Constructive Computer Architecture:

Multistage Pipelined Processors and modular refinement

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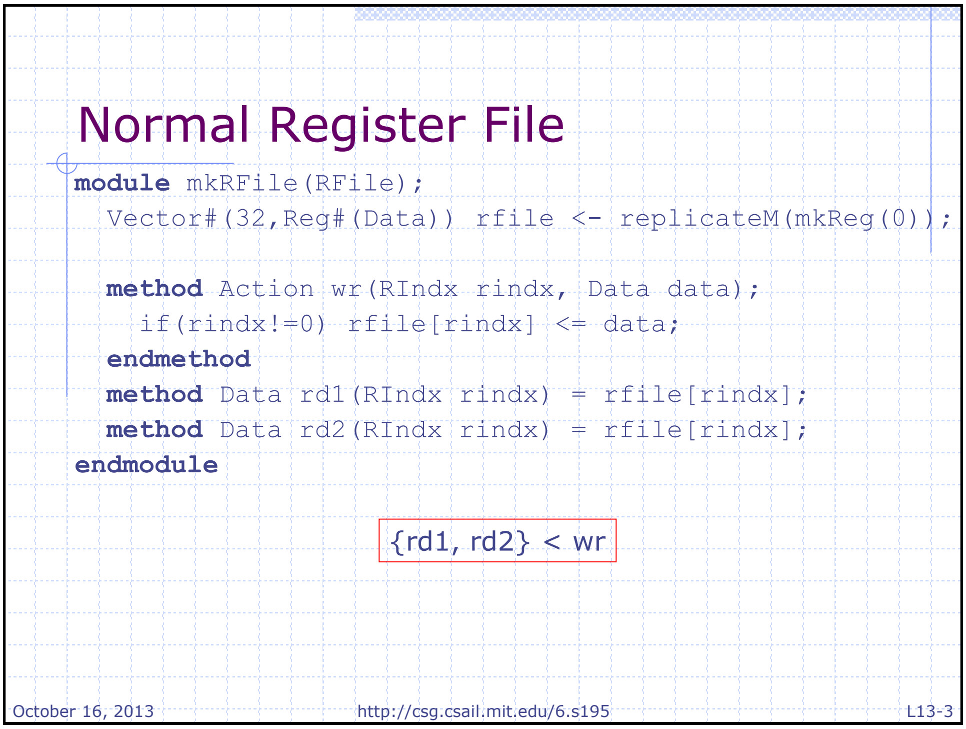
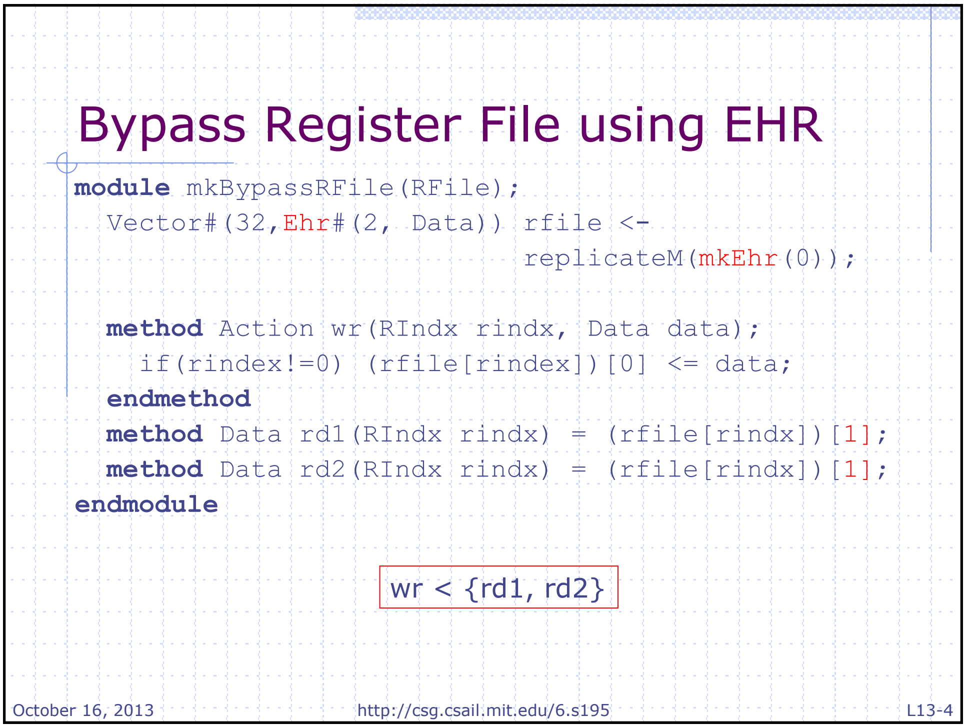


Normal Register File

```
module mkRFile(RFile);
  Vector#(32,Reg#(Data)) rfile <- replicateM(mkReg(0)));

  method Action wr(RIndx rindx, Data data);
    if(rindx!=0) rfile[rindx] <= data;
  endmethod
  method Data rd1(RIndx rindx) = rfile[rindx];
  method Data rd2(RIndx rindx) = rfile[rindx];
endmodule
```

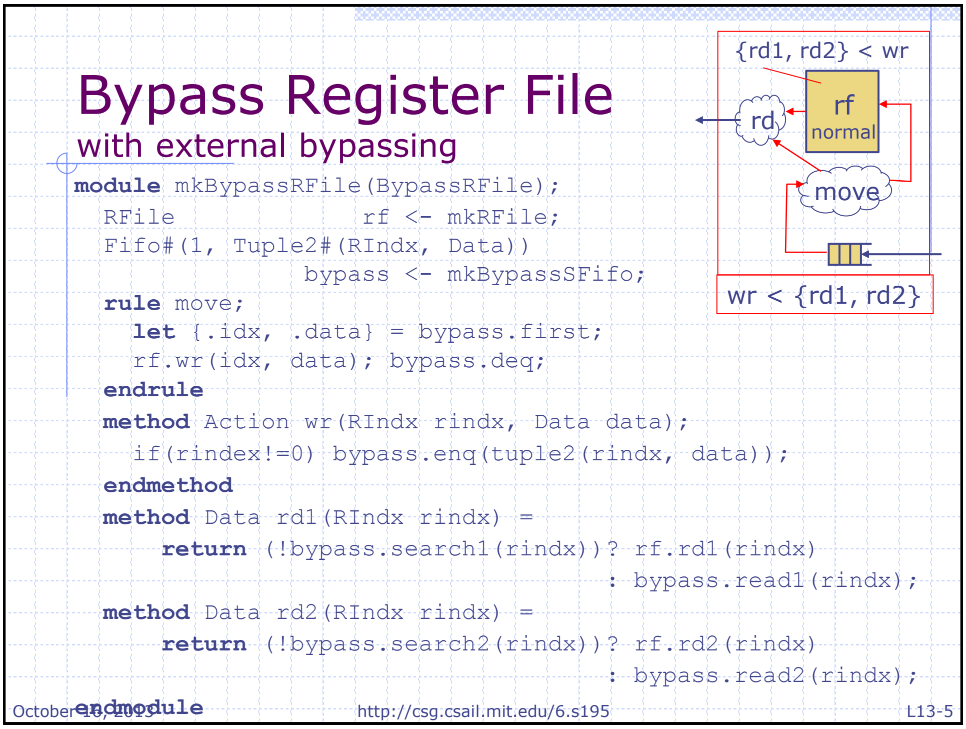
{rd1, rd2} < wr



Bypass Register File using EHR

```
module mkBypassRFile(RFile);
  Vector#(32,Ehr#(2, Data)) rfile <-
                           replicateM(mkEhr(0));

  method Action wr(RIndx rindx, Data data);
    if(rindex!=0) (rfile[rindex])[0] <= data;
  endmethod
  method Data rd1(RIndx rindx) = (rfile[rindx])[1];
  method Data rd2(RIndx rindx) = (rfile[rindx])[1];
endmodule
```

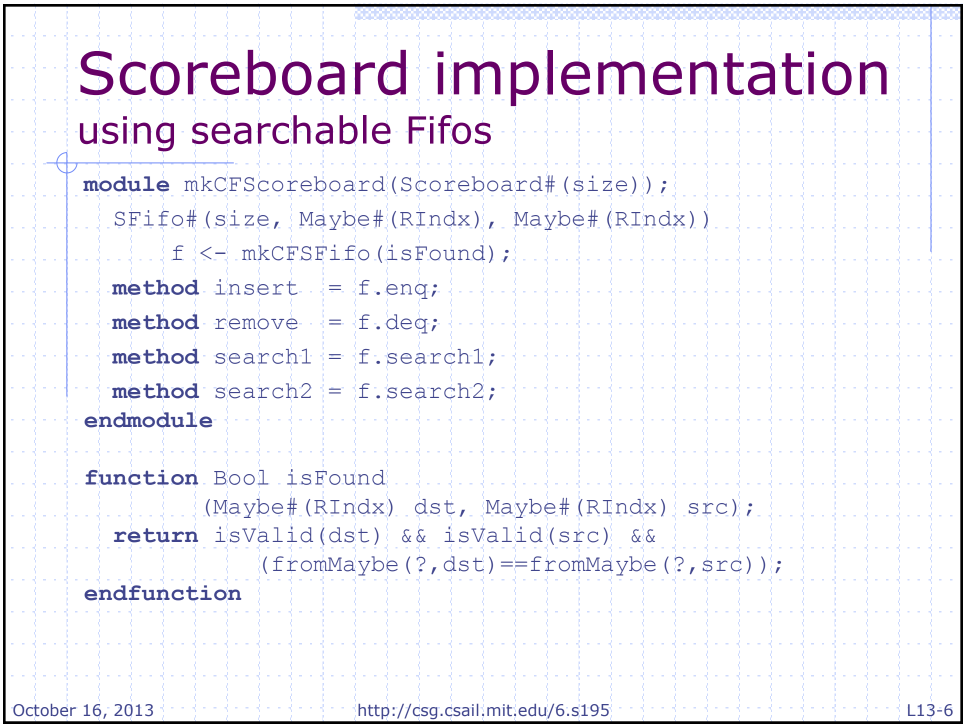
wr < {rd1, rd2}



Bypass Register File

with external bypassing

```
module mkBypassRFile(BypassRFile);
  RFile             rf <- mkRFile;
  Fifo#(1, Tuple2#(RIndx, Data))
                 bypass <- mkBypassSFifo;
  rule move;
    let {.idx, .data} = bypass.first;
    rf.wr(idx, data); bypass.deq;
  endrule
  method Action wr(RIndx rindx, Data data);
    if(rindex!=0) bypass.enq(tuple2(rindx, data));
  endmethod
  method Data rd1(RIndx rindx) =
      return (!bypass.search1(rindx))? rf.rd1(rindx)
                                     : bypass.read1(rindx);
  method Data rd2(RIndx rindx) =
      return (!bypass.search2(rindx))? rf.rd2(rindx)
                                     : bypass.read2(rindx);
endmodule
```

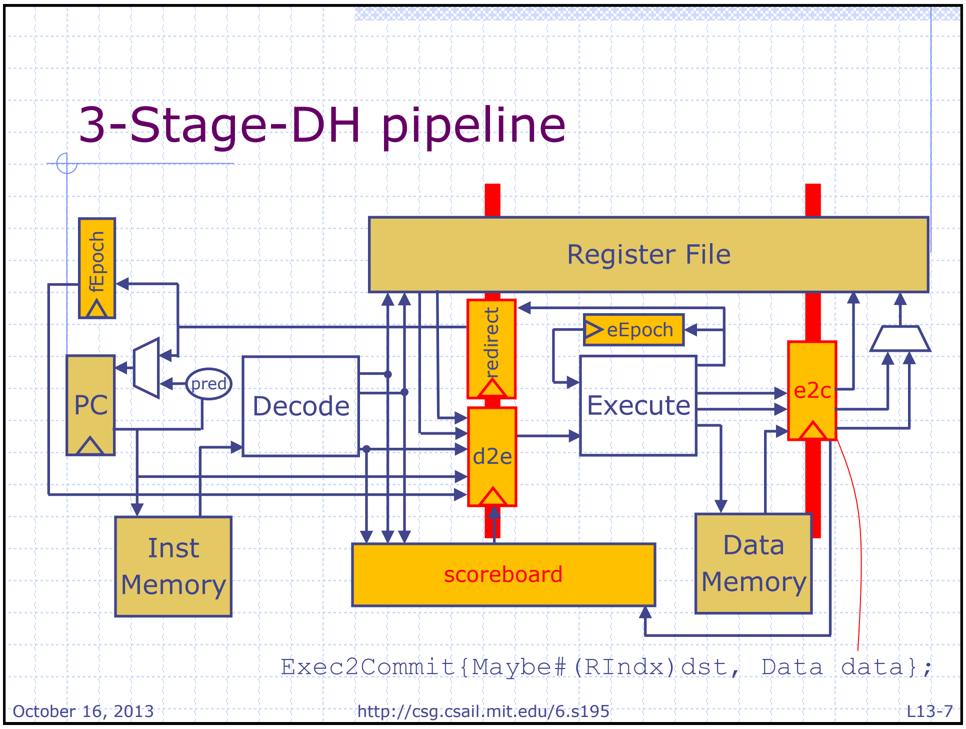


Scoreboard implementation

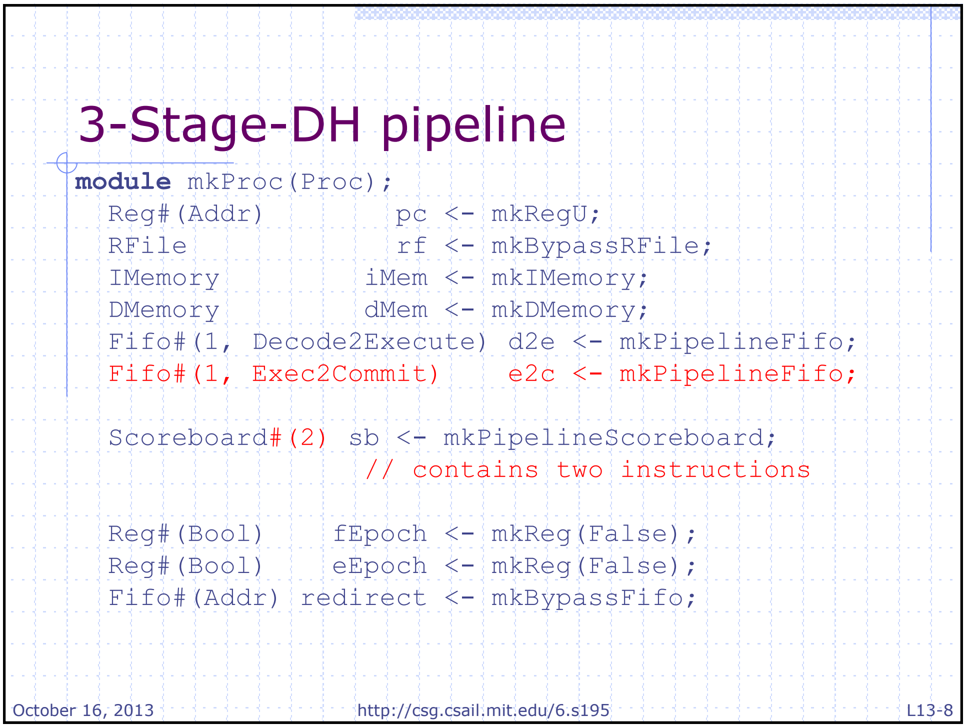
using searchable Fifos

```
module mkCFScoreboard(Scoreboard#(size));
  SFifo#(size, Maybe#(RIndx), Maybe#(RIndx))
      f <- mkCFSFifo(isFound);
  method insert  = f.enq;
  method remove  = f.deq;
  method search1 = f.search1;
  method search2 = f.search2;
endmodule

function Bool isFound
          (Maybe#(RIndx) dst, Maybe#(RIndx) src);
  return isValid(dst) && isValid(src) &&
              (fromMaybe(?,dst)==fromMaybe(?,src));
endfunction
```

3-Stage-DH pipeline

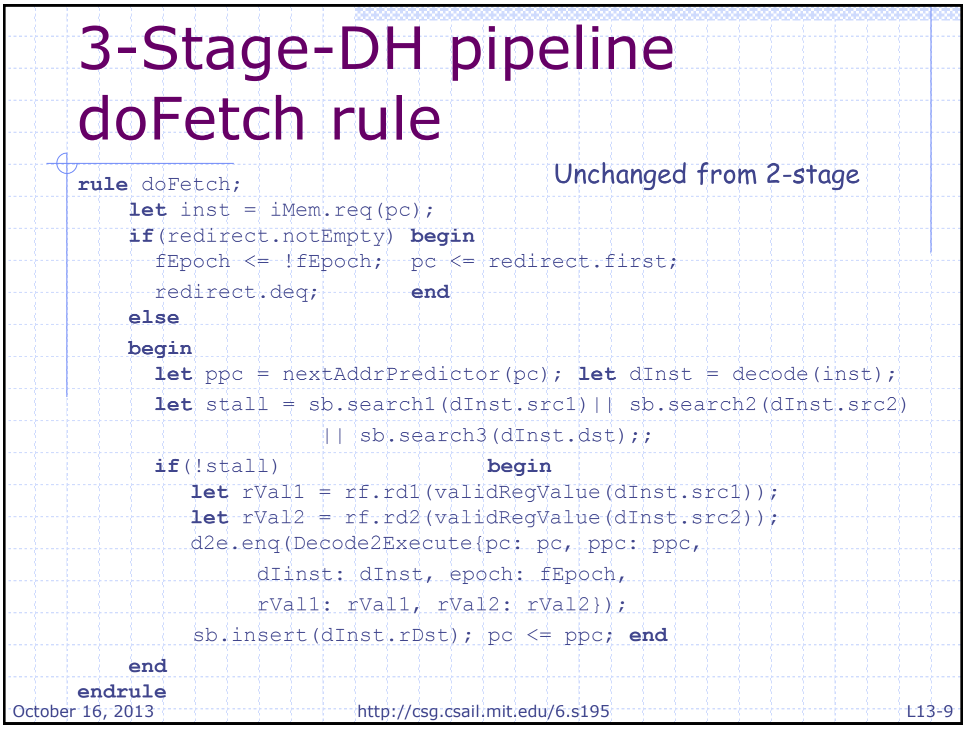


```
Exec2Commit{Maybe#(RIndx)dst, Data data};
```



3-Stage-DH pipeline

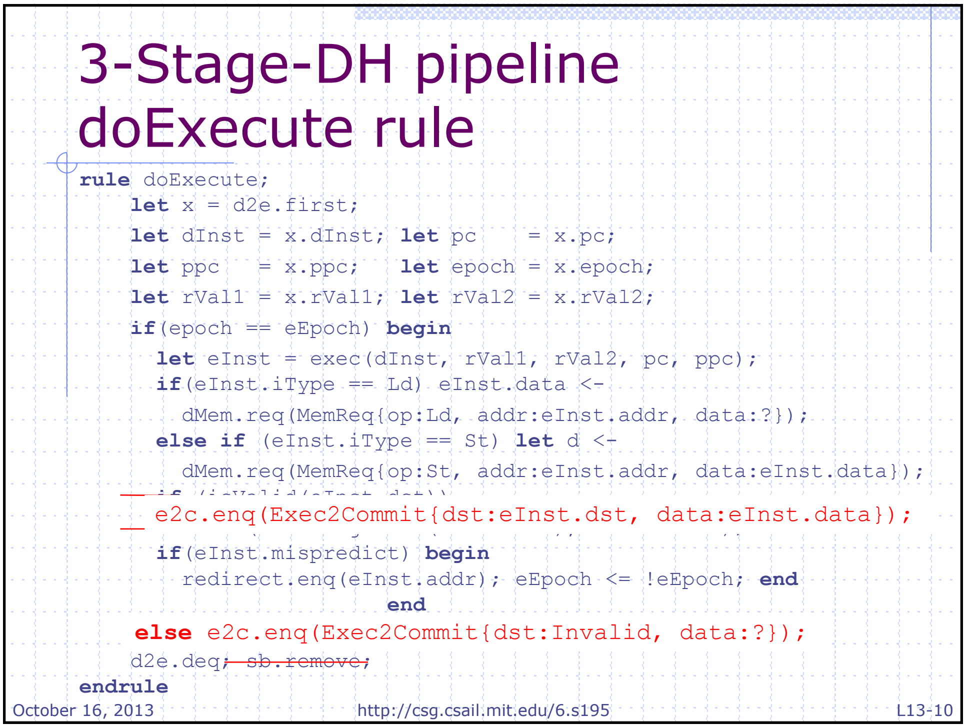
```
module mkProc(Proc);
  Reg#(Addr)          pc <- mkRegU;
  RFile               rf <- mkBypassRFile;
  IMemory           iMem <- mkIMemory;
  DMemory           dMem <- mkDMemory;
  Fifo#(1, Decode2Execute) d2e <- mkPipelineFifo;
  Fifo#(1, Exec2Commit)    e2c <- mkPipelineFifo;

  Scoreboard#(2) sb <- mkPipelineScoreboard;
                 // contains two instructions

  Reg#(Bool)     fEpoch <- mkReg(False);
  Reg#(Bool)     eEpoch <- mkReg(False);
  Fifo#(Addr)  redirect <- mkBypassFifo;
```



3-Stage-DH pipeline doFetch rule

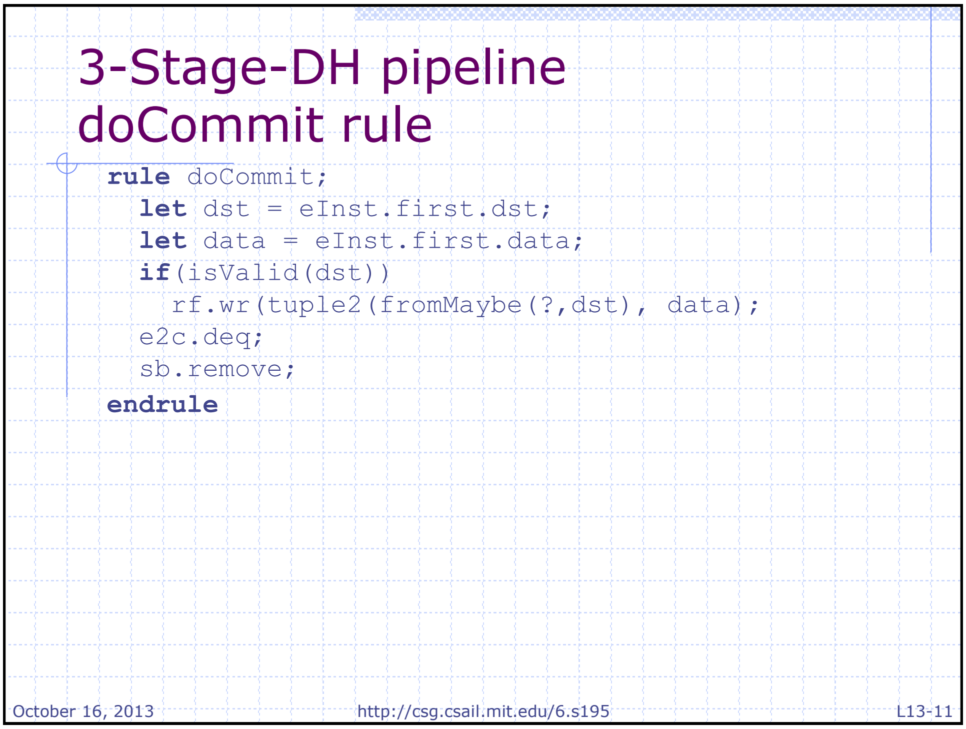
Unchanged from 2-stage

```
rule doFetch;
    let inst = iMem.req(pc);
    if(redirect.notEmpty) begin
      fEpoch <= !fEpoch;  pc <= redirect.first;
      redirect.deq;       end
    else
    begin
      let ppc = nextAddrPredictor(pc); let dInst = decode(inst);
      let stall = sb.search1(dInst.src1)|| sb.search2(dInst.src2)
                   || sb.search3(dInst.dst);;
      if(!stall)                  begin
         let rVal1 = rf.rd1(validRegValue(dInst.src1));
         let rVal2 = rf.rd2(validRegValue(dInst.src2));
         d2e.enq(Decode2Execute{pc: pc, ppc: ppc,
              dIinst: dInst, epoch: fEpoch,
              rVal1: rVal1, rVal2: rVal2});
         sb.insert(dInst.rDst); pc <= ppc; end
    end
endrule
```



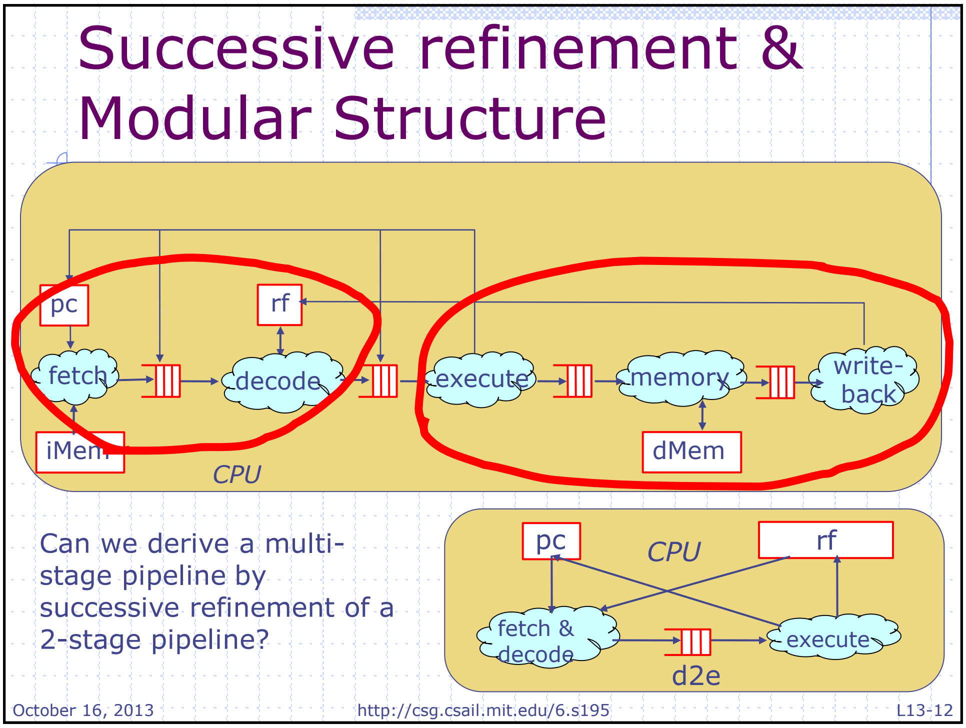
3-Stage-DH pipeline doExecute rule

```
rule doExecute;
    let x = d2e.first;
    let dInst = x.dInst; let pc    = x.pc;
    let ppc   = x.ppc;   let epoch = x.epoch;
    let rVal1 = x.rVal1; let rVal2 = x.rVal2;
    if(epoch == eEpoch) begin
      let eInst = exec(dInst, rVal1, rVal2, pc, ppc);
      if(eInst.iType == Ld) eInst.data <-
        dMem.req(MemReq{op:Ld, addr:eInst.addr, data:?});
      else if (eInst.iType == St) let d <-
        dMem.req(MemReq{op:St, addr:eInst.addr, data:eInst.data});
      ~~if (isValid(eInst.dst))~~
      e2c.enq(Exec2Commit{dst:eInst.dst, data:eInst.data});
      if(eInst.mispredict) begin
        redirect.enq(eInst.addr); eEpoch <= !eEpoch; end
                         end
     else e2c.enq(Exec2Commit{dst:Invalid, data:?});
    d2e.deq~~; sb.remove;~~
endrule
```



3-Stage-DH pipeline doCommit rule

```
rule doCommit;
  let dst = eInst.first.dst;
  let data = eInst.first.data;
  if(isValid(dst))
    rf.wr(tuple2(fromMaybe(?,dst), data);
  e2c.deq;
  sb.remove;
endrule
```



Successive refinement & Modular Structure

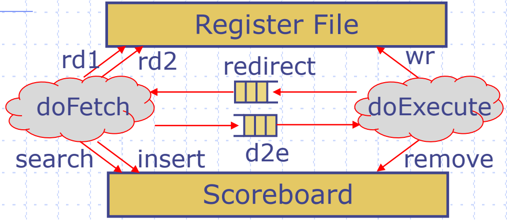
Can we derive a multi-stage pipeline by successive refinement of a 2-stage pipeline?

Architectural refinements

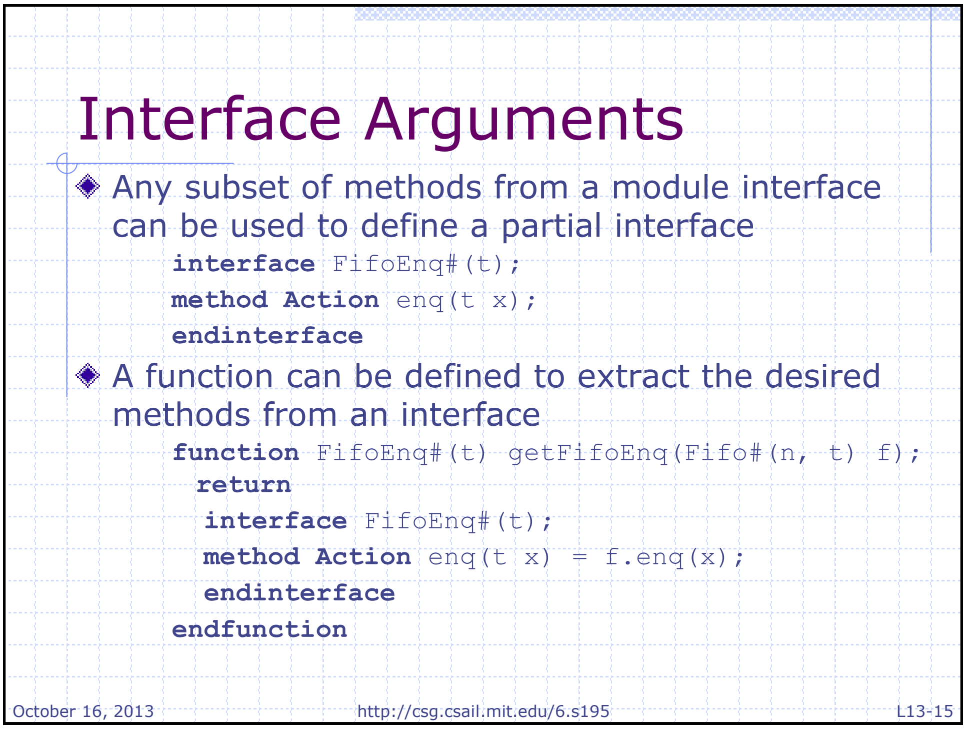
- Separating Fetch and Decode
- Replace magic memory by multicycle memory
- Multicycle functional units
- …

Nirav Dave, M.C. Ng, M. Pellauer, Arvind [Memocode 2010]
A design flow based on modular refinement

2-stage Processor Pipeline



- Encapsulate Fetch and Execute in their own modules respectively
- Pass methods of other modules as parameters
- For correctness, an instruction should be deleted from sb only after rf has been updated
  - remove and wr should happen atomically
  - search and rd1, rd2 should happen atomically



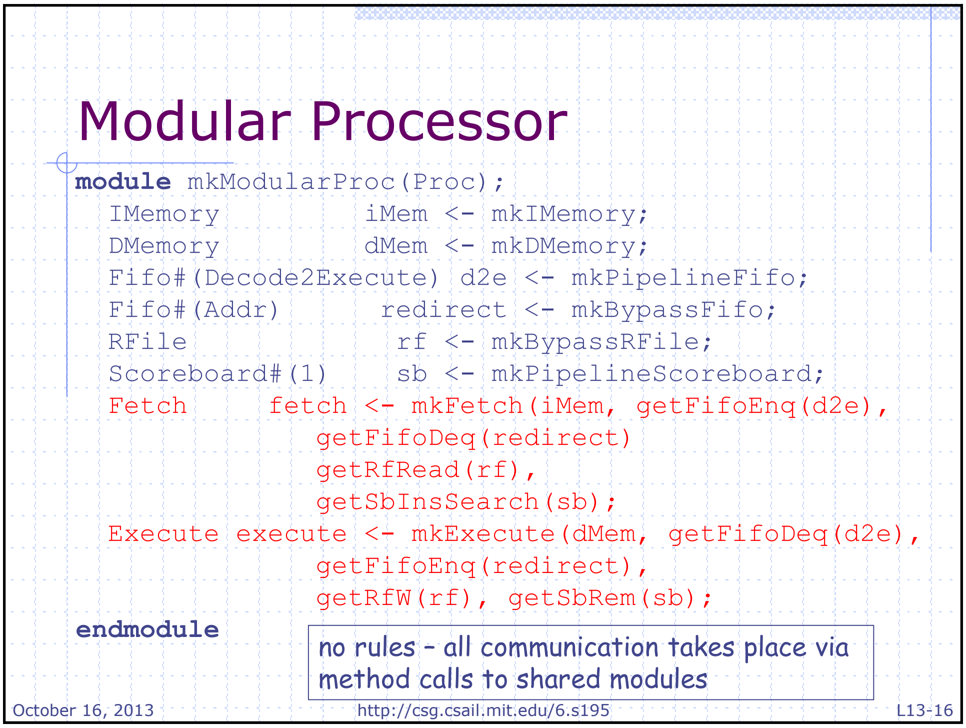
Interface Arguments

- Any subset of methods from a module interface can be used to define a partial interface

```
interface FifoEnq#(t);
method Action enq(t x);
endinterface
```

- A function can be defined to extract the desired methods from an interface

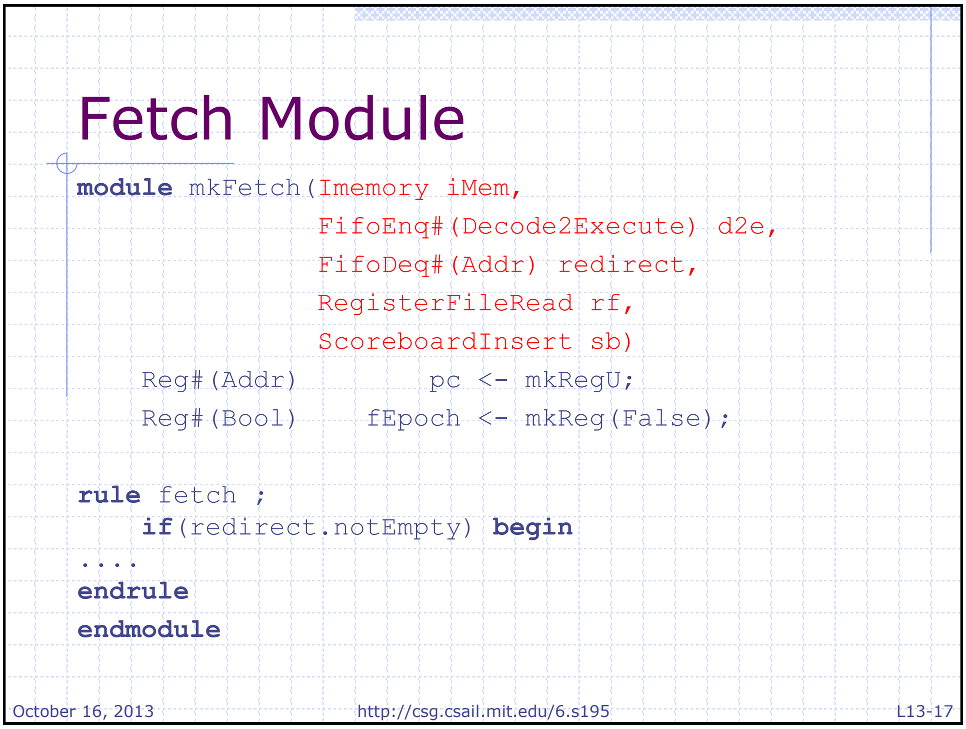
```
function FifoEnq#(t) getFifoEnq(Fifo#(n, t) f);
  return
   interface FifoEnq#(t);
   method Action enq(t x) = f.enq(x);
   endinterface
endfunction
```



Modular Processor

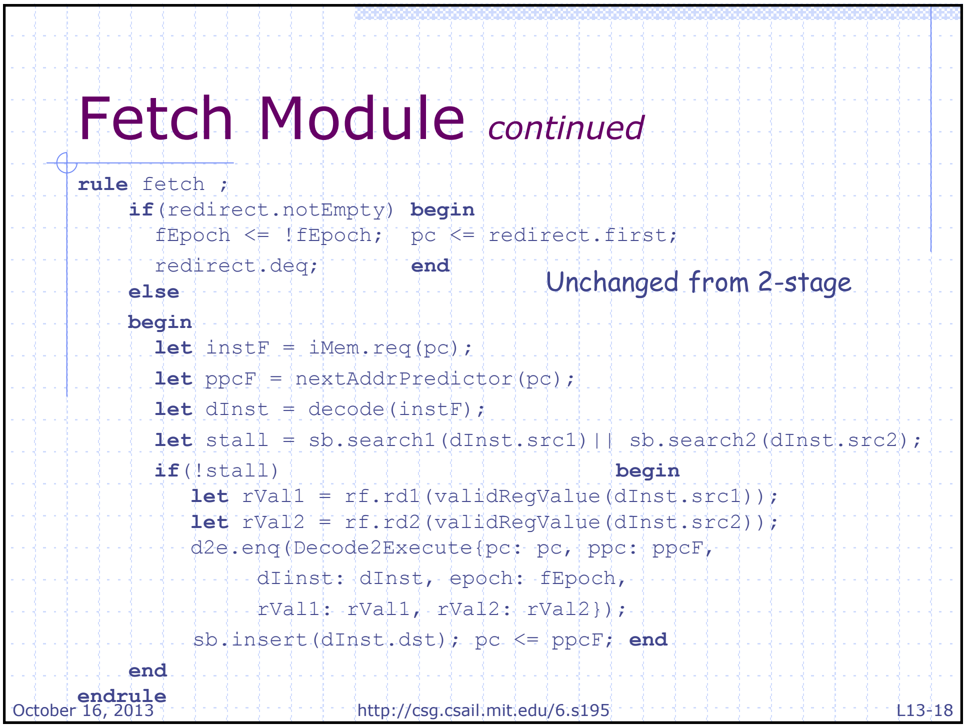
```
module mkModularProc(Proc);
   IMemory          iMem <- mkIMemory;
   DMemory          dMem <- mkDMemory;
   Fifo#(Decode2Execute) d2e <- mkPipelineFifo;
   Fifo#(Addr)       redirect <- mkBypassFifo;
   RFile               rf <- mkBypassRFile;
   Scoreboard#(1)      sb <- mkPipelineScoreboard;
   Fetch      fetch <- mkFetch(iMem, getFifoEnq(d2e),
                  getFifoDeq(redirect)
                  getRfRead(rf),
                  getSbInsSearch(sb);
   Execute execute <- mkExecute(dMem, getFifoDeq(d2e),
                  getFifoEnq(redirect),
                  getRfW(rf), getSbRem(sb);
endmodule
```

no rules – all communication takes place via method calls to shared modules



Fetch Module

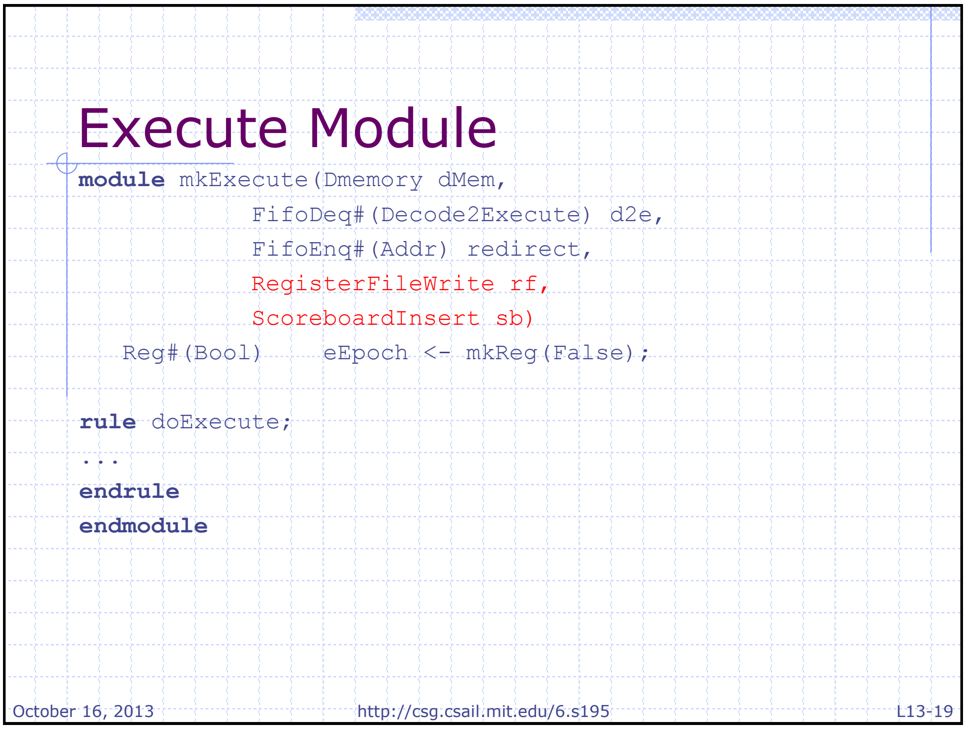
```
module mkFetch(Imemory iMem,
               FifoEnq#(Decode2Execute) d2e,
               FifoDeq#(Addr) redirect,
               RegisterFileRead rf,
               ScoreboardInsert sb)
    Reg#(Addr)        pc <- mkRegU;
    Reg#(Bool)    fEpoch <- mkReg(False);

rule fetch ;
    if(redirect.notEmpty) begin
....
endrule
endmodule
```



Fetch Module *continued*

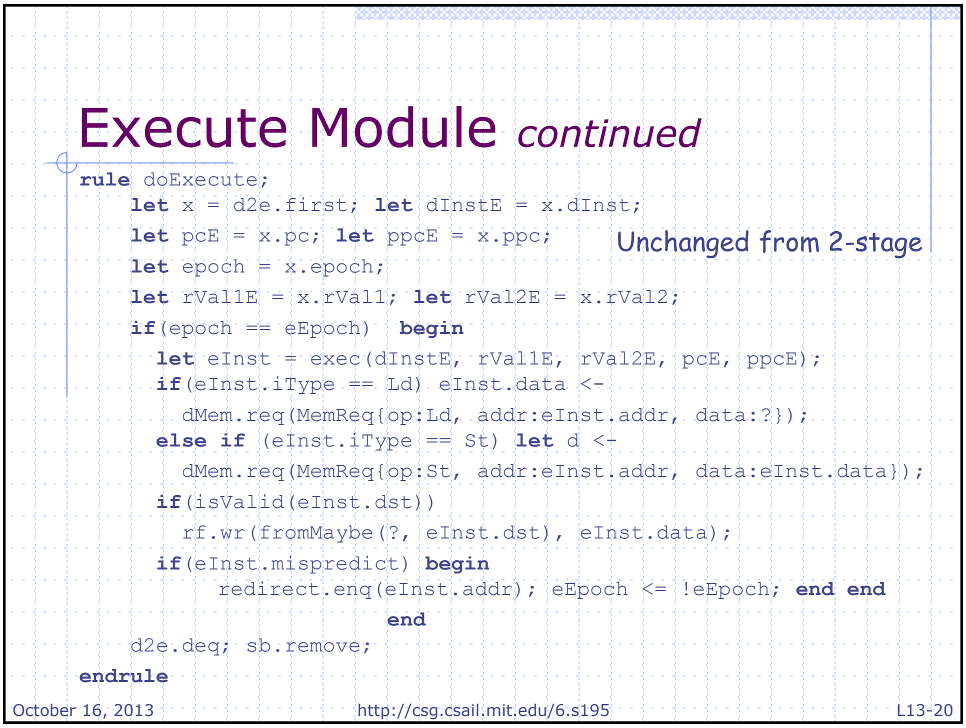
```
rule fetch ;
    if(redirect.notEmpty) begin
      fEpoch <= !fEpoch;  pc <= redirect.first;
      redirect.deq;       end
    else
    begin
      let instF = iMem.req(pc);
      let ppcF = nextAddrPredictor(pc);
      let dInst = decode(instF);
      let stall = sb.search1(dInst.src1)|| sb.search2(dInst.src2);
      if(!stall)                          begin
         let rVal1 = rf.rd1(validRegValue(dInst.src1));
         let rVal2 = rf.rd2(validRegValue(dInst.src2));
         d2e.enq(Decode2Execute{pc: pc, ppc: ppcF,
               dInst: dInst, epoch: fEpoch,
               rVal1: rVal1, rVal2: rVal2});
         sb.insert(dInst.dst); pc <= ppcF; end
    end
endrule
```

Unchanged from 2-stage



Execute Module

```
module mkExecute(Dmemory dMem,
            FifoDeq#(Decode2Execute) d2e,
            FifoEnq#(Addr) redirect,
            RegisterFileWrite rf,
            ScoreboardInsert sb)
   Reg#(Bool)    eEpoch <- mkReg(False);

rule doExecute;
...
endrule
endmodule
```

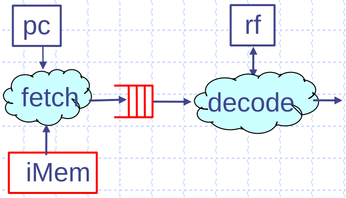


Execute Module *continued*

```
rule doExecute;
    let x = d2e.first; let dInstE = x.dInst;
    let pcE = x.pc; let ppcE = x.ppc;
    let epoch = x.epoch;
    let rVal1E = x.rVal1; let rVal2E = x.rVal2;
    if(epoch == eEpoch)  begin
      let eInst = exec(dInstE, rVal1E, rVal2E, pcE, ppcE);
      if(eInst.iType == Ld) eInst.data <-
        dMem.req(MemReq{op:Ld, addr:eInst.addr, data:?});
      else if (eInst.iType == St) let d <-
        dMem.req(MemReq{op:St, addr:eInst.addr, data:eInst.data});
      if(isValid(eInst.dst))
        rf.wr(fromMaybe(?, eInst.dst), eInst.data);
      if(eInst.mispredict) begin
           redirect.enq(eInst.addr); eEpoch <= !eEpoch; end end
                        end
    d2e.deq; sb.remove;
endrule
```

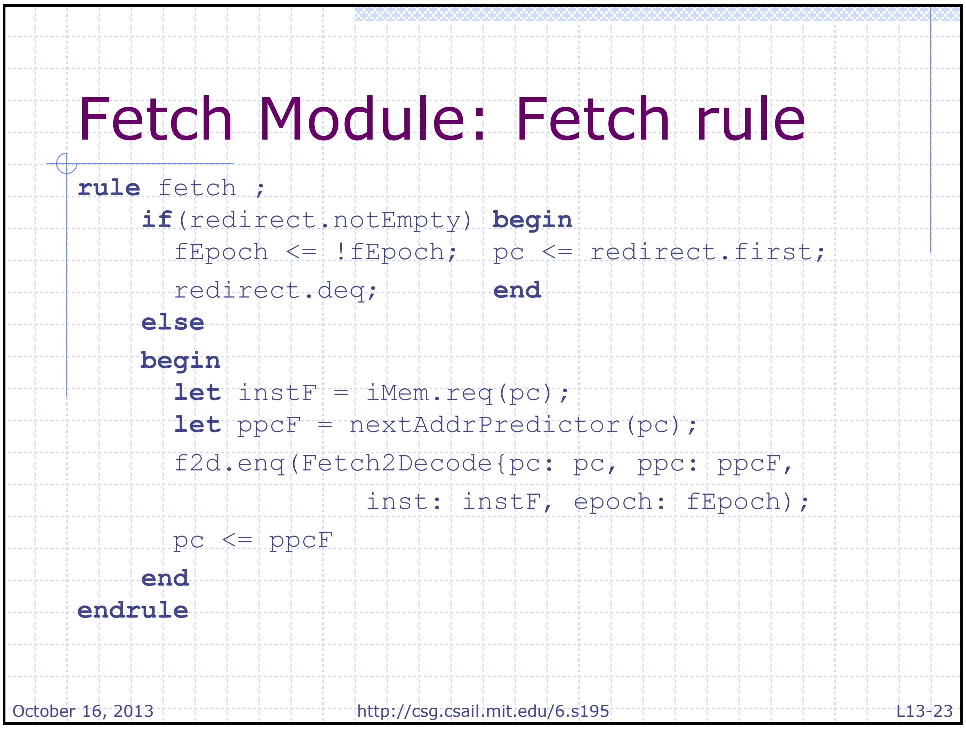
Unchanged from 2-stage

Modular refinement: Separating Fetch and Decode



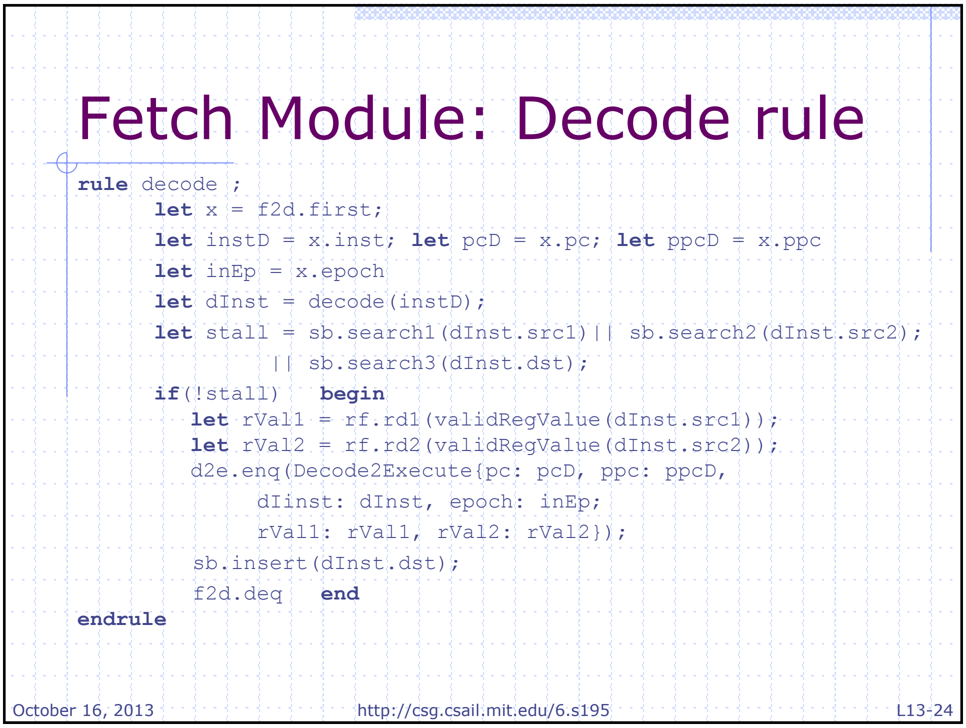
Fetch Module refinement

```
module mkFetch(Imemory iMem,
               FifoEnq#(Decode2Execute) d2e,
               FifoDeq#(Addr) redirect,
               RegisterFileRead rf,
               ScoreboardInsert sb)
    Reg#(Addr)        pc <- mkRegU;
    Reg#(Bool)    fEpoch <- mkReg(False);
    Fifo#(Fetch2Decode) f2d <- mkPipelineFifo;

rule fetch ;
    if(redirect.notEmpty) begin
....
endrule
rule decode ; .... endrule
endmodule
```



Fetch Module: Fetch rule

```
rule fetch ;
    if(redirect.notEmpty) begin
      fEpoch <= !fEpoch;  pc <= redirect.first;
      redirect.deq;       end
    else
    begin
      let instF = iMem.req(pc);
      let ppcF = nextAddrPredictor(pc);
      f2d.enq(Fetch2Decode{pc: pc, ppc: ppcF,
                  inst: instF, epoch: fEpoch);
      pc <= ppcF
    end
endrule
```



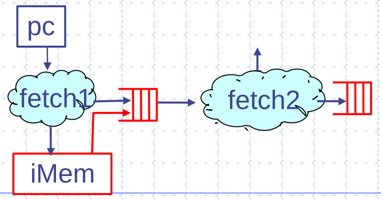
Fetch Module: Decode rule

```
rule decode ;
      let x = f2d.first;
      let instD = x.inst; let pcD = x.pc; let ppcD = x.ppc
      let inEp = x.epoch
      let dInst = decode(instD);
      let stall = sb.search1(dInst.src1)|| sb.search2(dInst.src2);
               || sb.search3(dInst.dst);
      if(!stall)   begin
        let rVal1 = rf.rd1(validRegValue(dInst.src1));
        let rVal2 = rf.rd2(validRegValue(dInst.src2));
        d2e.enq(Decode2Execute{pc: pcD, ppc: ppcD,
              dInst: dInst, epoch: inEp;
              rVal1: rVal1, rVal2: rVal2});
        sb.insert(dInst.dst);
        f2d.deq    end
endrule
```

Separate refinement

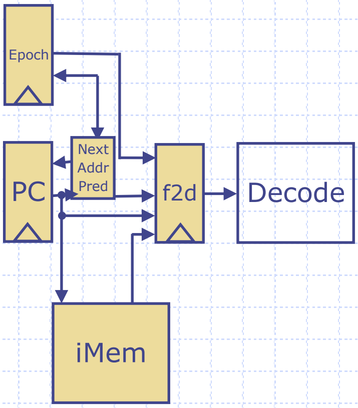
- Notice our refined Fetch&Decode module should work correctly with the old Execute module or its refinements
- This is a very important aspect of modular refinements

Modular refinement: Replace magic memory by multicycle memory



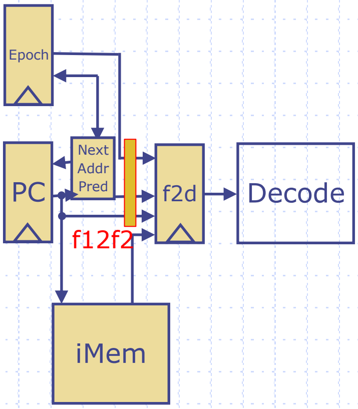
Memory and Caches

- Suppose iMem is replaced by a cache which takes 0 or 1 cycle in case of a hit and unknown number of variable cycles on a cache miss
- View iMem as a request/response system and split the fetch stage into two rules – to send a req and to receive a res

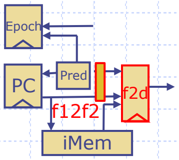


Splitting the fetch stage

- To split the fetch stage into two rules, insert a bypass FIFO’s to deal with (0,n) cycle memory response



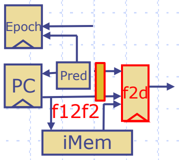
Fetch Module: 2nd refinement



```
module mkFetch(Imemory iMem,
               FifoEnq#(Decode2Execute) d2e,
               FifoDeq#(Addr) redirect,
               RegisterFileRead rf,
               ScoreboardInsert sb)
    Reg#(Addr)          pc <- mkRegU;
    Reg#(Bool)      fEpoch <- mkReg(False);
    Fifo#(Fetch2Decode) f2d <- mkPipelineFifo;
    Fifo#(Fetch2Decode) f12f2 <- mkBypassFifo;

rule fetch1 ; .... endrule
rule fetch1 ; .... endrule
rule decode ; .... endrule
endmodule
```

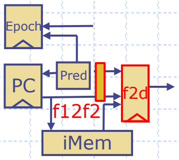
Fetch Module:

Fetch1 rule



```
rule fetch1 ;
    if(redirect.notEmpty) begin
      fEpoch <= !fEpoch;  pc <= redirect.first;
      redirect.deq;       end
    else
    begin
      let ppcF = nextAddrPredictor(pc); pc <= ppc;
      iCache.req(MemReq{op: Ld, addr: pc, data:?});
      f12f2.enq(Fetch2Decoode{pc: pc, ppc: ppcF,
                          inst: ?, epoch: fEpoch});
    end
endrule
```

Fetch Module:
Fetch2 rule



```
rule doFetch2;
  let inst <- iCache.resp;
  let x = f12f2.first;
  x.inst = inst;
  f12f2.deq;
  f2d.enq(x);
endrule
```

Takeaway

- Multistage pipelines are straightforward extensions of 2-stage pipelines
- Modular refinement is a powerful idea; lets different teams work on different modules with only an early implementation of other modules
- BSV compiler currently does not permit separate compilation of modules with interface parameters
- Recursive call structure amongst modules is supported by the compiler in a limited way.
  - The syntax is complicated
  - Compiler detects and rejects truly cyclic method calls