Systems I

Performance Analysis

Topics

- Measuring performance of systems
- Reasoning about performance
- Amdahl's law

Evaluation Tools

Benchmarks, traces, & mixes

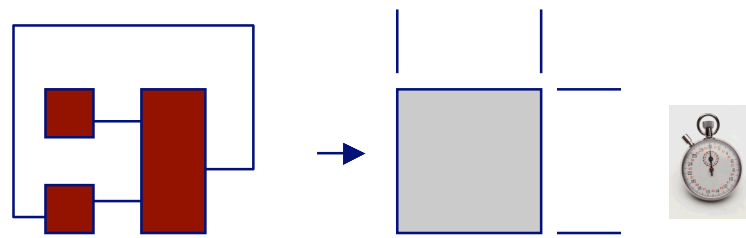
- **macrobenchmarks & suites**
  - **application execution time**
- **microbenchmarks**
  - **measure one aspect of performance**
- **traces**
  - **replay recorded accesses**
    - **cache, branch, register**

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

LD 5EA3
ST 31FF
….
LD 1EA2
….

Simulation at many levels

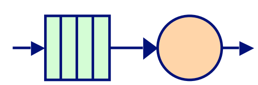
- **ISA, cycle accurate, RTL, gate, circuit**
  - **trade fidelity for simulation rate**



Area and delay estimation

Analysis

- **instructions, throughput, Amdahl's law**
- **e.g., queuing theory**



Metrics of Evaluation

Level of design ⇒ performance metric

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

Basis of Evaluation

Pros		Cons
• representative	Actual Target Workload	• very specific • non-portable • difficult to run, or measure • hard to identify cause
• portable • widely used • improvements useful in reality	Full Application Benchmarks	•less representative
• easy to run, early in design cycle	Small "Kernel" Benchmarks	• easy to "fool"
• identify peak capability and potential bottlenecks	Microbenchmarks	• "peak" may be a long way from application performance

Slide courtesy of D. Patterson

Some Warnings about Benchmarks

Benchmarks measure the <u>whole</u> 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

Response time and throughput often are in opposition

Slide courtesy of D. Patterson

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
  - Desktop
  - Scientific
  - Java
  - Media
  - Parallel
  - etc.
- TPC
  - Transaction Processing
- Graphics
  - 3D-Mark
  - Real games (Assassin's Creed, Call of Duty, Flight Simulator, etc.)

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 ⇒ SPEC2006....

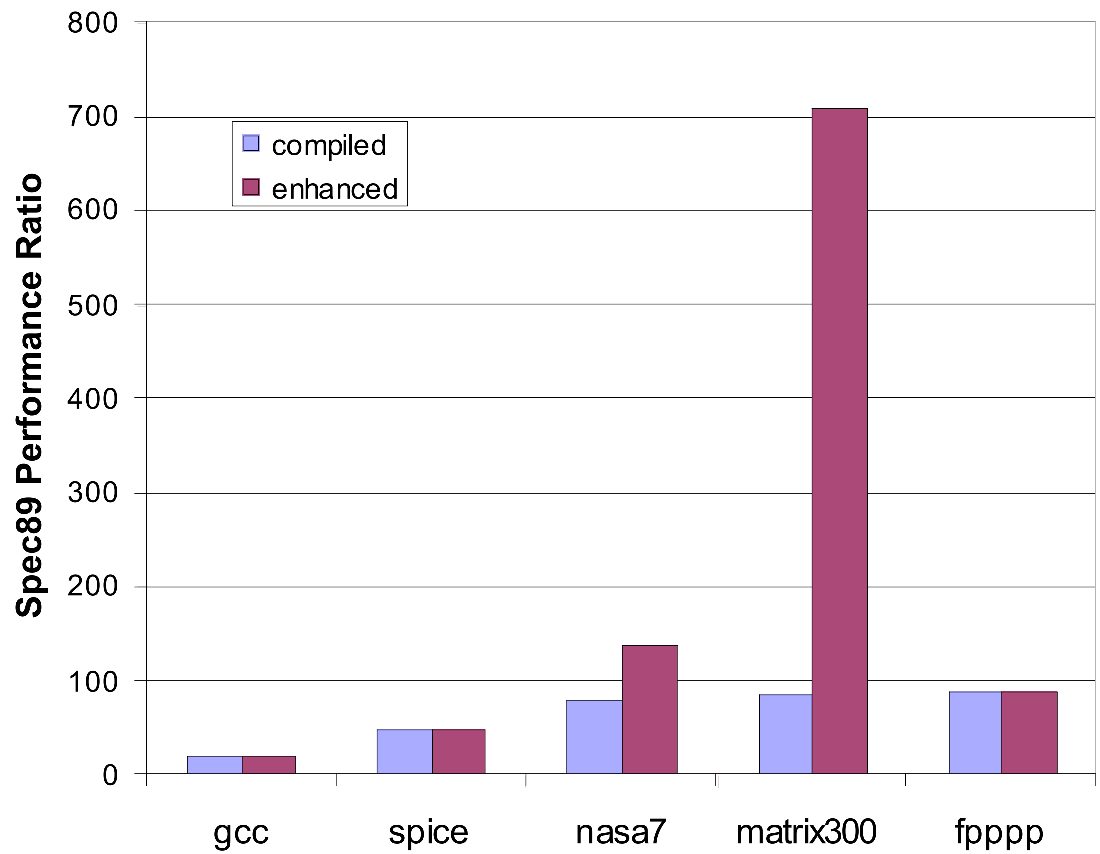
Categories

- CPU (most popular)
- JVM, JBB
- SpecWeb - web server performance
- SFS - file server performance

Benchmarks change with the times and technology

- Elimination of Matrix 300
- Compiler restrictions

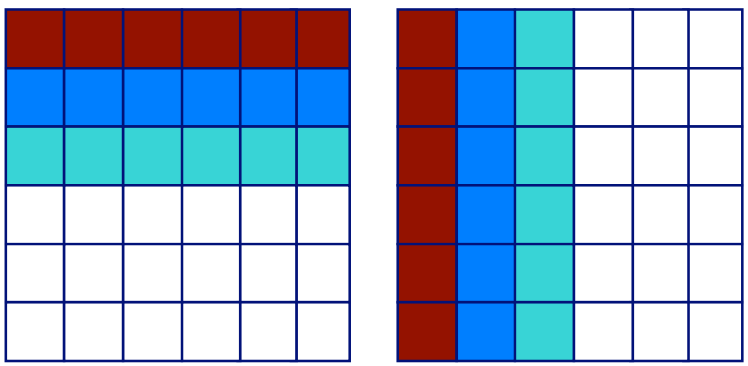
How to Compromise a Benchmark



The compiler reorganized the code!

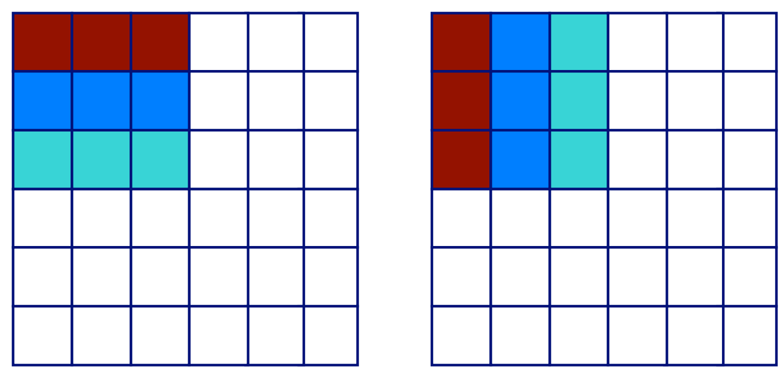
Change the memory system performance

- **Matrix multiply cache blocking**
- **You will see this later in "performance programming"**



Before

After



Spec2006 Suite

12 Integer benchmarks (C/C++)

- compression
- C compiler
- Perl interpreter
- Database
- Chess
- Bioinformatics

17 FP applications (Fortran/C)

- Shallow water model
- 3D graphics
- Quantum chromodynamics
- Computer vision
- Speech recognition

Characteristics

- Computationally intensive
- Little I/O
- Relatively small code size
- Variable data set sizes

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?

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	

Amdahl's Law

How much performance could you get if you could speed up some part of your program?

Performance improvements depend on:

- how good is enhancement
- how often is it used

Speedup due to enhancement E (fraction *p* sped up by factor *S*):

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

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

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

Amdahl's Law: Example

FP instructions improved by 2x

But….only 10% of instructions are FP

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

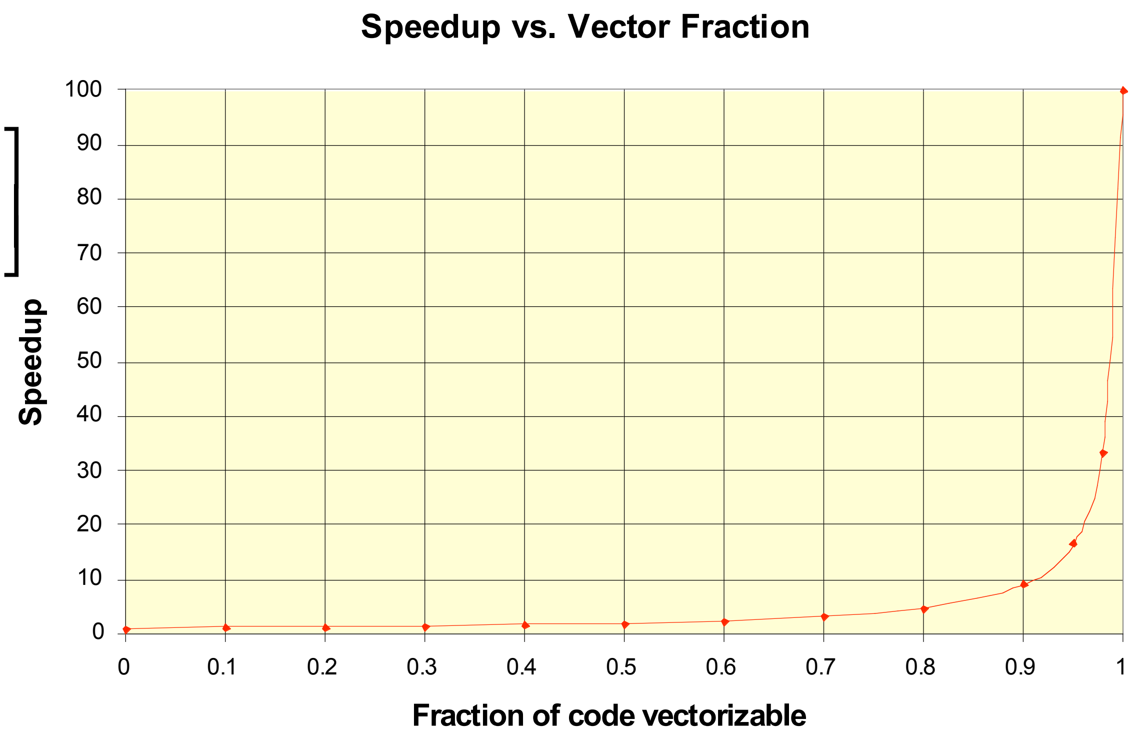
$$Speedup_{total} = \frac{1}{0.95} = 1.053$$

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

Amdahl's Law: Example 2

- Parallelize (vectorize) some portion of your program
  - Make it 100x faster?
- How much faster does the whole program get?

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



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

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

Throughput (a form of speed)

- An individual program isn't faster, but many more programs can be completed per unit time
- Example: Google search (processes many, many searches simultaneously)

Summary

Today

- Performance analysis overview
- Amdahl's law

Next Time

- Making the processor faster: pipelining