th>Eq</th>
<th>Literal</th>
<th>Arith</th>
<th>Ord</th>
<th>Bounded</th>
<th>Bitwise</th>
<th>Bit Reduction</th>
<th>Bit Extend</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>Fmt</code></td>
<td>✔</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Examples

```verilog
Reg#(Bit#(8)) count <= mkReg(0);
Fmt f = $format("("%0d) ", count + 1);
$display(" XYZ \th", f, " ", $format("("%0d) ", count));
```

\\value displayed: XYZ (6) (5)

### B.2.10 Void

The Void type is a type which has one literal `?` used for constructing concrete values of the type `void`. The Void type is part of the Bits and Literal typeclasses.

#### Type Classes for `Void`

<table>
<thead>
<tr>
<th></th>
<th>Bits</th>
<th>Eq</th>
<th>Literal</th>
<th>Arith</th>
<th>Ord</th>
<th>Bounded</th>
<th>Bitwise</th>
<th>Bit Reduction</th>
<th>Bit Extend</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>Void</code></td>
<td>✔</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Examples

```verilog
typedef union tagged {
  void Invalid;
data_t Valid;
} Maybe #(type data_t) deriving (Eq, Bits);
```

```verilog
typedef union tagged {
  void InvalidFile;
  Bit#(31) MCD;
  Bit#(31) FD;
} File;
```

### B.2.11 Maybe

The Maybe type is used for tagging values as either Valid or Invalid. If the value is Valid, the value contains a datatype `data_t`.

```verilog
typedef union tagged {
  void Invalid;
data_t Valid;
} Maybe #(type data_t) deriving (Eq, Bits);
```

#### Type Classes for `Maybe`

<table>
<thead>
<tr>
<th></th>
<th>Bits</th>
<th>Eq</th>
<th>Literal</th>
<th>Arith</th>
<th>Ord</th>
<th>Bounded</th>
<th>Bitwise</th>
<th>Bit Reduction</th>
<th>Bit Extend</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>Maybe</code></td>
<td>✔</td>
<td>✔</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Maybe data type provides functions to check if the value is Valid and to extract the valid value.
Maybe Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>fromMaybe</code></td>
<td>Extracts the Valid value out of a Maybe argument. If the tag is Invalid the default value, <code>defaultval</code>, is returned.</td>
</tr>
<tr>
<td></td>
<td>function <code>data_t fromMaybe( data_t defaultval, Maybe#(data_t) val )</code></td>
</tr>
<tr>
<td><code>isValid</code></td>
<td>Returns a value of True if the Maybe argument is Valid.</td>
</tr>
<tr>
<td></td>
<td>function <code>Bool isValid( Maybe#(data_t) val )</code></td>
</tr>
</tbody>
</table>

Examples

```verilog
typedef struct{
    a tpl_1;
    b tpl_2;
} Tuple2 #(type a, type b) deriving (Bits, Eq, Bounded);

typedef struct{
    a tpl_1;
    b tpl_2;
    c tpl_3;
} Tuple3 #(type a, type b, type c) deriving (Bits, Eq, Bounded);

typedef struct{
    a tpl_1;
    b tpl_2;
    c tpl_3;
    d tpl_4;
} Tuple4 #(type a, type b, type c, type d) deriving (Bits, Eq, Bounded);

typedef struct{
    a tpl_1;
    b tpl_2;
    c tpl_3;
    d tpl_4;
    e tpl_5;
} Tuple5 #(type a, type b, type c, type d, type e) deriving (Bits, Eq, Bounded);

typedef struct{
    a tpl_1;
    b tpl_2;
    c tpl_3;
    d tpl_4;
    e tpl_5;
    f tpl_6;
} Tuple6 #(type a, type b, type c, type d, type e, type f) deriving (Bits, Eq, Bounded);

typedef struct{
    a tpl_1;
    b tpl_2;
    c tpl_3;
    d tpl_4;
    e tpl_5;
    f tpl_6;
    g tpl_7;
} Tuple7 #(type a, type b, type c, type d, type e, type f, type g) deriving (Bits, Eq, Bounded);

typedef struct{
    a tpl_1;
    b tpl_2;
    c tpl_3;
    d tpl_4;
    e tpl_5;
    f tpl_6;
    g tpl_7;
    h tpl_8;
} Tuple8 #(type a, type b, type c, type d, type e, type f, type g, type h) deriving (Bits, Eq, Bounded);
```

B.2.12 Tuples

Tuples are predefined structures which group a small number of values together. The following pseudo code explains the structure of the tuples. You cannot define your own tuples, but must use the seven predefined tuples, `Tuple2` through `Tuple8`. As shown, `Tuple2` groups two items together, `Tuple3` groups three items together, up through `Tuple8` which groups eight items together.

```verilog
rule doit;
    Maybe#(int) mbi = rw_incr.wget(); // increment method is being invoked
    Maybe#(int) mbd = rw_decr.wget(); // decrement method is being invoked
    int di = fromMaybe (?, mbi);
    int dd = fromMaybe (?, mbd);
    if ( (isValid (mbi)) && (isValid (mbd)))
        noAction;
    else if ( isValid (mbi) && (isValid (mbd)))
        value2 <= value2 + di;
    else if (isValid (mbi)) && isValid (mbd))
        value2 <= value2 - dd;
    else // ( isValid (mbi) && isValid (mbd))
        value2 <= value2 + di - dd;
endrule
```


c tpl_3;
d tpl_4;
} Tuple4 #(type a, type b, type c, type d) deriving (Bits, Eq, Bounded);

typedef struct{
a tpl_1;
b tpl_2;
c tpl_3;
d tpl_4;
e tpl_5;
} Tuple5 #(type a, type b, type c, type d, type e)
deriving (Bits, Eq, Bounded);

typedef struct{
a tpl_1;
b tpl_2;
c tpl_3;
d tpl_4;
e tpl_5;
f tpl_6;
} Tuple6 #(type a, type b, type c, type d, type e, type f)
deriving (Bits, Eq, Bounded);

typedef struct{
a tpl_1;
b tpl_2;
c tpl_3;
d tpl_4;
e tpl_5;
f tpl_6;
g tpl_7;
} Tuple7 #(type a, type b, type c, type d, type e, type f, type g)
deriving (Bits, Eq, Bounded);

typedef struct{
a tpl_1;
b tpl_2;
c tpl_3;
d tpl_4;
e tpl_5;
f tpl_6;
g tpl_7;
h tpl_8;
} Tuple8 #(type a, type b, type c, type d, type e, type f, type g, type h)
deriving (Bits, Eq, Bounded);

<table>
<thead>
<tr>
<th>Type Classes for Tuples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>TupleN</td>
</tr>
</tbody>
</table>

Tuples cannot be manipulated like normal structures; you cannot create values of and select fields from tuples as you would a normal structure. Values of these types can be created only by applying a predefined family of constructor functions.
Bluespec SystemVerilog Reference Guide

Tuple Constructor Functions

<table>
<thead>
<tr>
<th>Tuple Constructor Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>tuple2 (e1, e2)</td>
<td>Creates a variable of type Tuple2 with component values e1 and e2.</td>
</tr>
<tr>
<td>tuple3 (e1, e2, e3)</td>
<td>Creates a variable of type Tuple3 with values e1, e2, and e3.</td>
</tr>
<tr>
<td>tuple4 (e1, e2, e3, e4)</td>
<td>Creates a variable of type Tuple4 with component values e1, e2, e3, and e4.</td>
</tr>
<tr>
<td>tuple5 (e1, e2, e3, e4, e5)</td>
<td>Creates a variable of type Tuple5 with component values e1, e2, e3, e4, and e5.</td>
</tr>
<tr>
<td>tuple6 (e1, e2, e3, e4, e5, e6)</td>
<td>Creates a variable of type Tuple6 with component values e1, e2, e3, e4, e5, and e6.</td>
</tr>
<tr>
<td>tuple7 (e1, e2, e3, e4, e5, e6, e7)</td>
<td>Creates a variable of type Tuple7 with component values e1, e2, e3, e4, e5, e6, and e7.</td>
</tr>
</tbody>
</table>

Fields of these types can be extracted only by applying a predefined family of selector functions.

Tuple Extract Functions

<table>
<thead>
<tr>
<th>Tuple Extract Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>tpl_1 (x)</td>
<td>Extracts the first field of x from a Tuple2 to Tuple8.</td>
</tr>
<tr>
<td>tpl_2 (x)</td>
<td>Extracts the second field of x from a Tuple2 to Tuple8.</td>
</tr>
<tr>
<td>tpl_3 (x)</td>
<td>Extracts the third field of x from a Tuple3 to Tuple8.</td>
</tr>
<tr>
<td>tpl_4 (x)</td>
<td>Extracts the fourth field of x from a Tuple4 to Tuple8.</td>
</tr>
<tr>
<td>tpl_5 (x)</td>
<td>Extracts the fifth field of x from a Tuple5 to Tuple8.</td>
</tr>
<tr>
<td>tpl_6 (x)</td>
<td>Extracts the sixth field of x from a Tuple6, Tuple7 or Tuple8.</td>
</tr>
<tr>
<td>tpl_7 (x)</td>
<td>Extracts the seventh field of x from a Tuple7 or Tuple8.</td>
</tr>
<tr>
<td>tpl_8 (x)</td>
<td>Extracts the seventh field of x from a Tuple8.</td>
</tr>
</tbody>
</table>

Examples

```plaintext
Tuple2#( Bool, int ) foo = tuple2( True, 25 );
Bool field1 = tpl_1( foo ); // this is value 1 in the list
int  field2 = tpl_2( foo ); // this is value 2 in the list
foo = tuple2( !field1, field2 );
```

B.2.13 Array

Array variables are generally declared anonymously, using the bracket syntax described in section 8.1. However, the type of such variables can be expressed with the type constructor Array, when an explicit type is needed.

<table>
<thead>
<tr>
<th>Type Classes for Array</th>
<th>Bits</th>
<th>Eq</th>
<th>Literal</th>
<th>Arith</th>
<th>Ord</th>
<th>Bounded</th>
<th>Bitwise</th>
<th>Bit Reduction</th>
<th>Bit Extend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For example, the following declarations using bracket syntax:

```plaintext
Bool arr[3];

function Bool fn(Bool bits[]);
```
are equivalent to the following declarations using the explicit type constructor:

```plaintext
Array#(Bool) arr;

function Bool fn(Array#(Bool) bits);
```

Note that, unlike `Vector`, the size of an array is not part of its type. In the first declaration, a size is given for the array `arr`. However, since `arr` is not assigned to a value, the size is unused here. If the array were assigned, the size would be used like a type declaration, to check that the assigned value has the declared size. Since it is not part of the type, this check would occur during elaboration, and not during type checking.

### B.2.14 Ordering

The `Ordering` type is used as the return type for the result of generic comparators, including the `compare` function defined in the `Ord` (Section B.1.7) type class. The valid values of `Ordering` are: `LT`, `GT`, and `EQ`.

```plaintext
typedef enum {
  LT,
  EQ,
  GT
} Ordering deriving (Eq, Bits, Bounded);
```

<table>
<thead>
<tr>
<th>Type Classes for Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Ordering</td>
</tr>
</tbody>
</table>

**Examples**

```plaintext
function Ordering onKey(Record r1, Record r2);
    return compare(r1.key,r2.key);
endfunction
```

### B.2.15 File

`File` is a defined type in BSV which is defined as:

```plaintext
typedef union tagged {
  void      InvalidFile ;
  Bit#(31)  MCD;
  Bit#(31)  FD;
} File;
```

<table>
<thead>
<tr>
<th>Type Classes for File</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>File</td>
</tr>
</tbody>
</table>

Note: `Bitwise` operations are valid only for subtype `MCD`.

The `File` type is used by the system tasks described in Section 12.8.
B.2.16 Clock

Clock is an abstract type of two components: a single Bit oscillator and a Bool gate.

```plaintext
typedef ... Clock ;
```

Clock is in the Eq type class, meaning two values can be compared for equality.

<table>
<thead>
<tr>
<th>Type Classes for Clock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>Clock</td>
</tr>
</tbody>
</table>

Examples

```plaintext
Clock clk <- exposeCurrentClock;
module mkTopLevel( Clock readClk, Reset readRst, Top ifc );
```

B.2.17 Reset

Reset is an abstract type.

```plaintext
typedef ... Reset ;
```

Reset is in the Eq type class, meaning two fields can be compared for equality.

<table>
<thead>
<tr>
<th>Type Classes for Reset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>Reset</td>
</tr>
</tbody>
</table>

Examples

```plaintext
Reset rst <- exposeCurrentReset;
module mkMod (Reset r2, (* reset_by="no_reset" *) Bool b,
              ModIfc ifc);
interface ResetGenIfc;
    interface Reset gen_rst;
endinterface
```

B.2.18 Inout

An Inout type is a first class type that is used to pass Verilog inouts through a BSV module. It takes an argument which is the type of the underlying signal:

```plaintext
Inout#(type t)
```

For example, the type of an Inout signal which communicates boolean values would be:
Inout#(Bool)

An Inout type is a valid subinterface type (like Clock and Reset). A value of an Inout type is clocked_by and reset_by a particular clock and reset.

Inouts are connectable via the Connectable typeclass. The use of mkConnection instantiates a Verilog module InoutConnect. The connected inouts must be on the same clock and the same reset. The clock and reset of the inouts may be different than the clock and reset of the parent module of the mkConnection.

    instance Connectable#(Inout#(a, x1), Inout#(a, x2))
        provisos (Bit#(a,sa));

A module with an Inout subinterface cannot leave that interface undefined since there is no way to create or examine inout values in BSV. For example, you cannot even write:

    Inout#(int) i = ?;  // not valid in BSV

The Inout type exists only so that RTL inout signals can be connected in BSV; the ultimate users of the signal will be outside the BSV code. An imported Verilog module might have an inout port that your BSV design doesn’t use, but which needs to be exposed at the top level. In this case, the submodule will introduce an inout signal that the BSV cannot read or write, but merely provides in its interfaces until it is exposed at the top level. Or, a design may contain two imported Verilog modules that have inout ports that expect to be connected. You can import these two modules, declaring that they each have a port of type Inout#(t) and connect them together. The compiler will check that both ports are of the same type t and that they are in the same clock domain with the same reset. Beyond that, BSV does not concern itself with the values of the inout signals.

**Examples**

Instantiating a submodule with an inout and exposing it at the next level:

    interface SubIfc;
    ...
    interface Inout#(Bool) b;
    endinterface

    interface TopIfc;
    ...
    interface Inout#(Bool) bus;
    endinterface

    module mkTop (TopIfc);
        SubIfc sub <- mkSub;
        ...
        interface bus = sub.b;
    endmodule

Connecting two submodules, using SubIfc defined above:
module mkTop(...);
...
SubIfc sub1 <- mkSub;
SubIfc sub2 <- mkSub;
mkConnection (sub1.b, sub2.b);
...
endmodule

B.2.19 Action/ActionValue

Any expression that is intended to act on the state of the circuit (at circuit execution time) is called an action and has type Action or ActionValue#(a). The type parameter a represents the type of the returned value.

<table>
<thead>
<tr>
<th>Type Classes for Action/ActionValue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>Action</td>
</tr>
</tbody>
</table>

The types Action and ActionValue are special keywords, and therefore cannot be redefined.

typedef abstract struct ActionValue#(type a);

<table>
<thead>
<tr>
<th>ActionValue type aliases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action</td>
</tr>
<tr>
<td>The Action type is a special case of the more general type ActionValue where nothing is returned. That is, the returns type is (void).</td>
</tr>
<tr>
<td>typedef ActionValue#(void) Action;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Action Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>noAction</td>
</tr>
<tr>
<td>An empty Action, this is an Action that does nothing.</td>
</tr>
<tr>
<td>function Action noAction();</td>
</tr>
</tbody>
</table>

Examples

method Action grab(Bit#(8) value);
  last_value <= value;
endmethod

interface IntStack;
  method Action push (int x);
  method ActionValue#(int) pop();
endinterface: IntStack

seq
  noAction;
endseq
B.2.20 Rules

A rule expression has type `Rules` and consists of a collection of individual rule constructs. Rules are first class objects, hence variables of type `Rules` may be created and manipulated. `Rules` values must eventually be added to a module in order to appear in synthesized hardware.

<table>
<thead>
<tr>
<th>Type Classes for Rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>Rules</td>
</tr>
</tbody>
</table>

The `Rules` data type provides functions to create, manipulate, and combine values of the type `Rules`.

### Rules Functions

- **emptyRules**
  - An empty rules variable.
  - Function: `function Rules emptyRules();`

- **addRules**
  - Takes rules `r` and adds them into a module. This function may only be called from within a module. The return type `Empty` indicates that the instantiation does not return anything.
  - Module: `module addRules#(Rules r) (Empty);`

- **rJoin**
  - Symmetric union of two sets of rules. A symmetric union means that neither set is implied to have any relation to the other: not more urgent, not execute before, etc.
  - Function: `function Rules rJoin(Rules x, Rules y);`

- **rJoinPreempts**
  - Union of two sets of rules, with rules on the left getting scheduling precedence and blocking the rules on the right. That is, if a rule in set `x` fires, then all rules in set `y` are prevented from firing. This is the same as specifying `descending_urgency` plus a forced conflict.
  - Function: `function Rules rJoinPreempts(Rules x, Rules y);`

- **rJoinDescendingUrgency**
  - Union of two sets of rules, with rules in the left having higher urgency. That is, if some rules compete for resources, then scheduling will select rules in set `x` set before set `y`. If the rules do not conflict, no conflict is added; the rules can fire together.
  - Function: `function Rules rJoinDescendingUrgency(Rules x, Rules y);`
### rJoinMutuallyExclusive

Union of two sets of rule, with rules in the all rules in the left set annotated as mutually exclusive with all rules in the right set. No relationship between the rules in the left set or between the rules in the right set is assumed. This annotation is used in scheduling and checked during simulation.

```verilog
function Rules rJoinMutuallyExclusive(Rules x, Rules y);
```

### rJoinExecutionOrder

Union of two sets of rule, with the rules in the left set executing before the rules in the right set. No relationship between the rules in the left set or between the rules in the right set is assumed. If any pair of rules cannot execute in the specified order in the same clock cycle, that pair of rules will conflict.

```verilog
function Rules rJoinExecutionOrder(Rules x, Rules y);
```

### rJoinConflictFree

Union of two sets of rule, with the rules in the left set annotated as conflict-free with the rules in the right set. This assumption is used during scheduling and checked during simulation. No relationship between the rules in the left set or between the rules in the right set is assumed.

```verilog
function Rules rJoinConflictFree(Rules x, Rules y);
```

### Examples (See Section 9.13 for complete example)

```verilog
function Rules incReg(Reg#(CounterType) a);
    return( rules
        rule addOne;
            a <= a + 1;
        endrule
    endrules);
endfunction

// Add incReg rule to increment the counter
addRules(incReg(asReg(counter)));  
```

### B.3 Operations on Numeric Types

#### B.3.1 Size Relationship/Provisos

These classes are used in provisos to express constraints between the sizes of types.

<table>
<thead>
<tr>
<th>Class</th>
<th>Proviso</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add</td>
<td>Add#(n1,n2,n3)</td>
<td>Assert n1 + n2 = n3</td>
</tr>
<tr>
<td>Mul</td>
<td>Mul#(n1,n2,n3)</td>
<td>Assert n1 * n2 = n3</td>
</tr>
<tr>
<td>Div</td>
<td>Div#(n1,n2,n3)</td>
<td>Assert ceiling n1/n2 = n3</td>
</tr>
<tr>
<td>Max</td>
<td>Max#(n1,n2,n3)</td>
<td>Assert max(n1,n2) = n3</td>
</tr>
<tr>
<td>Min</td>
<td>Min#(n1,n2,n3)</td>
<td>Assert min(n1,n2) = n3</td>
</tr>
<tr>
<td>Log</td>
<td>Log#(n1,n2)</td>
<td>Assert ceiling log_2(n1) = n2</td>
</tr>
</tbody>
</table>
Examples of Provisos using size relationships:

```verilog
instance Bits #( Vector#(vsize, element_type), tsize)
  provisos (Bits#(element_type, sizea),
            Mul#(vsize, sizea, tsize)); // vsize * sizea = tsize

function Vector#(vsize1, element_type)
  cons (element_type elem, Vector#(vsize, element_type) vect)
  provisos (Add#(1, vsize, vsize1)); // 1 + vsize = vsize1

function Vector#(mvsize, element_type)
  concat(Vector#(m, Vector#(n, element_type)) xss)
  provisos (Mul#(m, n, mvsize)); // m * n = mvsize
```

### B.3.2 Size Relationship Type Functions

These type functions are used when “defining” size relationships between data types, where the defined value need not (or cannot) be named in a proviso. They may be used in datatype definition statements when the size of the datatype may be calculated from other parameters.

<table>
<thead>
<tr>
<th>Type Function</th>
<th>Size Relationship</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAdd</td>
<td>TAdd#(n1, n2)</td>
<td>Calculate $n_1 + n_2$</td>
</tr>
<tr>
<td>TSub</td>
<td>TSub#(n1, n2)</td>
<td>Calculate $n_1 - n_2$</td>
</tr>
<tr>
<td>TMul</td>
<td>TMul#(n1, n2)</td>
<td>Calculate $n_1 * n_2$</td>
</tr>
<tr>
<td>TDiv</td>
<td>TDiv#(n1, n2)</td>
<td>Calculate ceiling $n_1 / n_2$</td>
</tr>
<tr>
<td>TLog</td>
<td>TLog#(n1)</td>
<td>Calculate ceiling $\log_2(n_1)$</td>
</tr>
<tr>
<td>TExp</td>
<td>TExp#(n1)</td>
<td>Calculate $2^{n_1}$</td>
</tr>
<tr>
<td>TMax</td>
<td>TMax#(n1, n2)</td>
<td>Calculate $\max(n_1, n_2)$</td>
</tr>
<tr>
<td>TMin</td>
<td>TMin#(n1, n2)</td>
<td>Calculate $\min(n_1, n_2)$</td>
</tr>
</tbody>
</table>

Examples using other arithmetic functions:

```verilog
Int#(TAdd#(5, n)); // defines a signed integer n+5 bits wide
  // n must be in scope somewhere

typedef TAdd#(vsize, 8) Bigsize#(numeric type vsize);
  // defines a new type Bigsize which
  // is 8 bits wider than vsize

typedef Bit#(TLog#(n)) CBToken#(numeric type n);
  // defines a new parameterized type,
  // CBToken, which is log(n) bits wide.

typedef 8 Wordsize;
  // Blocksize is based on Wordsize
typedef TAdd#(Wordsize, 1) Blocksize;
```

### B.3.3 valueOf and SizeOf pseudo-functions

Prelude provides these pseudo-functions to convert between types and numeric values. The pseudo-function `valueOf` (or `valueOf`) is used to convert a numeric type into the corresponding Integer value. The pseudo-function `SizeOf` is used to convert a type `t` into the numeric type representing its bit size.
valueOf

Converts a numeric type into its Integer value.

function Integer valueOf (t) ;

Examples

module mkFoo (Foo#(n));
    UInt#(n) x;
    Integer y = valueOf(n);
endmodule

SizeOf

Converts a type into a numeric type representing its bit size.

function t SizeOf#(any_type)
    provisos (Bits#(any_type, sa)) ;

Examples

any_type x = structIn;
Bit#(SizeOf#(any_type)) = pack(structIn);

B.4 Registers and Wires

<table>
<thead>
<tr>
<th>Name</th>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reg</td>
<td>B.4.1</td>
<td>Register interface</td>
</tr>
<tr>
<td>CReg</td>
<td>B.4.2</td>
<td>Implementation of a register with an array of Reg interfaces that sequence concurrently</td>
</tr>
<tr>
<td>RWire</td>
<td>B.4.3</td>
<td>Similar to the Reg interface with output wrapped in a Maybe type to indicate validity</td>
</tr>
<tr>
<td>Wire</td>
<td>B.4.4</td>
<td>Interchangeable with a Reg interface, validity of the data is implicit</td>
</tr>
<tr>
<td>BypassWire</td>
<td>B.4.5</td>
<td>Implementation of the Wire interface where the _write method is always_enabled</td>
</tr>
<tr>
<td>DWire</td>
<td>B.4.6</td>
<td>Implementation of the Wire interface where the _read method is always_ready by providing a default value</td>
</tr>
<tr>
<td>PulseWire</td>
<td>B.4.7</td>
<td>Similar to the RWire interface without any data</td>
</tr>
<tr>
<td>ReadOnly</td>
<td>B.4.8</td>
<td>Interface which provides a value</td>
</tr>
<tr>
<td>WriteOnly</td>
<td>B.4.9</td>
<td>Interface which writes a value</td>
</tr>
</tbody>
</table>

B.4.1 Reg

The most elementary module available in BSV is the register, which has a Reg interface. Registers are polymorphic, i.e., in principle they can hold a value of any type but, of course, ultimately registers store bits. Thus, the provisos on register modules indicate that the type of the value stored in the register must be in the Bits type class, i.e., the operations pack and unpack are defined on the type to convert into bits and back.

Note that all Bluespec registers are considered atomic units, which means that even if one bit is updated (written), then all the bits are considered updated. This prevents multiple rules from updating register fields in an inconsistent manner.
When scheduling register modules, reads occur before writes. That is, any rule which reads from a register must be scheduled earlier than any other rule which writes to the register. The value read from the register is the value written in the previous clock cycle.

**Interfaces and Methods**

The Reg interface contains two methods, \_write and \_read.

```v
interface Reg #(type a_type);
    method Action _write(a_type x1);
    method a_type _read();
endinterface: Reg
```

The \_write and \_read methods are rarely used. Instead, for writes, one uses the non-blocking assignment notation and, for reads, one just mentions the register interface in an expression.

<table>
<thead>
<tr>
<th>Reg Interface</th>
<th>Method</th>
<th>Arguments</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>_write</td>
<td>Action</td>
<td>x1</td>
<td>writes a value x1</td>
</tr>
<tr>
<td>_read</td>
<td>a_type</td>
<td></td>
<td>returns the value of the register</td>
</tr>
</tbody>
</table>

**Modules**

Prelude provides three modules to create a register: mkReg creates a register with a given reset value, mkRegU creates a register without any reset, and mkRegA creates a register with a given reset value and with asynchronous reset logic.

<table>
<thead>
<tr>
<th>mkReg</th>
<th>Make a register with a given reset value. Reset logic is synchronous.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkReg#(parameter a_type resetval)(Reg#(a_type))</td>
<td></td>
</tr>
<tr>
<td>provisos (Bits#(a_type, sizea));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkRegU</th>
<th>Make a register without any reset; initial simulation value is alternating 01 bits.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkRegU(Reg#(a_type))</td>
<td></td>
</tr>
<tr>
<td>provisos (Bits#(a_type, sizea));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkRegA</th>
<th>Make a register with a given reset value. Reset logic is asynchronous.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkRegA#(parameter a_type resetval)(Reg#(a_type))</td>
<td></td>
</tr>
<tr>
<td>provisos (Bits#(a_type, sizea));</td>
<td></td>
</tr>
</tbody>
</table>

**Scheduling**

When scheduling register modules, reads occur before writes. That is, any rule which reads from a register must be scheduled earlier than any other rule which writes to the register. The value read from the register is the value written in the previous clock cycle. Multiple rules can write to a register in a given clock cycle, with the effect that a later rule overwrites the value written by earlier rules.
Functions

Three functions are provided for using registers: `asReg` returns the register interface instead of the value of the register; `readReg` reads the value of a register, useful when managing vectors or lists of registers; and `writeReg` to write a value into a register, also useful when managing vectors or lists of registers.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>asReg</code></td>
<td>Treat a register as a register, i.e., suppress the normal behavior where the interface name implicitly represents the value that the register contains (the _read value). This function returns the register interface, not the value of the register.</td>
<td><code>function Reg#(a_type) asReg(Reg#(a_type) regIfc);</code></td>
</tr>
<tr>
<td><code>readReg</code></td>
<td>Read the value out of a register. Useful for giving as the argument to higher-order vector and list functions.</td>
<td><code>function a_type readReg(Reg#(a_type) regIfc);</code></td>
</tr>
<tr>
<td><code>writeReg</code></td>
<td>Write a value into a register. Useful for giving as the argument to higher-order vector and list functions.</td>
<td><code>function Action writeReg(Reg#(a_atype) regIfc, a_type din);</code></td>
</tr>
</tbody>
</table>

Examples

```verilog
Reg#(ta) res <- mkReg(0);

// create board[x][y]
Reg#(ta) pipe[depth];
for (Integer i=0; i<depth; i=i+1) begin
  Reg#(ta) c();
  mkReg#(0) xinst(c);
  pipe[i] = asReg(c);
end

function a readReg(Reg#(a) r);
  return(r);
endfunction
```

B.4.2 CReg

The basic register modules described in B.4.1 have scheduling annotations that do not allow two rules to read and write a register concurrently (that is, sequentially in the same clock cycle). Implementing
this concurrency requires bypassing, so that a value written by one rule is visible to the next rule that wants to read the register. This can create long paths, and so explicit input from the designer is preferred. Therefore, the basic registers do not support this bypassing. If a designer wants concurrent register access between rules, they must explicitly request and manage this, by instantiating one of the \texttt{CReg} family of modules.

These concurrent registers are also known as EHRs (Ephemeral History Registers) in work by Arvind and Rosenband [Ros04].

**Modules**

Prelude provides three modules to create a concurrent register: \texttt{mkCReg} creates a concurrent register with a given reset value, \texttt{mkCRegU} creates a concurrent register without any reset, and \texttt{mkCRegA} creates a concurrent register with a given reset value and with asynchronous reset logic.

<table>
<thead>
<tr>
<th>\textbf{mkCReg}</th>
<th>Make a concurrent register with a given number of ports and with a given reset value. Reset logic is synchronous.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkCReg#(parameter Integer n, parameter a_type resetval)</td>
<td></td>
</tr>
<tr>
<td>\hspace{1cm} \texttt{(Reg#(a_type) ifc[])}</td>
<td></td>
</tr>
<tr>
<td>\hspace{1cm} \texttt{provisos (Bits#(a_type, sizea));}</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>\textbf{mkCRegU}</th>
<th>Make a concurrent register with a given number of ports and without any reset. Initial simulation value is alternating 01 bits.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkCRegU#(parameter Integer n) (Reg#(a_type) ifc[])</td>
<td></td>
</tr>
<tr>
<td>\hspace{1cm} \texttt{provisos (Bits#(a_type, sizea));}</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>\textbf{mkCRegA}</th>
<th>Make a concurrent register with a given number of ports and with a given reset value. Reset logic is asynchronous.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkCRegA#(parameter Integer n, parameter a_type resetval)</td>
<td></td>
</tr>
<tr>
<td>\hspace{1cm} \texttt{(Reg#(a_type) ifc[])}</td>
<td></td>
</tr>
<tr>
<td>\hspace{1cm} \texttt{provisos (Bits#(a_type, sizea));}</td>
<td></td>
</tr>
</tbody>
</table>

As indicated by the bracket notation in the interface type, these modules provide an array of \texttt{Reg} interfaces, whose methods can be called concurrently in separate actions. The modules take a size parameter \texttt{n}, that indicates the size of the array to return. The minimum size is 0. An implementation may specify a maximum size (5, in the current implementation).

**Scheduling**

When a concurrent register is instantiated, it returns an array of \texttt{Reg} interfaces. The scheduling relationships for \_\texttt{read} and \_\texttt{write} in one \texttt{Reg} interface are the same as for the basic register modules in B.4.1. The methods of lower-numbered interfaces sequence before the methods of higher-numbered interfaces.

The designer manages the concurrency of the register accesses by choosing which interfaces to assign to which rules.
The `Reg` interfaces execute in sequence starting with element 0 of the array up through element \( n - 1 \). That is, the `_read` method of the first interface will return the value stored in the register from the previous clock cycle; if the `_write` method of the first interface is called, the `_read` method of the second interface will return the written value, otherwise it returns the registered value. And so on, with each `_read` method returning the last value written to any of the lower-numbered interfaces, or the register value if none of the lower-numbered `_write` methods were called. The value registered at the end of clock cycle is the value written by the highest-numbered write method that was called.

Examples

In the following example, the two rules can be scheduled concurrently in the same clock cycle, which would not have been possible if the register `byteCount` had been instantiated as a basic `mkReg` register. Further, if both rules execute in a given clock cycle, the value read in rule `doRecv` is the updated value that was written in rule `doSend`.

```systemverilog
Reg#(Bool) byteCount[2] <- mkCReg(2, True);
rule doSend (canSend);
    ...
    byteCount[0] <= byteCount[0] + len;
endrule
rule doRecv (canRecv);
    ...
endrule
```

In the above example, `mkCReg` returns an array of `Reg` interfaces. This type is expressed implicitly using the bracket syntax. The type can also be explicitly expressed with the name `Array`, when necessary. (See Section B.2.13 for more information on the `Array` type.) One place where this can be necessary is when the array type is a component of a larger type. A common example of this would be when instantiating a `Vector` of `mkCReg` modules:

```systemverilog
Vector#(N, Array#(Reg#(T))) regs <- replicateM(mkCReg(3,0));
```

The above instantiation can also be achieved using multidimensional arrays. Instead of a vector of arrays, one can use an array of arrays:

```systemverilog
Integer n = valueOf(N);
Reg#(T) regs[n][3];
for (Integer i=0; i<n; i=i+1)
    regs[i] <- mkCReg(3,0);
```
B.4.3 RWire

An RWire is a primitive stateless module whose purpose is to allow data transfer between methods and rules without the cycle latency of a register. That is, a RWire may be written in a cycle and that value can be read out in the same cycle; values are not stored across clock cycles.

When scheduling wire modules, since the value is read in the same cycle in which it is written, writes must occur before reads. That is, any rule which writes to a wire must be scheduled earlier than any other rule which reads from the wire. This is the reverse of how registers are scheduled.

Interfaces and Methods

The RWire interface is conceptually similar to a register’s interface, but the output value is wrapped in a Maybe type. The wset method places a value on the wire and sets the valid signal. The read-like method, wget, returns the value and a valid signal in a Maybe type. The output is only Valid if a write has occurred in the same clock cycle, otherwise the output is Invalid.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
<th>Arguments</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>wset</td>
<td>Action</td>
<td>writes a value and sets the valid signal</td>
<td>datain</td>
<td>data to be sent on the wire</td>
<td></td>
</tr>
<tr>
<td>wget</td>
<td>Maybe</td>
<td>returns the value and the valid signal</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

interface RWire#(type element_type) ;
    method Action wset(element_type datain) ;
    method Maybe#(element_type) wget() ;
endinterface: RWire

Modules

The mkRWireSBR, mkRWire, and mkUnsafeRWire modules are provided to create an RWire. The difference between the RWire modules is the scheduling annotations. In mkRWireSBR the wset is SBR with itself, allowing multiple wsets in the same clock cycle (though not, of course, in the same rule).

<table>
<thead>
<tr>
<th>mkRWireSBR</th>
<th>Creates an RWire. Output is only valid if a write has occurred in the same clock cycle. This is the recommended module to use to create an RWire.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkRWireSBR(RWire#(element_type)) provisos (Bits#(element_type, element_width)) ;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkRWire</th>
<th>Creates an RWire. Output is only valid if a write has occurred in the same clock cycle. The write (wset) must be sequenced before the read (wget) and they must be in different rules.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkRWire(RWire#(element_type)) provisos (Bits#(element_type, element_width)) ;</td>
</tr>
</tbody>
</table>
mkUnsafeRWire | Creates an RWire. Output is only valid if a write has occurred in the same clock cycle. The write (wset) must be sequenced before the read (wget) but they can be in the same rule.


```
module mkUnsafeRWire(RWire#(element_type))
  provisos (Bits#(element_type, element_width));
```

### Scheduling

When scheduling wire modules, since the value is read in the same cycle in which it is written, writes must occur before reads. That is, any rule which writes to a wire must be scheduled earlier than any other rule which reads from the wire. This is the reverse of how registers are scheduled.

<table>
<thead>
<tr>
<th>Scheduling Annotations</th>
<th>mkRWire</th>
<th>mkRWireSBR</th>
<th>mkUnsafeRWire</th>
</tr>
</thead>
<tbody>
<tr>
<td>wget</td>
<td>wget</td>
<td>wget</td>
<td>wget</td>
</tr>
<tr>
<td>wset</td>
<td>CF</td>
<td>SAR</td>
<td>SA</td>
</tr>
<tr>
<td></td>
<td>SAR</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Examples

```verilog
RWire#(int) rw_incr <- mkRWire();
rule doit;
  Maybe#(int) mbi = rw_incr.wget();
  int di = fromMaybe (?, mbi);
  if (!isValid (mbi))
    noAction;
  else // ( isValid (mbi))
    value2 <= value2 + di ;
endrule

rule doitdifferently;
  case (rw_incr.wget()) matches
    { tagged Invalid } : noAction;
    { tagged Valid .di} : value <= value + di;
  endcase
endrule

method Action increment (int di);
  rw_incr.wset (di);
endmethod
```

### B.4.4 Wire

The Wire interface and module are similar to RWire, but the valid bit is hidden from the user and the validity of the read is considered an implicit condition. The Wire interface works like the Reg interface, so mentioning the name of the wire gets (reads) its contents whenever they’re valid, and using <= writes the wire. Wire is an RWire that is designed to be interchangeable with Reg. You can replace a Reg with a Wire without changing the syntax.

### Interfaces and Methods
typedef Reg#(element_type) Wire#(type element_type);

<table>
<thead>
<tr>
<th>Method</th>
<th>Arguments</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>_write</td>
<td>Action</td>
<td>writes a value x1</td>
</tr>
<tr>
<td>_read</td>
<td>a_type</td>
<td>returns the value of the wire</td>
</tr>
</tbody>
</table>

**Modules**

The `mkWire` and `mkUnsafeWire` modules are provided to create a `Wire`. The only difference between the two modules are the scheduling annotations. The `mkWire` version requires that the the write and the read be in different rules.

**mkWire**

Creates a `Wire`. Validity of the output is automatically checked as an implicit condition of the read method. The write and the read methods must be in different rules.

```verilog
module mkWire(Wire#(element_type))
provisos (Bits#(element_type, element_width));
```

**mkUnsafeWire**

Creates a `Wire`. Validity of the output is automatically checked as an implicit condition of the read method. The write and the read methods can be in the same rule.

```verilog
module mkUnsafeWire(Wire#(element_type))
provisos (Bits#(element_type, element_width));
```

**Examples**

```verilog
module mkCounter_v2 (Counter);
  Reg#(int) value2 <- mkReg(0);
  Wire#(int) w_incr <- mkWire();

  rule r_incr;
    value2 <= value2 + w_incr;
  endrule

  method int read();
    return value2;
  endmethod

  method Action increment (int di);
    w_incr <= di;
  endmethod
endmodule
```
B.4.5 BypassWire

BypassWire is an implementation of the Wire interface where the \texttt{._write} method is an \texttt{always_enabled} method. The compiler will issue a warning if the method does not appear to be called every clock cycle. The advantage of this tradeoff is that the \texttt{._read} method of this interface does not carry any implicit condition (so it can satisfy a \texttt{no Implicit Conditions} assertion or an \texttt{always Ready} method).

\begin{verbatim}
module mkBypassWire(Wire#(element_type))
  provisos (Bits#(element_type, element_width));

mkBypassWire Creates a BypassWire. The write method is always_enabled.

module mkBypassWire(Wire#(element_type))
  provisos (Bits#(element_type, element_width));

Scheduling Annotations

\begin{tabular}{|c|c|c|}
\hline
mkBypassWire & \_read & \_write \\
\hline
\_read & CF & SAR \\
\_write & SBR & C \\
\hline
\end{tabular}

Examples

module mkCounter_v2 (Counter);
  Reg#(int) value2 <- mkReg(0);
  Wire#(int) w_incr <- mkBypassWire();

    rule r_incr;
      value2 <= value2 + w_incr;
    endrule

    method int read();
      return value2;
    endmethod

    method Action increment (int di);
      w_incr <= di;
    endmethod
endmodule

B.4.6 DWire

DWire is an implementation of the Wire interface where the \texttt{._read} method is an \texttt{always_ready} method and thus has no implicit conditions. Unlike the BypassWire however, the \texttt{._write} method need not be always enabled. On cycles when a DWire is written to, the \texttt{._read} method returns that value. On cycles when no value is written, the \texttt{._read} method instead returns a default value that is specified as an argument during instantiation.

There are two modules to create a DWire; the only difference being the scheduling annotations. A write is always scheduled before a read, however the \texttt{mkDWire} module requires that the write and read be in different rules.

\begin{verbatim}
module mkDWire#(a_type defaultval)(Wire#(element_type))
  provisos (Bits#(element_type, element_width));

mkDWire Creates a DWire. The read method is always_ready.

module mkDWire#(a_type defaultval)(Wire#(element_type))
  provisos (Bits#(element_type, element_width));

\end{verbatim}
**mkUnsafeDWire**

Creates a DWire. The read method is always _ready_.

```systemverilog
module mkUnsafeDWire#(a_type defaultval)(Wire#(element_type))
    provisos (Bits#(element_type, element_width));
```

<table>
<thead>
<tr>
<th>Scheduling Annotations</th>
<th>mkDWire</th>
<th>mkUnsafeDWire</th>
</tr>
</thead>
<tbody>
<tr>
<td>_read</td>
<td>CF</td>
<td>_read</td>
</tr>
<tr>
<td>_write</td>
<td>SAR</td>
<td>_write</td>
</tr>
</tbody>
</table>

Examples

```systemverilog
module mkCounter_v2 (Counter);
    Reg#(int) value2 <- mkReg(0);
    Wire#(int) w_incr <- mkDWire (0);

    rule r_incr;
        value2 <= value2 + w_incr;
    endrule

    method int read();
        return value2;
    endmethod

    method Action increment (int di);
        w_incr <= di;
    endmethod
endmodule
```

### B.4.7 PulseWire

**Interfaces and Methods**

The _PulseWire_ interface is an _RWire_ without any data. It is useful within rules and action methods to signal other methods or rules in the same clock cycle. Note that because the read method is called _read_, the register shorthand can be used to get its value without mentioning the method _read_ (it is implicitly added).

<table>
<thead>
<tr>
<th>PulseWire Interface</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>send</td>
<td>Action</td>
</tr>
<tr>
<td>_read</td>
<td>Bool</td>
</tr>
<tr>
<td></td>
<td>sends a signal down the wire</td>
</tr>
<tr>
<td></td>
<td>returns the valid signal</td>
</tr>
</tbody>
</table>

```systemverilog
interface PulseWire;
    method Action send();
    method Bool _read();
endinterface
```

Modules
Four modules are provided to create a PulseWire, the only difference being the scheduling annotations. In the OR versions the send method does not conflict with itself. Calling the send method for a mkPulseWire from 2 rules causes the two rules to conflict while in the mkPulseWireOR there is no conflict. In other words, the mkPulseWireOR acts a logical "OR". The Unsafe versions allow the send and _read methods to be in the same rule.

<table>
<thead>
<tr>
<th>mkPulseWire</th>
<th>The writing to this type of wire is used in rules and action methods to send a single bit to signal other methods or rules in the same clock cycle.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkPulseWire(PulseWire);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkPulseWireOR</th>
<th>Returns a PulseWire which acts like a logical &quot;Or&quot;. The send method of the same wire can be used in two different rules without conflict.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkPulseWireOR(PulseWire);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkUnsafePulseWire</th>
<th>The writing to this type of wire is used in rules and action methods to send a single bit to signal other methods or rules in the same clock cycle. The send and _read methods can be in the same rule.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkUnsafePulseWire(PulseWire);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkUnsafePulseWireOR</th>
<th>Returns a PulseWire which acts like a logical &quot;Or&quot;. The send method of the same wire can be used in two different rules without conflict. The send and _read methods can be in the same rule.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkUnsafePulseWireOR(PulseWire);</td>
<td></td>
</tr>
</tbody>
</table>

### Scheduling Annotations

<table>
<thead>
<tr>
<th>mkPulseWire _read</th>
<th>send</th>
</tr>
</thead>
<tbody>
<tr>
<td>_read</td>
<td>CF</td>
</tr>
<tr>
<td>send</td>
<td>SBR</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkUnsafePulseWire _read</th>
<th>send</th>
</tr>
</thead>
<tbody>
<tr>
<td>_read</td>
<td>CF</td>
</tr>
<tr>
<td>send</td>
<td>SB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkPulseWireOR _read</th>
<th>send</th>
</tr>
</thead>
<tbody>
<tr>
<td>_read</td>
<td>CF</td>
</tr>
<tr>
<td>send</td>
<td>SBR</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkUnsafePulseWireOR _read</th>
<th>send</th>
</tr>
</thead>
<tbody>
<tr>
<td>_read</td>
<td>CF</td>
</tr>
<tr>
<td>send</td>
<td>SB</td>
</tr>
</tbody>
</table>

**Counter Example - Using Reg and PulseWire**

```plaintext
interface Counter#(type size_t);
  method Bit#(size_t) read();
  method Action load(Bit#(size_t) newval);
  method Action increment();
```
module mkCounter(Counter#(size_t));
	Reg#(Bit#(size_t)) value <- mkReg(0); // define a Reg
	PulseWire increment_called <- mkPulseWire(); // define the PulseWires used
	PulseWire decrement_called <- mkPulseWire(); // to signal other methods or rules

    // whether rules fire is based on values of PulseWires
    rule do_increment(increment_called && !decrement_called);
        value <= value + 1;
    endrule

    rule do_decrement(!increment_called && decrement_called);
        value <= value - 1;
    endrule

method Bit#(size_t) read(); // read the register
    return value;
endmethod

method Action load(Bit#(size_t) newval); // load the register
    value <= newval; // with a new value
endmethod

method Action increment(); // sends the signal on the
    increment_called.send(); // PulseWire increment_called
endmethod

method Action decrement(); // sends the signal on the
    decrement_called.send(); // PulseWire decrement_called
endmethod
endmodule

B.4.8 ReadOnly

ReadOnly is an interface which provides a value. The _read shorthand can be used to read the value.

Interfaces and Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>_read</td>
<td>a_type</td>
</tr>
</tbody>
</table>

interface ReadOnly #( type a_type ) ;
method a_type _read() ;
endinterface

Functions
regToReadOnly | Converts a Reg interface into a ReadOnly interface. Useful for giving as the argument to higher-order vector and list functions.

function ReadOnly#(a_type) regToReadOnly(Reg#(a_type) regIfc);

pulseWireToReadOnly | Converts a PulseWire interface into a ReadOnly interface.

function ReadOnly#(Bool) pulseWireToReadOnly(PulseWire ifc);

readReadOnly | Takes a ReadOnly interface and returns a value.

function a_type readReadOnly(ReadOnly#(a_type) r);

Examples

```
interface AHBSlaveIFC;
  interface AHBSlave bus;
  interface Put#(AHBResponse) response;
  interface ReadOnly#(AHBRequest) request;
endinterface
...
interface ReadOnly request;
  method AHBRequest _read;
    let ctrl = AhbCtrl {command: write_wire,
                      size: size_wire,
                      burst: burst_wire,
                      transfer: transfer_wire,
                      prot: prot_wire,
                      addr: addr_wire} ;
    let value = AHBRequest {ctrl: ctrl, data: wdata_wire};
    return value;
  endmethod
endinterface
```

B.4.9 WriteOnly

WriteOnly is an interface which writes a value. The _write shorthand is used to write the value.

Interfaces and Methods

<table>
<thead>
<tr>
<th>WriteOnly Interface</th>
<th>Method</th>
<th>Arguments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Type</td>
<td>Description</td>
</tr>
<tr>
<td>_write</td>
<td>Action</td>
<td>Writes the data</td>
</tr>
</tbody>
</table>

```
interface WriteOnly #( type a_type ) ;
  method Action _write (a_type x) ;
endinterface
```
Examples

interface WriteOnly#(type a);
    method Action _write(a v);
endinterface

// module with an always-enabled port to tie to a default value
import "BVI" AlwaysWrite =
    module mkAlwaysWrite(WriteOnly#(a)) provisos(Bits#(a,sa));
        no_reset;
        parameter width = valueof(sa);
        method _write(D_IN) enable((*inhigh*)EN);
        schedule _write C _write;
endmodule

module mkDefaultValue1();
    WriteOnly#(UInt#(7)) d1 <- mkAlwaysWrite(clocked_by primMakeDisabledClock);
    rule handle_d1;
        d1 <= 5;
    endrule
endmodule

B.5 Miscellaneous Functions

B.5.1 Compile-time Messages

<table>
<thead>
<tr>
<th>error</th>
<th>Generate a compile-time error message, s, and halt compilation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function a_type error(String s);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>warning</th>
<th>When applied to a value v of type a, generate a compile-time warning message, s, and continue compilation, returning v.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function a_type warning(String s, a_type v);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>message</th>
<th>When applied to a value v of type a, generate a compile-time informative message, s, and continue compilation, returning v.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function a_type message(String s, a_type v);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>errorM</th>
<th>Generate a compile-time error message, s, and halt compilation in a monad.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function m#(void) errorM(String s) provisos (Monad#(m));</td>
<td></td>
</tr>
</tbody>
</table>
### B.5.2 Arithmetic Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>max</code></td>
<td>Returns the maximum of two values, x and y.</td>
</tr>
<tr>
<td></td>
<td><code>function a_type max(a_type x, a_type y)</code></td>
</tr>
<tr>
<td></td>
<td><code>provisos (Ord#a_type)</code></td>
</tr>
<tr>
<td><code>min</code></td>
<td>Returns the minimum of two values, x and y.</td>
</tr>
<tr>
<td></td>
<td><code>function a_type min(a_type x, a_type y)</code></td>
</tr>
<tr>
<td></td>
<td><code>provisos (Ord#a_type)</code></td>
</tr>
<tr>
<td><code>abs</code></td>
<td>Returns the absolute value of x.</td>
</tr>
<tr>
<td></td>
<td><code>function a_type abs(a_type x)</code></td>
</tr>
<tr>
<td></td>
<td><code>provisos (Arith#a_type), Ord#a_type)</code></td>
</tr>
<tr>
<td><code>signedMul</code></td>
<td>Performs full precision multiplication on two Int#(n) operands of different sizes.</td>
</tr>
<tr>
<td></td>
<td><code>function Int#(m) signedMul(Int#(n) x, Int#(k) y)</code></td>
</tr>
<tr>
<td></td>
<td><code>provisos (Add#(n,k,m))</code></td>
</tr>
<tr>
<td><code>unsignedMul</code></td>
<td>Performs full precision multiplication on two unsigned UInt#(n) operands of different sizes.</td>
</tr>
<tr>
<td></td>
<td><code>function UInt#(m) unsignedMul(UInt#(n) x, UInt#(k) y)</code></td>
</tr>
<tr>
<td></td>
<td><code>provisos (Add#(n,k,m))</code></td>
</tr>
<tr>
<td><code>signedQuot</code></td>
<td>Performs full precision division on two Int#(n) operands of different sizes.</td>
</tr>
<tr>
<td></td>
<td><code>function Int#(m) signedQuot(Int#(n) x, Int#(k) y)</code></td>
</tr>
</tbody>
</table>
### B.5.3 Operations on Functions

Higher order functions are functions which take functions as arguments and/or return functions as results. These are often useful with list and vector functions.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>unsignedQuot</code></td>
<td>Performs full precision division on two unsigned UInt#(n) operands of different sizes.</td>
<td><code>function UInt#(m) unsignedQuot(UInt#(n) x, UInt#(k) y) ;</code></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>compose</code></td>
<td>Creates a new function, <code>c</code>, made up of functions, <code>f</code> and <code>g</code>. That is, <code>c(a) = f(g(a))</code></td>
<td><code>function (function c_type (a_type x0)) compose(function c_type f(b_type x1), function b_type g(a_type x2));</code></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>composeM</code></td>
<td>Creates a new monadic function, <code>m#(c)</code>, made up of functions, <code>f</code> and <code>g</code>. That is, <code>c(a) = f(g(a))</code></td>
<td><code>function (function m#(c_type) (a_type x0)) composeM(function m#(c_type) f(b_type x1), function m#(b_type) g(a_type x2)) provisos # (Monad#(m));</code></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>id</code></td>
<td>Identity function, returns <code>x</code> when given <code>x</code>. This function is useful when the argument requires a function which doesn’t do anything.</td>
<td><code>function a_type id(a_type x);</code></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>constFn</code></td>
<td>Constant function, returns <code>x</code>.</td>
<td><code>function a_type constFn(a_type x, b_type y);</code></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>flip</code></td>
<td>Flips the arguments <code>x</code> and <code>y</code>, returning a new function.</td>
<td><code>function (function c_type new (b_type y, a_type x)) flip (function c_type old (a_type x, b_type y));</code></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>curry</code></td>
<td>This function converts a function on a pair (Tuple2) of arguments into a function which takes the arguments separately. The phrase <code>t0 f(t1 x, t2 y)</code> is the function returned by curry</td>
<td><code>function (function t0 f(t1 x, t2 y)) curry (function t0 g(Tuple2#(t1, t2) x));</code></td>
</tr>
</tbody>
</table>
uncurry

This function does the reverse of curry; it converts a function of two arguments into a function which takes a single argument, a pair (Tuple2).

function (function t0 g(Tuple2#(t1, t2) x))
uncurry (function t0 f(t1 x, t2 y));

Examples

//using constFn to set the initial values of the registers in a list
List#(Reg#(Resource)) items <- mapM( constFn(mkReg(initRes)),upto(1,numAdd) );

return(pack(map(compose(head0,toList),state)));

xs <- mapM(constFn(mkReg(False)),genList);

B.5.4 Bit Functions

The following functions operate on Bit#(n) variables.

parity

Returns the parity of the bit argument v. Example: parity( 5'b1) 
= 1, parity( 5'b3) = 0;

function Bit#(1) parity(Bit#(n) v);

reverseBits

Reverses the order of the bits in the argument x.

function Bit#(n) reverseBits(Bit#(n) x);

countOnes

Returns the count of the number of 1’s in the bit vector bin.

function UInt#(lgn1) countOnes ( Bit#(n) bin )
provisos (Add#(1, n, n1), Log#(n1, lgn1),
Add#(1, xx, lgn1) );

countZerosMSB

For the bit vector bin, count the number of 0s until the first 1, 
starting from the most significant bit (MSB).

function UInt#(lgn1) countZerosMSB ( Bit#(n) bin )
provisos (Add#(1, n, n1), Log#(n1, lgn1) );

countZerosLSB

For the bit vector bin, count the number of 0s until the first 1, 
starting from the least significant bit (LSB).

function UInt#(lgn1) countZerosLSB ( Bit#(n) bin )
provisos (Add#(1, n, n1), Log#(n1, lgn1) );
<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>truncateLSB</td>
<td>Truncates a Bit#(m) to a Bit#(n) by dropping bits starting with the LSB.</td>
<td>Bit#(6) f6 = truncateLSB(f);</td>
</tr>
<tr>
<td></td>
<td></td>
<td>let cmem = countZerosLSB(cfg.memoryAllocate);</td>
</tr>
<tr>
<td></td>
<td></td>
<td>let n = countOnes(neighbors);</td>
</tr>
</tbody>
</table>

### B.5.5 Integer Functions

The following functions can only be used for static elaboration.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>gcd</td>
<td>Calculate the greatest common divisor of two Integers.</td>
<td>function Integer gcd(Integer a, Integer b);</td>
</tr>
<tr>
<td>lcm</td>
<td>Calculate the least common multiple of two Integers.</td>
<td>function Integer lcm(Integer a, Integer b);</td>
</tr>
</tbody>
</table>

### B.5.6 Control Flow Function

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>while</td>
<td>Repeat a function while a predicate holds.</td>
<td>function a_type while(function Bool pred(a_type x1), function a_type f(a_type x1), a_type x);</td>
</tr>
<tr>
<td>when</td>
<td>Adds an implicit condition onto an expression.</td>
<td>function a when(Bool condition, a arg);</td>
</tr>
</tbody>
</table>

**Example - adding the implicit condition readCount==0 to the action**

```
function Action startReadSequence (BAddr startAddr,
                                 UInt#(6) count);
    return when ((readCount == 0), // implicit condition of the action
                   (action
                     readAddr <= startAddr ;
                     readCount <= count ;
                   endaction));
endfunction

rule readSeq; // readCount==0 is an implicit condition
    startReadSequence (addr, count);
endrule
```
B.6 Environment Values

The Environment section of the Prelude contains some value definitions that remain static within a compilation, but may vary between compilations.

Test whether the compiler is generating C.

<table>
<thead>
<tr>
<th>genC</th>
<th>Returns True if the compiler is generating C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Bool genC();</td>
<td></td>
</tr>
</tbody>
</table>

Test whether the compiler is generating Verilog.

<table>
<thead>
<tr>
<th>genVerilog</th>
<th>Returns True if the compiler is generating Verilog.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Bool genVerilog();</td>
<td></td>
</tr>
</tbody>
</table>

Examples

```snippetserver
if (genVerilog)
return (t + fromInteger(adj));
```

The following two variables provide access to the names of the package being compiled and the module being synthesized as strings.

<table>
<thead>
<tr>
<th>genPackageName</th>
<th>Returns a String containing the name of the package being compiled.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function String genPackageName;</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>genModuleName</th>
<th>Returns a String containing the name of the module being synthesized.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function String genModuleName;</td>
<td></td>
</tr>
</tbody>
</table>

Return the version of the compiler.

<table>
<thead>
<tr>
<th>compilerVersion</th>
<th>Returns a String containing the compiler version. This is the same string used with the -v flag.</th>
</tr>
</thead>
<tbody>
<tr>
<td>String compilerVersion;</td>
<td></td>
</tr>
</tbody>
</table>

Example:

The statement:

```snippetserver
$display("compiler version = %s", compilerVersion);
```

produces this output:

```
compiler version = version 3.8.56 (build 7084, 2005-07-22)
```
Return the build number of the version of the compiler.

<table>
<thead>
<tr>
<th>buildVersion</th>
<th>Returns a Bit#(32) containing the build number portion of the compiler version.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit#(32) buildVersion;</td>
<td></td>
</tr>
</tbody>
</table>

Example:
The statement:
```
$display("The build version of the compiler is %d", buildVersion);
```
produces this output:
"The build version of the compiler is 12345"

Get the current date and time.

<table>
<thead>
<tr>
<th>date</th>
<th>Returns a String containing the date.</th>
</tr>
</thead>
<tbody>
<tr>
<td>String date;</td>
<td></td>
</tr>
</tbody>
</table>

Example:
The statement:
```
$display("date = %s", date);
```
produces this output:
"date = Mon Feb 6 08:39:59 EST 2006"

Returns the number of seconds from the epoch (1970-01-01 00:00:00) to now.

<table>
<thead>
<tr>
<th>epochTime</th>
<th>Returns a Bit#(32) containing the number of seconds since the epoch, which is defined as 1970-01-01 00:00:00.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit#(32) epochTime;</td>
<td></td>
</tr>
</tbody>
</table>

Example:
The statement:
```
$display("Current epoch is %d", epochTime);
```
produces this output:
"Current epoch is 1235481642"

### B.7 Compile-time IO

These functions control file IO during elaboration. The functions are expressed as modules and can only be used as statements inside a `module...endmodule` block.

The type `Handle` is a primitive type for a file handle. The value is returned when you open a file and is used to specify the file by the other functions.

The flag `-fdir`, described in the *User Guide*, can be used to specify where relative file paths should be based from.

The type `IOMode` is an enumerated type with three values: `ReadMode`, `WriteMode`, and `AppendMode`:
typedef enum { ReadMode, WriteMode, AppendMode } IOMode;

When opening a file you specify the mode (IOMode) and the filename. Opening a file in write mode creates a new file; in append mode it adds to an existing file.

<table>
<thead>
<tr>
<th>openFile</th>
<th>Opens a file and returns the type Handle.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module openFile #(String filename, IOMode mode) (Handle);</td>
<td></td>
</tr>
</tbody>
</table>

The function hClose explicitly closes the file with the specified handle. The compiler will close any handles that are still open at the end of elaboration, or upon exiting with an error, but you shouldn't rely on this. Buffered files will be flushed when the file is closed.

<table>
<thead>
<tr>
<th>hClose</th>
<th>Closes the file with the specified handle.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module hClose #(Handle hdl) ();</td>
<td></td>
</tr>
</tbody>
</table>

The following functions provide query functions for handles.

<table>
<thead>
<tr>
<th>hIsEOF</th>
<th>Returns a Bool indicating if the end of file has been reached for the specified handle.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Bool hIsEOF (Handle hdl);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>hIsOpen</th>
<th>Returns true if the handle hdl is open.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Bool hIsOpen (Handle hdl);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>hIsClosed</th>
<th>Returns true if the handle hdl is closed.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Bool hIsClosed (Handle hdl);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>hIsReadable</th>
<th>Returns true if the handle has been opened in Readable mode and can be read from.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Bool hIsReadable (Handle hdl);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>hIsWriteable</th>
<th>Returns true if handle has been opened in Writeable mode and can be written to.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Bool hIsWriteable (Handle hdl);</td>
<td></td>
</tr>
</tbody>
</table>
The default buffering of files is determined by your system. If the system is buffering, you may not see any output until the handle is flushed or closed. You can override this by setting the buffering policy of the handle, so that writes are not buffered, or are line buffered. The file handle functions `hFlush`, `hGetBuffering`, and `hSetBuffering` allow you to control buffering.

At the end of elaboration, or upon exiting with an error, the compiler closes any file handles that were not otherwise closed. Any buffered files will be flushed at this point.

The data type `BufferMode` indicates the type of buffering.

```plaintext
typedef union tagged {
  void NoBuffering;
  void LineBuffering;
  Maybe#(Integer) BlockBuffering;
} BufferMode;
```

The functions `hFlush`, `hGetBuffering`, and `hSetBuffering` allow you to control buffering.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>hFlush</code></td>
<td>Explicitly flushes the buffer with the specified handle.</td>
<td><code>function Action hFlush(Handle hdl);</code></td>
</tr>
<tr>
<td><code>hGetBuffering</code></td>
<td>Returns the buffering policy of the file with the specified handle.</td>
<td><code>function ActionValue#(BufferMode) hGetBuffering(Handle hdl);</code></td>
</tr>
<tr>
<td><code>hSetBuffering</code></td>
<td>Sets the buffering mode for the file with the specified handle if the file system supports it.</td>
<td><code>function Action hSetBuffering(Handle hdl, BufferMode mode);</code></td>
</tr>
</tbody>
</table>

The functions `hPutStr` and `hPutStrLn` write strings to a file. The function `hPutStrLn` adds a newline to the end of the string.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>hPutStr</code></td>
<td>Writes the string to the file with the specified handle.</td>
<td><code>module hPutStr #(Handle hdl, String str) ();</code></td>
</tr>
<tr>
<td><code>hPutStrLn</code></td>
<td>Writes the string to the file with the specified handle and appends a newline to the end of the string.</td>
<td><code>module hPutStrLn #(Handle hdl, String str) ();</code></td>
</tr>
<tr>
<td><code>hPutChar</code></td>
<td>Writes the character to the file with the specified handle.</td>
<td><code>module hPutChar #(Handle hdl, Char c) ();</code></td>
</tr>
<tr>
<td>hGetChar</td>
<td>Reads the character from the file with the specified handle.</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>module hGetChar #(Handle hdl) (Char);</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>hGetLine</th>
<th>Reads a line from the file with the specified handle.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module hGetLine #(Handle hdl) (String);</td>
<td></td>
</tr>
</tbody>
</table>

Example: Creates a file named `sysBasicWrite.log` containing the line "Hello World".

```verilog
String fname = "sysBasicWrite.log";

module sysBasicWrite ();
    Handle hdl <- openFile(fname, WriteMode);
    hPutStr(hdl, "Hello");
    hClose(hdl);
    mkSub;
endmodule

module mkSub ();
    Handle hdl <- openFile(fname, AppendMode);
    hPutStrLn(hdl, " World");
    hClose(hdl);
endmodule
```
C AzureIP Foundation Libraries

Section B defined the standard Prelude package, which is automatically imported into every package. This section describes BSV’s large and continuously growing collection of AzureIP Foundation libraries. To use any of these libraries in a package you must explicitly import the library package using an `import` clause (Section 3).

Bluespec’s AzureIP intellectual property (IP) accelerates hardware design and modeling. All packages in the AzureIP Foundation library are provided as compiled code. Some of the packages are also provided as BSV source code to facilitate customization. When modifying these files, first copy them into a local directory and then modify your local copy. Use the `-p` flag when compiling, as described in the BSV Users Guide, to include the local directory in your path.

There are two AzureIP library families, Foundation and Premium:

- Foundation is an extensive family of components, types and functions that are included with the Bluespec toolsets for use in your models and designs – they serve as a foundational base for your modeling and implementation work.
- Premium is the designation for Bluespec’s fee-based AzureIP.

C.1 Storage Structures

C.1.1 Register File

Package

```
import RegFile :: * ;
```

Description

This package provides 5-read-port 1-write-port register array modules.

Note: In a design that uses RegFiles, some of the read ports may remain unused. This may generate a warning in various downstream tool. Downstream tools should be instructed to optimize away the unused ports.

Interfaces and Methods

The `RegFile` package defines one interface, `RegFile`. The `RegFile` interface provides two methods, `upd` and `sub`. The `upd` method is an `Action` method used to modify (or update) the value of an element in the register file. The `sub` method (from "sub"script) is a `Value` method which reads and returns the value of an element in the register file. The value returned is of a datatype `data_t`.

<table>
<thead>
<tr>
<th>Interface Name</th>
<th>Parameter name</th>
<th>Parameter Description</th>
<th>Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>RegFile</td>
<td>index_type</td>
<td>datatype of the index</td>
<td>must be in the <code>Bits</code> class</td>
</tr>
<tr>
<td></td>
<td>data_t</td>
<td>datatype of the element values</td>
<td>must be in the <code>Bits</code> class</td>
</tr>
</tbody>
</table>

```
interface RegFile #(type index_t, type data_t);
    method Action upd(index_t addr, data_t d);
    method data_t sub(index_t addr);
endinterface: RegFile
```
<table>
<thead>
<tr>
<th>Method</th>
<th>Arguments</th>
</tr>
</thead>
<tbody>
<tr>
<td>upd</td>
<td>Action</td>
</tr>
<tr>
<td>addr</td>
<td>index of the element to be changed, with a datatype of <code>index_t</code></td>
</tr>
<tr>
<td>d</td>
<td>new value to be stored, with a datatype of <code>data_t</code></td>
</tr>
<tr>
<td>sub</td>
<td><code>data_t</code></td>
</tr>
<tr>
<td>addr</td>
<td>index of the element, with a datatype of <code>index_t</code></td>
</tr>
</tbody>
</table>

### Modules

The `RegFile` package provides three modules: `mkRegFile` creates a RegFile with registers allocated from the `lo_index` to the `hi_index`; `mkRegFileFull` creates a RegFile from the minimum index to the maximum index; and `mkRegFileWCF` creates a RegFile from `lo_index` to `hi_index` for which the reads and the write are scheduled conflict-free. There is a second set of these modules, the `RegFileLoad` variants, which take as an argument a file containing the initial contents of the array.

**mkRegFile**

Create a RegFile with registers allocated from `lo_index` to `hi_index`. `lo_index` and `hi_index` are of the `index_t` datatype and the elements are of the `data_t` datatype.

```verilog
define module mkRegFile#( index_t lo_index, index_t hi_index )
    ( RegFile#(index_t, data_t) )
    provisos (Bits#(index_t, size_index),
              Bits#(data_t, size_data));
```

**mkRegFileFull**

Create a RegFile from min to max index where the index is of a datatype `index_t` and the elements are of datatype `data_t`. The min and max are specified by the `Bounded` typeclass instance (0 to N-1 for N-bit numbers).

```verilog
define module mkRegFileFull#( RegFile#(index_t, data_t) )
    provisos (Bits#(index_t, size_index),
              Bits#(data_t, size_data)
              Bounded#(index_t));
```

**mkRegFileWCF**

Create a RegFile from `lo_index` to `hi_index` for which the reads and the write are scheduled conflict-free. For the implications of this scheduling, see the documentation for `ConfigReg` (Section C.1.2).

```verilog
define module mkRegFileWCF#( index_t lo_index, index_t hi_index )
    ( RegFile#(index_t, data_t) )
    provisos (Bits#(index_t, size_index),
              Bits#(data_t, size_data));
```

The `RegFileLoad` variants provide the same functionality as `RegFile`, but each constructor function takes an additional file name argument. The file contains the initial contents of the array using the Verilog hex memory file syntax, which allows white spaces (including new lines, tabs, underscores, and form-feeds), comments, binary and hexadecimal numbers. Length and base format must not be specified for the numbers.
The generated Verilog for file load variants contains `$readmemb` and `$readmemh` constructs. These statements, as well as initial blocks generally, are considered simulation-only constructs because they are not supported consistently across synthesis tools. Therefore, in the generated Verilog the initial blocks are protected with a `translate_off` directive. When using a synthesis tool which supports these constructs you can remove the directives to allow the tool to processes the `$readmemb` and `$readmemh` tasks during synthesis.

<table>
<thead>
<tr>
<th>mkRegFileLoad</th>
<th>Create a RegFile using the file to provide the initial contents of the array.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkRegFileLoad#</td>
</tr>
<tr>
<td></td>
<td>( String file, index_t lo_index, index_t hi_index)</td>
</tr>
<tr>
<td></td>
<td>( RegFile#(index_t, data_t) )</td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(index_t, size_index),</td>
</tr>
<tr>
<td></td>
<td>Bits#(data_t, size_data));</td>
</tr>
<tr>
<td>mkRegFileFullLoad</td>
<td>Create a RegFile from min to max index using the file to provide the initial</td>
</tr>
<tr>
<td></td>
<td>contents of the array. The min and max are specified by the Bounded</td>
</tr>
<tr>
<td></td>
<td>typeclass instance (0 to N-1 for N-bit numbers).</td>
</tr>
<tr>
<td></td>
<td>module mkRegFileFullLoad#</td>
</tr>
<tr>
<td></td>
<td>( String file)</td>
</tr>
<tr>
<td></td>
<td>( RegFile#(index_t, data_t))</td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(index_t, size_index),</td>
</tr>
<tr>
<td></td>
<td>Bits#(data_t, size_data),</td>
</tr>
<tr>
<td></td>
<td>Bounded#(index_t));</td>
</tr>
<tr>
<td>mkRegFileWCFLoad</td>
<td>Create a RegFile from <code>lo_index</code> to <code>hi_index</code> for which the reads and the</td>
</tr>
<tr>
<td></td>
<td>write are scheduled conflict-free (see Section C.1.2), using the file to</td>
</tr>
<tr>
<td></td>
<td>provide the initial contents of the array.</td>
</tr>
<tr>
<td></td>
<td>module mkRegFileWCFLoad#</td>
</tr>
<tr>
<td></td>
<td>( String file, index_t lo_index, index_t hi_index)</td>
</tr>
<tr>
<td></td>
<td>( RegFile#(index_t, data_t) )</td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(index_t, size_index),</td>
</tr>
<tr>
<td></td>
<td>Bits#(data_t, size_data));</td>
</tr>
</tbody>
</table>

Examples

Use `mkRegFileLoad` to create Register files and then read the values.

```
Reg#(Cntr) count <- mkReg(0);

// Create Register files to use as inputs in a testbench
RegFile#(Cntr, Fp64) vecA <- mkRegFileLoad("vec.a.txt", 0, 9);
RegFile#(Cntr, Fp64) vecB <- mkRegFileLoad("vec.b.txt", 0, 9);

//read the values from the Register files
rule drivein (count < 10);
   Fp64 a = vecA.sub(count);
   Fp64 b = vecB.sub(count);
   uut.start(a, b);
   count <= count + 1;
endrule
```
Verilog Modules

RegFile modules correspond to the following Verilog modules, which are found in the Bluespec Verilog library, $BLUESPECDIR/Verilog/.

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Name</th>
<th>Defined in File</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkRegFile</td>
<td>RegFile</td>
<td>RegFile.v</td>
</tr>
<tr>
<td>mkRegFileFull</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mkRegFileWCF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mkRegFileLoad</td>
<td>RegFileLoad</td>
<td>RegFileLoad.v</td>
</tr>
<tr>
<td>mkRegFileFullLoad</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mkRegFileWCFLoad</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C.1.2 ConfigReg

Package

import ConfigReg :: * ;

Description

The ConfigReg package provides a way to create registers where each update clobbers the current value, but the precise timing of updates is not important. These registers are identical to the mkReg registers except that their scheduling annotations allows reads and writes to occur in either order during rule execution.

Rules which fire during the clock cycle where the register is written read a stale value (that is the value from the beginning of the clock cycle) regardless of firing order and writes which have occurred during the clock cycle. Thus if rule r1 writes to a ConfigReg cr and rule r2 reads cr later in the same cycle, the old or stale value of cr is read, not the value written in r1. If a standard register is used instead, rule r2’s execution will be blocked by r1’s execution or the scheduler may create a different rule execution order.

The hardware implementation is identical for the more common registers (mkReg, mkRegU and mkRegA), and the module constructors parallel these as well.

Interfaces

The ConfigReg interface is an alias of the Reg interface (section B.4.1).

typedef Reg#(a_type) ConfigReg #(type a_type);

Modules

The ConfigReg package provides three modules; mkConfigReg creates a register with a given reset value and synchronous reset logic, mkConfigRegU creates a register without any reset, and mkConfigRegA creates a register with a given reset value and asynchronous reset logic.

<table>
<thead>
<tr>
<th>mkConfigReg</th>
<th>Make a register with a given reset value. Reset logic is synchronous</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkConfigReg#(a_type resetval)(Reg#(a_type))</td>
<td></td>
</tr>
<tr>
<td>provisos (Bits#(a_type, sizea));</td>
<td></td>
</tr>
</tbody>
</table>
mkConfigRegU | Make a register without any reset; initial simulation value is alternating 01 bits.

module mkConfigRegU(Reg#(a_type))
    provisos (Bits#(a_type, sizea));

mkConfigRegA | Make a register with a given reset value. Reset logic is asynchronous.

module mkConfigRegA#(a_type, resetval)(Reg#(a_type))
    provisos (Bits#(a_type, sizea));

<table>
<thead>
<tr>
<th>Scheduling Annotations</th>
<th>mkConfigReg, mkConfigRegU, mkConfigRegA</th>
</tr>
</thead>
<tbody>
<tr>
<td>read</td>
<td>CF</td>
</tr>
<tr>
<td>write</td>
<td>CF</td>
</tr>
<tr>
<td></td>
<td>SBR</td>
</tr>
</tbody>
</table>

C.1.3 DReg

Package

import DReg :: * ;

Description

The DReg package allows a designer to create registers which store a written value for only a single clock cycle. The value written to a DReg is available to read one cycle after the write. If more than one cycle has passed since the register has been written however, the value provided by the register is instead a default value (that is specified during module instantiation). These registers are useful when wanting to send pulse values that are only asserted for a single clock cycle. The DReg is the register equivalent of a DWire B.4.6.

Modules

The DReg package provides three modules; mkDReg creates a register with a given reset/default value and synchronous reset logic, mkDRegU creates a register without any reset (but which still takes a default value as an argument), and mkDRegA creates a register with a given reset/default value and asynchronous reset logic.

<table>
<thead>
<tr>
<th>mkDReg</th>
<th>Make a register with a given reset/default value. Reset logic is synchronous</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkDReg#(a_type dflt_rst_val)(Reg#(a_type)) provisos (Bits#(a_type, sizea));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkDRegU</th>
<th>Make a register without any reset but with a specified default; initial simulation value is alternating 01 bits.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkDRegU#(a_type dflt_val)(Reg#(a_type)) provisos (Bits#(a_type, sizea));</td>
</tr>
</tbody>
</table>
mkDRegA | Make a register with a given reset/default value. Reset logic is asynchronous.

```verilog
module mkDRegA#(a_type, dflt_rst_val)(Reg#(a_type))
  provisos (Bits#(a_type, sizea));
```

<table>
<thead>
<tr>
<th>Scheduling Annotations</th>
<th>mkDReg, mkDRegU, mkDRegA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>read</td>
</tr>
<tr>
<td>read</td>
<td>CF</td>
</tr>
<tr>
<td>write</td>
<td>SA</td>
</tr>
</tbody>
</table>

**C.1.4 RevertingVirtualReg**

**Package**

`import RevertingVirtualReg :: * ;`

**Description**

The `RevertingVirtualReg` package allows a designer to force a schedule when scheduling attributes cannot be used. Since scheduling attributes cannot be put on methods, this allows a designer to control the schedule between two methods, or between a method and a rule by adding a virtual register between the two. The module `RevertingVirtualReg` creates a virtual register; no actual state elements are generated.

**Modules**

The `RevertingVirtualReg` package provides the module `mkRevertingVirtualReg`. The properties of the module are:

- it schedules exactly like an ordinary register;
- it reverts to its reset value at the end of each clock cycle.

These imply that all allowed reads will return the reset value (since they precede any writes in the cycle); thus the module neither needs nor instantiates any actual state element.

**, mkRevertingVirtualReg** Creates a virtual register reverting to the reset value at the end of each clock cycle.

```verilog
module mkRevertingVirtualReg#(a_type rst)(Reg#(a_type))
  provisos (Bits#(a_type, sizea));
```

<table>
<thead>
<tr>
<th>Scheduling Annotations</th>
<th>mkRevertingVirtualReg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>read</td>
</tr>
<tr>
<td>read</td>
<td>CF</td>
</tr>
<tr>
<td>write</td>
<td>SA</td>
</tr>
</tbody>
</table>

**Example** Use `mkRevertingVirtualReg` to create the execution order of the `rule` followed by the `method`
Reg#(Bool) virtualReg <- mkRevertingVirtualReg(True);

rule the_rule (virtualReg); // reads virtualReg
  ...
endrule

method Action the_method;
  virtualReg <= False; // writes virtualReg
  ...
endmethod

In a given cycle, reads always precede writes for a register. Therefore the reading of virtualReg by the_rule will precede the writing of virtualReg in the_method. The execution order will be the_rule followed by the_method.

C.1.5 BRAM

Package

import BRAM :: * ;

Description

The BRAM package provides types, interfaces, and modules to support FPGA BlockRams. The BRAM modules include FIFO wrappers to provide implicit conditions for proper flow control for the BRAM latency. Specific tools may determine whether modules are mapped to appropriate BRAM cells during synthesis.

The BRAM package is open-sourced and can be modified by the user. The low-level wrappers to the BRAM Verilog and Bluesim modules, which are not open-sourced and cannot be modified, are provided in the BRAMCore package, Section C.1.6.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Types and type classes

BRAM_Configure The BRAM_Configure structure specifies the underlying modules and their attributes for instantiation. Default values for the BRAM are defined with the DefaultValue instance and can easily be modified.
### BRAMConfigure Structure

<table>
<thead>
<tr>
<th>Field</th>
<th>Type</th>
<th>Description</th>
<th>Allowed or Recommended Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>memorySize</td>
<td>Integer</td>
<td>Number of words in the BRAM</td>
<td></td>
</tr>
<tr>
<td>latency</td>
<td>Integer</td>
<td>Number of stages in the read</td>
<td>1 (address is registered) 2 (address and data are registered)</td>
</tr>
<tr>
<td>loadFormat</td>
<td>LoadFormat</td>
<td>Describes the load file</td>
<td>None tagged Hex filename tagged Binary filename</td>
</tr>
<tr>
<td>outFIFODepth</td>
<td>Integer</td>
<td>The depth of the BypassFIFO after the BRAM for the BRAMServer module</td>
<td>latency + 2</td>
</tr>
<tr>
<td>allowWriteResponseBypass</td>
<td>Bool</td>
<td>Determines if write responses can directly be enqueued in the output fifo (latency = 0 for write).</td>
<td></td>
</tr>
</tbody>
</table>

The size of the BRAM is determined by the memorySize field given in number of words. The width of a word is determined by the polymorphic type data specified in the BRAM interface. If the memorySize field is 0, then memory size = 2^n, where n is the number of address bits determined from the address type.

The latency field has two valid values; 1 indicates that the address on the read is registered, 2 indicates that both the address on the read input and the data on the read output are registered. When latency = 2, the components in the dotted box in Figure 3 are included.

The outFIFODepth is used to determine the depth of the Bypass FIFO after the BRAM in the mkBRAMServer module. This value should be latency + 2 to allow full pipeline behavior.

The allowWriteResponseBypass field, when True, specifies that the write response is issued on the same cycle as the write request. If False, the write response is pipelined, which is the same behavior as the read request. When True, the schedule constraints between put and get are put SBR get. Otherwise, the annotation is get CF put (no constraint).

```plaintext
typedef struct {Integer memorySize ;
        Integer latency ; // 1 or 2 can extend to 3
        LoadFormat loadFormat; // None, Hex or Binary
        Integer outFIFODepth;
        Bool allowWriteResponseBypass;
} BRAM_Configure ;
```

The LoadFormat defines the type of the load file (None, Hex or Binary). The type None is used when there is no load file. When the type is Hex or Binary, the name of the load file is provided as a String.

```plaintext
typedef union tagged {
        void None;
        String Hex;
        String Binary;
    } LoadFormat
deriving (Eq, Bits);
```

The default values are defined in this package using the DefaultValue instance for BRAM_Configure. You can modify the default values by changing this instance or by modifying specific fields in your design.
Values defined in defaultValue

<table>
<thead>
<tr>
<th>Field</th>
<th>Type</th>
<th>Value</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>memorySize</td>
<td>Integer</td>
<td>0</td>
<td>$2^n$, where n is the number of address bits</td>
</tr>
<tr>
<td>latency</td>
<td>Integer</td>
<td>1</td>
<td>address is registered</td>
</tr>
<tr>
<td>outFIFODepth</td>
<td>Integer</td>
<td>3</td>
<td>latency + 2</td>
</tr>
<tr>
<td>loadFormat</td>
<td>LoadFormat</td>
<td>None</td>
<td>no load file is used</td>
</tr>
<tr>
<td>allowWriteResponseBypass</td>
<td>Bool</td>
<td>False</td>
<td>the write response is pipelined</td>
</tr>
</tbody>
</table>

instance DefaultValue #(BRAM_Configure);
   defaultValue = BRAM_Configure {memorySize : 0,
                                          latency : 1 // No output reg
                                          ,outFIFODepth : 3
                                          ,loadFormat : None
                                          ,allowWriteResponseBypass : False };
endinstance

To modify a default configuration for your design, set the field you want to change to the new value.
Example:

```verilog
BRAM_Configure cfg = defaultValue ;       //declare variable cfg
cfg.memorySize = 1024*32 ; //new value for memorySize
cfg.loadFormat = tagged Hex "ram.txt"; //value for loadFormat
BRAM2Port#(UInt#(15), Bit#(16)) bram <- mkBRAM2Server (cfg) ;
//instantiate 32K x 16 bits BRAM module
```

**BRAMRequest** The BRAM package defines 2 structures for a BRAM request: **BRAMRequest**, and the byte enabled version **BRAMRequestBE**.

### BRAMRequest Structure

<table>
<thead>
<tr>
<th>Field</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>write</td>
<td>Bool</td>
<td>Indicates whether this operation is a write (True) or a read (False).</td>
</tr>
<tr>
<td>responseOnWrite</td>
<td>Bool</td>
<td>Indicates whether a response should be received from this write command</td>
</tr>
<tr>
<td>address</td>
<td>addr</td>
<td>Word address of the read or write</td>
</tr>
<tr>
<td>datain</td>
<td>data</td>
<td>Data to be written. This field is ignored for reads.</td>
</tr>
</tbody>
</table>

typedef struct {Bool write;
                   Bool responseOnWrite;
                   addr address;
                   data datain;
               } BRAMRequest#(type addr, type data) deriving(Bits, Eq);

**BRAMRequestBE** The structure **BRAMRequestBE** allows for the byte enable signal.
BRAMRequestBE Structure

<table>
<thead>
<tr>
<th>Field</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>written</td>
<td>Bit#(n)</td>
<td>Byte-enable indicating whether this operation is a write (n ! = 0) or a read</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(n = 0).</td>
</tr>
<tr>
<td>responseOnWrite</td>
<td>Bool</td>
<td>Indicates whether a response should be received from this write command</td>
</tr>
<tr>
<td>address</td>
<td>addr</td>
<td>Word address of the read or write</td>
</tr>
<tr>
<td>datain</td>
<td>data</td>
<td>Data to be written. This field is ignored for reads.</td>
</tr>
</tbody>
</table>

typedef struct {Bit#(n) written;
    Bool responseOnWrite;
    addr address;
    data datain;
} BRAMRequestBE#(type addr, type data, numeric type n) deriving (Bits, Eq);

Interfaces and Methods

The interfaces for the BRAM are built on the Server interface defined in the ClientServer package, Section C.7.3. Some type aliases specific to the BRAM are defined here.

BRAM Server and Client interface types:

typedef Server#(BRAMRequest#(addr, data), data) BRAMServer#(type addr, type data);
typedef Client#(BRAMRequest#(addr, data), data) BRAMClient#(type addr, type data);

Byte-enabled BRAM Server and Client interface types:

typedef Server#(BRAMRequestBE#(addr, data, n), data)
    BRAMServerBE#(type addr, type data, numeric type n);
typedef Client#(BRAMRequestBE#(addr, data, n), data)
    BRAMClientBE#(type addr, type data, numeric type n);

The BRAM package defines 1 and 2 port interfaces, with write-enabled and byte-enabled versions. Each BRAM port interface contains a BRAMServer#(addr, data) subinterface and a clear action, which clears the output FIFO of any pending requests. The data in the BRAM is not cleared.

BRAM1Port Interface
  1 Port BRAM Interface

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>portA</td>
<td>BRAMServer#(addr, data)</td>
<td>Server subinterface</td>
</tr>
<tr>
<td>portAClear</td>
<td>Action</td>
<td>Method to clear the portA output FIFO</td>
</tr>
</tbody>
</table>

interface BRAM1Port#(type addr, type data);
    interface BRAMServer#(addr, data) portA;
    method Action portAClear;
endinterface: BRAM1Port

BRAM1PortBE Interface
  Byte enabled 1 port BRAM Interface

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>portA</td>
<td>BRAMServerBE#(addr, data, n)</td>
<td>Byte-enabled server subinterface</td>
</tr>
<tr>
<td>portAClear</td>
<td>Action</td>
<td>Method to clear the portA output FIFO</td>
</tr>
</tbody>
</table>
interface BRAM1PortBE#(type addr, type data, numeric type n);
  interface BRAMServerBE#(addr, data, n) portA;
  method Action portAClear;
endinterface: BRAM1PortBE

<table>
<thead>
<tr>
<th>BRAM2Port Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 port BRAM Interface</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>portA</td>
<td>BRAMServer#(addr, data)</td>
<td>Server subinterface for port A</td>
</tr>
<tr>
<td>portB</td>
<td>BRAMServer#(addr, data)</td>
<td>Server subinterface for port B</td>
</tr>
<tr>
<td>portAClear</td>
<td>Action</td>
<td>Method to clear the port A output FIFO</td>
</tr>
<tr>
<td>portBClear</td>
<td>Action</td>
<td>Method to clear the port B output FIFO</td>
</tr>
</tbody>
</table>

interface BRAM2Port#(type addr, type data);
  interface BRAMServer#(addr, data) portA;
  interface BRAMServer#(addr, data) portB;
  method Action portAClear;
  method Action portBClear;
endinterface: BRAM2Port

<table>
<thead>
<tr>
<th>BRAM2PortBE Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Byte enabled 2 port BRAM Interface</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>portA</td>
<td>BRAMServerBE#(addr, data, n)</td>
<td>Byte-enabled server subinterface for port A</td>
</tr>
<tr>
<td>portB</td>
<td>BRAMServerBE#(addr, data, n)</td>
<td>Byte-enabled server subinterface for port B</td>
</tr>
<tr>
<td>portAClear</td>
<td>Action</td>
<td>Method to clear the portA output FIFO</td>
</tr>
<tr>
<td>portBClear</td>
<td>Action</td>
<td>Method to clear the portB output FIFO</td>
</tr>
</tbody>
</table>

interface BRAM2PortBE#(type addr, type data, numeric type n);
  interface BRAMServerBE#(addr, data, n) portA;
  interface BRAMServerBE#(addr, data, n) portB;
  method Action portAClear;
  method Action portBClear;
endinterface: BRAM2PortBE

Modules

The BRAM modules defined in the **BRAMCore** package (Section C.1.6) are wrapped with control logic to turn the BRAM into a server, as shown in Figure 3. The BRAM Server modules include an output FIFO and logic to control its loading and to avoid overflow. A single port, single clock byte-enabled version is provided as well as 2 port and dual clock write-enabled versions.

<table>
<thead>
<tr>
<th>mkBRAM1Server</th>
<th>BRAM Server module including an output FIFO and logic to control loading and to avoid overflow.</th>
</tr>
</thead>
</table>
| module mkBRAM1Server #( BRAM_Configure cfg )
  ( BRAM1Port #(addr, data) )
  provisos(Bits#(addr, addr_sz),
            Bits#(data, data_sz),
            DefaultValue#(data)) |
### mkBRAM1ServerBE

Byte-enabled BRAM Server module.

```verilog
module mkBRAM1ServerBE #( BRAM_Configure cfg )
  ( BRAM1PortBE #(addr, data, n) )
provisos(Bits#(addr, addr_sz),
         Bits#(data, data_sz),
         Div#(data_sz, n, chunk_sz),
         Mul#(chunk_sz, n, data_sz),
         DefaultValue#(data));
```

### mkBRAM2Server

2 port BRAM Server module.

```verilog
module mkBRAM2Server #( BRAM_Configure cfg )
  ( BRAM2Port #(addr, data) )
provisos(Bits#(addr, addr_sz),
         Bits#(data, data_sz),
         DefaultValue#(data));
```

### mkBRAM2ServerBE

Byte-enabled 2 port BRAM Server module.

```verilog
module mkBRAM2ServerBE #( BRAM_Configure cfg )
  ( BRAM2PortBE #(addr, data, n) )
provisos(Bits#(addr, addr_sz),
         Bits#(data, data_sz),
         Div#(data_sz, n, chunk_sz),
         Mul#(chunk_sz, n, data_sz));
```

---

**Figure 3:** 1 port of a BRAM Server
mkSyncBRAM2Server

2 port, dual clock, BRAM Server module. The portA subinterface and portAClear methods are in the clkA domain; the portB subinterface and portBClear methods are in the clkB domain.

```verilog
(* no_default_clock, no_default_reset *)
module mkSyncBRAM2Server #( BRAM_Configure cfg,
  Clock clkA, Reset rstNA,
  Clock clkB, Reset rstNB
) (BRAM2Port #(addr, data) )
provisos(Bits#(addr, addr_sz),
  Bits#(data, data_sz),
  DefaultValue#(data) );
```

mkSyncBRAM2ServerBE

2 port, dual clock, byte-enabled BRAM Server module. The portA subinterface and portAClear methods are in the clkA domain; the portB subinterface and portBClear methods are in the clkB domain.

```verilog
(* no_default_clock, no_default_reset *)
module mkSyncBRAM2ServerBE #(BRAM_Configure cfg,
  Clock clkA, Reset rstNA,
  Clock clkB, Reset rstNB )
(BRAM2PortBE #(addr, data, n))
provisos(Bits#(addr, addr_sz),
  Bits#(data, data_sz),
  Div#(data_sz, n, chunk_sz),
  Mul#(chunk_sz, n, data_sz) );
```

**Example: Using a BRAM**

```verilog
import BRAM::*;
import StmtFSM::*;
import Clocks::*;

function BRAMRequest#(Bit#(8), Bit#(8)) makeRequest(Bool write, Bit#(8) addr, Bit#(8) data);
  return BRAMRequest{
    write: write,
    responseOnWrite:False,
    address: addr,
    datain: data
  };
endfunction

(* synthesize *)
module sysBRAMTest();
  BRAM_Configure cfg = defaultValue;
  cfg.allowWriteResponseBypass = False;
  BRAM2Port#(Bit#(8), Bit#(8)) dut0 <- mkBRAM2Server(cfg);
  cfg.loadFormat = tagged Hex "bram2.txt";
  BRAM2Port#(Bit#(8), Bit#(8)) dut1 <- mkBRAM2Server(cfg);

  //Define StmtFSM to run tests
```
Stmt test =
  (seq
    delay(10);
    ...
    action
dut1.portA.request.put(makeRequest(False, 8'h02, 0));
dut1.portB.request.put(makeRequest(False, 8'h03, 0));
  endaction
  action
    $display("dut1read[0] = %x", dut1.portA.response.get);
    $display("dut1read[1] = %x", dut1.portB.response.get);
  endaction
    ...
    delay(100);
  endseq);
  mkAutoFSM(test);
endmodule

C.1.6 BRAMCore

Package

import BRAMCore :: * ;

Description

The BRAMCore package, along with the BRAM package (Section C.1.5) provides types, interfaces, and modules to support FPGA BlockRAMS. Specific tools may determine whether modules are mapped to appropriate BRAM cells during synthesis.

Most designs should use the the BRAM package instead of BRAMCore, as the BRAM package provides implicit conditions provided by FIFO wrappers. The BRAMCore package should be used only if you want the low-level core BRAM modules without implicit conditions.

The BRAMCore package contains the low-level wrappers to the BRAM Verilog and Bluesim modules. Components are provided for single and dual port, byte-enabled, loadable, and dual clock versions.

Interfaces and Methods

The BRAMCore package defines four variations of a BRAM interface to support single and dual port BRAMs, as well as byte-enabled BRAMs.

The BRAM_PORT interface declares two methods; an Action method put, and a value method read.

The BRAM_DUAL_PORT interface is defined as two BRAM_PORT subinterfaces, one for each port.

<table>
<thead>
<tr>
<th>BRAM_PORT Interface</th>
<th>Method</th>
<th>Arguments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Type</td>
<td>Description</td>
</tr>
<tr>
<td>put</td>
<td>Action</td>
<td>Read or write values in the BRAM.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>read</td>
<td>data</td>
<td>Returns a value of type data.</td>
</tr>
</tbody>
</table>
interface BRAM_PORT#(type addr, type data);
  method Action put(Bool write, addr address, data datain);
  method data read();
endinterface: BRAM_PORT

interface BRAM_DUAL_PORT#(type addr, type data);
  interface BRAM_PORT#(addr, data) a;
  interface BRAM_PORT#(addr, data) b;
endinterface

Byte-enabled Interfaces

The BRAM_PORT_BE and BRAM_DUAL_PORT_BE interfaces are the byte-enabled versions of the BRAM interfaces. In this version, the argument written is of type Bit#(n), where n is the number of byte-enables. Your synthesis tools and targeted technology determine the restriction of data size and byte enable size. If n = 0, the action is a read.

The BRAM_DUAL_PORT_BE interface is defined as two BRAM_PORT_BE subinterfaces, one for each port.

<table>
<thead>
<tr>
<th>BRAM_PORT_BE Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
</tr>
<tr>
<td>Name</td>
</tr>
<tr>
<td>put</td>
</tr>
<tr>
<td>address</td>
</tr>
<tr>
<td>datain</td>
</tr>
<tr>
<td>read</td>
</tr>
</tbody>
</table>

(* always_ready *)

interface BRAM_PORT_BE#(type addr, type data, numeric type n);
  method Action put(Bit#(n) written, addr address, data datain);
  method data read();
endinterface: BRAM_PORT_BE

interface BRAM_DUAL_PORT_BE#(type addr, type data, numeric type n);
  interface BRAM_PORT_BE#(addr, data, n) a;
  interface BRAM_PORT_BE#(addr, data, n) b;
endinterface

Modules

The BRAMCore package provides 1 and 2 port BRAM core modules, in both write-enabled and byte-enabled versions. Note that there are no implicit conditions on the methods of these modules; if these are required consider using the modules in the BRAM package (Section C.1.5).

The BRAMCore package requires the caller to ensure the correct cycle to capture the read data, as determined by the hasOutputRegister flag. If hasOutputRegister is True, both the read address and the read data are registered; if False, only the read address is registered.

- If the output is registered (hasOutputRegister is True), the latency is 2; the read data is available 2 cycles after the request.
• If the output is not registered (hasOutputRegister is False), the latency is 1; the read data is available 1 cycle after the request.

The other argument required is memSize, an Integer specifying the memory size in number of words of type data.

The loadable BRAM modules require two additional arguments:

• file is a String containing the name of the load file.

• binary is a Bool indicating whether the data type of the load file is binary (True) or hex (False).

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Verilog Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkBRAMCore1</td>
<td>Single port BRAM</td>
<td>module mkBRAMCore1#(Integer memSize, Bool hasOutputRegister)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(BRAM_PORT#(addr, data))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>provisos(Bits#(addr, addr_sz), Bits#(data, data_sz));</td>
</tr>
<tr>
<td>mkBRAMCore1BE</td>
<td>Byte-enabled, single port BRAM</td>
<td>module mkBRAMCore1BE#(Integer memSize, Bool hasOutputRegister)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(BRAM_PORT_BE#(addr, data, n))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>provisos(Bits#(addr, addr_sz), Bits#(data, data_sz),</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Div#(data_sz, n, chunk_sz),</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mul#(chunk_sz, n, data_sz));</td>
</tr>
<tr>
<td>mkBRAMCore1Load</td>
<td>Loadable, single port BRAM where the initial</td>
<td>module mkBRAMCore1Load#(Integer memSize, Bool hasOutputRegister, String file,</td>
</tr>
<tr>
<td></td>
<td>contents are in file.</td>
<td>Bool binary)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(BRAM_PORT#(addr, data))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>provisos(Bits#(addr, addr_sz), Bits#(data, data_sz));</td>
</tr>
<tr>
<td>mkBRAMCore1BELoad</td>
<td>Loadable, single port, byte-enabled BRAM.</td>
<td>module mkBRAMCore1BELoad#(Integer memSize, Bool hasOutputRegister, String</td>
</tr>
<tr>
<td></td>
<td></td>
<td>file, Bool binary)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(BRAM_PORT_BE#(addr, data, n))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>provisos(Bits#(addr, addr_sz), Bits#(data, data_sz),</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Div#(data_sz, n, chunk_sz),</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mul#(chunk_sz, n, data_sz));</td>
</tr>
<tr>
<td>mkBRAMCore2</td>
<td>Dual port, single clock BRAM.</td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>--------------------------------</td>
<td></td>
</tr>
</tbody>
</table>
| module mkBRAMCore2#(Integer memSize, Bool hasOutputRegister)  
  (BRAM_DUAL_PORT#(addr, data))  
  provisos(Bits#(addr, addr_sz), Bits#(data, data_sz)); |

<table>
<thead>
<tr>
<th>mkBRAMCore2BE</th>
<th>Byte-enabled, dual port BRAM.</th>
</tr>
</thead>
</table>
| module mkBRAMCore2BE#(Integer memSize, Bool hasOutputRegister  
  ) (BRAM_DUAL_PORT_BE#(addr, data, n))  
  provisos(Bits#(addr, addr_sz),  
  Bits#(data, data_sz),  
  Div#(data_sz, n, chunk_sz),  
  Mul#(chunk_sz, n, data_sz)); |

<table>
<thead>
<tr>
<th>mkSyncBRAMCore2</th>
<th>Dual port, dual clock BRAM.</th>
</tr>
</thead>
</table>
| module mkSyncBRAMCore2#(Integer memSize, Bool hasOutputRegister,  
  Clock clkA, Reset rstNA,  
  Clock clkB, Reset rstNB)  
  (BRAM_DUAL_PORT#(addr, data))  
  provisos(Bits#(addr, addr_sz),Bits#(data, data_sz)); |

<table>
<thead>
<tr>
<th>mkSyncBRAMCore2BE</th>
<th>Dual port, dual clock byte-enabled BRAM.</th>
</tr>
</thead>
</table>
| module mkSyncBRAMCore2BE#(Integer memSize, Bool hasOutputRegister,  
  Clock clkA, Reset rstNA,  
  Clock clkB, Reset rstNB)  
  (BRAM_DUAL_PORT_BE#(addr, data, n))  
  provisos(Bits#(addr, addr_sz),  
  Bits#(data, data_sz),  
  Div#(data_sz, n, chunk_sz),  
  Mul#(chunk_sz, n, data_sz)); |

<table>
<thead>
<tr>
<th>mkBRAMCore2Load</th>
<th>Dual port, single clock, BRAM where the initial contents are in file. The parameter binary indicates whether the contents of file are binary (True) or hex (False).</th>
</tr>
</thead>
</table>
| module mkBRAMCore2Load#(Integer memSize, Bool hasOutputRegister,  
  String file, Bool binary)  
  (BRAM_DUAL_PORT#(addr, data))  
  provisos(Bits#(addr, addr_sz),Bits#(data, data_sz)); |
### mkBRAMCore2BELoad

Dual port, single clock, byte-enabled BRAM where the initial contents are in file. The parameter `binary` indicates whether the contents of file are binary (True) or hex (False).

```verilog
module mkBRAMCore2BELoad#(Integer memSize, Bool hasOutputRegister, String file, Bool binary )
(BRAM_DUAL_PORT_BE#(addr, data, n))
provisos(Bits#(addr, addr_sz),
Bits#(data, data_sz),
Div#(data_sz, n, chunk_sz),
Mul#(chunk_sz, n, data_sz));
```

### mkSyncBRAMCore2Load

Dual port, dual clock BRAM with initial contents in file.

```verilog
module mkSyncBRAMCore2Load#(Integer memSize, Bool hasOutputRegister, Clock clkA, Reset rstNA, Clock clkB, Reset rstNB, String file, Bool binary )
(BRAM_DUAL_PORT#(addr, data))
provisos(Bits#(addr, addr_sz), Bits#(data, data_sz));
```

### mkSyncBRAMCore2BELoad

Dual port, dual clock, byte-enabled BRAM with initial contents in file.

```verilog
module mkSyncBRAMCore2BELoad#(Integer memSize, Bool hasOutputRegister, Clock clkA, Reset rstNA, Clock clkB, Reset rstNB, String file, Bool binary )
(BRAM_DUAL_PORT_BE#(addr, data, n))
provisos(Bits#(addr, addr_sz),
Bits#(data, data_sz),
Div#(data_sz, n, chunk_sz),
Mul#(chunk_sz, n, data_sz));
```

## Verilog Modules

BRAM modules correspond to the following Verilog modules, which are found in the Bluespec Verilog library, `$BLUESPECDIR/Verilog/`. 
### C.2 FIFOs

#### C.2.1 FIFO Overview

The AzureIP Foundation library contains multiple FIFO packages. All library FIFO packages are supplied as compiled code. The FIFOs in the BRAMFIFO, SpecialFIFO, and AlignedFIFOs packages are also provided as BSV source code to facilitate customization.

<table>
<thead>
<tr>
<th>Package Name</th>
<th>Description</th>
<th>BSV Source provided</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIFO</td>
<td>Defines the FIFO interface and module constructors. FIFOs provided have implicit full and empty signals. Includes pipeline FIFO (mkLFIFO).</td>
<td></td>
<td>C.2.2</td>
</tr>
<tr>
<td>FIFOF</td>
<td>Defines the FIFOF interface and module constructors. FIFOs provided have explicit full and empty signals. Includes pipeline FIFOF (mkLFIFOF).</td>
<td></td>
<td>C.2.2</td>
</tr>
<tr>
<td>FIFOLevel</td>
<td>Enhanced FIFO interfaces and modules which include methods to indicate the level or current number of items stored in the FIFO. Single and dual clock versions are provided.</td>
<td></td>
<td>C.2.3</td>
</tr>
<tr>
<td>BRAMFIFO</td>
<td>FIFOs which utilize the Xilinx Block RAMs.</td>
<td>√</td>
<td>C.2.4</td>
</tr>
<tr>
<td>SpecialFIFOs</td>
<td>Additional pipeline and bypass FIFOs</td>
<td>√</td>
<td>C.2.5</td>
</tr>
<tr>
<td>AlignedFIFOs</td>
<td>Parameterized FIFO module for creating synchronizing FIFOs between clock domains with aligned edges.</td>
<td>√</td>
<td>C.2.6</td>
</tr>
<tr>
<td>Gearbox</td>
<td>FIFOs which change the frequency and data width of data across clock domains with aligned edges. The overall data rate stays the same.</td>
<td>√</td>
<td>C.2.7</td>
</tr>
<tr>
<td>Clocks</td>
<td>Generalized FIFOs to synchronize data being sent across clock domains</td>
<td></td>
<td>C.9.7</td>
</tr>
</tbody>
</table>

### C.2.2 FIFO and FIFOF packages

Packages

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkBRAMCore1</td>
<td>BRAM1.v</td>
</tr>
<tr>
<td>mkBRAMCore1Load</td>
<td>BRAM1Load.v</td>
</tr>
<tr>
<td>mkBRAMCore1BE</td>
<td>BRAM1BE.v</td>
</tr>
<tr>
<td>mkBRAMCore1BELoad</td>
<td>BRAM1BELoad.v</td>
</tr>
<tr>
<td>mkBRAMCore2</td>
<td>BRAM2.v</td>
</tr>
<tr>
<td>mkSyncBRAMCore2</td>
<td>BRAM2BE.v</td>
</tr>
<tr>
<td>mkSyncBRAMCore2BE</td>
<td>BRAM2BE.v</td>
</tr>
<tr>
<td>mkBRAMCore2Load</td>
<td>BRAM2Load.v</td>
</tr>
<tr>
<td>mkSyncBRAMCore2Load</td>
<td>BRAM2BELoad.v</td>
</tr>
<tr>
<td>mkBRAMCore2BELoad</td>
<td>BRAM2BELoad.v</td>
</tr>
</tbody>
</table>
import FIFO :: *;
import FIFOF :: *;

Description

The FIFO package defines the FIFO interface and four module constructors. The FIFO package is for FIFOs with implicit full and empty signals.

The FIFOF package defines FIFOs with explicit full and empty signals. The standard version of FIFOF has FIFOs with the enq, deq and first methods guarded by the appropriate (notFull or notEmpty) implicit conditions for safety and improved scheduling. Unguarded (UG) versions of FIFOF are available for the rare cases when implicit conditions are not desired. Guarded (G) versions of FIFOF are available which allow more control over implicit conditions. With the guarded versions the user can specify whether the enqueue or dequeue side is guarded.

Type classes

FShow The FIFOF type belongs to the FShow type class. A FIFOF can be turned into a Fmt type. The Fmt value returned depends on the values of the notEmpty and notFull methods.

```
<table>
<thead>
<tr>
<th>notEmpty</th>
<th>notFull</th>
<th>Fmt Object</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>True</td>
<td>True</td>
<td>&lt;first&gt;</td>
<td>3</td>
</tr>
<tr>
<td>True</td>
<td>False</td>
<td>&lt;first&gt; FULL</td>
<td>2 FULL</td>
</tr>
<tr>
<td>False</td>
<td>True</td>
<td>EMPTY</td>
<td>EMPTY</td>
</tr>
<tr>
<td>False</td>
<td>False</td>
<td>EMPTY</td>
<td>EMPTY</td>
</tr>
</tbody>
</table>

Note: <first> is the value of the first entry with the fshow function applied.
```

Interfaces and methods

The four common methods, enq, deq, first and clear are provided by both the FIFO and FIFOF interfaces.

```
interface FIFO #(type element_type);
    method Action enq(element_type x1);
    method Action deq();
    method element_type first();
    method Action clear();
endinterface: FIFO
```

FIFOF provides two additional methods, notFull and notEmpty.
Additional FIFOF Methods

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>notFull</td>
<td>Bool</td>
<td>returns a True value if there is space, you can enqueue an entry into the FIFO</td>
</tr>
<tr>
<td>notEmpty</td>
<td>Bool</td>
<td>returns a True value if there are elements the FIFO, you can dequeue from the FIFO</td>
</tr>
</tbody>
</table>

interface FIFOF #(type element_type);
  method Action enq(element_type x);
  method Action deq();
  method element_type first();
  method Bool notFull();
  method Bool notEmpty();
  method Action clear();
endinterface: FIFOF

The FIFOF interfaces belong to the ToGet and ToPut typeclasses. You can use the toGet and toPut functions to convert FIFO and FIFOF interfaces to Get and Put interfaces (Section C.7.1).

Modules

The FIFO and FIFOF interface types are provided by the module constructors: mkFIFO, mkFIFOF, mkSizedFIFO, mkDepthParamFIFO, and mkLFIFO. Each FIFO is safe with implicit conditions; they do not allow an enq when the FIFO is full or a deq or first when the FIFO is empty.

Most FIFOs do not allow simultaneous enqueue and dequeue operations when the FIFO is full or empty. The exceptions are pipeline and bypass FIFOs. A pipeline FIFO (provided as mkLFIFO in this package), allows simultaneous enqueue and dequeue operations when full. A bypass FIFO allows simultaneous enqueue and dequeue operations when empty. Additional pipeline and bypass FIFOs are provided in the SpecialFIFOs package (Section C.2.5). The FIFOs in the SpecialFIFOs package are provided as both compiled code and BSV source code, so they are customizable.

<table>
<thead>
<tr>
<th>FIFO type</th>
<th>FIFO Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>empty</td>
</tr>
<tr>
<td>mkFIFO</td>
<td>√</td>
</tr>
<tr>
<td>mkFIFOF</td>
<td>NA</td>
</tr>
<tr>
<td>mkFIFO1</td>
<td>NA</td>
</tr>
<tr>
<td>mkFIFOF1</td>
<td>NA</td>
</tr>
<tr>
<td>mkLFIFO</td>
<td>√</td>
</tr>
<tr>
<td>mkLFIFOF</td>
<td>NA</td>
</tr>
<tr>
<td>mkLFIFO1</td>
<td>NA</td>
</tr>
<tr>
<td>mkLFIFOF1</td>
<td>NA</td>
</tr>
</tbody>
</table>

Modules provided in SpecialFIFOs package C.2.5

<table>
<thead>
<tr>
<th></th>
<th>FIFO Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>empty</td>
</tr>
<tr>
<td>mkPipelineFIFO</td>
<td>NA</td>
</tr>
<tr>
<td>mkPipelineFIFOF</td>
<td>NA</td>
</tr>
<tr>
<td>mkBypassFIFO</td>
<td>√</td>
</tr>
<tr>
<td>mkBypassFIFOF</td>
<td>NA</td>
</tr>
<tr>
<td>mkSizedBypassFIFO</td>
<td>√</td>
</tr>
<tr>
<td>mkBypassFIFOLevel</td>
<td>√</td>
</tr>
</tbody>
</table>

For creating a FIFOF interface (providing explicit notFull and notEmpty methods) use the "F" version of the module, for example use mkFIFOF instead of mkFIFO.
### Module Name

<table>
<thead>
<tr>
<th>Module Name</th>
<th>BSV Module Declaration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FIFO or FIFOF of depth 2</strong></td>
<td></td>
</tr>
<tr>
<td>mkFIFO</td>
<td>module mkFIFO#(FIFO#(element_type)) provisos (Bits#(element_type, width_any));</td>
</tr>
<tr>
<td>mkFIFOF</td>
<td></td>
</tr>
<tr>
<td><strong>FIFO or FIFOF of depth 1</strong></td>
<td></td>
</tr>
<tr>
<td>mkFIFO1</td>
<td>module mkFIFO1#(FIFO#(element_type)) provisos (Bits#(element_type, width_any));</td>
</tr>
<tr>
<td>mkFIFOF1</td>
<td></td>
</tr>
<tr>
<td><strong>FIFO or FIFOF of given depth n</strong></td>
<td></td>
</tr>
<tr>
<td>mkSizedFIFO</td>
<td>module mkSizedFIFO#(Integer n)(FIFO#(element_type)) provisos (Bits#(element_type, width_any));</td>
</tr>
<tr>
<td>mkSizedFIFOF</td>
<td></td>
</tr>
<tr>
<td><strong>FIFO or FIFOF of given depth n where n is a Verilog parameter or computed from compile-time constants and Verilog parameters.</strong></td>
<td></td>
</tr>
<tr>
<td>mkDepthParamFIFO</td>
<td>module mkDepthParamFIFO#(UInt#(32) n)(FIFO#(element_type)) provisos (Bits#(element_type, width_any));</td>
</tr>
<tr>
<td>mkDepthParamFIFOF</td>
<td></td>
</tr>
</tbody>
</table>

Unguarded (UG) versions of FIFOF are available for the rare cases when implicit conditions are not desired. When using an unguarded FIFO, the implicit conditions for correct FIFO operations are NOT considered during rule and method processing, making it possible to enqueue when full and to dequeue when empty. These modules provide the FIFOF interface.

### Unguarded FIFOF of depth 2

<table>
<thead>
<tr>
<th>Module Name</th>
<th>BSV Module Declaration</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkUGFIFO</td>
<td>module mkUGFIFO#(FIFO#(element_type)) provisos (Bits#(element_type, width_any));</td>
</tr>
<tr>
<td>mkUGFIFOF</td>
<td></td>
</tr>
</tbody>
</table>

### Unguarded FIFOF of depth 1

<table>
<thead>
<tr>
<th>Module Name</th>
<th>BSV Module Declaration</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkUGFIFO1</td>
<td>module mkUGFIFO1#(FIFO#(element_type)) provisos (Bits#(element_type, width_any));</td>
</tr>
</tbody>
</table>

### Unguarded FIFOF of given depth n

<table>
<thead>
<tr>
<th>Module Name</th>
<th>BSV Module Declaration</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkUGSizedFIFO</td>
<td>module mkUGSizedFIFO#(Integer n)(FIFO#(element_type)) provisos (Bits#(element_type, width_any));</td>
</tr>
</tbody>
</table>

235
Unguarded FIFO of given depth n where n is a Verilog parameter or computed from compile-time constants and Verilog parameters.

```
mkUGDepthParamFIFOF module mkUGDepthParamFIFOF#(UInt#(32) n)(FIFOF#(element_type)) provisos (Bits#(element_type, width_any));
```

The guarded (G) versions of each of the FIFOFs allow you to specify which implicit condition you want to guard. These modules take two Boolean parameters; `ugenq` and `ugdeq`. Setting either parameter `TRUE` indicates the relevant methods (`enq` for `ugenq`, `first` and `deq` for `ugdeq`) are unguarded. If both are `TRUE` the FIFOF behaves the same as an unguarded FIFOF. If both are `FALSE` the behavior is the same as a regular FIFOF.

```
Guarded FIFO of depth 2.
mkGFIFOF module mkGFIFOF#(Bool ugenq, Bool ugdeq)(FIFOF#(element_type)) provisos (Bits#(element_type, width_any));
```

```
Guarded FIFO of depth 1
mkGFIFOF1 module mkGFIFOF1#(Bool ugenq, Bool ugdeq)(FIFOF#(element_type)) provisos (Bits#(element_type, width_any));
```

```
Guarded FIFO of given depth n
mkGSizedFIFOF module mkGSizedFIFOF#(Bool ugenq, Bool ugdeq, Integer n)(FIFOF#(element_type)) provisos (Bits#(element_type, width_any));
```

```
Guarded FIFO of given depth n where n is a Verilog parameter or computed from compile-time constants and Verilog parameters.
mkGDepthParamFIFOF module mkGDepthParamFIFOF#(Bool ugenq, Bool ugdeq, UInt#(32) n)(FIFOF#(element_type)) provisos (Bits#(element_type, width_any));
```

The LFIFOs (pipeline FIFOs) allow `enq` and `deq` in the same clock cycle when the FIFO is full. Additional BSV versions of the pipeline FIFO and also bypass FIFOs (allowing simultaneous `enq` and `deq` when the FIFO is empty) are provided in the `SpecialFIFOs` package (Section C.2.5). Both unguarded and guarded versions of the LFIFO are provided in the FIFOF package.
Pipeline FIFO of depth 1. `deq` and `enq` can be simultaneously applied in the same clock cycle when the FIFO is full.

| mkLFIFO   | module mkLFIFO#(FIFO#(element_type)) |
| mkLFIFOF  | provisos (Bits#(element_type, width_any)); |
| mkUGLFIFOF|

Guarded pipeline FIFOF of depth 1. `deq` and `enq` can be simultaneously applied in the same clock cycle when the FIFOF is full.

| mkGLFIFOF | module mkGLFIFOF#(Bool ugenq, Bool udegq)(FIFOF#(element_type)) |
|           | provisos (Bits#(element_type, width_any)); |

Functions

The FIFO package provides a function `fifofToFifo` to convert an interface of type `FIFOF` to an interface of type `FIFO`.

<table>
<thead>
<tr>
<th>Converts a FIFOF interface to a FIFO interface.</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>fifofToFifo</code></td>
</tr>
</tbody>
</table>

Example using the FIFO package

This example creates 2 input FIFOs and moves data from the input FIFOs to the output FIFOs.

```verilog
import FIFO::*;

typedef Bit#(24) DataT;

// define a single interface into our example block
interface BlockIFC;
  method Action push1 (DataT a);
  method Action push2 (DataT a);
  method ActionValue#(DataT) get();
endinterface

module mkBlock1( BlockIFC );
  Integer fifo_depth = 16;

  // create the first inbound FIFO instance
  FIFO#(DataT) inbound1 <- mkSizedFIFO(fifo_depth);

  // create the second inbound FIFO instance
  FIFO#(DataT) inbound2 <- mkSizedFIFO(fifo_depth);

  // create the outbound instance
  FIFO#(DataT) outbound <- mkSizedFIFO(fifo_depth);

  // rule for enqueue of outbound from inbound1
```
// implicit conditions ensure correct behavior
rule enq1 (True);
  DataT in_data = inbound1.first;
  DataT out_data = in_data;
  outbound.enq(out_data);
  inbound1.deq;
endrule: enq1

// rule for enqueue of outbound from inbound2
// implicit conditions ensure correct behavior
rule enq2 (True);
  DataT in_data = inbound2.first;
  DataT out_data = in_data;
  outbound.enq(out_data);
  inbound2.deq;
endrule: enq2

// Add an entry to the inbound1 FIFO
method Action push1 (DataT a);
  inbound1.enq(a);
endmethod

// Add an entry to the inbound2 FIFO
method Action push2 (DataT a);
  inbound2.enq(a);
endmethod

// Remove first value from outbound and return it
method ActionValue#(DataT) get();
  outbound.deq();
  return outbound.first();
endmethod
endmodule

Scheduling Annotations

Scheduling constraints describe how methods interact within the schedule. For example, a clear to a given FIFO must be sequenced after (SA) an enq to the same FIFO. That is, when both enq and clear execute in the same cycle, the resulting FIFO state is empty. For correct rule behavior the rule executing enq must be scheduled before the rule calling clear.

The table below lists the scheduling annotations for the FIFO modules mkFIFO, mkSizedFIFO, and mkFIFO1.

<table>
<thead>
<tr>
<th>Scheduling Annotations</th>
<th>enq</th>
<th>first</th>
<th>deq</th>
<th>clear</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkFIFO, mkSizedFIFO, mkFIFO1</td>
<td>C</td>
<td>CF</td>
<td>CF</td>
<td>SB</td>
</tr>
<tr>
<td>enq</td>
<td>CF</td>
<td>CF</td>
<td>SB</td>
<td>SB</td>
</tr>
<tr>
<td>first</td>
<td>CF</td>
<td>CF</td>
<td>SB</td>
<td>SB</td>
</tr>
<tr>
<td>deq</td>
<td>SA</td>
<td>SA</td>
<td>SA</td>
<td>SBR</td>
</tr>
</tbody>
</table>

The table below lists the scheduling annotations for the pipeline FIFO module, mkLFIFO. The pipeline FIFO has a few more restrictions since there is a combinational path between the deq side and the enq side, thus restricting deq calls before enq.
The `FIFOF` modules add the `notFull` and `notEmpty` methods. These methods have SB annotations with the Action methods that change FIFO state. These SB annotations model the atomic behavior of a FIFO, that is when `enq`, `deq`, or `clear` are called the state of `notFull` and `notEmpty` are changed. This is no different than the annotations on `mkReg` (which is `read` SB `write`), where actions are atomic and the execution module is one rule fires at a time. This does differ from a pure hardware module of a FIFO or register where the state does not change until the clock edge.

Verilog Modules

`FIFO` and `FIFOF` modules correspond to the following Verilog modules, which are found in the Bluespec Verilog library, `$BLUESPECDIR/Verilog/`.

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Names</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkFIFO</td>
<td>FIFO2.v</td>
<td></td>
</tr>
<tr>
<td>mkFIFOF</td>
<td>FIFO20.v</td>
<td></td>
</tr>
<tr>
<td>mkUGFIFOF</td>
<td>FIFO1.v</td>
<td></td>
</tr>
<tr>
<td>mkGFIFOF</td>
<td>FIFO10.v</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SizedFIFO.v</td>
<td></td>
</tr>
<tr>
<td>mkUGSizedFIFO</td>
<td>SizedFIFO0.v</td>
<td></td>
</tr>
<tr>
<td>mkGFIFOF</td>
<td>FIFO2.v</td>
<td></td>
</tr>
<tr>
<td>mkGSizeFIFO</td>
<td>FIFO20.v</td>
<td></td>
</tr>
</tbody>
</table>

If the depth of the FIFO = 1, then `FIFO1.v` and `FIFO10.v` are used, if the depth = 2, then `FIFO2.v` and `FIFO20.v` are used.
C.2.3 FIFOLevel

Package

import FIFOLevel :: * ;

Description

The BSV FIFOLevel library provides enhanced FIFO interfaces and modules which include methods to indicate the level or the current number of items stored in the FIFO. Both single clock and dual clock (separate clocks for the enqueue and dequeue sides) versions are included in this package.

Interfaces and methods

The FIFOLevelIfc interface defines methods to compare the current level to Integer constants for a single clock. The SyncFIFOLevelIfc defines the same methods for dual clocks; thus it provides methods for both the source (enqueue) and destination (dequeue) clock domains. Instead of methods to compare the levels, the FIFOCountIfc and SyncFIFOCountIfc define methods to return counts of the FIFO contents, for single clocks and dual clocks respectively.

<table>
<thead>
<tr>
<th>Interface Name</th>
<th>Parameter name</th>
<th>Parameter Description</th>
<th>Requirements of modules implementing the ifc</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIFOLevelIfc</td>
<td>element_type</td>
<td>type of the elements stored in the FIFO</td>
<td>must be in Bits class</td>
</tr>
<tr>
<td></td>
<td>fifoDepth</td>
<td>the depth of the FIFO</td>
<td>must be numeric type and &gt;= 2</td>
</tr>
<tr>
<td>FIFOCountIfc</td>
<td>element_type</td>
<td>type of the elements stored in the FIFO</td>
<td>must be in Bits class</td>
</tr>
<tr>
<td></td>
<td>fifoDepth</td>
<td>the depth of the FIFO</td>
<td>must be numeric type and &gt;= 2</td>
</tr>
<tr>
<td>SyncFIFOLevelIfc</td>
<td>element_type</td>
<td>type of the elements stored in the FIFO</td>
<td>must be in Bits class</td>
</tr>
<tr>
<td></td>
<td>fifoDepth</td>
<td>the depth of the FIFO</td>
<td>must be numeric type and must be a power of 2 and &gt;= 2</td>
</tr>
<tr>
<td>SyncFIFOCountIfc</td>
<td>element_type</td>
<td>type of the elements stored in the FIFO</td>
<td>must be in Bits class</td>
</tr>
<tr>
<td></td>
<td>fifoDepth</td>
<td>the depth of the FIFO</td>
<td>must be numeric type and must be a power of 2 and &gt;= 2</td>
</tr>
</tbody>
</table>

In addition to common FIFO methods, the FIFOLevelIfc interface defines methods to compare the current level to Integer constants. See Section C.2.2 for details on enq, deq, first, clear, notFull,
and notEmpty. Note that FIFOLevelIfc interface has a type parameter for the fifoDepth. This numeric type parameter is needed, since the width of the counter is dependent on the FIFO depth. The fifoDepth parameter must be > 2.

<table>
<thead>
<tr>
<th>Method</th>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>isLessThan</td>
<td>Bool</td>
<td>Returns True if the depth of the FIFO is less than the Integer constant, c1.</td>
</tr>
<tr>
<td>isGreaterThan</td>
<td>Bool</td>
<td>Returns True if the depth of the FIFO is greater than the Integer constant, c1.</td>
</tr>
</tbody>
</table>

FIFOCountIfc

<table>
<thead>
<tr>
<th>Method</th>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>count</td>
<td>UInt#(TLog#(TAdd#(fifoDepth,1)))</td>
<td>Returns the number of items in the FIFO.</td>
</tr>
</tbody>
</table>

interface FIFOLevelIfc#( type element_type, numeric type fifoDepth ) ;
    method Action enq( element_type x1 );
    method Action deq();
    method element_type first();
    method Action clear();

    method Bool notFull ;
    method Bool notEmpty ;

    method Bool isLessThan ( Integer c1 ) ;
    method Bool isGreaterThan( Integer c1 ) ;
endinterface

In addition to common FIFO methods, the FIFOCountIfc interface defines a method to return the current number of elements as an bit-vector. See Section C.2.2 for details on enq, deq, first, clear, notFull, and notEmpty. Note that the FIFOCountIfc interface has a type parameter for the fifoDepth. This numeric type parameter is needed, since the width of the counter is dependent on the FIFO depth. The fifoDepth parameter must be > 2.

interface FIFOCountIfc#( type element_type, numeric type fifoDepth ) ;
    method Action enq ( element_type sendData ) ;
    method Action deq () ;
    method element_type first () ;

    method Bool notFull ;
    method Bool notEmpty ;

    method UInt#(TLog#(TAdd#(fifoDepth,1))) count;

    method Action clear;
endinterface
The interfaces `SyncFIFOLevelIfc` and `SyncFIFOCountIfc` are dual clock versions of the `FIFOLevelIfc` and `FIFOCountIfc`. Methods are provided for both source and destination clock domains. The following table describes the dual clock `notFull` and `notEmpty` methods, as well as the dual clock `clear` methods, which are common to both interfaces. Note that the `SyncFIFOLevelIfc` and `SyncFIFOCountIfc` interfaces each have a type parameter for `fifoDepth`. This numeric type parameter is needed, since the width of the counter is dependent on the FIFO depth. The `fifoDepth` parameter must be a power of 2 and \( \geq 2 \).

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>sNotFull</code></td>
<td><code>Bool</code></td>
<td>Returns <code>True</code> if the FIFO appears as not full from the source side clock.</td>
</tr>
<tr>
<td><code>sNotEmpty</code></td>
<td><code>Bool</code></td>
<td>Returns <code>True</code> if the FIFO appears as not empty from the source side clock.</td>
</tr>
<tr>
<td><code>dNotFull</code></td>
<td><code>Bool</code></td>
<td>Returns <code>True</code> if the FIFO appears as not full from the destination side clock.</td>
</tr>
<tr>
<td><code>dNotEmpty</code></td>
<td><code>Bool</code></td>
<td>Returns <code>True</code> if the FIFO appears as not empty from the destination side clock.</td>
</tr>
<tr>
<td><code>sClear</code></td>
<td><code>Action</code></td>
<td>Clears the FIFO from the source side.</td>
</tr>
<tr>
<td><code>dClear</code></td>
<td><code>Action</code></td>
<td>Clears the FIFO from the destination side.</td>
</tr>
</tbody>
</table>

In addition to common FIFO methods (Section C.2.2) and the common dual clock methods above, the `SyncFIFOLevelIfc` interface defines methods to compare the current level to `Integer` constants. Methods are provided for both the source (enqueue side) and destination (dequeue side) clock domains.

<table>
<thead>
<tr>
<th>Method</th>
<th>Argument Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>sIsLessThan</code></td>
<td>( c1 ) an <code>Integer</code> compile-time constant</td>
</tr>
<tr>
<td><code>sIsGreaterThan</code></td>
<td>( c1 ) an <code>Integer</code> compile-time constant</td>
</tr>
<tr>
<td><code>dIsLessThan</code></td>
<td>( c1 ) an <code>Integer</code> compile-time constant</td>
</tr>
<tr>
<td><code>dIsGreaterThan</code></td>
<td>( c1 ) an <code>Integer</code> compile-time constant</td>
</tr>
</tbody>
</table>

```verilog
interface SyncFIFOLevelIfc#( type element_type, numeric type fifoDepth ) ;
method Action enq ( element_type sendData ) ;
method Action deq () ;
method element_type first () ;

method Bool sNotFull ;
method Bool sNotEmpty ;
```
method Bool dNotFull;
method Bool dNotEmpty;

method Bool sIsLessThan( Integer c1);
method Bool sIsGreaterThan( Integer c1);
method Bool dIsLessThan( Integer c1);
method Bool dIsGreaterThan( Integer c1);

method Action sClear;
method Action dClear;
endinterface

In addition to common FIFO methods (Section C.2.2) and the common dual clock methods above, the SyncFIFOCountIfc interface defines methods to return the current number of elements. Methods are provided for both the source (enqueue side) and destination (dequeue side) clock domains.

<table>
<thead>
<tr>
<th>SyncFIFOCountIfc Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>sCount</td>
</tr>
<tr>
<td>dCount</td>
</tr>
</tbody>
</table>

interface SyncFIFOCountIfc#( type element_type, numeric type fifoDepth);
    method Action enq( element_type sendData);
    method Action deq();
    method element_type first();

    method Bool sNotFull;
    method Bool sNotEmpty;
    method Bool dNotFull;
    method Bool dNotEmpty;

    method UInt#(TLog#(TAdd#(fifoDepth,1)))) sCount;
    method UInt#(TLog#(TAdd#(fifoDepth,1)))) dCount;

    method Action sClear;
    method Action dClear;
endinterface

The FIFOLevelIfc, SyncFIFOLevelIfc, FIFOCountIfc, and SyncFIFOCountIfc interfaces belong to the ToGet and ToPut typeclasses. You can use the toGet and toPut functions to convert these interfaces to Get and Put interfaces (Section C.7.1).

Modules

The module mkFIFOLevel provides the FIFOLevelIfc interface. Note that the implementation allows any number of isLessThan and isGreaterThan method calls. Each call with a unique argument adds an additional comparator to the design.

There is also available a guarded (G) version of FIFOLevel which takes three Boolean parameters; ugenq, ugdeq, and ugcount. Setting any of the parameters to TRUE indicates the method (enq for ugenq, deq for ugdeq, and isLessThan, isGreaterThan for ugcount) is unguarded. If all three are FALSE the behavior is the same as a regular FIFOLevel.
The module `mkFIFOCount` provides the interface `FIFOCountIfc`. There is also available a guarded (G) version of `FIFOCount` which takes three Boolean parameters; `ugenq`, `ugdeq`, and `ugcount`. Setting any of the parameters to `TRUE` indicates the method (enqueue for `ugenq`, dequeue for `ugdeq`, and count for `ugcount`) is unguarded. If all three are `FALSE` the behavior is the same as a regular `FIFOCount`.

The modules `mkSyncFIFOLevel` and `mkSyncFIFOCount` are dual clock FIFOs, where enqueue and dequeue methods are in separate clock domains, `sClkIn` and `dClkIn` respectively. Because of the synchronization latency, the flag indicators will not necessarily be identical between the source and the destination clocks. Note however, that the `sNotFull` and `dNotEmpty` flags always give proper (pessimistic) indications for the safe use of `enq` and `deq` methods; these are automatically included as implicit condition in the `enq` and `deq` (and `first`) methods.

The module `mkSyncFIFOLevel` provides the `SyncFIFOLevelIfc` interface.

<table>
<thead>
<tr>
<th>Module Name</th>
<th>BSV Module Declaration</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>mkFIFOLevel</code></td>
<td>module mkFIFOLevel (FIFOLevelIfc#(element_type, fifoDepth)) provisos( Bits#(element_type, width_element) Log#(TAdd#(fifoDepth,1),cntSize) ); Comment: width_element may be 0</td>
</tr>
<tr>
<td><code>mkGFIFOLevel</code></td>
<td>module mkGFIFOLevel#(Bool ugenq, Bool ugdeq, Bool ugcount) (FIFOLevelIfc#(element_type, fifoDepth)) provisos( Bits#(element_type, width_element), Log#(TAdd#(fifoDepth,1),cntSize)); Comment: width_element may be 0</td>
</tr>
<tr>
<td><code>mkFIFOCount</code></td>
<td>module mkFIFOCount(FIFOCountIfc#(element_type, fifoDepth) ifc ) provisos (Bits#(element_type, width_element)); Comment: width_element may be 0</td>
</tr>
<tr>
<td><code>mkGFIFOCount</code></td>
<td>module mkGFIFOCount#(Bool ugenq, Bool ugdeq, Bool ugcount) (FIFOCountIfc#(element_type, fifoDepth) ifc ) provisos (Bits#(element_type, width_element)); Comment: width_element may be 0</td>
</tr>
</tbody>
</table>
The module `mkSyncFIFOLevel`, as shown in Figure 4 provides the `SyncFIFOLevelIfc` interface. Because of the synchronization latency, the count reports may be different between the source and the destination clocks. Note however, that the `sCount` and `dCount` reports give pessimistic values with the appropriate side. That is, the count `sCount` (on the enqueue clock) will report the exact count of items in the FIFO or a larger count. The larger number is due to the synchronization delay in observing the dequeue action. Likewise, the `dCount` (on the dequeue clock) returns the exact count or a smaller count. The maximum disparity between `sCount` and `dCount` depends on the difference in clock periods between the source and destination clocks.

The module provides `sClear` and `dClear` methods, both of which cause the contents of the FIFO to be removed. Since the clears must be synchronized and acknowledged from one domain to the other, there is a non-trivial delay before the FIFO recovers from the clear and can accept additional enqueues or dequeues (depending on which side is cleared). The calling of either method immediately disables other activity in the calling domain. That is, calling `sClear` in cycle `n` causes the enqueue to become unready in the next cycle, `n+1`. Likewise, calling `dClear` in cycle `n` causes the dequeue to become unready in the next cycle, `n+1`. 

<table>
<thead>
<tr>
<th>Module Name</th>
<th>BSV Module Declaration</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkSyncFIFOLevel</td>
<td>module mkSyncFIFOLevel(</td>
</tr>
<tr>
<td></td>
<td>Clock sClkIn, Reset sRstIn,</td>
</tr>
<tr>
<td></td>
<td>Clock dClkIn,</td>
</tr>
<tr>
<td></td>
<td>SyncFIFOLevelIfc(element_type, fifoDepth) ifc )</td>
</tr>
<tr>
<td></td>
<td>provisos( Bits#(element_type, width_element),</td>
</tr>
<tr>
<td></td>
<td>Log#(TAdd#(fifoDepth,1),cntSize));</td>
</tr>
<tr>
<td>Comment: width_element may be 0</td>
<td></td>
</tr>
</tbody>
</table>
After the `sClear` method is called, the FIFO appears empty on the dequeue side after three `dClock` edges. Three `sClock` edges later, the FIFO returns to a state where new items can be enqueued. The latency is due to the full handshaking synchronization required to send the clear signal to `dClock` and receive the acknowledgement back.

For the `dClear` method call, the enqueue side is cleared in three `sClkIn` edges and items can be enqueued at the fourth edge. All items enqueued at or before the clear are removed from the FIFO.

Note that there is a ready signal associated with both `sClear` and `dClear` methods to ensure that the clear is properly sent between the clock domains. Also, `sRstIn` must be synchronized with the `sClkIn`.

<table>
<thead>
<tr>
<th>Module Name</th>
<th>BSV Module Declaration</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkSyncFIFOCount</td>
<td>module mkSyncFIFOCount(</td>
</tr>
<tr>
<td></td>
<td>Clock sClkIn, Reset sRstIn,</td>
</tr>
<tr>
<td></td>
<td>Clock dClkIn,</td>
</tr>
<tr>
<td></td>
<td>SyncFIFOLevelIfc#(element_type, fifoDepth) ifc</td>
</tr>
<tr>
<td></td>
<td>provisos( Bits#(element_type, width_element))</td>
</tr>
<tr>
<td></td>
<td>Comment: width_element may be 0</td>
</tr>
</tbody>
</table>

Example

The following example shows the use of `SyncFIFOLevel` as a way to collect data into a FIFO, and then send it out in a burst mode. The portion of the design shown, waits until the FIFO is almost full, and then sets a register, `burstOut` which indicates that the FIFO should dequeue. When the FIFO is almost empty, the flag is cleared, and FIFO fills again.

```verilog
// Define a fifo of Int(#23) with 128 entries
SyncFIFOLevelIfc#(Int#(23),128) fifo <- mkSyncFIFOLevel(sclk, rst, dclk);

// Define some constants
let sFifoAlmostFull = fifo.sIsGreaterThan( 120 ) ;
let dFifoAlmostFull = fifo.dIsGreaterThan( 120 ) ;
let dFifoAlmostEmpty = fifo.dIsLessThan( 12 ) ;

// a register to indicate a burst mode
Reg#(Bool) burstOut <- mkReg( False, clocked_by (dclk)) ;

// Set and clear the burst mode depending on fifo status
rule timeToDeque( dFifoAlmostFull && ! burstOut ) ;
    burstOut <= True ;
endrule

rule moveData ( burstOut ) ;
    let dataToSend = fifo.first ;
    fifo.deq ;
    burstOut <= !dFifoAlmostEmpty;
endrule
```
Scheduling Annotations

Scheduling constraints describe how methods interact within the schedule. The annotations for `mkFIFOLevel` and `mkSyncFIFOLevel` are the same, except that methods in different domains (source and destination) are always conflict free.

<table>
<thead>
<tr>
<th>Scheduling Annotations</th>
<th>enq</th>
<th>first</th>
<th>deq</th>
<th>clear</th>
<th>notFull</th>
<th>notEmpty</th>
<th>isLessThan</th>
<th>isGreaterThan</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkFIFOLevel, mkSyncFIFOLevel</td>
<td>C</td>
<td>CF</td>
<td>CF</td>
<td>SB</td>
<td>SA</td>
<td>SA</td>
<td>SA</td>
<td>SA</td>
</tr>
<tr>
<td></td>
<td>CF</td>
<td>CF</td>
<td>SB</td>
<td>SB</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
</tr>
<tr>
<td></td>
<td>SA</td>
<td>SA</td>
<td>C</td>
<td>SB</td>
<td>SA</td>
<td>SA</td>
<td>SA</td>
<td>SA</td>
</tr>
<tr>
<td></td>
<td>SA</td>
<td>SA</td>
<td>SB</td>
<td>SBR</td>
<td>SA</td>
<td>SA</td>
<td>SA</td>
<td>SA</td>
</tr>
<tr>
<td></td>
<td>SB</td>
<td>CF</td>
<td>SB</td>
<td>SB</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
</tr>
<tr>
<td></td>
<td>notEmpty</td>
<td>SB</td>
<td>CF</td>
<td>SB</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
</tr>
<tr>
<td></td>
<td>isLessThan</td>
<td>SB</td>
<td>CF</td>
<td>SB</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
</tr>
<tr>
<td></td>
<td>isGreaterThan</td>
<td>SB</td>
<td>CF</td>
<td>SB</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
</tr>
</tbody>
</table>

The annotations for `mkFIFOCount` and `mkSyncFIFOCount` are the same, except that methods in different domains (source and destination) are always conflict free.

<table>
<thead>
<tr>
<th>Scheduling Annotations</th>
<th>enq</th>
<th>first</th>
<th>deq</th>
<th>clear</th>
<th>notFull</th>
<th>notEmpty</th>
<th>count</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkFIFOCount, mkSyncFIFOCount</td>
<td>C</td>
<td>CF</td>
<td>CF</td>
<td>CB</td>
<td>SA</td>
<td>SA</td>
<td>SA</td>
</tr>
<tr>
<td></td>
<td>CF</td>
<td>CF</td>
<td>SB</td>
<td>SB</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
</tr>
<tr>
<td></td>
<td>SA</td>
<td>SA</td>
<td>SB</td>
<td>SBR</td>
<td>SA</td>
<td>SA</td>
<td>SA</td>
</tr>
<tr>
<td></td>
<td>SA</td>
<td>SA</td>
<td>SB</td>
<td>SBR</td>
<td>SA</td>
<td>SA</td>
<td>SA</td>
</tr>
<tr>
<td></td>
<td>notFull</td>
<td>SB</td>
<td>CF</td>
<td>SB</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
</tr>
<tr>
<td></td>
<td>notEmpty</td>
<td>SB</td>
<td>CF</td>
<td>SB</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
</tr>
<tr>
<td></td>
<td>count</td>
<td>SB</td>
<td>CF</td>
<td>SB</td>
<td>CF</td>
<td>CF</td>
<td>CF</td>
</tr>
</tbody>
</table>

Verilog Modules

The modules described in this section correspond to the following Verilog modules, which are found in the Bluespec Verilog library, `$BLUESPECDIR/Verilog/`.

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkFIFOLevel</td>
<td>SizedFIFO.v</td>
</tr>
<tr>
<td>mkFIFOCOUNT</td>
<td>SizedFIFO0.v</td>
</tr>
<tr>
<td>mkSyncFIFOLevel</td>
<td>SyncFIFOLevel.v</td>
</tr>
</tbody>
</table>

C.2.4 BRAMFIFO

Package
import BRAMFIFO :: * ;

Description

The BRAMFIFO package provides FIFO interfaces and are built around a BRAM memory. The BRAM is provided in the BRAMCore package described in Section C.1.6.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the "$BLUESPECDIR/BSVSource/Misc" directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Interfaces

The BRAMFIFO package provides FIFOF, FIFO, and SyncFIFOIfc interfaces, as defined in the FIFOF, FIFO, (both in Section C.2.2) and Clocks (Section C.9.7) packages.

Modules

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkSizedBRAMFIFOF</td>
<td>Provides a FIFOF interface of a given depth, n.</td>
</tr>
<tr>
<td>mkSizedBRAMFIFO</td>
<td>Provides a FIFO interface of a given depth, n.</td>
</tr>
<tr>
<td>mkSyncBRAMFIFO</td>
<td>Provides a SyncFIFOIfc interface to send data across clock domains. The enq method is in the source sClkIn domain, while the deq and first methods are in the destination dClkIn domain. The input and output clocks, along with the input and output resets, are explicitly provided. The default clock and reset are ignored.</td>
</tr>
<tr>
<td>mkSyncBRAMFIFOToCC</td>
<td>Provides a SyncFIFOIfc interface to send data from a second clock domain into the current clock domain. The output clock and reset are the current clock and reset.</td>
</tr>
</tbody>
</table>

```verilog
module mkSizedBRAMFIFOF#(Integer n) (FIFOF#(element_type))
provisos (Bits(element_type, width_any),
    Add#(1,z,width_any));

module mkSizedBRAMFIFO#(Integer n)(FIFO#(element_type))
provisos(Bits#(t, width_element),
    Add#(1, z, width_element ));

module mkSyncBRAMFIFO#(Integer depth,
    Clock sClkIn, Reset sRstIn,
    Clock dClkIn, Reset dRstIn)
    (SyncFIFOIfc#(element_type))
provisos(Bits#(element_type, width_element),
    Add#(1, z, width_element));

module mkSyncBRAMFIFOToCC#(Integer depth,
    Clock sClkIn, Reset sRstIn)
    (SyncFIFOIfc#(element_type))
provisos(Bits#(element_type, width_element),
    Add#(1, z, width_element));
```
C.2.5 SpecialFIFOs

Package

import SpecialFIFOs :: * ;

Description

The SpecialFIFOs package contains various FIFOs provided as BSV source code, allowing users to easily modify them to their own specifications. Included in the SpecialFIFOs package are pipeline and bypass FIFOs. The pipeline FIFOs are equivalent to the mkLFIFO (Section C.2.2); they allow simultaneous enqueue and dequeue operations in the same clock cycle when full. The bypass FIFOs allow simultaneous enqueue and dequeue in the same clock cycle when empty. FIFOF versions, with explicit full and empty signals, are provided for both pipeline and bypass FIFOs. The package also includes the DFIFOF, a FIFOF with unguarded dequeue and first methods (thus they have no implicit conditions).

<table>
<thead>
<tr>
<th>Module name</th>
<th>Interface</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkPipelineFIFO</td>
<td>FIFO</td>
<td>1 element pipeline FIFO; can enq and deq simultaneously when full.</td>
</tr>
<tr>
<td>mkPipelineFIFOF</td>
<td>FIFOF</td>
<td>1 element pipeline FIFO with explicit full and empty signals.</td>
</tr>
<tr>
<td>mkBypassFIFO</td>
<td>FIFO</td>
<td>1 element bypass FIFO; can enq and deq simultaneously when empty.</td>
</tr>
<tr>
<td>mkBypassFIFOF</td>
<td>FIFOF</td>
<td>1 element bypass FIFO with explicit full and empty signals.</td>
</tr>
<tr>
<td>mkSizedBypassFIFOF</td>
<td>FIFOF</td>
<td>Bypass FIFO of given depth, with explicit full and empty signals.</td>
</tr>
<tr>
<td>mkBypassFIFOLevel</td>
<td>FIFOF</td>
<td>Same as a FIFOFLevel (Section C.2.3), but can enq and deq when empty.</td>
</tr>
<tr>
<td>mkDFIFOF</td>
<td>FIFOF</td>
<td>A FIFOF with unguarded deq and first methods where the first method returns specified default value when the FIFO is empty.</td>
</tr>
<tr>
<td>Module Name</td>
<td>BSV Module Declaration</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>mkPipelineFIFO</td>
<td>module mkPipelineFIFO (FIFO#(element_type))</td>
<td></td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(element_type, width_any));</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-element pipeline FIFO; can <strong>enq</strong> and <strong>deq</strong> simultaneously when full.</td>
<td></td>
</tr>
<tr>
<td>mkPipelineFIFOF</td>
<td>module mkPipelineFIFOF (FIFOF#(element_type))</td>
<td></td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(element_type, width_any));</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-element pipeline FIFOF; can <strong>enq</strong> and <strong>deq</strong> simultaneously when full. Has explicit full and empty signals.</td>
<td></td>
</tr>
<tr>
<td>mkBypassFIFO</td>
<td>module mkBypassFIFO (FIFO#(element_type))</td>
<td></td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(element_type, width_any));</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-element bypass FIFO; can <strong>enq</strong> and <strong>deq</strong> simultaneously when empty.</td>
<td></td>
</tr>
<tr>
<td>mkBypassFIFOF</td>
<td>module mkBypassFIFOF (FIFO#(element_type))</td>
<td></td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(element_type, width_any));</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1-element bypass FIFOF; can <strong>enq</strong> and <strong>deq</strong> simultaneously when empty.</td>
<td></td>
</tr>
</tbody>
</table>

### Interfaces and methods

The modules defined in the `SpecialFIFOs` package provide the `FIFO`, `FIFOF`, and `FIFOLevelIfc` interfaces, as shown in the table above. These interfaces are described in Section C.2.2 (FIFO package) and Section C.2.3 (FIFOLevel package).

### Modules

<table>
<thead>
<tr>
<th>Module Name</th>
<th>BSV Module Declaration</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkPipelineFIFO</td>
<td>module mkPipelineFIFO (FIFO#(element_type))</td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(element_type, width_any));</td>
</tr>
<tr>
<td></td>
<td>1-element pipeline FIFO; can <strong>enq</strong> and <strong>deq</strong> simultaneously when full.</td>
</tr>
<tr>
<td>mkPipelineFIFOF</td>
<td>module mkPipelineFIFOF (FIFOF#(element_type))</td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(element_type, width_any));</td>
</tr>
<tr>
<td></td>
<td>1-element pipeline FIFOF; can <strong>enq</strong> and <strong>deq</strong> simultaneously when full. Has explicit full and empty signals.</td>
</tr>
<tr>
<td>mkBypassFIFO</td>
<td>module mkBypassFIFO (FIFO#(element_type))</td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(element_type, width_any));</td>
</tr>
<tr>
<td></td>
<td>1-element bypass FIFO; can <strong>enq</strong> and <strong>deq</strong> simultaneously when empty.</td>
</tr>
</tbody>
</table>

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the `$BLUESPECDIR/BSVSource/Misc` directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the `-p` option as described in the BSV Users Guide.
1-element bypass FIFO; can \texttt{enq} and \texttt{deq} simultaneously when empty. Has explicit full and empty signals.

| mkBypassFIFOF | \begin{verbatim}module mkBypassFIFOF (FIFOF#(element_type))
provisos (Bits#(element_type, width_any));\end{verbatim}|  

Bypass FIFO of given depth \texttt{fifoDepth} with explicit full and empty signals.

| mkSizedBypassFIFOF | \begin{verbatim}module mkSizedBypassFIFOF#(Integer fifoDepth)
(FIFOF#(element_type))
provisos (Bits#(element_type, width_any));\end{verbatim}|  

Bypass FIFO Level of given depth \texttt{fifoDepth}

| mkBypassFIFOLevel | \begin{verbatim}module mkBypassFIFOLevel(FIFOLevelIfc#(element_type, fifoDepth))
provisos( Bits#(element_type, width_any),
Log#(TAdd#(fifoDepth,1), cntSize));\end{verbatim}|  

A FIFO with unguarded \texttt{deq} and \texttt{first} methods (thus they have no implicit conditions). The \texttt{first} method returns a specified default value when the FIFO is empty.

| mkDFIFOF | \begin{verbatim}module mkDFIFOF#(element_type default_value)
(FIFOF#(element_type))
provisos (Bits#(element_type, width_any));\end{verbatim}|  

\section*{C.2.6 AlignedFIFOs}

\textbf{Package}

\begin{verbatim}
import AlignedFIFOs :: * ;
\end{verbatim}

\textbf{Description}

The AlignedFIFOs package contains a parameterized FIFO module intended for creating synchronizing FIFOs between clock domains with aligned edges for both types of clock domain crossings:

- slow-to-fast crossing - every edge in the source domain implies the existence of a simultaneous edge in the destination domain
- fast-to-slow crossing - every edge in the destination domain implies the existence of a simultaneous edge in the source domain
The FIFO is parameterized on the type of store used to hold the FIFO data, which is itself parameterized on the index type, value type, and read latency. Modules to construct stores based on a single register, a vector of registers and a BRAM are provided, and the user can supply their own store implementation as well.

The FIFO allows the user to control whether or not outputs are held stable during the full slow clock cycle or allowed to transition mid-cycle. Holding the outputs stable is the safest option but it slightly increases the minimum latency through the FIFO.

A primary design goal of this FIFO is to provide an efficient and flexible family of synchronizing FIFOs between aligned clock domains which are written in BSV and are fully compatible with Bluesim. These FIFOs (particularly ones using vectors of registers) may not be the best choice for ASIC synthesis due to the muxing to select the head value in the \texttt{first} method.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $\texttt{BLUESPECDIR/BSVSOURCE/Misc}$ directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the \texttt{-p} option as described in the BSV Users Guide.

### Interfaces and methods

**Store Interface** The \texttt{AlignedFIFO} is parameterized on the type of store used to hold the FIFO data. The three types of stores provided in the \texttt{AlignedFIFO} package (single-element, vector-of-registers, and BRAM) all return a \texttt{Store} interface.

The \texttt{Store} interface has a \texttt{prefetch} method which is used by some modules (the \texttt{mkBRAMStore} in this package). If a prefetch is used, the \texttt{read} method returns the value at the previously fetched index; the value of \texttt{idx} should be ignored. If a prefetch is not used, the \texttt{read} method index value determines the returned value.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{write}</td>
<td>\texttt{Action}</td>
<td>Writes the value at index \texttt{idx}.</td>
</tr>
<tr>
<td>\texttt{prefetch}</td>
<td>\texttt{Action}</td>
<td>Initiates a prefetch of the value at index \texttt{idx}.</td>
</tr>
<tr>
<td>\texttt{read}</td>
<td>\texttt{a}</td>
<td>Returns the value of type \texttt{a}. If prefetch is not used, returns the value at index \texttt{idx}. When prefetch is used, returns the value at the previously fetched index; the value of \texttt{idx} should be ignored.</td>
</tr>
</tbody>
</table>

```verbatim
definition Store#(type i, type a, numeric type n);
  method Action write(i idx, a value);
  method Action prefetch(i idx);
  method a read(i idx);
endinterface: Store
```

**AlignedFIFO Interface** The \texttt{AlignedFIFO} interface provides methods for both source (enqueue) and destination (dequeue) clock domains.
## AlignedFIFO Interface Methods

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>enq</td>
<td>Action</td>
<td>Adds an entry to the FIFO from the source clock domain.</td>
</tr>
<tr>
<td>first</td>
<td>a</td>
<td>Returns the first entry from the FIFO in the destination clock domain.</td>
</tr>
<tr>
<td>deq</td>
<td>Action</td>
<td>Removes the first entry from the FIFO in the destination clock domain.</td>
</tr>
<tr>
<td>dNotFull</td>
<td>Bool</td>
<td>Returns True if the FIFO appears not full from the destination clock domain.</td>
</tr>
<tr>
<td>dNotEmpty</td>
<td>Bool</td>
<td>Returns True if the FIFO appears not empty from the destination clock domain.</td>
</tr>
<tr>
<td>sNotFull</td>
<td>Bool</td>
<td>Returns True if the FIFO appears not full from the source clock domain.</td>
</tr>
<tr>
<td>sNotEmpty</td>
<td>Bool</td>
<td>Returns True if the FIFO appears not empty from the source clock domain.</td>
</tr>
<tr>
<td>dClear</td>
<td>Action</td>
<td>Clears the FIFO from the destination side.</td>
</tr>
<tr>
<td>sClear</td>
<td>Action</td>
<td>Clears the FIFO from the source side.</td>
</tr>
</tbody>
</table>

```verilog
type a;
method Action enq(a x);
method a first();
method Action deq();
method Bool dNotFull();
method Bool dNotEmpty();
method Bool sNotFull();
method Bool sNotEmpty();
method Action dClear();
method Action sClear();
endinterface: AlignedFIFO
```

### Modules

The `AlignedFIFO` module is parameterized on the type of store used to hold the FIFO data. The `AlignedFIFOs` package contains modules to construct stores based on a single register (`mkRegStore`), a vector of registers (`mkRegVectorStore`), and a BRAM (`mkBRAMStore`). Users can supply their own store implementation as well.

The `mkRegStore` instantiates a single-element store. The module returns a `Store` interface and does not use a prefetch.

<table>
<thead>
<tr>
<th>Module Name</th>
<th>BSV Module Declaration</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkRegStore</td>
<td>module mkRegStore(Clock sClock, Clock dClock, Store#(UInt#(0),a,0) ifc) provisos(Bits#(a,a_sz) );</td>
</tr>
</tbody>
</table>

The `mkRegVectorStore` module instantiates a vector-of-registers store. The module returns a `Store` interface and does not use a prefetch.
### Implementation of a vector-of-registers store

<table>
<thead>
<tr>
<th>mkRegVectorStore</th>
<th>module mkRegVectorStore(Clock sClock, Clock dClock, Store#(UInt#(w),a,0) ifc) provisos( Bits#(a,a_sz) );</th>
</tr>
</thead>
</table>

The `mkRegVectorStore` module returns a `Store` interface and uses a prefetch. This model assumes the read clock is a 2x divided version of the write clock.

<table>
<thead>
<tr>
<th>A BRAM-based store where the read clock is a 2x divided version of the write clock.</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkBRAMStore2W1R</td>
</tr>
</tbody>
</table>

The `mkBRAMStore2W1R` module returns a `Store` interface and uses a prefetch. This model assumes the read clock is a 2x divided version of the write clock.

<table>
<thead>
<tr>
<th>A BRAM-based store where the write clock is a 2x divided version of read clock.</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkBRAMStore1W2R</td>
</tr>
</tbody>
</table>

The `mkBRAMStore1W2R` module returns a `Store` interface and uses a prefetch. This model assumes the read clock is a 2x divided version of the write clock.

The `mkAlignedFIFO` module makes a synchronizing FIFO for aligned clocks, based on the given backing store (determined by the type of store instantiated). The store is assumed to have \(2^w\) slots addressed from 0 to \(2^w - 1\). The store will be written in the source clock domain and read in the destination clock domain.

The `enq` and `deq` methods will only be callable when the `allow_enq` and `allow_deq` inputs are high. For a slow-to-fast crossing use:

```verilog
alow_enq = constant True
allow_deq = pre-edge signal
```

For a fast-to-slow crossing, use:

```verilog
alow_enq = pre-edge signal
allow_deq = constant True
```

The pre-edge signal is `True` when the slow clock will rise in the next clock cycle. The `ClockNextRdy` from the `ClockDividerIfc` (Section C.9.3) can be used as the pre-edge signal.

These settings ensure that the outputs in the slow clock domain are stable for the entire cycle. Setting both inputs to constant `True` reduces the minimum latency through the FIFO, but allows outputs in the slow domain to transition mid-cycle. This is less safe and can interact badly with the `$displays` in a Verilog simulation.

It is not advisable to call both `dClear` and `sClear` simultaneously.

254
C.2.7 Gearbox

Package

import Gearbox :: *

Description

This package defines FIFO-like converters that convert N-wide data to and from 1-wide data at N-times the frequency. These converters change the frequency and the data width, while the overall data rate stays the same. The data width on the fast side is always 1, while the data width on the slow side is N. The converters are intended to be used between clock domains with aligned edges for both types of clock domain crossings (fast to slow and slow to fast). For example:

300 MHz at 8-bits converted to 100 MHz at 24-bits (fast to slow)
100 MHz at 24-bits converted to 300 MHz at 8-bits (slow to fast)

In both of these examples, the data type a is Bit#(8) and N=3.

These modules are written in pure BSV using a style that utilizes only mkNullCrossingReg to cross registered values between clock domains. Restricting the form of clock crossings is important to ensure that the module preserves atomic semantics and also that it is compatible with both Verilog and Bluesim backends.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Interfaces and methods

The Gearbox interface provides the following methods: enq, deq, first, notFull and notEmpty.
### Gearbox Interface

<table>
<thead>
<tr>
<th>Method Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>enq</td>
<td>Action</td>
<td>Adds an entry to the converter of type Vector#(in, a), where a is the datatype. If the input is the fast domain then in = 1, if the input is the slow domain, in = N.</td>
</tr>
<tr>
<td>deq</td>
<td>Action</td>
<td>Removes the first entry from the converter.</td>
</tr>
<tr>
<td>first</td>
<td>Vector#(out, a)</td>
<td>Returns the first entry from the converter. If the output domain is the fast side, out = 1, if the output domain is the slow side, out = N.</td>
</tr>
<tr>
<td>notFull</td>
<td>Bool</td>
<td>Returns a True value if there is space to enqueue an entry into the FIFO.</td>
</tr>
<tr>
<td>notEmpty</td>
<td>Bool</td>
<td>Returns a True value if there is are elements in the FIFO and you can dequeue from the FIFO.</td>
</tr>
</tbody>
</table>

```verilog
type Gearbox#(numeric type in, numeric type out, type a);
method Action enq(Vector#(in, a) din);
method Action deq();
method Vector#(out, a) first();
method Bool notFull();
method Bool notEmpty();
endinterface
```

### Modules

The package provides two modules: **mkNto1Gearbox** for slow to fast domain crossings, and **mk1toNGearbox** to for fast to slow domain crossings. These are intended for use between clock domains with aligned edges for both types of clock domain crossings.

**Note:** for both modules the resets in the source and destination domains (sReset and dReset) should be asserted together, otherwise only half the unit will be in reset.

With the **mkNto1Gearbox** module, 2xN elements of data storage are provided, grouped into 2 blocks of N elements each. Each block is writable in the source (slow) domain and readable in the destination (fast) domain.

```verilog
module mkNto1Gearbox(Clock sClock, Reset sReset, Clock dClock, Reset dReset, Gearbox#(in, out, a) ifc)
provisos(Bits#(a, a_sz), Add#(out, 0, 1), Add#(out, z, in));
```

With the **mk1toNGearbox** module, 2xN elements of data storage are provided, grouped into 2 blocks of N elements each. Each block is writable in the source (fast) domain and readable in the destination (slow) domain.
**C.2.8 MIMO**

**Package**

import MIMO :: *

**Description**

This package defines a Multiple-In Multiple-Out (MIMO), an enhanced FIFO that allows the designer to specify the number of objects enqueued and dequeued in one cycle. There are different implementations of the MIMO available for synthesis: BRAM, Register, and Vector.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the `-p` option as described in the BSV Users Guide.

**Types and type classes**

The `LUInt` type is a `UInt` defined as the log of the `n`.

```haskell
typedef UInt#(TLog#(TAdd#(n, 1))) LUInt#(numeric type n);
```

The `MIMOConfiguration` type defines whether the MIMO is guarded or unguarded, and whether it is based on a BRAM. There is an instance in the `DefaultValue` type class. The default MIMO is guarded and not based on a BRAM.

```haskell
typedef struct {
    Bool unguarded;
    Bool bram_based;
} MIMOConfiguration deriving (Eq);

instance DefaultValue#(MIMOConfiguration);
    defaultValue = MIMOConfiguration {
        unguarded: False,
        bram_based: False
    };
endinstance
```

**Interfaces and methods**

The MIMO interface is polymorphic and takes 4 parameters: `max_in`, `max_out`, `size`, and `t`.

---

**mk1toNGearbox**

<table>
<thead>
<tr>
<th><strong>mk1toNGearbox</strong></th>
<th>Moves data from a fast domain to a slow domain, changing the data width from a smaller width to a larger width. The data rate stays the same. The width of the input is 1, the width of the output is N.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mk1toNGearbox(Clock sClock, Reset sReset, Clock dClock, Reset dReset, Gearbox#(in, out, a) ifc)</td>
<td>provisos(Bits#(a, a_sz), Add#(in, 0, 1), Add#(in, z, out), Mul#(2, out, elements), Add#(1, w, elements), Add#(out, x, elements) );</td>
</tr>
</tbody>
</table>
### MIMO Interface Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>max_in</td>
<td>Maximum number of objects enqueued in one cycle. Must be numeric.</td>
</tr>
<tr>
<td>max_out</td>
<td>Maximum number of objects dequeued in one cycle. Must be numeric.</td>
</tr>
<tr>
<td>size</td>
<td>Total size of internal storage. Must be numeric.</td>
</tr>
<tr>
<td>t</td>
<td>Data type of the stored objects</td>
</tr>
</tbody>
</table>

The MIMO interface provides the following methods: `enq`, `first`, `deq`, `enqReady`, `enqReadyN`, `deqReady`, `deqReadyN`, `count`, and `clear`.

### MIMO methods

<table>
<thead>
<tr>
<th>Name</th>
<th>Method</th>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>enq</td>
<td>Action</td>
<td>LUInt#(max_in) Vector#(max_in, t) data)</td>
<td>adds an entry to the MIMO</td>
</tr>
<tr>
<td>first</td>
<td>Vector#(max_out, t)</td>
<td></td>
<td>Returns a Vector containing max_out items of type t.</td>
</tr>
<tr>
<td>deq</td>
<td>Action</td>
<td>LUInt#(max_out) count</td>
<td>Removes the first count entries</td>
</tr>
<tr>
<td>enqReady</td>
<td>Bool</td>
<td></td>
<td>Returns a True value if there is space to enqueue an entry</td>
</tr>
<tr>
<td>enqReadyN</td>
<td>Bool</td>
<td>LUInt#(max_in)</td>
<td>Returns a True value if there is an element to dequeue</td>
</tr>
<tr>
<td>deqReady</td>
<td>Bool</td>
<td></td>
<td>Returns a True value if there is are count elements to dequeue</td>
</tr>
<tr>
<td>deqReadyN</td>
<td>Bool</td>
<td></td>
<td></td>
</tr>
<tr>
<td>count</td>
<td>LUInt#(size)</td>
<td></td>
<td>Returns the log of the number of elements in the MIMO</td>
</tr>
<tr>
<td>clear</td>
<td>Action</td>
<td></td>
<td>Clears the MIMO</td>
</tr>
</tbody>
</table>

```verilog
interface MIMO#(numeric type max_in, numeric type max_out, numeric type size, type t);
  method Action enq(LUInt#(max_in) count, Vector#(max_in, t) data);
  method Vector#(max_out, t) first;
  method Action deq(LUInt#(max_out) count);
  method Bool enqReady;
  method Bool enqReadyN(LUInt#(max_in) count);
  method Bool deqReady;
  method Bool deqReadyN(LUInt#(max_out) count);
  method LUInt#(size) count;
  method Action clear;
endinterface
```

### Modules

The package provides modules to synthesize different implementations of the MIMO: the basic MIMO (mkMIMO), BRAM-based (mkMIMOBRAM), register-based (mkMIMOREg), and a Vector of registers (mkMIMOV).

All implementations must meet the following provisos:

- The object must have bit representation
• The object must have at least 2 elements of storage.
• The maximum number of objects enqueued (max_in) must be less than or equal to the total bits of storage (size)
• The maximum number of objects dequeued (max_out) must be less than or equal to the total bits of storage (size)

<table>
<thead>
<tr>
<th>mkMIMO</th>
<th>The basic implementation of MIMO. Object must be at least 1 bit in size.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkMIMO#(MIMOConfiguration cfg)(MIMO#(max_in, max_out, size, t));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkMIMOBram</th>
<th>Implementation of BRAM-based MIMO. Object must be at least 1 byte in size.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkMIMOBram#(MIMOConfiguration cfg)(MIMO#(max_in, max_out, size, t));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkMIMOReg</th>
<th>Implementation of register-based MIMO.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkMIMOReg#(MIMOConfiguration cfg)(MIMO#(max_in, max_out, size, t));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkMIMOV</th>
<th>Implementation of Vector-based MIMO. The object must have a default value defined.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkMIMOV(MIMO#(max_in, max_out, size, t));</td>
<td></td>
</tr>
</tbody>
</table>

C.3 Aggregation: Vectors

Package

import Vector :: * ;

Description

The Vector package defines an abstract data type which is a container of a specific length, holding elements of one type. Functions which create and operate on this type are also defined within this package. Because it is abstract, there are no constructors available for this type (like Cons and Nil for the List type).

typedef struct Vector#(type numeric vsize, type element_type);

Here, the type variable element_type represents the type of the contents of the elements while the numeric type variable vsize represents the length of the vector.

If the elements are in the Bits class, then the vector is as well. Thus a vector of these elements can be stored into Registers or FIFOs; for example a Register holding a vector of type int. Note that a vector can also store abstract types, such as a vector of Rules or a vector of Reg interfaces. These are useful during static elaboration although they have no hardware implementation.

Typeclasses
### Type Classes for Vector

<table>
<thead>
<tr>
<th></th>
<th>Bits</th>
<th>Eq</th>
<th>Literal</th>
<th>Arith</th>
<th>Ord</th>
<th>Bounded</th>
<th>Bitwise</th>
<th>Bit Reduction</th>
<th>Bit Extend</th>
<th>FShow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

#### Bits
A vector can be turned into bits if the individual elements can be turned into bits. When packed and unpacked, the zeroth element of the vector is stored in the least significant bits. The size of the resulting bits is given by \( tsize = vsize \ast \text{SizeOf} \#(\text{element_type}) \) which is specified in the provisions.

```verilog
define Bits #( Vector#(vsize, element_type), tsize)
  provisos (Bits#(element_type, sizea),
            Mul#(vsize, sizea, tsize));
```

Vectors are zero-indexed; the first element of a vector \( v \), is \( v[0] \). When vectors are packed, they are packed in order from the LSB to the MSB.

Example. Vector#(5, Bit#(7)) \( v1 \):

From the type, you can see that this will back into a 35-bit vector (5 elements, each with 7 bits).

<table>
<thead>
<tr>
<th>MSB</th>
<th>bit positions</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>v1[0]</td>
<td></td>
</tr>
</tbody>
</table>

Example. A vector with a structure:

```verilog
define struct { Bool a, UInt#(5) b} Newstruct deriving (Bits);
define Vector#(3, NewStruct) \( v2 \);
```

The structure, `Newstruct` packs into 6 bits. Therefore \( v2 \) will pack into an 18-bit vector. And its structure would look as follows:

<table>
<thead>
<tr>
<th>MSB</th>
<th>17 - 12</th>
<th>11</th>
<th>10 - 6</th>
<th>5</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>v2[2].a</td>
<td>v2[2].b</td>
<td>v2[1].a</td>
<td>v2[1].b</td>
<td>v2[0].a</td>
</tr>
</tbody>
</table>

#### Eq
Vectors can be compared for equality if the elements can. That is, the operators \( == \) and \( != \) are defined.

#### Bounded
Vectors are bounded if the elements are.

#### FShow
The FShow class provides the fshow function which can be applied to a Vector and returns an associated Fmt object showing:

```verilog
<V elem1 elem2 ...>
```

where the elemn are the elements of the vector with fshow applied to each element value.
### C.3.1 Creating and Generating Vectors

The following functions are used to create new vectors, with and without defined elements. There are no Bluespec SystemVerilog constructors available for this abstract type (and hence no pattern-matching is available for this type) but the following functions may be used to construct values of the `Vector` type.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>newVector</code></td>
<td>Generate a vector with undefined elements, typically used when vectors are declared.</td>
</tr>
<tr>
<td></td>
<td>Function: <code>Vector#(vsize, element_type) newVector();</code></td>
</tr>
<tr>
<td><code>genVector</code></td>
<td>Generate a vector containing integers 0 through n-1, vector[0] will have value 0.</td>
</tr>
<tr>
<td></td>
<td>Function: <code>Vector#(vsize, Integer) genVector();</code></td>
</tr>
<tr>
<td><code>replicate</code></td>
<td>Generate a vector of elements by replicating the given argument (c).</td>
</tr>
<tr>
<td></td>
<td>Function: <code>Vector#(vsize, element_type) replicate(element_type c);</code></td>
</tr>
<tr>
<td><code>genWith</code></td>
<td>Generate a vector of elements by applying the given function to 0 through n-1. The argument to the function is another function which has one argument of type <code>Integer</code> and returns an <code>element_type</code>.</td>
</tr>
<tr>
<td></td>
<td>Function: <code>Vector#(vsize, element_type) genWith(function element_type func(Integer x1));</code></td>
</tr>
<tr>
<td><code>cons</code></td>
<td>Adds an element to a vector creating a vector one element larger. The new element will be at the 0th position. This function can lead to large compile times, so it can be an inefficient way to create and populate a vector. Instead, the designer should build a vector, then set each element to a value.</td>
</tr>
<tr>
<td></td>
<td>Function: <code>Vector#(vsize1, element_type) cons(element_type elem, Vector#(vsize, element_type) vect)</code></td>
</tr>
<tr>
<td></td>
<td>provisos (Add#(1, vsize, vsize1));</td>
</tr>
<tr>
<td><code>nil</code></td>
<td>Defines a vector of size zero.</td>
</tr>
<tr>
<td></td>
<td>Function: <code>Vector#(0, element_type) nil;</code></td>
</tr>
</tbody>
</table>
Append two vectors containing elements of the same type, returning the combined vector. The resulting vector `result` will contain all the elements of `vecta` followed by all the elements of `vectb`. $result[0] = vecta[0], result[vsize-1] = vectb[v1size-1]$.

```vhdl
function Vector#(vsize, element_type)
  append( Vector#(v0size, element_type) vecta,
          Vector#(v1size, element_type) vectb)
  provisos (Add#(v0size, v1size, vsize)); // vsize = v0size + v1size
```

Append (concatenate) many vectors, that is a vector of vectors into one vector. $concat(xss)[0]$ will be $xss[0][0]$, provided $m$ and $n$ are non-zero.

```vhdl
function Vector#(mvsize, element_type)
  concat(Vector#(m, Vector#(n, element_type)) xss)
  provisos (Mul#(m, n, mvsize));
```

### Examples - Creating and Generating Vectors

Create a new vector, `my_vector`, of 5 elements of datatype `Int#(32)`, with elements which are undefined.

```vhdl
Vector #(5, Int#(32)) my_vector;
```

Create a new vector, `my_vector`, of 5 elements of datatype `Integer` with elements 0, 1, 2, 3 and 4.

```vhdl
Vector #(5, Integer) my_vector = genVector;
// my_vector is a 5 element vector {0,1,2,3,4}
```

Create a vector, `my_vector`, of five 1's.

```vhdl
Vector #(5,Int #(32)) my_vector = replicate (1);
// my_vector is a 5 element vector {1,1,1,1,1}
```

Create a vector, `my_vector`, by applying the given function `add2` to 0 through n-1.

```vhdl
function Integer add2 (Integer a);
  Integer c = a + 2;
  return(c);
endfunction

Vector #(5,Integer) my_vector = genWith(add2);
// a is the index of the vector, 0 to n-1
// my_vector = {2,3,4,5,6,}
```

Add an element to `my_vector`, creating a bigger vector `my_vector1`.

```vhdl
Vector#(3, Integer) my_vector = genVector();
// my_vector = {0, 1, 2}

let my_vector1 = cons(4, my_vector);
// my_vector1 = {4, 0, 1, 2}
```
Append vectors, `my_vector` and `my_vector1`, resulting in a vector `my_vector2`.

```systemverilog
Vector#(3, Integer) my_vector = genVector();
// my_vector = {0, 1, 2}

Vector#(3, Integer) my_vector1 = genWith(add2);
// my_vector1 = {2, 3, 4}

let my_vector2 = append(my_vector, my_vector1);
// my_vector2 = {0, 1, 2, 2, 3, 4}
```

### C.3.2 Extracting Elements and Sub-Vectors

These functions are used to select elements or vectors from existing vectors, while retaining the input vector.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>[i]</code></td>
<td>The square-bracket notation is available to extract an element from a vector or update an element within it. Extracts or updates the ith element, where the first element is <code>[0]</code>. Index i must be of an acceptable index type (e.g. <code>Integer</code>, <code>Bit#(n)</code>, <code>Int#(n)</code> or <code>UInt#(n)</code>). The square-bracket notation for vectors can also be used with register writes.</td>
</tr>
<tr>
<td><code>anyVector[i];</code></td>
<td></td>
</tr>
<tr>
<td><code>anyVector[i] = newValue;</code></td>
<td></td>
</tr>
<tr>
<td><code>select</code></td>
<td>The select function is another form of the subscript notation (<code>[i]</code>), mainly provided for backwards-compatibility. The select function is also useful as an argument to higher-order functions. The subscript notation is generally recommended because it will report a more useful position for any selection errors.</td>
</tr>
<tr>
<td><code>function element_type select(Vector#(vsize,element_type) vect, idx_type index);</code></td>
<td></td>
</tr>
<tr>
<td><code>update</code></td>
<td>Update an element in a vector returning a new vector with one element changed/updated. This function does not change the given vector. This is another form of the subscript notation (see above), mainly provided for backwards compatibility. The update function may also be useful as an argument to a higher-order function. The subscript notation is generally recommended because it will report a more useful position for any update errors.</td>
</tr>
</tbody>
</table>
| `function Vector#(vsize, element_type)
update(Vector#(vsize, element_type) vectIn,
       idx_type index,
       element_type newElem);` | |
### head

Extract the zeroth (head) element of a vector. The vector must have at least one element.

```vhdl
function element_type
head (Vector#(vsize, element_type) vect)
provisos(Add#(1,xxx,vxize)); // vsize >= 1
```

### last

Extract the highest (tail) element of a vector. The vector must have at least one element.

```vhdl
function element_type
last (Vector#(vsize, element_type) vect)
provisos(Add#(1,xxx,vxize)); // vsize >= 1
```

### tail

Remove the head element of a vector leaving its tail in a smaller vector.

```vhdl
function Vector#(vsize,element_type)
tail (Vector#(vsize1, element_type) xs)
provisos (Add#(1, vsize, vsize1));
```

### init

Remove the last element of a vector leaving its initial part in a smaller vector.

```vhdl
function Vector#(vsize,element_type)
init (Vector#(vsize1, element_type) xs)
provisos (Add#(1, vsize, vsize1));
```

### take

Take a number of elements from a vector starting from index 0. The number of elements to take is indicated by the type of the context where this is called, and is not specified as an argument to the function.

```vhdl
function Vector#(vxize2,element_type)
take (Vector#(vsize,element_type) vect)
provisos (Add#(vsize2,xxx,vsize)); // vsize2 <= vsize.
```
Bluespec SystemVerilog Reference Guide

<table>
<thead>
<tr>
<th>drop</th>
<th>takeTail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop a number of elements from the vector starting at the 0th position. The elements in the result vector will be in the same order as the input vector.</td>
<td></td>
</tr>
</tbody>
</table>

```systemverilog
define Vector#(vxize2,element_type) 
  drop (Vector#(vsize,element_type) vect) 
  provisos (Add#(vsize2,xxx,vsize)); // vsize2 <= vsize.

function Vector#(vxize2,element_type) 
  takeTail (Vector#(vsize,element_type) vect) 
  provisos (Add#(vsize2,xxx,vsize)); // vsize2 <= vsize.
```

<table>
<thead>
<tr>
<th>takeAt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take a number of elements starting at startPos. startPos must be a compile-time constant. If the startPos plus the output vector size extend beyond the end of the input vector, an error will be returned.</td>
</tr>
</tbody>
</table>

```systemverilog
define Vector#(vsize2,element_type) 
  takeAt (Integer startPos, Vector#(vsize,element_type) vect) 
  provisos (Add#(vsize2,xxx,vsize)); // vsize2 <= vsize
```

**Examples - Extracting Elements and Sub-Vectors**

Extract the element from a vector, my_vector, at the position of index.

// my_vector is a vector of elements {6,7,8,9,10,11}
// index = 3
// select or [ ] will generate a MUX

newvalue = select (my_vector, index);
newvalue = myvalue[index];
// newvalue = 9

Update the element of a vector, my_vector, at the position of index.

// my_vector is a vector of elements {6,7,8,9,10,11}
// index = 3

my_vector = update (my_vector, index, 0);
my_vector[index] = 0;
// my_vector = {6,7,8,0,10,11}

Extract the zeroth element of the vector my_vector.

// my_vector is a vector of elements {6,7,8,9,10,11}

newvalue = head(my_vector);
// newvalue = 6

Extract the last element of the vector my_vector.

// my_vector is a vector of elements {6,7,8,9,10,11}

newvalue = last(my_vector);
// newvalue = 11
Create a vector, `my_vector2`, of size 4 by removing the head (zeroth) element of the vector `my_vector1`.

```verilog
// my_vector1 is a vector with 5 elements {0,1,2,3,4}
Vector #(4, Int#(32)) my_vector2 = tail (my_vector1);
// my_vector2 is a vector of 4 elements {1,2,3,4}
```

Create a vector, `my_vector2`, of size 4 by removing the tail (last) element of the vector `my_vector1`.

```verilog
// my_vector1 is a vector with 5 elements {0,1,2,3,4}
Vector #(4, Int#(32)) my_vector2 = init (my_vector1);
// my_vector2 is a vector of 4 elements {0,1,2,3}
```

Create a 2 element vector, `my_vector2`, by taking the first two elements of the vector `my_vector1`.

```verilog
// my_vector1 is vector with 5 elements {0,1,2,3,4}
Vector #(2, Int#(4)) my_vector2 = take (my_vector1);
// my_vector2 is a 2 element vector {0,1}
```

Create a 3 element vector, `my_vector2`, by taking the last 3 elements of vector, `my_vector1`, using `takeTail`

```verilog
// my_vector1 is Vector with 5 elements {0,1,2,3,4}
Vector #(3,Int #(4)) my_vector2 = takeTail (my_vector1);
// my_vector2 is a 3 element vector {2,3,4}
```

Create a 3 element vector, `my_vector2`, by taking the 1st - 3rd elements of vector, `my_vector1`, using `takeAt`

```verilog
// my_vector1 is Vector with 5 elements {0,1,2,3,4}
Vector #(3,Int #(4)) my_vector2 = takeAt (1, my_vector1);
// my_vector2 is a 3 element vector {1,2,3}
```

### C.3.3 Vector to Vector Functions

The following functions generate a new vector by changing the position of elements within the vector.

<table>
<thead>
<tr>
<th>rotate</th>
<th>Move the zeroth element to the highest and shift each element lower by one. For example, the element at index ( n ) moves to index ( n-1 ).</th>
</tr>
</thead>
</table>
| function  | ```verilog
| Vector#(vsize,element_type) |
| rotate (Vector#(vsize,element_type) vect);                         |
| rotateR   | Move last element to the zeroth element and shift each element up by one. For example, the element at index \( n \) moves to index \( n+1 \). |
| function  | ```verilog
<p>| Vector#(vsize,element_type) |
| rotateR (Vector#(vsize,element_type) vect); |</p>
<table>
<thead>
<tr>
<th>rotateBy</th>
<th>Shift each element $n$ places. The last $n$ elements are moved to the beginning, the element at index 0 moves to index $n$, index 1 to index $n+1$, etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>function Vector#(vsize, element_type)</td>
</tr>
<tr>
<td></td>
<td>rotateBy (Vector#(vsize,element_type) vect, UInt#(log(v)) n) provisos (Log#(vsize, logv));</td>
</tr>
<tr>
<td>shiftInAt0</td>
<td>Shift a new element into the vector at index 0, bumping the index of all other element up by one. The highest element is dropped.</td>
</tr>
<tr>
<td></td>
<td>function Vector#(vsize,element_type)</td>
</tr>
<tr>
<td></td>
<td>shiftInAt0 (Vector#(vsize,element_type) vect, element_type newElement);</td>
</tr>
<tr>
<td>shiftInAtN</td>
<td>Shift a new element into the vector at index $n$, bumping the index of all other elements down by one. The 0th element is dropped.</td>
</tr>
<tr>
<td></td>
<td>function Vector#(vsize,element_type)</td>
</tr>
<tr>
<td></td>
<td>shiftInAtN (Vector#(vsize,element_type) vect, element_type newElement);</td>
</tr>
<tr>
<td>shiftOutFrom0</td>
<td>Shifts out $\text{amount}$ number of elements from the vector starting at index 0, bumping the index of all remaining elements down by $\text{amount}$. The shifted elements are replaced with the value $\text{default}$. This function is similar to a $\gg$ bit operation. $\text{amt_type}$ must be of an acceptable index type ($\text{Integer}$, $\text{Bit#(n)}$, $\text{Int#(n)}$ or $\text{UInt#(n)}$).</td>
</tr>
<tr>
<td></td>
<td>function Vector#(vsize,element_type)</td>
</tr>
<tr>
<td></td>
<td>shiftOutFrom0 (element_type default, Vector#(vsize,element_type) vect, $\text{amt_type} \text{amount}$);</td>
</tr>
<tr>
<td>shiftOutFromN</td>
<td>Shifts out $\text{amount}$ number of elements from the vector starting at index $\text{vsize-1}$ bumping the index of remaining elements up by $\text{amount}$. The shifted elements are replaced with the value $\text{default}$. This function is similar to a $\ll$ bit operation. $\text{amt_type}$ must be of an acceptable index type ($\text{Integer}$, $\text{Bit#(n)}$, $\text{Int#(n)}$ or $\text{UInt#(n)}$).</td>
</tr>
<tr>
<td></td>
<td>function Vector#(vsize,element_type)</td>
</tr>
<tr>
<td></td>
<td>shiftOutFromN (element_type default, Vector#(vsize,element_type) vect, $\text{amt_type} \text{amount}$);</td>
</tr>
</tbody>
</table>
## reverse
Reverse element order

```systemverilog
function Vector#(vsize,element_type) reverse(Vector#(vsize,element_type) vect);
```

## transpose
Matrix transposition of a vector of vectors.

```systemverilog
function Vector#(m,Vector#(n,element_type)) transpose ( Vector#(n,Vector#(m,element_type)) matrix );
```

## transposeLN
Matrix transposition of a vector of Lists.

```systemverilog
function Vector#(vsize, List#(element_type)) transposeLN( List#(Vector#(vsize, element_type)) lvs );
```

### Examples - Vector to Vector Functions

Create a vector by moving the last element to the first, then shifting each element to the right.

```systemverilog
// my_vector1 is a vector of elements with values {1,2,3,4,5}
my_vector2 = rotateR (my_vector1);
// my_vector2 is a vector of elements with values {5,1,2,3,4}
```

Create a vector which is the input vector rotated by 2 places.

```systemverilog
// my_vector1 is a vector of elements {1,2,3,4,5}
my_vector2 = rotateBy {my_vector1, 2};
// my_vector2 = {4,5,1,2,3}
```

Create a vector which shifts out 3 elements starting from 0, replacing them with the value F

```systemverilog
// my_vector1 is a vector of elements {5,4,3,2,1,0}
my_vector2 = shiftOutFrom0 (F, my_vector1, 3);
// my_vector2 is a vector of elements {F,F,F,5,4,3}
```

Create a vector which shifts out 3 elements starting from n-1, replacing them with the value F

```systemverilog
// my_vector1 is a vector of elements {5,4,3,2,1,0}
my_vector2 = shiftOutFromN (F, my_vector1, 3);
// my_vector2 is a vector of elements {2,1,0,F,F,F}
```

Create a vector which is the reverse of the input vector.

```systemverilog
// my_vector1 is a vector of elements {1,2,3,4,5}
my_vector2 = reverse (my_vector1);
// my_vector2 is a vector of elements {5,4,3,2,1}
```
Use transpose to create a new vector.

```verbatim
// my_vector1 is a Vector#(3, Vector#(5, Int#(8)))
// the result, my_vector2, is a Vector #(5,Vector#(3,Int #(8)))

// my_vector1 has the values:
// {{0,1,2,3,4},{5,6,7,8,9},{10,11,12,13,14}}

my_vector2 = transpose(my_vector1);
// my_vector2 has the values:
// {{0,5,10},{1,6,11},{2,7,12},{3,8,13},{4,9,14}}
```

### C.3.4 Tests on Vectors

The following functions are used to test vectors. The first set of functions are Boolean functions, i.e. they return `True` or `False` values.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>elem</code></td>
<td>Check if a value is an element of a vector.</td>
</tr>
<tr>
<td><code>function Bool elem (element_type x, Vector#(vsize,element_type) vect ) provisos (Eq#(element_type));</code></td>
<td></td>
</tr>
<tr>
<td><code>any</code></td>
<td>Test if a predicate holds for any element of a vector.</td>
</tr>
<tr>
<td><code>function Bool any(function Bool pred(element_type x1), Vector#(vsize,element_type) vect );</code></td>
<td></td>
</tr>
<tr>
<td><code>all</code></td>
<td>Test if a predicate holds for all elements of a vector.</td>
</tr>
<tr>
<td><code>function Bool all(function Bool pred(element_type x1), Vector#(vsize,element_type) vect );</code></td>
<td></td>
</tr>
<tr>
<td><code>or</code></td>
<td>Combine all elements in a vector of Booleans with a logical or. Returns True if any elements in the Vector are True.</td>
</tr>
<tr>
<td><code>function Bool or (Vector#(vsize, Bool) vect );</code></td>
<td></td>
</tr>
<tr>
<td><code>and</code></td>
<td>Combine all elements in a vector of Booleans with a logical and. Returns True if all elements in the Vector are True.</td>
</tr>
<tr>
<td><code>function Bool and (Vector#(vsize, Bool) vect );</code></td>
<td></td>
</tr>
</tbody>
</table>

The following two functions return the number of elements in the vector which match a condition.
### countElem

Returns the number of elements in the vector which are equal to a given value. The return value is in the range of 0 to vsise.

```verilog
define UInt#(logv1) countElem (element_type x, Vector#(vsize, element_type) vect)
  provisos (Eq#(element_type), Add#(vsize, 1, vsizel), Log#(vsize1, logv1));
```

### countIf

Returns the number of elements in the vector which satisfy a given predicate function. The return value is in the range of 0 to vsise.

```verilog
define UInt#(logv1) countIf (function Bool pred(element_type x1), Vector#(vsize, element_type) vect)
  provisos (Add#(vsize, 1, vsizel), Log#(vsize1, logv1));
```

### find

Returns the first element that satisfies the predicate or Nothing if there is none.

```verilog
define Maybe#(element_type) find (function Bool pred(element_type), Vector#(vsize, element_type) vect);
```

The following two functions return the index of an element.

### findElem

Returns the index of the first element in the vector which equals a given value. Returns an Invalid if not found or Valid with a value of 0 to vsise-1 if found.

```verilog
define Maybe#(UInt#(logv)) findElem (element_type x, Vector#(vsize, element_type) vect)
  provisos (Eq#(element_type), Add#(xx1, 1, vsize), Log#(vsize, logv));
```

### findIndex

Returns the index of the first element in the vector which satisfies a given predicate. Returns an Invalid if not found or Valid with a value of 0 to vsise-1 if found.

```verilog
define Maybe#(UInt#(logv)) findIndex
  (function Bool pred(element_type x1), Vector#(vsize, element_type) vect)
  provisos (Add#(xx1,1,vsize), Log#(vsize, logv));
```

### Examples - Tests on Vectors

Test that all elements of the vector `my_vector1` are positive integers.

```verilog
function Bool isPositive (Int #(32) a);
  return (a > 0)
```
endfunction

// function isPositive checks that "a" is a positive integer
// if my_vector1 has n elements, n instances of the predicate
// function isPositive will be generated.

if (all(isPositive, my_vector1))
    $display( "Vector contains all negative values" );

Test if any elements in the vector are positive integers.

// function isPositive checks that "a" is a positive integer
// if my_vector1 has n elements, n instances of the predicate
// function isPositive will be generated.

if (any(isPositive, my_vector1))
    $display( "Vector contains some negative values" );

Check if the integer 5 is in my_vector.

// if my_vector contains n elements, elem will generate n copies
// of the eq test
if (elem(5, my_vector))
    $display( "Vector contains the integer 5" );

Count the number of elements which match the integer provided.

// my_vector1 is a vector of {1,2,1,4,3}
x = countElem ( 1, my_vector1);
// x = 2
y = countElem (4, my_vector1);
// y = 1

Find the index of an element which equals a predicate.

let f = findIndex ( beIsGreaterThan( 3 ), my_vector );
if ( f matches tagged Valid .indx )
    begin
        printBE ( my_vector[ indx ] ) ;
        $display ( "Found data > 3 at index %d ", indx ) ;
    else
        begin
            $display ( "Did not find data > 3" ) ;
        end

C.3.5 Bit-Vector Functions

The following functions operate on bit-vectors.

<table>
<thead>
<tr>
<th>rotateBitsBy</th>
<th>Shift each bit to a higher index by n places. The last n bits are moved to the beginning and the bit at index (0) moves to index (n).</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Bit#(n) rotateBitsBy (Bit#(n) bvec, UInt#(logn) n) provisos (Log#(n, logn), Add#(1, xxx, n));</td>
<td></td>
</tr>
</tbody>
</table>
### C.3.6 Functions on Vectors of Registers

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>readVReg</td>
<td>Returns the values from reading a vector of registers (interfaces).</td>
<td>function Vector#(n,a) readVReg ( Vector#(n, Reg#(a)) vrin) ;</td>
</tr>
<tr>
<td>writeVReg</td>
<td>Returns an Action which is the write of all registers in vr with the data from vdin.</td>
<td>function Action writeVReg ( Vector#(n, Reg#(a)) vr, Vector#(n,a) vdin) ;</td>
</tr>
</tbody>
</table>

### C.3.7 Combining Vectors with Zip

The family of `zip` functions takes two or more vectors and combines them into one vector of Tuples. Several variations are provided for different resulting Tuples, as well as support for mis-matched vector sizes.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>zip</td>
<td>Combine two vectors into a vector of Tuples.</td>
<td>function Vector#(vsize,Tuple2 #(a_type, b_type)) zip( Vector#(vsize, a_type) vecta, Vector#(vsize, b_type) vectb);</td>
</tr>
<tr>
<td>zip3</td>
<td>Combine three vectors into a vector of Tuple3.</td>
<td>function Vector#(vsize,Tuple3 #(a_type, b_type, c_type)) zip3( Vector#(vsize, a_type) vecta, Vector#(vsize, b_type) vectb, Vector#(vsize, c_type) vectc);</td>
</tr>
</tbody>
</table>
### zip4
Combine four vectors into a vector of Tuple4.

```verilog
function Vector#(vsize,Tuple4 #(a_type, b_type, c_type, d_type))
    zip4( Vector#(vsize, a_type) vecta,
           Vector#(vsize, b_type) vectb,
           Vector#(vsize, c_type) vectc,
           Vector#(vsize, d_type) vectd);
```

### zipAny
Combine two vectors into one vector of pairs (2-tuples); result is as long as the smaller vector.

```verilog
function Vector#(vsize,Tuple2 #(a_type, b_type))
    zipAny(Vector#(m,a_type) vect1,
           Vector#(n,b_type) vect2);
    provisos (Max#(m,vsize,m), Max#(n, vsize, n));
```

### unzip
Separate a vector of pairs (i.e. a Tuple2#(a,b)) into a pair of two vectors.

```verilog
function Tuple2#(Vector#(vsize,a_type), Vector#(vsize, b_type))
    unzip(Vector#(vsize,Tuple2 #(a_type, b_type)) vectab);
```

### Examples - Combining Vectors with Zip
Combine two vectors into a vector of Tuples.

```verilog
// my_vector1 is a vector of elements {0,1,2,3,4}
// my_vector2 is a vector of elements {5,6,7,8,9}
my_vector3 = zip(my_vector1, my_vector2);
// my_vector3 is a vector of Tuples {(0,5),(1,6),(2,7),(3,8),(4,9)}
```

Separate a vector of pairs into a Tuple of two vectors.

```verilog
// my_vector3 is a vector of pairs {(0,5),(1,6),(2,7),(3,8),(4,9)}
Tuple2#(Vector #(5,Int #(5)),Vector #(5,Int #(5))) my_vector4 =
    unzip(my_vector3);
// my_vector4 is ({0,1,2,3,4},{5,6,7,8,9})
```

### C.3.8 Mapping Functions over Vectors
A function can be applied to all elements of a vector, using high-order functions such as map. These functions take as an argument a function, which is applied to the elements of the vector.

### map
Map a function over a vector, returning a new vector of results.

```verilog
function Vector#(vsize,b_type)
    map (function b_type func(a_type x),
         Vector#(vsize, a_type) vect);
```
Example - Mapping Functions over Vectors

Consider the following code example which applies the `extend` function to each element of `avector` into a new vector, `resultvector`.

```
Vector#(13, Bit#(5)) avector;
Vector#(13, Bit#(10)) resultvector;
...
resultvector = map( extend, avector ) ;
```

This is equivalent to saying:

```vhdl
for (Integer i=0; i<13; i=i+1)
    resultvector[i] = extend(avector[i]);
```

Map a negate function over a Vector

// my_vector1 is a vector of 5 elements {0,1,2,3,4}
// negate is a function which makes each element negative

```vhdl
Vector #(5, Int #(32)) my_vector2 = map (negate, my_vector1);
```

// my_vector2 is a vector of 5 elements {0,-1,-2,-3,-4}

C.3.9 ZipWith Functions

The zipWith functions combine two or more vectors with a function and generate a new vector. These functions combine features of map and zip functions.

<table>
<thead>
<tr>
<th>zipWith</th>
<th>Combine two vectors with a function.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Vector#(vsize,c_type)</td>
<td></td>
</tr>
<tr>
<td>zipWith (function c_type func(a_type x, b_type y),</td>
<td></td>
</tr>
<tr>
<td>Vector#(vsize,a_type) vecta,</td>
<td></td>
</tr>
<tr>
<td>Vector#(vsize,b_type) vectb );</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>zipWithAny</th>
<th>Combine two vectors with a function; result is as long as the smaller vector.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Vector#(vsize,c_type)</td>
<td></td>
</tr>
<tr>
<td>zipWithAny (function c_type func(a_type x, b_type y),</td>
<td></td>
</tr>
<tr>
<td>Vector#(m,a_type) vecta,</td>
<td></td>
</tr>
<tr>
<td>Vector#(n,b_type) vectb )</td>
<td></td>
</tr>
<tr>
<td>provisos (Max#(n, vsize, n), Max#(m, vsize, m));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>zipWith3</th>
<th>Combine three vectors with a function.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Vector#(vsize,d_type)</td>
<td></td>
</tr>
<tr>
<td>zipWith3(function d_type func(a_type x, b_type y, c_type z),</td>
<td></td>
</tr>
<tr>
<td>Vector#(vsize,a_type) vecta,</td>
<td></td>
</tr>
<tr>
<td>Vector#(vsize,b_type) vectb,</td>
<td></td>
</tr>
<tr>
<td>Vector#(vsize,c_type) vectc );</td>
<td></td>
</tr>
</tbody>
</table>
### zipWithAny3

Combine three vectors with a function; result is as long as the smallest vector.

```systemverilog
define function Vector#(vsizes, c_type)
    zipWithAny3(function d_type func(a_type x, b_type y, c_type z),
        Vector#(m, a_type) vecta,
        Vector#(n, b_type) vectb,
        Vector#(o, c_type) vectc)
    provisos (Max#(n, vsizes, n), Max#(m, vsizes, m), Max#(o, vsizes, o));
```

### Examples - ZipWith

Create a vector by applying a function over the elements of 3 vectors.

```systemverilog
// the function add3 adds 3 values
function Int#(n) add3 (Int #(n) a, Int #(n) b, Int #(n) c);
    Int#(n) d = a + b + c;
    return d;
endfunction

// Create the vector my_vector4 by adding the ith element of each of
// 3 vectors (my_vector1, my_vector2, my_vector3) to generate the ith
// element of my_vector4.

// my_vector1 = {0,1,2,3,4}
// my_vector2 = {5,6,7,8,9}
// my_vector3 = {10,11,12,13,14}

Vector #(5, Int #(8)) my_vector4 = zipWith3(add3, my_vector1, my_vector2, my_vector3);

// creates 5 instances of the add3 function in hardware.
my_vector4 = {15, 18, 21, 24, 27};
```

### C.3.10 Fold Functions

The `fold` family of functions reduces a vector to a single result by applying a function over all its elements. That is, given a vector of `element_type`, $V_0, V_1, V_2, ..., V_{n-1}$, a seed of type `b_type`, and a function `func`, the reduction for `foldr` is given by

```
func(V_0, func(V_1, ..., func(V_{n-2}, func(V_{n-1}, seed))))
```

Note that `foldr` start processing from the highest index position to the lowest, while `foldl` starts from the lowest index (zero), i.e. `foldl` is:

```
func(...(func(func(seed, V_0), V_1), ...)V_{n-1})
```

### foldr

Reduce a vector by applying a function over all its elements. Start processing from the highest index to the lowest.

```systemverilog
function b_type foldr(function b_type func(a_type x, b_type y),
                      b_type seed, Vector#(vsizes, a_type) vect);
```
foldl  |  Reduce a vector by applying a function over all its elements. Start processing from the lowest index (zero).

| function b_type foldl (function b_type func(b_type y, a_type x), b_type seed, Vector#(vsize,a_type) vect); |

foldr1  |  foldr function for a non-zero sized vector, using element $V_{n-1}$ as a seed. Vector must have at least 1 element. If there is only one element, it is returned.

| function element_type foldr1( function element_type func(element_type x, element_type y), Vector#(vsize,element_type) vect) provisos (Add#(1, xxx, vsize)); |

foldl1  |  foldl function for a non-zero sized vector, using element $V_0$ as a seed. Vector must have at least 1 element. If there is only one element, it is returned.

| function element_type foldl1 ( function element_type func(element_type y, element_type x), Vector#(vsize,element_type) vect) provisos (Add#(1, xxx, vsize)); |

The functions foldr1 and foldl1 use the first element as the seed. This means they only work on vectors of at least one element. Since the result type will be the same as the element type, there is no `b_type` as there is in the foldr and foldl functions.

The fold function also operates over a non-empty vector, but processing is accomplished in a binary tree-like structure. Hence the depth or delay through the resulting function will be $O(log_2(vsize))$ rather than $O(vsize)$.
**mapPairs**

Map a function over a vector consuming two elements at a time. Any straggling element is processed by the second function.

```systemverilog
definition void mapPairs() 
    fun b_type func1(a_type x, a_type y),
    fun b_type func2(a_type x),
    Vector#(vsize,a_type) vect )
        provisos (Div#(vsize, 2, vsize2));
```

**joinActions**

Join a number of actions together. `joinActions` is used for static elaboration only, no hardware is generated.

```systemverilog
function Action joinActions (Vector#(vsize,Action) vactions);
```

**joinRules**

Join a number of rules together. `joinRules` is used for static elaboration only, no hardware is generated.

```systemverilog
function Rules joinRules (Vector#(vsize,Rules) vrules);
```

**Example - Folds**

Use fold to find the sum of the elements in a vector.

```verilog
// my_vector1 is a vector of five integers {1,2,3,4,5}
// + is a function which returns the sum of the elements
// make sure you leave a space after the + and before the ,

// This will build an adder tree, instantiating 4 adders, with a maximum
// depth or delay of 3. If foldl1 or foldr1 were used, it would
// still instantiate 4 adders, but the delay would be 4.

my_sum = fold (+, my_vector1);
// my_sum = 15
```

Use fold to find the element with the maximum value.

```verilog
// my_vector1 is a vector of five integers {2,45,5,8,32}

my_max = fold (max, my_vector1);
// my_max = 45
```

Create a new vector using `mapPairs`. The function `sum` is applied to each pair of elements (the first and second, the third and fourth, etc.). If there is an uneven number of elements, the function `pass` is applied to the remaining element.

```verilog
// sum is defined as c = a+b
function Int#(4) sum (Int #(4) a,Int #(4) b);
    Int#(4) c = a + b;
    return(c);
```
endfunction

// pass is defined as a function Int #(4) pass (Int #(4) a);
  return(a);
endfunction

// my_vector1 has the elements {0,1,2,3,4}
my_vector2 = mapPairs(sum,pass,my_vector1);
// my_vector2 has the elements {1,5,4}
// my_vector2[0] = 0 + 1
// my_vector2[1] = 2 + 3
// my_vector2[2] = 4

C.3.11 Scan Functions

The scan family of functions applies a function over a vector, creating a new vector result. The scan function is similar to fold, but the intermediate results are saved and returned in a vector, instead of returning just the last result. The result of a scan function is a vector. That is, given a vector of element_type, \(V_0, V_1, \ldots, V_{n-1}\), an initial value \(\text{initb}\) of type b_type, and a function \(\text{func}\), application of the scanr functions creates a new vector \(W\), where

\[
\begin{align*}
W_n &= \text{init}; \\
W_{n-1} &= \text{func}(V_{n-1}, W_n); \\
W_{n-2} &= \text{func}(V_{n-2}, W_{n-1}); \\
&\vdots \\
W_1 &= \text{func}(V_1, W_2); \\
W_0 &= \text{func}(V_0, W_1);
\end{align*}
\]

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>scanr</strong></td>
<td>Apply a function over a vector, creating a new vector result. Processes elements from the highest index position to the lowest, and fill the resulting vector in the same way. The result vector is 1 element longer than the input vector.</td>
</tr>
</tbody>
</table>
| \[
\text{function Vector#(vsize1,b_type)} \\
\text{scanr(function b_type func(a_type x1, b_type x2),} \\
\text{ b_type initb,} \\
\text{ Vector#(vsize,a_type) vect)} \\
\text{provisos (Add#(1, vsize, vsize1));}
\] |
| **sscanr** | Apply a function over a vector, creating a new vector result. The elements are processed from the highest index position to the lowest. The \(W_n\) element is dropped from the result. Input and output vectors are the same size. |
| \[
\text{function Vector#(vsize,b_type)} \\
\text{sscanr(function b_type func(a_type x1, b_type x2),} \\
\text{ b_type initb,} \\
\text{ Vector#(vsize,a_type) vect );}
\] |
The `scanl` function creates the resulting vector in a similar way as `scanr` except that the processing happens from the zeroth element up to the $n^{th}$ element.

\[
\begin{align*}
W_0 &= \text{init}; \\
W_1 &= \text{func}(W_0, V_0); \\
W_2 &= \text{func}(W_1, V_1); \\
&\vdots \\
W_{n-1} &= \text{func}(W_{n-2}, V_{n-2}); \\
W_n &= \text{func}(W_{n-1}, V_{n-1});
\end{align*}
\]

The `sscanl` function drops the first result, `init`, shifting the result index by one.

<table>
<thead>
<tr>
<th>scanl</th>
<th>Apply a function over a vector, creating a new vector result. Processes elements from the zeroth element up to the $n^{th}$ element. The result vector is 1 element longer than the input vector.</th>
</tr>
</thead>
</table>
|       | function Vector#(vsize1, a_type)  
|       |   scanl(function a_type func(a_type x1, b_type x2), a_type q, Vector#(vsize, b_type) vect)  
|       |     provisos (Add#(1, vsize, vsize1)); |

<table>
<thead>
<tr>
<th>sscanl</th>
<th>Apply a function over a vector, creating a new vector result. Processes elements from the zeroth element up to the $n^{th}$ element. The first result, <code>init</code>, is dropped, shifting the result index up by one. Input and output vectors are the same size.</th>
</tr>
</thead>
</table>
|        | function Vector#(vsize, a_type)  
|        |   sscanl(function a_type func(a_type x1, b_type x2), a_type q, Vector#(vsize, b_type) vect ); |

<table>
<thead>
<tr>
<th>mapAccumL</th>
<th>Map a function, but pass an accumulator from head to tail.</th>
</tr>
</thead>
</table>
|           | function Tuple2 #(a_type, Vector#(vsize, c_type))  
|           |   mapAccumL (function Tuple2 #(a_type, c_type)  
|           |     func(a_type x, b_type y), a_type x0, Vector#(vsize,b_type) vect ); |

<table>
<thead>
<tr>
<th>mapAccumR</th>
<th>Map a function, but pass an accumulator from tail to head.</th>
</tr>
</thead>
</table>
|           | function Tuple2 #(a_type, Vector#(vsize, c_type))  
|           |   mapAccumR(function Tuple2 #(a_type, c_type)  
|           |     func(a_type x, b_type y), a_type x0, Vector#(vsize,b_type) vect ); |
Examples - Scan

Create a vector of factorials.

// \* is a function which returns the result of a multiplied by b
function Bit #(16) \* (Bit #(16) b, Bit #(8) a);
    return (extend (a) * b);
endfunction

// Create a vector of factorials by multiplying each input list element
// by the previous product (the output list element), to generate
// the next product. The seed is a Bit#(16) with a value of 1.
// The elements are processed from the zeroth element up to the $n^{th}$ element.

// my_vector1 = {1,2,3,4,5,6,7}
Vector#(8,Bit #(16)) my_vector2 = scanl (\*, 16'd1, my_vector1);
// 7 multipliers are generated

// my_vector2 = {1,1,2,6,24,120,720,5040}
// foldr with the same arguments would return just 5040.

C.3.12 Monadic Operations

Within Bluespec, there are some functions which can only be invoked in certain contexts. Two common examples are: ActionValue, and module instantiation. ActionValues can only be invoked within an Action context, such as a rule block or an Action method, and can be considered as two parts - the action and the value. Module instantiation can similarly be considered, modules can only be instantiated in the module context, while the two parts are the module instantiation (the action performed) and the interface (the result returned). These situations are considered monadic.

When a monadic function is to be applied over a vector using map-like functions such as map, zipWith, or replicate, the monadic versions of these functions must be used. Moreover, the context requirements of the applied function must hold. The common application for these functions is in the generation (or instantiation) of vectors of hardware components.

<table>
<thead>
<tr>
<th>mapM</th>
<th>Takes a monadic function and a vector, and applies the function to all vector elements returning the vector of corresponding results.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>function m#(Vector#(vsize, b_type))</td>
</tr>
<tr>
<td></td>
<td>mapM ( function m#(b_type) func(a_type x), Vector#(vsize, a_type) vecta )</td>
</tr>
<tr>
<td></td>
<td>provisos (Monad#(m));</td>
</tr>
<tr>
<td>-------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mapM_</th>
<th>Takes a monadic function and a vector, applies the function to all vector elements, and throws away the resulting vector leaving the action in its context.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>function m#(void) mapM_(function m#(b_type) func(a_type x), Vector#(vsize, a_type) vect)</td>
</tr>
<tr>
<td></td>
<td>provisos (Monad#(m));</td>
</tr>
</tbody>
</table>
### zipWithM

Take a monadic function (which takes two arguments) and two vectors; the function applied to the corresponding element from each vector would return an action and result. Perform all those actions and return the vector of corresponding results.

```verilog
function m#(Vector#(vsize, c_type))
    zipWithM( function m#(c_type) func(a_type x, b_type y),
              Vector#(vsize, a_type) vecta,
              Vector#(vsize, b_type) vectb )
    provisos (Monad#(m));
```

### zipWithM_

Take a monadic function (which takes two arguments) and two vectors; the function is applied to the corresponding element from each vector. This is the same as `zipWithM` but the resulting vector is thrown away leaving the action in its context.

```verilog
function m#(void)
    zipWithM_(function m#(c_type) func(a_type x, b_type y),
              Vector#(vsize, a_type) vecta,
              Vector#(vsize, b_type) vectb )
    provisos (Monad#(m));
```

### zipWith3M

Same as `zipWithM` but combines three vectors with a function. The function is applied to the corresponding element from each vector and returns an action and the vector of corresponding results.

```verilog
function m#(Vector#(vsize, c_type))
    zipWith3M( function m#(d_type)
                    func(a_type x, b_type y, c_type z),
                    Vector#(vsize, a_type) vecta,
                    Vector#(vsize, b_type) vectb,
                    Vector#(vsize, c_type) vectc )
    provisos (Monad#(m));
```

### genWithM

Generate a vector of elements by applying the given monadic function to 0 through n-1.

```verilog
function m#(Vector#(vsize, element_type))
    genWithM(function m#(element_type) func(Integer x))
    provisos (Monad#(m));
```
replicateM  Generate a vector of elements by using the given monadic value repeatedly.

```
function m#(Vector#(vsize, element_type))
  replicateM( m#(element_type) c)
provisos (Monad#(m));
```

### Examples - Creating a Vector of Registers

The following example shows some common uses of the `Vector` type. We first create a vector of registers, and show how to populate this vector. We then continue with some examples of accessing and updating the registers within the vector, as well as alternate ways to do the same.

```verilog
// First define a variable to hold the register interfaces.
// Notice the variable is really a vector of Interfaces of type Reg,
// not a vector of modules.
Vector#(10,Reg#(DataT)) vectRegs ;

// Now we want to populate the vector, by filling it with Reg type
// interfaces, via the mkReg module.
// Notice that the replicateM function is used instead of the
// replicate function since mkReg function is creating a module.
vectRegs <- replicateM( mkReg( 0 ) ) ;

// ...

// A rule showing a read and write of one register within the
// vector.
// The readReg function is required since the selection of an
// element from vectRegs returns a Reg#(DType) interface, not the
// value of the register. The readReg functions converts from a
// Reg#(DataT) type to a DataT type.
rule zerothElement ( readReg( vectRegs[0] ) > 20 ) ;
  // set 0 element to 0
  // The parentheses are required in this context to give
  // precedence to the selection over the write operation.
  (vectRegs[0]) <= 0 ;

// Set the 1st element to 5
// An alternate syntax
  vectRegs[1]._write( 5 ) ;
endrule

rule lastElement ( readReg( vectRegs[9] ) > 200 ) ;
  // Set the 9th element to -10000
  (vectRegs[9]) <= -10000 ;
endrule

// These rules defined above can execute simultaneously, since
// they touch independent registers

// Here is an example of dynamic selection, first we define a
// register to be used as the selector.
Reg#(UInt#(4)) selector <- mkReg(0) ;
```
// Now define another Reg variable which is selected from the
// vectReg variable. Note that no register is created here, just
// an alias is defined.
Reg#(DataT) thisReg = select(vectRegs, selector);

// The above statement is equivalent to:
// Reg#(DataT) thisReg = vectRegs[selector];

// If the selected register is greater than 20'h7_0000, then its
// value is reset to zero. Note that the vector update function is
// not required since we are changing the contents of a register
// not the vector vectReg.
rule reduceReg( thisReg > 20'h7_0000 );
    thisReg <= 0;
    selector <= (selector < 9) ? selector + 1 : 0;
endrule

// As an alternative, we can define N rules which each check the
// value of one register and update accordingly. This is done by
// generating each rule inside an elaboration-time for-loop.
Integer i; // a compile time variable
for (i = 0; i < 10; i = i + 1) begin
    rule checkValue( readReg(vectRegs[i]) > 20'h7_0000 );
        (vectRegs[i]) <= 0;
    endrule
end

C.3.13 Converting to and from Vectors

There are functions which convert between Vectors and other types.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>toList</td>
<td>Convert a Vector to a List.</td>
</tr>
<tr>
<td></td>
<td>function List#(element_type)</td>
</tr>
<tr>
<td></td>
<td>toList (Vector#(vsize, element_type) vect);</td>
</tr>
<tr>
<td>toVector</td>
<td>Convert a List to a Vector.</td>
</tr>
<tr>
<td></td>
<td>function Vector#(vsize, element_type)</td>
</tr>
<tr>
<td></td>
<td>toVector (List#(element_type) lst);</td>
</tr>
<tr>
<td>arrayToVector</td>
<td>Convert an array to a Vector.</td>
</tr>
<tr>
<td></td>
<td>function Vector#(vsize, element_type)</td>
</tr>
<tr>
<td></td>
<td>arrayToVector (element_type[ ] arr);</td>
</tr>
</tbody>
</table>
### vectorToArray

Convert a Vector to an array.

```verilog
define element_type [ ]
vectorToArray (Vector#(vsize, element_type) vect);
```

### toChunks

Convert a value to a Vector of chunks, possibly padding the final chunk. The input type and size as well as the chunk type and size are determined from their types.

```verilog
define Vector#(n_chunk, chunk_type) toChunks(type_x x)
  provisos( Bits#(chunk_type, chunk_sz), Bits#(type_x, x_sz)
    , Div#(x_sz, chunk_sz, n_chunk) );
```

---

#### Example - Converting to and from Vectors

Convert the vector `my_vector` to a list named `my_list`.

```verilog
Vector#(5,Int#(13)) my_vector;
List#(Int#(13)) my_list = toList(my_vector);
```

---

### C.3.14 ListN

#### Package name

```verilog
import ListN :: * ;
```

#### Description

ListN is an alternative implementation of Vector which is preferred for sequential list processing functions, such as head, tail, map, fold, etc. All Vector functions are available, by substituting ListN for Vector. See the Vector documentation (C.3) for details. If the implementation requires random access to items in the list, the Vector construct is recommended. Using ListN where Vectors is recommended (and visa-versa) can lead to very long static elaboration times.

The ListN package defines an abstract data type which is a ListN of a specific length. Functions which create and operate on this type are also defined within this package. Because it is abstract, there are no constructors available for this type (like Cons and Nil for the List type).

```verilog
struct ListN#(vsize,a_type)
  ... abstract ...
```

Here, the type variable “a_type” represents the type of the contents of the listN while type variable “vsize” represents the length of the ListN.

---

### C.4 Aggregation: Lists

#### Package

```verilog
import List :: * ;
```
Description
The List package defines a data type and functions which create and operate on this data type. Lists are similar to Vectors, but are used when the number of items on the list may vary at compile-time or need not be strictly enforced by the type system. All elements of a list must be of the same type. The list type is defined as a tagged union as follows.

```plaintext
typedef union tagged {
    void Nil;
    struct {
        a      head;
        List #(a) tail;
    } Cons;
} List #(type a);
```

A list is tagged Nil if it has no elements, otherwise it is tagged Cons. Cons is a structure of a single element and the rest of the list.

Lists are most often used during static elaboration (compile-time) to manipulate collections of objects. Since List#(element_type) is not in the Bits typeclass, lists cannot be stored in registers or other dynamic elements. However, one can have a list of registers or variables corresponding to hardware functions.

Data classes

FShow The FShow class provides the function fshow which can be applied to a List and returns an associated Fmt object showing:

<List elem1 elem2 ...>

where the elemn are the elements of the list with fshow applied to each element value.

C.4.1 Creating and Generating Lists

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cons</td>
<td>Adds an element to a list. The new element will be at the 0th position.</td>
</tr>
<tr>
<td>function List#(element_type) cons (element_type x, List#(element_type) xs);</td>
<td></td>
</tr>
<tr>
<td>upto</td>
<td>Create a list of Integers counting up over a range of numbers, from m to n. If m &gt; n, an empty list (Nil) will be returned.</td>
</tr>
<tr>
<td>function List#(Integer) upto(Integer m, Integer n);</td>
<td></td>
</tr>
<tr>
<td>replicate</td>
<td>Generate a list of n elements by replicating the given argument, elem.</td>
</tr>
<tr>
<td>function List#(element_type) replicate(Integer n, element_type elem);</td>
<td></td>
</tr>
</tbody>
</table>
append Append two lists, returning the combined list. The elements of both lists must be the same datatype, `element_type`. The combined list will contain all the elements of `xs` followed in order by all the elements of `ys`.

```
function List#(element_type)
  append(List#(element_type) xs, List#(element_type) ys);
```

concat Append (concatenate) many lists, that is a list of lists, into one list.

```
function List#(element_type)
  concat (List#(List#(element_type)) xss);
```

Examples - Creating and Generating Lists

Create a new list, `my_list`, of elements of datatytpe `Int#(32)` which are undefined

```
List #(Int#(32)) my_list;
```

Create a list, `my_list`, of five 1’s

```
List #(Int #(32)) my_list = replicate (5,32'd1);
```

```
//my_list = {1,1,1,1,1}
```

Create a new list using the `upto` function

```
List #(Integer) my_list2 = upto (1, 5);
```

```
//my_list2 = {1,2,3,4,5}
```

C.4.2 Extracting Elements and Sub-Lists

The square-bracket notation is available to extract an element from a list or update an element within it. Extracts or updates the ith element, where the first element is [0]. Index i must be of an acceptable index type (e.g. `Integer`, `Bit#(n)`, `Int#(n)` or `UInt#(n)`). The square-bracket notation for lists can also be used with register writes.

```
anyList[i];
anyList[i] = newValue;
```

select The select function is another form of the subscript notation ([i]), mainly provided for backwards-compatibility. The select function is also useful as an argument to higher-order functions. The subscript notation is generally recommended because it will report a more useful position for any selection errors.

```
function element_type
  select(List#(element_type) alist, idx_type index);
```
### update

Update an element in a list returning a new list with one element changed/updated. This function does not change the given list. This is another form of the subscript notation (see above), mainly provided for backwards compatibility. The update function may also be useful as an argument to a higher-order function. The subscript notation is generally recommended because it will report a more useful position for any update errors.

```verilog
define List#(element_type)
  function List#(element_type) update(List#(element_type) alist,
        idx_type index,
        element_type newElem);
```

### oneHotSelect

Select a list element with a Boolean list. The Boolean list should have exactly one element that is `True`, otherwise the result is undefined. The returned element is the one in the corresponding position to the `True` element in the Boolean list.

```verilog
define List#(element_type)
  function element_type oneHotSelect (List#(Bool) bool_list,
        List#(element_type) alist);
```

### head

Extract the first element of a list. The input list must have at least 1 element, or an error will be returned.

```verilog
define List#(element_type)
  function element_type head (List#(element_type) listIn);
```

### last

Extract the last element of a list. The input list must have at least 1 element, or an error will be returned.

```verilog
define List#(element_type)
  function element_type last (List#(element_type) alist);
```

### tail

Remove the head element of a list leaving the remaining elements in a smaller list. The input list must have at least 1 element, or an error will be returned.

```verilog
define List#(element_type)
  function List#(element_type) tail (List#(element_type) alist);
```

### init

Remove the last element of a list the remaining elements in a smaller list. The input list must have at least one element, or an error will be returned.

```verilog
define List#(element_type)
  function List#(element_type) init (List#(element_type) alist);
```
<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take</td>
<td>Take a number of elements from a list starting from index 0. The number to take is specified by the argument ( n ). If the argument is greater than the number of elements on the list, the function stops taking at the end of the list and returns the entire input list.</td>
</tr>
<tr>
<td>Drop</td>
<td>Drop a number of elements from a list starting from index 0. The number to drop is specified by the argument ( n ). If the argument is greater than the number of elements on the list, the entire input list is dropped, returning an empty list.</td>
</tr>
<tr>
<td>Filter</td>
<td>Create a new list from a given list where the new list has only the elements which satisfy the predicate function.</td>
</tr>
<tr>
<td>Find</td>
<td>Return the first element that satisfies the predicate or ( \text{Nothing} ) if there is none.</td>
</tr>
<tr>
<td>Lookup</td>
<td>Returns the value in an association list or ( \text{Nothing} ) if there is no matching value.</td>
</tr>
<tr>
<td>TakeWhile</td>
<td>Returns the first set of elements of a list which satisfy the predicate function.</td>
</tr>
</tbody>
</table>
takeWhileRev | Returns the last set of elements on a list which satisfy the predicate function.
---|---
function List#(element_type) 
    takeWhileRev (function Bool pred(element_type x), 
        List#(element_type) alist);

dropWhile | Removes the first set of elements on a list which satisfy the predicate function, returning a list with the remaining elements.
---|---
function List#(element_type) 
    dropWhile (function Bool pred(element_type x), 
        List#(element_type) alist);

dropWhileRev | Removes the last set of elements on a list which satisfy the predicate function, returning a list with the remaining elements.
---|---
function List#(element_type) 
    dropWhileRev (function Bool pred(element_type x), 
        List#(element_type) alist);

Examples - Extracting Elements and Sub-Lists

Extract the element from a list, my_list, at the position of index.

//my_list = {1,2,3,4,5}, index = 3
newvalue = select (my_list, index);
//newvalue = 4

Extract the zeroth element of the list my_list.

//my_list = {1,2,3,4,5}
newvalue = head(my_list);
//newvalue = 1

Create a list, my_list2, of size 4 by removing the head (zeroth) element of the list my_list1.

//my_list1 is a list with 5 elements, {0,1,2,3,4}
List #(Int #(32)) my_list2 = tail (my_list1);
List #(Int #(32)) my_list3 = tail(tail(tail(tail(tail(my_list1);

//my_list2 = {1,2,3,4}
//my_list3 = Nil

Create a 2 element list, my_list2, by taking the first two elements of the list my_list1.
//my_list1 is list with 5 elements, {0,1,2,3,4}
List #(Int #(4)) my_list2 = take (2,my_list1);
//my_list2 = {0,1}

The number of elements specified to take in `take` can be greater than the number of elements on the list, in which case the entire input list will be returned.

//my_list1 is list with 5 elements, {0,1,2,3,4}
List #(Int #(4)) my_list2 = take (7,my_list1);
//my_list2 = {0,1,2,3,4}

Select an element based on a boolean list.

//my_list1 is a list of unsigned integers, {1,2,3,4,5}
//my_list2 is a list of Booleans, only one value in my_list2 can be True.
//my_list2 = {False, False, True, False,False, False, False}.
result = oneHotSelect (my_list2, my_list1);
//result = 3

Create a list by removing the initial segment of a list that meets a predicate.

//the predicate function is a < 2

function Bool lessthan2 (Int #(4) a);
    return (a < 2);
endfunction

//my_list1 = {0,1,2,0,1,7,8}
List #(Int #(4)) my_result = (dropWhile(lessthan2, my_list1));
//my_result = {2,0,1,7,8}

### C.4.3 List to List Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>rotate</code></td>
<td>Move the first element to the last and shift each element to the next higher index.</td>
</tr>
<tr>
<td>function List#(element_type) rotate (List#(element_type) alist);</td>
<td></td>
</tr>
<tr>
<td><code>rotateR</code></td>
<td>Move last element to the beginning and shift each element to the next lower index.</td>
</tr>
<tr>
<td>function List#(element_type) rotateR (List#(element_type) alist);</td>
<td></td>
</tr>
<tr>
<td><code>reverse</code></td>
<td>Reverse element order</td>
</tr>
<tr>
<td>function List#(element_type) reverse(List#(element_type) alist);</td>
<td></td>
</tr>
<tr>
<td>Function</td>
<td>Description</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>transpose</td>
<td>Matrix transposition of a list of lists.</td>
</tr>
<tr>
<td></td>
<td>function List#(List#(element_type))</td>
</tr>
<tr>
<td></td>
<td>transpose ( List#(List#(element_type)) matrix );</td>
</tr>
<tr>
<td>sort</td>
<td>Uses the ordering defined for the element_type data type to return a list in ascending order.</td>
</tr>
<tr>
<td></td>
<td>The type element_type must be in the Ord type class.</td>
</tr>
<tr>
<td></td>
<td>function List#(element_type) sort(List#(element_type) alist)</td>
</tr>
<tr>
<td></td>
<td>provisos(Ord#(element_type)) ;</td>
</tr>
<tr>
<td>sortBy</td>
<td>Generalizes the sort function to use an arbitrary ordering function defined by the</td>
</tr>
<tr>
<td></td>
<td>comparison function comparef in place of the Ord instance for element_type.</td>
</tr>
<tr>
<td></td>
<td>function List#(element_type)</td>
</tr>
<tr>
<td></td>
<td>sortBy(function Ordering comparef(element_type x, element_type y), List#(element_type) alist);</td>
</tr>
<tr>
<td>group</td>
<td>Returns a list of the contiguous subsequences of equal elements (according to the Eq</td>
</tr>
<tr>
<td></td>
<td>instance for element_type) found in its input list. Every element in the input list will</td>
</tr>
<tr>
<td></td>
<td>appear in exactly one sublist of the result. Every sublist will be a non-empty list of equal</td>
</tr>
<tr>
<td></td>
<td>elements. For any list, x, concat(group(x)) == x.</td>
</tr>
<tr>
<td></td>
<td>function List#(List#(element_type)) group (List#(element_type) alist)</td>
</tr>
<tr>
<td></td>
<td>provisos(Eq#(element_type)) ;</td>
</tr>
<tr>
<td>groupBy</td>
<td>Generalizes the group function to use an arbitrary equivalence relation defined by the</td>
</tr>
<tr>
<td></td>
<td>comparison function eqf in place of the Eq instance for element_type.</td>
</tr>
<tr>
<td></td>
<td>function List#(List#(element_type))</td>
</tr>
<tr>
<td></td>
<td>groupBy(function Bool eqf(element_type x, element_type y), List#(element_type) alist);</td>
</tr>
</tbody>
</table>

**Examples - List to List Functions**

Create a list by moving the last element to the first, then shifting each element to the right.

```plaintext
//my_list1 is a List of elements with values {1,2,3,4,5}
my_list2 = rotateR (my_list1);
//my_list2 is a List of elements with values {5,1,2,3,4}
```

Create a list which is the reverse of the input List.
/my_list1 is a List of elements {1,2,3,4,5}

my_list2 = reverse (my_list1);

//my_list2 is a List of elements {5,4,3,2,1}

Use transpose to create a new list

//my_list1 has the values:
//{{0,1,2,3,4},{5,6,7,8,9},{10,11,12,13,14}}

my_list2 = transpose(my_list1);

//my_list2 has the values:
//{{0,5,10},{1,6,11},{2,7,12},{3,8,13},{4,9,14}}

Use sort to create a new list

//my_list1 has the values: {3,2,5,4,1}

my_list2 = sort(my_list1);

//my_list2 has the values: {1,2,3,4,5}

Use group to create a list of lists

//my_list1 is a list of elements {Mississippi}

my_list2 = group(my_list1);

//my_list2 is a list of lists:
//{{M},{i},{ss},{i},{ss},{i},{pp},{i}}

C.4.4 Tests on Lists

<table>
<thead>
<tr>
<th>==</th>
<th>Lists can be compared for equality if the elements in the list can be compared.</th>
</tr>
</thead>
<tbody>
<tr>
<td>!=</td>
<td></td>
</tr>
<tr>
<td>elem</td>
<td>Check if a value is an element in a list.</td>
</tr>
<tr>
<td></td>
<td>function Bool elem (element_type x, List#(element_type) alist )</td>
</tr>
<tr>
<td></td>
<td>proviso (Eq#(element_type));</td>
</tr>
<tr>
<td>length</td>
<td>Determine the length of a list. Can be done at elaboration time only.</td>
</tr>
<tr>
<td></td>
<td>function Integer length (List#(element_type) alist );</td>
</tr>
<tr>
<td>Function</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td><code>any</code></td>
<td>Test if a predicate holds for any element of a list.</td>
</tr>
<tr>
<td><code>all</code></td>
<td>Test if a predicate holds for all elements of a list.</td>
</tr>
<tr>
<td><code>or</code></td>
<td>Combine all elements in a Boolean list with a logical or. Returns True if any elements in the list are True.</td>
</tr>
<tr>
<td><code>and</code></td>
<td>Combine all elements in a Boolean list with a logical and. Returns True if all elements in the list are true.</td>
</tr>
</tbody>
</table>

Examples - Tests on Lists

Test that all elements of the list `my_list1` are positive integers.

```verilog
define Bool isPositive (Int #(32) a);
    return (a > 0)
endfunction

// function isPositive checks that "a" is a positive integer
// if my_list1 has n elements, n instances of the predicate
// function isPositive will be generated.

if (all(isPositive, my_list1))
    $display("List contains all negative values");
```

Test if any elements in the list are positive integers.

```verilog
// function isPositive checks that "a" is a positive integer
// if my_list1 has n elements, n instances of the predicate
// function isPositive will be generated.

if (any(pos, my_list1))
    $display("List contains some negative values");
```

Check if the integer 5 is in `my_list`.

```verilog
// if my_list contains n elements, elem will generate n copies
// of the eqt Test
if (elem(5,my_list))
    $display("List contains the integer 5");
```
### C.4.5 Combining Lists with Zip Functions

The family of `zip` functions takes two or more lists and combines them into one list of Tuples. Several variations are provided for different resulting Tuples. All variants can handle input lists of different sizes. The resulting lists will be the size of the smallest list.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Example Code</th>
</tr>
</thead>
</table>
| `zip`    | Combine two lists into a list of Tuples. | function `List#(Tuple2 #(a_type, b_type))
zip( List#(a_type) lista,
    List#(b_type) listb);` |
| `zip3`   | Combine 3 lists into a list of Tuple3. | function `List#(Tuple3 #(a_type, b_type, c_type))
zip3( List#(a_type) lista,
     List#(b_type) listb,
     List#(c_type) listc);` |
| `zip4`   | Combine 4 lists into a list of Tuple4. | function `List#(Tuple4 #(a_type, b_type, c_type, d_type))
zip4( List#(a_type) lista,
     List#(b_type) listb,
     List#(c_type) listc,
     List#(d_type) listd);` |
| `unzip`  | Separate a list of pairs (i.e. a Tuple2(a,b)) into a pair of two lists. | function `Tuple2#(List#(a_type), List#(b_type))
unzip(List#(Tuple2 #(a_type, b_type)) listab);` |

#### Examples - Combining Lists with Zip

Combine two lists into a list of Tuples

```plaintext
//my_list1 is a list of elements {0,1,2,3,4,5,6,7}
//my_list2 is a list of elements {True,False,True,True,False}

my_list3 = zip(my_list1, my_list2);
```

Separate a list of pairs into a Tuple of two lists

```plaintext
//my_list is a list of pairs {(0,True),(1,False),(2,True),(3, True),(4, False)}

Tuple2#(List#(Int#(5)),List#(Int#(5))) my_list2 = unzip(my_list);
```

`//my_list2 is {(0,1,2,3,4),(5,6,7,8,9)}`
C.4.6 Mapping Functions over Lists

A function can be applied to all elements of a list, using high-order functions such as map. These functions take as an argument a function, which is applied to the elements of the list.

<table>
<thead>
<tr>
<th>map</th>
<th>Map a function over a list, returning a new list of results.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function List#(b_type) map (function b_type func(a_type), List#(a_type) alist);</td>
<td></td>
</tr>
</tbody>
</table>

Example - Mapping Functions over Lists

Consider the following code example which applies the extend function to each element of alist creating a new list, resultlist.

```verilog
List#(Bit#(5)) alist;
List#(Bit#(10)) resultlist;
...
resultlist = map( extend, alist );
```

This is equivalent to saying:

```verilog
for (Integer i=0; i<13; i=i+1)
    resultlist[i] = extend(alist[i]);
```

Map a negate function over a list

```verilog
//my_list1 is a list of 5 elements {0,1,2,3,4}
//negate is a function which makes each element negative
List #(Int #(32)) my_list2 = map (negate, my_list1);
```

//my_list2 is a list of 5 elements {0,-1,-2,-3,-4}

C.4.7 ZipWith Functions

The zipWith functions combine two or more lists with a function and generate a new list. These functions combine features of map and zip functions.

<table>
<thead>
<tr>
<th>zipWith</th>
<th>Combine two lists with a function. The lists do not have to have the same number of elements.</th>
</tr>
</thead>
</table>
| function List#(c_type)
  zipWith (function c_type func(a_type x, b_type y), List#(a_type) listx, List#(b_type) listy); |
### zipWith3

Combine three lists with a function. The lists do not have to have the same number of elements.

```verilog
function List#(d_type) zipWith3
  (function d_type func(a_type x, b_type y, c_type z),
   List#(a_type) listx,
   List#(b_type) listy,
   List#(c_type) listz);
```

### zipWith4

Combine four lists with a function. The lists do not have to have the same number of elements.

```verilog
function List#(e_type) zipWith4
  (function e_type func(a_type x, b_type y, c_type z, d_type w),
   List#(a_type) listx,
   List#(b_type) listy,
   List#(c_type) listz,
   List#(d_type) listw);
```

#### Examples - ZipWith

Create a list by applying a function over the elements of 3 lists.

```verilog
//the function add3 adds 3 values
function Int#(8) add3 (Int #(8) a,Int #(8) b,Int #(8) c);
  Int#(8) d = a + b + c;
  return(d);
endfunction

//Create the list my_list4 by adding the ith element of each of
//3 lists (my_list1, my_list2, my_list3) to generate the ith
//element of my_list4.

//my_list1 = {0,1,2,3,4}
//my_list2 = {5,6,7,8,9}
//my_list3 = {10,11,12,13,14}

List #(Int #(8)) my_list4 = zipWith3(add3, my_list1, my_list2, my_list3);

//my_list4 = {15,18,21,24,27}

// This is equivalent to saying:
for (Integer i=0; i<5; i=i+1)
  my_list4[i] = my_list1[i] + my_list2[i] + my_list3[i];
```

#### C.4.8 Fold Functions

The fold family of functions reduces a list to a single result by applying a function over all its elements. That is, given a list of element_type, L₀, L₁, L₂, ..., Lₙ₋₁, a seed of type b_type, and a function func, the reduction for foldr is given by

```
func(L₀, func(L₁, ..., func(Lₙ₋₂, func(Lₙ₋₁, seed))));
```
Note that `foldr` start processing from the highest index position to the lowest, while `foldl` starts from the lowest index (zero), i.e.,

\[
func(...(func(func(seed, L_0), L_1), ...)L_{n-1})
\]

<table>
<thead>
<tr>
<th>foldr</th>
<th>Reduce a list by applying a function over all its elements. Start processing from the highest index to the lowest.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>function b_type foldr(b_type function func(a_type x, b_type y), b_type seed, List#(a_type) alist);</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>foldl</th>
<th>Reduce a list by applying a function over all its elements. Start processing from the lowest index (zero).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>function b_type foldl(b_type function func(b_type y, a_type x), b_type seed, List#(a_type) alist);</td>
</tr>
</tbody>
</table>

The functions `foldr1` and `foldl1` use the first element as the seed. This means they only work on lists of at least one element. Since the result type will be the same as the element type, there is no `b_type` as there is in the `foldr` and `foldl` functions.

<table>
<thead>
<tr>
<th>foldr1</th>
<th>foldr function for a non-zero sized list. Uses element ( L_{n-1} ) as the seed. List must have at least 1 element.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>function element_type foldr1(element_type function func(element_type x, element_type y), List#(element_type) alist);</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>foldl1</th>
<th>foldl function for a non-zero sized list. Uses element ( L_0 ) as the seed. List must have at least 1 element.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>function element_type foldl1(element_type function func(element_type y, element_type x), List#(element_type) alist);</td>
</tr>
</tbody>
</table>

The `fold` function also operates over a non-empty list, but processing is accomplished in a binary tree-like structure. Hence the depth or delay through the resulting function will be \( O(\log_2(lsize)) \) rather than \( O(lsize) \).
fold

Reduce a list by applying a function over all its elements, using a binary tree-like structure. The function returns the same type as the arguments.

```verilog
function element_type fold
  (element_type function func(element_type y, element_type x),
   List#(element_type) alist );
```

joinActions

Join a number of actions together.

```verilog
function Action joinActions (List#(Action) list_actions);
```

joinRules

Join a number of rules together.

```verilog
function Rules joinRules (List#(Rules) list_rules);
```

mapPairs

Map a function over a list consuming two elements at a time. Any straggling element is processed by the second function.

```verilog
function List#(b_type)
  mapPairs ( 
    function b_type func1(a_type x, a_type y),
    function b_type func2(a_type x),
    List#(a_type) alist );
```

Example - Folds

```verilog
// my_list1 is a list of five integers {1,2,3,4,5}
// + is a function which returns the sum of the elements

global def

my_sum = foldr (+, 0, my_list1));

// my_sum = 15

Use fold to find the element with the maximum value

```verilog
// my_list1 is a list of five integers {2,45,5,8,32}

global def

my_max = fold (max, my_list1);

// my_max = 45

Create a new list using mapPairs. The function `sum` is applied to each pair of elements (the first and second, the third and fourth, etc.). If there is an uneven number of elements, the function `pass` is applied to the remaining element.

```verilog
//sum is defined as c = a+b

function Int#(4) sum (Int #(4) a,Int #(4) b);
```
Int#(4) c = a + b;
return(c);
endfunction

//pass is defined as a
function Int#(4) pass (Int #(4) a);
return(a);
endfunction

//my_list1 has the elements {0,1,2,3,4}
my_list2 = mapPairs(sum,pass,my_list1);

//my_list2 has the elements {1,5,4}
//my_list2[0] = 0 + 1
//my_list2[1] = 2 + 3
//my_list2[3] = 4

C.4.9 Scan Functions

The scan family of functions applies a function over a list, creating a new List result. The scan function is similar to fold, but the intermediate results are saved and returned in a list, instead of returning just the last result. The result of a scan function is a list. That is, given a list of element_type, L_0, L_1, ..., L_{n-1}, an initial value initb of type b_type, and a function func, application of the scanr functions creates a new list W, where

\[
\begin{align*}
W_n &= \text{init}; \\
W_{n-1} &= \text{func}(L_{n-1}, W_n); \\
W_{n-2} &= \text{func}(L_{n-2}, W_{n-1}); \\
& \vdots \\
W_1 &= \text{func}(L_1, W_2); \\
W_0 &= \text{func}(L_0, W_1);
\end{align*}
\]

<table>
<thead>
<tr>
<th>scanr</th>
<th>Apply a function over a list, creating a new list result. Processes elements from the highest index position to the lowest, and fills the resulting list in the same way. The result list is one element longer than the input list.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function List#(b_type)</td>
<td></td>
</tr>
<tr>
<td>scanr(function b_type func(a_type x1, b_type x2), b_type initb, List#(a_type) alist);</td>
<td></td>
</tr>
<tr>
<td>Function</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td><strong>sscanr</strong></td>
<td>Apply a function over a list, creating a new list result. The elements are processed from the highest index position to the lowest. Drops the ( W_n ) element from the result. Input and output lists are the same size.</td>
</tr>
</tbody>
</table>
| **function List#(b_type)** | \[ \text{sscanr}(\text{function } b\_\text{type } \text{func}(a\_\text{type } x1, b\_\text{type } x2), \]
| | \[ \text{b\_type initb,} \]
| | \[ \text{List#(a\_\text{type}) } \text{alist}; \] |

The **scanl** function creates the resulting list in a similar way as **sscanr** except that the processing happens from the zeroth element up to the nth element.

\[
\begin{align*}
W_0 &= \textit{init}; \\
W_1 &= \text{func}(W_0, L_0); \\
W_2 &= \text{func}(W_1, L_1); \\
&\vdots \\
W_{n-1} &= \text{func}(W_{n-2}, L_{n-2}); \\
W_n &= \text{func}(W_{n-1}, L_{n-1});
\end{align*}
\]

The **sscanl** function drops the first result, \( \text{init} \), shifting the result index by one.

<table>
<thead>
<tr>
<th><strong>scanl</strong></th>
<th>Apply a function over a list, creating a new list result. Processes elements from the zeroth element up to the nth element. The result list is 1 element longer than the input list.</th>
</tr>
</thead>
</table>
| **function List#(a_type)** | \[ \text{scanl}(\text{function } a\_\text{type } \text{func}(a\_\text{type } x1, b\_\text{type } x2), \]
| | \[ \text{a\_type inita,} \]
| | \[ \text{List#(b\_\text{type}) } \text{alist}; \] |

<table>
<thead>
<tr>
<th><strong>sscanl</strong></th>
<th>Apply a function over a list, creating a new list result. Processes elements from the zeroth element up to the nth element. Drop the first result, ( \text{init} ), shifting the result index by one. The length of the input and output lists are the same.</th>
</tr>
</thead>
</table>
| **function List#(a_type)** | \[ \text{sscanl}(\text{function } a\_\text{type } \text{func}(a\_\text{type } x1, b\_\text{type } x2), \]
| | \[ \text{a\_type inita,} \]
| | \[ \text{List#(b) } \text{alist}; \] |

<table>
<thead>
<tr>
<th><strong>mapAccumL</strong></th>
<th>Map a function, but pass an accumulator from head to tail.</th>
</tr>
</thead>
</table>
| **function Tuple2 #(a_type, List#(c_type))** | \[ \text{mapAccumL}(\text{function } \text{Tuple2 } #(a\_\text{type}, c\_\text{type}) \]
| | \[ \text{func}(a\_\text{type } x, b\_\text{type } y), a\_\text{type } x0, \]
| | \[ \text{List#(b\_\text{type}) } \text{alist}); \] |
mapAccumR | Map a function, but pass an accumulator from tail to head.

```
function Tuple2 #(a_type, List#c_type)
    mapAccumR (function Tuple2 #(a_type, c_type)
        func(a_type x, b_type y), a_type x0,
        List#(b_type) alist);
```

Examples - Scan

Create a list of factorials

```
// the function my_mult multiplies element a by element b
function Bit #(16) my_mult (Bit #(16) b, Bit #(8) a);
    return (extend (a) * b);
endfunction

// Create a list of factorials by multiplying each input list element
// by the previous product (the output list element), to generate
// the next product. The seed is a Bit#(16) with a value of 1.
// The elements are processed from the zeroth element up to the nth element.
// my_list1 = {1,2,3,4,5,6,7}
List #(Bit #(16)) my_list2 = scanl (my_mult, 16'd1, my_list1);

// my_list2 = {1,1,2,6,24,120,720,5040}
```

C.4.10 Monadic Operations

Within Bluespec, there are some functions which can only be invoked in certain contexts. Two common examples are: ActionValue, and module instantiation. ActionValues can only be invoked within an Action context, such as a rule block or an Action method, and can be considered as two parts - the action and the value. Module instantiation can similarly be considered, modules can only be instantiated in the module context, while the two parts are the module instantiation (the action performed) and the interface (the result returned). These situations are considered monadic.

When a monadic function is to be applied over a list using map-like functions such as map, zipWith, or replicate, the monadic versions of these functions must be used. Moreover, the context requirements of the applied function must hold.

```
mapM | Takes a monadic function and a list, and applies the function to all list elements returning the list of corresponding results.

function m#(List#(b_type))
    mapM ( function m#(b_type) func(a_type x),
        List#(a_type) alist )
    provisos (Monad#(m));
```
<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>mapM_</code></td>
<td>Takes a monadic function and a list, applies the function to all list elements, and throws away the resulting list leaving the action in its context.</td>
</tr>
<tr>
<td></td>
<td>function m#((List#(b_type) mapM_(m#(b_type) c_type) provisos (Monad#(m)));</td>
</tr>
<tr>
<td><code>zipWithM</code></td>
<td>Take a monadic function (which takes two arguments) and two lists; the function applied to the corresponding element from each list would return an action and result. Perform all those actions and return the list of corresponding results.</td>
</tr>
<tr>
<td></td>
<td>function m#((List#(c_type)) zipWithM( function m#(c_type) func(a_type x, b_type y), List#(a_type) alist, List#(b_type) blist ) provisos (Monad#(m)));</td>
</tr>
<tr>
<td><code>zipWith3M</code></td>
<td>Same as <code>zipWithM</code> but combines three lists with a function. The function is applied to the corresponding element from each list and returns an action and the list of corresponding results.</td>
</tr>
<tr>
<td></td>
<td>function m#((List#(d_type)) zipWith3M( function m#(d_type) func(a_type x, b_type y, c_type z), List#(a_type) alist, List#(b_type) blist, List#(c_type) clist ) provisos (Monad#(m)));</td>
</tr>
<tr>
<td><code>replicateM</code></td>
<td>Generate a list of elements by using the given monadic value repeatedly.</td>
</tr>
<tr>
<td></td>
<td>function m#((List#(element_type)) replicateM( Integer n, m#(element_type) c) provisos (Monad#(m)));</td>
</tr>
</tbody>
</table>

### C.5 Math

#### C.5.1 Real

**Package**

```verbatim
import Real :: * ;
```

**Description**
The Real library package defines functions to operate on and manipulate real numbers. Real numbers are numbers with a fractional component. They are also of limited precision. The Real data type is described in section B.2.6.

Constants
The constant pi (π) is defined.

<table>
<thead>
<tr>
<th>pi</th>
<th>The value of the constant pi (π).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real pi;</td>
<td></td>
</tr>
</tbody>
</table>

Trigonometric Functions
The following trigonometric functions are provided: sin, cos, tan, sinh, cosh, tanh, asin, acos, atan, asinh, acosh, atanh, and atan2.

<table>
<thead>
<tr>
<th>sin</th>
<th>Returns the sine of x.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Real sin (Real x);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>cos</th>
<th>Returns the cosine of x.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Real cos (Real x);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>tan</th>
<th>Returns the tangent of x.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Real tan (Real x);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>sinh</th>
<th>Returns the hyperbolic sine of x.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Real sinh (Real x);</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>cosh</th>
<th>Returns the hyperbolic cosine of x.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function Real cosh (Real x);</td>
<td></td>
</tr>
</tbody>
</table>
### Hyperbolic Functions

#### tanh
Returns the hyperbolic tangent of \( x \).

```
function Real tanh (Real x);
```

#### asinh
Returns the inverse hyperbolic sine of \( x \).

```
function Real asinh (Real x);
```

#### acosh
Returns the inverse hyperbolic cosine of \( x \).

```
function Real acosh (Real x);
```

#### atanh
Returns the inverse hyperbolic tangent of \( x \).

```
function Real atanh (Real x);
```

#### atan2
Returns \( \tan^{-1}(x/y) \). \( \tan^{-1}(1,x) \) is equivalent to \( \tan^{-1}(x) \), but provides more precision when required by the division of \( x/y \).

```
function Real atan2 (Real y, Real x);
```

### Arithmetic Functions

#### pow
The element \( x \) is raised to the \( y \) power. An alias for \( x^{**} \). \( \text{pow}(x, y) = x^{**y} = x^y \).

```
function Real pow (Real x, Real y);
```

#### sqrt
Returns the square root of \( x \). Returns an error if \( x \) is negative.

```
function Real sqrt (Real x);
```

---

304
Conversion Functions

The following four functions are used to convert a Real to an Integer.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>trunc</code></td>
<td>Converts a Real to an Integer by removing the fractional part of x, which can be positive or negative. <code>trunc(1.1) = 1</code>, <code>trunc(-1.1) = -1</code>.</td>
<td></td>
</tr>
<tr>
<td><code>function Integer trunc (Real x);</code></td>
<td></td>
<td></td>
</tr>
<tr>
<td><code>round</code></td>
<td>Converts a Real to an Integer by rounding to the nearest whole number. .5 rounds up in magnitude. <code>round(1.5) = 2</code>, <code>round(-1.5) = -2</code>.</td>
<td></td>
</tr>
<tr>
<td><code>function Integer round (Real x);</code></td>
<td></td>
<td></td>
</tr>
<tr>
<td><code>ceil</code></td>
<td>Converts a Real to an Integer by rounding to the higher number, regardless of sign. <code>ceil(1.1) = 2</code>, <code>ceil(-1.1) = -1</code>.</td>
<td></td>
</tr>
<tr>
<td><code>function Integer ceil (Real x);</code></td>
<td></td>
<td></td>
</tr>
<tr>
<td><code>floor</code></td>
<td>Converts a Real to an Integer by rounding to the lower number, regardless of sign. <code>floor(1.1) = 1</code>, <code>floor(-1.1) = -2</code>.</td>
<td></td>
</tr>
<tr>
<td><code>function Integer floor (Real x);</code></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There are also two system functions `$realtobits` and `$bitstoreal`, defined in the Prelude (section B.2.6) which provide conversion to and from IEEE 64-bit vectors (Bit#(64)).

Introspection Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>isInfinite</code></td>
<td>Returns True if the value of x is infinite, False if x is finite.</td>
<td></td>
</tr>
<tr>
<td><code>function Bool isInfinite (Real x);</code></td>
<td></td>
<td></td>
</tr>
<tr>
<td><code>isNegativeZero</code></td>
<td>Returns True if the value of x is negative zero.</td>
<td></td>
</tr>
<tr>
<td><code>function Bool isNegativeZero (Real x);</code></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**splitReal**

Returns a Tuple containing the whole \( n \) and fractional \( f \) parts of \( x \) such that \( n + f = x \). Both values have the same sign as \( x \). The absolute value of the fractional part is guaranteed to be in the range \([0,1)\).

\[
\text{function Tuple2#(Integer, Real) splitReal (Real x);}
\]

**decodeReal**

Returns a Tuple3 containing the sign, the fraction, and the exponent of a real number. The second part (the first Integer) represents the fractional part as a signed Integer value. This can be converted to an \texttt{Int#(54)} (52 bits, plus hidden bit, plus the sign bit). The last value is a signed Integer representing the exponent, which can be be converted to an \texttt{Int#(11)} . The real number is represented exactly as \((\text{fractional} \times 2^{\text{exp}})\). The \texttt{Bool} represents the sign and is \texttt{True} for positive and positive zero, \texttt{False} for negative and negative zero. Since the second value is a signed value, the \texttt{Bool} is redundant except for zero values.

\[
\text{function Tuple3#(Bool, Integer, Integer) decodeReal (Real x);}
\]

**realToDigits**

Deconstructs a real number into its digits. The function takes a base and a real number and returns a list of digits and an exponent (ignoring the sign). In particular, if \( x \geq 0 \), and \text{realToDigits(base,x)} returned a list of digits \( d_1, d_2, \ldots, d_n \) and an exponent \( e \), then:

- \( n \geq 1 \)
- \( \text{abs}(x) = 0.d_1d_2\ldots d_n \times (\text{base}^e) \)
- \( 0 \leq d_i \leq \text{base}-1 \)

\[
\text{function Tuple2#(List#(Integer), Integer)
realToDigits (Integer base, Real r);}
\]

### C.5.2 OInt

**Package**

\texttt{import OInt :: \_*\;}

**Description**

The \texttt{OInt#(n)} type is an abstract type that can store a number in the range “0..\(n-1\)”. The representation of a \texttt{OInt#(n)} takes up \( n \) bits, where exactly one bit is a set to one, and the others are zero, i.e., it is a one-hot decoded version of the number. The reason to use a \texttt{OInt} number is that the \texttt{select} operation is more efficient than for a binary-encoded number; the code generated for select takes advantage of the fact that only one of the bits may be set at a time.

**Types and type classes**

Definition of \texttt{OInt}
typedef ... OInt #(numeric type n) ... ;

<table>
<thead>
<tr>
<th>Type Classes used by OInt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>OInt</td>
</tr>
</tbody>
</table>

Functions

A binary-encoded number can be converted to an OInt.

<table>
<thead>
<tr>
<th>toOInt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converts from a bit-vector in unsigned binary format to an OInt. An out-of-range number gives an unspecified result.</td>
</tr>
<tr>
<td>function OInt#(n) toOInt(Bit#(k) k) provisos(Log#(n,k)) ;</td>
</tr>
</tbody>
</table>

An OInt can be converted to a binary-encoded number.

<table>
<thead>
<tr>
<th>fromOInt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converts an OInt to a bit-vector in unsigned binary format.</td>
</tr>
<tr>
<td>function Bit#(k) fromOInt(OInt#(n) o) provisos(Log#(n,k)) ;</td>
</tr>
</tbody>
</table>

An OInt can be used to select an element from a Vector in an efficient way.

<table>
<thead>
<tr>
<th>select</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Vector select function, where the type of the index is an OInt.</td>
</tr>
<tr>
<td>function a_type select(Vector#(vsize, a_type) vecta, OInt#(vsize) index) provisos(Bits#(a_type, sizea)) ;</td>
</tr>
</tbody>
</table>

C.5.3 Complex

Package

import Complex :: * ;

Description

The Complex package provides a representation for complex numbers plus functions to operate on variables of this type. The basic representation is the Complex structure, which is polymorphic on the type of data it holds. For example, one can have complex numbers of type Int or of type FixedPoint. A Complex number is represented in two part, the real part (rel) and the imaginary part (img). These fields are accessible though standard structure addressing, i.e., foo.rel and foo.img where foo is of type Complex.

typedef struct {
    any_t rel ;
    any_t img ;
} Complex#(type any_t)
deriving( Bits, Eq ) ;
This package is provided as both a compiled library package and as BSV source code to facilitate customization. The source code file can be found in the $BLUESPACDIR/BSVSsource/Math directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Types and type classes

The Complex type belongs to the Arith, Literal, SaturatingArith, and FShow type classes. Each type class definition includes functions which are then also defined for the data type. The Prelude library definitions (Section B) describes which functions are defined for each type class.

<table>
<thead>
<tr>
<th>Type Classes used by Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>Complex</td>
</tr>
</tbody>
</table>

**Arith**  The type Complex belongs to the Arith type class, hence the common infix operators (+, -, *, and /) are defined and can be used to manipulate variables of type Complex. The remaining arithmetic operators are not defined for the Complex type. Note however, that some functions generate more hardware than may be expected. The complex multiplication (*) produces four multipliers in a combinational function; some other modules could accomplish the same function with less hardware but with greater latency. The complex division operator (/) produces 6 multipliers, and a divider and may not always be synthesizable with downstream tools.

```verbatim
instance Arith#(Complex#(any_type))
  provisos (Arith#(any_type));
```

**Literal**  The Complex type is a member of the Literal class, which defines a conversion from the compile-time Integer type to Complex type with the fromInteger function. This function converts the Integer to the real part, and sets the imaginary part to 0.

```verbatim
instance Literal#(Complex#(any_type))
  provisos (Literal#(any_type));
```

**SaturatingArith**  The SaturatingArith class provides the functions satPlus, satMinus, boundedPlus, and boundedMinus. These are modified plus and minus functions which saturate to values defined by the SaturationMode when the operations would otherwise overflow or wrap-around. The type of the complex value (any_type) must be in the SaturatingArith class.

```verbatim
instance SaturatingArith#(Complex#(any_type))
  provisos (SaturatingArith#(any_type));
```

**FShow**  An instance of FShow is available provided any_type is a member of FShow as well.

```verbatim
instance FShow#(Complex#(any_type))
  provisos (FShow#(any_type));
  function Fmt fshow (Complex#(any_type) x);
    return $format("<C ", fshow(x.rel), ",", fshow(x.img), ">");
  endfunction
endinstance
```

Functions
cmplx

A simple constructor function is provided to set the fields.

```systemsverilog
function Complex#(a_type) cmplx( a_type realA, a_type imagA ) ;
```

cmplxMap

Applies a function to each part of the complex structure. This is useful for operations such as extend, truncate, etc.

```systemsverilog
function Complex#(b_type) cmplxMap(
    function b_type mapFunc( a_type x),
    Complex#(a_type) cin ) ;
```

cmplxSwap

Exchanges the real and imaginary parts.

```systemsverilog
function Complex#(a_type) cmplxSwap( Complex#(a_type) cin ) ;
```

cmplxWrite

Displays a complex number given a prefix string, an infix string, a postscript string, and an Action function which writes each part. `cmplxWrite` is of type `Action` and can only be invoked in Action contexts such as Rules and Actions methods.

```systemsverilog
function Action cmplxWrite(String pre,
    String infix,
    String post,
    function Action writeaFunc( a_type x ),
    Complex#(a_type) cin );
```

Examples - Complex Numbers

```systemsverilog
// The following utility function is provided for writing data
// in decimal format. An example of its use is show below.

function Action writeInt( Int#(n) ain ) ;
    $write( "%0d", ain ) ;
endfunction

// Set the fields of the complex number using the constructor function cmplx
Complex#(Int#(6)) complex_value = cmplx(-2,7) ;

// Display complex_value as ( -2 + 7i ).
// Note that writeInt is passed as an argument to the cmplxWrite function.
cmplxWrite( "( ", " + ", "i)", writeInt, complex_value );
```
// Swap the real and imaginary parts.
swap_value = cmplxSwap( complex_value ) ;

// Display the swapped values. This will display ( -7 + 2i).
cmplxWrite( "( ", "+ ", "i)", writeInt, swap_value );

C.5.4 FixedPoint

Package

import FixedPoint :: * ;

Description

The FixedPoint library package defines a type for representing fixed-point numbers and corresponding functions to operate and manipulate variables of this type.

A fixed-point number represents signed numbers which have a fixed number of binary digits (bits) before and after the binary point. The type constructor for a fixed-point number takes two numeric types as argument; the first (isize) defines the number of bits to the left of the binary point (the integer part), while the second (fsize) defines the number of bits to the right of the binary point, (the fractional part).

The following data structure defines this type, while some utility functions provide the reading of the integer and fractional parts.

typedef struct {
    Bit#(isize) i;
    Bit#(fsize) f;
} FixedPoint#(numeric type isize, numeric type fsize )
deriving( Eq ) ;

This package is provided as both a compiled library package and as BSV source code to facilitate customization. The source code file can be found in the $BLUESPECDIR/BSVSource/Math directory.

To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Types and type classes

The FixedPoint type belongs to the following type classes; Bits, Eq, Literal, RealLiteral, Arith, Ord, Bounded, Bitwise, SaturatingArith, and FShow. Each type class definition includes functions which are then also defined for the data type. The Prelude library definitions (Section B) describes which functions are defined for each type class.

<table>
<thead>
<tr>
<th>Type Classes used by FixedPoint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>FixedPoint</td>
</tr>
</tbody>
</table>

Bits  The type FixedPoint belongs to the Bits type class, which allows conversion from type Bits to type FixedPoint.

instance Bits#( FixedPoint#(isize, fsize), bsize )
    provisos ( Add#(isize, fsize, bsize) );
Literal  The type FixedPoint belongs to the Literal type class, which allows conversion from (compile-time) type Integer to type FixedPoint. Note that only the integer part is assigned.

```verilog
instance Literal#( FixedPoint#(isize, fsize) )
  provisos( Add#(isize, fsize, bsize) );
```

RealLiteral  The type FixedPoint belongs to the RealLiteral type class, which allows conversion from type Real to type FixedPoint.

```verilog
instance RealLiteral#( FixedPoint#(isize, fsize) )
```

Example:

```verilog
FixedPoint#(4,10) mypi = 3.1415926; //Implied fromReal
FixedPoint#(2,14) cx = fromReal(cos(pi/4));
```

Arith  The type FixedPoint belongs to the Arith type class, hence the common infix operators (+, -, *, and /) are defined and can be used to manipulate variables of type FixedPoint. The arithmetic operator % is not defined.

```verilog
instance Arith#( FixedPoint#(isize, fsize) )
  provisos( Add#(isize, fsize, bsize) ) ;
```

For multiplication (*) and quotient (/), the operation is calculated in full precision and the result is then rounded and saturated to the resulting size. Both operators use the rounding function fxptTruncateRoundSat, with mode Rnd_Zero, Sat_Bound.

Ord  In addition to equality and inequality comparisons, FixedPoint variables can be compared by the relational operators provided by the Ord type class. i.e., <, >, <.=, and >.=.

```verilog
instance Ord#( FixedPoint#(isize, fsize) )
  provisos( Add#(isize, fsize, bsize) ) ;
```

Bounded  The type FixedPoint belongs to the Bounded type class. The range of values, $v$, representable with a signed fixed-point number of type FixedPoint#(isize, fsize) is $+(2^{isize-1} - 2^{-fsize}) \leq v \leq -2^{isize-1}$. The function epsilon returns the smallest representable quantum by a specific type, $2^{-fsize}$. For example, a variable $v$ of type FixedPoint#(2,3) type can represent numbers from 1.875 (1\frac{1}{8}) to -2.0 in intervals of $\frac{1}{8} = 0.125$, i.e. epsilon is 0.125. The type FixedPoint#(5,0) is equivalent to Int#(5).

```verilog
instance Bounded#( FixedPoint#(isize, fsize) )
  provisos( Add#(isize, fsize, bsize) ) ;
```

```verilog
function FixedPoint#(isize, fsize) epsilon () ;
```

Bitwise  Left and right shifts are provided for FixedPoint variables as part of the Bitwise type class. Note that the shift right (>>) function does an arithmetic shift, thus preserving the sign of the operand. Note that a right shift of 1 is equivalent to a division by 2, except when the operand is equal to $-\text{epsilon}$. The functions msb and lsb are also provided. The other methods of Bitwise type class are not provided since they have no operational meaning on FixedPoint variables; the use of these generates an error message.

```verilog
instance Bitwise#( FixedPoint#(isize, fsize) )
  provisos( Add#(isize, fsize, bsize) ) ;
```
**SaturatingArith**  The `SaturatingArith` class provides the functions `satPlus`, `satMinus`, `boundedPlus`, and `boundedMinus`. These are modified plus and minus functions which saturate to values defined by the `SaturationMode` when the operations would otherwise overflow or wrap-around.

```verilog
instance SaturatingArith#(FixedPoint#(isize, fsize));
```

**FShow**  The `FShow` class provides the function `fshow` which can be applied to a type to create an associated `Fmt` representation.

```verilog
instance FShow#(FixedPoint#(i,f));
    function Fmt fshow (FixedPoint#(i,f) value);
        Int#(i) i_part = fxptGetInt(value);
        UInt#(f) f_part = fxptGetFrac(value);
        return $format("<FP %b.%b>", i_part, f_part);
    endfunction
endinstance
```

**Functions**

Utility functions are provided to extract the integer and fractional parts.

<table>
<thead>
<tr>
<th><code>fxptGetInt</code></th>
<th>Extracts the integer part of the <code>FixedPoint</code> number.</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>function Int#(isize) fxptGetInt ( FixedPoint#(isize, fsize) x );</code></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><code>fxptGetFrac</code></th>
<th>Extracts the fractional part of the <code>FixedPoint</code> number.</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>function UInt#(fsize) fxptGetFrac ( FixedPoint#(isize, fsize) x );</code></td>
<td></td>
</tr>
</tbody>
</table>

To convert run-time `Int` and `UInt` values to type `FixedPoint`, the following conversion functions are provided. Both of these functions invoke the necessary extension of the source operand.

<table>
<thead>
<tr>
<th><code>fromInt</code></th>
<th>Converts run-time <code>Int</code> values to type <code>FixedPoint</code>.</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>function FixedPoint#(ir,fr) fromInt( Int#(ia) inta )</code></td>
<td></td>
</tr>
<tr>
<td><code>provisos ( Add#(ia, xxA, ir ) ); // ir &gt;= ia</code></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><code>fromUInt</code></th>
<th>Converts run-time <code>UInt</code> values to type <code>FixedPoint</code>.</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>function FixedPoint#(ir,fr) fromUInt( UInt#(ia) uinta )</code></td>
<td></td>
</tr>
<tr>
<td><code>provisos ( Add#(ia, 1, i1a), // i1a = ia + 1</code></td>
<td></td>
</tr>
<tr>
<td><code>Add#(ia1,xxB, ir ) ); // ir &gt;= i1a</code></td>
<td></td>
</tr>
</tbody>
</table>
Non-integer compile time constants may be specified by a rational number which is a ratio of two integers. For example, one-third may be specified by fromRational(1,3).

fromRational

Specify a FixedPoint with a rational number which is the ratio of two integers.

<table>
<thead>
<tr>
<th>fromRational</th>
</tr>
</thead>
<tbody>
<tr>
<td>function FixedPoint#(isize, fsize) fromRational(</td>
</tr>
<tr>
<td>Integer numerator, Integer denominator)</td>
</tr>
<tr>
<td>provisos ( Add#(isize, fsize, bsize ) ) ;</td>
</tr>
</tbody>
</table>

At times, full precision Arithmetic functions may be required, where the operands are not the same type (sizes), as is required for the infix Arith operators. These functions do not overflow on the result.

fxptAdd

Function for full precision addition. The operands do not have to be of the same type (size) and there is no overflow on the result.

<table>
<thead>
<tr>
<th>fxptAdd</th>
</tr>
</thead>
<tbody>
<tr>
<td>function FixedPoint#(ri,rf) fxptAdd( FixedPoint#(ai,af) a,</td>
</tr>
<tr>
<td>FixedPoint#(bi,bf) b )</td>
</tr>
<tr>
<td>provisos (Max#(ai,bi,rim)   // ri = 1 + max(ai, bi)</td>
</tr>
<tr>
<td>,Add#(1,rim, ri)</td>
</tr>
<tr>
<td>,Max#(af,bf,rf));   // rf = max (af, bf)</td>
</tr>
</tbody>
</table>

fxptSub

Function for full precision subtraction where the operands do not have to be of the same type (size) and there is no overflow on the result.

<table>
<thead>
<tr>
<th>fxptSub</th>
</tr>
</thead>
<tbody>
<tr>
<td>function FixedPoint#(ri,rf) fxptSub( FixedPoint#(ai,af) a,</td>
</tr>
<tr>
<td>FixedPoint#(bi,bf) b )</td>
</tr>
<tr>
<td>provisos (Max#(ai,bi,rim)   // ri = 1 + max(ai, bi)</td>
</tr>
<tr>
<td>,Add#(1,rim, ri)</td>
</tr>
<tr>
<td>,Max#(af,bf,rf));   // rf = max (af, bf)</td>
</tr>
</tbody>
</table>

fxptMult

Function for full precision multiplication, where the result is the sum of the field sizes of the operands. The operands do not have to be of the same type (size).

<table>
<thead>
<tr>
<th>fxptMult</th>
</tr>
</thead>
<tbody>
<tr>
<td>function FixedPoint#(ri,rf) fxptMult( FixedPoint#(ai,af) x,</td>
</tr>
<tr>
<td>FixedPoint#(bi,bf) y )</td>
</tr>
<tr>
<td>provisos ( Add#(ai,bi,ri)   // ri = ai + bi</td>
</tr>
<tr>
<td>,Add#(af,bf,rf)   // rf = af + bf</td>
</tr>
<tr>
<td>,Add#(ai,af,ab)</td>
</tr>
<tr>
<td>,Add#(bi,bf,bb)</td>
</tr>
<tr>
<td>,Add#(ab,bb,rb)</td>
</tr>
<tr>
<td>,Add#(ri,rf,rb) ) ;</td>
</tr>
</tbody>
</table>
**fxptQuot**

Function for full precision division where the operands do not have to be of the same type (size).

```vhdl
function FixedPoint#(ri,rf) fxptQuot (FixedPoint#(ai,af) a,
                                         FixedPoint#(bi,bf) b )
  provisos (Add#(ai1,bf,ri) // ri = ai + bf + 1
           ,Add#(ai,1,ai1)
           ,Add#(af,_xf,rf)); // rf >= af
```

**fxptTruncate** is a general truncate function which converts variables to `FixedPoint#(ai,af)` to type `FixedPoint#(ri,rf)`, where \( ai \geq ri \) and \( af \geq rf \). This function truncates bits as appropriate from the most significant integer bits and the least significant fractional bits.

```vhdl
function FixedPoint#(ri,rf) fxptTruncate( FixedPoint#(ai,af) a )
  provisos (Add#(xxA,ri,ai), // ai >= ri
             Add#(xxB,rf,af)); // af >= rf
```

Two saturating fixed-point truncation functions are provided: `fxptTruncateSat` and `fxptTruncateRoundSat`. They both use the `SaturationMode`, defined in Section B.1.12, to determine the final result.

```vhdl
typef enum { Sat_Wrap,
             ,Sat_Bound
             ,Sat_Zero
             ,Sat_Symmetric
         } SaturationMode deriving (Bits, Eq);
```

**fxptTruncateSat**

A saturating fixed point truncation. If the value cannot be represented in its truncated form, an alternate value, `minBound` or `maxBound`, is selected based on `smode`.

```vhdl
function FixedPoint#(ri,rf) fxptTruncateSat ( SaturationMode smode, FixedPoint#(ai,af) din)
  provisos (Add#(ri,idrop,ai)
           ,Add#(rf,_f,af));
```

The function `fxptTruncateRoundSat` rounds the saturated value, as determined by the value of `rmode` of type `RoundMode`. The rounding only applies to the truncation of the fractional component of the fixed-point number, though it may cause a wrap or overflow to the integer component which requires saturation.
A saturating fixed point truncate function which rounds the truncated fractional component as determined by the value of \( rmode \) (RoundMode). If the final value cannot be represented in its truncated form, the \( \text{minBound} \) or \( \text{maxBound} \) value is returned.

```vhdl
function FixedPoint#(ri,rf) fxptTruncateRoundSat
  (RoundMode rmode, SaturationMode smode,
   FixedPoint#(ai,af) din)
  provisos (Add#(ri,idrop,ai)
    ,Add#(rf,fdrop,af) );
```

typedef enum {
  Rnd_Plus_Inf,
  Rnd_Zero,
  Rnd_Minus_Inf,
  Rnd_Inf,
  Rnd_Conv,
  Rnd_Truncate,
  Rnd_Truncate_Zero
} RoundMode deriving (Bits, Eq);

These modes are equivalent to the SystemC values shown in the table below. The rounding mode determines how the value is rounded when the truncated value is equidistant between two representable values.

<table>
<thead>
<tr>
<th>Rounding Modes</th>
<th>SystemC Equivalent</th>
<th>Description</th>
<th>Action when truncated value equidistant between values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rnd_Plus_Inf</td>
<td>SC_RND</td>
<td>Round to plus infinity</td>
<td>Always increment</td>
</tr>
<tr>
<td>Rnd_Zero</td>
<td>SC_RND_ZERO</td>
<td>Round to zero</td>
<td>Move towards reduced magnitude (decrement positive value, increment negative value)</td>
</tr>
<tr>
<td>Rnd_Minus_Inf</td>
<td>SC_RND_MIN_INF</td>
<td>Round to minus infinity</td>
<td>Always decrement</td>
</tr>
<tr>
<td>Rnd_Inf</td>
<td>SC_RND_INF</td>
<td>Round to infinity</td>
<td>Always increase magnitude</td>
</tr>
<tr>
<td>Rnd_Conv</td>
<td>SC_RND_CONV</td>
<td>Round to convergence</td>
<td>Alternate increment and decrement based on even and odd values</td>
</tr>
<tr>
<td>Rnd_Truncate</td>
<td>SC_TRN</td>
<td>Truncate, no rounding</td>
<td></td>
</tr>
<tr>
<td>Rnd_Truncate_Zero</td>
<td>SC_TRN_ZERO</td>
<td>Truncate to zero</td>
<td>Move towards reduced magnitude</td>
</tr>
</tbody>
</table>

Consider what happens when you apply the function \( \text{fxptTruncateRoundSat} \) to a fixed-point number. The least significant fractional bits are dropped. If the dropped bits are non-zero, the remaining fractional component rounds towards the nearest representable value. If the remaining component is exactly equidistant between two representable values, the rounding mode \( rmode \) determines whether the value rounds up or down.

The following table displays the rounding value added to the LSB of the remaining fractional component. When the value is equidistant \((1/2)\), the algorithm may be dependent on whether the value of the variable is positive or negative.
### Rounding Value added to LSB of Remaining Fractional Component

<table>
<thead>
<tr>
<th>RoundMode</th>
<th>Value of Truncated Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 1/2</td>
</tr>
<tr>
<td></td>
<td>Pos</td>
</tr>
<tr>
<td>Rnd_Plus_Inf</td>
<td>0</td>
</tr>
<tr>
<td>Rnd_Zero</td>
<td>0</td>
</tr>
<tr>
<td>Rnd_Minus_Inf</td>
<td>0</td>
</tr>
<tr>
<td>Rnd_Inf</td>
<td>0</td>
</tr>
<tr>
<td>Rnd_Conv</td>
<td></td>
</tr>
<tr>
<td>Remaining LSB = 0</td>
<td>0</td>
</tr>
<tr>
<td>Remaining LSB = 1</td>
<td>0</td>
</tr>
</tbody>
</table>

The final two modes are truncates and are handled differently. The **Rnd_Truncate** mode simply drops the extra bits without changing the remaining number. The **Rnd_Truncate_Zero** mode decreases the magnitude of the variable, moving the value closer to 0. If the number is positive, the function simply drops the extra bits, if negative, 1 is added.

<table>
<thead>
<tr>
<th>RoundMode</th>
<th>Sign of Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rnd_Truncate</td>
<td>0</td>
<td>Truncate extra bits, no rounding</td>
</tr>
<tr>
<td>Rnd_Truncate_Zero</td>
<td>0, 1</td>
<td>Add 1 to negative number if truncated bits are non-zero</td>
</tr>
</tbody>
</table>

Example: Truncated values by Round type, where argument is `FixedPoint#(2,3)` type and result is a `FixedPoint#(2,1)` type. In this example, we’re rounding to the nearest 1/2, as determined by RoundMode.

<table>
<thead>
<tr>
<th>Argument</th>
<th>RoundMode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Binary</td>
</tr>
<tr>
<td>10.001</td>
<td>10.001</td>
</tr>
<tr>
<td>10.110</td>
<td>10.110</td>
</tr>
<tr>
<td>11.101</td>
<td>11.101</td>
</tr>
<tr>
<td>00.011</td>
<td>00.011</td>
</tr>
<tr>
<td>01.001</td>
<td>01.001</td>
</tr>
<tr>
<td>01.111</td>
<td>01.111</td>
</tr>
</tbody>
</table>

**fxptSignExtend**

A general sign extend function which converts variables of type `FixedPoint#(ai,af)` to type `FixedPoint#(ri,rf)`, where $ai \leq ri$ and $af \leq rf$. The integer part is sign extended, while additional 0 bits are added to least significant end of the fractional part.

```verilog
function FixedPoint#(ri,rf) fxptSignExtend( 
    FixedPoint#(ai,af) a )
provisos( Add#(xxA,ai,ri), // ri >= ai 
    Add#(fdiff,af,rf)); // rf >= af
```
### fxptZeroExtend

A general zero extend function.

```systemverilog
function FixedPoint#(ri,rf) fxptZeroExtend(
    FixedPoint#(ai,af) a )
provisos( Add#(xxA,ai,ri), // ri >= ai
         Add#(xB,af,rf)); // rf >= af
```

Displaying `FixedPoint` values in a simple bit notation would result in a difficult to read pattern. The following write utility function is provided to ease in their display. Note that the use of this function adds many multipliers and adders into the design which are only used for generating the output and not the actual circuit.

### fxptWrite

Displays a `FixedPoint` value in a decimal format, where `fwidth` give the number of digits to the right of the decimal point. `fwidth` must be in the inclusive range of 0 to 10. The displayed result is truncated without rounding.

```systemverilog
function Action fxptWrite( Integer fwidth,
        FixedPoint#(isize, fsize) a )
provisos( Add#(i, f, b),
         Add#(33,f,ff)); // 33 extra bits for computations.
```

**Examples - Fixed Point Numbers**

// The following code writes "x is 0.5156250"
FixedPoint#(1,6) x = half + epsilon ;
$write( "x is " ) ; fxptWrite( 7, x ) ; $display(" ");

A Real value can automatically be converted to a `FixedPoint` value:

FixedPoint#(3,10) foo = 2e-3;

FixedPoint#(2,3) x = 1.625 ;

### C.5.5 NumberTypes

**Package**

```systemverilog
import NumberTypes :: * ;
```

**Description**

The `NumberTypes` package defines two new number types for use as index types: `BuffIndex` and `WrapNumber`.

A `BuffIndex#(sz, ln)` is an unsigned integer which wraps around, where `sz` is the number of bits in its representation and `ln` is the size of the buffer it is to index. Often `sz` will be `TLog#(ln)`. `BuffIndex` is intended to be used as the index type for buffers of arbitrary size. The values of `BuffIndex` are not ordered; you cannot determine which of two values is ahead of the other because of the wrap-around.
A `WrapNumber#(sz)` is an unsigned integer which wraps around, where `sz` is the number of bits in its representation. The range is the entire value space (i.e. $2^{sz}$), but should be used in situations where at any time all valid values are in at most half of that space. The ordering of values can be defined taking wrap-around into account, so that the nearer distance apart is used to determine which value is ahead of the other.

This package is provided as both a compiled library package and as BSV source code to facilitate customization. The source code file can be found in the `$BLUESPECDIR/BSVSource/Math` directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the `-p` option as described in the BSV Users Guide.

Types and type classes

A `BuffIndex` has two numeric type parameters: the size in bits of the representation (`sz`), and the length of the buffer it is to index (`ln`).

```haskell
typedef struct { UInt#(sz) bix; } BuffIndex#(numeric type sz, numeric type ln)
   deriving (Bits, Eq);
```

A `WrapNumber#(sz)` has a single numeric type parameter, `sz`, which is the size in bits of the representation.

```haskell
typedef struct { UInt#(sz) wn; } WrapNumber#(numeric type sz)
   deriving (Bits, Eq, Arith, Literal, Bounded);
```

Both types belong to the `Bits`, `Eq`, `Arith`, and `Literal` typeclasses. The `WrapNumber` type also belongs to the `Ord` typeclass. Each type class definition includes functions which are then also defined for the data type. The Prelude library definitions (Section B) describes which functions are defined for each type class.

<table>
<thead>
<tr>
<th>Type Classes used by BuffIndex and WrapNumber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>WrapNumber</td>
</tr>
<tr>
<td>BuffIndex</td>
</tr>
</tbody>
</table>

**Literal**  Both `BuffIndex` and `WrapNumber` belong to the `Literal` typeclass, which allows conversion from (compile-time) type `Integer` to these types.

For the `BuffIndex` type, the `fromInteger` and `inLiteralRange` functions are defined as:

```haskell
instance Literal#(BuffIndex#(sz,ln));
   function fromInteger(i) = BuffIndex {bix: fromInteger(i) };
   function inLiteralRange(x,i) = (i>=0 && i < valueof(ln));
endinstance
```

**Arith**  The type class `Arith` defines the common infix operators. Addition and subtraction are the only meaningful arithmetic operations for `WrapNumber` and `BuffIndex`.  

318
Ord  WrapNumber belongs to the Ord typeclass, so values of WrapNumber can be compared by the relational operators <, >, <=, and >=. Since the ordering of WrapNumber types takes into account wrap-around, the nearer distance apart is used to determine which value is ahead of the other.

Functions

Utility functions to convert a BuffIndex to a UInt and for adding and subtracting BuffIndex and UInt values are provided.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>unwrapBI</td>
<td>Converts a BuffIndex to a UInt</td>
<td>function UInt#(sz) unwrapBI(BuffIndex#(sz,ln) x);</td>
</tr>
<tr>
<td>addBIUInt</td>
<td>Adds a UInt to a BuffIndex, returning a BuffIndex</td>
<td>function BuffIndex#(sz,ln) addBIUInt(BuffIndex#(sz,ln) bin, UInt#(sz) i);</td>
</tr>
<tr>
<td>sbtrctBIUInt</td>
<td>Subtracts a UInt from a BuffIndex, returning a BuffIndex</td>
<td>function BuffIndex#(sz,ln) sbtrctBIUInt(BuffIndex#(sz,ln) bin, UInt#(sz) i);</td>
</tr>
</tbody>
</table>

Utility functions to convert between a WrapNumber and a UInt, and a function to add a UInt to a WrapNumber are provided.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>wrap</td>
<td>Converts a UInt to a WrapNumber</td>
<td>function WrapNumber#(sz) wrap(UInt#(sz) x);</td>
</tr>
<tr>
<td>unwrap</td>
<td>Converts a WrapNumber to a UInt</td>
<td>function UInt#(sz) unwrap(WrapNumber#(sz) x);</td>
</tr>
<tr>
<td>addUInt</td>
<td>Adds a UInt to a WrapNumber, returning a WrapNumber</td>
<td>function WrapNumber#(sz) addUInt(WrapNumber#(sz) wn, UInt#(sz) i);</td>
</tr>
</tbody>
</table>

C.6 FSM

C.6.1 StmtFSM

Package

import StmtFSM :: *;
Description

The StmtFSM package provides a procedural way of defining finite state machines (FSMs) which are automatically synthesized.

First, one uses the Stmt sublanguage to compose the actions of an FSM using sequential, parallel, conditional and looping structures. This sublanguage is within the expression syntactic category, i.e., a term in the sublanguage is an expression whose value is of type Stmt. This value can be bound to identifiers, passed as arguments and results of functions, held in static data structures, etc., like any other value. Finally, the FSM can be instantiated into hardware, multiple times if desired, by passing the Stmt value to the module constructor mkFSM. The resulting module interface has type FSM, which has methods to start the FSM and to wait until it completes.

The Stmt sublanguage

The state machine is automatically constructed from the procedural description given in the Stmt definition. Appropriate state counters are created and rules are generated internally, corresponding to the transition logic of the state machine. The use of rules for the intermediate state machine generation ensures that resource conflicts are identified and resolved, and that implicit conditions are properly checked before the execution of any action.

The names of generated rules (which may appear in conflict warnings) have suffixes of the form “1<nn><nn>”, where the <nn> are line or column numbers, referring to the statement which gave rise to the rule.

A term in the Stmt sublanguage is an expression, introduced at the outermost level by the keywords seq or par. Note that within the sublanguage, if, while and for statements are interpreted as statements in the sublanguage and not as ordinary statements, except when enclosed within action/endaction keywords.

```
exprPrimary ::= seqFsmStmt | parFsmStmt

fsmStmt ::= exprFsmStmt
  | seqFsmStmt
  | parFsmStmt
  | ifFsmStmt
  | whileFsmStmt
  | repeatFsmStmt
  | forFsmStmt
  | returnFsmStmt

exprFsmStmt ::= regWrite ;
  | expression ;

seqFsmStmt ::= seq fsmStmt { fsmStmt } endseq

parFsmStmt ::= par fsmStmt { fsmStmt } endpar

ifFsmStmt ::= if expression fsmStmt
  [ else fsmStmt ]

whileFsmStmt ::= while ( expression )
  loopBodyFsmStmt

forFsmStmt ::= for ( fsmStmt ; expression ; fsmStmt )
  loopBodyFsmStmt

returnFsmStmt ::= return ;

repeatFsmStmt ::= repeat ( expression )
  loopBodyFsmStmt
```
The simplest kind of statement is an `exprFsmStmt`, which can be a register assignment or, more generally, any expression of type `Action` (including action method calls and `action-endaction` blocks or of type `Stmt`). Statements of type `Action` execute within exactly one clock cycle, but of course the scheduling semantics may affect exactly which clock cycle it executes in. For example, if the actions in a statement interfere with actions in some other rule, the statement may be delayed by the schedule until there is no interference. In all the descriptions of statements below, the descriptions of time taken by a construct are minimum times; they could take longer because of scheduling semantics.

Statements can be composed into sequential, parallel, conditional and loop forms. In the sequential form (`seq-endseq`), the contained statements are executed one after the other. The `seq` block terminates when its last contained statement terminates, and the total time (number of clocks) is equal to the sum of the individual statement times.

In the parallel form (`par-endpar`), the contained statements (“threads”) are all executed in parallel. Statements in each thread may or may not be executed simultaneously with statements in other threads, depending on scheduling conflicts; if they cannot be executed simultaneously they will be interleaved, in accordance with normal scheduling. The entire `par` block terminates when the last of its contained threads terminates, and the minimum total time (number of clocks) is equal to the maximum of the individual thread times.

In the conditional form (`if (b) s_1 else s_2`), the boolean expression `b` is first evaluated. If true, `s_1` is executed, otherwise `s_2` (if present) is executed. The total time taken is `t` cycles, if the chosen branch takes `t` cycles.

In the `while (b) s` loop form, the boolean expression `b` is first evaluated. If true, `s` is executed, and the loop is repeated. Each time the condition evaluates true, the loop body is executed, so the total time is `n × t` cycles, where `n` is the number of times the loop is executed (possibly zero) and `t` is the time for the loop body statement.

The `for (s_1;b;s_2) s_B` loop form is equivalent to:

```
s_1; while (b) seq s_B; s_2 endseq
```

i.e., the initializer `s_1` is executed first. Then, the condition `b` is executed and, if true, the loop body `s_B` is executed followed by the “increment” statement `s_2`. The `b`, `s_B`, `s_2` sequence is repeated as long as `b` evaluates true.

Similarly, the `repeat (n) s_B` loop form is equivalent to:

```
while (repeat_count < n) seq s_B; repeat_count <= repeat_count + 1 endseq
```

where the value of `repeat_count` is initialized to 0. During execution, the condition `(repeat_count < n)` is executed and, if true, the loop body `s_B` is executed followed by the “increment” statement `repeat_count <= repeat_count + 1`. The sequence is repeated as long as `repeat_count < n` evaluates true.

In all the loop forms, the loop body statements can contain the keywords `continue` or `break`, with the usual semantics, i.e., `continue` immediately jumps to the start of the next iteration, whereas `break` jumps out of the loop to the loop sequel.

It is important to note that this use of loops, within a `Stmt` context, expresses time-based (temporal) behavior.

**Interfaces and Methods**
Two interfaces are defined with this package, **FSM** and **Once**. The **FSM** interface defines a basic state machine interface while the **Once** interface encapsulates the notion of an action that should only be performed once. A **Stmt** value can be instantiated into a module that presents an interface of type **FSM**.

There is a one clock cycle delay after the **start** method is asserted before the FSM starts. This insulates the **start** method from many of the FSM schedule constraints that change depending on what computation is included in each specific FSM. Therefore, it is possible that the StmtFSM is enabled when the **start** method is called, but not on the next cycle when the FSM actually starts. In this case, the FSM will stall until the conditions allow it to continue.

<table>
<thead>
<tr>
<th>Interfaces</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSM</td>
<td>The state machine interface</td>
<td></td>
</tr>
<tr>
<td>Once</td>
<td>Used when an action should only be performed once</td>
<td></td>
</tr>
</tbody>
</table>

- **FSM Interface**

The **FSM** interface provides four methods; **start**, **waitTillDone**, **done** and **abort**. Once instantiated, the FSM can be started by calling the **start** method. One can wait for the FSM to stop running by waiting explicitly on the boolean value returned by the **done** method. The **done** method is **True** before the FSM has run the first time. Alternatively, one can use the **waitTillDone** method in any action context (including from within another FSM), which (because of an implicit condition) cannot execute until this FSM is done. The user must not use **waitTillDone** until after the FSM has been started because the FSM comes out of a reset as **done**. The **abort** method immediately exits the execution of the FSM.

```verilog
interface FSM;
    method Action start();
    method Action waitTillDone();
    method Bool done();
    method Action abort();
endinterface: FSM
```

<table>
<thead>
<tr>
<th>FSM Interface</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Type</td>
</tr>
<tr>
<td>start</td>
<td>Action</td>
</tr>
<tr>
<td>waitTillDone</td>
<td>Action</td>
</tr>
<tr>
<td>done</td>
<td>Bool</td>
</tr>
<tr>
<td>abort</td>
<td>Action</td>
</tr>
</tbody>
</table>

- **Once Interface**

The **Once** interface encapsulates the notion of an action that should only be performed once. The **start** method performs the action that has been encapsulated in the **Once** module. After **start** has been called **start** cannot be called again (an implicit condition will enforce this). If the **clear** method is called, the **start** method can be called once again.

```verilog
interface Once;
    method Action start();
    method Action clear();
    method Bool done();
endinterface: Once
```
### Once Interface

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>start</td>
<td>Action</td>
<td>Performs the action that has been encapsulated in the Once module, but once start has been called it cannot be called again (an implicit condition will enforce this).</td>
</tr>
<tr>
<td>clear</td>
<td>Action</td>
<td>If the clear method is called, the start method can be called once again.</td>
</tr>
<tr>
<td>done</td>
<td>Bool</td>
<td>Asserted when the state machine is done and is ready to rerun.</td>
</tr>
</tbody>
</table>

### Modules

Instantiation is performed by passing a Stmt value into the module constructor mkFSM. The state machine is automatically constructed from the procedural description given in the definition described by state machine of type Stmt named seq_stmt. During construction, one or more registers of appropriate widths are created to track state execution. Upon start action, the registers are loaded and subsequent state changes then decrement the registers.

```verilog
module mkFSM#( Stmt seq_stmt ) ( FSM );
```

The mkFSMWithPred module is like mkFSM above, except that the module constructor takes an additional boolean argument (the predicate). The predicate condition is added to the condition of each rule generated to create the FSM. This capability is useful when using the FSM in conjunction with other rules and/or FSMs. It allows the designer to explicitly specify to the compiler the conditions under which the FSM will run. This can be used to eliminate spurious rule conflict warnings (between rules in the FSM and other rules in the design).

```verilog
module mkFSMWithPred#( Stmt seq_stmt, Bool pred ) ( FSM );
```

The mkAutoFSM module is also like mkFSM above, except the state machine runs automatically immediately after reset and a $finish(0) is called upon completion. This is useful for test benches. Thus, it has no interface, that is, it has an empty interface.

```verilog
module mkAutoFSM#( seq_stmt ) ();
```

The mkOnce function is used to create a Once interface where the action argument has been encapsulated and will be performed when start is called.

```verilog
module mkOnce#( Action a ) ( Once );
```

The implementation for Once is a 1 bit state machine (with a state register named onceReady) allowing the action argument to occur only one time. The ready bit is initially True and then cleared when the action is performed. It might not be performed right away, because of implicit conditions or scheduling conflicts.
### Function Declaration

<table>
<thead>
<tr>
<th>Name</th>
<th>Function Declaration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>awaiting</td>
<td>function Action awaiting( Bool cond ) ;</td>
<td>Creates an Action which does nothing, but can only execute when the condition is True.</td>
</tr>
<tr>
<td>delay</td>
<td>function Stmt delay( a_type value ) ;</td>
<td>Creates a Stmt which executes noAction for value number of cycles. a_type must be in the Arith class and Bits class and (&lt; ) 32 bits.</td>
</tr>
</tbody>
</table>

### Example - Initializing a single-ported SRAM.

Since the SRAM has only a single port, we can write to only one location in each clock. Hence, we need to express a temporal sequence of writes for all the locations to be initialized.

```verilog
Reg#(int) i <- mkRegU; // instantiate register with interface i
Reg#(int) j <- mkRegU; // instantiate register with interface j

// Define fsm behavior
Stmt s = seq
    for (i <= 0; i < M; i <= i + 1)
        for (j <= 0; j < N; j <= j + 1)
            sram.write (i, j, i+j);
```
endseq;

FSM fsm(); // instantiate FSM interface
mkFSM#(s) (fsm); // create fsm with interface fsm and behavior s

... rule initSRAM (start_reset);
  fsm.start; // Start the fsm
endrule

When the start_reset signal is true, the rule kicks off the SRAM initialization. Other rules can wait on fsm.done, if necessary, for the SRAM initialization to be completed.

In this example, the seq-endseq brackets are used to enter the Stmt sublanguage, and then for represents Stmt sequencing (instead of its usual role of static generation). Since seq-endseq contains only one statement (the loop nest), par-endpar brackets would have worked just as well.

Example - Defining and instantiating a state machine.

import StmtFSM :: *;
import FIFO :: *;

module testSizedFIFO();

  // Instantiation of DUT
  FIFO#(Bit#(16)) dut <- mkSizedFIFO(5);

  // Instantiation of reg's i and j
  Reg#(Bit#(4)) i <- mkRegA(0);
  Reg#(Bit#(4)) j <- mkRegA(0);

  // Action description with stmt notation
  Stmt driversMonitors =
    (seq
      // Clear the fifo
      dut.clear;

      // Two sequential blocks running in parallel
      par
        // Enque 2 times the Fifo Depth
        for(i <= 1; i <= 10; i <= i + 1)
          seq
            dut.enq({0,i});
            $display(" Enque %d", i);
          endseq

        // Wait until the fifo is full and then deque
        seq
          while (i < 5)
            seq
              noAction;
            endseq

          while (i <= 10)
            action
dut.deq;
$display("Value read \%d", dut.first);
endaction
endseq
endpar

$finish(0);
endseq);

// stmt instantiation
FSM test <- mkFSM(driversMonitors);

// A register to control the start rule
Reg#(Bool) going <- mkReg(False);

// This rule kicks off the test FSM, which then runs to completion.
rule start (!going);
    going <= True;
    test.start;
endrule
endmodule

Example - Defining and instantiating a state machine to control speed changes
import StmtFSM::*;
import Common::*;

interface SC_FSM_ifc;
    method Speed xcvrspeed;
    method Bool devices_ready;
    method Bool out_of_reset;
endinterface

module mkSpeedChangeFSM(Speed new_speed, SC_FSM_ifc ifc);
    Speed initial_speed = FS;

    Reg#(Bool) outofReset_reg <- mkReg(False);
    Reg#(Bool) devices_ready_reg <- mkReg(False);
    Reg#(Speed) device_xcvr_speed_reg <- mkReg(initial_speed);

    // the following lines define the FSM using the Stmt sublanguage
    // the state machine is of type Stmt, with the name speed_change_stmt
    Stmt speed_change_stmt =
        (seq
            action outofReset_reg <= False; devices_ready_reg <= False; endaction
            noAction; noAction; // same as: delay(2);

            device_xcvr_speed_reg <= new_speed;
            noAction; noAction; // same as: delay(2);

            outofReset_reg <= True;
            if (device_xcvr_speed_reg==HS)
                seq noAction; noAction; endseq
            // or seq delay(2); endseq
else
    seq noAction; noAction; noAction; noAction; noAction; noAction; endseq
    // or seq delay(6); endseq
devices_ready_reg <= True;
endseq);
// end of the state machine definition

// the statemachine is instantiated using mkFSM
FSM speed_change_fsm <- mkFSM(speed_change_stmt);

// the rule change_speed starts the state machine
// the rule checks that previous actions of the state machine have completed
rule change_speed ((device_xcvr_speed_reg != new_speed || !outofReset_reg) &
    speed_change_fsm.done);
        speed_change_fsm.start;
endrule

method xcvrspeed = device_xcvr_speed_reg;
method devices_ready = devices_ready_reg;
method out_of_reset = outofReset_reg;
endmodule

Example - Defining a state machine and using the await function

// This statement defines this brick’s desired behavior as a state machine:
// the subcomponents are to be executed one after the other:
Stmt brickAprog =
    seq
    // Since the following loop will be executed over many clock
    // cycles, its control variable must be kept in a register:
    for (i <= 0; i < 0-1; i <= i+1)
        // This sequence requests a RAM read, changing the state;
        // then it receives the response and resets the state.
        seq
            action
                // This action can only occur if the state is Idle
                // the await function will not let the statements
                // execute until the condition is met
                await(ramState==Idle);
                ramState <= DesignReading;
                ram.request.put(tagged Read i);
            endaction
            action
                let rs <- ram.response.get();
                ramState <= Idle;
                obufin.put(truncate(rs));
            endaction
        endseq
        // Wait a little while:
        for (i <= 0; i < 200; i <= i+1)
            action
        endaction
        // Set an interrupt:
        action
            inrpt.set;
endaction
endseq

// end of the state machine definition

FSM brickAfsm <- mkFSM#(brickAprog); // instantiate the state machine

// A register to remember whether the FSM has been started:
Reg#(Bool) notStarted();
mkReg#(True) the_notStarted(notStarted);

// The rule which starts the FSM, provided it hasn’t been started
// previously and the brick is enabled:
rule start_Afsm (notStarted && enabled);
  brickAfsm.start; // start the state machine
  notStarted <= False;
endrule

Creating FSM Server Modules

Instantiation of an FSM server module is performed in a manner analogous to that of a standard FSM
module constructor (such as mkFSM). Whereas mkFSM takes a Stmt value as an argument, however,
mkFSMServer takes a function as an argument. More specifically, the argument to mkFSMServer is a
function which takes an argument of type a and returns a value of type RStmt#(b).

module mkFSMServer#(function RStmt#(b) seq_func (a input)) ( FSMServer#(a, b) );

The RStmt type is a polymorphic generalization of the Stmt type. A sequence of type RStmt#(a)
allows valued return statements (where the return value is of type a). Note that the Stmt type is
equivalent to RStmt#(Bit#(0)).

typedef RStmt#(Bit#(0)) Stmt;

The mkFSMServer module constructor provides an interface of type FSMServer#(a, b).

interface FSMServer#(type a, type b);
  interface Server#(a, b) server;
  method Action abort();
endinterface

The FSMServer interface has one subinterface of type Server#(a, b) (from the ClientServer
package) as well as an Action method called abort; The abort method allows the FSM inside the
FSMServer module to be halted if the client FSM is halted.

An FSMServer module is accessed using the callServer function from within an FSM statement
block. callServer takes two arguments. The first is the interface of the FSMServer module. The
second is the input value being passed to the module.

result <- callServer(serv_ifc, value);

Note the special left arrow notation that is used to pass the server result to a register (or more
generally to any state element with a Reg interface). A simple example follows showing the definition
and use of a mkFSMServer module.

Example - Defining and instantiating an FSM Server Module
// State elements to provide inputs and store results
Reg#(Bit#(8)) count <- mkReg(0);
Reg#(Bit#(16)) partial <- mkReg(0);
Reg#(Bit#(16)) result <- mkReg(0);

// A function which creates a server sequence to scale a Bit#(8)
// input value by an integer scale factor. The scaling is accomplished
// by a sequence of adds.
function RStmt#(Bit#(16)) scaleSeq (Integer scale, Bit#(8) value);
  seq
    partial <= 0;
    repeat (fromInteger(scale))
      action
        partial <= partial + {0,value};
      endaction
    return partial;
  endseq;
endfunction

// Instantiate a server module to scale the input value by 3
FSMServer#(Bit#(8), Bit#(16)) scale3_serv <- mkFSMServer(scaleSeq(3));

// A test sequence to apply the server
let test_seq = seq
  result <- callServer(scale3_serv, count);
  count <= count + 1;
endseq;

let test_fsm <- mkFSM(test_seq);

// A rule to start test_fsm
rule start;
  test_fsm.start;
endrule
// finish after 6 input values
rule done (count == 6);
  $finish;
endrule

C.7 Connectivity

The packages in this section provide useful components, primarily interfaces, to connect hardware
elements in a design.

The basic interfaces, Get and Put are defined in the package GetPut. The typeclass Connectable
indicates that two related types can be connected together. The package ClientServer provides
interfaces using Get and Put for modules that have a request-response type of interface. The package
CGetPut defines a type of the Get and Put interfaces that is implemented with a credit based FIFO.

C.7.1 GetPut

Package

import GetPut :: *;
**Description**

A common paradigm between two blocks is the get/put mechanism: one side *gets* or retrieves an item from an interface and the other side *puts* or gives an item to an interface. These types of interfaces are used in *Transaction Level Modeling* or TLM for short. This pattern is so common in system design that BSV provides the `GetPut` library package for this purpose.

The `GetPut` package provides basic interfaces to implement the TLM paradigm, along with interface transformer functions and modules to transform to/from FIFO implementations. The `ClientServer` package in Section C.7.3 defines more complex interfaces based on the `Get` and `Put` interfaces to support request-response interfaces. The `GetPut` package must be imported when using the `ClientServer` package.

**Typeclasses**

The `GetPut` package defines two typeclasses: `ToGet` and `ToPut`. The types with instances defined in these typeclasses provide the functions `toGet` and `toPut`, used to create associated `Get` and `Put` interfaces from these other types.

`ToGet` defines the class to which the function `toGet` can be applied to create an associated `Get` interface.

```haskell
typeclass ToGet#(a, b);
    function Get#(b) toGet(a ax);
endtypeclass
```

`ToPut` defines the class to which the function `toPut` can be applied to create an associated `Put` interface.

```haskell
typeclass ToPut#(a, b);
    function Put#(b) toPut(a ax);
endtypeclass
```

Instances of `ToGet` and `ToPut` are defined for the following interfaces:

<table>
<thead>
<tr>
<th>Type (Interface)</th>
<th>Defined Instances for ToGet and ToPut</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>toGet ✓</td>
<td>toGet returns value a</td>
</tr>
<tr>
<td>ActionValue#(a)</td>
<td>toGet ✓</td>
<td>toGet performs the Action and returns the value</td>
</tr>
<tr>
<td>function Action fn(a)</td>
<td>✓</td>
<td>toPut calls Action function fn with argument a</td>
</tr>
<tr>
<td>Get#(a)</td>
<td>✓</td>
<td>identity function: returns Get#(a)</td>
</tr>
<tr>
<td>Put#(a)</td>
<td>✓</td>
<td>identity function: returns Put#(a)</td>
</tr>
<tr>
<td>Reg#(a)</td>
<td>✓</td>
<td>toGet returns _read, toPut calls _write</td>
</tr>
<tr>
<td>RWire#(a)</td>
<td>✓</td>
<td>toGet returns wget, toPut calls wset</td>
</tr>
<tr>
<td>ReadOnly#(a)</td>
<td>✓</td>
<td>toGet returns _read</td>
</tr>
<tr>
<td>FIFO#(a)</td>
<td>✓</td>
<td>toGet calls deq returns first, toPut calls enq</td>
</tr>
<tr>
<td>FIFO#(a)</td>
<td>✓</td>
<td>toGet calls deq returns first, toPut calls enq</td>
</tr>
<tr>
<td>SyncFIFOIfc#(a)</td>
<td>✓</td>
<td>toGet calls deq returns first, toPut calls enq</td>
</tr>
<tr>
<td>FIFOLevelIfc#(a)</td>
<td>✓</td>
<td>toGet calls deq returns first, toPut calls enq</td>
</tr>
<tr>
<td>SyncFIFOLevelIfc#(a)</td>
<td>✓</td>
<td>toGet calls deq returns first, toPut calls enq</td>
</tr>
<tr>
<td>FIFOCountIfc#(a)</td>
<td>✓</td>
<td>toGet calls deq returns first, toPut calls enq</td>
</tr>
<tr>
<td>SyncFIFOCountIfc#(a)</td>
<td>✓</td>
<td>toGet calls deq returns first, toPut calls enq</td>
</tr>
</tbody>
</table>

Example - Using `toPut`
module mkTop (Put#(UInt#(64)));
    Reg#(UInt#(64)) inValue <- mkReg(0);
    Reg#(Bool) startit <- mkReg(True);
    ...
    StimIfc stim_gen <- mkStimulusGen;

    rule startTb (startit && inValue!=0); // Get the value
        let val = inValue;
        stim_gen.start(val);
        startit <= False;
    endrule
    ...
    return (toPut(asReg(inValue)));
endmodule: mkTop

Interfaces and methods

The Get interface defines the get method, similar to a dequeue, which retrieves an item from an interface and removes it at the same time. The Put interface defines the put method, similar to an enqueue, which gives an item to an interface. Also provided is the GetS interface, which defines separate methods for the dequeue (deq) and retrieving the item (first) from the interface.

You can design your own Get and Put interfaces with implicit conditions on the get/put to ensure that the get/put is not performed when the module is not ready. This would ensure that a rule containing get method would not fire if the element associated with it is empty and that a rule containing put method would not fire if the element is full.

The following interfaces are defined in the GetPut package. They each take a single parameter, element_type which must be in the Bits typeclass.

<table>
<thead>
<tr>
<th>Interface Name</th>
<th>Description</th>
<th>Methods</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Get</td>
<td>Retrieves item from an interface</td>
<td>get</td>
<td>ActionValue</td>
</tr>
<tr>
<td>Put</td>
<td>Adds an item to an interface</td>
<td>put</td>
<td>Action</td>
</tr>
<tr>
<td>GetS</td>
<td>Retrieves an item from an interface with 2 methods, separating the return of the value from the dequeue</td>
<td>first</td>
<td>Value</td>
</tr>
<tr>
<td></td>
<td></td>
<td>deq</td>
<td>Action</td>
</tr>
<tr>
<td>GetPut</td>
<td>Combination of a Get and a Put in a Tuple2</td>
<td>get</td>
<td>ActionValue</td>
</tr>
<tr>
<td></td>
<td></td>
<td>put</td>
<td>Action</td>
</tr>
</tbody>
</table>

Get

The Get interface is where you retrieve (get) data from an object. The Get interface is provides a single ActionValue method, get, which retrieves an item of data from an interface and removes it from the object. A get is similar to a dequeue, but it can be associated with any interface. A Get interface is more abstract than a FIFO interface; it does not describe the underlying hardware.

<table>
<thead>
<tr>
<th>Method</th>
<th>Argument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Description</td>
</tr>
<tr>
<td>get</td>
<td>ActionValue</td>
</tr>
</tbody>
</table>
interface Get#(type element_type);
  method ActionValue#(element_type) get();
endinterface: Get

Example - adding your own Get interface:
module mkMyFifoUpstream (Get#(int));
...
  method ActionValue#(int) get();
  f.deq;
  return f.first;
endmethod

Put

The Put interface is where you can give (put) data to an object. The Put interface provides a single Action method, put, which gives an item to an interface. A put is similar to an enqueue, but it can be associated with any interface. A Put interface is more abstract than a FIFO interface; it does not describe the underlying hardware.

<table>
<thead>
<tr>
<th>Method</th>
<th>Argument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Type</td>
</tr>
<tr>
<td>put</td>
<td>Action</td>
</tr>
</tbody>
</table>

interface Put#(type element_type);
  method Action put(element_type x1);
endinterface: Put

Example - adding your own Put interface:
module mkMyFifoDownstream (Put#(int));
...
  method Action put(int x);
  F.enq(x);
endmethod

GetS

The GetS interface is like a Get interface, but separates the get method into two methods: a first and a deq.

<table>
<thead>
<tr>
<th>GetS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>first</td>
</tr>
<tr>
<td>deq</td>
</tr>
</tbody>
</table>

interface GetS#(type element_type);
  method element_type first();
  method Action deq();
endinterface: GetS
GetPut

The library also defines an interface `GetPut` which associates `Get` and `Put` interfaces into a `Tuple2`.

```verilog
typedef Tuple2#(Get#(element_type), Put#(element_type)) GetPut#(type element_type);
```

Type classes

The class `Connectable` (Section C.7.2) is meant to indicate that two related types can be connected in some way. It does not specify the nature of the connection.

A `Get` and `Put` is an example of connectable items. One object will `put` an element into the interface and the other object will `get` the element from the interface.

```verilog
instance Connectable#(Get#(element_type), Put#(element_type));
```

Modules

There are three modules provided by the `GetPut` package which provide the `GetPut` interface with a type of `FIFO`. These FIFOs use `Get` and `Put` interfaces instead of the usual `enq` interfaces. To use any of these modules the `FIFO` package must be imported. You can also write your own modules providing a `GetPut` interface for other hardware structures.

<table>
<thead>
<tr>
<th>mkGP_FIFO</th>
<th>Creates a FIFO of depth 2 with a <code>GetPut</code> interface.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkGP_FIFO (GetPut#(element_type))</td>
<td></td>
</tr>
<tr>
<td><em>provisos</em> (Bits#(element_type, width_elem));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkGP_FIFO1</th>
<th>Creates a FIFO of depth 1 with a <code>GetPut</code> interface.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkGP_FIFO1 (GetPut#(element_type))</td>
<td></td>
</tr>
<tr>
<td><em>provisos</em> (Bits#(element_type, width_elem));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkGPSized_FIFO</th>
<th>Creates a FIFO of depth n with a <code>GetPut</code> interface.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkGPSized_FIFO# (Integer n) (GetPut#(element_type))</td>
<td></td>
</tr>
<tr>
<td><em>provisos</em> (Bits#(element_type, width_elem));</td>
<td></td>
</tr>
</tbody>
</table>

Functions

There are three functions defined in the `GetPut` package that change a `FIFO` interface to a `Get`, `GetS` or `Put` interface. Given a FIFO we can use the function `fifoToGet` to obtain a `Get` interface, which is a combination of `deq` and `first`. Given a FIFO we can use the function `fifoToPut` to obtain a `Put` interface using `enq`. The functions `toGet` and `toPut` (C.7.1) are recommended instead of the `fifoToGet` and `fifoToPut` functions. The function `fifoToGetS` returns the `GetS` methods as `fifo` methods.
fifoToGet

Returns a Get interface. It is recommended that you use the function toGet (C.7.1) instead of this function.

function Get#(element_type) fifoToGet(FIFO#(element_type) f);

fifoToGetS

Returns a GetS interface.

function GetS#(element_type) fifoToGet(FIFO#(element_type) f);

fifoToPut

Returns a Put interface. It is recommended that you use the function toPut (C.7.1) instead of this function.

function Put#(element_type) fifoToPut(FIFO#(element_type) f);

Example of creating a FIFO with a GetPut interface

import GetPut::*;
import FIFO::*;

... module mkMyModule (MyInterface);
  GetPut#(StatusInfo) aFifoOfStatusInfoStructures <- mkGPFIFO;
...
endmodule: mkMyModule

Example of a protocol monitor

This is an example of how you might write a protocol monitor that watches bus traffic between a bus and a bus target device

import GetPut::*;
import FIFO::*;

// Watch bus traffic between a bus and a bus target interface ProtocolMonitorIfc;
  // These subinterfaces are defined inside the module interface Put#(Bus_to_Target_Request) bus_to_targ_req_ifc;
  interface Put#(Target_to_Bus_Response) targ_to_busResp_ifc;
endinterface

... module mkProtocolMonitor (ProtocolMonitorIfc);
  // Input FIFOs that have Put interfaces added a few lines down FIFO#(Bus_to_Target_Request) bus_to_targ_reqs <- mkFIFO;
  FIFO#(Target_to_Bus_Response) targ_to_bus_resps <- mkFIFO;
...
  // Define the subinterfaces: attach Put interfaces to the FIFOs, and
  // then make those the module interfaces interface bus_to_targ_req_ifc = fifoToPut (bus_to_targ_reqs);
interface targ_to_bus_resp_ifc = fifoToPut (targ_to_bus_resps);
end module: mkProtocolMonitor

// Top-level module: connect mkProtocolMonitor to the system:
module mkSys (Empty);
    ProtocolMonitorIfc pmon <- mkProtocolInterface;
    ...
rule pass_bus_req_to_interface;
    let x <- bus.bus_ifc.get; // definition not shown
    pmon.but_to_targ_ifc.put (x);
endrule
...
endmodule: mkSys

C.7.2 Connectable

Package

import Connectable :: * ;

Description
The Connectable package contains the definitions for the class Connectable and instances of Connectables.

Types and Type-Classes
The class Connectable is meant to indicate that two related types can be connected in some way. It does not specify the nature of the connection. The Connectables type class defines the module mkConnection, which is used to connect the pairs.

typeclass Connectable#(type a, type b);
    module mkConnection#(a x1, b x2)(Empty);
endtypeclass

Instances

Get and Put One instance of the typeclass of Connectable is Get and Put. One object will put an element into an interface and the other object will get the element from the interface.

instance Connectable#(Get#(a), Put#(a));

Tuples If we have Tuple2 of connectable items then the pair is also connectable, simply by connecting the individual items.

instance Connectable#(Tuple2#(a, c), Tuple2#(b, d))
    provisos (Connectable#(a, b), Connectable#(c, d));

The proviso shows that the first component of one tuple connects to the first component of the other tuple, likewise, the second components connect as well. In the above statement, a connects to b and c connects to d. This is used by ClientServer (Section C.7.3) to connect the Get of the Client to the Put of the Server and visa-versa.

This is extensible to all Tuples (Tuple3, Tuple4, etc.). As long as the items are connectable, the Tuples are connectable.
**Vector** Two Vectors are connectable if their elements are connectable.

```verilog
instance Connectable#(Vector#(n, a), Vector#(n, b))
    provisos (Connectable#(a, b));
```

**ListN** Two ListNs are connectable if their elements are connectable.

```verilog
instance Connectable#(ListN#(n, a), ListN#(n, b))
    provisos (Connectable#(a, b));
```

**Action, ActionValue** An ActionValue method (or function) which produces a value can be connected to an Action method (or function) which takes that value as an argument.

```verilog
instance Connectable#(ActionValue#(a), function Action f(a x));
instance Connectable#(function Action f(a x), ActionValue#(a));
```

A Value method (or value) can be connected to an Action method (or function) which takes that value as an argument.

```verilog
instance Connectable#(a, function Action f(a x));
instance Connectable#(function Action f(a x), a);
```

**Inout** Inouts are connectable via the Connectable typeclass. The use of `mkConnection` instantiates a Verilog module `InoutConnect`. The Inouts must be on the same clock and the same reset. The clock and reset of the Inouts may be different than the clock and reset of the parent module of the `mkConnection`.

```verilog
instance Connectable#(Inout#(a, x1), Inout#(a, x2))
    provisos (Bit#(a, sa));
```

### C.7.3 ClientServer

#### Package

```verilog
import ClientServer :: * ;
```

#### Description

The `ClientServer` package provides two interfaces, `Client` and `Server` which can be used to define modules which have a request-response type of interface. The `GetPut` package must be imported when using this package because the `Get` and `Put` interface types are used.

#### Interfaces and methods

The interfaces `Client` and `Server` can be used for modules that have a request-response type of interface (e.g. a RAM). The server accepts requests and generates responses, the client accepts responses and generates requests. There are no assumptions about how many (if any) responses a request generates.

<table>
<thead>
<tr>
<th>Interface</th>
<th>Parameter name</th>
<th>Parameter Description</th>
<th>Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Client</td>
<td><code>req_type</code></td>
<td>type of the client request</td>
<td>must be in the Bits class</td>
</tr>
<tr>
<td></td>
<td><code>resp_type</code></td>
<td>type of the client response</td>
<td>must be in the Bits class</td>
</tr>
<tr>
<td>Server</td>
<td><code>req_type</code></td>
<td>type of the server request</td>
<td>must be in the Bits class</td>
</tr>
<tr>
<td></td>
<td><code>resp_type</code></td>
<td>type of the server response</td>
<td>must be in the Bits class</td>
</tr>
</tbody>
</table>
Client

The Client interface provides two subinterfaces, request and response. From a Client, one gets a request and puts a response.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>request</td>
<td>Get(#(req_type))</td>
<td>the interface through which the outside world retrieves (gets) a request</td>
</tr>
<tr>
<td>response</td>
<td>Put(#(resp_type))</td>
<td>the interface through which the outside world returns (puts) a response</td>
</tr>
</tbody>
</table>

interface Client\(#(type req_type, type resp_type)\);
  interface Get\(#(req_type)\) request;
  interface Put\(#(resp_type)\) response;
endinterface: Client

Server

The Server interface provides two subinterfaces, request and response. From a Server, one puts a request and gets a response.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>request</td>
<td>Put(#(req_type))</td>
<td>the interface through which the outside world returns (puts) a request</td>
</tr>
<tr>
<td>response</td>
<td>Get(#(resp_type))</td>
<td>the interface through which the outside world retrieves (gets) a response</td>
</tr>
</tbody>
</table>

interface Server\(#(type req_type, type resp_type)\);
  interface Put\(#(req_type)\) request;
  interface Get\(#(resp_type)\) response;
endinterface: Server

ClientServer

A Client can be connected to a Server and vice versa. The request (which is a Get interface) of the client will connect to response (which is a Put interface) of the Server. By making the ClientServer tuple an instance of the Connectable typeclass, you can connect the Get of the client to the Put of the server, and the Put of the client to the Get of the server.

instance Connectable\(#(Client\(#(type req_type, type resp_type)\), Server\(#(type req_type, type resp_type)\))\);
instance Connectable\(#(Server\(#(type req_type, type resp_type)\), Client\(#(type req_type, type resp_type)\))\);

This Tuple2 can be redefined to be called ClientServer
typedef Tuple2\(#(Client\(#(type req_type, type resp_type)\), Server\(#(type req_type, type resp_type)\))\) ClientServer\(#(type req_type, type resp_type)\);

Example Connecting a bus to a target

interface Bus_Ifc;
  interface Server\(#(RQ, RS)\) to_initor;
  interface Client\(#(RQ, RS)\) to_targ;
endinterface
typedef Server#(RQ, RS) Target_Ifc;
typedef Client#(RQ, RS) Initiator_Ifc;

module mkSys (Empty);
    // Instantiate subsystems
    Bus_Ifc bus <- mkBus;
    Target_Ifc targ <- mkTarget;
    Initiator_Ifc initor <- mkInitiator;

    // Connect bus and targ (to_targ is a Client ifc, targ is a Server ifc)
    Empty x <- mkConnection (bus.to_targ, targ);

    // Connect bus and initiator (to_initor is a Server ifc, initor is a Client ifc)
    mkConnection (bus.to_initor, initor);
    // Since mkConnection returns an interface of type Empty, it does
    // not need to be specified (but may be as above)
...
endmodule: mkSys

Functions

The ClientServer package includes functions which return a Client interface or a Server interface
from separate request and response interfaces taken as arguments. The argument interfaces must
be able to be converted to Get and Put interfaces, as indicated by the ToGet and ToPut provisos.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>toGPClient</td>
<td>Function that returns a Client interface from two arguments (request and response interfaces). The arguments must be able to be converted to Get and Put interfaces.</td>
</tr>
<tr>
<td>toGPClient</td>
<td>function Client#(req_type, resp_type)</td>
</tr>
<tr>
<td></td>
<td>toGPClient(req_ifc_type req_ifc, resp_ifc_type resp_ifc)</td>
</tr>
<tr>
<td></td>
<td>provisos (ToGet#(req_ifc_type, req_type), ToPut#(resp_ifc_type, resp_type));</td>
</tr>
<tr>
<td>toGPServer</td>
<td>Function that returns a Server interface from two arguments (request and response interfaces). The arguments must be able to be converted to Get and Put interfaces.</td>
</tr>
<tr>
<td>toGPServer</td>
<td>function Server#(req_type, resp_type)</td>
</tr>
<tr>
<td></td>
<td>toGPServer(req_ifc_type req_ifc, resp_ifc_type resp_ifc)</td>
</tr>
<tr>
<td></td>
<td>provisos (ToPut#(req_ifc_type, req_type), ToGet#(resp_ifc_type, resp_type));</td>
</tr>
</tbody>
</table>

C.7.4 Memory

Package

import Memory :: * ;

Description
The **Memory** package provides the memory structures **MemoryRequest** and **MemoryResponse** which can be used to define a Client/Server memory structure.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the `-p` option as described in the BSV Users Guide.

**Types and type classes**

A **MemoryRequest** is a polymorphic structure of a request containing a `write` bit, a byte enable (`byteen`), the `address` and the `data` for a memory request:

```systemverilog
typedef struct {
  Bool write;
  Bit#(TDiv#(d,8)) byteen;
  Bit#(a) address;
  Bit#(d) data;
} MemoryRequest#(numeric type a, numeric type d) deriving (Bits, Eq);
```

The **MemoryResponse** contains the data:

```systemverilog
typedef struct {
  Bit#(d) data;
} MemoryResponse#(numeric type d) deriving (Bits, Eq);
```

**Interfaces and Methods**

The interfaces **MemoryServer** and **MemoryClient** are defined from the **Server** and **Client** interfaces defined in **ClientServer** package (Section C.7.3) using the **MemoryRequest** and **MemoryResponse** types.

The **MemoryServer** accepts requests and generates responses, the **MemoryClient** accepts responses and generates requests. There are no assumptions about how many (if any) responses a request generates.

```systemverilog
typedef Server#(MemoryRequest#(a,d), MemoryResponse#(d))
    MemoryServer#(numeric type a, numeric type d);

typedef Client#(MemoryRequest#(a,d), MemoryResponse#(d))
    MemoryClient#(numeric type a, numeric type d);
```

Default value instances are defined for both **MemoryRequest** and **MemoryResponse**:

```systemverilog
instance DefaultValue#(MemoryRequest#(a,d));
  defaultValue = MemoryRequest {
    write: False,
    byteen: '1,
    address: 0,
    data: 0
  };
endinstance

instance DefaultValue#(MemoryResponse#(d));
  defaultValue = MemoryResponse {
    data: 0
  };
endinstance
```
An instance of the TieOff class (Section C.8.10) is defined for MemoryClient:

```verilog
ingstance TieOff#(MemoryClient#(a, d));
```

### Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>updateDataWithMask</td>
<td>Replaces the original data with new data. The data must be divisible an 8-bit multiple of the mask. The mask indicates which bits to replace.</td>
</tr>
</tbody>
</table>

```verilog
function Bit#(d) updateDataWithMask(Bit#(d) origdata, Bit#(d) newdata, Bit#(d8) mask);
```

### C.7.5 CGetPut

#### Package

```verilog
import CGetPut :: * ;
```

#### Description

The interfaces CGet and CPut are similar to Get and Put, but the interconnection of them (via Connectable) is implemented with a credit-based FIFO. This means that the CGet and CPut interfaces have completely registered input and outputs, and furthermore that additional register buffers can be introduced in the connection path without any ill effect (except an increase in latency, of course).

In the absence of additional register buffers, the round-trip time for communication between the two interfaces is 4 clock cycles. Call this number \( r \). The first argument to the type, \( n \), specifies that transfers will occur for a fraction \( n/r \) of clock cycles (note that the used cycles will not necessarily be evenly spaced). \( n \) also specifies the depth of the buffer used in the receiving interface (the transmitter side always has only a single buffer). So (in the absence of additional buffers) use \( n = 4 \) to allow full-bandwidth transmission, at the cost of sufficient registers for quadruple buffering at one end; use \( n = 1 \) for minimal use of registers, at the cost of reducing the bandwidth to one quarter; use intermediate values to select the optimal trade-off if appropriate.

#### Interfaces and methods

The interface types are abstract to avoid any improper use of the credit signaling protocol.

<table>
<thead>
<tr>
<th>Interfaces</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Interface Name</td>
<td>Parameter name</td>
</tr>
<tr>
<td>CGet</td>
<td>( n )</td>
</tr>
<tr>
<td></td>
<td>( \text{element_type} )</td>
</tr>
<tr>
<td>CPut</td>
<td>( n )</td>
</tr>
<tr>
<td></td>
<td>( \text{element_type} )</td>
</tr>
</tbody>
</table>

- CGet
  ```verilog
  interface CGet#(numeric type n, type element_type);
  ...
  ```
• **CPut**
  
  ```
  interface CPut#(numeric type n, type element_type);
  ...
  ...
  ```

• **Connectables**

  The **CGet** and **CPut** interfaces are connectable.

  ```
  instance Connectable#(CGet#(n, element_type), CPut#(n, element_type));
  instance Connectable#(CPut#(n, element_type), CGet#(n, element_type));
  ```

• **CClient and CServer**

  The same idea may be extended to clients and servers.

  ```
  interface CClient#(type n, type req_type, type resp_type);
  interface CServer#(type n, type req_type, type resp_type);
  ```

---

### Modules

<table>
<thead>
<tr>
<th>mkCGetPut</th>
<th>Create an n depth FIFO with a CGet interface on the dequeue side and a Put interface on the enqueue side.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkCGetPut(Tuple2#(CGet#(n, element_type), Put#(element_type)))</td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(element_type));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkGetCPut</th>
<th>Create an n depth FIFO with a Get interface on the dequeue side and a CPut interface on the enqueue side.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkGetCPut(Tuple2#(Get#(element_type), CPut#(n, element_type)))</td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(element_type));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkClientCServer</th>
<th>Create a CServer with a mkCGetPut and a mkGetCPut. Provides a CServer interface and a regular Client interface.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkClientCServer(Tuple2#(Client#(req_type, resp_type), CServer#(n, req_type, resp_type)))</td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(req_type), Bits#(resp_type));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkCClientServer</th>
<th>Create a CClient with a mkCGetPut and a mkGetCPut. Provides a CClient interface and a regular Server interface.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkCClientServer(Tuple2#(CClient#(n, req_type, resp_type), Server#(req_type, resp_type)))</td>
</tr>
<tr>
<td></td>
<td>provisos (Bits#(req_type), Bits#(resp_type));</td>
</tr>
</tbody>
</table>
C.7.6 CommitIfc

Package

import CommitIfc :: * ;

Description

The CommitIfc package defines a Commit/Accept protocol and interfaces to implement a combinational connection between two modules without adding an AND gate in the connection. The protocols implemented by FIFO and Get/Put connections add an AND gate between the modules being connected. This combinatorial loop in the connection of the interfaces can cause complications in FPGA applications and in partitioning for FPGAs. Additionally, some synthesis tools require a connection level without any gates. By using the CommitIfc protocol the AND gate is moved out of the connection and into the connecting modules.

The CommitIfc package defines two interfaces, SendCommit and RecvCommit, which model the opposite ends of a FIFO. The protocol does not apply an execution order between the dataout and ack or datain and accept methods. That is, one can signal accept before the data arrives.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Interfaces

The CommitIfc package defines two interfaces: SendCommit and RecvCommit.

The SendCommit interface declares two methods: a value method dataout and an Action method ack. No execution order is applied between the dataout and the ack; one can signal that the data is accepted before the data arrives.

<table>
<thead>
<tr>
<th>SendCommit Interface</th>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>dataout</td>
<td>a_type</td>
<td>value</td>
<td>The data being sent. There is an implicit RDY indicating the data is valid.</td>
</tr>
<tr>
<td>ack</td>
<td>Action</td>
<td>Action</td>
<td>Signal that data has been accepted.</td>
</tr>
</tbody>
</table>

interface SendCommit#(type a_type);
    method a_type dataout;
    (*always_ready*)
    method Action ack;
endinterface

The RecvCommit interface declares two methods: an Action method with the data, datain, and a value method accept, returning a Bool indicating if the interface can accept data (comparable to a notFull).

<table>
<thead>
<tr>
<th>RecvCommit Interface</th>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>datain</td>
<td>Action</td>
<td>Receives, or enqueues, the value din, of type a_type.</td>
<td></td>
</tr>
<tr>
<td>accept</td>
<td>Bool</td>
<td>A boolean indicating if the interface can accept data, comparable to a notFull.</td>
<td></td>
</tr>
</tbody>
</table>
interface RecvCommit#(type a_type);
    (*always_ready*)
    method Action datain (a_type din);
    (*always_ready*)
    method Bool accept ;
endinterface

Connectable Instances
The CommitIfc package defines instances of the Connectable type class for the SendCommit and RecvCommit interfaces, defining how the types can be connected. The Connectable type class defines a mkConnection module for each set of pairs.

instance Connectable#(SendCommit#(a_type), RecvCommit#(a_type));
instance Connectable#(RecvCommit#(a_type), SendCommit#(a_type));

FIFOF The SendCommit and RecvCommit interfaces can be connected to FIFOF interfaces.

instance Connectable#(SendCommit#(a_type), FIFOF#(a_type))
    provisos (Bits#(a_type, size_a));
instance Connectable#(FIFOF#(a_type), SendCommit#(a_type))
    provisos (Bits#(a_type, size_a));
instance Connectable#(RecvCommit#(a_type), FIFOF#(a_type))
    provisos (Bits#(a_type, size_a));
instance Connectable#(FIFOF#(a_type), RecvCommit#(a_type))
    provisos (Bits#(a_type, size_a));

SyncFIFOIfc The SendCommit and RecvCommit interfaces can be connected to SyncFIFOIfc interfaces.

instance Connectable#(SendCommit#(a_type), SyncFIFOIfc#(a_type))
    provisos (Bits#(a_type, size_a));
instance Connectable#(SyncFIFOIfc#(a_type), SendCommit#(a_type))
    provisos (Bits#(a_type, size_a));
instance Connectable#(RecvCommit#(a_type), SyncFIFOIfc#(a_type))
    provisos (Bits#(a_type, size_a));
instance Connectable#(SyncFIFOIfc#(a_type), RecvCommit#(a_type))
    provisos (Bits#(a_type, size_a));

Typeclasses
The CommitIfc package defines typeclasses for converting to these interfaces from other interface types. These must use a module since rules and wires are required.

typeclass ToSendCommit#(type a_type , type b_type)
    dependencies (a_type determines b_type);
    module mkSendCommit#(a_type x) (SendCommit#(b_type));
endtypeclass
typeclass ToRecvCommit#(type a_type, type b_type)
  dependencies (a_type determines b_type);
  module mkRecvCommit#(a_type x) (RecvCommit#(b_type));
endtypeclass

Instances

Instances for the ToSendCommit and ToRecvCommit type classes are defined to convert to convert from FIFO, FIFOF, SyncFIFOIfc, Get and Put interfaces.

FIFO

instance ToSendCommit#(FIFO#(a), a);

Note: ToRecvCommit#(FIFO#(a_type), a_type) is not possible, because it would need to have a notFull signal.

FIFOF

The FIFOF instances assume that the fifo has proper implicit conditions.

instance ToSendCommit#(FIFOF#(a_type), a_type);
  module mkSendCommit #(FIFOF#(a) f) (SendCommit#(a));

instance ToRecvCommit#(FIFOF#(a_type), a_type)
  provisos(Bits#(a,sa));
  module mkRecvCommit #(FIFOF#(a) f) (RecvCommit#(a));

SyncFIFOIfc

The SyncFIFOIfc instances assume that the fifo has proper implicit conditions.

instance ToSendCommit#(SyncFIFOIfc#(a_type), a_type);
  module mkSendCommit #(SyncFIFOIfc#(a) f) (SendCommit#(a));

instance ToRecvCommit#(SyncFIFOIfc#(a_type), a_type)
  provisos(Bits#(a,sa));
  module mkRecvCommit #(SyncFIFOIfc#(a) f) (RecvCommit#(a));

Get and Put

These convert from Get and Put interfaces but introduce additional latency:

instance ToSendCommit#(Get#(a_type), a_type)
  provisos (Bits#(a,sa));
  module mkSendCommit #(Get#(a_type) g) (SendCommit#(a_type));

instance ToRecvCommit#(Put#(a_type), a_type)
  provisos(Bits#(a,sa));
  module mkRecvCommit #(Put#(a_type) p) (RecvCommit#(a_type));

These add FIFOs, but maintain loopless behavior:

instance Connectable#(SendCommit#(a_type), Put#(a_type))
  provisos (ToRecvCommit#(Put#(a_type), a_type));

instance Connectable#(Put#(a_type), SendCommit#(a_type))
provisos (ToRecvCommit#(Put#(a_type), a_type));

instance Connectable#(RecvCommit#(a_type), Get#(a_type))
  provisos (ToSendCommit#(Get#(a_type), a_type));

instance Connectable#(Get#(a_type), RecvCommit#(a_type))
  provisos (ToSendCommit#(Get#(a_type), a_type));

Client/Server Variations

The SendCommit and RecvCommit interfaces can be combined into ClientCommit and ServerCommit type interfaces, similar to the Client and Server interfaces described in Section C.7.3.

A Client provides two subinterfaces, a Get and a Put. The ClientCommit interface combines a SendCommit request with a RecvCommit response.

interface ClientCommit#(type req, type resp);
  interface SendCommit#(req) request;
  interface RecvCommit#(resp) response;
endinterface

The mkClientFromClientCommit module takes a ClientCommit interface and provides a Client interface:

<table>
<thead>
<tr>
<th>mkClientFromClientCommit</th>
<th>Provides a Client interface from a ClientCommit interface.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkClientFromClientCommit#(ClientCommit#(req, resp) c)</td>
<td></td>
</tr>
<tr>
<td>(Client#(req,resp))</td>
<td></td>
</tr>
<tr>
<td>provisos ( Bits#(resp,<em>,x), Bits#(req,</em>,y));</td>
<td></td>
</tr>
</tbody>
</table>

A Server interface provides a Put request with a Get response. The ServerCommit interface combines a RecvCommit request with a SendCommit response.

interface ServerCommit#(type req, type resp);
  interface RecvCommit#(req) request;
  interface SendCommit#(resp) response;
endinterface

ClientCommit and ServerCommit interfaces are connectable to each other.

instance Connectable#(ClientCommit#(req,resp), ServerCommit#(req,resp));

instance Connectable#(ServerCommit#(req,resp), ClientCommit#(req,resp));

ClientCommit and ServerCommit interfaces are connectable to Clients and Servers.

instance Connectable #(ClientCommit#(req,resp), Server#(req,resp))
  provisos ( Bits#(resp,_,x), Bits#(req,_,y));

instance Connectable #(Server#(req,resp), ClientCommit#(req,resp))
  provisos ( Bits#(resp,_,x), Bits#(req,_,y));
instance Connectable #(ServerCommit#(req,resp), Client#(req,resp))
  provisos (Bits#(resp,_x), Bits#(req,_y));

instance Connectable #(Client#(req,resp), ServerCommit#(req,resp))
  provisos (Bits#(resp,_x), Bits#(req,_y));

The SendCommit and RecvCommit can be defined as instances of ToGet and ToPut. These functions introduce a combinational loop between the Commit interface methods.

instance ToGet#(SendCommit#(a_type, a_type));
instance ToPut#(RecvCommit#(a_type, a_type));

C.8 Utilities

C.8.1 LFSR

Package

import LFSR :: * ;

Description

The LFSR package implements Linear Feedback Shift Registers (LFSRs). LFSRs can be used to obtain reasonable pseudo-random numbers for many purposes (though not good enough for cryptography). The seed method must be called first, to prime the algorithm. Then values may be read using the value method, and the algorithm stepped on to the next value by the next method. When a LFSR is created the start value, or seed, is 1.

Interfaces and Methods

The LFSR package provides an interface, LFSR, which contains three methods: seed, value, and next. To prime the LFSR the seed method is called with the parameter seed_value, of datatype a_type. The value is read with the value method. The next method is used to shift the register on to the next value.

<table>
<thead>
<tr>
<th>Interface LFSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
</tr>
<tr>
<td>Name</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>seed</td>
</tr>
<tr>
<td>value</td>
</tr>
<tr>
<td>next</td>
</tr>
</tbody>
</table>

interface LFSR #(type a_type);
  method Action seed(a_type seed_value);
  method a_type value();
  method Action next();
endinterface: LFSR
Modules

The module `mkFeedLFSR` creates a LFSR where the polynomial is specified by the mask used for feedback.

<table>
<thead>
<tr>
<th>mkFeedLFSR</th>
<th>Creates a LFSR where the polynomial is specified by the mask (feed) used for feedback.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><code>module mkFeedLFSR#( Bit#(n) feed )( LFSR#(Bit#(n)) );</code></td>
</tr>
</tbody>
</table>

For example, the polynomial \( x^7 + x^3 + x^2 + x + 1 \) is defined by the expression `mkFeedLFSR#(8'b1000_1111)`

Using the module `mkFeedLFSR`, the following maximal length LFSR’s are defined in this package.

<table>
<thead>
<tr>
<th>Module Name</th>
<th>feed</th>
<th>Module Definition</th>
</tr>
</thead>
</table>
| mkLFSR_4    | 4'h9 | module mkLFSR_4 (LFSR#(Bit#(4)));
|             | \( x^3 + 1 \) |                         |
| mkLFSR_8    | 8'h8E| module mkLFSR_8 (LFSR#(Bit#(8)));
| mkLFSR_16   | 16'h8016 | module mkLFSR_16 (LFSR#(Bit#(16)));
| mkLFSR_32   | 32'h80000057 | module mkLFSR_32 (LFSR#(Bit#(32)));

For example,

`mkLFSR_4 = mkFeedLFSR( 4'h9 );`

The module `mkLFSR_4` instantiates the interface LFSR with the value `Bit#(4)` to produce a 4 bit shift register. The module uses the polynomial defined by the mask `4'h9 (x^3 + 1)` and the module `mkFeedLFSR`.

The `mkRCounter` function creates a counter with a LFSR interface. This is useful during debugging when a non-random sequence is desired. This function can be used in place of the other `mkLFSR` module constructors, without changing any method calls or behavior.

<table>
<thead>
<tr>
<th>mkRCounter</th>
<th>Creates a counter with a LFSR interface.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><code>module mkRCounter#( Bit#(n) seed ) ( LFSR#(Bit#(n)) );</code></td>
</tr>
</tbody>
</table>

Example - Random Number Generator

```verilog
import GetPut::*;
import FIFO::*;
import LFSR::*;

// We want 6-bit random numbers, so we will use the 16-bit version of
// LFSR and take the most significant six bits.

// The interface for the random number generator is parameterized on bit
```
typedef Get#(Bit#(n)) RandI#(type n);

module mkRn_6(RandI#(6));
  // First we instantiate the LFSR module
  LFSR#(Bit#(16)) lfsr <- mkLFSR_16;

  // Next comes a FIFO for storing the results until needed
  FIFO#(Bit#(6)) fi <- mkFIFO;

  // A boolean flag for ensuring that we first seed the LFSR module
  Reg#(Bool) starting <- mkReg(True);

  // This rule fires first, and sends a suitable seed to the module.
  rule start (starting);
    starting <= False;
    lfsr.seed('h11);
  endrule: start

  // After that, the following rule runs as often as it can, retrieving
  // results from the LFSR module and enqueueing them on the FIFO.
  rule run (!starting);
    fi.enq(lfsr.value[10:5]);
    lfsr.next;
  endrule: run

  // The interface for mkRn_6 is a Get interface. We can produce this from a
  // FIFO using the fifoToGet function. We therefore don't need to define any
  // new methods explicitly in this module: we can simply return the produced
  // Get interface as the "result" of this module instantiation.
  return fifoToGet(fi);
endmodule

C.8.2 Randomizable

Package

import Randomizable :: *;

Description

The Randomizable package includes interfaces and modules to generate random values of a given
data type.

This package is provided as both a compiled library package and as BSV source code as document-
tation. The source code file can be found in the ${BLUESPECDIR}/BSVSource/Misc directory. To
customize a package, copy the file into a local directory and then include the local directory in the
path when compiling. This is done by specifying the search path with the -p option as described in
the BSV Users Guide.

Typeclasses

The Randomizable package includes the Randomizable typeclass.
typeclass Randomizable#(type t);
    module mkRandomizer (Randomize#(t));
endtypeclass

Interfaces and Methods

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cntrl</td>
<td>Interface</td>
<td>Control interface provided by the module.</td>
</tr>
<tr>
<td>next</td>
<td>ActionValue</td>
<td>Returns the next value of type a.</td>
</tr>
</tbody>
</table>

interface Randomize#(type a);
    interface Control cntrl;
    method ActionValue#(a) next();
endinterface

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>init</td>
<td>Control</td>
<td>Action method to initialize the randomizer.</td>
</tr>
</tbody>
</table>

interface Control;
    method Action init();
endinterface

Modules

The Randomizable package includes two modules which return random values of type a. The difference between the two modules is how the min and max values are determined. The module mkGenericRandomizer uses the min and max values of the type, while the module mkConstrainedRandomizer uses arguments to set the min and max values. The type a must be in the Bounded class for both modules.

<table>
<thead>
<tr>
<th>Module</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkGenericRandomizer</td>
<td>This module provides a Randomize interface, which will return the next random value when the next method is invoked. The min and max values are the values defined by the type a which must be in the Bounded class.</td>
</tr>
</tbody>
</table>
|                    | module mkGenericRandomizer (Randomize#(a))
|                    |     provisos (Bits#(a, sa), Bounded#(a));                                   |

<table>
<thead>
<tr>
<th>Module</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkConstrainedRandomizer</td>
<td>This module provides a Randomize interface, which will give the next random value when the next method is invoked. When instantiated, the min and max values are provided as arguments. Type a must be in the Bounded class.</td>
</tr>
</tbody>
</table>
|                    | module mkConstrainedRandomizer#(a min, a max) (Randomize#(a))
|                    |     provisos (Bits#(a, sa), Bounded#(a));                                  |
Example

The mkTLMRandomizer module, shown below, uses the Randomize package to generate random values for TLM packets. The mkConstrainedRandomizer module is for fields with specific allowed values or ranges, while the mkGenericRandomizer module is for field where all values of the type are allowed.

```verilog
module mkTLMRandomizer#(Maybe#(TLMCommand) m_command) (Randomize#(TLMRequest#('TLM_TYPES)))
  provisos(Bits#(RequestDescriptor#('TLM_TYPES), s0),
           Bounded#(RequestDescriptor#('TLM_TYPES)),
           Bits#(RequestData#('TLM_TYPES), s1),
           Bounded#(RequestData#('TLM_TYPES)));

  // Use mkGeneric Randomizer - entire range valid
  Randomize#(RequestDescriptor#('TLM_TYPES)) descriptor_gen <- mkGenericRandomizer;
  Randomize#(Bit#(2)) log_wrap_gen <- mkGenericRandomizer;
  Randomize#(RequestData#('TLM_TYPES)) data_gen <- mkGenericRandomizer;

  // Use mkConstrainedRandomizer to Avoid UNKNOWN
  Randomize#(TLMCommand) command_gen <- mkConstrainedRandomizer(READ, WRITE);
  Randomize#(TLMBurstMode) burst_mode_gen <- mkConstrainedRandomizer(INCREMENT, WRAP);

  // Use mkConstrainedRandomizer to set legal sizes between 1 and 16
  Randomize#(TLMUInt#('TLM_TYPES)) burst_length_gen <- mkConstrainedRandomizer(1,16);
...
```

C.8.3 Arbiter

Package

import Arbiter :: * ;

Description

The Arbiter package includes interfaces and modules to implement two different arbiters: a fair arbiter with changing priorities (round robin) and a sticky arbiter, also round robin, but which gives the current owner priority.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Interfaces and Methods

The Arbiter package includes three interfaces: a arbiter client interface, an arbiter request interface and an arbiter interface which is a vector of client interfaces.

ArbiterClient_IFC The ArbiterClient_IFC interface has two methods: an Action method to make the request and a Boolean value method to indicate the request was granted. The lock method is unused in this implementation.
interface ArbiterClient_IFC;
  method Action request();
  method Action lock();
  method Bool grant();
endinterface

ArbiterRequest_IFC  The ArbiterRequest_IFC interface has two methods: an Action method to grant the request and a Boolean value method to indicate there is a request. The lock method is unused in this implementation.

interface ArbiterRequest_IFC;
  method Bool request();
  method Bool lock();
  method Action grant();
endinterface

The ArbiterClient_IFC interface and the ArbiterRequest_IFC interface are connectable.

instance Connectable#(ArbiterClient_IFC, ArbiterRequest_IFC);

Arbiter_IFC  The Arbiter_IFC has a subinterface which is a vector of ArbiterClient_IFC interfaces. The number of items in the vector equals the number of clients.

interface Arbiter_IFC#(type count);
  interface Vector#(count, ArbiterClient_IFC) clients;
endinterface

Modules

The mkArbiter module is a fair arbiter with changing priorities (round robin). The mkStickyArbiter gives the current owner priority - they can hold priority as long as they keep requesting it. The modules all provide a Arbiter_IFC interface.

| mkArbiter | This module is a fair arbiter with changing priorities (round robin). If fixed is True, the current client holds the priority, if fixed is False, it moves to the next client. mkArbiter provides a Arbiter_IFC interface. Initial priority is given to client 0. |
| module mkArbiter#(Bool fixed) (Arbiter_IFC#(count)); |

| mkStickyArbiter | As long as the client currently with the grant continues to assert request, it can hold the grant. It provides a Arbiter_IFC interface. |
| module mkStickyArbiter (Arbiter_IFC#(count)); |
C.8.4 Cntrs

Package

import Cntrs :: * ;

Description

The Cntrs package provides interfaces and modules to implement typed and untyped up/down counters.

The Count interface and associated mkCount module provides an up/down counter which allows atomic simultaneous increment and decrement operations. The scheduled order of operations in a single cycle is:

read SB update SB (incr,decr) SB write

If there are simultaneous update, incr, and decr operations, the final result will be:

update_val + incr_val - decr_val

A write sets the new value to write_val regardless of the other methods called in the cycle.

The UCount interface and associated mkUCount module provide an untyped version of an up/down counter; that is the counter width can be determined at elaboration time rather than type check time. The value of the counter is represented by an UInt#(n) where the width of the counter is determined by the maxValue (0 ≤ maxValue < 2^{32}) argument. There are no methods to access the counter value directly; you can only access the value through the comparison operations.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Interfaces and Methods

The Cntrs package provides two interfaces; Count which is a typed interface and UCount which is an untyped interface.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>incr</td>
<td>Action</td>
<td>Increments the counter by incr_val</td>
</tr>
<tr>
<td>decr</td>
<td>Action</td>
<td>Decrements the counter by decr_val</td>
</tr>
<tr>
<td>update</td>
<td>Action</td>
<td>Sets the value to update_val. Final value will include increment and decrement values.</td>
</tr>
<tr>
<td>_write</td>
<td>Action</td>
<td>Sets the final value to write_val regardless of other operations in the cycle.</td>
</tr>
<tr>
<td>_read</td>
<td>t</td>
<td>Returns the value of the counter.</td>
</tr>
</tbody>
</table>

interface Count#(type t);
method Action incr (t incr_val);
method Action decr (t decr_val);
method Action update (t update_val);
method Action _write (t write_val);
method t _read;
endinterface
<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>incr</td>
<td>Action</td>
<td>Increments the counter by incr_val</td>
</tr>
<tr>
<td>decr</td>
<td>Action</td>
<td>Decrements the counter by decr_val</td>
</tr>
<tr>
<td>update</td>
<td>Action</td>
<td>Sets the value to update_val. Final value will include increment and decrement values.</td>
</tr>
<tr>
<td>_write</td>
<td>Action</td>
<td>Sets the final value to write_val regardless of other operations in the cycle.</td>
</tr>
<tr>
<td>isEqual</td>
<td>Bool</td>
<td>Returns true if val is equal to the value of the counter.</td>
</tr>
<tr>
<td>isLessThan</td>
<td>Bool</td>
<td>Returns true if val is less than the value of the counter.</td>
</tr>
<tr>
<td>isGreaterThan</td>
<td>Bool</td>
<td>Returns true if val is greater than the value of the counter.</td>
</tr>
</tbody>
</table>

interface UCount;
method Action update (Integer update_val);
method Action _write (Integer write_val);
method Action incr (Integer incr_val);
method Action decr (Integer decr_val);
method Bool isEqual (Integer val);
method Bool isLessThan (Integer val);
method Bool isGreaterThan (Integer val);
endinterface

Modules

<table>
<thead>
<tr>
<th>mkCounter</th>
<th>Instantiates a Counter where read precedes update precedes an increment or decrement precedes a write. The ModArith provisos limits its use to module 2 arithmetic types: UInt, Int, and Bit. Widths of size 0 are supported.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkCount #(t resetVal) (Count#(t)) provisos ( Arith#(t), ModArith#(t), Bits#(t,st));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkUCount</th>
<th>Instantiates a counter which can count from 0 to maxVal inclusive. maxVal must be known at compile time. The initValue and maxVal must be Integers.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkUCount#(Integer initValue, Integer maxVal) (UCount);</td>
</tr>
</tbody>
</table>

Verilog Modules

mkCounter and mkUCount corresponds to the following Verilog module, which are found in the Bluespec Verilog library, $BLUESPECDIR/Verilog/.

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Name</th>
<th>Defined in File</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkCounter</td>
<td>vCount</td>
<td>Counter.v</td>
</tr>
<tr>
<td>mkUCount</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
C.8.5 GrayCounter

Package

import GrayCounter :: * ;

Description

The GrayCounter package provides an interface and a module to implement a gray-coded counter with methods for both binary and Gray code. This package is designed for use in the BRAMFIFO module, Section C.2.4. Since BRAMs have registered address inputs, the binary outputs are not registered. The counter has two domains, source and destination. Binary and Gray code values are written in the source domain. Both types of values can be read from the source and the destination domains.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the \$BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Types

The GrayCounter package uses the type Gray, defined in the Gray package, Section C.8.6. The Gray package is imported by the GrayCounter package.

Interfaces and Methods

The GrayCounter package includes one interface, GrayCounter.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>incr</td>
<td>Action</td>
<td>Increments the counter by 1</td>
</tr>
<tr>
<td>decr</td>
<td>Action</td>
<td>Decrements the counter by 1</td>
</tr>
<tr>
<td>sWriteBin</td>
<td>Action</td>
<td>Writes a binary value into the counter in the source domain.</td>
</tr>
<tr>
<td>sReadBin</td>
<td>Bit#(n)</td>
<td>Returns a binary value from the source domain of the counter. The output is not registered.</td>
</tr>
<tr>
<td>sWriteGray</td>
<td>Action</td>
<td>Writes a Gray code value into the counter in the source domain.</td>
</tr>
<tr>
<td>sReadGray</td>
<td>Gray#(n)</td>
<td>Returns the Gray code value from the source domain of the counter. The output is registered.</td>
</tr>
<tr>
<td>dReadBin</td>
<td>Bit#(n)</td>
<td>Returns the binary value from the destination domain of the counter. The output is not registered.</td>
</tr>
<tr>
<td>dReadGray</td>
<td>Gray#(n)</td>
<td>Returns the Gray code value from the destination domain of the counter. The output is registered.</td>
</tr>
</tbody>
</table>

interface GrayCounter#(numeric type n);
method Action incr;
method Action decr;
method Action sWriteBin(Bit#(n) value);
method Bit#(n) sReadBin;
method Action sWriteGray(Gray#(n) value);
method Gray#(n) sReadGray;
method Bit#(n) dReadBin;
method Gray#(n) dReadGray;
endinterface: GrayCounter
Modules
The module `mkGrayCounter` instantiates a Gray code counter with methods for both binary and Gray code.

<table>
<thead>
<tr>
<th>mkGrayCounter</th>
<th>Instantiates a Gray counter with an initial value <code>initval</code>.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module <code>mkGrayCounter#(Gray#(n) initval, Clock dClk, Reset dRstN)</code></td>
<td></td>
</tr>
<tr>
<td>(GrayCounter#(n))</td>
<td></td>
</tr>
<tr>
<td>provisos(Add#(1, msb, n));</td>
<td></td>
</tr>
</tbody>
</table>

C.8.6 Gray

Package

`import Gray :: * ;`

Description
The `Gray` package defines a datatype, `Gray` and functions for working with the Gray type. This type is used by the `GrayCounter` package.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the `$BLUESPECDIR/BSVSource/Misc` directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the `-p` option as described in the BSV Users Guide.

Types and type classes
The datatype `Gray` is a representation for Gray code values. The basic representation is the `Gray` structure, which is polymorphic on the size of the value.

```plaintext
typedef struct {
  Bit#(n) code;
} Gray#(numeric type n) deriving (Bits, Eq);
```

The `Gray` type belongs to the `Literal` and `Bounded` type classes. Each type class definition includes functions which are then also defined for the data type. The Prelude library definitions (Section B) describes which functions are defined for each type class.

<table>
<thead>
<tr>
<th>Type Classes used by Gray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>Gray</td>
</tr>
</tbody>
</table>

**Literal** The `Gray` type is a member of the `Literal` class, which defines an encoding from the compile-time `Integer` type to `Gray` type with the `fromInteger` and `grayEncode` functions. The `fromInteger` converts the value to a bit pattern, and then calls `grayEncode`.

```plaintext
instance Literal #( Gray#(n) )
  provisos(Add#(1, msb, n));
```
**Bounded**  The Gray type is a member of the Bounded class, which provides the functions minBound and maxBound to define the minimum and maximum Gray code values.

- minimum: ’b0
- maximum: ’b10...0

```verilog
instance Bounded # ( Gray#(n) )
    provisos(Add#(1, msb, n));
```

**Functions**

<table>
<thead>
<tr>
<th>function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>grayEncode</td>
<td>This function takes a binary value of type Bit#(n) and returns a Gray type with the Gray code value.</td>
</tr>
<tr>
<td></td>
<td>function Gray#(n) grayEncode(Bit#(n) value)</td>
</tr>
<tr>
<td></td>
<td>provisos(Add#(1, msb, n));</td>
</tr>
<tr>
<td>grayDecode</td>
<td>This function takes a Gray code value of size n and returns the binary value.</td>
</tr>
<tr>
<td></td>
<td>function Bit#(n) grayDecode(Gray#(n) value)</td>
</tr>
<tr>
<td></td>
<td>provisos(Add#(1, msb, n));</td>
</tr>
<tr>
<td>grayIncrDecr</td>
<td>This function takes a Gray code value and a Boolean, decrement. If decrement is True, the value returned is one less than the input value. If decrement is False, the value returned is one greater.</td>
</tr>
<tr>
<td></td>
<td>function Gray#(n) grayIncrDecr(Bool decrement, Gray#(n) value)</td>
</tr>
<tr>
<td></td>
<td>provisos(Add#(1, msb, n));</td>
</tr>
<tr>
<td>grayIncr</td>
<td>Takes a Gray code value and returns a Gray code value incremented by 1.</td>
</tr>
<tr>
<td></td>
<td>function Gray#(n) grayIncr(Gray#(n) value)</td>
</tr>
<tr>
<td></td>
<td>provisos(Add#(1, msb, n));</td>
</tr>
<tr>
<td>grayDecr</td>
<td>Takes a Gray code value a returns a Gray code value decremented by 1.</td>
</tr>
<tr>
<td></td>
<td>function Gray#(n) grayDecr(Gray#(n) value)</td>
</tr>
<tr>
<td></td>
<td>provisos(Add#(1, msb, n));</td>
</tr>
</tbody>
</table>

**C.8.7 CompletionBuffer**

**Package**
import CompletionBuffer :: *;

**Description**

A **CompletionBuffer** is like a FIFO except that the order of the elements in the buffer is independent of the order in which the elements are entered. Each element obtains a token, which reserves a slot in the buffer. Once the element is ready to be entered into the buffer, the token is used to place the element in the correct position. When removing elements from the buffer, the elements are delivered in the order specified by the tokens, not in the order that the elements were written.

Completion Buffers are useful when multiple tasks are running, which may complete at different times, in any order. By using a completion buffer, the order in which the elements are placed in the buffer can be controlled, independent of the order in which the data becomes available.

**Interface and Methods**

The CompletionBuffer interface provides three subinterfaces. The **reserve** interface, a **Get**, allows the caller to reserve a slot in the buffer by returning a token holding the identity of the slot. When data is ready to be placed in the buffer, it is added to the buffer using the **complete** interface of type **Put**. This interface takes a pair of values as its argument - the token identifying its slot, and the data itself. Finally, using the **drain** interface, of type **Get**, data may be retrieved from the buffer in the order in which the tokens were originally allocated. Thus the results of quick tasks might have to wait in the buffer while a lengthy task ahead of them completes.

The type of the elements to be stored is **element_type**. The type of the required size of the buffer is a numeric type **n**, which is also the type argument for the type for the tokens issued, **CBToken**. This allows the type-checking phase of the synthesis to ensure that the tokens are the appropriate size for the buffer, and that all the buffer’s internal registers are of the correct sizes as well.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>reserve</td>
<td>Get</td>
<td>Used to reserve a slot in the buffer. Returns a token, <strong>CBToken #(n)</strong>, identifying the slot in the buffer.</td>
</tr>
<tr>
<td>complete</td>
<td>Put</td>
<td>Enters the element into the buffer. Takes as arguments the slot in the buffer, <strong>CBToken#(n)</strong>, and the element to be stored in the buffer.</td>
</tr>
<tr>
<td>drain</td>
<td>Get</td>
<td>Removes an element from the buffer. The elements are returned in the order the tokens were allocated.</td>
</tr>
</tbody>
</table>

```verilog
interface CompletionBuffer #(numeric type n, type element_type);
    interface Get#(CBToken#(n)) reserve;
    interface Put#(Tuple2 #(CBToken#(n), element_type)) complete;
    interface Get#(element_type) drain;
endinterface: CompletionBuffer
```

**Datatypes**

The **CBToken** type is abstract to avoid misuse.

```verilog
typedef union tagged { ... } CBToken #(numeric type n) ...;
```

**Modules**

The **mkCompletionBuffer** module is used to instantiate a completion buffer. It takes no size arguments, as all that information is already contained in the type of the interface it produces.
**Example- Using a Completion Buffer in a server farm of multipliers**

A server farm is a set of identical servers, which can each perform the same task, together with a controller. The controller allocates incoming tasks to any server which happens to be available (free), and sends results back to its caller.

The time needed to complete each task depends on the value of the multiplier argument; there is therefore no guarantee that results will become available in the order the tasks were started. It is required, however, that the controller return results to its caller in the order the tasks were received. The controller accordingly must instantiate a special mechanism for this purpose. The appropriate mechanism is a Completion Buffer.

```verilog
import List::*;
import FIFO::*;
import GetPut::*;
import CompletionBuffer::*;

typedef Bit#(16) Tin;
typedef Bit#(32) Tout;

// Multiplier interface
interface Mult_IFC;
    method Action start (Tin m1, Tin m2);
    method ActionValue#(Tout) result();
endinterface

typedef Tuple2#(Tin,Tin) Args;
typedef 8 BuffSize;
typedef CBToken#(BuffSize) Token;

// This is a farm of multipliers, mkM. The module
// definition for the multipliers mkM is not provided here.
// The interface definition, Mult_IFC, is provided.
module mkFarm#( module#(Mult_IFC) mkM ) ( Mult_IFC );

    // make the buffer twice the size of the farm
    Integer n = div(valueof(BuffSize),2);

    // Declare the array of servers and instantiate them:
    Mult_IFC mults[n];
    for (Integer i=0; i<n; i=i+1)
        begin
            Mult_IFC s <- mkM;
            mults[i] = s;
        end

    FIFO#(Args) infifo <- mkFIFO;
```
// instantiate the Completion Buffer, cbuff, storing values of type Tout
// buffer size is Buffsize, data type of values is Tout
CompletionBuffer#(BuffSize,Tout) cbuff <- mkCompletionBuffer;

// an array of flags telling which servers are available:
Reg#(Bool) free[n];
// an array of tokens for the jobs in progress on the servers:
Reg#(Token) tokens[n];
// this loop instantiates n free registers and n token registers
// as well as the rules to move data into and out of the server farm
for (Integer i=0; i<n; i=i+1)
begin

  // Instantiate the elements of the two arrays:
  Reg#(Bool) f <- mkReg(True);
  free[i] = f;
  Reg#(Token) t <- mkRegU;
  tokens[i] = t;

  Mult_IFC s = mults[i];

  // The rules for sending tasks to this particular server, and for
  // dealing with returned results:
  rule start_server (f); // start only if flag says it's free
      // Get a token
      CBToken#(BuffSize) new_t <- cbuff.reserve.get;
      Args a = infifo.first;
      Tin a1 = tpl_1(a);
      Tin a2 = tpl_2(a);
      infifo.deq;

      f <= False;
      t <= new_t;
      s.start(a1,a2);
    endrule

  rule end_server (!f);
      Tout x <- s.result;
      // Put the result x into the buffer, at the slot t
      cbuff.complete.put(tuple2(t,x));
      f <= True;
    endrule
end

method Action start (m1, m2);
  infifo.enq(tuple2(m1,m2));
endmethod

// Remove the element from the buffer, returning the result
// The elements will be returned in the order that the tokens were obtained.
method result = cbuff.drain.get;
endmodule
C.8.8 UniqueWrappers

Package

import UniqueWrappers :: * ;

Description

The UniqueWrappers package takes a piece of combinational logic which is to be shared and puts it into its own protective shell or wrapper to prevent its duplication. This is used in instances where a separately synthesized module is not possible. It allows the designer to use a piece of logic at several places in a design without duplicating it at each site.

There are times where it is desired to use a piece of logic at several places in a design, but it is too bulky or otherwise expensive to duplicate at each site. Often the right thing to do is to make the piece of logic into a separately synthesized module – then, if this module is instantiated only once, it will not be duplicated, and the tool will automatically generate the scheduling and multiplexing logic to share it among the sites which use its methods. Sometimes, however, this is not convenient. One reason might be that the logic is to be incorporated into a submodule of the design which is itself polymorphic – this will probably cause difficulties in observing the constraints necessary for a module which is to be separately synthesized. And if a module is not separately synthesized, the tool will inline its logic freely wherever it is used, and thus duplication will not be prevented as desired.

This package covers the case where the logic to be shared is combinational and cannot be put into a separately synthesized module. It may be thought of as surrounding this combinational function with a protective shell, a unique wrapper, which will prevent its duplication. The module mkUniqueWrapper takes a one-argument function as a parameter; both the argument type a and the result type b must be representable as bits, that is, they must both be in the Bits typeclass.

Interfaces

The UniqueWrappers package provides an interface, Wrapper, with one actionvalue method, func, which takes an argument of type a and produces a method of type ActionValue#(b). If the module is instantiated only once, the logic implementing its parameter will be instantiated just once; the module’s method may, however, be used freely at several places.

Although the function supplied as the parameter is purely combinational and does not change state, the method is of type ActionValue. This is because actionvalue methods have enable signals and these signals are needed to organize the scheduling and multiplexing between the calling sites.

Variants of the interface Wrapper are also provided for handling functions of two or three arguments; the interfaces have one and two extra parameters respectively. In each case the result type is the final parameter, following however many argument type parameters are required.

<table>
<thead>
<tr>
<th>Wrapper Interfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wrapper</strong></td>
</tr>
<tr>
<td>interface Wrapper#(type a_type, type b_type);</td>
</tr>
<tr>
<td>method ActionValue#(b_type) func (a_type x);</td>
</tr>
</tbody>
</table>

| **Wrapper2**       | Similar to the Wrapper interface, but it takes two arguments. |
|--------------------|
| interface Wrapper2#(type a1_type, type a2_type, type b_type); |
| method ActionValue#(b_type) func (a1_type x, a2_type y); |

360
Wrapper3

Similar to the Wrapper interface, but it takes three arguments.

```systemverilog
interface Wrapper3#(type a1_type, type a2_type, type a3_type,
                     type b_type);
    method ActionValue#(b_type) func (a1_type x, a2_type y, a3_type z);
```

### Modules

The interfaces Wrapper, Wrapper2, and Wrapper3 are provided by the modules mkUniqueWrapper, mkUniqueWrapper2, and mkUniqueWrapper3. These modules vary only in the number of arguments in the parameter function.

If a function has more than three arguments, it can always be rewritten or wrapped as one which takes the arguments as a single tuple; thus the one-argument version `mkUniqueWrapper` can be used with this function.

### mkUniqueWrapper

Takes a function, `func`, with a single parameter `x` and provides the interface `Wrapper`.

```systemverilog
module mkUniqueWrapper#(function b_type func(a_type x))
    (Wrapper#(a_type, b_type))
    provisos (Bits#(a_type, sizea), Bits#(b_type, sizeb));
```

### mkUniqueWrapper2

Takes a function, `func`, with two parameters, `x` and `y`, and provides the interface `Wrapper2`.

```systemverilog
module mkUniqueWrapper2#(function b_type func(a1_type x, a2_type y))
    (Wrapper2#(a1_type, a2_type, b_type))
    provisos (Bits#(a1_type, sizea1), Bits#(a2_type, sizea2),
              Bits#(b_type, sizeb));
```

### mkUniqueWrapper3

Takes a function, `func`, with three parameters, `x`, `y`, and `z`, and provides the interface `Wrapper3`.

```systemverilog
module mkUniqueWrapper3#(function b_type
                          func(a1_type x, a2_type y, a3_type z))
    (Wrapper3#(a1_type, a2_type, a3_type, b_type))
    provisos (Bits#(a1_type, sizea1), Bits#(a2_type, sizea2),
              Bits#(a3_type, sizea3), Bits#(b_type, sizeb));
```

### Example: Complex Multiplication

```systemverilog
// This module defines a single hardware multiplier, which is then
// used by multiple method calls to implement complex number
// multiplication (a + bi)(c + di)
```
typedef Int#(18) CFP;

module mkComplexMultFifo( ArithOpGP2#(CFP) ) ;
  FIFO#(ComplexP#(CFP)) infifo1 <- mkFIFO;
  FIFO#(ComplexP#(CFP)) infifo2 <- mkFIFO;
  let arg1 = infifo1.first ;
  let arg2 = infifo2.first ;

  FIFO#(ComplexP#(CFP)) outfifo <- mkFIFO;

  Reg#(CFP) rr <- mkReg(0) ;
  Reg#(CFP) ii <- mkReg(0) ;
  Reg#(CFP) ri <- mkReg(0) ;
  Reg#(CFP) ir <- mkReg(0) ;

  // Declare and instantiate an interface that takes 2 arguments, multiplies them
  // and returns the result. It is a Wrapper2 because there are 2 arguments.
  Wrapper2#(CFP,CFP, CFP) smult <- mkUniqueWrapper2( \* ) ;

  // Define a sequence of actions
  // Since smult is a UnqiueWrapper the method called is smult.func
  Stmt multSeq =
    seq
      action
        let mr <- smult.func( arg1.rel, arg2.rel ) ;
        rr <= mr ;
      endaction
      action
        let mr <- smult.func( arg1.img, arg2.img ) ;
        ii <= mr ;
      endaction
      action
        // Do the first add in this step
        let mr <- smult.func( arg1.img, arg2.rel ) ;
        ir <= mr ;
        rr <= rr - ii ;
      endaction
      action
        let mr <- smult.func( arg1.rel, arg2.img ) ;
        ri <= mr ;
        // We are done with the inputs so deq the in fifos
        infifo1.deq ;
        infifo2.deq ;
      endaction
      action
        let ii2 = ri + ir ;
        let res = Complex{ rel: rr , img: ii2 } ;
        outfifo.enq( res ) ;
      endaction
    endseq;

  // Now convert the sequence into a FSM ;
  // Bluespec can assign the state variables, and pick up implicit
  // conditions of the actions
FSM multfsm <- mkFSM(multSeq);
rule startFSM;
    multfsm.start;
endrule
endmodule

C.8.9 DefaultValue

Package

import DefaultValue :: * ;

Description

This package defines a type class of DefaultValue and instances of the type class for many commonly used datatypes. Users can create their own default value instances for other types. This type class is particularly useful for defining default values for user-defined structures.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Typeclasses

typeclass DefaultValue #( type t );
    t defaultValue ;
endtypeclass

The following instances are defined in the DefaultValue package. You can define your own instances for user-defined structures and other types.

<table>
<thead>
<tr>
<th>DefaultValue Instances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literal#(t)</td>
</tr>
<tr>
<td>Any type t in the Literal class can have a default value which is defined here as 0. The types in the Literal class include Bit#(n), Int#(n), UInt#(n), Real, Integer, FixedPoint, and Complex.</td>
</tr>
<tr>
<td>instance DefaultValue # (t)</td>
</tr>
<tr>
<td>provisos (Literal#(t));</td>
</tr>
<tr>
<td>defaultValue = fromInteger (0);</td>
</tr>
<tr>
<td>Bool</td>
</tr>
<tr>
<td>The default value for a Bool is defined as False.</td>
</tr>
<tr>
<td>instance DefaultValue #( Bool );</td>
</tr>
<tr>
<td>defaultValue = False ;</td>
</tr>
<tr>
<td>void</td>
</tr>
<tr>
<td>The default value for a void is defined as ?.</td>
</tr>
<tr>
<td>instance DefaultValue #(void);</td>
</tr>
<tr>
<td>defaultValue = ?;</td>
</tr>
<tr>
<td>Maybe</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

The default value for a `Tuple` is composed of the default values of each member type. Instances are defined for `Tuple2` through `Tuple8`.

<table>
<thead>
<tr>
<th>Tuple2#(a,b)</th>
<th>The default value of a Tuple2 is the default value of element a and the default value of element b.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><code>instance DefaultValue #( Tuple2#(a,b) )</code></td>
</tr>
<tr>
<td></td>
<td><code>provisos (DefaultValue#(a) , DefaultValue#(b) );</code></td>
</tr>
<tr>
<td></td>
<td><code>defaultValue = tuple2 (defaultValue, defaultValue );</code></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vector</th>
<th>The default value for a Vector replicates the element’s default value type for each element.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><code>instance DefaultValue #( Vector#(n,t) )</code></td>
</tr>
<tr>
<td></td>
<td><code>provisos (DefaultValue#(t));</code></td>
</tr>
<tr>
<td></td>
<td><code>defaultValue = replicate (defaultValue );</code></td>
</tr>
</tbody>
</table>

Examples

Example 1: Specifying the initial or reset values for a structure.

```verilog
Reg#(Int#(17)) rint <- mkReg#(defaultValue); // initial value 0
Reg#(Tuple2#(Bool,UInt#(5))) tbui <- mkReg#(defaultValue); // value is(False,0)
Reg#(Vector#(n,Bool) vbool <- mkReg#(defaultValue); // initial value all False
```

Example 2: Using default values to replace the unsafe use of unpack.

```verilog
import DefaultValue :: *;

typedef struct {
  UInt#(4) size;
  UInt#(3) depth;
} MyStruct

deriving (Bits, Eq);

instance DefaultValue #( MyStruct );
  defaultValue = MyStruct { size : 0,
    depth : 1 }; endinstance

then you can use:

Reg#(MyStruct) mstr <- mkReg(defaultValue);
```

364
instead of:

```verilog
Reg#(MyStruct) mybad <- mkReg(unpack(0)); // Bad use of unpack
```

Example 3: Module instantiation which requires a large structure as an argument.

```verilog
ModParam modParams = defaultValue ; // generate default value
modParams.field1 = 5 ; // override some default values
modParams.field2 = 1.4 ;
ModIfc <- mkMod (modArgs) ; // construct the module
```

C.8.10 TieOff

Package

```verilog
import TieOff :: * ;
```

Description

This package provides a typeclass `TieOff#(t)` which may be useful to provide default enable methods of some interface `t`, some of which must be `always_enabled` or require some action.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the `$BLUESPECDIR/BSVSource/Misc` directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the `-p` option as described in the BSV Users Guide.

Typeclasses

```verilog
typeclass TieOff #(type t);
    module mkTieOff#(t ifc) (Empty);
endtypeclass
```

Example: Defining a TieOff for a Get interface

This is a sink module which pulls data from the Get interface and displays the data.

```verilog
instance TieOff #(Get #(t) )
    provisos (Bits#(t,st),
              FShow#(t));
    module mkTieOff ( Get#(t) ifc, Empty inf);
    rule getSink (True);
        t val <- ifc.get;
        $display( "Get tieoff %m", fshow(val) );
    endrule
endmodule
endinstance
```
C.8.11  Assert

Package

import Assert :: *;

Description

The Assert package contains definitions to test assertions in the code. The check-assert flag must be set during compilation. By default, the flag is set to False and assertions are ignored. The flag, when set, instructs the compiler to abort compilation if an assertion fails.

Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>staticAssert</td>
<td>Compile time assertion. Can be used anywhere a compile-time statement is valid.</td>
</tr>
<tr>
<td></td>
<td>module staticAssert(Bool b, String s);</td>
</tr>
<tr>
<td>dynamicAssert</td>
<td>Run time assertion. Can be used anywhere an Action is valid, and is tested whenever it is executed.</td>
</tr>
<tr>
<td></td>
<td>function Action dynamicAssert(Bool b, String s);</td>
</tr>
<tr>
<td>continuousAssert</td>
<td>Continuous run-time assertion (expected to be True on each clock). Can be used anywhere a module instantiation is valid.</td>
</tr>
<tr>
<td></td>
<td>function Action continuousAssert(Bool b, String s);</td>
</tr>
</tbody>
</table>

Examples using Assertions:

import Assert :: *;
module mkAssert_Example ();
// A static assert is checked at compile-time
// This code checks that the indices are within range
for (Integer i=0; i<length(cs); i=i+1)
    begin
        Integer new_index = (cs[i]).index;
        staticAssert(new_index < valueOf(n),
            strConcat("Assertion index out of range: ", integerToString(new_index)));
    end

rule always_fire (True);
    counter <= counter + 1;
endrule
// A continuous assert is checked on each clock cycle
continuousAssert (!fail, "Failure: Fail becomes True");

// A dynamic assert is checked each time the rule is executed
rule test_assertion (True);
    dynamicAssert (!fail, "Failure: Fail becomes True");
endrule
endmodule: mkAssert_Example

C.8.12 Probe

Package

import Probe :: * ;

Description

A Probe is a primitive used to ensure that a signal of interest is not optimized away by the compiler and that it is given a known name. In terms of BSV syntax, the Probe primitive is used just like a register except that only a write method exists. Since reads are not possible, the use of a Probe has no effect on scheduling. In the generated Verilog, the associated signal will be named just like the port of any Verilog module, in this case <instance_name>$PROBE. No actual Probe instance will be created however. The only side effects of a BSV Probe instantiation relate to the naming and retention of the associated signal in the generated Verilog.

Interfaces

interface Probe #(type a_type);
    method Action _write(a_type x1);
endinterface: Probe

Modules

The module mkProbe is used to instantiate a Probe.

<table>
<thead>
<tr>
<th>mkProbe</th>
<th>Instantiates a Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkProbe(Probe#(a_type))</td>
<td></td>
</tr>
<tr>
<td>provisos (Bits#(a_type, sizea));</td>
<td></td>
</tr>
</tbody>
</table>

Example - Creating and writing to registers and probes

import FIFO::*;
import ClientServer::*;
import GetPut::*;
import Probe::*;

typedef Bit#(32) LuRequest;
typedef Bit#(32) LuResponse;

module mkMesaHwLpm(ILpm);
    // Create registers for requestB32 and responseB32
    Reg#(LuRequest) requestB32 <- mkRegU();
    Reg#(LuResponse) responseB32 <- mkRegU();

    // Create a probe responseB32_probe
    Probe#(LuResponse) responseB32_probe <- mkProbe();
    ....
    // Define the interfaces:

367
interface GetResponse;
method get();
actionvalue
  let resp <- completionBuffer.drain.get();
  // record response for debugging purposes:
  let {r,t} = resp;
  responseB32 <= r; // a write to a register
  responseB32_probe <= r; // a write to a probe
  // count responses in status register
  return(resp);
endactionvalue
endmethod: get
endinterface: GetResponse
endmodule

C.8.13 Reserved Package

import Reserved :: *;

Description

The Reserved package defines three abstract data types which only have the purpose of taking up space. They are useful when defining a struct where you need to enforce a certain layout and want to use the type checker to enforce that the value is not accidentally used. One can enforce a layout unsafely with Bit#(n), but Reserved#(n) gives safety. A value of type Reserved#(n) takes up exactly n bits.

typedef ... abstract ... Reserved#(type n);

Types and Type classes

There are three types defined in the Reserved package: Reserved, ReservedZero, and ReservedOne. The Reserved type is an abstract data type which takes up exactly n bits and always returns an unspecified value. The ReservedZero and ReservedOne data types are equivalent to the Reserved type except that ReservedZero always returns '0 and ReservedOne always returns '1.

<table>
<thead>
<tr>
<th>Type Classes used by Reserved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>Reserved</td>
</tr>
<tr>
<td>ReservedZero</td>
</tr>
<tr>
<td>ReservedOne</td>
</tr>
</tbody>
</table>

- Bits The only purpose of these types is to allow the value to exist in hardware (at port boundaries and in states). The user should have no reason to use pack/unpack directly.

Converting Reserved to or from Bits returns a don’t care (?).

Converting ReservedZero to or from Bits returns a '0.
Converting `ReservedOne` to or from `Bits` returns a '1'.

- **Eq and Ord**
  Any two `Reserved`, `ReservedZero`, or `ReservedOne` values are considered to be equal.

- **Bounded**
  The upper and lower bound return don’t care (?), '1' or '0' values depending on the type.

**Example: Structure with a 8 bits reserved.**

typedef struct {
  Bit#(8) header; // Frame.header
  Vector#(2, Bit#(8)) payload; // Frame.payload
  Reserved#(8) dummy; // Can’t access 8 bits reserved
  Bit#(8) trailer; // Frame.trailer
} Frame;

<table>
<thead>
<tr>
<th>header</th>
<th>payload0</th>
<th>payload1</th>
<th>dummy</th>
<th>trailer</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

**C.8.14 TriState**

**Package**

import TriState :: * ;

**Description**

The `TriState` package implements a tri-state buffer, as shown in Figure 5. Depending on the value of the `output_enable`, `inout` can be an input or an output.

![TriState Buffer](image)

Figure 5: TriState Buffer

The buffer has two inputs, an input of type `value_type` and a Boolean `output_enable` which determines the direction of `inout`. If `output_enable` is True, the signal is coming in from `input` and out through `inout` and `output`. If `output_enable` is False, then a value can be driven in from `inout`, and the `output` value will be the value of `inout`. The behavior is described in the tables below.

<table>
<thead>
<tr>
<th>output_enable = 0</th>
<th>output = inout</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
<td></td>
</tr>
<tr>
<td>input</td>
<td>inout</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>input</td>
<td>Outputs</td>
</tr>
<tr>
<td>-------</td>
<td>---------</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

This module is not supported in Bluesim.

**Interfaces and Methods**

The TriState interface is composed of an Inout interface and a _read method. The _read method is similar to the _read method of a register in that to read the method you reference the interface in an expression.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>io</td>
<td>Inout#(value_type)</td>
<td>Inout subinterface providing a value of type</td>
</tr>
<tr>
<td></td>
<td></td>
<td>value_type</td>
</tr>
<tr>
<td>_read</td>
<td>value_type</td>
<td>Returns the value of output</td>
</tr>
</tbody>
</table>

(* always_ready, always_enabled *)

interface TriState#(type value_type);
  interface Inout#(value_type)  io;
  method value_type _read;
endinterface: TriState

**Modules and Functions**

The TriState package provides a module constructor function, mkTriState, which provides the TriState interface. The interface includes an Inout subinterface and the value of output.

<table>
<thead>
<tr>
<th>mkTriState</th>
<th>Creates a module which provides the TriState interface.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkTriState#(Bool output_enable, value_type input)</td>
</tr>
<tr>
<td></td>
<td>(TriState#(value_type))</td>
</tr>
<tr>
<td></td>
<td>provisos(Bits#(value_type, size_value));</td>
</tr>
</tbody>
</table>

**Verilog Modules**

The TriState module is implemented by the Verilog module TriState.v which can be found in the Bluespec Verilog library, $BLUESPECDIR/Verilog/.

**C.8.15 ZBus**

**Package**

import ZBus :: * ;
Description

BSV provides the ZBus library to allow users to implement and use tri-state buses. Since BSV does not support high-impedance or undefined values internally, the library encapsulates the tri-state bus implementation in a module that can only be accessed through predefined interfaces which do not allow direct access to internal signals (which could potentially have high-impedance or undefined values).

The Verilog implementation of the tri-state module includes a number of primitive submodules that are implemented using Verilog tri-state wires. The BSV representation of the bus, however, only models the values of the bus at the associated interfaces and thus the need to represent high-impedance or undefined values in BSV is avoided.

A ZBus consists of a series of clients hanging off of a bus. The combination of the client and the bus is provided by the ZBusDualIFC interface which consists of 2 subinterfaces, the client and the bus. The client subinterface is provided by the ZBusClientIFC interface. The bus subinterface is provided by the ZBusBusIFC interface. The user never needs to manipulate the bus side, this is all done internally. The user builds the bus out of ZBusDualIFCs and then drives values onto the bus and reads values from the bus using the ZBusClientIFC.

Interfaces and Methods

There are three interfaces are defined in this package; ZBusDualIFC, ZBusClientIFC, and ZBusBusIFC.

The ZBusDualIFC interface provides two subinterfaces; a ZBusBusIFC and a ZBusClientIFC. For a given bus, one ZBusDualIFC interface is associated with each bus client.

<table>
<thead>
<tr>
<th>ZBusDualIFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>busIFC</td>
</tr>
<tr>
<td>clientIFC</td>
</tr>
</tbody>
</table>

interface ZBusDualIFC #(type value_type) ;
  interface ZBusBusIFC#(value_type) busIFC;
  interface ZBusClientIFC#(value_type) clientIFC;
endinterface

The ZBusClientIFC allows a BSV module to connect to the tri-state bus. The drive method is used to drive a value onto the bus. The get() and fromBusValid() methods allow each bus client to access the current value on the bus. If the bus is in an invalid state (i.e. has a high-impedance value or an undefined value because it is being driven by more than one client simultaneously), then the get() method will return 0 and the fromBusValid() method will return False. In all other cases, the fromBusValid() method will return True and the get() method will return the current value of the bus.

<table>
<thead>
<tr>
<th>ZBusClientIFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
</tr>
<tr>
<td>drive</td>
</tr>
<tr>
<td>get</td>
</tr>
<tr>
<td>fromBusValid</td>
</tr>
</tbody>
</table>
interface ZBusClientIFC #(type value_type) ;
  method Action drive(value_type value);
  method value_type get();
  method Bool fromBusValid();
endinterface

The ZBusBusIFC interface connects to the bus structure itself using tri-state values. This interface is never accessed directly by the user.

interface ZBusBusIFC #(type value_type) ;
  method Action fromBusSample(ZBit#(value_type) value, Bool isValid);
  method ZBit#(t) toBusValue();
  method Bool toBusCtl();
endinterface

Modules and Functions

The library provides a module constructor function, mkZBusBuffer, which allows the user to create a module which provides the ZBusDualIFC interface. This module provides the functionality of a tri-state buffer.

<table>
<thead>
<tr>
<th>mkZBusBuffer</th>
<th>Creates a module which provides the ZBusDualIFC interface.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkZBusBuffer (ZBusDualIFC #(value_type))</td>
<td></td>
</tr>
<tr>
<td>provisos (Eq#(value_type), Bits#(value_type, size_value));</td>
<td></td>
</tr>
</tbody>
</table>

The mkZBus module constructor function takes a list of ZBusBusIFC interfaces as arguments and creates a module which ties them all together in a bus.

<table>
<thead>
<tr>
<th>mkZBus</th>
<th>Ties a list of ZBusBusIFC interfaces together in a bus.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkZBus#(List#(ZBusBusIFC#(value_type)) ifc_list)(Empty)</td>
<td></td>
</tr>
<tr>
<td>provisos (Eq#(value_type), Bits#(value_type, size_value));</td>
<td></td>
</tr>
</tbody>
</table>

Examples - ZBus

Creating a tri-state buffer for a 32 bit signal. The interface is named buffer_0.

ZBusDualIFC#(Bit#(32)) buffer_0();
mkZBusBuffer inst_buffer_0(buffer_0);

Drive a value of 12 onto the associated bus.

buffer_0.clientIFC.drive(12);

The following code fragment demonstrates the use of the module mkZBus.

ZBusDualIFC#(Bit#(32)) buffer_0();
mkZBusBuffer inst_buffer_0(buffer_0);

ZBusDualIFC#(Bit#(32)) buffer_1();
mkZBusBuffer inst_buffer_1(buffer_1);
import CRC :: * ;

Description
CRC’s are designed to protect against common types of errors on communication channels. The CRC package defines modules to calculate a check value for each 8-bit block of data, which can then be verified to determine if data was transmitted and/or received correctly. There are many commonly used and standardized CRC algorithms. The CRC package provides both a generalized CRC module as well as module implementations for the CRC-CCITT, CRC-16-ANSI, and CRC-32 (IEEE 802.3) standards. The size of the CRC polynomial is polymorphic and the data size is a byte (Bit#(8)), which is relevant for many applications. The generalized module uses five arguments to define the CRC algorithm: the CRC polynomial, the initial CRC value, a fixed bit pattern to Xor with the remainder, a boolean indicating whether to reverse the data bit order and a boolean indicating whether to reverse the result bit order. By specifying these arguments, you can implement many CRC algorithms. This package provides modules for three specific algorithms by defining the arguments for those algorithms.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Interfaces and Methods
The CRC modules provide the CRC interface. The add method is used to calculate the check value on the data argument. In this package, the argument is always a Bit#(8).

<table>
<thead>
<tr>
<th>CRC Interface</th>
<th>Method</th>
<th>Description</th>
<th>Arguments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>add</td>
<td>Update the CRC</td>
<td>Bit#(8) data 8-bit data block</td>
</tr>
<tr>
<td></td>
<td>clear</td>
<td>Reset to the initial value</td>
<td></td>
</tr>
<tr>
<td></td>
<td>result</td>
<td>Returns the current value of the check value</td>
<td></td>
</tr>
<tr>
<td></td>
<td>complete</td>
<td>Return the result and reset</td>
<td></td>
</tr>
</tbody>
</table>
interface CRC#(numeric type n);
    method Action add(Bit#(8) data);
    method Action clear();
    method Bit#(n) result();
    method ActionValue#(Bit#(n)) complete();
endinterface

Modules
The implementation of the generalized CRC module takes the following five arguments:

- Bit#(n) polynomial: the crc operation polynomial, for example \(x^{16} + x^{12} + x^5 + 1\) is written as \(\text{h}1021\)
- Bit#(n) initval: the initial CRC value
- Bit#(n) finalXor: the result is xor’d with this value if desired
- Bool reflectData: if True, reverse the data bit order
- Bool reflectRemainder: if True, reverse the result bit order

<table>
<thead>
<tr>
<th>mkCRC</th>
<th>The generalized CRC module. The provisos enforce the requirement that polynomial and initial value must be at least 8 bits.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkCRC#( Bit#(n) polynomial, Bit#(n) initval, Bit#(n) finalXor, Bool reflectData, Bool reflectRemainder )(CRC#(n)) provisos( Add#(8, n8, n) );</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>polynomial</th>
<th>initval</th>
<th>finalXor</th>
<th>reflectData</th>
<th>reflectRemainder</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRC-CCITT</td>
<td>'h1021</td>
<td>'hFFFF</td>
<td>'h0000</td>
<td>False</td>
<td>False</td>
</tr>
<tr>
<td>CRC-16-ANSI</td>
<td>'h8005</td>
<td>'h0000</td>
<td>'h0000</td>
<td>True</td>
<td>True</td>
</tr>
<tr>
<td>CRC-32 (IEEE 802.3)</td>
<td>'h04C11DB7</td>
<td>'hFFFFFF</td>
<td>'hFFFFFFFF</td>
<td>True</td>
<td>True</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkCRC_CCIT</th>
<th>Implements the 16-bit CRC-CCITT standard. ((x^{16} + x^{15} + x^2 + 1)).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkCRC_CCIT(CRC#(16));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkCRC16</th>
<th>Implementation of the 16-bit CRC-16-ANSI standard. ((x^{16} + x^{15} + x^2 + 1)).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module mkCRC16(CRC#(16));</td>
</tr>
</tbody>
</table>
Implementation of the 32-bit CRC-32 (IEEE 802.3) standard.
\[(x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x^1 + 1)\]

```
module mkCRC32(CRC#(32));
```

The `reflect` function reverses the data bits if the value of `reflectData` is True.

```
function Bit#(a) reflect(Bool doIt, Bit#(a) data);
    return (doIt) ? reverseBits(data) : data;
endfunction
```

## C.8.17 OVLAssertions

### Package

```verilog
import OVLAssertions :: *;
```

### Description

The OVLAssertions package provides the BSV interfaces and wrapper modules necessary to allow BSV designs to include assertion checkers from the Open Verification Library (OVL). The OVL includes a set of assertion checkers that verify specific properties of a design. For more details on the complete OVL, refer to the Accellera Standard OVL Library Reference Manual (http://www.accellera.org).

### Interfaces and Methods

The following interfaces are defined for use with the assertion modules. Each interface has one or more `Action` methods. Each method takes a single argument which is either a `Bool` or polymorphic.

**AssertTest_IFC** Used for assertions that check a test expression on every clock cycle.

<table>
<thead>
<tr>
<th>AssertTest_IFC</th>
<th>Method</th>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Type</td>
<td>Name</td>
<td>Type</td>
</tr>
<tr>
<td><code>test</code></td>
<td><code>Action</code></td>
<td><code>test_value</code></td>
<td><code>a_type</code></td>
</tr>
</tbody>
</table>

```
interface AssertTest_IFC #(type a_type);
    method Action test(a_type test_value);
endinterface
```

**AssertSampleTest_IFC** Used for assertions that check a test expression on every clock cycle only if the sample, indicated by the boolean value `sample_test` is asserted.

<table>
<thead>
<tr>
<th>AssertSampleTest_IFC</th>
<th>Method</th>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Type</td>
<td>Name</td>
<td>Type</td>
</tr>
<tr>
<td><code>sample</code></td>
<td><code>Action</code></td>
<td><code>sample_test</code></td>
<td><code>Bool</code></td>
</tr>
<tr>
<td><code>test</code></td>
<td><code>Action</code></td>
<td><code>test_value</code></td>
<td><code>a_type</code></td>
</tr>
</tbody>
</table>
interface AssertSampleTest_IFC #(type a_type);
    method Action sample(Bool sample_test);
    method Action test(a_type test_value);
endinterface

**AssertStartTest_IFC**  Used for assertions that check a test expression only subsequent to a
start_event, specified by the Boolean value **start_test**.

<table>
<thead>
<tr>
<th>Method</th>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>start</td>
<td>start_test</td>
<td>Assertion only checked after start is asserted.</td>
</tr>
<tr>
<td>test</td>
<td>test_value</td>
<td>Expression to be checked.</td>
</tr>
</tbody>
</table>

interface AssertStartTest_IFC #(type a_type);
    method Action start(Bool start_test);
    method Action test(a_type test_value);
endinterface

**AssertStartStopTest_IFC**  Used to check a test expression between a start_event and a stop_event.

<table>
<thead>
<tr>
<th>Method</th>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>start</td>
<td>start_test</td>
<td>Assertion only checked after start is asserted.</td>
</tr>
<tr>
<td>stop</td>
<td>stop_test</td>
<td>Assertion only checked until the stop is asserted.</td>
</tr>
<tr>
<td>test</td>
<td>test_value</td>
<td>Expression to be checked.</td>
</tr>
</tbody>
</table>

interface AssertStartStopTest_IFC #(type a_type);
    method Action start(Bool start_test);
    method Action stop(Bool stop_test);
    method Action test(a_type test_value);
endinterface

**AssertTransitionTest_IFC**  Used to check a test expression that has a specified start state and
next state, i.e. a transition.

<table>
<thead>
<tr>
<th>Method</th>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>test</td>
<td>test_value</td>
<td>Expression that should transition to the next_value.</td>
</tr>
<tr>
<td>start</td>
<td>start_test</td>
<td>Expression that indicates the start state for the assertion check. If the value of <strong>start_test</strong> equals the value of <strong>test_value</strong>, the check is performed.</td>
</tr>
<tr>
<td>next</td>
<td>next_value</td>
<td>Expression that indicates the only valid next state for the assertion check.</td>
</tr>
</tbody>
</table>
interface AssertTransitionTest_IFC #(type a_type);
    method Action test(a_type test_value);
    method Action start(a_type start_value);
    method Action next(a_type next_value);
endinterface

AssertQuiescentTest_IFC  Used to check that a test expression is equivalent to the specified expression when the sample state is asserted.

<table>
<thead>
<tr>
<th>Method</th>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>sample</td>
<td>Action</td>
<td>Expression which initiates the quiescent assertion check when it transitions to true.</td>
</tr>
<tr>
<td>state</td>
<td>Action</td>
<td>Expression that should have the same value as check_value</td>
</tr>
<tr>
<td>check</td>
<td>Action</td>
<td>Expression \texttt{state_value} is compared to.</td>
</tr>
</tbody>
</table>

interface AssertQuiescentTest_IFC #(type a_type);
    method Action sample(Bool sample_test);
    method Action state(a_type state_value);
    method Action check(a_type check_value);
endinterface

AssertFifoTest_IFC  Used with assertions checking a FIFO structure.

<table>
<thead>
<tr>
<th>Method</th>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>push</td>
<td>Action</td>
<td>Expression which indicates the number of push operations that will occur during the current cycle.</td>
</tr>
<tr>
<td>pop</td>
<td>Action</td>
<td>Expression which indicates the number of pop operations that will occur during the current cycle.</td>
</tr>
</tbody>
</table>

interface AssertFifoTest_IFC #(type a_type, type b_type);
    method Action push(a_type push_value);
    method Action pop(b_type pop_value);
endinterface

Datatypes
The parameters \texttt{severity\_level}, \texttt{property\_type}, \texttt{msg}, and \texttt{coverage\_level} are common to all assertion checkers.
## Common Parameters for all Assertion Checkers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Valid Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>severity_level</td>
<td>OVL_FATAL, OVL_ERROR, OVL_WARNING, OVL_Info</td>
</tr>
<tr>
<td>property_type</td>
<td>OVL_ASSERT, OVL_ASSUME, OVL_IGNORE</td>
</tr>
<tr>
<td>msg</td>
<td>OVL_VIOLATION</td>
</tr>
<tr>
<td>coverage_level</td>
<td>OVL_COVER_NONE, OVL_COVER_ALL, OVL_COVER_SANITY, OVL_COVER_BASIC, OVL_COVER_CORNER, OVL_COVER_STATISTIC</td>
</tr>
</tbody>
</table>

Each assertion checker may also use some subset of the following parameters.

## Other Parameters for Assertion Checkers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Valid Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>action_on_new_start</td>
<td>OVL_IGNORE_NEW_START, OVL_RESET_ON_NEW_START, OVL_ERROR_ON_NEW_START</td>
</tr>
<tr>
<td>edge_type</td>
<td>OVL_NOEDGE, OVL_POSEDGE, OVL_NEGEDGE, OVL_ANYEDGE</td>
</tr>
<tr>
<td>necessary_condition</td>
<td>OVL_TRIGGER_ON_MOST_PIPE, OVL_TRIGGER_ON_FIRST_PIPE, OVL_TRIGGER_ON_FIRST_NOPipe</td>
</tr>
<tr>
<td>inactive</td>
<td>OVL_ALL_zeros, OVL_ALLONES, OVL_ONE_COLD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Valid Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>num_cks</td>
<td>Int#(32)</td>
</tr>
<tr>
<td>min_cks</td>
<td>Int#(32)</td>
</tr>
<tr>
<td>max_cks</td>
<td>Int#(32)</td>
</tr>
<tr>
<td>min_ack_cycle</td>
<td>Int#(32)</td>
</tr>
<tr>
<td>max_ack_cycle</td>
<td>Int#(32)</td>
</tr>
<tr>
<td>max_ack_length</td>
<td>Int#(32)</td>
</tr>
<tr>
<td>req_drop</td>
<td>Int#(32)</td>
</tr>
<tr>
<td>deassert_count</td>
<td>Int#(32)</td>
</tr>
<tr>
<td>depth</td>
<td>Int#(32)</td>
</tr>
<tr>
<td>value</td>
<td>a_type</td>
</tr>
<tr>
<td>min</td>
<td>a_type</td>
</tr>
<tr>
<td>max</td>
<td>a_type</td>
</tr>
<tr>
<td>check_overlapping</td>
<td>Bool</td>
</tr>
<tr>
<td>check_missing_start</td>
<td>Bool</td>
</tr>
<tr>
<td>simultaneous_push_pop</td>
<td>Bool</td>
</tr>
</tbody>
</table>
Setting Assertion Parameters

Each assertion checker module has a set of associated parameter values that can be customized for each module instantiation. The values for these parameters are passed to each checker module in the form of a single struct argument of type OVLDefaults#(a). A typical use scenario is illustrated below:

```verilog
let defaults = mkOVLDefaults;

defaults.min_clks = 2;
defaults.max_clks = 3;

AssertTest_IFC#(Bool) assertWid <- bsv_assert_width(defaults);
```

The defaults struct (created by mkOVLDefaults) includes one field for each possible parameter. Initially each field includes the associated default value. By editing fields of the struct, individual parameter values can be modified as needed to be non-default values. The modified defaults struct is then provided as a module argument during instantiation.

Modules

Each module in this package corresponds to an assertion checker from the Open Verification Library (OVL). The BSV name for each module is the same as the OVL name with bsv_ appended to the beginning of the name.

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_always</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Concurrent assertion that the value of the expression is always True.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_always#(OVLDefaults#(Bool) defaults) (AssertTest_IFC#(Bool));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_always_on_edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Checks that the test expression evaluates True whenever the sample method is asserted.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertSampleTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>edge_type (default value = OVL_NOEDGE)</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_always_on_edge#(OVLDefaults#(Bool) defaults)(AssertSampleTest_IFC#( Bool));</td>
</tr>
<tr>
<td>Module</td>
<td>bsv_assert_change</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Description</td>
<td>Checks that once the start method is asserted, the expression will change value within num_cks cycles.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertStartTest_IFC</td>
</tr>
</tbody>
</table>
| Parameters | common assertion parameters  
action_on_new_start (default value = OVL_IGNORE_NEW_START)  
um_cks (default value = 1) |
| Module Declaration | module bsv_assert_change#(OVLDefaults#(a_type) defaults)  
  (AssertStartTest_IFC#(a_type))  
  provisos (Bits#(a_type, sizea),  
  Bounded#(a_type), Eq#(a_type)); |

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_cycle_sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that if a specified necessary condition occurs, it is followed by a specified sequence of events.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
</tbody>
</table>
| Parameters | common assertion parameters  
necessary_condition (default value = OVL_TRIGGER_ON_MOST_PIPE) |
| Module Declaration | module bsv_assert_cycle_sequence#(OVLDefaults#(a_type) defaults)(AssertTest_IFC#(a_type))  
  provisos (Bits#(a_type, sizea),  
  Bounded#(a_type), Eq#(a_type)); |

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_decrement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that the expression decrements only by the value specified.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
</tbody>
</table>
| Parameters | common assertion parameters  
value (default value = 1) |
| Module Declaration | module bsv_assert_decrement#(OVLDefaults#(a_type) defaults)  
  (AssertTest_IFC#(a_type))  
  provisos (Bits#(a_type, sizea), Literal#(a_type),  
  Bounded#(a_type), Eq#(a_type)); |

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that the expression always changes by a value within the range specified by min and max.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
</tbody>
</table>
| Parameters | common assertion parameters  
min (default value = 1)  
max (default value = 1) |
| Module Declaration | module bsv_assert_delta#(OVLDefaults#(a_type) defaults)  
  (AssertTest_IFC#(a_type))  
  provisos (Bits#(a_type, sizea), Literal#(a_type),  
  Bounded#(a_type), Eq#(a_type)); |
<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_even_parity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that value of a specified expression has even parity, that is an even number of bits in the expression are active high.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_even_parity#(OVLDefaults#(a_type) defaults) (AssertTest_IFC#(a_type)) provisos (Bits#(a_type, sizea), Bounded#(a_type), Eq#(a_type));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_fifo_index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that a FIFO-type structure never overflows or underflows. This checker can be configured to support multiple pushes (FIFO writes) and pops (FIFO reads) during the same clock cycle.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertFifoTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>depth (default value = 1) simultaneous_push_pop (default value = True)</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_fifo_index#(OVLDefaults#(Bit#(0)) defaults)(AssertFifoTest_IFC#(a_type, b_type)) provisos (Bits#(a_type, sizea), Bits#(b_type, sizeb));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Checks that once the start method is asserted, the test expression evaluates true not before min_cks clock cycles and not after max_cks clock cycles.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertStartTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>action_on_new_start (default value = OVL_IGNORE_NEW_START) min_cks (default value = 1) max_cks (default value = 1)</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_frame#(OVLDefaults#(Bool) defaults) (AssertStartTest_IFC#(Bool));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_handshake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that the specified request and acknowledge signals follow a specified handshake protocol.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertStartTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>action_on_new_start (default value = OVL_IGNORE_NEW_START) min_ack_cycle (default value = 1) max_ack_cycle (default value = 1)</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_handshake#(OVLDefaults#(Bool) defaults) (AssertStartTest_IFC#(Bool));</td>
</tr>
<tr>
<td>Module</td>
<td>bsv_assert_implication</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Description</td>
<td>Ensures that a specified consequent expression is True if the specified antecedent expression is True.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertStartTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_implication#(OVLDefaults#(Bool) defaults) (AssertStartTest_IFC#(Bool));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensure that the test expression always increases by the value of specified by value.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters value (default value = 1)</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_increment#(OVLDefaults#(a_type) defaults) (AssertTest_IFC#(a_type)) provisos (Bits#(a_type, sizea), Literal#(a_type), Bounded#(a_type), Eq#(a_type));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_never</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that the value of a specified expression is never True.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_never#(OVLDefaults#(Bool) defaults) (AssertTest_IFC#(Bool));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_never_unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that the value of a specified expression contains only 0 and 1 bits when a qualifying expression is True.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertStartTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_never_unknown#(OVLDefaults#(a_type) defaults)(AssertStartTest_IFC#(a_type)) provisos (Bits#(a_type, sizea), Bounded#(a_type), Eq#(a_type));</td>
</tr>
<tr>
<td>Module</td>
<td>bsv_assert_never_unknown_async</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>Description</td>
<td>Ensures that the value of a specified expression always contains only 0 and 1 bits</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_never_unknown_async#(OVLDefaults#(a_type) defaults) (AssertTest_IFC#(a_type)) provisos (Bits#(a_type, sizea), Literal#(a_type), Bounded#(a_type), Eq#(a_type));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_next</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that the value of the specified expression is true a specified number of cycles after a start event.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertStartTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters num_cks (default value = 1) check_overlapping (default value = True) check_missing_start (default value = False)</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_next#(OVLDefaults#(Bool) defaults) (AssertStartTest_IFC#(Bool));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_no_overflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that the value of the specified expression does not overflow.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters min (default value = minBound) max (default value = maxBound)</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_no_overflow#(OVLDefaults#(a_type) defaults) (AssertTest_IFC#(a_type)) provisos (Bits#(a_type, sizea), Bounded#(a_type), Eq#(a_type));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_no_transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that the value of a specified expression does not transition from a start state to the specified next state.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTransitionTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_no_transition#(OVLDefaults#(a_type) defaults) (AssertTransitionTest_IFC#(a_type)) provisos (Bits#(a_type, sizea), Bounded#(a_type), Eq#(a_type));</td>
</tr>
<tr>
<td>Module</td>
<td>bsv_assert_no_underflow</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Description</td>
<td>Ensures that the value of the specified expression does not underflow.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td></td>
<td>min (default value = minBound)</td>
</tr>
<tr>
<td></td>
<td>max (default value = maxBound)</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_no_underflow#(OVLDefaults#(a_type) defaults)(AssertTest_IFC#(a_type)) provisos (Bits#(a_type, sizea), Bounded#(a_type), Eq#(a_type));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_odd_parity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that the specified expression had odd parity; that an odd number of bits in the expression are active high.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_odd_parity#(OVLDefaults#(a_type) defaults)(AssertTest_IFC#(a_type)) provisos (Bits#(a_type, sizea), Bounded#(a_type), Eq#(a_type));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_one_cold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that exactly one bit of a variable is active low.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td></td>
<td>inactive (default value = OLV_ONE_COLD)</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_one_cold#(OVLDefaults#(a_type) defaults) (AssertTest_IFC#(a_type)) provisos (Bits#(a_type, sizea), Bounded#(a_type), Eq#(a_type));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_one_hot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that exactly one bit of a variable is active high.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_one_hot#(OVLDefaults#(a_type) defaults) (AssertTest_IFC#(a_type)) provisos (Bits#(a_type, sizea), Bounded#(a_type), Eq#(a_type));</td>
</tr>
<tr>
<td>Module</td>
<td>bsv_assert_proposition</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Description</td>
<td>Ensures that the test expression is always combinationally True. Like assert_always except that the test expression is not sampled by the clock.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_proposition#(OVLDefaults#(Bool) defaults) (AssertTest_IFC#(Bool));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_quiescent_state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that the value of a specified state expression equals a corresponding check value if a specified sample event has transitioned to TRUE.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertQuiescentTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_quiescent_state#(OVLDefaults#(a_type) defaults)(AssertQuiescentTest_IFC#(a_type)) provisos (Bits#(a_type, sizea), Bounded#(a_type), Eq#(a_type));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensure that an expression is always within a specified range.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td></td>
<td>min (default value = minBound)</td>
</tr>
<tr>
<td></td>
<td>max (default value = maxBound)</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_range#(OVLDefaults#(a_type) defaults) (AssertTest_IFC#(a_type)) provisos (Bits#(a_type, sizea), Bounded#(a_type), Eq#(a_type));</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module</th>
<th>bsv_assert_time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Ensures that the expression remains True for a specified number of clock cycles after a start event.</td>
</tr>
<tr>
<td>Interface Used</td>
<td>AssertStartTest_IFC</td>
</tr>
<tr>
<td>Parameters</td>
<td>common assertion parameters</td>
</tr>
<tr>
<td></td>
<td>action_on_new_start (default value = OVL_IGNORE_NEW_START)</td>
</tr>
<tr>
<td></td>
<td>num_cks (default value = 1)</td>
</tr>
<tr>
<td>Module Declaration</td>
<td>module bsv_assert_time#(OVLDefaults#(Bool) defaults) (AssertStartTest_IFC#(Bool));</td>
</tr>
<tr>
<td>Module</td>
<td>Description</td>
</tr>
<tr>
<td>--------------------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>bsv_assert_transition</td>
<td>Ensures that the value of a specified expression transitions properly from a start state to the specified next state.</td>
</tr>
<tr>
<td>bsv_assert_unchange</td>
<td>Ensures that the value of the specified expression does not change during a specified number of clock cycles after a start event initiates checking.</td>
</tr>
<tr>
<td>bsv_assert_width</td>
<td>Ensures that when the test expression goes high it stays high for at least min and at most max clock cycles.</td>
</tr>
<tr>
<td>bsv_assert_win_change</td>
<td>Ensures that the value of a specified expression changes in a specified window between a start event and a stop event.</td>
</tr>
</tbody>
</table>
Module

<table>
<thead>
<tr>
<th>bsv_assert_win_unchange</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td><strong>Interface Used</strong></td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
</tr>
<tr>
<td><strong>Module Declaration</strong></td>
</tr>
</tbody>
</table>

```
module bsv_assert_win_unchange#(OVLDefaults#(a_type) defaults)(AssertStartStopTest_IFC#(a_type))
    prosis (Bits#(a_type, sizea),
    Bounded#(a_type), Eq#(a_type));
```

Module

<table>
<thead>
<tr>
<th>bsv_assert_window</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td><strong>Interface Used</strong></td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
</tr>
<tr>
<td><strong>Module Declaration</strong></td>
</tr>
</tbody>
</table>

```
module bsv_assert_window#(OVLDefaults#(Bool) defaults) (AssertStartStopTest_IFC#(Bool));
```

Module

<table>
<thead>
<tr>
<th>bsv_assert_zero_one_hot</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
</tr>
<tr>
<td><strong>Interface Used</strong></td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
</tr>
<tr>
<td><strong>Module Declaration</strong></td>
</tr>
</tbody>
</table>

```
module bsv_assert_zero_one_hot#(OVLDefaults#(a_type) defaults)(AssertTest_IFC#(a_type))
    prosis (Bits#(a_type, sizea),
    Bounded#(a_type), Eq#(a_type));
```

**Example using bsv_assert_increment**

This example checks that a test expression is always incremented by a value of 3. The assertion passes for the first 10 increments and then starts failing when the increment amount is changed from 3 to 1.

```
import OVLAssertions::*; // import the OVL Assertions package

module assertIncrement (Empty);
    Reg#(Bit#(8)) count <- mkReg(0);
    Reg#(Bit#(8)) test_expr <- mkReg(0);

    // set the default values
    let defaults = mkOVLDefaults;
    // override the default increment value and set = 3
    defaults.value = 3;
```
// instantiate an instance of the module bsv_assert_increment using
// the name assert_mod and the interface AssertTest_IFC
AssertTest_IFC#(Bit#(8)) assert_mod <- bsv_assert_increment(defaults);

rule every (True); // Every clock cycle
  assert_mod.test(test_expr); // the assertion is checked
endrule

rule increment (True);
  count <= count + 1;
  if (count < 10) // for 10 cycles
    test_expr <= test_expr + 3; // increment the expected amount
  else if (count < 15)
    test_expr <= test_expr + 1; // then start incrementing by 1
  else
    $finish;
endrule

endmodule

Using The Library

In order to use the OVLAssertions package, a user must first download the source OVL library from Accellera (http://www.accellera.org). In addition, that library must be made available when building a simulation executable from the BSV generated Verilog.

If the bsc compiler is being used to generate the Verilog simulation executable, the BSC_VSIM_FLAGS environment variable can be used to set the required simulator flags that enable use of the OVL library.

For instance, if the iverilog simulator is being used and the OVL library is located in the directory shared/std_ovl, the BSC_VSIM_FLAGS environment variable can be set to "-I shared/std_ovl -Y .vlib -y shared/std_ovl -DOVL_VERILOG=1 -DOVL_ASSERT_ON=1". These flags:

- Add shared/std_ovl to the Verilog and include search paths.
- Set .vlib as a possible file suffix.
- Set flags used in the OVL source code.

The exact flags to be used will differ based on what OVL behavior is desired and which Verilog simulator is being used.

C.8.18 Printf

Package

import Printf:: * ;

Description

The Printf package provides the sprintf function to allow users to construct strings using typical C printf patterns. The function supports a full range of C-style format options.

The sprintf function uses two advanced features, type classes (Section 14.1) and partial function application, to implement a variable number of arguments. That is why the type signature of the function includes a proviso for SPrintfType, also defined in this package.
This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Type classes

The Printf package includes the SPrintf and PrintfArg typeclasses. The proviso SPrintf specifies that the function can take a variable number of arguments, and further the types of those arguments can be displayed. This last requirement is captured by the PrintfArg typeclass, which is the class of types that can be displayed.

typeclass SPrintfType#(type t);
  function t sp(String fmt, List#(UPrintf) args);
endtypeclass

The PrintfArg typeclass defines a separate conversion for each type in the class.

typeclass PrintfArg#(type t);
  function UPrintf toUPrintf(t arg);
endtypeclass

Functions

<table>
<thead>
<tr>
<th>sprintf</th>
<th>Constructs a string given a C-style format string and any input values for that format.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function r sprintf(String fmt) provisos (SPrintfType#(r));</td>
<td></td>
</tr>
</tbody>
</table>

The sprintf function constructs a string from a format string followed by a variable number of arguments. Examples:

String s1 = sprintf("Hello");

Bit#(8) x = 0;
String s2 = sprintf("x = %d", x);

Real r = 1.2;
String s3 = sprintf("x = %d, r = %g", x, r);

The behavior of sprintf depends on the types of the arguments. If the type of an argument is unclear, you may be required to give specific types to those arguments.

For instance, an integer literal can represent many types, so you need to specify which one you are using:

String s4 = sprintf("%d, %d", 1, 2); // ambiguous

// Example of two ways to specify the type
UInt#(8) n = 1;
String s4 = sprintf("%d, %d", n, Bit#(4)'(2));

When calling sprintf on a value whose type is not known, as in a polymorphic function, you may be required to add a proviso to the function for the type variable.

The PrintfArg proviso on polymorphic functions is required when the type of the argument is not known. The type class instances define the conversion functions for each printable type.
function Action disp(t x);
    action
        String s = sprintf("x=%d", x);
        $display(s);
    endaction
endfunction

will generate an error message. By adding the proviso, the function compiles correctly:

function Action disp(t x)
    provisos( PrintfArg#(t) );
    action
        String s = sprintf("x=%d", x);
        $display(s);
    endaction
endfunction

C.8.19 BuildVector

Package

import BuildVector :: * ;

Description

The BuildVector package provides the BuildVector type class to implement a vector construction function which can take any number of arguments (>0).

In pseudo code, we can show this as:

function Vector#(n, a) vec(a v1, a v2, ..., a vn);

Examples:

Vector#(3, Bool) v1 = vec(True, False, True);
Vector#(4, Integer) v2 = vec(2, 17, 22, 42);

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>vec</td>
<td>A function for creating a Vector of size n from n arguments. The variable number of arguments is implemented via the BuildVector typeclass, which is a proviso of this function.</td>
</tr>
<tr>
<td>function r vec(a x) provisos(BuildVector#(a,r,0));</td>
<td></td>
</tr>
</tbody>
</table>
C.9 Multiple Clock Domains and Clock Generators

Package

import Clocks :: *;

Description

The BSV Clocks library provides features to access and change the default clock. Moreover, there are hardware primitives to generate clocks of various shapes, plus several primitives which allow the safe crossing of signals and data from one clock domain to another.

The Clocks package uses the data types Clock and Reset as well as clock functions which are described below but defined in the Prelude package.

Each section describes a related group of modules, followed by a table indicating the Verilog modules used to implement the BSV modules.

Types and typeclasses

The Clocks package uses the abstract data types Clock and Reset, which are defined in the Prelude package. These are first class objects. Both Clock and Reset are in the Eq type class, meaning two values can be compared for equality.

Clock is an abstract type of two components: a single Bit oscillator and a Bool gate.

typedef ... Clock;

Reset is an abstract type.

typedef ... Reset;

<table>
<thead>
<tr>
<th>Type Classes for Clock and Reset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bits</td>
</tr>
<tr>
<td>Clock</td>
</tr>
<tr>
<td>Reset</td>
</tr>
</tbody>
</table>

Example: Declaring a new clock

Clock clk0;

Example: Instantiating a register with clock and reset

Reg#(Byte) a <- mkReg(0, clocked_by clks0, reset_by rst0);

Functions

The following functions are defined in the Prelude package but are used with multiple clock domains.

<table>
<thead>
<tr>
<th>Clock Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>exposeCurrentClock</td>
</tr>
<tr>
<td>module exposeCurrentClock ( Clock c );</td>
</tr>
</tbody>
</table>

391
exposeCurrentReset | This function returns a value of type Reset, which is the current reset of the module.

| module exposeCurrentReset ( Reset r ); |

Both exposeCurrentClock and exposeCurrentReset use the module instantiation syntax (←) to return the value. Hence these can only be used from within a module.

**Example: setting a reset to the current reset**

    Reset reset_value <- exposeCurrentReset;

**Example: setting a clock to the current clock**

    Clock clock_value <- exposeCurrentClock;

sameFamily | A Boolean function which returns True if the clocks are in the same family, False if the clocks are not in the same family. Clocks in the same family have the same oscillator but may have different gate conditions.

| function Bool sameFamily ( Clock clka, Clock clkb ); |

isAncestor | A Boolean function which returns True if clka is an ancestor of clkb, that is clkb is a gated version of clka (clka itself may be gated) or if clka and clkb are the same clock. The ancestry relation is a partial order (ie., reflexive, transitive and antisymmetric).

| function Bool isAncestor ( Clock clka, Clock clkb ); |

clockOf | Returns the current clock of the object obj.

| function Clock clockOf ( a_type obj ); |

noClock | Specifies a null clock, a clock where the oscillator never rises.

| function Clock noClock() ; |

resetOf | Returns the current reset of the object obj.

| function Reset resetOf ( a_type obj ); |
noReset

Specifies a null reset, a reset which is never asserted.

function Reset noReset();

invertCurrentClock

Returns a value of type Clock, which is the inverted current clock of the module.

module invertCurrentClock(Clock);

invertCurrentReset

Returns a value of type Reset, which is the inverted current reset of the module.

module invertCurrentReset(Reset);

C.9.1 Clock Generators and Clock Manipulation

Description

This section provides modules to generate new clocks and to modify the existing clock.

The modules mkAbsoluteClock, mkAbsoluteClockFull, mkClock, and mkUngatedClock all define a new clock, one not based on the current clock. Both mkAbsoluteClock and mkAbsoluteClockFull define new oscillators and are not synthesizable. mkClock and mkUngatedClock use an existing oscillator to create a clock, and is synthesizable. The modules, mkGatedClock and mkGatedClockFromCC use existing clocks to generate another clock in the same family.

Interfaces and Methods

The MakeClockIfc supports user-defined clocks with irregular waveforms created with mkClock and mkUngatedClock, as opposed to the fixed-period waveforms created with the mkAbsoluteClock family.

<table>
<thead>
<tr>
<th>MakeClockIfc Interface</th>
<th>Method and subinterfaces</th>
<th>Arguments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Type</td>
<td>Description</td>
</tr>
<tr>
<td>setClockValue</td>
<td>Action</td>
<td>Changes the value of the clock at the next edge of the clock</td>
</tr>
<tr>
<td>getClockValue</td>
<td>one_bit_type</td>
<td>Retrieves the last value of the clock</td>
</tr>
<tr>
<td>setGateCond</td>
<td>Action</td>
<td>Changes the gating condition</td>
</tr>
<tr>
<td>getGateCond</td>
<td>Bool</td>
<td>Retrieves the last gating condition set</td>
</tr>
<tr>
<td>new_clk</td>
<td>Interface</td>
<td>Clock interface provided by the module</td>
</tr>
</tbody>
</table>
interface MakeClockIfc#(type one_bit_type);
  method Action setClockValue(one_bit_type value);
  method one_bit_type getClockValue();
  method Action setGateCond(Bool gate);
  method Bool getGateCond();
  interface Clock new_clk;
endinterface

The GatedClockIfc is used for adding a gate to an existing clock.

<table>
<thead>
<tr>
<th>GatedClockIfc Interface Method and subinterfaces</th>
<th>Arguments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Type</td>
</tr>
<tr>
<td>setGateCond</td>
<td>Action</td>
</tr>
<tr>
<td>getGateCond</td>
<td>Bool</td>
</tr>
<tr>
<td>new_clk</td>
<td>Interface</td>
</tr>
</tbody>
</table>

interface GatedClockIfc;
  method Action setGateCond(Bool gate);
  method Bool getGateCond();
  interface Clock new_clk;
endinterface

Modules

The mkClock module creates a Clock type from a one-bit oscillator and a Boolean gate condition. There is no family relationship between the current clock and the clock generated by this module. The initial values of the oscillator and gate are passed as parameters to the module. When the module is out of reset, the oscillator value can be changed using the setClockValue method and the gate condition can be changed by calling the setGateCond method. The oscillator value and gate condition can be queried with the getClockValue and getGateCond methods, respectively. The clock created by mkClock is available as the new_clk subinterface. When setting the gate condition, the change does not affect the generated clock until it is low, to prevent glitches.

The mkUngatedClock module is an ungated version of the mkClock module. It takes only an oscillator argument (no gate argument) and returns the same new_clock interface. Since there is no gate, an error is returned if the design calls the setGetCond method. The getGateCond method always returns True.

<table>
<thead>
<tr>
<th>mkClock</th>
<th>Creates a Clock type from a one-bit oscillator input, and a Boolean gate condition. There is no family relationship between the current clock and the clock generated by this module.</th>
</tr>
</thead>
</table>
| module mkClock #( one_bit_type initVal, Bool initGate)
  ( MakeClockIfc#(one_bit_type) ifc )
provisos( Bits#(one_bit_type, 1) ) |                                                                                                                                                                                                  |
Bluespec SystemVerilog Reference Guide

Figure 6: Clock Generator

<table>
<thead>
<tr>
<th>mkUngatedClock</th>
<th>Creates an ungated Clock type from a one-bit oscillator input. There is no family relationship between the current clock and the clock generated by this module.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkUngatedClock #( one_bit_type initVal) ( MakeClockIfc#(one_bit_type) ifc ) provisos( Bits#(one_bit_type, 1) ) ;</td>
<td></td>
</tr>
</tbody>
</table>

The mkGatedClock module adds (logic and) a Boolean gate condition to an existing clock, thus creating another clock in the same family. The source clock is provided as the argument clk_in. The gate condition is controlled by an asynchronously-reset register inside the module. The register is set with the setGateCond Action method of the interface and can be read with getGateCond method. The reset value of the gate condition register is provided as an instantiation parameter. The clock for the register (and thus these set and get methods) is the default clock of the module; to specify a clock other than the default clock, use the clocked_by directive.

Figure 7: Gated Clock Generator

<table>
<thead>
<tr>
<th>mkGatedClock</th>
<th>Creates another clock in the same family by adding logic and a Boolean gate condition to the current clock.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkGatedClock#(Bool v) ( Clock clk_in, GatedClockIfc ifc ) ;</td>
<td></td>
</tr>
</tbody>
</table>
For convenience, we provide an alternate version in which the source clock is the default clock of the module

```
module mkGatedClockFromCC#(Bool v) ( GatedClockIfc ifc );
```

The modules `mkAbsoluteClock` and `mkAbsoluteClockFull` provide parametizable clock generation modules which are *not* synthesizable, but may be useful for testbenches. In `mkAbsoluteClock`, the first rising edge (start) and the period are defined by parameters. These parameters are measured in Verilog delay times, which are usually specified during simulation with the `timescale` directive. Refer to the Verilog LRM for more details on delay times. Additional parameters are provided by `mkAbsoluteClockFull`.

```
module mkAbsoluteClock #( Integer start, Integer period ) ( Clock );
```

```
module mkAbsoluteClockFull #( Integer start, Bit#(1) initValue, Integer compValTime, Integer initValTime ) ( Clock );
```

**Verilog Modules**

The BSV modules correspond to the following Verilog modules, which are found in the Bluespec Verilog library, `$BLUESPECDIR/Verilog/`.

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkAbsoluteClock</td>
<td>ClockGen.v</td>
</tr>
<tr>
<td>mkAbsoluteClockFull</td>
<td></td>
</tr>
<tr>
<td>mkUngatedClock</td>
<td>MakeClock.v</td>
</tr>
<tr>
<td>mkGatedClock</td>
<td>GatedClock.v</td>
</tr>
<tr>
<td>mkGatedClockFromCC</td>
<td></td>
</tr>
</tbody>
</table>
C.9.2 Clock Multiplexing

Description

Bluespec provides two gated clock multiplexing primitives: a simple combinational multiplexor and a stateful module which generates an appropriate reset signal when the clock changes. The first multiplexor uses the interface MuxClockIfc, which includes an Action method to select the clock along with a Clock subinterface. The second multiplexor uses the interface SelectClockIfc which also has a Reset subinterface.

Ungated versions of these modules are also provided. The ungated versions are identical to the gated versions, except that the input and output clocks are ungated.

Interfaces and Methods

<table>
<thead>
<tr>
<th>MuxClockIfc Interface</th>
<th>Arguments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method and subinterfaces</td>
<td>Name</td>
</tr>
<tr>
<td>select Action Method used to select the clock based on the Boolean value ab</td>
<td>ab if True, clock_out is taken from aclk</td>
</tr>
<tr>
<td>clock_out Interface Clock interface</td>
<td></td>
</tr>
</tbody>
</table>

```verilog
interface MuxClkIfc;
  method Action select (Bool ab);
  interface Clock clock_out;
endinterface
```

<table>
<thead>
<tr>
<th>SelectClockIfc Interface</th>
<th>Arguments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method and subinterfaces</td>
<td>Name</td>
</tr>
<tr>
<td>select Action Method used to select the clock based on the Boolean value ab</td>
<td>ab if True, clock_out is taken from aclk</td>
</tr>
<tr>
<td>clock_out Interface Clock interface</td>
<td></td>
</tr>
<tr>
<td>reset_out Interface Reset interface</td>
<td></td>
</tr>
</tbody>
</table>

```verilog
interface SelectClkIfc;
  method Action select (Bool ab);
  interface Clock clock_out;
  interface Reset reset_out;
endinterface
```

Modules

The mkClockMux module is a simple combinational multiplexor with a registered clock selection signal, which selects between clock inputs aclk and bclk. The provided Verilog module does not provide any glitch detection or removal logic; it is the responsibility of the user to provide additional logic to provide glitch-free behavior. The mkClockMux module uses two arguments and provides a Clock interface. The aclk is selected if ab is True, while bclk is selected otherwise.

The mkUngatedClockMux module is identical to the mkClockMux module except that the input and output clocks are ungated. The signals aclkgate, bClkgate, and outClkgate in figure 8 don’t exist.
The **mkClockSelect** module is a clock multiplexor containing additional logic which generates a reset whenever a new clock is selected. As such, the interface for the module includes an Action method to select the clock (if ab is True clock_out is taken from aClk), provides a Clock interface, and also a Reset interface.

The constructor for the module uses two clock arguments, and provides the MuxClockIfc interface. The underlying Verilog module is ClockSelect.v; it is expected that users can substitute their own modules to meet any additional requirements they may have. The parameter stages is the number of clock cycles in which the reset is asserted after the clock selection changes.

The **mkUngatedClockSelect** module is identical to the mkClockSelect module except that the input and output clocks are ungated. The signals aClkgate, bClkgate, and outClk_gate in figure 9 don’t exist.

The **mkClockMux** module is a simple combinational multiplexor, which selects between aClk and bClk.

```
module mkClockMux ( Clock aClk, Clock bClk )
( MuxClkIfc ) ;
```

The **mkUngatedClockMux** module is simple combinational multiplexor, which selects between aClk and bClk. None of the clocks are gated.

```
module mkUngatedClockMux ( Clock aClk, Clock bClk )
( MuxClkIfc ) ;
```

The **mkClockSelect** module is a clock multiplexor containing additional logic which generates a reset whenever a new clock is selected.

```
module mkClockSelect #( Integer stages,
                   Clock aClk,
                   Clock bClk,
                   ( SelectClockIfc )
                   )
```

The diagram shows a clock multiplexor with inputs aClk and bClk, select control, and outputs clk and outClk_gate.
Figure 9: Clock Multiplexor with reset

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkClockMux</td>
<td>ClockMux.v</td>
</tr>
<tr>
<td>mkClockSelect</td>
<td>ClockSelect.v</td>
</tr>
<tr>
<td>mkUngatedClockMux</td>
<td>UngatedClockMux.v</td>
</tr>
<tr>
<td>mkUngatedClockSelect</td>
<td>UngatedClockSelect.v</td>
</tr>
</tbody>
</table>

C.9.3 Clock Division

Description

A clock divider provides a derived clock and also a ClkNextRdy signal, which indicates that the divided clock will rise in the next cycle. This signal is associated with the input clock, and can only be used within that clock domain.

The AlignedFIFOs package (Section C.2.6) contains parameterized FIFO modules for creating synchronizing FIFOs between clock domains with aligned edges.

Data Types

The ClkNextRdy is a Boolean signal which indicates that the slow clock will rise in the next cycle.
typedef Bool ClkNextRdy;

**Interfaces and Methods**

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>fastClock</td>
<td>Interface</td>
<td>The original clock</td>
</tr>
<tr>
<td>slowClock</td>
<td>Interface</td>
<td>The derived clock</td>
</tr>
<tr>
<td>clockReady</td>
<td>Bool</td>
<td>Boolean value which indicates that the slow clock will rise in the next cycle. The method is in the clock domain of the fast clock.</td>
</tr>
</tbody>
</table>

```
interface ClockDividerIfc;
  interface Clock fastClock;
  interface Clock slowClock;
  method ClkNextRdy clockReady();
endinterface
```

**Modules**

The divider parameter may be any integer greater than 1. For even dividers the generated clock’s duty cycle is 50%, while for odd dividers, the duty cycle is \((\text{divider}/2)/\text{divider}\). Since divisor is an integer, the remainder is truncated when divided. The current clock (or the clocked_by argument) is used as the source clock.

![Figure 10: Clock Divider](image)

The `mkClockDivider` module provides a clock divider where the rising edge can be defined relative to other clock dividers which have the same divisor. An offset of value 2 will produce a rising edge one fast clock after a divider with offset 1. `mkClockDivider` is just `mkClockDividerOffset` with an offset of value 0.

```
module mkClockDivider #( Integer divisor )
  ( ClockDividerIfc )
```

```
module mkGatedClockDivider #( Integer divisor )
  ( ClockDividerIfc )
```

400
The `mkClockDividerOffset` module provides a clock divider, where the rising edge can be defined relative to other clock dividers which have the same divisor. The `mkClockDividerOffset` module is defined as follows:

```
module mkClockDividerOffset #( Integer divisor,
                            Integer offset )
                           ( ClockDividerIfc ) ;
```

The `mkClockInverter` and `mkGatedClockInverter` modules generate an inverted clock having the same period but opposite phase as the current clock. The `mkGatedClockInverter` is a gated version of `mkClockInverter`. The output clock includes a gate signal derived from the gate of the input clock.

```
module mkClockInverter ( ClockDividerIfc ) ;
```

```
module mkGatedClockInverter ( ClockDividerIfc ifc ) ;
```

Verilog Modules

The BSV modules correspond to the following Verilog modules, which are found in the Bluespec Verilog library, `$BLUESPECDIR/Verilog/`.

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkClockDivider</td>
<td>ClockDiv.v</td>
</tr>
<tr>
<td>mkClockDividerOffset</td>
<td></td>
</tr>
<tr>
<td>mkGatedClockDivider</td>
<td>GatedClockDiv.v</td>
</tr>
<tr>
<td>mkClockInverter</td>
<td>ClockInverter.v</td>
</tr>
<tr>
<td>mkGatedClockInverter</td>
<td>GatedClockInverter.v</td>
</tr>
</tbody>
</table>

C.9.4 Bit Synchronizers

Description

Bit synchronizers are used to safely transfer one bit of data from one clock domain to another. More complicated synchronizers are provided in later sections.

Interfaces and Methods

The `SyncBitIfc` interface provides a `send` method which transmits one bit of information from one clock domain to the `read` method in a second domain.
## SyncBitIfc Interface

<table>
<thead>
<tr>
<th>Method</th>
<th>Type</th>
<th>Description</th>
<th>Arguments</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>send</code></td>
<td><code>Action</code></td>
<td>Transmits information from one clock domain to the second domain</td>
<td><code>bitData</code></td>
<td>One bit of information transmitted</td>
</tr>
<tr>
<td><code>read</code></td>
<td><code>one_bit_type</code></td>
<td>Reads one bit of data sent from a different clock domain</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

```verilog
type_one_bit_type interface SyncBitIfc #(type one_bit_type) ;
    method Action send ( one_bit_type bitData ) ;
    method one_bit_type read () ;
endinterface
```

### Modules

The `mkSyncBit`, `mkSyncBitFromCC` and `mkSyncBitToCC` modules provide a `SyncBitIfc` across clock domains. The `send` method is in one clock domain, and the `read` method is in a second clock domain, as shown in Figure 11. The `FromCC` and `ToCC` versions differ in that the `FromCC` module moves data *from* the current clock (module’s clock), while the `ToCC` module moves data *to* the current clock domain. The hardware implementation is a two register synchronizer, which can be found in `SyncBit.v` in the Bluespec Verilog library directory.

![Figure 11: Bit Synchronizer](image)

<table>
<thead>
<tr>
<th><code>mkSyncBit</code></th>
<th>Moves data across clock domains. The in and out clocks, along with the input reset, are explicitly provided. The default clock and reset are ignored.</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>module mkSyncBit #( Clock sClkIn, Reset sRst, Clock dClkIn )</code></td>
<td>( SyncBitIfc #(one_bit_type) ) provisos( Bits#(one_bit_type, 1)) ;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><code>mkSyncBitFromCC</code></th>
<th>Moves data from the current clock (the module’s clock) to a different clock domain. The input clock and reset are the current clock and reset.</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>module mkSyncBitFromCC #( Clock dClkIn )</code></td>
<td>( SyncBitIfc #(one_bit_type) ) provisos( Bits#(one_bit_type, 1)) ;</td>
</tr>
</tbody>
</table>
The `mkSyncBit15` module (one and a half) and its variants provide the same interface as the `mkSyncBit` modules, but the underlying hardware is slightly modified, as shown in Figure 12. For these synchronizers, the first register clocked by the destination clock triggers on the falling edge of the clock.

*Figure 12: Bit Synchronizer 1.5 - first register in destination domain triggers on falling edge*

---

### mkSyncBitToCC

Moves data into the current clock domain. The output clock is the current clock. The current reset is ignored.

```verilog
module mkSyncBitToCC #( Clock sClkIn, Reset sRstIn )
  ( SyncBitIfc #(one_bit_type) )
provisos( Bits#(one_bit_type, 1)) ;
```

---

### mkSyncBit15

Similar to `mkSyncBit` except it triggers on the falling edge of the clock. The in and out clocks, along with the input reset, are explicitly provided. The default clock and reset are ignored.

```verilog
module mkSyncBit15 #( Clock sClkIn, Reset sRst, Clock dClkIn )
  ( SyncBitIfc #(one_bit_type) )
provisos( Bits#(one_bit_type, 1)) ;
```

---

### mkSyncBit15FromCC

Moves data from the current clock and is triggered on the falling edge of the clock. The input clock and reset are the current clock and reset.

```verilog
module mkSyncBit15FromCC #(Clock dClkIn)
  (SyncBitIfc #(one_bit_type))
provisos( Bits#(one_bit_type, 1)) ;
```

---

### mkSyncBit15ToCC

Moves data into the current clock domain and is triggered on the falling edge of the clock. The output clock is the current clock. The current reset is ignored.

```verilog
module mkSyncBit15ToCC #( Clock sClkIn, Reset sRstIn )
  ( SyncBitIfc #(one_bit_type) )
provisos( Bits#(one_bit_type, 1)) ;
```
The `mkSyncBit1` module, shown in Figure 13, also provides the same interface but only uses one register in the destination domain. Synchronizers like this, which use only one register, are not generally used since meta-stable output is more probable. However, one can use this synchronizer provided special meta-stable resistant flops are selected during physical synthesis or (for example) if the output is immediately registered.

![Figure 13: Bit Synchronizer 1.0 - single register in destination domain](image)

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>mkSyncBit1</code></td>
<td>Moves data from one clock domain to another clock domain, with only one register in the destination domain. The in and out clocks, along with the input reset, are explicitly provided. The default clock and reset are ignored.</td>
</tr>
<tr>
<td><code>module mkSyncBit1 #( Clock sClkIn, Reset sRst, Clock dClkIn )</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( SyncBitIfc #(one_bit_type) )</td>
</tr>
<tr>
<td></td>
<td>provisos( Bits#(one_bit_type, 1)) ;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>mkSyncBit1FromCC</code></td>
<td>Moves data from the current clock domain, with only one register in the destination domain. The input clock and reset are the current clock and reset.</td>
</tr>
<tr>
<td><code>module mkSyncBit1FromCC #( Clock dClkIn )</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( SyncBitIfc #(one_bit_type) )</td>
</tr>
<tr>
<td></td>
<td>provisos( Bits #(one_bit_type, 1)) ;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>mkSyncBit1ToCC</code></td>
<td>Moves data into the current clock domain, with only one register in the destination domain. The output clock is the current clock. The current reset is ignored.</td>
</tr>
<tr>
<td><code>module mkSyncBit1ToCC #( Clock sClkIn, Reset sRstIn )</code></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( SyncBitIfc #(one_bit_type) )</td>
</tr>
<tr>
<td></td>
<td>provisos( Bits#(one_bit_type, 1)) ;</td>
</tr>
</tbody>
</table>

The `mkSyncBit05` module is similar to `mkSyncBit1`, but the destination register triggers on the falling edge of the clock, as shown in Figure 14.
Figure 14: Bit Synchronizer .5 - first register in destination domain triggers on falling edge

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Verilog Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkSyncBit05</td>
<td>Moves data from one clock domain to another clock domain, with only one register in the destination domain. The destination register triggers on the falling edge of the clock. The in and out clocks, along with the input reset, are explicitly provided. The default clock and reset are ignored.</td>
<td>module mkSyncBit05 #( Clock sClkIn, Reset sRst, Clock dClkIn )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( SyncBitIfc #(one_bit_type) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>provisos( Bits#(one_bit_type, 1))</td>
</tr>
<tr>
<td>mkSyncBit05FromCC</td>
<td>Moves data from the current clock domain, with only one register in the destination domain, the destination register triggers on the falling edge of the clock. The input clock and reset are the current clock and reset.</td>
<td>module mkSyncBit05FromCC #( Clock dClkIn )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(SyncBitIfc #(one_bit_type) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>provisos( Bits#(one_bit_type, 1))</td>
</tr>
<tr>
<td>mkSyncBit05ToCC</td>
<td>Moves data into the current clock domain, with only one register in the destination domain, the destination register triggers on the falling edge of the clock. The output clock is the current clock. The current reset is ignored.</td>
<td>module mkSyncBit05ToCC #( Clock sClkIn, Reset sRstIn )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( SyncBitIfc #(one_bit_type) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>provisos( Bits#(one_bit_type, 1))</td>
</tr>
</tbody>
</table>

**Verilog Modules**

The BSV modules correspond to the following Verilog modules, which are found in the Bluespec Verilog library, $BLUESPECDIR/Verilog/.

405
### C.9.5 Pulse Synchronizers

#### Description
Pulse synchronizers are used to transfer a pulse from one clock domain to another.

#### Interfaces and Methods
The `SyncPulseIfc` interface provides an Action method, `send`, which when invoked generates a True value on the `pulse` method in a second clock domain.

<table>
<thead>
<tr>
<th>Method</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>send</code></td>
<td>Action</td>
<td>Starts transmitting a pulse from one clock domain to the second clock domain.</td>
</tr>
<tr>
<td><code>pulse</code></td>
<td>Bool</td>
<td>Where the pulse is received in the second domain. <code>pulse</code> is True if a pulse is received in this cycle.</td>
</tr>
</tbody>
</table>

```vhdl
interface SyncPulseIfc ;
    method Action send () ;
    method Bool pulse () ;
endinterface
```

#### Modules
The `mkSyncPulse`, `mkSyncPulseFromCC` and `mkSyncPulseToCC` modules provide clock domain crossing modules for pulses. When the `send` method is called from the one clock domain, a pulse will be seen on the `read` method in the second. Note that there is no handshaking between the domains, so when sending data from a fast clock domain to a slower one, not all pulses sent may be seen in the slower receiving clock domain. The pulse delay is two destination clock cycles.

```verilog
module mkSyncPulse #( Clock sClkIn, Reset sRstIn, 
                      Clock dClkIn )
                     ( SyncPulseIfc ) ;
```
Bluespec SystemVerilog Reference Guide

Figure 15: Pulse Synchronizer - no handshake

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkSyncPulseFromCC</td>
<td>Sends a pulse from the current clock domain to the other clock domain. The input clock and reset are the current clock and reset.</td>
<td>module mkSyncPulseFromCC #( Clock dClkIn )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( SyncPulseIfc )</td>
</tr>
<tr>
<td>mkSyncPulseToCC</td>
<td>Sends a pulse from the other clock domain to the current clock domain. The output clock is the current clock. The current reset is ignored.</td>
<td>module mkSyncPulseToCC #( Clock sClkIn, Reset sRstIn )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( SyncPulseIfc )</td>
</tr>
</tbody>
</table>

The mkSyncHandshake, mkSyncHandshakeFromCC and mkSyncHandshakeToCC modules provide clock domain crossing modules for pulses in a similar way as mkSyncPulse modules, except that a handshake is provided in the mkSyncHandshake versions. The handshake enforces that another send does not occur before the first pulse crosses to the other domain. Note that this only guarantees that the pulse is seen in one clock cycle of the destination; it does not guarantee that the system on that side reacted to the pulse before it was gone. It is up to the designer to ensure this, if necessary. The modules are not ready in reset.

The pulse delay from the send method to the read method is two destination clocks. The send method is re-enabled in two destination clock cycles plus two source clock cycles after the send method is called.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkSyncHandshake</td>
<td>Sends a pulse from one clock domain to another clock domain with handshaking. The in and out clocks, along with the input reset, are explicitly provided. The default clock and reset are ignored.</td>
<td>module mkSyncHandshake #( Clock sClkIn, Reset sRstIn, Clock dClkIn )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( SyncPulseIfc )</td>
</tr>
<tr>
<td>mkSyncHandshakeFromCC</td>
<td>Sends a pulse with a handshake from the current clock domain. The input clock and reset are the current clock and reset.</td>
<td>module mkSyncHandshakeFromCC #( Clock dClkIn )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( SyncPulseIfc )</td>
</tr>
</tbody>
</table>
**Verilog Modules**

The BSV modules correspond to the following Verilog modules, which are found in the Bluespec Verilog library, `$BLUESPECDIR/Verilog/`.

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkSyncPulse</td>
<td>SyncPulse.v</td>
</tr>
<tr>
<td>mkSyncPulseFromCC</td>
<td></td>
</tr>
<tr>
<td>mkSyncPulseToCC</td>
<td></td>
</tr>
<tr>
<td>mkSyncHandshake</td>
<td>SyncHandshake.v</td>
</tr>
<tr>
<td>mkSyncHandshakeFromCC</td>
<td></td>
</tr>
<tr>
<td>mkSyncHandshakeToCC</td>
<td></td>
</tr>
</tbody>
</table>

**C.9.6 Word Synchronizers**

**Description**

Word synchronizers are used to provide word synchronization across clock domains. The crossings are handshaked, such that a second write cannot occur until the first is acknowledged (that the data has been received, but the value may not have been read) by the destination side. The destination read is registered.

**Interfaces and Methods**
Word synchronizers use the common `Reg` interface (redescribed below), but there are a few subtle differences which the designer should be aware. First, the `_read` and `_write` methods are in different clock domains and, second, the `_write` method has an implicit “ready” condition which means that some synchronization modules cannot be written every clock cycle. Both of these conditions are handled automatically by the Bluespec compiler relieving the designer of these tedious checks.

<table>
<thead>
<tr>
<th>Method</th>
<th>Arguments</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>_write</code></td>
<td>Action</td>
<td>Writes a value <code>x1</code></td>
</tr>
<tr>
<td><code>_read</code></td>
<td><code>a_type</code></td>
<td>Returns the value of the register</td>
</tr>
</tbody>
</table>

```plaintext
interface Reg #(a_type);
  method Action _write(a_type x1);
  method a_type _read();
endinterface: Reg
```

**Modules**

The `mkSyncReg`, `mkSyncRegToCC` and `mkSyncRegFromCC` modules provide word synchronization across clock domains.

```
module mkSyncReg #( a_type initValue, Clock sClkIn, Reset sRstIn, Clock dClkIn )
  ( Reg #(a_type) )
provisos (Bits#(a_type, sa) ) ;
```

Figure 17: Register Synchronization Module (see Figure 16 for the pulse synchronizer with handshake)
<table>
<thead>
<tr>
<th>mkSyncRegFromCC</th>
<th>Provides word synchronization from the current clock domain. The input clock and reset are the current clock and reset.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkSyncRegFromCC #( a_type initValue, Clock dClkIn )</td>
<td></td>
</tr>
<tr>
<td>( Reg #(a_type) )</td>
<td></td>
</tr>
<tr>
<td>provisos (Bits#(a_type, sa));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkSyncRegToCC</th>
<th>Provides word synchronization to the current clock domain. The output clock is the current clock. The current reset is ignored.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkSyncRegToCC #( a_type initValue, Clock sClkIn, Reset sRstIn )</td>
<td></td>
</tr>
<tr>
<td>( Reg #(a_type) )</td>
<td></td>
</tr>
<tr>
<td>provisos (Bits#(a_type, sa));</td>
<td></td>
</tr>
</tbody>
</table>

**Verilog Modules**

The BSV modules correspond to the following Verilog modules, which are found in the Bluespec Verilog library, `$BLUESPECDIR/Verilog/`.

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkSyncReg</td>
<td>SyncRegister.v</td>
</tr>
<tr>
<td>mkSyncRegFromCC</td>
<td></td>
</tr>
<tr>
<td>mkSyncRegToCC</td>
<td></td>
</tr>
</tbody>
</table>

**C.9.7 FIFO Synchronizers**

**Description**

The SyncFIFO modules use FIFOs to synchronize data being sent across clock domains, providing registered full and empty signals (notFull and notEmpty). Additional FIFO synchronizers, SyncFIFOLevel and SyncFIFOCount can be found in the FIFOLevel package (Section C.2.3).

**Interfaces and Methods**

The SyncFIFOIfc interface defines an interface similar to the FIFOF interface, except it does not have a clear method.
### SyncFIFOIfc Interface

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Description</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>enq</td>
<td>Action</td>
<td>Adds an entry to the FIFO</td>
<td>sendData</td>
<td>Data to be added</td>
</tr>
<tr>
<td>deq</td>
<td>Action</td>
<td>Removes the first entry from the FIFO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>first</td>
<td>a_type</td>
<td>Returns the first entry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>notFull</td>
<td>Bool</td>
<td>Returns True if there is space and you can enq into the FIFO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>notEmpty</td>
<td>Bool</td>
<td>Returns True if there are elements in the FIFO and you can deq from the FIFO</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

```verilog
interface SyncFIFOIfc #(type a_type) ;
    method Action enq ( a_type sendData ) ;
    method Action deq () ;
    method a_type first () ;
    method Bool notFull () ;
    method Bool notEmpty () ;
endinterface
```

### Modules

The `mkSyncFIFO`, `mkSyncFIFOFromCC` and `mkSyncFIFOToCC` modules provide FIFOs for sending data across clock domains. Data items enqueued on the source side will arrive at the destination side and remain there until they are dequeued. The depth of the FIFO is specified by the `depth` parameter. The full and empty signals are registered. The module `mkSyncFIFO1` is a 1 element synchronized FIFO.
<table>
<thead>
<tr>
<th>mkSyncFIFO</th>
<th>Provides a FIFO for sending data across clock domains. The <code>enq</code> method is in the source (sClkIn) domain, while the <code>deq</code> and <code>first</code> methods are in the destination (dClkIn) domain. The in and out clocks, along with the input reset, are explicitly provided. The default clock and reset are ignored.</th>
</tr>
</thead>
</table>
| **module mkSyncFIFO #( Integer depth, Clock sClkIn, Reset sRstIn, Clock dClkIn )**  
  ( SyncFIFOIfc #(a_type) )  
  provisos (Bits#(a_type, sa)); | |

<table>
<thead>
<tr>
<th>mkSyncFIFOFromCC</th>
<th>Provides a FIFO to send data from the current clock domain into a second clock domain. The input clock and reset are the current clock and reset.</th>
</tr>
</thead>
</table>
| **module mkSyncFIFOFromCC #( Integer depth, Clock dClkIn )**  
  ( SyncFIFOIfc #(a_type) )  
  provisos (Bits#(a_type, sa)); | |

<table>
<thead>
<tr>
<th>mkSyncFIFOToCC</th>
<th>Provides a FIFO to send data from a second clock domain into the current clock domain. The output clock is the current clock. The current reset is ignored.</th>
</tr>
</thead>
</table>
| **module mkSyncFIFOToCC #( Integer depth, Clock sClkIn, Reset sRstIn )**  
  ( SyncFIFOIfc #(a_type) )  
  provisos (Bits#(a_type, sa)); | |

<table>
<thead>
<tr>
<th>mkSyncFIFO1</th>
<th>Provides a 1 element FIFO for sending data across clock domains. The 1 element module does not have a dedicated output register and registers for full and empty, as in the depth &gt; 1 module. This module should be used in clock crossing applications where complete FIFO handshaking is required, but data throughput or storage is minimal.</th>
</tr>
</thead>
</table>
| **module mkSyncFIFO #( Clock sClkIn, Reset sRstIn, Clock dClkIn )**  
  ( SyncFIFOIfc #(a_type) )  
  provisos (Bits#(a_type, sa)); | |

**Verilog Modules**

The BSV modules correspond to the following Verilog modules, which are found in the Bluespec Verilog library, `$BLUESPECDIR/Verilog/`.  

412
### C.9.8 Asynchronous RAMs

**Description**

An asynchronous RAM provides a domain crossing by having its read and write methods in separate clock domains.

**Interfaces and Methods**

<table>
<thead>
<tr>
<th>DualPortRamIfc Interface</th>
<th>Method</th>
<th>Arguments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Type</td>
<td>Description</td>
</tr>
<tr>
<td>write</td>
<td>Action</td>
<td>Writes data to an address in a RAM</td>
</tr>
<tr>
<td>read</td>
<td>data_t</td>
<td>Reads the data from the RAM</td>
</tr>
</tbody>
</table>

```verilog
define interface DualPortRamIfc #(type addr_t, type data_t);
    method Action write( addr_t wr_addr, data_t din );
    method data_t read ( addr_t rd_addr);
endinterface: DualPortRamIfc
```

![Figure 19: Asynchronous RAM](image)

**mkDualRam**

Provides an asynchronous RAM for when the read and the write methods are in separate clock domains. The write method is clocked by the default clock, the read method is not clocked.

```verilog
module mkDualRam( DualPortRamIfc #(addr_t, data_t) )
    provisos ( Bits#(addr_t, sa),
               Bits#(data_t, da) );
```
Verilog Modules

The BSV modules correspond to the following Verilog modules, which are found in the Bluespec Verilog library, "$BLUESPECDIR/Verilog/".

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkDualRam</td>
<td>DualPortRam.v</td>
</tr>
</tbody>
</table>

C.9.9 Null Crossing Primitives

Description

In these primitives, no synchronization is actually done. It is up to the designer to verify that it is safe for the signal to be used in the other domain. The `mkNullCrossingWire` is a wire synchronizer. The `mkNullCrossingReg` modules are equivalent to a register (`mkReg`, `mkRegA`, or `mkRegU` depending on the module) followed by a `mkNullCrossingWire`.

The older `mkNullCrossing` primitive is deprecated.

Interfaces

The `mkNullCrossingWire` module, shown in Figure 20, provides the `ReadOnly` interface which is defined in the Prelude library B.4.8.

The `mkNullCrossingReg` modules provide the `CrossingReg` interface.

Interfaces and Methods

**CrossingReg Interface**

<table>
<thead>
<tr>
<th>Method</th>
<th>Type</th>
<th>Description</th>
<th>Arguments</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>_write</td>
<td>Action</td>
<td>Writes a value <code>datain</code></td>
<td><code>datain</code></td>
<td>Data to be written.</td>
</tr>
<tr>
<td>_read</td>
<td><code>a_type</code></td>
<td>Returns the value of the register in the source clock domain</td>
<td><code>datain</code></td>
<td></td>
</tr>
<tr>
<td>crossed</td>
<td><code>a_type</code></td>
<td>Returns the value of the register in the destination clock domain</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

```verilog
interface CrossingReg #( type a_type ) ;
    method Action _write(a datain) ;
    method a_type _read() ;
    method a_type crossed() ;
endinterface
```

Modules

<table>
<thead>
<tr>
<th>Module</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>mkNullCrossingWire</code></td>
<td>Defines a synchronizer that contains only a wire. It is left up to the designer to ensure the clock crossing is safe.</td>
</tr>
</tbody>
</table>

```verilog
module mkNullCrossingWire #( Clock dClk, a_type dataIn )
    ( ReadOnly#(a_type) )
    provisos (Bits#(a_type, sa));
```
**Figure 20: Wire synchronizer**

**Figure 21: Register with wire synchronizer**

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Module Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkNullCrossingReg</td>
<td>Defines a synchronizer that contains a register with a synchronous reset value, followed by a wire synchronizer. It is left up to the designer to ensure the clock crossing is safe.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>module mkNullCrossingReg(Clock dClk, a_type resetval, CrossingReg#(a_type) ifc ) provisos (Bits#(a_type, sz_a)) ;</td>
</tr>
<tr>
<td>mkNullCrossingRegA</td>
<td>Defines a synchronizer that contains a register with a given reset value where reset is asynchronous, followed by a wire synchronizer. It is left up to the designer to ensure the clock crossing is safe.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>module mkNullCrossingRegA(Clock dClk, a_type resetval, CrossingReg#(a_type) ifc ) provisos (Bits#(a_type, sz_a)) ;</td>
</tr>
<tr>
<td>mkNullCrossingRegU</td>
<td>Defines a synchronizer that contains a register without a reset, followed by a wire synchronizer. It is left up to the designer to ensure the clock crossing is safe.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>module mkNullCrossingRegU(Clock dClk, CrossingReg#(a_type) ifc ) provisos (Bits#(a_type, sz_a)) ;</td>
</tr>
</tbody>
</table>

**Example: instantiating a null synchronizer**

```verilog
// domain2sig is domain1sig synchronized to clk0 with just a wire.
ReadOnly#(Bit#(2)) domain2sig <- mkNullCrossingWire(clk0, domain1sig);
```
Note: no synchronization is actually done. This is purely a way to tell BSC that it is safe to use the signal in the other domain. It is the responsibility of the designer to verify that this is correct.

There are some restrictions on the use of a `mkNullCrossingWire`. The expression used as the data argument must not have an implicit condition, and there cannot be another rule which is required to schedule before any method called in the expression.

`mkNullCrossingWires` may not be used in sequence to pass a signal across multiple clock boundaries without synchronization. Once a signal has been crossed from one domain to a second domain without synchronization, it cannot be subsequently passed unsynchronized to a third domain (or back to the first domain).

**Verilog Modules**

The BSV modules correspond to the following Verilog modules, which are found in the Bluespec Verilog library, `$BLUESPECDIR/Verilog`.

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Name</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>mkNullCrossingWire</code></td>
<td>BypassWire.v</td>
</tr>
</tbody>
</table>

### C.9.10 Reset Synchronization and Generation

**Description**

This section describes the interfaces and modules used to synchronize reset signals from one clock domain to another and to create reset signals. Reset generation converts a Boolean type to a Reset type, where the reset is associated with the default or `clocked_by` clock domain.

**Interfaces and Methods**

The `MakeResetIfc` interface is provided by the reset generators `mkReset` and `mkResetSync`.

```verilog
interface MakeResetIfc;
    method Action assertReset();
    method Bool isAsserted();
    interface Reset new_rst;
endinterface
```

The interface `MuxRstIfc` is provided by the `mkResetMux` module.

```verilog
interface MuxRstIfc;
    method Action select();
    method Bool isAsserted();
    interface Reset reset_out;
endinterface
```

<table>
<thead>
<tr>
<th>MakeResetIfc Interface</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Type</td>
</tr>
<tr>
<td>assertReset</td>
<td>Action</td>
</tr>
<tr>
<td>isAsserted</td>
<td>Bool</td>
</tr>
<tr>
<td>new_rst</td>
<td>Reset</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MuxRstIfc Interface</th>
<th>Arguments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Type</td>
</tr>
<tr>
<td>select</td>
<td>Action</td>
</tr>
<tr>
<td>reset_out</td>
<td>Reset</td>
</tr>
</tbody>
</table>
interface MuxRstIfc;
    method Action select ( Bool ab );
    interface Reset reset_out;
endinterface

Modules

Reset Synchronization  To synchronize resets from one clock domain to another, both synchronous and asynchronous modules are provided. The stages argument is the number of full clock cycles the output reset is held for after the input reset is deasserted. This is shown as the number of flops in figures 22 and 23. Specifying a 0 for the stages argument results in the creation of a simple wire between sRst and dRstOut.

417
Figure 23: Module for synchronous resets

<table>
<thead>
<tr>
<th><strong>mkSyncReset</strong></th>
<th>Provides synchronization of a source reset ((sRst)) to the destination domain. The reset is asserted at the next rising edge of the clock.</th>
</tr>
</thead>
</table>
| module mkSyncReset #( Integer stages
| Reset sRst, |
| Clock dClkIn ) |
| ( Reset ) ; |
|-----------------|----------------------------------------------------------------------------------------------------------------------------------|

<table>
<thead>
<tr>
<th><strong>mkSyncResetFromCR</strong></th>
<th>Provides synchronization of the current reset to the destination domain. The reset is asserted at the next rising edge of the clock.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module mkSyncResetFromCR #( Integer stages</td>
<td></td>
</tr>
<tr>
<td>Clock dClkIn )</td>
<td></td>
</tr>
<tr>
<td>( Reset ) ;</td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>

**Example: instantiating a reset synchronizer**

// 2 is the number of stages
Reset rstn2 <- mkAsyncResetFromCR (2, clk0);

// if stages = 0, the default reset is used directly
Reset rstn0 <- mkAsyncResetFromCR (0, clk0);

**Reset Generation** Two modules are provided for reset generation, **mkReset** and **mkResetSync**, where each module has one parameter, **stages**. The **stages** parameter is the number of full clock cycles the output reset is held after the **inRst**, as seen in figure 24, is deasserted. Specifying a 0 for the **stages** parameter results in the creation of a simple wire between the input register and the output reset. That is, the reset is asserted immediately and not held after the input reset is deasserted. It becomes the designer’s responsibility to ensure that the input reset is asserted for sufficient time to allow the design to reset properly. The reset is controlled using the **assertReset** method of the **MakeResetIfc** interface.

The difference between **mkReset** and **mkResetSync** is that for the former, the assertion of reset is immediate, while the later asserts reset at the next rising edge of the clock. Note that use of **mkResetSync** is less common, since the reset requires clock edges to take effect; failure to assert reset for a clock edge will result in a reset not being seen at the output reset.
<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
</table>
| mkReset           | Provides conversion of a Boolean type to a Reset type, where the reset is associated with `dClkIn`. This module uses the model in figure 24. `startInRst` indicates the reset value of the register. If `startInRst` is True, the reset value of the register is 0, which means the output reset will be asserted whenever the currentReset (sRst) is asserted. `rst_out` will remain asserted for the number of clock cycles given by the stages parameter after sRst is deasserted. If `startInRst` is False, the output reset will not be asserted when sRst is asserted, but only when the `assert_reset` method is invoked. At the start of simulation `rst_out` will only be asserted if `startInRst` is True and sRst is initially asserted.ᄀ
module mkReset #( Integer stages,
                   Bool startInRst,
                   Clock dClkIn )
   ( MakeResetIfc ) ;

| mkResetSync       | Provides conversion of a Boolean type to a Reset type, where the reset is associated with `dClkIn` and the assertion of reset is at the next rising edge of the clock. This module uses the model in figure 24. `startInRst` indicates the reset value of the register. If `startInRst` is True, the reset value of the register is 0, which means the output reset will be asserted whenever the currentReset (sRst) is asserted. `rst_out` will remain asserted for the number of clock cycles given by the stages parameter after sRst is deasserted. If `startInRst` is False, the output reset will not be asserted when sRst is asserted, but only when the `assert_reset` method is invoked. At the start of simulation `rst_out` will only be asserted if `startInRst` is True and sRst is initially asserted.ᄀ
module mkResetSync #( Integer stages,
                      Bool startInRst,
                      Clock dClkIn )
   ( MakeResetIfc ) ;
A reset multiplexor \texttt{mkResetMux}, as seen in figure 25, creates one reset signal by selecting between two existing reset signals.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{reset_mux.png}
\caption{Reset Multiplexor}
\end{figure}

### \texttt{mkResetMux}

Multiplexor which selects between two input resets, \texttt{aRst} and \texttt{bRst}, to create a single output reset \texttt{rst\_out}. The reset is selected through a Boolean value provided to the \texttt{select} method where True selects \texttt{aRst}.

\begin{verbatim}
module mkResetMux #( Reset aRst, Reset bRst )
  ( MuxRstIfc rst_out ) ;
\end{verbatim}

For testbenches, in which an absolute clock is being created, it is helpful to generate a reset for that clock. The module \texttt{mkInitialReset} is available for this purpose. It generates a reset which is asserted at the start of simulation. The reset is asserted for the number of cycles specified by the parameter \texttt{cycles}, counting the start of time as 1 cycle. Therefore, a \texttt{cycles} value of 1 will cause the reset to turn off at the first clock tick. This module is not synthesizable.

### \texttt{mkInitialReset}

Generates a reset for \texttt{cycles} cycles, where the \texttt{cycles} parameter must be greater than zero. The \texttt{clocked\_by} clause indicates the clock the reset is associated with. This module is not synthesizable.

\begin{verbatim}
module mkInitialReset #( Integer cycles )
  ( Reset ) ;
\end{verbatim}

Example:

\begin{verbatim}
Clock c <- mkAbsoluteClock (10, 5);
// a reset associated with clock c:
Reset r <- mkInitialReset (2, clocked\_by c);
\end{verbatim}

When two reset signals need to be combined so that some logic can be reset when either input reset is asserted, the \texttt{mkResetEither} module can be used.

### \texttt{mkResetEither}

Generates a reset which is asserted whenever either input reset is asserted.

\begin{verbatim}
module mkResetEither ( Reset aRst,
  Reset bRst)
  ( Reset out\_ifc ) ;
\end{verbatim}
Figure 26: Reset Either

Example:

```
Reset r <- mkResetEither(rst1, rst2);
```

<table>
<thead>
<tr>
<th>BSV Module Name</th>
<th>Verilog Module Name</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>mkASyncReset</td>
<td>SyncReset0.v</td>
<td></td>
</tr>
<tr>
<td>mkASyncResetFromCR</td>
<td>SyncResetA.v</td>
<td></td>
</tr>
<tr>
<td>mkSyncReset</td>
<td>SyncReset0.v</td>
<td>when stages==0</td>
</tr>
<tr>
<td>mkSyncResetFromCR</td>
<td>SyncReset.v</td>
<td></td>
</tr>
<tr>
<td>mkReset</td>
<td>MakeReset0.v</td>
<td>when stages==0</td>
</tr>
<tr>
<td>mkResetSync</td>
<td>MakeResetA.v</td>
<td>when stages==0</td>
</tr>
<tr>
<td></td>
<td>MakeReset0.v</td>
<td>instantiates SyncResetA</td>
</tr>
<tr>
<td>mkResetMux</td>
<td>ResetMux.v</td>
<td></td>
</tr>
<tr>
<td>mkResetEither</td>
<td>ResetEither.v</td>
<td></td>
</tr>
<tr>
<td>mkResetInverter</td>
<td>ResetInverter.v</td>
<td></td>
</tr>
<tr>
<td>isResetAsserted</td>
<td>ResetToBool.v</td>
<td></td>
</tr>
</tbody>
</table>

C.10 Special Collections

C.10.1 ModuleContext

Package
import ModuleContext :: * ;

Description

An ordinary Bluespec module, when instantiated, adds state elements and rules to the growing accumulation of elements and rules already in the design. In some designs, items other than state elements and rules must be accumulated as well. While there is a need to add these items, it is also desirable to keep these additional design details separate from the main design, keeping the natural structure of the design intact.

The ModuleContext package provides the capability of accumulating items and maintaining the compile-time state of additional items, in such a way that it doesn’t change the structure of the original design.

The ModuleContext mechanism allows the designer to hide the details of the additional interfaces. Before the module can be synthesized, it must be converted (or exposed) into a module containing only rules and state elements, as the compiler does not know how to handle the other items. The ModuleContext package provides the mechanisms to allow additional items to be collected, processed, and exposed.

This package is provided as both a compiled library package and as BSV source code to facilitate customization. The source code file can be found in the $BLUESPECDIR/BSVSource/Contexts directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Types and Type Classes

The default BSV module type is Module, but you can define other BSV module types as well. The ModuleContext type is a variation on the Module type that allows additional items, other than states and rules, to be collected while elaborating the module structure.

The ModuleContext package defines the typeclass Context, which includes functions getContext and putContext. A Context typeclass has two type parameters: a module type (mc1) and the context (c2).

```
typeclass Context#(type mc1, type c2);
  module [mc1] getContext(c2) provisos (IsModule#(mc1, a));
  module [mc1] putContext#(c2 s)(Empty) provisos (IsModule#(mc1, a));
endtypeclass
```

A regular module type (Module) will have a context of void:

```
instance Context#(Module, void);
```

A module type of ModuleContext will return the context of the module:

```
instance Context#(ModuleContext#(st1), st1);
```

An instance is defined where the context type st1 of the ModuleContext and the context type st2 are different, but Gettable (as defined in Hlist Section C.10.4):

```
instance Context#(ModuleContext#(st1), st2)
  provisos (Gettable#(st1, st2));
```
The modules `applyToContext` and `applyToContextM` are used to apply a function over a context. The `applyToContextM` modules is used for monadic functions.

<table>
<thead>
<tr>
<th>applyToContext</th>
<th>Applies a function over a context.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module [mc1] applyToContext#(function c2 f(c2 c))(Empty) provisos (IsModule#(mc1, a), Context#(mc1, c2));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>applyToContextM</th>
<th>Applies a monadic function over a context.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module [mc1] applyToContextM#(function module#(c2) m(c2 c)) (Empty) provisos (IsModule#(mc1, a), Context#(mc1, c2));</td>
<td></td>
</tr>
</tbody>
</table>

**ClockContext**

The structure `ClockContext` is defined to be comprised of two clocks: `clk1` and `clk2` and two resets: `rst1` and `rst2`.

```haskell
typedef struct {
    Clock clk1;
    Clock clk2;
    Reset rst1;
    Reset rst2;
} ClockContext;
```

An `initClockContext` is defined with the values of both clocks set to `noClock` and both resets set to `noReset`:

```haskell
ClockContext initClockContext = ClockContext {
    clk1: noClock, clk2: noClock, rst1: noReset, rst2: noReset
};
```

**Expose**

The `Expose` typeclass converts a context to an interface for a synthesis boundary, converting it to a module type of `Module`. The `Expose` typeclass provides the modules `unburyContext` and `unburyContextWithClocks`.

```haskell
typeclass Expose#(type c, type ifc)
    dependencies (c determines ifc);
```

An `HList` of contexts is convertible if its elements are, and results in a `Tuple` of subinterfaces.

```haskell
instance Expose#(HList1#(ct1), ifc1)
    provisos (Expose#(ct1,ifc1));

instance Expose#(HCons#(c1,c2), Tuple2#(ifc1,ifc2))
    provisos (Expose#(c1,ifc1), Expose#(c2,ifc2));

instance Expose#(ClockContext, Empty);
```
The `unburyContext` module is for use at the top level of a module to be separately synthesized. It takes as an argument a module which is to be instantiated in a particular context, and an initial state for that context. The module is instantiated, and the final context converted into an extra interface, returned in pair with the instantiated module’s own interface.

<table>
<thead>
<tr>
<th>unburyContext</th>
<th>Converts a context to an interface for a synthesis boundary. An HList of contexts is convertible if its elements are, and results in a tuple of subinterfaces.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module <code>unburyContext#(c x)(ifc);</code></td>
</tr>
<tr>
<td></td>
<td>module <code>unburyContext#(HList1#(ct1) c1)(ifc1);</code></td>
</tr>
<tr>
<td></td>
<td>module <code>unburyContext#(HCons#(c1,c2) c12)(Tuple2#(ifc1,ifc2));</code></td>
</tr>
<tr>
<td></td>
<td>module <code>unburyContext#(ClockContext x)();</code></td>
</tr>
</tbody>
</table>

The `unburyContextWithClocks` takes a `ClockContext` along with the Context it is specifically handling.

<table>
<thead>
<tr>
<th>unburyContextWithClocks</th>
<th>Converts a context to an interface for a synthesis boundary and takes a <code>ClockContext</code> as a second argument.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module <code>unburyContextWithClocks#(c x, ClockContext cc)(ifc);</code></td>
</tr>
<tr>
<td></td>
<td>module <code>unburyContextWithClocks#(HList1#(ct1) c1, ClockContext cc)(ifc1);</code></td>
</tr>
<tr>
<td></td>
<td>module <code>unburyContextWithClocks#(HCons#(c1,c2) c12, ClockContext cc)(Tuple2#(ifc1,ifc2));</code></td>
</tr>
<tr>
<td></td>
<td>module <code>unburyContextWithClocks#(ClockContext x, ClockContext cc)();</code></td>
</tr>
</tbody>
</table>

**Hide**

The `Hide` typeclass provides the module `reburyContext`, which takes an interface as an argument (and provides an Empty interface). It is intended to be run in a context which can absorb the information from the interface. As with `Expose`, a `Tuple` of interfaces can be hidden if each element can be hidden.

<table>
<thead>
<tr>
<th>reburyContext</th>
<th>Connects the provided interface with the surrounding context.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>module <code>[mc] reburyContext#(ifc i)(Empty);</code></td>
</tr>
<tr>
<td></td>
<td>module <code>[mc] reburyContext#(Empty i)(Empty);</code></td>
</tr>
<tr>
<td></td>
<td>module `[mc] reburyContext#(Tuple2#(ifc1,ifc2) i12)(Empty);</td>
</tr>
</tbody>
</table>

**ContextRun**
The `ContextRun` and `ContextsRun` typeclasses provides modules to run modules in contexts. The module `runWithContext` runs a module with an entirely new context.

```plaintext
typeclass ContextRun#(type m, type c1, type ctx2)
dependencies ((m, c1) determines ctx2);

typeclass ContextsRun#(type m, type c1, type ctx2)
dependencies ((m, c1) determines ctx2);
```

<table>
<thead>
<tr>
<th>runWithContext</th>
<th>Runs a module with an entirely new context.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module [m] runWithContext #(c1 initState, ModuleContext#(ctx2, ifcType) mkI) (Tuple2#(c1, ifcType));</td>
<td></td>
</tr>
<tr>
<td>module [ModuleContext#(ctx)] runWithContext#(c1 initState, ModuleContext#(HCons#(c1, ctx), ifcType) mkI) (Tuple2#(c1, ifcType));</td>
<td></td>
</tr>
<tr>
<td>module [Module] runWithContext#(c1 initState, ModuleContext#(c1, ifcType) mkI) (Tuple2#(c1, ifcType));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>runWithContexts</th>
<th>Runs a module with an entirely new context.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module [m] runWithContexts#(c1 initState, ModuleContext#(ctx2, ifcType) mkI) (Tuple2#(c1, ifcType));</td>
<td></td>
</tr>
<tr>
<td>module [ModuleContext#(ctx)] runWithContexts#(c1 initState, ModuleContext#(ctx2, ifcType) mkI) (Tuple2#(c1, ifcType));</td>
<td></td>
</tr>
<tr>
<td>module [Module] runWithContexts#(c1 initState, ModuleContext#(c1, ifcType) mkI) (Tuple2#(c1, ifcType));</td>
<td></td>
</tr>
</tbody>
</table>

**Contexts.defines**

Bluespec provides macros in the `Context.defines` file to handle the treatment of the module contexts at synthesis boundaries.

1. The designer defines a leaf or intermediate node module, with module type `ErrorReporter` or `ErrorReporterA`, appending a 0 to its name (e.g. `mkM0`). Elsewhere in the package the appropriate macro is chosen from the macros `SynthBoundary` and `SynthBoundaryWithClocks`.

2. The macro defines a synthesizable version of the module, `mkMV`, which provides the original interface together with an error-reporting subinterface. It also defines a module with the original name `mkM` to be used for instantiating the original module. It uses the Context mechanism to re-bury the error-reporting plumbing and returns the original interface of the original `mkM` module.
These macros assume that the complete module context (such as an HList of individual contexts) is named `CompleteContext` and that its initial value may be obtained from either `mkInitialCompleteContext` or `mkInitialCompleteContextWithClocks`.

Example Without Clocks

```verilog
SynthBoundary(mkM, IM)

 Becomes

(*synthesize*)
module [Module] mkMV(Tuple2#(CompleteContextIfc, IM));
    let init <- mkInitialCompleteContext;
    let _ifc <- unbury(init, mkMO);
    return _ifc;
endmodule

module [ModuleContext#(CompleteContext)] mkM(IM);
    let _ifc <- rebury(mkMV);
    return _ifc;
endmodule
```

Example With Clocks

```verilog
SynthBoundaryWithClocks(mkM, IM)

 Becomes

(*synthesize*)
module [Module] mkMV#(Clock c1, Reset r1, Clock c2, Reset r2)(Tuple2#(CompleteContextIfc, IM));
    let init <- mkInitialCompleteContextWithClocks(c1, r1, c2, r2);
    let _ifc <- unburyWithClocks(initialCompleteContext, c1, r1, c2, r2, mkMO);
    return _ifc;
endmodule

module [ModuleContext#(CompleteContext)] mkM(IM);
    let _ifc <- reburyWithClocks(mkMV);
    return _ifc;
endmodule
```

C.10.2 ModuleCollect

Package

```verilog
import ModuleCollect :: *;
```

Description

The `ModuleCollect` package provides the capability of adding additional items, such as configuration bus connections, to a design in such a way that it does not change the structure of the design. This section provides a brief overview of the package. For a more detailed description of its usage, see the `CBus` package (C.10.3), which utilizes `ModuleCollect`. There is also a detailed example and more complete discussion of the `CBus` package in the configbus tutorial in the BSV/tutorials directory.
An ordinary Bluespec module, when instantiated, adds its own state elements and rules to the growing accumulation of state elements and rules defined in the design. In some designs, for example a configuration bus, additional items, such as the logic for the bus address decoding must be accumulated as well. While there is a need to add these items, it is also desirable to keep these additional design details separate from the main design, keeping the natural structure of the design intact.

The ModuleCollect mechanism allows the designer to hide the details of the additional interfaces. A module which is going to be synthesized must contain only rules and state elements, as the compiler does not know how to handle the additional items. Therefore, the collection must be brought into the open, or exposed, before the module can be synthesized. The ModuleCollect package provides the mechanisms to allow these additional items to be collected, processed and exposed.

This package is provided as both a compiled library package and as BSV source code to facilitate customization. The source code file can be found in the $BLUESPECDIR/BSVSource/Contexts directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Types and Type Classes

The ModuleCollect type is a variation on the Module type that allows additional items, other than states and rules, to be collected while elaborating the module structure. A module defining the accumulation of a special collection will have the type of ModuleCollect which is defined as a type of ModuleContext (Section C.10.1):

\[
\text{typedef ModuleContext#(HList1#(UAList#(a))) ModuleCollect#(type a_type)};
\]

where a_type defines the type of the items being collected. The collection is kept as an HList, therefore each item in the collection does not have the same type.

Your new type of module is a ModuleCollect defined to collect a specific type. It is often convenient to give a name to your new type of module using the typedef keyword. For example:

\[
\text{typedef ModuleCollect#(element_type, ifc_device) MyModuleType#(type ifc_device)};
\]

specifies a type named MyModuleType.

An ordinary module, one defined with the keyword module without a type in square brackets immediately after it, can be of any module type. It is polymorphic, and when instantiated takes the type of the surrounding module context. Only modules of type Module can be synthesized, so the *synthesize* attribute forces the type to be Module. This is equivalent to writing:

\[
\text{module [Module]...}
\]

Normally, all the modules instantiated inside a synthesized module take the type Module.

A module which is accumulating a collection must have the appropriate type, specified in square brackets immediately after the keyword, as shown in the following example:

\[
\text{module [AssertModule] mkAssertionReg...}
\]

The complete example is found later in this section. This implies that any module instantiating mkAssertionReg is no longer polymorphic, its type is constrained by the inner module, so it will have to be explicitly given the AssertModule type too. Note, however, that you can continue to instantiate other modules not concerned with the collection (for example, mkReg, mkFIFO, etc.) alongside mkAssertReg just as before. But now they will take the type AssertModule from the context instead of the type Module.
Since only modules of type `Module` can be synthesized, before this group of `AssertModule` instantiations can be synthesized, you must use `exposeCollection` to contain the collection in a top-level module of type `Module`.

**Interfaces**

The `IWithCollection` interface couples the normal module interface (the `device` interface) with the collection of collected items (the `collection` interface). This is the interface provided by the `exposeCollection` function. It separates the collection list and the device module interface, to allow the module to be synthesized.

```markdown
interface IWithCollection #(type a, type i);
    method i device();
    method List#(a) collection();
endinterface: IWithCollection

OLD:

interface IWithCollection #(type collection_type, type item_type);
    interface item_type device();
    interface List#(collection_type) collection();
endinterface: IWithCollection
```

**Modules and Functions**

In the course of evaluating a module body during its instantiation, an item may be added to the current collection by using the function `addToCollection`.

```markdown
<table>
<thead>
<tr>
<th>addToCollection</th>
<th>Adds an item to the collection.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function ModuleCollect#(a_type, ifc)</td>
<td></td>
</tr>
<tr>
<td>addToCollection(a_type item);</td>
<td></td>
</tr>
</tbody>
</table>
```

Once a set of items has been collected, those items must be exposed before synthesis. The `exposeCollection` module constructor is used to bring the collection out into the open. The `exposeCollection` module takes as an argument a `ModuleCollect` module (m) with interface `ifc`, and provides an `IWithCollection` interface.

```markdown
<table>
<thead>
<tr>
<th>exposeCollection</th>
<th>Expose the collection to allow the module to be synthesized.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module exposeCollection#(ModuleCollect#(a_type, ifc) m)</td>
<td></td>
</tr>
<tr>
<td>(IWithCollection#(a_type, ifc));</td>
<td></td>
</tr>
</tbody>
</table>
```

Finally, the `ModuleCollect` package provides a function, `mapCollection`, to apply a function to each item in the current collection.

```markdown
<table>
<thead>
<tr>
<th>mapCollection</th>
<th>Apply a function to each item added to the collection within the second argument.</th>
</tr>
</thead>
<tbody>
<tr>
<td>function ModuleCollect#(a_type, ifc)</td>
<td></td>
</tr>
<tr>
<td>mapCollection(function a_type x1(a_type x1),</td>
<td></td>
</tr>
<tr>
<td>ModuleCollect#(a_type, ifc) x2);</td>
<td></td>
</tr>
</tbody>
</table>
```

**Example - Assertion Wires**
// This example shows excerpts of a design which places various
// test conditions (Boolean expressions) at random places in a design,
// and lights an LED (setting an external wire to 1), if the condition
// is ever satisfied.

import ModuleCollect::*;
import List::*;
import Vector::*;
import Assert::*;

// The desired interface at the top level is:
interface AssertionWires#(type n);
  method Bit#(n) wires;
  method Action clear;
endinterface

// The "wires" method tells which conditions have been set, and the
// "clear" method resets them all to 0.
// The items in our extra collection will be interfaces of the
// following type:

interface AssertionWire;
  method Integer index; // Indicates which wire is to be set if
  method Bool fail;     // fail method ever returns true.
  method Action clear;
endinterface

// We next define the "AssertModule" type. This is to behave like an
// ordinary module providing an interface of type "i", except that it
// also can collect items of type "AssertionWire":

typedef ModuleCollect#(AssertionWire, i) AssertModule#(type i);
typedef Tuple2#(AssertionWires#(n), i) AssertIfc#(type i, type n);
...

// The next definition shows how items are added to the collection.
// This is the module which will be instantiated at various places in
// the design, to test various conditions. It takes one static
// parameter, "ix", to specify which wire is to carry this condition,
// and one dynamic parameter (one varying at run-time) "c", giving the
// value of the condition itself.

interface AssertionReg;
  method Action set;
  method Action clear;
endinterface

module [AssertModule] mkAssertionReg#(Integer ix)(AssertionReg);
  Reg#(Bool) cond <- mkReg(False);
  // an item is defined and added to the collection
let item = (interface AssertionWire;
  method index;
    return (ix);
  endmethod
  method fail;
    return(cond);
  endmethod
  method Action clear;
    cond <= False;
  endmethod
endinterface);
addToCollection(item);
...
endmodule

// the collection must be exposed before synthesis
module [Module] exposeAssertionWires#(AssertModule#(i) mkI)(AssertIfc#(i, n));

  IWithCollection#(AssertionWire, i) ecs <- exposeCollection(mkI);

  ...(c_ifc is created from the list ecs.collection)

  // deliver the array of values in the registers
  let dut_ifc = ecs.device;

  // return the values in the collection, and the ifc of the device
  return(tuple2(c_ifc, dut_ifc));
endmodule

C.10.3 CBus

Package

import CBus :: * ;

Description

The CBus package provides the interface, types and modules to implement a configuration bus capability providing access to the control and status registers in a given module hierarchy. This package utilizes the ModuleCollect package and functionality, as described in section C.10.2. The ModuleCollect package allows items in addition to usual state elements and rules to be accumulated. This is required to collect up the interfaces of the control status registers included in a module and to add the associated logic and ports required to allow them to be accessed via a configuration bus.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

For a more complete discussion of the CBus package, consult the configbus tutorial in the BSV/tutorials directory.

Types and Type Classes

The type CBusItem defines the type of item to be collected by ModuleCollect. The items to be collected are the same as the ifc which we will later expose, so we use a type alias:
typedef CBus#(size_address, size_data) CBusItem #(type size_address, type size_data);

The type ModWithCBus defines the type of module which is collecting CBusItems. An ordinary module, one not collecting anything other than state elements and rules, has the type Module. Since CBusItems are being collected, a module type ModWithCBus is defined. When the module type is not Module, the type must be specified in square brackets immediately after the module keyword in the module definition.

typedef ModuleCollect#(CBusItem#(size_address, size_data), item) ModWithCBus#(type size_address, type size_data, type item);

Interface and Methods

The CBus interface provides read and write methods to access control status registers. It is polymorphic in terms of the size of the address bus (size_address) and size of the data bus (size_data).

<table>
<thead>
<tr>
<th>CBus Interface</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>read</td>
<td>Returns the value of the associated register if and only if addr matches the register address. In all other cases the read method returns an Invalid value.</td>
</tr>
<tr>
<td>write</td>
<td>Writes the data value to the register if and only if the value of addr matches the address of the register.</td>
</tr>
</tbody>
</table>

```verilog
typedef CBus#(type size_address, type size_data);
method Action write(Bit#(size_address) addr, Bit#(size_data) data);
(* always_ready *)
method ActionValue#(Bit#(size_data)) read(Bit#(size_address) addr);
endinterface
```

The IWithCBus interface combines the CBus interface with a normal module interface. It is defined as a structured interface with two subinterfaces: cbus_ifc (the associated configuration bus interface) and device_ifc (the associated device interface). It is polymorphic in terms of the type of the configuration bus interface and the type of the device interface.

```verilog
interface IWithCBus#(type cbus_IFC, type device_IFC);
  interface cbus_IFC cbus_ifc;
  interface device_IFC device_ifc;
endinterface
```

Modules

The collectCBusIFC module takes as an argument a module with an IWithCBus interface, adds the associated CBus interface to the current collection (using addToCollection from the ModuleCollect package), and returns a module with the normal interface. Note that collectCBusIFC is of module type ModWithCBus.

```verilog
collectCBusIFC module ModWithCBus#(size_address, size_data)]
collectCBusIFC#(Module#(IWithCBus#( 
CBus#(size_address,size_data),i)) m)(i);"
The exposeCBusIFC module is used to create an IWithCBus interface given a module with a normal interface and an associated collection of CBusItems. This module takes as an argument a module of type ModWithCBus and provides an interface of type IWithCBus. The exposeCBusIFC module exposes the collected CBusItems, processes them, and provides a new combined interface. This module is synthesizable, because it is of type Module.

<table>
<thead>
<tr>
<th>exposeCBusIFC</th>
<th>A module wrapper that takes a module with a normal interface, processes the collected CBusItems and provides an IWithCBus interface.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module [Module] exposeCBusIFC#(ModWithCBus#(size_address, size_data, item) sm) (IWithCBus#(CBus#(size_address, size_data), item));</td>
<td></td>
</tr>
</tbody>
</table>

The CBus package provides a set of module primitives each of which adds a CBus interface to the collection and provides a normal Reg interface from the local block point of view. These modules are used in designs where a normal register would be used, and can be read and written to as registers from within the design.

<table>
<thead>
<tr>
<th>mkCBRegR</th>
<th>A wrapper to provide a read only CBus interface to the collection and a normal Reg interface to the local block.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module [ModWithCBus#(size_address, size_data)] mkCBRegR#(CRAddr#(size_address2) addr, r x) (Reg#(r)) provisos (Bits#(r, sr), Add#(k, sr, size_data), Add#(ignore, size_address2, size_address));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkCBRegRW</th>
<th>A wrapper to provide a read/write CBus interface to the collection and a normal Reg interface to the local block.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module [ModWithCBus#(size_address, size_data)] mkCBRegRW#(CRAddr#(size_address2) addr, r x) (Reg#(r)) provisos (Bits#(r, sr), Add#(k, sr, size_data), Add#(ignore, size_address2, size_address));</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>mkCBRegW</th>
<th>A wrapper to provide a write only CBus interface to the collection and a normal Reg interface to the local block.</th>
</tr>
</thead>
<tbody>
<tr>
<td>module [ModWithCBus#(size_address, size_data)] mkCBRegW#(CRAddr#(size_address2) addr, r x) (Reg#(r)) provisos (Bits#(r, sr), Add#(k, sr, size_data), Add#(ignore, size_address2, size_address));</td>
<td></td>
</tr>
</tbody>
</table>
mkCBRegRC

A wrapper to provide a read/clear CBus interface to the collection and a normal Reg interface to the local block. This register can read from the config bus but the write is clear mode; for each write bit a 1 means clear, while a 0 means don’t clear.

```vhd
module [ModWithCBus#(size_address, size_data)]
  mkCBRegRC#(CRAddr#(size_address2) addr, r x)
  (Reg#(r))
  provisos (Bits#(r, sr), Add#(k, sr, size_data),
           Add#(ignore, size_address2, size_address));
```

The mkCBRegFile module wrapper adds a CBus interface to the collection and provides a RegFile interface to the design. This module is used in designs as a normal RegFile would be used.

```vhd
mkCBRegFile

A wrapper to provide a normal RegFile interface and automatically add the CBus interface to the collection.

```vhd
module [ModWithCBus#(size_address, size_data)]
  mkCBRegFile#(Bit#(size_address) reg_addr,
               Bit#(size_address) size)
  (RegFile#(Bit#(size_address), r))
  provisos (Bits#(r, sr), Add#(k, sr, size_data));
```

Example

Provided here is a simple example of a CBus implementation. The example is comprised of three packages: CfgDefines, Block, and Tb. The CfgDefines package contains the definition for the configuration bus, Block is the design block, and Tb is the testbench which executes the block.

The Block package contains the local design. As seen in Figure 27, the configuration bus registers look like a single field from the CBus (cfgResetAddr, cfgStateAddr, cfgStatusAddr), while each field (reset, init, cnt, etc.) in the configuration bus registers looks like a regular register from the local block point of view.

```
import CBus::*; // this is a Bluespec library
```

---

**Figure 27:** CBus Registers used in Block example

```
DCBusAddrWidth = 2
```

---

433
import CfgDefines::*; // user defines - address, registers, etc

interface Block;
  // TODO: normally this block would have at least a few methods
  // Cbus interface is hidden, but it is there
endinterface

// In order to access the CBus at this parent, we need to expose the bus.
// Only modules of type [Module] can be synthesized.
module [Module] mkBlock(IWithCBus#(DCBus, Block));
  let ifc <- exposeCBusIFC( mkBlockInternal );
  return ifc;
endmodule

// Within this module the CBus looks like normal Registers.
// This module can't be synthesized directly.
// How these registers are combined into CBus registers is
// defined in the CfgDefines package.

module [DModWithCBus] mkBlockInternal( Block );
  // all registers are read/write from the local block point of view
  // config register interface types can be
  // mkCBRegR -> read only from config bus
  // mkCBRegRW -> read/write from config bus
  // mkCBRegW -> write only from config bus
  // mkCBRegRC -> read from config bus, write is clear mode
  // i.e. for each bit a 1 means clear, 0 means don't clear
  // reset bit is write only from config bus
  // we presume that you use this bit to fire some local rules, etc
  Reg#(TCfgReset) reg_reset_reset <- mkCBRegW(cfg_reset_reset, 0 /* init val */);
  Reg#(TCfgInit) reg_setup_init <- mkCBRegRW(cfg_setup_init, 0 /* init val */);
  Reg#(TCfgTz) reg_setup_tz <- mkCBRegRW(cfg_setup_tz, 0 /* init val */);
  Reg#(TCfgCnt) reg_setup_cnt <- mkCBRegRW(cfg_setup_cnt, 1 /* init val */);
  Reg#(TCfgOnes) reg_status_ones <- mkCBRegRC(cfg_status_ones, 0 /* init val */);
  Reg#(TCfgError) reg_status_error <- mkCBRegRC(cfg_status_error, 0 /* init val */);

  // USER: you know have registers, so do whatever it is you do with registers :)
  // for instance
  rule bumpCounter ( reg_setup_cnt != unpack('1) );
    reg_setup_cnt <= reg_setup_cnt + 1;
  endrule

  rule watch4ones ( reg_setup_cnt == unpack('1) );
    reg_status_ones <= 1;
  endrule
endmodule

The CfgDefines package contains the user defines describing how the local registers are combined into the configuration bus.

package CfgDefines;
import CBus::*;
basic defines

width of the address bus, it’s easiest to use only the width of the bits needed
but you may have other reasons for passing more bits around (even if some address
bits are always 0)
typedef 2 DCBusAddrWidth; // roof( log2( number_of_config_registers ) )

the data bus width is probably defined in your spec
typedef 32 DCBusDataWidth; // how wide is the data bus

Define the CBus

typedef CBus#( DCBusAddrWidth,DCBusDataWidth) DCBus;
typedef CRAddr#(DCBusAddrWidth,DCBusDataWidth) DCAddr;
typedef ModWithCBus#(DCBusAddrWidth, DCBusDataWidth, i) DModWithCBus#(type i);

Configuration Register Types

these are configuration register from your design. The basic
idea is that you want to define types for each individual field
and later on we specify which address and what offset bits these
// go to. This means that config register address fields can
// actually be split across modules if need be.

typedef bit TCfgReset;
typedef Bit#(4) TCfgInit;
typedef Bit#(6) TCfgTz;
typedef UInt#(8) TCfgCnt;
typedef bit TCfgOnes;
typedef bit TCfgError;

configuration bus addresses

Bit#(DCBusAddrWidth) cfgResetAddr = 0; //
Bit#(DCBusAddrWidth) cfgStateAddr = 1; //
Bit#(DCBusAddrWidth) cfgStatusAddr = 2; // maybe you really want this to be 0,4,8 ???

Configuration Register Locations

DCAddr is a structure with two fields
DCBusAddrWidth a ; // this is the address
// Bit#(n) o ; // this is the offset that this register
// starts reading and writing at

DCAddr cfg_reset_reset = DCAddr {a: cfgResetAddr, o: 0}; // bits 0:0
DCAddr cfg_setup_init = DCAddr {a: cfgStateAddr, o: 0}; // bits 0:0
DCAddr cfg_setup_tz = DCAddr {a: cfgStateAddr, o: 4}; // bits 9:4
DCAddr cfg_setup_cnt = DCAddr {a: cfgStateAddr, o: 16}; // bits 24:16

DCAddr cfg_status_ones = DCAddr {a: cfgStatusAddr, o: 0}; // bits 0:0
DCAddr cfg_status_error = DCAddr {a: cfgStatusAddr, o: 0}; // bits 1:1

endpackage

The Tb package executes the block.

import CBus::*; // bluespec library
import CfgDefines::*; // address defines, etc
import Block::*; // test block with cfg bus
import StmtFSM::*; // just for creating a test sequence

(* synthesize *)
module mkTb ()
    // In order to access this cfg bus we need to use IWithCBus type
    IWithCBus#(DCBus,Block) dut <- mkBlock;

    Stmt test =
        seq
            // write the bits need to the proper address
            // generally this comes from software or some other packing scheme
            // you can, of course, create functions to pack up several fields
            // and drive that to bits of the correct width
            // For that matter, you could have your own shadow config registers
            // up here in the testbench to do the packing and unpacking for you
            dut.cbus_ifc.write( cfgResetAddr, unpack('1) );

            // put some ones in the status bits
            dut.cbus_ifc.write( cfgStateAddr, unpack('1) );

            // show that only the valid bits get written
            $display("TOP: state = %x at ", dut.cbus_ifc.read( cfgStateAddr ), $time);

            // clear out the bits
            dut.cbus_ifc.write( cfgStateAddr, 0 );

            // but the 'ones' bit was set when it saw all ones on the count
            // so read it to see that...
            $display("TOP: status = %x at ", dut.cbus_ifc.read( cfgStatusAddr ), $time);

            // now clear it
            dut.cbus_ifc.write( cfgStatusAddr, 1 );

            // see that it's clear
            $display("TOP: status = %x at ", dut.cbus_ifc.read( cfgStatusAddr ), $time);
// and if we had other interface methods, that where not part of CBUS
// we would access them via dut.device_ifc
endseq;

mkAutoFSM( test );
endmodule

C.10.4 HList

Package

import HList :: * ;

Description

The HList package defines a datatype HList which stores a list of data of different types. The package also provides typeclasses and functions to perform various list operations on the HList type.

The primitive data structures for an HList are HNil and the polymorphic HCons. The various functions are provided by typeclasses, one for each function.

The package defines a typeclass Gettable for finding (getIt) and replacing (putIt) items in an HList. This requires that all the items in the HList are different types. If two types are the same, they must be disambiguated by encapsulating at least one of them (but preferably each of them) in a new struct type. The functions of the Gettable typeclass require that the HList be flat (no nested HLists) and well-formed (terminating in HNil). That is, the target of a recursive search must be either the complete hHead or found within the hTail.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the $BLUESPECDIR/BSVSource/Misc directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the -p option as described in the BSV Users Guide.

Types and type classes

The HList packages defines a typeclass HList:

typeclass HList#(type l);

The HNil datatype defines a nil instance, the empty set. An HList is usually terminated by a HNil.

typedef struct {} HNil deriving (Eq);

The HCons datatype is a structure with two members, a head of datatype e and a tail of datatype l.

typedef struct {
    e hd;
    l tl;
} HCons#(type e, type l) deriving (Eq);

Functions

The various functions for heterogenous lists are provided by typeclasses, one for each functions.
<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
</table>
| HHead        | Returns the first element of the list.                                       | `typeclass HHead#(type l, type h)
dependencies (l determines h);
function h HHead(l x);
endtypeclass
instance HHead#(HCons#(e, 1), e);` |
| HTail        | Returns the tail element from the list.                                      | `typeclass HTail#(type l, type lt)
dependencies (l determines lt);
function lt HTail(l xs);
endtypeclass
instance HTail#(HCons#(e, 1), 1);` |
| HLength      | Returns a numeric value with the length of the list. For a HNil, will return 0. | `typeclass HLength#(type l, numeric type n);
endtypeclass
instance HLength#(HNil, 0);
instance HLength#(HCons#(e, 1), nPlus1)
  provisos (HLength#(l, n), Add#(n,1,nPlus1));` |
| HAppend      | Appends two lists, returning the combined list. The elements do not have to be of the same data type. The combined list will be of type l2, and will contain all the elements of xs followed in order by all the elements of ys. | `typeclass HAppend#(type l, type l1, type l2)
dependencies ((l, l1) determines l2);
function l2 HAppend(l xs, l1 ys);
instance HAppend#(HNil, 1, 1);
instance HAppend#(HCons#(e, 1), l1, HCons#(e, 12))
  provisos (HList#(l), HAppend#(l, l1, l2));` |
The `hSplit` function takes an `HList` of type `l` and returns a `Tuple2` of two `HLists`. This function is the inverse of `hAppend`.

```plaintext
typeclass HSplit#(type l, type l1, type l2);
  function Tuple2#(l1,l2) hSplit(l xs);
endtypeclass

instance HSplit#(HNil, HNil, HNil);
instance HSplit#(l, HNil, l);
instance HSplit#(HCons#(hd,tl), HCons#(hd,l3), l2)
  provisos (HSplit#(tl,l3,l2));
```

This typeclass is for finding (`getIt`) and replacing (`putIt`) a particular element in an `HList`. All items in the `HList` must be of different types. If two types are the same, they should be disambiguated by encapsulating at least one of them (and preferably both of them) in a new struct type.

```plaintext
typeclass Gettable#(type c1, type c2);
  function c2 getIt(c1 x);
  function c1 putIt(c1 x, c2 y);
endtypeclass

instance Gettable#(HCons#(t1, t2), t1);
instance Gettable#(HCons#(t1, t2), t3)
  provisos (Gettable#(t2, t3));
```

**Small Lists**

The `HList` package provides type definitions for small lists, ranging from 1 element to 8 elements, along with constructor functions to build the lists.

**HList1**

```plaintext
typedef HCons#(t, HNil)
  HList1#(type t);

function HList1#(t1) hList1(t1 x1) = hCons(x1, hNil);
```

**HList2**

```plaintext
typedef HCons#(t1, HCons#(t2, HNil))
  HList2#(type t1, type t2);

function HList2#(t1, t2) hList2(t1 x1, t2 x2) = hCons(x1, hCons(x2, hNil));
```

**HList3**

```plaintext
typedef HCons#(t1, HCons#(t2, HCons#(t3, HNil)))
  HList3#(type t1, type t2, type t3);
```
function HList3#(t1, t2, t3) hList3(t1 x1, t2 x2, t3 x3)
    = hCons(x1, hCons(x2, hCons(x3, hNil)));

HList4

typedef HCons#(t1, HCons#(t2, HCons#(t3, HCons#(t4, HNil))))
    HList4#(type t1, type t2, type t3, type t4);

function HList4#(t1, t2, t3, t4) hList4(t1 x1, t2 x2, t3 x3, t4 x4)
    = hCons(x1, hCons(x2, hCons(x3, hCons(x4, hNil))));

HList5

typedef HCons#(t1, HCons#(t2, HCons#(t3, HCons#(t4, HCons#(t5, HNil)))))
    HList5#(type t1, type t2, type t3, type t4, type t5);

function HList5#(t1, t2, t3, t4, t5) hList5(t1 x1, t2 x2, t3 x3, t4 x4, t5 x5)
    = hCons(x1, hCons(x2, hCons(x3, hCons(x4, hCons(x5, hNil)))));

HList6

typedef HCons#(t1, HCons#(t2, HCons#(t3, HCons#(t4, HCons#(t5, HCons#(t6, HNil)))))
    HList6#(type t1, type t2, type t3, type t4, type t5, type t6);

function HList6#(t1, t2, t3, t4, t5, t6)
    hList6(t1 x1, t2 x2, t3 x3, t4 x4, t5 x5, t6 x6)
    = hCons(x1, hCons(x2, hCons(x3, hCons(x4, hCons(x5, hCons(x6, hNil))))));

HList7

typedef HCons#(t1, HCons#(t2, HCons#(t3, HCons#(t4, HCons#(t5, HCons#(t6, HCons#(t7, HNil)))))))
    HList7#(type t1, type t2, type t3, type t4, type t5, type t6, type t7);

function HList7#(t1, t2, t3, t4, t5, t6, t7)
    hList7(t1 x1, t2 x2, t3 x3, t4 x4, t5 x5, t6 x6, t7 x7)
    = hCons(x1, hCons(x2, hCons(x3, hCons(x4, hCons(x5, hCons(x6, hCons(x7, hNil)))))));

HList8

typedef HCons#(t1, HCons#(t2, HCons#(t3, HCons#(t4, HCons#(t5, HCons#(t6, HCons#(t7, HCons#(t8, HNil)))))))
    HList8#(type t1, type t2, type t3, type t4, type t5, type t6, type t7, type t8);

function HList8#(t1, t2, t3, t4, t5, t6, t7, t8)
    hList8(t1 x1, t2 x2, t3 x3, t4 x4, t5 x5, t6 x6, t7 x7, t8 x8)
    = hCons(x1, hCons(x2, hCons(x3, hCons(x4, hCons(x5, hCons(x6, hCons(x7, hCons(x8, hNil))))))));

C.10.5 UnitAppendList

Package

import UnitAppendList :: *;

Description

This provides a representation of lists for which append(x,y) is O(1), rather than O(length(x)) as in the normal representation; the downside is that there is no longer a unique representation for a given list. These lists are useful for situations in which the list is constructed by recursively amalgamating lists from sub-computations, and then subsequently processed. Functions for `map` and `mapM` are provided for processing sublists during construction. For final processing it is almost always preferable first to flatten the list (by a function also provided) into the conventional representation, thus eliminating empty subtrees.

This package is provided as both a compiled library package and as BSV source code as documentation. The source code file can be found in the "$BLUESPACEDIR/BSVSource/Misc" directory. To customize a package, copy the file into a local directory and then include the local directory in the path when compiling. This is done by specifying the search path with the `-p` option as described in the BSV Users Guide.

Types and type classes

The `UnitAppendList` package defines the structure `UAList`:

```haskell
typedef union tagged {
    void NoItems;
    a One;
    Tuple2#(UAList#(a),UAList#(a)) Append;
} UAList#(type a);
```

`UAList` is a member of the `DefaultValue` typeclass, which defines a default value for user-defined structures. The default value for `UAList` is defined as:

```haskell
instance DefaultValue#(UAList#(a));
    defaultValue = NoItems;
endinstance
```

Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>flatten0</code></td>
<td>Given a <code>UAList#(a)</code> and a <code>List#(a)</code>, returns a conventional list of type <code>List</code>.</td>
</tr>
<tr>
<td></td>
<td><code>function List#(a) flatten0(UAList#(a) c, List#(a) xs);</code></td>
</tr>
<tr>
<td><code>flatten</code></td>
<td>Converts a list of type <code>UAList</code> into a conventional list of type <code>List</code>.</td>
</tr>
<tr>
<td></td>
<td><code>function List#(a) flatten(UAList#(a) c) = flatten0(c, Nil);</code></td>
</tr>
<tr>
<td><code>uaMap</code></td>
<td>Maps a function of a list of type <code>UAList</code>, returning a <code>UAList</code>.</td>
</tr>
<tr>
<td></td>
<td><code>function UAList#(b) uaMap(function b f(a x), UAList#(a) c);</code></td>
</tr>
<tr>
<td>uaMapM</td>
<td>Maps a monadic function of a list of type UAList, returning a UAList.</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>module uaMapM#(function module#(b) f(a x), UAList#(a) c)(UAList#(b));</td>
</tr>
</tbody>
</table>

## D Other Libraries

The release contains a directory for packages which may be helpful to the user, but are not supported or systematically tested by Bluespec. These libraries are provided on an as-is basis and may include contributions by 3rd parties. The contributed libraries can be found at $BLUESPECDIR/BSVSource/Contrib.
Index

<< (Bitwise class method), 163
>> (Bitwise class method), 163
| (BitReduction class method), 163
| (Bitwise class method), 162
π (Real constant), 302
&& (Bool operator), 172
(..) (exporting member names), 20
* (Arith class method), 157
** (Arith class method), 157
*/ (close nested comment), 14
+(String concatenation operator), 174
+(Arith class method), 157
- (Arith class method), 157
,, see structs, member selection
/ (Arith class div method), 157
/*@ (open block comment), 14
// (one-line comment), 14
/= (Eq class method), 155
< (Ord class method), 159
<= (Reg assignment), 59
<= (Ord class method), 159
== (Eq class method), 155
> (Ord class method), 159
>= (Ord class method), 159
? (don’t-care expression), 17, 67
[] (bit/part select from bit array), 69
$bitstoreal (Real system function), 97, 174
$display, 91
$displayb, 91
$displayh, 91
$displayo, 91
$dumpoff, 97
$dumpon, 97
$dumpvars, 97
$fclose, 93
$fdisplay, 94
$fdisplayb, 94
$fdisplayh, 94
$fdisplayo, 94
$fflush, 96
$fgetc, 96
$finish, 96
 fopen, 93
$fwrite, 94
$fwriteb, 94
fwriteh, 94
fwriteo, 94
$realtobits (Real system function), 97, 174
$sformat, 95
$sformatAV, 95
$stime, 97
$stop, 96
$fwrite, 95
$swriteAV, 95
$swriteb, 95
$swritehAV, 95
$swriteh, 95
$swriteoAV, 95
$swriteo, 95
$test$plusargs, 97
$time, 97
$ungetc, 96
$write, 91
fwriteb, 91
fwriteh, 91
fwriteo, 91
$+$ (Arith class method), 157
%(Arith class mod method), 157
&(BitReduction class method), 163
&(Bitwise class method), 162
_read (PulseWire interface method), 199
_read (Reg interface method), 89, 190
_write (Reg interface method), 89, 190
{} (concatenation of bit arrays), 69
%(character in identifiers), 14
_ (character in identifiers), 14
’, see compiler directives
^~ (BitReduction class method), 163
^~ (BitReduction class method), 163
^~ (Bitwise class method), 162
^& (BitReduction class method), 163
^~ (Bitwise class method), 162
^~ (BitReduction class method), 163
^~ (Bitwise class method), 162
^~ (Bitwise class method), 163
^~ (Bitwise class method), 162
abs (function), 204
abs (Arith class method), 157
acosh (Real function), 303
Action (type), 186
actions
Action (type), 71
action (keyword), 71
combining, 71
ActionValue (type), 72, 186
Add (type provisos), 25, 188
addBIUInt (function), 318
addRules (Rules function), 187
addToCollection (ModuleCollect function), 427
addUInt (function), 318
Alias, 51, 167
AlignedFIFOs (package), 250
all (List function), 291
all (Vector function), 268
always_enabled (attribute), 101
always_ready (attribute), 101
ancestor (BVI import statement), 141
and (List function), 292
and (Vector function), 268
any (List function), 291
any (Vector function), 268
AOF (clock ancestor attribute), 112
append (List function), 284
append (Vector function), 260
application
of functions to arguments, 74
of methods to arguments, 74
applyToContext (module), 422
applyToContextM (module), 422
Arbiter (package), 349
Arith (type class), 24, 157
Unsigned, Int type instances, 88
Array (type), 182
example, 194
array
anonymous type, 56
named type, 182
example, 194
arrays
update, 57
arrayToVector (Vector function), 282
asIfc (interface pseudo-function), 90
asInh (Real function), 303
asReg (Reg function), 90, 190
Assert (package), 365
AssertFifoTest_IFC (interface), 376
AssertQuiescentTest_IFC (interface), 376
AssertSampleTest_IFC (interface), 374
AssertStartStopTest_IFC (interface), 375
AssertStartTest_IFC (interface), 375
AssertTest_IFC (interface), 374
AssertTransitionTest_IFC (interface), 375
assignment statements
pattern matching in, 86
atan2 (Real function), 303
atanh (Real function), 303
attribute
always_enabled, 101
always_ready, 101
clock_ancestors, 112
clock_family, 112
clock_prefix, 110
clocked_by, 114
conflict_free, 107
default_clock_gate, 112
default_clock_osc, 112
default_reset, 112
default_gate_inhigh, 112
default_gateUnused, 112
descending_urgency, 105
doc, 116
enable, 100
evaluation_order, 107
fire_when_enabled, 102
gate, 113
gate_default_clock, 111
gate_inhigh, 113
gate_input_clocks, 111
gate_prefix, 110
gate_unused, 113
mutually_exclusive, 107
no_implicit_conditions, 103
noinline, 99
nosplit, 109
osc, 113
parameter, 115
port, 100, 115
preempts, 108
prefix, 100
ready, 100
reset, 113
reset_by, 115
reset_prefix, 110
result, 100
split, 109
synthesize, 98
attributes, 98
await (StmtFSM function), 323
begin (keyword), 61, 70
begin-end expression blocks, 70
begin-end statement blocks, 61
Bit (type), 87, 169
bit (type), 87, 170
bitconcat (Bit concatenation operator), 170
BitExtend (type class), 24, 165
Unsigned, Int type instances, 88
BitReduction (type class), 24, 163
Unsigned, Int type instances, 88
Bits (type class), 24, 123, 154
deriving, 124
representation of data types, 124
Unsigned, Int type instances, 88
Bitwise (type class), 24, 162
Unsigned, Int type instances, 88
Bool (type), 172
Bounded (type class), 24, 161
  deriving, 126
    Uint, Int type instances, 88
BRAM (interface type), 222
BRAM (package), 219
BRAM_Configure (type), 219
BRAM_DUAL_PORT (interface type), 226
BRAM_PORT (interface type), 226
BRAMCore (package, 226
BRAMFIFO (package), 246
BRAMRequest (type), 221
  bsv_assert_always (module), 378
  bsv_assert_always_on_edge (module), 378
  bsv_assert_change (module), 378
  bsv_assert_cycle_sequence (module), 379
  bsv_assert_decrement (module), 379
  bsv_assert_delta (module), 379
  bsv_assert_even_parity (module), 380
  bsv_assert_fifo_index (module), 380
  bsv_assert_frame (module), 380
  bsv_assert_handshake (module), 380
  bsv_assert_implication (module), 381
  bsv_assert_increment (module), 381
  bsv_assert_never (module), 381
  bsv_assert_never_unknown (module), 381
  bsv_assert_never_unknown_async (module), 381
  bsv_assert_next (module), 382
  bsv_assert_no_overflow (module), 382
  bsv_assert_no_transition (module), 382
  bsv_assert_odd_parity (module), 383
  bsv_assert_one_cold (module), 383
  bsv_assert_one_hot (module), 383
  bsv_assert_proposition (module), 383
  bsv_assert_quiescent_state (module), 384
  bsv_assert_range (module), 384
  bsv_assert_time (module), 384
  bsv_assert_transition (module), 384
  bsv_assert_UNCHANGE (module), 385
  bsv_assert_width (module), 385
  bsv_assert_win_change (module), 385
  bsv_assert_win_change (module), 385
  bsv_assert_window (module), 386
  bsv_assert_zero_one_hot (module), 386
BufferMode (type), 211
BuildVector (package), 389
buildVersion, 209
BVI import (keyword)
  in interfacing to Verilog, 131
BypassWire (interface), 198
C (scheduling annotations), 49
  case (keyword), 62, 83, 84
  case expression, 84
  case statements
    ordinary, 62
    pattern matching, 83
  casting, type, 75
CBus (interface), 430
CBus (package), 429
clock (Real function), 304
CF (scheduling annotations), 49
CGetPut (package), 339
Char (type), 88, 176
clear (FIFO interface method), 91
clear (FIFO interface method), 90
Client (interface), 335
ClientServer (package), 335
Clock (type), 184, 390
clock_ancestors= (attribute), 112
  clock_family= (attribute), 112
  clock_prefix= (attribute), 110
ClockDividerIfc (interface), 398
clocked_by, 33
clocked_by= (attribute), 114
  clockOf (function), 391
  Clocks (package), 390
cmplx (complex function), 307
cmplxMap (complex function), 308
cmplxSwap (complex function), 308
cmplxWrite (complex function), 308
  Cntrs (package), 351
  collectCBusIFC (module), 430
comment
  block, 14
  one-line, 14
  CommitIfc (package), 341
compare (Ord class method), 159
  compiler directives, 17
  compilerVersion, 208
  CompletionBuffer (interface), 356
  CompletionBuffer (package), 355
  Complex (package), 306
  compose (function), 205
  composeM (function), 205
concat (List function), 285
concat (Vector function), 261
  conditional expressions, 68
  pattern matching in, 86
  conditional statements, 62
  ConfigReg (package,interface), 216
  conflict_free (attribute), 107
Connectable (class), 334
Connectable (package), 334
Cons (List constructor), 284
cons (List function), 284
cons (Vector function), 260
constFn (function), 205
context, see provisos
context too weak (overloading resolution), 120
continuousAssert, 365
Control (interface), 348
cos (Real function), 302
cosh (Real function), 302
countElem (Vector function), 268
countIf (Vector function), 269
countOnes (function), 206
countOnesAlt (bit-vector function), 270
countZerosLSB (function), 206
countZerosMSB (function), 206
CRC (package), 372
curry (function), 205
date, 209
decodeReal (Real function), 305
default (keyword), 62, 83
default_clock (BVI import statement), 136
default_clock_gate= (attribute), 112
default_clock_osc= (attribute), 112
default_gate_inhigh (attribute), 112
default_gate_unused (attribute), 112
default_reset (BVI import statement), 139
default_reset= (attribute), 112
DefaultValue (package), 362
'define (compiler directive), 18
delay (StmtFSM function), 323
deq (FIFOF interface method), 91
deq (FIFO interface method), 90
deriving
  Bits, 124
  Bounded, 126
  Eq, 126
  FShow, 126
    brief description, 26
    for isomorphic types, 128
descending_urgency (attribute), 105
Div (type provisos), 25, 188
div (Integer function), 171
doc= (attribute), 116
documentation attributes, 116
don't-care expression, see ?
DReg (package, interface), 217
drop (List function), 287
drop (Vector function), 263
dropWhile (List function), 288
dropWhileRev (List function), 288
DualPortRamIfc (interface), 412
dumpoff, 97
dumpon, 97
dumpvars, 97
DWire (interface), 198
dynamicAssert, 365
elem (List function), 291
elem (Vector function), 268
'else (compiler directive), 19
else (keyword), 62
'elsif (compiler directive), 19
Empty (interface), 30
emptyRules (Rules variable), 187
enable= (attribute), 100
end (keyword), 61, 70
'endif (compiler directive), 19
endpackage (keyword), 20
enq (FIFOF interface method), 91
enq (FIFU interface method), 90
enum, 51
everification, 51
epochTime, 209
epsilon (FixedPoint function), 310
Eq (type class), 24, 155
  deriving, 126
    UInt, Int type instances, 88
error (forced error), 203
errorM (forced error), 203
execution_order (attribute), 107
exp_e (Arith class method), 157
export (keyword), 20
export, identifiers from a package, 20
exposeCBusIFC (module), 431
exposeCollection (ModuleCollect function), 427
exposeCurrentClock (function), 390
exposeCurrentReset (function), 390
extend (BitExtend class method), 165
False (Bool constant), 172
FIFO (package), 231
FIFO (interface type), 90
FIFOCountIfc (interface), 240
FIFOF (package), 231
FIFOF (interface type), 91
fifofToFifo (function), 236
FIFOLevel (package), 239
FIFOLevelIfc (interface), 239
fifoToGet (GetPut function), 332, 333
fifoToPut (GetPut function), 333
File (type), 183
select (filter function), 287
find (List function), 287
find (Vector function), 269
findElem (Vector function), 269
findIndex (Vector function), 269
finite state machines, 87
fire_when_enabled (attribute), 102
first (FIFOF interface method), 91
first (FFIO interface method), 90
FixedPoint (package), 309
flatten (function), 440
flatten0 (function), 440
flip (function), 205
floor (Real function), 304
fold (List function), 296
fold (Vector function), 275
foldl (List function), 296
foldl (Vector function), 274
foldl1 (List function), 296
foldl1 (Vector function), 275
fromInt (FixedPoint function), 311
fromInteger (Literal class method), 15, 156, 172
fromMaybe (Maybe function), 179
fromReal (RealLiteral class method), 156
fromSizedInteger (SizedLiteral class method), 15, 157
fromUInt (FixedPoint function), 311
FShow (type class), 167
deriving, 126
FSMs, 87
function calls, 74
function definitions, 65
fxptAdd (FixedPoint function), 312
fxptGetFrac (FixedPoint function), 311
fxptGetInt (FixedPoint function), 311
fxptMult (FixedPoint function), 312
fxptQuot (FixedPoint function), 313
fxptSignExtend (FixedPoint function), 315
fxptSub (FixedPoint function), 312
fxptTruncate (FixedPoint function), 313
fxptTruncateRoundSat (FixedPoint function), 313
fxptTruncateSat (FixedPoint function), 313
fxptWrite (FixedPoint function), 316
fxptZeroExtend (FixedPoint function), 315
gate= (attribute), 113
gate_default_clock (attribute), 111
gate_inhigh (attribute), 113
gate_input_clocks= (attribute), 111
gate_prefix= (attribute), 110
gate_unused (attribute), 113
GatedClockIfc (interface), 393
gcd (function), 207
Gearbox (interface), 254
Gearbox (package), 254
genC, 208
generated clock port renaming, 110
genModuleName, 208
genPackage Nam e, 208
genVector (Vector function), 260
genVerilog, 208
genWith (Vector function), 260
genWithM (Vector function), 280
Get (interface), 328
GetPut (package), 328
Gettable (typeclass), 438
grammar, 13
Gray (package), 354
GrayCounter (package), 353
grayDecode (function), 355
grayDecr (function), 355
grayEncode (function), 355
grayIncr (function), 355
grayIncrDecr (function), 355
group (List function), 290
groupBy (List function), 290
HAppend (typeclass), 437
hClose, 210
head (List function), 286
head (Vector function), 262
hFlush, 211
hGetBuffering, 211
hGetChar, 211
hGetLine, 212
HHead (typeclass), 436
higher order functions, 129
hIsClosed, 210
hIsEOF, 210
hIsOpen, 210
hIsReadable, 210
hIsWriteable, 210
HLength (typeclass), 437
HList (package), 436
hPutChar, 211
hPutStr, 211
hPutStrLn, 211
hSetBuffering, 211
HSplit (typeclass), 437
HTail (typeclass), 437
id (function), 205
Identifier (grammar terminal), 14
identifier (grammar terminal), 14
identifiers, 14
case sensitivity, 14
export from a package, 20
import into a package, 21
qualified, 21
static scoping, 21
with $ as first letter, 14
if (keyword), 62
   in method implicit conditions, 36
if statements, 62
   pattern matching in, 85
if-else statements, 62
ifdef (compiler directive), 19
ifndef (compiler directive), 19
implicit conditions, 36
on interface methods, 36
import (keyword), 20
import "BDPI" (keyword), 145
import "BVI" (keyword), 131
import, identifiers into a package, 21
include (compiler directive), 18
infix operators
   associativity, 68
   precedence, 68
   predefined, 68
init (List function), 286
init (Vector function), 263
Inout (type), 184
inout (BVI import statement), 144
input_clock (BVI import statement), 135
input_reset (BVI import statement), 138
instance (of overloading group), 119
instance (of type class), 119
instantiation (module), 33
Int (type), 88, 171
int (type), 88, 171
Integer (type), 88, 171
Integer literals, 14
interface
   expression, 78
   instantiation, 33
interface (BVI import statement), 144
interface (keyword)
   in interface declarations, 28
   in interface expressions, 78
interfaces, 28
   definition of, 27
Invalid
   tagged union member of Maybe type, 55
Invalid (type constructor), 179
invert (Bitwise class method), 162
invertCurrentClock (function), 392
invertCurrentReset (function), 392
isAncestor (function), 391
isInfinite (Real function), 304
isNegativeZero (Real function), 304
isResetAsserted (module), 420
isValid (Maybe function), 179
IWithCBus (interface), 430
joinActions (List function), 297
joinActions (Vector function), 276
joinRules (List function), 297
joinRules (Vector function), 276
last (List function), 286
last (Vector function), 263
lcm (function), 207
length (List function), 291
let, 58
LevelFIFO, see FIFOLevel
LFSR (package), 345
‘line (compiler directive), 18
List (type), 283
ListN (type), 283
Literal (type class), 24, 156
   UInt, Int type instances, 88
Literals
   Integer, 14
   Real, 16
   String, 16
Log (type provisos), 25, 188
log (Arith class method), 157
log10 (Arith class method), 157
log2 (Arith class method), 157
logb (Arith class method), 157
lookup (List function), 287
loop statements
   statically unrolled, 63
   temporal, in FSMs, 320
lsb (Bitwise class method), 163
LUInt (type), 256
macro invocation (compiler directive), 19
MakeClockIfc (interface), 392
MakeResetIfc (interface), 415
map (List function), 294
map (Vector function), 272
mapAccumL (List function), 299
mapAccumL (Vector function), 278
mapAccumR (List function), 299
mapAccumR (Vector function), 278
mapCollection (ModuleCollect function), 427
mapM (Monad function on List), 300
mapM (Monad function on Vector), 279
mapM_ (List function), 300
mapM_ (Vector function), 279
mapPairs (List function), 297
mapPairs (Vector function), 275
match (keyword), 86
Max (type provisos), 25, 188
max ( Ord class method), 159
max (function), 204
maxBound (Bounded class method), 161
Maybe (type), 55, 179
Memory (package), 337
message (compilation message), 203
messageM (compilation message), 204
meta notation, see grammar
method (BVI import statement), 134
method calls, 74
methods
  of an interface, 28
  pattern matching in, 86
MIMO (interface), 256
MIMO (package), 256
MIMOConfiguration (type), 256
Min (type provisos), 188
min (Ord class method), 159
min (function), 204
minBound (Bounded class method), 161
mk1toNGearbox (module), 255
mkAbsoluteClock (module), 395
mkAbsoluteClockFull (module), 395
mkAlignedFIFO (module), 253
mkArbiter (module), 350
mkAsyncReset (module), 416
mkAsyncResetFromCR (module), 416
mkAutoFSM, 322
mkBRAM1Server (module), 223
mkBRAM1ServerBE (module), 223
mkBRAM2Server (module), 224
mkBRAMCore1 (module), 228
mkBRAMCore1BE (module), 228
mkBRAMCore1BELoad (module), 228
mkBRAMCore1Load (module), 228
mkBRAMCore2 (module), 228
mkBRAMCore2BE (module), 229
mkBRAMCore2BELoad (module), 229
mkBRAMCore2Load (module), 229
mkBRAMStore1W2R (module), 253
mkBRAMStore2W1R (module), 253
mkBypassFIFO (module), 249
mkBypassFIFO2 (module), 249
mkBypassFIFO2Level (module), 250
mkBypassWire (module), 198
mkCBRegFile (module), 432
mkCBRegR (module), 431
mkCBRegRC (module), 431
mkCBRegRW (module), 431
mkCBRegW (module), 431
mkCClientsServer (function), 340
mkCGetPut (function), 340
mkClientsServer (function), 340
mkClock (module), 393
mkClockDivider (module), 398
mkClockDividerOffset (module), 398
mkClockInverter (module), 398
mkClockMux (module), 396
mkClockSelect (module), 397
mkCompletionBuffer (module), 356
mkConfigReg (module), 216
mkConfigRegA (module), 216
mkConfigRegU (module), 216
mkConstrainedRandomizer (module), 348
mkCounter (module), 352
mkCRTC (module), 373
mkCRC16 (module), 373
mkCRC32 (module), 374
mkCRC_CCIT (module), 373
mkCReg (module), 192
mkCRegA (module), 192
mkCRegU (module), 192
mkDepthParamFIFO (module), 234
mkDepthParamFIFO2 (module), 234
mkDFIFO (module), 250
mkDReg (module), 217
mkDRegA (module), 217
mkDRegU (module), 217
mkDualRam (module), 412
mkDWire (module), 198
mkFeedLFSR (module), 346
mkFIFO (module), 90, 233
mkFIFO1 (module), 234
mkFIFO2 (module), 234
mkFIFOCount (module), 243
mkFIFO2 (module), 91, 233
mkFIFO2 (module), 234
mkFIFO2 (module), 242
mkFSM, 322
mkFSMServer, 327
mkFSMWithPred, 322
mkGatedClock (module), 394
mkGatedClockDivider (module), 398
mkGateClockFromCC (module), 395
mkGatedClockInverter (module), 398
mkGDepthParamFIFO (module), 235
mkGenericRandomizer (module), 348
mkGetCPut (function), 340
mkGFIFO (module), 235
mkGFIFO1 (module), 235
mkGFIFO2 (module), 235
mkGFIFO2 (module), 243
mkGFIFO2 (module), 235
mkGFIFO2 (module), 234
mkGLFIFO (module), 236
mkGPFIFO (module), 332
mkGPFIFO1 (module), 332
mkGPSizedFIFO (module), 332
mkGrayCounter (module), 354
mkLFSR (module), 354
mkLFSR (module), 247
mkLFSR (module), 235
mkLFSR (module), 235
mkLFSR (module), 235
mkLFSR (module), 235
Reference Guide

mkLFIFO (module), 235
mkMMO (module), 258
mkMMOBram (module), 258
mkMMOReg (module), 258
mkMIMO (module), 258
mkNullCrossingReg (module), 414
mkNullCrossingRegA (module), 414
mkNullCrossingRegU (module), 414
mkNullCrossingWire (module), 413
mkOnce, 322
mkPipelineFIFO (module), 249
mkPipelineFIFOF (module), 249
mkPulseWire (module), 199
mkPulseWireOR (module), 199
mkReg (module), 89, 190
mkRegA (module), 190
mkRegFile (RegFile module), 213
mkRegFileFull (RegFile module), 213
mkRegFileFullFile (RegFileLoad function), 214
mkRegFileLoad (RegFileLoad function), 214
mkRegStore (module), 252
mkRegU (module), 89, 190
mkRegVectorStore (module), 252
mkReset (module), 417
mkResetEither (module), 419
mkResetInverter (module), 420
mkResetMux (module), 418
mkResetSync (module), 417
mkRevertingVirtualReg (module), 218
mkRWire (RWire module), 195
mkRWireSBR (RWire module), 195
mkSizedBramFifo (module), 247
mkSizedBramFIFOF (module), 247
mkSizedBypassFifo (module), 250
mkSizedFifo (module), 90, 234
mkSizedFIFOF (module), 91, 234
mkStickyArbiter (module), 350
mkSyncBit (module), 401
mkSyncBit05 (module), 403
mkSyncBit05FromCC (module), 404
mkSyncBit05ToCC (module), 404
mkSyncBit1 (module), 403
mkSyncBit15 (module), 402
mkSyncBit15FromCC (module), 402
mkSyncBit15ToCC (module), 402
mkSyncBit1FromCC (module), 403
mkSyncBit1ToCC (module), 403
mkSyncBitFromCC (module), 401
mkSyncBitToCC (module), 402
mkSyncBram2Server (module), 224
mkSyncBram2ServerBE (module), 225
mkSyncBramCore2 (module), 229
mkSyncBramCore2BE (module), 229
mkSyncBramCore2BEload (module), 230
mkSyncBramCore2Load (module), 230
mkSyncBramFifo (module), 247
mkSyncBramFIFOF (module), 247
mkSyncBramFIFOFfromCC (module), 247
mkSyncBramFIFOToCC (module), 247
mkSyncFifo (module), 410
mkSyncFIFO1 (module), 411
mkSyncFIFOCount (module), 244
mkSyncFIFOfromCC (module), 411
mkSyncFIFOLevel (module), 243
mkSyncFIFOToCC (module), 411
mkSyncHandshake (module), 406
mkSyncHandshakeFromCC (module), 406
mkSyncHandshakeToCC (module), 407
mkSyncPulse (module), 405
mkSyncPulseFromCC (module), 406
mkSyncPulseToCC (module), 406
mkSyncReg (module), 408
mkSyncRegFromCC (module), 408
mkSyncRegToCC (module), 409
mkSyncReset (module), 416
mkSyncResetFromCR (module), 416
mkTriState, 369
mkUGDepthParamFIFOF (module), 235
mkUGFIFOF (module), 234
mkUGFIFOF1 (module), 234
mkUGLIFIFOF (module), 235
mkUGSizedFIFOF (module), 234
mkUndaggedClock (module), 393
mkUndaggedClockMux (module), 397
mkUndaggedClockSelect (module), 397
mkUniqueWrappers (UniqueWrappers module), 359
mkUnsafeDWire (module), 198
mkUnsafePulseWire (module), 199
mkUnsafePulseWireOR (module), 199
mkUnsafeRWire (RWire module), 195
mkUnsafeWire (module), 197
mkWire (module), 197
mkZBus (function), 371
mkZBusBuffer (function), 371
mod (Integer function), 171
module
definition of, 31
instantiation, 33
ModuleCollect (package), 425
ModuleCollect (type), 426
ModuleContext (package), 420
modules
definition of, 27
module (keyword), 31
Monad (type class), 129
msb (Bitwise class method), 163
450
Mul (type provisos), 25, 188
mutually_exclusive (attribute), 107
MuxClockIfc (interface), 396
MuxRstIfc (interface), 415

negate (Arith class method), 157
newVector (Vector function), 260
Nil (List constructor), 284
nil (Vector function), 260
no_implicit_conditions (attribute), 103
noAction (empty action), 71, 186
noClock (function), 391
noline (attribute), 99
noReset (function), 392
nosplit (attribute), 109
not (Bool function), 172
NumAlias, 51, 167
NumberTypes (package), 316

0Int (package), 305
0Int (type), 305
oneHotSelect (List function), 286
openFile, 209
operators
  infix, 68
  prefix, 68
or (List function), 292
or (Vector function), 268
Ord (type class), 24, 119, 120, 159
  UInt, Int type instances, 88
Ordering (type), 183
osc= (attribute), 113
output_clock(BVI import statement), 138
output_reset(BVI import statement), 141
overloading groups, see type classes
overloading, of types, 119
OVLAssertions (package), 374

pack (Bits type class overloaded function), 123, 154
package, 20
package (keyword), 20
parameter, 31
parameter= (BVI import statement), 133
parameter= (attribute), 115
parity (function), 206
path(BVI import statement), 143

in rules, 86
patterns, 81
pi (Real constant), 302
polymorphism, 24
port(BVI import statement), 135
port= (attribute), 100, 115
pow (Real function), 303
preempts (attribute), 108
prefix= (attribute), 100
Prelude, see Standard Prelude
Printf (package), 387
Probe (package), 366
provisos, 120, 188
  brief description, 24
PulseWire (interface), 199
pulseWireToReadOnly (function), 202
Put (interface), 328

quot (Integer function), 171
Randomizable (package), 347
Randomize (interface), 348
ReadOnly (interface), 201
readReadOnly (function), 202
readReg (Reg function), 190
readRReg (Vector function), 271
ready= (attribute), 100
Real (package), 301
Real (type), 173
real (type), 173
Real literals, 16
RealLiteral (type class), 156
realToDigits (Real function), 305
reburyContext (module), 423
records, see struct
reduceAnd (BitReduction class method), 163
reduceNand (BitReduction class method), 163
reduceNor (BitReduction class method), 163
reduceOr (BitReduction class method), 163
reduceXnor (BitReduction class method), 163
reduceXor (BitReduction class method), 163
reflect (CRC function), 374
Reg (interface), 408
Reg (type), 89, 190
RegFile (interface type), 213
RegFileLoad (package), 214
register assignment, 59
  array element, 60
  partial, 60
register writes, 59
regToReadOnly (function), 201
rem (Integer function), 171
replicate (List function), 284
replicate (Vector function), 260
replicateM (List function), 301
replicateM (Vector function), 280
Reserved (type), 367
Reserved (package), 367
ReservedOne (type), 367
ReservedZero (type), 367
Reset (type), 184, 390
clear, 318
reset= (attribute), 113
reset_by, 33
reset_prefix= (attribute), 110
'mresetall (compiler directive), 19
resetOf (function), 391
result= (attribute), 100
reverse (List function), 289
reverse (Vector function), 266
reverseBits (function), 206
RevertingVirtualReg (package), 218
rJoin (Rules operator), 187
rJoinConflictFree (Rules operator), 187
rJoinDescendingUrgency (Rules operator), 187
rJoinExecutionOrder (Rules operator), 187
rJoinMutuallyExclusive (Rules operator), 187
rJoinPreempts (Rules operator), 187
rotate (List function), 289
rotate (Vector function), 265
rotateBitsBy (bit-vector function), 270
rotateBy (Vector function), 265
rotateR (List function), 289
rotateR (Vector function), 265
round (Real function), 304
rules, 39
expression, 80
pattern matching in, 86
Rules (type), 80, 187
runWithContext (function), 424
runWithContexts (function), 424
RWire, 195
SA (scheduling annotations), 49
same_family (BVI import statement), 141
sameFamily (function), 391
SAR (scheduling annotations), 49
satMinus (SaturatingArith class method), 166
satPlus (SaturatingArith class method), 166
SaturatingArith (type class), 166
SB (scheduling annotations), 49
SBR (scheduling annotations), 49
subtrctBLUInt (function), 318
scanl (List function), 299
scanl (Vector function), 278
scanr (List function), 298
scanr (Vector function), 277
schedule (BVI import statement), 142
scheduling annotations, 49
select (List function), 285
select (Vector function), 262
SelectClockIfc (interface), 396
send (PulseWire interface method), 199
Server (interface), 336
shiftInAt0 (Vector function), 266
shiftInAtN (Vector function), 266
shiftOutFrom0 (Vector function), 266
shiftOutFromN (Vector function), 266
signedMul (function), 204
signedQuot (function), 204
signExtend (BitExtend class method), 165
signum (Arith class method), 157
sin (Real function), 302
sinh (Real function), 302
size types, 23
type classes for constraints, 25
SizedLiteral (type class), 157
SizeOf (pseudo-function on types), 124, 189
sort (List function), 290
sortBy (List function), 290
SpecialFIFOs (package), 248
split (Bit function), 88, 170
split (attribute), 109
splitReal (Real function), 305
sprintf (function), 388
sqrt (Real function), 303
sscanl (List function), 299
sscanl (Vector function), 278
sscanr (List function), 298
sscanr (Vector function), 277
Standard Prelude, 22, 71, 87, 88, 121, 154
start, 318
staticAssert, 365
StmtFSM (package), 318
strConcat (String concatenation operator), 174
String (type), 88, 174
String literals, 16
StringLiteral (type class), 169
struct
type definition, 53
'struct', 53
structs
member selection, 76
update, 57
sub (RegFile interface method), 213
subinterfaces
declaration of, 30
definition of, 37
SyncBitIfc (interface), 400
SyncFIFOCountIfc (interface), 242
SyncFIFOIfc (interface), 409
SyncFIFOLevelIfc (interface), 241
SyncPulseIfc (interface), 405
synthesize
modules, 42
synthesize (attribute), 98
system functions, 91
$bitstoreal, 97
$realtobits, 97
$stime, 97
$test$plusargs, 97
$time, 97
system tasks, 91
$display, 91
$displayb, 91
$displayh, 91
$displayo, 91
$dumpoff, 97
$dumpon, 97
$dumpvars, 97
$close, 93
$display, 94
$displayb, 94
$displayh, 94
$displayo, 94
$flush, 96
$getc, 96
$finish, 96
$open, 93
$write, 94
$writeb, 94
$writeh, 94
$writeo, 94
$sformat, 95
$sformatAV, 95
$stop, 96
$write, 95
$writeAV, 95
$writeb, 95
$writebAV, 95
$writeh, 95
$writehAV, 95
$writeo, 95
$writeoAV, 95
$ungetc, 96
$write, 91
$writeb, 91
$writeh, 91
$writeo, 91
TAdd (type functions), 189
’tagged’, see union
tagged union
member selection, see pattern matching
member selection using dot notation, 77
type definition, 53
update, 58
tail (List function), 286
tail (Vector function), 263
take (List function), 286
take (Vector function), 263
takeAt (Vector function), 264
takeWhile (List function), 287
takeWhileRev (List function), 287
tan (Real function), 302
tanh (Real function), 303
TDiv (type functions), 189
TExp (type functions), 189
TieOff (package), 364
TLog (type functions), 189
TMax (type functions), 189
TMin (type functions), 189
TMul (type functions), 189
toChunks (Vector function), 283
toGet (function), 329
toGPClient (function), 337
toGPServer (function), 337
toList (Vector function), 282
toPut (function), 329
toVector (Vector function), 282
transpose (List function), 289
transpose (Vector function), 267
transposeLN (Vector function), 267
TriState (interface), 369
TriState (package), 368
True (Bool constant), 172
trunc (Real function), 304
truncate (BitExtend class method), 165
truncateLSB (function), 207
TSub (type functions), 189
tuples
expressions, 89, 181
patterns, 89
selecting components, 89, 182
type definition, 89, 180
type assertions
static, 75
type casting, 75
type classes, 119, 154
type declaration, 22
type variables, 24
typedef (keyword), 50
types, 22
parameterized, 23
polymorphic, 24
uaMap (function), 440
uaMapM (function), 440
UInt (type), 88, 171
unburyContext (module), 423
unburyContextWithClocks (module), 423
uncurry (function), 206
‘undef (compiler directive), 19
underscore, see _
‘union’, 53
union tagged
type definition, 53
UnitAppendList (package), 440
unpack (Bits type class overloaded function), 123, 154
unsignedMul (function), 204
unsignedQuot (function), 205
unwrap (function), 318
unwrapBI (function), 318
unzip (List function), 293
unzip (Vector function), 272
ud (RegFile interface method), 213
update (List function), 285
update (Vector function), 262
updateDataWithMask (module), 339
upto (List function), 284
Valid
tagged union member ofMaybe type, 55
Valid (type constructor), 179
Value Change Dump, 97
valueOf (pseudo-function of size types), 26, 189
valueof (pseudo-function of size types), 189
variable assignment, 57
variable declaration, 56
variable initialization, 56
variables, 56
VCD, 95, 97
Vector, 258
vectorToArray (Vector function), 282
Void (type), 179
void (type, in tagged unions), 53
warning (forced warning), 203
warningM (forced warning), 203
wset (RWire interface method), 195
ZBus (package), 369
ZBusBusIFC (interface), 371
ZBusClientIFC (interface), 371
ZBusDualIFC (interface), 370
zeroExtend (BitExtend class method), 165
zip (List function), 293
zip (Vector function), 271
zip3 (List function), 293
zip3 (Vector function), 271
zip4 (List function), 293
zip4 (Vector function), 271
zipAny (Vector function), 272
zipWith (List function), 294
zipWith (Vector function), 273
zipWith3 (List function), 294
zipWith3 (Vector function), 273
zipWith3M (List function), 301
zipWith3M (Vector function), 280
zipWith4 (List function), 295
zipWithAny (Vector function), 273
zipWithAny3 (Vector function), 273
zipWithM (List function), 301
zipWithM (Vector function), 279
Function and Module by Package

AlignedFIFOs
- mkAlignedFIFO, 253
- mkBRAMStore1W2R, 253
- mkBRAMStore2W1R, 253
- mkRegStore, 252
- mkRegVectorStore, 252

BRAM
- mkBRAM1Server, 223
- mkBRAM1ServerBE, 223
- mkBRAM2Server, 224
- mkBRAMCore1, 228
- mkBRAMCore1BE, 228
- mkBRAMCore1BELoad, 228
- mkBRAMCore1Load, 228
- mkBRAMCore2, 228
- mkBRAMCore2BE, 229
- mkBRAMCore2BELoad, 229
- mkBRAMCore2Load, 229
- mkSyncBRAM2Server, 224
- mkSyncBRAM2ServerBE, 225
- mkSyncBRAMCore2, 229
- mkSyncBRAMCore2BE, 229
- mkSyncBRAMCore2BELoad, 230
- mkSyncBRAMCore2Load, 230

BRAMFIFO
- mkSizedBRAMFIFO, 247
- mkSizedBRAMFIFOF, 247
- mkSyncBRAMFIFO, 247
- mkSyncBRAMFIFOFromCC, 247
- mkSyncBRAMFIFOToCC, 247

CBus
- collectCBusIFC, 430
- exposeCBusIFC, 431
- mkCBRegFile, 432
- mkCBRegR, 431
- mkCBRegRC, 431
- mkCBRegRW, 431
- mkCBRegW, 431

ClientServer
- toGPServer, 337
- toGPClient, 337

Clocks
- clockOf, 391
- exposeCurrentClock, 390
- exposeCurrentReset, 390
- invertCurrentClock, 392
- invertCurrentReset, 392

isAncestor, 391
isResetAsserted, 420
mkAbsoluteClock, 395
mkAbsoluteClockFull, 395
mkAsyncReset, 416
mkAsyncResetFromCR, 416
mkClock, 393
mkClockDivider, 398
mkClockDividerOffset, 398
mkClockInverter, 398
mkClockMux, 396
mkClockSelect, 397
mkDualRam, 412
mkGatedClock, 394
mkGatedClockDivider, 398
mkGatedClockFromCC, 395
mkGatedClockInverter, 398
mkInitialReset, 417
mkNullCrossingReg, 414
mkNullCrossingRegA, 414
mkNullCrossingRegU, 414
mkNullCrossingWire, 413
mkReset, 417
mkResetEither, 419
mkResetInverter, 420
mkResetMux, 418
mkResetSync, 417
mkSyncBit, 401
mkSyncBit05, 403
mkSyncBit05FromCC, 404
mkSyncBit05ToCC, 404
mkSyncBit1, 403
mkSyncBit15, 402
mkSyncBit15FromCC, 402
mkSyncBit15ToCC, 402
mkSyncBit1FromCC, 403
mkSyncBit1ToCC, 403
mkSyncBitFromCC, 401
mkSyncBitToCC, 402
mkSyncFIFO, 410
mkSyncFIFO1, 411
mkSyncFIFOFromCC, 411
mkSyncFIFOToCC, 411
mkSyncHandshake, 406
mkSyncHandshakeFromCC, 406
mkSyncHandshakeToCC, 407
mkSyncPulse, 405
mkSyncPulseFromCC, 406
mkSyncPulseToCC, 406
mkSyncReg, 408
Reference Guide

Bluespec SystemVerilog

mkSyncRegFromCC, 408
mkSyncRegToCC, 409
mkSyncReset, 416
mkSyncResetFromCR, 416
mkUngatedClock, 393
mkUngatedClockMux, 397
mkUngatedClockSelect, 397
noClock, 391
noReset, 392
resetOf, 391
sameFamily, 391
Counter
mkCounter, 352

FIFO
fifoToFifo, 236
mkDepthParamFIFO, 234
mkFIFO, 233
mkFIFO1, 234
mkLFIFO, 235
mkSizedFIFO, 234

FIFO
mkDepthParamFIFOF, 234
mkFIFO, 233
mkFIFO1, 234
mkGFIFO, 235
mkGFIFO1, 235
mkGLFIFO, 236
mkGSizedFIFOF, 235
mkLFIFOF, 235
mkSizedFIFO, 234
mkUGDepthParamFIFOF, 235
mkUGFIFO, 234
mkUGFIFO1, 234
mkUGLFIIFOF, 235
mkUGSizedFIFOF, 234

FIFOLevel
mkFIFOCount, 243
mkFIFOLevel, 242
mkGFIFOCount, 243
mkGFIFOLevel, 243
mkSyncFIFOCount, 244
mkSyncFIFOLevel, 243

FixedPoint
fxptTruncateSat, 313

Gearbox
mk1toNGearbox, 255
mkNto1Gearbox, 255

GetPut
fifoToGet, 332, 333
fifoToPut, 333
mkGPFIFO, 332

mkGPFIFO1, 332
mkGPSizedFIFO, 332
toGet, 329
toPut, 329

Gray
grayDecode, 355
grayDecr, 355
grayEncode, 355
grayIncr, 355
grayIncrDecr, 355

mkGrayCounter, 354

HList
Gettable, 438
HAppend, 437
HHead, 436
HLength, 437
hSplit, 437
HTail, 437

List
all, 291
and, 292
any, 291
append, 284
concat, 285
cons, 284
drop, 287
dropWhile, 288
dropWhileRev, 288
elem, 291
filter, 287
find, 287
fold, 296
foldl, 296
foldl1, 296
foldr, 296
foldr1, 296
group, 290
groupBy, 290
head, 286
init, 286
joinActions, 297
joinRules, 297
last, 286
length, 291
lookup, 287
map, 294
mapAccumL, 299
mapAccumR, 299
mapM, 300
mapM_, 300
mapPairs, 297
oneHotSelect, 286
or, 292
replicate, 284
replicateM, 301
reverse, 289
rotate, 289
rotateR, 289
scanl, 299
scanr, 298
select, 285
sort, 290
sortBy, 290
sscanl, 299
sscanr, 298
tail, 286
take, 286
takeWhile, 287
takeWhileRev, 287
transpose, 289
unzip, 293
update, 285
upto, 284
zip, 293
zip3, 293
zip4, 293
zipWith, 294
zipWith3, 294
zipWith3M, 301
zipWith4, 295
zipWithM, 301

Memory
updateDataWithMask, 339

MIMO
mkMIMO, 258
mkMIMOBRAM, 258
mkMIMOReg, 258
mkMIMOV, 258

ModuleContext
applyToContext, 422
applyToContextM, 422
reburyContext, 423
runWithContext, 424
unburyContext, 423
unburyContextWithClocks, 423

NumberTypes
addBIUInt, 318
addUInt, 318
subtractBIUInt, 318
unwrap, 318
unwrapBI, 318
wrap, 318

OVLAssertions
bsv_assert_always, 378
bsv_assert_always_on_edge, 378
bsv_assert_change, 378
bsv_assert_cycle_sequence, 379
bsv_assert_decrement, 379
bsv_assert_delta, 379
bsv_assert_even_parity, 380
bsv_assert_fifo_index, 380
bsv_assert_frame, 380
bsv_assert_handshake, 380
bsv_assert_implication, 381
bsv_assert_increment, 381
bsv_assert_never, 381
bsv_assert_never_unknown, 381
bsv_assert_never_unknown_async, 381
bsv_assert_next, 382
bsv_assert_no_overflow, 382
bsv_assert_no_transition, 382
bsv_assert_no_underflow, 382
bsv_assert_odd_parity, 383
bsv_assert_one_cold, 383
bsv_assert_one_hot, 383
bsv_assert_proposition, 383
bsv_assert_quiescent_state, 384
bsv_assert_range, 384
bsv_assert_time, 384
bsv_assert_transition, 384
bsv_assert_unchange, 385
bsv_assert_width, 385
bsv_assert_win_change, 385
bsv_assert_win_unchange, 385
bsv_assert_window, 386
bsv_assert_zero_one_hot, 386

Prelude
!=, 155
<<, 163
>>>, 163
|, 162, 163
*, 157
**, 157
+, 157, 174
-, 157
/, 157
<, 159
<=, 159
==, 155
>, 159
>=, 159
$bitstoreal, 174
$realtobits, 174
%, 157
&, 162, 163
^, 162, 163
```, 162, 163
```, 162, 163
`, 162, 163
`|`, 163
```, 162, 163
abs, 157, 204
addRules, 187
asReg, 190
bitsToDigit, 176
bitsToHexDigit, 176
buildVersion, 209
charToInteger, 176
charToString, 176
cmp, 159
cmpVersion, 208
cmp, 205
cmpM, 205
cmpFn, 205
countOnes, 206
countZerosLSB, 206
countZerosMSB, 206
curry, 205, 206
date, 209
digitToBits, 176
digitToInteger, 176
div, 171
doubleQuote, 174
epochTime, 209
error, 203
errorM, 203
exp, 157
extend, 165
flip, 205
fromInteger, 156, 172
fromMaybe, 179
fromReal, 156
fromSizedInteger, 157
fromString, 169
fshow, 167
gcd, 207
genC, 208
genModuleName, 208
genPackageName, 208
genVerilog, 208
hClose, 210
hexDigitToBits, 176
hexDigitToInteger, 176
hFlush, 211
hGetBuffering, 211
hGetChar, 211
hGetLine, 212
hIsClosed, 210
hIsEOF, 210
hIsOpen, 210
hIsReadable, 210
hIsWriteable, 210
hPutChar, 211
hPutStr, 211
hPutStrLn, 211
hSetBuffering, 211
id, 205
integerToChar, 176
integerToDigit, 176
integerToHexDigit, 176
invert, 162
isAlpha, 176
isAlphaNum, 176
isDigit, 176
isHexDigit, 176
isLower, 176
isOctDigit, 176
isSpace, 176
isUpper, 176
isValid, 179
lcm, 207
log, 157
log10, 157
log2, 157
logb, 157
lsb, 163
max, 159, 204
maxBound, 161
message, 203
messageM, 204
min, 159, 204
minBound, 161
mkBypassWire, 198
mkCReg, 192
mkCRegA, 192
mkCRegU, 192
mkDWire, 198
mkPulseWire, 199
mkPulseWireOR, 199
mkReg, 190
mkRegA, 190
mkRegU, 190
mkRWire, 195
mkRWireSBR, 195
mkUnsafeDWire, 198
mkUnsafePulseWire, 199
mkUnsafePulseWireOR, 199
mkUnsafeRWire, 195
mkUnsafeWire, 197
mkWire, 197
mod, 171
msb, 163
negate, 157
not, 172
openFile, 209
<table>
<thead>
<tr>
<th>pack</th>
<th>154</th>
</tr>
</thead>
<tbody>
<tr>
<td>parity</td>
<td>206</td>
</tr>
<tr>
<td>pulseWireToReadOnly</td>
<td>202</td>
</tr>
<tr>
<td>quot</td>
<td>171</td>
</tr>
<tr>
<td>quote</td>
<td>174</td>
</tr>
<tr>
<td>readReadOnly</td>
<td>202</td>
</tr>
<tr>
<td>readReg</td>
<td>190</td>
</tr>
<tr>
<td>reduceAnd</td>
<td>163</td>
</tr>
<tr>
<td>reduceNand</td>
<td>163</td>
</tr>
<tr>
<td>reduceNor</td>
<td>163</td>
</tr>
<tr>
<td>reduceOr</td>
<td>163</td>
</tr>
<tr>
<td>reduceXnor</td>
<td>163</td>
</tr>
<tr>
<td>reduceXor</td>
<td>163</td>
</tr>
<tr>
<td>regToReadOnly</td>
<td>201</td>
</tr>
<tr>
<td>rem</td>
<td>171</td>
</tr>
<tr>
<td>reverseBits</td>
<td>206</td>
</tr>
<tr>
<td>rJoin</td>
<td>187</td>
</tr>
<tr>
<td>rJoinConflictFree</td>
<td>187</td>
</tr>
<tr>
<td>rJoinDescendingUrgency</td>
<td>187</td>
</tr>
<tr>
<td>rJoinExecutionOrder</td>
<td>187</td>
</tr>
<tr>
<td>rJoinMutuallyExclusive</td>
<td>187</td>
</tr>
<tr>
<td>rJoinPreempts</td>
<td>187</td>
</tr>
<tr>
<td>satMinus</td>
<td>166</td>
</tr>
<tr>
<td>satPlus</td>
<td>166</td>
</tr>
<tr>
<td>sharListToString</td>
<td>174</td>
</tr>
<tr>
<td>signedMul</td>
<td>204</td>
</tr>
<tr>
<td>signedQuot</td>
<td>204</td>
</tr>
<tr>
<td>signExtend</td>
<td>165</td>
</tr>
<tr>
<td>signum</td>
<td>157</td>
</tr>
<tr>
<td>SizeOf</td>
<td>189</td>
</tr>
<tr>
<td>split</td>
<td>170</td>
</tr>
<tr>
<td>strConcat</td>
<td>174</td>
</tr>
<tr>
<td>stringCons</td>
<td>174</td>
</tr>
<tr>
<td>stringHead</td>
<td>174</td>
</tr>
<tr>
<td>stringLength</td>
<td>174</td>
</tr>
<tr>
<td>stringSplit</td>
<td>174</td>
</tr>
<tr>
<td>stringTail</td>
<td>174</td>
</tr>
<tr>
<td>stringToCharList</td>
<td>174</td>
</tr>
<tr>
<td>TAdd</td>
<td>189</td>
</tr>
<tr>
<td>TDiv</td>
<td>189</td>
</tr>
<tr>
<td>TExp</td>
<td>189</td>
</tr>
<tr>
<td>TLog</td>
<td>189</td>
</tr>
<tr>
<td>TMax</td>
<td>189</td>
</tr>
<tr>
<td>TMin</td>
<td>189</td>
</tr>
<tr>
<td>TMul</td>
<td>189</td>
</tr>
<tr>
<td>toLower</td>
<td>176</td>
</tr>
<tr>
<td>toUpper</td>
<td>176</td>
</tr>
<tr>
<td>truncate</td>
<td>165</td>
</tr>
<tr>
<td>truncateLSB</td>
<td>207</td>
</tr>
<tr>
<td>TSub</td>
<td>189</td>
</tr>
<tr>
<td>unpack</td>
<td>154</td>
</tr>
<tr>
<td>unsignedMul</td>
<td>204</td>
</tr>
<tr>
<td>unsignedQuot</td>
<td>205</td>
</tr>
<tr>
<td>valueOf</td>
<td>189</td>
</tr>
<tr>
<td>warning</td>
<td>203</td>
</tr>
<tr>
<td>warningM</td>
<td>203</td>
</tr>
<tr>
<td>when</td>
<td>207</td>
</tr>
<tr>
<td>while</td>
<td>207</td>
</tr>
<tr>
<td>writeReg</td>
<td>190</td>
</tr>
<tr>
<td>zeroExtend</td>
<td>165</td>
</tr>
</tbody>
</table>

### Printf

- sprintf, 388

### Real

- acosh, 303
- asinh, 303
- atan2, 303
- atanh, 303
- ceil, 304
- cos, 302
- cosh, 302
- decodeReal, 305
- floor, 304
- isInfinite, 304
- isNegativeZero, 304
- pow, 303
- realToDigits, 305
- round, 304
- sin, 302
- sinh, 302
- splitReal, 305
- sqrt, 303
- tan, 302
- tanh, 303
- trunc, 304

### SpecialFIFOs

- mkBypassFIFO, 249
- mkBypassFIFOF, 249
- mkBypassFIFOLevel, 250
- mkDFIFOF, 250
- mkPipelineFIFO, 249
- mkPipelineFIFOF, 249
- mkSizedBypassFIFOF, 250

### StmtFSM

- await, 323
- callServer, 327
- delay, 323
- mkAutoFSM, 322
- mkFSM, 322
- mkFSMServer, 327
- mkFSMwithPred, 322
- mkOnce, 322

### UnitAppendList

- flatten, 440
- flatten0, 440
- uaMap, 440
- uaMapM, 440
Vector, 282
all, 268
and, 268
any, 268
append, 260
arrayToVector, 282
concat, 261
cons, 260
countElem, 268
countIf, 269
countOnesAlt, 270
drop, 263
elem, 268
find, 269
findElem, 269
findIndex, 269
fold, 275
foldl, 274
foldl1, 275
foldr, 274
foldr1, 275
genVector, 260
genWith, 260
genWithM, 280
head, 262
init, 263
joinActions, 276
joinRules, 276
last, 263
map, 272
mapAccumL, 278
mapAccumR, 278
mapM, 279
mapM_, 279
mapPairs, 275
newVector, 260
nil, 260
or, 268
readVReg, 271
replicate, 260
replicateM, 280
reverse, 266
rotate, 265
rotateBitsBy, 270
rotateBy, 265
rotateR, 265
scanl, 278
scanr, 277
select, 262
shiftInAt0, 266
shiftInAtN, 266
shiftOutFrom0, 266
shiftOutFromN, 266
sscanl, 278
sscanr, 277
tail, 263
take, 263
takeAt, 264
toChunks, 283
toList, 282
transpose, 267
transposeLN, 267
unzip, 272
update, 262
vectorToArray, 282
writeVReg, 271
zip, 271
zip3, 271
zip4, 271
zipAny, 272
zipWith, 273
zipWith3, 273
zipWith3M, 280
zipWithAny, 273
zipWithAny3, 273
zipWithM, 279
Packages provided as BSV source code

AlignedFIFOs, 250
Arbiter, 349
BRAM, 219
BRAMFIFO, 246
CBus, 429
CommitIfc, 341
Complex, 306
DefaultValue, 362
FixedPoint, 309
Gearbox, 254
Gray, 354
GrayCounter, 353
HList, 436
MIMO, 256
ModuleContext, 420
NumberTypes, 316
Randomizable, 347
SpecialFIFOs, 248
TieOff, 364
UnitAppendList, 440
Typeclasses

Alias, 167
Arith, 157

BitExtend, 165
BitReduction, 163
Bits, 154
Bitwise, 162
Bounded, 161

Connectable, 334

DefaultValue, 362

Eq, 155

FShow, 167

Literal, 156

Monad, 129

NumAlias, 167

Ord, 159

Randomizable, 347
RealLiteral, 156

SaturatingArith, 166
SizedLiteral, 157
StringLiteral, 169

TieOff, 364
ToGet, 329
ToPut, 329