CS61C
Introduction to Pipelining

Lecture 25

April 28, 1999

Dave Patterson
(http.cs.berkeley.edu/~patterson)

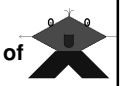
www-inst.eecs.berkeley.edu/~cs61c/schedule.html

Outline

- Review Parameter Passing on Stacks
- Pipelining Analogy
- Pipelining Instruction Execution
- Administrivia, "What's this Stuff Bad for?"
- Hazards to Pipelining
- Solutions to Hazards
- Advanced Pipelining Concepts by Analogy
- Conclusion

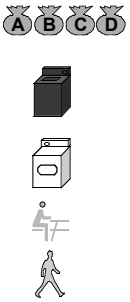
Review 1/1

- Every machine has a convention for how arguments are passed.
- In MIPS, where do the arguments go if you are passing more than 4 words? Stack!
- It is sometimes useful to have a variable number of arguments.
  - The C convention is to use "..."
  - *fmt is used to determine the number of variables and their types.

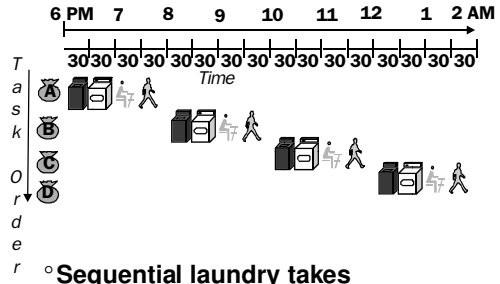


Pipelining is Natural! Laundry Example

- Ann, Brian, Cathy, Dave each have one load of clothes to wash, dry, fold, and put away
- Washer takes 30 minutes
- Dryer takes 30 minutes
- "Folder" takes 30 minutes
- "Stasher" takes 30 minutes to put clothes into drawers

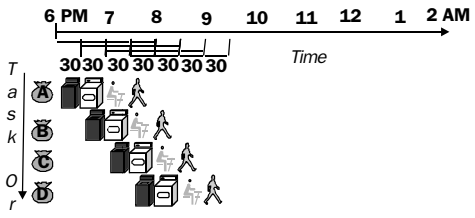


Sequential Laundry



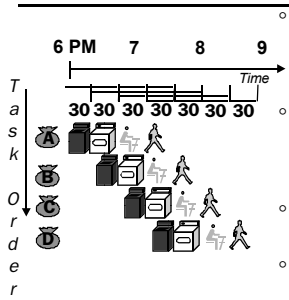
- Sequential laundry takes 8 hours for 4 loads

Pipelined Laundry: Start work ASAP



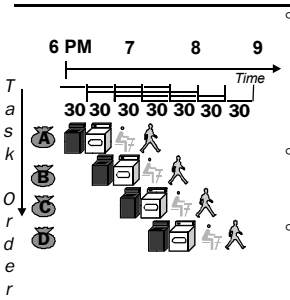
- Pipelined laundry takes 3.5 hours for 4 loads!

Pipelining Lessons



- Pipelining doesn't help latency of single task, it helps throughput of entire workload
- Multiple tasks operating simultaneously using different resources
- Potential speedup = Number pipe stages
- Time to "fill" pipeline and time to "drain" it reduces speedup: 2.3X v. 4X in this example

Pipelining Lessons



- Suppose new Washer takes 20 minutes, new Stasher takes 20 minutes. How much faster is pipeline?
- Pipeline rate limited by slowest pipeline stage
- Unbalanced lengths of pipe stages also reduces speedup

Review: Steps in Executing MIPS (Lec. 20)

1) Ifetch: Fetch Instruction, Increment PC

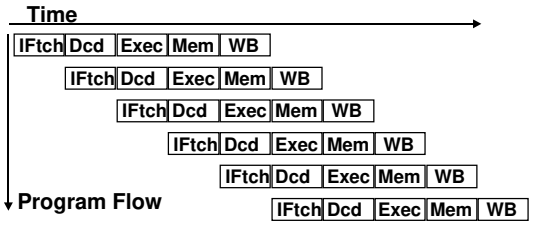
2) Decode Instruction, Read Registers

3) Execute:
   - Mem-ref: Calculate Address
   - Arith-log: Perform Operation
   - Branch: Compare if operands ==

4) Memory:
   - Load: Read Data from Memory
   - Store: Write Data to Memory
   - Branch: if operands ==, Change PC

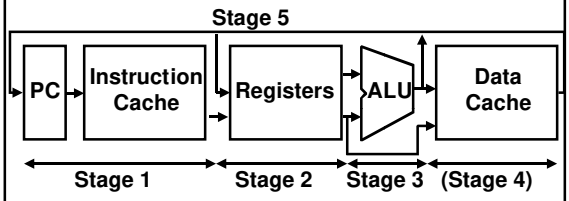
5) Write Back: Write Data to Register

Pipelined Execution Representation

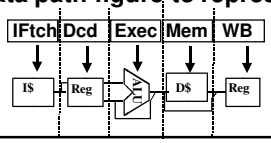


- Every instruction takes same number of steps, also called pipeline "stages"

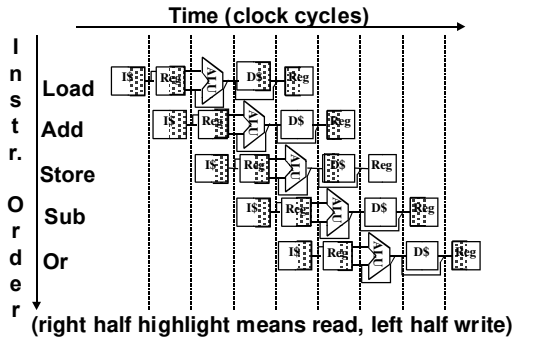
Review: A Datapath for MIPS (Lec. 20)



- Use data path figure to represent pipeline



Graphical Pipeline Representation



(right half highlight means read, left half write)

Example

- Suppose 2 ns for memory access, 2 ns for ALU operation, and 1 ns for register file read or write
- Nonpipelined Execution:
  - lw : IF + Read Reg + ALU + Memory + Write Reg = 2 + 1 + 2 + 2 + 1 = 8 ns
  - add: IF + Read Reg + ALU + Write Reg = 2 + 1 + 2 + 1 = 6 ns
- Pipelined Execution:
  - Max(IF,Read Reg,ALU, Memory,Write Reg) = 2 ns

Administrivia

- Project 6 (last): Due Today
- Next Readings: 7.5
- 11th homework (last): Due Friday 4/30 7PM
  - Exercises 2.6, 2.13, 6.1, 6.3, 6.4

Administrivia: Rest of 61C

F 4/30 Review: Caches/TLB/VM; Section 7.5

M 5/3 Deadline to correct your grade record

W 5/5 Review: Interrupts / Polling; A.7
F 5/7 61C Summary / Your Cal heritage / HKN Course Evalution
(Due: Final 61C Survey in lab; Return)

Sun 5/9 Final Review starting 2PM (1 Pimintel)

W 5/12 Final (5PM 1 Pimintel)

- Need Alternative Final? Contact mds@cory

"What's This Stuff (Potentially) Bad For?"

Linking Entertainment to Violence 100s of studies in recent decades have revealed a direct correlation between exposure to media violence--including video games--and increased aggression.

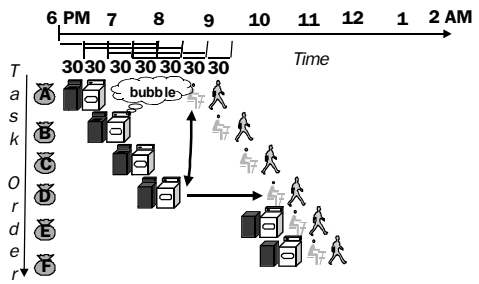
•"We are reaching that stage of desensitization at which the inflicting of pain and suffering has become a source of entertainment; vicarious pleasure rather than revulsion. We are learning to kill, and we are learning to like it." Like the tobacco industry, "the evidence is there."

• The 14-year-old boy who opened fire on a prayer group in a Ky. school foyer in 1997 was a video-game expert. He had never fired a pistol before, but in the ensuing melee, he fired 8 shots, hit 8 people, and killed 3. The average law enforcement officer in the United States, at a distance of 7 yards, hits fewer than 1 in 5 shots.

• Because of freedom of speech is a value that we don't want to compromise, "it really comes down to the people creating these games. That's where the responsibility lies."

N.Y. Times, 4/26/99

Pipeline Hazard: Matching socks in later load

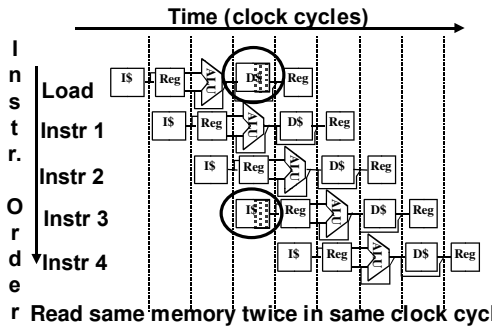


A depends on D; stall since folder tied up

Problems for Computers

- Limits to pipelining: Hazards prevent next instruction from executing during its designated clock cycle
  - Structural hazards: HW cannot support this combination of instructions (single person to fold and put clothes away)
  - Control hazards: Pipelining of branches & other instructions stall the pipeline until the hazard "bubbles" in the pipeline
  - Data hazards: Instruction depends on result of prior instruction still in the pipeline (missing sock)

Single Memory is a Structural Hazard



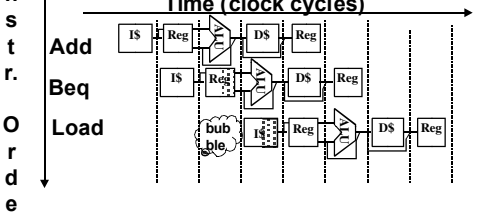
Read same memory twice in same clock cycle

Structural Hazards limit performance

- Example: if 1.3 memory accesses per instruction (30% of instructions executed loads and stores) and only one memory access per cycle then
  - Average CPI ≥ 1.3
  - Otherwise resource is more than 100% utilized

Control Hazard Solutions

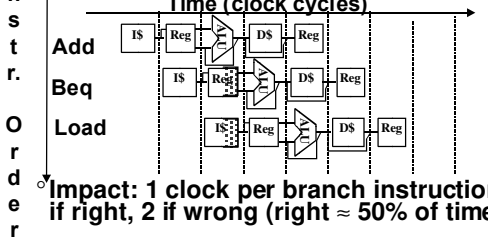
- Stall: wait until decision is clear
  - Move up decision to 2nd stage by adding hardware to check registers as being read



- Impact: 2 clock cycles per branch instruction ⇒ slow

Control Hazard Solutions

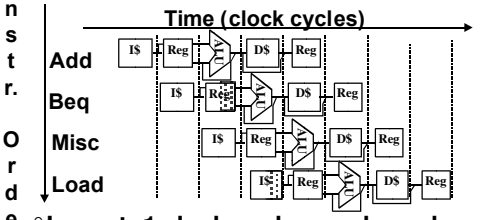
- Predict: guess one direction, then back up if wrong
  - For example, Predict not taken



- Impact: 1 clock per branch instruction if right, 2 if wrong (right ≈ 50% of time)
- More dynamic scheme: history of 1 branch (≈ 90%)

Control Hazard Solutions

- Redefine branch behavior (takes place after next instruction) "delayed branch"



- Impact: 1 clock cycles per branch instruction if can find instruction to put in "slot" (≈ 50% of time)

Example Nondelayed vs. Delayed Branch

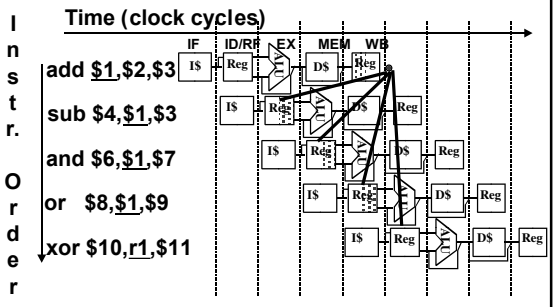
Nondelayed Branch	Delayed Branch
or $8, $9 ,$10	add $1 ,$2,$3
add $1 ,$2,$3	sub $4, $5,$6
sub $4, $5,$6	beq $1, $4, Exit
beq $1, $4, Exit	or $8, $9 ,$10
xor $10, $1,$11	xor $10, $1,$11
Exit:	Exit:

Data Hazard on Register $1

```
add $1 ,$2,$3
sub $4, $1 ,$3
and $6, $1 ,$7
or  $8, $1 ,$9
xor $10, $1 ,$11
```

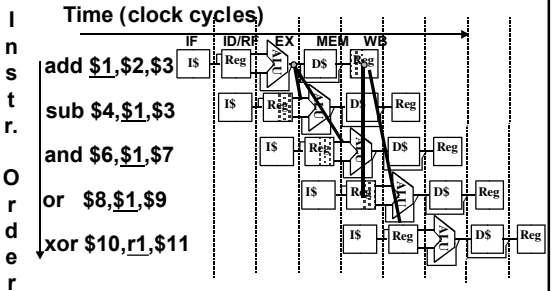

Data Hazard on $1:

Dependencies backwards in time are hazards



Data Hazard Solution:

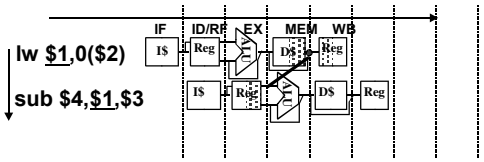
- "Forward" result from one stage to another



- "or" OK if define read/write properly

Forwarding (or Bypassing): What about Loads

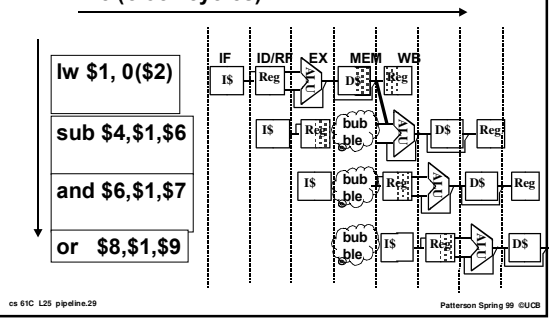
- Dependencies backwards in time are hazards



- Can't solve with forwarding
- Must stall instruction dependent on loads

Data Hazard Even with Forwarding

- Must insert stall or bubble in pipeline



Software Scheduling to Avoid Load Hazards

Try producing fast code for

```
a = b + c;
d = e - f;
```

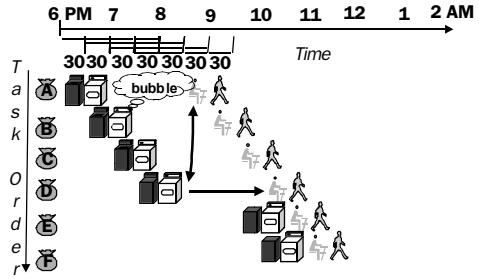
a, b, c, d ,e, and f in memory

Slow code:		Fast code:	
lw	$2,b	lw	$2,b
lw	$3,c	lw	$3,c
add	$1,$2,$3	lw	$5,e
sw	$1,a	add	$1,$2,$3
lw	$5,e	lw	$6,f
lw	$6,f	sw	$1,a
sub	$4,$5,$6	sub	$4,$5,$6
sw	$4,d	sw	$4,d

Advanced Pipelining Concepts (if time)

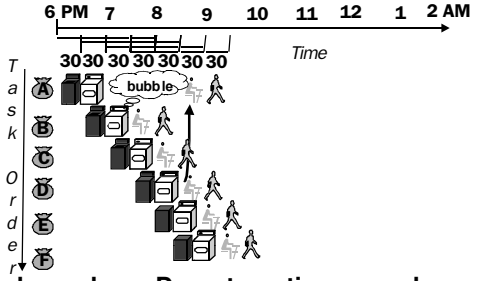
- Out-of-order Execution
- Superscalar execution
- State-of-the-Art Microprocessor

Pipeline Hazard: Stall



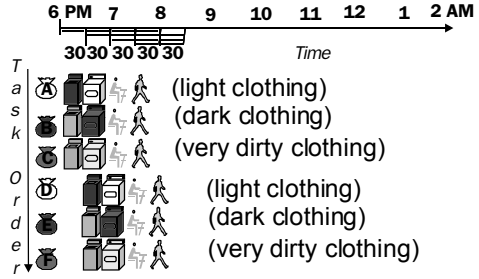
A depends on D; stall since folder tied up

Out-of-Order Laundry: Don't Wait



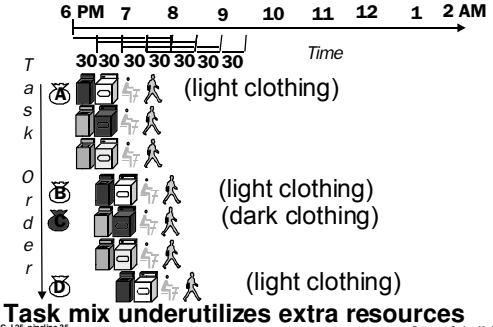
A depends on D; rest continue; need more resources to allow out-of-order

Superscalar Laundry: Parallel per stage



More resources, HW to match mix of parallel tasks?

Superscalar Laundry: Mismatch Mix



Task mix underutilizes extra resources

State of the Art: Alpha 21264

- 15 Million transistors
- 2 64KB caches on chip; 16MB L2 cache off chip
- Clock cycle time <1.7 nsec, or Clock Rate >600 MHz (Fastest Cray Supercomputer: T90 2.2 nsec)
  - 90 watts per chip!
- Superscalar: fetch up to 6 instructions/clock cycle, retires up to 4 instruction/clock cycle
- Execution out-of-order

Summary 1/2: Pipelining Introduction

- Pipelining is a fundamental concept
  - Multiple steps using distinct resources
  - Exploiting parallelism in instructions
- What makes it easy? (MIPS vs. 80x86)
  - All instructions are the same length
    ⇒ simple instruction fetch
  - Just a few instruction formats
    ⇒ read registers before decode instruction
  - Memory operands only in loads and stores
    ⇒ fewer pipeline stages
  - Data aligned ⇒ 1 memory access / load, store

Summary 2/2: Pipelining Introduction

- What makes it hard?
- Structural hazards: suppose we had only one cache?
  ⇒ Need more HW resources
- Control hazards: need to worry about branch instructions?
  ⇒ Branch prediction, delayed branch
- Data hazards: an instruction depends on a previous instruction?
  ⇒ need forwarding, compiler scheduling