Computer architecture
Computer performance

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

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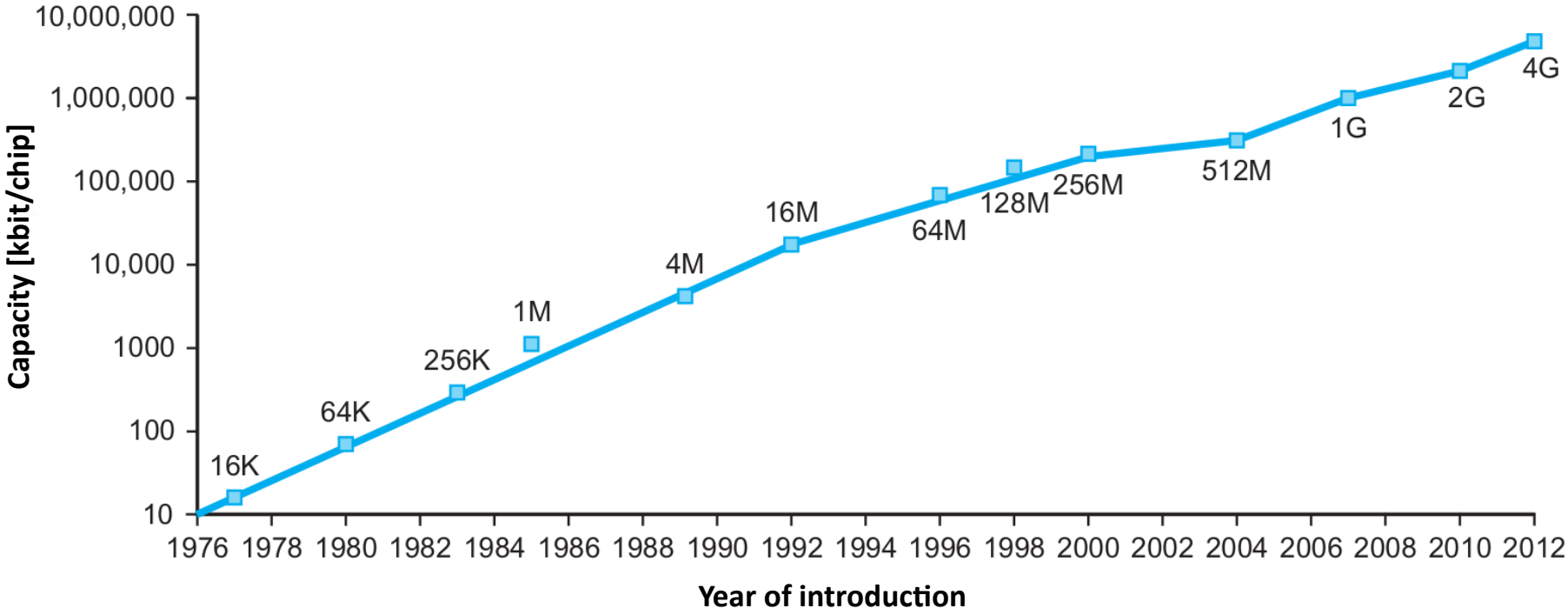
faculty of mathematics and physics

Relative performance per unit cost

Year	Technology	Relative performance / unit cost
1951	Vacuum tube	1
1965	Transistor	35
1975	Integrated circuit (low integration)	900
1995	Integrated circuit (very large scale integration, VLSI)	2 400 000
2013	Integrated circuit (ultra large scale integration, ULSI)	250 000 000 000

Growth of capacity per DRAM chip



Source: P&H

Great ideas in computer architecture

- Design for Moore's law
- Use abstraction to simplify design
- Make the common cast fast
- Performance via parallelism
- Performance via pipelining
- Performance via prediction
- Hierarchy of memories
- Dependability via redundancy

Moore's "law"

- **Gordon Moore (*1929)**
  - On of the founders of Intel
  - **Prediction:** The number of transistors integrated on a single chip will double every 18 – 24 months
    - 1960s
    - Smaller transistors allow higher speeds and capacities
    - Often applied to other domains
      - Storage capacity, network bandwidth

Moore's "law" (2)

- **Exponential growth in the last 40 years!**
  - Keeping Moore's "law" valid requires **tremendous and continuous** advances in technology
    - So far in a single domain (semiconductor transistors)
    - There are hard physical limits (quantum tunnel effect, waste heat, quantum noise)
  - Compromises needed
    - Number of transistors does not correspond to computational power for sequential algorithms

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

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 747?

Airplane	Capacity [persons]	Range [km]	Cruising speed [km/h]	Throughput [pers·km/h]
Boeing 777	375	9000	905	339375
Boeing 747	470	7700	905	425350
Concorde	132	7400	2158	284856
Douglas DC-8-50	146	16000	810	118260

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**

$$Performance_X > Performance_Y$$

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

$$Execution\,time_Y > Execution\,time_X$$

Relative performance

- **Relating performance of two computers**
  - X is n-times faster than Y

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

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

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

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

Alternative view of program performance

Component	Affects what?	Affects how?
Algorithm	Instruction count CPI	Number and kind of source program statements and operations, data types (integer vs. floating point)
Programming Language	Instruction count CPI	Kind of source program statements, abstractions used to express the algorithm.
Compiler	Instruction count CPI	How program statements are translated to machine code, choice and layout of instructions.
Instruction set architecture	Instruction count CPI 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)

$$MIPS = \frac{Instruction\,count}{10^6 \times Execution\,time}$$

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 algorith, 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

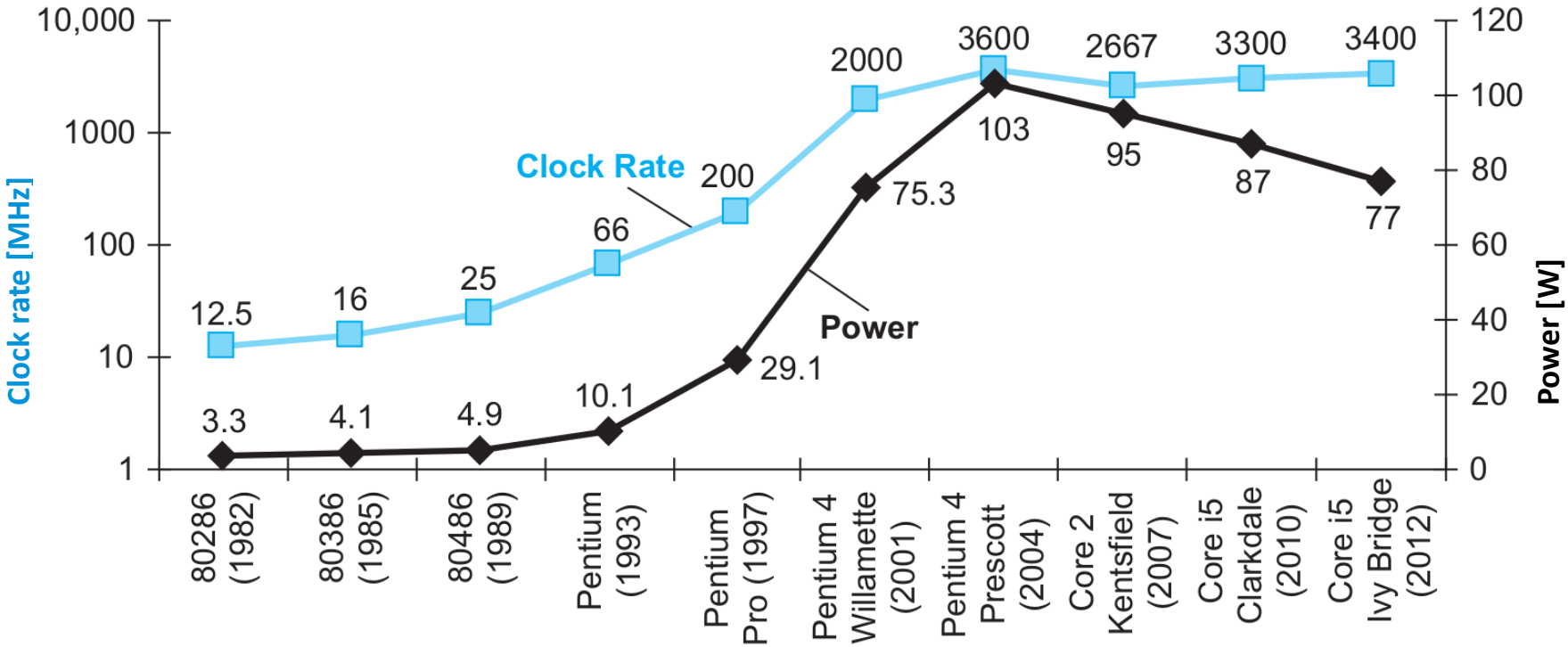
Description	Name	Instruction Count x 10^9	CPI	Clock cycle time (seconds x 10^{-9})	Execution Time (seconds)	Reference Time (seconds)	SPECratio
Interpreted string processing	perl	2252	0.60	0.376	508	9770	19.2
Block-sorting compression	bzip2	2390	0.70	0.376	629	9650	15.4
GNU C compiler	gcc	794	1.20	0.376	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

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.
    - Compared to a processor based on the previous technology,
      a new processor would only consume 52% of the power

The Power Wall (4)

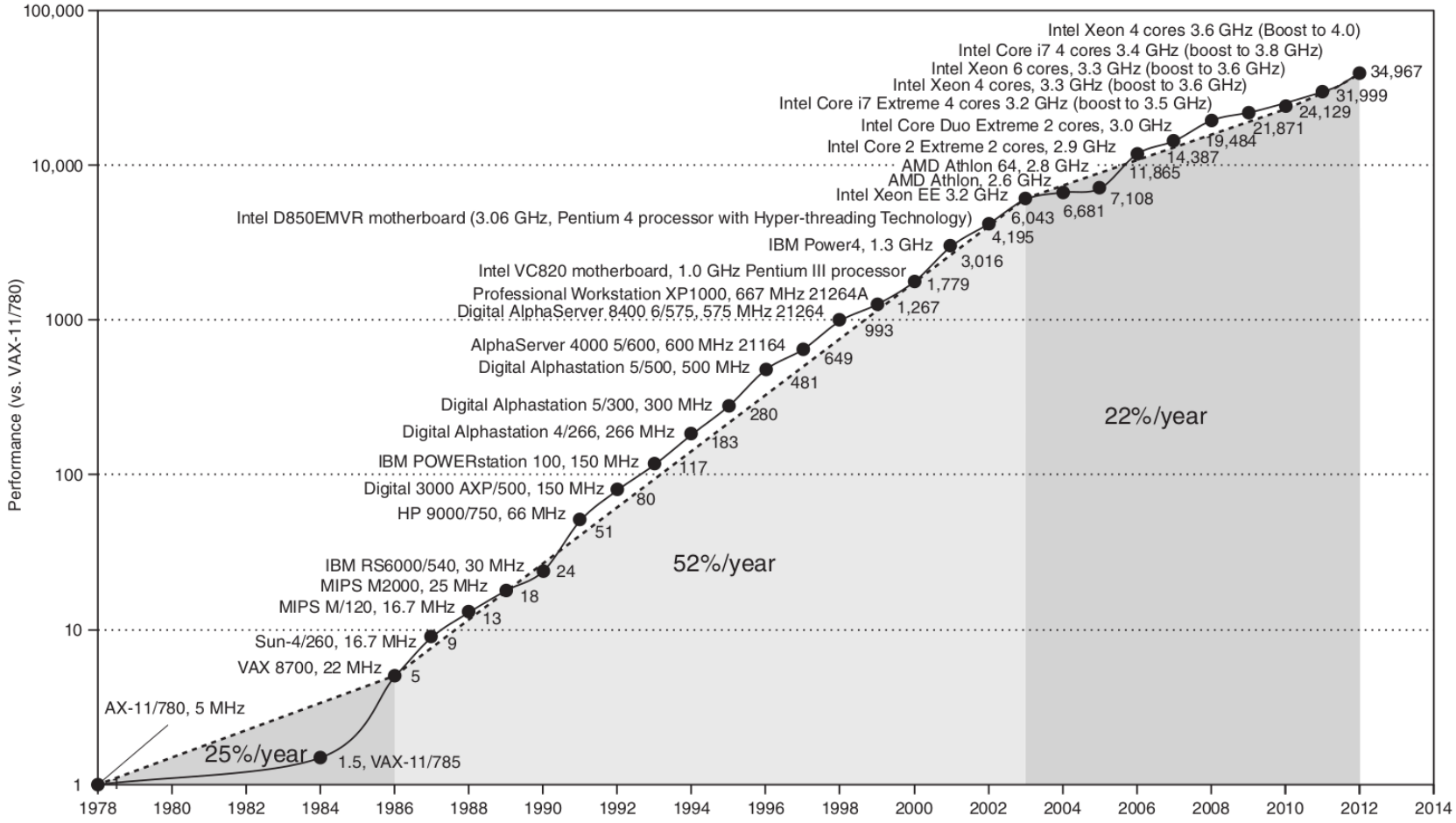
- **Further lowering of voltage difficult/impossible**
  - Makes transistors too leaky
  - 40% of power consumption in server chips is due to leakage
  - Low signal/noise ratio
    - Difficult to tell ones from zeroes reliably
- **Cooling cannot be easily improved**
  - Power dissipated from a rather 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
  - Now the whole 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)

- **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