Advanced Computer Architecture

COMP 5123

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Computer Science Department

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Chapter 2. Performance Issues

- Designing for Performance
- Multicore, MICs, and GPGPUs
- Basic Measures of Computer Performance
- Calculating Mean
- Benchmarks and SPEC

Designing for Performance

- The cost of computer systems continues to drop dramatically
- Today's laptops have the computing power of an IBM mainframe from 10 -15 years ago
- Processors are so inexpensive that we now have microprocessors we throw away
- Desktop applications
  - Image processing
  - Three-dimensional rendering
  - Speech recognition
  - Videoconferencing
  - Multimedia authoring
  - Voice and video annotation of files
  - Simulation modeling

- Businesses are relying powerful servers to handle transaction and database processing and massive client/server networks
- Cloud service providers use massive high-performance banks of servers

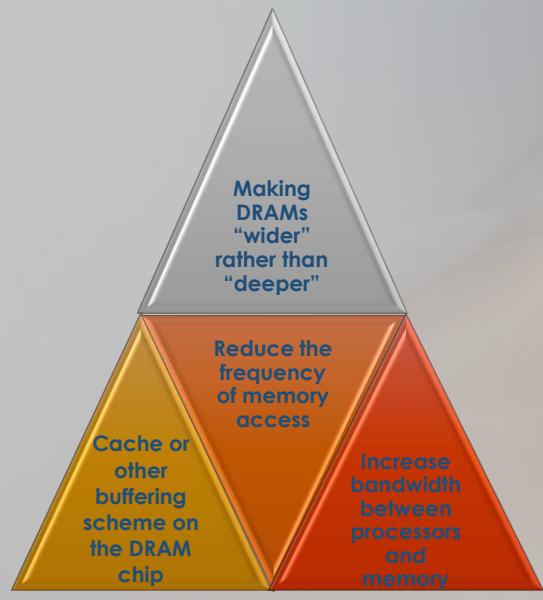
Microprocessor Speed

Techniques built into contemporary processors include:

Pipelining	•Processor moves data or instructions into a conceptual pipe with all stages of the pipe processing simultaneously
Branch prediction	•Processor looks ahead in the instruction code fetched from memory and predicts which branches, or groups of instructions, are likely to be processed next
Superscalar execution	•This is the ability to issue more than one instruction in every processor clock cycle. (In effect, multiple parallel pipelines are used.)
Data flow analysis	•Processor analyzes which instructions are dependent on each other's results, or data, to create an optimized schedule of instructions
Speculative execution	•Using branch prediction and data flow analysis, speculatively execute instructions ahead, holding the results in temporary locations, keeping execution engines as busy as possible

Performance Balance

- Adjust the organization and architecture to compensate for the mismatch among the capabilities of the various components
- Architectural examples include:



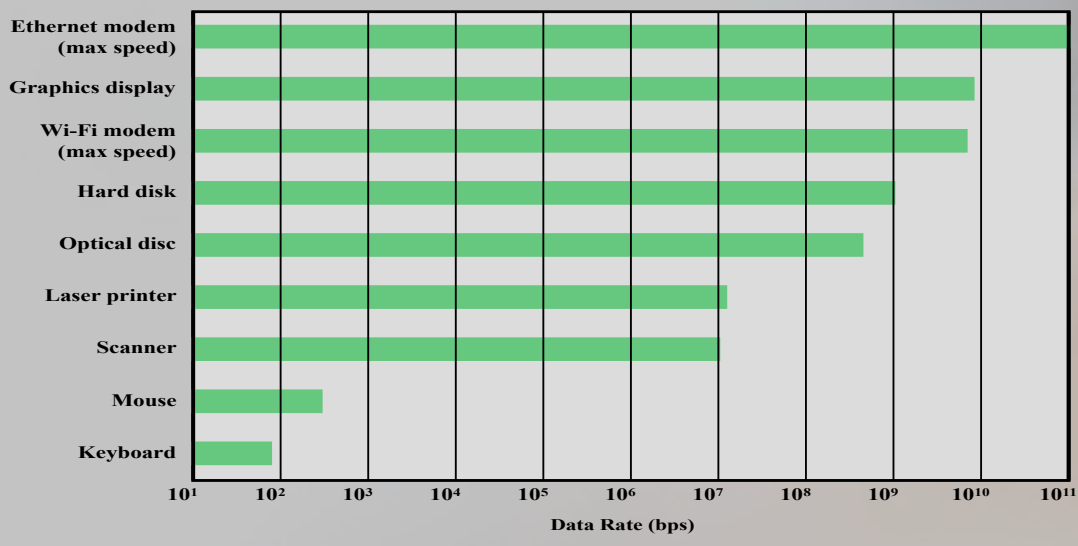
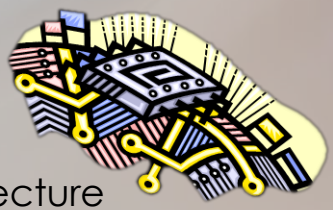


Figure 2.1 Typical I/O Device Data Rates

Improvements in Chip Organization and Architecture

- Increase hardware speed of processor
  - Fundamentally due to shrinking logic gate size
    - More gates, packed more tightly, increasing clock rate
    - Propagation time for signals reduced
- Increase size and speed of caches
  - Dedicating part of processor chip
    - Cache access times drop significantly
- Change processor organization and architecture
  - Increase effective speed of instruction execution
  - Parallelism



Problems with Clock Speed and Logic Density

- Power
  - Power density increases with density of logic and clock speed
  - Dissipating heat
- RC delay
  - Speed at which electrons flow limited by resistance and capacitance of metal wires connecting them
  - Delay increases as the RC product increases
  - As components on the chip decrease in size, the wire interconnects become thinner, increasing resistance
  - Also, the wires are closer together, increasing capacitance
- Memory latency
  - Memory speeds lag processor speeds

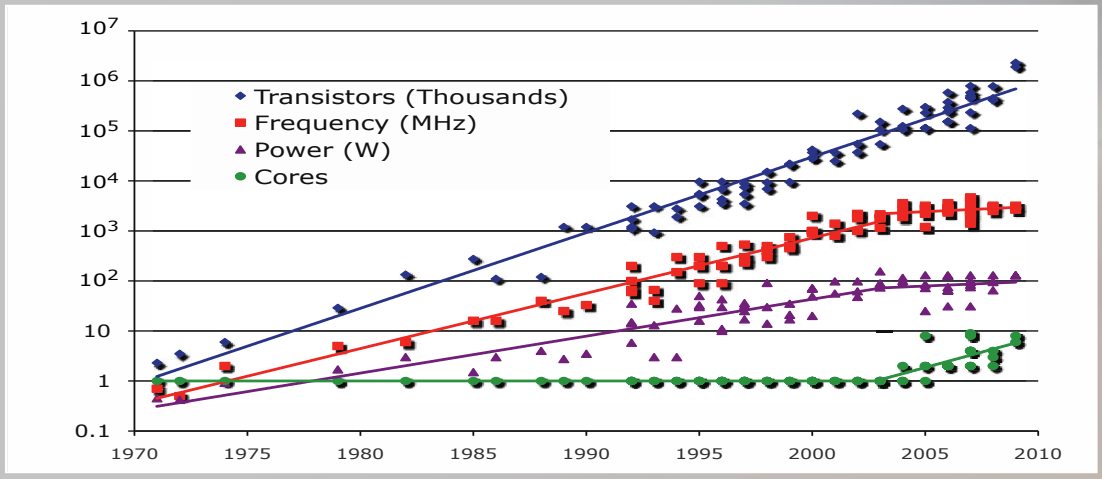
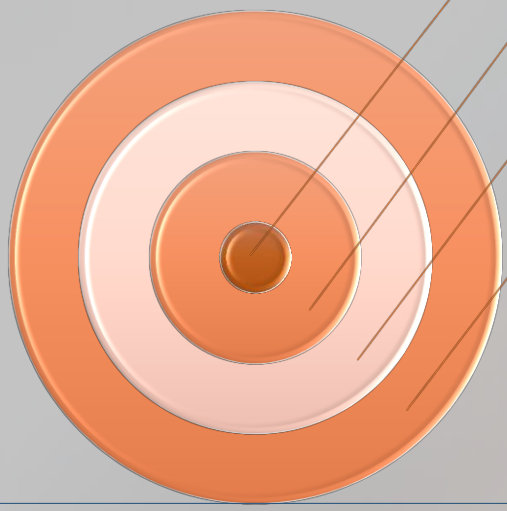


Figure 2.2 Processor Trends

Multicore



The use of multiple processors on the same chip provides the potential to increase performance without increasing the clock rate

Strategy is to use two simpler processors on the chip rather than one more complex processor

With two processors larger caches are justified

As caches became larger it made performance sense to create two and then three levels of cache on a chip

Many Integrated Core (MIC) Graphics Processing Unit (GPU)

MIC

- Leap in performance as well as the challenges in developing software to exploit such a large number of cores
- homogeneous collection of general purpose processors on a single chip

GPU

- Core designed to perform parallel operations on graphics data
- Found on a plug-in graphics card, used to encode and render 2D and 3D
- Used as vector processors for repetitive computations

Amdahl's Law

- Proposed by Gene Amdahl [AMDA67]
  - Potential speed up of program using multiple processors
- How much can we speed up a program on a multiple processor machine?
  - T = execution time on a **single processor** machine
  - T' = execution time on **N processors**
  - f = ratio of code that can be executed in **parallel**
  - (1-f) = ratio of code that needs **serial** execution

$$Speedup = \frac{\text{time to execute program on a single processor}}{\text{time to execute program on } N \text{ parallel processors}} = \frac{T(1-f)+Tf}{T(1-f)+\frac{Tf}{N}} = \frac{1}{(1-f)+\frac{f}{N}}$$

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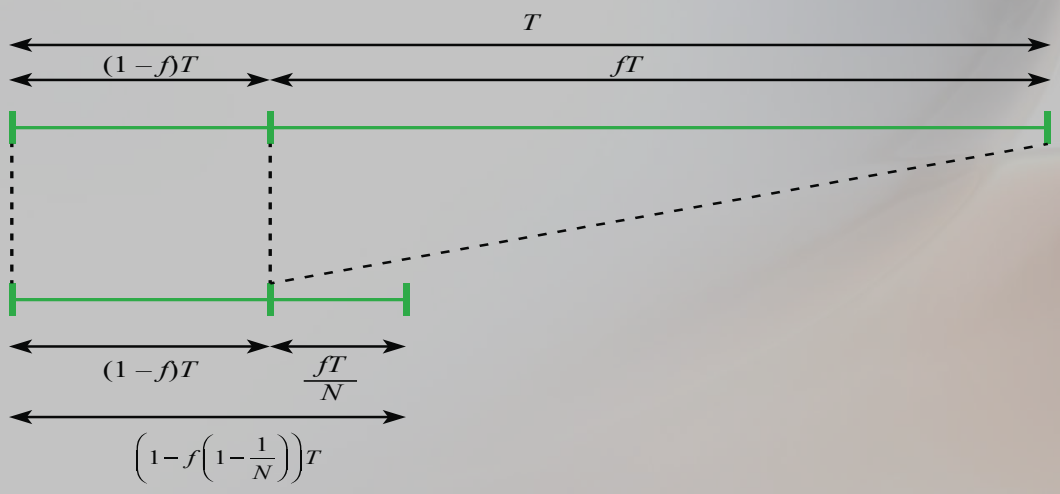

Figure 2.3 Illustration of Amdahl's Law

Amdahl's Law (cont)

$$Speedup = \frac{\text{time to execute program on a single processor}}{\text{time to execute program on } N \text{ parallel processors}} = \frac{T(1-f)+Tf}{T(1-f)+\frac{Tf}{N}} = \frac{1}{(1-f)+\frac{f}{N}}$$

- Observations
  - When f is small, parallel processors has little effect
  - N ->∞, speedup bound by 1/(1 – f)
  - Diminishing returns for using more processors
- Illustrates the problems in the development of multi-core machines
  - Software must be adapted to a highly parallel execution environment to exploit the power of parallel processing
- Can be generalized to evaluate and design technical improvement in a computer system

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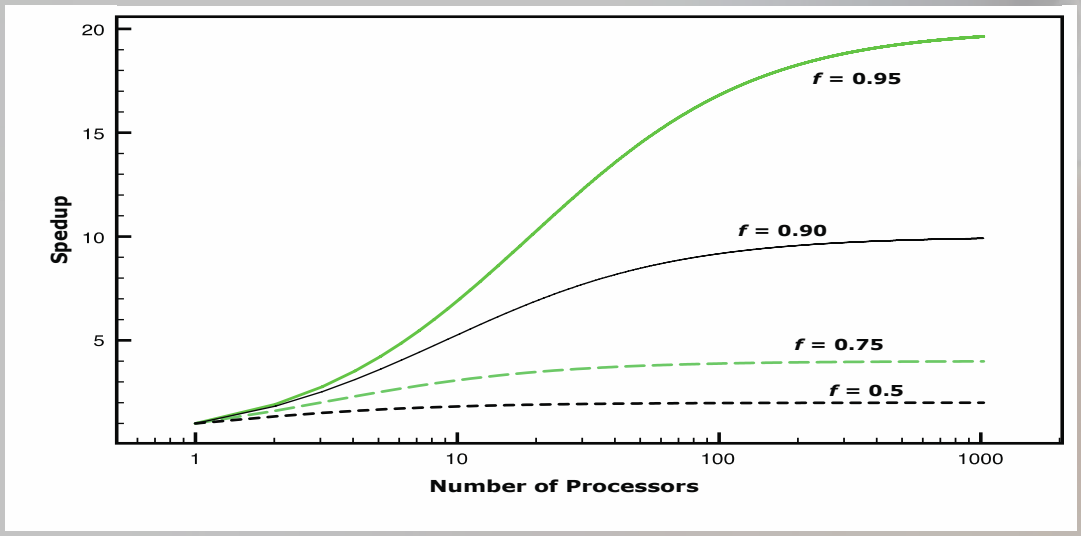

Figure 2.4 Amdahl's Law for Multiprocessors

Example 1

- Consider
  - Your program runs for **100 minutes** on one processor
  - If you have **100 processors**, how long would it take? (Assume there is no I/O, or memory operation)
  - 1 minute?
- Amdahl's law gives an answer
  - Expected speedup of parallelized implementations of an algorithm relative to the serial algorithm

    Execution time after improvement =
    exec time unaffected + exec time affected / # improvement

  - If 10% of your program must run serially, it will be
    (10 minutes + 90 minutes/100)

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Example 2

- Amdahl's law can be generalized to evaluate a technical improvement of a system
- Consider
  - A program runs **100 seconds**
  - **80 second** is spent on multiplication
  - How much do I need to improve **multiplication** to achieve **5 times speed up**? (i.e., make the execution time 20 seconds)
- Amdahl's law says
  - After 5 times speedup, the execution time must be 20 seconds. Solve n for

    20 second + 80sec / n = 20 second
  - Impossible to achieve such a goal!

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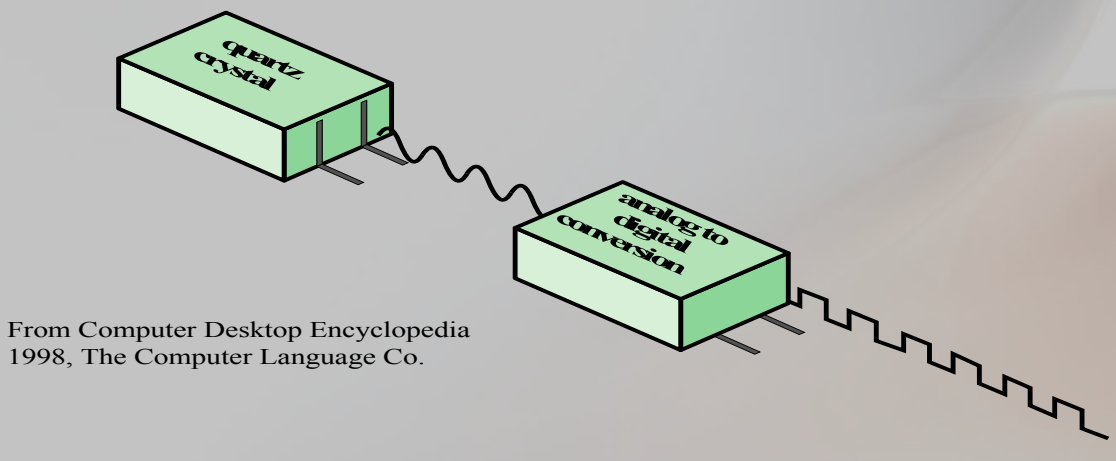
Little's Law

- Fundamental and simple relation with broad applications
- Can be applied to almost any system that is statistically in steady state, and in which there is no leakage
- Queuing system
  - If server is idle an item is served immediately, otherwise an arriving item joins a queue
  - There can be a single queue for a single server or for multiple servers, or multiple queues with one being for each of multiple servers

Little's Law

- Average number of items in a queuing system (L) equals the average rate at which items arrive (λ)multiplied by the time that an item spends in the system (w)
  - $L = \lambda W$
  - Relationship requires very few assumptions
  - Because of its simplicity and generality it is extremely useful



From Computer Desktop Encyclopedia
1998, The Computer Language Co.

Figure 2.5 System Clock

Performance factors

- Definitions
  - Clock frequency = f
  - Cycle time = τ
  - Thus, $\tau = 1/f$
- Cycles per instruction (CPI)
  - Since number of cycles vary per instructions, we take the average

$$CPI = \frac{\sum_{i=1}^{n} (CPI_i \times I_i)}{I_c}$$

  - CPI_i = number of cycles for instruction type *i*
  - I_c = Instruction Count

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Performance factors (cont)

- Processor time *T* need to execute a program
  - **$T = I_c \times CPI \times \tau$**
  - Instruction Count x CPI x Clock Cycle Time
- A closer look at CPI
  - Execution time = processor time + memory transfer time
    - Let p = **number of processor cycle** for decode and execution
    - m = number of memory cycle needed
    - k = ratio between memory cycle time and processor cycle time
  - **CPI = [p + (m x k)]**

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Performance factors

$T = I_c \times [\, p + (m \times k)\,] \times \tau$

Heavily dependent on instruction set, compiler design, processor implementation, cache & memory hierarchy

Table 2.9 Performance Factors and System Attributes

	I_c	p	m	k	τ
Instruction set architecture	X	X			
Compiler technology	X	X	X		
Processor implementation		X			X
Cache and memory hierarchy				X	X

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MIPS example

- 2 million instructions on 400 MHz processor
- Average CPI =

  1 x 0.6 +
  2 x 0.18 +
  4 x 0.12 +
  8 x 0.1 +
  = 2.24

Instruction type	CPI	Instruction mix
Arithmetic and Logic	1	60%
Load/store with cache hit	2	18%
Branch	4	12%
Memory reference with cache miss	8	10%

- MIPS rate = $\dfrac{I_c}{T \times 10^6} = \dfrac{f}{CPI \times 10^6}$

400,000,000 / (2.24 x 1,000,000) = approx. 178

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Limitations of MIPS

- Consider
  A = B + C
- On CISC

```
add     mem(B), mem(C), mem(A)
```

- On RISC

```
Load    mem(B),  reg (1);
Load    mem (C), reg (2);
Add     reg (1), reg (2), reg (3);
Store   reg (3), mem (A);
```

- MIPS cannot compare different architectures
  - RISC vs. CISC (MIPS rate is higher with RISC, but they do the same)
  - Different applications

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Standardized Benchmarks

- Standard Performance Evaluation Corporation (SPEC)
  - Offers dozen different benchmark sets – CPU, graphics, HPC, network, disk…
  - Benchmarks distributed in source code
  - Members of consortium select workload (typically used program)
    - 30+ companies, 40+ universities, research labs
  - Compiler, machine designers target benchmarks, so try to change every 5 years
  - Some are free, some are not
  - www.spec.org/osg/cpu2006/

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Benchmark Principles

- Desirable characteristics of a benchmark program:

1. It is written in a high-level language, making it portable across different machines
2. It is representative of a particular kind of programming domain or paradigm, such as systems programming, numerical programming, or commercial programming
3. It can be measured easily
4. It has wide distribution

SPEC CPU 2006

- They measure
  - System speed (SPECint2006, SPECfp2006)
  - System throughput (SPECint_rate2006, SPECfp_rate2006)
- Two modes
  - Base (SPECint_base2006, SPECint_rate_base2006): compiled with default flags
  - Aggressive (SPECint2006, SPECint_rate2006): optimized flags for target system
- Results are normalized
  - Base machine exec time / Measured exec time
  - Reference machine: Sun Ultra Enterprise 2 w/296 MHz UltraSPARC II
    - Taking 12 days to run benchmark

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SPEC Speed metric

- Base runtime is defined for each benchmark using reference machine
- Results are reported as ratio of reference time to system run time
  - $Tref_i$: execution time for benchmark *i* on reference machine
  - $Tsut_i$: execution time of benchmark *i* on test system (sut: system under test)

$$r_i = \frac{Tref_i}{Tsut_i}$$

- Overall performance calculated by averaging ratios for all 12 integer benchmarks
  - Use **geometric mean**
  - Appropriate for normalized numbers such as ratios

$$r_G = \left(\prod_{i=1}^{n} r_i \right)^{1/n}$$

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	Computer A time (secs)	Computer B time (secs)	Computer C time (secs)	Computer A rate (MFLOPS)	Computer B rate (MFLOPS)	Computer C rate (MFLOPS)
Program 1 (10^8 FP ops)	2.0	1.0	0.75	50	100	133.33
Program 2 (10^8 FP ops)	0.75	2.0	4.0	133.33	50	25
Total execution time	2.75	3.0	4.75			
Arithmetic mean of times	1.38	1.5	2.38			
Inverse of total execution time (1/sec)	0.36	0.33	0.21			
Arithmetic mean of rates				91.67	75.00	79.17
Harmonic mean of rates				72.72	66.67	42.11

Table 2.2

A Comparison of Arithmetic and Harmonic Means for Rates

Table 2.3 A Comparison of Arithmetic and Geometric Means for Normalized Results

(a) Results normalized to Computer A

	Computer A time	Computer B time	Computer C time
Program 1	2.0 (1.0)	1.0 (0.5)	0.75 (0.38)
Program 2	0.75 (1.0)	2.0 (2.67)	4.0 (5.33)
Total execution time	2.75	3.0	4.75
Arithmetic mean of normalized times	1.00	1.58	2.85
Geometric mean of normalized times	1.00	1.15	1.41

(b) Results normalized to Computer B

	Computer A time	Computer B time	Computer C time
Program 1	2.0 (2.0)	1.0 (1.0)	0.75 (0.75)
Program 2	0.75 (0.38)	2.0 (1.0)	4.0 (2.0)
Total execution time	2.75	3.0	4.75
Arithmetic mean of normalized times	1.19	1.00	1.38
Geometric mean of normalized times	0.87	1.00	1.22

Table 2.4 Another Comparison of Arithmetic and Geometric Means for Normalized Results

(a) Results normalized to Computer A

	Computer A time	Computer B time	Computer C time
Program 1	2.0 (1.0)	1.0 (0.5)	0.20 (0.1)
Program 2	0.4 (1.0)	2.0 (5.0)	4.0 (10)
Total execution time	2.4	3.00	4.2
Arithmetic mean of normalized times	1.00	2.75	5.05
Geometric mean of normalized times	1.00	1.58	1.00

(b) Results normalized to Computer B

	Computer A time	Computer B time	Computer C time
Program 1	2.0 (2.0)	1.0 (1.0)	0.20 (0.2)
Program 2	0.4 (0.2)	2.0 (1.0)	4.0 (2)
Total execution time	2.4	3.00	4.2
Arithmetic mean of normalized times	1.10	1.00	1.10
Geometric mean of normalized times	0.63	1.00	0.63

Benchmark	Reference time (hours)	Instr count (billion)	Language	Application Area	Brief Description
400.perlbench	2.71	2,378	C	Programming Language	PERL programming language interpreter, applied to a set of three programs.
401.bzip2	2.68	2,472	C	Compression	General-purpose data compression with most work done in memory, rather than doing I/O.
403.gcc	2.24	1,064	C	C Compiler	Based on gcc Version 3.2, generates code for Opteron.
429.mcf	2.53	327	C	Combinatorial Optimization	Vehicle scheduling algorithm.
445.gobmk	2.91	1,603	C	Artificial Intelligence	Plays the game of Go, a simply described but deeply complex game.
456.hmmer	2.59	3,363	C	Search Gene Sequence	Protein sequence analysis using profile hidden Markov models.
458.sjeng	3.36	2,383	C	Artificial Intelligence	A highly ranked chess program that also plays several chess variants.
462.libquantum	5.76	3,555	C	Physics / Quantum Computing	Simulates a quantum computer, running Shor's polynomial-time factorization algorithm.
464.h264ref	6.15	3,731	C	Video Compression	H.264/AVC (Advanced Video Coding) Video compression.
471.omnetpp	1.74	687	C++	Discrete Event Simulation	Uses the OMNet++ discrete event simulator to model a large Ethernet campus network.
473.astar	1.95	1,200	C++	Path-finding Algorithms	Pathfinding library for 2D maps.
483.xalancbmk	1.92	1,184	C++	XML Processing	A modified version of Xalan-C++, which transforms XML documents to other document types.

Table 2.5

SPEC CPU2006 Integer Benchmarks

(Table can be found on page 69 in the textbook.)

Benchmark	Reference time (hours)	Instr count (billion)	Language	Application Area	Brief Description
410.bwaves	3.78	1,176	Fortran	Fluid Dynamics	Computes 3D transonic transient laminar viscous flow.
416.gamess	5.44	5,189	Fortran	Quantum Chemistry	Quantum chemical computations.
433.milc	2.55	937	C	Physics / Quantum Chromodynamics	Simulates behavior of quarks and gluons
434.zeusmp	2.53	1,566	Fortran	Physics / CFD	Computational fluid dynamics simulation of astrophysical phenomena.
435.gromacs	1.98	1,958	C, Fortran	Biochemistry / Molecular Dynamics	Simulate Newtonian equations of motion for hundreds to millions of particles.
436.cactusADM	3.32	1,376	C, Fortran	Physics / General Relativity	Solves the Einstein evolution equations.
437.leslie3d	2.61	1,273	Fortran	Fluid Dynamics	Model fuel injection flows.
444.namd	2.23	2,483	C++	Biology / Molecular Dynamics	Simulates large biomolecular systems.
447.dealII	3.18	2,323	C++	Finite Element Analysis	Program library targeted at adaptive finite elements and error estimation.
450.soplex	2.32	703	C++	Linear Programming, Optimization	Test cases include railroad planning and military airlift models.
453.povray	1.48	940	C++	Image Ray-tracing	3D Image rendering.
454.calculix	2.29	3,04`	C, Fortran	Structural Mechanics	Finite element code for linear and nonlinear 3D structural applications.
459.GemsFDTD	2.95	1,320	Fortran	Computational Electromagnetics	Solves the Maxwell equations in 3D.
465.tonto	2.73	2,392	Fortran	Quantum Chemistry	Quantum chemistry package, adapted for crystallographic tasks.
470.lbm	3.82	1,500	C	Fluid Dynamics	Simulates incompressible fluids in 3D.
481.wrf	3.10	1,684	C, Fortran	Weather	Weather forecasting model
482.sphinx3	5.41	2,472	C	Speech recognition	Speech recognition software.

Table 2.6

SPEC CPU2006 Floating-Point Benchmarks

(Table can be found on page 70 in the textbook.)

Terms Used in SPEC Documentation

- Benchmark
  - A program written in a high-level language that can be compiled and executed on any computer that implements the compiler
- System under test
  - This is the system to be evaluated
- Reference machine
  - This is a system used by SPEC to establish a baseline performance for all benchmarks
    - Each benchmark is run and measured on this machine to establish a reference time for that benchmark
- Base metric
  - These are required for all reported results and have strict guidelines for compilation
- Peak metric
  - This enables users to attempt to optimize system performance by optimizing the compiler output
- Speed metric
  - This is simply a measurement of the time it takes to execute a compiled benchmark
- Rate metric
  - This is a measurement of how many tasks a computer can accomplish in a certain amount of time
    - This is called a throughput, capacity, or rate measure
    - Allows the system under test to execute simultaneous tasks to take advantage of multiple processors

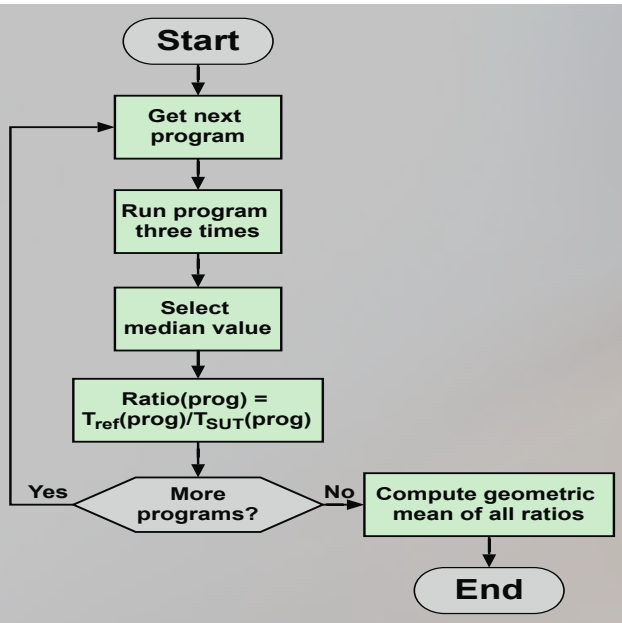

Figure 2.7 SPEC Evaluation Flowchart

Table 2.7 Some SPEC CINT2006 Results

(a) Sun Blade 1000

Benchmark	Execution time	Execution time	Execution time	Reference time	Ratio
400.perlbench	**3077**	3076	3080	9770	3.18
401.bzip2	**3260**	3263	3260	9650	2.96
403.gcc	2711	2701	**2702**	8050	2.98
429.mcf	2356	**2331**	2301	9120	3.91
445.gobmk	3319	**3310**	3308	10490	3.17
456.hmmer	2586	**2587**	2601	9330	3.61
458.sjeng	3452	**3449**	3449	12100	3.51
462.libquantum	**10318**	10319	10273	20720	2.01
464.h264ref	5246	5290	**5259**	22130	4.21
471.omnetpp	2565	**2572**	2582	6250	2.43
473.astar	2522	**2554**	2565	7020	2.75
483.xalancbmk	2014	2018	**2018**	6900	3.42

(b) Sun Blade X6250

Benchmark	Execution time	Execution time	Execution time	Reference time	Ratio	Rate
400.perlbench	497	497	**497**	9770	19.66	78.63
401.bzip2	613	614	**613**	9650	15.74	62.97
403.gcc	529	**529**	529	8050	15.22	60.87
429.mcf	**472**	472	473	9120	19.32	77.29
445.gobmk	637	637	**637**	10490	16.47	65.87
456.hmmer	446	446	**446**	9330	20.92	83.68
458.sjeng	**631**	632	630	12100	19.18	76.70
462.libquantum	**614**	614	614	20720	33.75	134.98
464.h264ref	830	**830**	830	22130	26.66	106.65
471.omnetpp	619	620	**619**	6250	10.10	40.39
473.astar	580	580	**580**	7020	12.10	48.41
483.xalancbmk	**422**	422	422	6900	16.35	65.40

Summary

Chapter 2

- Designing for performance
  - Microprocessor speed
  - Performance balance
  - Improvements in chip organization and architecture
- Multicore
- MICs
- GPGPUs
- Amdahl's Law
- Little's Law

Performance Issues

- Basic measures of computer performance
  - Clock speed
  - Instruction execution rate
- Calculating the mean
  - Arithmetic mean
  - Harmonic mean
  - Geometric mean
- Benchmark principles
- SPEC benchmarks

Megahertz Myth video

- https://www.youtube.com/watch?v=LA1ZBxVMwBU