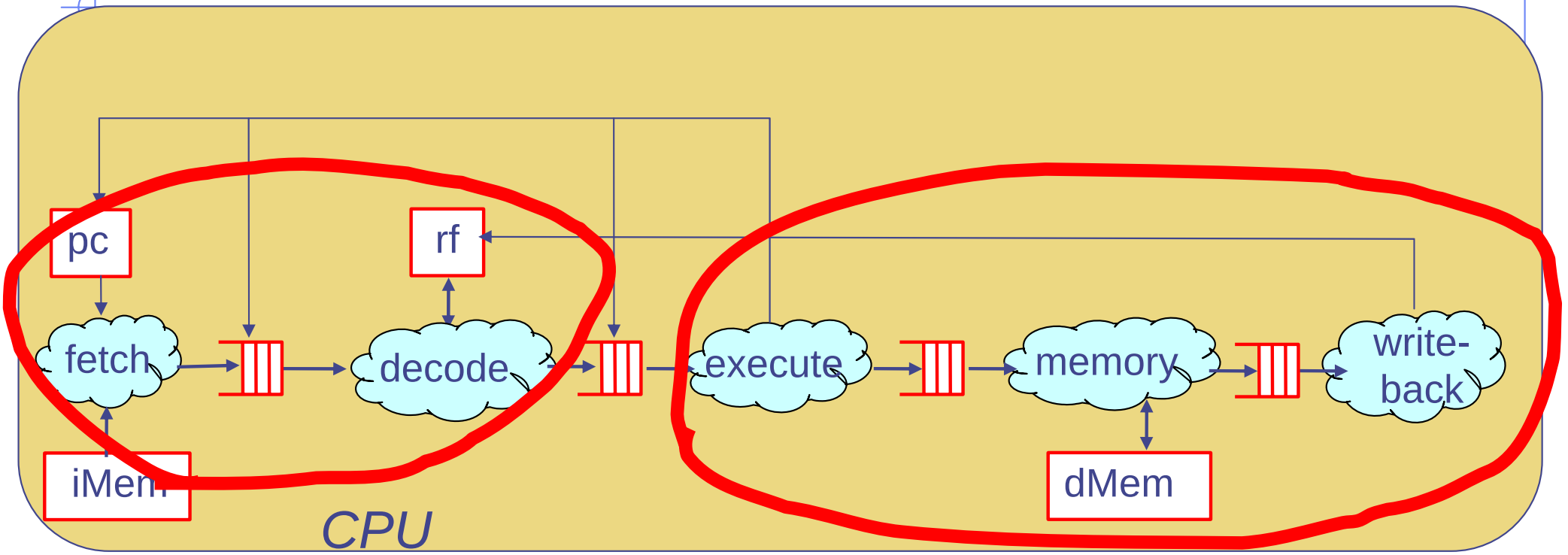
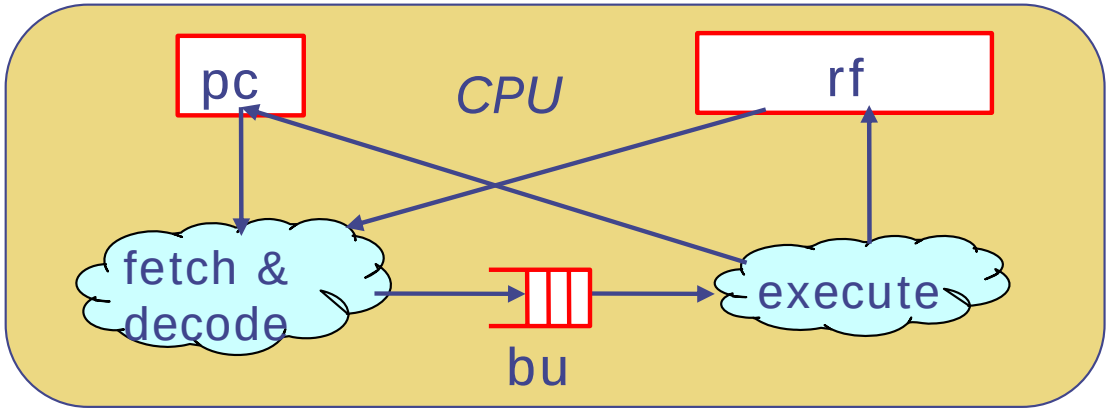
Bluespec-8: Modules and Interfaces

Arvind
Computer Science & Artificial Intelligence Lab
Massachusetts Institute of Technology

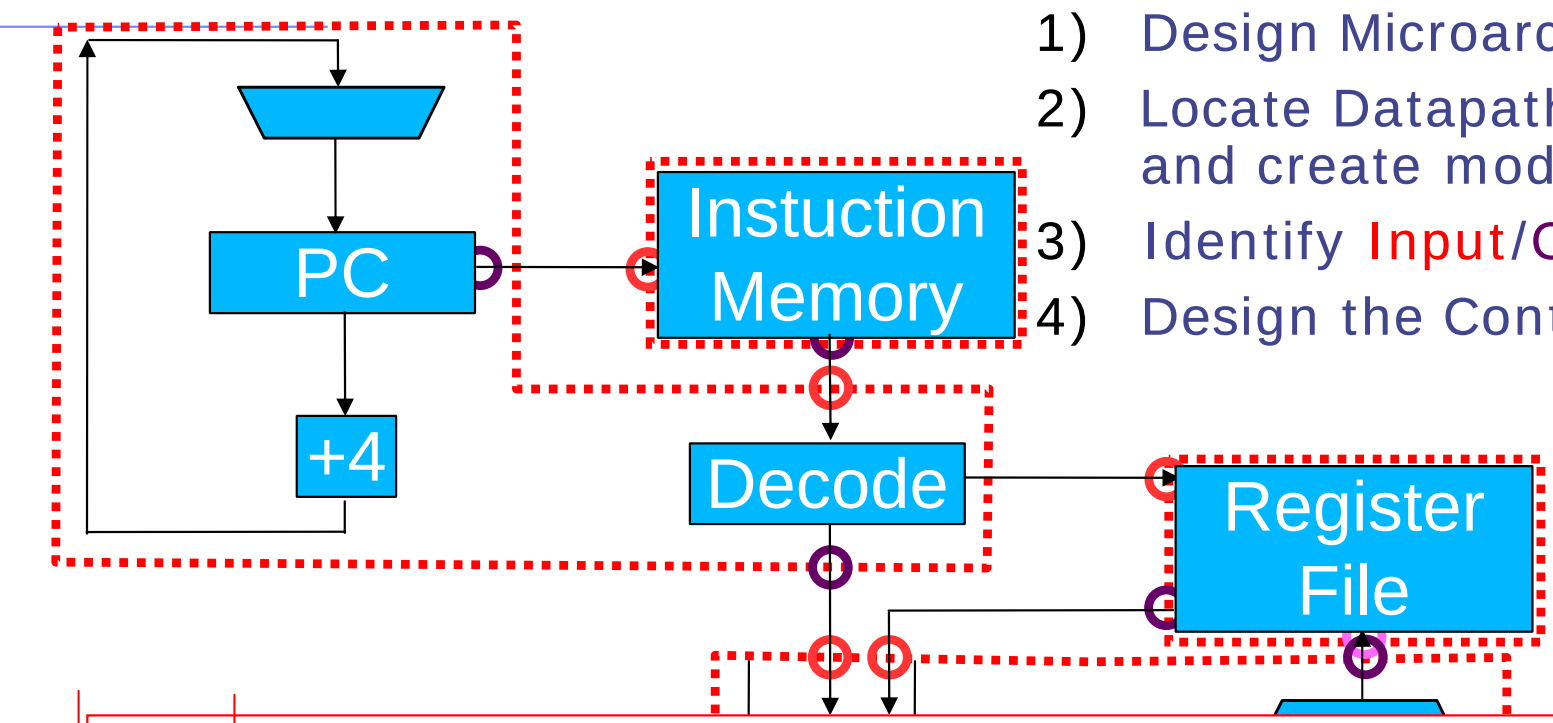
Successive refinement & Modular Structure



Can we derive the 5-stage pipeline by successive refinement of a 2-stage pipeline?



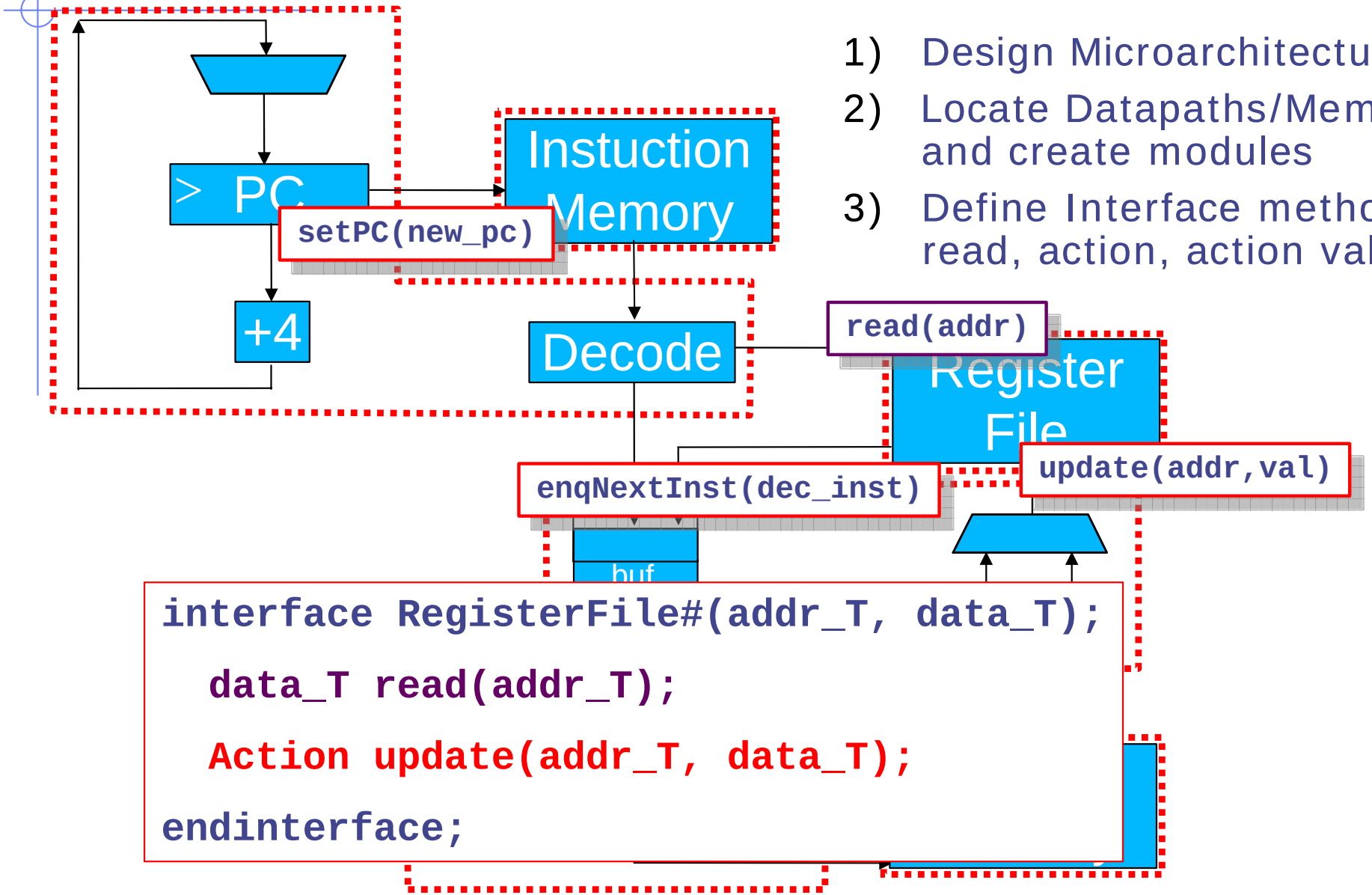
A 2-Stage Processor in RTL



1) Design Microarchitecture
2) Locate Datapaths/Memories and create modules
3) Identify Input/Output ports
4) Design the Controller (FSM)

```
module regfile (
    input  [4:0]  wa,  //address for write port
    input  [31:0] wd,  //write data
    input         we,  //write enable (active high)
    input  [4:0]  ra1, //address for read port 1
    output [31:0] rd1, //read data for port 1
    ...
```

Designing a 2-Stage Processor with GAA



1) Design Microarchitecture
2) Locate Datapaths/Memories and create modules
3) Define Interface methods: read, action, action value

Outline

- Single module structure
  - Performance issue
- Modular structure issues

Instuctions & Templates

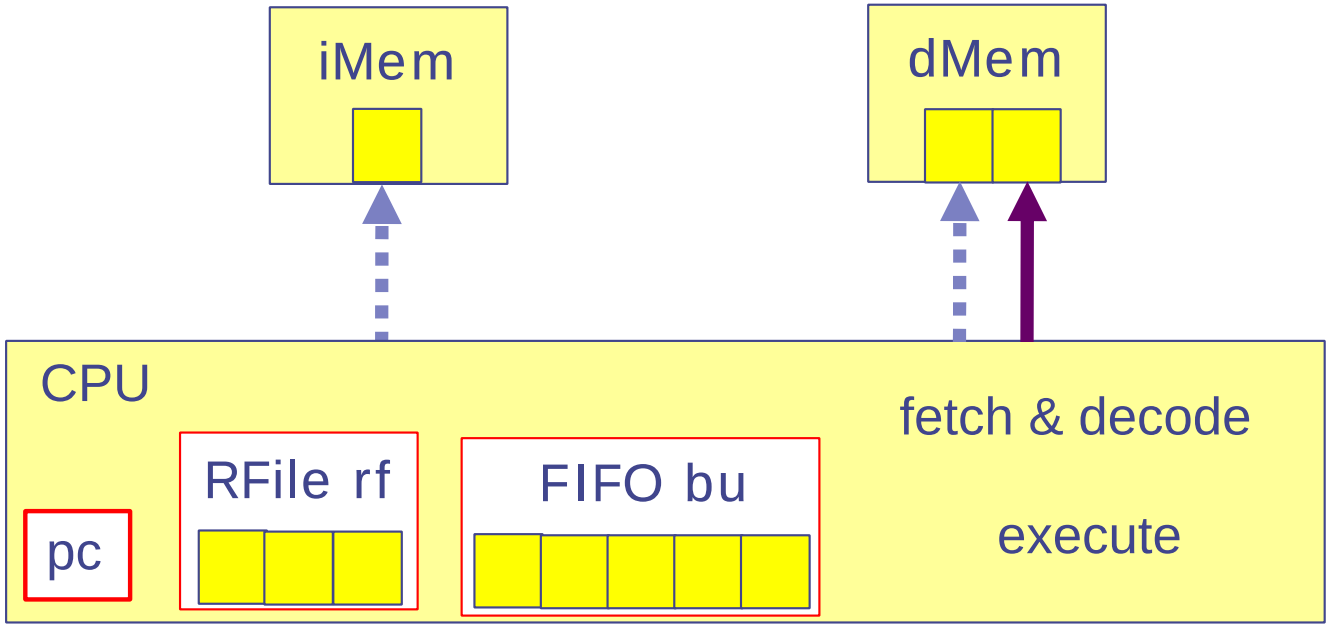
```
typedef union tagged {
  struct {RName dst; RName src1; RName src2} Add;
  struct {RName cond; RName addr}            Bz;
  struct {RName dst; RName addr}             Load;
  struct {RName value; RName addr}           Store;
} Inst deriving(Bits, Eq);

typedef union tagged
{ struct {RName dst; Value op1; Value op2} EAdd;
  struct {Value cond; Iaddress tAddr}      EBz;
  struct {RName dst; Daddress addr}        ELoad;
  struct {Value data; Daddress addr}       EStore;
} InstTemplate deriving(Eq, Bits);

typedef Bit#(32) Iaddress;
typedef Bit#(32) Daddress;
typedef Bit#(32) Value;
```

you have seen this before

CPU as one module



Method calls embody both data and control (i.e., protocol)

Read method call

Action method call

CPU as one module

```
module mkCPU#(Mem iMem, Mem dMem)();
// Instantiating state elements
      Reg#(Iaddress) pc <- mkReg(0);
      RegFile#(RName, Value) rf
                           <- mkRegFileFull();
            SFIFO#(InstTemplate, RName) bu
                           <- mkSFifo(findf);
// Some definitions
      Instr     instr = iMem.read(pc);
      Iaddress predIa = pc + 1;
// Rules
      rule fetch_decode ...
      rule execute ...
endmodule
```

you have seen this before

Fetch & Decode Rule

```
rule fetch_and_decode (!stallfunc(instr, bu));
        bu.enq(newIt(instr,rf));
        pc <= predIa;
endrule

function InstrTemplate newIt(Instr instr,
                             RegFile#(RName, Value) rf);
    case (instr) matches
        tagged Add {dst:.rd,src1:.ra,src2:.rb}:
            return EAdd{dst:rd,op1:rf[ra],op2:rf[rb]};
        tagged Bz  {cond:.rc,addr:.addr}:
            return EBz{cond:rf[rc],addr:rf[addr]};
        tagged Load {dst:.rd,addr:.addr}:
            return ELoad{dst:rd,addr:rf[addr]};
        tagged Store{value:.v,addr:.addr}:
            return EStore{value:rf[v],addr:rf[addr]};
    endcase
endfunction
```

you have seen this before

The Stall Function

```
function Bool stallfunc (Instr instr,
         SFIFO#(InstTemplate, RName) bu);
  case (instr) matches
   tagged Add {dst:.rd,src1:.ra,src2:.rb}:
      return (bu.find(ra) || bu.find(rb));
   tagged Bz    {cond:.rc,addr:.addr}:
      return (bu.find(rc) || bu.find(addr));
   tagged Load  {dst:.rd,addr:.addr}:
      return (bu.find(addr));
   tagged Store  {value:.v,addr:.addr}:
      return (bu.find(v)) || bu.find(addr));
  endcase
endfunction
```

you have seen this before

The findf function

```
function Bool findf (RName r, InstrTemplate it);
  case (it) matches
    tagged EAdd{dst:.rd,op1:.ra,op2:.rb}:
                                  return (r == rd);
    tagged EBz {cond:.c,addr:.a}:
                                  return (False);
    tagged ELoad{dst:.rd,addr:.a}:
                                  return (r == rd);
    tagged EStore{value:.v,addr:.a}:
                                  return (False);
  endcase
endfunction
```

mkSFifo is parameterized by the search function!

```
SFIFO#(InstrTemplate, RName) bu <- mkSFifo(findf);
```

you have seen this before

Execute Rule

```
rule execute (True);
  case (it) matches
    tagged EAdd{dst:.rd,src1:.va,src2:.vb}: begin
         rf.upd(rd, va+vb); bu.deq();
        end
    tagged EBz {cond:.cv,addr:.av}:
         if (cv == 0) then begin
              pc <= av; bu.clear(); end
         else bu.deq();
    tagged ELoad{dst:.rd,addr:.av}: begin
         rf.upd(rd, dMem.read(av)); bu.deq();
        end
    tagged EStore{value:.vv,addr:.av}: begin
         dMem.write(av, vv); bu.deq();
        end
  endcase
endrule
```

you have seen this before

Transformation for Performance

```
rule fetch_and_decode (!stallfunc(instr, bu)[1]);
        bu.enq[1](newIt(instr,rf));
        pc <= predIa;
endrule
```

execute < fetch_and_decode
➔ $rf.upd^0 < rf.sub^1$
$bu.first^0 < \{bu.deq^0, bu.clear^0\} < bu.find^1 < bu.enq^1$

```
rule execute (True);
  case (it) matches
    tagged EAdd{dst:.rd,src1:.va,src2:.vb}: begin
         rf.upd[0](rd, va+vb); bu.deq[0](); end
    tagged EBz {cond:.cv,addr:.av}:
         if (cv == 0) then begin
              pc <= av; bu.clear[0](); end
         else bu.deq[0]();
    tagged ELoad{dst:.rd,addr:.av}: begin
         rf.upd[0](rd, dMem.read(av)); bu.deq[0](); end
    tagged EStore{value:.vv,addr:.av}: begin
         dMem.write(av, vv); bu.deq[0](); end
  endcase endrule
```

After Renaming

- Things will work
  - both rules can fire concurrently

Programmer Specifies:

$$R_{execute} < R_{fetch}$$

Compiler Derives:

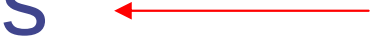
$$(first^0, deq^0) < (find^1, deq^1)$$

What if the programmer wrote this?

$$R_{execute} < R_{execute} < R_{fetch} < R_{fetch}$$

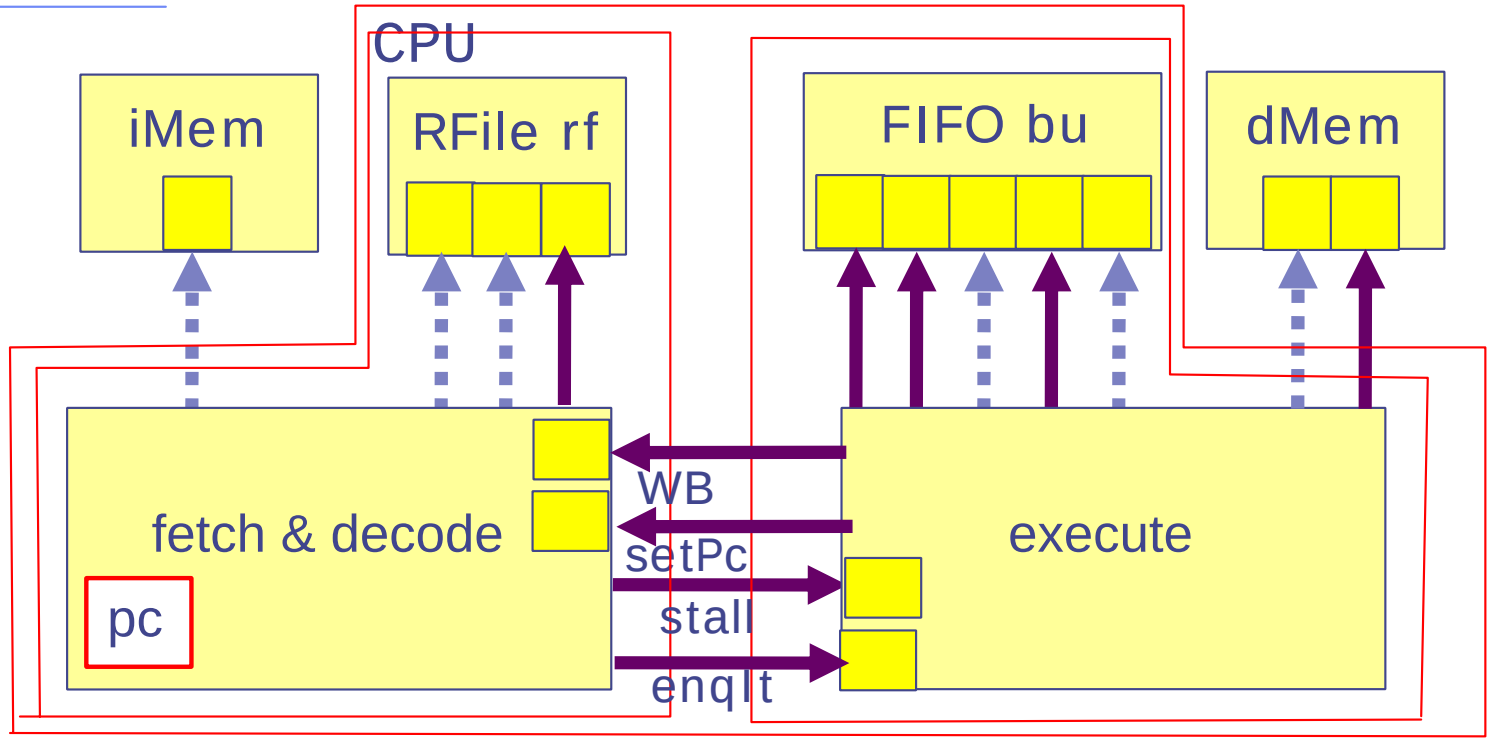
Outline

- Single module structure
- Modular structure issues



A Modular organization:

recursive modules



Modules call each other

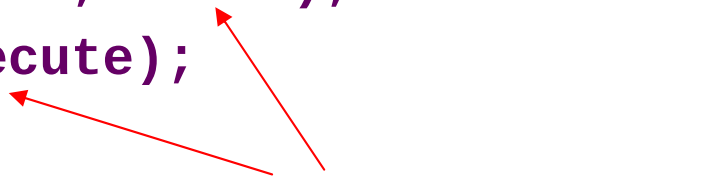
- bu part of Execute
- rf and pc part of Fetch&Decode
- fetch delivers decoded instructions to Execute

Recursive modular organization

```
module mkCPU2#(Mem iMem, Mem dMem)();
  Execute  execute  <- mkExecute(dMem, fetch);
  Fetch fetch  <- mkFetch(iMem, execute);
endmodule

interface Fetch;
  method Action setPC (Iaddress cpc);
  method Action writeback (RName dst, Value v);
endinterface

interface Execute;
  method Action enqIt(InstTemplate it);
  method Bool stall(Instr instr)
endinterface
```



Fetch Module

```
module mkFetch#(Execute execute) (Fetch);
   Instr    instr  = iMem.read(pc);
   Iaddress predIa = pc + 1;

   Reg#(Iaddress) pc <- mkReg(0);
   RegFile#(RName, Bit#(32)) rf <- mkRegFileFull();

   rule fetch_and_decode (!execute.stall(instr));
        execute.enqIt(newIt(instr,rf));
        pc <= predIa;
   endrule

   method Action writeback(RName rd, Value v);
        rf.upd(rd,v);
   endmethod
   method Action setPC(Iaddress newPC);
        pc <= newPC;
   endmethod
endmodule
```

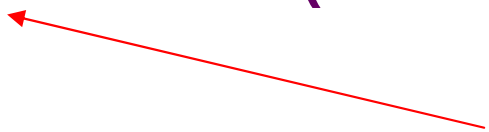
Execute Module

```
module mkExecute#(Fetch fetch) (Execute);

   SFIFO#(InstTemplate) bu <- mkSFifo(findf);
   InstTemplate it  = bu.first;

   rule execute …

   method Action enqIt(InstTemplate it);
       bu.enq(it);
   endmethod
   method Bool stall(Instr instr);
       return (stallfunc(instr,bu));
   endmethod
endmodule
```



Execute Module Rule

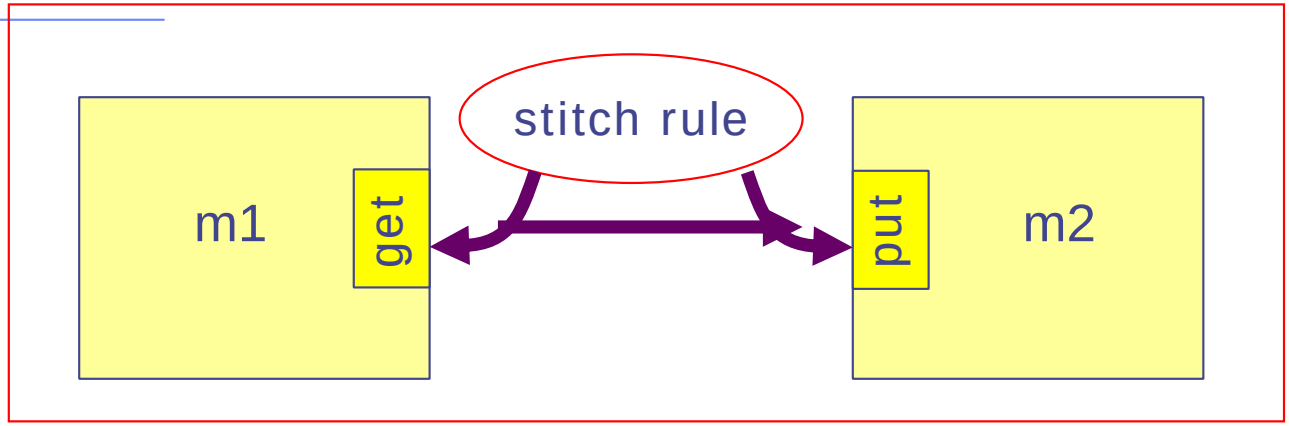
```
rule execute (True);
  case (it) matches
    tagged EAdd{dst:.rd,src1:.va,src2:.vb}: begin
              fetch.writeback(rd, va+vb); bu.deq();
       end
    tagged EBz {cond:.cv,addr:.av}:
       if (cv == 0) then begin
              fetch.setPC(av); bu.clear(); end
       else bu.deq();
    tagged ELoad{dst:.rd,addr:.av}: begin
              fetch.writeback(rd, dMem.read(av)); bu.deq();
       end
    tagged EStore{value:.vv,addr:.av}: begin
              dMem.write(av, vv); bu.deq();
       end
  endcase
endrule
```

Issue

- A recursive call structure can be wrong in the sense of “circular calls”; fortunately the compiler can perform this check
- Unfortunately recursive call structure amongst modules is not supported by the compiler.

So what should we do?

Connectable Methods



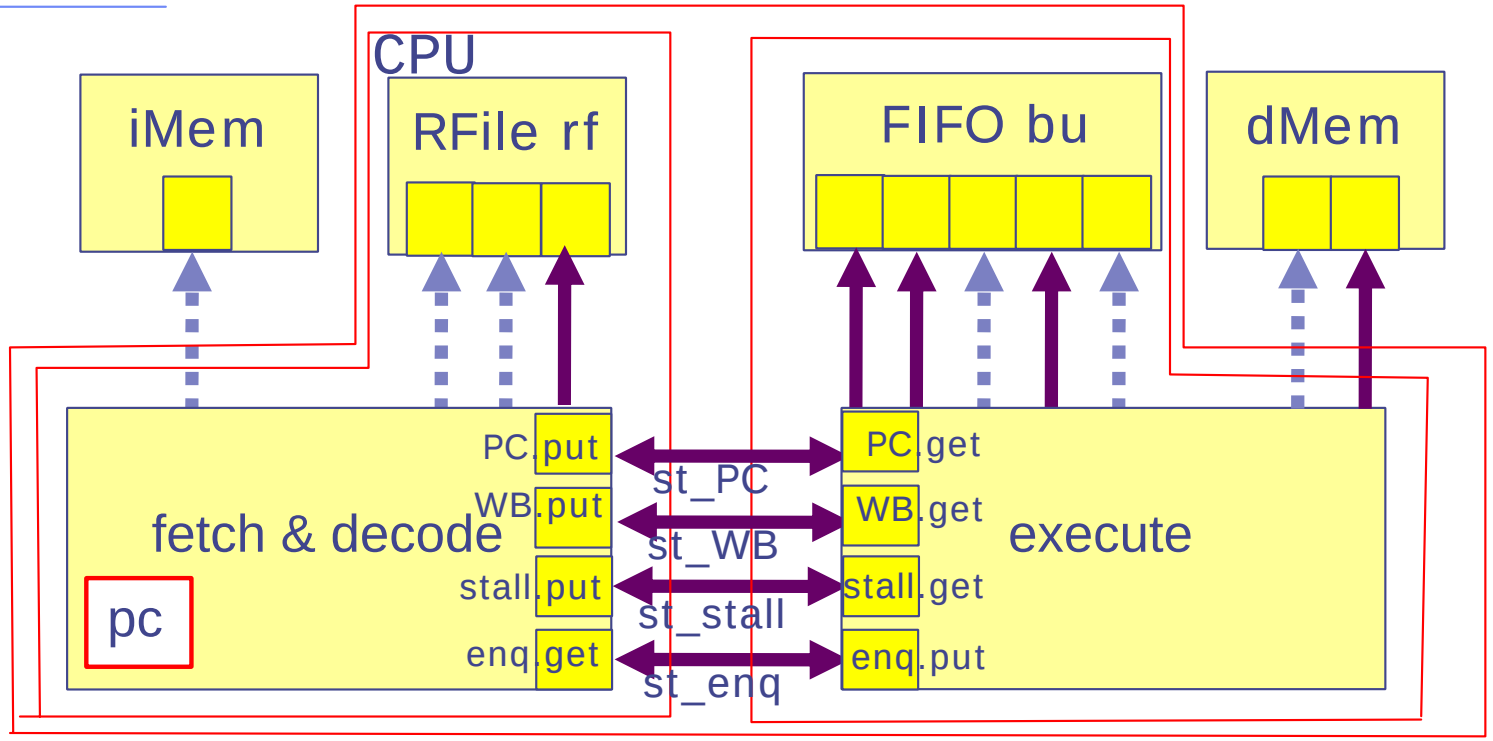

```
interface Get#(data_T);
  ActionValue#(data_T) get();
endinterface
```

```
interface Put#(data_T);
  Action put(data_T x);
endinterface
```

```
module mkConnection#(Get#(data_T) m1, Put#(data_T) m2) ();
    rule stitch(True);
      data_T res <- m1.get();
      m2.put(res);
    endrule
endmodule
```

m1 and m2 are separately compilable

Connectable Organization



Both ends completely separately compilable

- bu still part of Execute
- rf still part of Fetch&Decode

stall: Get/Put?

Can we automatically transform the recursive structure into this get-put structure?

Step 1: Break up Rules

only one recursive method call per rule …

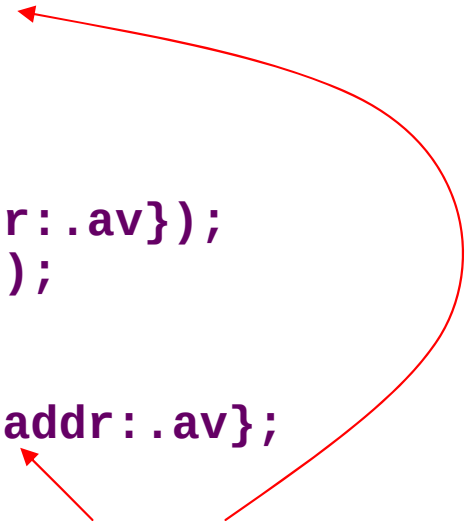
```
rule exec_EAdd(it matches EAdd{dst:.rd, op1:.va, op2:.vb});
   fetch.writeback(rd, va+vb); bu.deq();
endrule

rule exec_EBz_Taken (it matches EBz{cond:.cv, addr:.av})
                        && cv == 0);
   fetch.setPC(av); bu.clear();
endrule

rule exec_EBz_NotTaken (it matches EBz{cond:.cv, addr:.av}
                         && cv != 0);
   bu.deq();
endrule

rule exec_ELoad(it matches ELoad {dst:.rd, addr:.av});
   fetch.writeback(rd, dMem.read(av)); bu.deq();
endrule

rule exec_EStore(it matches EStore{value:.vv, addr:.av};
   dMem.write(av,vv); bu.deq();
endrule
```



Don’t need to change these rules

Step 2: Change a rule to a method

```
rule exec_EBz_Taken (it matches EBz{cond:.cv, addr:.av})
                        && cv == 0);
      fetch.setPC(av); bu.clear();
endrule
```

```
method ActionValue#(IAddress) getNewPC()
     if ((it matches EBz{cond:.cv,addr:.av} &&& (cv == 0));
  bu.clear();
  return(av);
endmethod
```

instead of sending av to the fetch module, we are simply providing av to the outside world under suitable conditions

Step 2: Merging multiple rules into one method *not always easy*

```
rule exec_EAdd(it matches EAdd{dst:.rd, op1:.va, op2:.vb});
   fetch.writeback(rd, va + vb); bu.deq();
endrule
rule exec_ELoad(it matches ELoad {dst:.rd, addr:.av});
   fetch.writeback(rd, dMem.get(av)); bu.deq();
endrule
```

Need to combine all calls to fetch.writeback into one method!

```
method Tuple2#(RName, Value) getWriteback() if (canDoWB);
  bu.deq();
  case (it) matches
    tagged EAdd {dst:.rd, op1:.va, op2:.vb}:
                    return(tuple2(rd, va+vb));
    tagged ELoad{dst:.rd, addr:.av}:
                    return(tuple2(rd, dMem.get(av)));
    default:              return(?); // should never occur
  endcase
endmethod
```

canDoWB means **(it) matches "Eadd or Eload"**

Step-1 is not always possible:

Jump&Link instruction

```
rule exec_EJAL(it matches EJAL{rd:.rd, pc:.pc, addr:.av};
   fetch.writeback(rd, pc);
   fetch.setPC(av); bu.clear();
endrule
```

RWire to the rescue

1. Create an RWire for each method
2. Replace calls with RWire writes
3. Connect methods to RWire reads
4. Restrict schedule to maintain atomicity

Using RWires

```
rule exec_EBz_Taken (it matches EBz{cond:.cv, addr:.av})
                        && cv == 0);
      PC_wire.wset(av); bu.clear();
endrule
```

```
method ActionValue#(IAddress) getNewPC()
                if (PC_wire.wget matches tagged Valid .x);
       return(x);
endmethod
```

Dangerous -- if the outsider does not pick up the value, it is gone!

Reading and writing of a wire is not an atomic action

Jump&Link using RWires

steps 1 & 2

```
Rwire#(Tuple2#(RName, Value))  wb_wire <- mkRWire();
Rwire#(Iaddress)               getPC_wire <- mkRWire();

rule exec_EJAL(it matches EJAL{rd:.rd, pc: .pc, addr:.av};
   wb_wire.wset(tuple2(rd, pc));
   getPC_wire.wset(av); bu.clear();
endrule

rule exec_EAdd(it matches EAdd{dst:.rd, op1:.va, op2:.vb});
   wb_wire.wset(tuple2(rd, va + vb)); bu.deq();
endrule

rule exec_EBz_Taken(it matches EBz{cond:.cv, addr:.av}
                    && cv == 0);
   getPC_wire.wset(av); bu.clear();
endrule

rule exec_ELoad(it matches ELoad {dst:.rd, addr:.av});
   wb_wire.wset(tuple2(rd, dMem.get(av))); bu.deq();
endrule
```

Jump&Link Connectable Version
step 3

```
method ActionValue#(...) writeback_get()
       if (wb_wire.wget() matches tagged Valid .x);
  return x;
endmethod

method ActionValue#(Iaddress) setPC_get()
       if (getPC_wire.wget() matches tagged Valid .x);
  return x;
endmethod
```

Atomicity violations?

1. dropped values on RWires
2. Get-Put rule is no longer a single atomic action

My recommendation

- If recursive modules are the natural way to express a design – do that first
- Transform it by turning some rules into methods
- Sometimes EHRs and bypass FIFO can solve the problem (we have not shown you this)
- If all fails consult the staff

Modular Structure

- Different modular structures generate the "same hardware"
  - modular structure choice is more about design convenience
- Recursive modular organizations are natural but
  - there are some theoretical complications
- Transforming a recursive structure into a non-recursive one is always possible using RWires but prides avenues for abuse