

# Metrics and Evaluation

## Introduction

1. In order to build better computers, we need to define “better”
  - Determining the right metrics for evaluating performance

## Performance

1. Latency: Time between start and finish
2. Throughput: number/unit time
  - $\text{Throughput} = 1 / \text{Latency}$  due to pipelining
  - Example: Cars on an assembly line
    - Entire process takes 4 hours with 20 steps
    - Latency = 4 hours
    - Throughput = 5 cars / hour

## Latency and Throughput Quiz

1. Website with 2 servers
  - Order request assigned to a server
  - Server takes 1 millisecond to process an order
  - Server cannot do anything else while processing an order
  - Throughput of website = 2000 orders/second
  - Latency of website = 1 millisecond

## Comparing Performance

1. “X is N times faster than Y”
  - $\text{Speedup} = N \rightarrow \text{Speed}(X) / \text{Speed}(Y)$
  - $N = \text{Throughput}(X) / \text{Throughput}(Y)$ 
    - Since higher latency is better
  - $N = \text{Latency}(Y) / \text{Latency}(X)$ 
    - Since lower latency is better

## Performance Comparison Quiz 1

1. Old laptop can compress video in 4 hours
2. New laptop can compress video in 10 minutes
  - $\text{Speedup}(\text{new vs old}) = 4 * 60 / 10 = 24$
  - $\text{Speedup}(\text{old vs new}) = 10 / 4 / 60 = 0.041666$

## Speedup

1.  $\text{Speedup} > 1$  = Improved performance
  - Shorter execution time
  - Higher throughput
2.  $\text{Speedup} < 1$  = Worse performance
  - Higher execution time
  - Lower throughput
3. Performance  $\sim$  Throughput
4. Performance  $\sim 1 / \text{Latency}$

## Measuring Performance

1. Performance = 1 / Execution time
  - On what workload? Potentially actual user workload, but...
    - Requires running many programs
    - Not representative of other users
    - How do we get workload data?
  - Instead, typically use a benchmark workload

## Benchmarks

1. Programs and input data agreed upon by users for performance measurements
2. Benchmark suite
  - Multiple programs
  - Each representative of some type of application

## Types of Benchmarks

1. Real applications
  - Most representative
  - Most difficult to set up (full OS, graphics card, hard drives)
  - Good for comparing actual machines
2. Kernels
  - Find most time-consuming part of an application
  - Isolate loop and use it for testing
  - Still too difficult in early stages of prototyping (no compiler)
  - Good for prototyping
3. Synthetic benchmarks
  - Behave similarly to kernels but simpler to compile
  - Good for design studies
4. Peak performance
  - Maximum number of instructions/second
  - Good for marketing

## Performance Reporting Quiz

1. Which of these use code from real applications, but not all of the code?
  - Application kernel

## Benchmark Standards

1. Benchmarking organization
  - Takes input from user groups, experts in academia, manufacturers
  - Creates a standard benchmark suite
2. Industry standard benchmarks
  - TPC: Databases, web servers, data mining, transaction processing
  - EEMBC: Embedded processing (cars, phones, etc)
  - SPEC: Engineering workstations and raw processors (not very I/O intensive)
    - GCC
    - Bwaves, LBM
    - PERL
    - Cactus ADM
    - Xalanc BMK
    - Calculix, Deall
    - Bzip

- Go, Sjong

## Summarizing Performance

1. Average execution time
  - Can't simply average speedup for individual applications; not equivalent to average speedup overall
    - Instead, use geometric mean
    - Geometric mean =  $\text{nth root}(\text{product}(\text{vals}))$
  - Simple arithmetic mean should not be used on ratios of times

Application	Computer X	Computer Y	Speedup
A	9 secs	18 secs	2
B	10 secs	7 secs	0.7
C	5 secs	11 secs	2.2
Average	8 secs	12 secs	1.5
Geometric	7.66 secs	11.15 secs	1.456

## Speedup Averaging Quiz

1. Old laptop to new laptop
2. Homework formatting application gives speedup of 2
3. Virus scan application gives speedup of 8
4. Overall speedup =  $\sqrt{2 * 8} = 4$

## Iron Law of Performance

1. CPU time = # instructions in program \* cycles per instruction \* clock cycle time
  - CPU time =  $(\text{insts} / \text{program}) * (\text{cycles} / \text{insts}) * (\text{seconds} / \text{cycle})$
2. Instructions in program
  - Algorithm
  - Compiler
  - Instruction set
3. Cycles per instruction
  - Instruction set
  - Processor design
4. Clock cycle time
  - Processor design
  - Circuit design
  - Transistor physics
5. Computer architecture affects the instruction set and processor design
  - Complex instructions: Fewer instructions, more cycles per instruction
  - Simpler instructions: More instructions, fewer cycles per instruction
  - Short clock cycle: More cycles per instruction
  - Longer clock cycle: Fewer cycles per instruction
  - Goal is to balance

## Iron Law Quiz 1

1. Program executes 3 billion instructions
2. Processor spends 2 cycles per instruction
3. Processor clock speed is 3 GHz
4. Execution time =  $3e9 * 2 * (1/3e9) = 2$  seconds

## Iron Law of Unequal Instruction Times

1. Execution time of instructions can vary
2. CPU time =  $\sum (IC_i * CPI_i) * (\text{time} / \text{cycle})$

## Iron Law Quiz 2

1. Program executes 50 billion instructions
  - 10 billion are branches (CPI=4)
  - 15 billion are loads (CPI=2)
  - 5 billion are stores (CPI=3)
  - The rest are integer add (CPI=1)
2. Clock at 4 GHz
3. Execution time =  $(4 * 10e9 + 2 * 15e9 + 3 * 5e9 + 20 * 1e9) / 4e9 = 26.25$

## Amdahl's Law

1. Used to speed up part of the program (only some instructions)
2. What is overall speedup?
  - $\text{Speedup} = 1 / ((1 - \text{FRAC}_{\text{enh}}) + (\text{FRAC}_{\text{enh}} / \text{SPEEDUP}_{\text{enh}}))$
  - $\text{FRAC}_{\text{enh}}$  = percentage of original execution time affected by enhancement

## Amdahl's Law Quiz 1

1. Program has 50 billion instructions
2. Clock frequency is 2 GHz
3. Improve branch instruction from 4 to 2 CPI
4. Can't just plug into Amdahl's law since these are percentages of instructions, not execution times
  - $(0.4 * 1 + 0.2 * 4 + 0.3 * 2 + 0.1 * 3) * 1e9 / 2e9 = 1.05$  (before enhancement)
  - $(0.4 * 1 + 0.2 * 2 + 0.3 * 2 + 0.1 * 3) * 1e9 / 2e9 = 0.85$  (after enhancement)
  - $1.05 / 0.85 = 1.24$

Inst Type	% in program	CPI
Interrupt	40%	1
Branch	20%	4
Load	30%	2
Store	10%	3

## Amdahl's Law Implications

1. Enhancement 1: Speedup of 20 on 10% of time
  - $1 / ((1 - 0.1) + (0.1 / 20)) = 1.105$
  - Even if infinite speedup, overall speedup is only 1.111
2. Enhancement 2: Speedup of 1.6 on 80% of time
  - $1 / ((1 - 0.8) + (0.8 / 1.6)) = 1.43$
3. Conclusion: Make common case fast
  - Better to affect lots of code a little than a small amount of code a lot

## Amdahl's Law Quiz 2

1. Program has 50 billion instructions
2. Clock frequency is 2 GHz
3. Possible improvements
  - Branch CPI 4 -> 3

- Increase clock frequency 2 -> 2.3
  - Store CPI 3 -> 2
4. Which is best?
- Branch:  $1 / ((1 - 0.2) + 0.2 / (4 / 3)) = 1.05$
  - Clock:  $1 / ((1 - 1) + 1 / (2.3 / 2)) = 1.15$
  - Store:  $1 / ((1 - 0.1) + 0.1 / (3 / 2)) = 1.034$

Inst Type	% in program	CPI
Interrupt	40%	1
Branch	20%	4
Load	30%	2
Store	10%	3

## Lhadma's Law

1. Amdahl: Make common case fast
2. Lhadma: Do not mess up uncommon case too badly
3. Example:
  - Improvement of 2x on 90%
  - Slow down the rest by 10x
  - Speedup =  $1 / (0.1/0.1 + 0.9/2) = 1 / 1.45 = 0.7$  so overall speed is worse

## Diminishing Returns

1. Don't go overboard improving the same thing
  - As percentage of execution time decreases, overall speedup also decreases
  - Additionally, once the easier optimizations are complete, more time is required for further improvements



$$SPEEDUP = \frac{1}{0.5 + \frac{0.5}{2}} = 1.33$$



$$SPEEDUP = \frac{1}{0.67 + \frac{0.33}{2}} = 1.2$$

Diminishing Returns

## Conclusion

1. Overall performance improvement requires balancing improvements to an aspect without detriment to another aspect