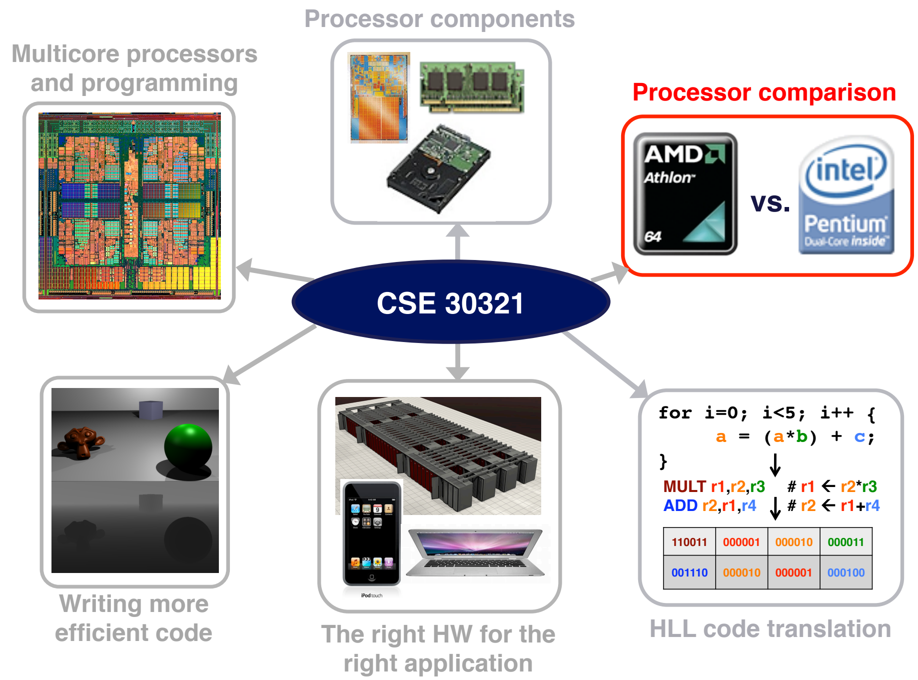
Lectures 04
Architectural-level Performance Metrics

Suggested reading:
(the remainder of HP Chapter 1)



Fundamental lesson(s)

- How to quantitatively compare and contrast different computer architectures

Why it's important…

- You'll use the analysis techniques discussed today for the rest of the semester …
  - … so in order to get a good grade in the class, you should be sure that your comfortable with the material
- If you're making / designing HW, you need to hit certain performance metrics
- If you're buying hardware, you want to make sure it meets your software needs
  - i.e. you may want to achieve a certain execution time, etc.

Which is "the best"?





Measuring and improving performance (if planes were computers)

Which is best?

Plane	People	Range (miles)	Speed (mph)	Avg. Cost (millions)
737-800	162	3,060	530	63.5
747-8I	467	8000	633	257.5
777-300	368	5995	622	222
787-8	230	8000	630	153

An "architecture" example

1 GHz clock rate, each instruction takes ~1.2 cycles to execute

How do we determine which machine is better?

2 GHz clock rate, each instruction takes ~1.8 cycles to execute

```
...
MOV R1, d(8)
Add R2, R3, R1
Sub R5, R2, R1
MOV d(9) R5
Add R4, R3, R0
...
```


May be a minimum performance requirement

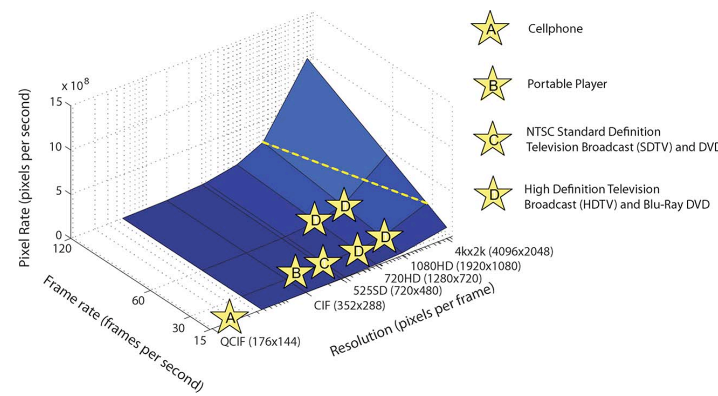


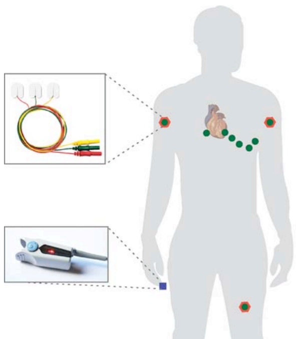
Fig. 1. *Performance requirements for various applications based on frame rate and resolution [6]. Yellow dashed line shows limit of H.264/AVC standard. Next-generation standard is expected to reach above this line.*

Technologies for Ultradynamic Voltage Scaling

By Anantha P. Chandrakasan, *Fellow IEEE*, Denis C. Daly, *Member IEEE*, Daniel Frederic Finchelstein, *Member IEEE*, Joyce Kwong, *Student Member IEEE*, Yogesh Kumar Ramadass, *Member IEEE*, Mahmut Ersin Sinangil, *Student Member IEEE*, Vivienne Sze, *Student Member IEEE*, and Naveen Verma, *Member IEEE*

Vol. 98, No. 2, February 2010 | Proceedings of the IEEE

Power and energy are important too



Monitoring	Sample Rate	# Cycles / Sample	Processor Frequency
■ Pulseoximetry	1kHz	331	331kHz
● Single-lead ECG	200Hz	4990	1MHz
● 12-lead ECG	1kHz	25700	25.7MHz

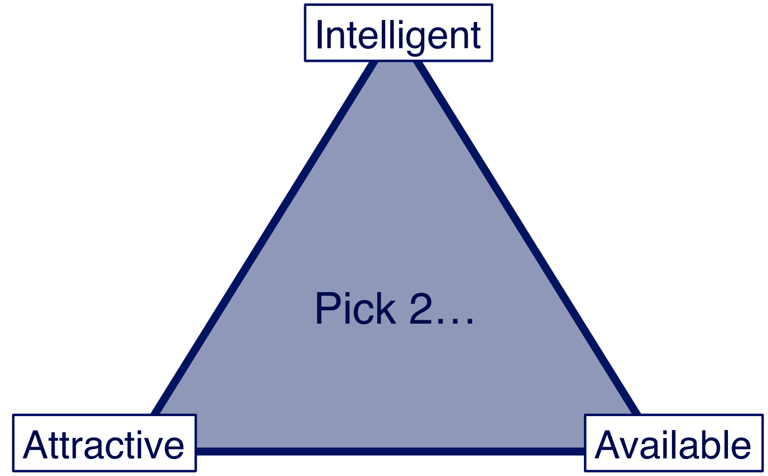
Fig. 2. *Scenarios for monitoring cardiac activity with varying real-time processing demands. For each application, locations of electrodes/probes on the body are shown, as well as the required clock frequency of the sensor processor. (Photos courtesy of GANFYD.)*

Technologies for Ultradynamic Voltage Scaling

By Anantha P. Chandrakasan, *Fellow IEEE*, Denis C. Daly, *Member IEEE*, Daniel Frederic Finchelstein, *Member IEEE*, Joyce Kwong, *Student Member IEEE*, Yogesh Kumar Ramadass, *Member IEEE*, Mahmut Ersin Sinangil, *Student Member IEEE*, Vivienne Sze, *Student Member IEEE*, and Naveen Verma, *Member IEEE*

Vol. 98, No. 2, February 2010 | Proceedings of the IEEE

Architecture: kinda like dating…

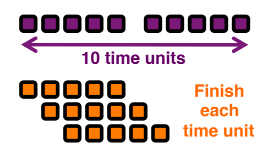


Characterizing Performance

- How can one computer's performance be understood or two computers be compared?
- What factors go into achieving "good performance"?
  - Raw CPU speed?
  - Memory speed or bandwidth?
  - I/O speed or bandwidth?
  - The operating system's overhead?
  - The compiler?
  - Battery life?
- Critical to succinctly summarize performance, and meaningfully compare.

Common (and good) performance metrics

- latency: response time, execution time
  - good metric for fixed amount of work (minimize time)
- throughput: work per unit time
  - = (1 / latency) when there is NO OVERLAP
  - > (1 / latency) when there is overlap
    - in real processors there is always overlap
  - good metric for fixed amount of time (maximize work)



- comparing performance
  - A is N times faster than B if and only if:
    - perf(A)/perf(B) = **time(B)/time(A) = N**
  - A is X% faster than B if and only if:
    - perf(A)/perf(B) = **time(B)/time(A) = 1 + X/100**

Throughput vs. Latency

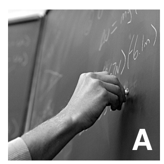
- What is better?
  - A machine that always takes 1 ns to do “task X” 1 time
  - A machine that takes 15 ns to do “task X” 30 times…
    - …but 5 ns to do “task X” 1 time
  - Machine 1:
    - a lower latency for a single operation…
  - Machine 2:
    - better throughput for multiple operations
  - What’s better?
    - depends on what kind of computation you need to do

Take away?

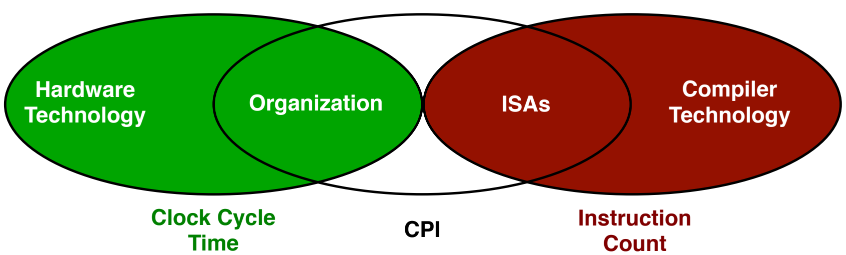
- Execution time and throughput are really good performance metrics in that they’re “lowest common denominators”
- (i.e. if X finishes in 5 seconds and Y finishes in 10, its hard to make the case that Y is faster!)

A CPU : The Bigger Picture

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

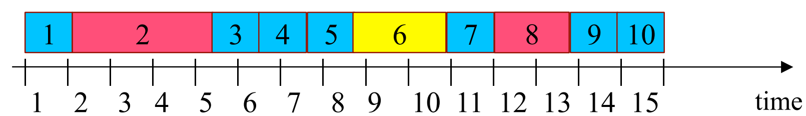


- We can see CPU performance dependent on:
  - Clock rate, CPI, and instruction count
- CPU time is directly proportional to all 3:
  - Therefore an x % improvement in any one variable leads to an x % improvement in CPU performance
- But, everything usually affects everything:



IC, CPI and IPC

Consider the following:



Total Execution Time = 15 cycles

Instruction Count (IC) = Number of Instructions = 10

Average number of cycles per instruction (CPI) = 15/10 = 1.5

Instructions per Cycle (IPC) = 10/15 = 0.66

Can CPI < 1?

Different Types of Instructions

- Multiplication takes more time than addition
- Floating point operations take longer than integer operations
- Memory accesses take more time than register accesses

$$\text{CPU Clock Cycles} = \sum_{i=1}^{n} CPI_i * IC_i = AvgCPI * IC$$

- NOTE:
  - changing the cycle time often affects the number of cycles an instruction will take

Question: Measurement Comparison

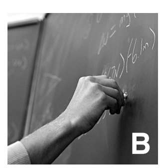
- Given that two machines have the same ISA, which measurement is always the same for both machines running program P?
  - Clock Rate:
  - CPI:
  - Execution Time:
  - Number of Instructions:

The Power of Compiler

A compiler designer is trying to decide between two code sequences for a particular machine. The machine supports three classes of instructions: A, B, and C, which take one, two, and three cycles (respectively):

Sequence 1 contains: 2 A's, 1 B, and 2 C's
Sequence 2 contains: 4 A's, 1 B, and 1 C

Which sequence is faster? By how much? What is the CPI of each?



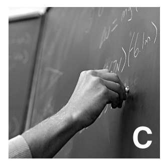
Metrics

- Metrics Discussed:
  - Execution time (instructions, cycles, seconds)
  - Machine throughput (programs/second)
  - Cycles Per Instruction (CPI)
  - Instructions Per Cycle (IPC)
- Other Common Measures
  - millions of instructions per second (MIPS)
  - millions of floating point operations per second (MFLOPS)

$$\text{MIPS} = \frac{IC}{\text{seconds x } 10^6} = \text{IPC x } f_{clk} \text{ (MHz)}$$

Not all benchmarks are good…

- Example: MIPS (millions of instructions per second)
  - instruction count is not a reliable indicator of work
    - Prob #1: some optimizations add instructions
    - Prob #2: work per instruction varies
      - (FP mult >> register move)
    - Prob #3: ISAs not equal (3 Pentium instrs != 3 AMD instrs)
      - You'll see more when we talk about addressing modes
        - » Addi vs. no Addi from Lecture 03 is a good example
        - » Addi = 1 instruction, 3 cycles;
        - » If no Addi, need 2 instructions – and 6 CCs!



Good Benchmarks: Real Programs

- real programs
  - (plus) only accurate way to characterize performance
  - (minus) requires considerable work (porting)
- Standard Performance Evaluation Corporation (SPEC)
  - http://www.spec.org
  - collects, standardizes and distributes benchmark suites
  - consortium made up of industry leaders
  - SPEC CPU (CPU intensive benchmarks)
    - SPEC89, SPEC92, SPEC95, SPEC2000, SPEC2006
  - other benchmark suites
    - SPECjvm, SPECmail, SPECweb
- Other benchmark suite examples: TPC-C, TPC-H for databases

SPEC CPU 2000

- 12 integer programs (C, C++)
  - **gcc** (compiler), **perl** (interpreter), **vortex** (database)
  - **bzip2**, **gzip** (compression tools), **crafty** (chess)
  - **eon** (rendering), **gap** (group theoretic enumerations)
  - **twolf**, **vpr** (FPGA place and route)
  - **parser** (grammar checker), **mcf** (network optimization)
- 14 floating point programs (C, FORTRAN)
  - **swim** (shallow water model), **mgrid** (multigrid field solver)
  - **applu** (partial diffeq's), **apsi** (air pollution simulation)
  - **wupwise** (quantum chromodynamics), **mesa** (OpenGL library)
  - **art** (neural network image recognition),
  - **equake** (wave propagation)
  - **fma3d** (crash simulation), **sixtrack** (accelerator design)
  - **lucas** (primality testing), **galgel** (fluid dynamics), **ammp** (chemistry)

What to expect from a benchmark suite

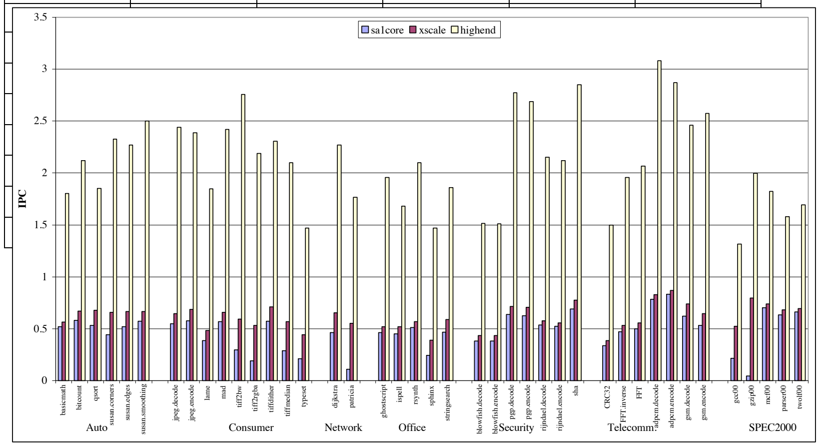
- Different programs in the suite stress different parts of the architecture
  - For example:
    - One benchmark may be memory intensive…
    - …another may be compute intensive…
    - …another may be I/O intensive…
  - Ideally, show wins on all aspects
    - (but most often not the case – which is OK)

Other suites

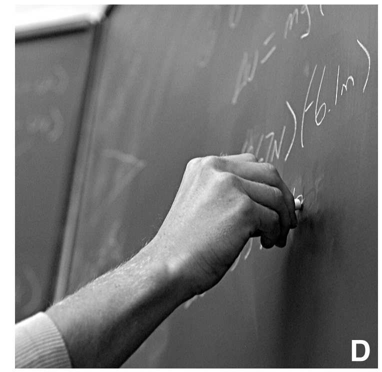
MiBench: A free, commercially representative embedded benchmark suite

Table 1: MiBench Benchmarks

Auto./Industrial	Consumer	Office	Network	Security	Telecomm.



Some additional examples



Amdahl's Law

- Qualifies performance gain
- Amdahl's Law defined…
  - The performance improvement to be gained from using some faster mode of execution is limited by the amount of time the enhancement is actually used.
- Amdahl's Law defines speedup:

$$\text{Speedup} = \frac{\text{Execution time for entire task without enhancement}}{\text{Execution time for entire task using enhancement when possible}}$$

Amdahl's Law and Speedup

- Speedup tells us how much faster the machine will run with an enhancement
- 2 things to consider:
  - 1st…
    - Fraction of the computation time in the original machine that can use the enhancement
    - i.e. if a program executes in 30 seconds and 15 seconds of exec. uses enhancement, fraction = ½ (always < 1)
  - 2nd…
    - Improvement gained by enhancement (i.e. how much faster does the program run overall)
    - i.e. if enhanced task takes 3.5 seconds and original task took 7, we say the speedup is 2 (always > 1)

Deriving the previous formula

$$\text{Speedup}_{overall} = \frac{\text{Execution Time}_{old}}{\text{Execution Time}_{new}} = \frac{1}{(1 - \text{Fraction}_{enhanced}) + \frac{\text{Fraction}_{enhanced}}{\text{Speedup}_{enhanced}}}$$

$$\frac{1}{(1 - \text{Fraction}_{enhanced}) + \frac{\text{Fraction}_{enhanced}}{\text{Speedup}_{enhanced}}}$$

1 ← normalized old execution time

$(1 - \text{Fraction}_{enhanced})$: 1 - % enhanced (i.e. part of the task will take the same amount of time as before)

$\frac{\text{Fraction}_{enhanced}}{\text{Speedup}_{enhanced}}$ → $\frac{\text{\% of task that will run faster}}{\text{how much faster it will run}}$

(note: # should be < 1)
(otherwise, performance gets worse)
(represents new component of ex. time)

Amdahl's Law examples