# Computer Architecture
# Computer performance

http://d3s.mff.cuni.cz/teaching/computer_architecture/

*Lubomír Bulej*

bulej@d3s.mff.cuni.cz

CHARLES UNIVERSITY IN PRAGUE

faculty of mathematics and physics

# Why care about performance?

- **Comparing/ranking computers**
  - Cheaper and/or better product wins
    - Personal computers: fierce performance competition
    - Embedded computers: optimize price of final product
  - Important for buyers → important for designers and producers

- **Performance impact of architectural changes**
  - Systematic assessment is the only indication whether some progress is really a progress

# How to define computer performance?

- **Computer A is “better” than computer B**
  - What does it mean? Better in what?
  - Is a truck “better” car than a sports car?
  - Is a Concorde “better” plane than a Boeing 777?

| Airplane | Capacity [persons] | Range [km] | Cruising speed [km/h] | Throughput [pers·km/h] |
|---|---|---|---|---|
| Boeing 737 | 240 | 4828 | 907 | 217680 |
| BAC/Sud Concorde | 132 | 6437 | 2172 | 286704 |
| Boeing 777-200LR | 301 | 15120 | 892 | 268492 |
| Airbus A380-800 | 853 | 13642 | 944 | 805232 |

# Program performance

| HW or SW component | Impact on performance |
|---|---|
| Algorithm | Number of source-level statements and of I/O operations executed |
| Programming language, compiler, computer architecture | Number of instructions for each source-level statement |
| Processor, memory | How fast instructions can be executed |
| I/O system (hardware, operating system) | How fast I/O operations can be executed |

# How to define computer performance?

- Basic criteria
  - What do we need?
  - What do we compare?
- Basic metrics
  - Execution time (response time)
    - Time to complete a particular task
    - Important for users
  - Throughput
    - Amount of work completed in unit time
    - Important for server or data center operators

# How to define computer performance?

- **Performance based on execution time**
  - We desire: higher number = higher performance
  - Execution time is the opposite → needs fixing

$$Performance_X = \frac{1}{Execution\ time_X}$$

- **Now we can compare performance**

$$Performance_X > Performance_Y$$

$$\frac{1}{Execution\ time_X} > \frac{1}{Execution\ time_Y}$$

$$Execution\ time_X < Execution\ time_Y$$

# Relative performance

- **Relating performance of two computers**
  - X is n-times faster than Y (has higher performance)

$$\frac{Performance_X}{Performance_Y} = n$$

  - If X is n-times faster than Y, then execution time on Y is n-times longer than on X

$$\frac{Performance_X}{Performance_Y} = \frac{Execution\ time\ Y}{Execution\ time\ X} = n$$

# Performance: user perspective

- **Total execution time**
  - *Wall-clock time, response time, elapsed time*
  - Includes waiting for I/O operations, OS overhead, etc.
    - Including sharing resources (CPU) with other users
  - Reflects whole-system performance
- **Processor time**
  - *CPU execution time, CPU time*
  - Time when the program was actually executing
    - Does not include waiting for I/O operations
    - Does not include time when to program was not running
    - Includes OS overhead (**user** vs **system** CPU time)
  - Reflects processor performance

# Performance: CPU designer perspective

- **Speed for executing instructions**
  - Clock rate
  - Clock cycle length

$$CPU\ execution\ time = \frac{CPU\ clock\ cycles}{CPU\ clock\ rate}$$

$$CPU\ execution\ time = CPU\ clock\ cycles \times CPU\ clock\ cycle\ time$$

# Performance: compiler perspective

- **Average number of cycles per instruction**
  - *Clock cycles per instruction* (CPI)
  - Specific to a particular program or its part
  - Allows comparing different implementations of the same architecture
    - Given a fixed number of instructions

$$CPU\ clock\ cycles = CPI \times Number\ of\ instructions$$

# Classic processor performance equation

- **Relates number of instructions, CPI and clock cycle length**
  - 3 different factors influencing performance
    - Allows comparing different implementations
    - Allows assessing alternative architectures

$$CPU\ execution\ time = CPI \times Number\ of\ instructions \times CPU\ clock\ cycle\ time$$

$$CPU\ execution\ time = \frac{CPI \times Number\ of\ instructions}{CPU\ clock\ rate}$$

# Program performance (2)

| Component | Affects what? | Affects how? |
|---|---|---|
| Algorithm | Instruction count<br>CPI | Number and kind of source program statements and operations, data types (integer vs. floating point) |
| Programming Language | Instruction count<br>CPI | Kind of source program statements, abstractions used to express the algorithm. |
| Compiler | Instruction count<br>CPI | How program statements are translated to machine code, choice and layout of instructions. |
| Instruction set architecture | Instruction count<br>CPI<br>Clock rate | Instructions available to compiler, cost in cycles for each instruction, overall clock rate. |

# Pitfall: Unrealistic expectations

- **Expecting the improvement of *one* aspect of a computer to increase *overall* performance by an amount proportional to the size of the improvement.**
  - **Total execution time:** 100 s
    - **Out of which multiplication operations:** 80 s
  - How much do we need to improve multiplication to make the program run 5× faster?

# Pitfall: Unrealistic expectations (2)

- **Some „back of the envelope“ calculations**

$$Execution_{fast} = \frac{Execution_{slow}}{5}$$

$$Execution_{slow} = 80 + 20$$

$$Execution_{fast} = \frac{80}{n} + 20$$

$$\frac{80}{n} + 20 = \frac{80+20}{5}$$

$$\frac{80}{n} + 20 = 20$$

$$\frac{80}{n} = 0$$

$$80 \neq 0$$

# Pitfall: Wrong performance metrics

- **Using a subset of the performance equation as a performance metric**
  - Using a single factor is almost always wrong
  - Using two factors may be valid in limited context
    - Easily misused: dependencies between factors
  - Other metrics dressing up other known factors

# Pitfall: Wrong performance metrics (2)

- **MIPS (Million Instructions Per Second)**
  - Instruction execution rate
  - Intuitive (higher number → faster computer)
  - Problems
    - Ignores instruction capabilities, execution time of individual instructions, different number of instructions for different ISAs
      - Impossible to compare computers with different ISA
    - Depends on the instruction mix of a particular program (a single value to not represent the performance of a computer)
      - CPI can vary significantly on the same processor

$$MIPS = \frac{InstructionCount}{10^6 \times ExecutionTime} = \frac{InstructionCount}{10^6 \times \frac{InstructionCount \times CPI}{ClockRate}} = \frac{ClockRate}{10^6 \times CPI}$$

# Processor performance

- **Performance while executing a particular program**
  - Depends on the number of instructions, average number of cycles per instructions (CPI), clock cycle length (or clock rate)
  - **No single factor can completely express performance** ☠
    - Reducing number of instructions → architecture with lower clock frequency or higher CPI
    - CPI depends on the **instruction mix** (frequency and type of executed instructions) of a given program
      - Code with the lowest number of instructions is not necessarily the fastest

# Processor performance (2)

- **Performance while executing a particular program**
  - The only complete and reliable metrics is processor time
    - Does not tell anything about processor time for other programs

# Performance evaluation

- **Comparing performance of different computers**
  - Easy for one specific program (processor execution time)
  - Comparing isolated components (clock rate, CPI, number of instructions) not indicative for other programs
  - How to approximate performance with respect to a set of programs?

# Performance evaluation (2)

- **Workload**
  - A set of programs and tasks capturing a user's workload
  - Compare execution time of the workload on different computers
  - Difficult to define (domain specific)
  - Difficult to automate (repeated execution)
- **Benchmark**
  - Program specifically made to measure performance
  - Set of benchmarks
    - Statistically relevant representative of a typical workload
    - Hoping that benchmark results will reflect how well a computer will perform with the user's workload

# Performance evaluation (3)

- **SPEC (Standard Performance Evaluation Corporation)**
  - Funded by commercial and non-commercial entities
    - Manufacturers of processors and computers
    - Producers of compilers, operating systems
    - Research institutes
  - **Goal:** Define a standard set of benchmarks to enable comparison of computer systems’ performance
    - Different benchmarks for different workloads
    - Primarily focusing on CPU performance
    - Now CPU power, GPU performance & power, compilers, databases, e-mail systems, transaction processing, etc.

# SPEC CPU 2006

- **Processor performance**
  - CINT2006 (integer computation)
    - 12 benchmarks (C compiler, chess algorithm, quantum computer simulation, etc.)
  - CFP2006 (floating point computation)
    - 17 benchmarks (finite elements, molecular dynamics, etc.)
  - SPECratio
    - Ratio of reference vs. measured benchmark execution time
    - Summary score (single number): geometric mean

$$\sqrt[n]{\prod_{i=1}^{n} SPECratio_i}$$

# SPEC CINT2006 on AMD Opteron X4

| Description | Name | Instruction Count × $10^9$ | CPI | Clock cycle time (seconds × $10^9$) | Execution Time (seconds) | Reference Time (seconds) | SPECratio |
|---|---|---|---|---|---|---|---|
| Interpreted string processing | perl | 2,118 | 0.75 | 0.4 | 637 | 9,770 | 15.3 |
| Block-sorting compression | bzip2 | 2,389 | 0.85 | 0.4 | 817 | 9,650 | 11.8 |
| GNU C compiler | gcc | 1,050 | 1.72 | 0.4 | 724 | 8,050 | 11.1 |
| Combinatorial optimization | mcf | 336 | 10.00 | 0.4 | 1,345 | 9,120 | 6.8 |
| Go game (AI) | go | 1,658 | 1.09 | 0.4 | 721 | 10,490 | 14.6 |
| Search gene sequence | hmmer | 2,783 | 0.80 | 0.4 | 890 | 9,330 | 10.5 |
| Chess game (AI) | sjeng | 2,176 | 0.96 | 0.4 | 837 | 12,100 | 14.5 |
| Quantum computer simulation | libquantum | 1,623 | 1.61 | 0.4 | 1,047 | 20,720 | 19.8 |
| Video compression | h264avc | 3,102 | 0.80 | 0.4 | 993 | 22,130 | 22.3 |
| Discrete event simulation library | omnetpp | 587 | 2.94 | 0.4 | 690 | 6,250 | 9.1 |
| Games/path finding | astar | 1,082 | 1.79 | 0.4 | 773 | 7,020 | 9.1 |
| XML parsing | xalancbmk | 1,058 | 2.70 | 0.4 | 1,143 | 6,900 | 6.0 |
| Geometric Mean | | | | | | | 11.7 |

*Source: P&H*

# SPEC CINT2006 on 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 |

*Source: P&H*

# SPECspeed 2017 on Intel Xeon E5-2650L

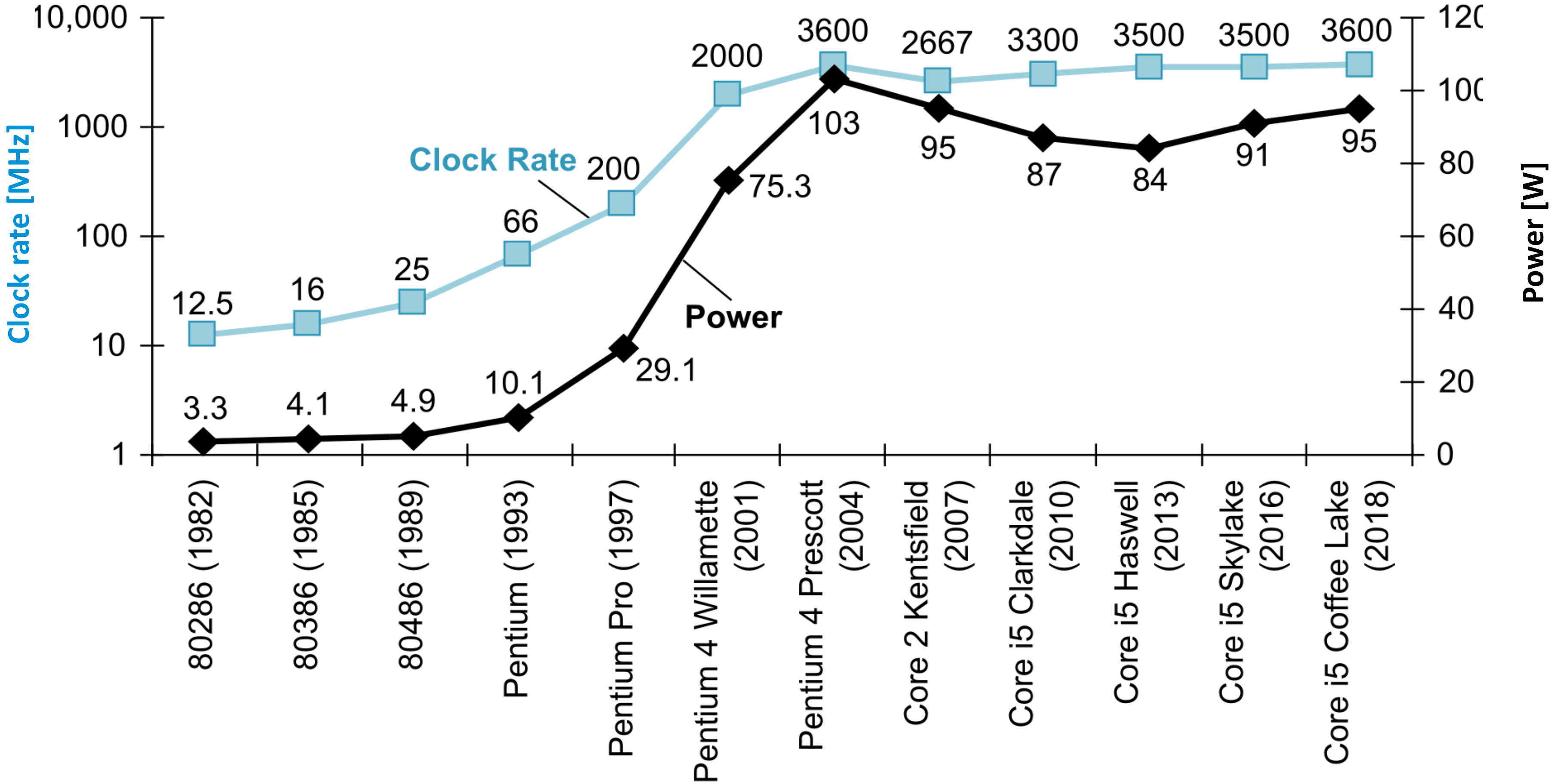
| Description | Name | Instruction Count x $10^9$ | CPI | Clock cycle time (seconds x $10^{-9}$) | Execution Time (seconds) | Reference Time (seconds) | SPECratio |
|---|---|---|---|---|---|---|---|
| Perl interpreter | perlbench | 2684 | 0.42 | 0.556 | 627 | 1774 | 2.83 |
| GNU C compiler | gcc | 2322 | 0.67 | 0.556 | 863 | 3976 | 4.61 |
| Route planning | mcf | 1786 | 1.22 | 0.556 | 1215 | 4721 | 3.89 |
| Discrete Event simulation - computer network | omnetpp | 1107 | 0.82 | 0.556 | 507 | 1630 | 3.21 |
| XML to HTML conversion via XSLT | xalancbmk | 1314 | 0.75 | 0.556 | 549 | 1417 | 2.58 |
| Video compression | x264 | 4488 | 0.32 | 0.556 | 813 | 1763 | 2.17 |
| Artificial Intelligence: alpha-beta tree search (Chess) | deepsjeng | 2216 | 0.57 | 0.556 | 698 | 1432 | 2.05 |
| Artificial Intelligence: Monte Carlo tree search (Go) | leela | 2236 | 0.79 | 0.556 | 987 | 1703 | 1.73 |
| Artificial Intelligence: recursive solution generator (Sudoku) | exchange2 | 6683 | 0.46 | 0.556 | 1718 | 2939 | 1.71 |
| General data compression | xz | 8533 | 1.32 | 0.556 | 6290 | 6182 | 0.98 |
| Geometric mean | – | – | – | – | – | – | 2.36 |

*Source: P&H*

# Program performance (3)

**End of the golden era**

# The Power Wall




*Source: P&H*

# The Power Wall (2)

- ***Complementary Metal Oxide Semiconductor (CMOS)***
  - Dominant technology for integrated circuits
  - Very low static consumption
  - Dynamic power consumption
    - Capacitive load (conductors, transistors, output load)
    - Operating voltage (affects switching speed)
    - Switching frequency (function of clock rate)

$$Power \approx \frac{1}{2} \times Capacitive\ load \times Voltage^2 \times Frequency\ switched$$

# The Power Wall (3)

- **Real-world impact**
  - In the last 20 years
    - Clock rate growth by factor of 1000
    - Power growth (only) by factor of 30
    - How: voltage dropped from 5 V to 1 V
      - 15% reduction with each generation
- **Example**
  - New technology results in 85% capacitive load of old technology. Also, the operating voltage and switching frequency can be reduced by 15% to save power.

$$\frac{Power_{new}}{Power_{old}} = \frac{(CapacitiveLoad \times 0.85) \times (Voltage \times 0.85) \times (FrequencySwitched \times 0.85)}{CapacitiveLoad \times Voltage \times FrequencySwitched} = 0.85^4 = 0.52$$

# The Power Wall (4)

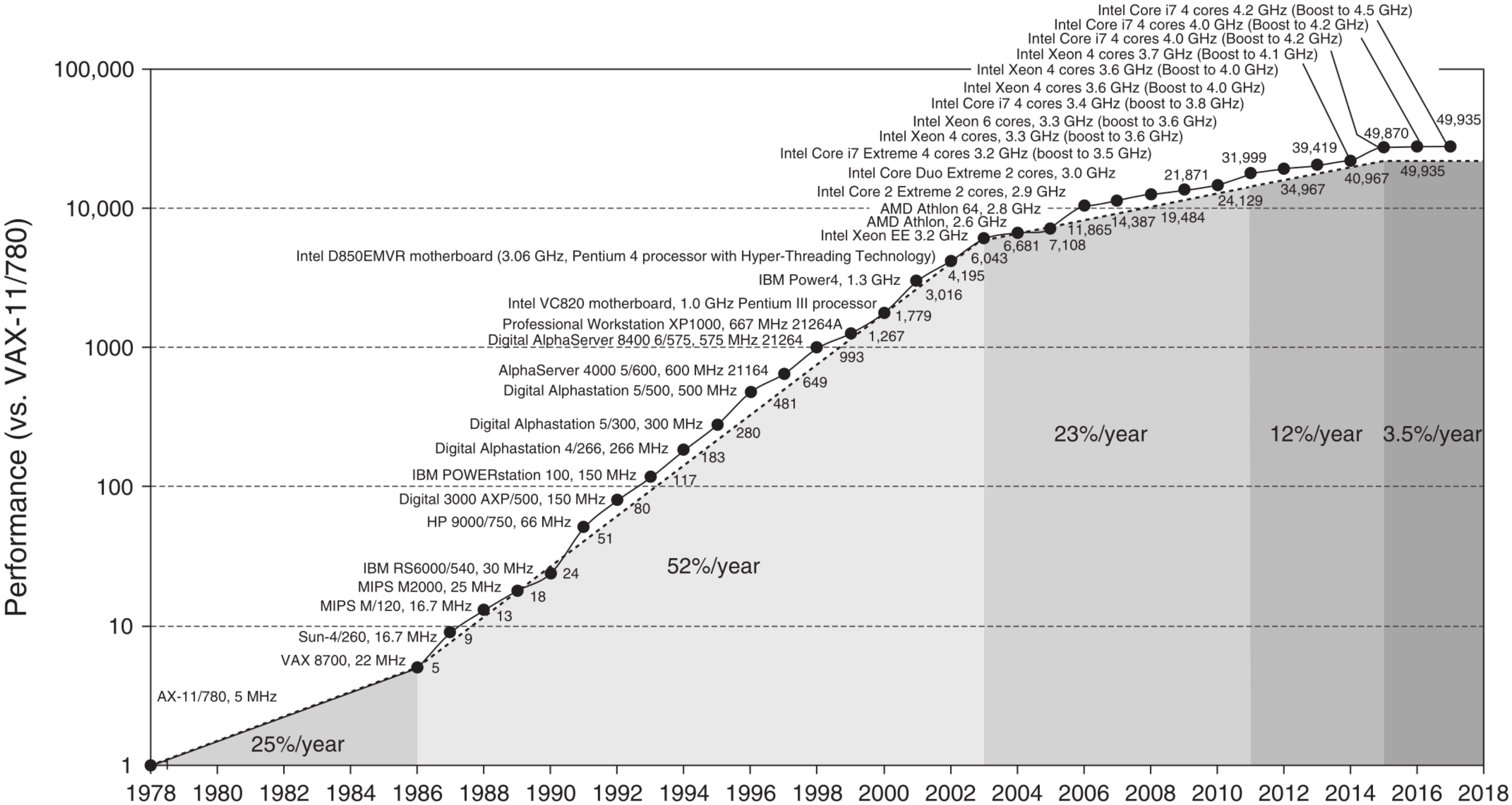
- **Further lowering of voltage difficult/impossible**
  - Makes transistors too leaky
  - 40% of power consumption in server chips is due to leakage
  - Low signal/noise ratio
    - Difficult to tell ones from zeroes reliably
- **Cooling cannot be easily improved**
  - Power dissipated from a rather small area of the chip
  - Parts of chip not used in a clock cycle can be turned off
  - Water (and other) cooling techniques too complex/expensive
    - Not even an option for personal mobile devices

# The Power Wall (5)

- **New way to improve performance needed**
  - Dramatic change in microprocessor design

**The switch from**
**Uniprocessors to Multiprocessors**

# Growth in processor performance




*Source: P&H*

# Multiprocessor systems

- **Then**
  - Multiple physical processors (*multiprocessor*)
  - Where: Supercomputers, high-end servers
  - Rare in personal and embedded computers
- **Now**
  - Multiple processor **cores** in a single microprocessor package
    - Post-Moore's „law" world, shrinking transistors difficult/expensive,
      but we can still put more of then on a single (bigger) chip
  - Where: everywhere

# Multicore systems

- **Impact on performance**
  - Increased throughput
    - Processing more requests in parallel
  - Clock rate and CPI remain the same
    - Performance of sequential algorithms stays the same
- **Impact on programmers**
  - Technology does not make programs faster (anymore)
  - Programs need to take advantage of multiple cores
    - Better APIs needed (executor frameworks, parallel collections, ...)
  - Programs need to be improved as number of cores increases
    - Increasing number of cores from 4 to 32 will not make a parallel program 8 times faster

# Why is this such a big deal?

- **Fundamental change in HW/SW interface**
  - Parallelism was always important, but used to be hidden
    - Instruction-level parallelism, pipelining, and other techniques
    - Programmer and compiler alike produced sequential code
  - Now parallelism needs to be explicit!
- **Parallel architectures known for 40+ years...**
  - … but whoever relied on explicit parallelism failed!
    - Programmers never accepted the new paradigm
  - Yet the IT industry bets on programmers to switch to explicit parallelism

# Why is parallel programming difficult?

- **Programming focused on performance**
  - Increases difficult of programming
    - Not only does the program need to be correct, it also needs to be fast
    - If you don‘t need performance, just write a sequential program.
  - People think “sequentially” in a “single thread”

- **Problem: split work equally between processors**
  - Ensure that the overhead of planning and coordinating the work does not take away the performance benefit

# Why is parallel programming difficult? (2)

- **Real-world analogy**
  - 1 reporter writes 1 article in 2 hours
    - Can we get 8 reporters to write 1 article in 15 minutes?
  - Actual problems
    - Scheduling
      - Who writes what?
    - Load balancing
      - No reporter is idle
    - Communication and synchronization overhead
      - How to put the final article together?

# Amdahl's law

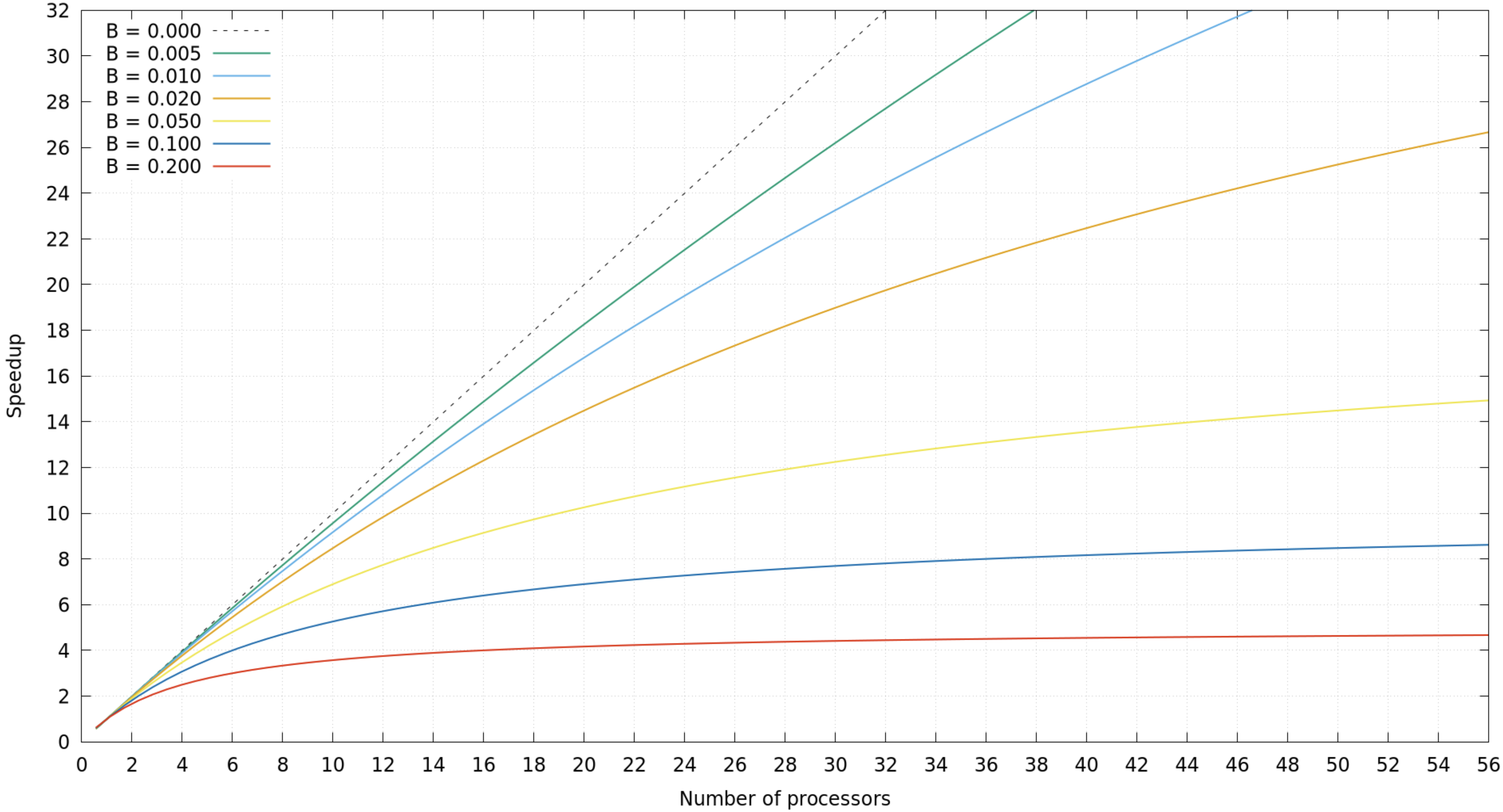
- **Gene Amdahl (* 1922)**
  - Multiple variants
  - Most general for theoretical speed-up of a sequential algorithm using multiple threads (formulated in 1967)
  - A quantitative versions of the law of diminishing returns
    - ***The performance enhancement possible with a given improvement is limited by the amount that the improved feature is used.***

[1]

$$Speedup(n) = \frac{1}{B + \frac{1}{n}(1-B)} \qquad n \in \mathbb{N} \qquad B \in \langle 0, 1 \rangle$$

# Amdahl's law (2)

## Speedup potential (ideal case)



# Amdahl's law (3)

- **Practical impact**
  - *Make the common case fast*
    *Optimize for the common case*
  - Optimization impacts the common case the most
    - The common case is often much simpler than the special cases, and therefore easier to optimize
  - Even massive optimization of special cases often provide only very little benefit compared to modest optimization of the common cases