Introduction to Electrical and Computer Engineering

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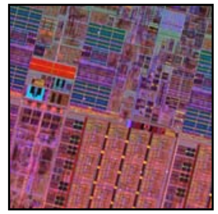
School of Electrical and Computer Engineering
Cornell University

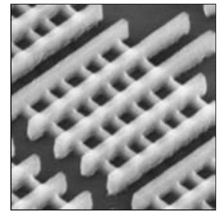
ENGRG 1060 Explorations in Engineering Seminar
Summer 2012

Power Systems

Computer Engineering



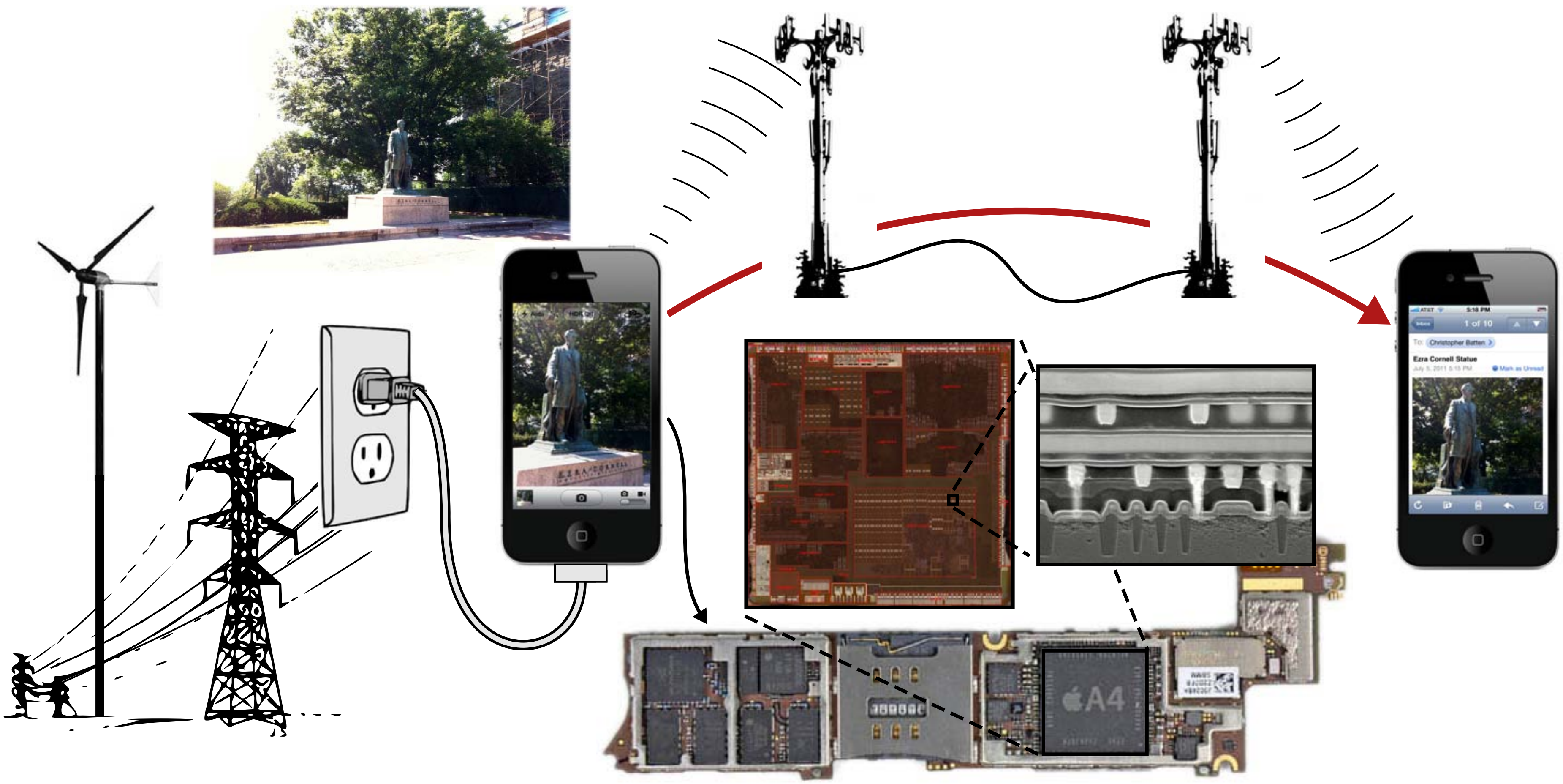
Electrical Circuits



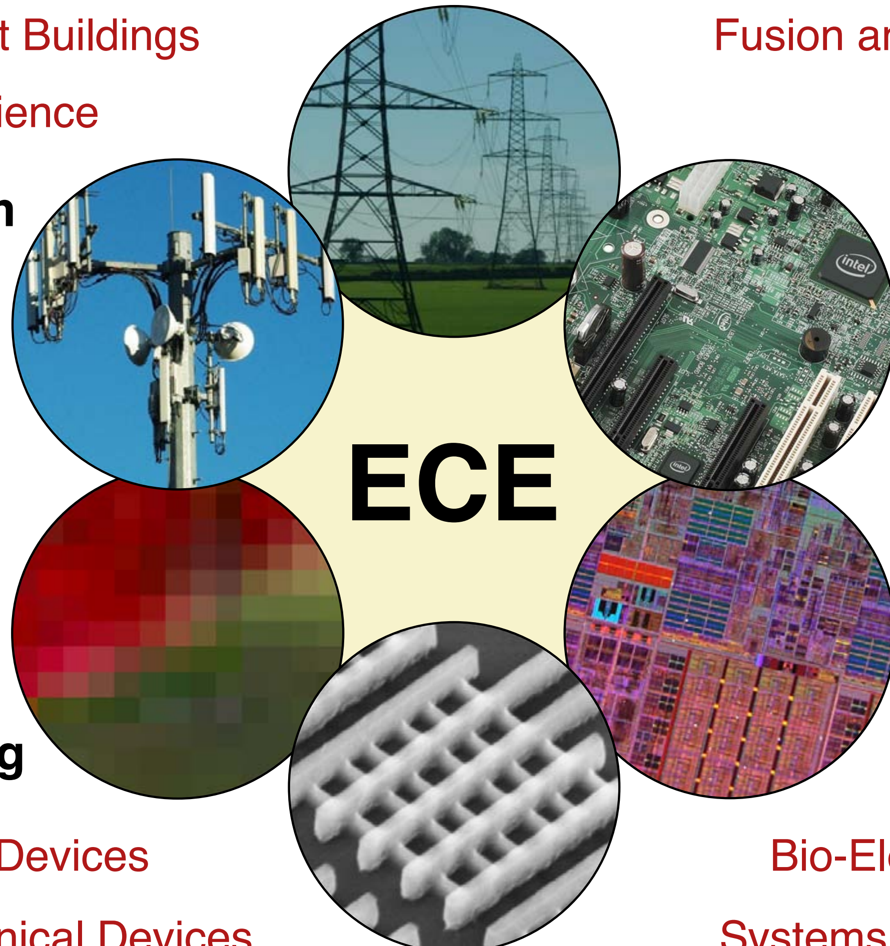
Electrical Devices

Signal Processing

Telecomm



ECE is the Study and Application of Electricity, Micro-Electronics, and Electro-Magnetism



Power Systems

Smart Grid and Smart Buildings

Atmospheric Science

Fusion and Plasma Physics

Control Theory

Telecomm

Information Theory

Network Protocols and Optimization

Computer Engineering

Robotics

Computer-Aided Design

Image, Audio, Video Processing

Signal Processing

Analog and Digital Circuits

Electrical Circuits

Opto-Electrical Devices

Micro-Electro-Mechanical Devices

Bio-Electrical Engineering

Systems and Synthetic Biology

Electrical Devices

ECE is everywhere!

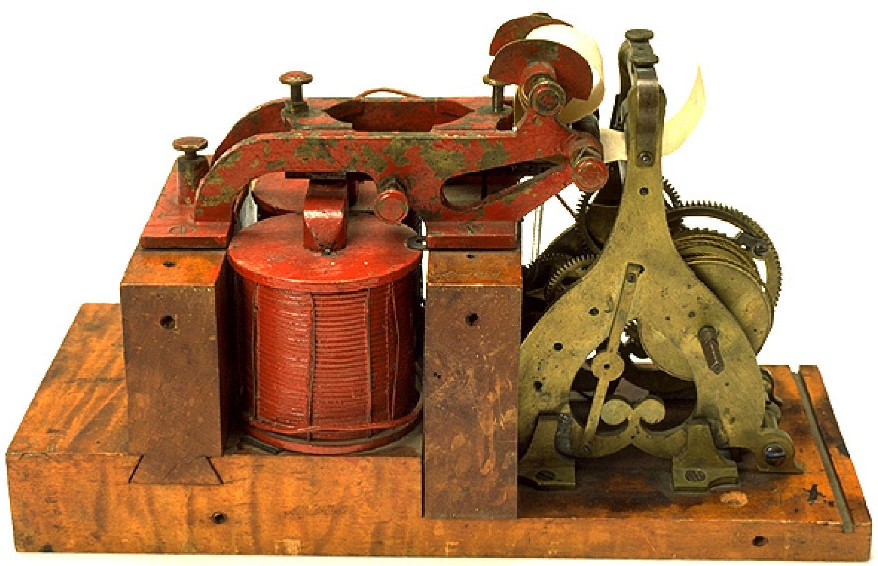
What can one do with a background in ECE?

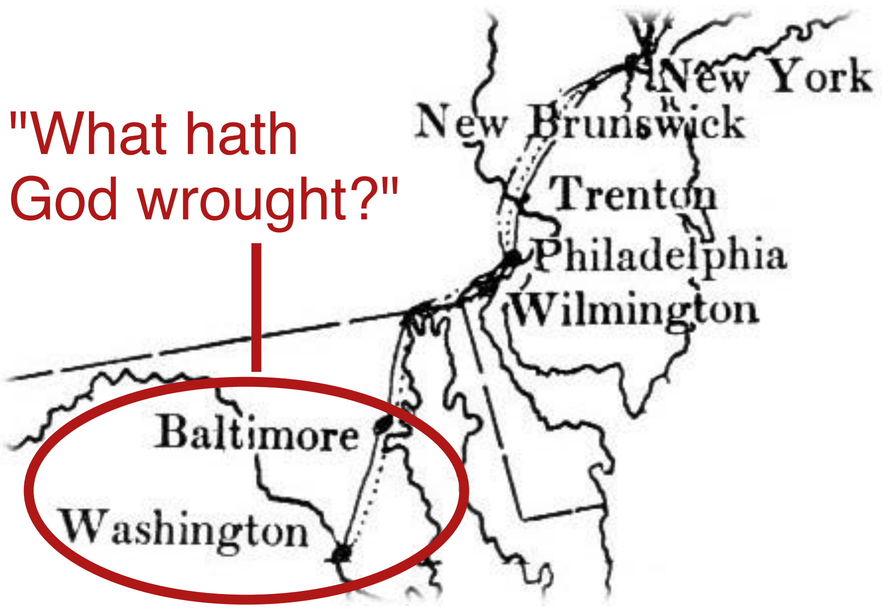
- **ECE Industry**: Intel, AMD, Analog Devices, NVIDIA, HP, Apple
- **General Engineering Industry**: GE, Lockheed Martin, Raytheon
- **Software Industry**: Microsoft, Amazon, Mathworks
- **Join a Startup**: Achronix, Hillcrest Labs
- **Research Lab**: Sandia National Labs, Draper Labs, NASA
- **Consulting**: McKinsey, Accenture, Deloitte, Booz Allen Hamilton
- **Finance**: Deutsche Bank, Capital One, UBS, Bloomberg
- **Graduate School**: Law School, Business School, Med School
- **Found a university!**

Cornell was founded because of ECE!

Samuel Morse invented the telegraph (a digital communication device), but needed help building the network

Ezra Cornell built the first telegraph line (the beginning of telecommunications), and invested in the Western Union Telegraph Co

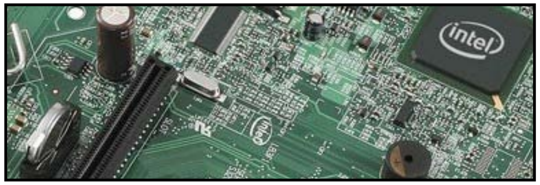


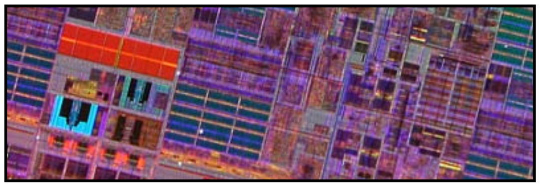


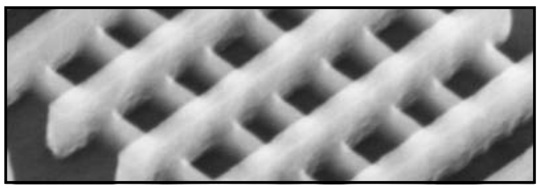
Ezra Cornell's investments created the fortune that eventually enabled the founding of Cornell University

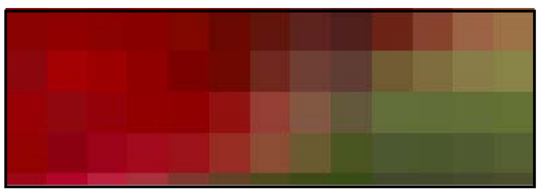
"Optional Homework"

- Visit the statue of Ezra Cornell on the Arts Quad
- Does something on the back of the statue relate to ECE?
- Take a picture with your cellphone and send it to your friend!
  - Power systems
  - Computer engineering
  - Electrical circuits
  - Electrical devices
  - Signal processing
  - Telecommunications









Talk Outline

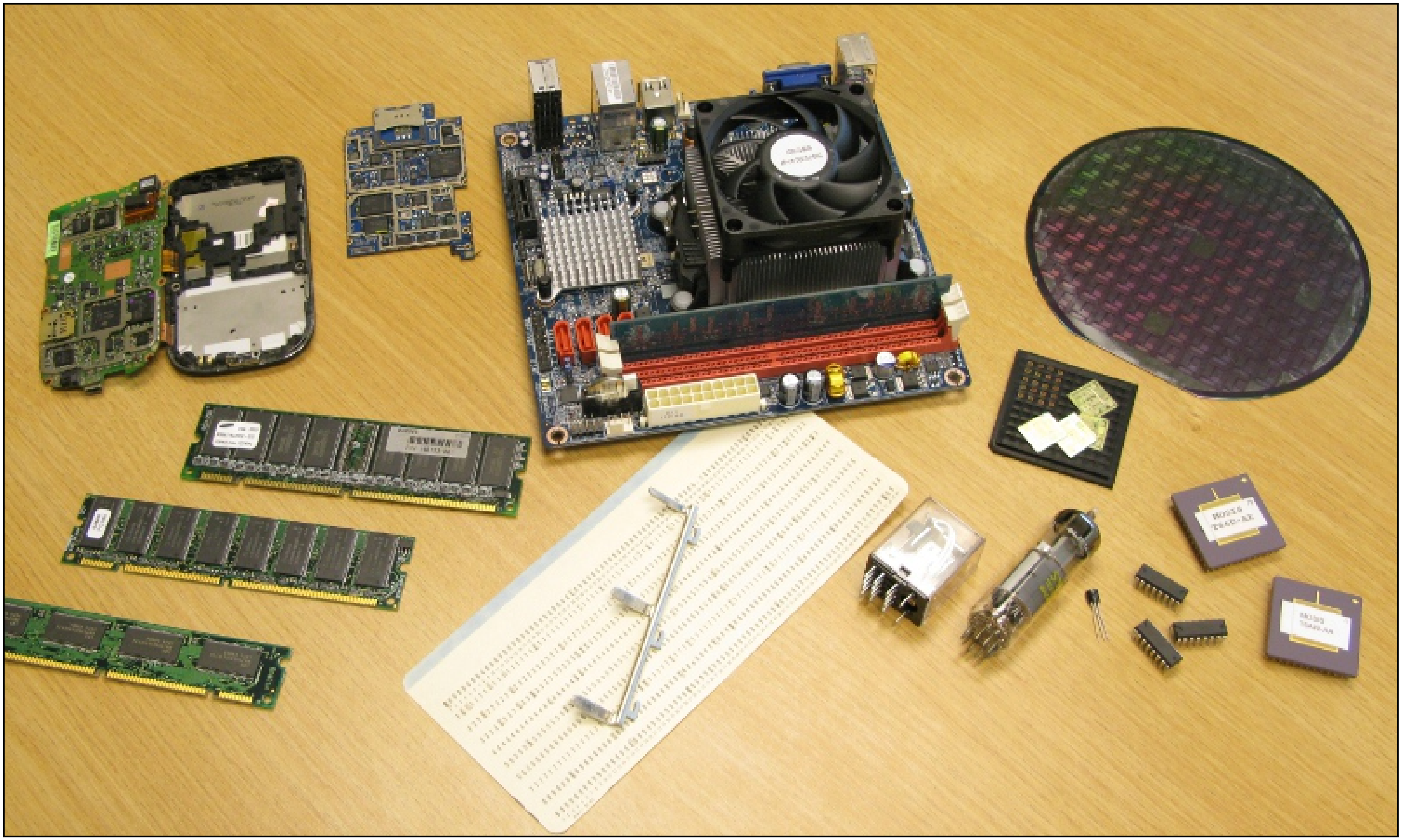
ECE Overview

What is Computer Engineering?

Trends in Computer Engineering

Computer Engineering Design

Computer Engineering Artifacts



The Computer Systems Stack

Application

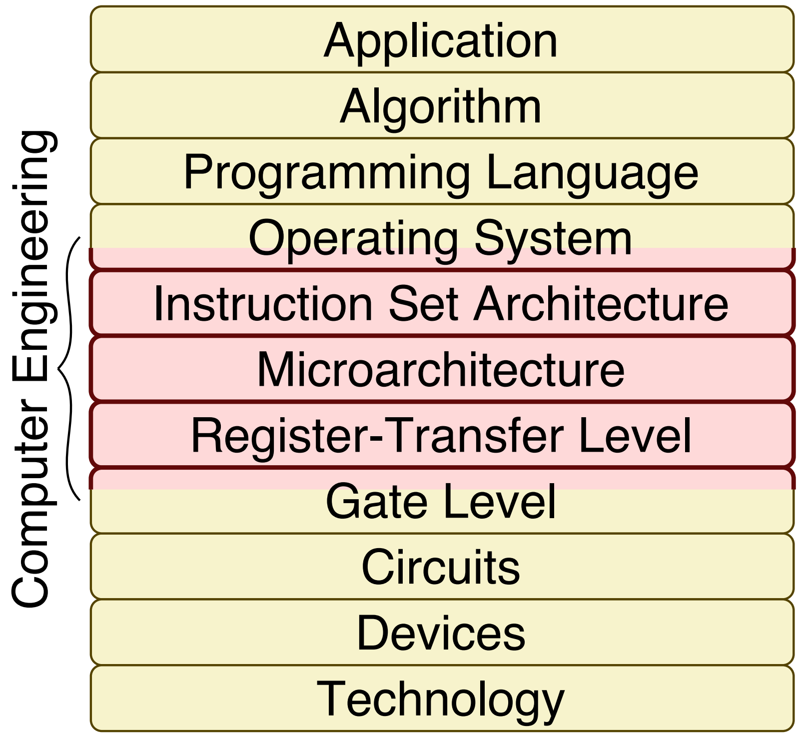
↕

Technology

Gap too large to bridge in one step
(but there are exceptions,
e.g., a magnetic compass)

In its broadest definition, computer system design is the development of the abstraction/implementation layers that allow us to execute information processing applications efficiently using available manufacturing technologies

The Computer Systems Stack



Sort an array of numbers

2,6,3,8,4,5 -> 2,3,4,5,6,8

Insertion sort algorithm

1. Find minimum number in input array
2. Move minimum number into output array
3. Repeat steps 1 and 2 until finished

C implementation of insertion sort

```
void isort( int b[], int a[], int n ) {
  for ( int idx, k = 0; k < n; k++ ) {
    int min = 99
    for ( int i = 0; i < n; i++ ) {
      if ( a[i] < min ) {
        min = a[i];
        idx = i;
      }
    }
    b[k]   = min;
    a[idx] = 99;
  }
}
```

The Computer Systems Stack

- Application
- Algorithm
- Programming Language
- Operating System
- Instruction Set Architecture
- Microarchitecture
- Register-Transfer Level
- Gate Level
- Circuits
- Devices
- Technology

Computer Engineering

Mac OS X, Windows, Linux
Handles low-level hardware management

MIPS32 Instruction Set
Instructions that machine executes

```
blez  $a2, done
move  $a7, $zero
li    $t4, 99
move  $a4, $a1
move  $v1, $zero
li    $a3, 99
lw    $a5, 0($a4)
addiu $a4, $a4, 4
slt   $a6, $a5, $a3
movn  $v0, $v1, $a6
addiu $v1, $v1, 1
movn  $a3, $a5, $a6
```

The Computer Systems Stack

- Application
- Algorithm
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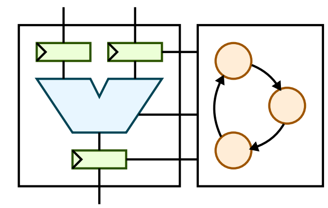
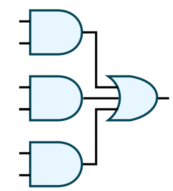
Computer Engineering

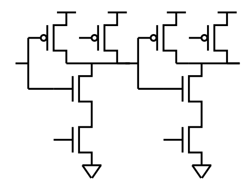
How data flows through system



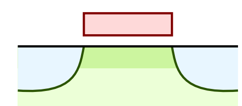
Boolean logic gates and functions



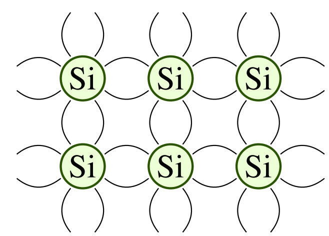
Combining devices to do useful work



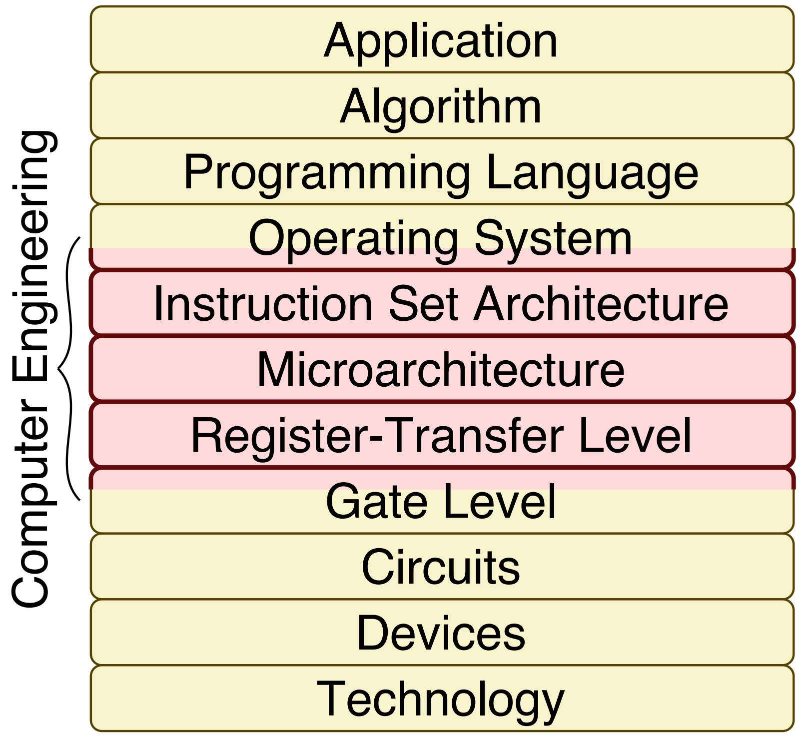
Transistors and wires



Silicon process technology



Computer Systems: CS vs. EE vs. CE



Traditional Computer Science

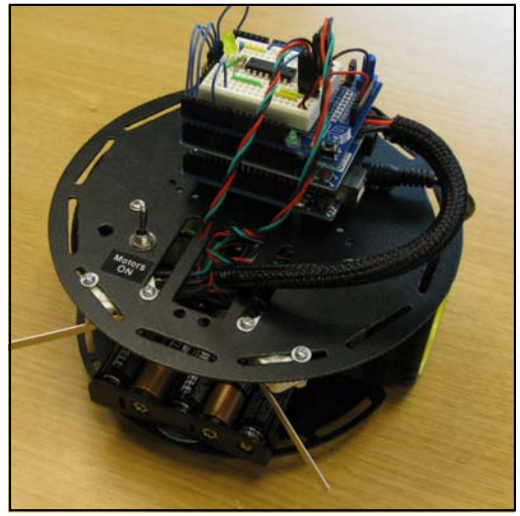
Computer Engineering is at the interface between hardware and software and considers the entire system

Traditional Electrical Engineering

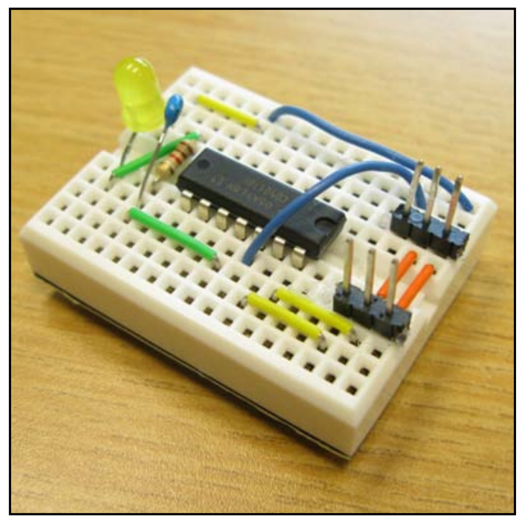
ENGRG 1060 Computer Systems Labs

Computer Engineering

- Application
- Algorithm
- Programming Language
- Operating System
- Instruction Set Architecture
- Microarchitecture
- Register-Transfer Level
- Gate Level
- Circuits
- Devices
- Technology

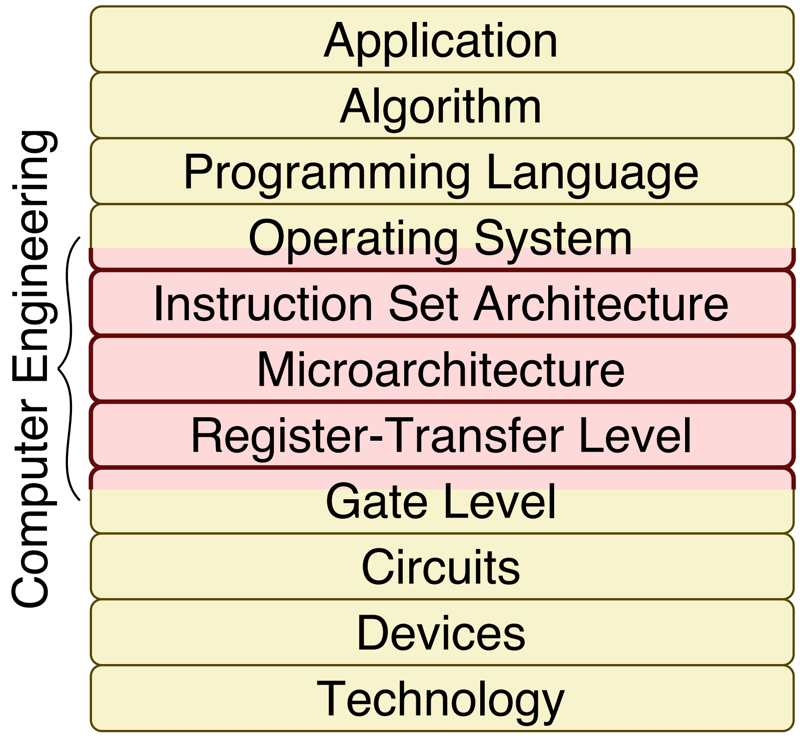


Lab 4
Software pushing towards hardware (CS,CE)



Lab 2
Hardware pushing towards software (EE,CE)

Application Requirements vs. Technology Constraints



Application Requirements

- Suggest how to improve architecture
- Provide revenue to fund development

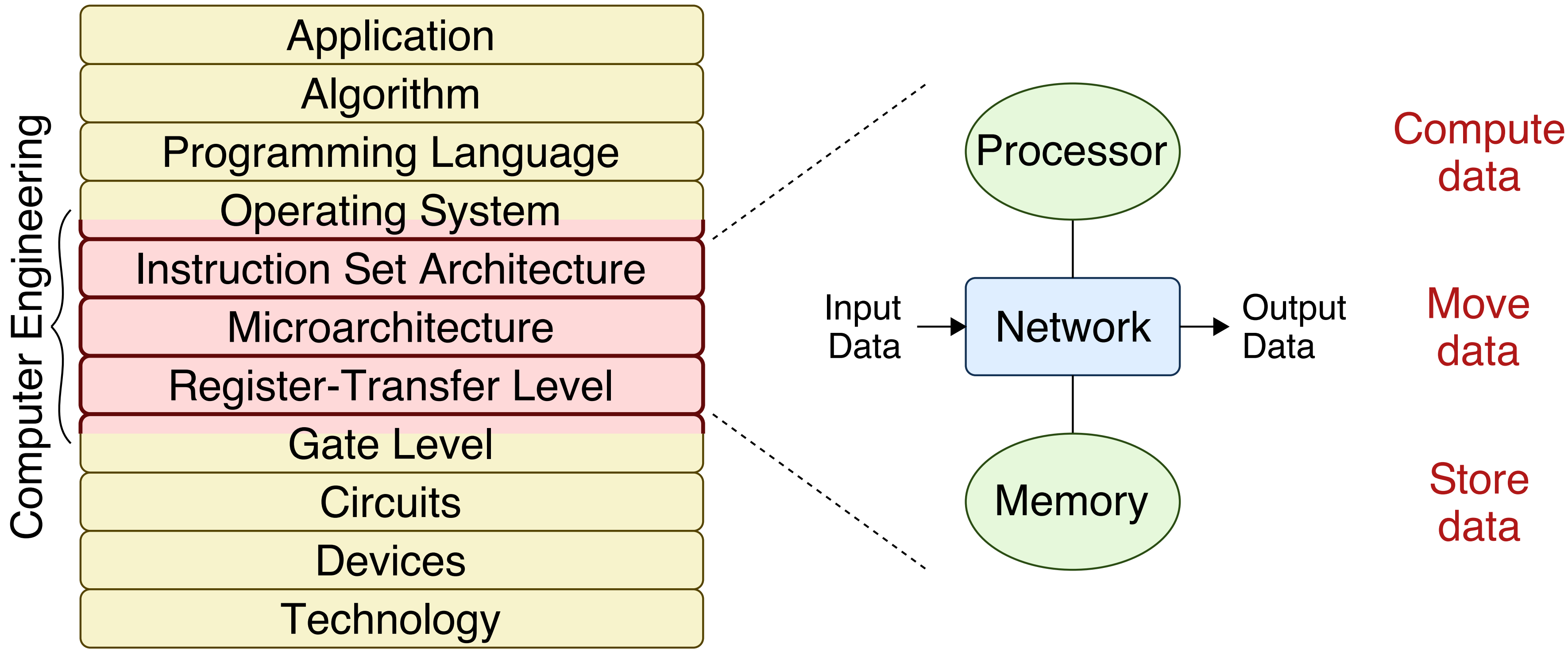
Computer engineers provide feedback to guide application and technology research directions

Technology Constraints

- Restrict what can be done efficiently
- New technologies make new arch possible

In its broadest definition, computer system design is the development of the abstraction/implementation layers that allow us to execute information processing applications efficiently using available manufacturing technologies

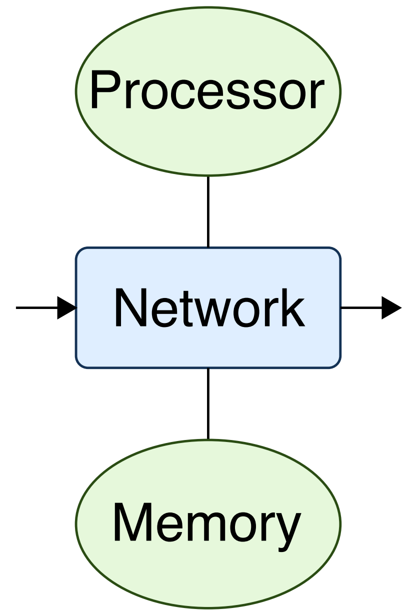
Processors, Memories, and Networks



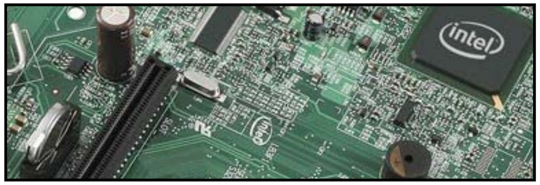
Computer engineering basic building blocks

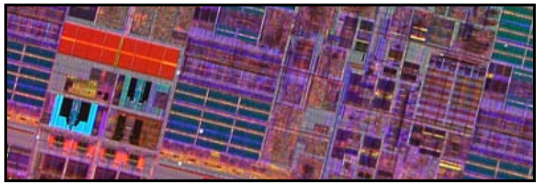
- Processors for computation
- Memories for storage
- Networks for communication

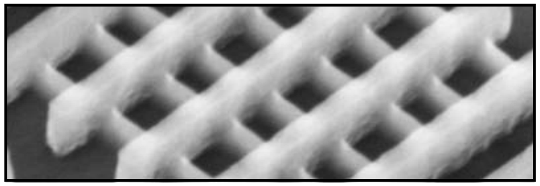
Activity #1: Sorting with a Sequential Processor

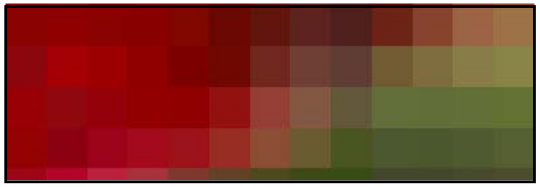


- **Application:** Sort 32 numbers
- **Simulated Sequential Computing System**
  - Processor: You!
  - Memory: Worksheet, read input data, write output data
  - Network: Passing/collecting the worksheets
- **Activity Steps**
  - 1. Discuss strategy with neighbors
  - 2. When instructor starts timer, flip over worksheet
  - 3. Sort 32 numbers as fast as possible
  - 4. Lookup when completed and write time on worksheet
  - 5. Raise hand
  - 6. When everyone is finished, then analyze data









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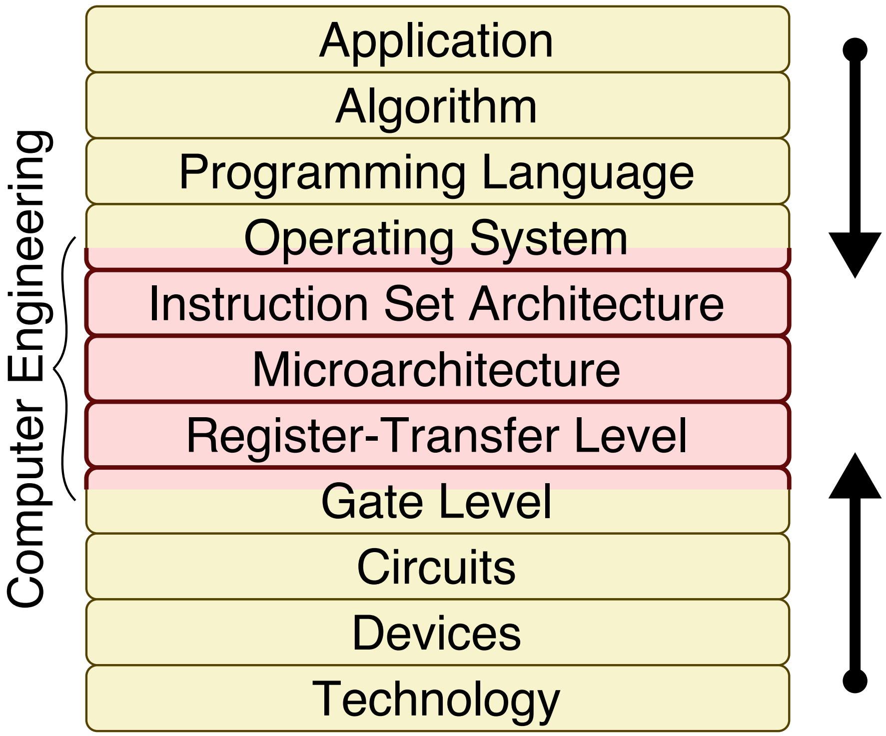


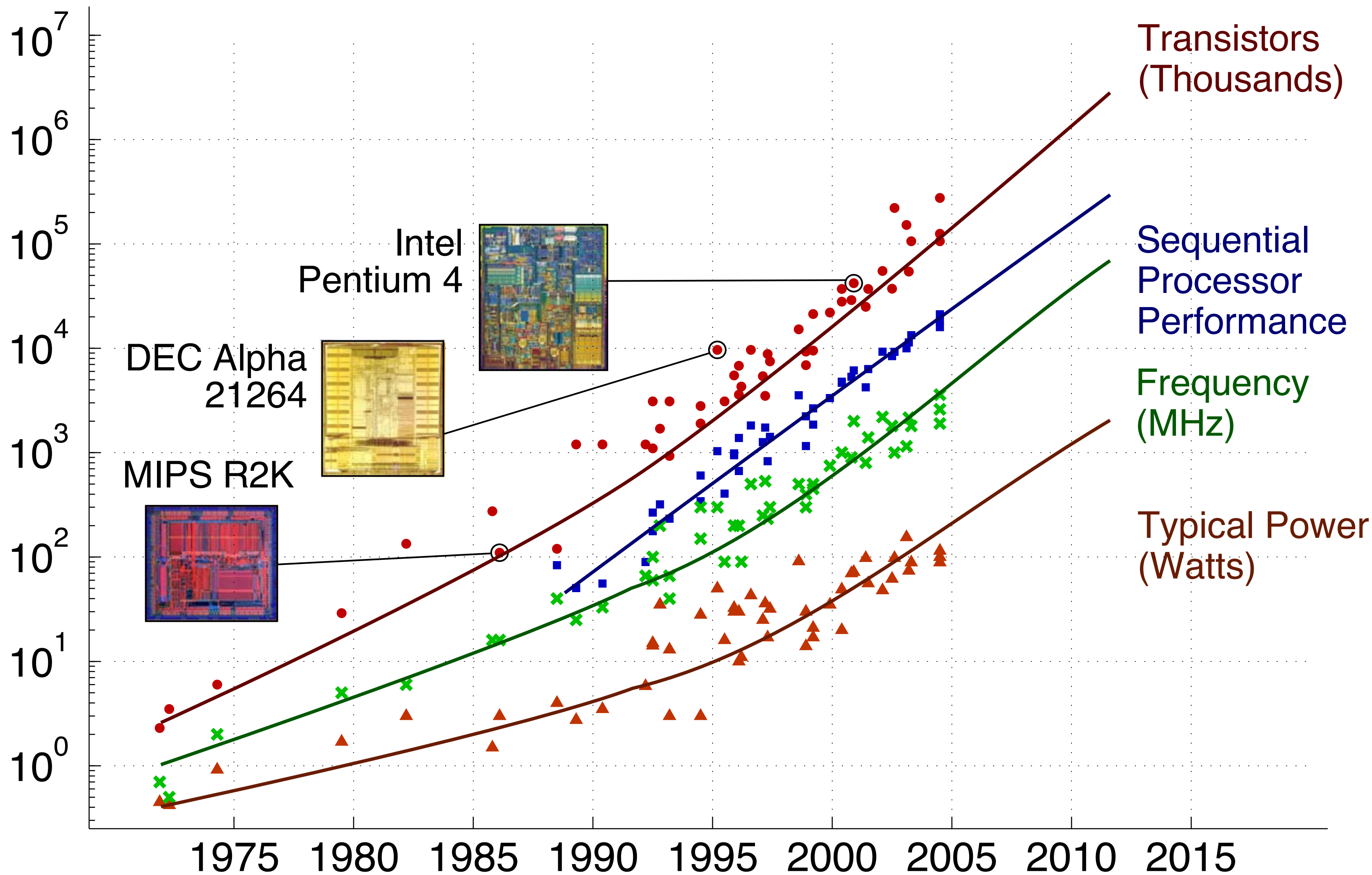
Traditional
Application Requirements

- As much processor compute as possible
- As much memory capacity as possible
- As much network bandwidth as possible

Traditional
Technology Constraints

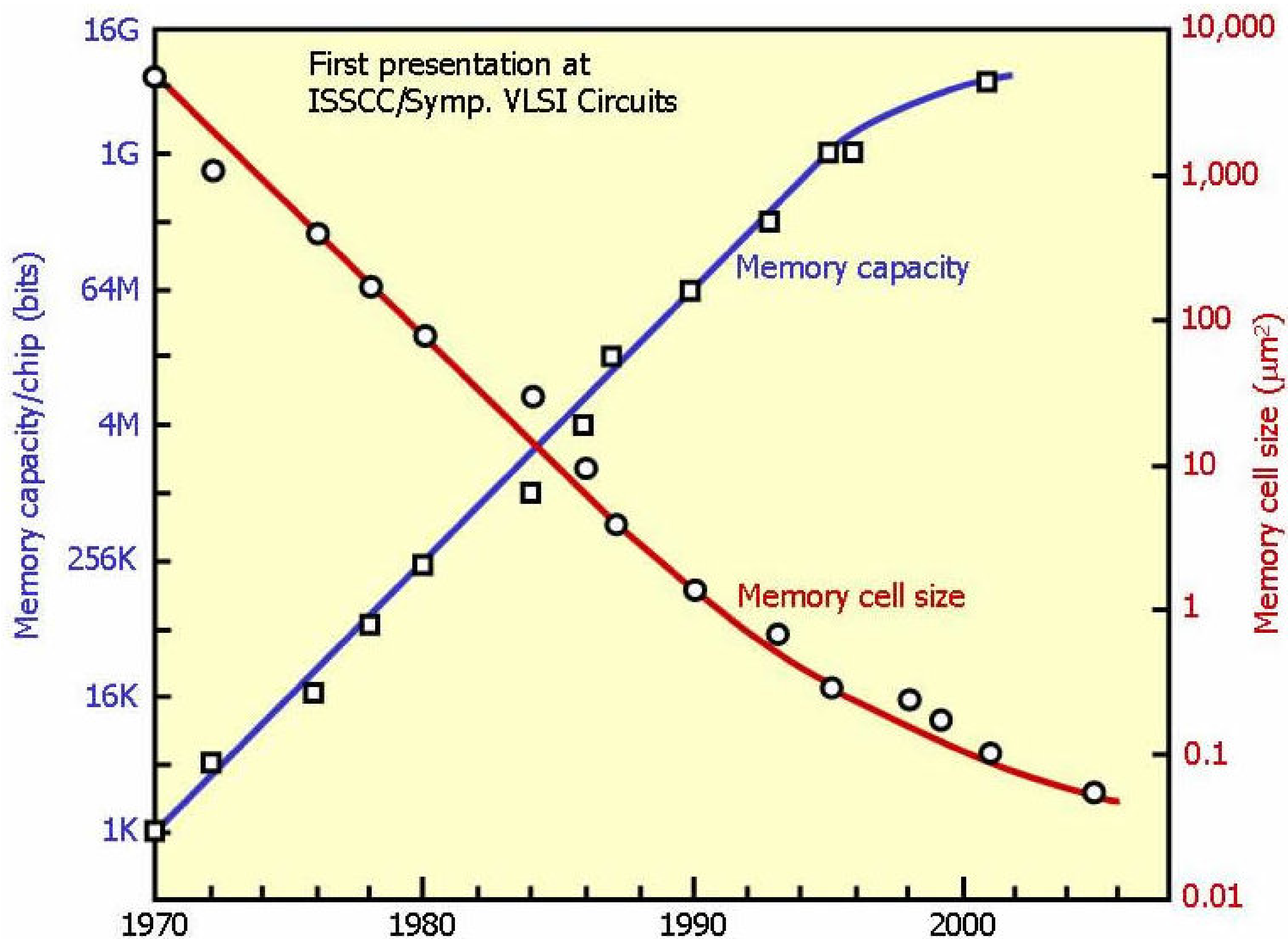
- Exponential scaling of resources

Exponential Scaling for Processor Computation



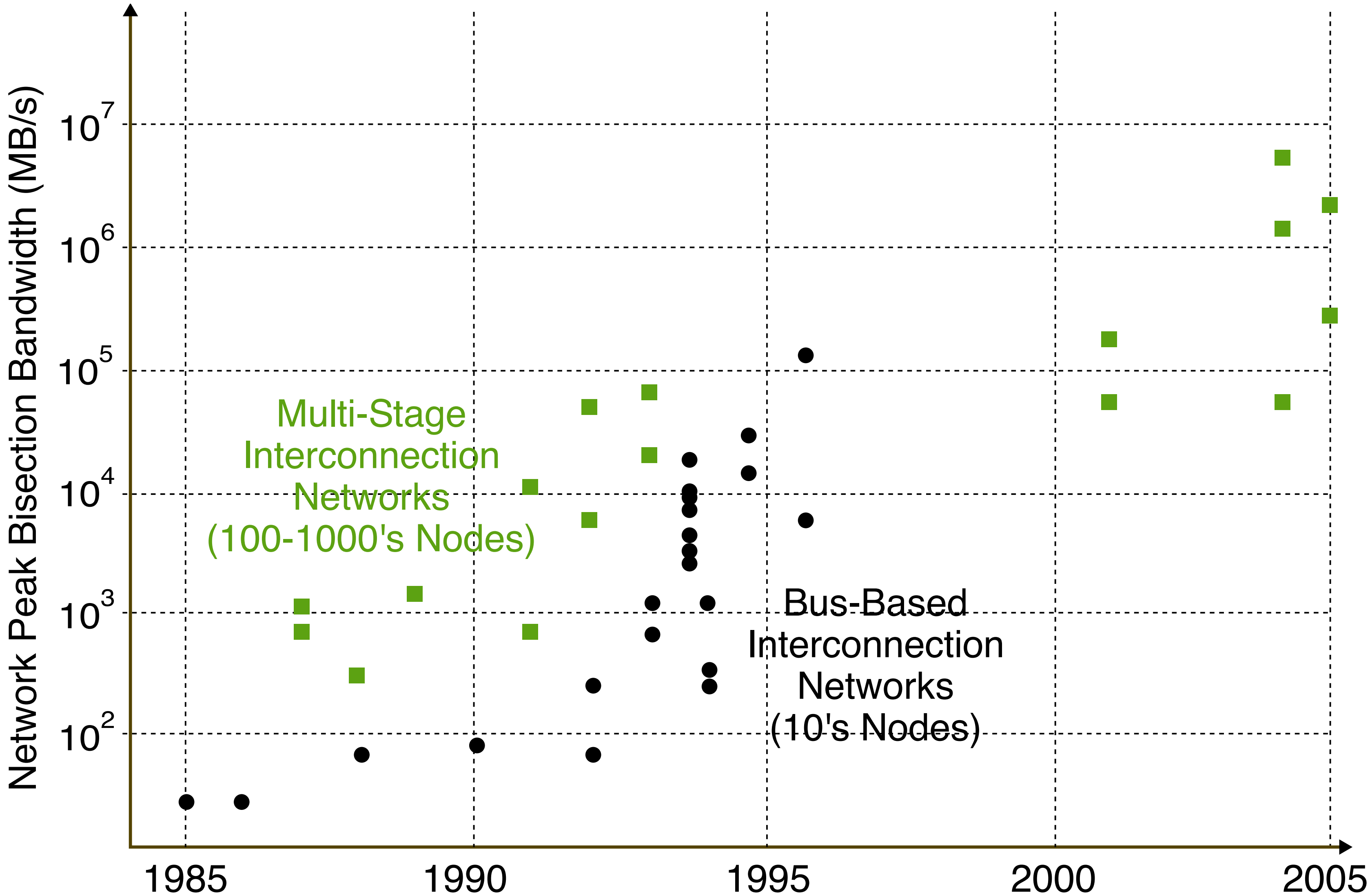
Data partially collected by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond

Exponential Scaling for Memory Capacity

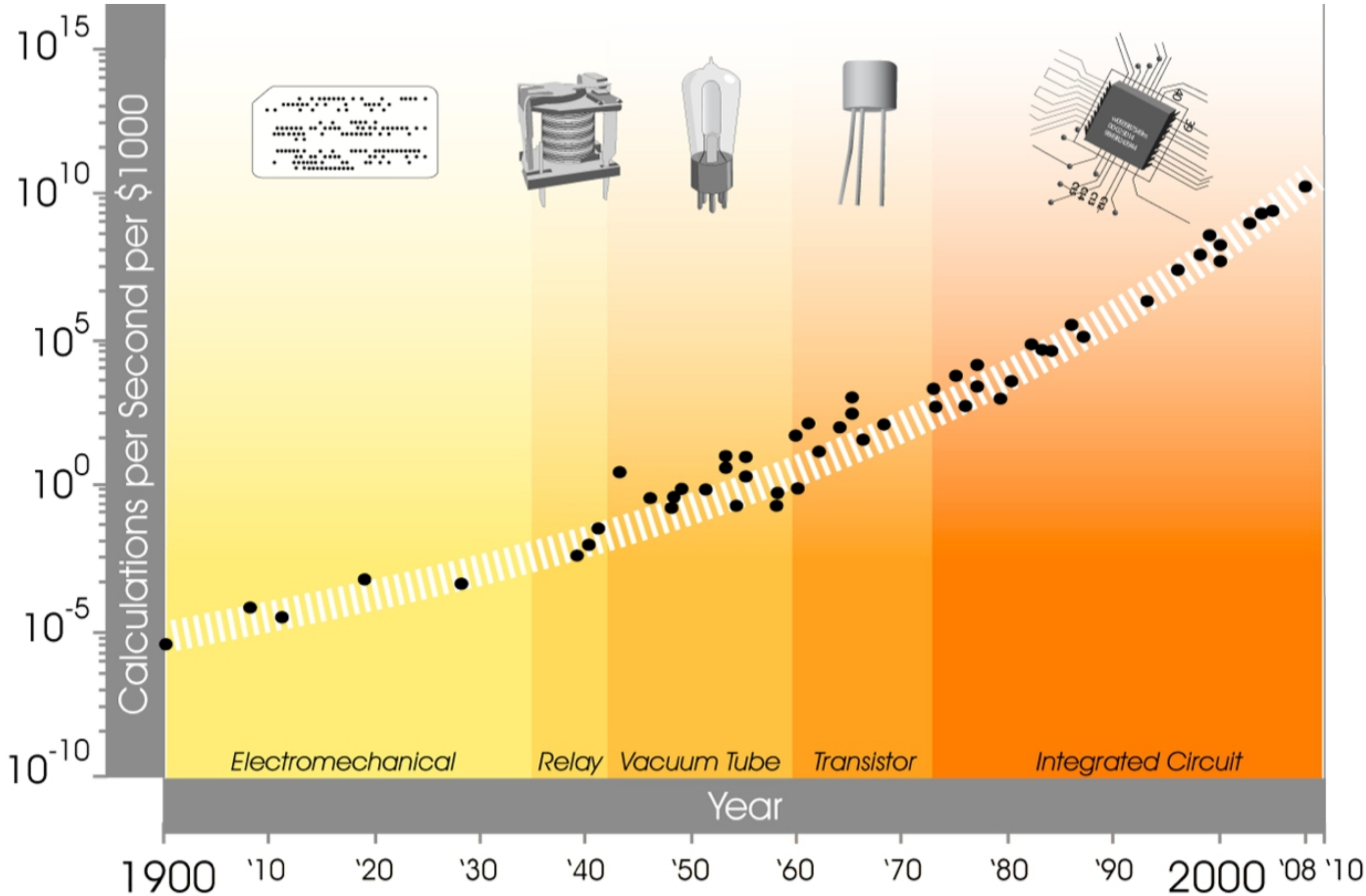


Adapted from [Itoh'07]

Exponential Scaling for Network Bandwidth

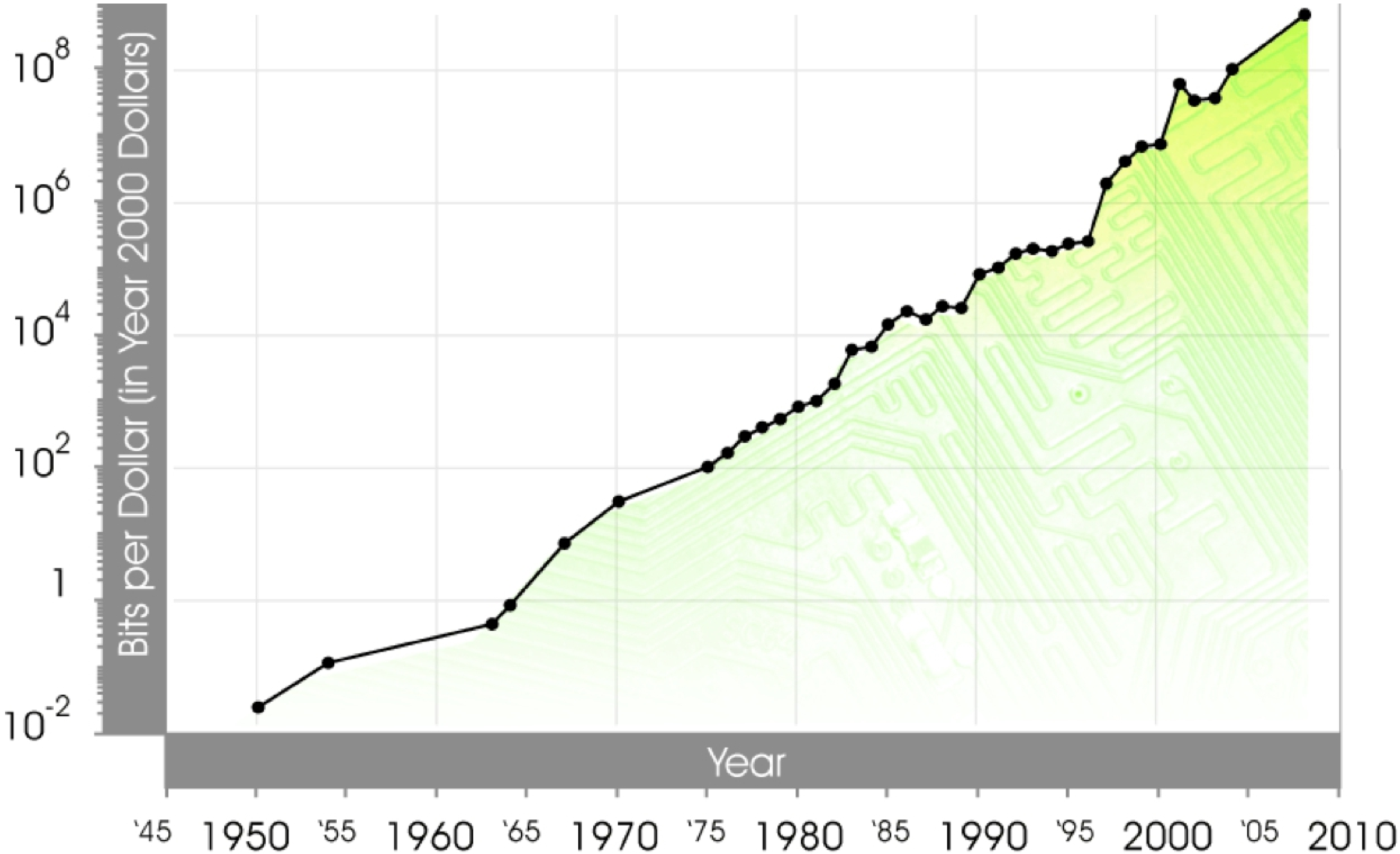


Exponential Scaling for Processor Compute/Dollar



Adapted from [Kurzweil'09]

Exponential Scaling of Memory Capacity/Dollar



Adapted from [Kurzweil'09]

Key trends in the application requirements and technology constraints over the past decade have resulted in a radical rethinking of the

processors, memories, and networks

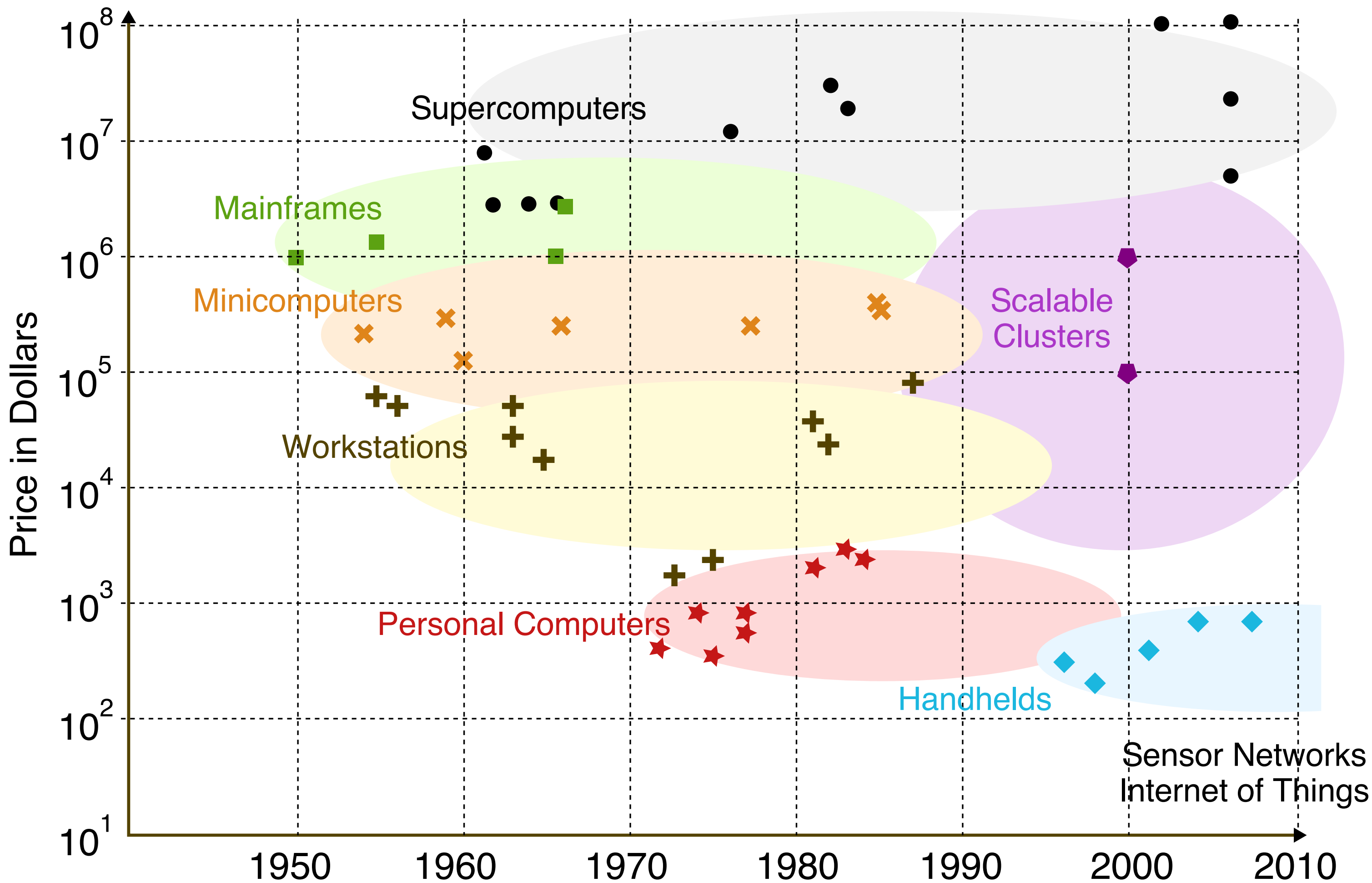
used in modern computing systems

Three Key Trends in Computer Engineering

1. Growing diversity in application requirements motivate growing diversity in computing systems
2. Energy and power constraints motivate transition to multiple processors integrated onto a single chip
3. Technology scaling challenges motivate new emerging processor, memory, and network device technologies

Trend 1: Bell's Law

Roughly every decade a new, lower priced computer class forms based on a new programming platform resulting in new usage and industries



Trend 1: Growing Diversity in Apps & Systems

Trend 2: Energy/Power Constrain All Modern Systems

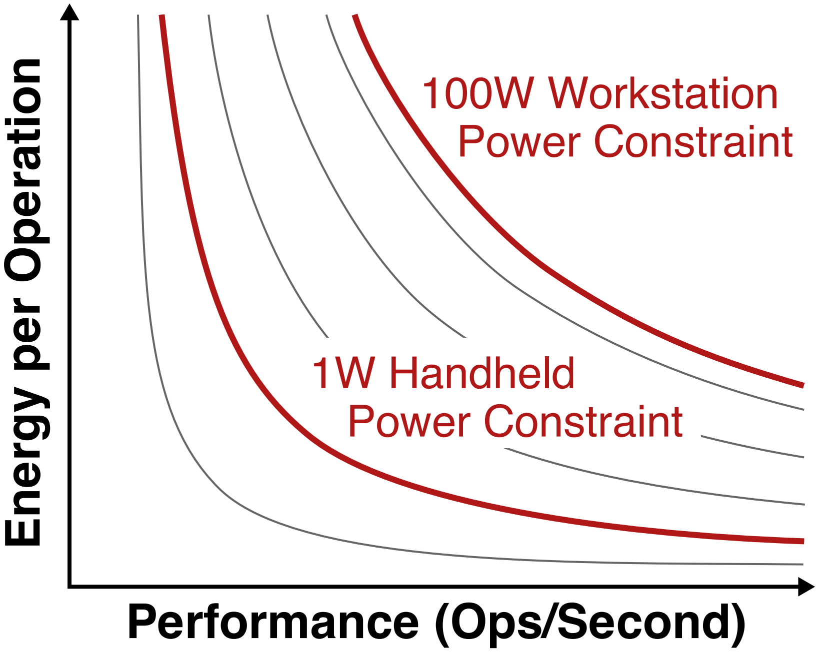
$$\text{Power} = \frac{\text{Energy}}{\text{Second}} = \frac{\text{Energy}}{\text{Op}} \times \frac{\text{Ops}}{\text{Second}}$$

Power

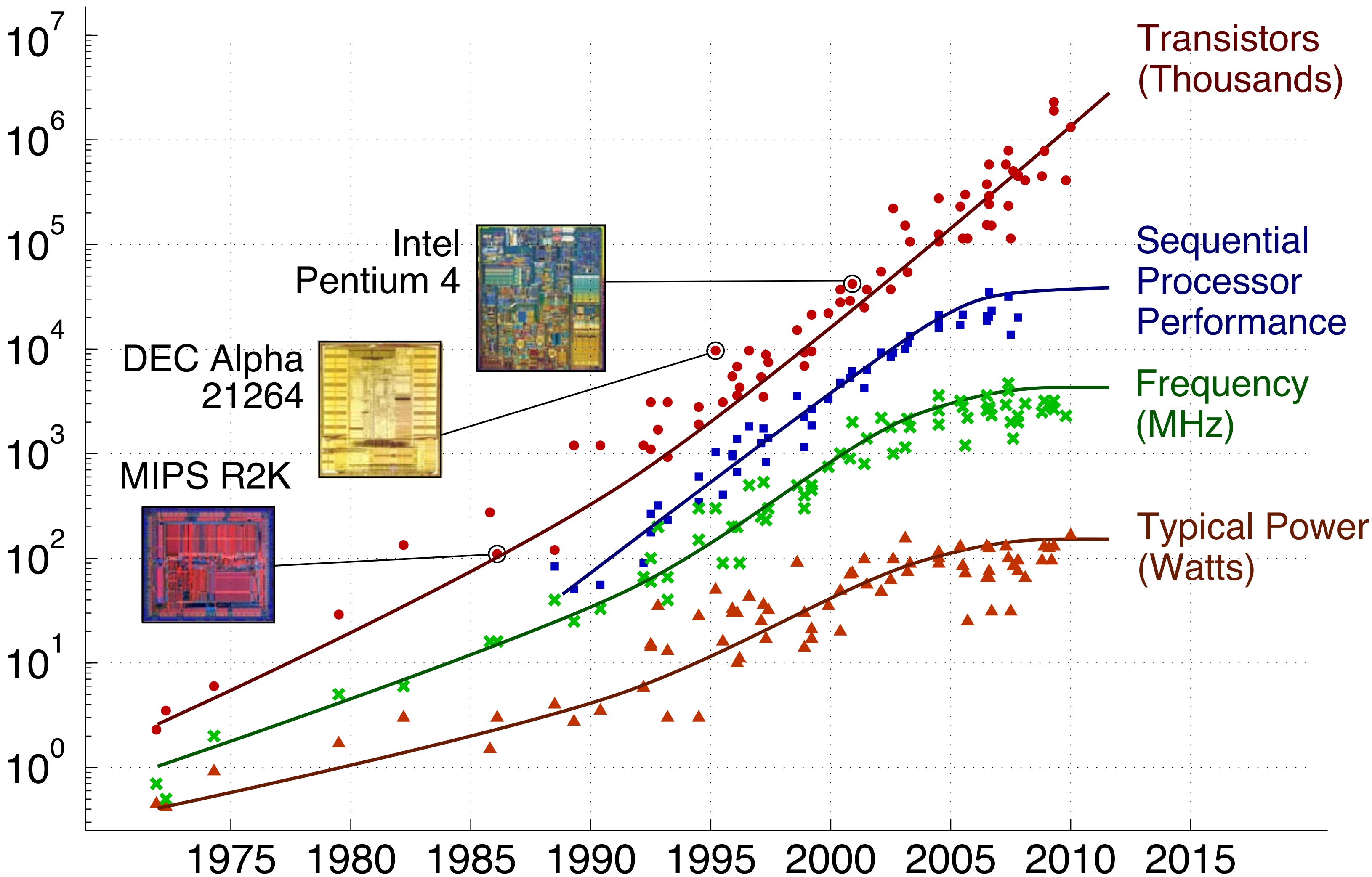
Chip Packaging
Chip Cooling
System Noise
Case Temperature
Data-Center Air Conditioning

Energy

Battery Life
Electricity Bill
Mobile Device Weight



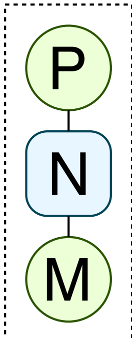
Trend 2: Power Constrains Single-Processor Scaling



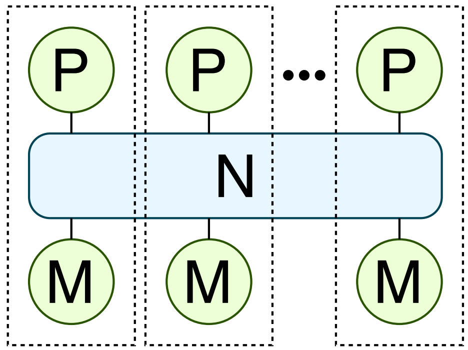
Data partially collected by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond

Trend 2: Transition to Multicore Processors

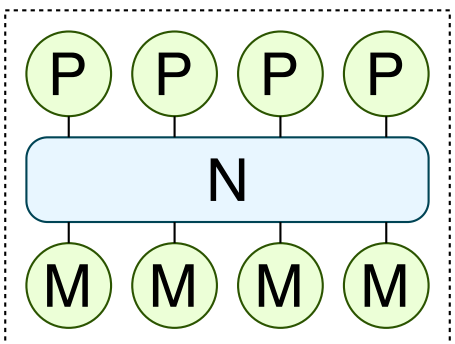
Intel Pentium 4
Single monolithic processor

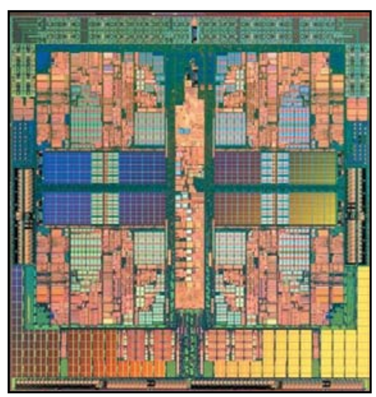


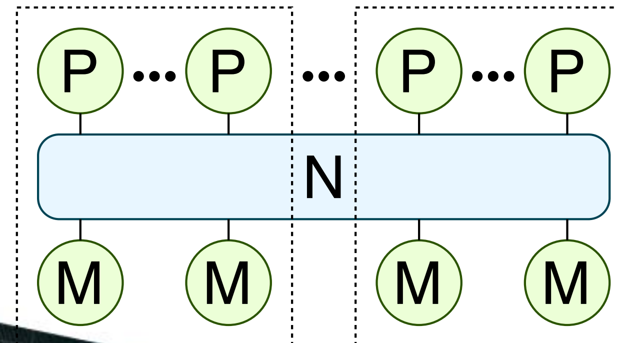
Cray XT3 Supercomputer
1024 single-core processors



AMD Quad-Core Opteron
Four cores on the same die

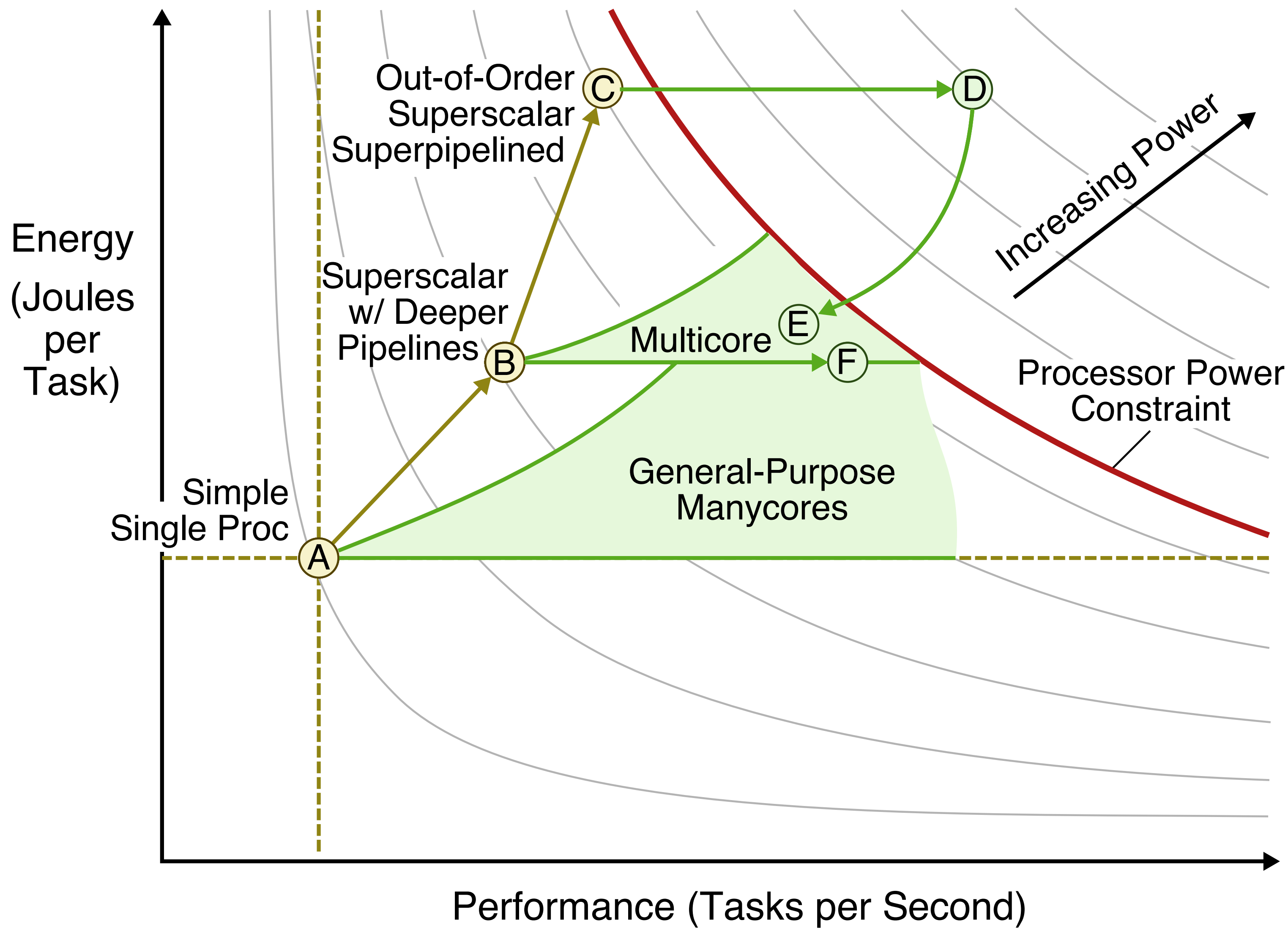




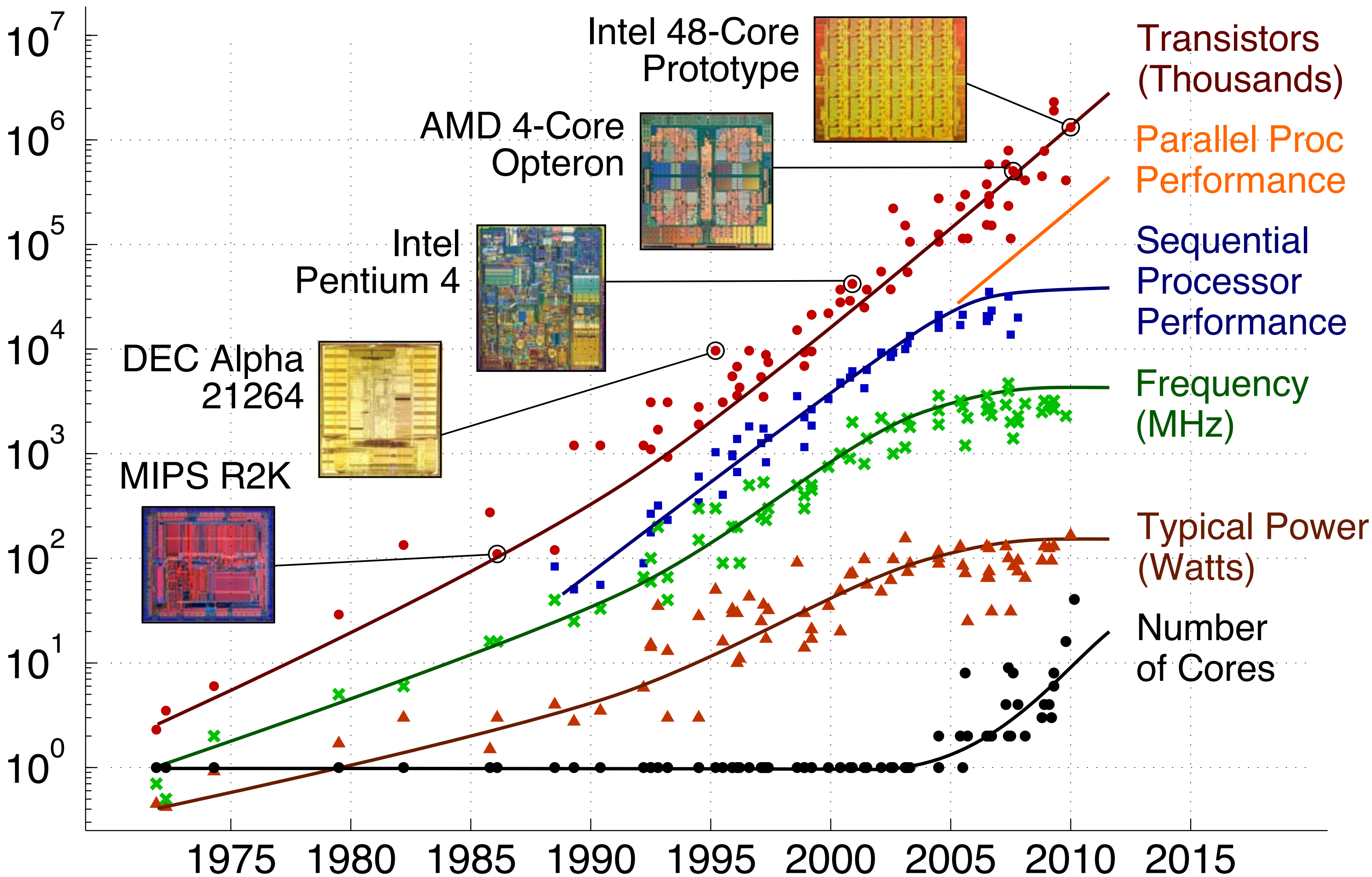


IBM Blue Gene Q Supercomputer
Thousands of 18-core processors

Trend 2: Energy and Performance of Multicores



Trend 2: Multicore Performance Scaling



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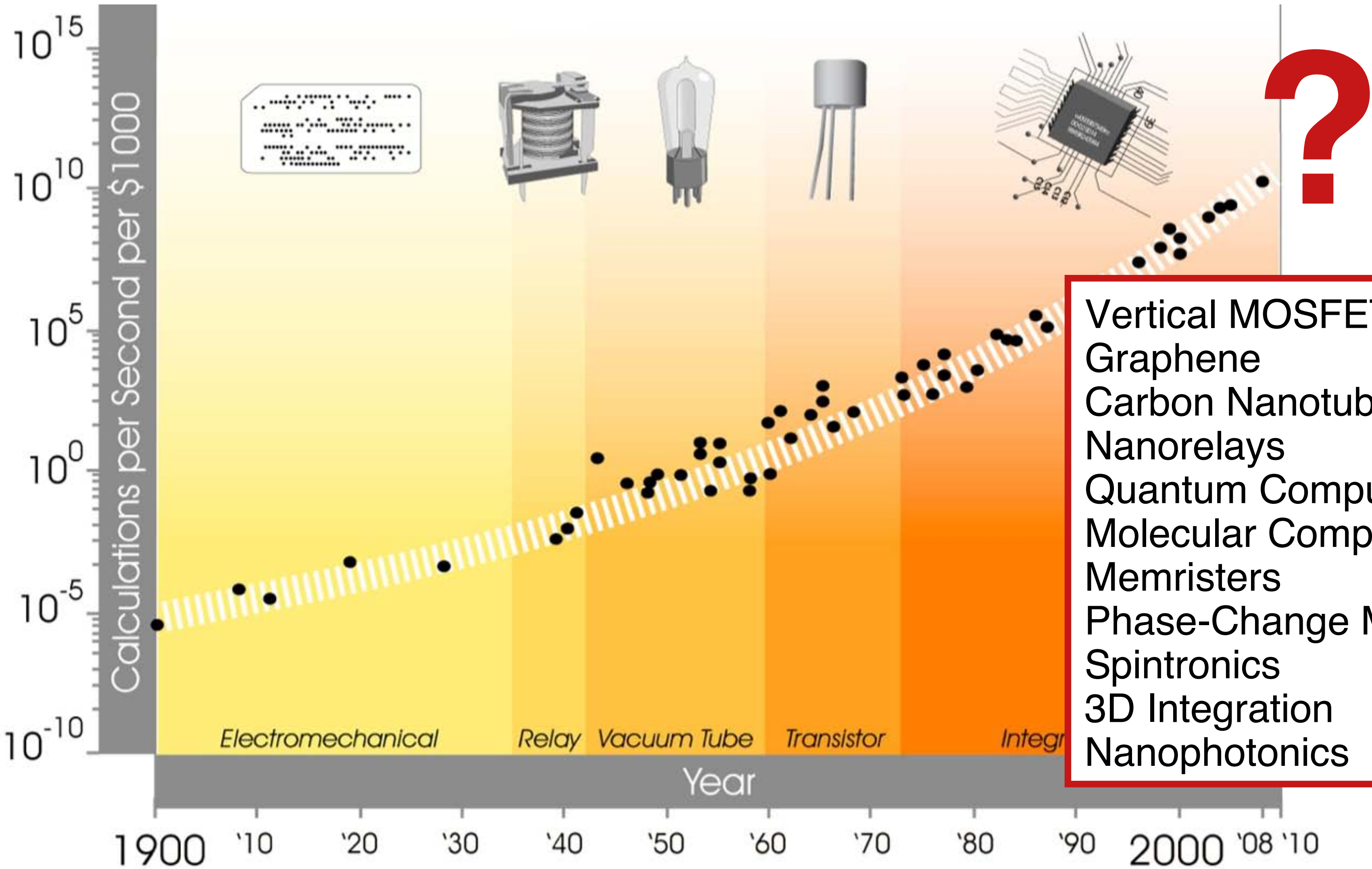
Trend 3: Emerging Device Technologies



- Vertical MOSFETs
- Graphene
- Carbon Nanotubes
- Nanorelays
- Quantum Computing
- Molecular Computing
- Memristers
- Phase-Change Mem
- Spintronics
- 3D Integration
- Nanophotonics

Adapted from [Kurzweil'09]

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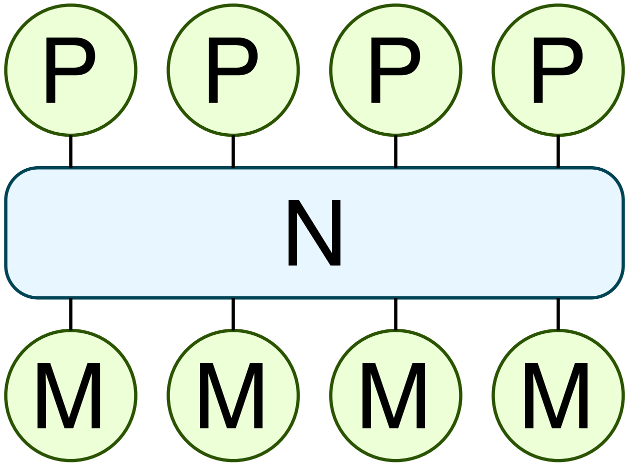
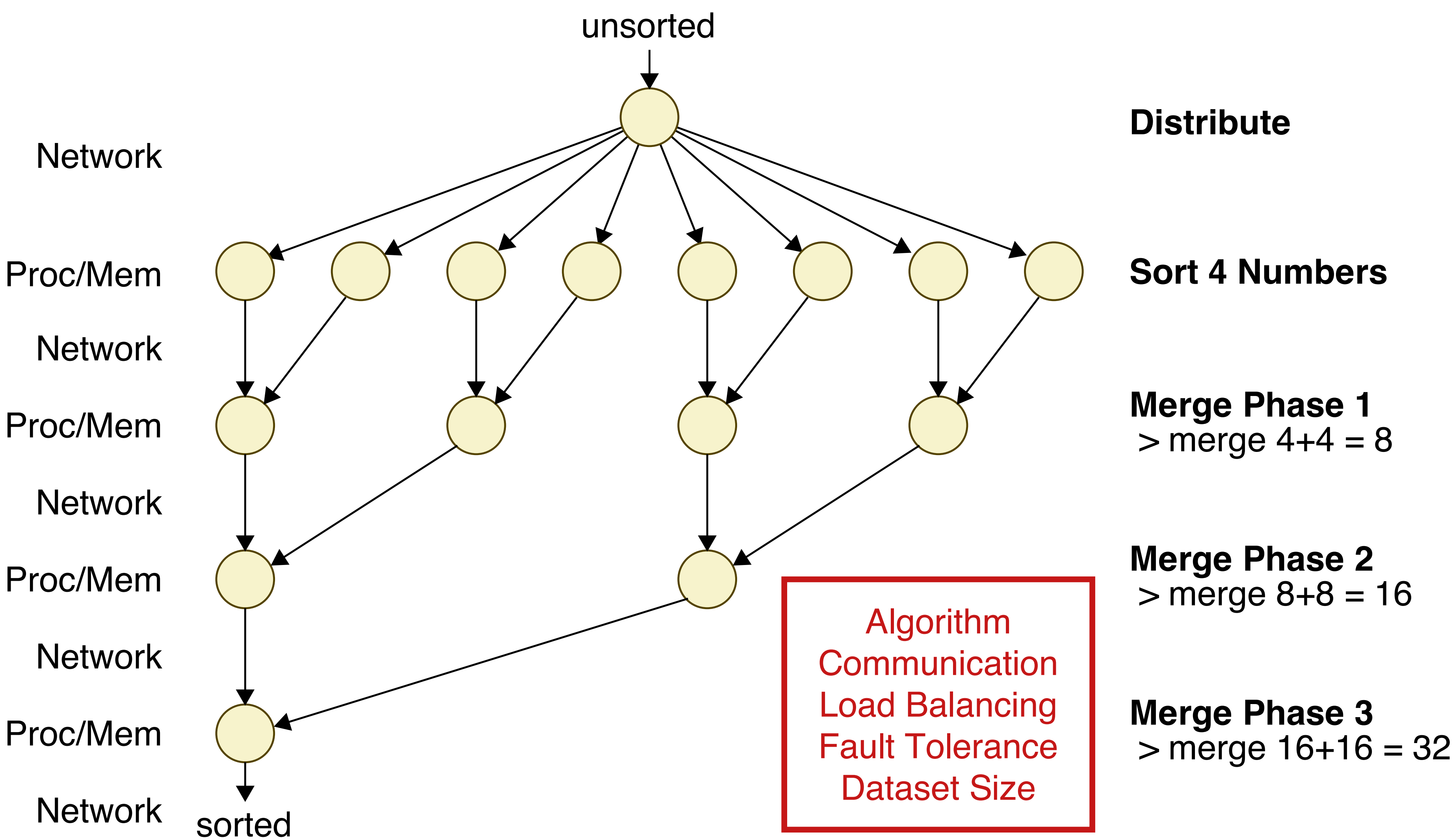
Activity #2: Sorting with a Parallel Processor

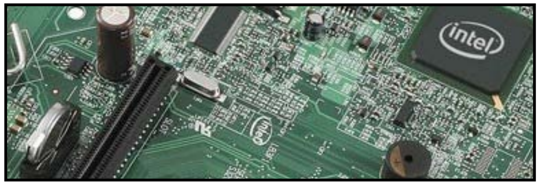
- **Application:** Sort 32 numbers
- **Simulated Parallel Computing System**
  - Processor: Group of 2–8 students
  - Memory: Worksheet, scratch paper
  - Network: Communicating between students

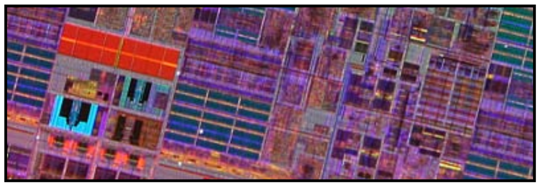


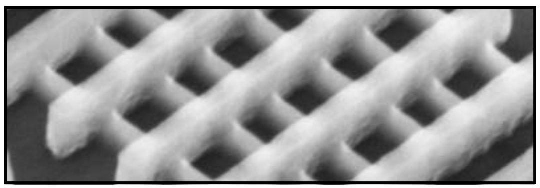
- **Activity Steps**
  - 1. Discuss strategy with group
  - 2. When instructor starts timer, master processor flips over worksheet
  - 3. Sort 32 numbers as fast as possible
  - 4. Lookup when completed and write time on worksheet
  - 5. *Master processor only* raises hand
  - 6. When everyone is finished, then analyze data

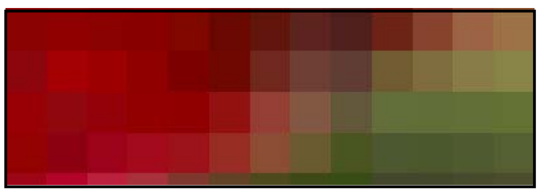
Activity #2: Discussion











Talk Outline

ECE Overview

What is Computer Engineering?

Trends in Computer Engineering

Computer Engineering Design

What do computer engineers actually do?

General Science

Discover truths about nature

Ask question about nature

↓

Construct hypothesis

↓

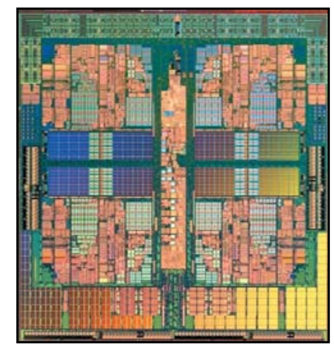
Test with experiment

↓

Analyze results and draw conclusions

Computer Engineering

Explore design space for a given system



Design and build initial system

↓

Ask question about system

↓

Modify system or build/design alternative

↓

Test with experiment to compare alternatives

↓

Analyze results and draw conclusions

How do we design something so incredibly complex?

Computer Engineering

Explore design space
for a given system

Design and build
initial system

↓

Ask question
about system

↓

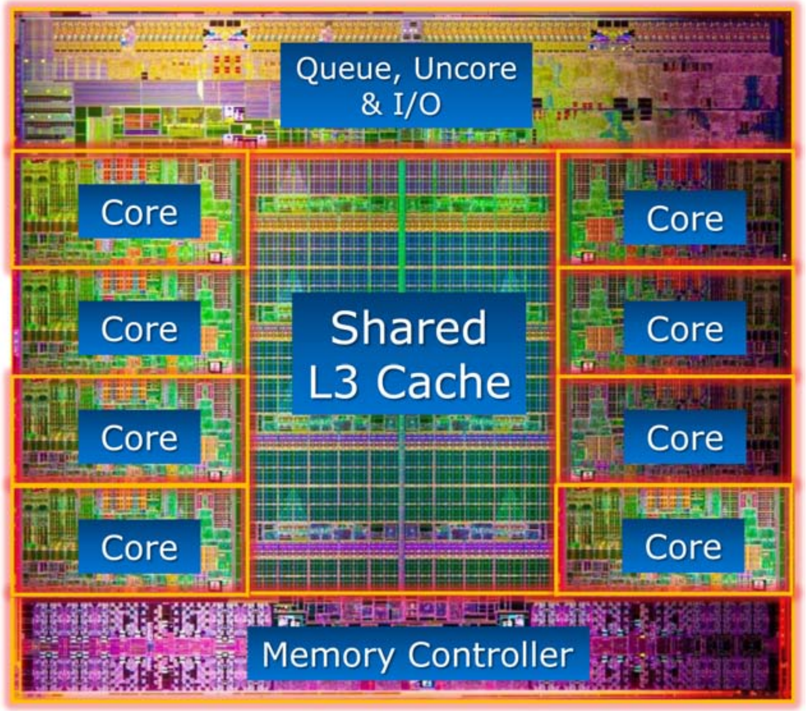
Modify system or
build/design alternative

↓

Test with experiment
to compare alternatives

↓

Analyze results and
draw conclusions



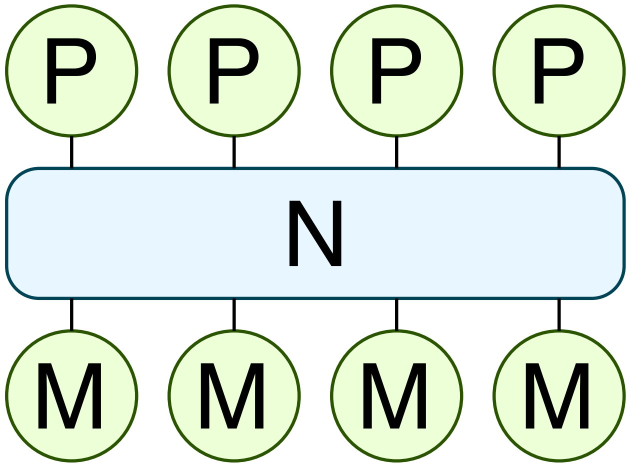
Fighter Airplane: ~100,000 parts
Intel Sandy Bridge E: 2.27 Billion transistors

Design Principles

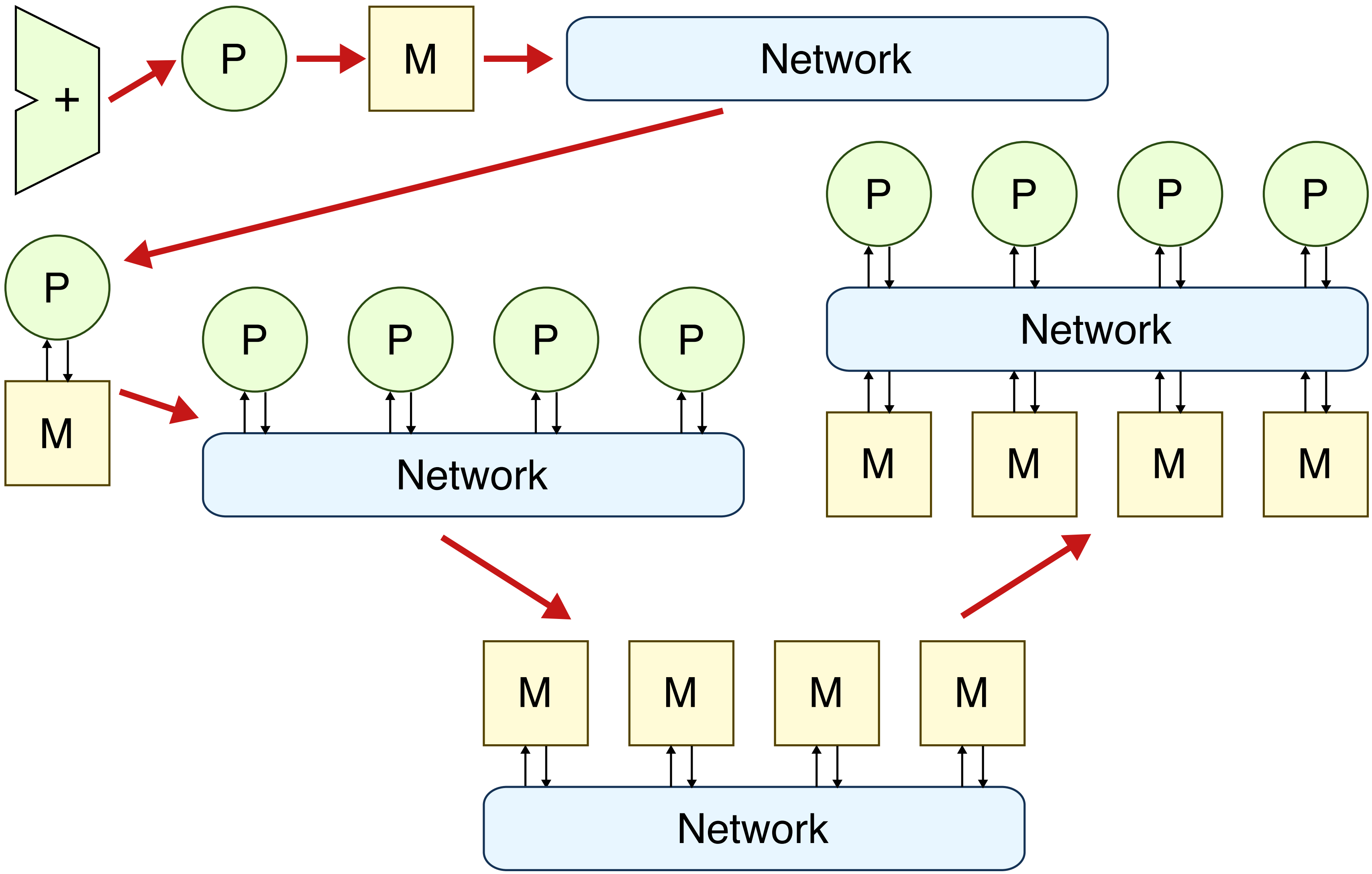
- Abstraction – Hide low-level details to create higher-level models
- Hierarchy – Structurally decompose design; e.g., net → router → queues
- Regularity – Structural and physical regularity; e.g., uniform tiles
- Modularity – Well-defined interfaces; e.g., latency insensitive net interface
- Encapsulation – Hide implementation details; e.g., processor microarch
- Extensibility – Design for future extensions; e.g., new network topo

Design Methodologies

- Incremental design
- Test-driven design

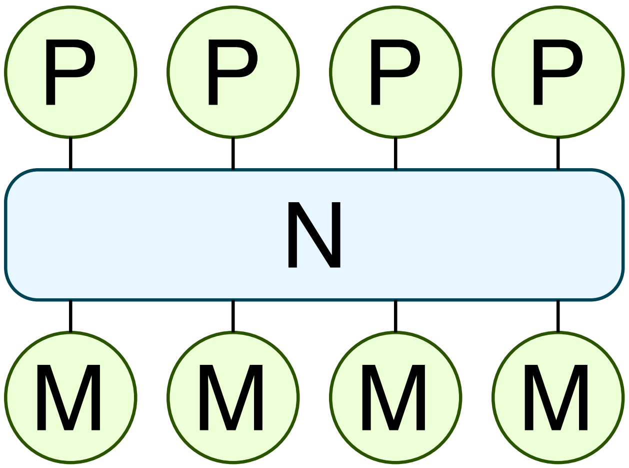


Incremental Design



Test-Driven Design

- Test Types
  - Unit tests
  - Directed vs. random tests
  - Whitebox vs. blackbox tests
  - Integration tests



- Goal is to write tests first then implement design to pass these tests
- Write tests for higher level of abstraction, refine implementation until passes tests, add new tests
- Capture design bugs with new tests

Single-Core to Multi-Core Design Example

Computer Engineering

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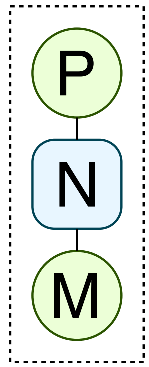
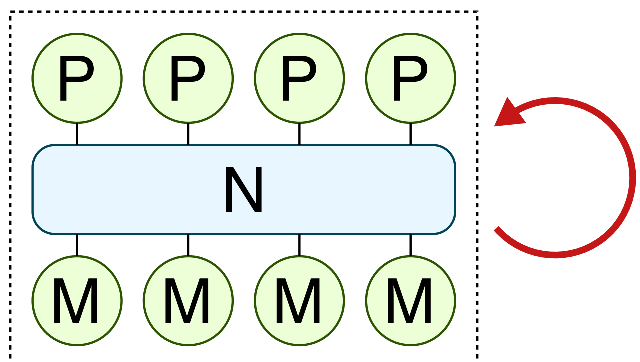
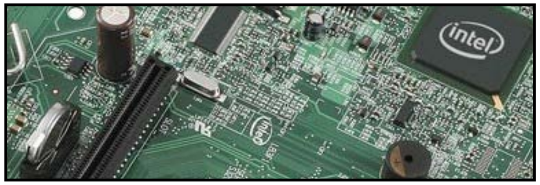
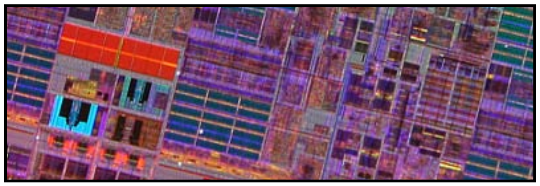
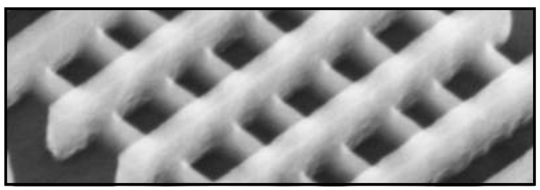


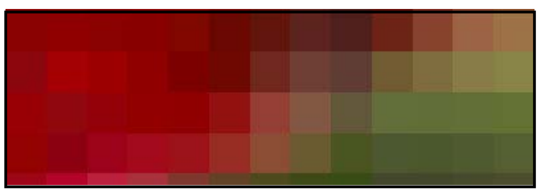
Our "experiments" during
the previous activities
illustrate the design process











Take-Away Points

- ECE is a broad field focused on the study and application of electricity, micro-electronics, and electro-magnetism
- Computer engineering is the process of designing abstraction and implementation layers to meet application requirements within physical technology constraints
- We are entering an exciting new era of computer engineering with emerging applications and systems, a remarkable shift towards mainstream parallel processing, and significant technology challenges