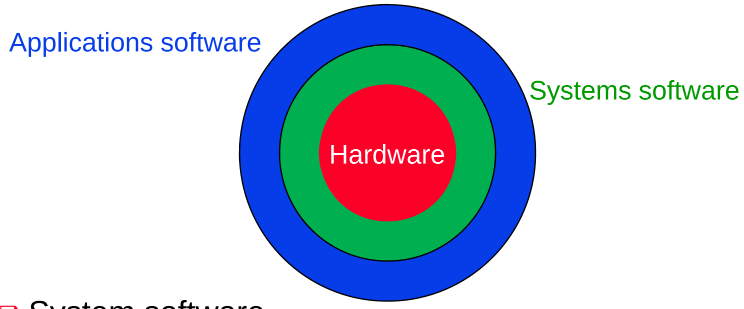
COSC 3327
Computer Architecture

Chapter 1: Performance

[Adapted from *Computer Organization and Design, 5th Edition*,
and addition material from Mary Jane Irwin, PSU]

Below the Program



- System software
  - Operating system – supervising program that interfaces the user's program with the hardware (e.g., Linux, MacOS, Windows)
    - Handles basic input and output operations
    - Allocates storage and memory
    - Provides for protected sharing among multiple applications
  - Compiler – translate programs written in a high-level language (e.g., C, Java) into instructions that the hardware can execute

Below the Program, Con’t

- High-level language program (in C)

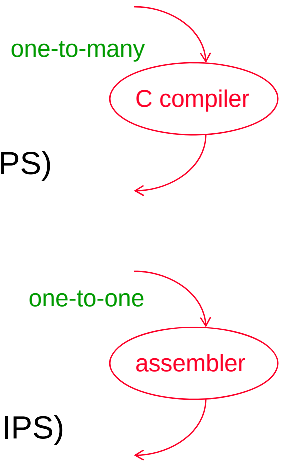
```
swap (int v[], int k)
(int temp;
       temp = v[k];
       v[k] = v[k+1];
       v[k+1] = temp;
)
```

- Assembly language program (for MIPS)

```
swap:  sll    $2, $5, 2
       add    $2, $4, $2
       lw     $15, 0($2)
       lw     $16, 4($2)
       sw     $16, 0($2)
       sw     $15, 4($2)
       jr     $31
```

- Machine (object, binary) code (for MIPS)

```
000000 00000 00101 0001000010000000
000000 00100 00010 0001000000100000
 . . .
```



one-to-many

C compiler

one-to-one

assembler

Advantages of Higher-Level Languages ?

- Higher-level languages

- As a result, very little programming is done today at the assembler level

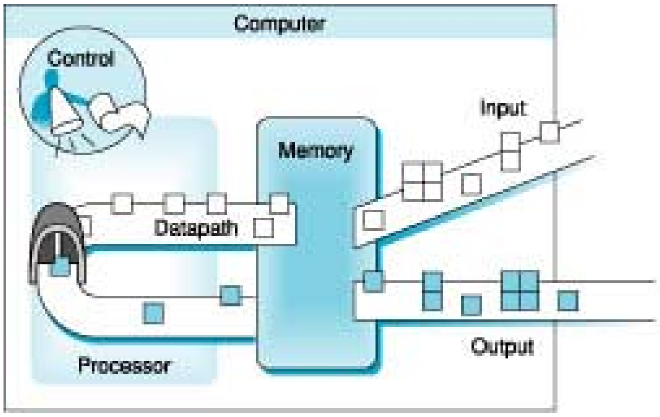
Advantages of Higher-Level Languages ?

- ❑ Higher-level languages
  - Allow the programmer to think in a more natural language and for their intended use (Fortran for scientific computation, Cobol for business programming, Lisp for symbol manipulation, Java for web programming, …)
  - Improve programmer productivity – more understandable code that is easier to debug and validate
  - Improve program maintainability
  - Allow programs to be independent of the computer on which they are developed (compilers and assemblers can translate high-level language programs to the binary instructions of any machine)
  - Emergence of optimizing compilers that produce very efficient assembly code optimized for the target machine
- ❑ As a result, very little programming is done today at the assembler level

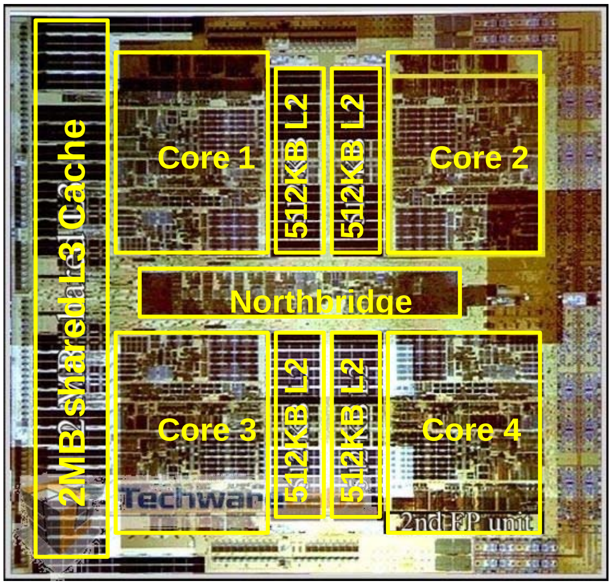
Under the Covers

- ❑ Five classic components of a computer – input, output, memory, datapath, and control

- ❑ datapath + control = processor (CPU)



AMD’s Barcelona Multicore Chip



- Four out-of-order cores on one chip
- 1.9 GHz clock rate
- 65nm technology
- Three levels of caches (L1, L2, L3) on chip
- Integrated Northbridge

http://www.techwarelabs.com/reviews/processors/barcelona/

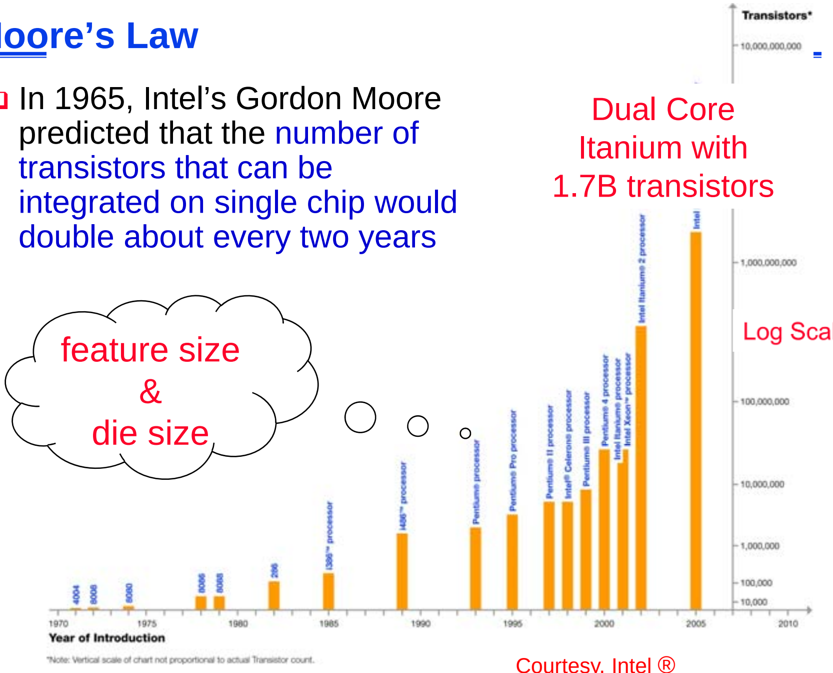
Instruction Set Architecture (ISA)

- ISA, or simply architecture – the abstract interface between the hardware and the lowest level software that encompasses all the information necessary to write a machine language program, including instructions, registers, memory access, I/O, …
  - Enables implementations of varying cost and performance to run identical software

- The combination of the basic instruction set (the ISA) and the operating system interface is called the application binary interface (ABI)
  - ABI – The user portion of the instruction set plus the operating system interfaces used by application programmers. Defines a standard for binary portability across computers.

Moore’s Law

- In 1965, Intel’s Gordon Moore predicted that the number of transistors that can be integrated on single chip would double about every two years



Dual Core Itanium with 1.7B transistors

Log Scale

feature size & die size

*Note: Vertical scale of chart not proportional to actual Transistor count.

Courtesy, Intel ®

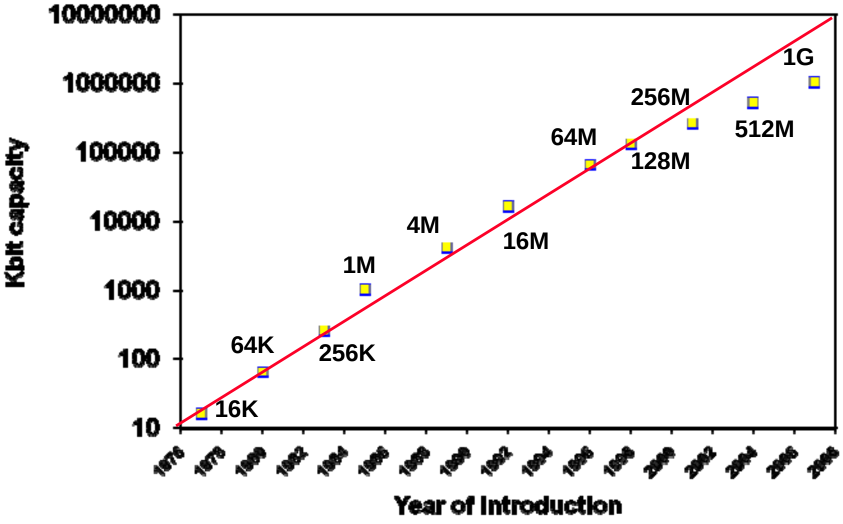
Technology Scaling Road Map (ITRS)

Year	2004	2006	2008	2010	2012
Feature size (nm)	90	65	45	32	22
Intg. Capacity (BT)	2	4	6	16	32

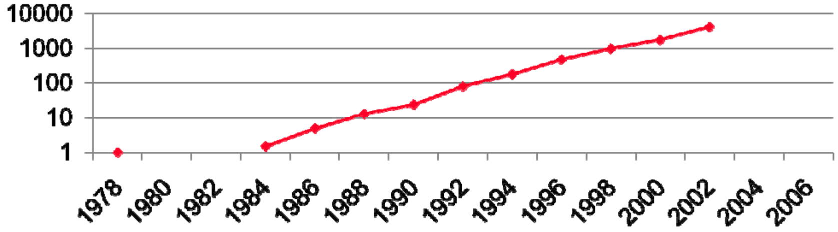
- Fun facts about 45nm transistors
  - 30 million can fit on the head of a pin
  - You could fit more than 2,000 across the width of a human hair
  - If car prices had fallen at the same rate as the price of a single transistor has since 1968, a new car today would cost about 1 cent

Another Example of Moore’s Law Impact

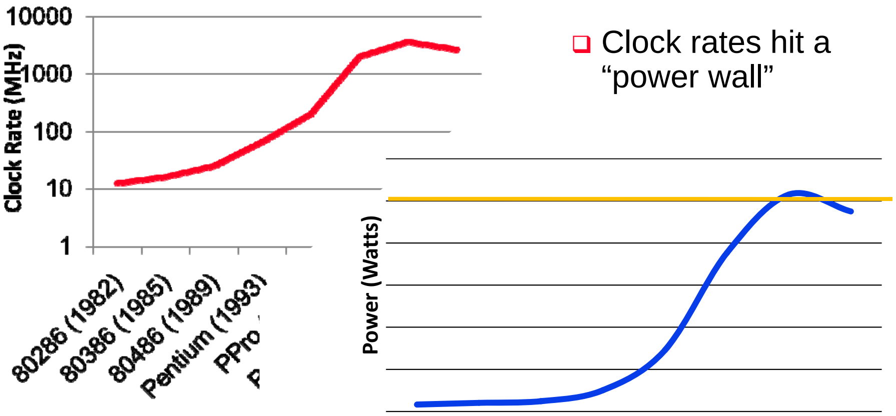
DRAM capacity growth over 3 decades



Replace with Figure 1.16 when available



But What Happened to Clock Rates and Why?



- ❑ Clock rates hit a "power wall"

"For the P6, success criteria included performance above a certain level and failure criteria included power dissipation above some threshold."

Bob Colwell, Pentium Chronicles

A Sea Change is at Hand

- The power challenge has forced a change in the design of microprocessors
  - Since 2002 the rate of improvement in the response time of programs on desktop computers has slowed from a factor of 1.5 per year to less than a factor of 1.2 per year
- As of 2006 all desktop and server companies are shipping microprocessors with multiple processors – cores – per chip

Product	AMD Barcelona	Intel Nehalem	IBM Power 6	Sun Niagara 2
Cores per chip	4	4	2	8
Clock rate	2.5 GHz	~2.5 GHz?	4.7 GHz	1.4 GHz
Power	120 W	~100 W?	~100 W?	94 W

- Plan of record is to double the number of cores per chip per generation (about every two years)

- End of Lecture 1

Performance Metrics

- Purchasing perspective
  - given a collection of machines, which has the
    - best performance ?
    - least cost ?
    - best cost/performance?
- Design perspective
  - faced with design options, which has the
    - best performance improvement ?
    - least cost ?
    - best cost/performance?
- Both require
  - basis for comparison
  - metric for evaluation
- Our goal is to understand what factors in the architecture contribute to overall system performance and the relative importance (and cost) of these factors

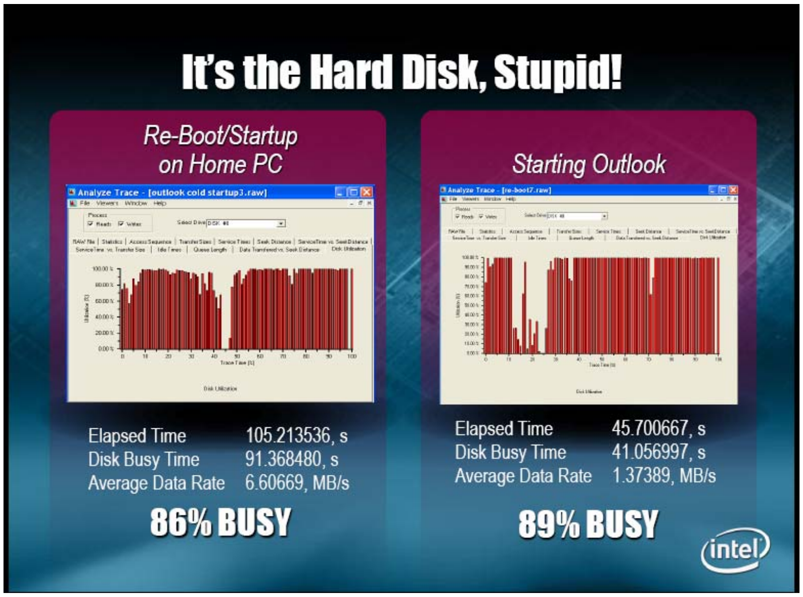
"Never let an engineer get away with simply presenting the data. Always insist that he or she lead off with the conclusions to which the data led."

Bob Colwell, Pentium Chronicles

Throughput versus Response Time

- Response time (execution time) – the time between the start and the completion of a task
  - Important to individual users
- Throughput (bandwidth) – the total amount of work done in a given time
  - Important to data center managers
- Will need different performance metrics as well as a different set of applications to benchmark embedded and desktop computers, which are more focused on response time, versus servers, which are more focused on throughput

Response Time Matters



It's the Hard Disk, Stupid!

Re-Boot/Startup on Home PC

Analyze Trace - [outlook cold startup3.raw]
Disk Utilization
Trace Time [s]

Elapsed Time 105.213536, s
Disk Busy Time 91.368480, s
Average Data Rate 6.60669, MB/s

86% BUSY

Starting Outlook

Analyze Trace - [re-boot7.raw]
Disk Utilization
Trace Time [s]

Elapsed Time 45.700667, s
Disk Busy Time 41.056997, s
Average Data Rate 1.37389, MB/s

89% BUSY

Justin Rattner's ISCA'08 Keynote (VP and CTO of Intel)

Defining (Speed) Performance

- To maximize performance, need to minimize execution time

$$\text{performance}_X = 1 / \text{execution\_time}_X$$

If X is n times faster than Y, then

$$\frac{\text{performance}_X}{\text{performance}_Y} = \frac{\text{execution\_time}_Y}{\text{execution\_time}_X} = n$$

- Decreasing response time almost always improves throughput

A Relative Performance Example

- If computer A runs a program in 10 seconds and computer B runs the same program in 15 seconds, how much faster is A than B?

Relative Performance Example

- If computer A runs a program in 10 seconds and computer B runs the same program in 15 seconds, how much faster is A than B?

We know that A is n times faster than B if

$$\frac{\text{performance}_A}{\text{performance}_B} = \frac{\text{execution\_time}_B}{\text{execution\_time}_A} = n$$

The performance ratio is $\frac{15}{10} = 1.5$

So A is 1.5 times faster than B

Performance Factors

- CPU execution time (CPU time) – time the CPU spends working on a task
  - Does not include time waiting for I/O or running other programs

$$\begin{array}{c}\text{CPU execution time}\\ \text{for a program}\end{array} = \begin{array}{c}\text{\# CPU clock cycles}\\ \text{for a program}\end{array} \times \text{ clock cycle time}$$

or

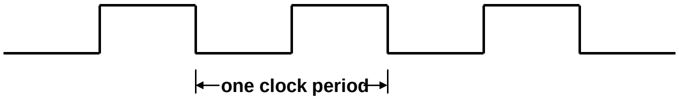
$$\begin{array}{c}\text{CPU execution time}\\ \text{for a program}\end{array} = \frac{\text{\# CPU clock cycles for a program}}{\text{clock rate}}$$

- Can improve performance by reducing either the length of the clock cycle or the number of clock cycles required for a program

Review: Machine Clock Rate

- Clock rate (clock cycles per second in MHz or GHz) is inverse of clock cycle time (clock period)

$$CC = 1 / CR$$



10 nsec clock cycle	=>	100 MHz clock rate
5 nsec clock cycle	=>	200 MHz clock rate
2 nsec clock cycle	=>	500 MHz clock rate
1 nsec (10^{-9}) clock cycle	=>	1 GHz (10^{9}) clock rate
500 psec clock cycle	=>	2 GHz clock rate
250 psec clock cycle	=>	4 GHz clock rate
200 psec clock cycle	=>	5 GHz clock rate

Improving Performance Example

- A program runs on computer A with a 2 GHz clock in 10 seconds. What clock rate must a computer B run at to run this program in 6 seconds? Unfortunately, to accomplish this, computer B will require 1.2 times as many clock cycles as computer A to run the program.

Improving Performance Example

- A program runs on computer A with a 2 GHz clock in 10 seconds. What clock rate must computer B run at to run this program in 6 seconds? Unfortunately, to accomplish this, computer B will require 1.2 times as many clock cycles as computer A to run the program.

$$\text{CPU time}_A = \frac{\text{CPU clock cycles}_A}{\text{clock rate}_A}$$

$$\text{CPU clock cycles}_A = 10 \text{ sec x } 2 \text{ x } 10^9 \text{ cycles/sec}$$
$$= 20 \text{ x } 10^9 \text{ cycles}$$

$$\text{CPU time}_B = \frac{1.2 \text{ x } 20 \text{ x } 10^9 \text{ cycles}}{\text{clock rate}_B}$$

$$\text{clock rate}_B = \frac{1.2 \text{ x } 20 \text{ x } 10^9 \text{ cycles}}{6 \text{ seconds}} = 4 \text{ GHz}$$

Clock Cycles per Instruction

- Not all instructions take the same amount of time to execute
  - One way to think about execution time is that it equals the number of instructions executed multiplied by the average time per instruction

$$\begin{array}{c}\text{\# CPU clock cycles}\\ \text{for a program}\end{array} = \begin{array}{c}\text{\# Instructions}\\ \text{for a program}\end{array} \text{ x } \begin{array}{c}\text{Average clock cycles}\\ \text{per instruction}\end{array}$$

- Clock cycles per instruction (CPI) – the average number of clock cycles each instruction takes to execute
  - A way to compare two different implementations of the same ISA

	CPI for this instruction class		
	A	B	C
CPI	1	2	3

Using the Performance Equation

- Computers A and B implement the same ISA. Computer A has a clock cycle time of 250 ps and an effective CPI of 2.0 for some program and computer B has a clock cycle time of 500 ps and an effective CPI of 1.2 for the same program. Which computer is faster and by how much?

Using the Performance Equation

- Computers A and B implement the same ISA. Computer A has a clock cycle time of 250 ps and an effective CPI of 2.0 for some program and computer B has a clock cycle time of 500 ps and an effective CPI of 1.2 for the same program. Which computer is faster and by how much?

Each computer executes the same number of instructions, *I*, so

$$\text{CPU time}_A = I \times 2.0 \times 250 \text{ ps} = 500 \times I \text{ ps}$$

$$\text{CPU time}_B = I \times 1.2 \times 500 \text{ ps} = 600 \times I \text{ ps}$$

Clearly, A is faster … by the ratio of execution times

$$\frac{\text{performance}_A}{\text{performance}_B} = \frac{\text{execution\_time}_B}{\text{execution\_time}_A} = \frac{600 \times I \text{ ps}}{500 \times I \text{ ps}} = 1.2$$

Effective (Average) CPI

- Computing the overall effective CPI is done by looking at the different types of instructions and their individual cycle counts and averaging

$$\text{Overall effective CPI} = \sum_{i=1}^{n} (\text{CPI}_i \times \text{IC}_i)$$

  - Where IC_i is the count (percentage) of the number of instructions of class i executed
  - CPI_i is the (average) number of clock cycles per instruction for that instruction class
  - n is the number of instruction classes

- The overall effective CPI varies by instruction mix – a measure of the dynamic frequency of instructions across one or many programs

THE Performance Equation

- Our basic performance equation is then

$$\text{CPU time} = \text{Instruction\_count} \times \text{CPI} \times \text{clock\_cycle}$$

or

$$\text{CPU time} = \frac{\text{Instruction\_count} \times \text{CPI}}{\text{clock\_rate}}$$

- These equations separate the three key factors that affect performance
  - Can measure the CPU execution time by running the program
  - The clock rate is usually given
  - Can measure overall instruction count by using profilers/ simulators without knowing all of the implementation details
  - CPI varies by instruction type and ISA implementation for which we must know the implementation details

Determinates of CPU Performance

CPU time = Instruction_count x CPI x clock_cycle

	Instruction_ count	CPI	clock_cycle
Algorithm			
Programming language			
Compiler			
ISA			
Core organization			
Technology			

Determinates of CPU Performance

CPU time = Instruction_count x CPI x clock_cycle

	Instruction_ count	CPI	clock_cycle
Algorithm	X	X	
Programming language	X	X	
Compiler	X	X	
ISA	X	X	X
Core organization		X	X
Technology			X

A Simple Example

Op	Freq	CPI_i	Freq x CPI_i
ALU	50%	1	.
Load	20%	5	
Store	10%	3	
Branch	20%	2	
			$\Sigma =$

- ❑ How much faster would the machine be if a better data cache reduced the average load time to 2 cycles?
- ❑ How does this compare with using branch prediction to shave a cycle off the branch time?
- ❑ What if two ALU instructions could be executed at once?

A Simple Example

Op	Freq	CPI_i	Freq x CPI_i			
ALU	50%	1	.5	.5	.5	.25
Load	20%	5	1.0	.4	1.0	1.0
Store	10%	3	.3	.3	.3	.3
Branch	20%	2	.4	.4	.2	.4
			$\Sigma =$ 2.2	1.6	2.0	1.95

- ❑ How much faster would the machine be if a better data cache reduced the average load time to 2 cycles?

  CPU time new = 1.6 x IC x CC so 2.2/1.6 means 37.5% faster
- ❑ How does this compare with using branch prediction to shave a cycle off the branch time?

  CPU time new = 2.0 x IC x CC so 2.2/2.0 means 10% faster
- ❑ What if two ALU instructions could be executed at once?

  CPU time new = 1.95 x IC x CC so 2.2/1.95 means 12.8% faster

Workloads and Benchmarks

- Benchmarks – a set of programs that form a “workload” specifically chosen to measure performance
- SPEC (System Performance Evaluation Cooperative) creates standard sets of benchmarks starting with SPEC89. The latest is SPEC CPU2006 which consists of 12 integer benchmarks (CINT2006) and 17 floating-point benchmarks (CFP2006).

www.spec.org

- There are also benchmark collections for power workloads (SPECpower_ssj2008), for mail workloads (SPECmail2008), for multimedia workloads (mediabench), …

Old SPEC Benchmarks

Integer benchmarks		FP benchmarks	
gzip	compression	wupwise	Quantum chromodynamics
vpr	FPGA place & route	swim	Shallow water model
gcc	GNU C compiler	mgrid	Multigrid solver in 3D fields
mcf	Combinatorial optimization	applu	Parabolic/elliptic pde
crafty	Chess program	mesa	3D graphics library
parser	Word processing program	galgel	Computational fluid dynamics
eon	Computer visualization	art	Image recognition (NN)
perlbmk	perl application	equake	Seismic wave propagation simulation
gap	Group theory interpreter	facerec	Facial image recognition
vortex	Object oriented database	ammp	Computational chemistry
bzip2	compression	lucas	Primality testing
twolf	Circuit place & route	fma3d	Crash simulation fem
		sixtrack	Nuclear physics accel
		apsi	Pollutant distribution

SPEC CINT2006 on Barcelona (CC = 0.4 x 10^9)

Name	ICx10^9	CPI	ExTime	RefTime	SPEC ratio
perl	2,1118	0.75	637	9,770	15.3
bzip2	2,389	0.85	817	9,650	11.8
gcc	1,050	1.72	724	8,050	11.1
mcf	336	10.00	1,345	9,120	6.8
go	1,658	1.09	721	10,490	14.6
hmmer	2,783	0.80	890	9,330	10.5
sjeng	2,176	0.96	837	12,100	14.5
libquantum	1,623	1.61	1,047	20,720	19.8
h264avc	3,102	0.80	993	22,130	22.3
omnetpp	587	2.94	690	6,250	9.1
astar	1,082	1.79	773	7,020	9.1
xalancbmk	1,058	2.70	1,143	6,900	6.0
Geometric Mean					11.7

Comparing and Summarizing Performance

❑ How do we summarize the performance for benchmark set with a single number?

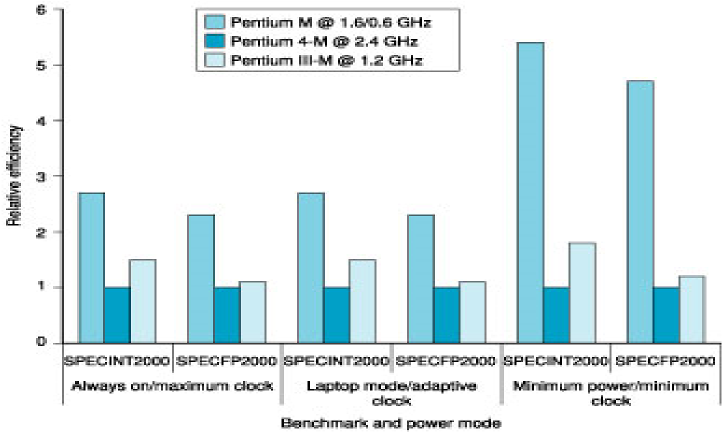
- First the execution times are normalized giving the “SPEC ratio” (bigger is faster, i.e., SPEC ratio is the inverse of execution time)
- The SPEC ratios are then “averaged” using the geometric mean (GM)

$$\text{GM} \;=\; \sqrt[n]{\prod_{i=1}^{n} \text{SPEC ratio}_i}$$

❑ Guiding principle in reporting performance measurements is reproducibility – list everything another experimenter would need to duplicate the experiment (version of the operating system, compiler settings, input set used, specific computer configuration (clock rate, cache sizes and speed, memory size and speed, etc.))

Other Performance Metrics

- ❑ Power consumption – especially in the embedded market where battery life is important
  - For power-limited applications, the most important metric is energy efficiency

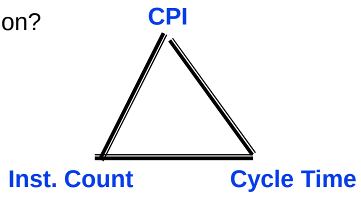


Summary: Evaluating ISAs

- ❑ Design-time metrics:
  - Can it be implemented, in how long, at what cost?
  - Can it be programmed? Ease of compilation?
- ❑ Static Metrics:
  - How many bytes does the program occupy in memory?
- ❑ Dynamic Metrics:
  - How many instructions are executed? How many bytes does the processor fetch to execute the program?
  - How many clocks are required per instruction?
  - How "lean" a clock is practical?

Best Metric: Time to execute the program!

depends on the instructions set, the processor organization, and compilation techniques.



CPI
Inst. Count
Cycle Time