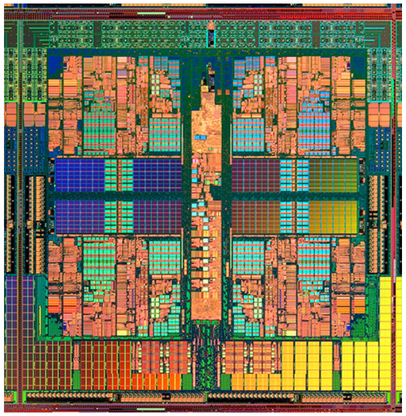
Lectures 04
Architectural-level Performance Metrics

Suggested reading:

(the remainder of HP Chapter 1)

CSE 30321

Multicore processors and programming

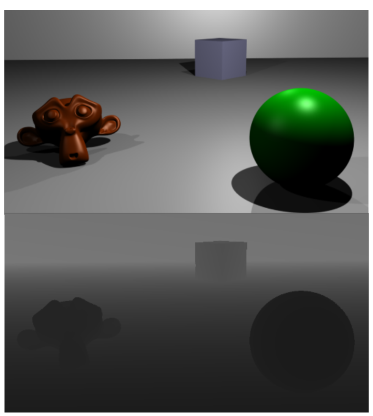


Processor components

Processor comparison

AMD Athlon 64 vs. intel Pentium Dual-Core inside

Writing more efficient code



The right HW for the right application

HLL code translation

```
for i=0; i<5; i++ {
      a = (a*b) + c;
}
```

```
MULT r1,r2,r3    # r1 ← r2*r3
ADD r2,r1,r4     # r2 ← r1+r4
```

110011	000001	000010	000011
001110	000010	000001	000100

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

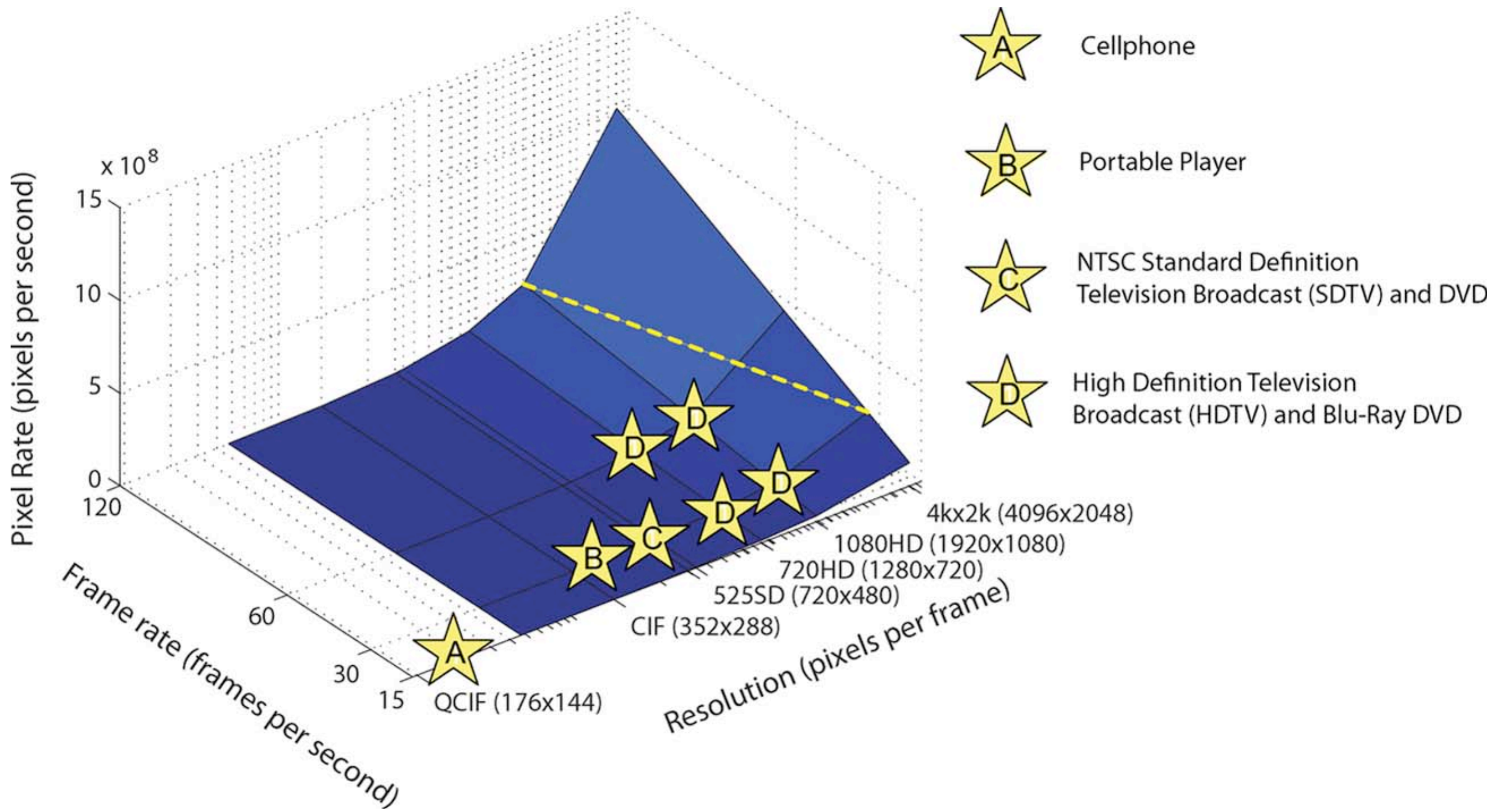


Fig. 1. ***Performance requirements for various applications based on frame rate and resolution [6]. Yellow dashed line shows limit of H.264/AVC standard. Next-generation standard is expected to reach above this line.***

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*

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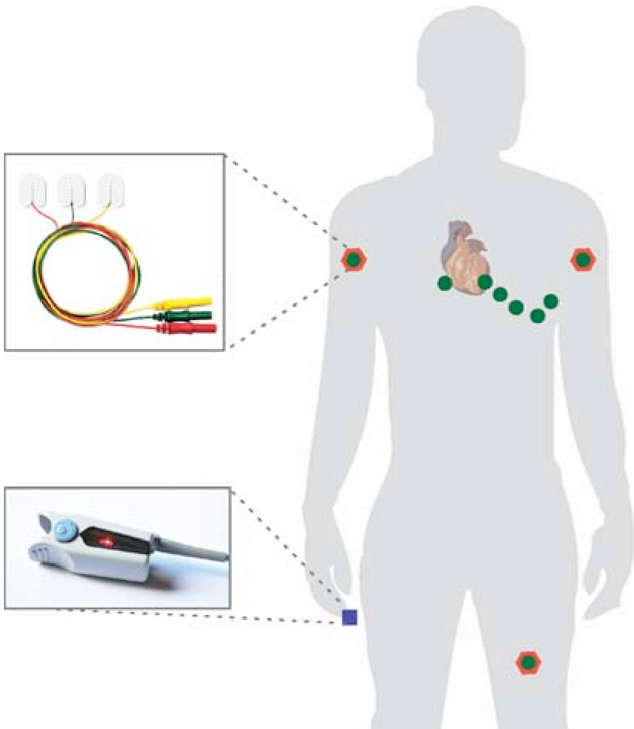
Power and energy are important too



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.)***

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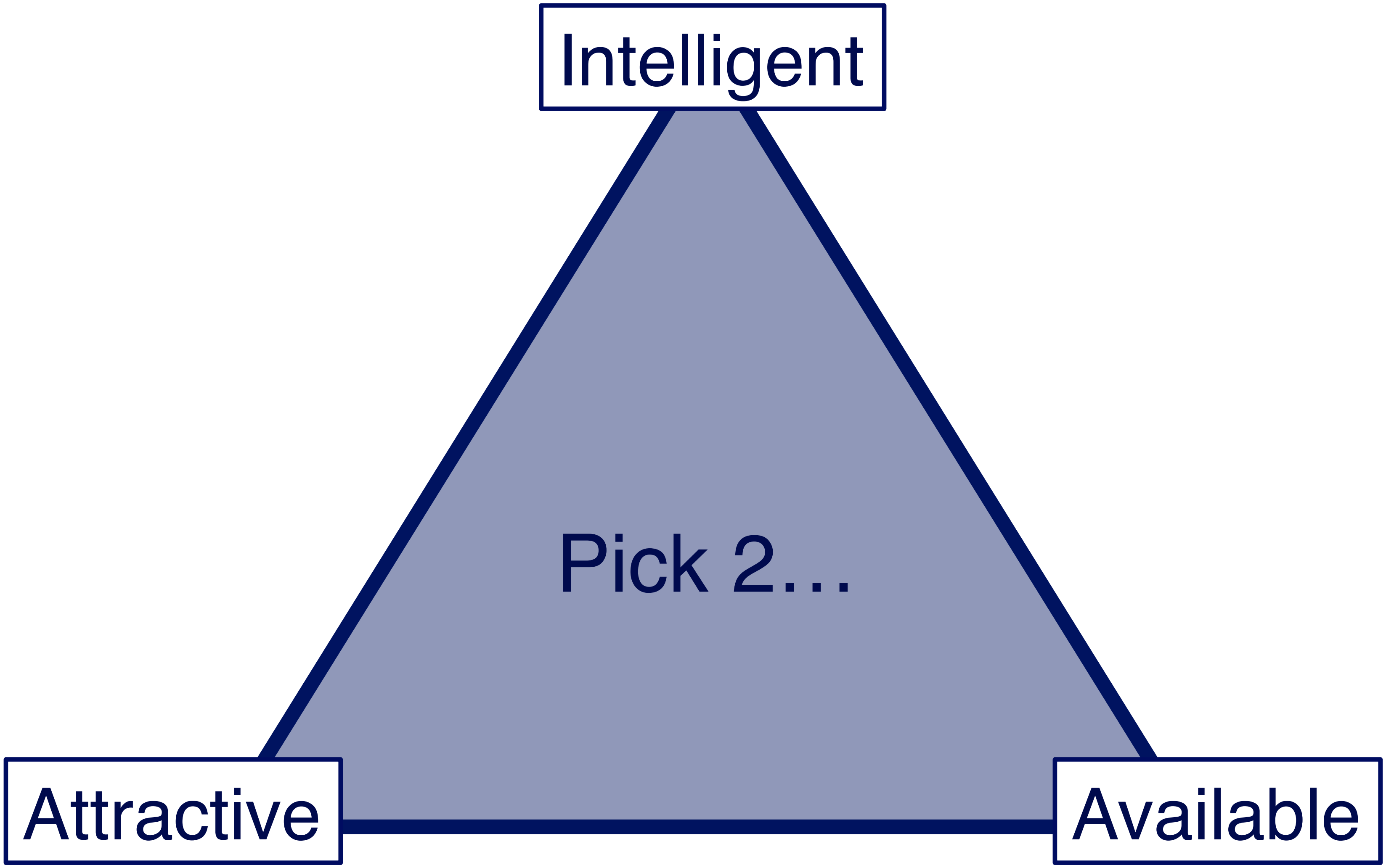
Architecture: kinda like dating…



Characterizing Performance

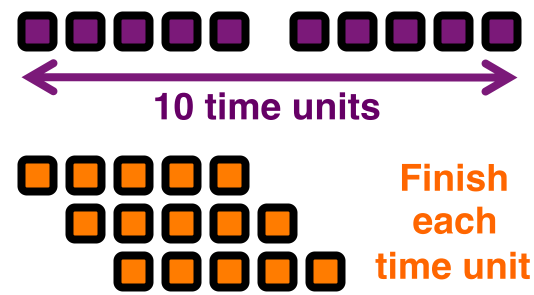
- How can one computer's performance be understood or two computers be compared?

- 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

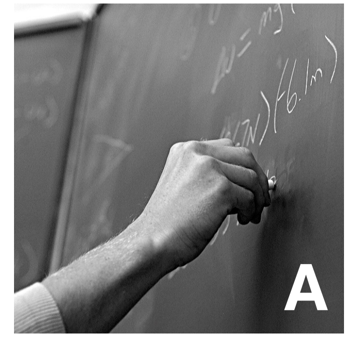
Take away?

- Execution time and throughput are really good performance metrics in that they're "lowest common denominators"

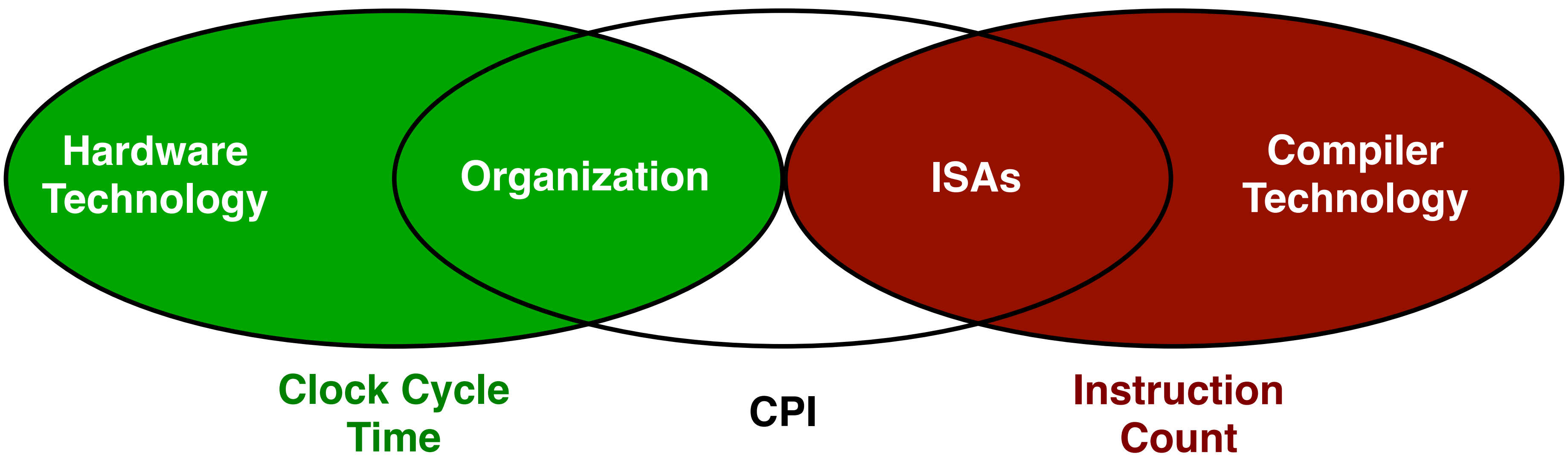
- (i.e. if X finishes in 5 seconds and Y finishes in 10, its hard to make the case that Y is faster!)

A CPU : The Bigger Picture

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

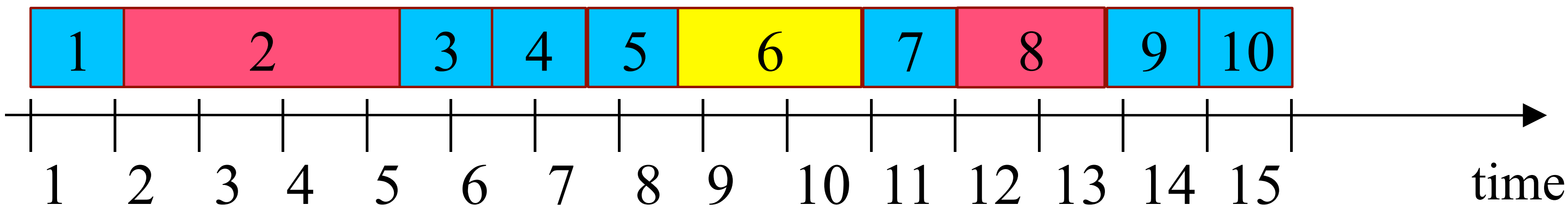


- **We can see CPU performance dependent on:**
  - **Clock rate, CPI, and instruction count**
- **CPU time is directly proportional to all 3:**
  - **Therefore an x % improvement in any one variable leads to an x % improvement in CPU performance**
- **But, everything usually affects everything:**



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

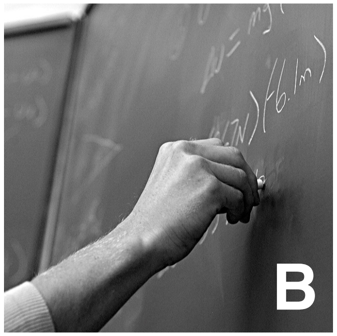
- Given that two machines have the same ISA, which measurement is always the same for both machines running program P?
  - Clock Rate:
  - CPI:
  - Execution Time:
  - Number of Instructions:

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

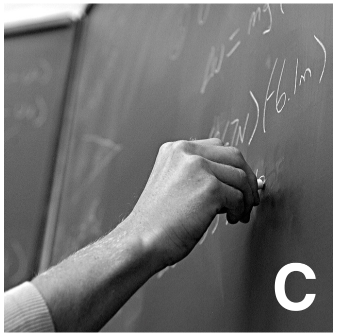
- **Metrics Discussed:**
  - Execution time (instructions, cycles, seconds)
  - Machine throughput (programs/second)
  - Cycles Per Instruction (CPI)
  - Instructions Per Cycle (IPC)

- **Other Common Measures**
  - millions of instructions per second (MIPS)
  - millions of floating point operations per second (MFLOPS)

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

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

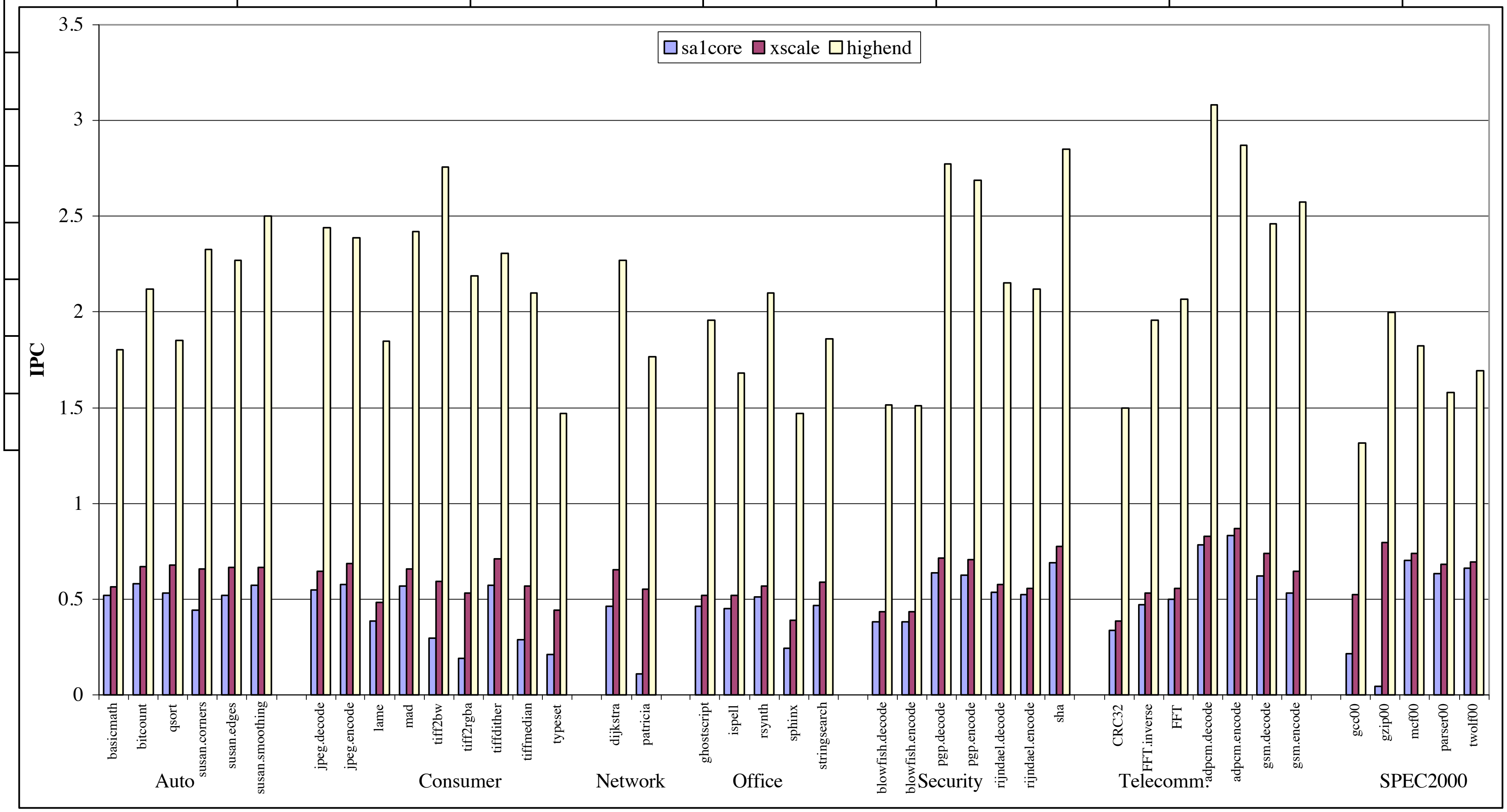
- Different programs in the suite stress different parts of the architecture
  - For example:
    - One benchmark may be memory intensive...
    - ...another may be compute intensive...
    - ...another may be I/O intensive...
  - Ideally, show wins on all aspects
    - (but most often not the case –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

Other suites

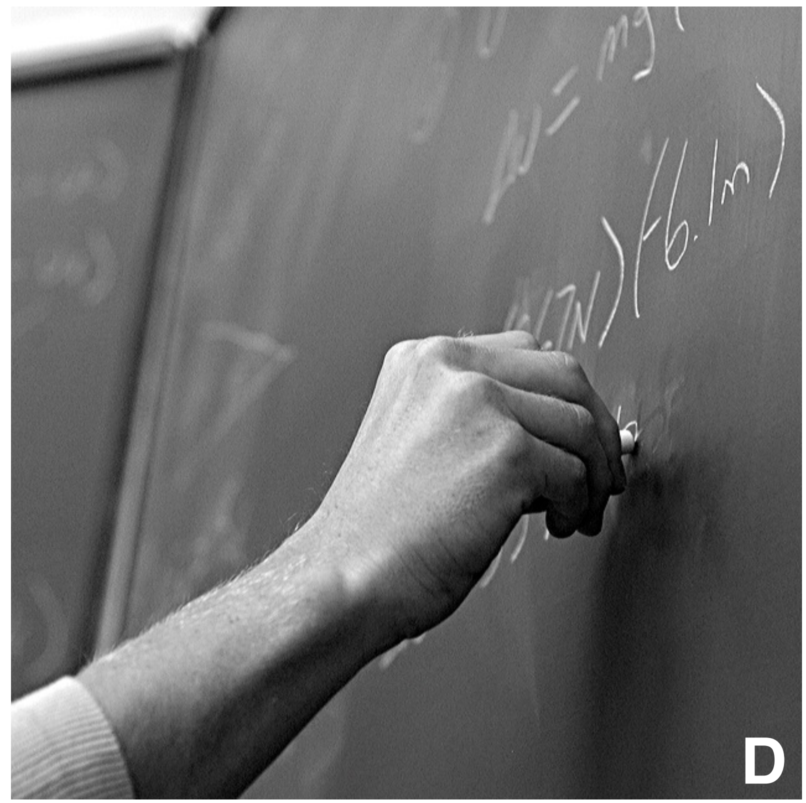
MiBench: A free, commercially representative embedded benchmark suite

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

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

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

1 ← normalized old execution time

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

$\dfrac{\text{Fraction}_{\text{enhanced}}}{\text{Speedup}_{\text{enhanced}}}$ →

$$\frac{\text{\% of task that will run faster}}{\text{how much faster it will run}}$$

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

Amdahl's Law examples