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

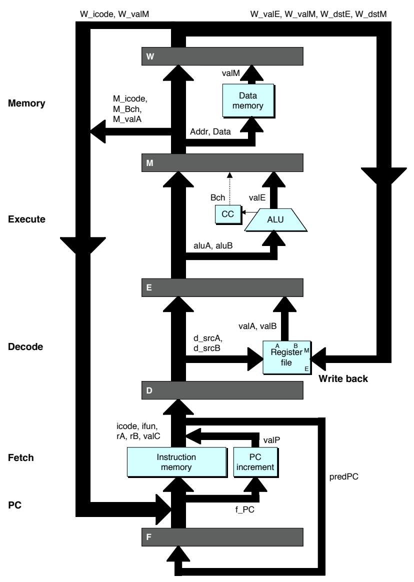
- Operate ALU

Memory

- Read or write data memory

Write Back

- Update register file

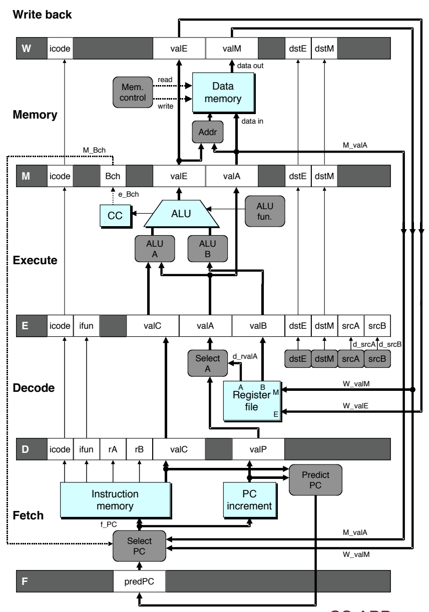


PIPE- Hardware

- Pipeline registers hold intermediate values from instruction execution

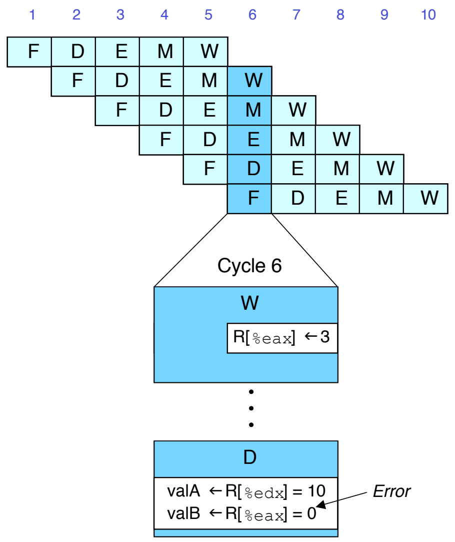
Forward (Upward) Paths

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



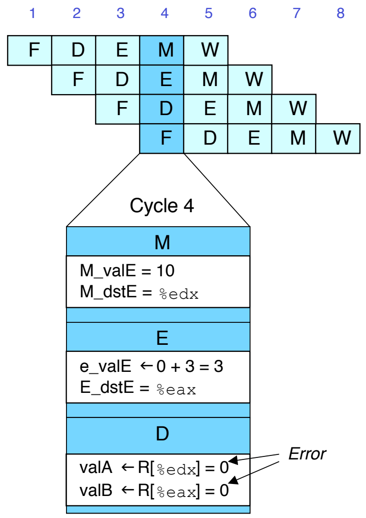
Data Dependencies: 2 Nop's

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



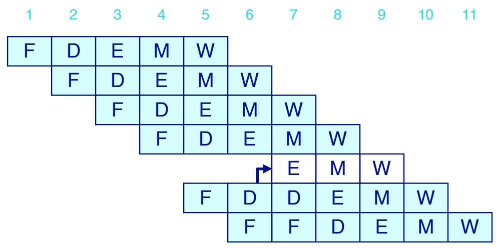
Data Dependencies: No Nop

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



Stalling for Data Dependencies

```
# demo-h2.ys
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

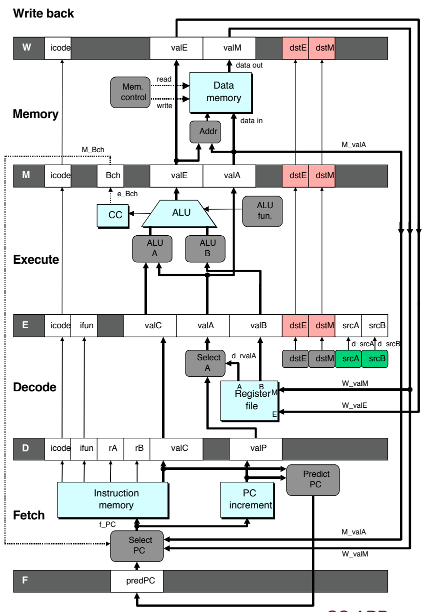
- srcA and srcB of current instruction in decode stage

Destination Registers

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

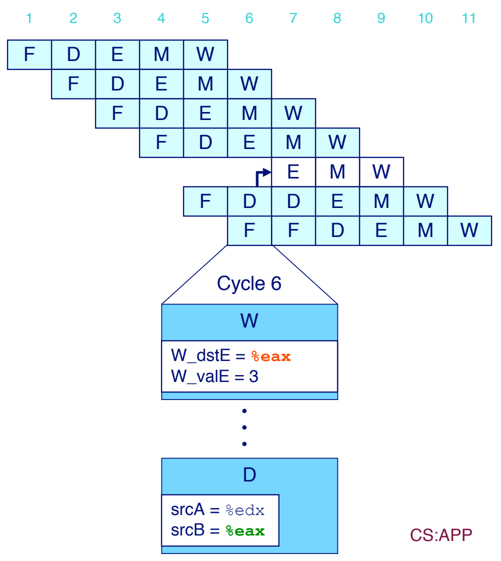
Special Case

- Don't stall for register ID 8
  - Indicates absence of register operand



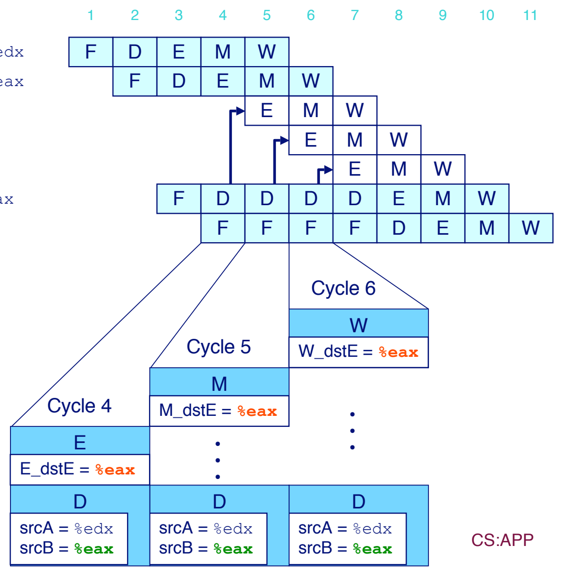
Detecting Stall Condition

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



Stalling X3

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



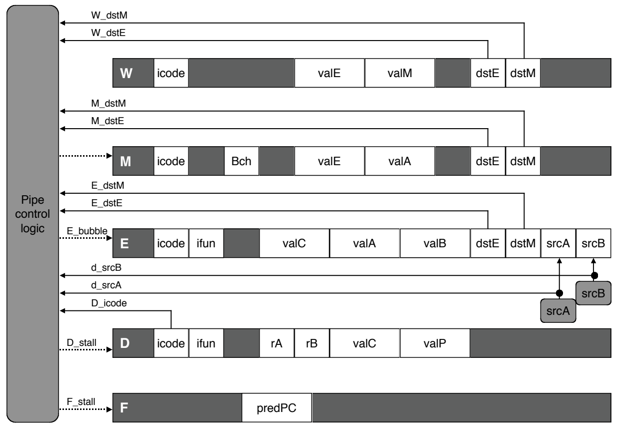
What Happens When Stalling?

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

	Cycle 8
Write Back	***bubble***
Memory	***bubble***
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

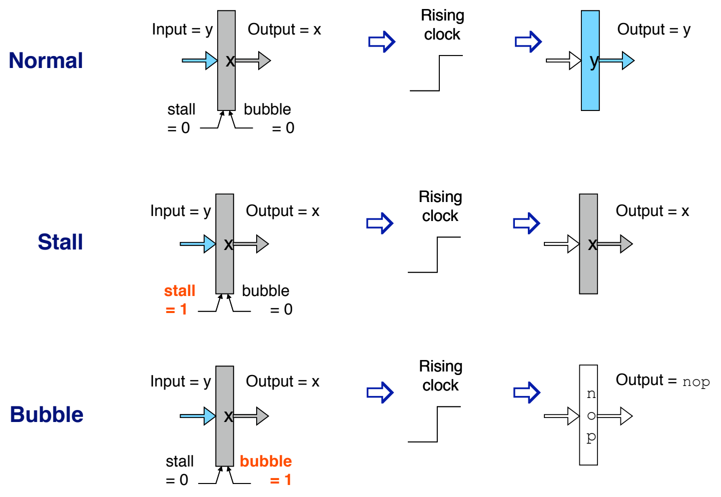


Pipe control logic
W_dstM
W_dstE
W icode valE valM dstE dstM
M_dstM
M_dstE
M icode Bch valE valA dstE dstM
E_dstM
E_dstE
E_bubble
E icode ifun valC valA valB dstE dstM srcA srcB
d_srcB
d_srcA
D_icode
srcB
srcA
D_stall
D icode ifun rA rB valC valP
F_stall
F predPC

Pipeline Control

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

Pipeline Register Modes



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

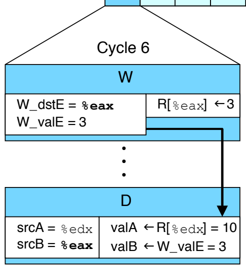
Trick

- 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
```

1	2	3	4	5	6	7	8	9	10
F	D	E	M	W					
	F	D	E	M	W				
		F	D	E	M	W			
			F	D	E	M	W		
				F	D	E	M	W	
					F	D	E	M	W



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

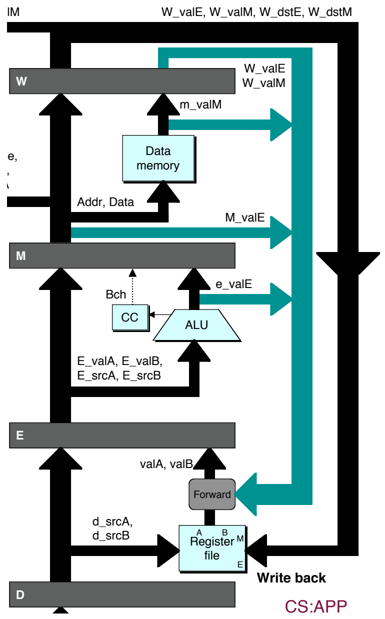
Bypass Paths

Decode Stage

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

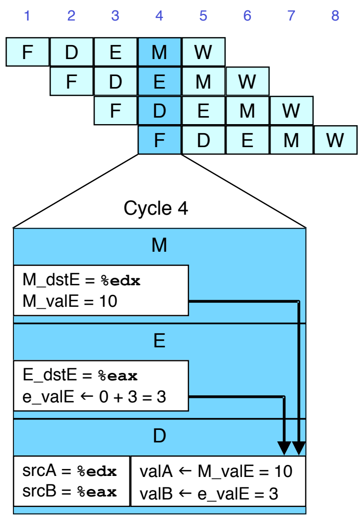
Forwarding Sources

- 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
```

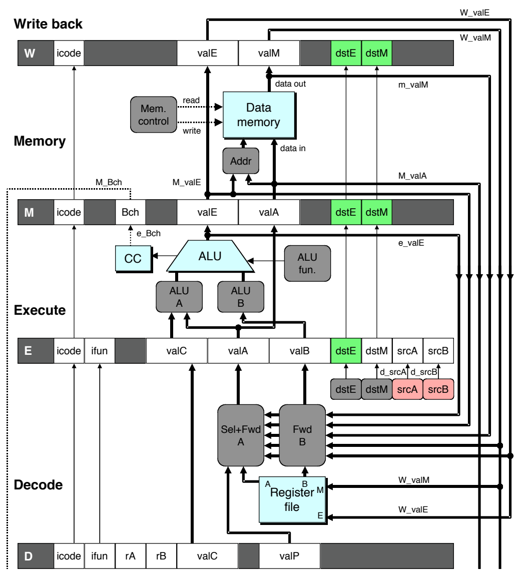


Register %edx

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

Register %eax

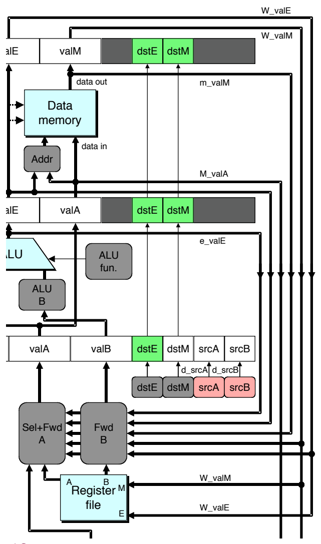
- Value just generated by ALU
- Forward from execute as valB



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

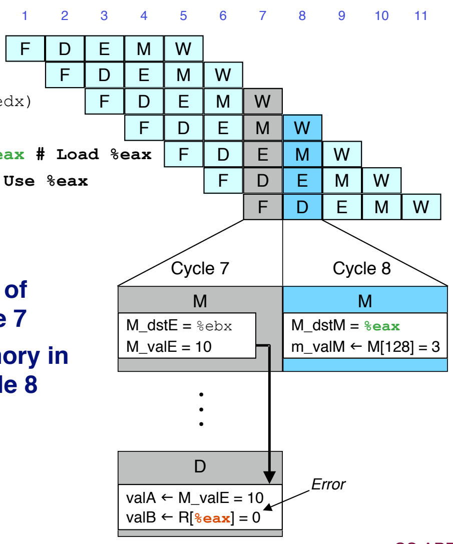
Implementing Forwarding



```
## 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
```

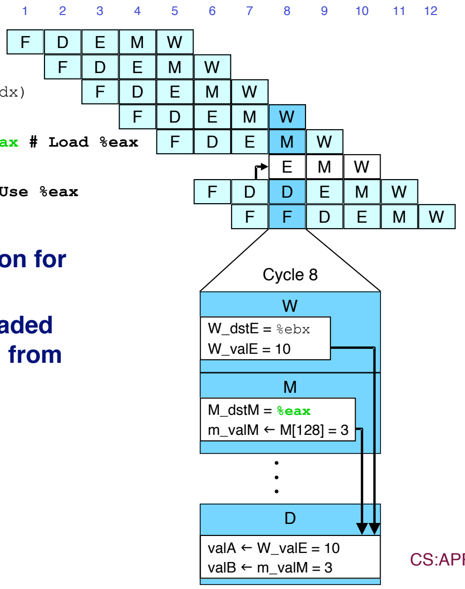


Load-use dependency

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

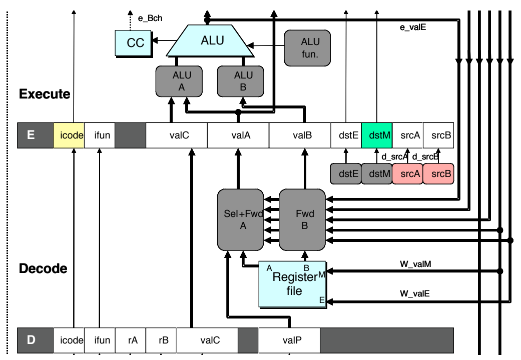
Avoiding Load/Use Hazard

```
# 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

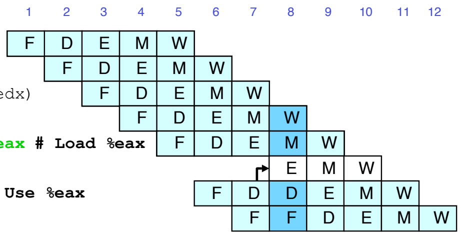
Detecting Load/Use Hazard



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
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

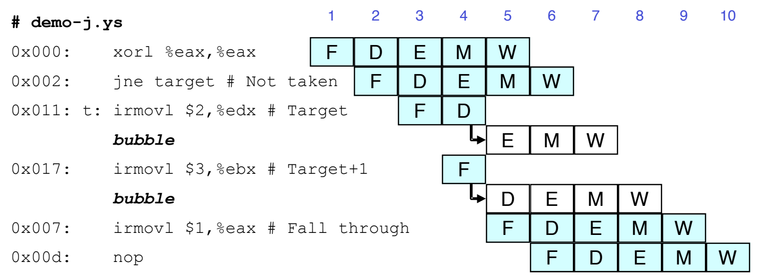
Branch Misprediction Example

```
demo-j.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 8 instructions

Handling Misprediction



```
# demo-j.ys                             1  2  3  4  5  6  7  8  9  10
0x000:    xorl %eax,%eax                F  D  E  M  W
0x002:    jne target # Not taken           F  D  E  M  W
0x011: t: irmovl $2,%edx # Target             F  D
          bubble                                    E  M  W
0x017:    irmovl $3,%ebx # Target+1                F
          bubble                                    D  E  M  W
0x007:    irmovl $1,%eax # Fall through            F  D  E  M  W
0x00d:    nop                                          F  D  E  M  W
```

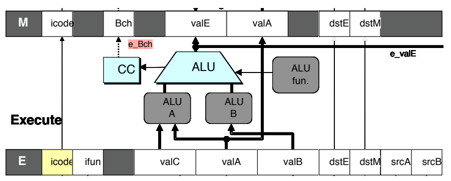
Predict branch as taken

- Fetch 2 instructions at target

Cancel when mispredicted

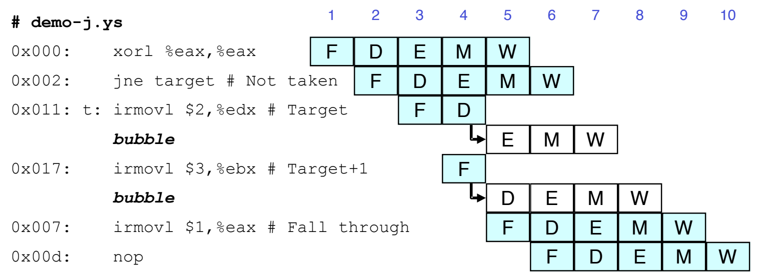
- Detect branch not-taken in execute stage
- On following cycle, replace instructions in execute and decode by bubbles
- No side effects have occurred yet

Detecting Mispredicted Branch



Condition	Trigger
Mispredicted Branch	E_icode = IJXX & !e_Bch

Control for Misprediction



```
# demo-j.ys                             1  2  3  4  5  6  7  8  9  10
0x000:    xorl %eax,%eax                F  D  E  M  W
0x002:    jne target # Not taken           F  D  E  M  W
0x011: t: irmovl $2,%edx # Target             F  D
          bubble                                    E  M  W
0x017:    irmovl $3,%ebx # Target+1                F
          bubble                                    D  E  M  W
0x007:    irmovl $1,%eax # Fall through            F  D  E  M  W
0x00d:    nop                                          F  D  E  M  W
```

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

Return Example

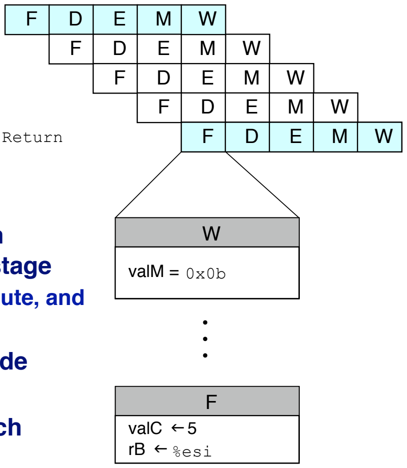
demo-retb.ys

```
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

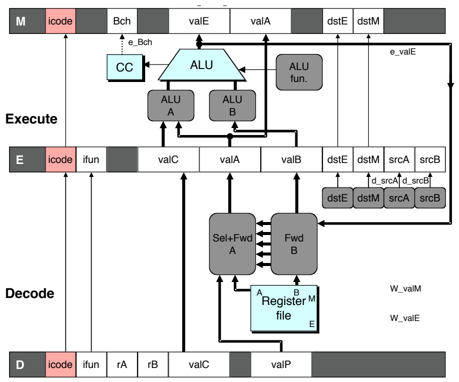
Correct Return Example

```
# 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

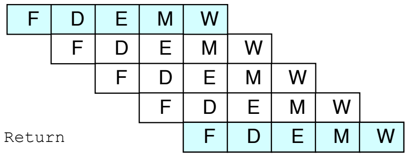
Detecting Return



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

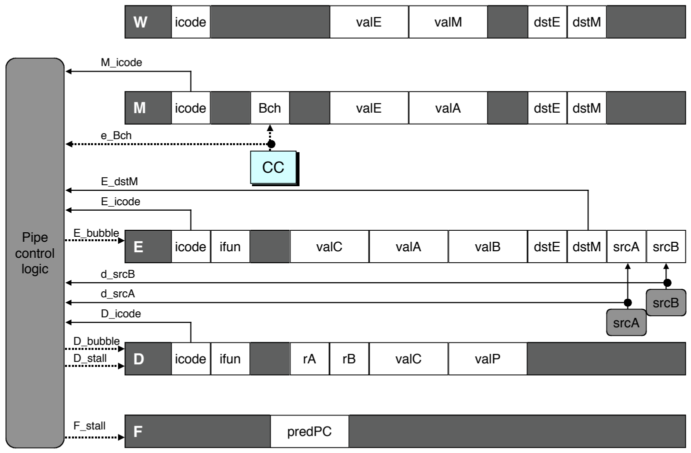
Detection

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

Implementing Pipeline Control



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

Initial Version of Pipeline Control

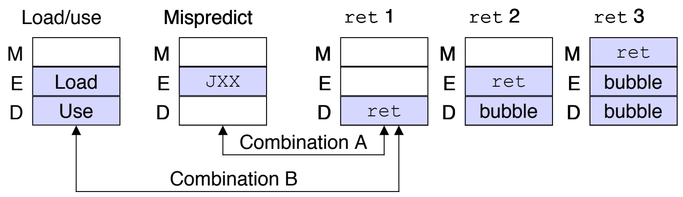
```
bool F_stall =
     # Conditions for a load/use hazard
     E_icode in { IMRMOVL, IPOPL } && E_dstM in { d_srcA, d_srcB } ||
     # Stalling at fetch while ret passes through pipeline
     IRET in { D_icode, E_icode, M_icode };

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_Bch) ||
     # 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_Bch) ||
     # 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

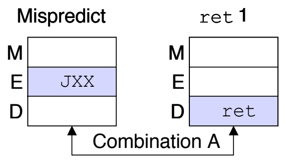
Combination A

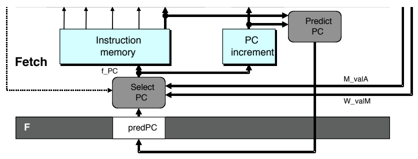
- Not-taken branch
- `ret` instruction at branch target

Combination B

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

Control Combination A

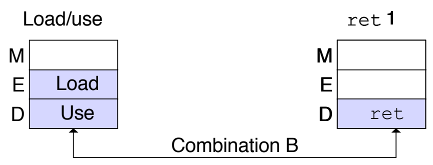




Condition	F	D	E	M	W
Processing ret	stall	bubble	normal	normal	normal
Mispredicted Branch	normal	bubble	bubble	normal	normal
Combination	*stall*	*bubble*	*bubble*	*normal*	*normal*

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

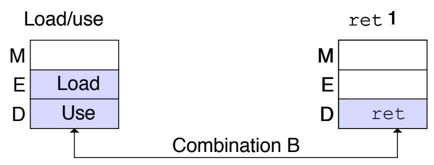
Control Combination B



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
Combination	*stall*	*stall*	*bubble*	*normal*	*normal*

- 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_Bch) ||
     # 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
Combination	*stall*	*stall*	*bubble*	*normal*	*normal*

- 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