Appendix C: Pipelining: Basic and Intermediate Concepts
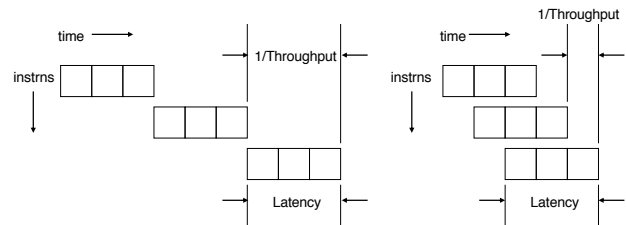
Key ideas and simple pipeline (Section C.1)
Hazards (Sections C.2 and C.3)
    Structural hazards
    Data hazards
    Control hazards
Exceptions (Section C.4)
Multicycle operations (Section C.5)

Pipelining - Key Idea

Ideally,

$$Time_{pipeline} = \frac{Time_{sequential}}{Pipeline\ Depth}$$

$$Speedup = \frac{Time_{sequential}}{Time_{pipeline}} = Pipeline\ Depth$$

Practical Limit 1 – Unbalanced Stages

Consider an instruction that requires *n* stages

    $s_1, s_2, \ldots, s_n$, taking time $t_1, t_2, \ldots, t_n$.
Let $T = \Sigma t_i$

Without pipelining	With an n-stage pipeline
Throughput =	Throughput =
Latency =	Latency =

Speedup

Practical Limit 2 - Overheads

Let $\Delta > 0$ be extra delay per stage
    e.g., latches
Δ limits the useful depth of a pipeline.

With an nstage pipeline

$$Throughput = \frac{1}{\Delta + max\ t_i} < \frac{n}{T}$$

$$Latency = n \times (\Delta + max\ t_i) \geq n\Delta + T$$

$$Speedup = \frac{\Sigma t_i}{\Delta + max\ t_i} < n$$

Example

Let $t_{1,2,3}$ = 8, 12, 10 *ns and* Δ = 2 *ns*

Throughput =

Latency =

Speedup =

Practical Limit 3 - Hazards

$$Pipeline\ Speedup = \frac{Time_{sequential}}{Time_{pipeline}} = \frac{CPI_{sequential}}{CPI_{pipeline}} \times \frac{Cycle\ Time_{sequential}}{Cycle\ Time_{pipeline}}$$

If we ignore cycle time differences:

$$CPI_{ideal\text{-}pipeline} = \frac{CPI_{sequential}}{Pipeline\ Depth}$$

$$Pipeline\ Speedup = \frac{CPI_{ideal\text{-}pipeline} \times Pipeline\ Depth}{CPI_{ideal\text{-}pipeline} + Pipeline\ stall\ cycles}$$

Pipelining a Basic RISC ISA

Assumptions:

Only loads and stores affect memory

Base register + immediate offset = effective address

ALU operations

Only access registers

Two sources – two registers, or register and immediate

Branches and jumps

Address = PC + offset

Comparison between a register and zero

The last assumption is different from the 6th edition of the text and results in a slightly different pipeline. We will discuss reasons and implications in class.

A Simple Five Stage RISC Pipeline

Pipeline Stages

IF – Instruction Fetch

ID – Instruction decode, register read, branch computation

EX – Execution and Effective Address

MEM – Memory Access

WB – Writeback

```
     1   2   3   4   5   6   7   8   9
i   IF  ID  EX  MEM WB
i+1     IF  ID  EX  MEM WB
i+2         IF  ID  EX  MEM WB
i+3             IF  ID  EX  MEM WB
i+4                 IF  ID  EX  MEM WB
```
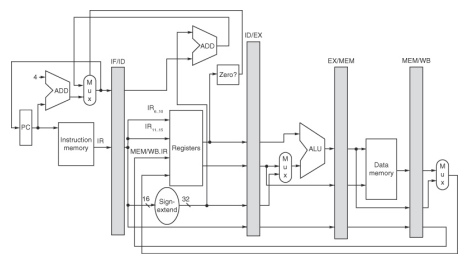
Pipelining really isn't this simple

A Naive Pipeline Implementation

Figure C.28 of 5th edition

Copyright © 2011, Elsevier Inc. All rights Reserved.

Pipelining really isn't this simple

Hazards

Hazards

Structural Hazards

Data Hazards

Control Hazards

Handling Hazards

Pipeline interlock logic
  Detects hazard and takes appropriate action
Simplest solution: stall
  Increases CPI
  Decreases performance
Other solutions are harder, but have better performance

Structural Hazards

When two *different* instructions want to use the *same* hardware resource in the *same* cycle
Stall (cause bubble)
  + Low cost, simple
    Increases CPI
    Use for rare events
    E.g., ??
Duplicate Resource
  + Good performance
    Increases cost (and maybe cycle time for interconnect)
    Use for cheap resources
    E.g., ALU and PC adder

Structural Hazards, cont.

Pipeline Resource

+ Good performance

    Often complex to do

    Use when simple to do

    E.g., write & read registers every cycle

Structural hazards are avoided if each instruction uses a resource

    At most once

    Always in the same pipeline stage

    For one cycle

    ($\Rightarrow$ no cycle where two instructions use the same resource)

Structural Hazard Example

Loads/stores (MEM) use same memory port as instrn fetches (IF)

30% of all instructions are loads and stores

Assume CPI_{old} is 1.5

```
     1   2   3   4   5   6   7   8   9
 i   IF  ID  EX  MEM WB <- a load
 i+1     IF  ID  EX  MEM WB
 i+2         IF  ID  EX  MEM WB
 i+3         **  IF  ID  EX  MEM WB
 i+4                 IF  ID  EX MEM WB
```

How much faster could a new machine with two memory ports be?

Data Hazards

When two different instructions use the same location, it must appear as if instructions execute one at a time and in the specified order

```
 i    ADD r1,r2,
 i+1  SUB r2,,r1
 i+2  OR  r1,--,
```

Read-After-Write (RAW, data-dependence)
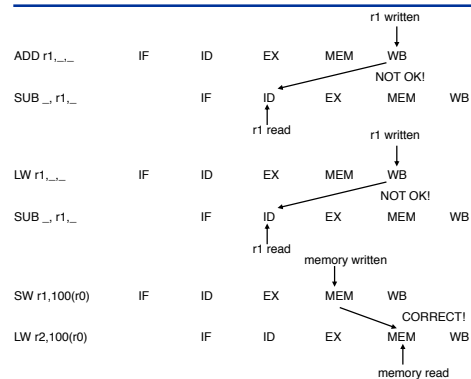
    A true dependence

    MOST IMPORTANT

Write-After-Read (WAR, anti-dependence)

Write-After-Write (WAW, output-dependence)

NOT: Read-After-Read (RAR)

Example Read-After-Write Hazards

(Unless LW instrn is at address 100(r0))

RAW Solutions

Solutions must first detect RAW, and then ...

Stall

					r1 written			

| ADD r1,_,_ | IF | ID | EX | MEM | WB | | | |
| SUB _, r1,_ | | IF | ID | stall | stall | EX | MEM | WB |

r1 read
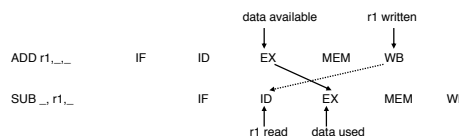
(Assumes registers written then read each cycle)

+ Low cost, simple

    Increases CPI (plus 2 per stall in 5 stage pipeline)

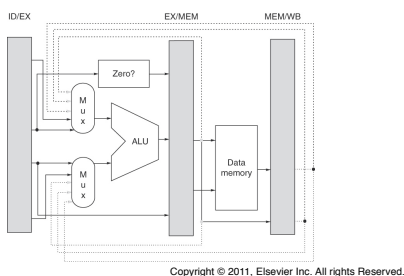   Use for rare events

RAW Solutions

Bypass/Forward/ShortCircuit

data available   r1 written

| ADD r1,_,_ | IF | ID | EX | MEM | WB | |
| SUB _, r1,_ | | IF | ID | EX | MEM | WB |

r1 read   data used

Use data before it is in register

+ Reduces (avoids) stalls

    More complex

    Critical for common RAW hazards

Bypass, cont.

Figure C.27

5th edition

Additional hardware

    Muxes supply correct result to ALU

Additional control

    Interlock logic must control muxes

RAW Solutions, cont.

Hybrid solution sometimes required:

data available r1 written

| LW r1,_,_ | IF | ID | EX | MEM | WB | |
| SUB _, r1,_ | | IF | ID | stall | EX | MEM | WB |

r1 read   data used
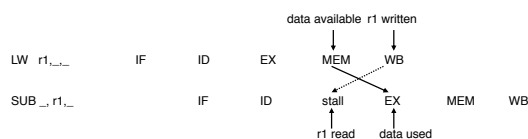
One cycle bubble if result of load used by next instruction

Pipeline scheduling at compile time

    Moves instructions to eliminate stalls

Pipeline Scheduling Example

```
Before:                          After:
a = b + c;  LW  Rb,b     a = b + c;  LW  Rb,b
            LW  Rc,c                 LW  Rc,c
                 <- stall            LW  Re,e
            ADD Ra,Rb,Rc             ADD Ra,Rb,Rc
            SW  a, Ra

d = e - f;  LW  Re,e     d = e - f;  LW  Rf,f
            LW  Rf,f                 SW  a, Ra
                 <- stall            SUB Rd,Re,Rf
            SUB Rd,Re, Rf            SW  d, Rd
            SW  d, Rd
```

Other Data Hazards

```
i    ADD r1,r2,
i+1  SUB r2,,r1
i+2  OR  r1,,
```

Write-After-Read (WAR, anti-dependence)

```
i    MULT , (r2), r1 /* RX mult */
i+1  LW   , (r1)+ /* autoincrement */
```

Write-After-Write (WAW, output-dependence)

```
i    DIVF fr1, ,  /* slow */
i+1
i+2  ADDF fr1, ,  /* fast */
```

Control Hazards

When an instruction affects which instructions are executed *next* -- branches, jumps, calls

```
i    BEQZ r1,#8
i+1  SUB ,,
       ...
i+8  OR  ,,
i+9  ADD ,,

1   2   3   4   5   6   7   8   9
i   IF  ID  EX  MEM WB
i+1     IF (aborted)
i+8         IF  ID  EX  MEM WB
i+9             IF  ID  EX  MEM
```

Handling control hazards is very important

Handling Control Hazards

Branch Prediction
    Guess the direction of the branch
    Minimize penalty when right
    May increase penalty when wrong
Techniques
    Static – At compile time
    Dynamic – At run time
Static Techniques
    Predict NotTaken
    Predict Taken
    Delayed Branches
Dynamic techniques and more powerful static techniques later…

Handling Control Hazards, cont.

Predict NOT-TAKEN Always

NotTaken:
```
    1   2   3   4   5   6   7   8
i   IF  ID  EX  MEM WB
i+1     IF  ID  EX  MEM WB
i+2         IF  ID  EX  MEM WB
i+3             IF  ID  EX  MEM WB
```

Taken:
```
    1   2   3   4   5   6   7   8
i   IF  ID  EX  MEM WB
i+1     IF (aborted)
i+8         IF  ID  EX  MEM WB
i+9             IF  ID  EX  MEM WB
```

Don't change machine state until branch outcome is known

Basic pipeline: State always changes late (WB)

Handling Control Hazards, cont.

Predict TAKEN Always
```
     1   2   3   4   5   6   7   8
i    IF  ID  EX  MEM WB
i+8  'IF' ID  EX  MEM WB
i+9       IF  ID  EX  MEM WB
i+10          IF  ID  EX  MEM WB
```

Must know what address to fetch at BEFORE branch is decoded

Not practical for our basic pipeline

Handling Control Hazards, cont.

Delayed branch

Execute next instruction regardless (of whether branch is taken)

What do we execute in the DELAY SLOT?

Delay Slots

Fill from before branch

When:

Helps:

Fill from target

When:

Helps:

Fill from fall through

When:

Helps:

Delay Slots (Cont.)

Cancelling or nullifying branch

- Instruction includes direction of prediction
- Delay instruction squashed if wrong prediction
- Allows second and third case of previous slide to be more aggressive

Comparison of Branch Schemes

Suppose 14% of all instructions are branches

Suppose 65% of all branches are taken

Suppose 50% of delay slots usefully filled

CPIpenalty = % branches ×

(% Taken × Taken-Penalty + % Not-Taken × Not-Taken penalty)

Branch Scheme	Taken Penalty	Not-Taken Penalty	CPI Penalty
Basic Branch	1	1	.14
Not-Taken	1	0	.09
Taken0	0	1	.05
Taken1	1	1	.14
Delayed Branch	.5	.5	.07

Real Processors

MIPS R4000: 3 cycle branch penalty

- First cycle: cancelling delayed branch (cancel if not taken)
- Next two cycles: Predict not taken

Recent architectures:

- Because of deeper pipelines, delayed branches not very useful
- Processors rely more on hardware prediction (will see later) or may include both delayed and nondelayed branches

Interrupts

Interrupts (a.k.a. faults, exceptions, traps) often require

- Surprise jump
- Linking of return address
- Saving of PSW (including CCs)
- State change (e.g., to kernel mode)

Some examples

- Arithmetic overflow
- I/O device request
- O.S. call
- Page fault

Make pipelining hard

One Classification of Interrupts

1a. Synchronous

   function of program and memory state

   (e.g., arithmetic overflow, page fault)

1b. Asynchronous

   external device or hardware malfunction

   (printer ready, bus error)

Handling Interrupts

Precise Interrupts (Sequential Semantics)

   Complete instrns before offending one

   Squash (effects of) instrns after

   Save PC

   Force trap instrn into IF

Must handle simultaneous interrupts

   IF –

   ID –

   EX –

   MEM –

   WB –

Which interrupt should be handled first?

Interrupts, cont.

Example: Data Page Fault

```
      1   2   3   4   5   6   7   8
i   IF  ID  EX  MEM WB
i+1     IF  ID  EX  MEM WB <— page fault (MEM)
i+2         IF  ID  EX  MEM WB <— squash
i+3             IF  ID  EX  MEM WB <— squash
i+4                 IF  ID  EX  MEM WB <— squash
i+5             trap —> IF  ID  EX  MEM WB
i+6         trap handler —> IF  ID  EX  MEM WB
```

Preceding instruction already complete

Squash succeeding instructions

   Prevent from modifying state

'Trap' instruction jumps to trap handler

Hardware saves PC in IAR

Trap handler must save IAR

Interrupts, cont.

Example: Arithmetic Exception

```
      1   2   3   4   5   6   7   8
i   IF  ID  EX  MEM WB
i+1     IF  ID  EX  MEM WB
i+2         IF  ID  EX  MEM WB <— Exception (EX)
i+3             IF  ID  EX  MEM WB <— squash
i+4                 IF  ID  EX  MEM WB <— squash
i+5             trap —> IF  ID  EX  MEM WB
i+6         trap handler —> IF  ID  EX  MEM WB
```

Let preceding instructions complete

Squash succeeding instruction

Interrupts, cont.

Example: Illegal Opcode

```
      1   2   3   4   5   6   7   8
i    IF  ID  EX  MEM WB
i+1      IF  ID  EX  MEM WB
i+2          IF  ID  EX  MEM WB
i+3              IF  ID  EX  MEM WB <- ill. op (ID)
i+4                  IF  ID  EX  MEM WB <- squash
i+5              trap -> IF  ID  EX  MEM WB
i+6          trap handler -> IF  ID  EX  MEM WB
```

Let preceding instructions complete

Squash succeeding instruction

Interrupts, cont.

Example: Out-of-order Interrupts

```
      1   2   3   4   5   6   7   8
i    IF  ID  EX  MEM WB  <- page fault (MEM)
i+1      IF  ID  EX  MEM WB  <- page fault (IF)
i+2          IF  ID  EX  MEM WB
i+3              IF  ID  EX  MEM WB
```

Which page fault should we take?

For precise interrupts – Post interrupts on a status vector associated with instruction, disable later writes in pipeline

      Check interrupt bit on entering WB

      Longer latency

For imprecise interrupts – Handle immediately

      Interrupts may occur in different order than on a sequential machine

      May cause implementation headaches

Interrupts, cont.

Other complications

    Odd bits of state (e.g., CCs)

    Earlywrites (e.g., autoincrement)

    Outoforder execution

Interrupts come at random times

    The frequent case isn't everything

    The rare case MUST work correctly

Multicycle Operations

Not all operations complete in one cycle

    Floating point arithmetic is inherently slower than integer arithmetic

    2 to 4 cycles for multiply or add

    20 to 50 cycles for divide

Extend basic 5-stage pipeline

    EX stage may repeat multiple times

    Multiple function units

    Not pipelined for now

Handling Multicycle Operations

Four Functional Units
- EX: Integer unit
- E*: FP/integer multiplier
- E+: FP adder
- E/: FP/integer divider

Assume
- EX takes one cycle & all FP units take 4
- Separate integer and FP registers
- All FP arithmetic from FP registers

Worry about
- Structural hazards
- RAW hazards & forwarding
- WAR & WAW between integer & FP ops

Simple Multicycle Example

```
     1   2   3   4   5   6   7   8   9   10   11
int  IF  ID  EX  MEM WB
fp*      IF  ID  E*  E*  E*  E*  MEM WB
int          IF  ID  EX  MEM WB? (1)
fp/              IF  ID  E/  E/  E/  E/  MEM  WB
int                  IF  ID  EX  **  MEM WB (2)
fp/              (3) IF  ID  **  **  E/  E/
int                  (4) IF  **  **  ID  EX
```

Notes
- (1) WAW possible only if?
- (2) Stall forced by?
- (3) Stall forced by?
- (4) Stall forced by?

FP Instruction Issue

Check for RAW data hazard (in ID)
- Wait until source registers are not used as destinations by instructions in EX that will not be available when needed

Check for forwarding
- Bypass data from other stages, if necessary

Check for structural hazard in function unit
- Wait until function unit is free (in ID)

Check for structural hazard in MEM / WB
- Instructions stall in ID
- Instructions stall before MEM
  - Static priority (e.g., FU with longest latency)

FP Instruction Issue (Cont.)

Check for WAW hazards
```
DIVF F0, F2, F4
SUBF F0, F8, F10
```
- SUBF completes first
  - (1) Stall SUBF
  - (2) Abort DIVF's WB

WAR hazards?

More Multicycle Operations

Problems with Interrupts

```
DIVF F0, F2, F4
ADDF F2, F8, F10
SUBF F6, F4, F10
```

ADDF and SUBF complete before DIVF

Out-of-order completion

    Possible imprecise interrupt

What happens if DIVF generates an exception after ADDF and
    SUBF complete??

We'll discuss solutions later