Computer Architecture

Lec 2: Performance & Benchmarking

This Lecture

- 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
  - 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**

CPU Performance

Basic Performance Equation

- 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)

Cycles per Instruction (CPI) and IPC

- **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
  - **Warning**: 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 (e.g., gem5)
    - \+ Measure exactly what you want … and impact of potential fixes!
    - Method of choice for many micro-architects

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)
- **partial performance metrics are dangerous!**

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

Producing Wrong Data Without Doing Anything Obviously Wrong!

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Abstract

This paper presents a surprising result: changing a seemingly innocuous aspect of an experimental setup can cause a sys-

1. Introduction

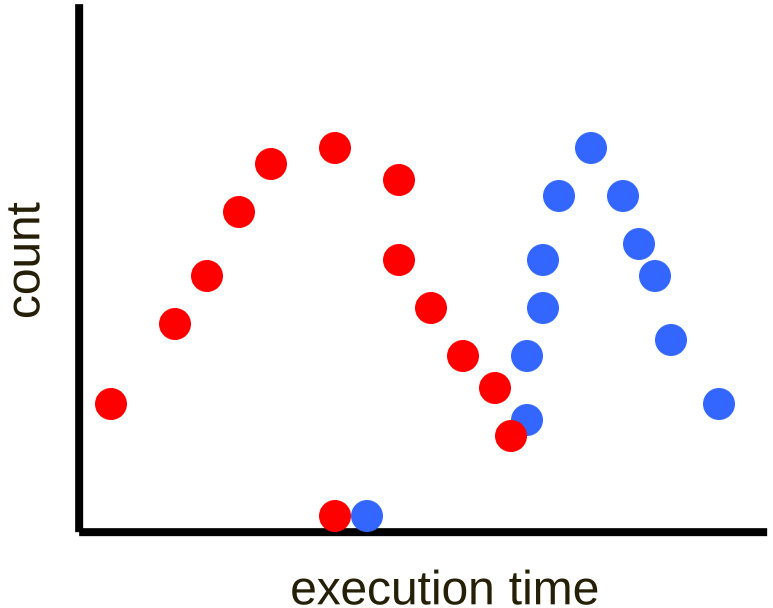
Systems researchers often use experiments to drive their work: they use experiments to identify bottlenecks and then

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

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 ±1.74 seconds
- What if we want a smaller CI?

CI example

- Setup
  - 130 experiments
- What's the 95%
- t = 1.962 (deper
  - look it up in a st
- at 95% CI, perfo
- What if we want

t 分布表							
	0.1	0.05	0.025	0.01	0.005	0.0005	(片側)
	0.2	0.1	0.05	0.02	0.01	0.001	(両側)
1	3.07768	6.31375	12.70620	31.82052	63.65674	636.61925	
2	1.88562	2.91999	4.30265	6.96456	9.92484	31.59905	
3	1.63774	2.35336	3.18245	4.54070	5.84091	12.92398	
4	1.53321	2.13185	2.77645	3.74695	4.60409	8.61030	
5	1.47588	2.01505	2.57058	3.36493	4.03214	6.86883	
6	1.43976	1.94318	2.44691	3.14267	3.70743	5.95882	
7	1.41492	1.89458	2.36462	2.99795	3.49948	5.40788	
8	1.39682	1.85955	2.30600	2.89646	3.35539	5.04131	
9	1.38303	1.83311	2.26216	2.82144	3.24984	4.78091	
10	1.37218	1.81246	2.22814	2.76377	3.16927	4.58689	
11	1.36343	1.79588	2.20099	2.71808	3.10581	4.43698	
12	1.35622	1.78229	2.17881	2.68100	3.05454	4.31779	
13	1.35017	1.77093	2.16037	2.65031	3.01228	4.22083	
14	1.34503	1.76131	2.14479	2.62449	2.97684	4.14045	
15	1.34061	1.75305	2.13145	2.60248	2.94671	4.07277	
16	1.33676	1.74588	2.11991	2.58349	2.92078	4.01500	
17	1.33338	1.73961	2.10982	2.56693	2.89823	3.96513	
18	1.33039	1.73406	2.10092	2.55238	2.87844	3.92165	
19	1.32773	1.72913	2.09302	2.53948	2.86093	3.88341	
20	1.32534	1.72472	2.08596	2.52798	2.84534	3.84952	
21	1.32319	1.72074	2.07961	2.51765	2.83136	3.81928	

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

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 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

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

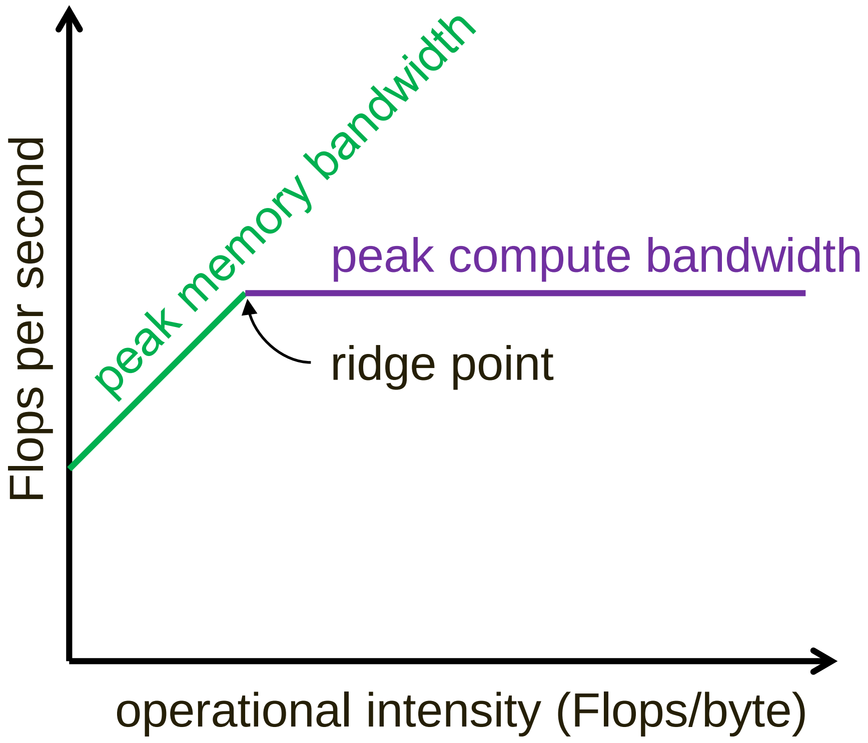
Little's Law for Computing Systems

- 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

Optimizing Performance

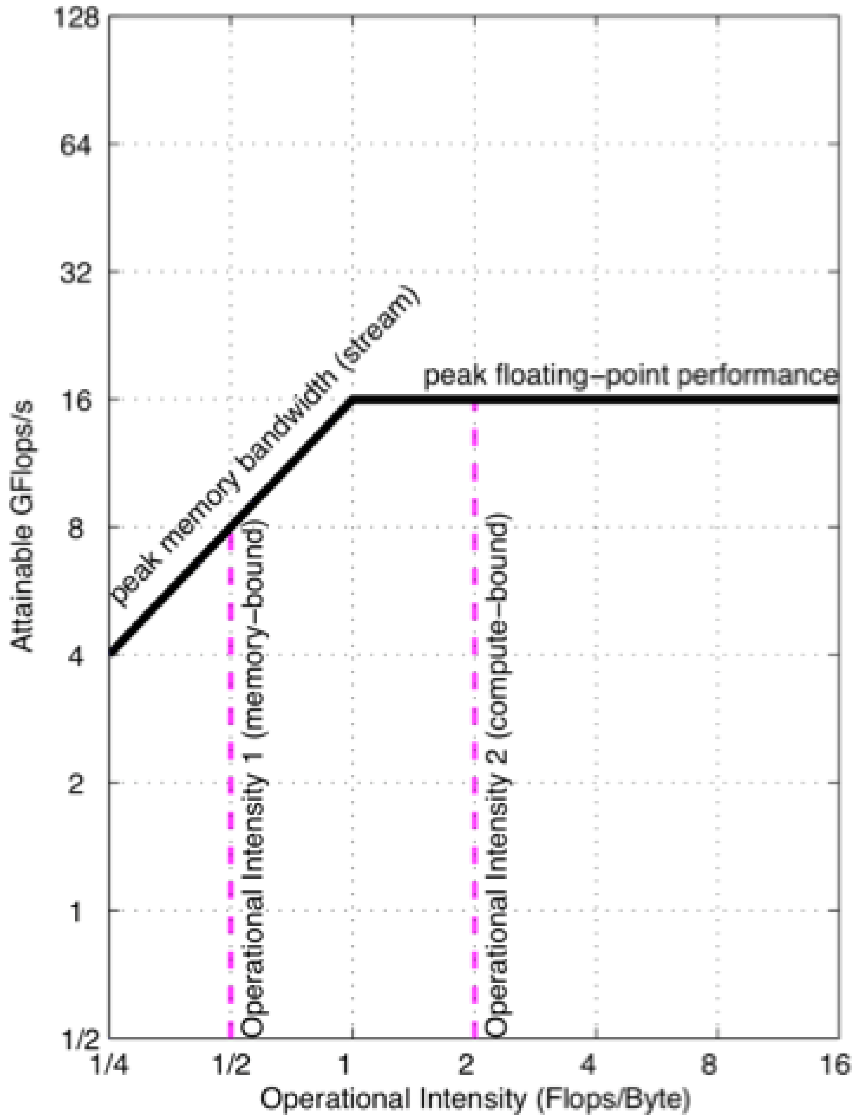
When can I stop optimizing?

- use the Roofline model
- am I keeping the ALUs fed?



Roofline example

- Roofline model for AMD Opteron X2 CPU
  - log-log plot
  - 17.6 GFlops/sec compute bw
  - 15 GB/sec memory bw



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?
  - can you 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