CIS 501: Computer Architecture

Unit 5: Performance & Benchmarking

Slides developed by Joe Devietti, Milo Martin & Amir Roth at Upenn
with sources that included University of Wisconsin slides
by Mark Hill, Guri Sohi, Jim Smith, and David Wood

This Unit

- Metrics
- CPU Performance
- Comparing Performance
- Benchmarks
- Performance Laws

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 (e.g., bread)
  - Often contradictory (latency **vs.** throughput)
    - Will see many examples of this
  - Choose definition of performance that matches your goals
    - Scientific program? latency. web server? throughput.
- Example: move people 10 miles
  - Car: capacity = 5, speed = 60 miles/hour
  - Bus: capacity = 60, speed = 20 miles/hour
  - Latency: **car = 10 min**, bus = 30 min
  - Throughput: car = 15 PPH (count return trip), **bus = 60 PPH**
- Fastest way to send 10TB of data? (1+ gbits/second)

Amazon Does This!

Available Internet Connection	Theoretical Min. Number of Days to Transfer 100TB at 80% Network Utilization	When to Consider AWS Snowball?
T3 (44.736Mbps)	269 days	2TB or more
100Mbps	120 days	5TB or more
1000Mbps	12 days	60TB or more

"Never underestimate the bandwidth of a station wagon full of tapes hurtling down the highway."

Andrew Tanenbaum

Computer Networks, 4th ed., p. 91

CPU Performance

Frequency as a performance metric

- 1 Hertz = 1 cycle per second
  1 Ghz is 1 cycle per nanosecond, 1 Ghz = 1000 Mhz
- (Micro-)architects often ignore dynamic instruction count…
- … but general public (mostly) also ignores CPI
  - and instead equate 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
  - Core i7 faster clock-per-clock than Core 2
  - Same ISA and compiler!
- **partial performance metrics are dangerous!**

MIPS (performance metric, not the ISA)

- (Micro) architects often ignore dynamic instruction count
  - Typically work in one ISA/one compiler → treat it as fixed
- CPU performance equation becomes
  - Latency: seconds / insn = (cycles / insn) * (seconds / cycle)
  - Throughput: **insn / second** = (insn / cycle) * (cycles / second)
- **MIPS** (millions of instructions per second)
  - **Cycles / second**: clock frequency (in MHz)
  - Example: CPI = 2, clock = 500 MHz → 0.5 * 500 MHz = 250 MIPS
- Pitfall: may vary inversely with actual performance
  - – Compiler removes insns, program gets faster, MIPS goes down
  - – Work per instruction varies (e.g., multiply vs. add, FP vs. integer)

Cycles per Instruction (CPI)

- **CPI**: Cycle/instruction **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
  - A program executes equal: integer, floating point (FP), memory ops
  - Cycles per instruction type: integer = 1, memory = 2, FP = 3
  - What is the CPI? (33% * 1) + (33% * 2) + (33% * 3) = 2
  - **Caveat**: this sort of calculation ignores many effects
    - Back-of-the-envelope arguments only

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

Measuring CPI

- How are CPI and execution-time actually measured?
  - Execution time? stopwatch timer (Unix "time" command)
  - CPI = (CPU time * clock frequency) / dynamic insn count
  - How is dynamic instruction count measured?

- More useful is CPI breakdown (CPI_{CPU}, CPI_{MEM}, etc.)
  - So we know what performance problems are and what to fix
  - Hardware event counters
    - Available in most processors today
    - One way to measure dynamic instruction count
    - Calculate CPI using counter frequencies / known event costs
  - Cycle-level micro-architecture simulation
    - \+ Measure exactly what you want … and impact of potential fixes!
    - Method of choice for many micro-architects

Comparing Performance

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? Car is 3 times (and 200%) faster than bus
  - Throughput? Bus is 4 times (and 300%) faster than car

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: ((350 – 200)/200) * 100 = 75%
  - % decrease: ((350 - 200)/350) * 100 = 42.3%
- Speedup:
  - 350/200 = 1.75 – Program A is 1.75x faster than program B
  - As a percentage: (1.75 – 1) * 100 = 75%

- If program C is 1x faster than A, how many cycles does C run for? – 200 (the same as A)
  - What if C is 1.5x faster? 133 cycles (50% faster than A)

Mean (Average) Performance Numbers

- **Arithmetic**: $(1/N) * \sum_{P=1..N}$ P_latency
  - For units that are proportional to time (e.g., latency)
- **Harmonic**: $N / \sum_{P=1..N}$ 1/P_throughput
  - 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)
    - 1 mile @ 30 miles/hour + 1 mile @ 90 miles/hour
    - Average is **not** 60 miles/hour
- **Geometric**: $\sqrt[N]{\prod_{P=1..N}}$ P_speedup
  - For unitless quantities (e.g., speedup ratios)

For Example…

- 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

- 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
  - 0.02222 hours per mile on average
  - = 45 miles per hour

Measurement Challenges

Measurement Challenges

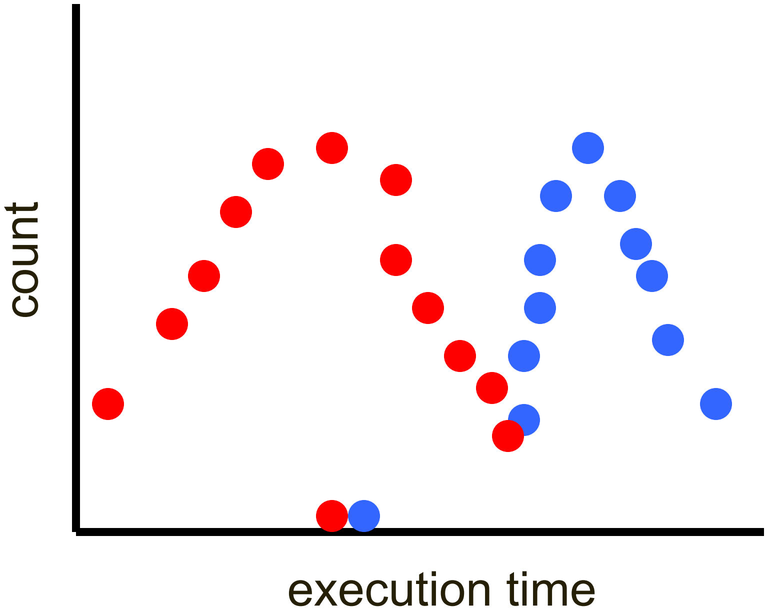
- Are –O3 compiler optimizations really faster than –O0?
- Why might they not be?
  - other processes running
  - not enough runs
  - not using a high-resolution timer
  - cold-start effects
  - managed languages: JIT/GC/VM startup
- solution: experiment design + statistics

Experiment Design

- Two kinds of errors: **systematic** and **random**
- removing **systematic error**
  - aka "measurement bias" or "not measuring what you think you are"
  - Run on an unloaded system
  - Measure something that runs for *at least* several seconds
  - Understand the system being measured
    - simple empty-for-loop test => compiler optimizes it away
  - Vary experimental setup
  - Use appropriate statistics
- removing **random error**
  - Perform many runs: how many is enough?

Determining performance differences

- Program runs in 20s on **machine A**, 20.1s on **machine B**
- Is this a meaningful difference?



the distribution matters!

Confidence Intervals

- Compute mean *and* confidence interval (CI)

$$\pm t \frac{s}{\sqrt{n}}$$

t = critical value from t-distribution
s = sample standard error
n = # experiments in sample

- Meaning of the 95% confidence interval $x \pm 1.3$
  - collected 1 **sample** with *n* experiments
  - given repeated sampling, *x* will be within 1.3 of the true mean 95% of the time
- If CIs overlap, differences not statistically significant

CI example

- setup
  - 130 experiments, mean = 45.4s, stderr = 10.1s
- What's the 95% CI?
- t = 1.962 (depends on %CI and # experiments)
  - look it up in a stats textbook or online
- at 95% CI, performance is 45.4 $\pm$1.74 seconds
- What if we want a smaller CI?

Benchmarking

Processor Performance and Workloads

- Q: what does performance of a chip mean?
- A: nothing, there must be some associated workload
  - **Workload**: set of tasks someone (you) cares about

- **Benchmarks**: standard workloads
  - Used to compare performance across machines
  - Either are, or highly representative of, actual programs people run

- **Micro-benchmarks**: non-standard non-workloads
  - Tiny programs used to isolate certain aspects of performance
  - Not representative of complex behaviors of real applications
  - Examples: binary tree search, towers-of-hanoi, 8-queens, etc.

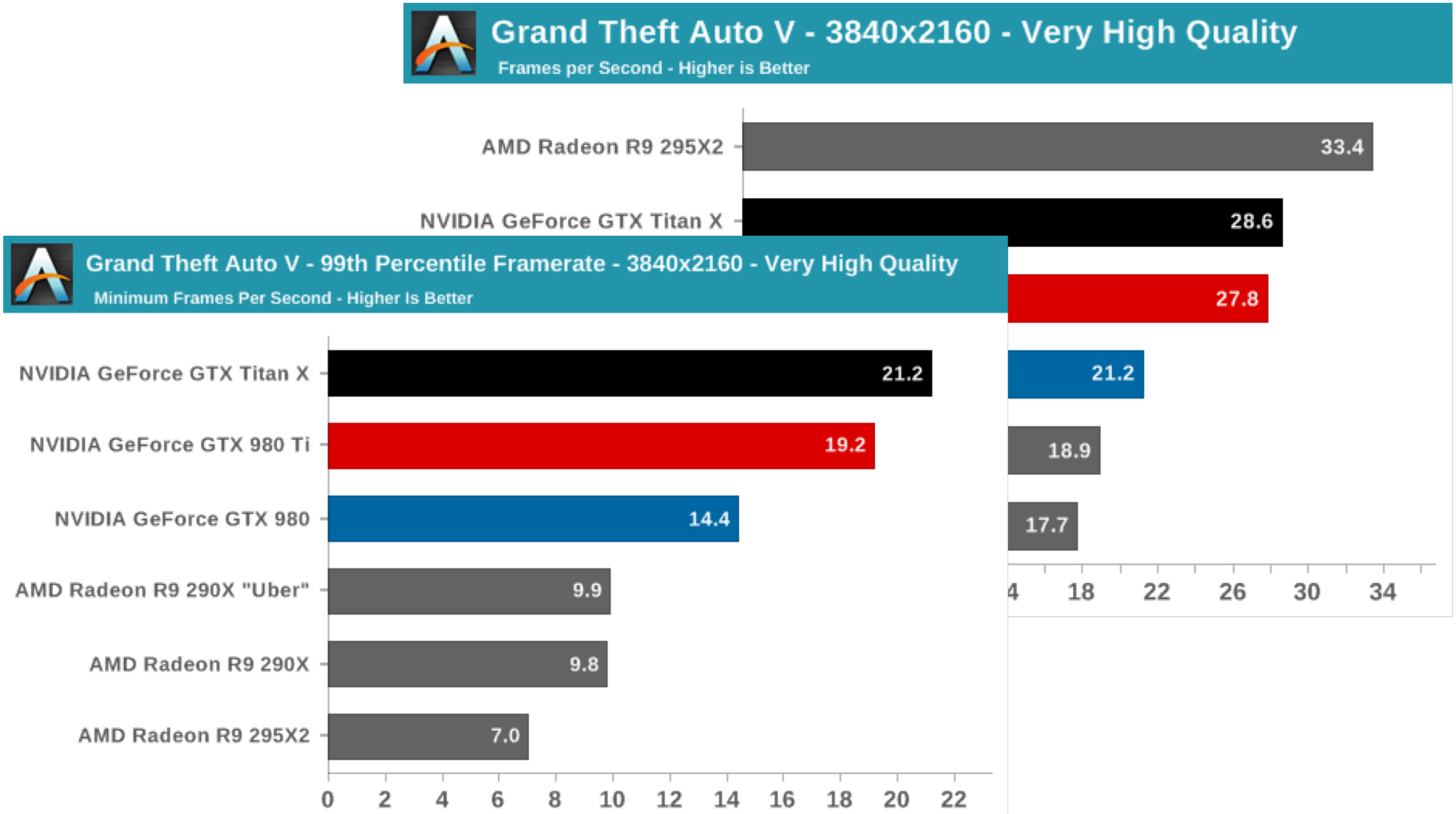
Example: SPECmark 2006/2017

- performance wrt reference machine
- Latency SPECmark
  - For each benchmark
    - Take odd number of samples
    - Choose median
    - Take speedup (reference machine / your machine)
  - Take “average” (Geometric mean) of ***speedups*** over all benchmarks
- Throughput SPECmark
  - Run multiple benchmarks in parallel on multiple-processor system

Example: GeekBench

- Set of cross-platform multicore benchmarks
  - Can run on iPhone, Android, laptop, desktop, etc
- Tests integer, floating point, memory bandwidth performance
- GeekBench stores all results online
  - Easy to check scores for many different systems, processors
- Pitfall: Workloads are simple, may not be a completely accurate representation of performance
  - We know they evaluate compared to a baseline benchmark

Example: GTA V



http://www.anandtech.com/show/9306/the-nvidia-geforce-gtx-980-ti-review

Performance Laws

Amdahl's Law

$$\frac{1}{(1-P)+\frac{P}{S}}$$

How much will an optimization improve performance?

P = proportion of running time affected by optimization
S = speedup

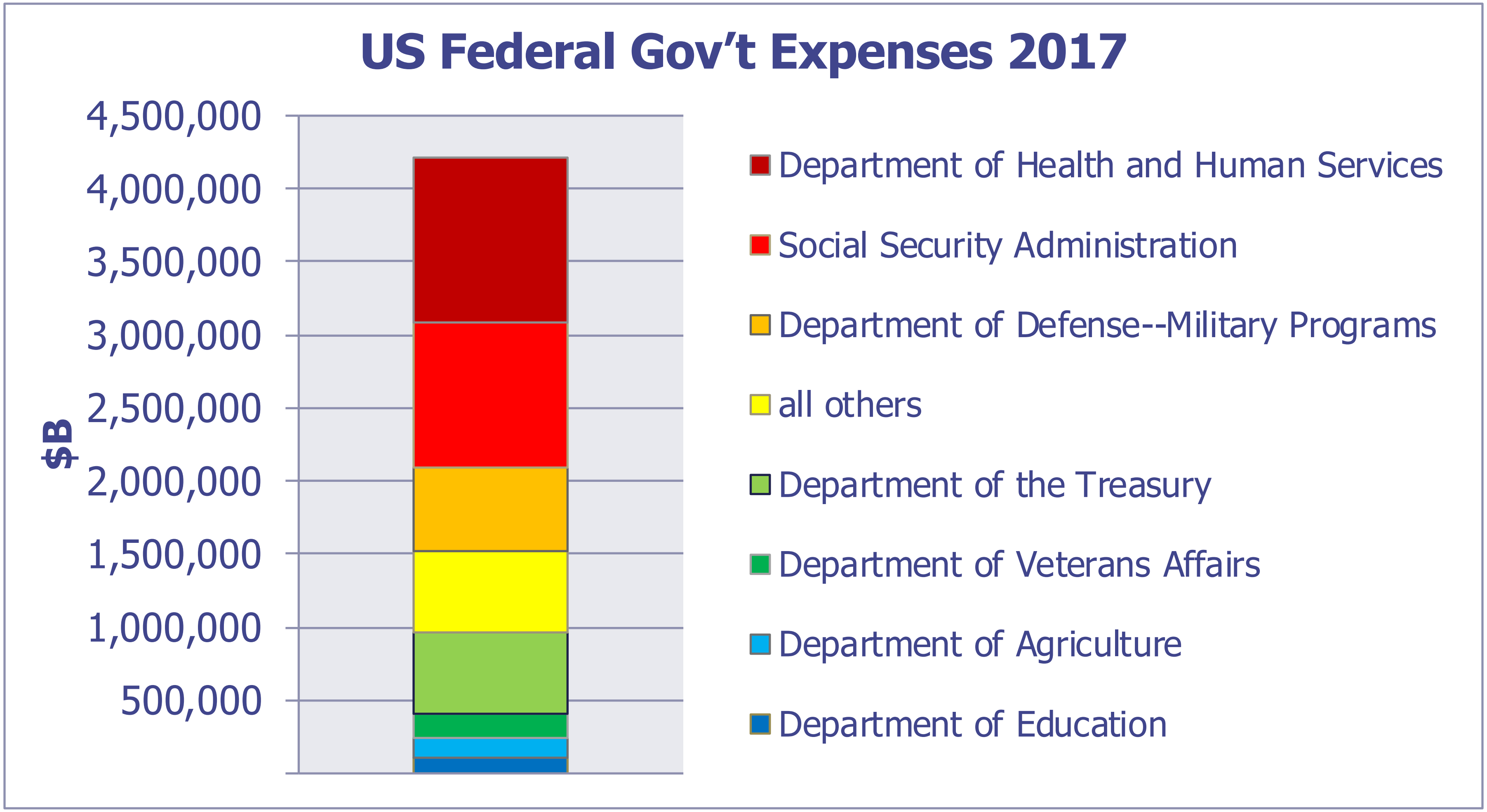
What if I speedup 25% of a program's execution by 2x?

1.14x speedup

What if I speedup 25% of a program's execution by ∞?

1.33x speedup

Amdahl's Law for the US Budget



https://www.whitehouse.gov/omb/historical-tables/

scrapping Dept of Education ($111B) cuts budget by 2.7%

Amdahl's Law for Parallelization

$$\frac{1}{(1-P)+\frac{P}{N}}$$

How much will parallelization improve performance?

P = proportion of parallel code
N = threads

What is the max speedup for a program that's 10% serial?

What about 1% serial?

Increasing proportion of parallel code

- Amdahl's Law requires *extremely* parallel code to take advantage of large multiprocessors
- two approaches:
  - **strong scaling**: shrink the serial component
    - \+ same problem runs faster
    - – becomes harder and harder to do
  - **weak scaling**: increase the problem size
    - \+ natural in many problem domains: internet systems, scientific computing, video games
    - – doesn't work in other domains

How long am I going to be in this line?

Use Little's Law!

Little's Law

$$L = \lambda W$$

L = items in the system

λ = average arrival rate

W = average wait time

- Assumption:
  - system is in steady state, i.e., average arrival rate = average departure rate
- No assumptions about:
  - arrival/departure/wait time distribution or service order (FIFO, LIFO, etc.)
- Works on **any** queuing system
- Works on **systems of systems**

Little's Law for Computing Systems

- Only need to measure two of L, λ and W
  - often difficult to measure L directly
- Describes how to meet performance requirements
  - e.g., to get high throughput (λ), we need either:
    - low latency per request (small W)
    - service requests in parallel (large L)
- Addresses many computer performance questions
  - sizing queue of L1, L2, L3 misses
  - sizing queue of outstanding network requests for 1 machine
    - or the whole datacenter
  - calculating average latency for a design

Performance Rules of Thumb

- Design for actual performance, **not peak performance**
  - Peak performance: "Performance you are guaranteed not to exceed"
  - Greater than "actual" or "average" or "sustained" performance
    - Why? Caches misses, branch mispredictions, limited ILP, etc.
  - For actual performance X, machine capability must be > X

- Easier to "buy" bandwidth than latency
  - say we want to transport more cargo via train:
    - (1) build another track or (2) make a train that goes twice as fast?
  - Use bandwidth to reduce latency

- **Build a balanced system**
  - Don't over-optimize 1% to the detriment of other 99%
  - System performance often determined by slowest component

Measuring LC-4 Processor Performance

Benchmarking the LC-4 processors

- Fixed workload: **wireframe trace**
- Focus on improving frequency with pipelining
  - measure frequency with Vivado timing reports
- Focus on improving IPC with superscalar
  - see how many cycles the wireframe trace takes

Summary

- Latency = seconds / program =
  - (instructions / program) * (cycles / instruction) * (seconds / cycle)
- **Instructions / program**: dynamic instruction count
  - Function of program, compiler, instruction set architecture (ISA)
- **Cycles / instruction**: CPI
  - Function of program, compiler, ISA, micro-architecture
- **Seconds / cycle**: clock period
  - Function of micro-architecture, technology parameters

- Optimize each component
  - this class focuses mostly on CPI (caches, parallelism)
  - …but some on dynamic instruction count (compiler, ISA)
  - …and some on clock frequency (pipelining, technology)