CS 61C:
Great Ideas in Computer Architecture
Performance

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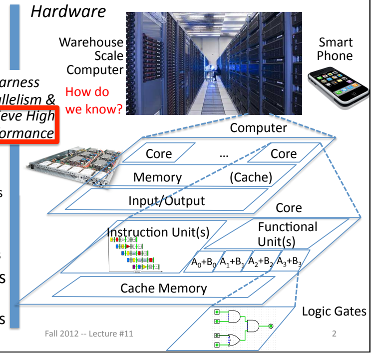
New-School Machine Structures (It's a bit more complicated!)

Software | *Hardware*

- Parallel Requests
  Assigned to computer
  e.g., Search "Katz"
- Parallel Threads
  Assigned to core
  e.g., Lookup, Ads
- Parallel Instructions
  >1 instruction @ one time
  e.g., 5 pipelined instructions
- Parallel Data
  >1 data item @ one time
  e.g., Add of 4 pairs of words
- Hardware descriptions
  All gates @ one time
- Programming Languages



Review

- Five main components of a computer
  – Control, Datapath, Memory, Input, Output
- Five stages of MIPS instruction execution
  – Fetch instruction
  – Decode/read registers
  – ALU (including address add)
  – Memory access (for loads and stores)
  – Writeback (if needed)

What is Performance?

- *Latency* (or *response time* or *execution time*)
  – Time to complete one task
- *Bandwidth* (or *throughput*)
  – Tasks completed per unit time

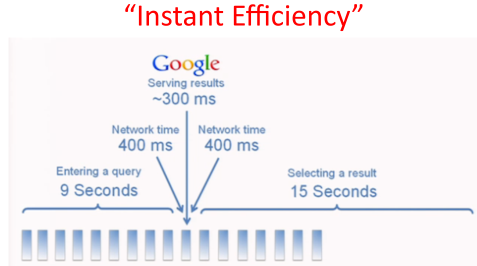
Cloud Performance: Why Application Latency Matters

Server Delay (ms)	Increased time to next click (ms)	Queries/ user	Any clicks/ user	User satisfac-tion	Revenue/ User
50	--	--	--	--	--
200	500	--	-0.3%	-0.4%	--
500	1200	--	-1.0%	-0.9%	-1.2%
1000	1900	-0.7%	-1.9%	-1.6%	-2.8%
2000	3100	-1.8%	-4.4%	-3.8%	-4.3%

Figure 6.10 Negative impact of delays at Bing search server on user behavior [Brutlag and Schurman 2009].

- Key figure of merit: application responsiveness
  – Longer the delay, the fewer the user clicks, the less the user happiness, and the lower the revenue per user

Google Instant Search "Instant Efficiency"



Typical search takes 24 seconds, Google's search algorithm is only 300 ms of this
"It's not search 'as you type', but 'search before you type'!"
"We can predict what you are likely to type and give you those results in real time"

Defining CPU Performance

- What does it mean to say X is faster than Y?
- Ferrari vs. School Bus?
- 2009 Ferrari 599 GTB
  - 2 passengers, 11.1 secs in quarter mile
- 2009 Type D school bus
  - 54 passengers, quarter mile time?

http://www.youtube.com/watch?v=KwyCoQuhUNA

- *Response Time/Latency*: e.g., time to travel ¼ mile
- *Throughput/Bandwidth*: e.g., passenger-mi in 1 hour

Defining Relative CPU Performance

- $\text{Performance}_X = 1/\text{Program Execution Time}_X$
- $\text{Performance}_X > \text{Performance}_Y$ =>
  $1/\text{Execution Time}_X > 1/\text{Execution Time}_y$ =>
  $\text{Execution Time}_Y > \text{Execution Time}_X$
- Computer X is N times faster than Computer Y
  $\text{Performance}_X / \text{Performance}_Y = N$ or
  $\text{Execution Time}_Y / \text{Execution Time}_X = N$
- Bus is to Ferrari as 12 is to 11.1:
  Ferrari is 1.08 times faster than the bus!

Measuring CPU Performance

- Computers use a clock to determine when events takes place within hardware
- *Clock cycles:* discrete time intervals
  - aka clocks, cycles, clock periods, clock ticks
- *Clock rate* or *clock frequency:* clock cycles per second (inverse of clock cycle time)
- 3 GigaHertz clock rate
  => clock cycle time = $1/(3\text{x}10^9)$ seconds
  clock cycle time = 333 picoseconds (ps)

CPU Performance Factors

- To distinguish between processor time and I/O, *CPU time* is time spent in processor
- `CPU Time/Program`
  `= Clock Cycles/Program`
  `x Clock Cycle Time`
- Or
  `CPU Time/Program`
  `= Clock Cycles/Program ÷ Clock Rate`

CPU Performance Factors

- But a program executes instructions
- `CPU Time/Program`
  `= Clock Cycles/Program x Clock Cycle Time`
  `= Instructions/Program`
  `x Average Clock Cycles/Instruction`
  `x Clock Cycle Time`
- 1st term called *Instruction Count*
- 2nd term abbreviated *CPI* for average ***C****lock Cycles* ***P****er* ***I****nstruction*
- 3rd term is 1 / Clock rate

Restating Performance Equation

- $\text{Time} = \dfrac{\text{Seconds}}{\text{Program}}$

  $= \dfrac{\text{Instructions}}{\text{Program}} \times \dfrac{\text{Clock cycles}}{\text{Instruction}} \times \dfrac{\text{Seconds}}{\text{Clock Cycle}}$

This is the "Iron Law" of processor performance

What Affects Each Component? Instruction Count, CPI, Clock Rate

Hardware or software component?	Affects What?
Algorithm	
Programming Language	
Compiler	
Instruction Set Architecture	

Computer A clock cycle time 250 ps, $CPI_A = 2$
Computer B clock cycle time 500 ps, $CPI_B = 1.2$
Assume A and B have same instruction set
Which statement is true?

- ☐ Computer A is ≈1.2 times faster than B
- ☐ Computer A is ≈4.0 times faster than B
- ☐ Computer B is ≈1.7 times faster than A
- ☐ Computer B is ≈3.4 times faster than A

Workload and Benchmark

- *Workload:* Set of programs run on a computer
  - Actual collection of applications run or made from real programs to approximate such a mix
  - Specifies both programs and relative frequencies
- *Benchmark:* Program selected for use in comparing computer performance
  - Benchmarks form a workload
  - Usually standardized so that many use them

SPEC (System Performance Evaluation Cooperative)

- Computer Vendor cooperative for benchmarks, started in 1989
- SPECCPU2006
  - 12 Integer Programs
  - 17 Floating-Point Programs
- Often turn into number where bigger is faster
- *SPECratio*: reference execution time on old reference computer divide by execution time on new computer to get an effective speed-up

SPECINT2006 on AMD Barcelona

Description	Instruc-tion Count (B)	CPI	Clock cycle time (ps)	Execu-tion Time (s)	Refer-ence Time (s)	SPEC-ratio
Interpreted string processing	2,118	0.75	400	637	9,770	15.3
Block-sorting compression	2,389	0.85	400	817	9,650	11.8
GNU C compiler	1,050	1.72	400	724	8,050	11.1
Combinatorial optimization	336	10.0	400	1,345	9,120	6.8
Go game	1,658	1.09	400	721	10,490	14.6
Search gene sequence	2,783	0.80	400	890	9,330	10.5
Chess game	2,176	0.96	400	837	12,100	14.5
Quantum computer simulation	1,623	1.61	400	1,047	20,720	19.8
Video compression	3,102	0.80	400	993	22,130	22.3
Discrete event simulation library	587	2.94	400	690	6,250	9.1
Games/path finding	1,082	1.79	400	773	7,020	9.1
XML parsing	1,058	2.70	400	1,143	6,900	6.0

Summarizing Performance …

System	Rate (Task 1)	Rate (Task 2)
A	10	20
B	20	10

Flashcard Quiz: Which system is faster?

System A
System B
Same performance
Unanswerable question!

… Depends Who's Selling

System	Rate (Task 1)	Rate (Task 2)	Average
A	10	20	15
B	20	10	15

Average throughput

System	Rate (Task 1)	Rate (Task 2)	Average
A	0.50	2.00	1.25
B	1.00	1.00	1.00

Throughput relative to B

System	Rate (Task 1)	Rate (Task 2)	Average
A	1.00	1.00	1.00
B	2.00	0.50	1.25

Throughput relative to A

Summarizing SPEC Performance

- Varies from 6x to 22x faster than reference computer
- *Geometric mean* of ratios: N-th root of product of N ratios $\sqrt[n]{\prod_{i=1}^{n} \text{Execution time ratio}_i}$
  - Geometric Mean gives same relative answer no matter what computer is used as reference
- Geometric Mean for Barcelona is 11.7

Administrivia

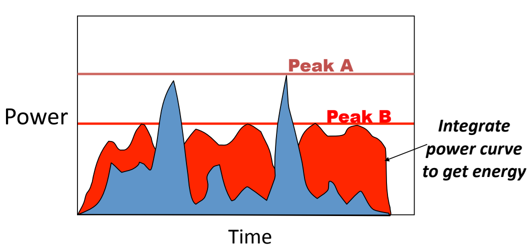
Energy and Power

(Energy = Power x Time)

- Energy to complete operation (Joules)
  - Corresponds approximately to battery life
- Peak power dissipation (Watts = Joules/s)
  - Affects heat (and cooling demands)
  - IT equipment's power is in the denominator of the Power Utilization Efficiency (PUE) equation, a WSC figure of merit

Peak Power vs. Lower Energy

(Power x Time = Energy)



- Which system has higher peak power?
- Which system has higher energy?

Student Roulette?

Energy "Iron Law"

Performance = Power * Energy Efficiency
(Tasks/Second) (Joules/Second) (Tasks/Joule)

Energy-Proportional Computing

"The Case for Energy-Proportional Computing," Luiz André Barroso, Urs Hölzle, *IEEE Computer* December 2007

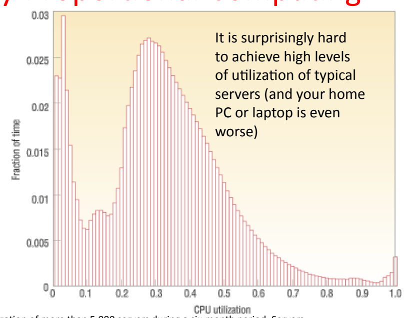


Figure 1. Average CPU utilization of more than 5,000 servers during a six-month period. Servers are rarely completely idle and seldom operate near their maximum utilization, instead operating most of the time at between 10 and 50 percent of their maximum

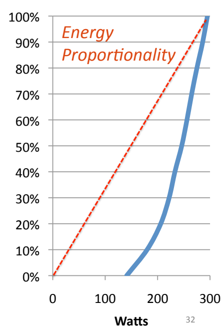
SPECPower

- Increasing importance of power and energy: create benchmark for performance and power
- Most servers in WSCs have average utilization between 10% & 50%, so measure power at medium as well as at high load
- Measure best performance and power, then step down request rate to measure power for every 10% reduction in performance
- Java server benchmark performance is *operations per second (ssj_ops)*, so metric is *ssj_ops/Watt*

$$\text{overall ssj\_ops per Watt} = \left(\sum_{i=0}^{10} \text{ssj\_ops}_i\right) \Big/ \left(\sum_{i=0}^{10} \text{power}_i\right)$$

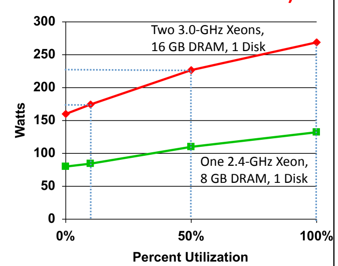
SPECPower on Barcelona

Target Load %	Performance (ssj_ops)	Avg. Power (Watts)
100%	231,867	295
90%	211,282	286
80%	185,803	275
70%	163,427	265
60%	140,160	256
50%	118,324	246
40%	92,035	233
30%	70,500	222
20%	47,126	206
10%	23,066	180
0%	0	141
Sum	1,283,590	2,605
	ssj_ops/Watt	493



Which is Better? (1 Red Machine vs. 5 Green Machines)

- Five machines running at 10% utilization
  - Total Power =
- One machine running at 50% utilization
  - Total Power =



85% Peak Power@50% utilization
65% Peak Power@10% utilization

Other Benchmark Attempts

- Rather than run a collection of real programs and take their average (geometric mean), create a single program that matches the average behavior of a set of programs
- Called a *synthetic benchmark*
- First example called *Whetstone* in 1972 for floating-point-intensive programs in Fortran
- Second example called *Dhrystone* in 1985 for integer programs in Ada and C
  – Pun on Wet vs. Dry ("Whet" vs. "Dhry")

Dhystone Shortcomings

- Dhrystone features unusual code that is not usually representative of real-life programs
- Dhrystone susceptible to compiler optimizations
- Dhrystone's small code size means always fits in caches (<2KB), so not representative
- Yet still used in hand-held, embedded CPUs!

EE Times Articles

"Samsung and Intrinsity announced they have 1st silicon for Hummingbird, an ARM Cortex A8 that … delivers more than 2,000 Dhrystone Mips while consuming 640 mW power" 7/24/09

Compiled Size of Dhystone 9/7/2010

Architecture	Enhanced 8051	Generic MSP430	MSP430F5438 (large memory model)	ARM Cortex-M0	ARM Cortex-M3
Tools	Keil µVision 3.8 PK51 8.18	IAR Embedded Workbench 4.20.1	IAR Embedded Workbench 4.20.1	RVDS 4.0-SP2 with MicroLIB	RVDS 4.0-SP2 with MicroLIB
Program size in bytes*	3186 8 BIT	923 16 BIT	1079 16 BIT	912 32 BIT	900 32 BIT

*All of the compiled results are optimized for size.

Measuring Time

- UNIX time command measures in seconds
- *Time Stamp Counter*
  - 64-bit counter of clock cycles on Intel 80x86 instruction set computers
  - 80x86 instruction RDTSC (Read TSC) returns TSC in regs EDX (upper 32 bits) and EAX (lower 32 bits)
  - Can read, but can't set
  - How long can measure?
  - Measures overall time, not just time for 1 program

How to get RDTSC access in C?

```
static inline unsigned long long RDTSC(void)
{
  unsigned hi, lo;
  asm volatile ("rdtsc" : "=a"(lo), "=d"(hi));
  return ( (unsigned long long) lo) |
  ( ((unsigned long long) hi) <<32 );
}
```


`gcc` Optimization Experiment

	BubbleSort.c	Dhrystone.c
No Opt		
-O1		
-O2		
-O3		

Where Do You Spend the Time in Your Program?

- Profiling a program (e.g., using, `gprof`) shows where it spends its time by function, so you can determine which code consumes most of the execution time
- Usually a 90/10 rule: 10% of code is responsible for 90% of execution time
  - Or 80/20 rule, where 20% of code responsible for 80% of time

`gprof`

- Learn where program spent its time
- Learn functions called while it was executing
  - And which functions call other functions
- Three steps:
  - Compile & link program with profiling enabled
    - cc –pg x.c *{in addition to other flags use}*
  - Execute program to generate a profile data file
  - Run `gprof` to analyze the profile data

`gprof` example

% time	Cumulative (secs)	Self (secs)	calls	Self ms/call	Total ms/call	name
18.18	0.06	0.06	23480	0.00	0.00	find_char_unquote
12.12	0.10	0.04	120	0.33	0.73	pattern_search
9.09	0.13	0.03	5120	0.01	0.01	collapse_continuations
9.09	0.16	0.03	148	0.20	0.88	update_file_1
9.09	0.19	0.03	37	0.81	4.76	eval
6.06	0.21	0.02	12484	0.00	0.00	file_hash_1
6.06	0.23	0.02	6596	0.00	0.00	get_next_mword
3.03	0.24	0.01	29981	0.00	0.00	hash_find_slot
3.03	0.25	0.01	14769	0.00	0.00	next_token
3.03	0.26	0.01	5800	0.00	0.00	variable_expand_string

See http://linuxgazette.net/100/vinayak.html

Cautionary Tale

- "More computing sins are committed in the name of efficiency (without necessarily achieving it) than for any other single reason - including blind stupidity"
  -- William A. Wulf
- "We should forget about small efficiencies, say about 97% of the time: premature optimization is the root of all evil"
  -- Donald E. Knuth

And In Conclusion, …

- Time (seconds/program) is measure of performance

$$= \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Clock cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Clock Cycle}}$$

- Benchmarks stand in for real workloads to as standardized measure of relative performance
- Power of increasing concern, and being added to benchmarks
- Time measurement via clock cycles, machine specific
- Profiling tools as way to see where spending time in your program
- Don't optimize prematurely!