Systems I

Pipelining III

Topics

- Hazard mitigation through pipeline forwarding
- Hardware support for forwarding
- Forwarding to mitigate control (branch) hazards

How do we fix the Pipeline?

Pad the program with NOPs

- Yuck!

Stall the pipeline

- Data hazards
  - Wait for producing instruction to complete
  - Then proceed with consuming instruction
- Control hazards
  - Wait until new PC has been determined
  - Then begin fetching
- How is this better than putting NOPs into the program?

Forward data within the pipeline

- Grab the result from somewhere in the pipe
  - After it has been computed
  - But before it has been written back
- This gives an opportunity to avoid performance degradation due to hazards!

Data Forwarding

Naïve Pipeline

- Register isn't written until completion of write-back stage
- Source operands read from register file in decode stage
  - Needs to be in register file at start of stage

Observation

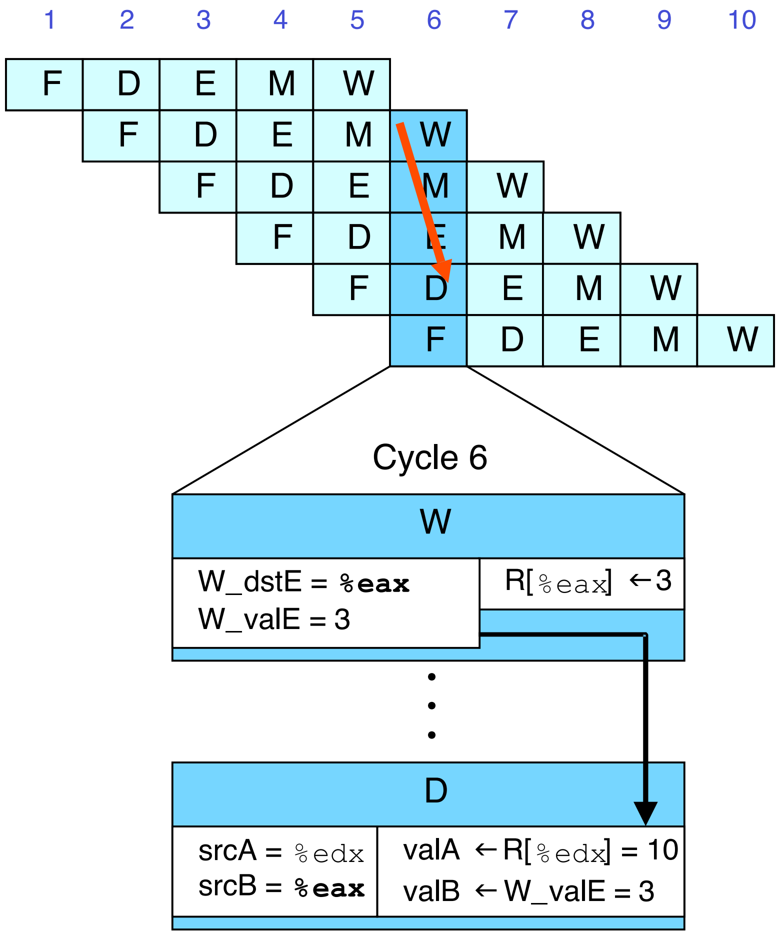
- Value generated in execute or memory stage

Trick

- Pass value directly from generating instruction to decode stage
- Needs to be available at end of decode stage

Data Forwarding Example

```
# demo-h2.ys
0x000: irmovl $10,%edx
0x006: irmovl  $3,%eax
0x00c: nop
0x00d: nop
0x00e: addl %edx,%eax
0x010: halt
```



- `irmovl` in write-back stage
- Destination value in W pipeline register
- Forward as valB for decode stage

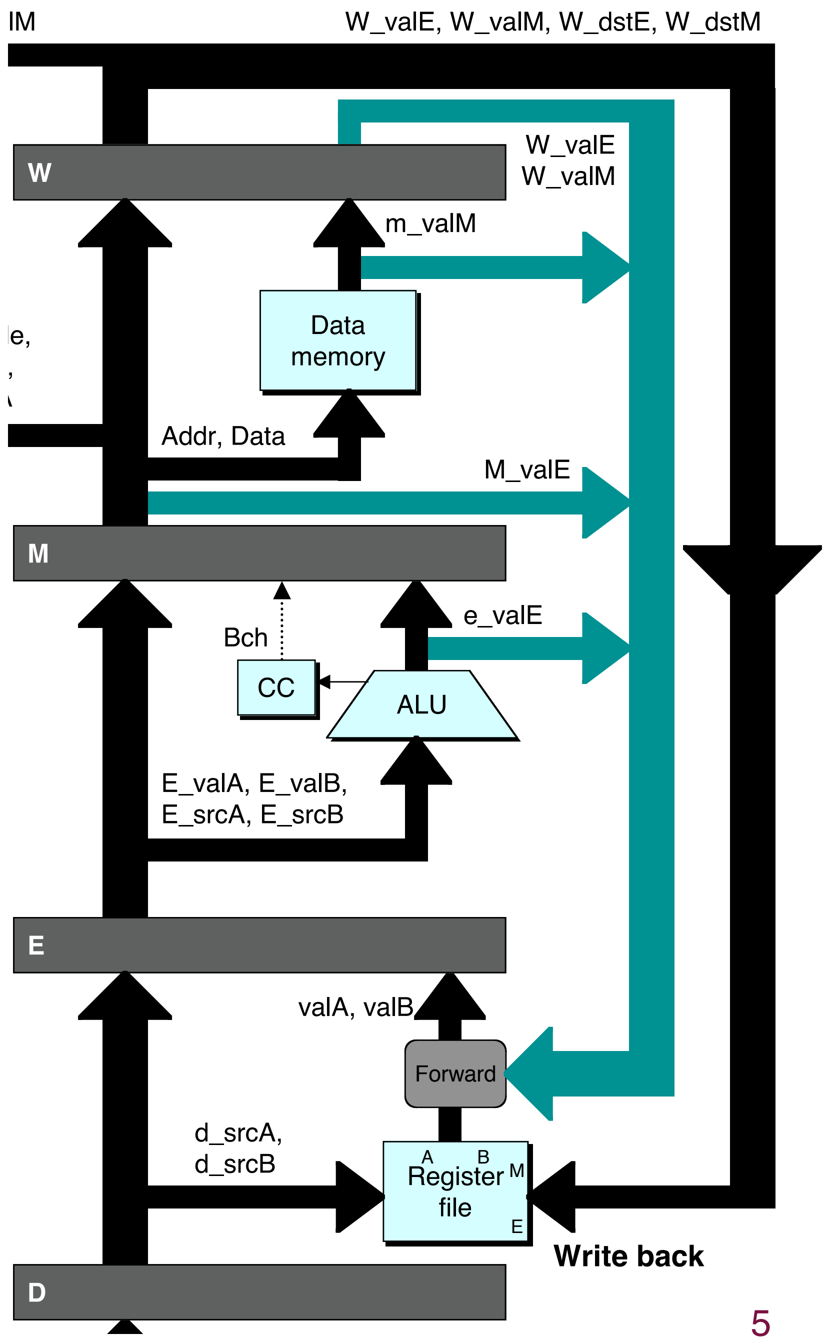
Bypass Paths

Decode Stage

- Forwarding logic selects valA and valB
- Normally from register file
- Forwarding: get valA or valB from later pipeline stage

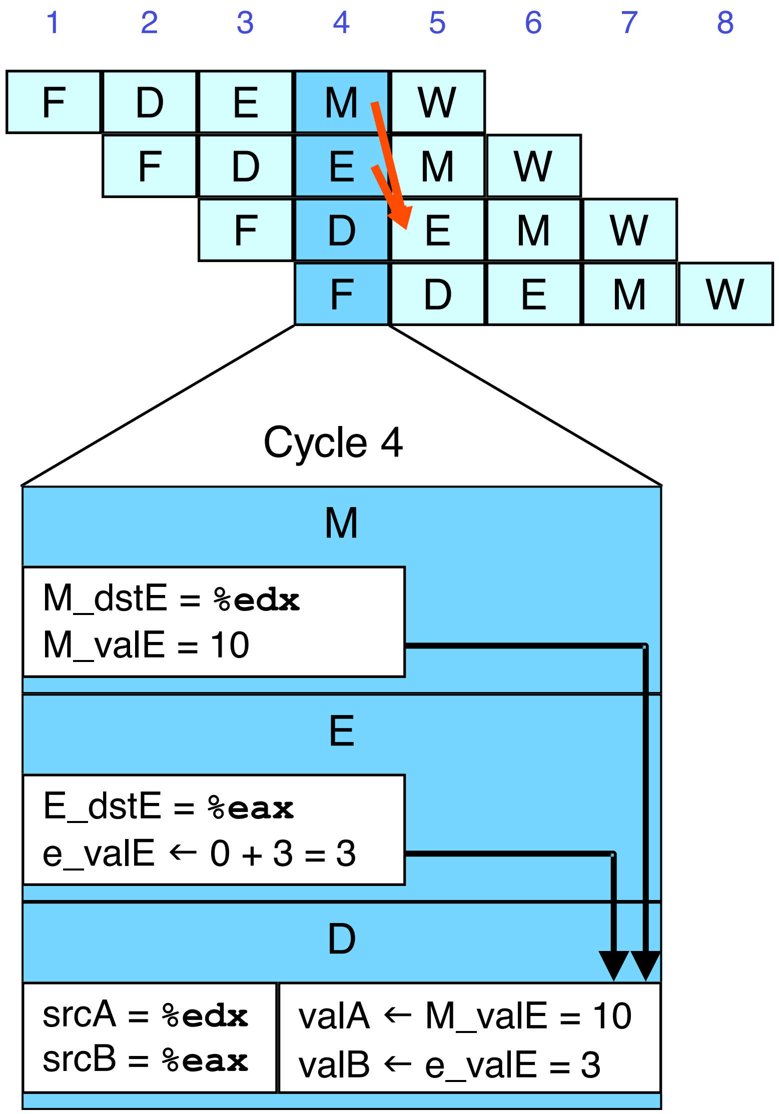
Forwarding Sources

- Execute: valE
- Memory: valE, valM
- Write back: valE, valM



Data Forwarding Example #2

```
# demo-h0.ys
0x000: irmovl $10,%edx
0x006: irmovl  $3,%eax
0x00c: addl %edx,%eax
0x00e: halt
```



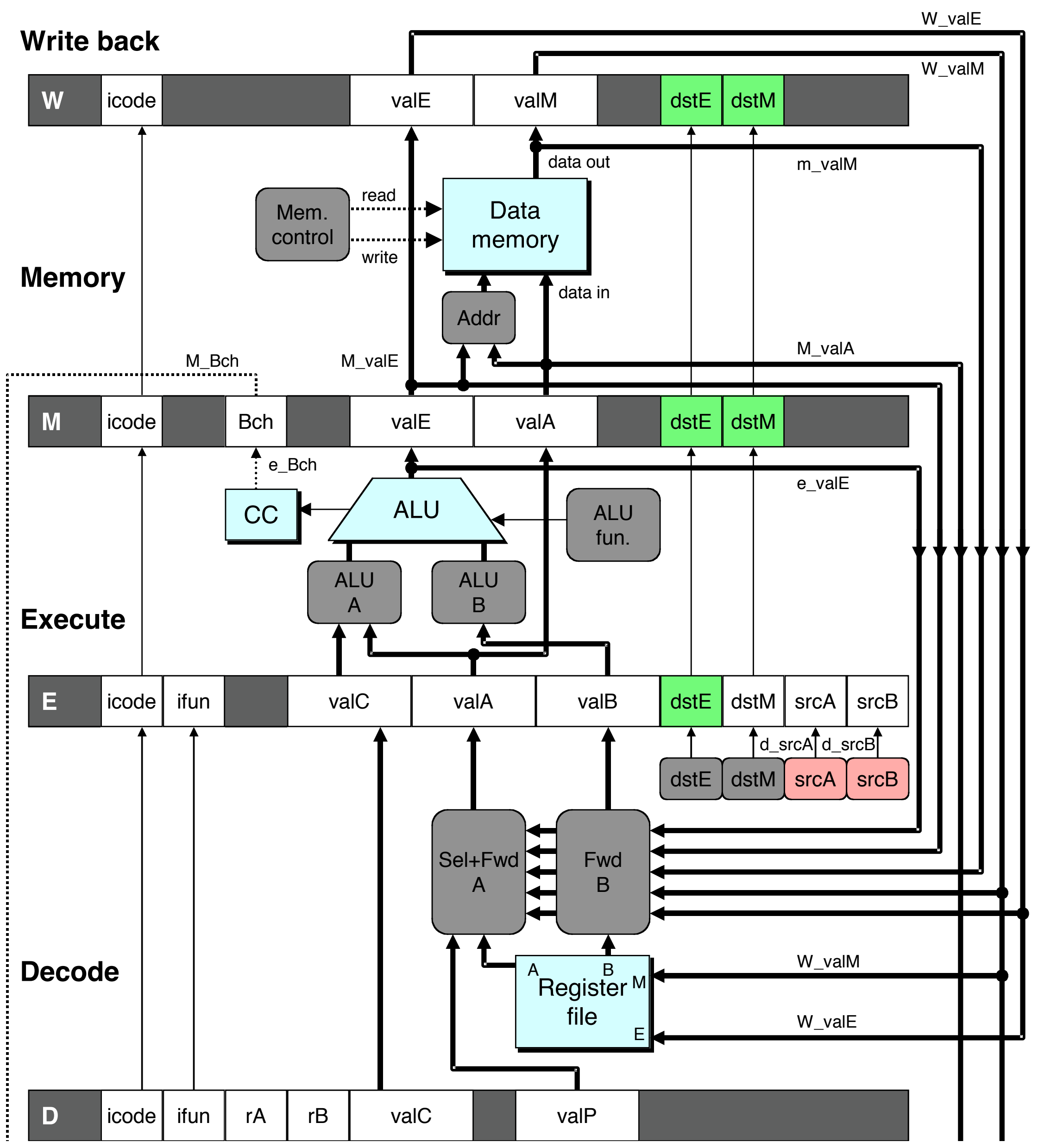
Register `%edx`

- Generated by ALU during previous cycle
- Forward from memory as valA

Register `%eax`

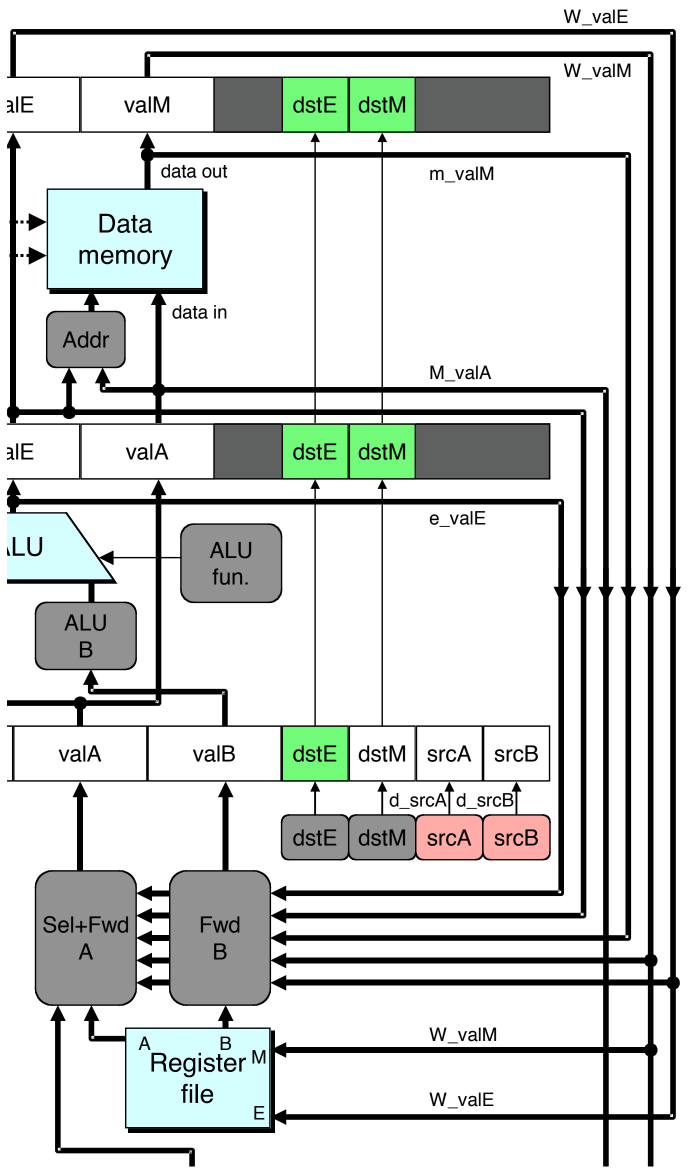
- Value just generated by ALU
- Forward from execute as valB

Implementing Forwarding



- Add additional feedback paths from E, M, and W pipeline registers into decode stage
- Create logic blocks to select from multiple sources for valA and valB in decode stage

Implementing Forwarding

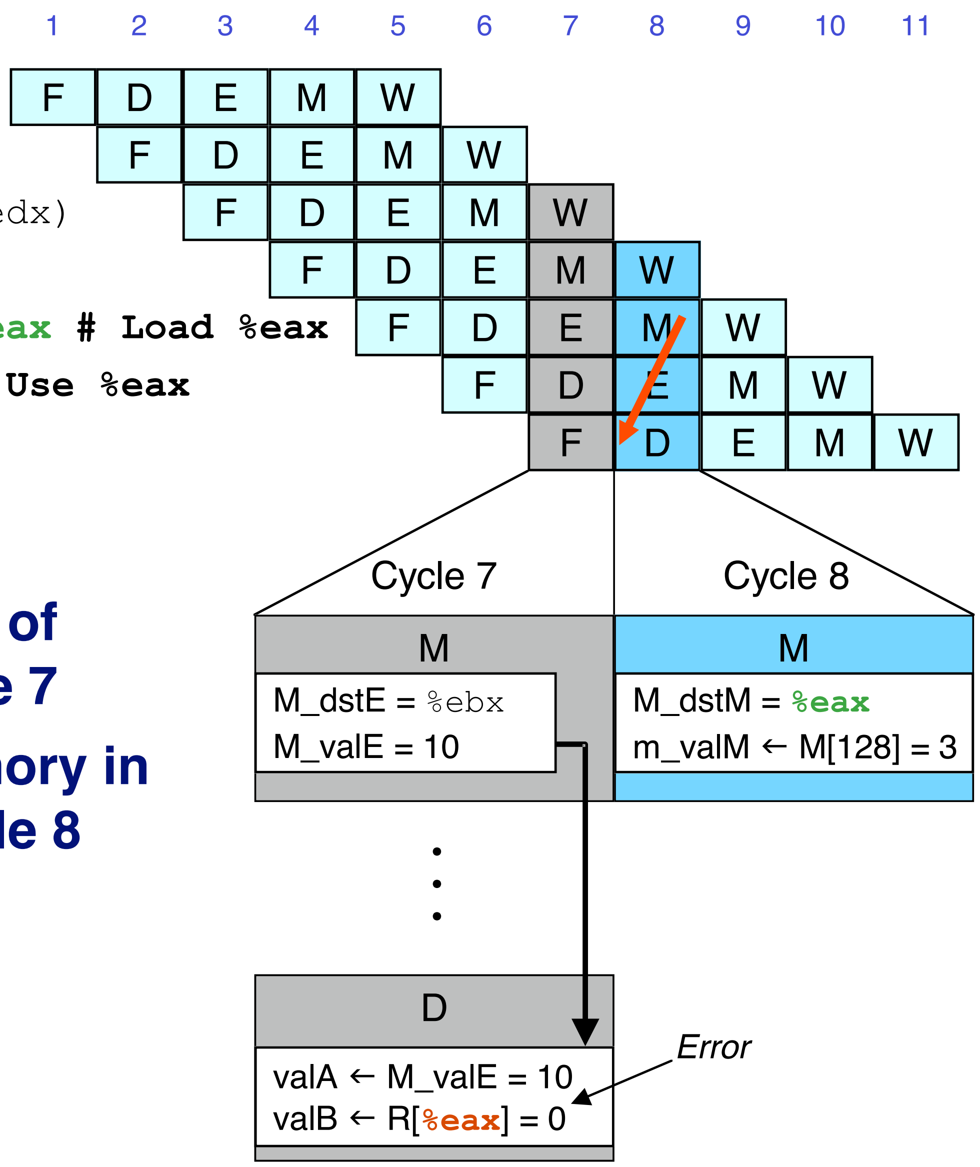


```
## What should be the A value?
int new_E_valA = [
  # Use incremented PC
     D_icode in { ICALL, IJXX } : D_valP;
  # Forward valE from execute
     d_srcA == E_dstE : e_valE;
  # Forward valM from memory
     d_srcA == M_dstM : m_valM;
  # Forward valE from memory
     d_srcA == M_dstE : M_valE;
  # Forward valM from write back
d_srcA == W_dstM : W_valM;
  # Forward valE from write back
     d_srcA == W_dstE : W_valE;
  # Use value read from register file
     1 : d_rvalA;
];
```

Limitation of Forwarding

```
# demo-luh.ys

0x000: irmovl $128,%edx
0x006: irmovl  $3,%ecx
0x00c: rmmovl %ecx, 0(%edx)
0x012: irmovl $10,%ebx
0x018: mrmovl 0(%edx),%eax # Load %eax
0x01e: addl %ebx,%eax # Use %eax
0x020: halt
```



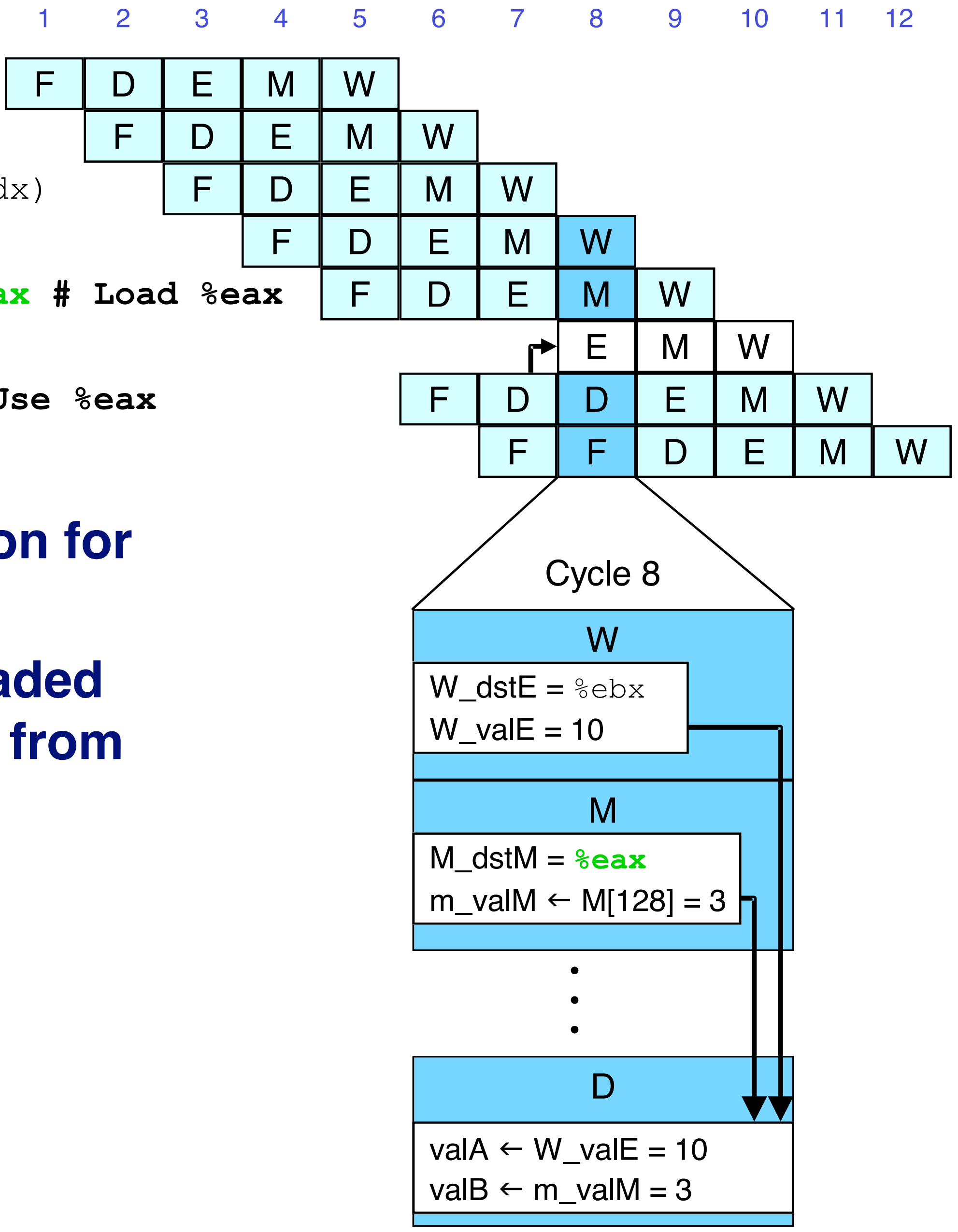
Load-use dependency

- Value needed by end of decode stage in cycle 7
- Value read from memory in memory stage of cycle 8

Avoiding Load/Use Hazard

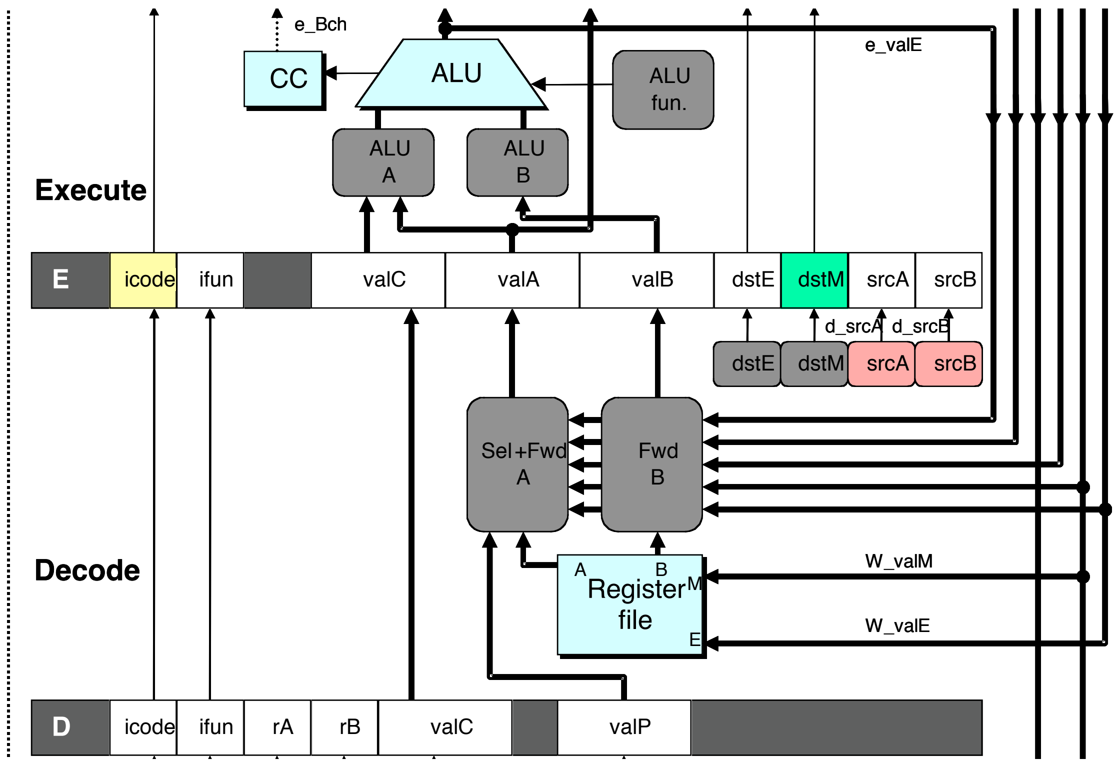
```
# demo-luh.ys

0x000: irmovl $128,%edx
0x006: irmovl  $3,%ecx
0x00c: rmmovl %ecx, 0(%edx)
0x012: irmovl $10,%ebx
0x018: mrmovl 0(%edx),%eax # Load %eax
       bubble
0x01e: addl %ebx,%eax # Use %eax
0x020: halt
```



- Stall using instruction for one cycle
- Can then pick up loaded value by forwarding from memory stage

Detecting Load/Use Hazard



Condition	Trigger
Load/Use Hazard	E_icode in { IMRMOVL, IPOPL } && E_dstM in { d_srcA, d_srcB }

Control for Load/Use Hazard

`# demo-luh.ys`	1	2	3	4	5	6	7	8	9	10	11	12
`0x000: irmovl $128,%edx`	F	D	E	M	W							
`0x006: irmovl  $3,%ecx`		F	D	E	M	W						
`0x00c: rmmovl %ecx, 0(%edx)`			F	D	E	M	W					
`0x012: irmovl $10,%ebx`				F	D	E	M	W				
`0x018: mrmovl 0(%edx),%eax # Load %eax`					F	D	E	M	W			
bubble								E	M	W		
`0x01e: addl %ebx,%eax # Use %eax`						F	D	D	E	M	W	
`0x020: halt`							F	F	D	E	M	W

- **Stall instructions in fetch and decode stages**
- **Inject bubble into execute stage**

Condition	F	D	E	M	W
Load/Use Hazard	stall	stall	bubble	normal	normal

Branch Misprediction Example

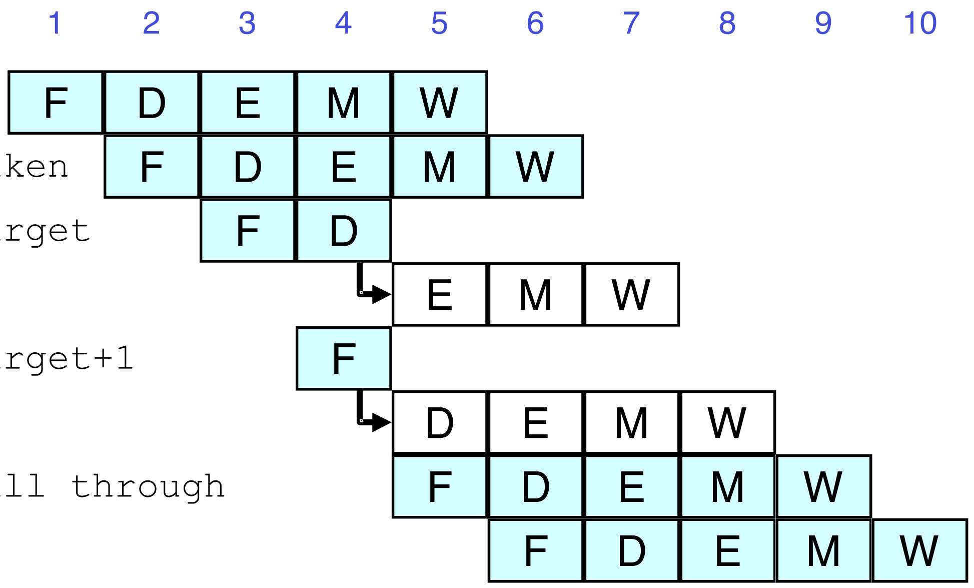
demo-j.ys

```
0x000:    xorl %eax,%eax
0x002:    jne  t              # Not taken
0x007:    irmovl $1, %eax     # Fall through
0x00d:    nop
0x00e:    nop
0x00f:    nop
0x010:    halt
0x011: t: irmovl $3, %edx     # Target (Should not execute)
0x017:    irmovl $4, %ecx     # Should not execute
0x01d:    irmovl $5, %edx     # Should not execute
```

- Should only execute first 7 instructions

Handling Misprediction

```
# demo-j.ys
0x000:    xorl %eax,%eax
0x002:    jne target # Not taken
0x011: t: irmovl $2,%edx # Target
          bubble
0x017:    irmovl $3,%ebx # Target+1
          bubble
0x007:    irmovl $1,%eax # Fall through
0x00d:    nop
```



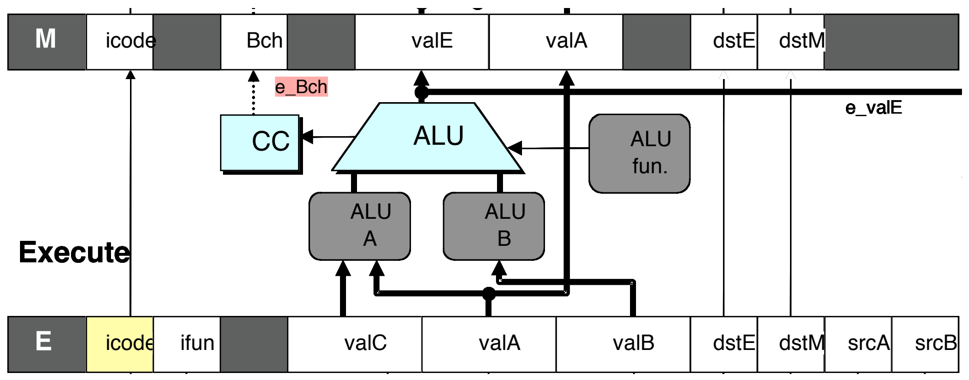
Predict branch as taken

- Fetch 2 instructions at target

Cancel when mispredicted

- Detect branch not-taken in execute stage
- On following cycle, replace instructions in execute and decode by bubbles
- No side effects have occurred yet

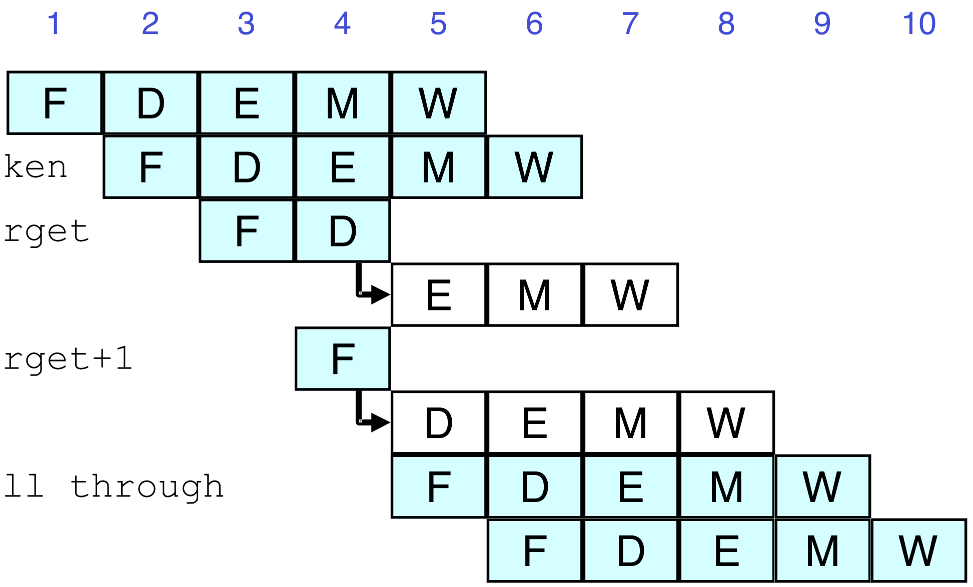
Detecting Mispredicted Branch



Condition	Trigger
Mispredicted Branch	E_icode = IJXX & !e_Bch

Control for Misprediction

```
# demo-j.ys
0x000:    xorl %eax,%eax
0x002:    jne target # Not taken
0x011: t: irmovl $2,%edx # Target
          bubble
0x017:    irmovl $3,%ebx # Target+1
          bubble
0x007:    irmovl $1,%eax # Fall through
0x00d:    nop
```



Condition	F	D	E	M	W
Mispredicted Branch	normal	bubble	bubble	normal	normal

Return Example

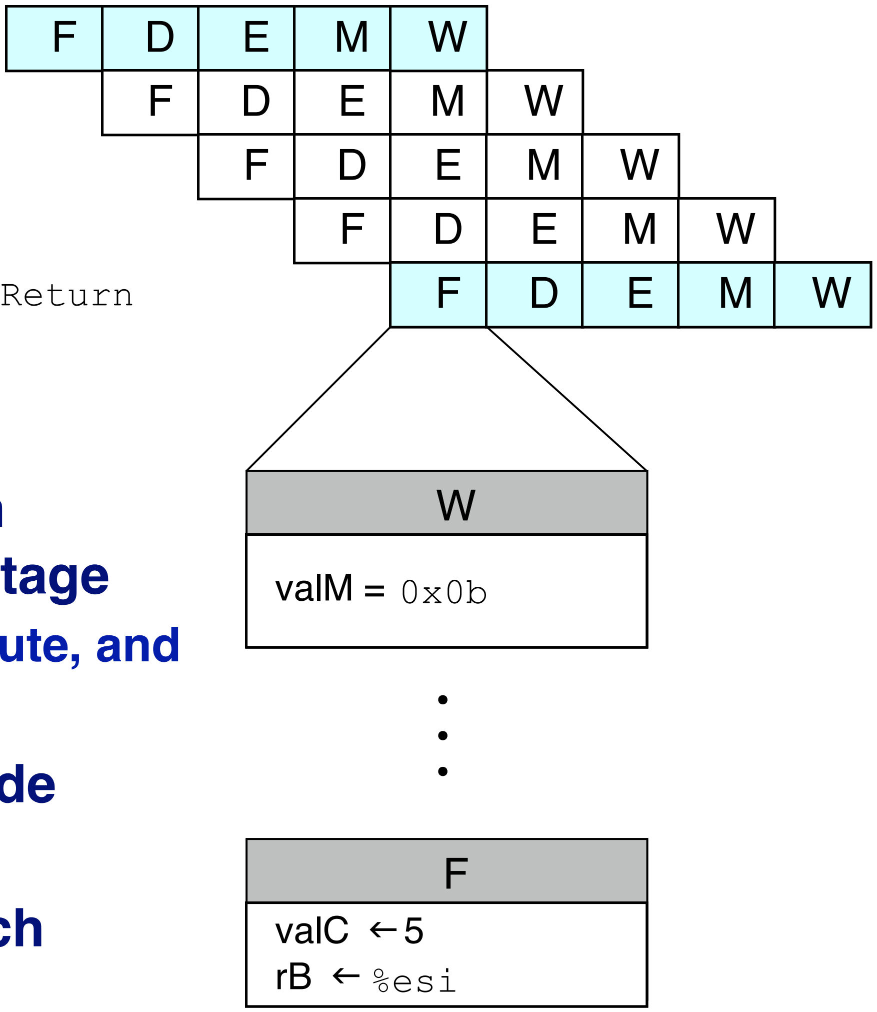
`demo-retb.ys`

```
0x000:     irmovl Stack,%esp   # Initialize stack pointer
0x006:     call p              # Procedure call
0x00b:     irmovl $5,%esi      # Return point
0x011:     halt
0x020: .pos 0x20
0x020: p:  irmovl $-1,%edi     # procedure
0x026:     ret
0x027:     irmovl $1,%eax      # Should not be executed
0x02d:     irmovl $2,%ecx      # Should not be executed
0x033:     irmovl $3,%edx      # Should not be executed
0x039:     irmovl $4,%ebx      # Should not be executed
0x100: .pos 0x100
0x100: Stack:                  # Stack: Stack pointer
```

- **Previously executed three additional instructions**

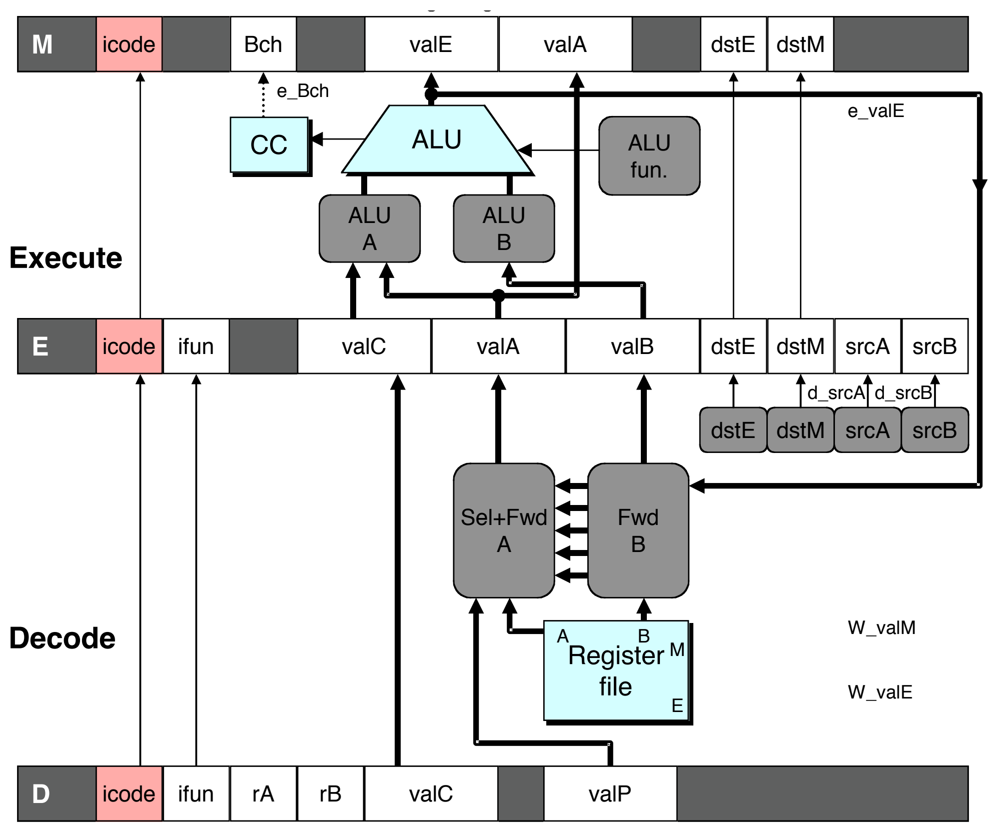
Correct Return Example

```
# demo-retb
0x026:    ret
          bubble
          bubble
          bubble
0x00b:    irmovl $5,%esi # Return
```



- As `ret` passes through pipeline, stall at fetch stage
  - While in decode, execute, and memory stage
- Inject bubble into decode stage
- Release stall when reach write-back stage

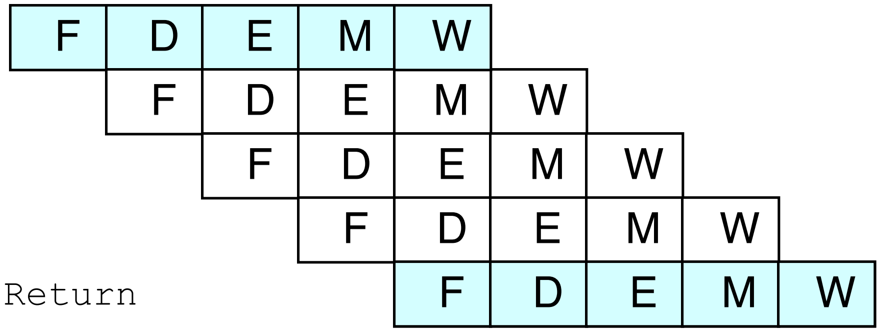
Detecting Return



Condition	Trigger
Processing ret	IRET in { D_icode, E_icode, M_icode }

Control for Return

```
# demo-retb
0x026:    ret
          bubble
          bubble
          bubble
0x00b:    irmovl $5,%esi # Return
```



Condition	F	D	E	M	W
Processing ret	stall	bubble	normal	normal	normal

Special Control Cases

Detection

Condition	Trigger
Processing ret	IRET in { D_icode, E_icode, M_icode }
Load/Use Hazard	E_icode in { IMRMOVL, IPOPL } && E_dstM in { d_srcA, d_srcB }
Mispredicted Branch	E_icode = IJXX & !e_Bch

Action (on next cycle)

Condition	F	D	E	M	W
Processing ret	stall	bubble	normal	normal	normal
Load/Use Hazard	stall	stall	bubble	normal	normal
Mispredicted Branch	normal	bubble	bubble	normal	normal

Summary

Today

- Hazard mitigation through pipeline forwarding
- Hardware support for forwarding
- Forwarding to mitigate control (branch) hazards

Next Time

- Implementing pipeline control
- Pipelining and performance analysis