

Computer Systems Architecture CMSC 411 Unit 1 – Computer Design and Evaluation

Alan Sussman
September 2, 2003

Administrivia

- Class web pages are at <http://www.cs.umd.edu/class/fall2003/cmssc411-0101>
 - and linked in from CS dept. class web pages
- Class accounts for project will be on CSIC Linux cluster
- First homework, for Unit 1, announced Thursday, 9/4
- Start reading Ch. 1 of H&P

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Introduction

- Why are you taking this course?
 - You really liked the material in 311 and want to learn more?
 - The course time fit into your schedule well?
 - You needed upper level CS courses and chose this one at random?
 - All the courses you really wanted to take were filled?

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What can you expect to learn in this course?

- What to look for in buying a PC (brag to parents and friends!)
- How computer architecture affects programming style
- Variations on interconnection networks
- A great deal of jargon

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Syllabus

- More on web page
- Importance of *doing the homework*.
- Lecture notes available on the web - you can print them before coming to class and then add your own notes (I will try to put them up in time)
- I'll correct any typos/errors after each lecture and re-post

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The Textbook – H&P

- Everyone complains about it
- Virtually all of the top schools use it
- You can handle it, but you have to work at it – *do the reading*
- Through lecture notes, other references, etc., I'll try to help you put it all together

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Chapter 1 of H&P

- Read Chapter 1; you can skip the economics of *cost vs. price*
- Historical Perspective - Section 1.11
 - Computers as we know them are roughly 55 years old
 - The *von Neumann machine* model that underlies computer design is only partially von Neumann's
 - Why does Konrad Zuse say he had "the bad luck of being too early"?
 - Optional: Read his own recollections in TR 180 of ETH, Zürich, <http://www.inf.ethz.ch/research/publications/show.php?what=180&lang=en&type=tr> (contains both German and English)
 - No one was able to successfully patent the idea of a stored-program computer, much to the dismay of Eckert and Mauchly

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Early development steps

- Make input and output easier than wiring circuit boards and reading lights
- Make programming more easy by developing higher level programming languages, so that users did not need to use binary machine code instructions
- Develop storage devices

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Later development steps

- Faster
- More storage
- Cheaper
- Networking and parallel computing
- Better user interfaces
- Ubiquitous applications
- Development of standards

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Perspective: An example

- Most powerful computer in 1988: CRAY Y-MP
- 1993: a desktop workstation (IBM Power-2) matched its power at less than 10% of the cost
- How did this happen?
 - hardware improvements, e.g., squeezing more circuits into a smaller area
 - improvements in instruction-set design, e.g., making the machine faster on a small number of frequently used instructions
 - improvements in compilation, e.g., optimizing code to reduce memory accesses and make use of faster machine instructions

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Computer Architecture

- instruction set architecture:
 - which elementary instructions are basic to programming the machine
- organization:
 - memory systems to store information,
 - bus systems to move information,
 - logical design of CPU (recall from 311)
- hardware:
 - what physical components are used to form the computer

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Why a computer scientist should care

- to choose an architecture that matches a user's needs
- to compare and benchmark different computers
- to decide whether an upgrade is cost-efficient
- to write a program that exploits the strengths of a given computer

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Technology is rapidly changing

- From Sections 1.3 & 1.4
 - The average program hogs twice as much memory each year
 - Example: Microsoft
 - Transistor density increases by 50% each year
 - Dynamic random access memory (DRAM) density increases by 60% each year
 - Disk density increases by 50% each year
 - Lifespan of a computer is about 5 years
 - Cost of DRAM drops by about 40% each year

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Costs

- From Figure 1.9 in H&P
- The cost of components in a \$1000 PC in 2001 are:
 - CPU – 22%
 - Monitor – 19%
 - Hard drive – only 9%
 - DRAM – only 5% (for 128MB)
 - Software – 20% (OS & basic office suite)

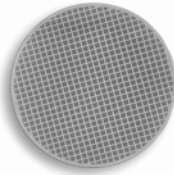
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Manufacture of DRAM and other chips

- Chips are manufactured on **wafers** - circular disks containing many dies (chips).
- The wafer is tested and chopped into **dies**.

Fig. 1.8 in H&P



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Wafers and dies

- To find the cost of a die:
 - Number of dies per wafer is *at most* the area of the wafer divided by the area of the die.
 - The cost of the wafer divided by the number of **working** dies per wafer is the cost of each die.
- The fraction of working dies is called the *die yield*, which decreases as the area of the die increases.
- Rule of thumb (p. 20): Cost of die is proportional to the square of the die area

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Comparing performance of two machines

- Definition: **Performance** is equal to 1 divided by execution time
- Problem: How to measure execution time?

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What is time?

- Unix time command example (p.26):
 - 90.7u 12.9s 2:39 65%
 - The user used the CPU for 90.7 seconds (user CPU time)
 - The system used it for 12.9 seconds (system CPU time)
 - Elapsed time from the user's request to completion of the task was 2 minutes, 39 seconds (159 seconds)
 - And $(90.7 + 12.9) / 159 = 65\%$
 - the rest of the time was spent waiting for I/O or running other programs

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Time (cont.)

- Usual measurements of time:
 - **system performance** measures the elapsed time on unloaded (single user) system
 - **CPU performance** measures user CPU time on unloaded system

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Administrivia

- Homework #1, on Ch. 1, posted
 - due 9/16
- Read Ch. 1 of H&P

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Last time

- Computer architecture
 - Instruction set architecture
 - Organization
 - Hardware
- Technology primer
 - transistor density, DRAM, disk, etc. getting bigger, faster cheaper at high rate
 - cost of a chip proportional to square of chip area
- Comparing performance of 2 machines
 - performance is inverse of execution time
 - Unix time command

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How to measure CPU performance

- **Benchmark:** a program used to measure performance
 - real programs - what is reality?
 - kernels - loops in which most of time is spent in a real program
 - toy programs
 - synthetic programs
- Fact: Computer manufacturers tune their product to the popular benchmarks.
 - "Your results may vary," unless you run benchmark programs and nothing else
 - See Figure 1.12 listing programs in the SPEC CPU2000 benchmark suite

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Reproducibility

- Benchmarking is a laboratory experiment, and needs to be documented as fully as a well-run chemistry experiment
 - Identify each variable hardware component
 - Identify compiler flags and measure variability
 - Verify reproducibility and provide data for others to reproduce the benchmarking results

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Reporting results

- Example of parameters for SPEC CINT2000 benchmark is in H&P Figure 1.14
 - for a Dell workstation running Windows NT4.0
 - data on hardware - CPU (how many, primary and secondary caches), memory, disk
 - data on software – OS, compilers, file system type, and compiler flags used (very important!)
- How to summarize results?

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Sample results

From Figure 1.15 in H&P – which machine is fastest?

	Computer A	Computer B	Computer C
Program P1 (sec)	1	10	20
Program P2 (sec)	1000	100	20
Program P3 (sec)	1001	110	40

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Statistical reporting

- “It is rare indeed when advertisers, politicians, pop economists, and drumbeaters for medical programs offer a statistical argument that is not either misleading or downright deceptive.” - Martin Gardner
- “... in mathematics you don't understand things, you just get used to them.” - John von Neumann
- “... if you torture your data long enough, they will tell you what you want to hear.” - James L. Mills, M.D.

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Statistical reporting (cont.)

- The **average** execution time is the **arithmetic mean**:
 - sum the execution times for each program and divide by the number of programs n
- The **harmonic mean** is n divided by the sum of some function of each execution time
- Often, both of these means are modified to give more weight to more important programs

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Statistical reporting (cont.)

- Arithmetic mean is good if the weights represent your own workload - then you can compare how each machine will perform for you
 - Don't set the weights based on performance on any particular machine; Figure 1.16 illustrates confusing results obtained by doing that
- Harmonic mean gives same sort of information, but is used when rates (e.g., instructions per second) are measured instead of times

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Geometric mean

- To measure relative performance, use the **geometric mean**
 - Choose a *reference machine*, divide all execution times by the corresponding times on the reference machine, multiply those ratios together, and take the n th root of the product
- Geometric means have the nice property that you get consistent results regardless of which machine is used to normalize (Figure 1.17)

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How to make computers faster

- **Make the common case faster!**
- Example: Put more effort and funds into optimizing the hardware for addition than to optimize square root
- **Amdahl's law** quantifies this principle:
 - Define **speedup** as the time the task took originally divided by the time the task takes after improvement

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Amdahl's Law

- Then Amdahl tells us what the speedup of a particular task is, given
 - fraction f of the original execution time that the task could use the improvement
 - the speedup s of a task that always uses the improvement
- Then what is the speedup of the task?

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Amdahl's Law (cont.)

- Suppose that the original task runs for 1 second so it takes f seconds in the critical piece, and $1-f$ in other things
- Then the task on the improved machine will take only f/s seconds in the critical piece, but will still take $1-f$ seconds in other things
- $$\text{speedup} = \frac{\text{old_time}}{\text{new_time}} = \frac{1}{(1-f) + \frac{f}{s}}$$

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Example 1

- Suppose we work very hard improving the square root hardware, and that our task originally spends 1% of its time doing square roots. Even if the improvement reduces the square root time to zero, the speedup is no better than
- $$\text{speedup} = \frac{1}{1-f} = \frac{1}{.99} = 1.01$$
- *And we might be better off putting our effort into a more important part of the task*

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Example 2

- Suppose that, for the same cost, we can speed up integer arithmetic by a factor of 20, or speed up floating point arithmetic by a factor of 2. If our task spends 10% of its time in integer arithmetic, and 40% of its time in floating point arithmetic, which should we do?

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Example 2 (cont.)

- Option 1:
$$\text{speedup} = \frac{1}{.9 + \frac{.1}{20}} = 1.105$$
- Option 2:
$$\text{speedup} = \frac{1}{.6 + \frac{.4}{2}} = 1.25$$

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CPU Performance

- More jargon ...
- Something new happens in a computer during every **clock cycle**
- The clock rate is what manufacturers usually advertise to indicate a chip's speed:
 - e.g., a 1.8GHz Pentium 4
- But how fast the machine is depends on the clock rate *and* the number of clock cycles per instruction (CPI)

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CPU Performance (cont.)

- So total CPU time = instruction count (IC) times CPI divided by clock rate (MHz/GHz)
 - $IC * CPI / MHz$
- There's an example on p. 44 that illustrates the overall effect
- Note: CPI is not a good measure of performance all by itself since it varies by type of instruction!

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How to design a fast computer

- Amdahl's law says put your effort into optimizing instructions that are often used.
- **The locality of reference** rule-of-thumb says that a program spends 90% of its time in 10% of the code, so we should put effort into taking advantage of this, through a **memory hierarchy**
- For data accesses, 2 types of locality
 - temporal
 - spatial

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Take advantage of parallelism

- At system level
 - e.g., use multiple CPUs (Unit 7), disks (Unit 6)
- At processor level
 - among instructions (Unit 4)
 - e.g., pipelining (Unit 3)
- At digital design level
 - e.g., set associative caches (Unit 5), carry-lookahead in ALU design

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Performance/Price Performance

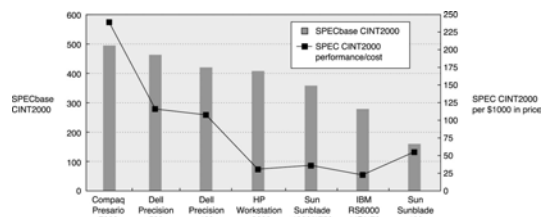
For desktop systems (H&P Figure 1.18) – 512MB ECC SDRAM, July 2001

Model	Processor	Clock rate (MHz)	Price
Compaq 7000	AMD Athlon	1400	\$2091
Dell 420	Pentium III	1000	\$3834
Dell 530	Pentium 4	1700	\$4175
HP c3600	PA 8600	552	\$12,631
IBM RS6000 44P/170	IBM Power III-2	450	\$13,889
Sunblade 100	UltraSPARC II-e	500	\$2950
Sunblade 1000	UltraSPARC III	750	\$9950

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SPEC CINT2000 – H&P 1.19

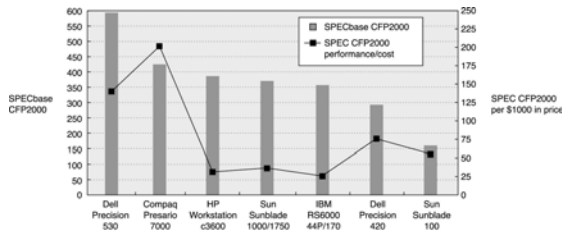


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SPEC CFP2000 – H&P 1.20



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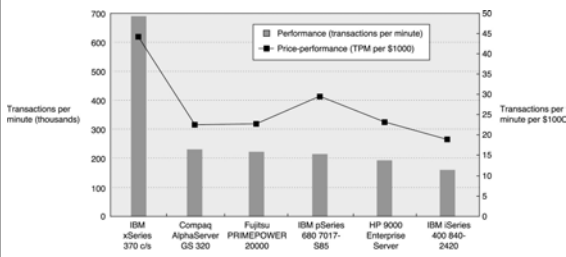
Performance/Price Performance

- For OLTP systems
- See Figure 1.21 (and www.tpc.org) for system details
 - both high total performance, and high price performance systems
- No uniprocessor systems
 - one cluster (IBM with 280 Pentium IIIs)
 - others multiprocessors (SMPs)

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High performing OLTP systems



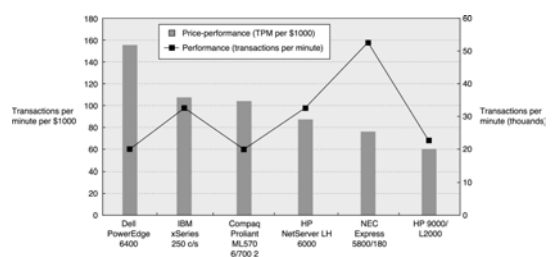
H&P Figure 1.22

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High price/performance systems



H&P Figure 1.23

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Alan Sussman
September 9, 2003

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- Homework #1 due Tuesday, 9/16
- Read Ch. 2 of H&P
- Homework #2 out soon

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Last time

- Benchmarking
 - reproducibility
 - report *all* parameters for the runs
- Statistical reporting
 - arithmetic mean & harmonic mean for absolute performance, with weighting
 - geometric mean for relative performance
- Amdahl's law to compute speedup
 - make the common case faster
- CPU performance
 - total CPU time = IC * CPI / MHz

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Fallacies

- MIPS (Millions of Instructions Per Second) or MFLOPS (Millions of Floating Point Operations) is a good way to compare performance
- **Fallacy:** One computer may have more powerful instructions than another, and MIPS/MFLOPS depends on the instruction mix that you choose

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Fallacies (cont.)

- Relative performance of 2 processors with same ISA can be judged by clock rate or by single benchmark suite
- **Fallacy:** other factors matter too, e.g., pipeline structure, memory system

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Fallacies (cont.)

- Synthetic benchmarks predict performance of real programs
- **Fallacy:** they don't reflect program behavior for factors not measured, and are very susceptible to compiler and hardware optimizations that may not work on real programs

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Fallacies (cont.)

- Benchmarks remain valid indefinitely
- **Fallacy:** Needs change, hardware changes, languages change, compilers change (esp. better optimization), ...

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Fallacies (cont.)

- Peak performance tracks observed performance
- **Fallacy:** Peak performance is a speed limit, the *guaranteed-not-to-be-exceeded* performance, and virtually never seen in practice

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Pitfalls

- Comparing hand-coded assembly and compiler-generated high-level language performance
- **Pitfall:** hand-coding most applications not possible – because of high software development costs – even though it is possible for key loops, performance critical kernels

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Pitfalls (cont.)

- Neglecting software costs in evaluating a system or for cost-performance analysis
- **Pitfall:** software costs can be a large fraction of both purchase cost and operational (maintenance) costs of a system
 - e.g., Microsoft Windows + Office costs ~\$300 for a PC system with hardware costing ~\$1000, so software costs are ~25% of the total cost (and higher if not bundled with the hardware)

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