Performance

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CS 3410

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The slides are the product of many rounds of teaching CS 3410 by Professors Weatherspoon, Bala, Bracy, and Sirer.

Goals for today

Performance

- What is performance?
- How to get it?

Performance

Complex question

- How fast is the processor?
- How fast your application runs?
- How quickly does it respond to you?
- How fast can you process a big batch of jobs?
- How much power does your machine use?

Measures of Performance

Clock speed

- 1 KHz, 10^3 Hz: cycle is 1 millisecond, ms, (10^{-6})
- 1 MHz, 10^6 Hz: cycle is 1 microsecond, us, (10^{-6})
- 1 Ghz, 10^9 Hz: cycle is 1 nanosecond, ns, (10^{-9})
- 1 Thz, 10^{12} Hz: cycle is 1 picosecond, ps, (10^{-12})

Instruction/application performance

- MIPs (Millions of instructions per second)
- FLOPs (Floating point instructions per second)
  - GPUs: GeForce GTX Titan (2,688 cores, 4.5 Tera flops, 7.1 billion transistors, 42 Gigapixel/sec fill rate, 288 GB/sec)
- Benchmarks (SPEC)

Measures of Performance

CPI: "Cycles per instruction"→Cycle/instruction for **on average**

- **IPC** = 1/CPI
  - Used more frequently than CPI
  - Favored because "bigger is better", but harder to compute with
- Different instructions have different cycle costs
  - E.g., "add" typically takes 1 cycle, "divide" takes >10 cycles
- Depends on relative instruction frequencies

CPI example

- Program has equal ratio: integer, memory, floating point
- Cycles per insn type: integer = 1, memory = 2, FP = 3
- What is the CPI? (33% * 1) + (33% * 2) + (33% * 3) = 2
- *Caveat:* calculation ignores many effects
  - Back-of-the-envelope arguments only

Measures of Performance

General public (mostly) ignores CPI

- Equates clock frequency with performance!

Which processor would you buy?

- Processor A: CPI = 2, clock = 5 GHz
- Processor B: CPI = 1, clock = 3 GHz
- Probably A, but B is faster (assuming same ISA/compiler)

Classic example

- 800 MHz PentiumIII faster than 1 GHz Pentium4!
- Example: Core i7 faster clock-per-clock than Core 2
- Same ISA and compiler!

Meta-point: danger of partial performance metrics!

Measures of Performance

Latency

- How long to finish my program
  - Response time, elapsed time, wall clock time
  - CPU time: user and system time

Throughput

- How much work finished per unit time

Ideal: Want high throughput, low latency

… also, low power, cheap ($$) etc.

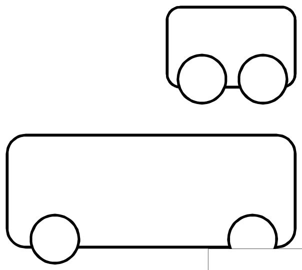
iClicker Question #1: Car vs. Bus

Car: speed = 60 miles/hour, capacity = 5

Bus: speed = 20 miles/hour, capacity = 60

Task: transport passengers 10 miles

	Latency (min)	Throughput (PPH)
Car	10 min	
Bus	30 min	



CLICKER QUESTIONS:

#1 Car Throughput

A. 10
B. 15
C. 20
D. 60
E. 120

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Task: transport passengers 10 miles

	Latency (min)	Throughput (PPH)
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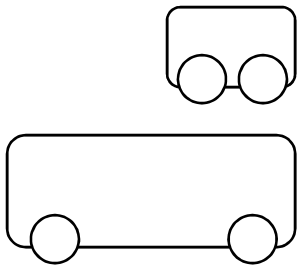
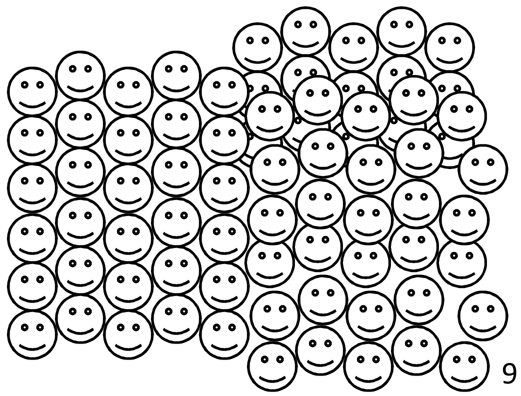




How to make the computer faster?

Decrease latency

Critical Path

- Longest path determining the minimum time needed for an operation
- Determines minimum length of clock cycle
  i.e. determines maximum clock frequency

Optimize for latency on the critical path

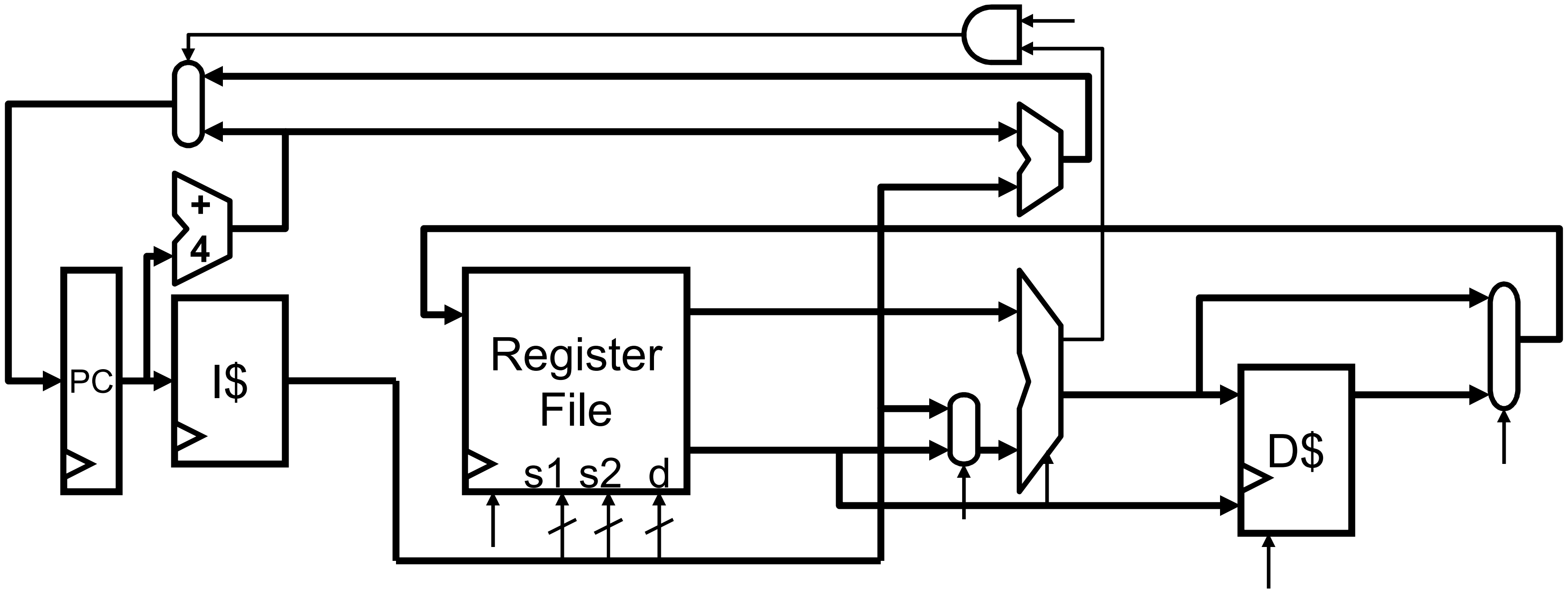
- – Parallelism (like carry look ahead adder)
- – Pipelining
- – Both

Latency: Optimize Delay on Critical Path

E.g. Adder performance

32 Bit Adder Design	**Space**	**Time**
Ripple Carry	≈ 300 gates	≈ 64 gate delays
2-Way Carry-Skip	≈ 360 gates	≈ 35 gate delays
3-Way Carry-Skip	≈ 500 gates	≈ 22 gate delays
4-Way Carry-Skip	≈ 600 gates	≈ 18 gate delays
2-Way Look-Ahead	≈ 550 gates	≈ 16 gate delays
Split Look-Ahead	≈ 800 gates	≈ 10 gate delays
Full Look-Ahead	≈ 1200 gates	≈ 5 gate delays

Review: Single-Cycle Datapath



Single-cycle datapath: true "atomic" F/EX loop

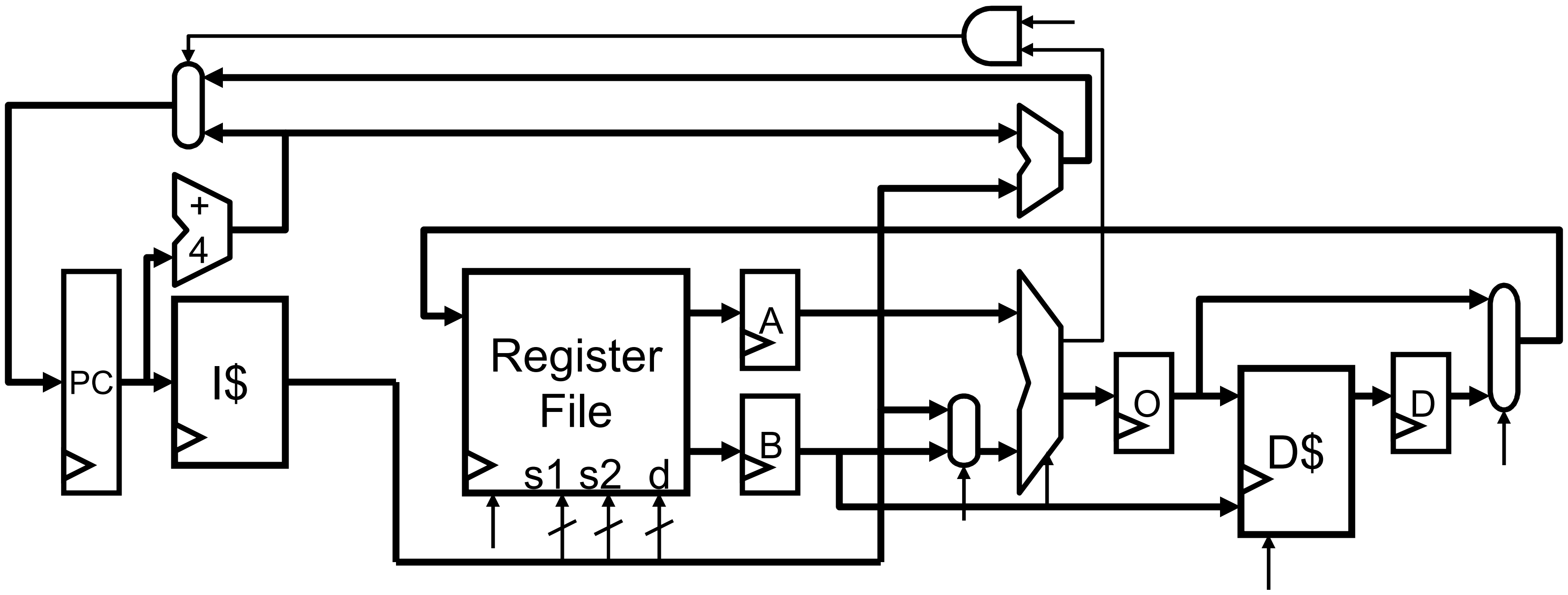
Fetch, decode, execute one instruction/cycle

+ Low CPI (later): 1 by definition

– Long clock period: accommodate slowest insn

(PC → I$ → RF → ALU → D$ → RF)

New: Multi-Cycle Datapath



Multi-cycle datapath: attacks slow clock

Fetch, decode, execute one insn over multiple cycles

Allows insns to take different number of cycles

±Opposite of single-cycle: short clock period, high CPI

Single- vs. Multi-cycle Performance

Single-cycle

- Clock period = 50ns, CPI = 1
- Performance = **50ns/insn**

Multi-cycle: opposite performance split

- + Shorter clock period
- – Higher CPI

Example

- branch: 20% (**3** cycles), ld: 20% (**5** cycles), ALU: 60% (**4** cycle)
- Clock period = **11ns**, CPI = (20%*3)+(20%*5)+(60%*4) = 4
  - – Why is clock period 11ns and not 10ns?
- Performance = **44ns/insn**

Aside: CISC makes perfect sense in multi-cycle datapath

Multi-Cycle Instructions

But what to do when operations take diff. times?

E.g: Assume:

- load/store: 100 ns $\longleftarrow$ 10 MHz
- arithmetic: 50 ns $\longleftarrow$ 20 MHz
- branches: 33 ns $\longleftarrow$ 30 MHz

ms = 10^{-3} second
us = 10^{-6} seconds
ns = 10^{-9} seconds
ps = 10^{-12} seconds

Single-Cycle CPU

10 MHz (100 ns cycle) with

– 1 cycle per instruction

Multi-Cycle Instructions

Multiple cycles to complete a single instruction

E.g: Assume:

- load/store: 100 ns $\leftarrow$ 10 MHz
- arithmetic: 50 ns $\leftarrow$ 20 MHz
- branches: 33 ns $\leftarrow$ 30 MHz

ms = 10^{-3} second
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Which one is faster: Single- or Multi-Cycle CPU?

Single-Cycle CPU

10 MHz (100 ns cycle) with

- 1 cycle per instruction

Multi-Cycle CPU

30 MHz (33 ns cycle) with

- 3 cycles per load/store
- 2 cycles per arithmetic
- 1 cycle per branch

Cycles Per Instruction (CPI)

Instruction mix for some program P, assume:

- 25% load/store (3 cycles / instruction)
- 60% arithmetic (2 cycles / instruction)
- 15% branches (1 cycle / instruction)

Multi-Cycle performance for program P:

3 * .25 + 2 * .60 + 1 * .15 = 2.1

average *cycles per instruction* (CPI) = 2.1

Multi-Cycle @ 30 MHz $\longleftarrow$ 30M cycles/sec ÷2.1 cycles/instr = $\boxed{\text{15 MIPS}}$

vs

$\swarrow$ $\boxed{\text{10 MIPS}}$ = 10M cycles/sec ÷ 1 cycle/instr

Single-Cycle @ 10 MHz

MIPS = millions of instructions per second

Total Time

$$\boxed{\text{CPU Time} = \#\ \text{Instructions} \times \text{CPI} \times \text{Clock Cycle Time}}$$

sec/prgrm = Instr/prgm x cycles/instr x seconds/cycle

Instructions per program: “dynamic instruction count”

- Runtime count of instructions executed by the program
- Determined by program, compiler, ISA

Cycles per instruction: “CPI”   (typical range: 2 to 0.5)

- How many *cycles* does an instruction take to execute?
- Determined by program, compiler, ISA, micro-architecture

Seconds per cycle: clock period, length of each cycle

- Inverse metric: cycles/second (Hertz) or cycles/ns (Ghz)
- Determined by micro-architecture, technology parameters

For lower latency (=better performance) minimize all three

- Difficult: ***often pull against one another***

Total Time

$$\boxed{\text{CPU Time = \# Instructions x CPI x Clock Cycle Time}}$$

sec/prgrm = Instr/prgm x cycles/instr x seconds/cycle

E.g. Say for a program with 400k instructions, 30 MHz:

CPU [Execution] Time = ?

Total Time

CPU Time = # Instructions x CPI x Clock Cycle Time

sec/prgrm = Instr/prgm x cycles/instr x seconds/cycle

E.g. Say for a program with 400k instructions, 30 MHz:

CPU [Execution] Time = 400k x 2.1 x 33 ns = 27 ms

Total Time

CPU Time = # Instructions x CPI x Clock Cycle Time

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E.g. Say for a program with 400k instructions, 30 MHz:

CPU [Execution] Time = 400k x 2.1 x 33 ns = 27 ms

How do we increase performance?

- Need to reduce CPU time
  - Reduce #instructions
  - Reduce CPI
  - Reduce Clock Cycle Time

Example

Goal: Make Multi-Cycle @ 30 MHz CPU (15MIPS) run 2x faster by making arithmetic instructions faster

Instruction mix (for P):

- 25% load/store, CPI = 3
- 60% arithmetic, CPI = 2
- 15% branches, CPI = 1

CPI = 0.25 x 3 + 0.6 x 2 + 0.15 x 1
= 2.1

Goal: Make processor run 2x faster,
i.e. 30 MIPS instead of 15 MIPS

Example

Goal: Make Multi-Cycle @ 30 MHz CPU (15MIPS) run 2x faster by making arithmetic instructions faster

Instruction mix (for P):

- 25% load/store, CPI = 3
- 60% arithmetic, CPI = ~~2~~ 1
- 15% branches, CPI = 1

$$\text{CPI} = 0.25 \times 3 + 0.6 \times \underline{1} + 0.15 \times 1$$

$$\boxed{= 1.5}$$

First lets try CPI of 1 for arithmetic.

Is that 2x faster overall? No

How much does it improve performance?

Example

Goal: Make Multi-Cycle @ 30 MHz CPU (15MIPS) run 2x faster by making arithmetic instructions faster

Instruction mix (for P):

- 25% load/store, CPI = 3
- 60% arithmetic, CPI = ~~2~~ X
- 15% branches, CPI = 1

$$\text{CPI} = 1.05 = 0.25 \times 3 + 0.6 \times \underline{X} + 0.15 \times 1$$

$$1.05 = .75 + 0.6X + 0.15$$

$$X = 0.25$$

But, want to half our CPI from 2.1 to 1.05.

Let new arithmetic operation have a CPI of X. X =?

Then, X = 0.25, which is a significant improvement

Example

Goal: Make Multi-Cycle @ 30 MHz CPU (15MIPS) run 2x faster by making arithmetic instructions faster

Instruction mix (for P):

- 25% load/store, CPI = 3
- 60% arithmetic, CPI = ~~2~~ 0.25
- 15% branches, CPI = 1

To double performance CPI for arithmetic operations have to go from 2 to 0.25

Amdahl's Law

Amdahl's Law

Execution time after improvement =

$$\frac{\text{execution time affected by improvement}}{\text{amount of improvement}} + \text{execution time unaffected}$$

Or: Speedup is limited by popularity of improved feature

Corollary: Make the common case fast

- Don't optimize 1% to the detriment of other 99%
- Don't over-engineer capabilities that cannot be utilized

Caveat: Law of diminishing returns

Performance Recap

iClicker Question

What is the minimal, additional metric(s) that you need to decide which processor is faster?

(If 1 metric is enough, only list 1. Include more if needed.)

A. MIPS
B. CPI
C. Dynamic Instruction Count
D. Clock Rate
E. Nothing. Enough information has been given

Processor A and Processor B execute the program in the same number of cycles

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