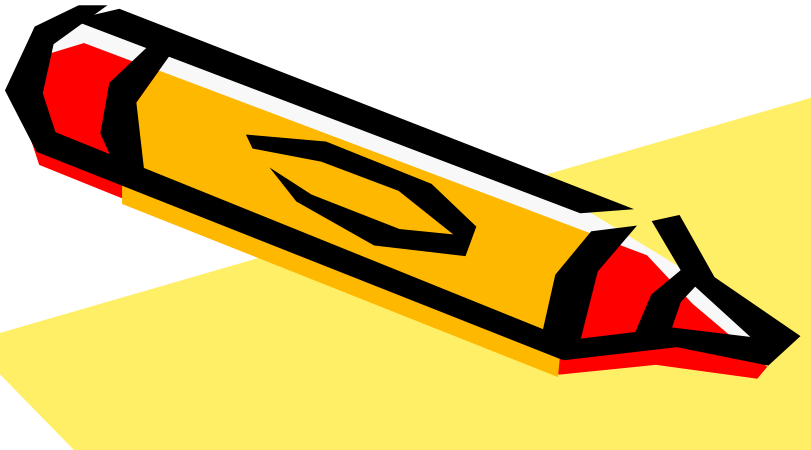

Computer Architecture

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Today's Topics

- Performance Evaluation
- Standard Benchmarks

Copyright Notice

- 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 (?)

• A is X% faster than B if
• Latency(A) = Latency(B) / (1+X/100)
•Throughput(A) = Throughput(B) * (1+X/100)

A is X times faster than B if :
Latency(A) = Latency(B) /X
Throughput (A) = Throughput (B)/X

Throughput vs. Latency

- Example: Boeing 747 vs. BAC Concorde
  - $Speed_{Concorde} > Speed_{Boeing}$
    - $Latency_{Concorde} < Latency_{Boeing}$
  - 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

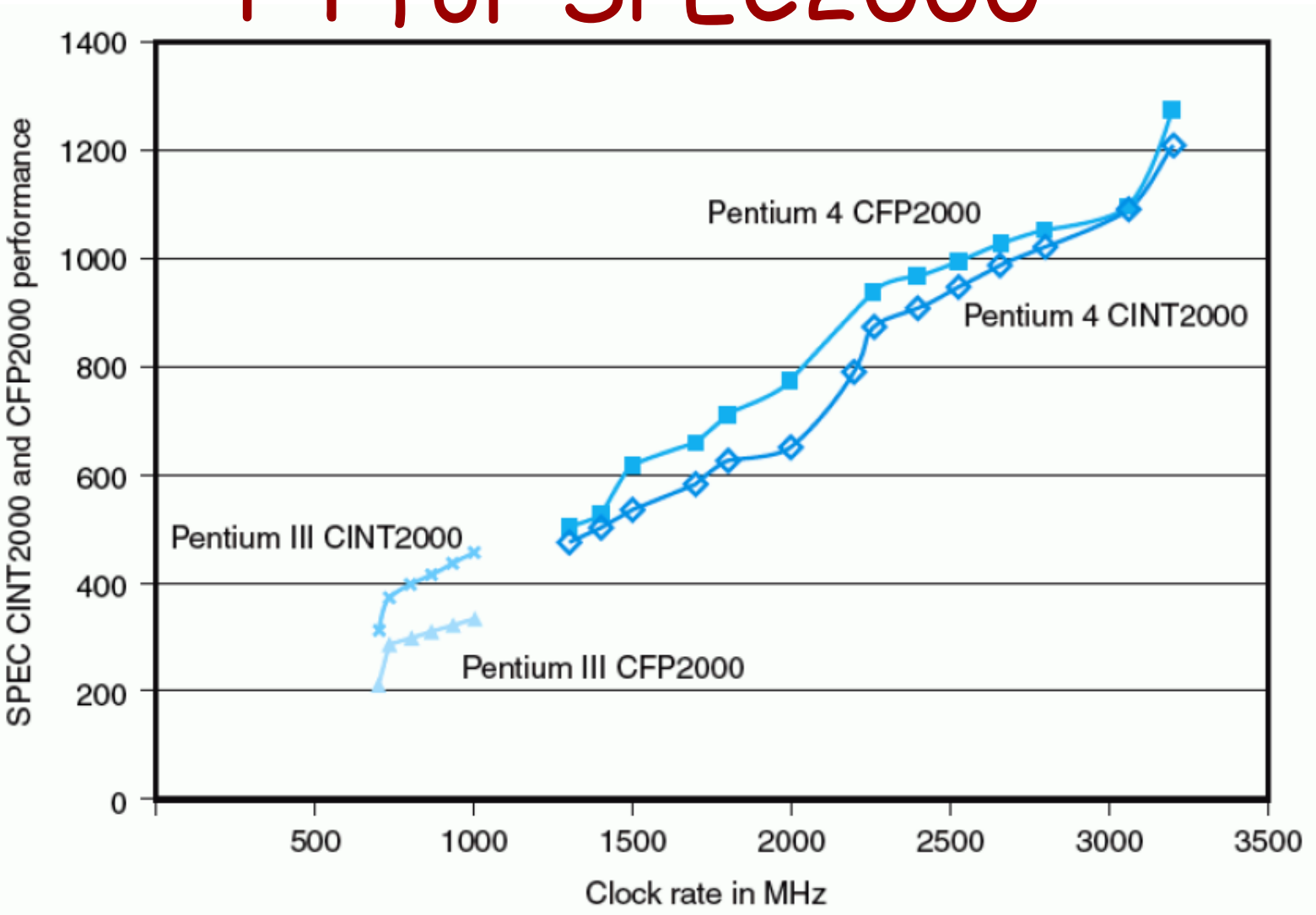
Integer Benchmarks (12)		FP Benchmarks (14)	
Name	Description	Name	Description
gzip	Compression	ammp	Computation chemistry
vpr	FPGA circuit P&R	swim	Shallow water model
gcc	C compiler	art	Image recognition using neural network
parser	Word processing program	galgel	Computational fluid dynamics

Easy Practice

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

اگر بتوانند این کار را انجام دهند بسیار عالی می باشد چون اگرطراحان بتوانند برای تمام برنامه های موجود در benchmark پردازنده خود را بهبود دهند آنگاه این پردازنده ها برای بسیاری از برنامه ها عمکرد بسیار خوبی دارد

Performance of PIII and P4 for SPEC2000



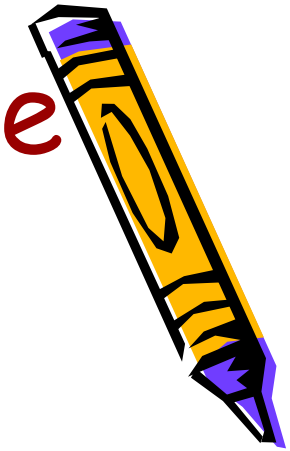
Experiment Setup

- 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

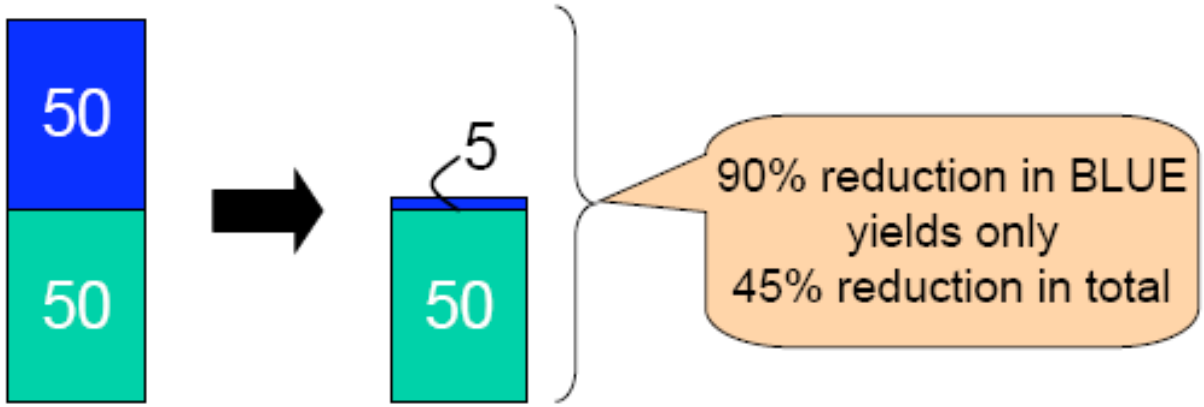
System	Processor	Number of disk drives	Number of CPUs	Number of networks	Clock rate (GHz)	Result
1550/1000	Pentium III	2	2	2	1	2765
1650	Pentium III	3	2	1	1.4	1810
2500	Pentium III	8	2	4	1.13	3435
2550	Pentium III	1	2	1	1.26	1454
2650	Pentium 4 Xeon	5	2	4	3.06	5698
4600	Pentium 4 Xeon	10	2	4	2.2	4615
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.)

$$\mathbf{ExecTime_{new}} = ExecTime_{old} \times \{(1-Frac_{enhanced})+(Frac_{enhanced}/Speedup_{enhanced})\}$$

$$\mathbf{Speedup_{overall}} = ExecTime_{old} / ExecTime_{new} = \frac{1}{(1-Frac_{enhanced})+(Frac_{enhanced}/Speedup_{enhanced})}$$

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
  = (FP ops/program) x (program/time) x 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