Review: What is computer architecture?

“Technology”
Logic Gates
SRAM
DRAM
Circuit Techniques
Packaging
Magnetic Storage
Flash Memory

Plans

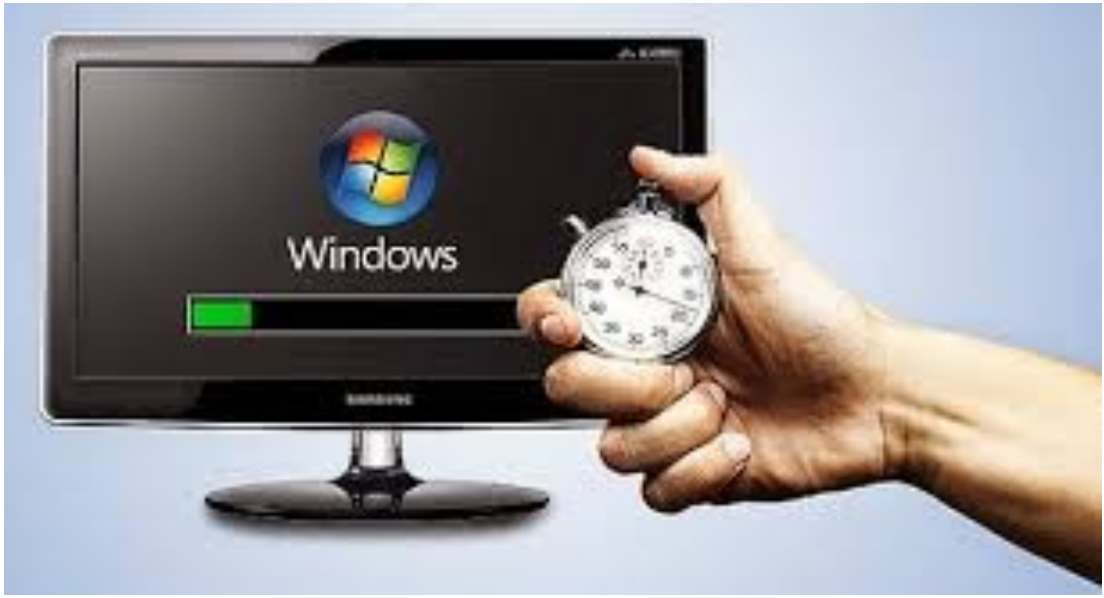
Applications/Domains
Desktop
Servers
Mobile Phones
Supercomputers
Game Consoles
Embedded

Goals
Function
Performance
Reliability
Cost/Manufacturability
Energy Efficiency
Time to Market

Today: Performance

- Performance metrics
  - Latency and throughput
  - Speedup
  - Averaging

- CPU Performance



Lots of in-class exercises/examples

Performance Metrics

Performance: Latency vs. Throughput

- **Latency (execution time)**: time to finish a fixed task
- **Throughput (bandwidth)**: number of tasks per unit time
  - Different: exploit parallelism for throughput, not latency

- Choose definition of performance that matches your goals
  - Scientific program? latency.
  - Web server? throughput.

Examples

- How to measure the performance of moving people for 10 miles round trip?
  - Car: capacity = 5, speed = 60 miles/hour
  - Bus: capacity = 60, speed = 20 miles/hour
  - Latency: how long does ~ take to move one person for 20 miles?
  - Throughput: how many people can ~ move per hour?

Answer:

- Latency: **car = 20 min**, bus = 60 min
- Throughput: car = 15 PPH, **bus = 60 PPH**

Examples

- Fastest way to send 10TB of data from US to UK?

  FTP, SMB, Rsync / Robocopy, other?

  Used FedEx overnight to deliver the drive

  Even 1 Gbps data transfer takes days!

Overnight
EXPRESS Shipping

Amazon Does This…

Available Internet Connection	Theoretical Min. Number of Days to Transfer 1TB at 80% Network Utilization	When to Consider AWS Import/Export?
T1 (1.544Mbps)	82 days	100GB or more
10Mbps	13 days	600GB or more
T3 (44.736Mbps)	3 days	2TB or more
100Mbps	1 to 2 days	5TB or more
1000Mbps	Less than 1 day	60TB or more

amazon webservices™ AWS IMPORT/EXPORT CALCULATOR

Amazon Web Services » AWS Import/Export » AWS Import/Export Calculator

Operation Type		Import to S3
Location	AWS Region	US Standard Region
AWS Import/Export Data Load	Total Terabytes to Load	1 TB
	Number of Devices	1
	Wipe Device After Import	No
Estimated Transfer Speed	Average File Size*	1 MB
	Interface Type	eSATA
	Transfer Speed**	22.51 MB/sec

What we learned

Measuring performance

Latency & throughput

Comparing Performance - Speedup

- Speedup of A over B
  - X = Latency(B)/Latency(A) (divide by the faster)
  - X = Throughput(A)/Throughput(B) (divide by the slower)
- A is X% faster than B if
  - X = ((Latency(B)/Latency(A)) – 1) * 100
  - X = ((Throughput(A)/Throughput(B)) – 1) * 100
  - Latency(A) = Latency(B) / (1+(X/100))
  - Throughput(A) = Throughput(B) * (1+(X/100))

- Car/bus example
  - Latency?
  - Throughput?
  - See next slide…

Car/bus example

- Latency: **car = 20 min**, bus = 60 min
- Throughput: car = 15 PPH, **bus = 60 PPH**

Speedup?

- Latency:
  - Speedup of car over bus is 3
  - Car is 200% faster than bus
- Throughput:
  - Speedup of bus over car is 4
  - Bus is 300% faster than car

Comparing Performance - Speedup

- Program A runs for 200 cycles
- Program B runs for 350 cycles

What is "cycle"?
Execution time * clock frequency
i.e., second * Hz

- Speedup of A over B?
  - Speedup = 350/200 = 1.75
  - As a percentage: (1.75 – 1) * 100 = 75% (Program A runs 75% faster than program B)

- If program C is 50% faster than A, how many cycles does C run for?
  - 133 cycles

Note

- Speedup of A over B
  - X = Latency(B)/Latency(A)
  - X = Throughput(A)/Throughput(B)

What if X < 1?

-- means A is slower than B

Speedup and % Increase and Decrease

- Program A runs for 200 cycles
- Program B runs for 350 cycles
- Percent increase and decrease are not the same.
  - % increase of cycles: ((350 – 200)/200) * 100 = 75%
  - % decrease of cycles: ((350 - 200)/350) * 100 = 42.3%

What we learned

Comparing performance

Speedup

Performance metrics

Latency, throughput, speedup

Averaging performance

Mean (Average) Performance Numbers

- **Arithmetic**: $(1/N) * \sum_{P=1..N}$ Latency(P)
  - For units that are proportional to time (e.g., latency)

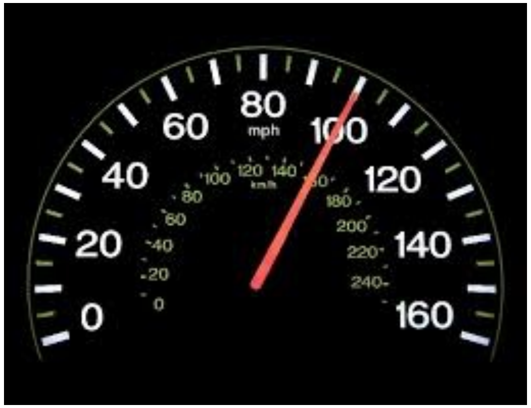
- **Harmonic**: $N / \sum_{P=1..N}$ 1/Throughput(P)
  - For units that are inversely proportional to time (e.g., throughput)

- You can add latencies, but not throughputs
  - Latency(P1+P2, A) = Latency(P1, A) + Latency(P2, A)
  - Throughput(P1+P2, A) != Throughput(P1, A) + Throughput(P2, A)

- **Geometric**: $\sqrt[N]{\prod_{P=1..N}}$ Speedup(P)
  - For unitless quantities (e.g., speedup ratios)

For Example…

1 mile @ 30 miles/hour + 1 mile @ 90 miles/hour



- You drive two miles
  - 30 miles per hour for the first mile
  - 90 miles per hour for the second mile
- Question: what was your average speed?
  - Hint: the answer is not 60 miles per hour
  - Why?

Answer: 45 miles/hour

- You drive two miles
  - 30 miles per hour for the first mile
  - 90 miles per hour for the second mile

- Question: what was your average speed?
  - Hint: the answer is not 60 miles per hour
  - 0.03333 hours per mile for 1 mile
  - 0.01111 hours per mile for 1 mile
  - 0.04444 hours for 2 miles
  - = 45 miles per hour
  - != (30 + 90) / 2

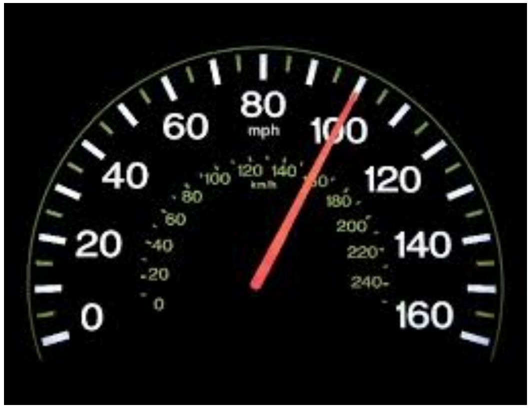
What we learned

Averaging performance

Arithmetic mean for latency

Harmonic mean for throughput

Geometric mean for speedup



CPU Performance

How to evaluate

Latency, throughput, and speedup

CPU Performance Equation

- Latency = seconds / program =
  - (insns / program) * (cycles / insns) * (seconds / cycle)

  - **Insns / program**: insn count
    - Impacted by program, compiler, ISA
  - **Cycles / insn**: **CPI**
    - Impacted by program, compiler, ISA, **micro-arch**
  - **Seconds / cycle**: **clock period**
    - Impacted by micro-arch, technology
- For low latency (better performance) minimize all three
  - Difficult: often pull against one another
  - Example we have seen: RISC vs. CISC ISAs
    - ±RISC: low CPI/clock period, high insn count
    - ±CISC: low insn count, high CPI/clock period

Cycles per Instruction (CPI)

- **CPI**: Cycles/instruction
  - **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 (what if idle)

- CPI example
  - A program executes equal: integer, floating point (FP), memory ops
  - Cycles per instruction type: integer = 1, memory = 2, FP = 3
  - What is the CPI? (1 cycle+2 cycles +3 cycles) / 3 instrs= 2

    Calculated in another way: 33% x 1 + 33% x 2 + 33% x 3 = 2

CPI Example

- Assume a processor with instruction frequencies and costs
  - Integer ALU: 50%, 1 cycle
  - Load: 20%, 5 cycle
  - Store: 10%, 1 cycle
  - Branch: 20%, 2 cycle

- Which change would improve performance more?
  - A. "Branch prediction" to reduce branch cost to 1 cycle?
  - B. Faster data memory to reduce load cost to 3 cycles?
- Compute CPI
  - Base = 0.5*1 + 0.2*5 + 0.1*1 + 0.2*2 = 2 CPI
  - A = 0.5*1 + 0.2*5 + 0.1*1+ 0.2*1 = 1.8 CPI (1.11x or 11% faster)
  - B = 0.5*1 + 0.2*3 + 0.1*1 + 0.2*2 = 1.6 CPI (1.25x or 25% faster)
    - **B is the winner**

Measuring CPI

- How are CPI and execution-time actually measured?
  - Execution time? stopwatch timer (Unix "time" command)
  - Cycles = execution time * clock frequency
  - How is instruction count measured? → truly executed insn
- Hardware event counters
  - Available in most processors today
  - One way to measure instruction count
- Cycle-level micro-architecture simulation
  - \+ Measure exactly what you want … and impact of potential fixes!
  - Method of choice for many micro-architects
- More useful is CPI breakdown (CPI_{CPU}, CPI_{MEM}, etc.)
  - So we know what performance problems are and what to fix

Summary: Performance Metrics

- Performance metrics: Latency & throughput
- Comparing performance: Speedup
- Averaging performance:
  - Arithmetic mean
  - Harmonic mean
  - Geometric mean
- Measuring CPU performance: CPI (IPC)