Lecture 3: Evaluating Computer Architectures

- Announcements
  - Automatic drops – missing preq's or repeating course
  - HW #1 is due Tuesday Feb 1 (one week from today)
- Last Time – constraints imposed by technology
  - Computer elements
  - Circuits and timing
- Today
  - Performance analysis
    - Amdahl's Law
    - Performance equation
  - Computer benchmarks

How to design something:

- List goals
- List constraints
- Generate ideas for possible designs
- Evaluate the different designs
- Pick the best design
- Refine it

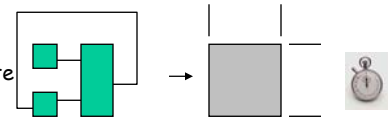
Evaluation Tools

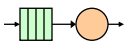
- **Benchmarks, traces, & mixes**
  - macrobenchmarks & suites
    - application execution time
  - microbenchmarks
    - measure one aspect of performance
  - traces
    - replay recorded accesses
      - cache, branch, register

MOVE	39%
BR	20%
LOAD	20%
STORE	10%
ALU	11%

LD 5EA3
ST 31FF
....
LD 1EA2
....

- Simulation at many levels
  - ISA, cycle accurate, RTL, gate, circuit
    - trade fidelity for simulation rate
- Area and delay estimation
- Analysis
  - e.g., queuing theory





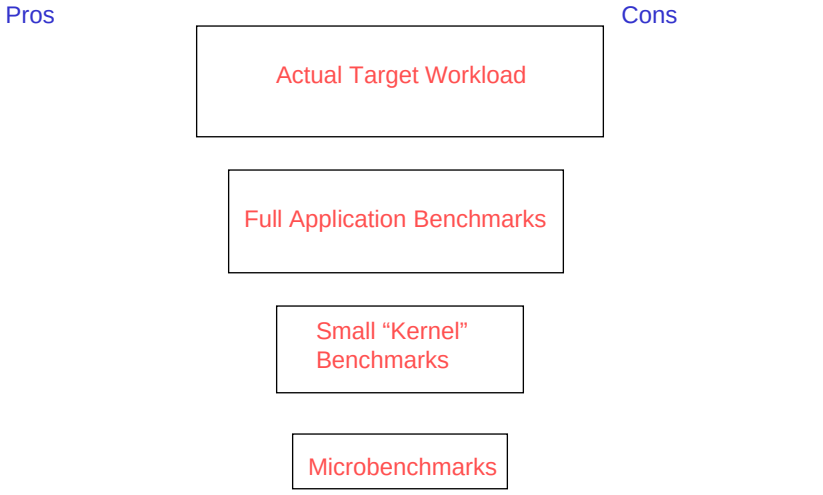
Evaluation metrics

- Metric = something we measure
- Goal: Evaluate how good/bad a design is
- Examples
  - Execution time for a program
  - Cycles per instruction
  - Clock rate
  - Power consumed by a program

Different metrics for different purposes

- Chose a metric that's appropriate for design level
- Examples
  - Applications perspective
    - Time to run task (Response Time)
    - Tasks run per second (Throughput)
  - Systems perspective
    - Millions of instructions per second (MIPS)
    - Millions of FP operations per second (MFLOPS)
  - Bus/network bandwidth: megabytes per second
  - Function Units: cycles per instruction (CPI)
  - Fundamental elements (transistors, wires, pins): clock rate

Each metric has strengths and weaknesses



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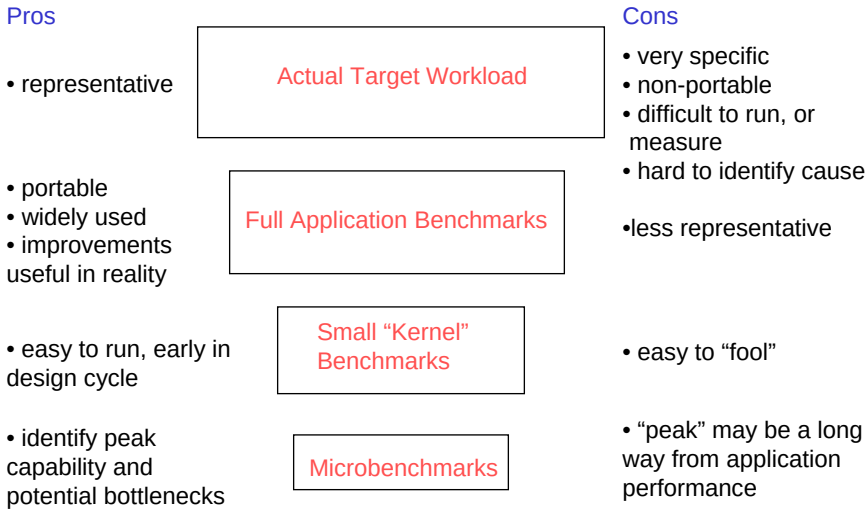


Some Warnings about Benchmarks

- Benchmarks measure the whole system
  - application
  - compiler
  - operating system
  - architecture
  - implementation
- Popular benchmarks typically reflect yesterday's programs
  - what about the programs people are running today?
  - need to design for tomorrow's problems
- Benchmark timings are sensitive
  - alignment in cache
  - location of data on disk
  - values of data
- Danger of *inbreeding* or positive feedback
  - if you make an operation fast (slow) it will be used more (less) often
    - therefore you make it faster (slower)
      - and so on, and so on…
  - the optimized NOP

Know what you are measuring!

- Compare apples to apples
- Example
  - Wall clock execution time:
    - User CPU time
    - System CPU time
    - Idle time (multitasking, I/O)

```
csh> time latex lecture2.tex
csh> 0.68u 0.05s 0:01.60 45.6%
```

user, system, elapsed, **% CPU time**

Two notions of "performance"

Plane	DC to Paris	Speed	Passengers	Throughput (pmph)
Boeing 747	6.5 hours	610 mph	470	286,700
Concorde	3 hours	1350 mph	132	178,200

Which has higher performance?

° **Time to do the task (Execution Time)**
– execution time, response time, latency

° **Tasks per day, hour, week, sec, ns. .. (Performance)**
– throughput, bandwidth

Tradeoff: latency vs. throughput

- Pizza delivery example
  - Do you want your pizza hot?
  - Or do you want your pizza to be inexpensive?
  - Two different delivery strategies for pizza company!

In this course:

We will focus primarily on latency
(execution time for a single task)

Definitions

- Performance is in units of things-per-second
  - bigger is better
- If we are primarily concerned with response time
  - performance(x) = $\frac{1}{\text{execution\_time}(x)}$

" X is n times faster than Y" means

$$n = \frac{\text{Performance(X)}}{\text{Performance(Y)}}$$

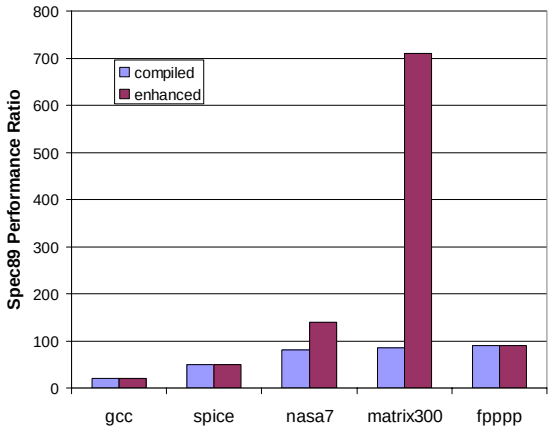
Brief History of Benchmarking

- Early days (1960s)
  - Single instruction execution time
  - Average instruction time [Gibson 1970]
  - Pure MIPS (1/AIT)
- Simple programs(early 70s)
  - Synthetic benchmarks (Whetstone, etc.)
  - Kernels (Livermore Loops)
- Relative Performance (late 70s)
  - VAX 11/780 ≡ 1-MIPS
    - but was it?
  - MFLOPs
- "Real" Applications (late 80s-now)
  - SPEC
    - Scientific
    - Irregular
  - TPC
    - Transaction Processing
  - Winbench
    - Desktop
  - Graphics
    - Quake III, Doom 3
    - MediaBench

SPEC: Standard Performance Evaluation Corporation (www.spec.org)

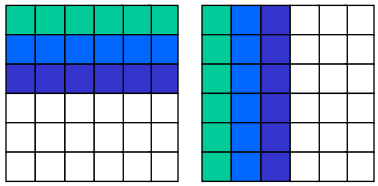
- System Performance and Evaluation Cooperative
  - HP, DEC, Mips, Sun
  - Portable O/S and high level languages
- Spec89 ⇒ Spec92 ⇒ Spec95 ⇒ Spec2000 ⇒ ....
- Categories
  - CPU (most popular)
  - JVM
  - SpecWeb - web server performance
  - SFS - file server performance
- Benchmarks change with the times and technology
  - Elimination of Matrix 300
  - Compiler restrictions

How to Compromise a Benchmark



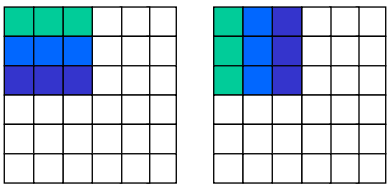
The compiler reorganized the code!

- Change the memory system performance
  - Matrix multiply cache blocking



Before

After



Spec2000 Suite

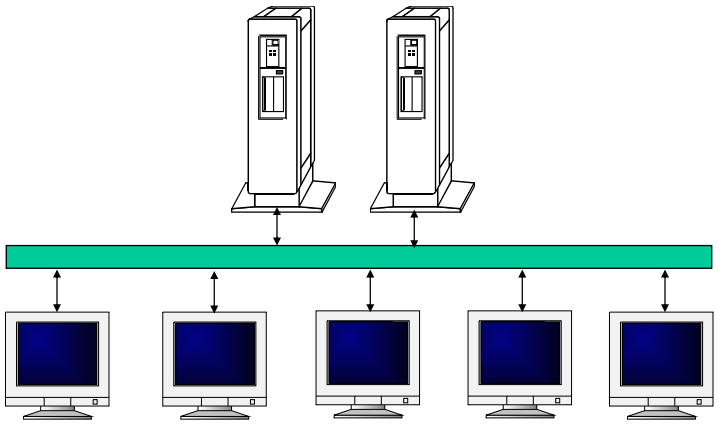
- 12 Integer benchmarks (C/C++)
  - compression
  - C compiler
  - Perl interpreter
  - Database
  - Chess
- 14 FP applications (Fortran/C)
  - Shallow water model
  - 3D graphics
  - Quantum chromodynamics
  - Computer vision
- Characteristics
  - Computationally intensive
  - Little I/O
  - Small code size
  - Variable data set sizes

SPEC Leaders (4/00)

	Intel Pentium III	AMD Athlon	Compaq Alpha 21264	Sun Ultra-2	IBM Power3	HP PA-8600
Clock rate	1000MHz	1000 MHz	700MHz	450MHz	400MHz	552MHz
Issue rate	3 x86	3 x86	4	4	4	4
Cache (I/D)	16/16/256K	64K/64K	64K/64K	16K/16K	32K/64K	512K/1M
# transistors	24 million	22 million	15.2 million	3.8 million	23 million	130 million
Technology	0.18μm	0.18μm	0.25μm	0.29μm	0.22μm	0.25μm
Die Size	106mm^2	102mm^2	205mm^2	126mm^2	163mm^2	477mm^2
Estimated mfg. Cost	$40	$70	$160	$70	$110	$330
SPECint95	46.6	42.0	34.7	16.2	23.5	38.4
SPECfp95	31.9	29.4	54.5	24.6	46.0	61.0

12/2003: AMD Opteron 148, 2.0 GHz:
SPECint2000base 16.3
SPECfp2000base 17.5

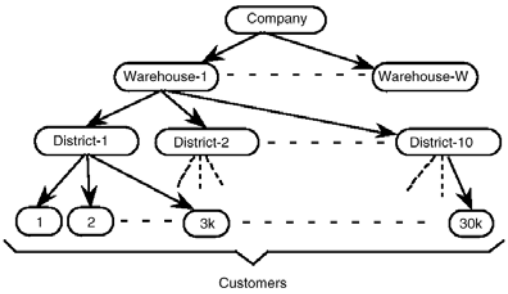
Transaction-based Systems



TPC - Transaction Processing Council

- Established in 1988
- Measure whole system performance and cost
  - Maximum TPS (transactions per second)
  - $/TPS
- Test specifies high level functional requirements
  - Independent of platform
- Workload scales
- Transaction rate constrained by response time requirement
  - 90% of transactions complete in < 2 seconds

TPC-C: OLTP



- W warehouses
- 10 districts/warehouse
- 3,000 customers/district
- 100,000 items

- 10 items per order
- 1% not in stock at regional warehouse
- Frequent reads and writes

TPC-C Results (8/00)

- IBM Netfinity 8500R
  - Platform
    - 32 servers, 4 CPUs each
    - 700MHz PentiumIII - Xeon
    - 128 GB memory
    - 4TB disk
    - Windows 2000 server
    - IBM DB2 database server
    - 368,640 users
  - Results
    - Cost: $14.2M
    - Throughput: 440K tpm
    - Price/perf: $32/tpm
- Compaq ProLiant ML570
  - Platform
    - 2 servers, 3 CPUs
    - 700MHz PentiumIII - Xeon
    - 2.5 GB memory
    - 1.5TB disk
    - Windows 2000 server
    - Microsoft SQL
    - 16,200 users
  - Results
    - Cost: $200K
    - Throughput: 20K tpm
    - Price/perf: $10/tpm

Desktop/Graphics Benchmarks

- WinStone
  - Corel WordPerfect suite, Lotus Smartsuite, Microsoft Office
  - High end: Photoshop
- CPU Mark99
  - Synthetic benchmark - tests CPU, caches, external memory
- 3DMark2003
  - Synthetic benchmark for 3-D rendering

Improving Performance: Fundamentals

- Suppose we have a machine with two instructions
  - Instruction A executes in 100 cycles
  - Instruction B executes in 2 cycles
- We want better performance….
  - Which instruction do we improve?

Amdahl's Law

- Performance improvements depend on:
  - how good is enhancement (factor **S**)
  - how often is it used (fraction **p**)
- Speedup due to enhancement E:

$$\text{Speedup(E)} = \frac{\text{ExTime w/out E}}{\text{ExTime w/ E}} = \frac{\text{Perf w/ E}}{\text{Perf w/out E}}$$

$$ExTime_{new} = ExTime_{old} * \left[(1 - p) + \frac{p}{S} \right]$$

$$Speedup(E) = \frac{ExTime_{old}}{ExTime_{new}} = \frac{1}{(1 - p) + \frac{p}{S}}$$

Amdahl's Law: Example

- FP instructions improved by 2x
- But….only 10% of instructions are FP

$$ExTime_{new} = ExTime_{old} * \left(0.9 + \frac{0.1}{2} \right) = 0.95 * ExTime_{old}$$

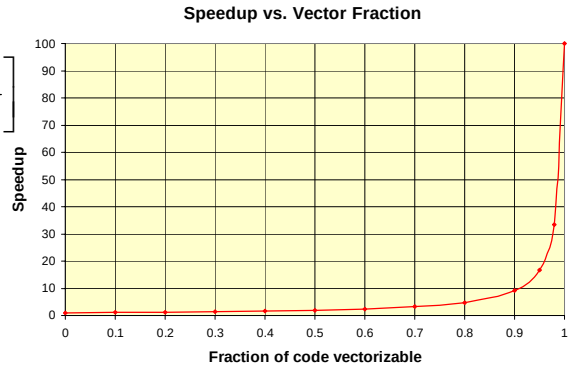
$$Speedup_{total} = \frac{1}{0.95} = 1.053$$

- Speedup bounded by $\frac{1}{\text{fraction of time not enhanced}}$

Amdahl's Law: Example 2

• Speed up vectorizable code by 100x

$$T_1 = T_0\left[(1-p)+\frac{p}{S}\right]$$



Amdahl's Law: Summary message

- Make the common case fast
- Examples:
  - All instructions require instruction fetch, only fraction require data
    ⇒ optimize instruction access first
  - Data locality (spatial, temporal), small memories faster
    ⇒storage hierarchy: most frequent accesses to small, local memory

CPU Performance Equation

- 3 components to execution time:

$$\text{CPU time} = \frac{\text{Seconds}}{\text{Program}} = \frac{\text{Instructions}}{\text{Program}} * \frac{\text{Cycles}}{\text{Instruction}} * \frac{\text{Seconds}}{\text{Cycle}}$$

- Factors affecting CPU execution time:

	Inst. Count	CPI	Clock Rate
Program	X		
Compiler	X	(X)	
Inst. Set	X	X	(X)
Organization		X	X
MicroArch		X	X
Technology			X

• Consider all three elements when optimizing
• Workloads change!

Cycles Per Instruction (CPI)

- Depends on the instruction

$$CPI_i = \text{Execution time of instruction } i * \text{Clock Rate}$$

- Average cycles per instruction

$$CPI = \sum_{i=1}^{n} CPI_i * F_i \quad \text{where } F_i = \frac{IC_i}{IC_{tot}}$$

- Example:

Op	Freq	Cycles	CPI(i)	%time
ALU	50%	1	0.5	33%
Load	20%	2	0.4	27%
Store	10%	2	0.2	13%
Branch	20%	2	0.4	27%
		CPI(total)	1.5	

Comparing and Summarizing Performance

- Fair way to summarize performance?
- Capture in a single number?
- Example: Which of the following machines is best?

	Computer A	Computer B	Computer C
Program 1	1	10	20
Program 2	1000	100	20
Total Time	1001	110	40

Means

Arithmetic mean $\frac{1}{n}\sum_{i=1}^{n} T_i$

Can be weighted: $a_i T_i$

Represents total execution time

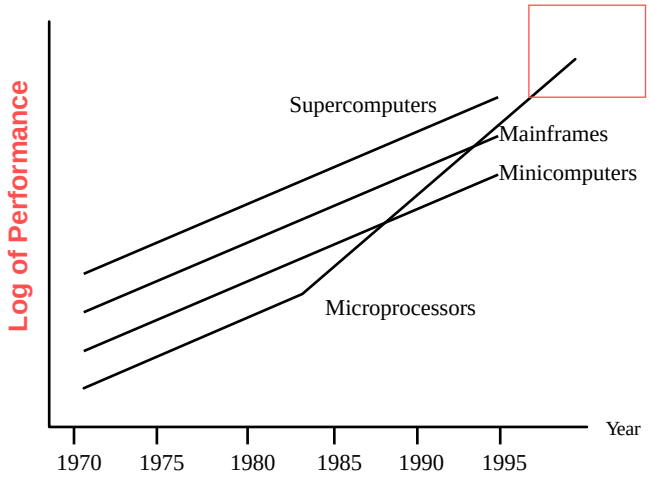
Harmonic mean $\frac{n}{\sum_{i=1}^{n} \frac{1}{R_i}}$

$R_i = 1/T_i$

Geometric mean $\left(\prod_{i=1}^{n} \frac{T_i}{T_{ri}}\right)^{\frac{1}{n}}$

Good for mean of ratios,
where the ratio is with respect to a reference.

Platform Performance Trends



Is Speed the Last Word in Performance?

- Depends on the application!
- Cost
  - Not just processor, but other components (ie. memory)
- Power consumption
  - Trade power for performance in many applications
- Capacity
  - Many database applications are I/O bound and disk bandwidth is the precious commodity

Summary

- Best benchmarks are real programs
  - Spec, TPC, Doom3
- Pitfalls still exist
  - Whole system measurement
  - Workload may not match user's
- Key concepts
  - Throughput and Latency
  - Equations: CPI, Amdahl's Law, …
- Next time
  - Instruction set architectures (ISA)
  - Read P&H 2.1 – 2.6