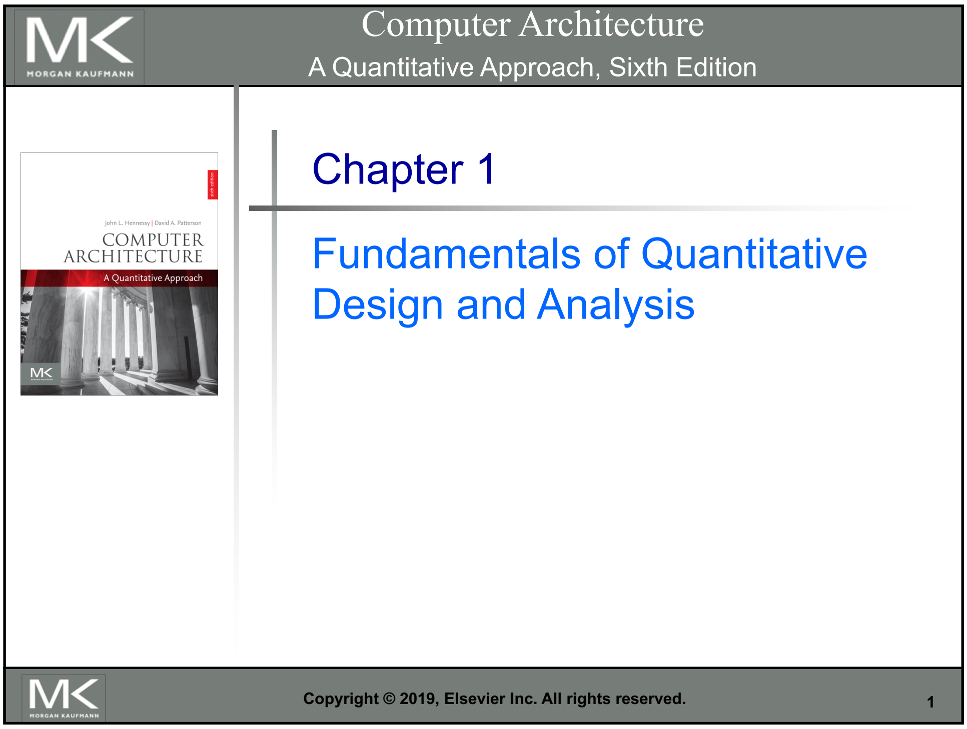


Computer Architecture

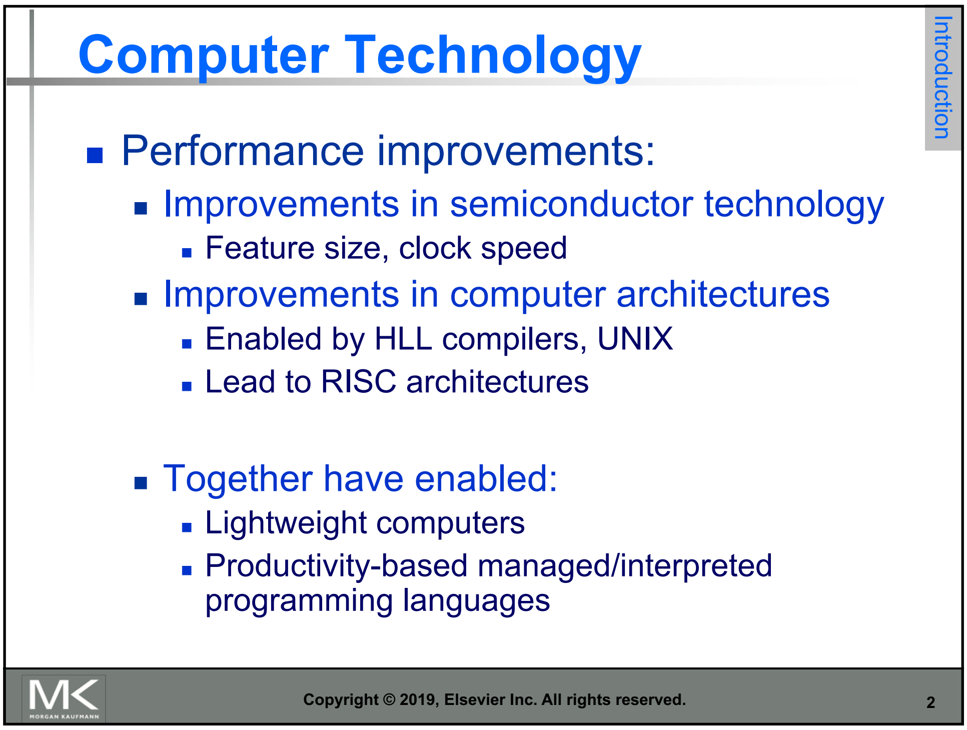
A Quantitative Approach, Sixth Edition

Chapter 1

Fundamentals of Quantitative Design and Analysis

MORGAN KAUFMANN
John L. Hennessy | David A. Patterson
COMPUTER ARCHITECTURE
A Quantitative Approach

1



Computer Technology

Introduction

- Performance improvements:
  - Improvements in semiconductor technology
    - Feature size, clock speed
  - Improvements in computer architectures
    - Enabled by HLL compilers, UNIX
    - Lead to RISC architectures
  - Together have enabled:
    - Lightweight computers
    - Productivity-based managed/interpreted programming languages

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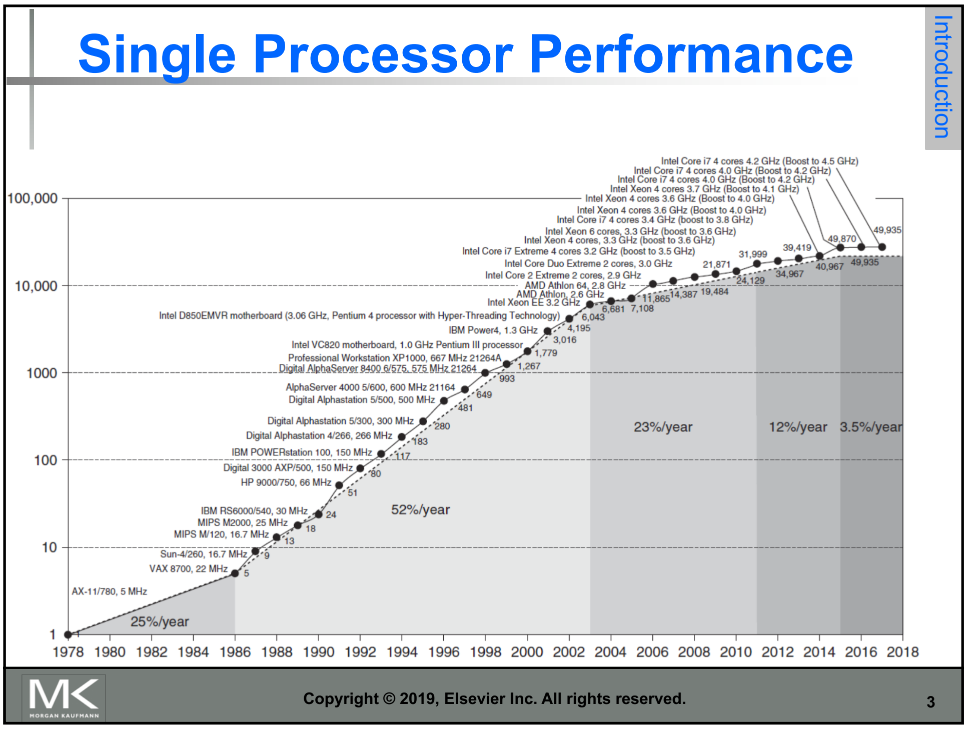

Single Processor Performance

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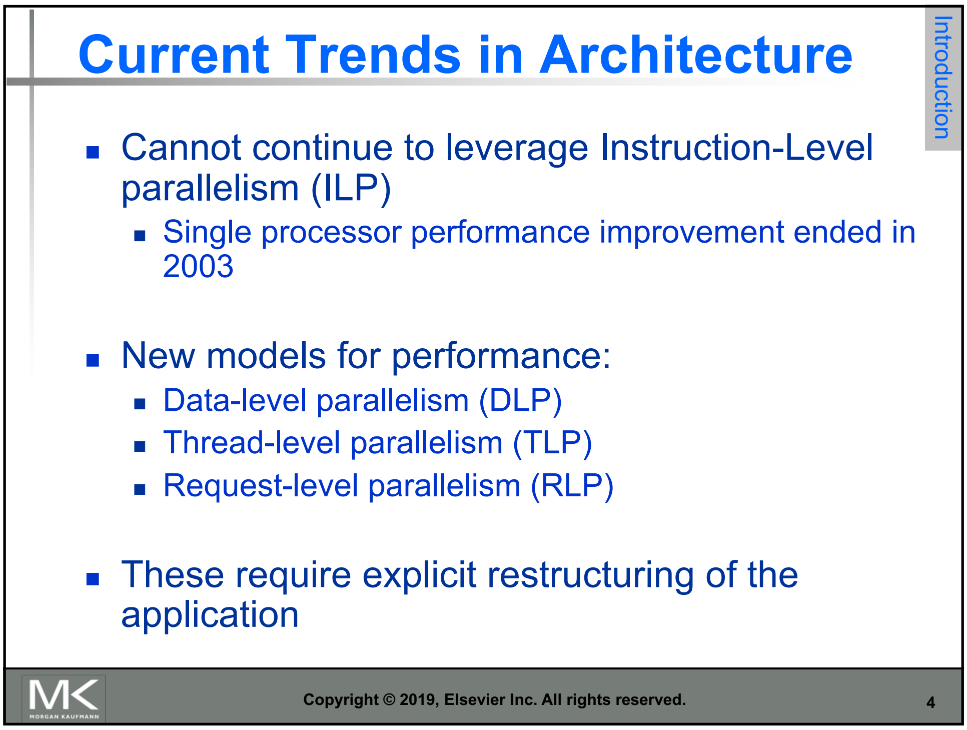

Current Trends in Architecture

Introduction
MK MORGAN KAUFMANN

- Cannot continue to leverage Instruction-Level parallelism (ILP)
  - Single processor performance improvement ended in 2003
- New models for performance:
  - Data-level parallelism (DLP)
  - Thread-level parallelism (TLP)
  - Request-level parallelism (RLP)
- These require explicit restructuring of the application

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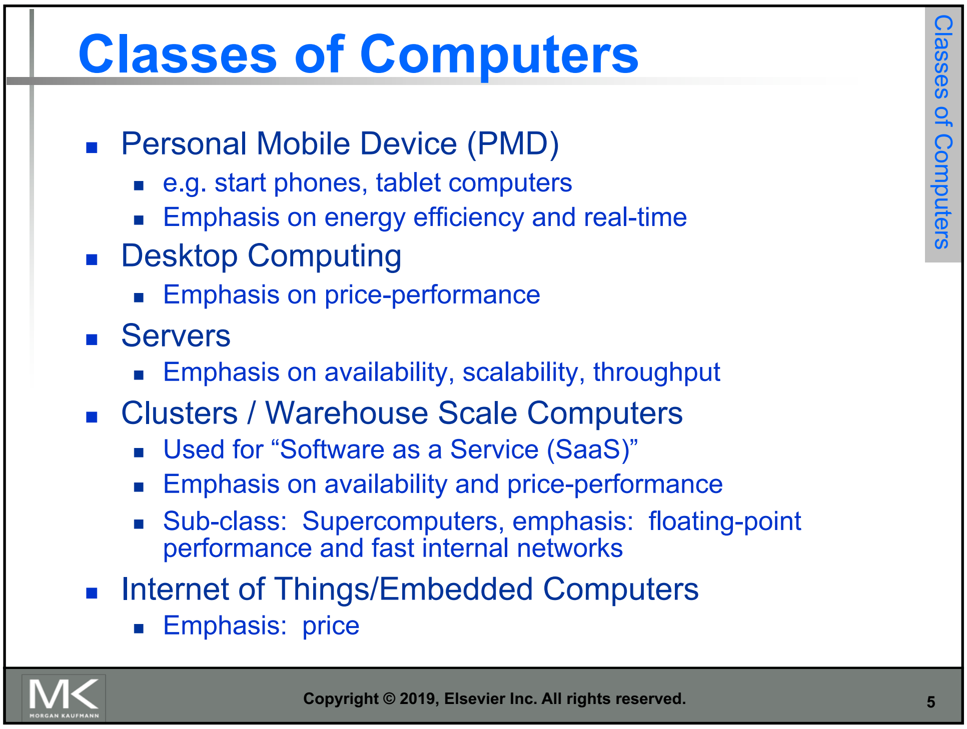
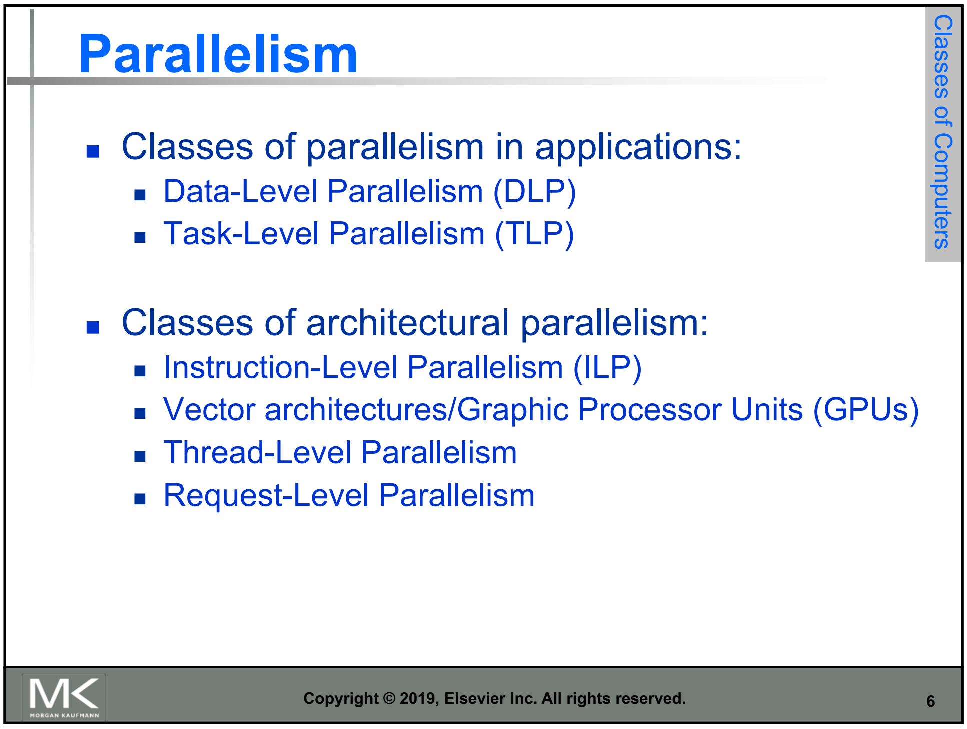


Classes of Computers

Classes of Computers

- Personal Mobile Device (PMD)
  - e.g. start phones, tablet computers
  - Emphasis on energy efficiency and real-time
- Desktop Computing
  - Emphasis on price-performance
- Servers
  - Emphasis on availability, scalability, throughput
- Clusters / Warehouse Scale Computers
  - Used for "Software as a Service (SaaS)"
  - Emphasis on availability and price-performance
  - Sub-class: Supercomputers, emphasis: floating-point performance and fast internal networks
- Internet of Things/Embedded Computers
  - Emphasis: price

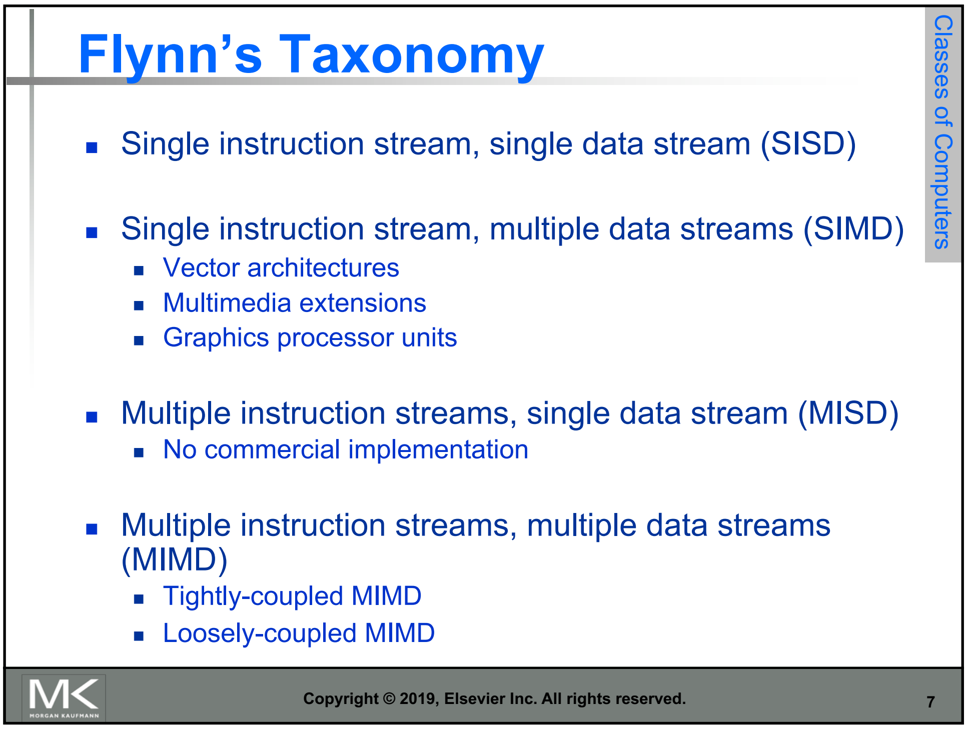


Parallelism

Classes of Computers

- Classes of parallelism in applications:
  - Data-Level Parallelism (DLP)
  - Task-Level Parallelism (TLP)

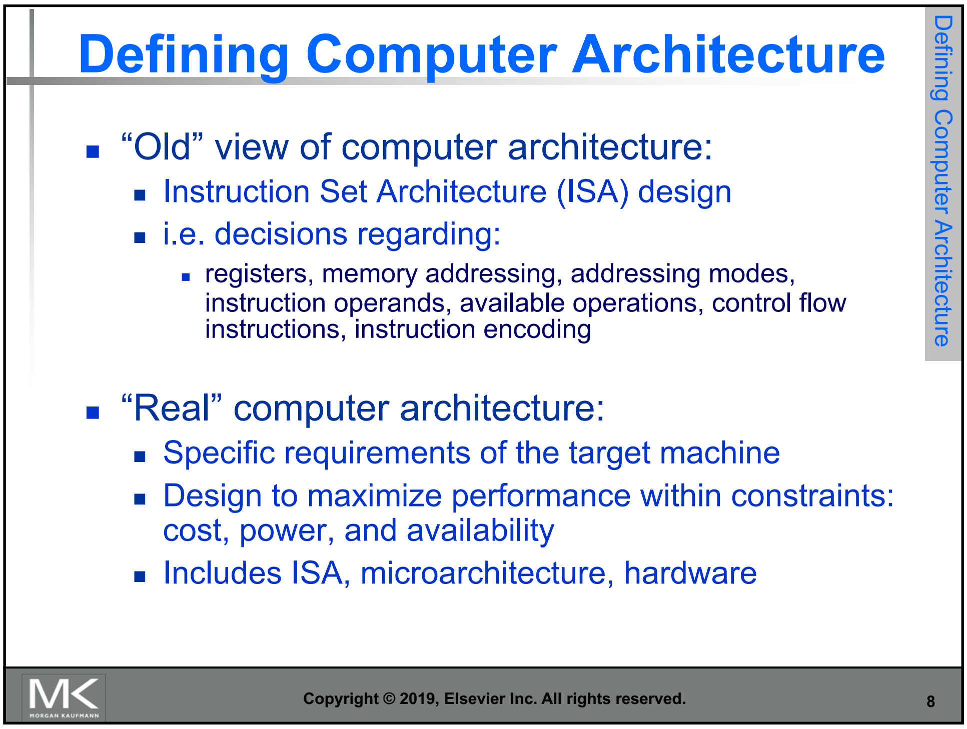
- Classes of architectural parallelism:
  - Instruction-Level Parallelism (ILP)
  - Vector architectures/Graphic Processor Units (GPUs)
  - Thread-Level Parallelism
  - Request-Level Parallelism



Flynn’s Taxonomy

Classes of Computers

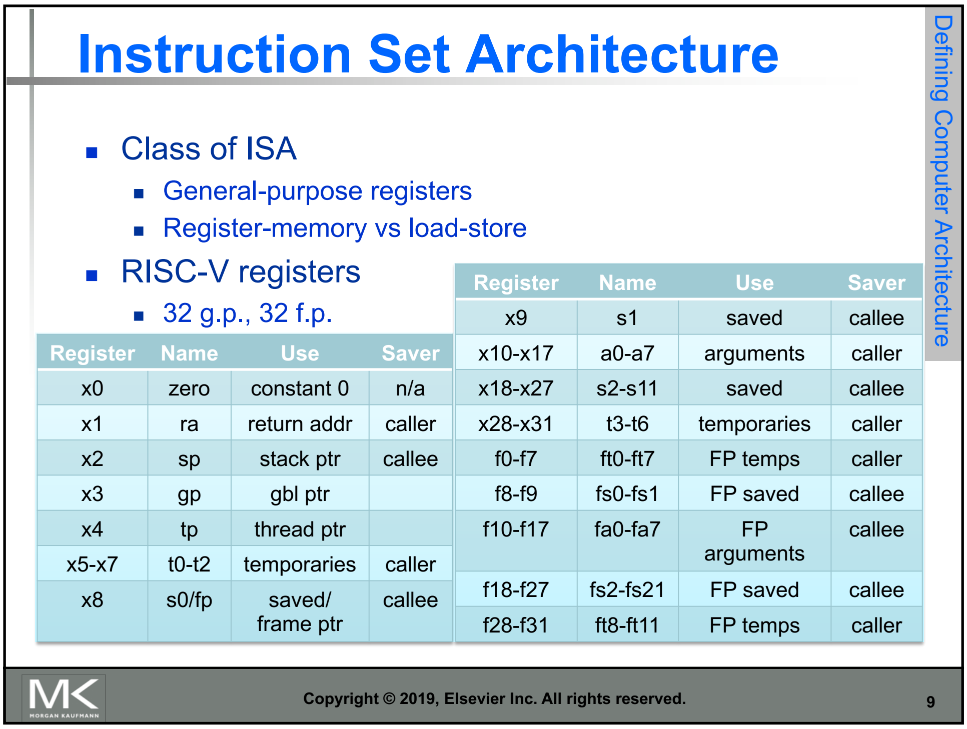
- Single instruction stream, single data stream (SISD)
- Single instruction stream, multiple data streams (SIMD)
  - Vector architectures
  - Multimedia extensions
  - Graphics processor units
- Multiple instruction streams, single data stream (MISD)
  - No commercial implementation
- Multiple instruction streams, multiple data streams (MIMD)
  - Tightly-coupled MIMD
  - Loosely-coupled MIMD



Defining Computer Architecture

Defining Computer Architecture

- “Old” view of computer architecture:
  - Instruction Set Architecture (ISA) design
  - i.e. decisions regarding:
    - registers, memory addressing, addressing modes, instruction operands, available operations, control flow instructions, instruction encoding
- “Real” computer architecture:
  - Specific requirements of the target machine
  - Design to maximize performance within constraints: cost, power, and availability
  - Includes ISA, microarchitecture, hardware



Instruction Set Architecture

- Class of ISA
  - General-purpose registers
  - Register-memory vs load-store
- RISC-V registers
  - 32 g.p., 32 f.p.

Register	Name	Use	Saver
x0	zero	constant 0	n/a
x1	ra	return addr	caller
x2	sp	stack ptr	callee
x3	gp	gbl ptr	
x4	tp	thread ptr	
x5-x7	t0-t2	temporaries	caller
x8	s0/fp	saved/ frame ptr	callee
x9	s1	saved	callee
x10-x17	a0-a7	arguments	caller
x18-x27	s2-s11	saved	callee
x28-x31	t3-t6	temporaries	caller
f0-f7	ft0-ft7	FP temps	caller
f8-f9	fs0-fs1	FP saved	callee
f10-f17	fa0-fa7	FP arguments	callee
f18-f27	fs2-fs21	FP saved	callee
f28-f31	ft8-ft11	FP temps	caller

Defining Computer Architecture

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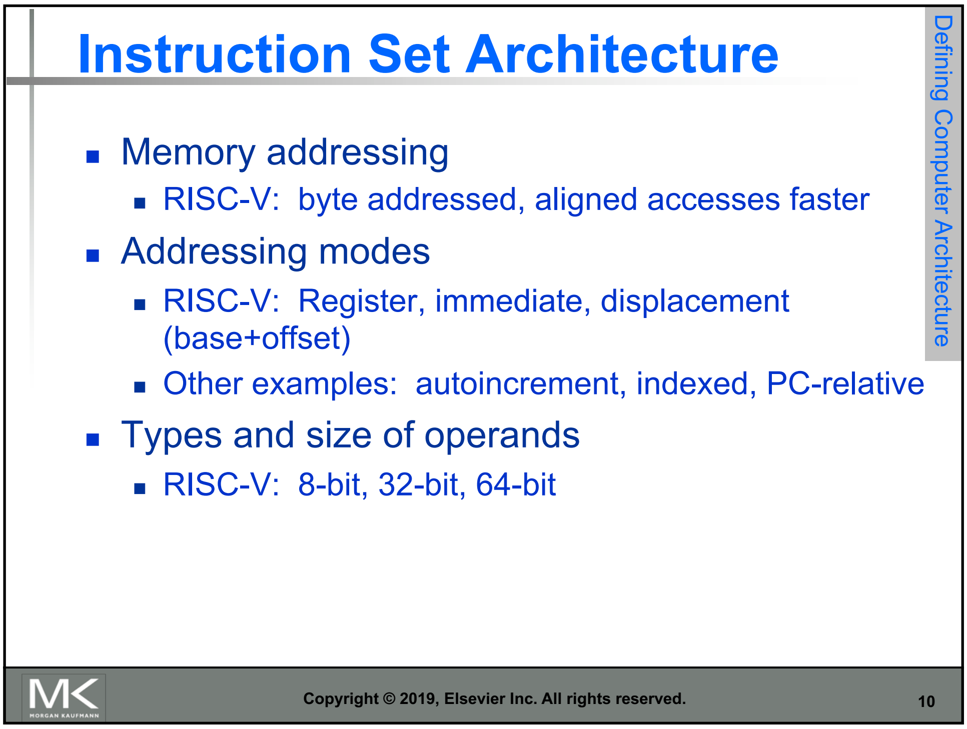

Instruction Set Architecture

- Memory addressing
  - RISC-V: byte addressed, aligned accesses faster
- Addressing modes
  - RISC-V: Register, immediate, displacement (base+offset)
  - Other examples: autoincrement, indexed, PC-relative
- Types and size of operands
  - RISC-V: 8-bit, 32-bit, 64-bit

Defining Computer Architecture

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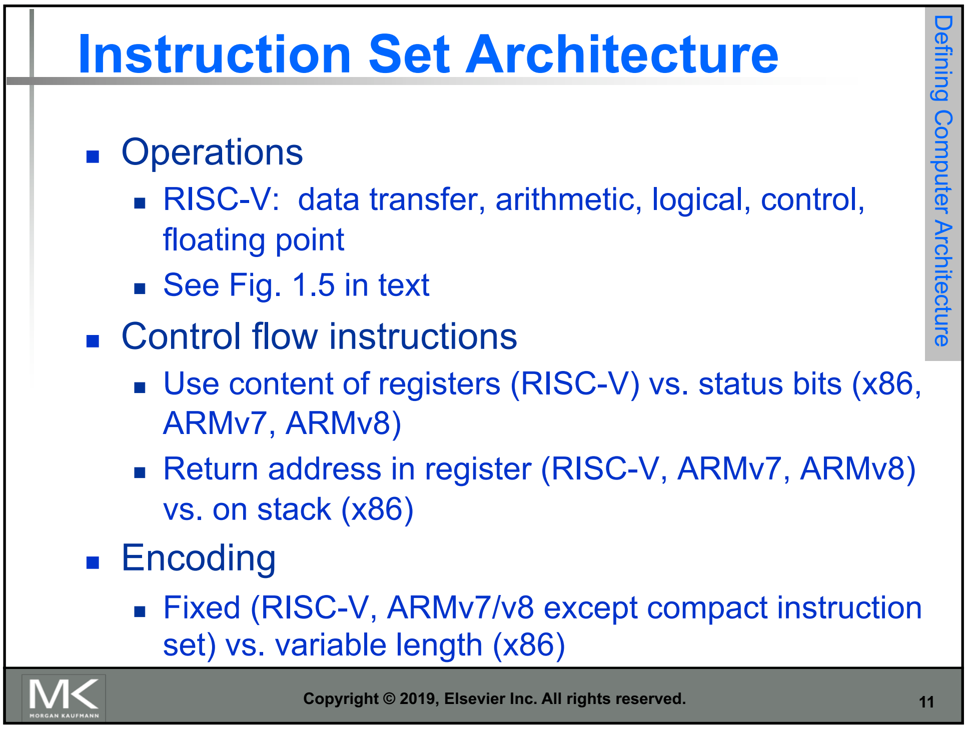

Instruction Set Architecture

Defining Computer Architecture

- Operations
  - RISC-V: data transfer, arithmetic, logical, control, floating point
  - See Fig. 1.5 in text
- Control flow instructions
  - Use content of registers (RISC-V) vs. status bits (x86, ARMv7, ARMv8)
  - Return address in register (RISC-V, ARMv7, ARMv8) vs. on stack (x86)
- Encoding
  - Fixed (RISC-V, ARMv7/v8 except compact instruction set) vs. variable length (x86)

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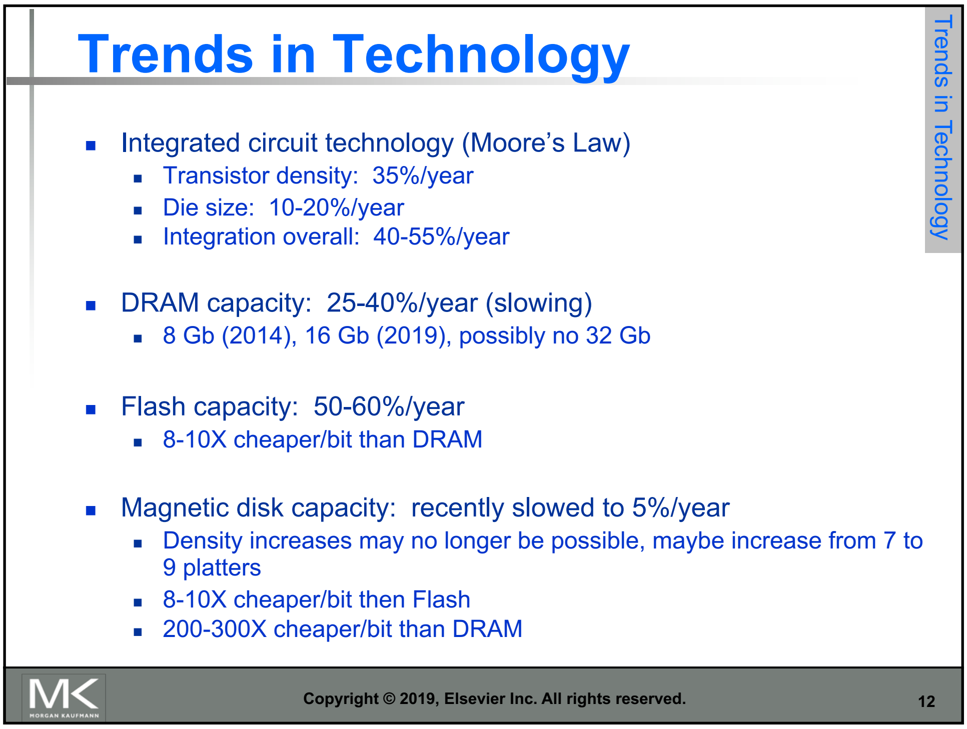

Trends in Technology

Trends in Technology

- Integrated circuit technology (Moore's Law)
  - Transistor density: 35%/year
  - Die size: 10-20%/year
  - Integration overall: 40-55%/year
- DRAM capacity: 25-40%/year (slowing)
  - 8 Gb (2014), 16 Gb (2019), possibly no 32 Gb
- Flash capacity: 50-60%/year
  - 8-10X cheaper/bit than DRAM
- Magnetic disk capacity: recently slowed to 5%/year
  - Density increases may no longer be possible, maybe increase from 7 to 9 platters
  - 8-10X cheaper/bit then Flash
  - 200-300X cheaper/bit than DRAM

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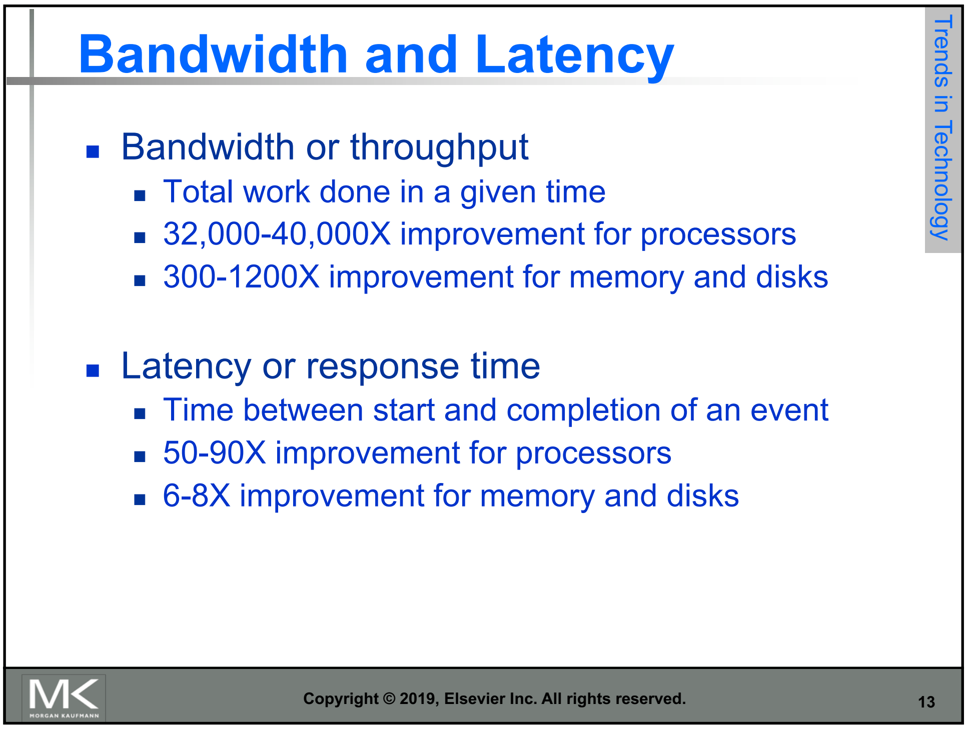

Bandwidth and Latency

Trends in Technology

- Bandwidth or throughput
  - Total work done in a given time
  - 32,000-40,000X improvement for processors
  - 300-1200X improvement for memory and disks
- Latency or response time
  - Time between start and completion of an event
  - 50-90X improvement for processors
  - 6-8X improvement for memory and disks

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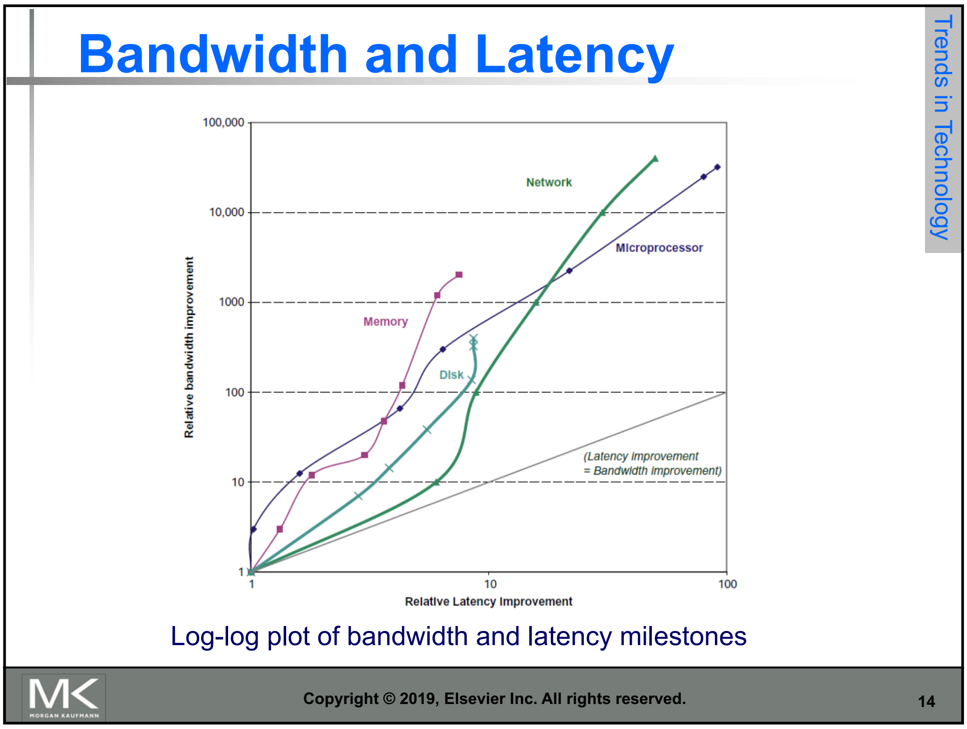

Bandwidth and Latency

Trends in Technology

Log-log plot of bandwidth and latency milestones

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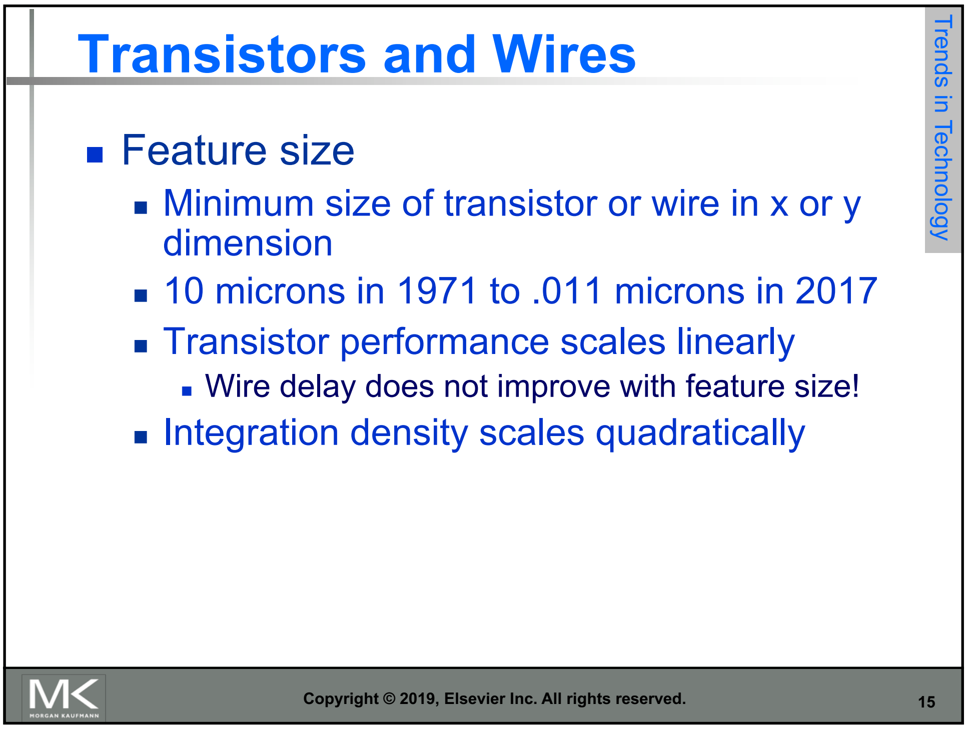
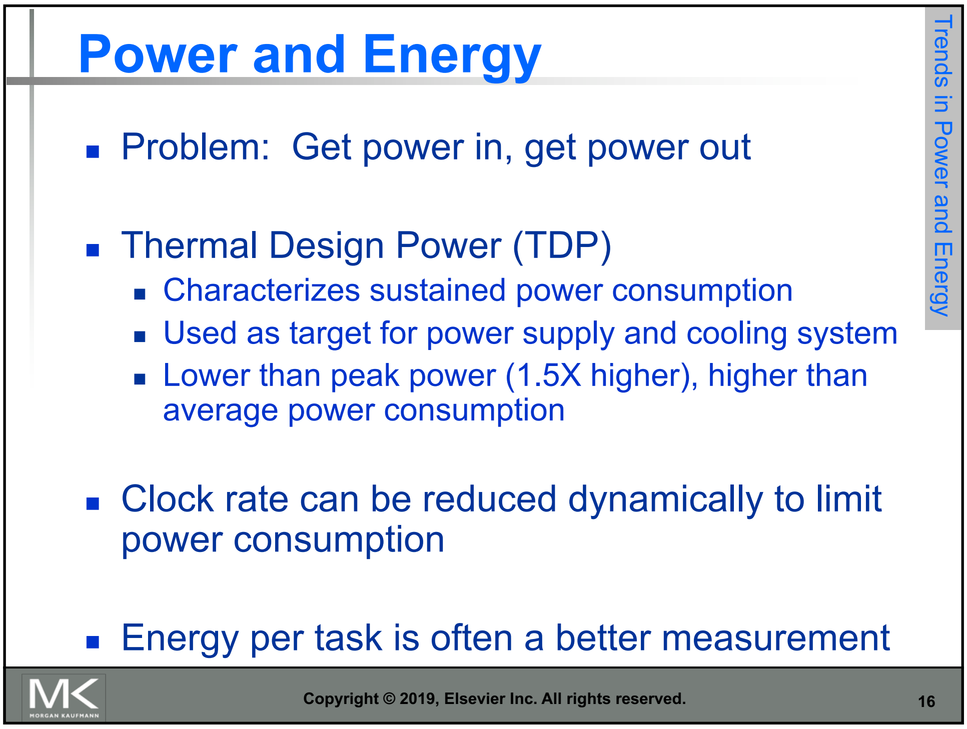


Transistors and Wires

Trends in Technology

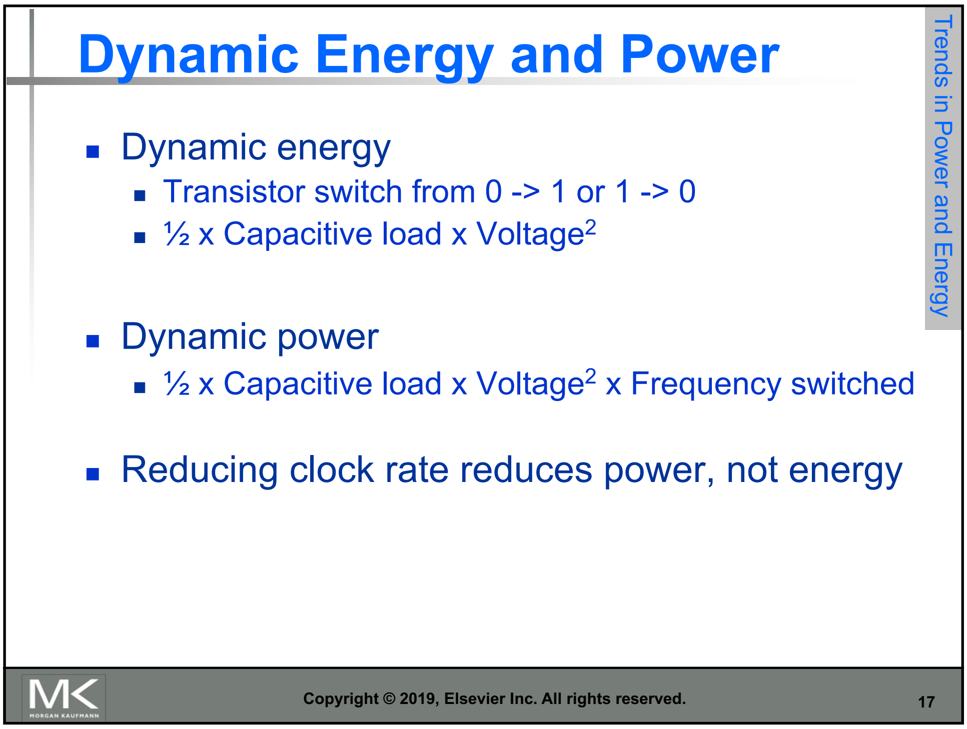
- Feature size
  - Minimum size of transistor or wire in x or y dimension
  - 10 microns in 1971 to .011 microns in 2017
  - Transistor performance scales linearly
    - Wire delay does not improve with feature size!
  - Integration density scales quadratically



Power and Energy

Trends in Power and Energy

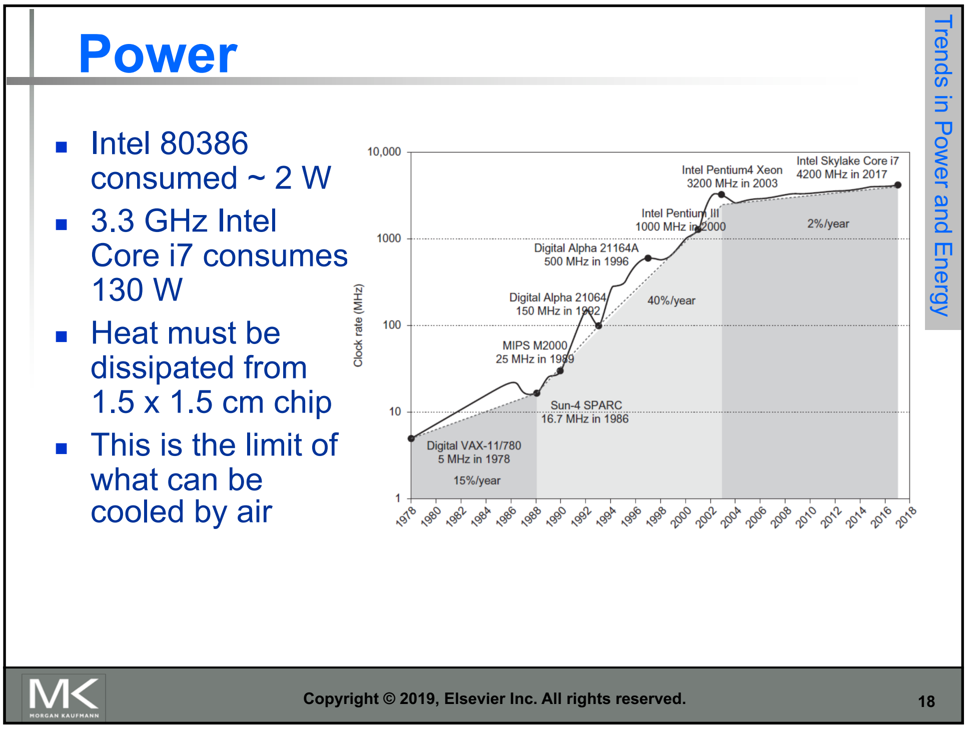
- Problem: Get power in, get power out
- Thermal Design Power (TDP)
  - Characterizes sustained power consumption
  - Used as target for power supply and cooling system
  - Lower than peak power (1.5X higher), higher than average power consumption
- Clock rate can be reduced dynamically to limit power consumption
- Energy per task is often a better measurement



Dynamic Energy and Power

Trends in Power and Energy

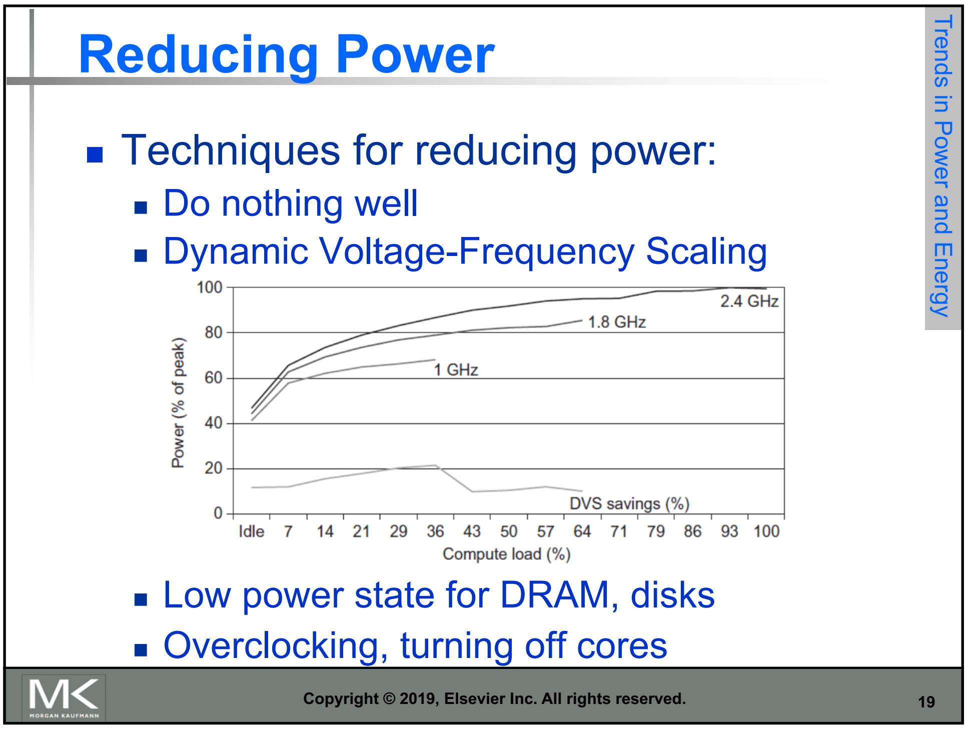
- Dynamic energy
  - Transistor switch from 0 -> 1 or 1 -> 0
  - ½ x Capacitive load x Voltage^2
- Dynamic power
  - ½ x Capacitive load x Voltage^2 x Frequency switched
- Reducing clock rate reduces power, not energy



Power

Trends in Power and Energy

- Intel 80386 consumed ~ 2 W
- 3.3 GHz Intel Core i7 consumes 130 W
- Heat must be dissipated from 1.5 x 1.5 cm chip
- This is the limit of what can be cooled by air

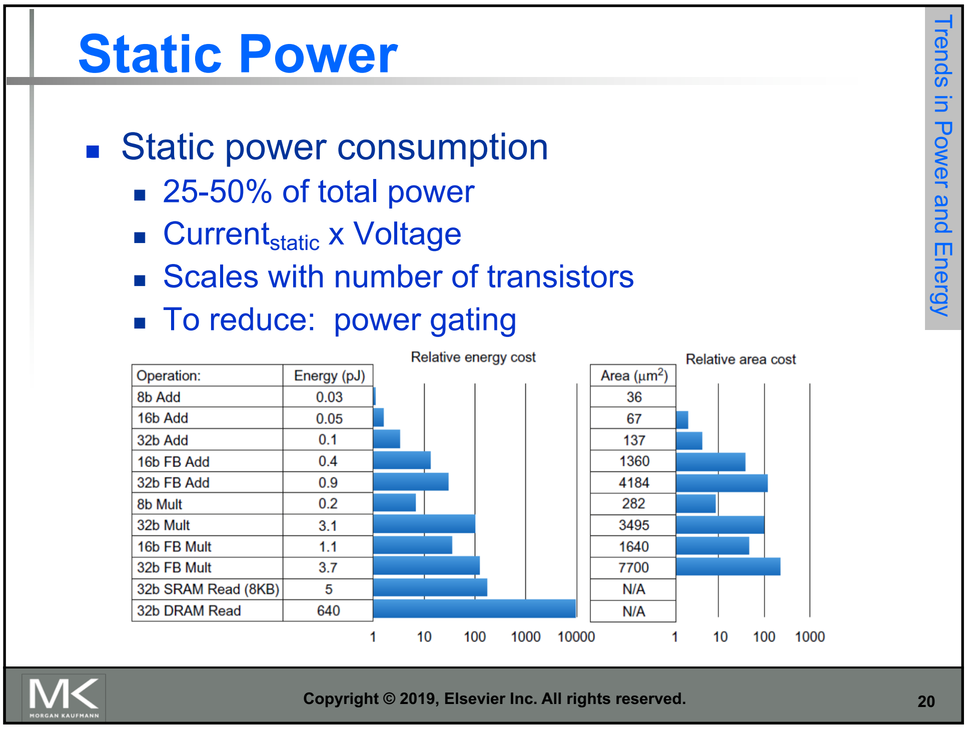


Reducing Power

- Techniques for reducing power:
  - Do nothing well
  - Dynamic Voltage-Frequency Scaling

  - Low power state for DRAM, disks
  - Overclocking, turning off cores

Trends in Power and Energy

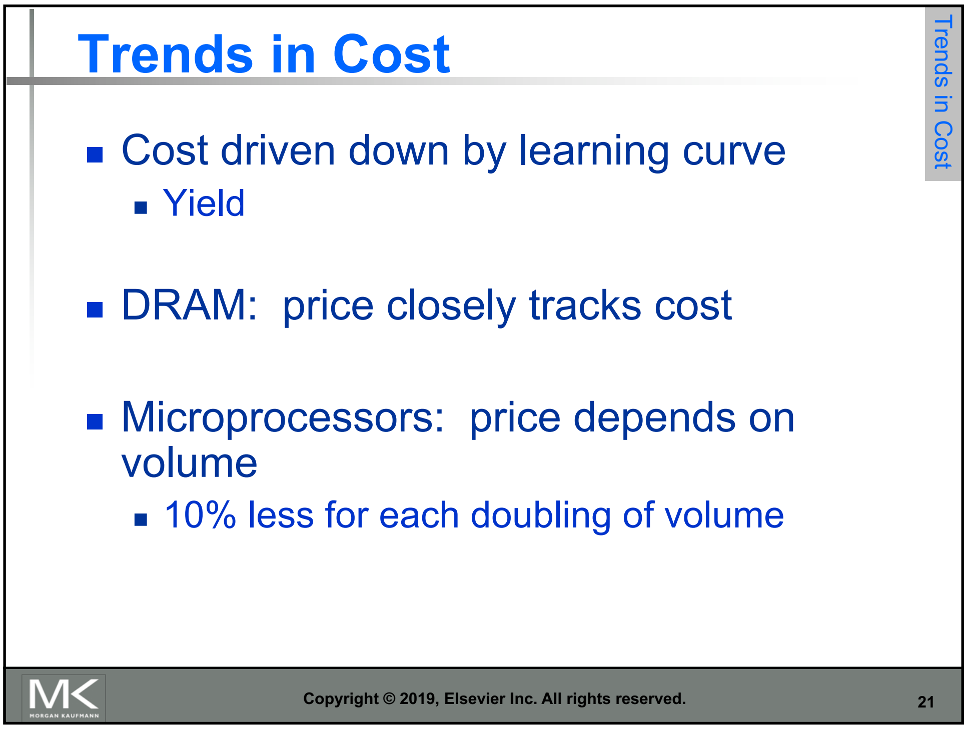


Static Power

- Static power consumption
  - 25-50% of total power
  - Current$_{static}$ x Voltage
  - Scales with number of transistors
  - To reduce: power gating

Operation:	Energy (pJ)	Area (μm^2)
8b Add	0.03	36
16b Add	0.05	67
32b Add	0.1	137
16b FB Add	0.4	1360
32b FB Add	0.9	4184
8b Mult	0.2	282
32b Mult	3.1	3495
16b FB Mult	1.1	1640
32b FB Mult	3.7	7700
32b SRAM Read (8KB)	5	N/A
32b DRAM Read	640	N/A

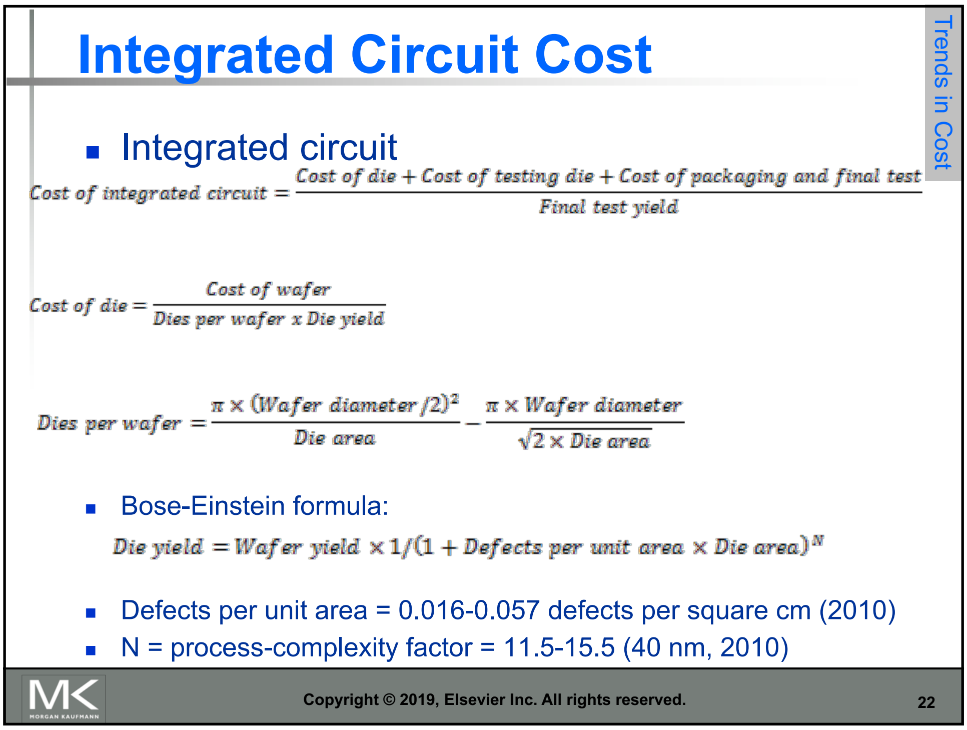
Trends in Power and Energy



Trends in Cost

- Cost driven down by learning curve
  - Yield
- DRAM: price closely tracks cost
- Microprocessors: price depends on volume
  - 10% less for each doubling of volume

Trends in Cost



Integrated Circuit Cost

- Integrated circuit

$$\mathit{Cost\ of\ integrated\ circuit} = \frac{\mathit{Cost\ of\ die} + \mathit{Cost\ of\ testing\ die} + \mathit{Cost\ of\ packaging\ and\ final\ test}}{\mathit{Final\ test\ yield}}$$

$$\mathit{Cost\ of\ die} = \frac{\mathit{Cost\ of\ wafer}}{\mathit{Dies\ per\ wafer\ x\ Die\ yield}}$$

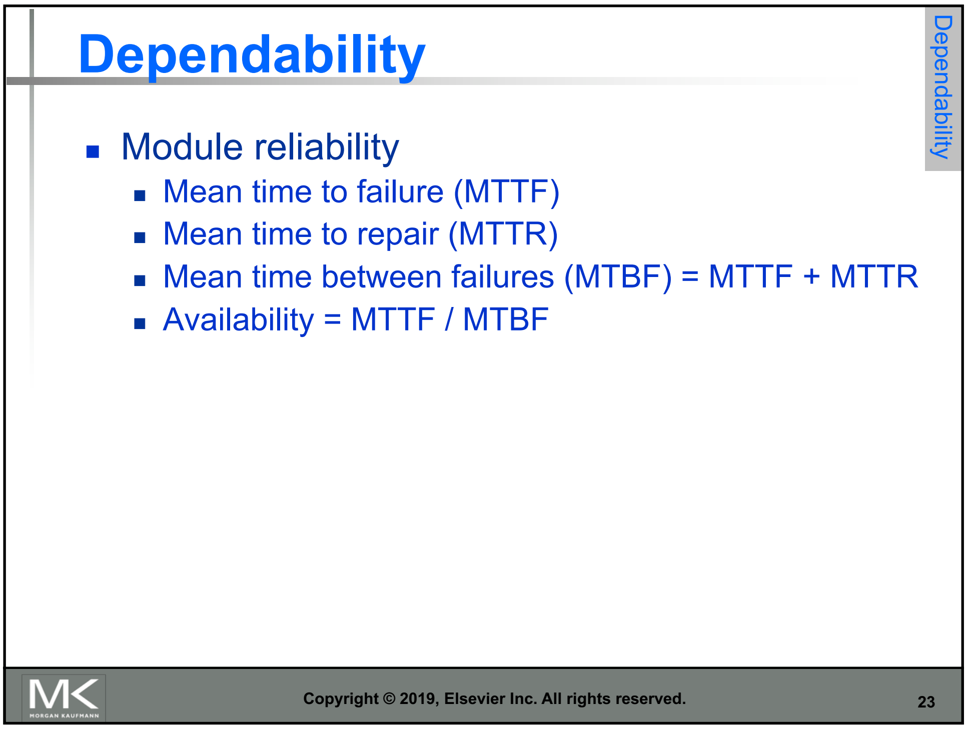
$$\mathit{Dies\ per\ wafer} = \frac{\pi \times (\mathit{Wafer\ diameter}/2)^2}{\mathit{Die\ area}} - \frac{\pi \times \mathit{Wafer\ diameter}}{\sqrt{2 \times \mathit{Die\ area}}}$$

- Bose-Einstein formula:

$$\mathit{Die\ yield} = \mathit{Wafer\ yield} \times 1/(1 + \mathit{Defects\ per\ unit\ area} \times \mathit{Die\ area})^N$$

- Defects per unit area = 0.016-0.057 defects per square cm (2010)
- N = process-complexity factor = 11.5-15.5 (40 nm, 2010)

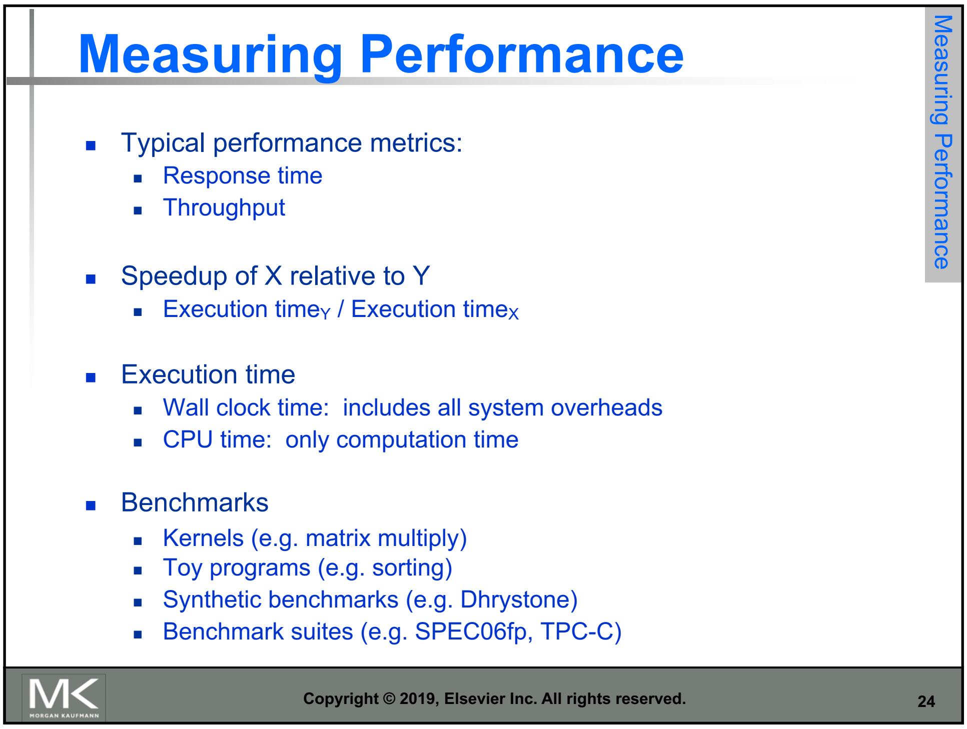
Trends in Cost



Dependability

Dependability

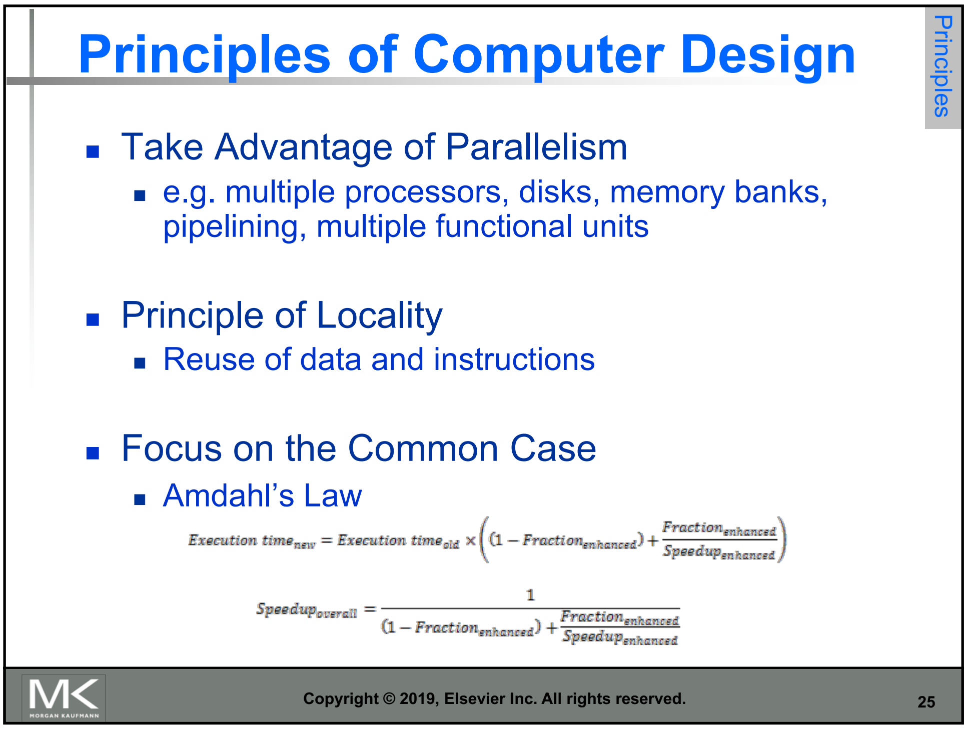
- Module reliability
  - Mean time to failure (MTTF)
  - Mean time to repair (MTTR)
  - Mean time between failures (MTBF) = MTTF + MTTR
  - Availability = MTTF / MTBF



Measuring Performance

Measuring Performance

- Typical performance metrics:
  - Response time
  - Throughput
- Speedup of X relative to Y
  - Execution time$_Y$ / Execution time$_X$
- Execution time
  - Wall clock time: includes all system overheads
  - CPU time: only computation time
- Benchmarks
  - Kernels (e.g. matrix multiply)
  - Toy programs (e.g. sorting)
  - Synthetic benchmarks (e.g. Dhrystone)
  - Benchmark suites (e.g. SPEC06fp, TPC-C)



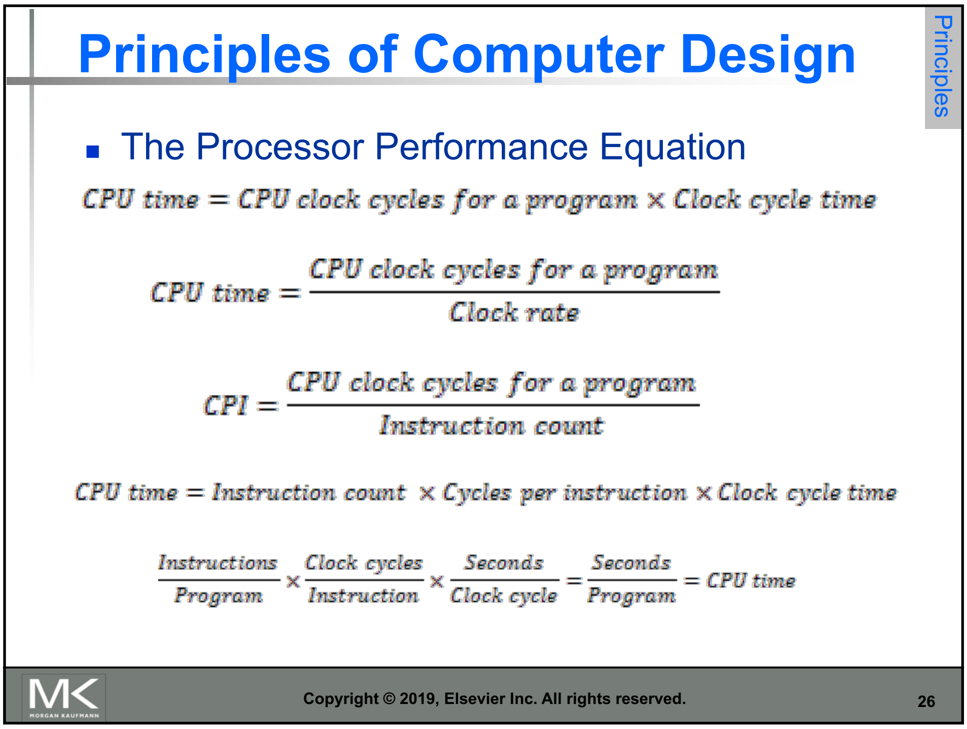
Principles of Computer Design

Principles

- Take Advantage of Parallelism
  - e.g. multiple processors, disks, memory banks, pipelining, multiple functional units
- Principle of Locality
  - Reuse of data and instructions
- Focus on the Common Case
  - Amdahl's Law

$$Execution\ time_{new} = Execution\ time_{old} \times \left((1 - Fraction_{enhanced}) + \frac{Fraction_{enhanced}}{Speedup_{enhanced}} \right)$$

$$Speedup_{overall} = \frac{1}{(1 - Fraction_{enhanced}) + \frac{Fraction_{enhanced}}{Speedup_{enhanced}}}$$



Principles of Computer Design

Principles

- The Processor Performance Equation

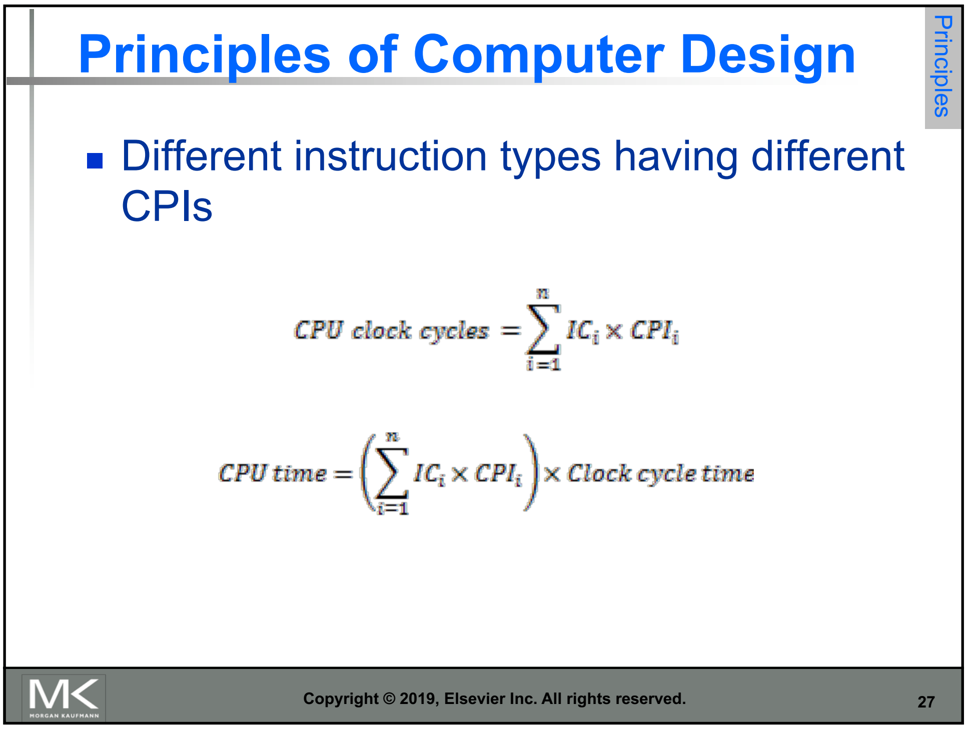
$$CPU\ time = CPU\ clock\ cycles\ for\ a\ program \times Clock\ cycle\ time$$

$$CPU\ time = \frac{CPU\ clock\ cycles\ for\ a\ program}{Clock\ rate}$$

$$CPI = \frac{CPU\ clock\ cycles\ for\ a\ program}{Instruction\ count}$$

$$CPU\ time = Instruction\ count\ \times Cycles\ per\ instruction \times Clock\ cycle\ time$$

$$\frac{Instructions}{Program} \times \frac{Clock\ cycles}{Instruction} \times \frac{Seconds}{Clock\ cycle} = \frac{Seconds}{Program} = CPU\ time$$



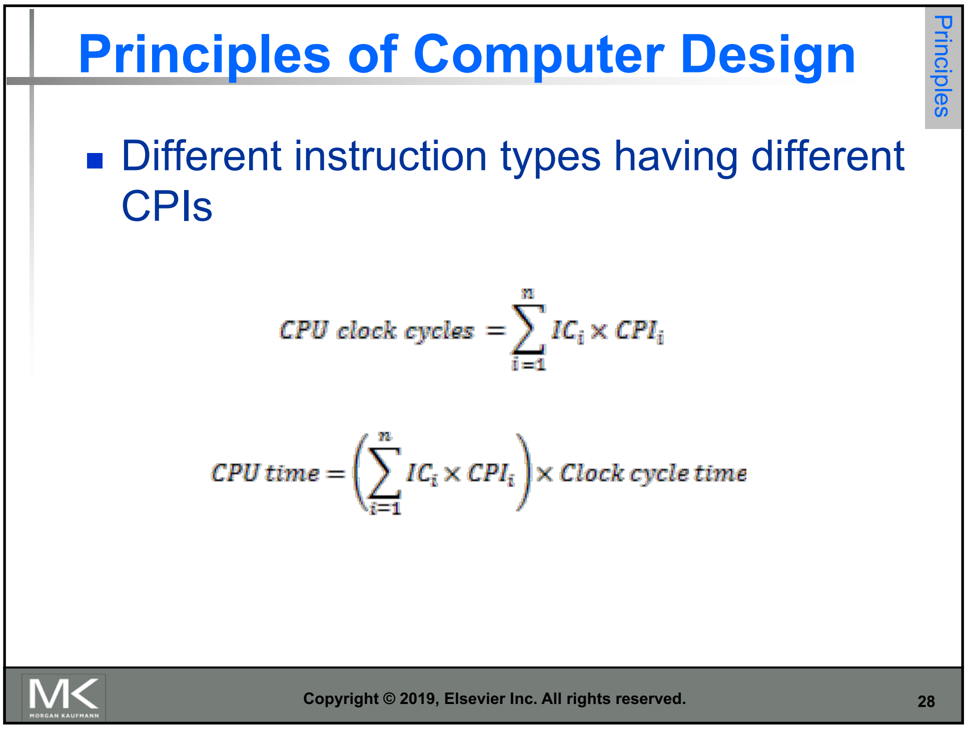
Principles of Computer Design

- Different instruction types having different CPIs

$$CPU\ clock\ cycles = \sum_{i=1}^{n} IC_i \times CPI_i$$

$$CPU\ time = \left(\sum_{i=1}^{n} IC_i \times CPI_i\right) \times Clock\ cycle\ time$$

Principles



Principles of Computer Design

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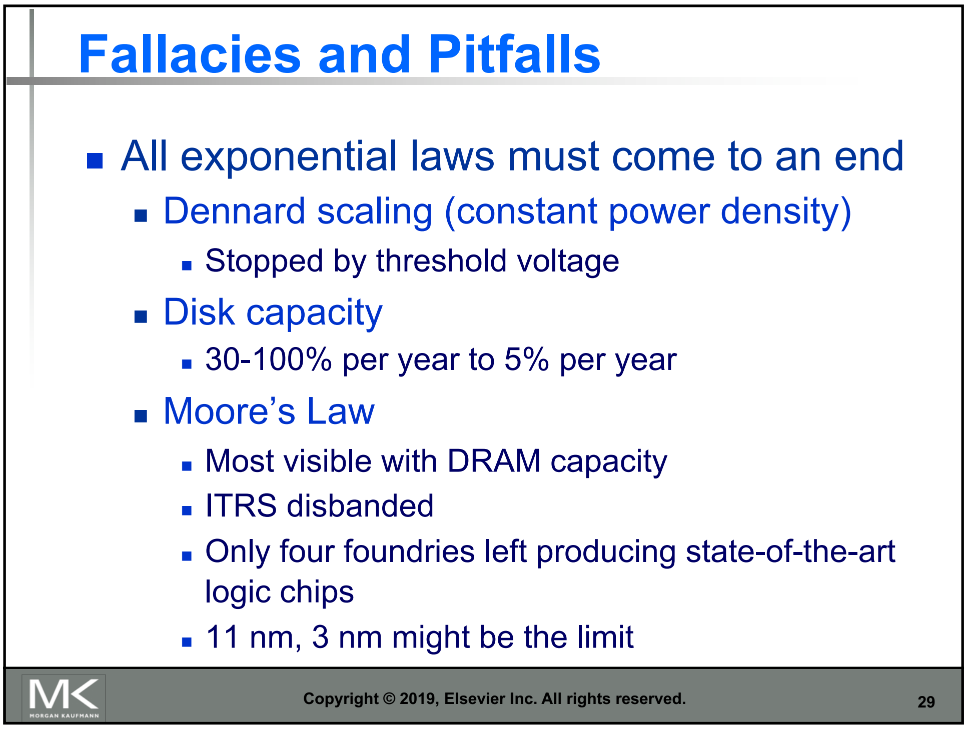
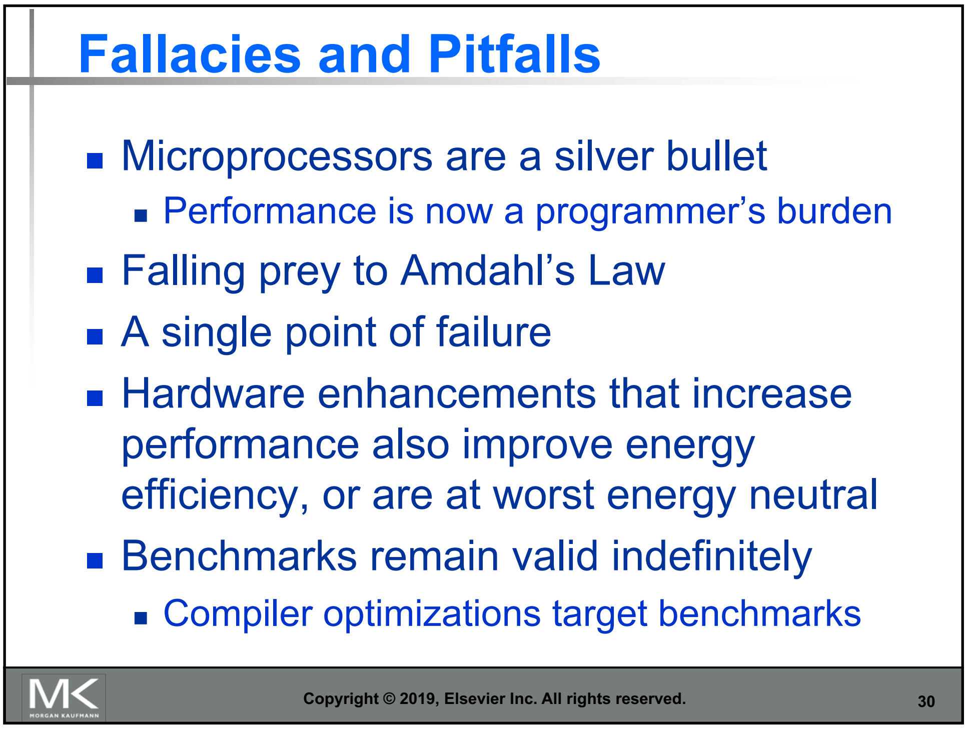
Principles



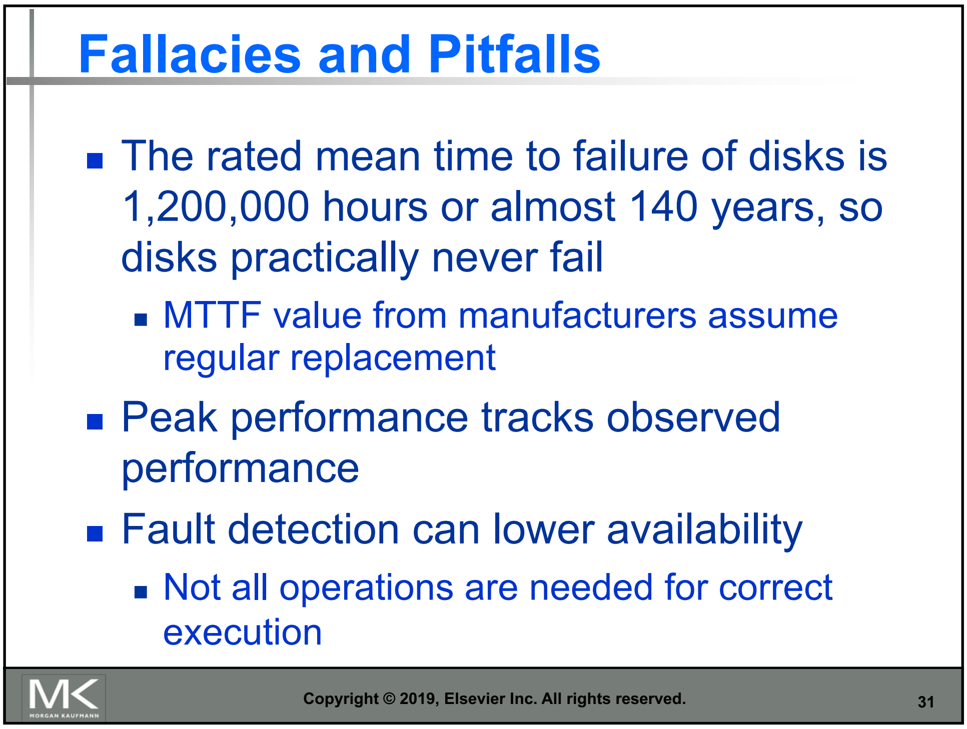
Fallacies and Pitfalls

- All exponential laws must come to an end
  - Dennard scaling (constant power density)
    - Stopped by threshold voltage
  - Disk capacity
    - 30-100% per year to 5% per year
  - Moore's Law
    - Most visible with DRAM capacity
    - ITRS disbanded
    - Only four foundries left producing state-of-the-art logic chips
    - 11 nm, 3 nm might be the limit



Fallacies and Pitfalls

- Microprocessors are a silver bullet
  - Performance is now a programmer's burden
- Falling prey to Amdahl's Law
- A single point of failure
- Hardware enhancements that increase performance also improve energy efficiency, or are at worst energy neutral
- Benchmarks remain valid indefinitely
  - Compiler optimizations target benchmarks



Fallacies and Pitfalls

- The rated mean time to failure of disks is 1,200,000 hours or almost 140 years, so disks practically never fail
  - MTTF value from manufacturers assume regular replacement
- Peak performance tracks observed performance
- Fault detection can lower availability
  - Not all operations are needed for correct execution