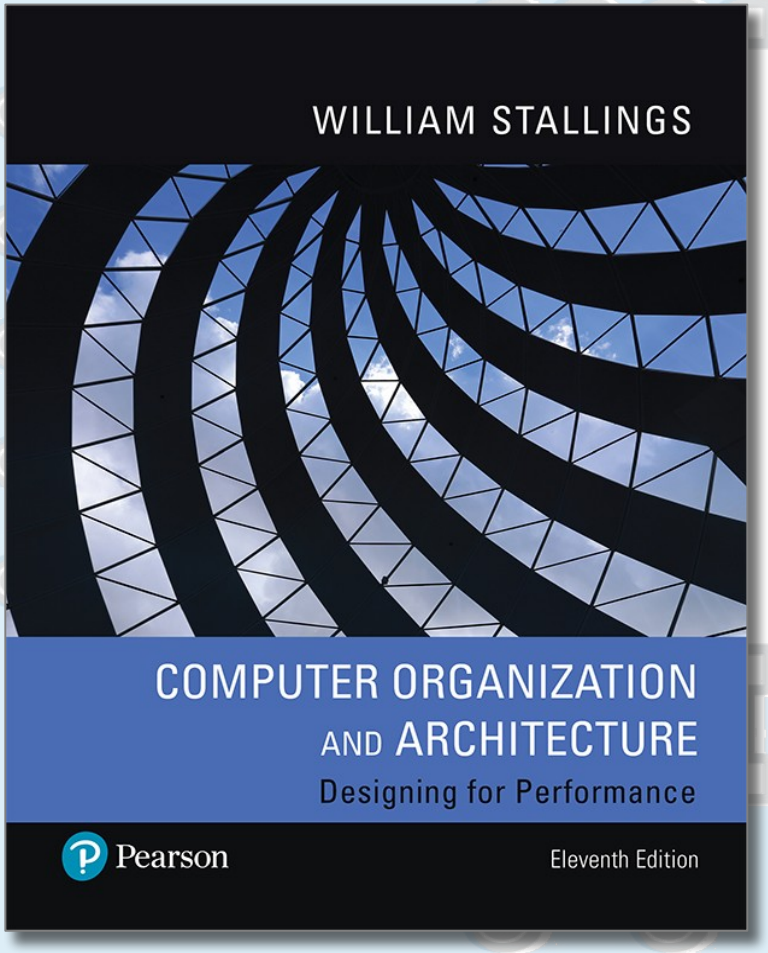
# Computer Organization and Architecture

## Designing for Performance

11th Edition




## Chapter 2

Performance Concepts

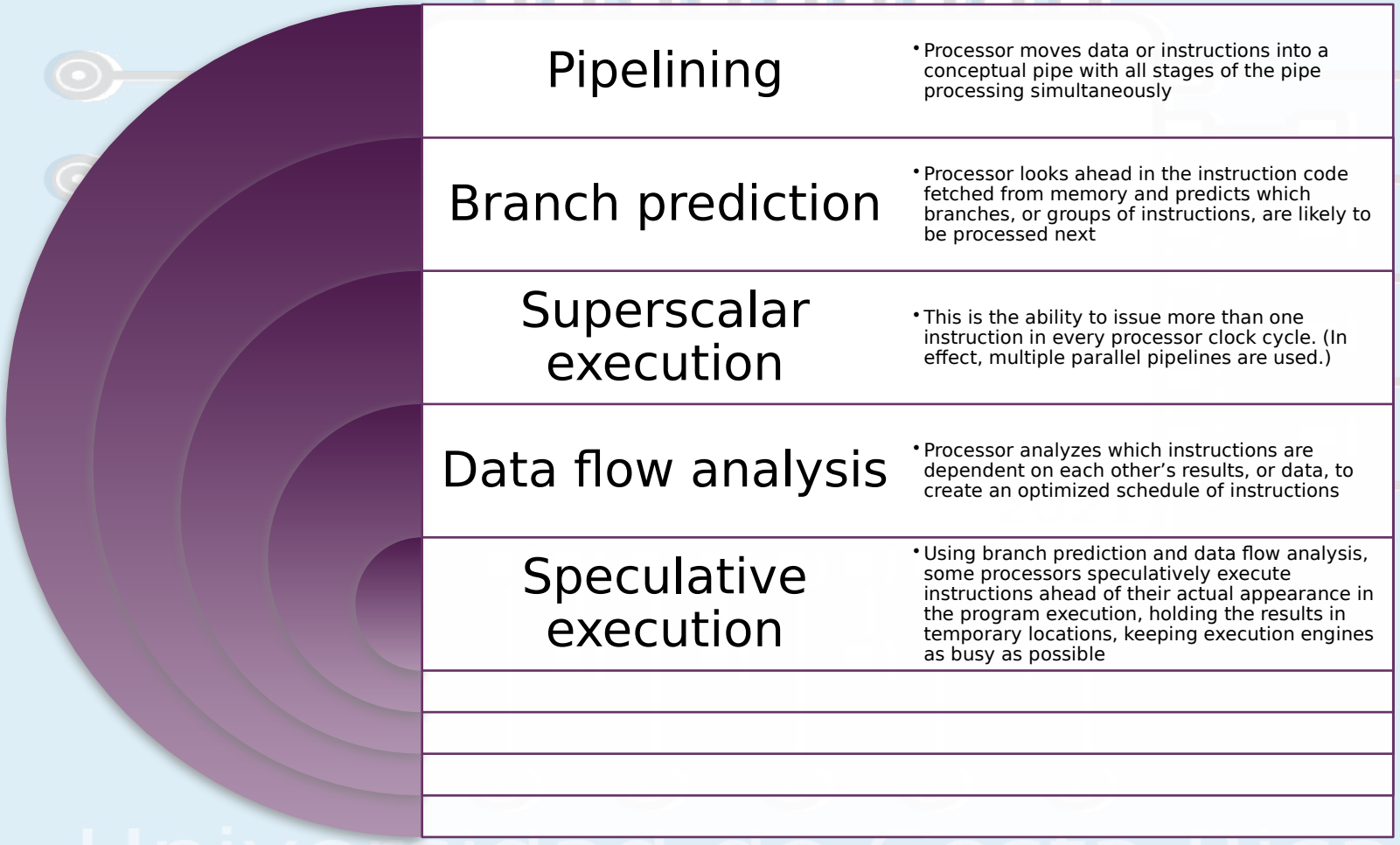
2021

# Designing for Performance

- The cost of computer systems continues to drop dramatically, while the performance and capacity of those systems continue to rise equally dramatically
- Today's laptops have the computing power of an IBM mainframe from 10 or 15 years ago
- Processors are so inexpensive that we now have microprocessors we throw away
- Desktop applications that require the great power of today's microprocessor-based systems include:
  - Image processing
  - Three-dimensional rendering
  - Speech recognition
  - Videoconferencing
  - Multimedia authoring
  - Voice and video annotation of files
  - Simulation modeling
- Businesses are relying on increasingly powerful servers to handle transaction and database processing and to support massive client/server networks that have replaced the huge mainframe computer centers of yesteryear
- Cloud service providers use massive high-performance banks of servers to satisfy high-volume, high-transaction-rate applications for a broad spectrum of clients

# 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, some processors speculatively execute instructions ahead of their actual appearance in the program execution, holding the results in temporary locations, keeping execution engines as busy as possible |
| | |
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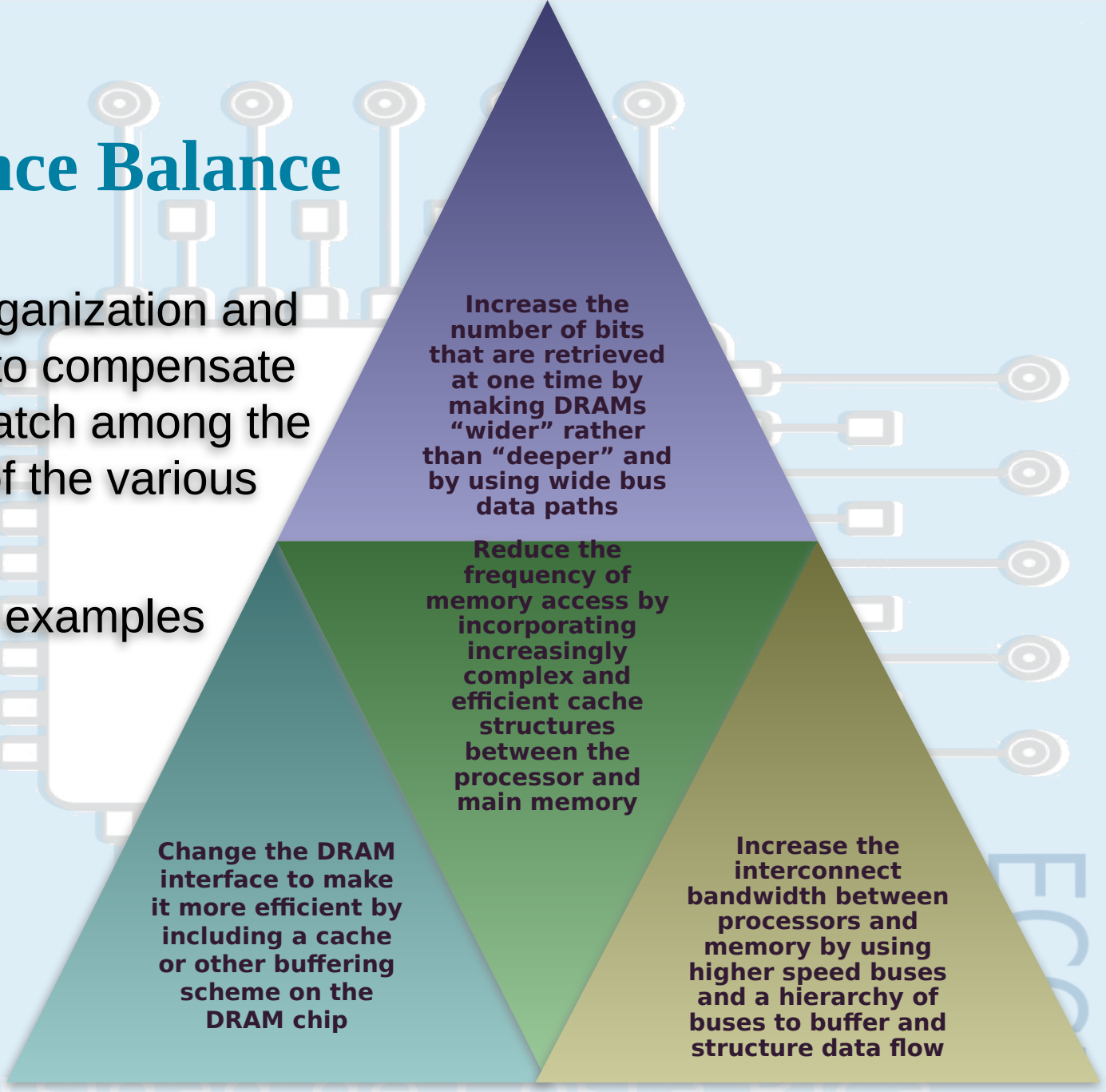
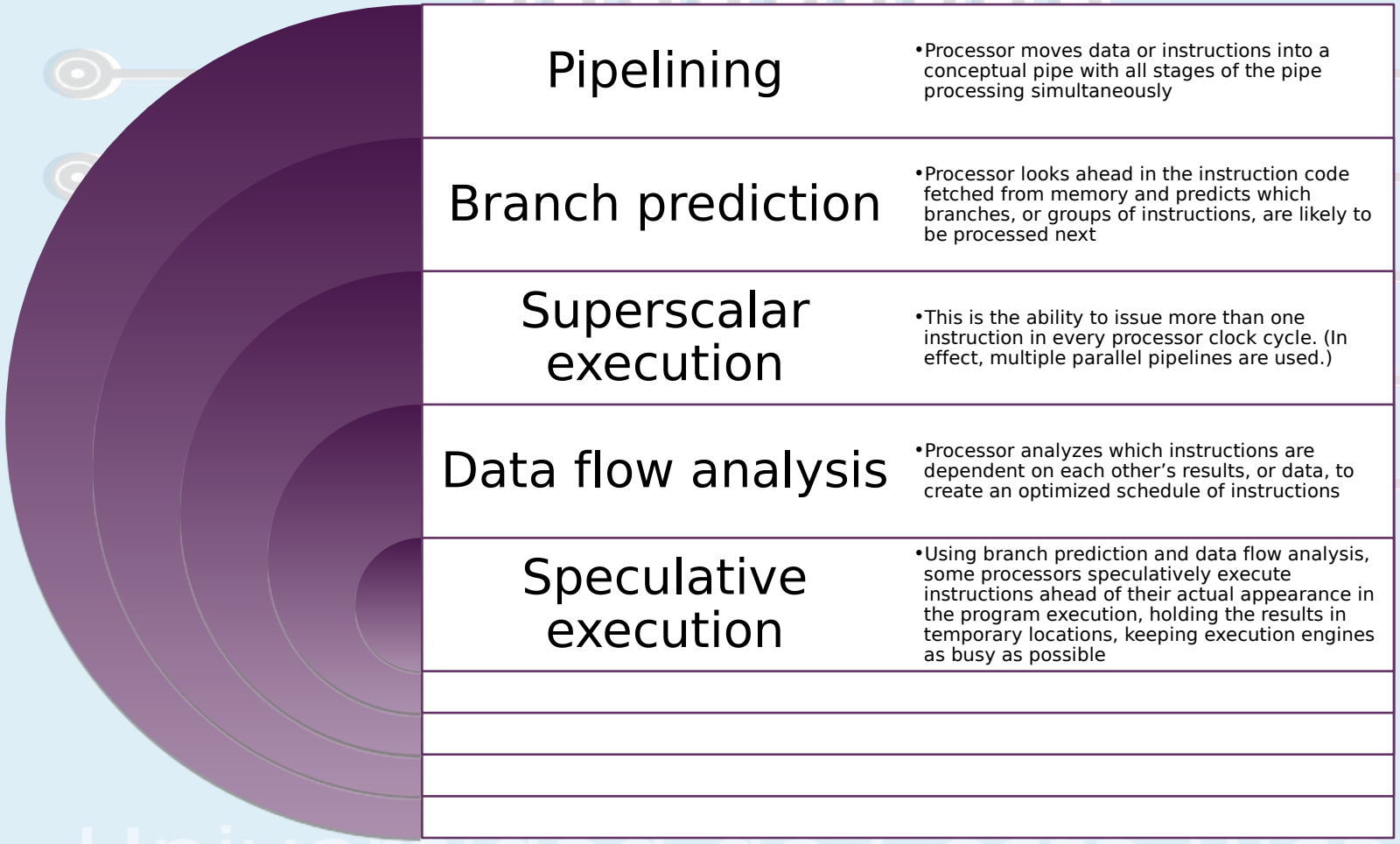
# Performance Balance

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



# Figure 2.1

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 |
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| | |
| | |
| | |
| | |

# 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 and throughput
  - Memory access speed (latency) and transfer speed (throughput) lag processor speeds

# Figure 2.2

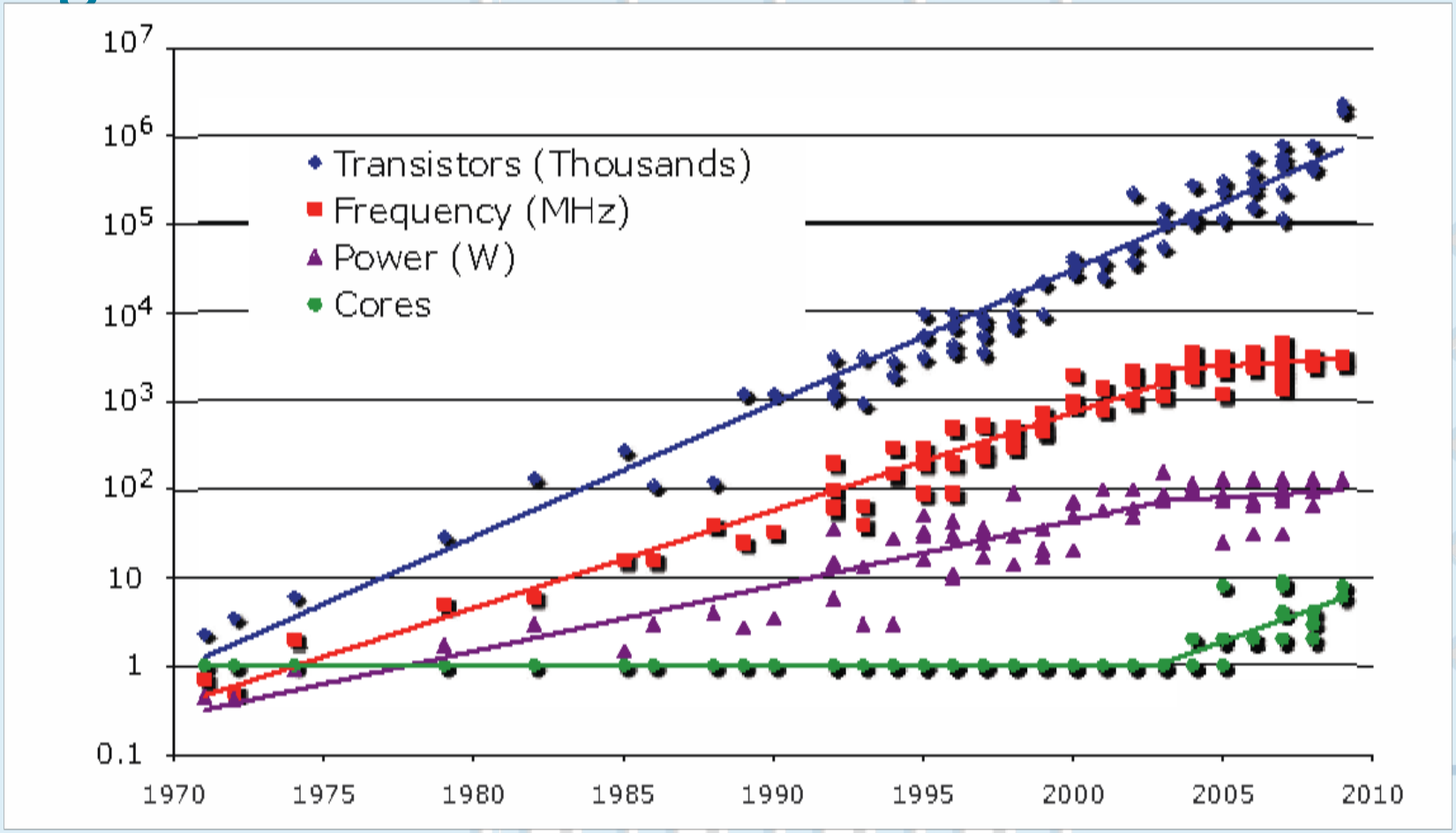
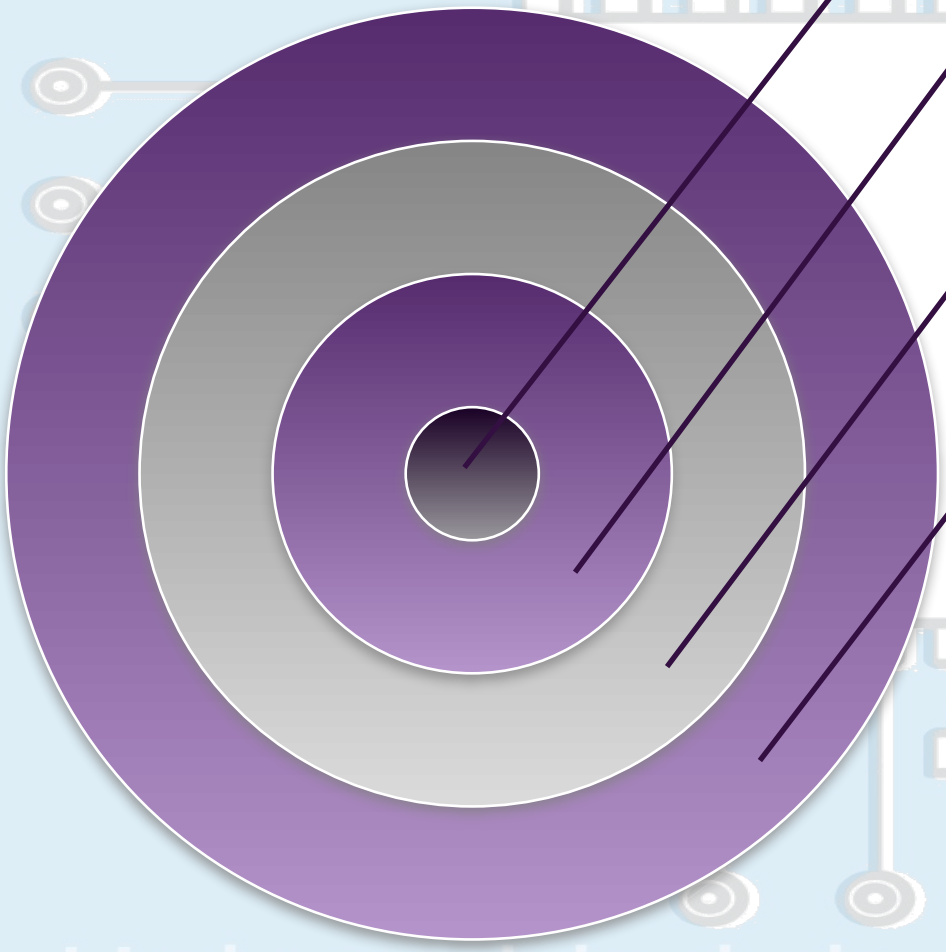



Figure 2.2 Processor Trends

# 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

2021

# 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
- The multicore and MIC strategy involves a homogeneous collection of general purpose processors on a single chip

GPU

- Core designed to perform parallel operations on graphics data
- Traditionally found on a plug-in graphics card, it is used to encode and render 2D and 3D graphics as well as process video
- Used as vector processors for a variety of applications that require repetitive computations

# Amdahl's Law

- Gene Amdahl
- Deals with the potential speedup of a program using multiple processors compared to a single processor
- Illustrates the problems facing industry 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

# Figure 2.3

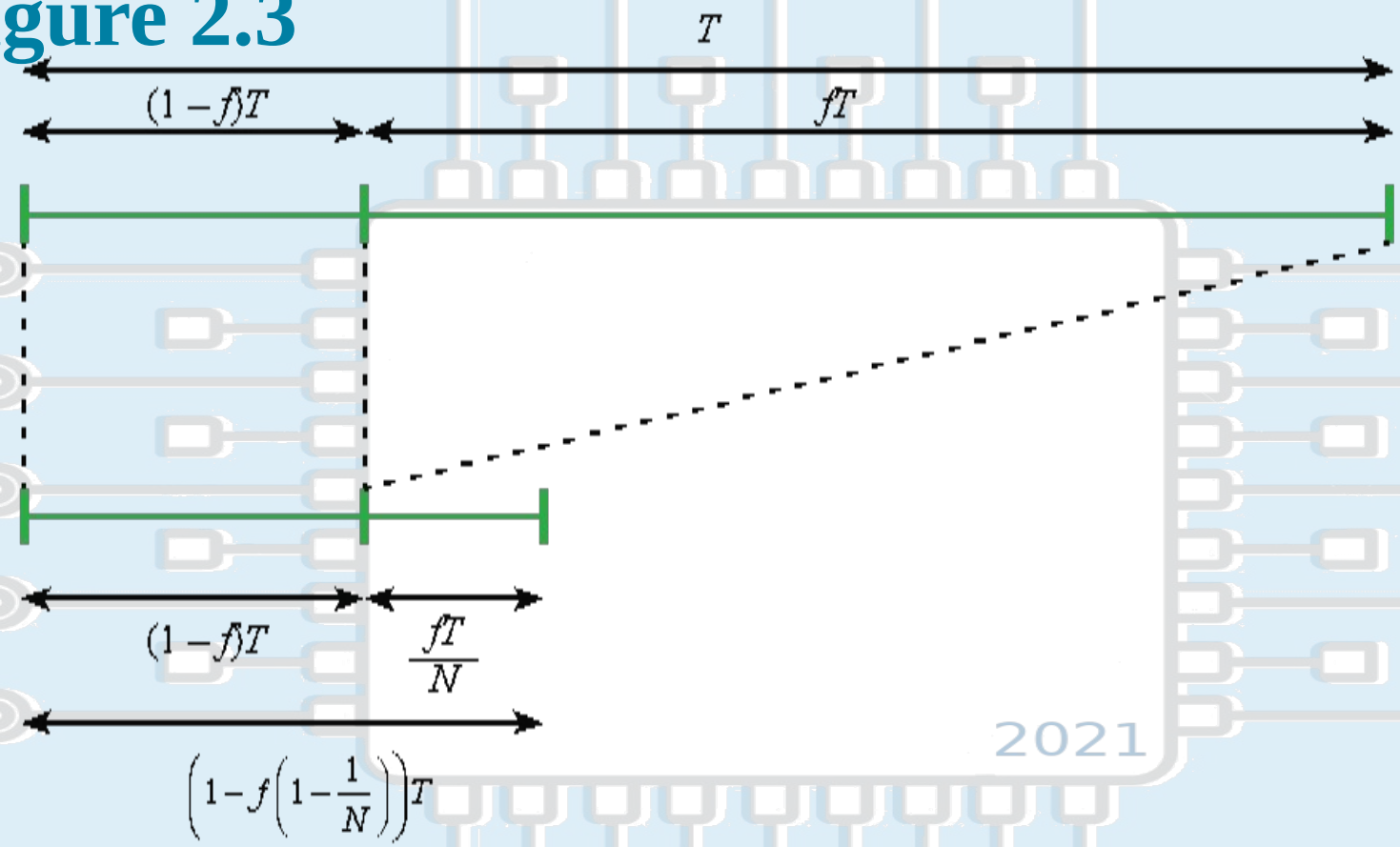



**Figure 2.3 Illustration of Amdahl's Law**

# Figure 2.4

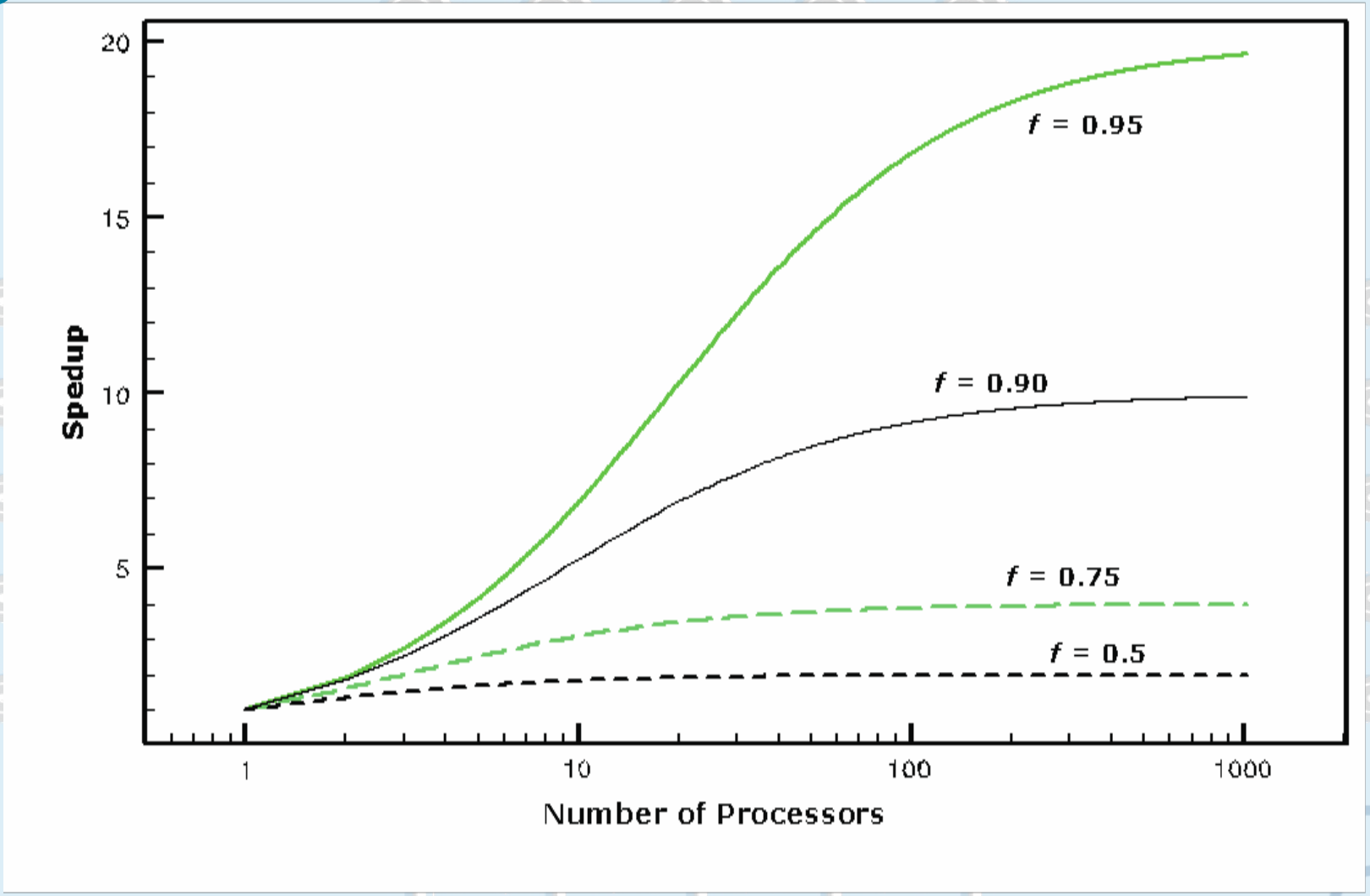



**Figure 2.4 Amdahl's Law for Multiprocessors**

# 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
- Average number of items in a queuing system equals the average rate at which items arrive multiplied by the  time that an item spends in the system
  - Relationship requires very few assumptions
  - Because of its simplicity and generality it is extremely useful

# Figure 2.5

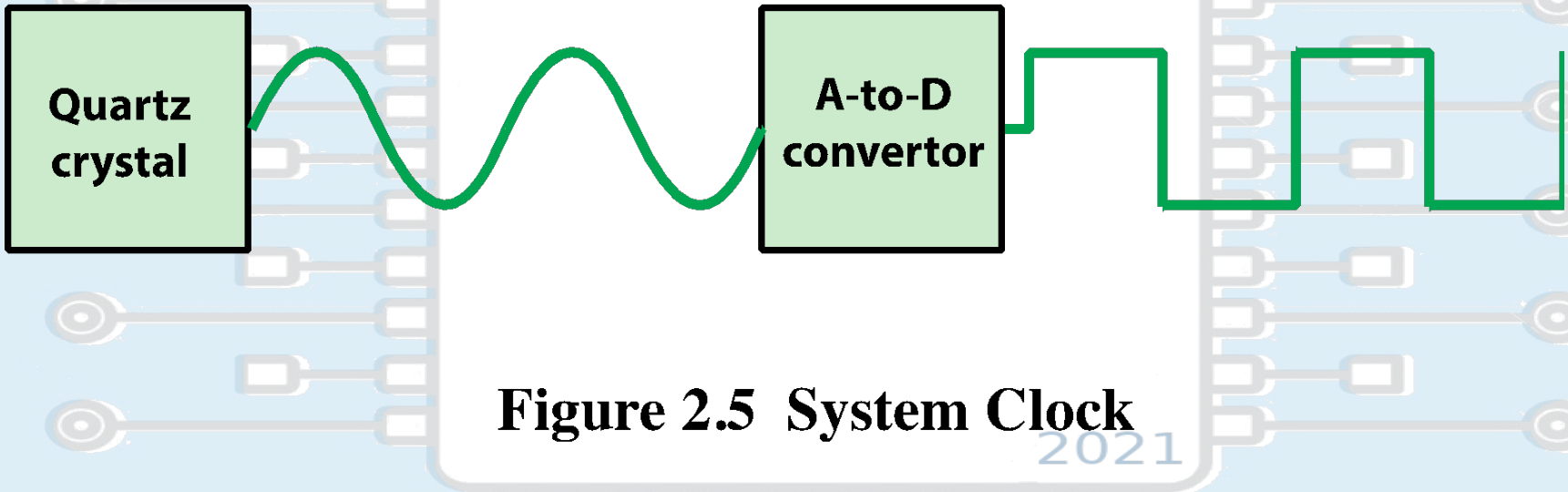



Figure 2.5 System Clock

# Table 2.1 Performance Factors and System Attributes

| | *Ic* | *p* | *m* | *k* | $\tau$ |
|---|---|---|---|---|---|
| Instruction set architecture | X | X | | | |
| Compiler technology | X | X | X | | |
| Processor implementation | | X | | | X |
| Cache and memory hierarchy | | | | X | X |

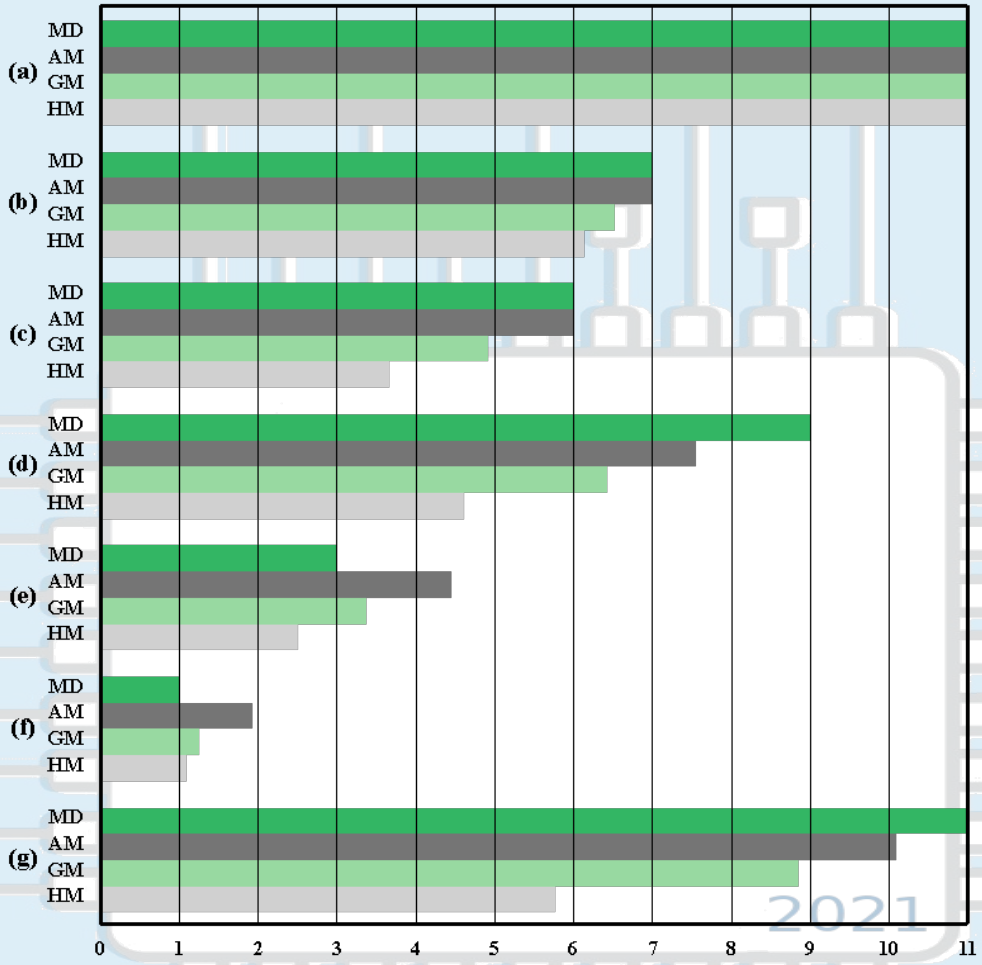
# Calculating the Mean

The use of benchmarks to compare systems involves calculating the mean value of a set of data points lated to execution time

The three common formulas used for calculating a mean are:

- Arithmetic
- Geometric
- Harmonic

# Figure 2.6




(a) Constant (11, 11, 11, 11, 11, 11, 11, 11, 11, 11, 11)
(b) Clustered around a central value (3, 5, 6, 6, 7, 7, 7, 8, 8, 9, 1 1)
(c) Uniform distribution (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 1 1)
(d) Large-number bias (1, 4, 4, 7, 7, 9, 9, 10, 10, 1 1, 11)
(e) Small-number bias(1, 1, 2, 2, 3, 3, 5, 5, 8, 8, 1 1)
(f) Upper outlier (11, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1)
(g) Lower outlier (1, 11, 11, 11, 11, 11, 11, 11, 11, 11, 11)

MD = median
AM = arithmetic mean
GM = geometric mean
HM = harmonic mean

**Figure 2.6 Comparison of Means on Various Data Sets (each set has a maximum data point value of 11)**

# Arithmetic Mean

- An Arithmetic Mean (AM) is an appropriate measure if the sum of all the measurements is a meaningful and interesting value

- The AM is a good candidate for comparing the execution time performance of several systems

> For example, suppose we were interested in using a system for large-scale simulation studies and wanted to evaluate several alternative products. On each system we could run the simulation multiple times with different input values for each run, and then take the average execution time across all runs. The use of multiple runs with different inputs should ensure that the results are not heavily biased by some unusual feature of a given input set. The AM of all the runs is a good measure of the system's performance on simulations, and a good number to use for system comparison.

- The AM used for a time-based variable, such as program execution time, has the important property that it is directly proportional to the total time
- If the total time doubles, the mean value doubles

# Table 2.2
# A Comparison of Arithmetic and Harmonic Means for Rates

| | 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 1 ($10^8$ 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 2.3
# 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 |

**(a) 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 (10.0) |
| 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 |

**(a) 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 (2.0) |
| Total execution time | 2.4 | 3.0 | 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 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

# System Performance Evaluation Corporation (SPEC)

- Benchmark suite
  - A collection of programs, defined in a high-level language
  - Together attempt to provide a representative test of a computer in a particular application or system programming area
- SPEC
  - An industry consortium
  - Defines and maintains the best known collection of benchmark suites aimed at evaluating computer systems
  - Performance measurements are widely used for comparison and research purposes

# SPEC CPU2017

- Best known SPEC benchmark suite
- Industry standard suite for processor intensive applications
- Appropriate for measuring performance for applications that spend most of their time doing computation rather than I/O
- Consists of 20 integer benchmarks and 23 floating-point benchmarks written in C, C++, and Fortran
- For all of the integer benchmarks and most of the floating-point benchmarks, there are both rate and speed benchmark programs
- The suite contains over 11 million lines of code

| Rate | Speed | Language | Kloc | Application Area |
|---|---|---|---|---|
| **500.perlbench_r** | 600.perlbench_s | C | 363 | Perl interpreter |
| **502.gcc_r** | 602.gcc_s | C | 1304 | GNU C compiler |
| **505.mcf_r** | 605.mcf_s | C | 3 | Route planning |
| **520.omnetpp_r** | 620.omnetpp_s | C++ | 134 | Discrete event simulation - computer network |
| **523.xalancbmk_r** | 623.xalancbmk_s | C++ | 520 | XML to HTML conversion via XSLT |
| **525.x264_r** | 625.x264_s | C | 96 | Video compression |
| **531.deepsjeng_r** | 631.deepsjeng_s | C++ | 10 | AI: alpha-beta tree search (chess) |
| **541.leela_r** | 641.leela_s | C++ | 21 | AI: Monte Carlo tree search (Go) |
| **548.exchange2_r** | 648.exchange2_s | Fortran | 1 | AI: recursive solution generator (Sudoku) |
| **557.xz_r** | 657.xz_s | C | 33 | General data compression |

## Table 2.5 (A)

## SPEC CPU2017 Benchmarks

Kloc = line count (including comments/whitespace) for source files used in a build/1000 (Table can be found on page 61 in the textbook.)

| Rate | Speed | Language | Kloc | Application Area |
|---|---|---|---|---|
| **503.bwaves_r** | 603.bwaves_s | Fortran | 1 | Explosion modeling |
| **507.cactuBSSN_r** | 607.cactuBSSN_s | C++, C, Fortran | 257 | Physics; relativity |
| **508.namd_r** | | C++, C | 8 | Molecular dynamics |
| **510.parest_r** | | C++ | 427 | Biomedical imaging; optical tomography with finite elements |
| **511.povray_r** | | C++ | 170 | Ray tracing |
| **519.ibm_r** | 619.ibm_s | C | 1 | Fluid dynamics |
| **521.wrf_r** | 621.wrf_s | Fortran, C | 991 | Weather forecasting |
| **526.blender_r** | | C++ | 1577 | 3D rendering and animation |
| **527.cam4_r** | 627.cam4_s | Fortran, C | 407 | Atmosphere modeling |
| | 628.pop2_s | Fortran, C | 338 | Wide-scale ocean modeling (climate level) |
| **538.imagick_r** | 638.imagick_s | C | 259 | Image manipulation |
| **544.nab_r** | 644.nab_s | C | 24 | Molecular dynamics |
| **549.fotonik3d_r** | 649.fotonik3d_s | Fortran | 14 | Computational electromagnetics |
| **554.roms_r** | 654.roms_s | Fortran | 210 | Regional ocean modeling. |

## Table 2.5 (B)

## SPEC CPU2017 Benchmarks

Kloc = line count (including comments/whitespace) for source files used in a build/1000 (Table can be found on page 61 in the textbook.)

| Benchmark | Base | | Peak | |
|---|---|---|---|---|
| | Seconds | Rate | Seconds | Rate |
| 500.perlbench_r | 1141 | 1070 | 933 | 1310 |
| 502.gcc_r | 1303 | 835 | 1276 | 852 |
| 505.mcf_r | 1433 | 866 | 1378 | 901 |
| 520.omnetpp_r | 1664 | 606 | 1634 | 617 |
| 523.xalancbmk_r | 722 | 1120 | 713 | 1140 |
| 525.x264_r | 655 | 2053 | 661 | 2030 |
| 531.deepsjeng_r | 604 | 1460 | 597 | 1470 |
| 541.leela_r | 892 | 1410 | 896 | 1420 |
| 548.exchange2_r | 833 | 2420 | 770 | 2610 |
| 557.xz_r | 870 | 953 | 863 | 961 |

# Table 2.6

## SPEC CPU 2017 Integer Benchmarks for HP Integrity Superdome X

## (a) Rate Result (768 copies)

(Table can be found on page 64 in the textbook.)

| Benchmark | Base | | Peak | |
|---|---|---|---|---|
| | Seconds | Ratio | Seconds | Ratio |
| 600.perlbench_s | 358 | 4.96 | 295 | 6.01 |
| 602.gcc_s | 546 | 7.29 | 535 | 7.45 |
| 605.mcf_s | 866 | 5.45 | 700 | 6.75 |
| 620.omnetpp_s | 276 | 5.90 | 247 | 6.61 |
| 623.xalancbmk_s | 188 | 7.52 | 179 | 7.91 |
| 625.x264_s | 283 | 6.23 | 271 | 6.51 |
| 631.deepsjeng_s | 407 | 3.52 | 343 | 4.18 |
| 641.leela_s | 469 | 3.63 | 439 | 3.88 |
| 648.exchange2_s | 329 | 8.93 | 299 | 9.82 |
| 657.xz_s | 2164 | 2.86 | 2119 | 2.92 |

# Table 2.6

## SPEC CPU 2017 Integer Benchmarks for HP Integrity Superdome X

## (b) Speed Result (384 threads)

(Table can be found on page 64 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
    - Used for comparing the ability of a computer to complete single tasks
- 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

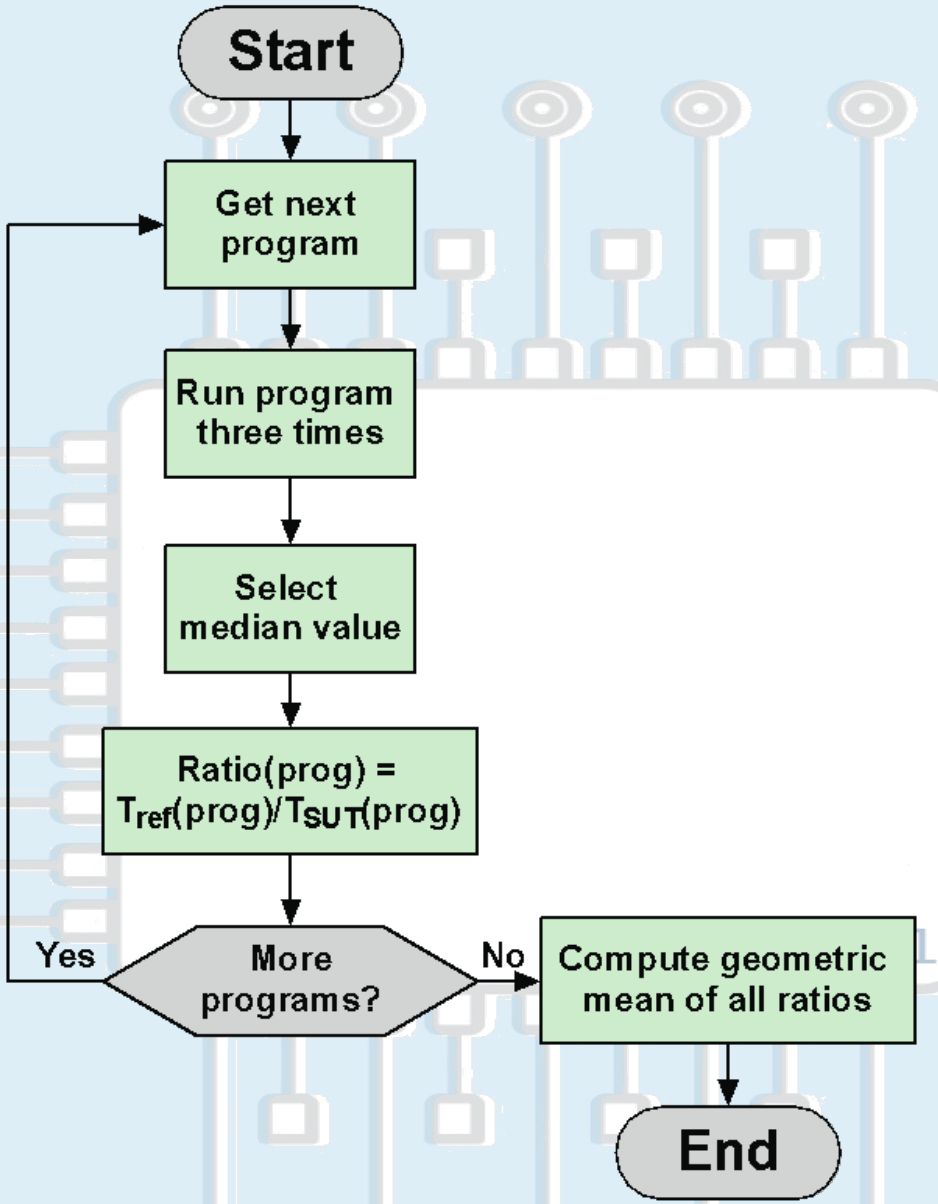



**Figure 2.7 SPEC Evaluation Flowchart**

| Benchmark | Seconds | Energy (kJ) | Average Power (W) | Maximum Power (W) |
|---|---|---|---|---|
| 600.perlbench_s | 1774 | 1920 | 1080 | 1090 |
| 602.gcc_s | 3981 | 4330 | 1090 | 1110 |
| 605.mcf_s | 4721 | 5150 | 1090 | 1120 |
| 620.omnetpp_s | 1630 | 1770 | 1090 | 1090 |
| 623.xalancbmk_s | 1417 | 1540 | 1090 | 1090 |
| 625.x264_s | 1764 | 1920 | 1090 | 1100 |
| 631.deepsjeng_s | 1432 | 1560 | 1090 | 1130 |
| 641.leela_s | 1706 | 1850 | 1090 | 1090 |
| 648.exchange2_s | 2939 | 3200 | 1080 | 1090 |
| 657.xz_s | 6182 | 6730 | 1090 | 1140 |

## Table 2.7

**SPECspeed 2017_int_base Benchmark Results for Reference Machine (1 thread)**

(...ge 66 in the textbook.)

# 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
- Concepts

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