Computer Fundamentals
Metrics and Performance

Computer Organization

Sunday, 18 September 2022

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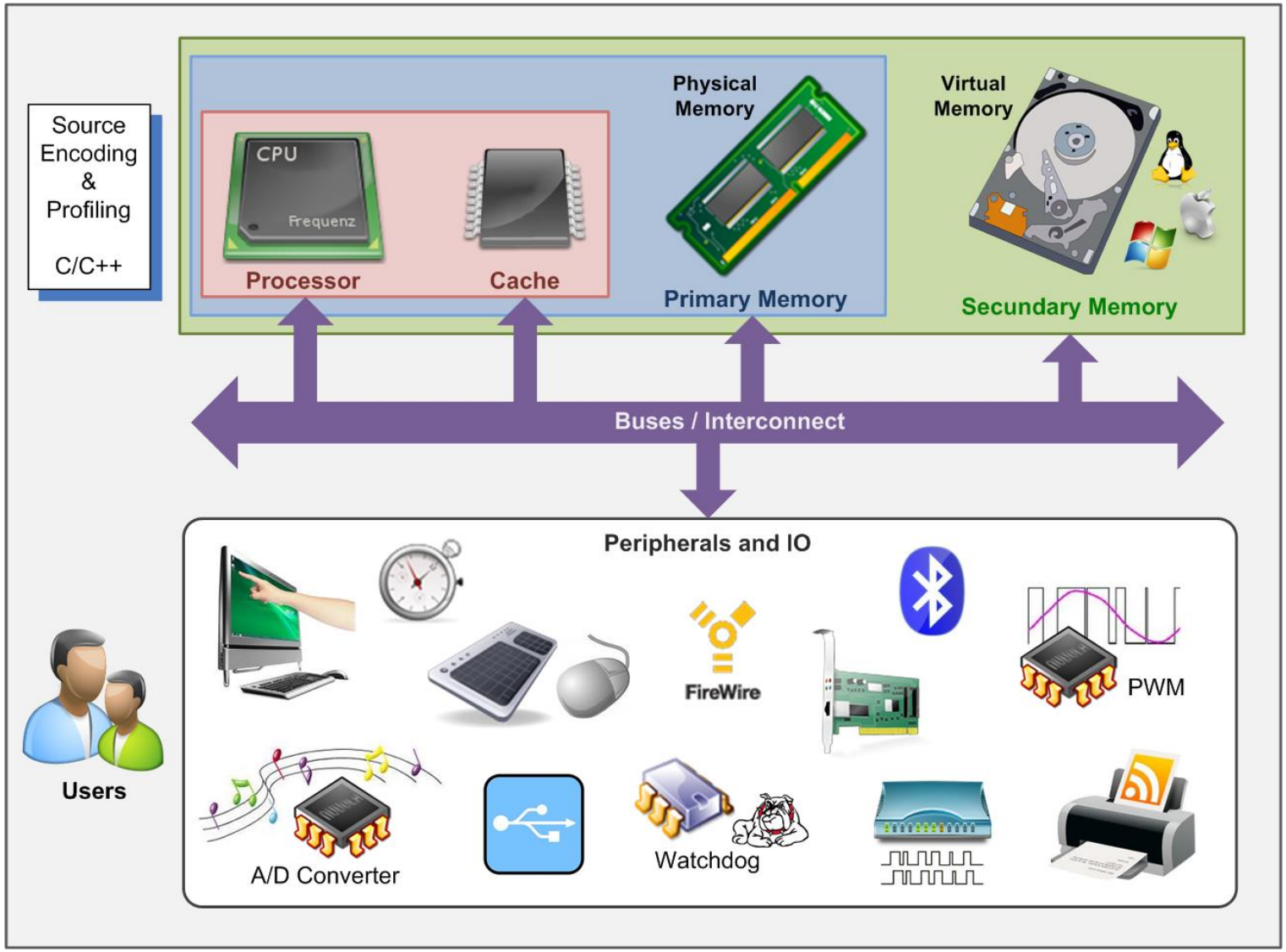
Many slides adapted from:
Computer Organization and Design,
Patterson & Hennessy
5th Edition, © 2014, MK

Chap. 1

Summary

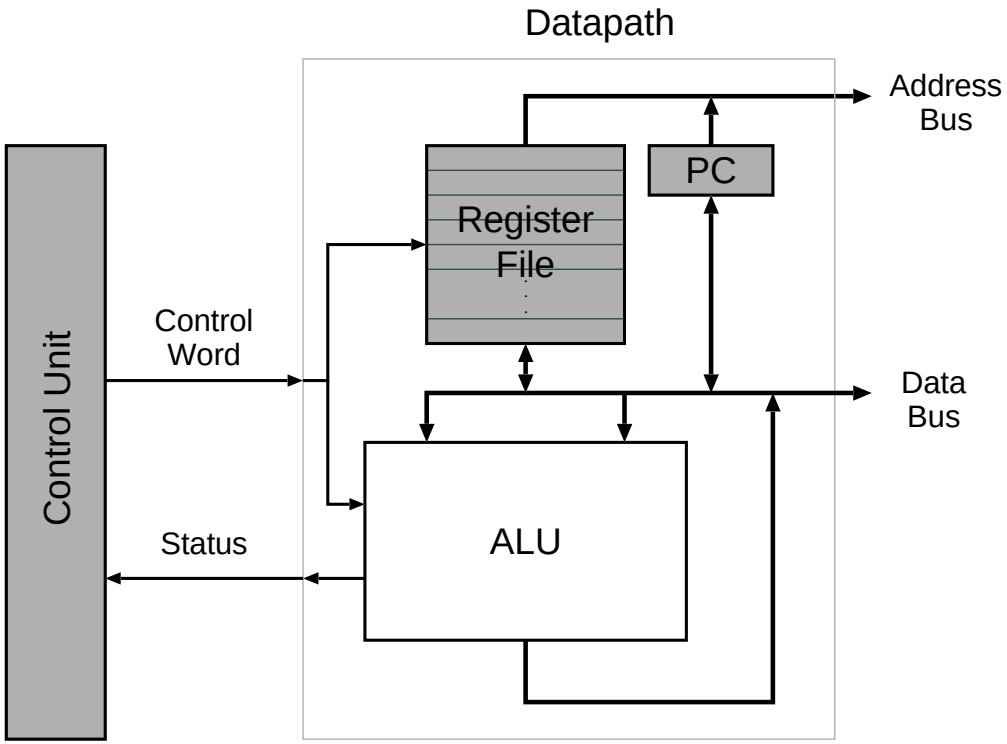
- Fundamentals of computer architecture
  - Main elements of a computer
  - Inside the processor
  - Assembly language
- Performance metrics
  - Clock rate
  - CPI

Computer System



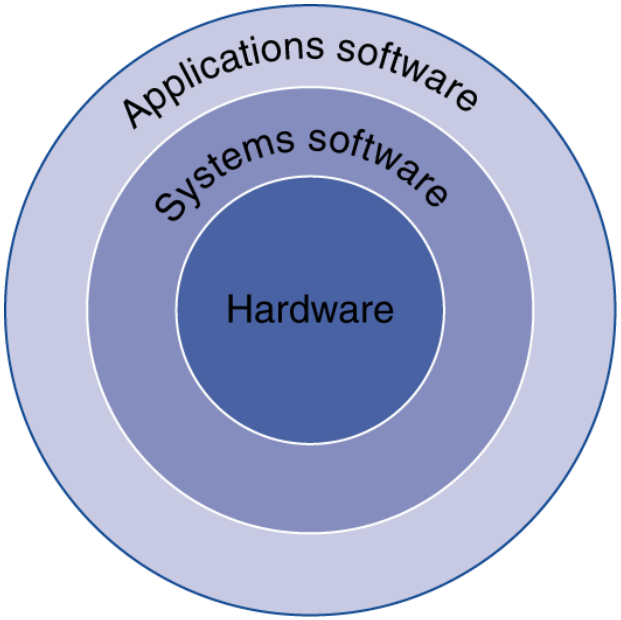
Inside the Processor (CPU)

- Datapath: performs operations on data
- Control: sequences datapath, memory, …



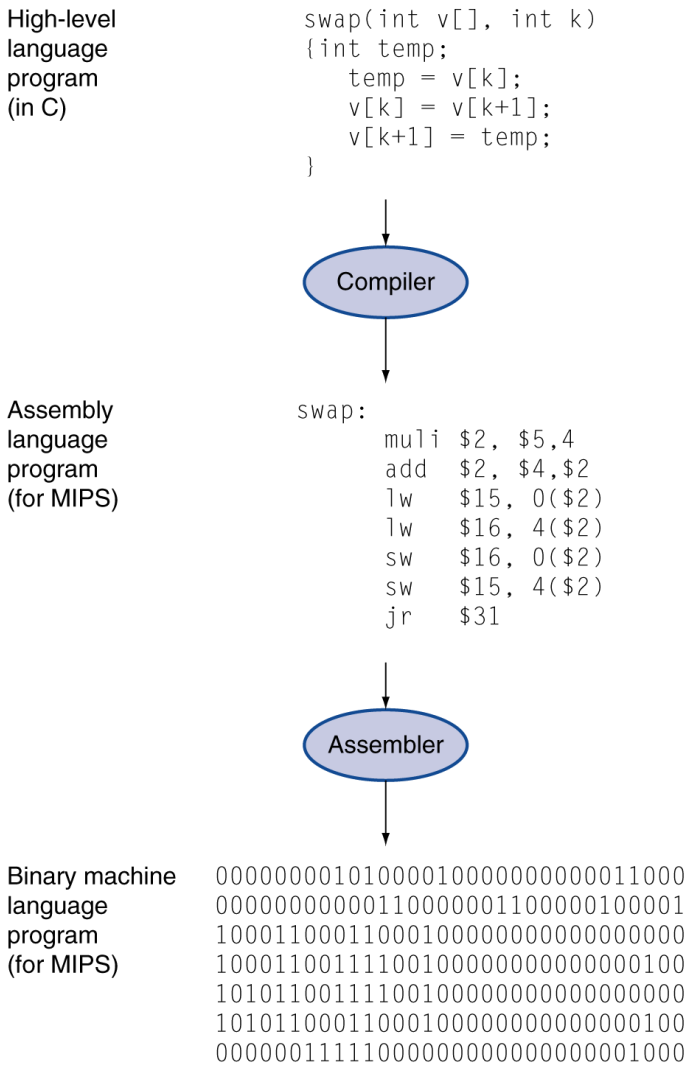
Below Your Program

- Application software
  - Written in high-level language (HLL)
- System software
  - Compiler: translates HLL code to machine code
  - Operating System: service code
    - Handling input/output
    - Managing memory and storage
    - Scheduling tasks & sharing resources
- Hardware
  - Processor, memory, I/O controllers



Levels of Program Code

- High-level language
  - Level of abstraction closer to problem domain
  - Provides for productivity and portability
- Assembly language
  - Textual representation of instructions
- Hardware representation
  - Binary digits (bits)
  - Encoded instructions and data

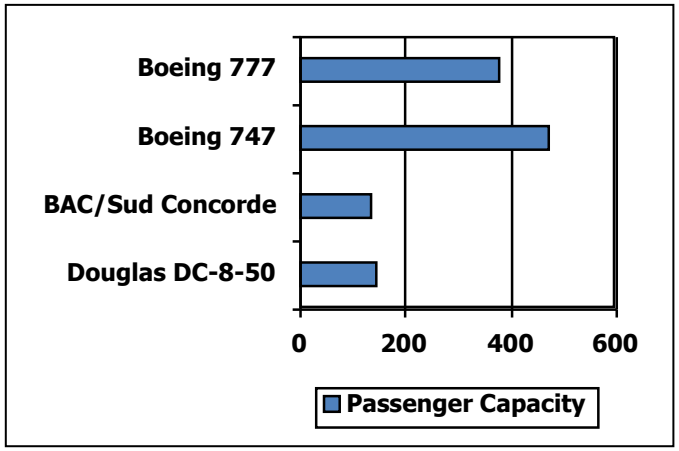


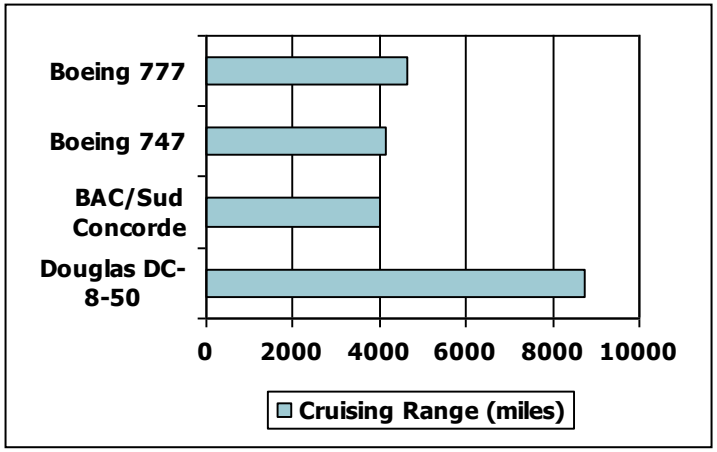
Understanding Performance

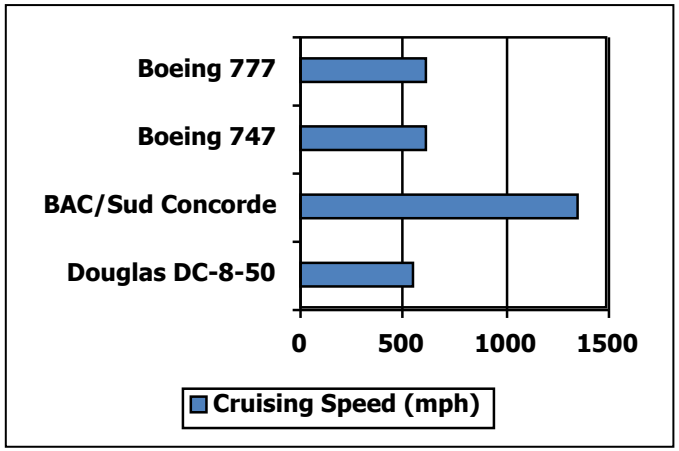
- Algorithm
  - Determines number of operations executed
- Programming language, compiler, architecture
  - Determine number of machine instructions executed per operation
- Processor and memory system
  - Determine how fast instructions are executed
- I/O system (including OS)
  - Determines how fast I/O operations are executed

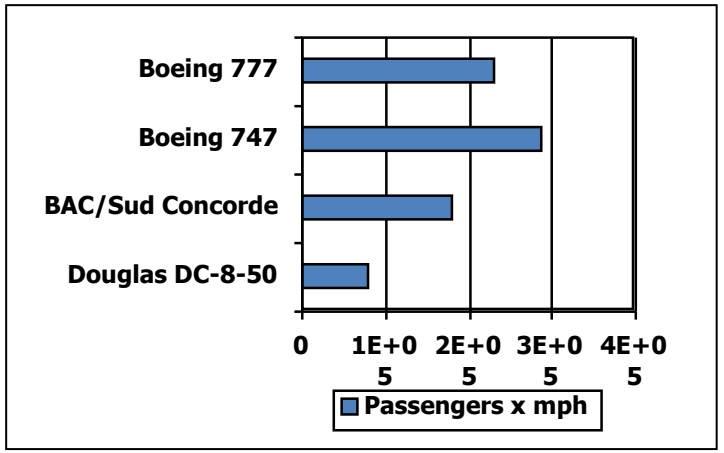
Defining Performance

Which airplane has the best performance?









Response Time and Throughput

- Response time
  - How long it takes to do a task
- Throughput
  - Total work done per unit time
    - e.g., tasks/transactions/… per hour
- How are response time and throughput affected by
  - Replacing the processor with a faster version?
  - Adding more processors?
- We'll focus on response time for now…

Relative Performance

- Define: Performance = 1 / Execution Time
- "X is *n* times faster than Y"

$$SpeedUp = \frac{\text{Performance}_X}{\text{Performance}_Y} = \frac{\text{Execution Time}_Y}{\text{Execution Time}_X} = n$$

- Example: time taken to run a program
  - 10s on A, 15s on B
  - Execution Time$_B$ / Execution Time$_A$= 15s / 10s = 1.5
  - So A is 1.5 times faster than B

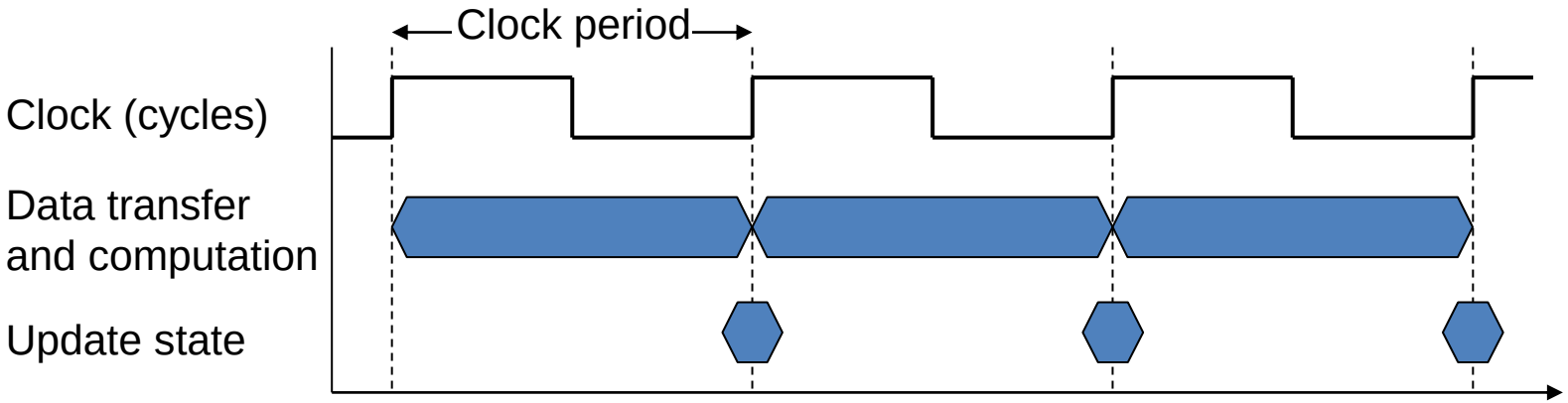
Measuring Execution Time

- Elapsed time
  - Total response time, including all aspects
    - Processing, I/O, OS overhead, idle time
  - Determines system performance

- CPU time
  - Time spent processing a given job
    - Discounts I/O time, other jobs' shares
  - Comprises user CPU time and system CPU time
  - Different programs are affected differently by CPU and system performance

CPU Clocking

Operation of digital hardware governed by a constant-rate clock



- Clock period: duration of a clock cycle

  e.g., T_{clk} = 250ps = 0.25ns = 250×10^{-12}s

- Clock frequency (rate): cycles per second

  e.g., $f_{clk} = 1/T_{clk}$ = 4.0GHz = 4,000MHz = 4.0×10^{9}Hz

CPU Time

$$\text{CPU Time} = \text{CPU Clock Cycles} \times \text{Clock Cycle Time}$$

$$= \frac{\text{CPU Clock Cycles}}{\text{Clock Rate}}$$

- Performance improved by
  - Reducing number of clock cycles
  - Increasing clock rate
  - Hardware designer must often trade off clock rate against cycle count

CPU Time Example

- Computer A: 2GHz clock, 10s CPU time
- Designing Computer B
  - Aim for 6s CPU time
  - Can do faster clock, but causes 1.2 × clock cycles
- How fast must Computer B clock be?

$$\text{Clock Rate}_B = \frac{\text{Clock Cycles}_B}{\text{CPU Time}_B} = \frac{1.2 \times \text{Clock Cycles}_A}{6\text{s}}$$

$$\text{Clock Cycles}_A = \text{CPU Time}_A \times \text{Clock Rate}_A$$

$$= 10\text{s} \times 2\text{GHz} = 20 \times 10^9$$

$$\text{Clock Rate}_B = \frac{1.2 \times 20 \times 10^9}{6\text{s}} = \frac{24 \times 10^9}{6\text{s}} = 4\text{GHz}$$

Instruction Count and CPI

- Instruction Count for a program
  - Determined by program, ISA and compiler
- Average cycles per instruction (CPI)
  - Determined by CPU hardware
  - If different instructions have different CPI
    - Average CPI affected by instruction mix

$$\text{Clock Cycles} = \text{Instruction Count} \times \text{Cycles per Instruction}$$

$$\text{CPU Time} = \text{Instruction Count} \times \text{CPI} \times \text{Clock Cycle Time}$$

$$= \frac{\text{Instruction Count} \times \text{CPI}}{\text{Clock Rate}}$$

CPI Example

- Computer A: Cycle Time = 250ps, CPI = 2.0
- Computer B: Cycle Time = 500ps, CPI = 1.2
- Same ISA
- Which is faster, and by how much?

$$\text{CPU Time}_A = \text{Instruction Count} \times \text{CPI}_A \times \text{Cycle Time}_A$$
$$= I \times 2.0 \times 250\text{ps} = I \times 500\text{ps}$$

A is faster…

$$\text{CPU Time}_B = \text{Instruction Count} \times \text{CPI}_B \times \text{Cycle Time}_B$$
$$= I \times 1.2 \times 500\text{ps} = I \times 600\text{ps}$$

$$SpeedUp = \frac{\text{CPU Time}_B}{\text{CPU Time}_A} = \frac{I \times 600\text{ps}}{I \times 500\text{ps}} = 1.2$$

…by this much

CPI in More Detail

If different instruction classes take different numbers of cycles:

$$\text{Clock Cycles} = \sum_{i=1}^{n} (\text{CPI}_i \times \text{Instruction Count}_i)$$

Weighted average CPI:

$$\text{CPI} = \frac{\text{Clock Cycles}}{\text{Instruction Count}} = \sum_{i=1}^{n} \left(\text{CPI}_i \times \underbrace{\frac{\text{Instruction Count}_i}{\text{Instruction Count}}}_{\text{Relative frequency}} \right)$$

CPI Example

- Alternative compiled code sequences using instructions in classes A, B, C

IC = Instruction Count

Class	A	B	C
CPI for class	1	2	3
IC in sequence 1	2	1	2
IC in sequence 2	4	1	1

Sequence 1:

IC = 5

Clock Cycles =
= 2×1 + 1×2 + 2×3
= 10

Avg. CPI = 10/5 = 2.0

Sequence 2:

IC = 6

Clock Cycles =
= 4×1 + 1×2 + 1×3
= 9

Avg. CPI = 9/6 = 1.5

A Simple Example

Op	Freq	CPI_i	Freq x CPI_i
ALU	50%	1	.5
Load	20%	5	1.0
Store	10%	3	.3
Branch	20%	2	.4
		CPI =	2.2

CC = Clock Cycles

.5	.5	.25
.4	1.0	1.0
.3	.3	.3
.4	.2	.4
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 CPU_{old}/CPU_{new} = 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 CPU_{old}/CPU_{new} = 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 CPU_{old}/CPU_{new} = 2.2/1.95 means 12.8% faster

Performance Summary

- Performance depends on
  - Algorithm: affects IC, possibly CPI
  - Programming language: affects IC, CPI
  - Compiler: affects IC, CPI
  - Instruction set architecture: affects IC, CPI, T_{clk}

$$\text{CPU Time} = \frac{\text{Instructions}}{\text{Program}} \times \underbrace{\frac{\text{Clock cycles}}{\text{Instruction}}}_{\text{CPI}} \times \underbrace{\frac{\text{Seconds}}{\text{Clock cycle}}}_{T_{clk}}$$

MIPS as a Performance Metric

MIPS: Millions of Instructions Per Second

- Pitfall: Doesn't account for
  - Differences in ISAs between computers
  - Differences in complexity between instructions

$$\text{MIPS} = \frac{\text{Instruction count}}{\text{Execution time} \times 10^6}$$

$$= \frac{\text{Instruction count}}{\frac{\text{Instruction count} \times \text{CPI}}{\text{Clock rate}} \times 10^6} = \frac{\text{Clock rate}}{\text{CPI} \times 10^6}$$

- CPI varies between programs on a given CPU

SPEC CPU Benchmark

- Programs used to measure performance
  - Supposedly typical of actual workload
- Standard Performance Evaluation Corp (SPEC)
  - Develops benchmarks for CPU, I/O, Web, …
- SPEC CPU2006
  - Elapsed time to execute a selection of programs
    - Negligible I/O, so focuses on CPU performance
  - Normalize relative to reference machine
  - Summarize as geometric mean of performance ratios
    - CINT2006 (integer) and CFP2006 (floating-point)

$$\sqrt[n]{\prod_{i=1}^{n} \text{Execution time ratio}_i}$$

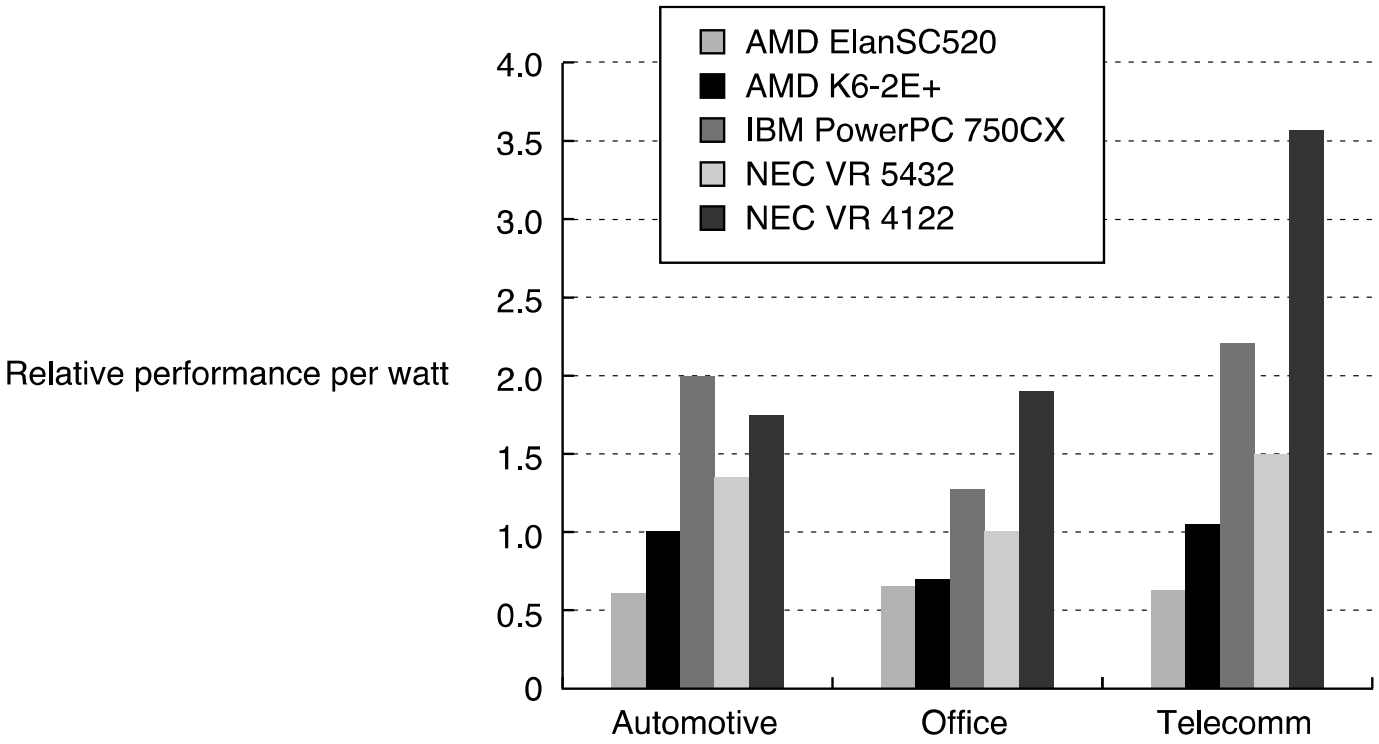
Check@home: CINT2006 for Intel Core i7 920

Description	Name	Instruction Count x 10^9	CPI	Clock cycle time (seconds x 10^{-9})	Execution Time (seconds)	Reference Time (seconds)	SPECratio
Interpreted string processing	perl	2252	0.60	0.376	508	9770	19.2
Block-sorting compression	bzip2	2390	0.70	0.376	629	9650	15.4
GNU C compiler	gcc	794	1.20	0.376	358	8050	22.5
Combinatorial optimization	mcf	221	2.66	0.376	221	9120	41.2
Go game (AI)	go	1274	1.10	0.376	527	10490	19.9
Search gene sequence	hmmer	2616	0.60	0.376	590	9330	15.8
Chess game (AI)	sjeng	1948	0.80	0.376	586	12100	20.7
Quantum computer simulation	libquantum	659	0.44	0.376	109	20720	190.0
Video compression	h264avc	3793	0.50	0.376	713	22130	31.0
Discrete event simulation library	omnetpp	367	2.10	0.376	290	6250	21.5
Games/path finding	astar	1250	1.00	0.376	470	7020	14.9
XML parsing	xalancbmk	1045	0.70	0.376	275	6900	25.1
Geometric mean	–	–	–	–	–	–	25.7

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



Check@home: Comparing Relative Performance

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 and memory sizes and speed, etc.

Benchmark set revised periodically:

- Designers target performance specifically for common benchmarks

Amdahl's Law

Pitfall: Improving an aspect of a computer and expecting a proportional improvement in overall performance

$$T_{improved} = \frac{T_{affected}}{improvement\ factor} + T_{unaffected}$$

$$= \left(\frac{f}{improvement\ factor} + (1-f) \right) T_{original}$$

$$Speedup = \frac{T_{original}}{T_{improved}} = \frac{1}{\frac{f}{improvement\ factor} + (1-f)}$$

Corollary: make the common case fast!

Next Class

- Assembly Instructions
- Instruction Set Architecture (ISA)
- MIPS ISA
- Binary Representation

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