ECE/CS 552: Performance and Cost

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Lecture notes partially based on set created by Mark Hill.

Performance and Cost

- Which of the following airplanes has the best performance?

Airplane	Passengers	Range (mi)	Speed (mph)
Boeing 737-100	101	630	598
Boeing 747	470	4150	610
BAC/Sud Concorde	132	4000	1350
Douglas DC-8-50	146	8720	544

- How much faster is the Concorde vs. the 747
- How much bigger is the 747 vs. DC-8?

Performance and Cost

- Which computer is fastest?
- Not so simple
  - Scientific simulation – FP performance
  - Program development – Integer performance
  - Database workload – Memory, I/O

Performance of Computers

- Want to buy the fastest computer for what you want to do?
  - Workload is all-important
  - Correct measurement and analysis
- Want to design the fastest computer for what the customer wants to pay?
  - Cost is an important criterion

Forecast

- Time and performance
- Iron Law
- MIPS and MFLOPS
- Which programs and how to average
- Amdahl's law

Defining Performance

- What is important to whom?
- Computer system user
  - Minimize elapsed time for program = time_end – time_start
  - Called response time
- Computer center manager
  - Maximize completion rate = #jobs/second
  - Called throughput

Response Time vs. Throughput

- Is throughput = 1/av. response time?
  - Only if NO overlap
  - Otherwise, throughput > 1/av. response time
  - E.g. a lunch buffet – assume 5 entrees
  - Each person takes 2 minutes/entrée
  - Throughput is 1 person every 2 minutes
  - BUT time to fill up tray is 10 minutes
  - Why and what would the throughput be otherwise?
    - 5 people simultaneously filling tray (overlap)
    - Without overlap, throughput = 1/10

What is Performance for us?

- For computer architects
  - CPU time = time spent running a program
- Intuitively, bigger should be faster, so:
  - Performance = 1/X time, where X is response, CPU execution, etc.
- Elapsed time = CPU time + I/O wait
- We will concentrate on CPU time

Improve Performance

- Improve (a) response time or (b) throughput?
  - Faster CPU
    - Helps both (a) and (b)
  - Add more CPUs
    - Helps (b) and perhaps (a) due to less queueing

Performance Comparison

- Machine A is n times faster than machine B iff perf(A)/perf(B) = time(B)/time(A) = n
- Machine A is x% faster than machine B iff
  - perf(A)/perf(B) = time(B)/time(A) = 1 + x/100
- E.g. time(A) = 10s, time(B) = 15s
  - 15/10 = 1.5 => A is 1.5 times faster than B
  - 15/10 = 1.5 => A is 50% faster than B

Breaking Down Performance

- A program is broken into instructions
  - H/W is aware of instructions, not programs
- At lower level, H/W breaks instructions into cycles
  - Lower level state machines change state every cycle
- For example:
  - 1GHz Snapdragon runs 1000M cycles/sec, 1 cycle = 1ns
  - 2.5GHz Core i7 runs 2.5G cycles/sec, 1 cycle = 0.25ns

Iron Law

$$\text{Processor Performance} = \frac{\text{Time}}{\text{Program}}$$

$$= \underbrace{\frac{\text{Instructions}}{\text{Program}}}_{\text{(code size)}} \times \underbrace{\frac{\text{Cycles}}{\text{Instruction}}}_{\text{(CPI)}} \times \underbrace{\frac{\text{Time}}{\text{Cycle}}}_{\text{(cycle time)}}$$

Architecture --> Implementation --> Realization

Compiler Designer · Processor Designer · Chip Designer

Iron Law

- Instructions/Program
  - Instructions executed, not static code size
  - Determined by algorithm, compiler, ISA
- Cycles/Instruction
  - Determined by ISA and CPU organization
  - Overlap among instructions reduces this term
- Time/cycle
  - Determined by technology, organization, clever circuit design

Our Goal

- Minimize time which is the product, NOT isolated terms
- Common error to miss terms while devising optimizations
  - E.g. ISA change to decrease instruction count
  - BUT leads to CPU organization which makes clock slower
- Bottom line: terms are inter-related

Other Metrics

- MIPS and MFLOPS
- MIPS = instruction count/(execution time x 10^6)
  = clock rate/(CPI x 10^6)
- But MIPS has serious shortcomings

Problems with MIPS

- E.g. without FP hardware, an FP op may take 50 single-cycle instructions
- With FP hardware, only one 2-cycle instruction
- Thus, adding FP hardware:
  - CPI increases (why?) 50/50 => 2/1
  - Instructions/program decreases (why?) 50 => 1
  - Total execution time decreases 50 => 2
- BUT, MIPS gets worse! 50 MIPS => 2 MIPS

Problems with MIPS

- Ignores program
- Usually used to quote peak performance
  - Ideal conditions => guaranteed not to exceed!
- When is MIPS ok?
  - Same compiler, same ISA
  - E.g. same binary running on AMD Phenom, Intel Core i7
  - Why? Instr/program is constant and can be ignored

Other Metrics

- MFLOPS = FP ops in program/(execution time x 10^6)
- Assuming FP ops independent of compiler and ISA
  - Often safe for numeric codes: matrix size determines # of FP ops/program
  - However, not always safe:
    - Missing instructions (e.g. FP divide)
    - Optimizing compilers
- Relative MIPS and normalized MFLOPS
  - Adds to confusion

Rules

- Use ONLY Time
- Beware when reading, especially if details are omitted
- Beware of Peak
  - "Guaranteed not to exceed"

Iron Law Example

- Machine A: clock 1ns, CPI 2.0, for program x
- Machine B: clock 2ns, CPI 1.2, for program x
- Which is faster and how much?

  Time/Program = instr/program x cycles/instr x sec/cycle
  Time(A) = N x 2.0 x 1 = 2N
  Time(B) = N x 1.2 x 2 = 2.4N
  Compare: Time(B)/Time(A) = 2.4N/2N = 1.2
- So, Machine A is 20% faster than Machine B for this program

Iron Law Example

Keep clock(A) @ 1ns and clock(B) @2ns

For equal performance, if CPI(B)=1.2, what is CPI(A)?

Time(B)/Time(A) = 1 = (Nx2x1.2)/(Nx1xCPI(A))

CPI(A) = 2.4

Iron Law Example

- Keep CPI(A)=2.0 and CPI(B)=1.2
- For equal performance, if clock(B)=2ns, what is clock(A)?

Time(B)/Time(A) = 1 = (N x 2.0 x clock(A))/(N x 1.2 x 2)

clock(A) = 1.2ns

Which Programs

- Execution time of what program?
- Best case – your always run the same set of programs
  - Port them and time the whole workload
- In reality, use benchmarks
  - Programs chosen to measure performance
  - Predict performance of actual workload
  - Saves effort and money
  - Representative? Honest? Benchmarketing…

How to Average

	Machine A	Machine B
Program 1	1	10
Program 2	1000	100
Total	1001	110

- One answer: for total execution time, how much faster is B? 9.1x

How to Average

- Another: arithmetic mean (same result)
- Arithmetic mean of times: $\left\{\sum_{i=1}^{n} time(i)\right\} \times \frac{1}{n}$
- AM(A) = 1001/2 = 500.5
- AM(B) = 110/2 = 55
- 500.5/55 = 9.1x
- Valid only if programs run equally often, so use weighted arithmetic mean:

$$\left\{\sum_{i=1}^{n} (weight(i) \times time(i))\right\} \times \frac{1}{n}$$

Other Averages

- E.g., 30 mph for first 10 miles, then 90 mph for next 10 miles, what is average speed?
- Average speed = (30+90)/2 **WRONG**
- Average speed = total distance / total time
  = (20 / (10/30 + 10/90))
  = 45 mph

Harmonic Mean

- Harmonic mean of rates = $\frac{n}{\left\{\sum_{i=1}^{n} \frac{1}{rate(n)}\right\}}$
- Use HM if forced to start and end with rates (e.g. reporting MIPS or MFLOPS)
- Why?
  - Rate has time in denominator
  - Mean should be proportional to inverse of sums of time (not sum of inverses)
  - See: J.E. Smith, "Characterizing computer performance with a single number," CACM Volume 31 , Issue 10 (October 1988), pp. 1202-1206.

Dealing with Ratios

	Machine A	Machine B
Program 1	1	10
Program 2	1000	100
Total	1001	110

- If we take ratios with respect to machine A

	Machine A	Machine B
Program 1	1	10
Program 2	1	0.1

Dealing with Ratios

- Average for machine A is 1, average for machine B is 5.05
- If we take ratios with respect to machine B

	Machine A	Machine B
Program 1	0.1	1
Program 2	10	1
Average	5.05	1

- Can't both be true!!!
- Don't use arithmetic mean on ratios!

Geometric Mean

- Use geometric mean for ratios
- Geometric mean of ratios = $\sqrt[n]{\prod_{i=1}^{n} ratio(i)}$
- Independent of reference machine
- In the example, GM for machine a is 1, for machine B is also 1
  - Normalized with respect to either machine

But…

- GM of ratios is not proportional to total time
- AM in example says machine B is 9.1 times faster
- GM says they are equal
- If we took total execution time, A and B are equal only if
  - Program 1 is run 100 times more often than program 2
- Generally, GM will mispredict for three or more machines

Summary

- Use AM for times
- Use HM if forced to use rates
- Use GM if forced to use ratios

- Best of all, use unnormalized numbers to compute time

Benchmarks: SPEC2000

- System Performance Evaluation Cooperative
  - Formed in 80s to combat benchmarketing
  - SPEC89, SPEC92, SPEC95, SPEC2000
- 12 integer and 14 floating-point programs
  - Sun Ultra-5 300MHz reference machine has score of 100
  - Report GM of ratios to reference machine

Benchmarks: SPEC CINT2000

Benchmark	Description
164.gzip	Compression
175.vpr	FPGA place and route
176.gcc	C compiler
181.mcf	Combinatorial optimization
186.crafty	Chess
197.parser	Word processing, grammatical analysis
252.eon	Visualization (ray tracing)
253.perlbmk	PERL script execution
254.gap	Group theory interpreter
255.vortex	Object-oriented database
256.bzip2	Compression
300.twolf	Place and route simulator

Benchmarks: SPEC CFP2000

Benchmark	Description
168.wupwise	Physics/Quantum Chromodynamics
171.swim	Shallow water modeling
172.mgrid	Multi-grid solver: 3D potential field
173.applu	Parabolic/elliptic PDE
177.mesa	3-D graphics library
178.galgel	Computational Fluid Dynamics
179.art	Image Recognition/Neural Networks
183.equake	Seismic Wave Propagation Simulation
187.facerec	Image processing: face recognition
188.ammp	Computational chemistry
189.lucas	Number theory/primality testing
191.fma3d	Finite-element Crash Simulation
200.sixtrack	High energy nuclear physics accelerator design
301.apsi	Meteorology: Pollutant distribution

Benchmark Pitfalls

- Benchmark not representative
  - Your workload is I/O bound, SPEC is useless
- Benchmark is too old
  - Benchmarks age poorly; benchmarketing pressure causes vendors to optimize compiler/hardware/software to benchmarks
  - Need to be periodically refreshed

Amdahl's Law

- Motivation for optimizing common case
- Speedup = old time / new time = new rate / old rate
- Let an optimization speed fraction *f* of time by a factor of *s*

$$Speedup = \frac{[(1-f)+f] \times oldtime}{[(1-f) \times oldtime] + \frac{f}{s} \times oldtime}$$
$$= \frac{1}{1-f+\frac{f}{s}}$$

Amdahl's Law Example

- Your boss asks you to improve performance by:
  - Improve the ALU used 95% of time by 10%
  - Improve memory pipeline used 5% of time by 10x
- Let f=fraction sped up and s = speedup on that fraction

  New_time = (1-f) x old_time + (f/s) x old_time

  Speedup = old_time / new_time

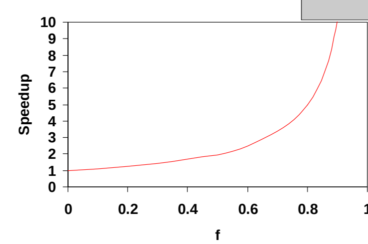
  Speedup = old_time / ((1-f) x old_time + (f/s) x old_time)
- Amdahl's Law: $Speedup = \frac{1}{1-f+\frac{f}{s}}$

Amdahl's Law Example, cont'd

f	s	Speedup
95%	1.10	1.094
5%	10	1.047
5%	∞	1.052

Amdahl's Law: Limit

- Make common case fast: $\lim_{s \to \infty} \frac{1}{1-f+\frac{f}{s}} = \frac{1}{1-f}$



Amdahl's Law: Limit

- Consider uncommon case! $\lim_{s \to \infty} \frac{1}{1-f+\frac{f}{s}} = \frac{1}{1-f}$
- If (1-f) is nontrivial
  - Speedup is limited!
- Particularly true for exploiting parallelism in the large, where large s is not cheap
  - GPU with e.g. 1024 processors (shader cores)
  - Parallel portion speeds up by s (1024x)
  - Serial portion of code (1-f) limits speedup
  - E.g. 10% serial limits to 10x speedup!

Summary

- Time and performance: Machine A n times faster than Machine B
  - Iff Time(B)/Time(A) = n
- Iron Law: Performance = Time/program =

$$= \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Cycles}}{\text{Instruction}} \times \frac{\text{Time}}{\text{Cycle}}$$

(code size) (CPI) (cycle time)

Summary Cont'd

- Other Metrics: MIPS and MFLOPS
  - Beware of peak and omitted details
- Benchmarks: SPEC2000
- Summarize performance:
  - AM for time
  - HM for rate
  - GM for ratio
- Amdahl's Law:

$$Speedup = \frac{1}{1 - f + \frac{f}{s}}$$