

# *Chapter 1: Fundamentals of Computer Design (Part 2)*

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What is computer architecture?

Why study computer architecture?

## **Common principles**

Performance

What is performance: latency, throughput

The performance equation

Measuring performance

Improving performance: parallelism, locality, Amdahl's law

Power

Cost

Reliability

# ***What is Performance?***

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## Two Metrics

Latency (or response time or execution time)

Throughput (or bandwidth)

# ***What is Performance?\****

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## Two Metrics

Latency (or response time or execution time)

Time from start to finish of a task

Throughput (or bandwidth)

# *What is Performance?\**

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## Two Metrics

Latency (or response time or execution time)

Time from start to finish of a task

Throughput (or bandwidth)

Rate of task completion

= Rate of task initiation

=  $1 / (\text{time between task completions})$

# *What is Performance?\**

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## Two Metrics

Latency (or response time or execution time)

Time from start to finish of a task

Throughput (or bandwidth)

Rate of task completion

= Rate of task initiation

=  $1 / (\text{time between task completions})$

Example: Automobile assembly line starts one car per hour and holds 20 cars

Latency = 20 hours

Throughput = one car per hour

Throughput  $> 1/\text{Latency}$  due to overlap

## *Performance (Cont.)*

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Definition: X is n% faster than Y if

$$\frac{\textit{Execution Time}_Y}{\textit{Execution Time}_X} = 1 + \frac{n}{100}$$

Example: X = 1 minute, Y = 2 minutes

X is 100% faster than Y

# Key Performance Equation

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$$CPU_{time} = \frac{instructions}{program} \times \frac{cycles}{instruction} \times \frac{time}{cycle}$$

Instructions per program (path length)

ISA and compiler

Cycles per instruction (CPI)

ISA and organization (e.g., cache misses)

Time per cycle (clock time, cycle time)

Organization and hardware

# Measuring Performance

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MIPS, MFLOPS don't mean much

Benchmarks

Real programs

Representative of real workload

Only way to characterize performance

SPEC89 → SPEC92 → SPEC95 → SPEC CPU2000 → CPU2006 →  
CPU2017

SPECFS, SPECWeb, SPECjbb, SPECvirt\_Sc2010, TPC

Kernels

``Representative'' program fragments

Often not representative of full applications

EEMBC for embedded systems

Toy benchmarks and synthetic benchmarks

Don't mean much



# *Improving Performance – Basic Principles*

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Parallelism

Locality

Focus on common case – Amdahl's law

# *Improving Performance – Basic Principles\*\**

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Parallelism

Pipelining (review next)

Multiple issue

Multiprocessors

Locality

Focus on common case – Amdahl's law

# *Improving Performance – Basic Principles\*\**

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Parallelism

Pipelining (review next)

Multiple issue

Multiprocessors

Locality

Caches (review later)

Focus on common case – Amdahl's law

# Amdahl's Law

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(Or why the common case matters most)

Let

$$\text{Speedup} = \frac{\text{new rate}}{\text{old rate}} = \frac{\text{old latency}}{\text{new latency}}$$

Consider an enhancement  $x$  that speeds up fraction  $f_x$  of a task by  $S_x$

$$\begin{aligned} \text{Speedup}_{\text{overall}} &= \frac{\text{old latency}}{\text{new latency}} \\ &= \frac{\{(1 - f_x) + (f_x)\} \times \text{old latency}}{(1 - f_x) \times \text{old latency} + f_x / S_x \times \text{old latency}} \end{aligned}$$

Amdahl's law gives

$$\text{Speedup}_{\text{overall}} = \frac{1}{(1 - f_x) + f_x / S_x}$$

## Amdahl's Law, cont.

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Example:  $f_x = 95\%$  and  $S_x = 1.10$

$$\text{Speedup}_{overall} = \frac{1}{(1 - 0.95) + (0.95/1.10)} = 1.094$$

Example:  $f_x = 5\%$  and  $S_x = 10$

$$\text{Speedup}_{overall} = \frac{1}{(1 - 0.05) + (0.05/10)} = 1.047$$

Example:  $f_x = 5\%$  and  $S_x = \infty$

$$\text{Speedup}_{overall} = \frac{1}{(1 - 0.05) + (0.05/\infty)} = 1.052$$

## Amdahl's Law Corollary

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Since  $S_x \rightarrow \infty$  implies

$$Speedup_{overall} = \frac{1}{(1 - f_x) + (f_x / \infty)}$$

For all real speedups:

$$Speedup_{overall} < \frac{1}{1 - f_x}$$

Example

| $f_x$ | $1/(1-f_x)$ |
|-------|-------------|
| 1%    | 1.01        |
| 2%    | 1.02        |
| 5%    | 1.05        |
| 10%   | 1.11        |
| 20%   | 1.25        |
| 50%   | 2.00        |

*Or make the common case fast*

An application?

# *Power*

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Power

Energy

Temperature

# *Power\*\**

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Power = Voltage x Current

Energy = Power x Time

Temperature = Complex function of power, determined by max power drawn (averaged over short intervals)



# *Power and Energy*

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Power = Dynamic power + Static power

Energy = Power \* Time

Dynamic Power  $\propto$  Capacitance \* Voltage<sup>2</sup> \* Frequency

Static power = Static current \* Voltage

# *Power and Energy\*\**

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Clock gating reduces switching to reduce power

Reducing voltage reduces power

But also requires reducing frequency

Increases execution time

But reduction in power (and energy) more than increase in time

*Dynamic voltage-frequency scaling (DVFS)*

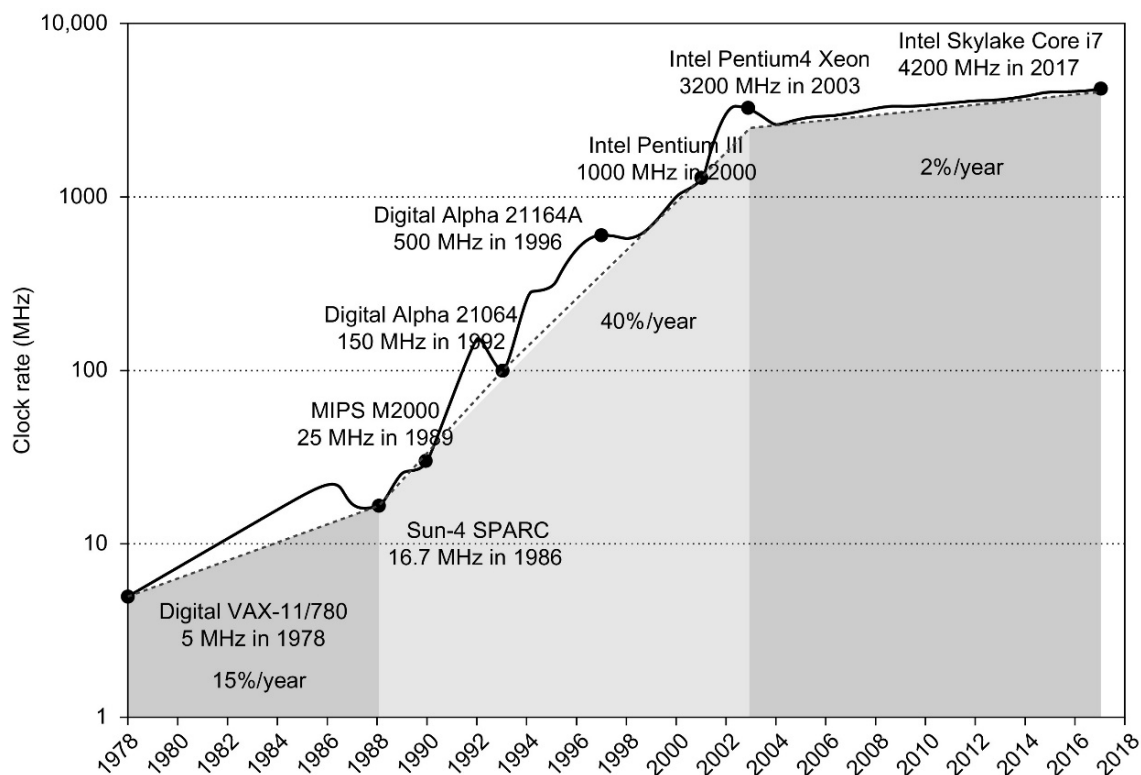
Static power = Static current \* Voltage

Power gating reduces static (and dynamic) power

System strategy for energy: Race-to-halt

New reality: Dark Silicon

# Growth in Clock Rate



**Figure 1.11 Growth in clock rate of microprocessors in Figure 1.1.** Between 1978 and 1986, the clock rate improved less than 15% per year while performance improved by 22% per year. During the “renaissance period” of 52% performance improvement per year between 1986 and 2003, clock rates shot up almost 40% per year. Since then, the clock rate has been nearly flat, growing at less than 2% per year, while single processor performance improved recently at just 3.5% per year.

# *Cost*

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Cost is very important in most real designs

But usually hard to quantify for the architect

Costs change over time

Learning curve lowers manufacturing costs

Technology improvements lower costs

Focus on IC costs next

# A Wafer

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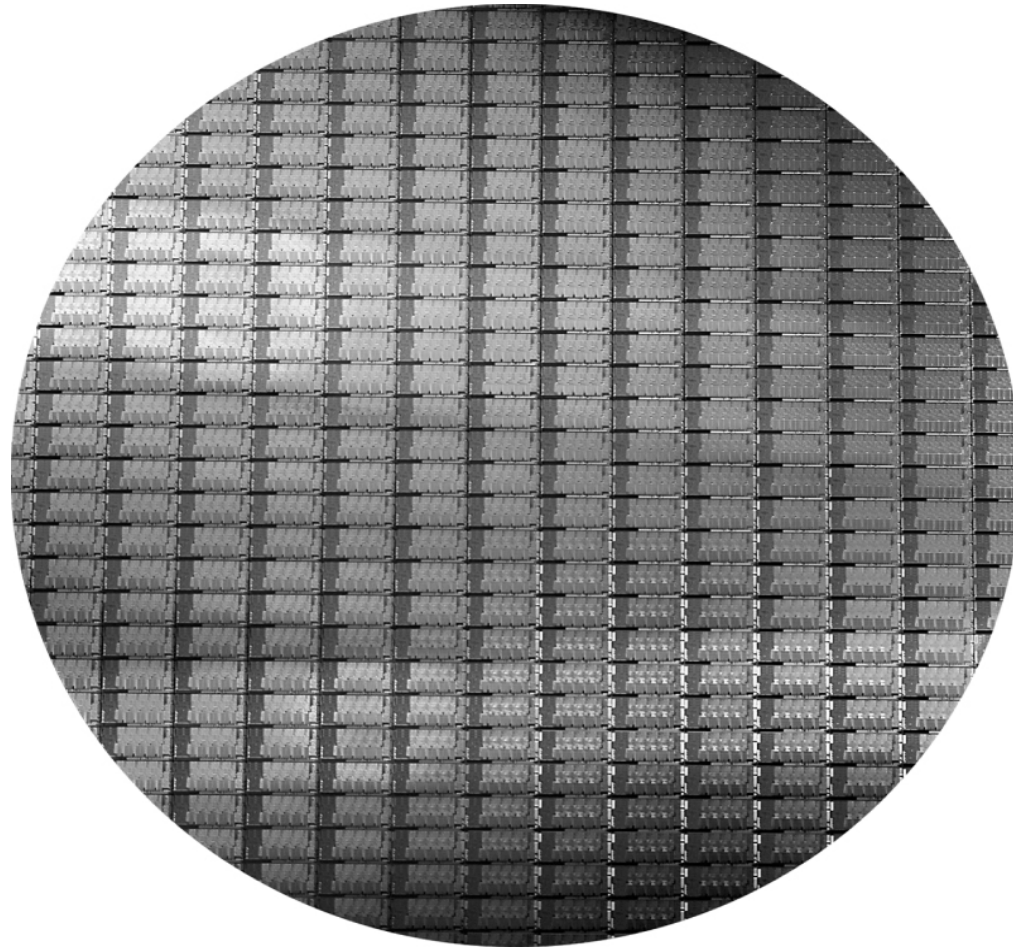
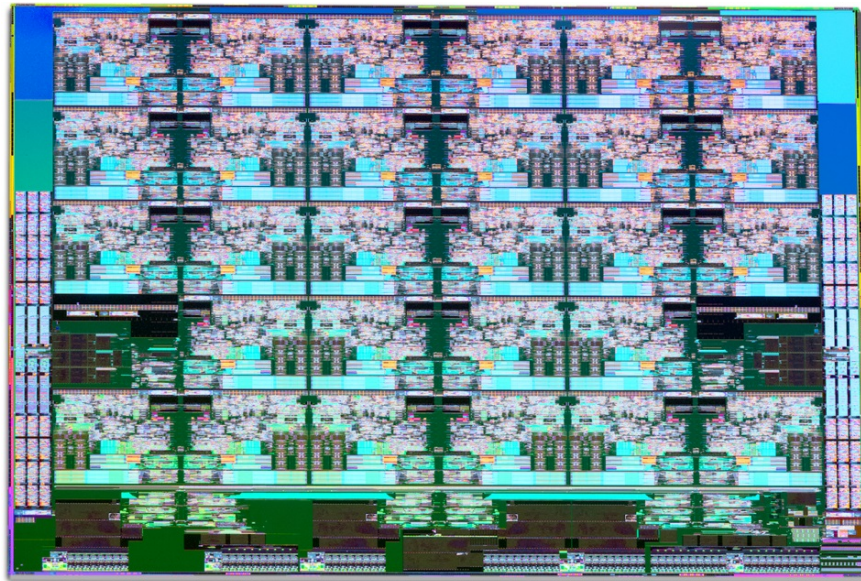


Figure 1.15 This 300 mm wafer contains 280 full Sandy Bridge dies, each 20.7 by 10.5 mm in a 32 nm process. (Sandy Bridge is Intel's successor to Nehalem used in the Core i7.) At 216 mm<sup>2</sup>, the formula for dies per wafer estimates 282. (Courtesy Intel.)

# *A Die*

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**Figure 1.14** Photograph of an Intel Skylake microprocessor die, which is evaluated in Chapter 4.

# A Die with Parts Labeled

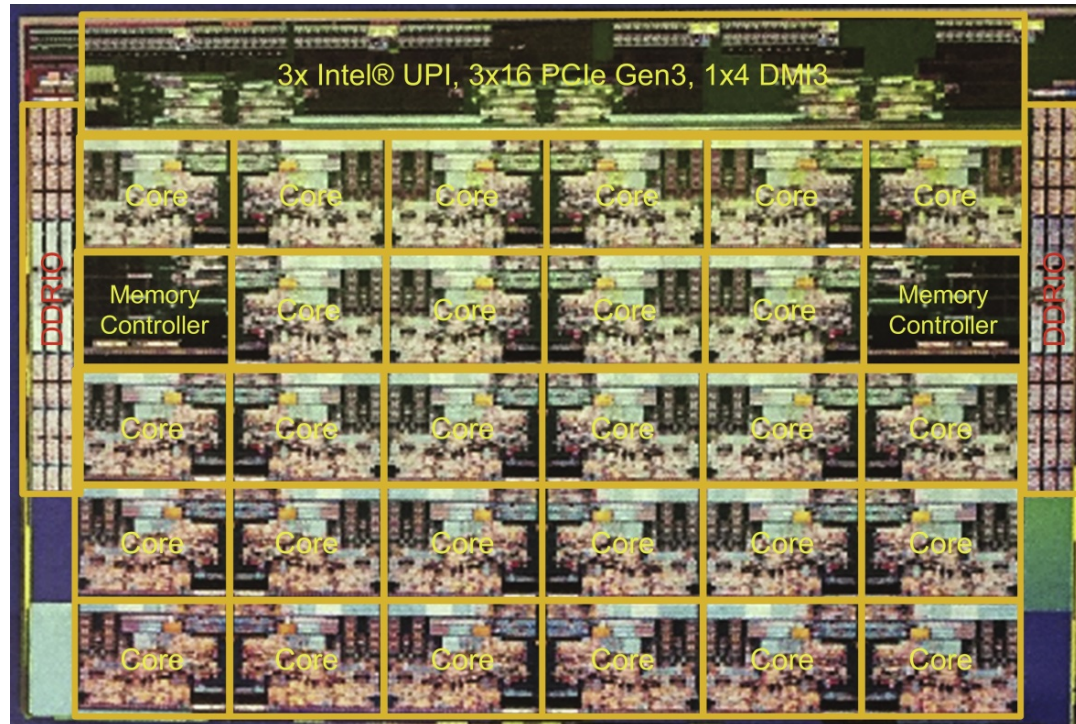


Figure 1.15 The components of the microprocessor die in Figure 1.14 are labeled with their functions.

# Integrated Circuit Cost

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$$\text{Cost of IC} = \frac{\text{Cost of Die} + \text{Cost of Testing} + \text{Cost of Packaging}}{\text{Final Test Yield}}$$

$$\text{Cost of Die} = \frac{\text{Cost of Wafer}}{\text{Dies per Wafer} \times \text{Die Yield}}$$

$$\text{Dies per Wafer} = \left( \frac{\pi \times (\text{Wafer Diameter}/2)^2}{\text{Die Area}} \right) -$$

(Correction factor for Edge Effects)

$$\text{Die Yield} = \text{Wafer Yield} \times \frac{1}{(1 + \text{Defects per unit area} \times \text{Die Area})^\alpha}$$

$\alpha = 10$  to  $14$  for  $16\text{nm}$  in 2017

Bottom line: Cost per die grows roughly as the square of the die area

Cost different from price; cost of manufacturing different from cost of operation



# *Reliability*

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Many sources of unreliability

Soft errors due to radiation, hard errors due to wearout, ...

Common metrics

Mean time to failure – MTTF

For exponentially distributed time to failure

Define failures in time or FITs

FIT = failures in a billion hours

$\text{FIT} \propto 1/\text{MTTF}$

FIT of system = Sum of FITs of components

Common solution

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Common solution

Redundancy in time, space, information

But must be cheap

Many recent innovations