Computer Architecture

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Today's Topics

- Performance Evaluation
- Standard Benchmarks

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- Parts (text & figures) of this lecture adopted from:
  - Computer Organization & Design, The Hardware/Software Interface, 4th Edition, by D. Patterson and J. Hennessey, MK publishing, 2012.
  - "Intro to Computer Architecture" handouts, by Prof. Hoe, CMU, Spring 2009.
  - "Computer Architecture & Engineering" handouts, by Prof. Kubiatowicz, UC Berkeley, Spring 2004.
  - "Intro to Computer Architecture" handouts, by Prof. Hoe, UWisc, Spring 2019.
  - "Computer Arch I" handouts, by Prof. Garzarán, UIUC, Spring 2009.

Performance Metrics

- Latency
  - Time between start and finish of a single task
- Throughput
  - Number of tasks finished in a given unit of time
- Question:
  - Throughput = 1 / Latency (?)
  - Latency = 1 / Throughput (?)

Throughput vs. Latency

- Example: Boeing 747 vs. BAC Concorde
  - $\text{Speed}_{\text{Concorde}} > \text{Speed}_{\text{Boeing}}$
    - $\text{Latency}_{\text{Concorde}} < \text{Latency}_{\text{Boeing}}$
  - Throughput???
    - How to define throughput?

Airplane	Passenger Capacity	Speed (mph)
Boeing 747	470	610
Concorde	132	1350

Throughput vs. Latency (cont.)

- Throughput = Passenger Capacity * Speed

Airplane	Passenger Capacity	Speed (mph)	Passenger Throughput
Boeing 747	470	610	286,700
Concorde	132	1350	178,200

Throughput vs. Latency: Single-Core Example

- Consider Two Single-Core Computers
  - Less latency (response time)
    - The one that finishes tasks faster
  - More throughput
    - The one that finishes more jobs
      - Or the one that finishes tasks faster
  - In this example
    - Latency ⇩ ➔ Throughput ⇧
    - Latency ⇧ ➔ Throughput ⇩
  - Not always true!

Throughput vs. Latency: Multi-Core Example

- Computer A
  - Two cores, running at 3Mhz
- Computer B
  - Four cores, running at 2.5Mhz
- $Latency_A < Latency_B$
- $Throughput_A < Throughput_B$

Computer	Frequency	# of cores
Type A	3 Mhz	2
Type B	2.5 Mhz	4

Performance Definition

- Response Time
  - Total time to complete a task (program)
  - Also called, wall-clock time, elapsed time

- Performance = 1 / response time
  - Response time ⇩ ➔ Performance ⇧
  - Performance(x) / Performance(y) =

    Execution time (y) / Execution time (x)

Performance Definition (cont.)

- Response Time Consists of:
  - CPU time
    - CPU time spent on a program
  - I/O time
    - Time elapsed to wait for I/O transactions
- CPU Time
  - User CPU time
    - CPU time directly spent on a program
  - System CPU time
    - CPU time spent in OS doing tasks on behalf of a program

Performance Definition (cont.)

- System Performance
  - 1 / Elapsed time
- CPU Performance
  - 1 / User CPU time
- Clock Cycles
  - Clock periods, cycles, clock ticks, ticks, clocks

Response Time vs. Throughput

- Which One is More Important?
  - Response time or throughput
- User Perspective
  - Response time more visible
    - Unless a user runs bunch of tasks together
- System Admin Perspective
  - Throughput more visible

CPU Time

= CPU Clock Cycles * Clock Cycle Time

= CPU Clock Cycles / Clock Rate

- Example
  - CPU_A(clock rate) = 4 Ghz
  - CPU_B(clock rate) = 3 Ghz
  - Which one runs program X faster?
    - Depends on number of clock cycles spend on program X

CPU Time (cont.)

= CPU Clock Cycles * Clock Cycle Time

= CPU Clock Cycles / Clock Rate

- CPU Clock Cycles
  = # of Instructions of a program * CPI
- CPI?
  - Average Clock Cycles per Instruction

CPU Time (cont.)

= Instr. Count * CPI * Clock Cycle Time

= (Instr. Count * CPI) / Clock Rate

$$\text{Processor Performance} = \frac{\text{Time}}{\text{Program}}$$

$$= \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Cycles}}{\text{Instruction}} \times \frac{\text{Time}}{\text{Cycle}}$$

(code size) (CPI) (cycle time)

CPU Time (cont.)

- Example
  - Instruction count (IC) = 10,000
  - CPI = 4
  - Clock cycle time = 500ps or 0.5 ns

  ➔ CPU time = 10,000 * 4 * 0.5 = 20 us
- Question:
  - IC same as code size or lines of code?

CPU Time (cont.)

- How these Parameters Determined?
  - Instruction count
  - CPI
  - Clock cycle time

CPU Time (cont.)

- Instruction Count (IC)
  - Determined by program
  - ISA
  - Compiler
- CPI
  - Determined by uArch
    - The way processor is implemented
  - Code CPI also depends on program
- Clock Cycle Time
  - Determined by uArch and Technology

Easy Practice

- Assume:
  - A C program compiled on two computers
    - Computer A with a RISC ISA
    - Computer B with a CISC ISA
  - Q1: which one would have higher IC?
  - Q2: which one would have smaller CPI?
  - Q3: which one would have higher performance?
  - Q4: can we have CPI less than one?

CPI Classes

- Question:
  - Do all instructions have same CPI?
    - No

	CPI for instruction classes		
	A	B	C
CPI	1	2	3

Code Sequence	Instruction count		
	A	B	C
1	2	1	2
2	4	1	1

CPI Classes (cont.)

- CPU Clock Cycles

  $= CPI_1 * IC_1 + CPI_2 * IC_2 + \ldots + CPI_n * IC_n$

	CPI for instruction classes		
	A	B	C
CPI	1	2	3

Code Sequence	Instruction count		
	A	B	C
1	2	1	2
2	4	1	1

Performance Evaluation of Computers

- So Far
  - Learnt how to measure CPU Performance
- Consider Two CPUs
  - CPU1 runs faster than CPU2 on program A
  - CPU2 runs faster than CPU1 on program B
- Questions:
  - How we can decide which CPU is faster?
  - Which candidate programs should we choose to compare CPU1 and CPU2?

Performance Evaluation of Computers (cont.)

- Assume
  - A user typically runs programs *A*, B, and *C* in his computer (CPU1)
  - "Workload"
    - Set of programs *A*, B, and *C*
  - If CPU2 runs this workload faster
    - ➔ Performance(CPU2) > Performance(CPU1)
  - In reality, we use a set of programs called benchmarks to compare performance of processors

Performance Evaluation of Computers (cont.)

- Which CPU Runs a Workload Faster?
  - Depends on type of average we take over execution times
    - Simple arithmetic mean
    - Weighted arithmetic mean
    - Average over ratios
    - Geometric mean

CPI	Computer A	Computer B
Program 1	1	10
Program 2	1000	100
Total Time	1001	110

Performance Evaluation of Computers (cont.)

- Another Question:
  - Why not just running one simple program to compare performance of CPUs?
    - Agreeing on one simple program very hard
    - Designers can optimize processors towards fast running that simple program

Performance Evaluation of Computers (cont.)

- Which Programs to Choose?
  - Real programs such as MS-Word, Internet explorer, latex compilers
  - Synthetic benchmarks
    - Emulate frequency of different instructions in real programs
  - Standard benchmarks
    - Examine processor and memory hierarchy

Performance Evaluation of Computers (cont.)

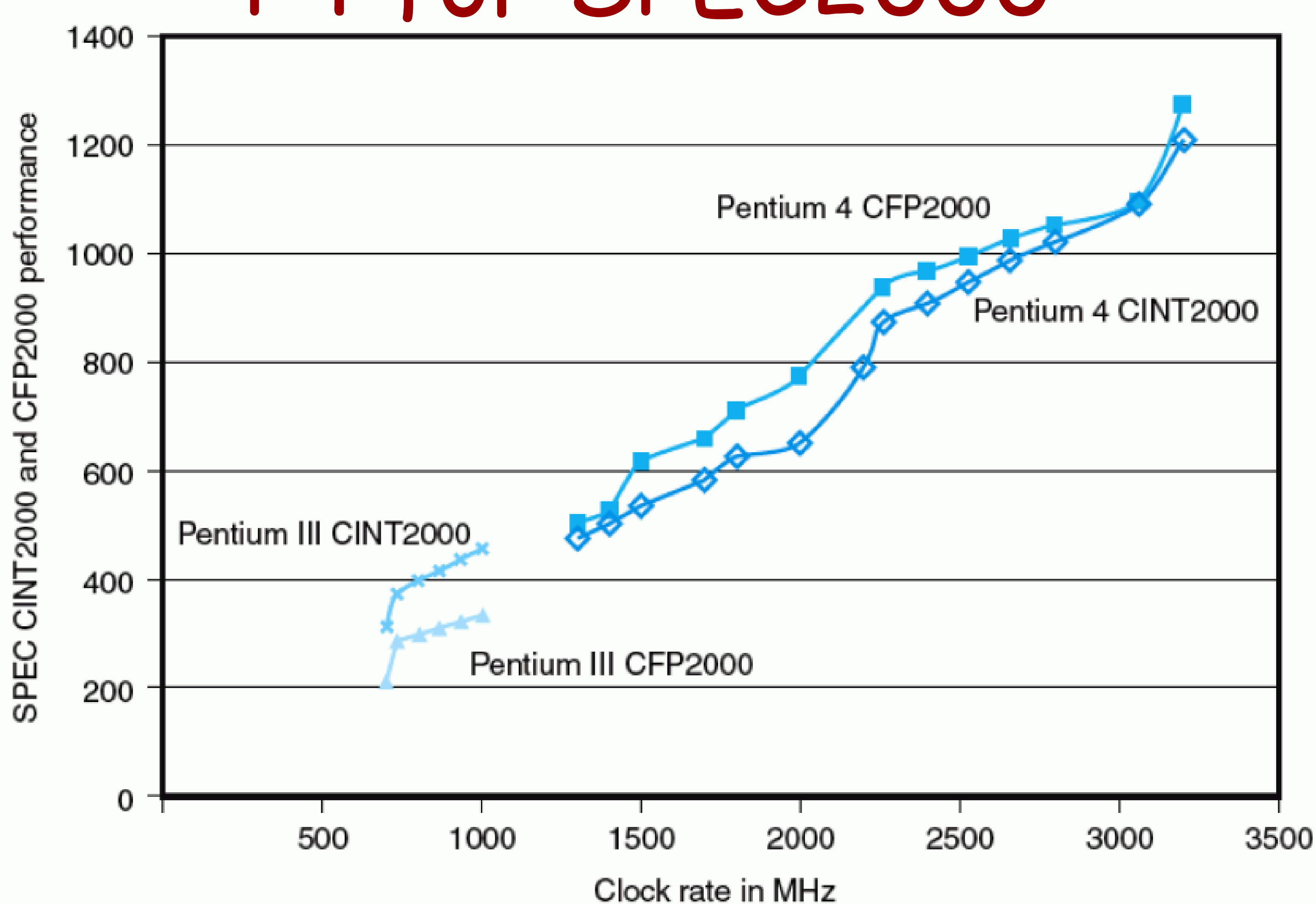
- Which Programs to Choose?
  - Programs from different applications
  - SPEC CPU2000 benchmarks

Integer Benchmarks (12)		FP Benchmarks (14)	
Name	Description	Name	Description
gzip	Compression	ammp	Computation chemistry
vpr	FPGA circuit P&R	swim	Shallow water model
gcc	C compiler	art	Image recognition using neural network
parser	Word processing program	galgel	Computational fluid dynamics

Easy Practice

- Question:
  - Can microprocessor designers optimize their architecture to optimize performance of SPEC2000 or other benchmark program?

Performance of PIII and P4 for SPEC2000



Experiment Setup

- How to Report Experiment Setup?
  - CPU frequency is NOT enough!
  - Need to Report both HW & SW config.
- Software
  - Operating system: WinXP prof. SP1
  - Compiler: Microsoft Visual Studio.NET
    - 7.0.xxx
  - File system type: NTFS
  - System state: default
  - Benchmark, Program, Input to program

Experiment Setup (cont.)

- Hardware
  - Hardware vender: Dell
  - Model number: Precision WorkStation 360
  - CPU: Intel Pentium 4 (800 MHz system bus)
  - CPU MHz: 3200
  - FPU: Integrated
  - Primary cache: 12KB (I), 8KB (D), both on-chip
  - Secondary cache: 512KB (I+D), on-chip
  - L3 cache: 2048KB (I+D), on-chip
  - Memory: 4x512MB ECC DDR400 SDRAM CL3
  - Disk subsystem: 1x80GB ATA/100 7200 RPM

CPU/Memory/IO Intensive Benchmarks

- SPEC Benchmarks
  - CPU/Memory intensive benchmarks
  - Some stress CPU
  - Some stress memory subsystem
- SPEC-Web
  - I/O intensive benchmarks
  - Mostly stress I/O subsystem
    - Disk subsystem, network connections, …

SPECWeb99 Performance for Variety of Systems

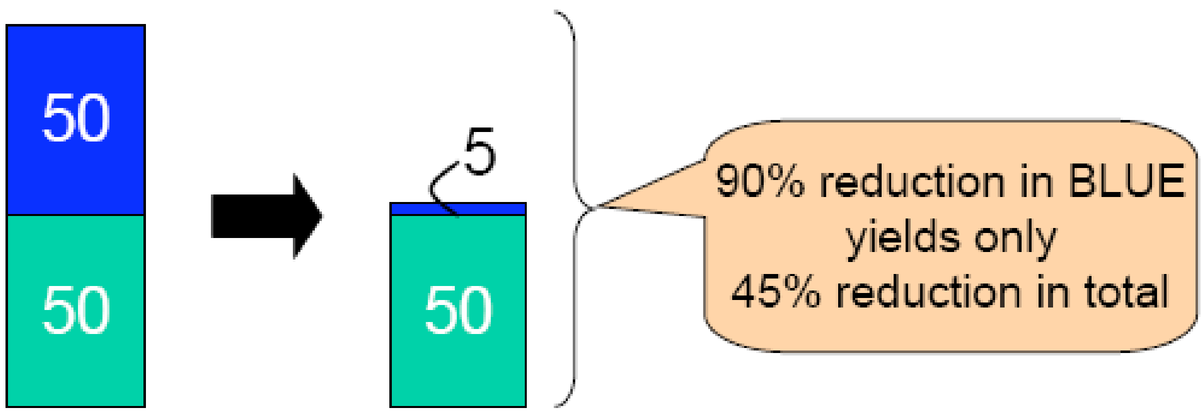
System	Processor	Number of disk drives	Number of CPUs	Number of networks	Clock rate (GHz)	Result
1550/1000	Pentium III	2	2	2	1	2765
1650	Pentium III	3	2	1	1.4	1810
2500	Pentium III	8	2	4	1.13	3435
2550	Pentium III	1	2	1	1.26	1454
2650	Pentium 4 Xeon	5	2	4	3.06	5698
4600	Pentium 4 Xeon	10	2	4	2.2	4615
6400/700	Pentium III Xeon	5	4	4	0.7	4200
6600	Pentium 4 Xeon MP	8	4	8	2	6700
8450/700	Pentium III Xeon	7	8	8	0.7	8001

Speedup

- Speedup = $time_{original}$ / $time_{improved}$
- Example
  - $time_{original}$ = 100 s
  - $time_{improved}$ = 98 s
  - Speedup = 100/98 = 1.02

Amdahl's Law

- Amdahl's Law Says
  - Speedup limited to fraction improved
    - Obvious, but fundamental observation



Amdahl's Law (cont.)

- Obvious but Common Mistakes
  - CPU upgraded from 1.5Ghz to 3Ghz
    - But not seeing 100% improvement in performance
  - Combinational upgrade 1
    - CPU from 1.5Ghz to 3Ghz
    - Memory from 1GB-90nm to 2GB-45nm
  - Combinational upgrade 2
    - CPU from 1.5Ghz to 3Ghz
    - Memory from 1GB-90nm to 2GB-45nm
    - L1 from 16KB to 32KB & L2 from 1MB to 2MB

Speedup (cont.)

ExecTime_{new}

$= \text{ExecTime}_{old} \times$

$\{(1-\text{Frac}_{enhanced})+(\text{Frac}_{enhanced}/\text{Speedup}_{enhanced})\}$

$\text{Speedup}_{overall}$ $= \text{ExecTime}_{old} / \text{ExecTime}_{new} =$

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

MIPS: Performance Metric

- MIPS
  - Million Instructions Per Second = Instruction Count / (Execution time x 10^6)
- Drawbacks?

MIPS: Performance Metric (cont.)

- Drawbacks
  - Not taking into account capabilities of instructions
    - Comparing two different ISAs not fair
  - Not realistic metric even on same CPU
    - Two programs: program A and program B
    - MIPS(A) > MIPS(B) ➔ Perf.(A) > Perf.(B) ???
  - Some optimization tech. add more code

MIPS: Performance Metric (cont.)

- Example:
  - Machine A
    - Special instruction for performing square root
    - It takes 100 cycles to execute
  - Machine B
    - Doesn't have special instruction
    - must perform square root in software using simple instructions
    - e.g, Add, Mult, Shift each take 1 cycle to execute
  - Clock cycle = 1us
  - Machine A: 1/100 MIPS = 0.01 MIPS
  - Machine B: 1 MIPS

MFLOPS: Performance Metric

- MFLOPS
  $= (\text{FP ops/program}) \times (\text{program/time}) \times 10^{-6}$

- Popular in scientific computing
  - FP ops were previously much slower than regular instructions (i.e., off-chip, sequential execution)
- Not great for "predicting" performance
  - Ignores other instructions (e.g., load/store)
  - Not all FP ops have common format
  - Depends on how FP-intensive program is

Backup