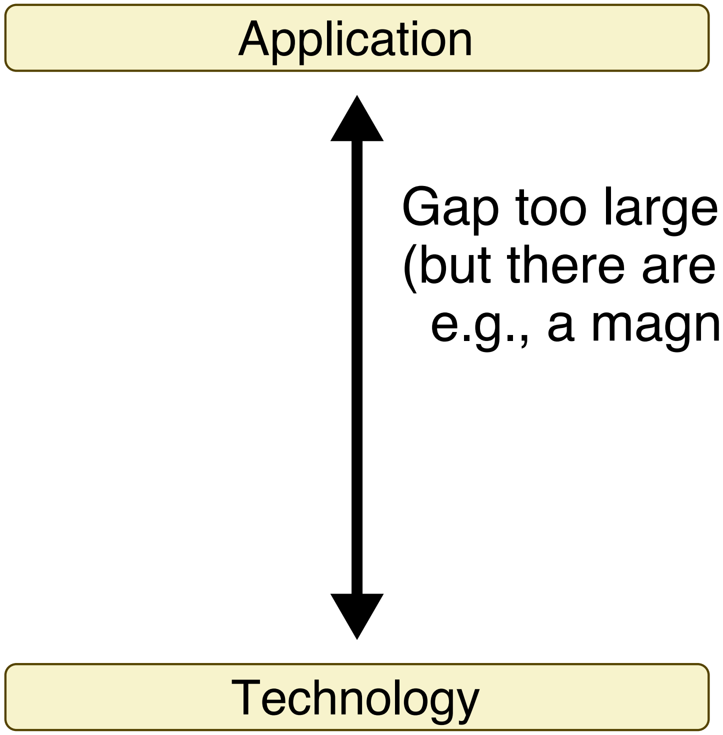
# ECE 4750 Computer Architecture Course Overview

Christopher Batten

School of Electrical and Computer Engineering
Cornell University

`http://www.csl.cornell.edu/courses/ece4750`

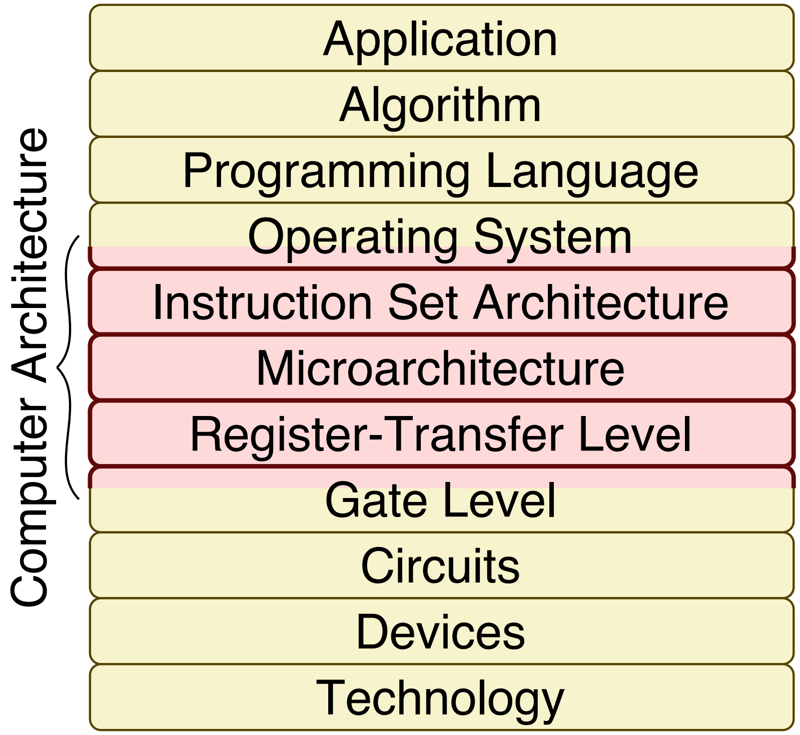
# The Computer Systems Stack



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

In its broadest definition, computer architecture 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



Computer Architecture

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

**Sort an array of numbers**

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

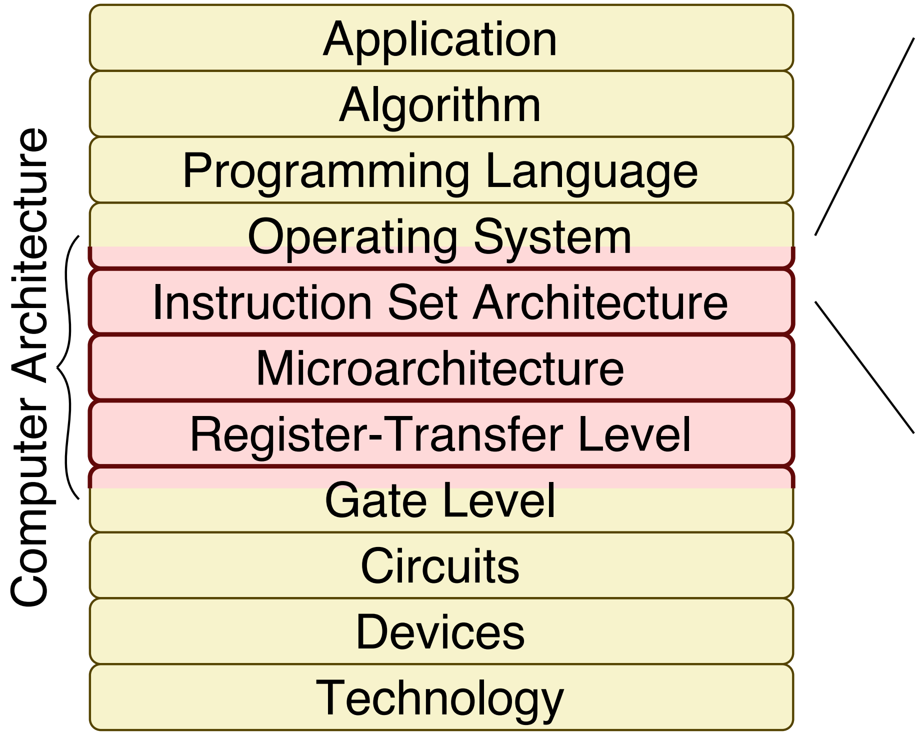
**Out-of-place selection sort algorithm**

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

**C implementation of selection sort**

```
void sort( int b[], int a[], int n ) {
  for ( int idx, k = 0; k < n; k++ ) {
    int min = 100;
    for ( int i = 0; i < n; i++ ) {
      if ( a[i] < min ) {
        min = a[i];
        idx = i;
      }
    }
    b[k]   = min;
    a[idx] = 100;
  }
}
```

# The Computer Systems Stack

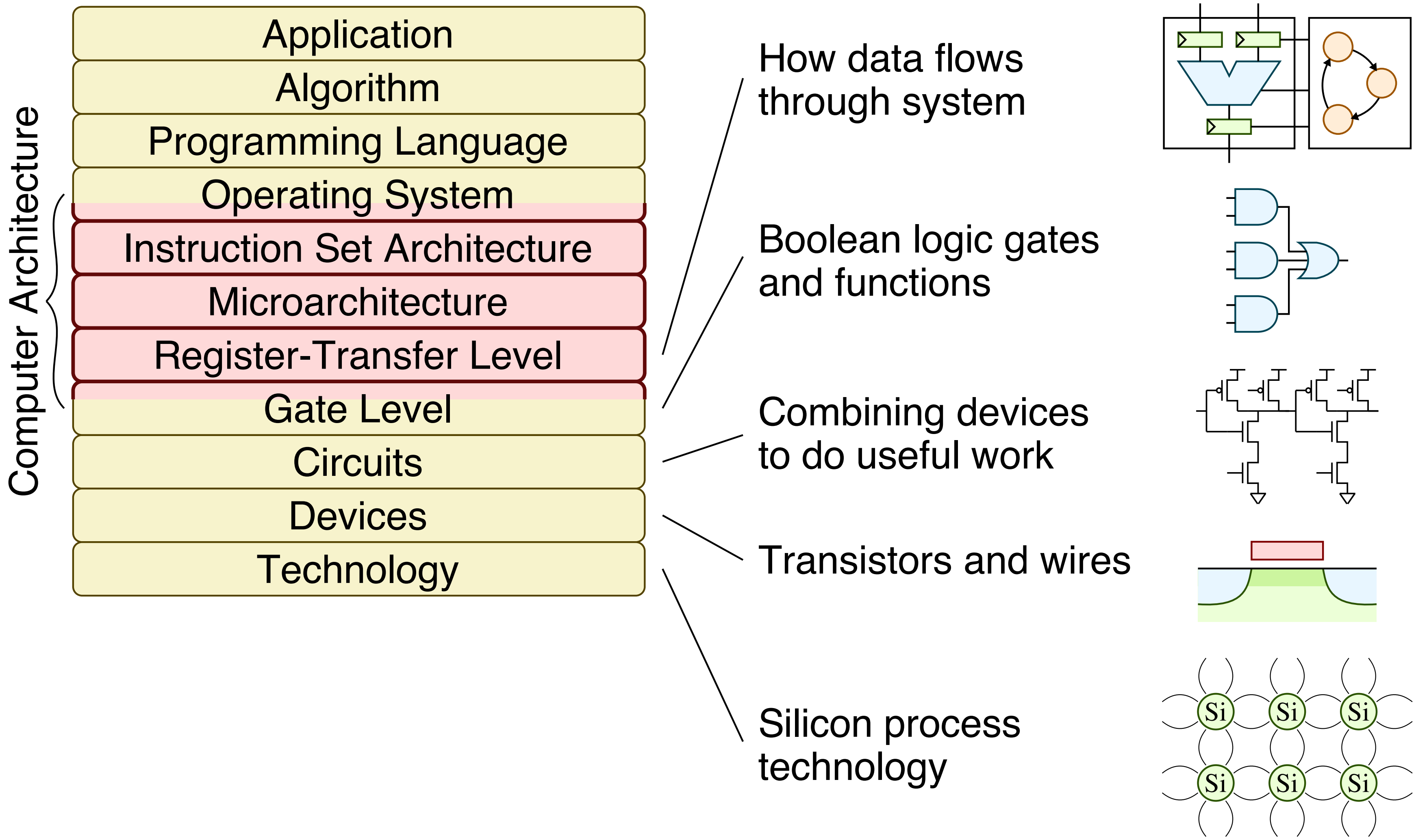


**Mac OS X, Windows, Linux**
Handles low-level hardware management

**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



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How data flows through system

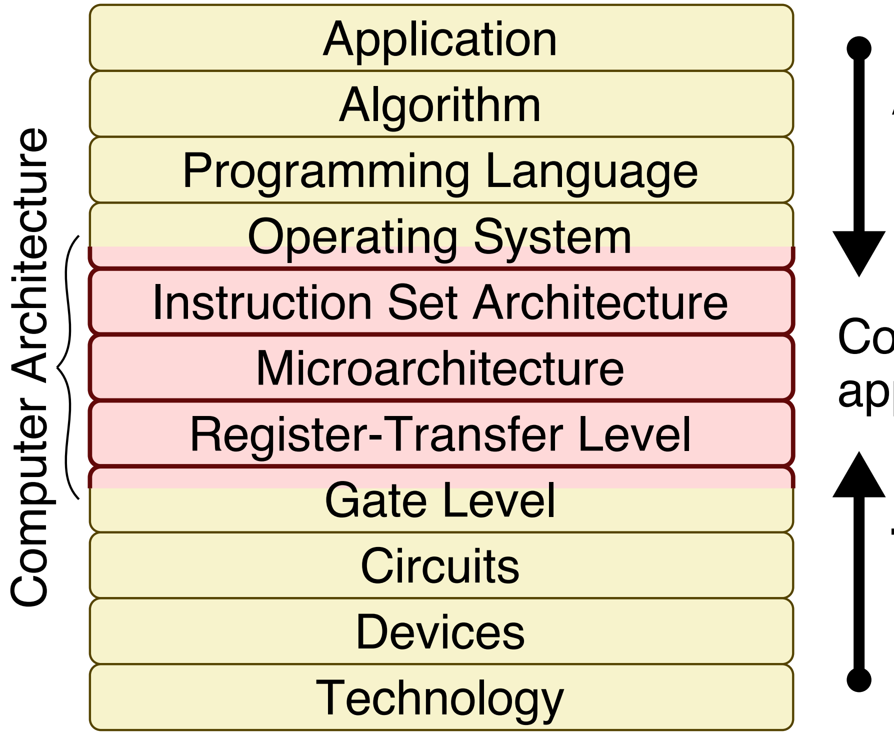
Boolean logic gates and functions

Combining devices to do useful work

Transistors and wires

Silicon process technology

# Application Requirements vs. Technology Constraints



Application
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Devices
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Computer Architecture

**Application Requirements**

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

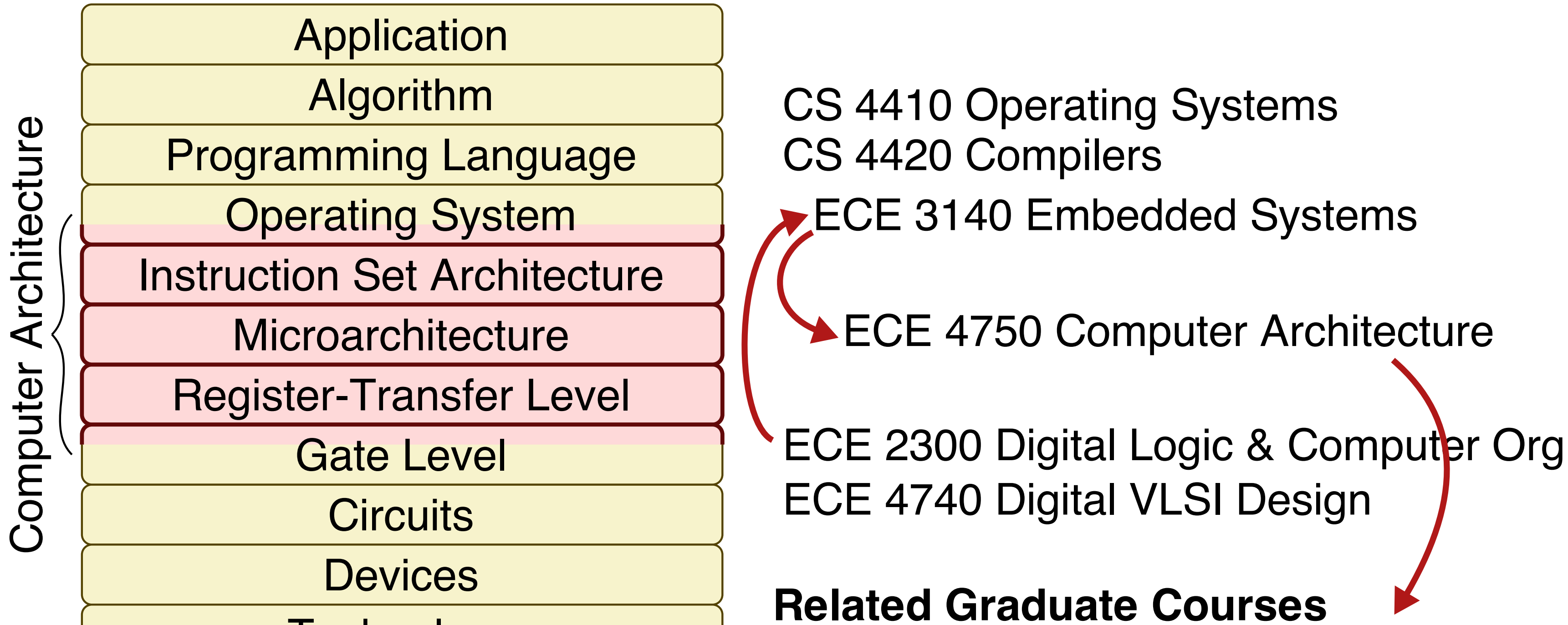
Computer engineers provide feedback to guide application and technology research directions

**Technology Constraints**

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

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

# Computer Architecture in the ECE/CS Curriculum



CS 4410 Operating Systems
CS 4420 Compilers
ECE 3140 Embedded Systems

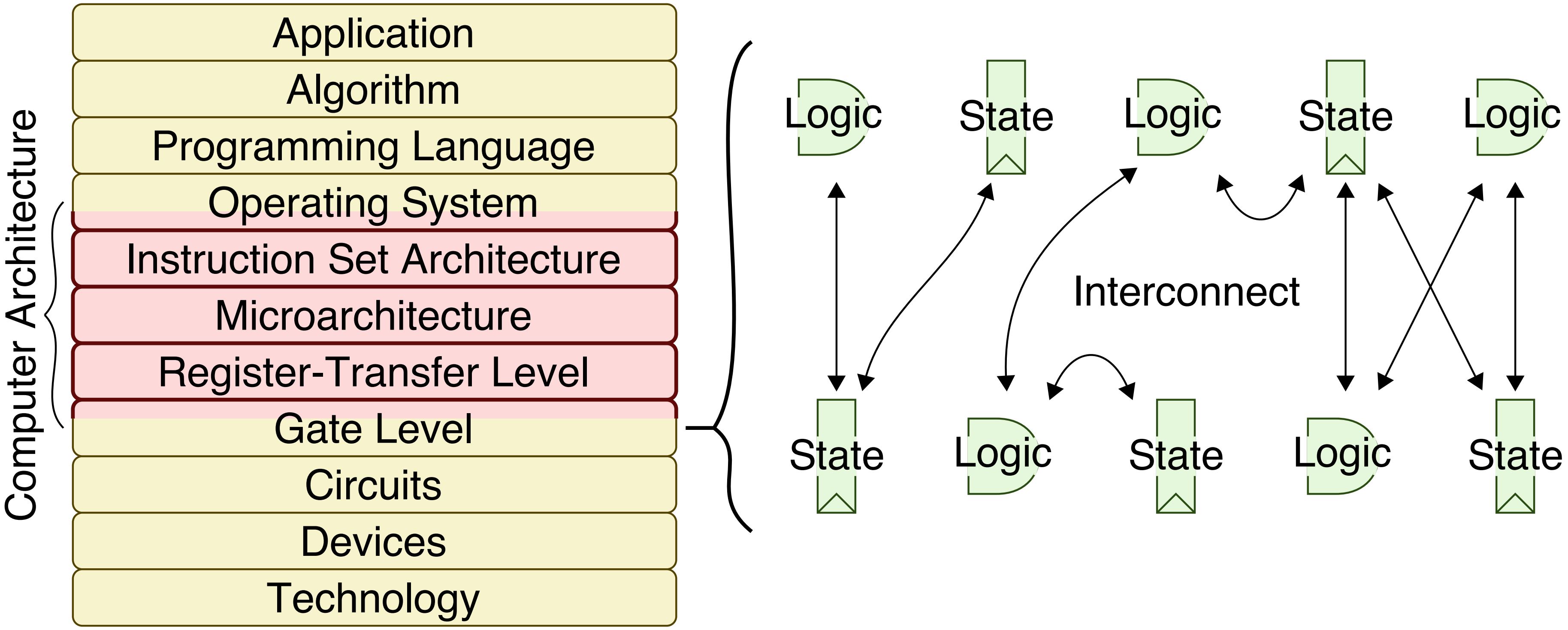
ECE 4750 Computer Architecture

ECE 2300 Digital Logic & Computer Org
ECE 4740 Digital VLSI Design

**Related Graduate Courses**

- ECE 5760 Advanced Microcontroller Design
- ECE 5750 Advanced Computer Architecture
- ECE 5730 Memory Systems
- ECE 5770 Resilient Computer Systems
- ECE 5745 Complex Digital ASIC Design
- ECE 5775 High-Level Design Automation

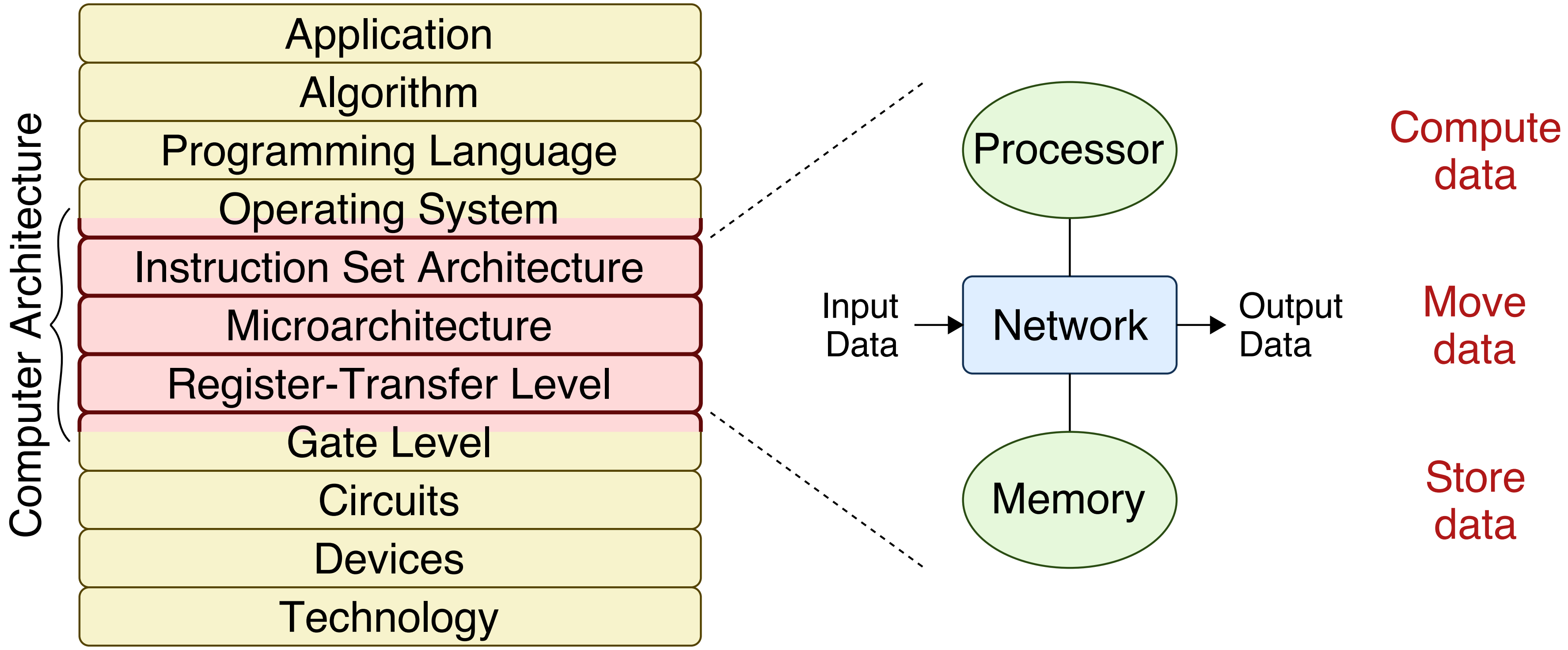
# Logic, State, and Interconnect



Digital systems are implemented with three basic building blocks

- Logic to process data
- State to store data
- Interconnect to move data

# Processors, Memories, and Networks



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Computer Architecture

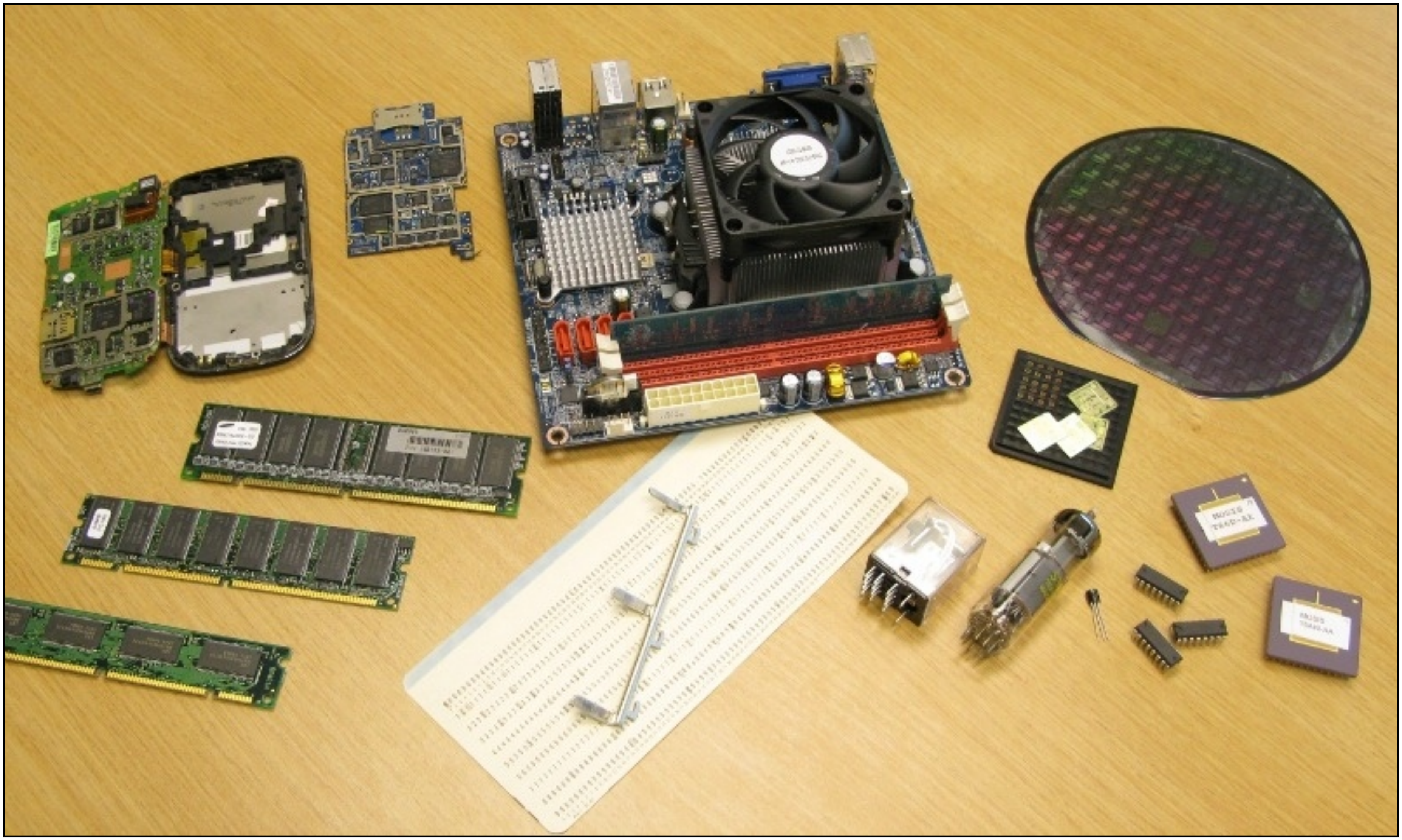
Processor
Input Data
Network
Output Data
Memory

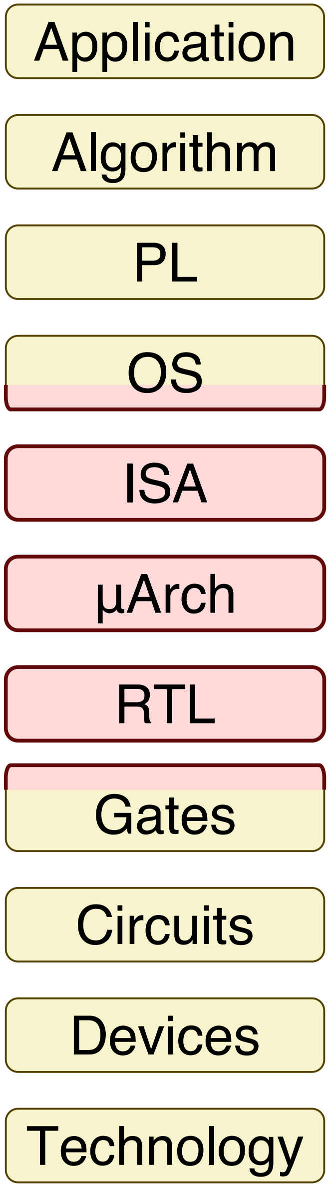
Compute data
Move data
Store data

Computer engineering basic building blocks

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

# Computer Architecture Artifacts





Application
Algorithm
PL
OS
ISA
µArch
RTL
Gates
Circuits
Devices
Technology

# Agenda

What is Computer Architecture?

Activity 1

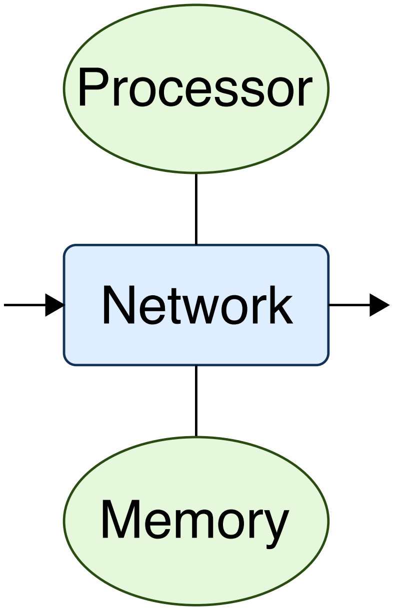
Trends in Computer Architecture

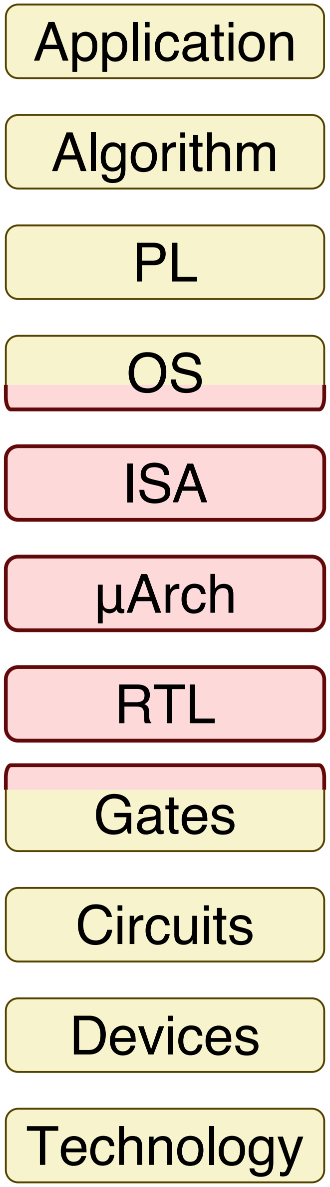
Activity 2

Computer Architecture Design

# 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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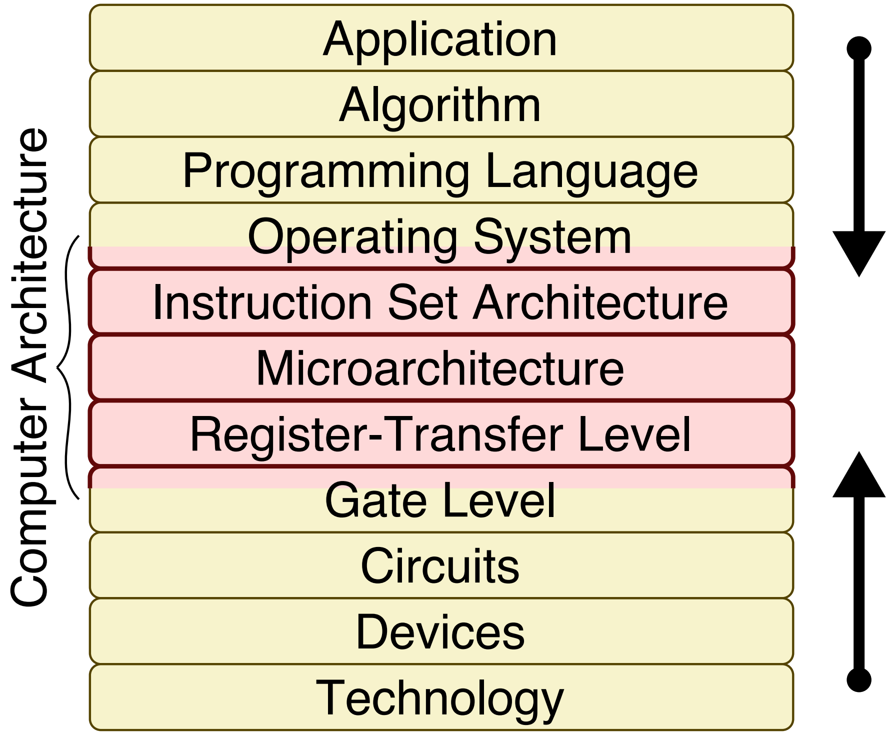
# Application Requirements vs. Technology Constraints



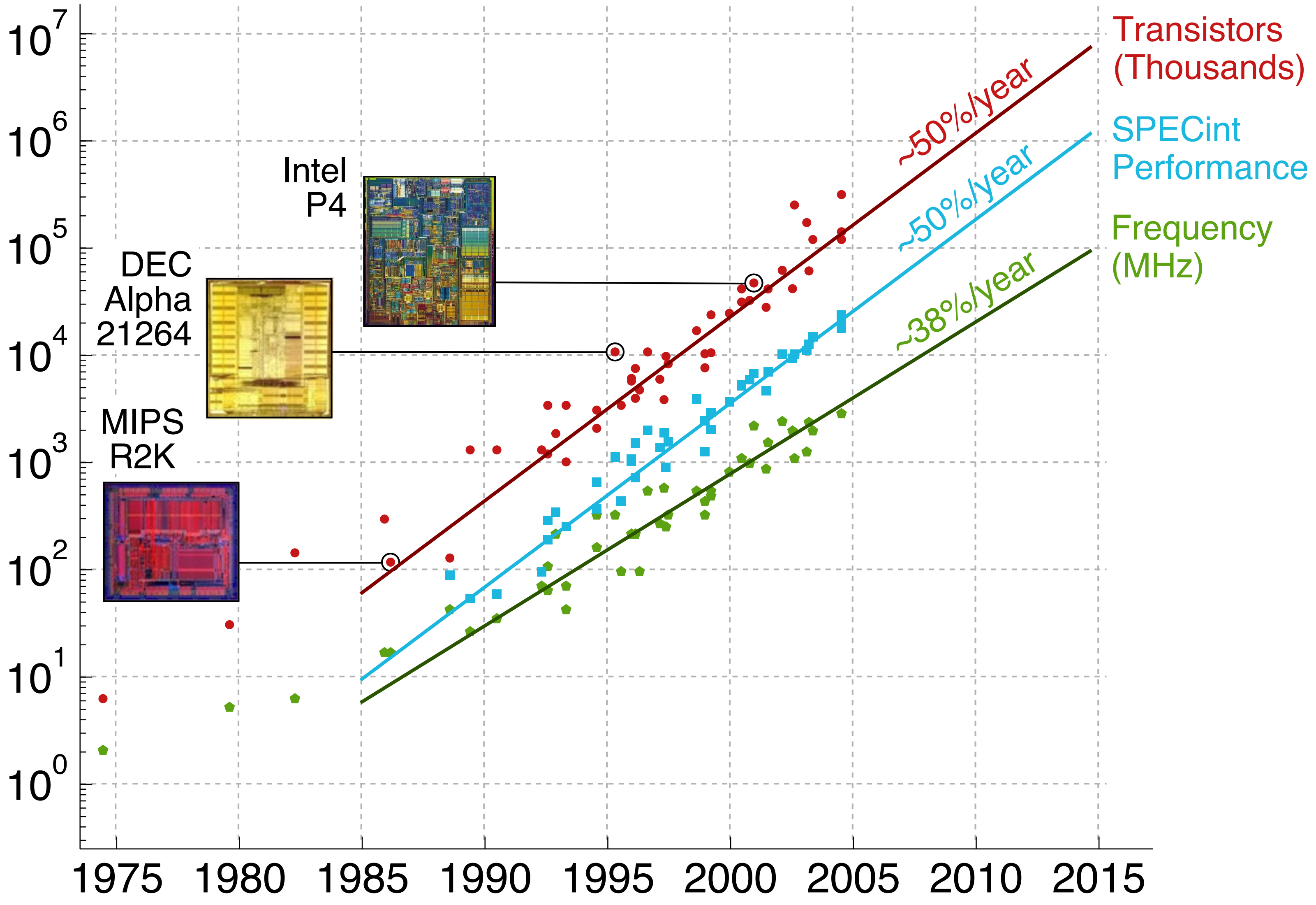
**Traditional**
**Application Requirements**

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

**Traditional**
**Technology Constraints**

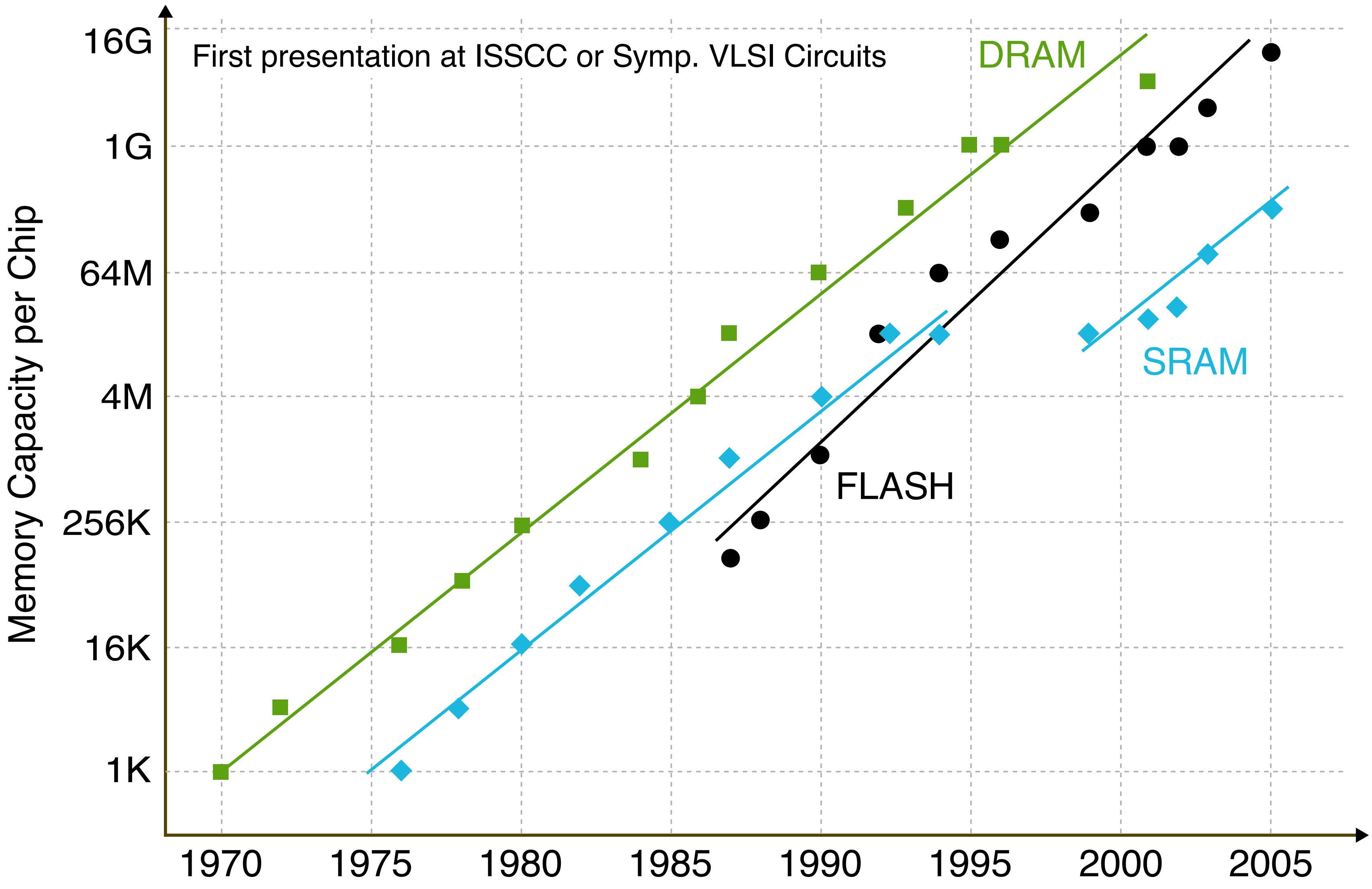
- Exponential scaling of resources

# Exponential Scaling for Processor Computation



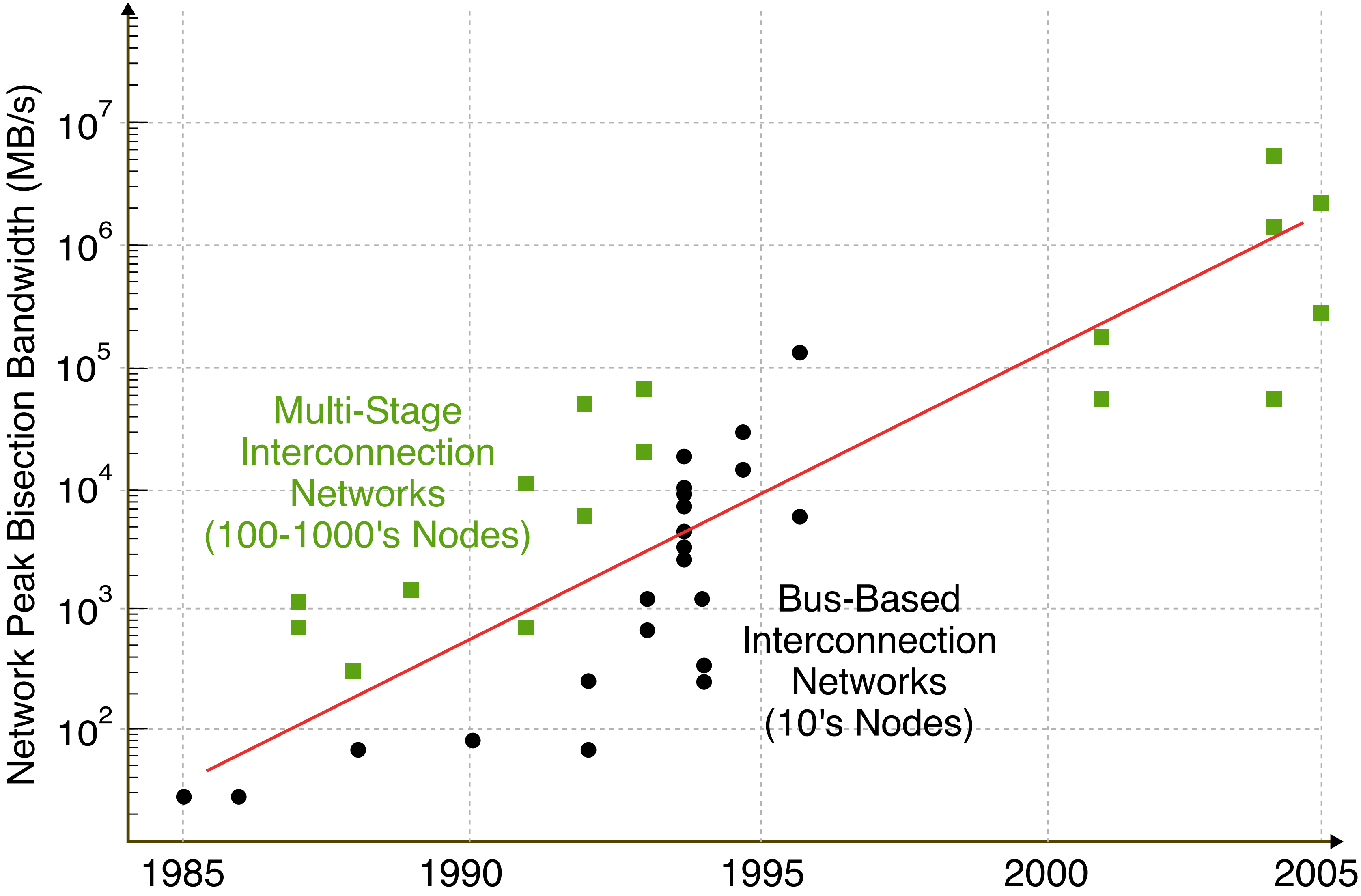
Data collected by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, C. Batten

# Exponential Scaling for Memory Capacity



Adapted from K. Itoh et al. “Ultra-Low Voltage Nano-Scale Memories.” Spring 2007.

# Exponential Scaling for Network Bandwidth



Data from Hennessy & Patterson, Morgan Kaufmann, 2nd & 5th eds., 1996 & 2011; D.E. Culler et al., Morgan Kaufmann, 1999.

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

processors, memories, and networks

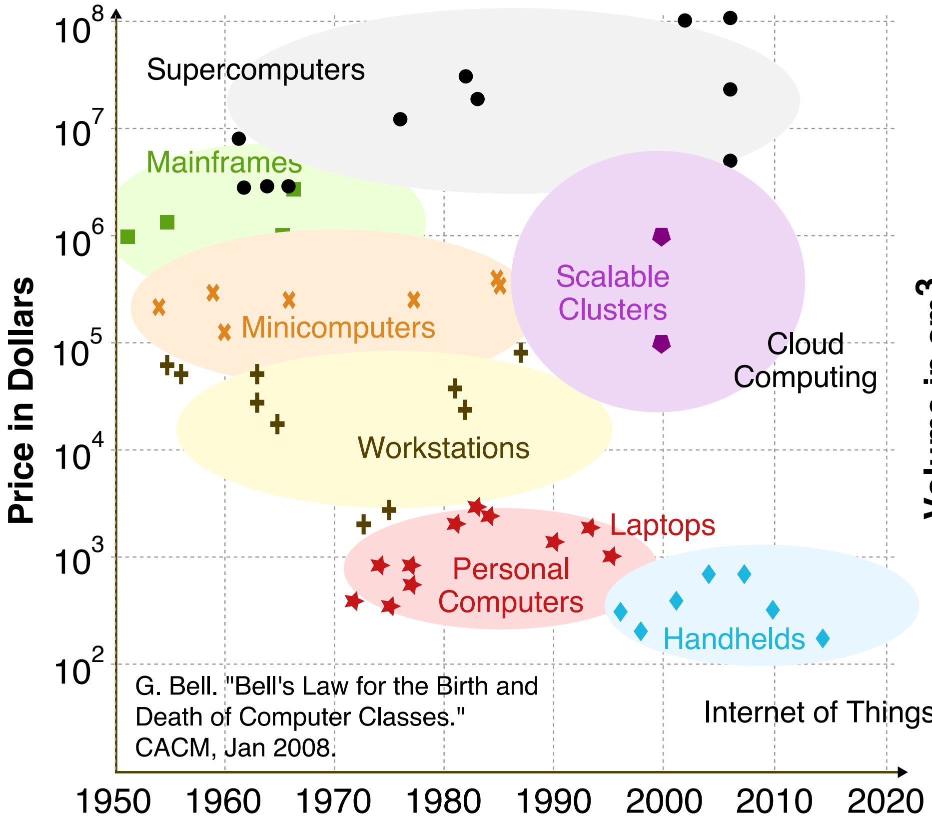
used in modern computing systems

## Five Key Trends in Computer Architecture

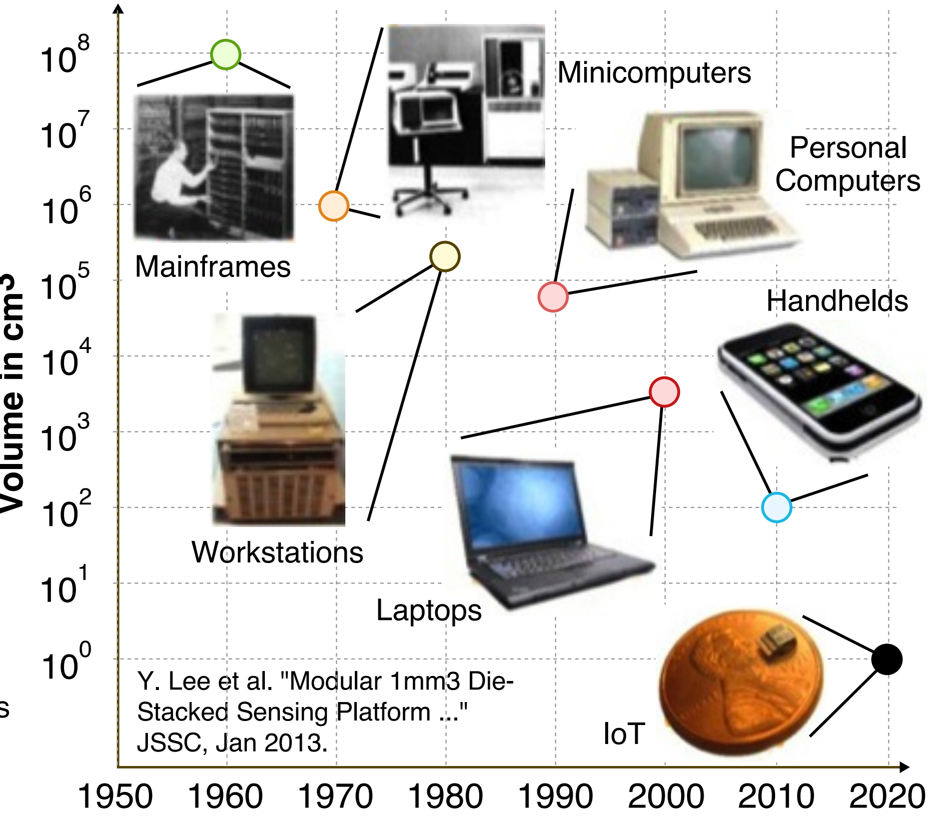
1. Growing diversity in application requirements motivate growing diversity in computing systems pushing towards the cloud and IoT
2. Energy & power constrain systems across the computing spectrum
3. Transition to multiple cores integrated onto a single chip
4. Transition to heterogeneous systems-on-chip
5. Technology scaling challenges motivate new emerging compute, storage, and communication device technologies

# Trend 1: Bell's Law

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



G. Bell. "Bell's Law for the Birth and Death of Computer Classes." CACM, Jan 2008.



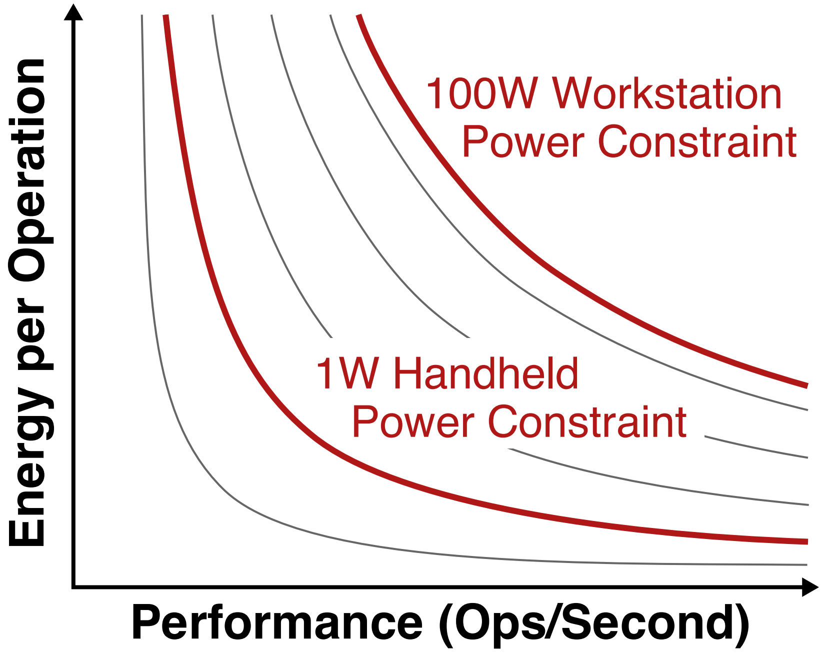
Y. Lee et al. "Modular 1mm3 Die-Stacked Sensing Platform ..." JSSC, Jan 2013.

# Trend 1: Growing Diversity in Apps & Systems

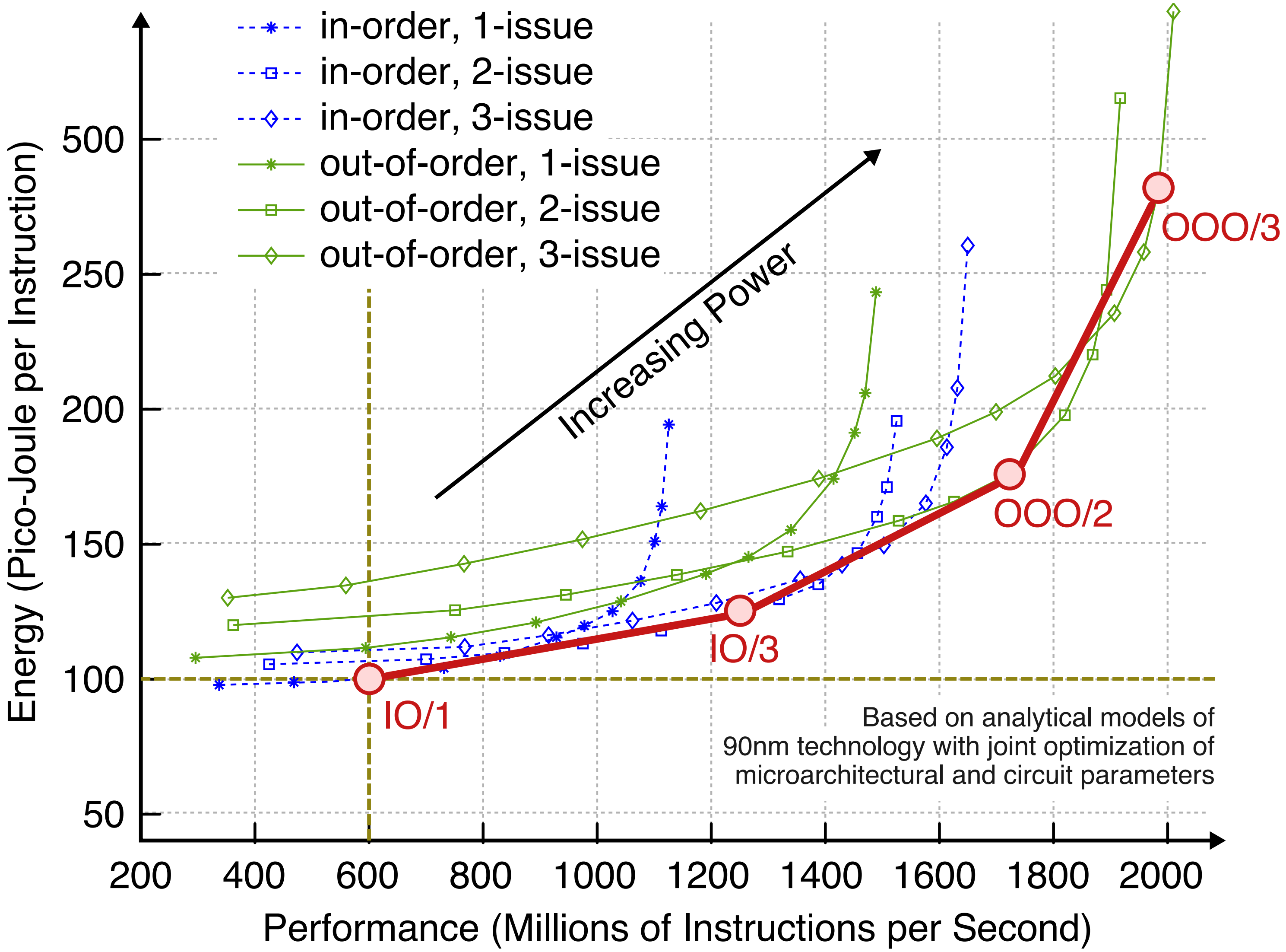
# Trend 2: Energy and Power Constraints

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

| **Power** | **Energy** |
|---|---|
| Chip Packaging | Battery Life |
| Chip Cooling | Electricity Bill |
| System Noise | Mobile Device Weight |
| Case Temperature | |
| Data-Center Air Conditioning | |

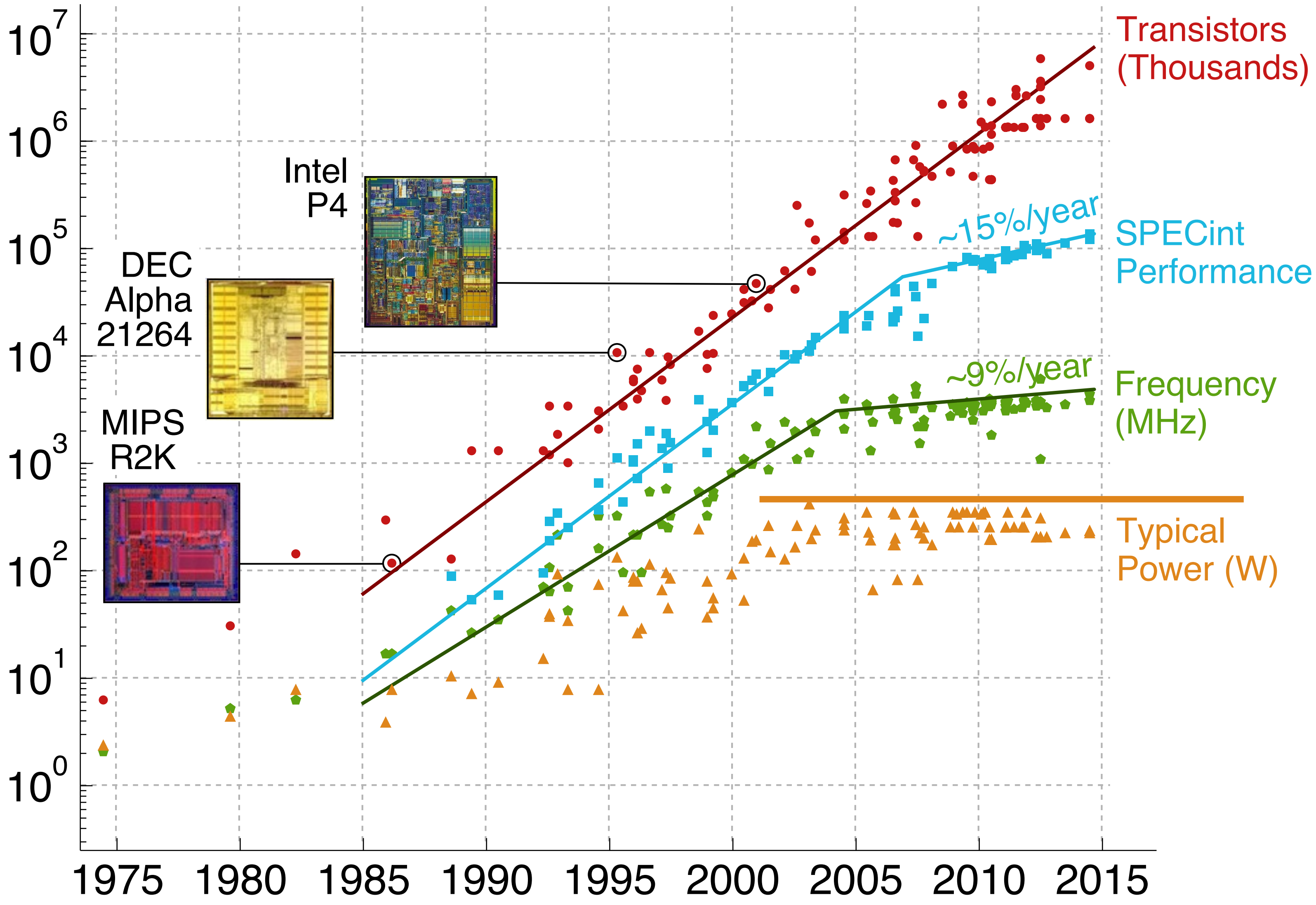


# Trend 2: Energy and Performance of Single Processor



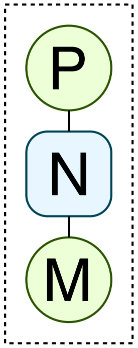
Adpated from O. Azizi et al. “Energy-Performance Tradeoffs ...” ISCA, 2010.

# Trend 2: Power Constrains Single-Processor Scaling

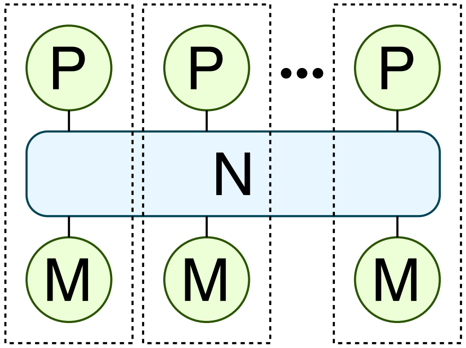


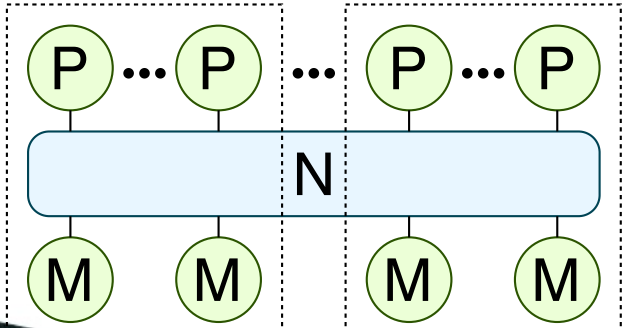
# Trend 3: Transition to Multicore Processors

**Intel Pentium 4**
Single monolithic processor

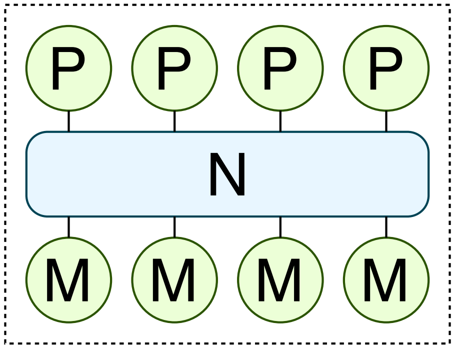


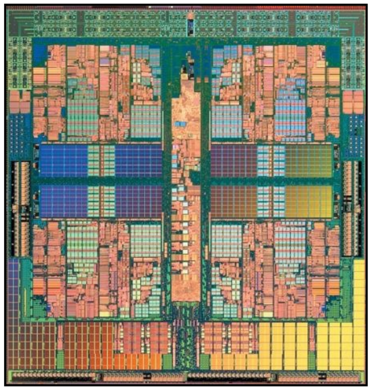
**Cray XT3 Supercomputer**
1024 single-core processors





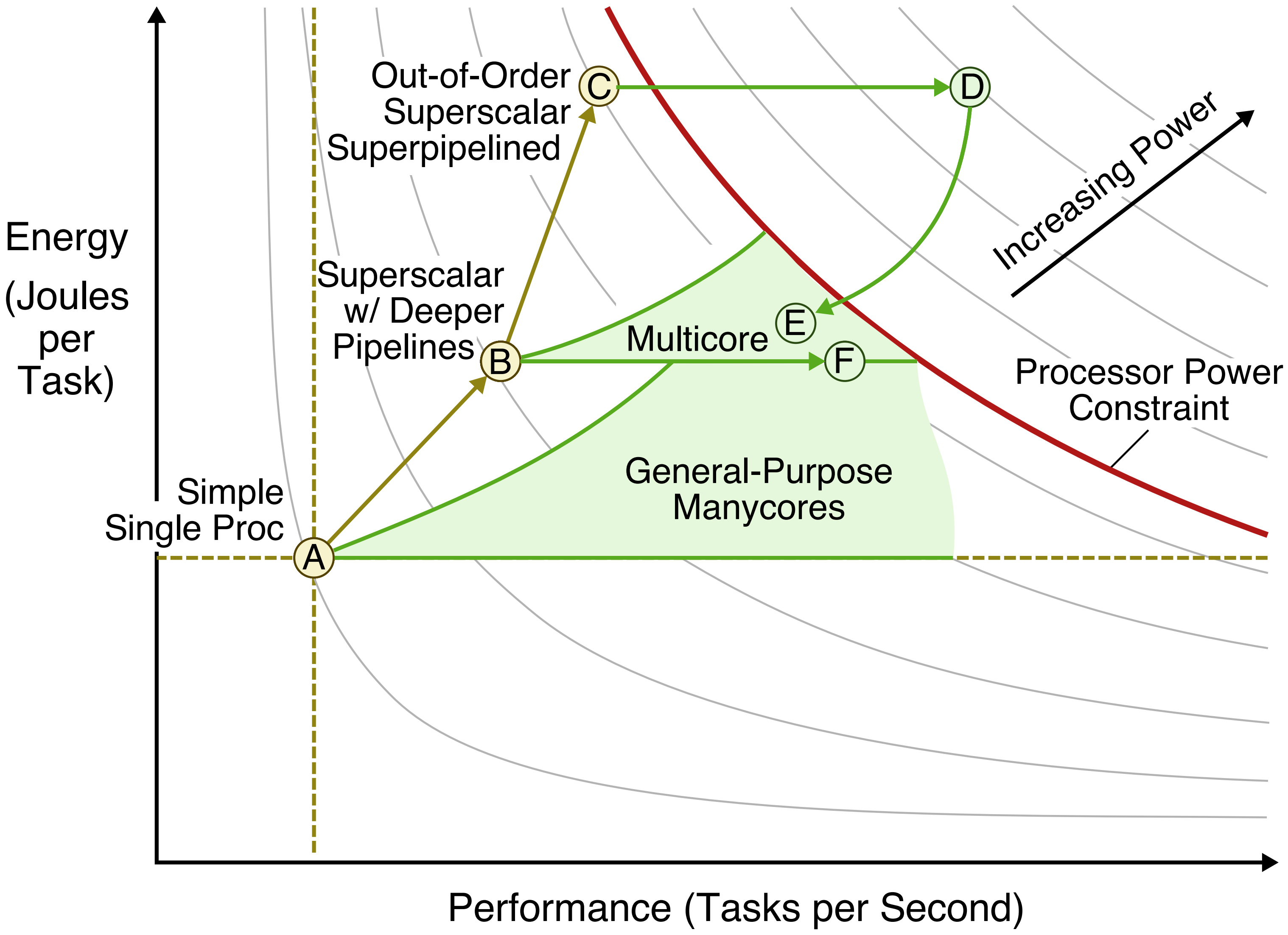
**AMD Quad-Core Opteron**
Four cores on the same die



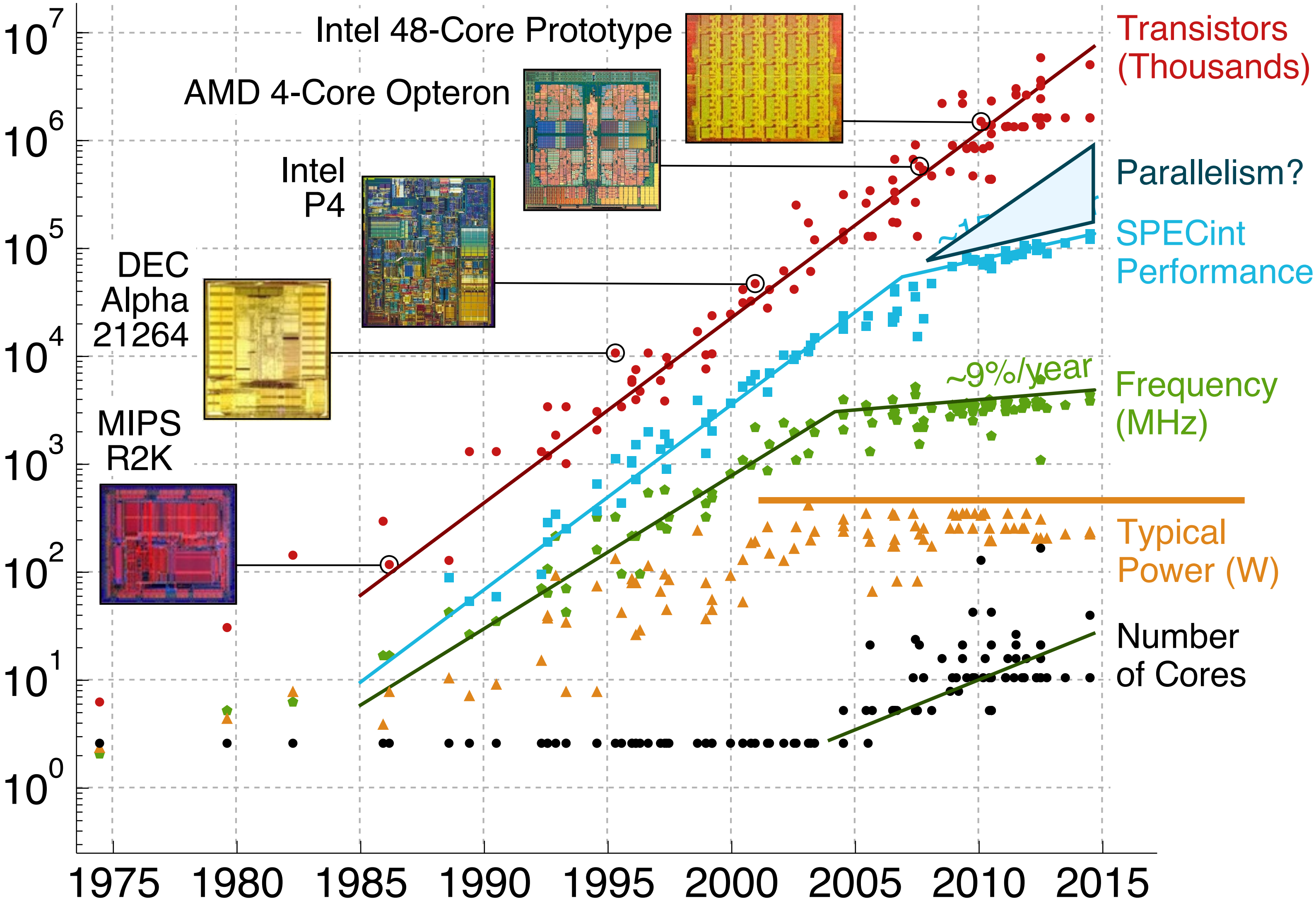


**IBM Blue Gene Q**
**Supercomputer**
Thousands of
18-core processors

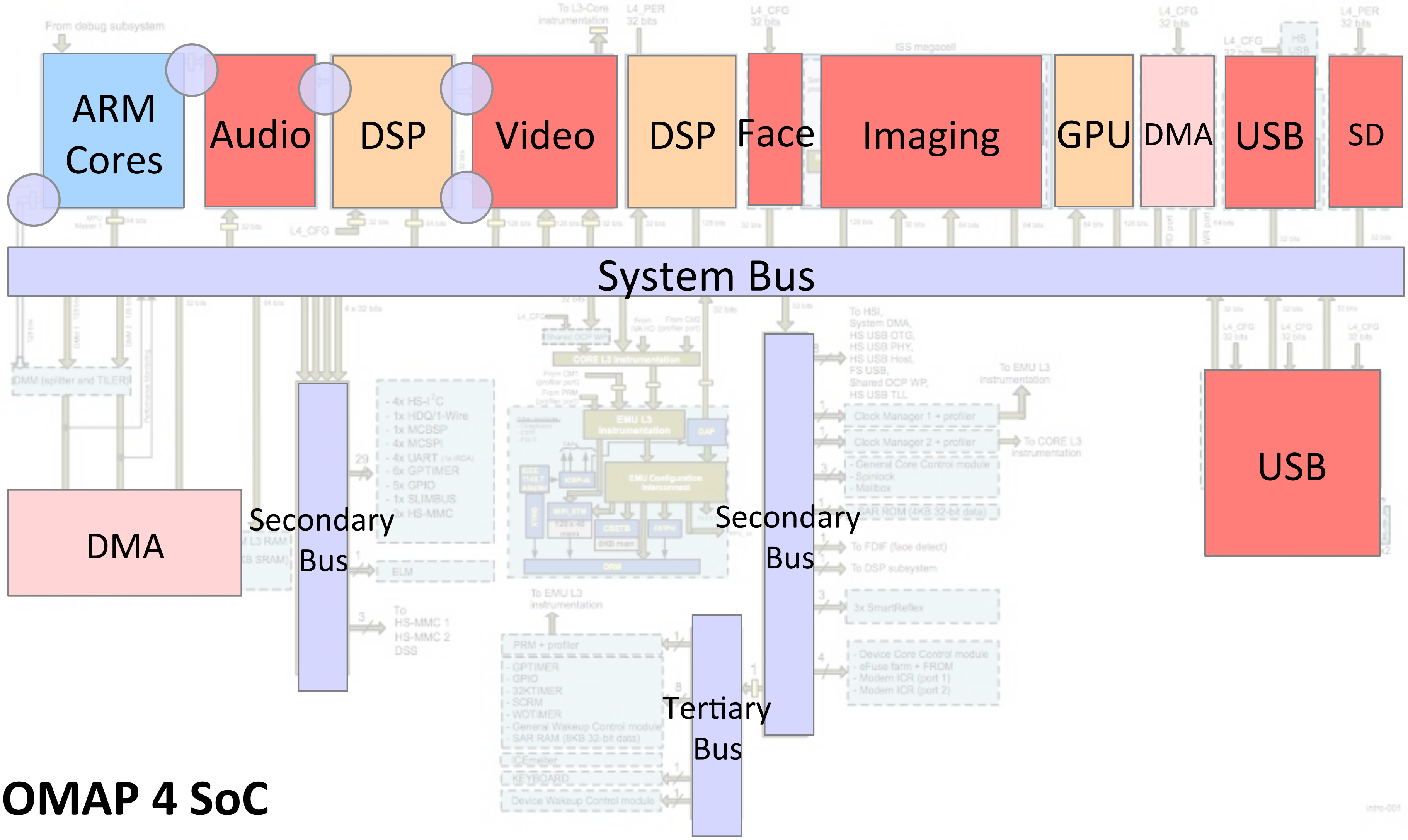
# Trend 3: Energy and Performance of Multicores



# Trend 3: The Multicore "Hail Mary Pass"



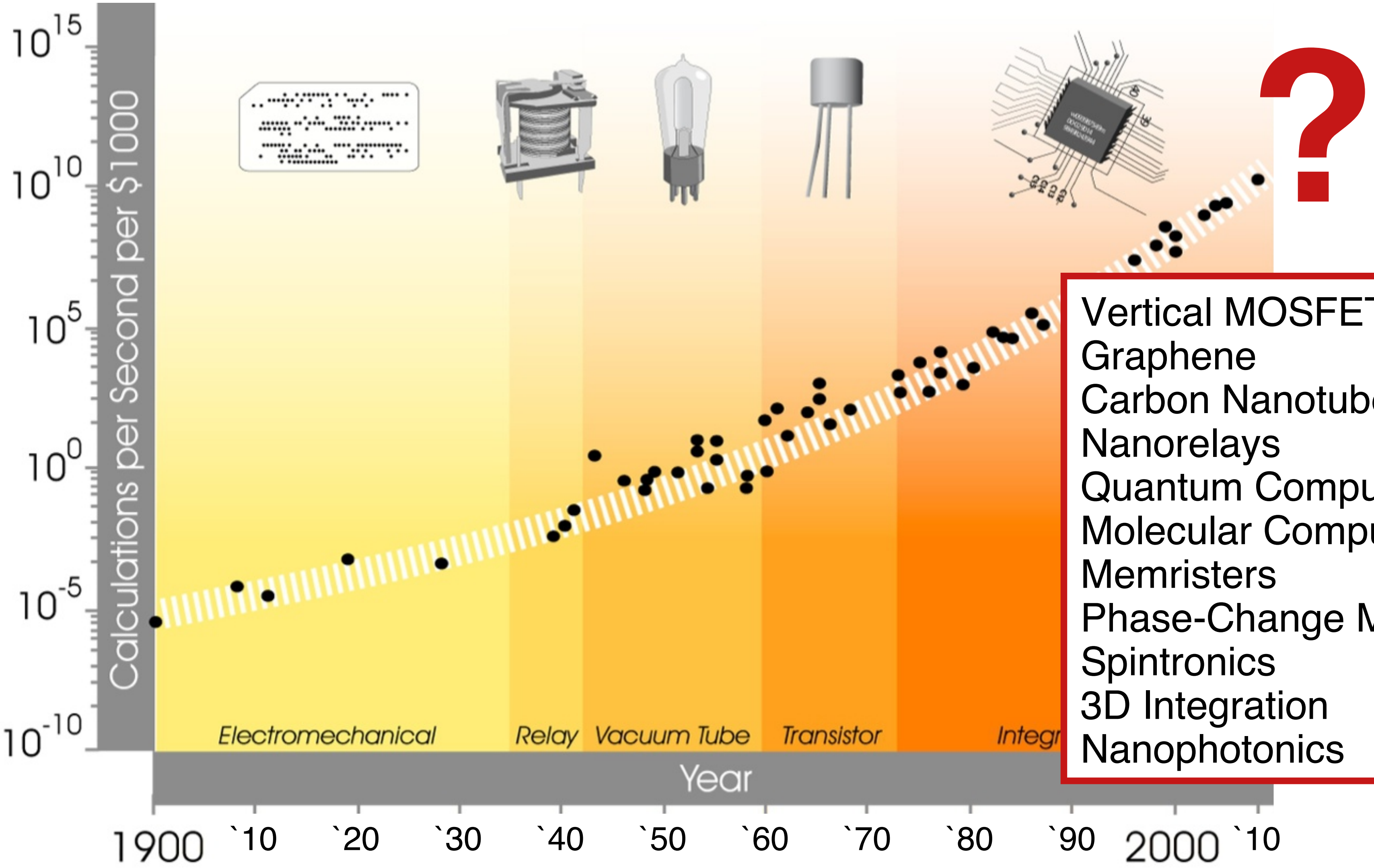
# Trend 4: Heterogeneous Systems-on-Chip



**OMAP 4 SoC**

Adapted from D. Brooks Keynote at NSF XPS Workshop, May 2015.

# Trend 5: Emerging Device Technologies



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

Adapted from R. Kurzweil. “The Singularity is Near.” Penguin Books, 2006.

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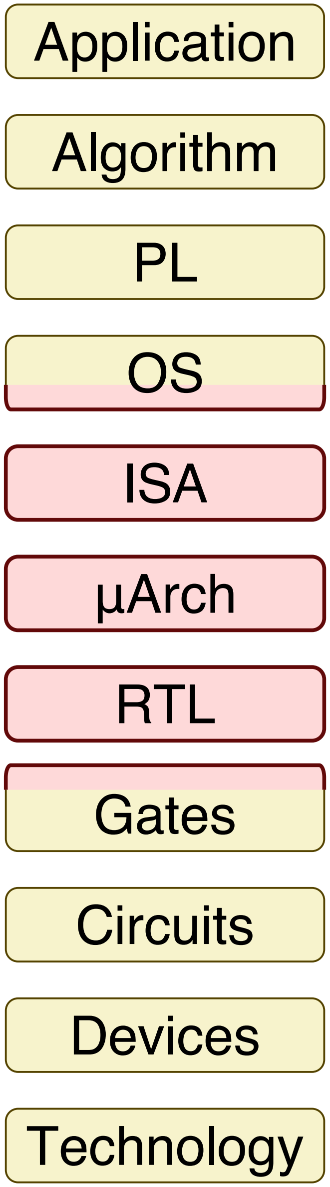

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What is Computer Architecture?

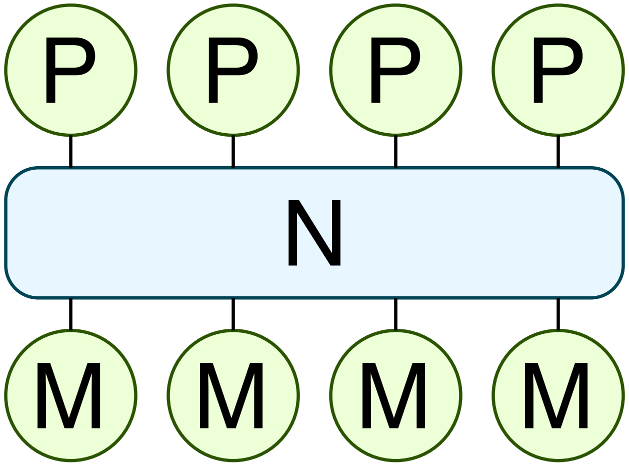
Activity 1

Trends in Computer Architecture

**Activity 2**

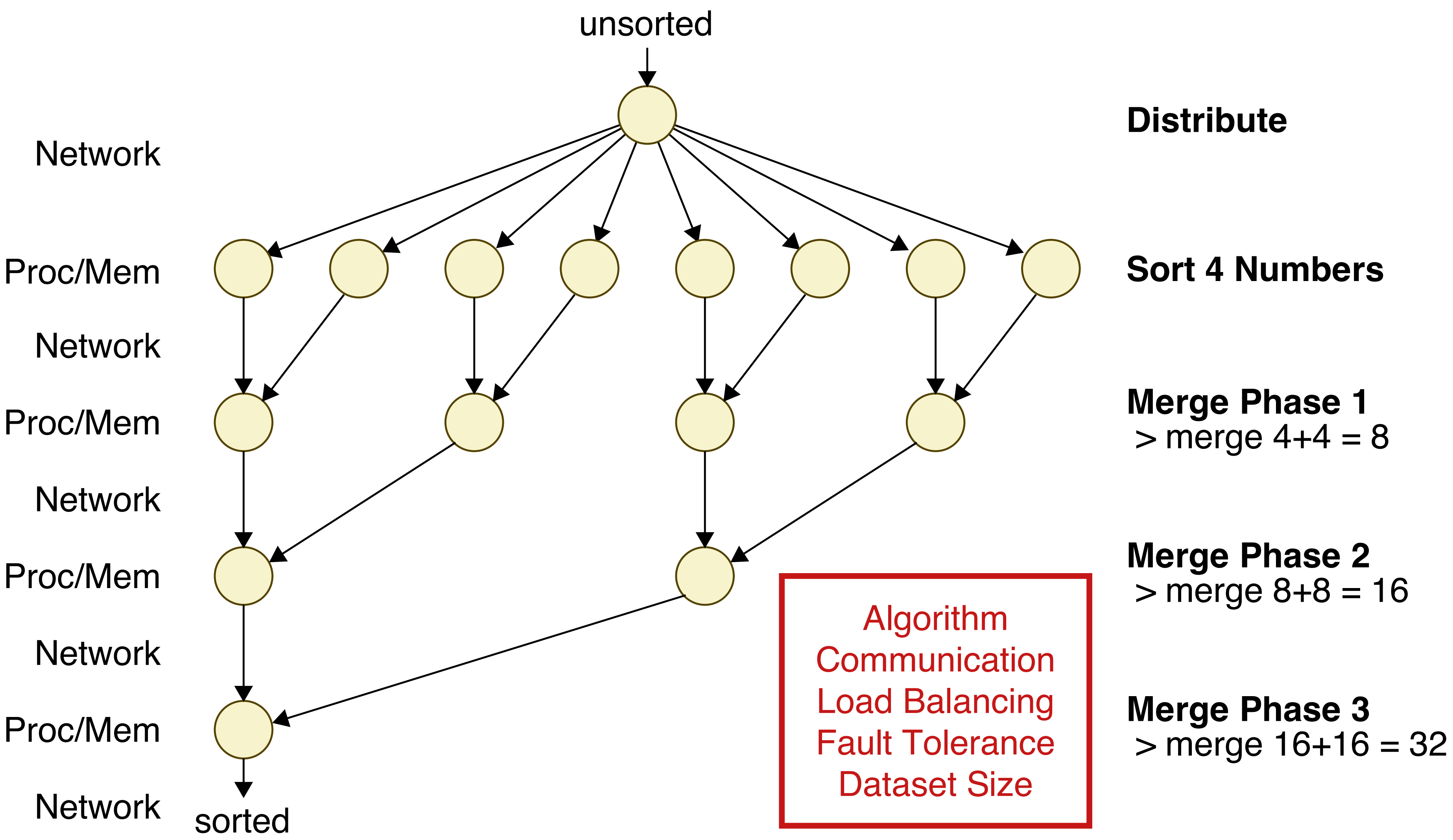
Computer Architecture Design

# 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



unsorted

Network

**Distribute**

Proc/Mem

**Sort 4 Numbers**

Network

Proc/Mem

**Merge Phase 1**
> merge 4+4 = 8

Network

Proc/Mem

**Merge Phase 2**
> merge 8+8 = 16

Network

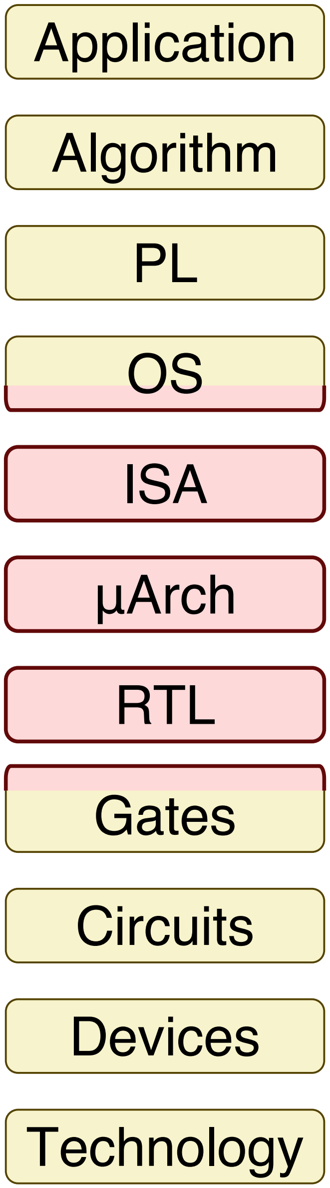
Proc/Mem

**Merge Phase 3**
> merge 16+16 = 32

Network

sorted

Algorithm
Communication
Load Balancing
Fault Tolerance
Dataset Size



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# What do computer architects actually do?

## General Science

Discover truths about nature

Ask question about nature

↓

Construct hypothesis

↓

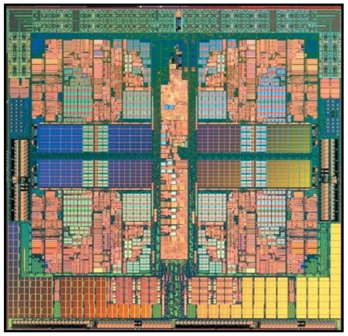
Test with experiment

↓

Analyze results and draw conclusions

## Computer Engineering

Explore design space for a new system



Design and model baseline system

↓

Ask question about system

↓

Test with experiment

↓

Analyze results and draw conclusions

↙ ↘

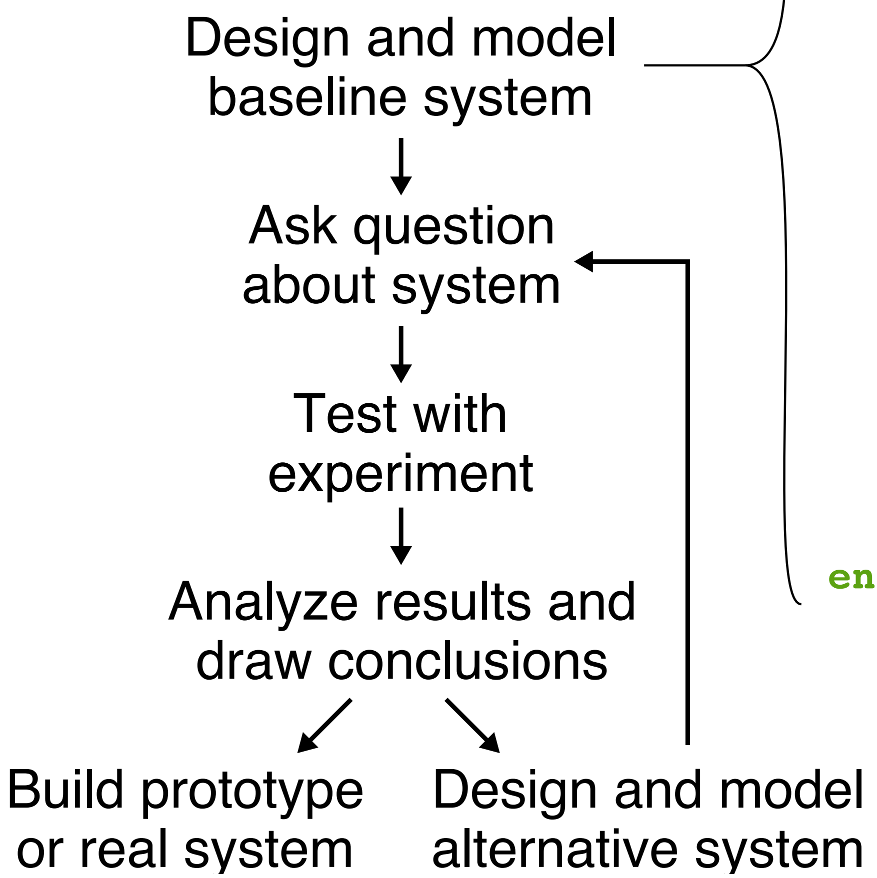
Build prototype or real system

Design and model alternative system

# Modeling in Computer Architecture

**Computer Engineering**

Explore design space for a new system



Design and model baseline system

Ask question about system

Test with experiment

Analyze results and draw conclusions

Build prototype or real system

Design and model alternative system

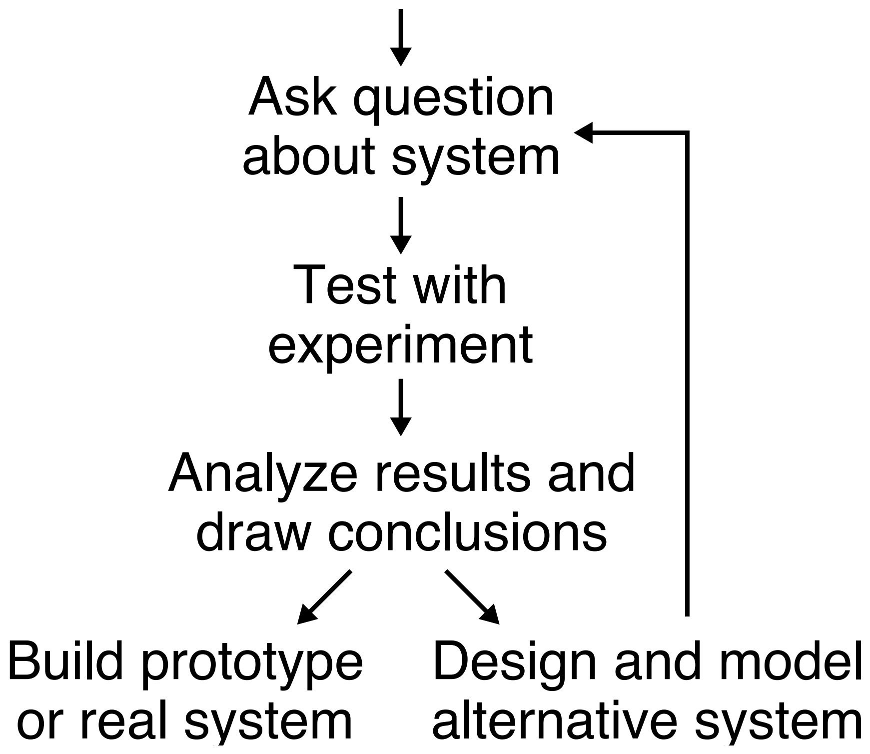
```
// rdy is OR of the AND of reqs and grants
assign in_rdy = | (reqs & grants);

reg [2:0] reqs;
always @(*) begin
  if ( in_val ) begin

    // eject packet if it is for this tile
    if ( dest == p_router_id )
      reqs = 3'b010;

    // otherwise, just pass it along ring
    else
      reqs = 3'b001;

  end else begin
    // if !val, don't request any ports
    reqs = 3'b000;
  end
end
```

**Verilog • SystemVerilog • VHDL**
**C++ • SystemC**
**Bluespec • Chisel • Python**

# How do we design something so incredibly complex?

**Computer Engineering**

Explore design space for a new system



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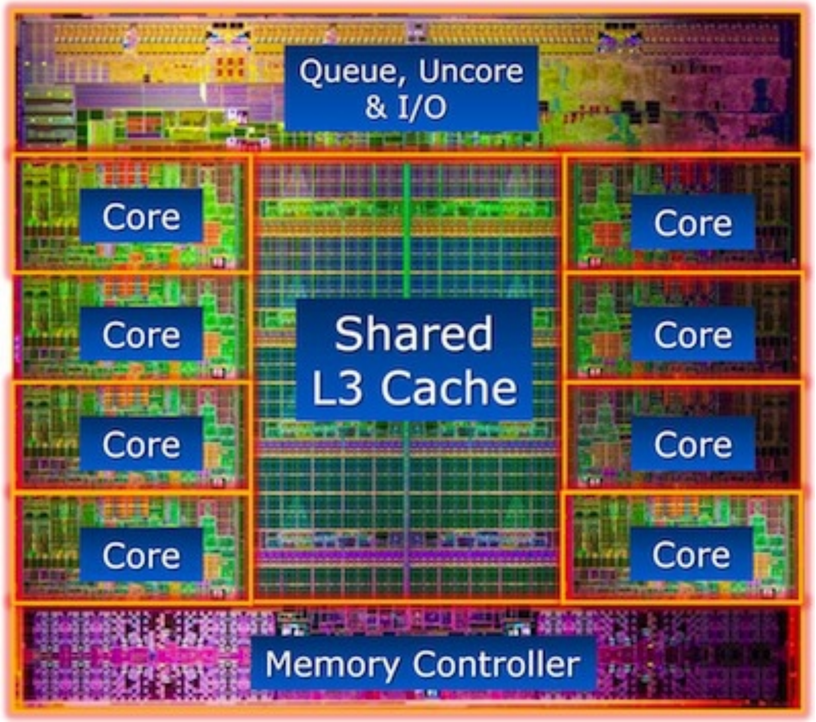
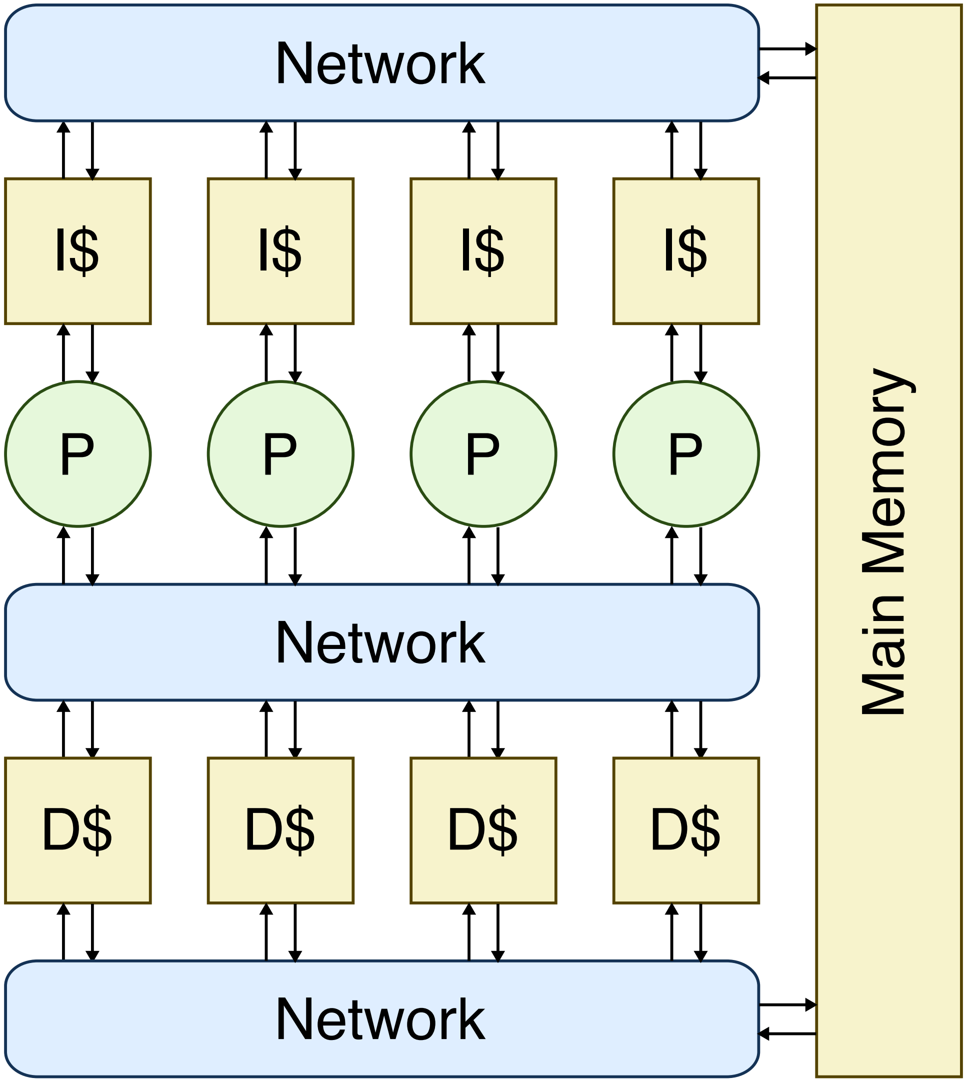


**Fighter Airplane:** ~100,000 parts

**Intel Sandy Bridge E:**
2.27 Billion transistors

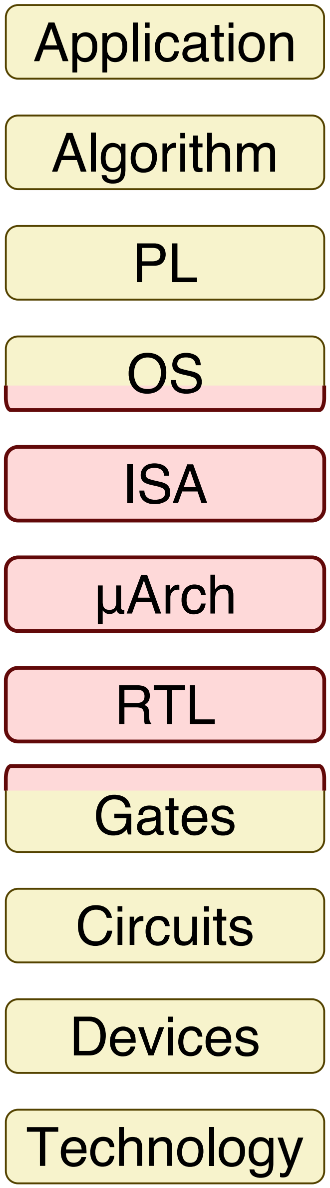
- **Design Principles**
  - Modularity – Decompose into components with well-defined interfaces
  - Hierarchy – Recursively apply modularity principle
  - Encapsulation – Hide implementation details from interfaces
  - Regularity – Leverage structure at various levels of abstraction
  - Extensibility – Include mechanisms/hooks to simplify future changes
- **Design Patterns**
  - Processors, Memories, Networks
  - Control/Datapath Split
  - Single-Cycle, FSM, Pipelined Control
  - Raw Port, Message, Method Interfaces
- **Design Methodologies**
  - Agile Hardware Development
  - Test-driven Development
  - Incremental Development

# Final Goal for Lab Assignments



Quad-core processor with private L1 instruction caches and a shared, banked L1 data cache interconnected through various ring networks implemented at the register-transfer-level and capable running real parallel programs

Lab assignments will use an agile hardware development methodology based on a Python hardware modeling framework, the Verilog hardware description language (optional), the GitHub repository hosting site, and and the TravisCI continuous integration service



# Take-Away Points

- Computer architecture is the process of building computing systems to meet given application requirements within physical technology constraints
- We are entering an exciting new era of computer architecture with growing diversity in applications and systems, a remarkable industrial shift towards mainstream parallel processing and SoCs, and significant technology scaling challenges
- This era offers tremendous challenges and opportunities, which makes it a wonderful time to study and contribute to the field of computer architecture