6.375 Supplemental Resource

BSV and Labs 2-3

Overview

- Basic BSV
  - Slides 3-26
- BSV related to Labs 2 and 3
  - Slides 27-43
- More BSV types
  - Slides 44-55

Basic Bluespec

Modules

- Interfaces
  - Methods provide a way for the outside world to interact with the module
- State elements and sub-modules
  - Registers, FIFOs, BRAMs, FIR filters (Lab 1)
- Rules
  - *Guarded atomic actions to* describe how the state elements should change

Part 1:
Declare Interfaces

- Contain methods for other modules to interact with the given module
  - Interfaces can also contain sub-interfaces

```
interface MyIfc;
    method ActionValue#(Bit#(32)) f();
    interface SubIfc s;
endinterface
```

- Special interface: Empty
  - No method, used in testbench

```
module mkTb(Empty);
module mkTb(); // () are necessary
```

Interface Methods

- Value
  - Returns value, doesn't change state
  - `method Bit#(32) first;`
- Action
  - Changes state, doesn't return value
  - `method Action enq(Bit#(32) x);`
- ActionValue
  - Changes state, returns value
  - `method ActionValue#(Bit#(32)) deqAndGet;`

Calling Interface Methods

- Value: Call inside or outside of a rule since it only returns a value
  - `Bit#(32) a = aQ.first;`
  - `Bit#(32) sum = aQ.first + aQ.first + bQ.first;`
- Action: Can call *once* within a rule
  - `aQ.enq(sum);`
- ActionValue: Can call *once* within a rule
  - Use "<-" operator *inside* a rule to apply the action and return the value
  - `Bit#(32) prod` **`<-`** `multiplier.deqAndGet;`

Part 2:
Defining a Module

- `module mkAdder( Adder#(32) );`
    - Adder#(32) is the interface
- Module can be parametrized
    - `module name#(params)(args …, interface);`

```
module mkMul#(Bool signed)(Adder#(n) a, Mul#(n) x);
```

Part 3:
Instantiating sub-modules

- Examples: Registers, FIFOs, RAMs, FIR filter (from Lab 1)
- Instantiation:
  - The " <- " *outside* a rule is used to instantiate a module
  - `MyIfc instOfModule <- mkModule();`
  - `Reg#(Bit#(32)) counter <- mkReg(0);`
  - `FIFO#(Uint#(32)) aQ <- mkFIFO();`

Part 4: Rules

- Rules describe the actions to be applied atomically
  - Modifies state
- Rules have guards to determine when they can fire
  - Implicit or explicit

Rule Execution

- One rule at a time:
  - Choose an *enabled* rule
  - Apply *all* of the *actions* of the rule
  - Repeat
- Conceptually rules execute one at a time in global order, but compiler aggressively *schedules* multiple rules to execute in the same clock cycle
  - Scheduling will be covered in detail in upcoming lectures

Hello World

```
module mkHelloWorld (Empty);
  rule sayhello (True);
    $display("hello, world");
  endrule
endmodule
```

- What does this do?
  - Print “hello, world” infinitely

Hello World with State

```
module mkHelloWorldOnce ();
   Reg#(Bool) said <- mkReg(False);
   rule sayhello (!said);
      $display("hello, world");
      said <= True;
   endrule

   rule goodbye (said);
      $finish();
   endrule
endmodule
```

When *can* a rule fire?

- Guard is true (explicit)
- *All* actions/methods in rule are ready (implicit)

```
rule doCompute if (started);
   Bit#(32) a = aQ.first(); //aQ is a FIFO
   Bit#(32) b = bQ.first(); //bQ is a FIFO
   aQ.deq();
   bQ.deq();
   outQ.enq( {a, b} ); //outQ is a FIFO
endrule
```

- *Will* it fire?
  - That depends on scheduling

Part 5:
Implement Interface

```
interface MyIfc#(numeric type n);
    method ActionValue#(Bit#(n)) f();
    interface SubIfc#(n) s;
endinterface
module mkDut(MyIfc#(n));
    ……
    method ActionValue#(Bit#(n)) f();
        ……
    endmethod
    interface SubIfc s; // no param "n"
        // methods of SubIfc
    endinterface
endmodule
```

- Methods, just like rules, have can have implicit and explicit guards

Expressions vs. Actions

- Expressions
  - Have no side effects (state changes)
  - Can be used outside of rules and modules in assignments
- Actions
  - Can have side effects
  - Can only take effect when used inside of rules
  - Can be found in other places intended to be called from rules
    - Action/ActionValue methods
    - functions that return actions

Variable vs. States

- Variables are used to name intermediate values
- Do not hold values over time
- Variable are **bound** to values
  - Statically elaborated

```
Bit#(32) firstElem = aQ.first();
rule process;
    aReg <= firstElem;
endrule
```

Scoping

- Any use of an identifier refers to its declaration in the nearest textually surrounding scope

```
Bit#(32) a = 1;
rule process;
    aReg <= a;
endrule
```

```
module mkShift( Shift#(a) );
   function Bit#(32) f();
     return fromInteger(valueOf(a))<<2;
   endfunction
   rule process;
     aReg <= f();
   endrule
endmodule
```

- Functions can take variables from surrounding scope

Guard Lifting

- Last Time: implicit/explicit guards
  - But there is more to it when there are conditionals (if/else) within a rule
- Compiler option `-aggressive-conditions` tells the compiler to peek into the rule to generate more aggressive enable signals
  - Almost always used

Guard Examples

```
rule process;
   if (aReg==True)
      aQ.deq();
   else
      bQ.deq();
   $display(“fire”);
endrule
```

(aReg==True && aQ.notEmpty) ||
(aReg==False && bQ.notEmpty) ||

```
rule process;
   aQ.deq();
   $display(“fire”);
endrule
```

aQ.notEmpty

```
rule process;
   if (aQ.notEmpty)
      aQ.deq();
   $display(“fire”);
endrule
```

(aQ.notEmpty && aQ.notEmpty) ||
(!aQ.notEmpty) ➔ Always fires

Vector Sub-interface

- Sub-interface can be vector

```
interface VecIfc#(numeric type m, numeric type n);
    interface Vector#(m, SubIfc#(n)) s;
endinterface
```

```
Vector#(m, SubIfc) vec = ?;
for(Integer i=0; i<valueOf(m); i=i+1) begin
    // implement vec[i]
end
VecIfc ifc = (interface VecIfc;
    interface Vector s = vec; // interface s = vec;
Endinterface);
```

- BSV reference guide Section 5

BSV Debugging
Display Statements

- See a bug, not sure what causes it
- Add display statements
- Recompile
- Run
- Still see bug, but you have narrowed it down to a smaller portion of code
- Repeat with more display statements…
- Find bug, fix bug, and remove display statements

BSV Display Statements

- The $display() command is an action that prints statements to the simulation console
- Examples:
  - `$display(“Hello World!”);`
  - `$display(“The value of x is %d”, x);`
  - `$display(“The value of y is “, fshow(y));`

Ways to Display Values

Format Specifiers

- %d – decimal
- %b – binary
- %o – octal
- %h – hexadecimal
- %0d, %0b, %0o, %0h
    - Show value without extra whitespace padding

Ways to Display Values

fshow

- fshow is a function in the FShow typeclass
- It can be derived for enumerations and structures
  - FixedPoint is also a FShow typeclass
- Example:

```
typedef emun {Red, Blue} Colors deriving(FShow);
Color c = Red;
$display("c is ", fshow(c));
```

Prints "c is Red"

Warning about $display

- $display is an Action within a rule
- Guarded methods called by $display will be part of implicit guard of rule

```
rule process;
   if (aQ.notEmpty)
      aQ.deq();
   $display(“first elem is %x”, aQ.first);
endrule
```

Useful Labs 2 and 3 Topics

Vector

- Type:
  - `Vector#(numeric type size, type data_type)`
- Values:
  - newVector(), replicate(val)
- Functions:
  - Access an element: []
  - Range of vectors: take, takeAt
  - Rotate functions
  - Advanced functions: zip, map, fold
- Can contain registers or modules
- Must have ‘import Vector::*;’ in BSV file

Vectors: Example

```
FIFO#(Vector#(FFT_POINTS, ComplexSample))
      inputFIFO  <- mkFIFO();
```

Instantiating a single FIFO, holding vectors of samples

```
Vector#(TAdd#(1,FFT_LOG_POINTS),Vector#(FFT_POINTS,
ComplexSample)) stage_data = newVector();
```

Declaring a vector of vectors

```
for (Integer i=0; i < 10; i=i+1) begin
   stage_data[i][0] = func(i);
end
```

Assigning values to a vector

Reg and Vector

- Register of Vectors
  - `Reg#( Vector#(32, Bit#(32) ) ) rfile;`
  - `rfile <- mkReg( `**`replicate`**`(0) );`
- Vector of Registers
  - `Vector#( 32, Reg#(Bit#(32)) ) rfile;`
  - `rfile <- `**`replicateM`**`( mkReg(0) );`
  - Similarly:

    `fifoVec <- `**`replicateM`**`( mkFIFO() );`
- Each has its own advantages and disadvantages

Partial Writes

- Reg#(Bit#(8)) r;
  - r[0] <= 0 counts as a read & write to the entire reg r
    - let r_new = r; r_new[0] = 0; r <= r_new
- Reg#(Vector#(8, Bit#(1))) r
  - Same problem, r[0] <= 0 counts as a read and write to the entire register
  - r[0] <= 0; r[1] <= 1 counts as two writes to register
    - double write problem
- Vector#(8,Reg#(Bit#(1))) r
  - r is 8 different registers
  - r[0] <= 0 is only a write to register r[0]
  - r[0] <= 0 ; r[1] <= 1 is not a double write problem

Polymorphic Interfaces

- Declaring a polymorphic interface

```
interface DSP#(numeric type w, type dType);
  method Action putSample(Bit#(w) a, dType b);
  method Vector#(w, dType) getVal();
endinterface
```

- Using polymorphic interfaces

```
module mkDSP ( DSP#(w, dType) );
  Reg#(Bit#(w)) aReg <- mkReg(0);
  Reg#(dType) bReg <- mkRegU();
  …
endmodule
```

- Instantiating a module with polymorphic ifc

```
module mkTb();
  DSP#(8, UInt#(32)) dspInst <- mkDSP();
endmodule
```

Get/Put Interfaces

- Pre-defined interface in BSV
- Provides a simple handshaking mechanism for getting data from a module or putting data into it

```
import GetPut::*
interface Get#(type t);
    method ActionValue#(t) get();
endinterface

interface Put#(type t);
    method Action put(t x);
endinterface
```

Using Get/Put Interfaces

```
import FIFO::*;
import GetPut::*;
interface FooIfc;
   interface Put#(Bit#(32))  request;
   interface Get#(Bit#(32))  response;
endinterface

module mkFoo (FooIfc);
   FIFO#(Bit#(32))  reqQ <- mkFIFO;
   FIFO#(Bit#(32)) respQ <- mkFIFO;
   interface Put request;
      method Action put (Bit#(32) req);
          reqQ.enq (req);
      endmethod
   endinterface
   interface Get response;
      method ActionValue#(Bit#(32)) get ();
          let resp = respQ.first;
          respQ.deq;
          return resp;
      endmethod
   endinterface
endmodule
```

Get/Put with FIFOs

```
import FIFO::*;
import GetPut::*;
interface FooIfc;
   interface Put#(Bit#(32))  request;
   interface Get#(Bit#(32))  response;
endinterface
module mkFoo (FooIfc);
   FIFO#(Bit#(32))  reqQ <- mkFIFO;
   FIFO#(Bit#(32)) respQ <- mkFIFO;
   interface request = toPut(reqQ);
   interface response = toGet(respQ);
endmodule
```

Server Interfaces

- Extension of Get/Put

```
import ClientServer::*;

interface Server #(type req_t, type rsp_t);
   interface Put#(req_t)  request;
   interface Get#(rsp_t)  response;
endinterface
```

Server Interfaces

```
import FIFO::*;
import GetPut::*;
import ClientServer::*;

typedef Server#(Bit#(32), Bit#(32)) FooIfc;

module mkFoo (FooIfc);
   FIFO#(Bit#(32))  reqQ <- mkFIFO;
   FIFO#(Bit#(32)) respQ <- mkFIFO;
   interface Put request = toPut(reqQ);
   interface Get response = toGet(respQ);
endmodule
```

Provisos

- Tell compiler that type `t` can do "+"
  - Add provisos (compile error without provisos)

```
function t adder(t a, t b) provisos(Arith#(t));
  return a + b;
endfunction
```

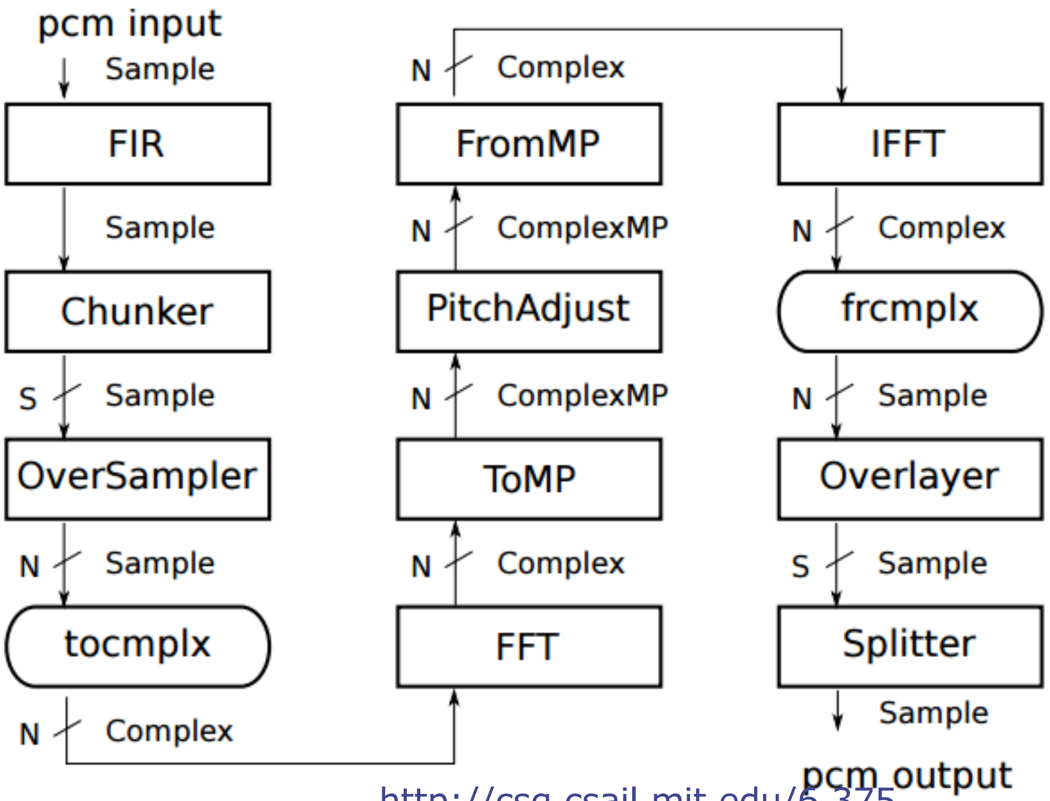
- Provisos
  - Tell compiler additional information about the parametrized types
  - Compiler can type check based on the info

Type Conversions

- Numeric type: type parameters
  - Often natural numbers
  - Bit#(w); Vector#(n, Uint#(w))
- Integers
  - Not synthesizable in hardware (vs Int#())
  - Often used in static elaboration (for loops)
- Numeric type -> Integer: `valueOf(w)`
- Integer -> Numeric type: not possible
- Integer -> Bit#(), Int#() etc.: `fromInteger(i)`
- Numeric type -> Bit#(), Int#() etc: `fromInteger(valueOf(w))`

Lab 3: Overview

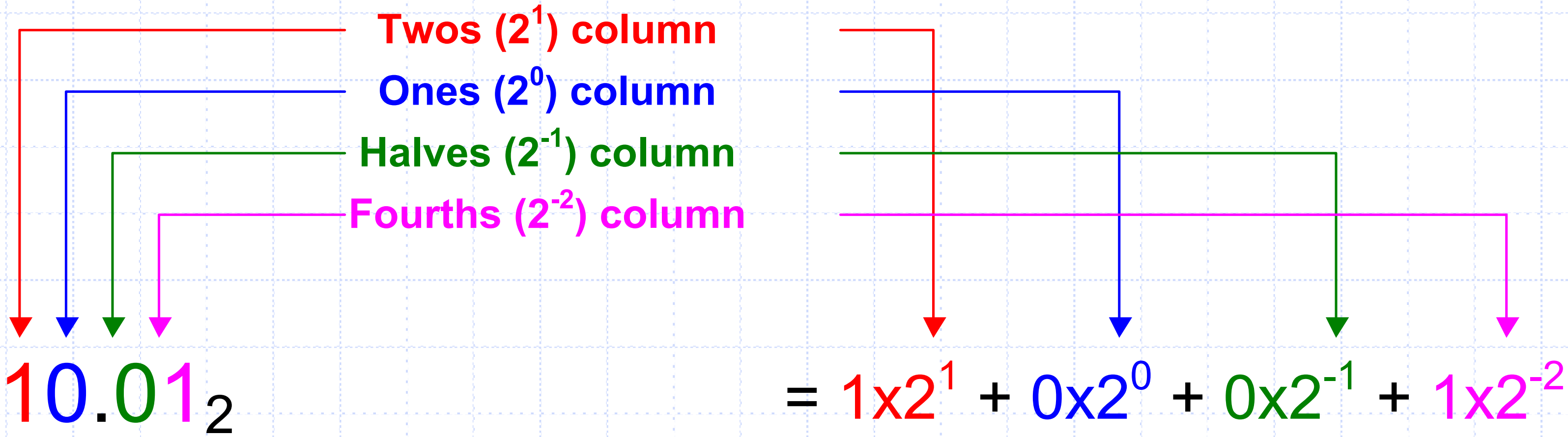
- Completing the audio pipeline:
  - PitchAdjust
  - FromMP, ToMP



Converting C to Hardware

- Think about what states you need to keep
- Loops in C are sequentially executed; loops in BSV are statically elaborated
  - Unrolled

Fixed Point



Twos (2^1) column

Ones (2^0) column

Halves (2^{-1}) column

Fourths (2^{-2}) column

$$10.01_2 = 1x2^{1} + 0x2^{0} + 0x2^{-1} + 1x2^{-2}$$

```
typedef struct {
  Bit#(isize) i;
  Bit#(fsize) f;
} FixedPoint#(numeric type isize, numeric type fsize )
```

Fixed Point Arithmetic

- Useful FixedPoint functions:
  - fxptGetInt: extracts integer portion
  - fxptMult: full precision multiply
  - *: full multiply followed by rounding/saturation to the output size
- Other useful bit-wise functions:
  - truncate, truncateLSB
  - zeroExtend, extend

More Types

Bit#(numeric type n)

- Literal values:
  - Decimal: 0, 1, 2, … (each have type Bit#(n)
  - Binary: 5’b01101, 2’b11
  - Hex: 5’hD, 2’h3, 16’h1FF0
- Common functions:
  - Bitwise Logic: |, &, ^, ~, etc.
  - Arithmetic: +, -, *, %, etc.
  - Indexing: a[i], a[3:1]
  - Concatenation: {a, b}
  - truncate, truncateLSB
  - zeroExtend, signExtend

Bool

- Literal values:
  - True, False
- Common functions:
  - Boolean Logic: ||, &&, !, ==, !=, etc.
- All comparison operators (==, !=, >, <, >=, <=) return Bools

Int#(n), UInt#(n)

- Literal values:
  - Decimal:
    - 0, 1, 2, … (Int#(n) and UInt#(n))
    - -1, -2, … (Int#(n))
- Common functions:
  - Arithmetic: +, -, *, %, etc.
    - Int#(n) performs signed operations
    - UInt#(n) performs unsigned operations
  - Comparison: >, <, >=, <=, ==, !=, etc.

Constructing new types

- Renaming types:
  - typedef
- Enumeration types:
  - enum
- Compound types:
  - struct
  - vector
  - maybe
  - tagged union

typedef

- Syntax:
  - `typedef <type> <new_type_name>;`
- Basic:
  - `typedef 8 BitsPerWord;`
  - `typedef Bit#(BitsPerWord) Word;`
    - Can’t be used with parameter: `Word#(n)`
- Parameterized:
  - `typedef Bit#(TMul#(BitsPerWord,n)) Word#(numeric type n);`
    - Can’t be used *without* parameter: `Word`

enum

```
typedef enum {Red, Blue} Color
deriving (Bits, Eq);
```

- Creates the type `Color` with values `Red` and `Blue`
- Can create registers containing colors
  - `Reg#(Color)`
- Values can be compared with `==` and `!=`

struct

```
typedef struct {
    Bit#(12) addr;
    Bit#(8) data;
    Bool wren;
} MemReq deriving (Bits, Eq);
```

- Elements from `MemReq x` can be accessed with `x.addr`, `x.data`, `x.wren`
- Struct Expression
  - `X = MemReq{addr: 0, data: 1, wren: True};`

struct

```
typedef struct {
    t a;
    Bit#(n) b;
} Req#(type t, numeric type n)
deriving (Bits, Eq);
```

- Parametrized struct

Tuple

- Types:
  - Tuple2#(type t1, type t2)
  - Tuple3#(type t1, type t2, type t3)
  - up to Tuple8
- Construct tuple: tuple2(x, y), tuple3(x, y, z) …
- Accessing an element:
  - tpl_1(tuple2(x, y)) // x
  - tpl_2(tuple3(x, y, z)) // y
  - Pattern matching

```
Tuple2#(Bit#(2), Bool) tup = tuple2(2, True);
match {.a, .b} = tup;
// a = 2, b = True
```

Maybe#(t)

- Type:
  - Maybe#(type t)
- Values:
  - tagged Invalid
  - tagged Valid x (where x is a value of type t)
- Functions:
  - isValid(x)
    - Returns true if x is valid
  - fromMaybe(default, m)
    - If m is valid, returns the valid value of m if m is valid, otherwise returns default
    - Commonly used fromMaybe(?, m)

Reg#(t)

- Main state element in BSV
- Type: Reg#(type data_type)
- Instantiated differently from normal variables
  - Uses <- notation
- Written to differently from normal variables
  - Uses <= notation
  - Can only be done inside of rules and methods

```
Reg#(Bit#(32)) a_reg <- mkReg(0); // value set to 0
Reg#(Bit#(32)) b_reg <- mkRegU(); // uninitialized
```