

CS:APP Chapter 4
Computer Architecture
Pipelined
Implementation
Part II

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Overview

Make the pipelined processor work!

Data Hazards

- Instruction having register R as source follows shortly after instruction having register R as destination
- Common condition, don't want to slow down pipeline

Control Hazards

- Mispredict conditional branch
 - Our design predicts all branches as being taken
 - Naïve pipeline executes two extra instructions
- Getting return address for `ret` instruction
 - Naïve pipeline executes three extra instructions

Making Sure It Really Works

- What if multiple special cases happen simultaneously?

Pipeline Stages

Fetch

- Select current PC
- Read instruction
- Compute incremented PC

Decode

- Read program registers

Execute

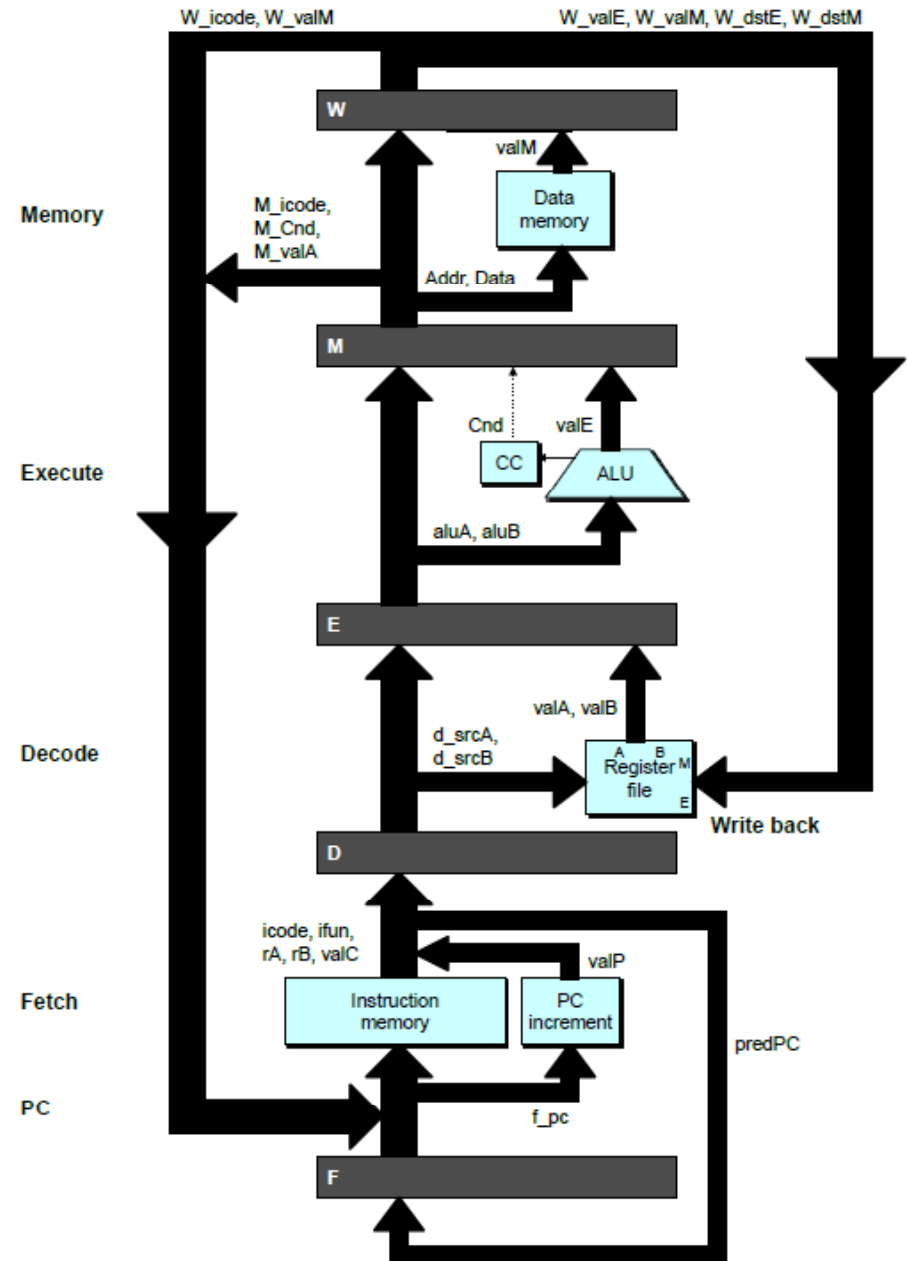
- Operate ALU

Memory

- Read or write data memory

Write Back

- Update register file

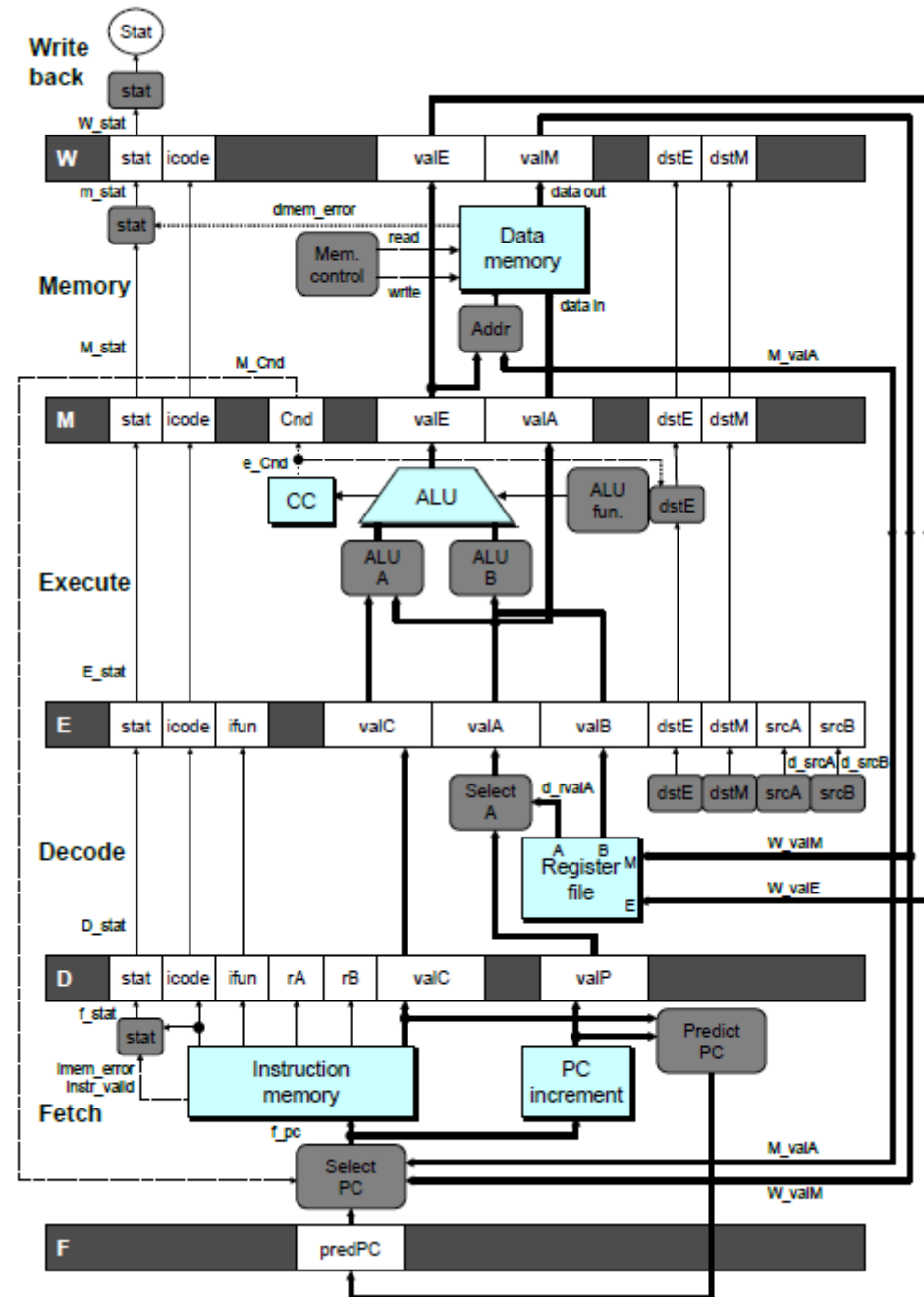


PIPE- Hardware

- Pipeline registers hold intermediate values from instruction execution

Forward (Upward) Paths

- Values passed from one stage to next
- Cannot jump past stages
 - e.g., valC passes through decode



Data Dependencies: 2 Nop's

demo-h2.y

0x000: irmovl \$10,%edx

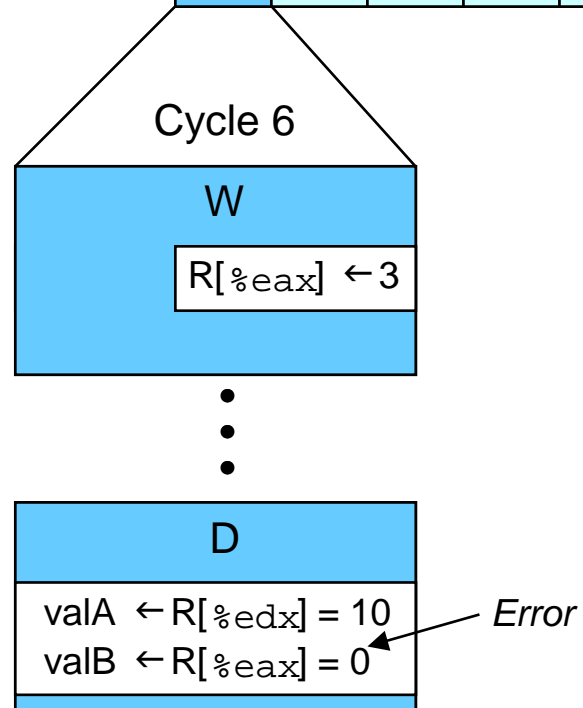
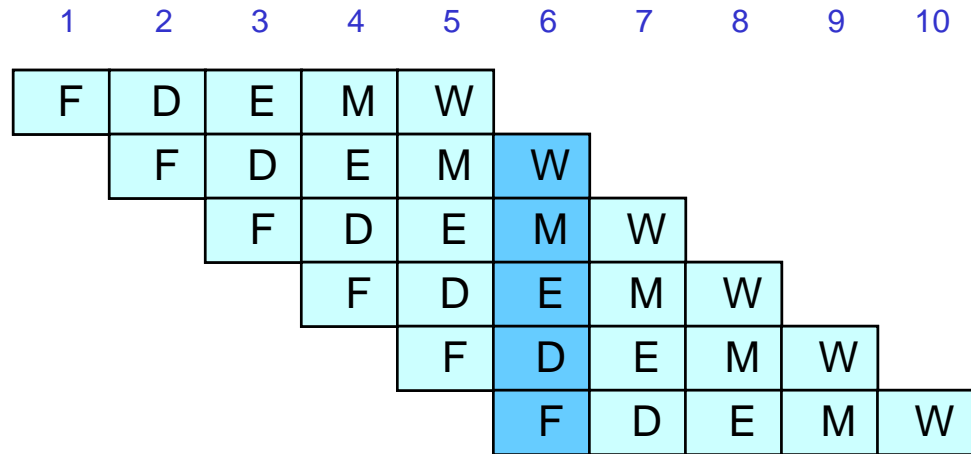
0x006: irmovl \$3,%eax

0x00c: nop

0x00d: nop

0x00e: addl %edx,%eax

0x010: halt



Data Dependencies: No Nop

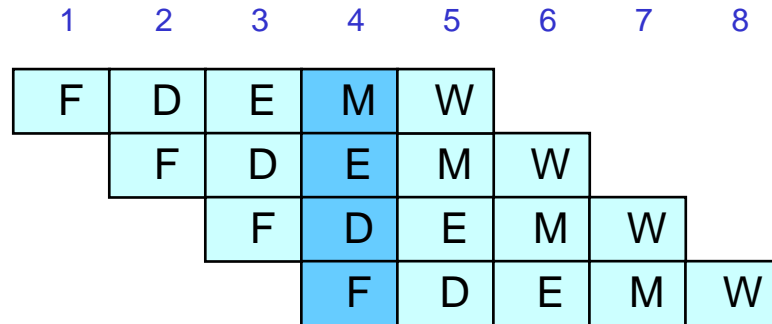
```
# demo-h0.ys
```

```
0x000: irmovl $10,%edx
```

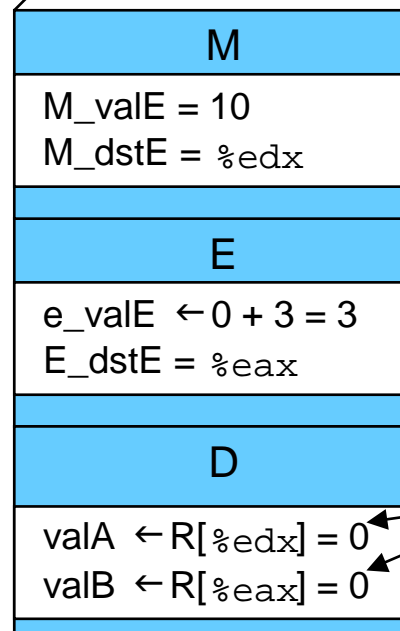
```
0x006: irmovl $3,%eax
```

```
0x00c: addl %edx,%eax
```

```
0x00e: halt
```



Cycle 4



Error

Stalling for Data Dependencies

```
# demo-h2.y
```

```
0x000: irmovl $10,%edx
```

```
0x006: irmovl $3,%eax
```

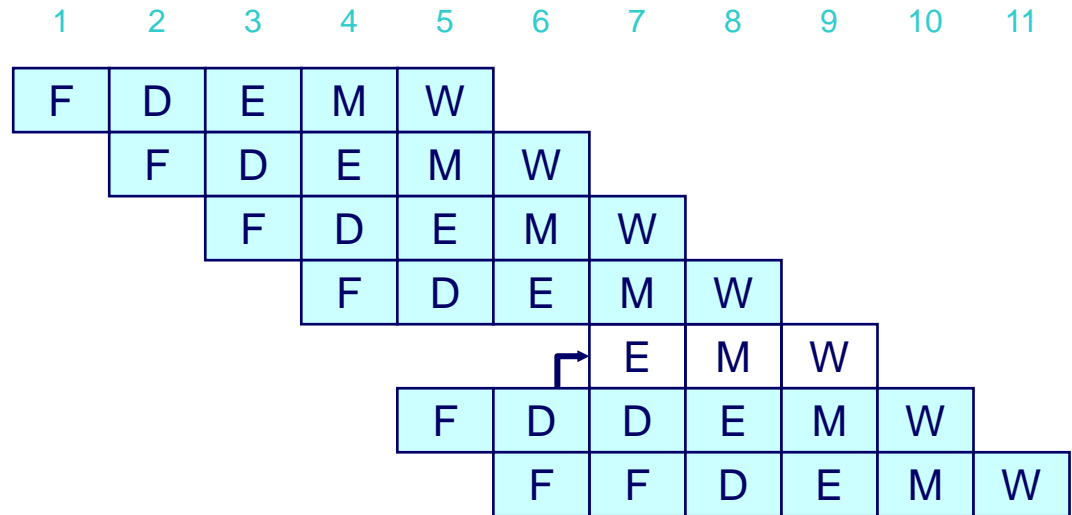
```
0x00c: nop
```

```
0x00d: nop
```

```
    bubble
```

```
0x00e: addl %edx,%eax
```

```
0x010: halt
```



- If instruction follows too closely after one that writes register, slow it down
- Hold instruction in decode
- Dynamically inject nop into execute stage

Stall Condition

Source Registers

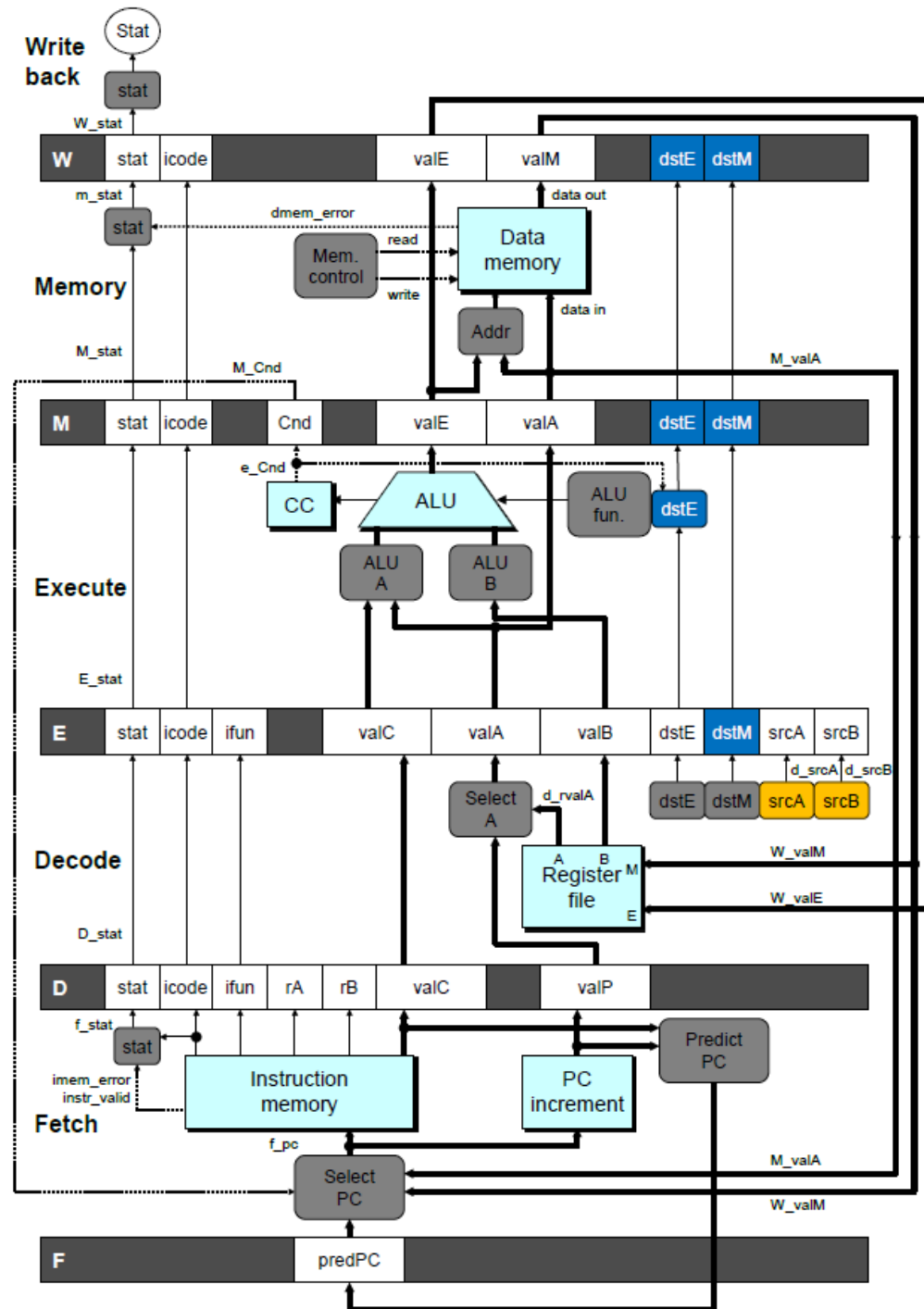
- srcA and srcB of current instruction in decode stage

Destination Registers

- dstE and dstM fields
- Instructions in execute, memory, and write-back stages

Special Case

- Don't stall for register ID 15 (0xF)
 - Indicates absence of register operand
- Don't stall for failed conditional move



Detecting Stall Condition

```
# demo-h2.y
```

```
0x000: irmovl $10,%edx
```

```
0x006: irmovl $3,%eax
```

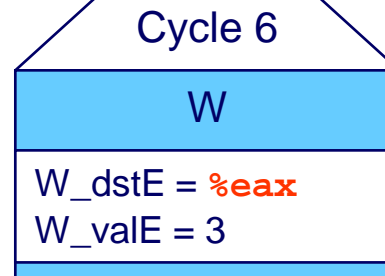
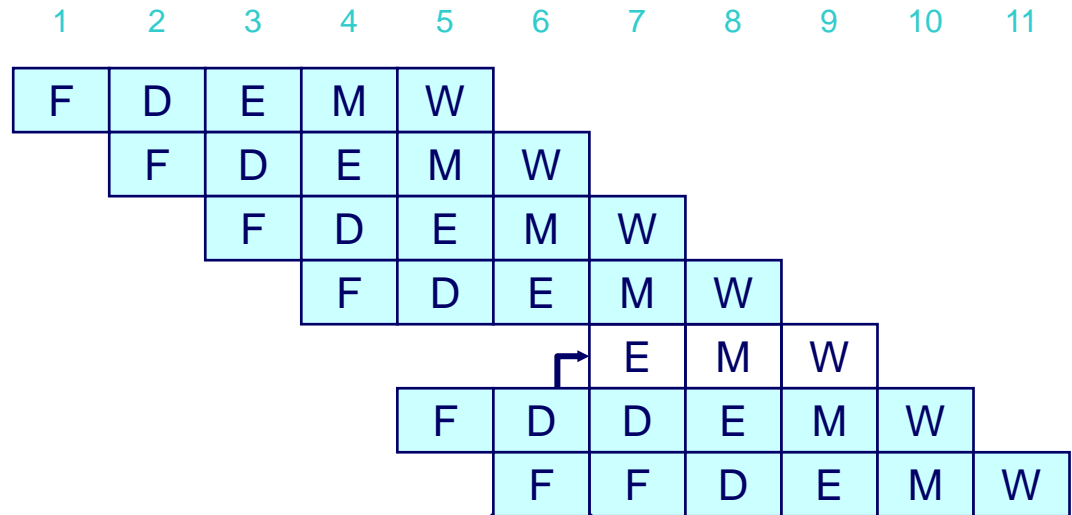
```
0x00c: nop
```

```
0x00d: nop
```

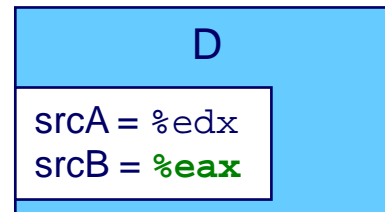
bubble

```
0x00e: addl %edx,%eax
```

```
0x010: halt
```

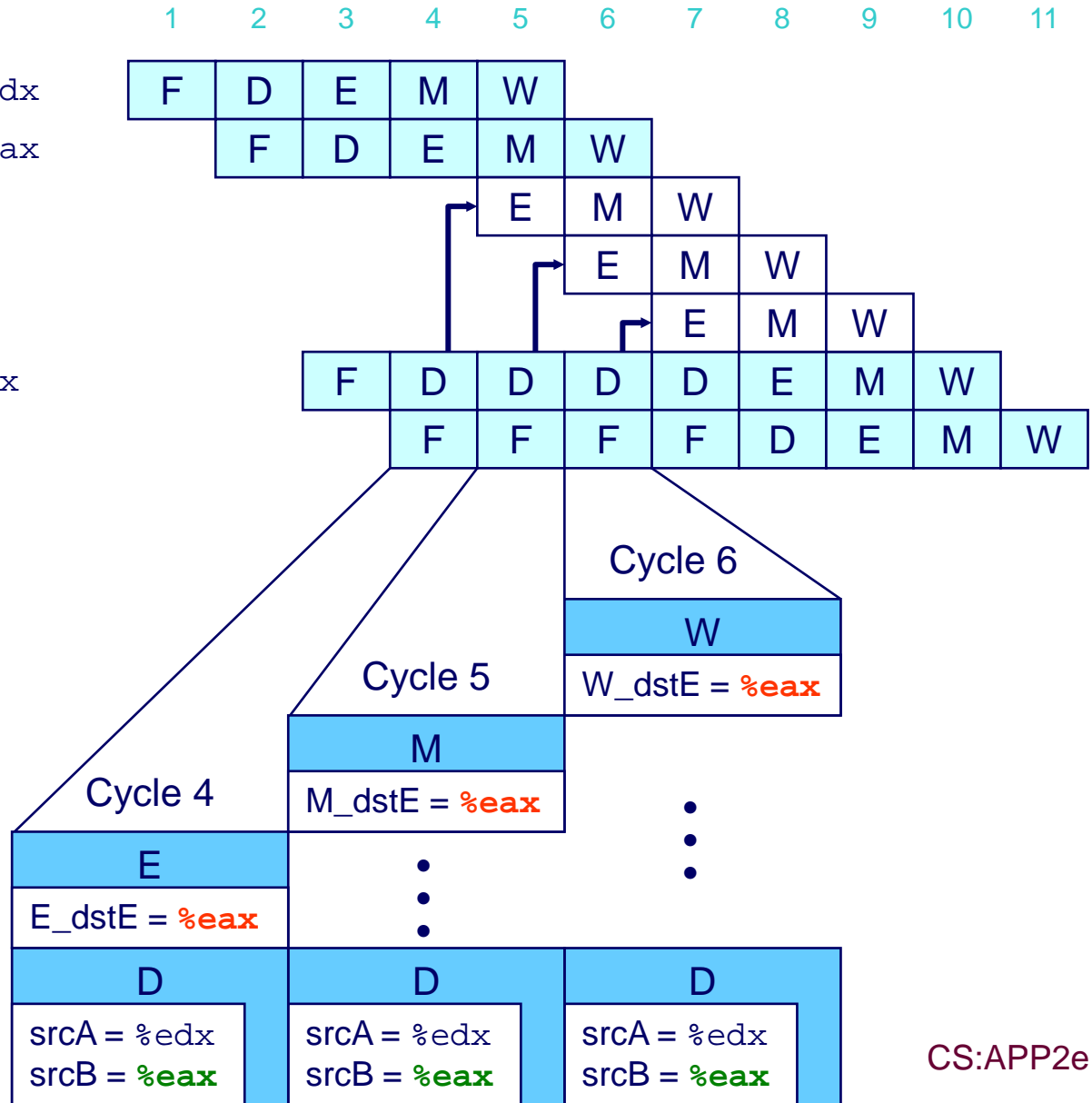


⋮



Stalling X3

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



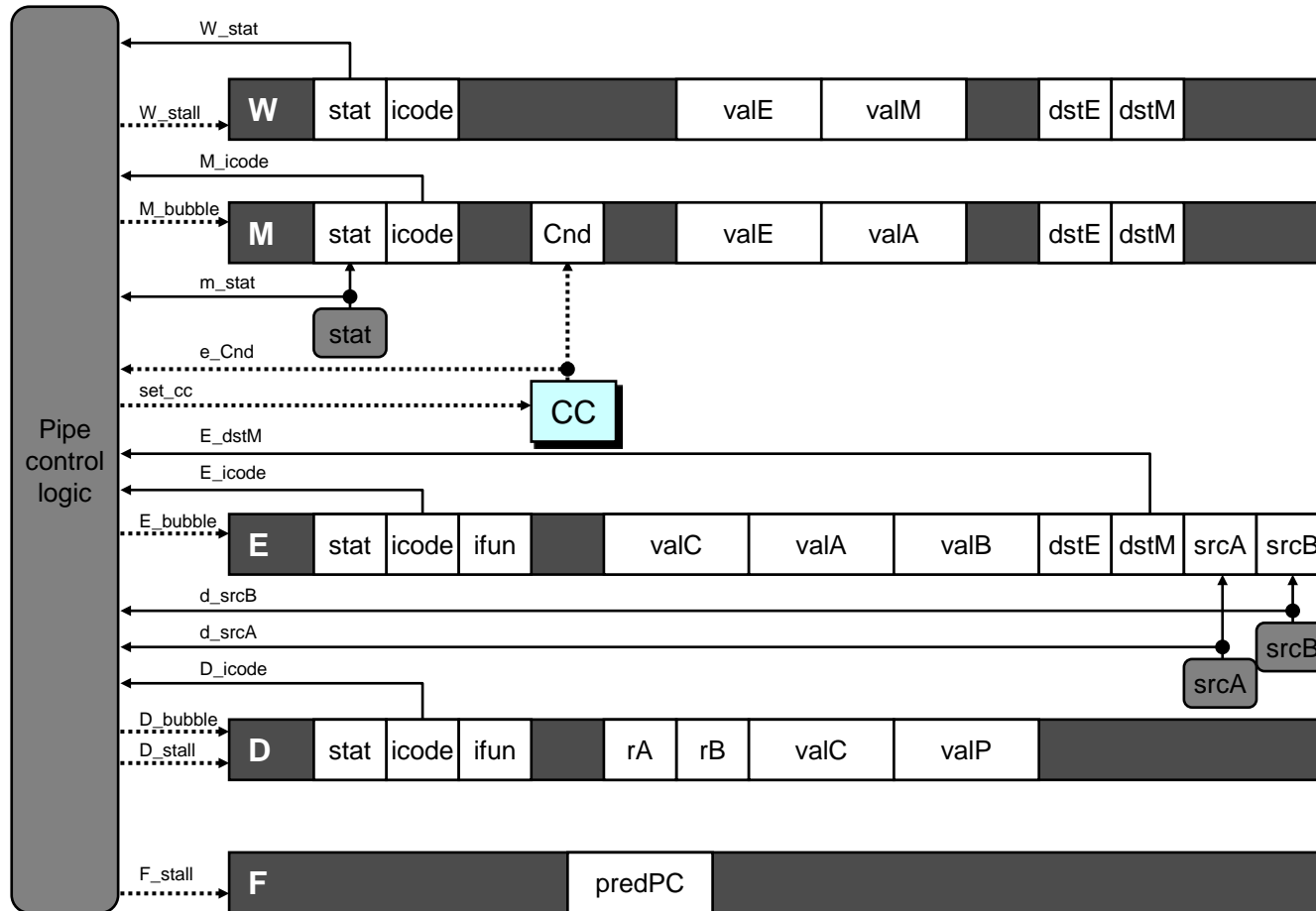
What Happens When Stalling?

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

Cycle 8	
Write Back	<i>bubble</i>
Memory	<i>bubble</i>
Execute	0x00c: addl %edx,%eax
Decode	0x00e: halt
Fetch	

- **Stalling instruction held back in decode stage**
- **Following instruction stays in fetch stage**
- **Bubbles injected into execute stage**
 - Like dynamically generated nop's
 - Move through later stages

Implementing Stalling

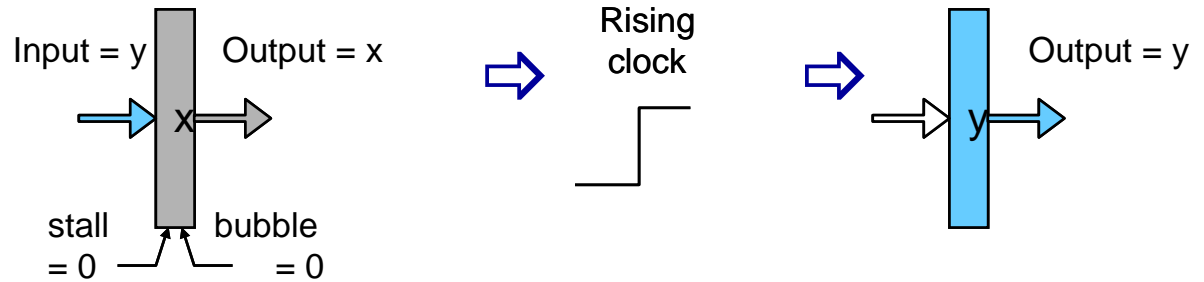


Pipeline Control

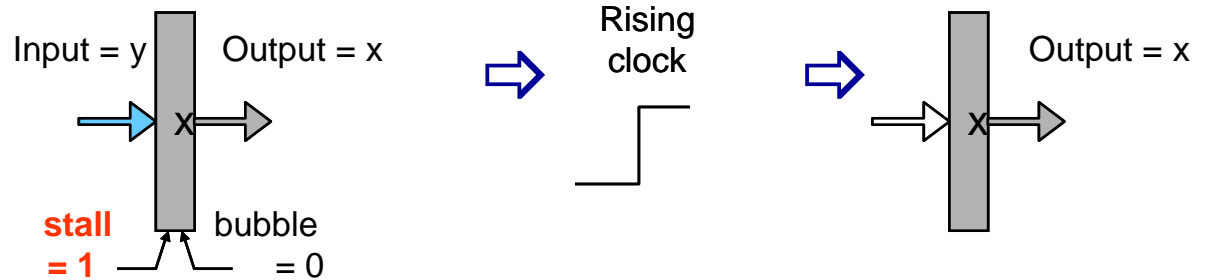
- Combinational logic detects stall condition
- Sets mode signals for how pipeline registers should update

Pipeline Register Modes

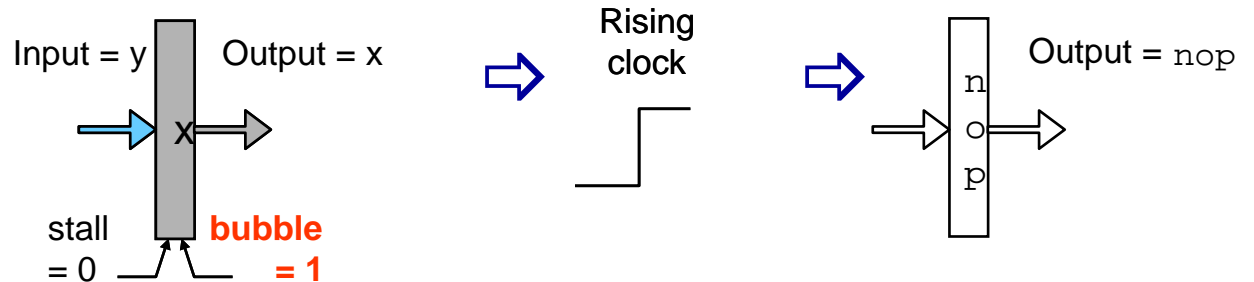
Normal



Stall



Bubble



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

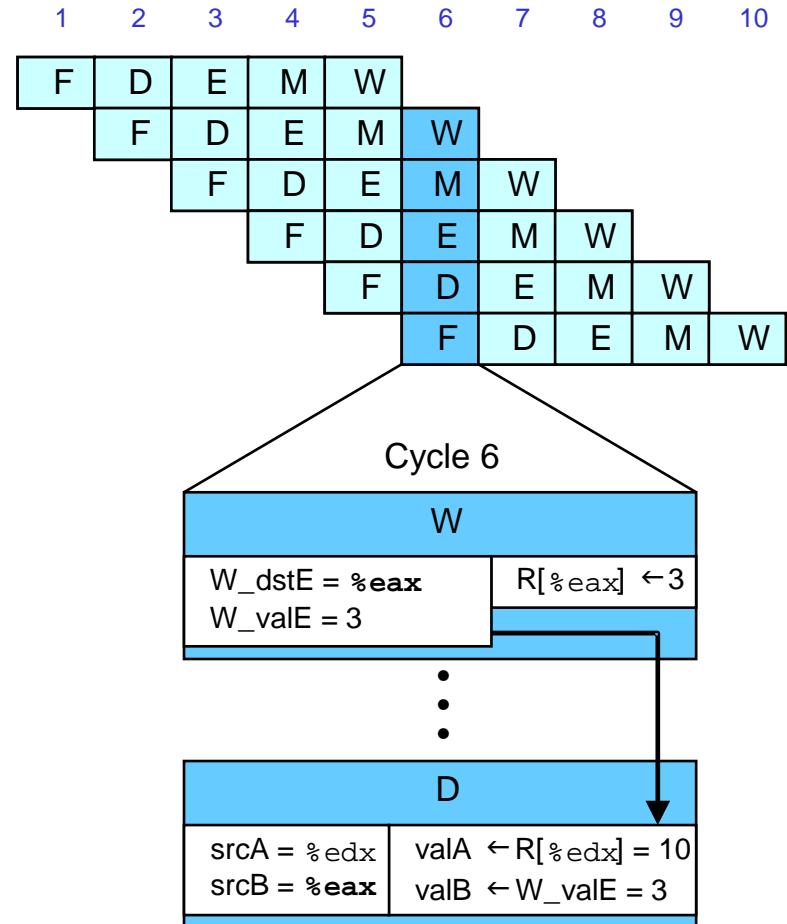
Trick

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

Data Forwarding Example

```
# demo-h2.y
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



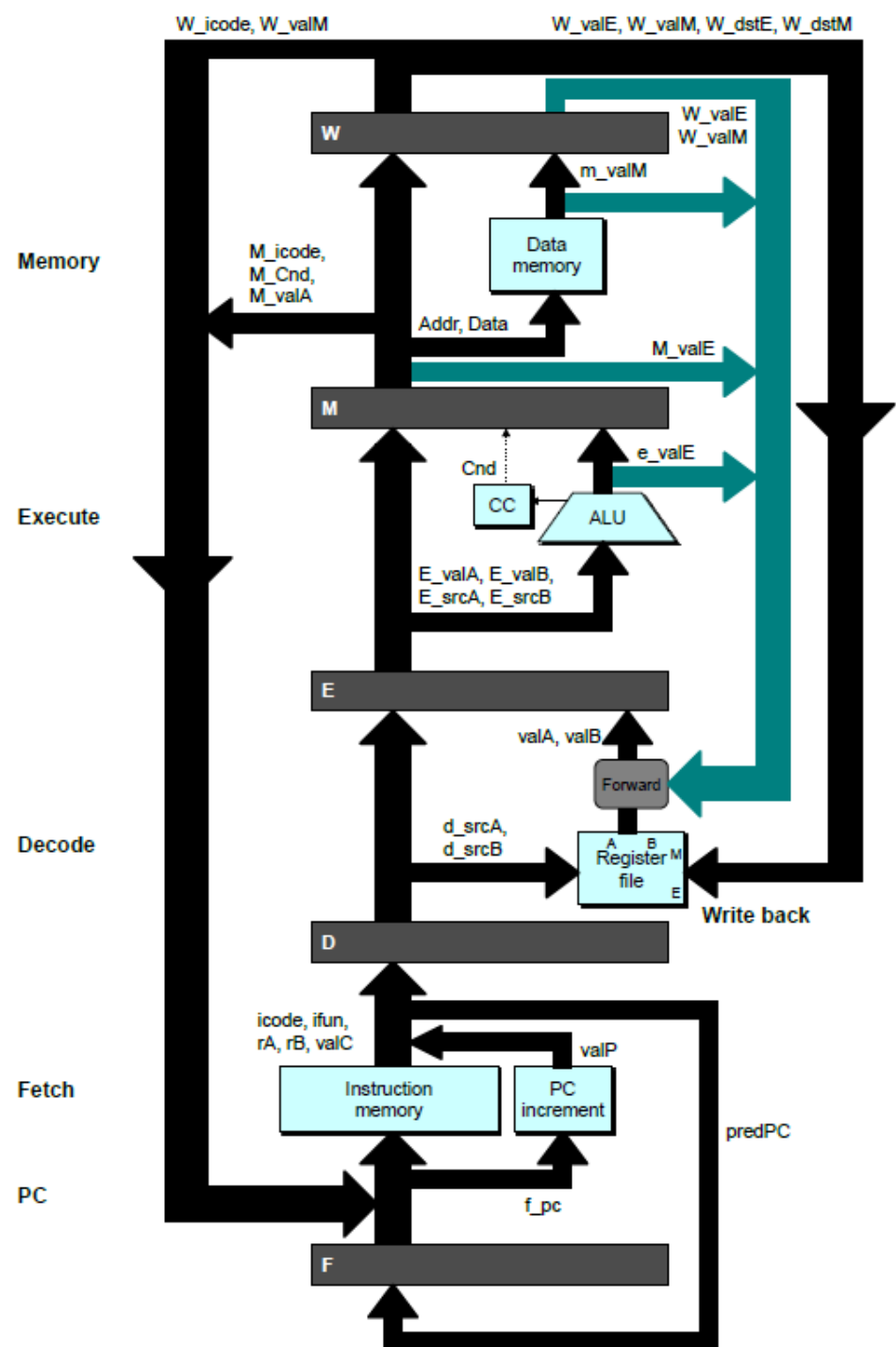
Bypass Paths

Decode Stage

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

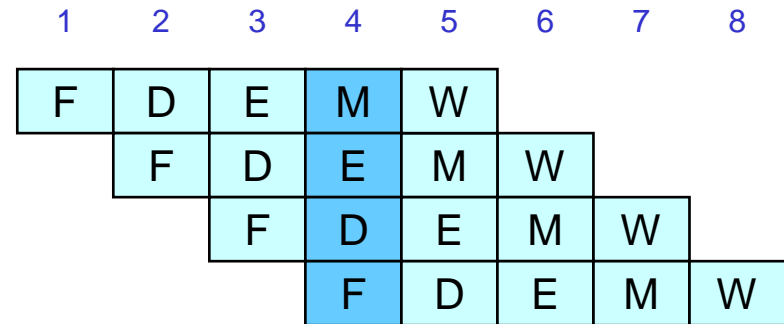
Forwarding Sources

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



Data Forwarding Example #2

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

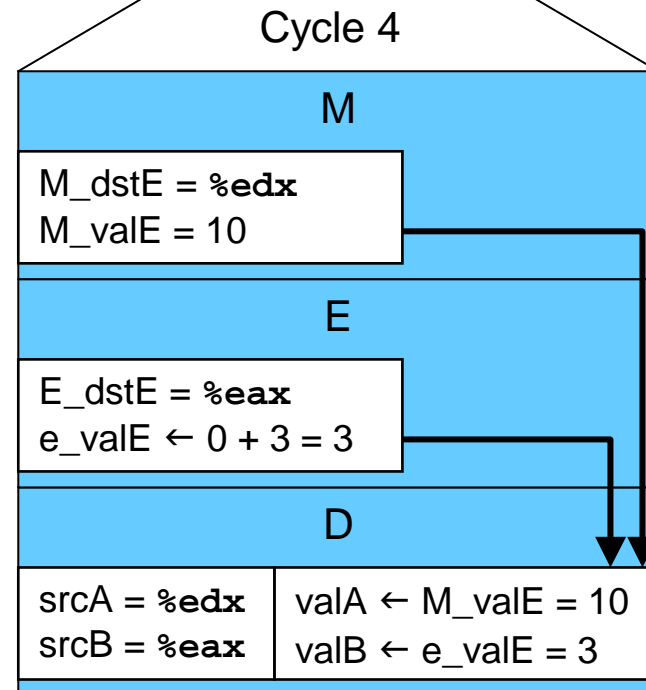


Register %edx

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

Register %eax

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



Forwarding Priority

```
# demo-priority.js
```

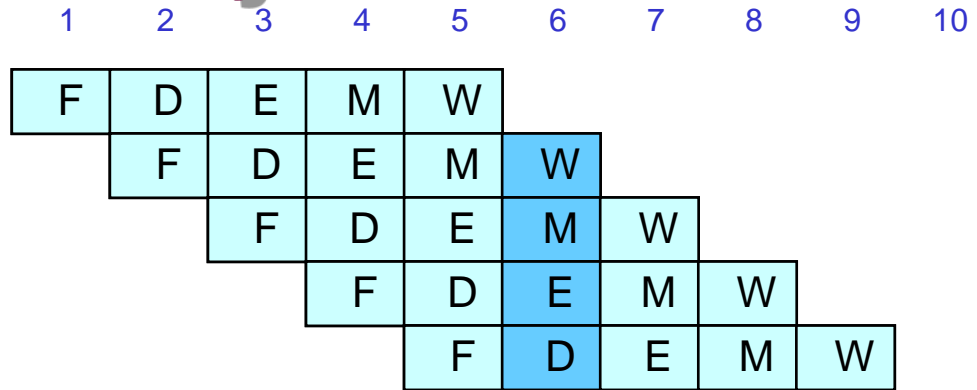
```
0x000: irmovl $1, %eax
```

```
0x006: irmovl $2, %eax
```

```
0x00c: irmovl $3, %eax
```

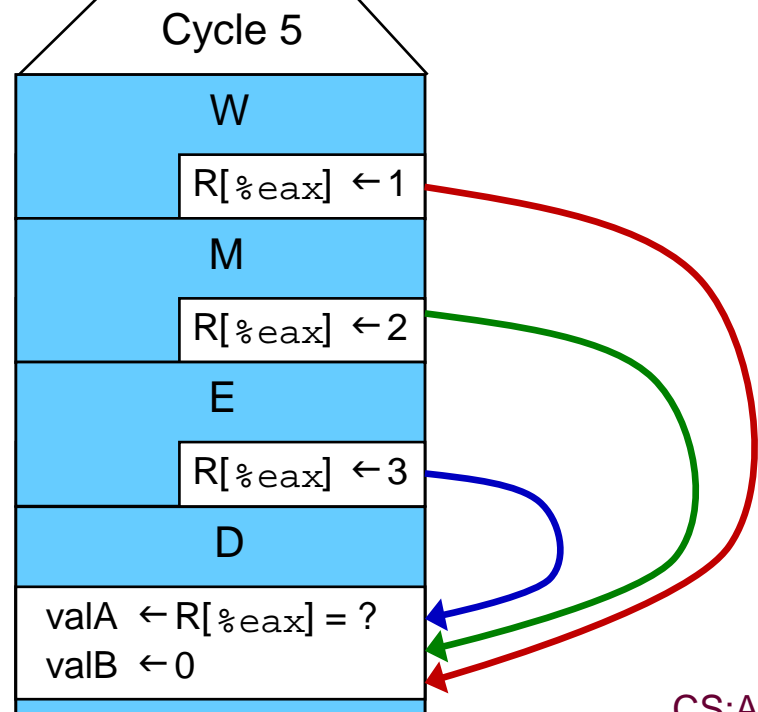
```
0x012: rrmovl %eax, %edx
```

```
0x014: halt
```

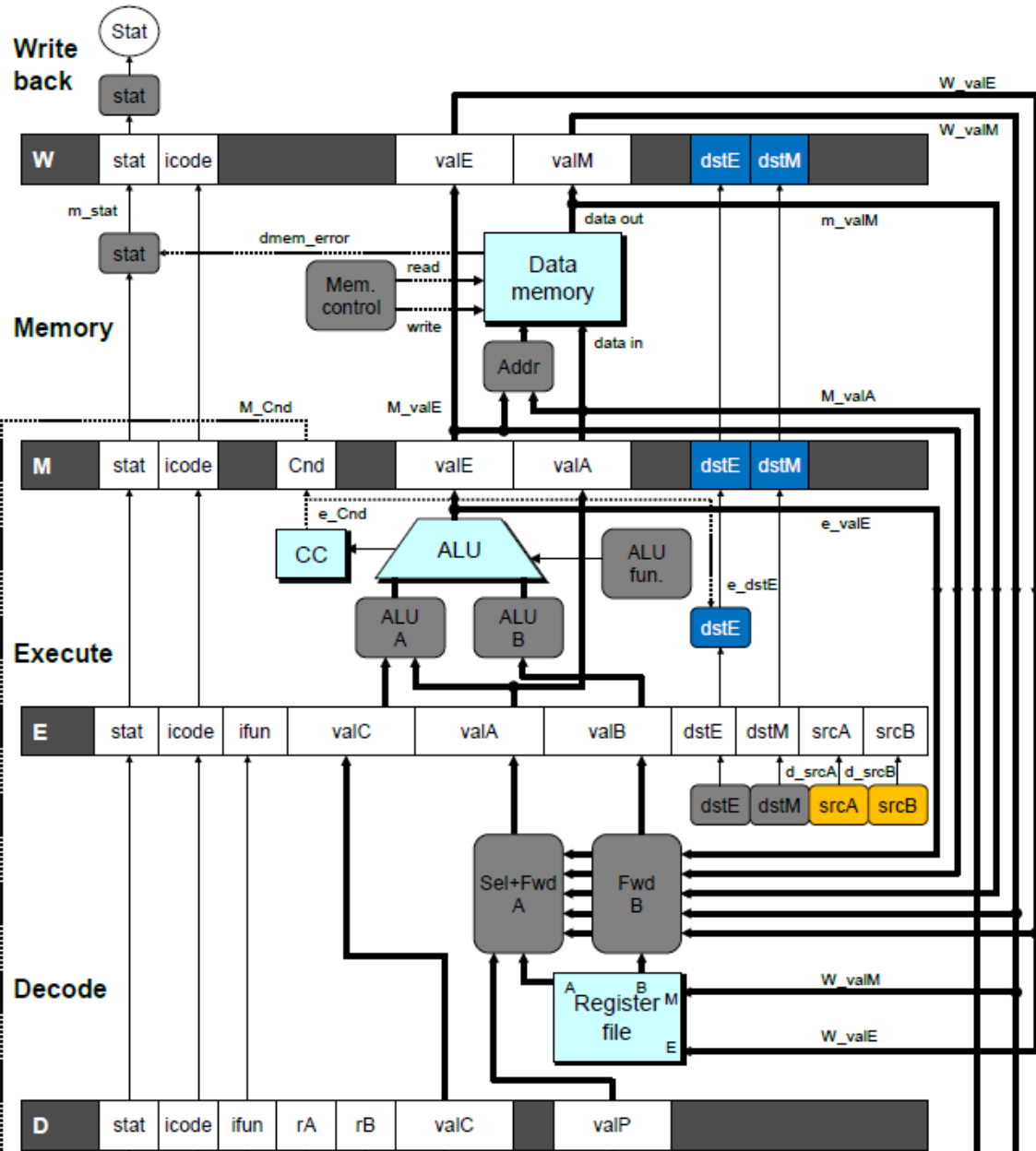


Multiple Forwarding Choices

- Which one should have priority
- Match serial semantics
- Use matching value from earliest pipeline stage



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

Limitation of Forwarding

demo-luh.y

0x000: irmovl \$128,%edx

0x006: irmovl \$3,%ecx

0x00c: rmmovl %ecx, 0(%edx)

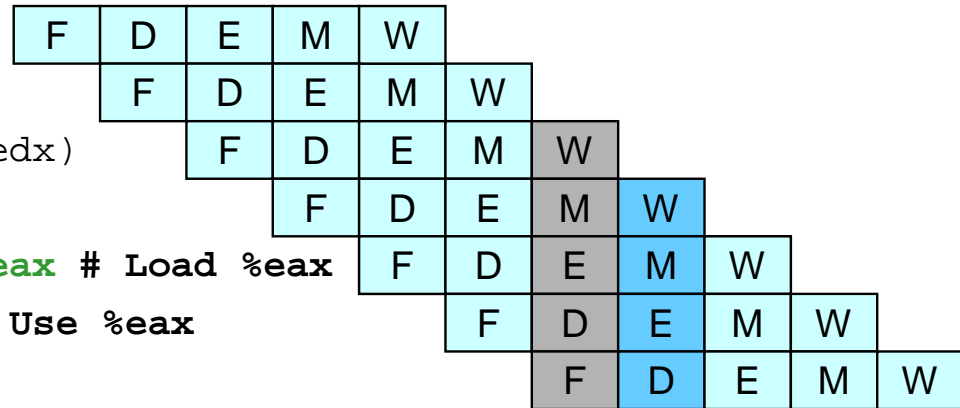
0x012: irmovl \$10,%ebx

0x018: mrmovl 0(%edx),%eax # Load %eax

0x01e: addl %ebx,%eax # Use %eax

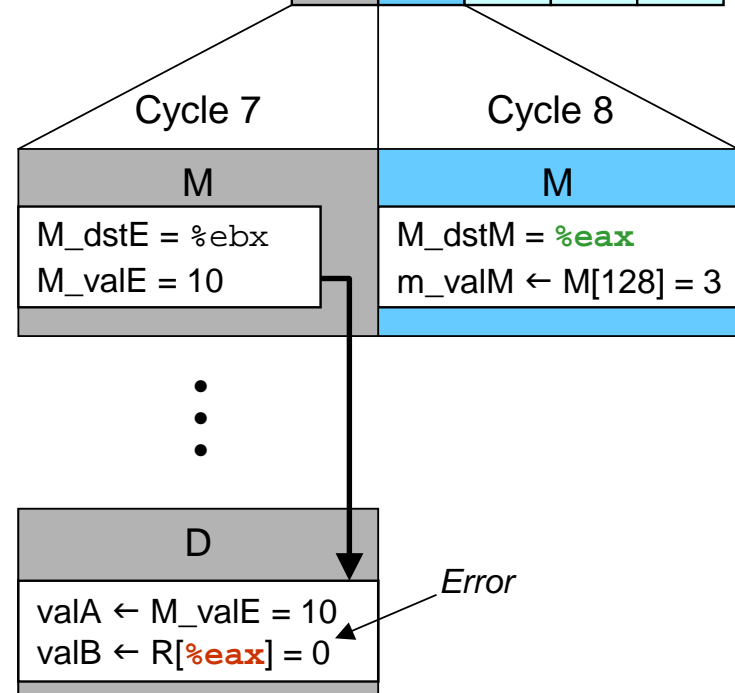
0x020: halt

1 2 3 4 5 6 7 8 9 10 11



Load-use dependency

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



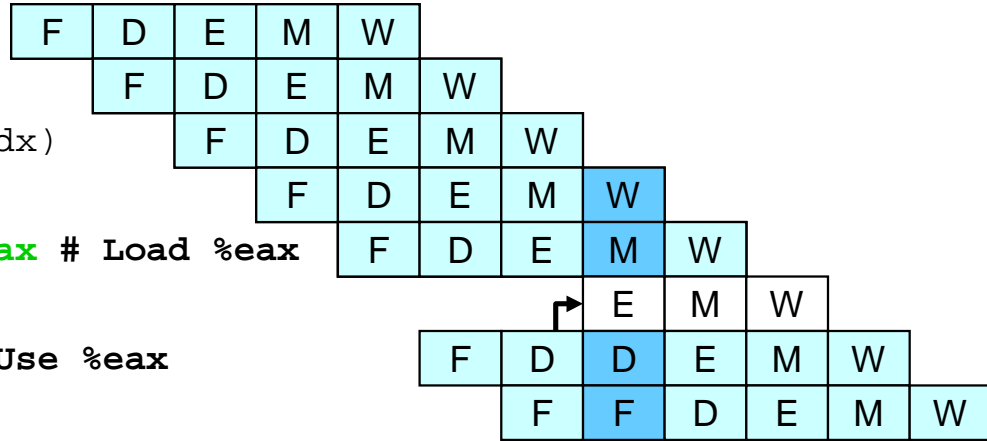
Avoiding Load/Use Hazard

demo-luh.js

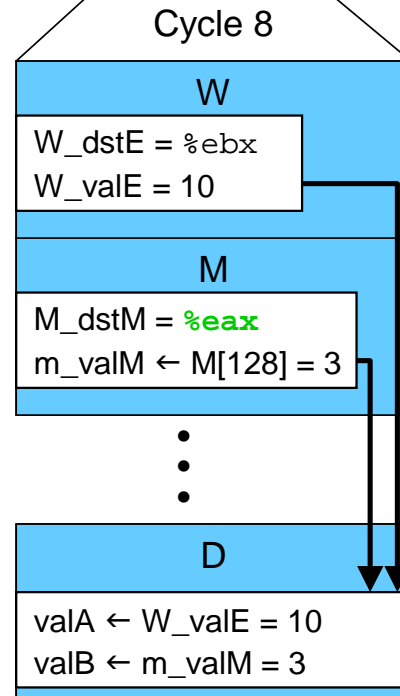
```

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
  
```

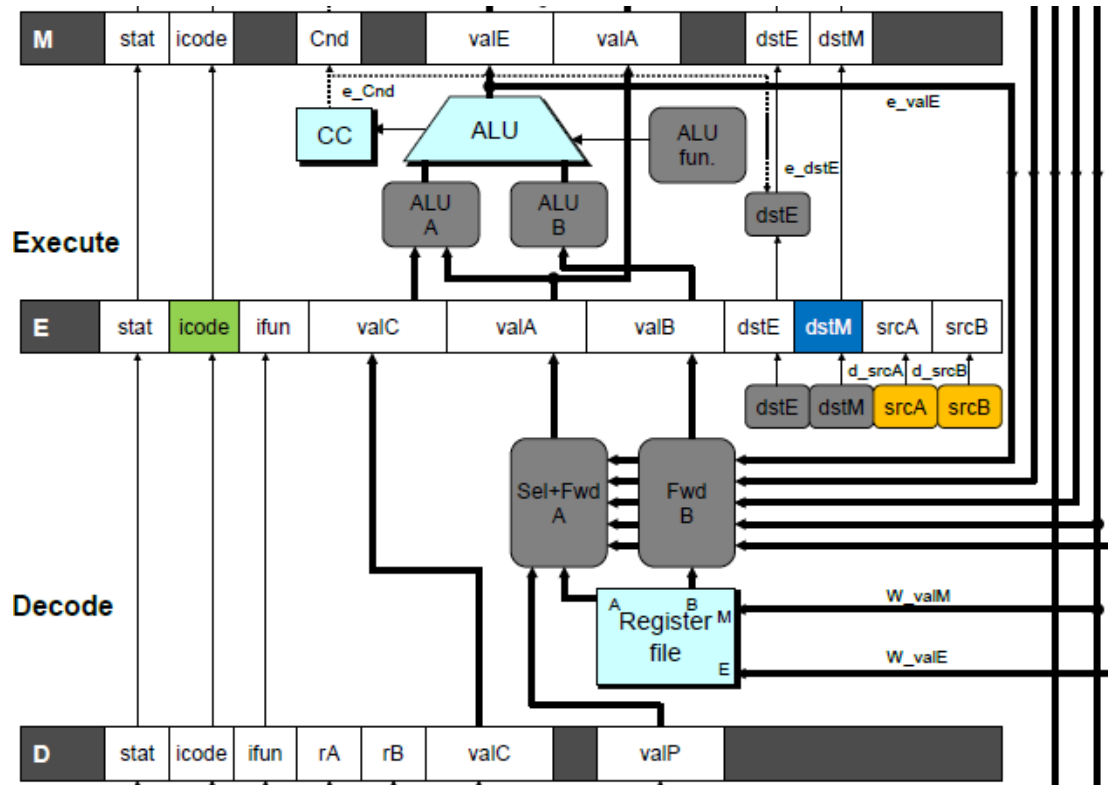
1 2 3 4 5 6 7 8 9 10 11 12



- 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.js

0x000: irmovl \$128,%edx

0x006: irmovl \$3,%ecx

0x00c: rmmovl %ecx, 0(%edx)

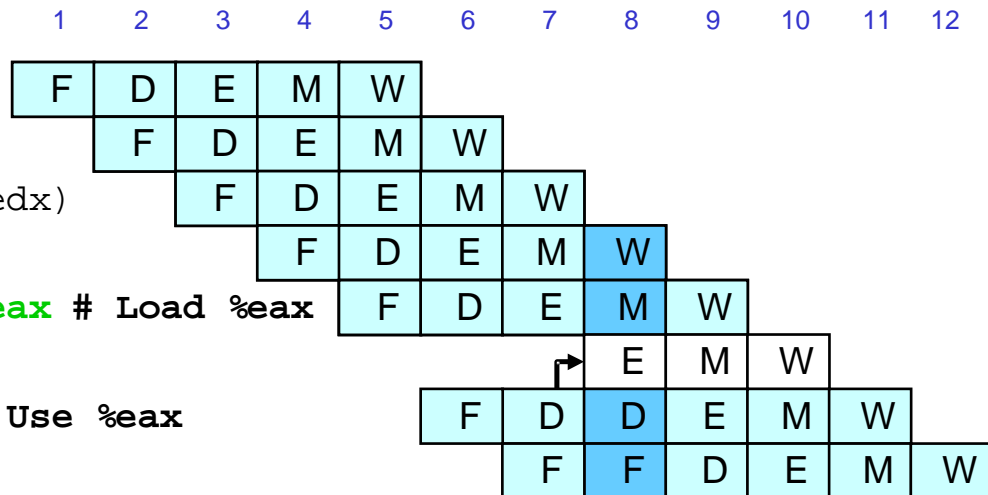
0x012: irmovl \$10,%ebx

0x018: mrmovl 0(%edx),%eax # Load %eax

bubble

0x01e: addl %ebx,%eax # Use %eax

0x020: halt



- Stall 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

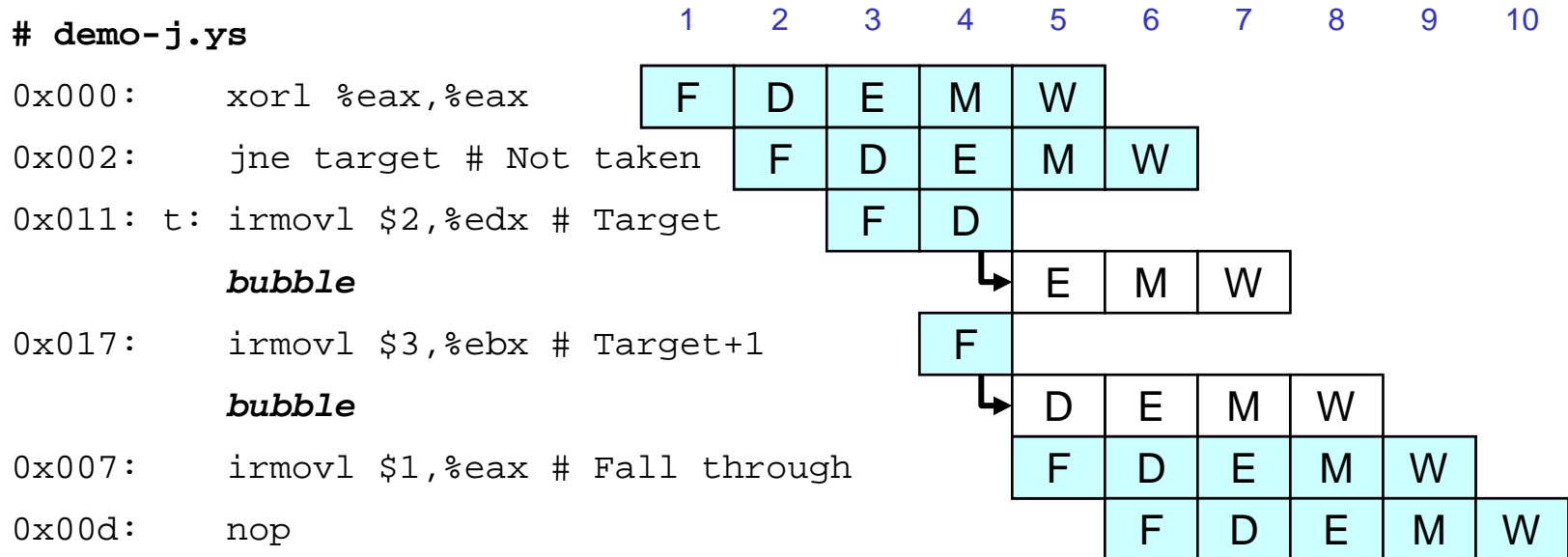
Branch Misprediction Example

demo-j.js

```
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 8 instructions

Handling Misprediction



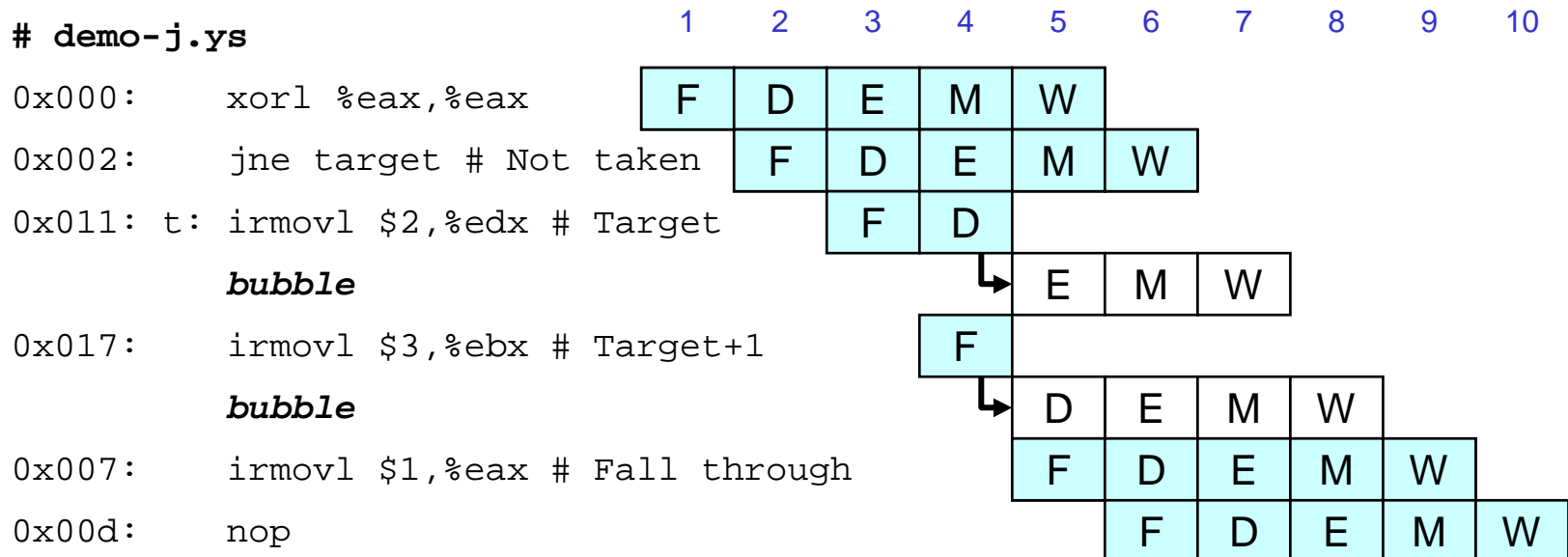
Predict branch as taken

- 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

Control for Misprediction



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
```

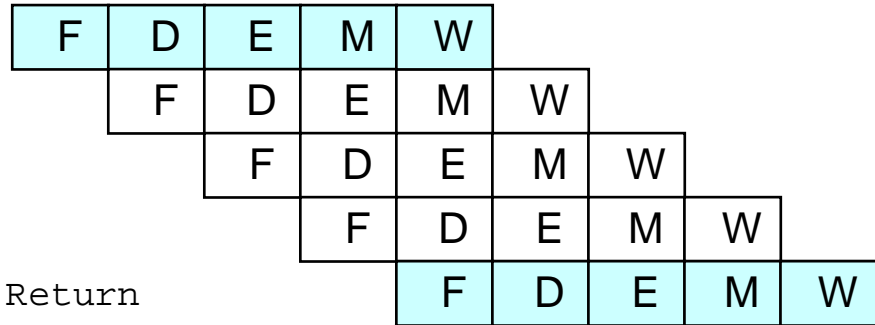
```
0x026:  ret
```

```
    bubble
```

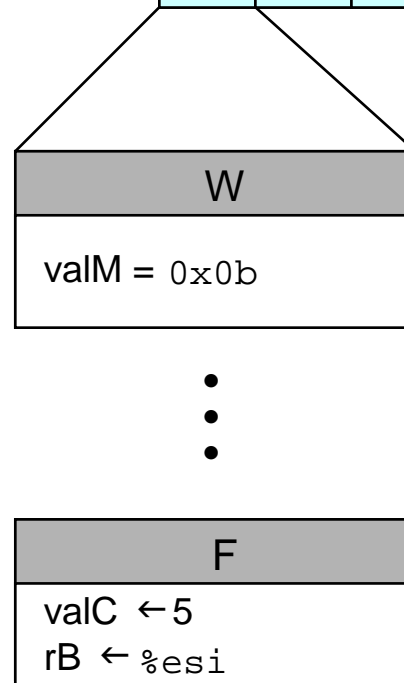
```
    bubble
```

```
    bubble
```

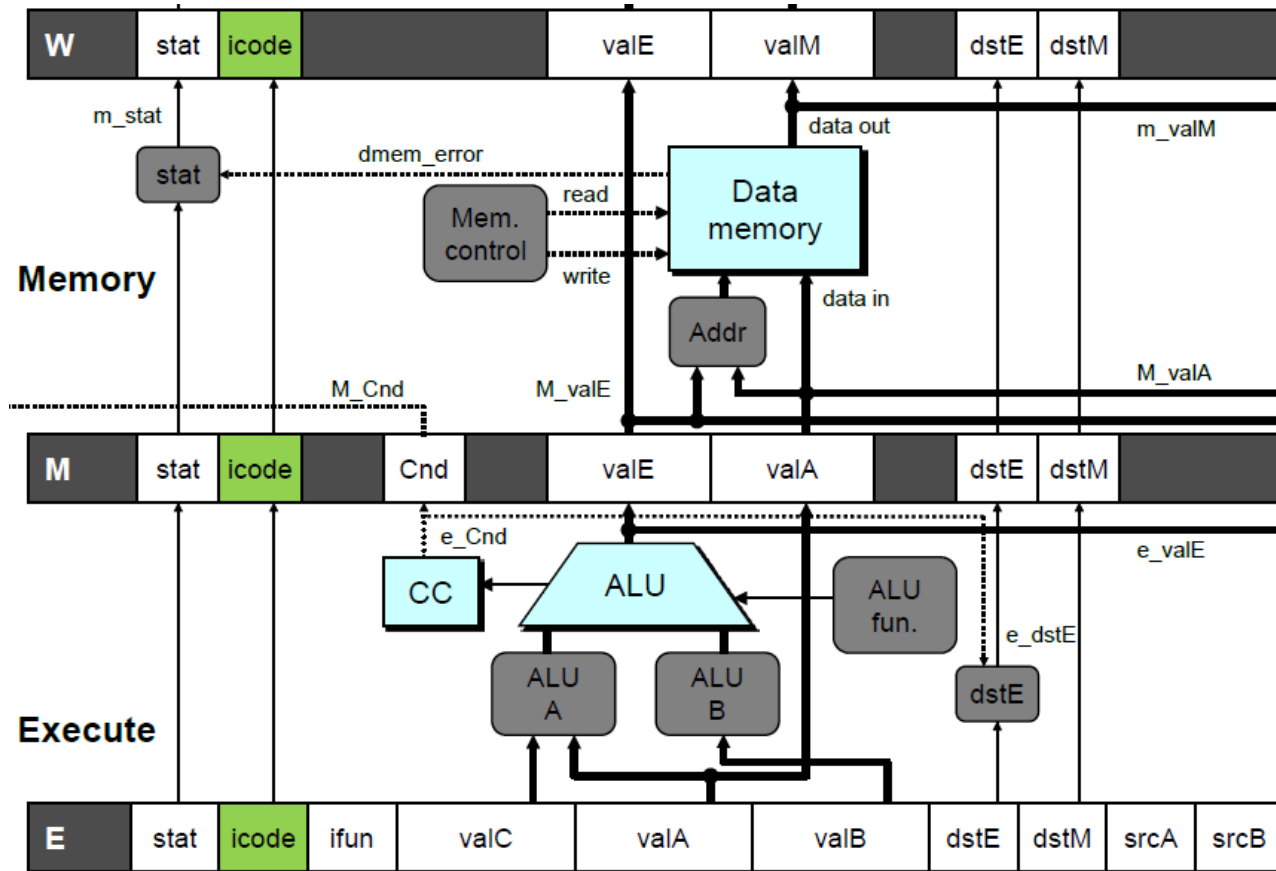
```
0x00b:  irmovl $5,%esi # Return
```



- 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

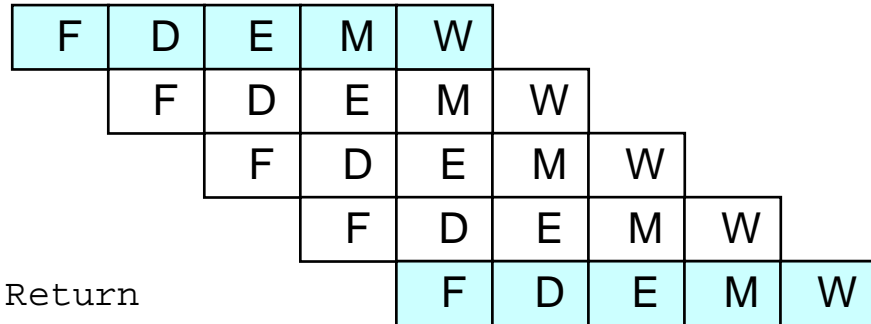
0x026: ret

bubble

bubble

bubble

0x00b: irmovl \$5,%esi # Return



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

Special Control Cases

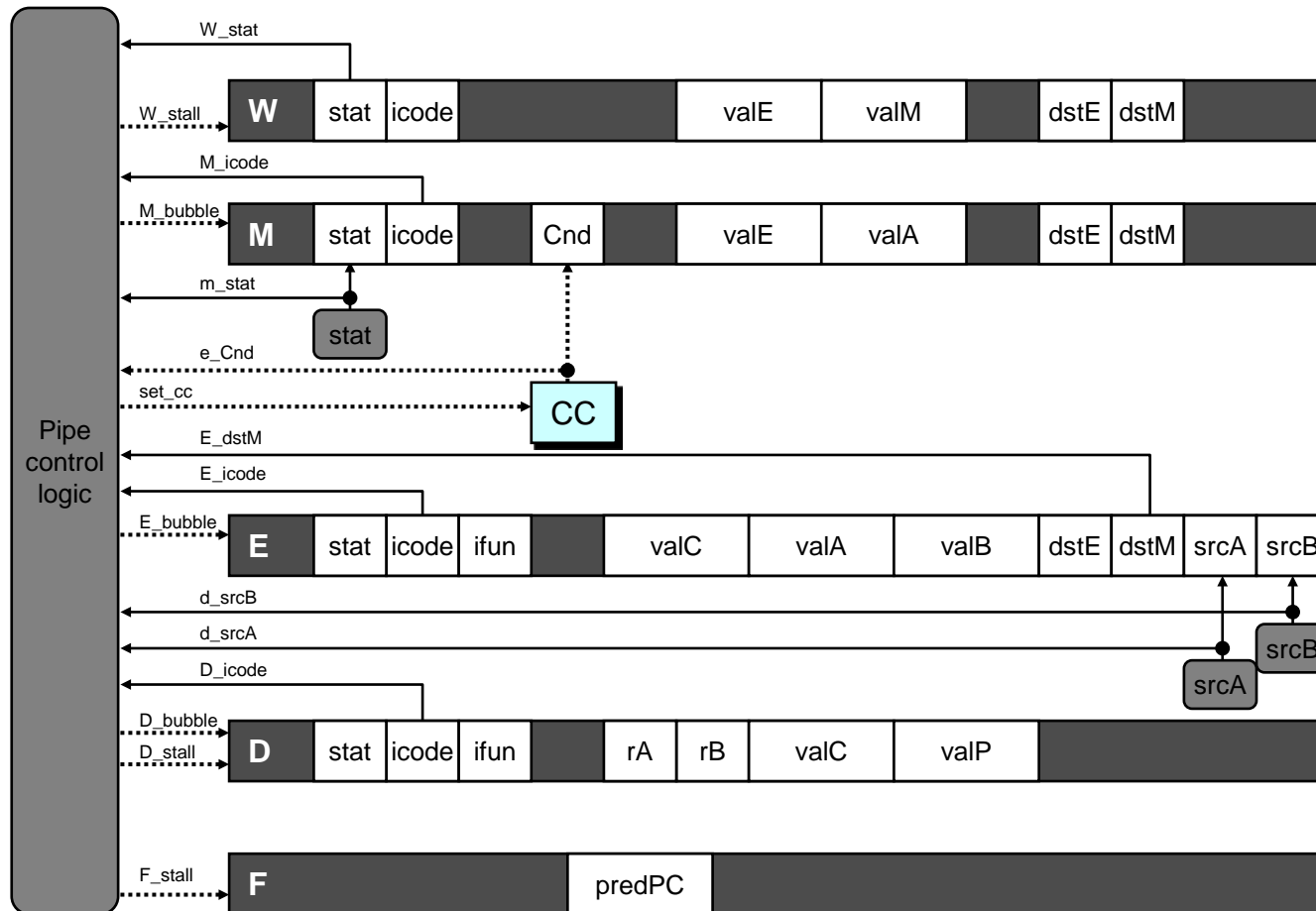
Detection

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_Cnd

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

Implementing Pipeline Control



- Combinational logic generates pipeline control signals
- Action occurs at start of following cycle

Initial Version of Pipeline Control

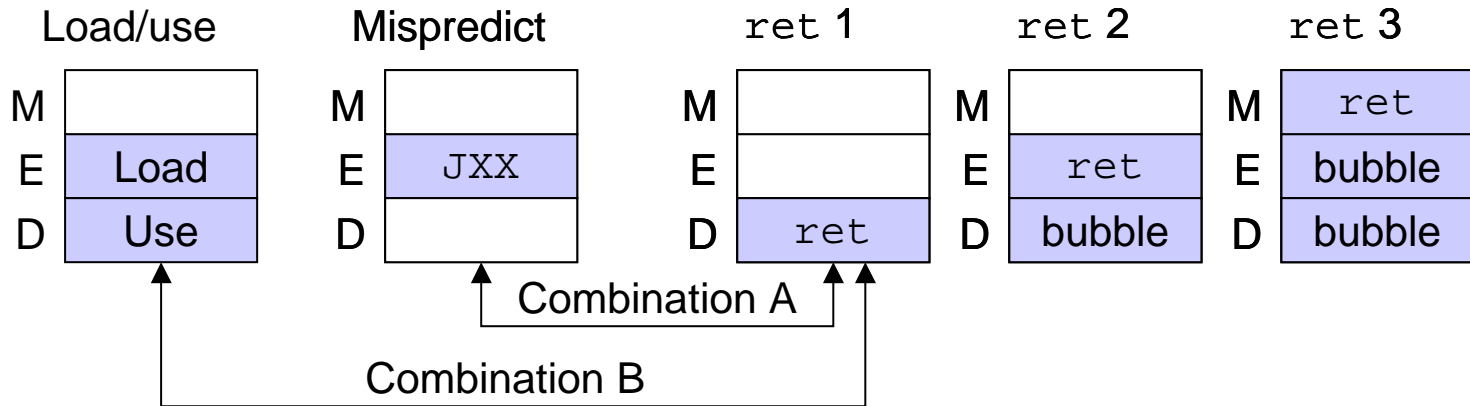
```
bool F_stall =
    # Conditions for a load/use hazard
    E_icode in { IMRMOVL, IPOPL } && E_dstM in { d_srcA, d_srcB } ||
    # Stalling at fetch while ret passes through pipeline
    IRET in { D_icode, E_icode, M_icode };

bool D_stall =
    # Conditions for a load/use hazard
    E_icode in { IMRMOVL, IPOPL } && E_dstM in { d_srcA, d_srcB };

bool D_bubble =
    # Mispredicted branch
    (E_icode == IJXX && !e_Cnd) ||
    # Stalling at fetch while ret passes through pipeline
    IRET in { D_icode, E_icode, M_icode };

bool E_bubble =
    # Mispredicted branch
    (E_icode == IJXX && !e_Cnd) ||
    # Load/use hazard
    E_icode in { IMRMOVL, IPOPL } && E_dstM in { d_srcA, d_srcB };
```

Control Combinations



- Special cases that can arise on same clock cycle

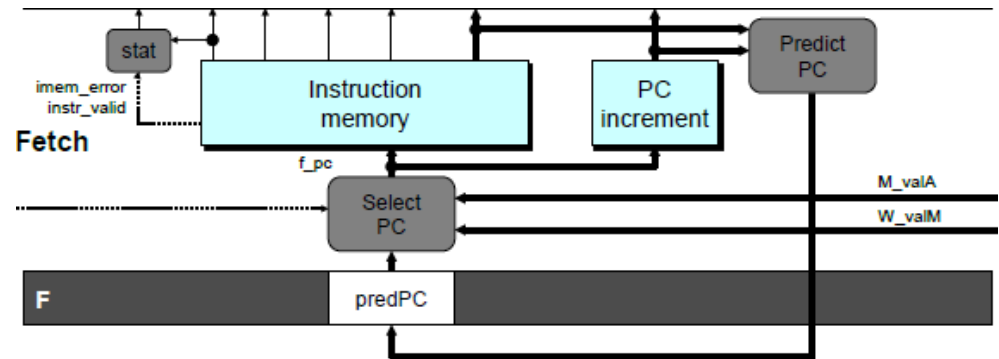
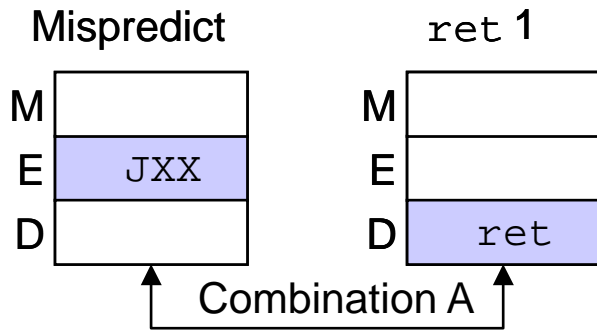
Combination A

- Not-taken branch
- `ret` instruction at branch target

Combination B

- Instruction that reads from memory to `%esp`
- Followed by `ret` instruction

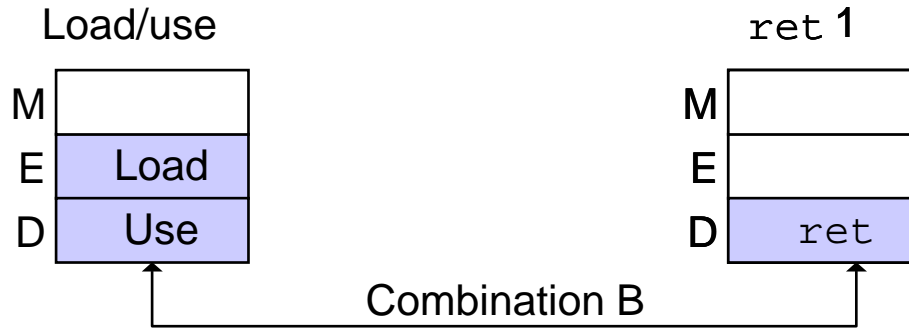
Control Combination A



Condition	F	D	E	M	W
Processing ret	stall	bubble	normal	normal	normal
Mispredicted Branch	normal	bubble	bubble	normal	normal
<i>Combination</i>	<i>stall</i>	<i>bubble</i>	<i>bubble</i>	<i>normal</i>	<i>normal</i>

- Should handle as mispredicted branch
- Stalls F pipeline register
- But PC selection logic will be using M_valM anyhow

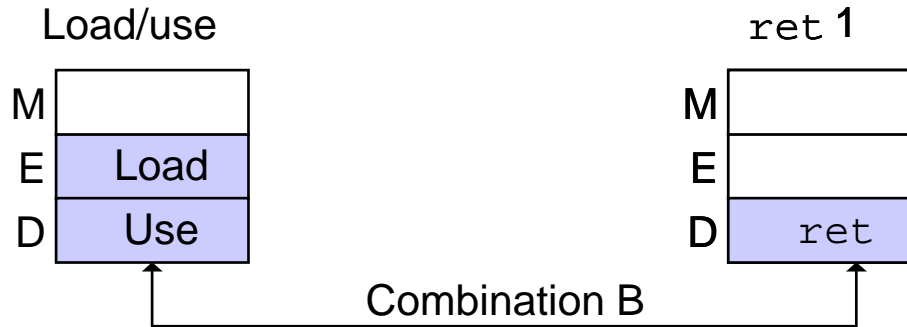
Control Combination B



Condition	F	D	E	M	W
Processing ret	stall	bubble	normal	normal	normal
Load/Use Hazard	stall	stall	bubble	normal	normal
Combination	stall	bubble + stall	bubble	normal	normal

- Would attempt to bubble *and* stall pipeline register D
- Signaled by processor as pipeline error

Handling Control Combination B



Condition	F	D	E	M	W
Processing ret	stall	bubble	normal	normal	normal
Load/Use Hazard	stall	stall	bubble	normal	normal
<i>Combination</i>	<i>stall</i>	<i>stall</i>	<i>bubble</i>	<i>normal</i>	<i>normal</i>

- Load/use hazard should get priority
- `ret` instruction should be held in decode stage for additional cycle

Corrected Pipeline Control Logic

```
bool D_bubble =  
    # Mispredicted branch  
    (E_icode == IJXX && !e_Cnd) ||  
    # Stalling at fetch while ret passes through pipeline  
    IRET in { D_icode, E_icode, M_icode }  
    # but not condition for a load/use hazard  
    && !(E_icode in { IMRMOVL, IPOPL }  
        && E_dstM in { d_srcA, d_srcB }));
```

Condition	F	D	E	M	W
Processing ret	stall	bubble	normal	normal	normal
Load/Use Hazard	stall	stall	bubble	normal	normal
<i>Combination</i>	<i>stall</i>	<i>stall</i>	<i>bubble</i>	<i>normal</i>	<i>normal</i>

- Load/use hazard should get priority
- `ret` instruction should be held in decode stage for additional cycle

Pipeline Summary

Data Hazards

- Most handled by forwarding
 - No performance penalty
- Load/use hazard requires one cycle stall

Control Hazards

- Cancel instructions when detect mispredicted branch
 - Two clock cycles wasted
- Stall fetch stage while `ret` passes through pipeline
 - Three clock cycles wasted

Control Combinations

- Must analyze carefully
- First version had subtle bug
 - Only arises with unusual instruction combination