ECE 4750 Computer Architecture
Course Overview

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

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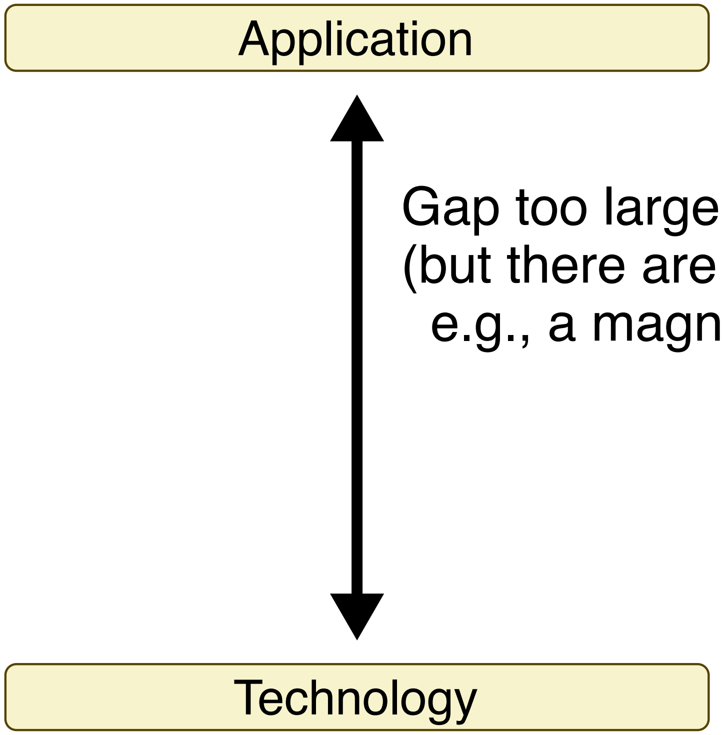
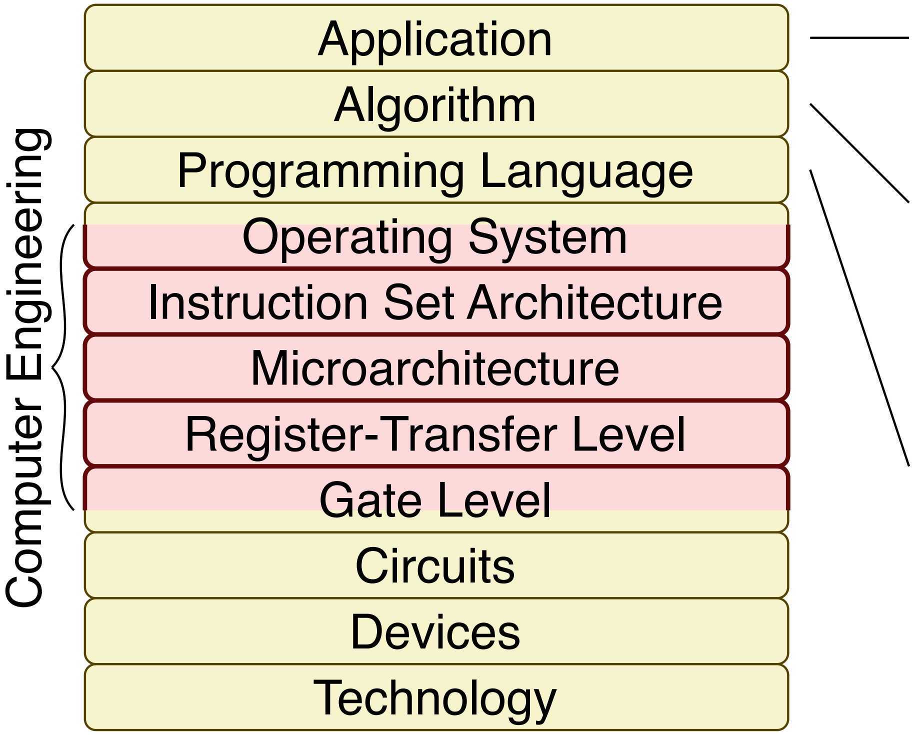
The Computer Systems Stack



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

In its broadest definition, computer engineering 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



Application

Algorithm

Programming Language

Operating System

Instruction Set Architecture

Microarchitecture

Register-Transfer Level

Gate Level

Circuits

Devices

Technology

Computer Engineering

Sort an array of numbers

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

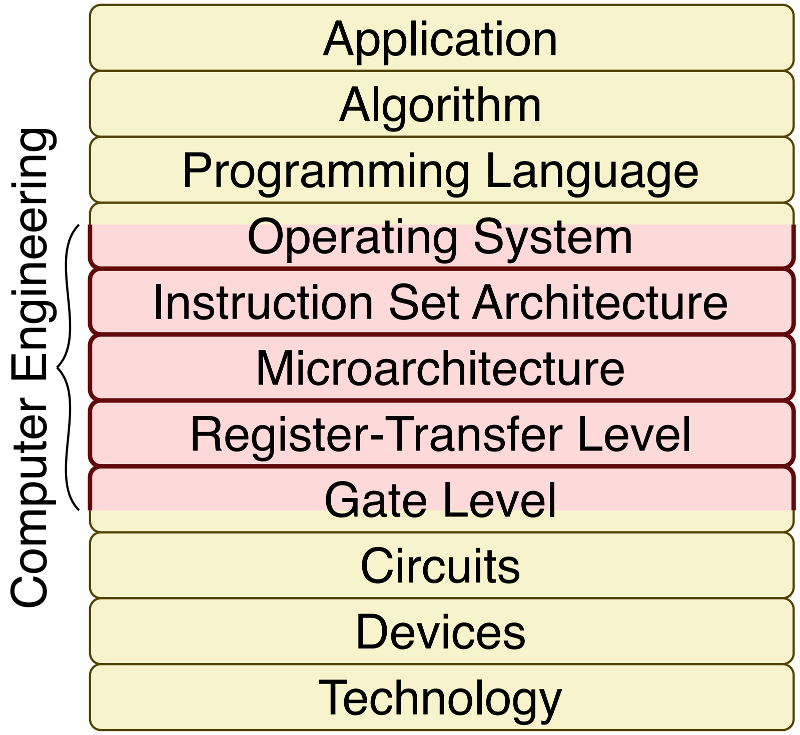
Out-of-place selection sort algorithm

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

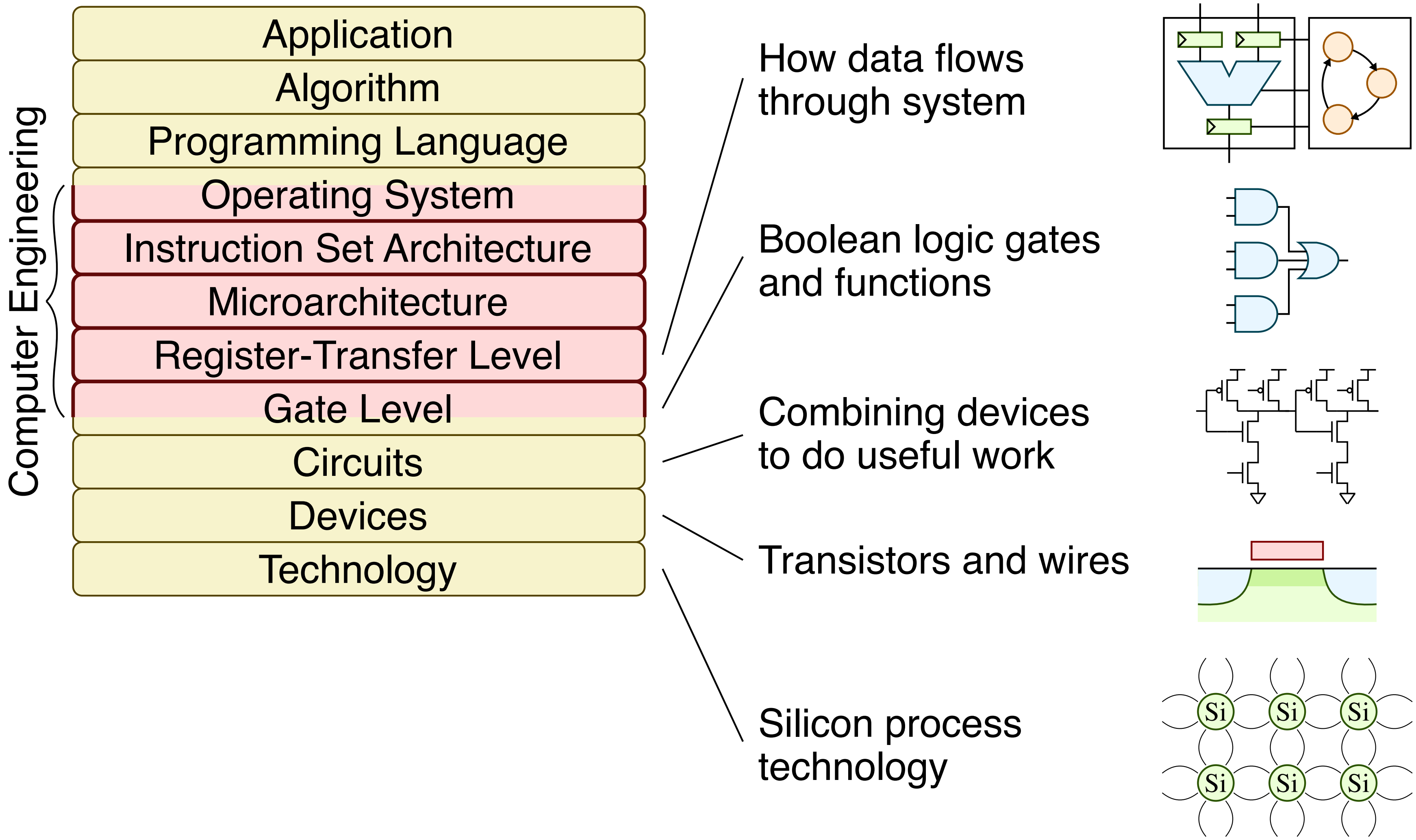
Handles low-level hardware management

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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Technology

Computer Engineering

How data flows through system

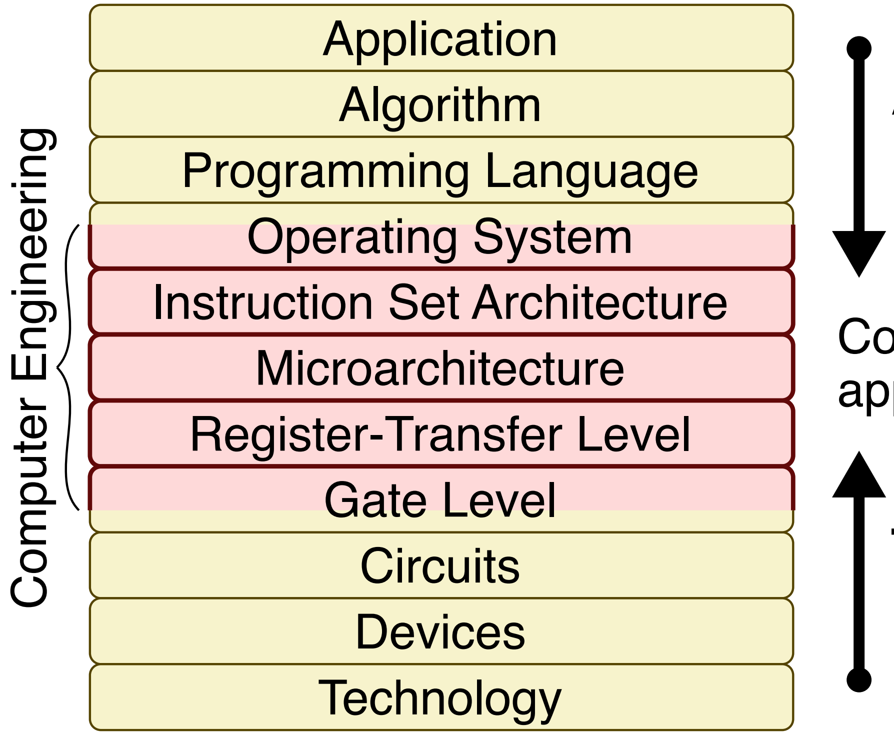
Boolean logic gates and functions

Combining devices to do useful work

Transistors and wires

Silicon process technology

Application Requirements vs. Technology Constraints



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Computer Engineering

Application Requirements

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

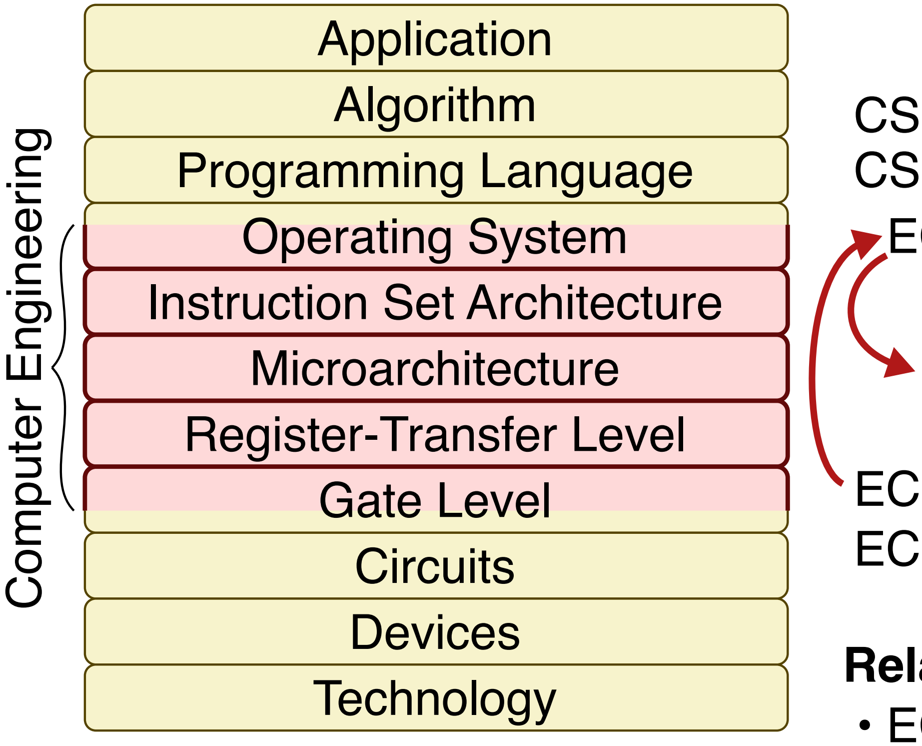
Computer architects provide feedback to guide application and technology research directions

Technology Constraints

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

In its broadest definition, computer engineering 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

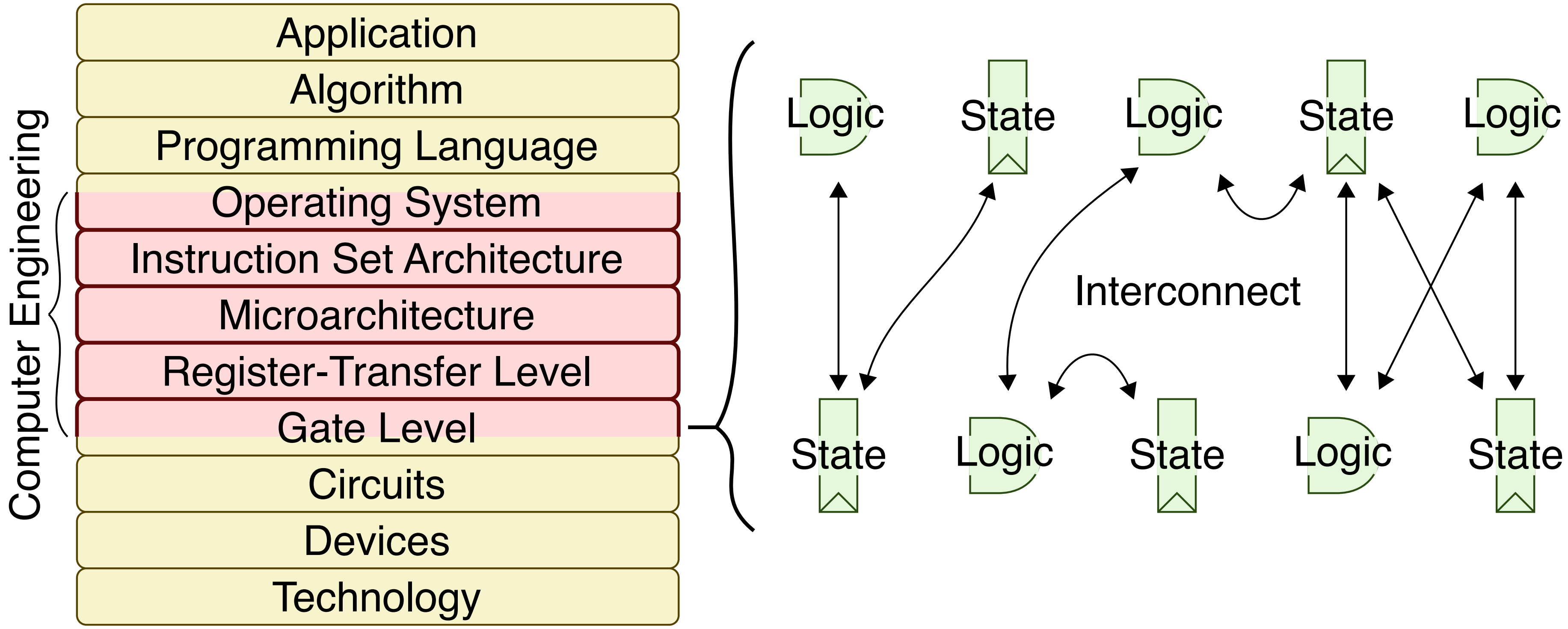
ECE 4760 Design with Microcontrollers
ECE 4750 Computer Architecture

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

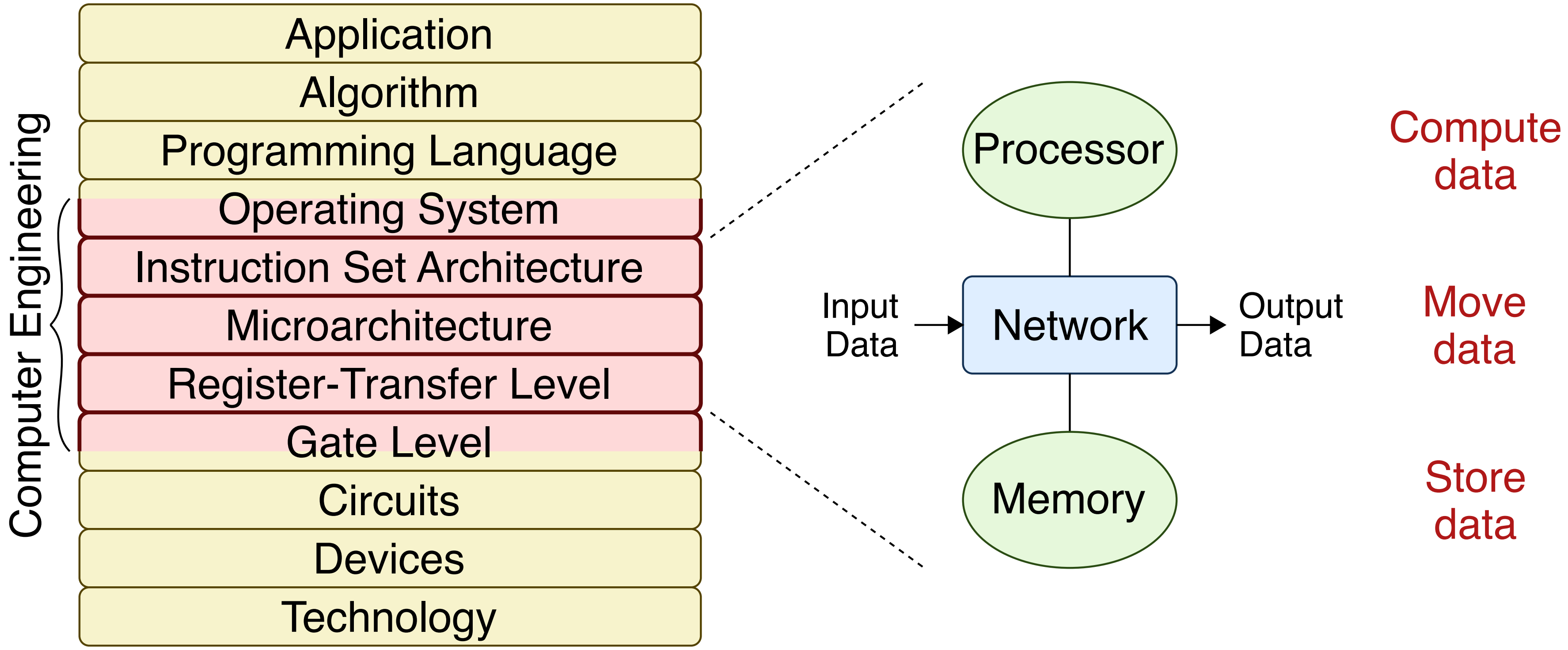
Logic, State, and Interconnect



Digital systems are implemented with three basic building blocks

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

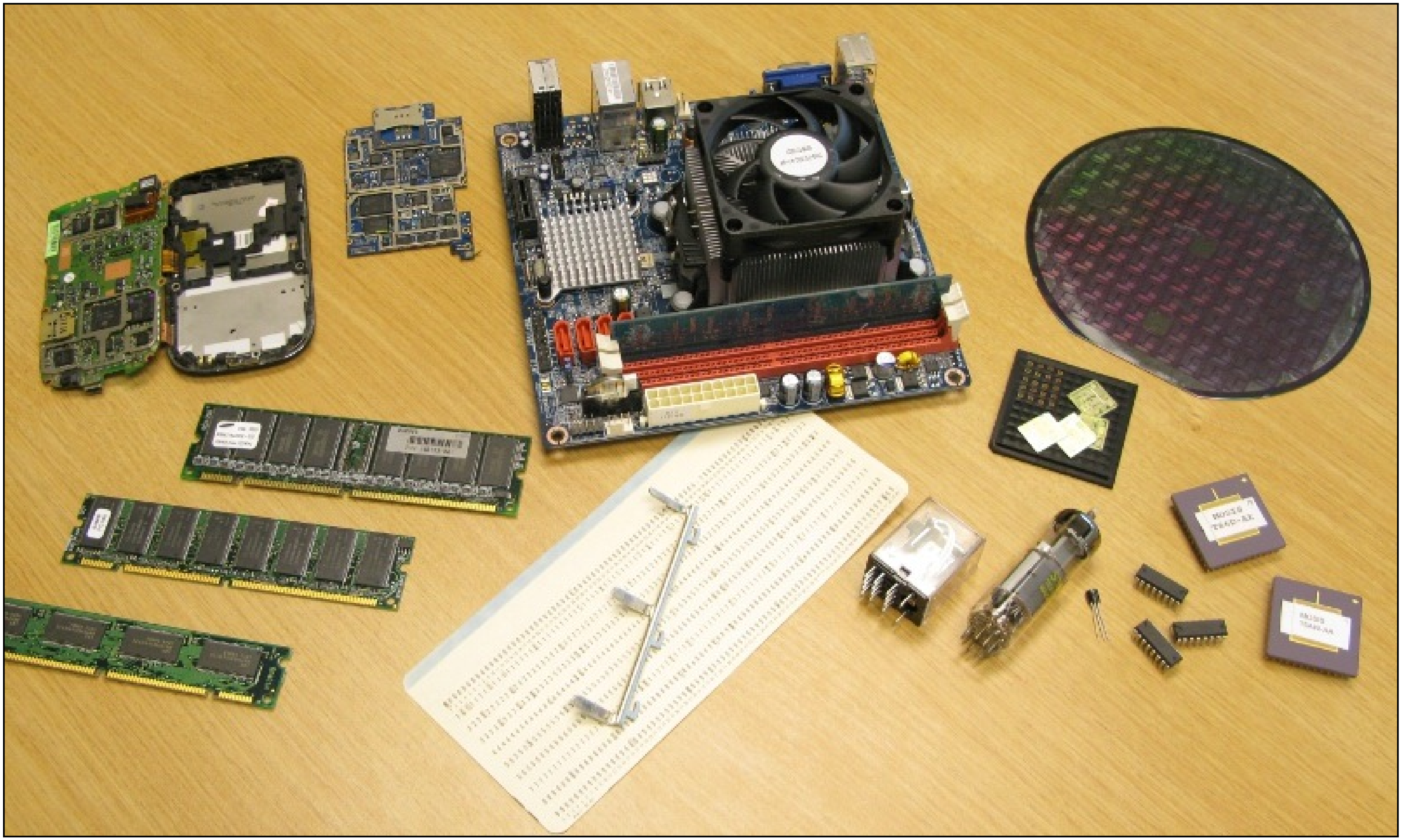
Processors, Memories, and Networks

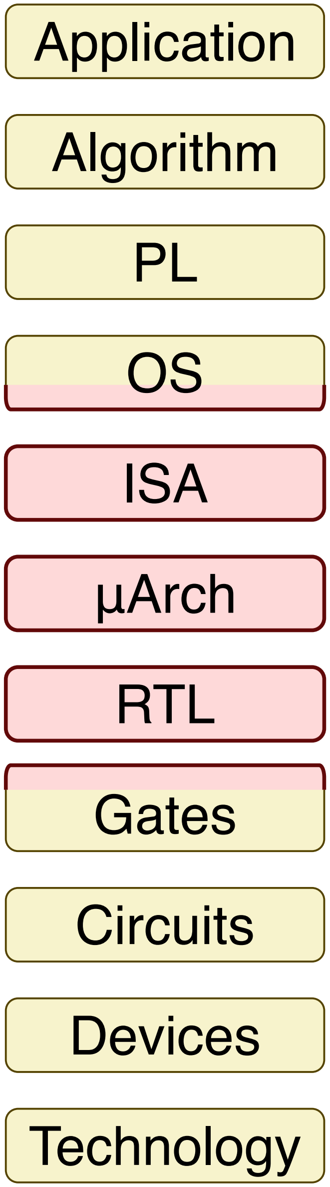


Computer engineering basic building blocks

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

Computer Architecture Artifacts





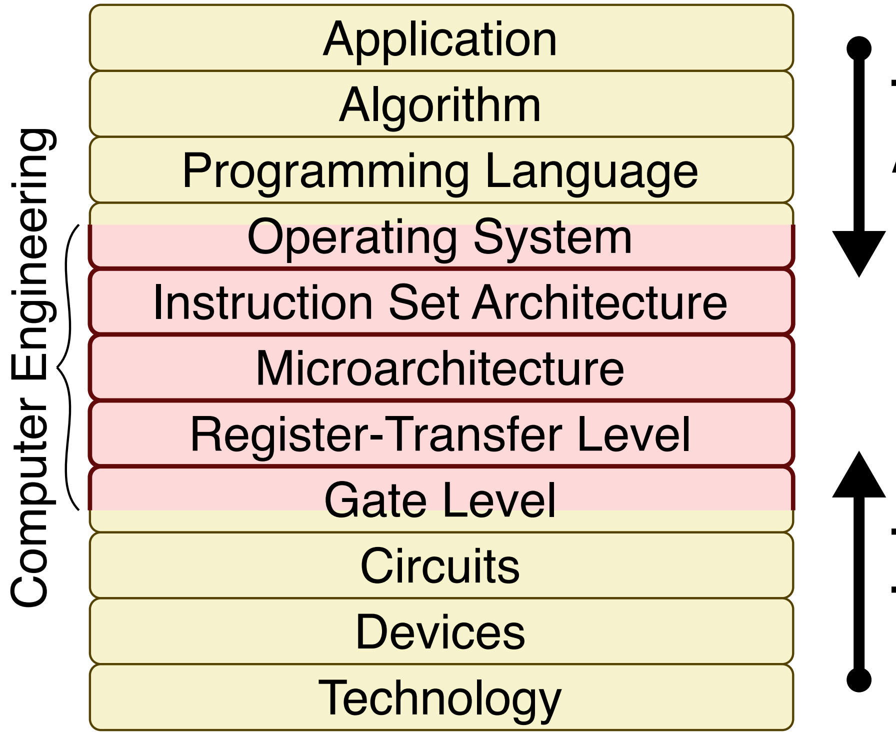
Agenda

What is Computer Architecture?

Trends in Computer Architecture

Computer Architecture Design

Application Requirements vs. Technology Constraints



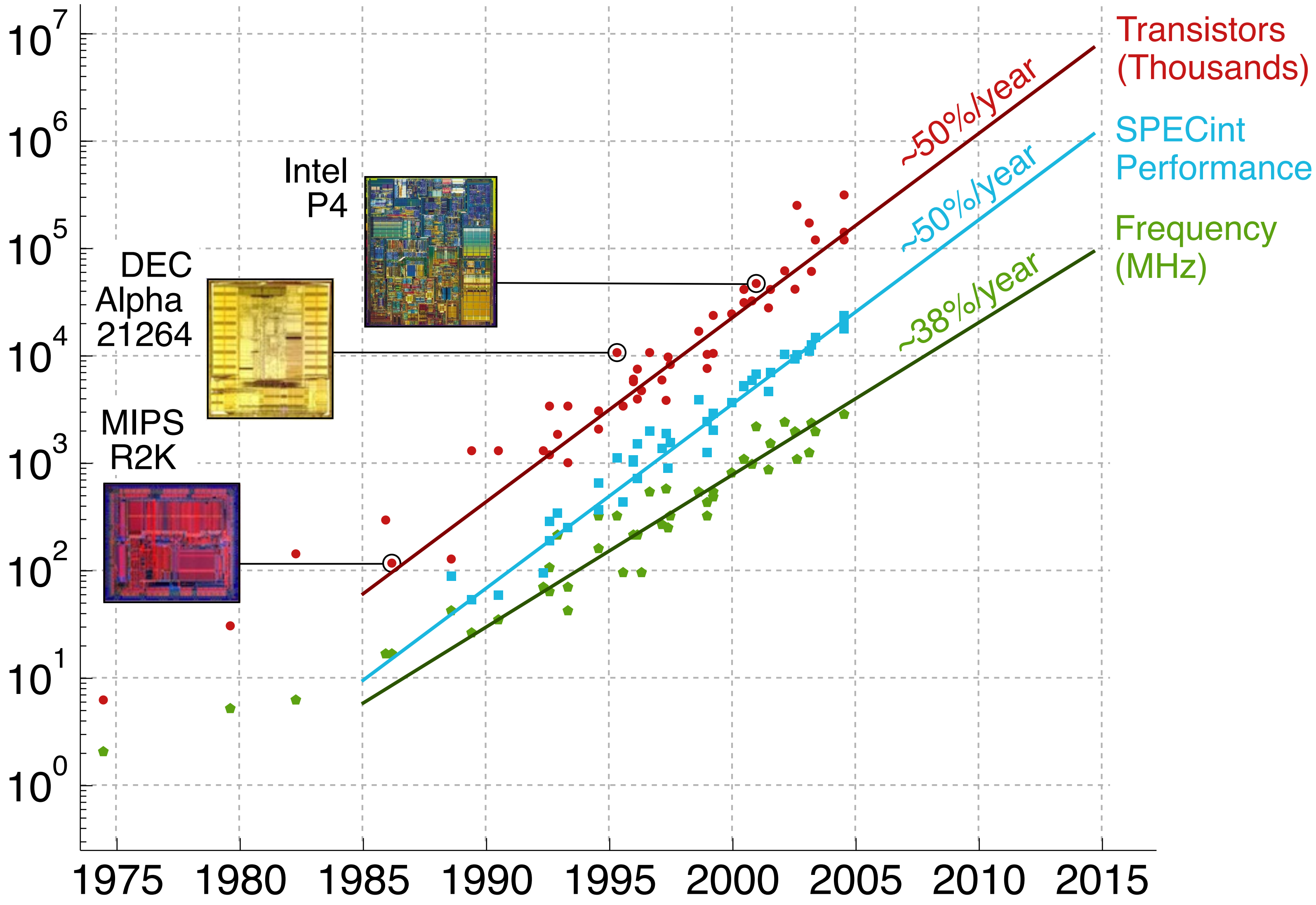
Traditional
Application Requirements

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

Traditional
Technology Constraints

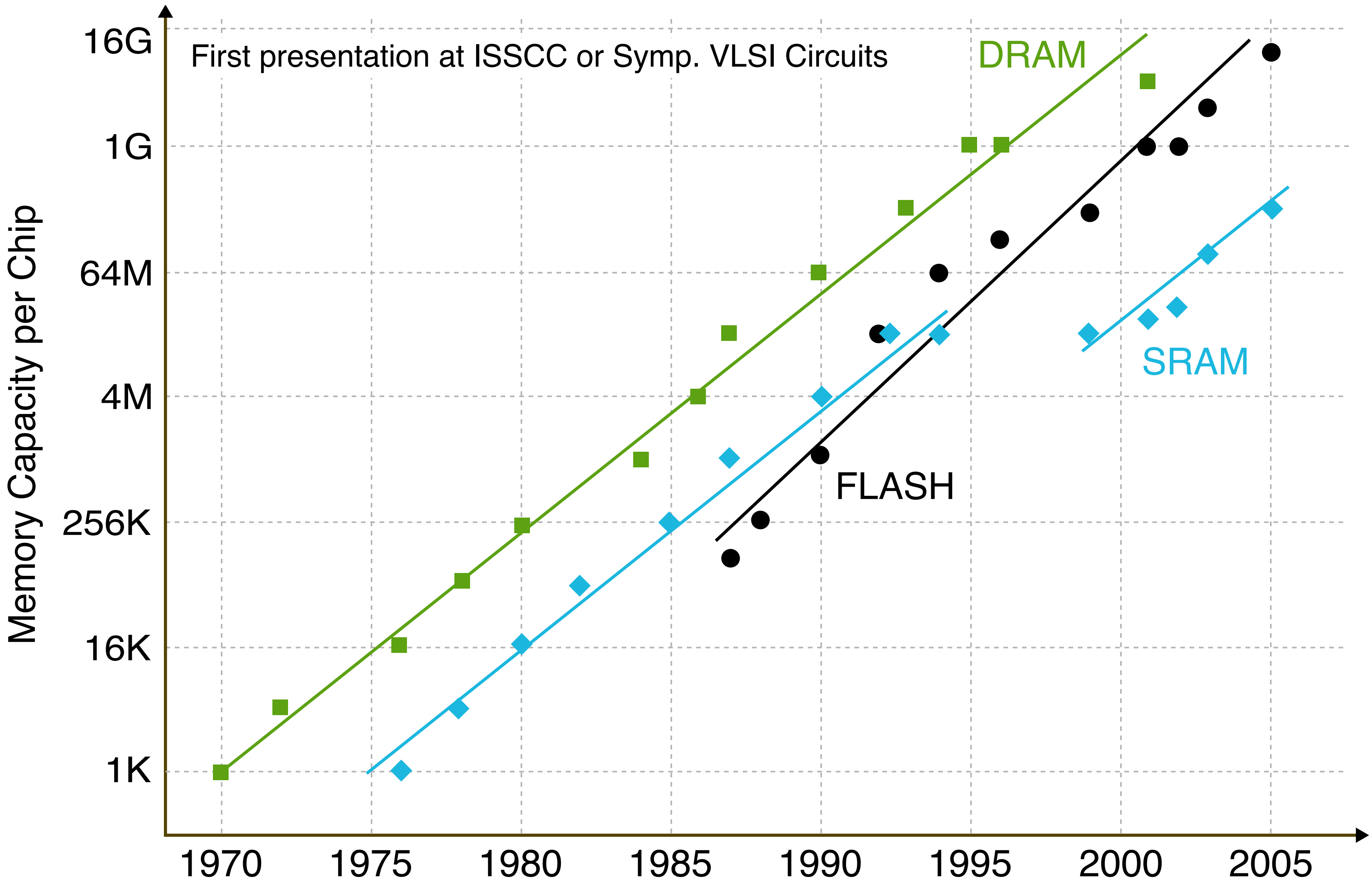
- Exponential scaling of resources

Exponential Scaling for Processor Computation



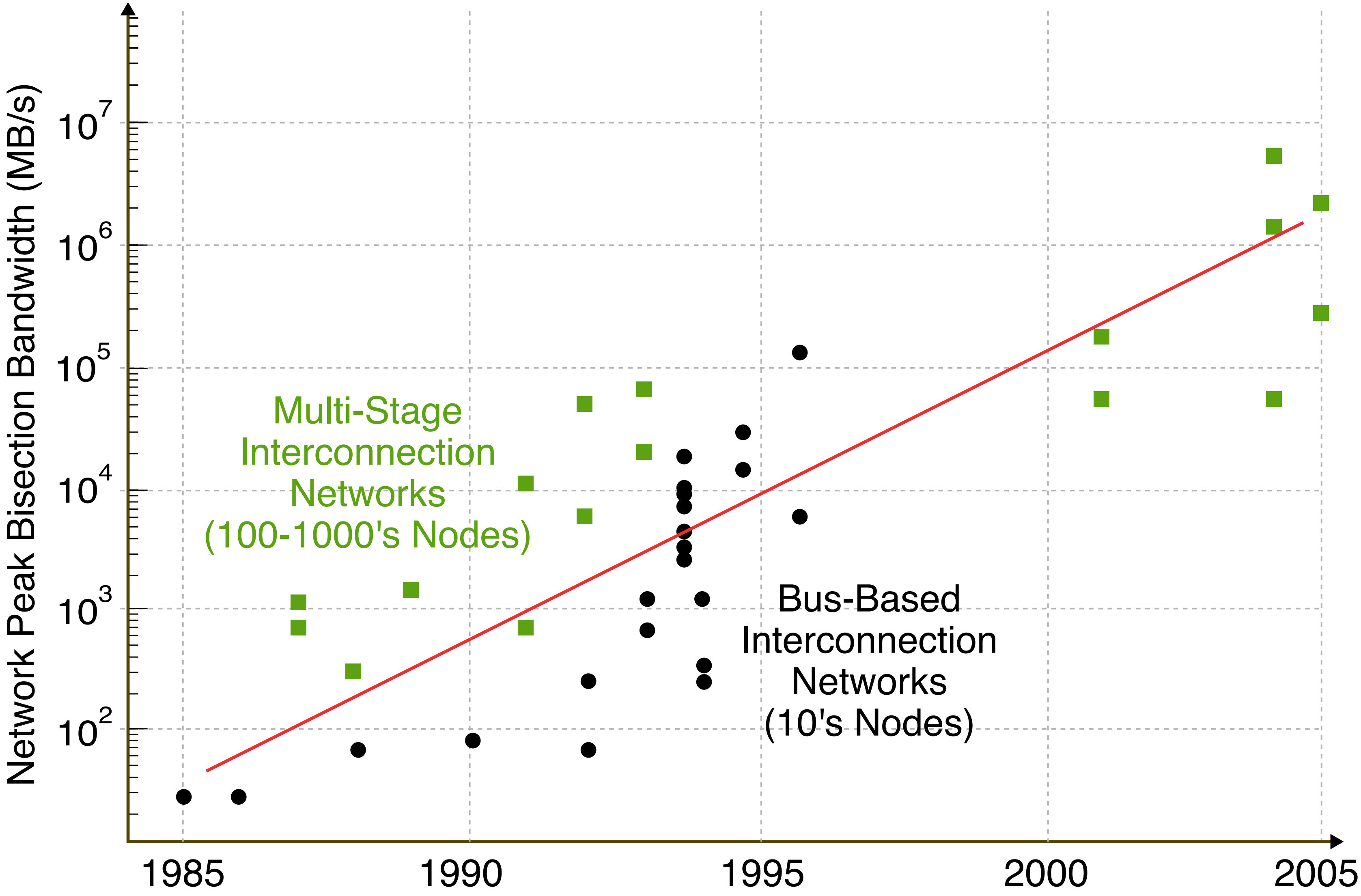
Data collected by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, C. Batten

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

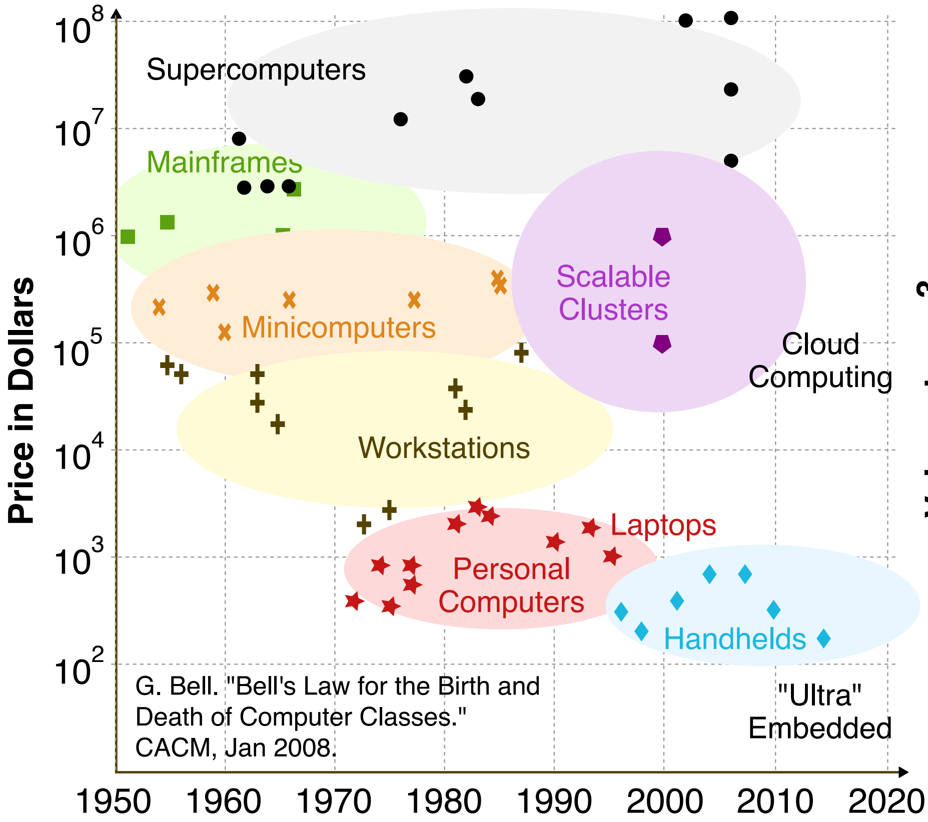
used in modern computing systems

Five Key Trends in Computer Architecture

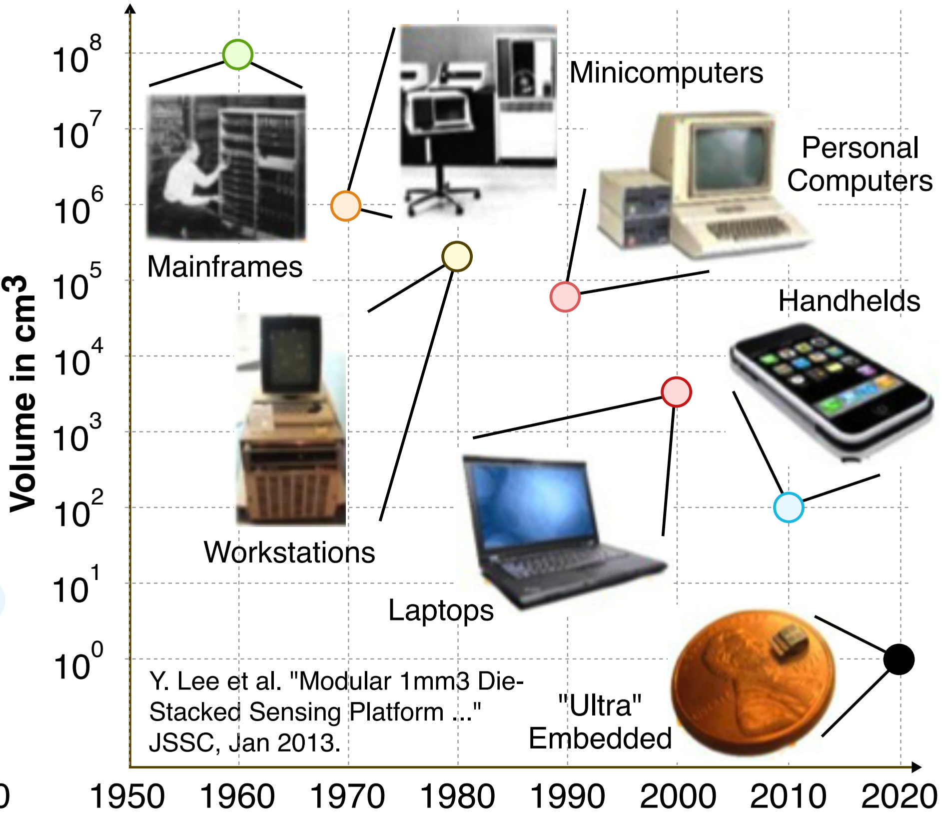
1. Growing diversity in application requirements motivate growing diversity in computing systems pushing towards the cloud and IoT
2. Energy & power constrain systems across the computing spectrum
3. Transition to multiple cores integrated onto a single chip
4. Transition to heterogeneous systems-on-chip
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.



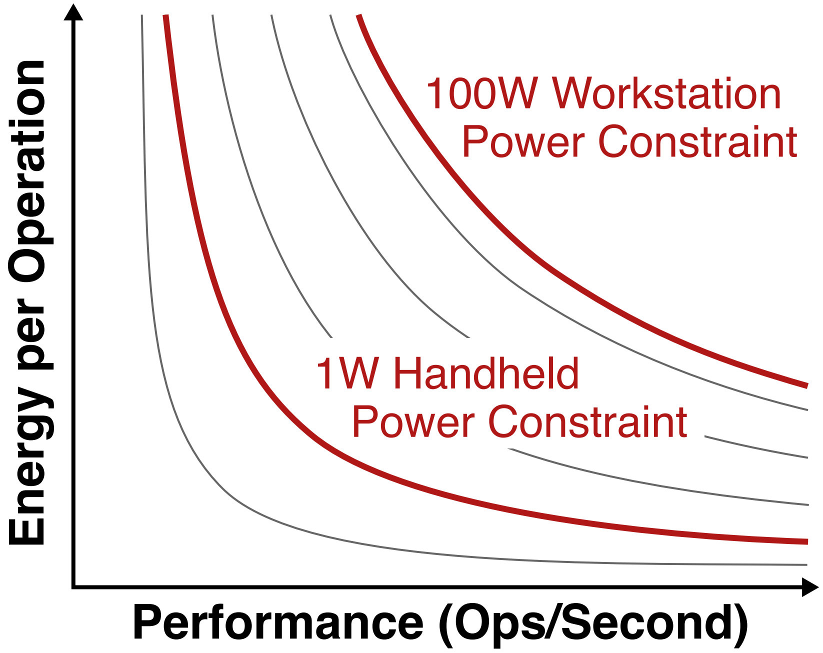
Y. Lee et al. "Modular 1mm3 Die-Stacked Sensing Platform ..." JSSC, Jan 2013.

Trend 1: Growing Diversity in Apps & Systems

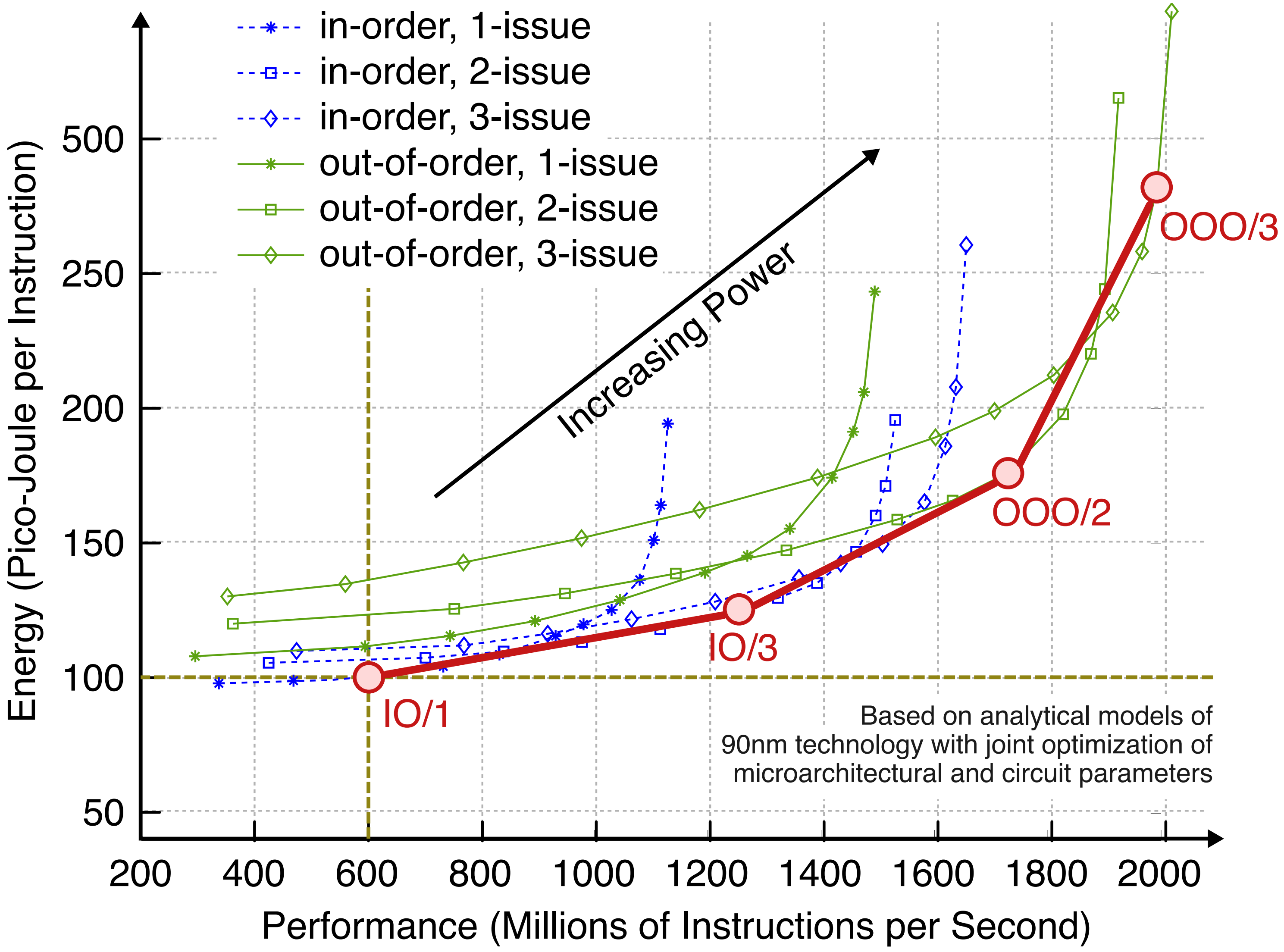
Trend 2: Energy and Power Constraints

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

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



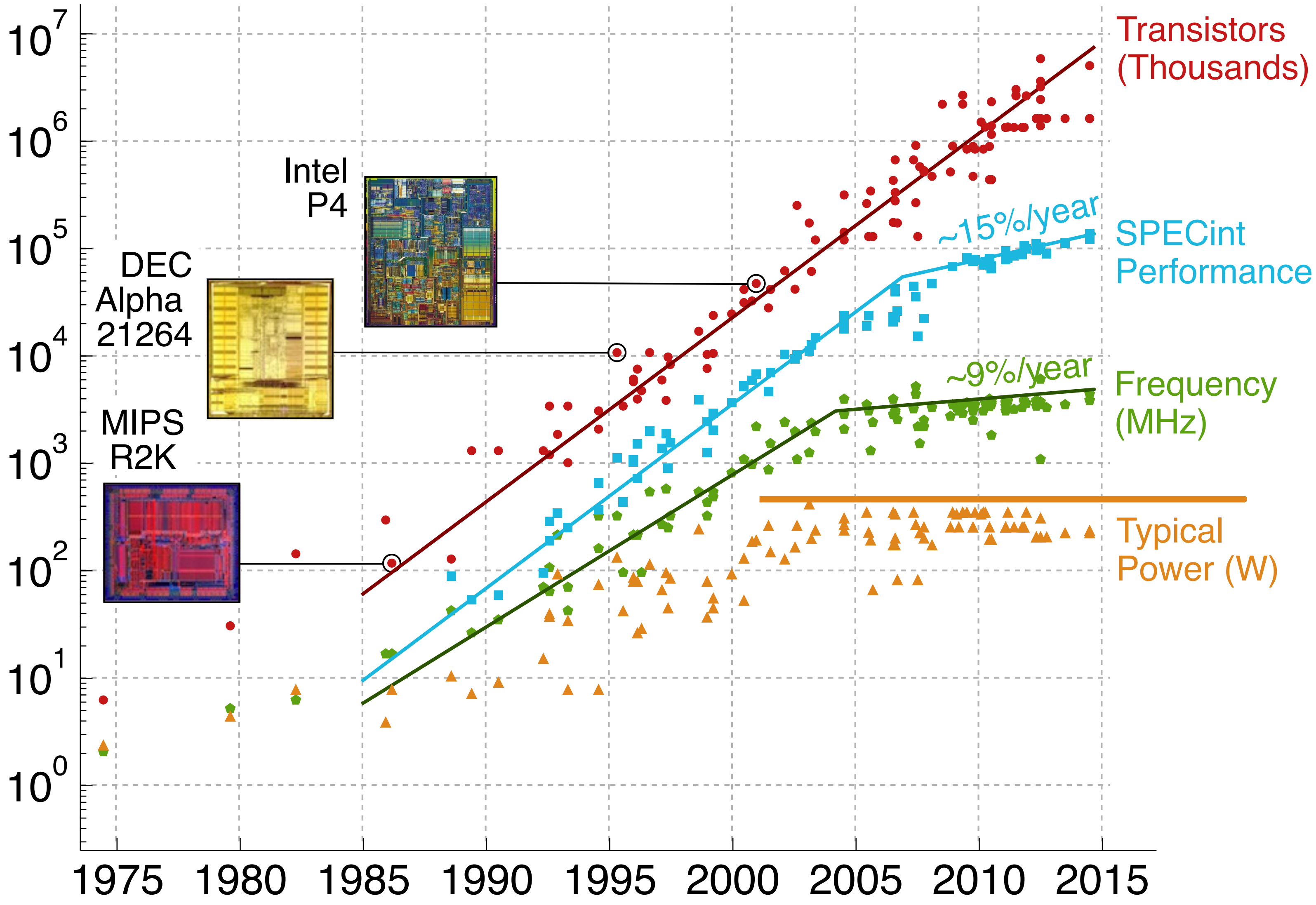
Trend 2: Energy and Performance of Single Processor



Based on analytical models of 90nm technology with joint optimization of microarchitectural and circuit parameters

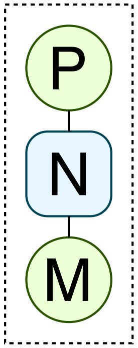
Adpated from O. Azizi et al. “Energy-Performance Tradeoffs ...” ISCA, 2010.

Trend 2: Power Constrains Single-Processor Scaling

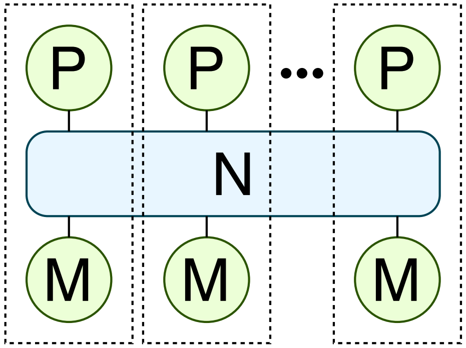


Trend 3: Transition to Multicore Processors

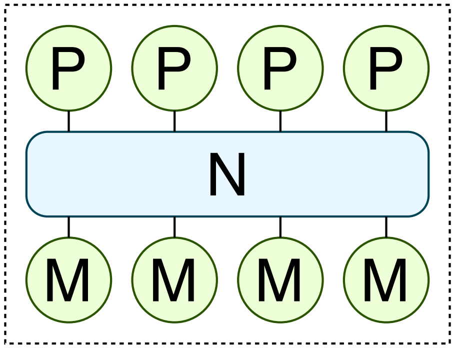
Intel Pentium 4
Single monolithic processor

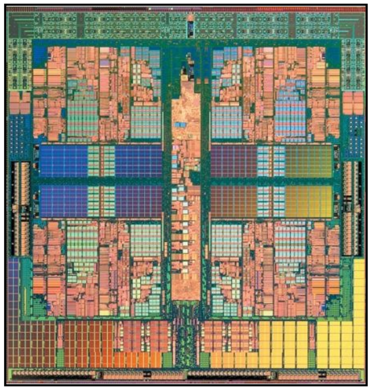


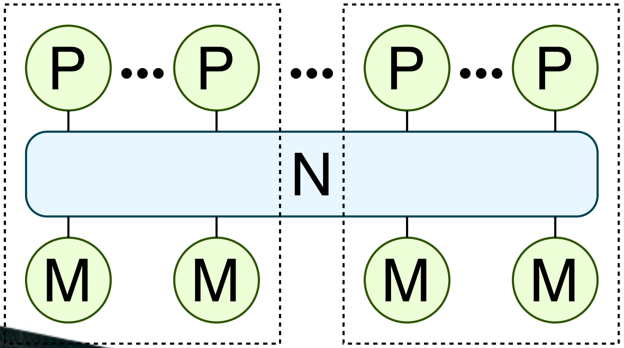
Cray XT3 Supercomputer
1024 single-core processors



AMD Quad-Core Opteron
Four cores on the same die

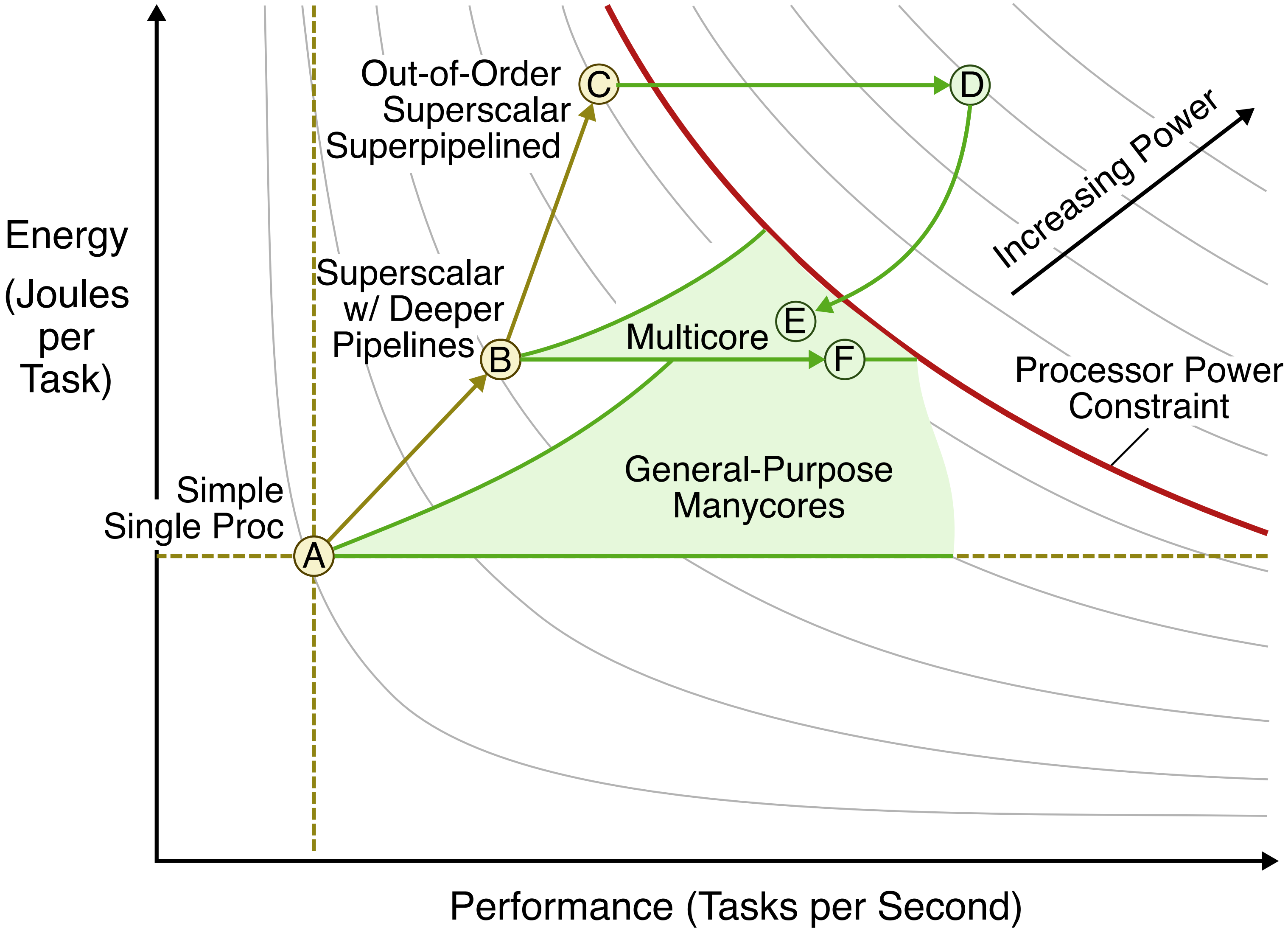




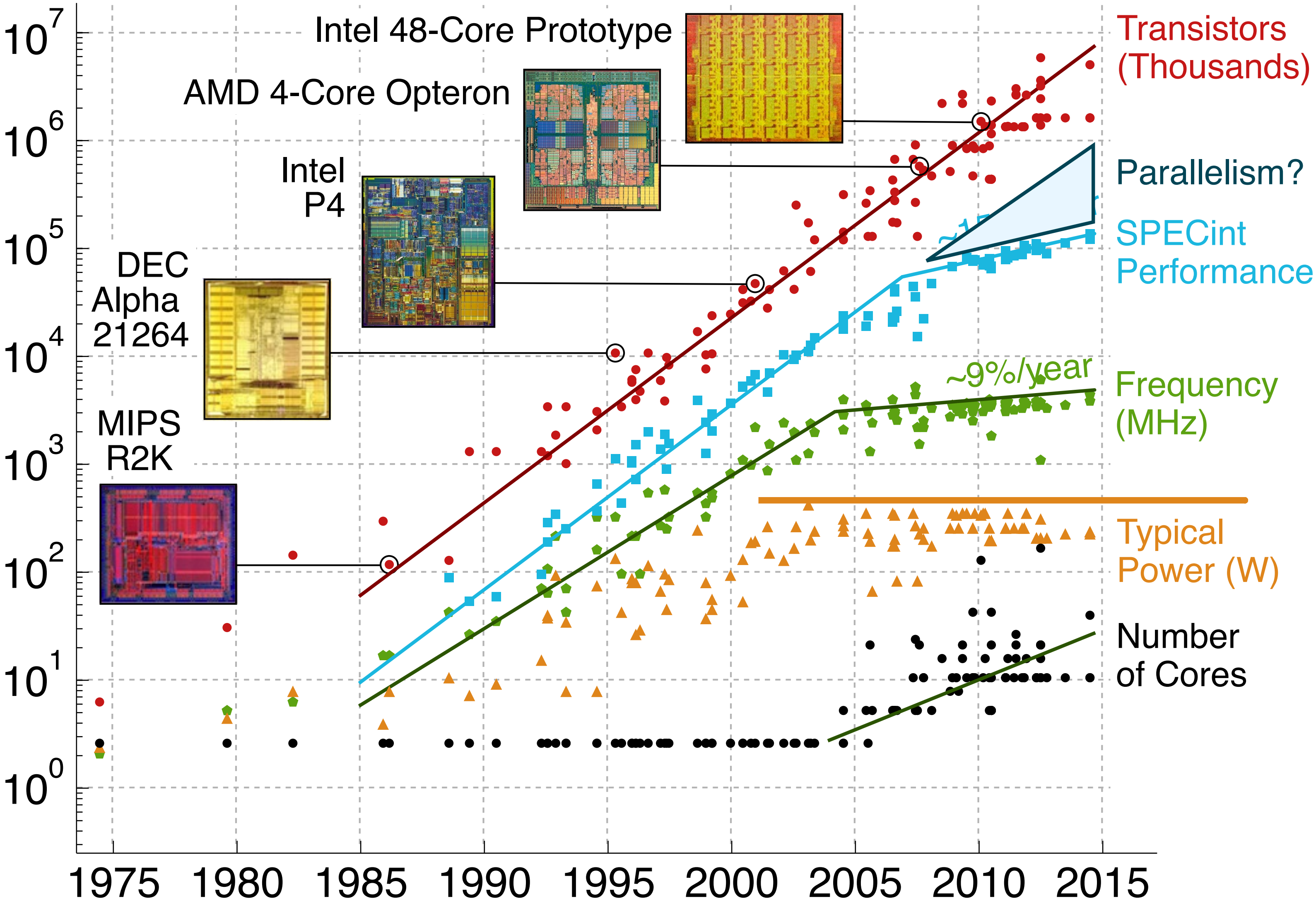


IBM Blue Gene Q Supercomputer
Thousands of
18-core processors

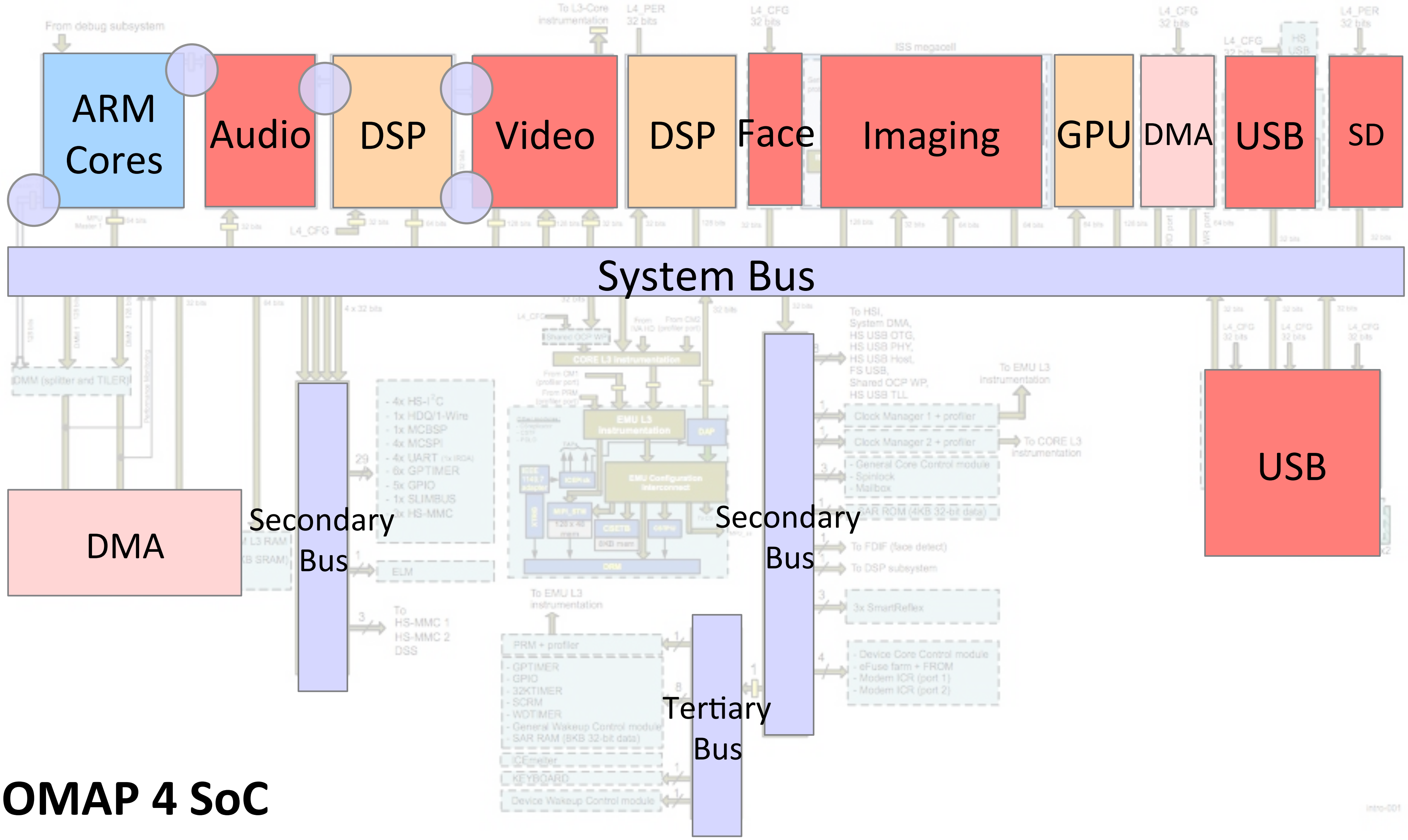
Trend 3: Energy and Performance of Multicores



Trend 3: The Multicore "Hail Mary Pass"



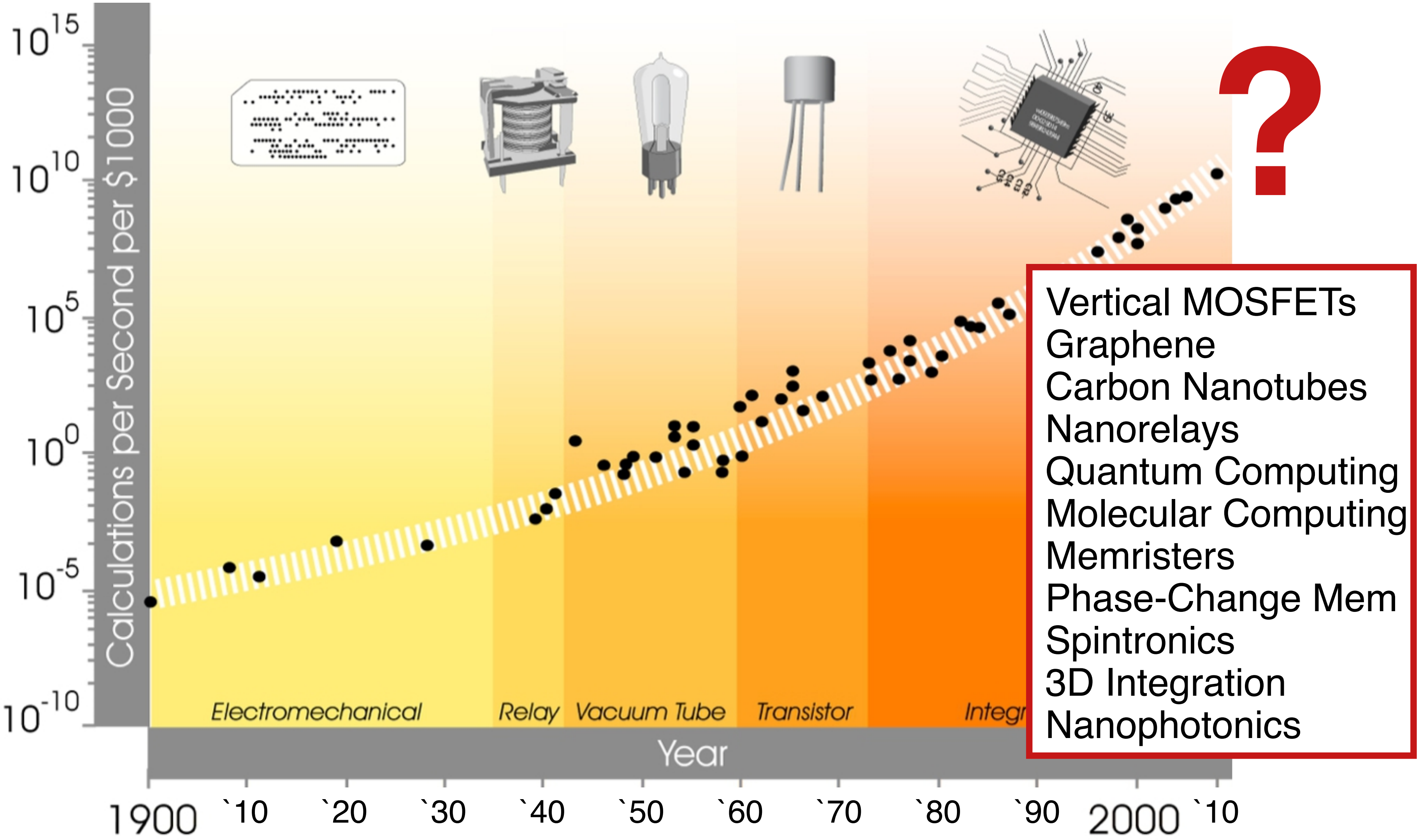
Trend 4: Heterogeneous Systems-on-Chip



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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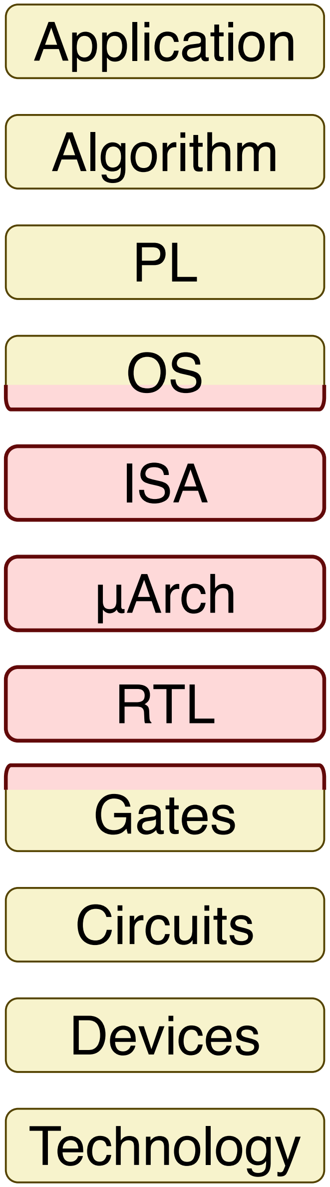


Application
Algorithm
PL
OS
ISA
µArch
RTL
Gates
Circuits
Devices
Technology

Agenda

What is Computer Architecture?

Trends in Computer Architecture

Computer Architecture Design

What do computer architects actually do?

General Science

Discover truths about nature

Ask question about nature

↓

Construct hypothesis

↓

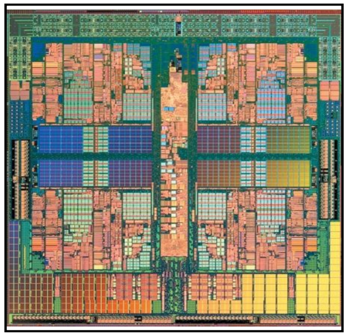
Test with experiment

↓

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

↙ ↘

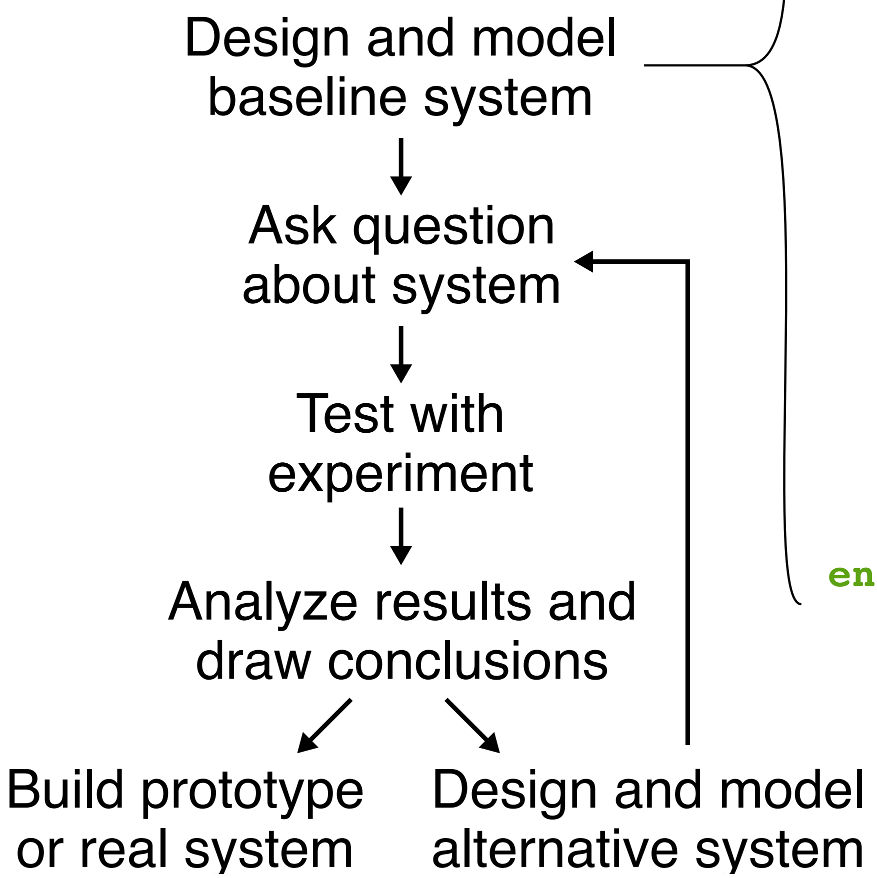
Build prototype or real system

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

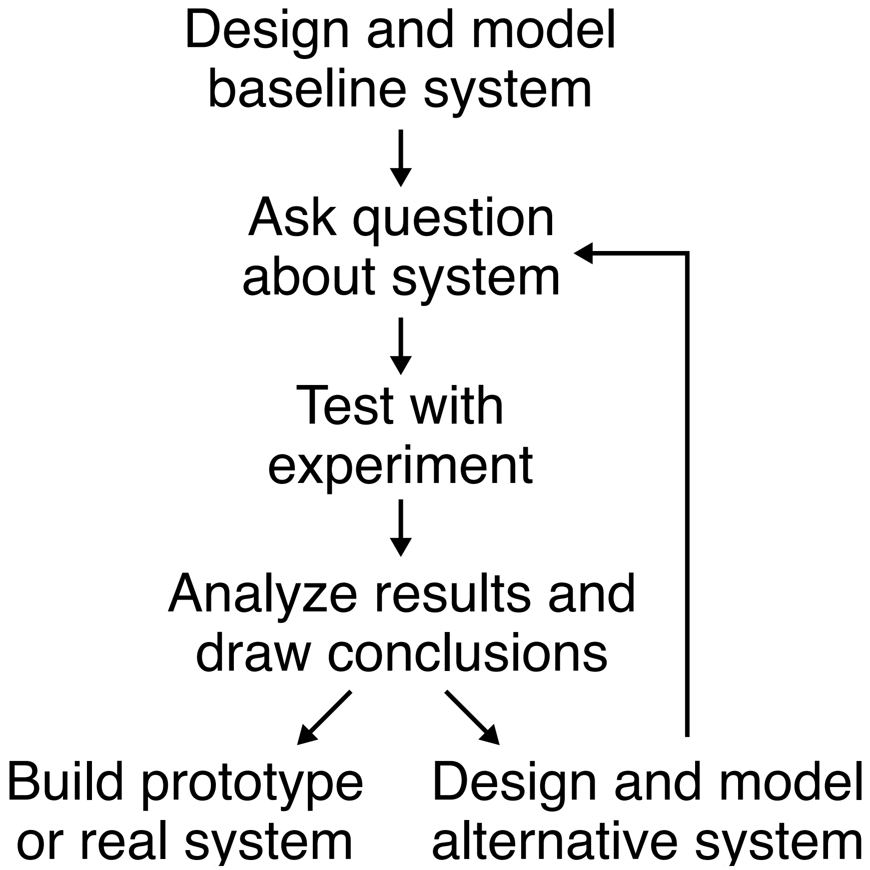
```
// rdy is OR of the AND of reqs and grants
assign in_rdy = | (reqs & grants);

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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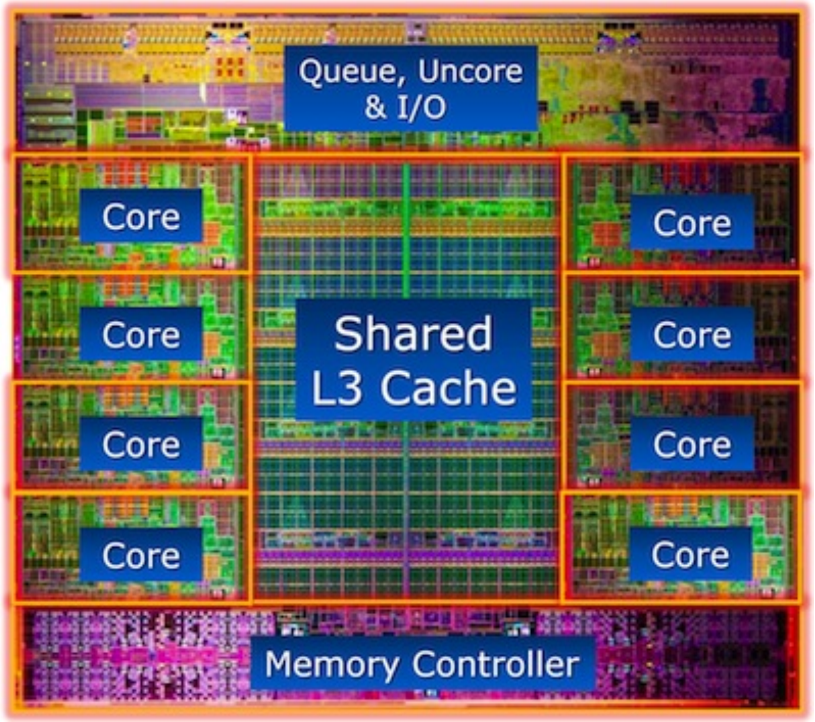
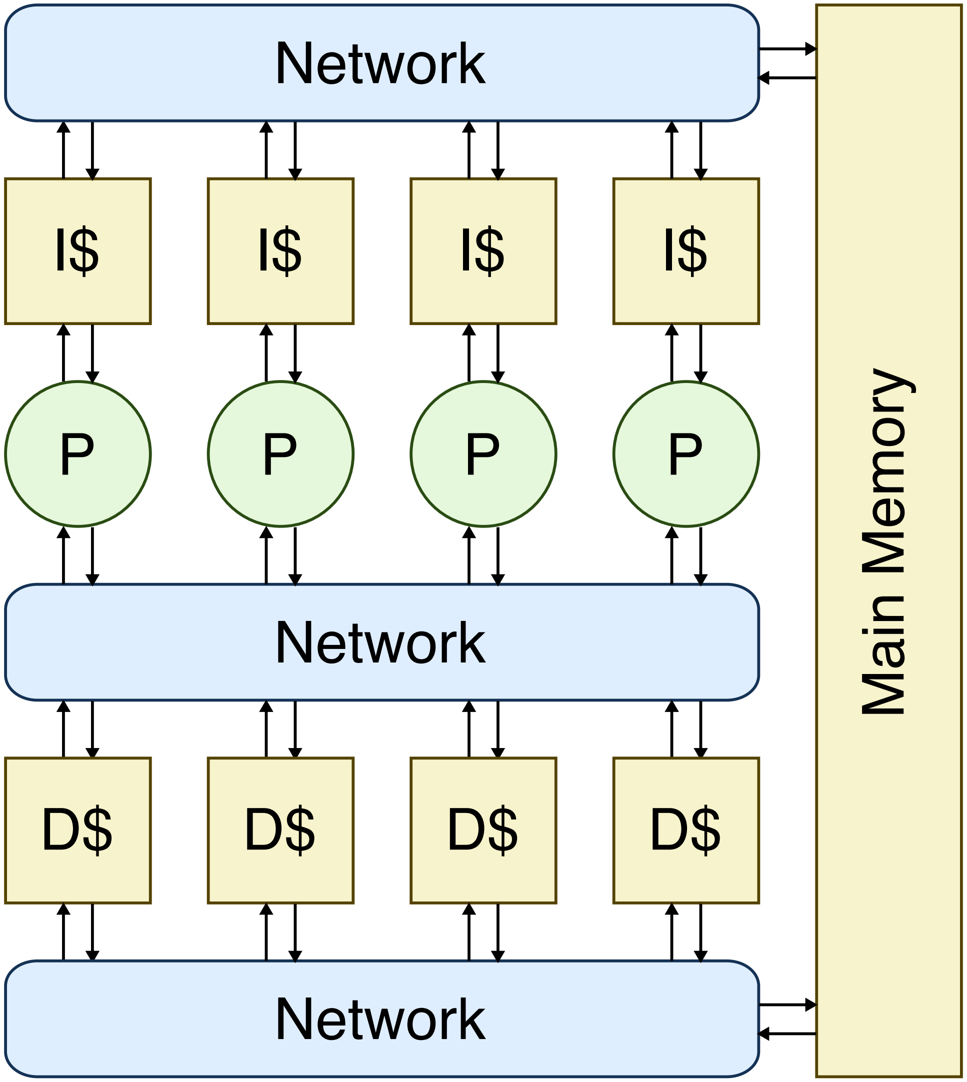


Fighter Airplane: ~100,000 parts

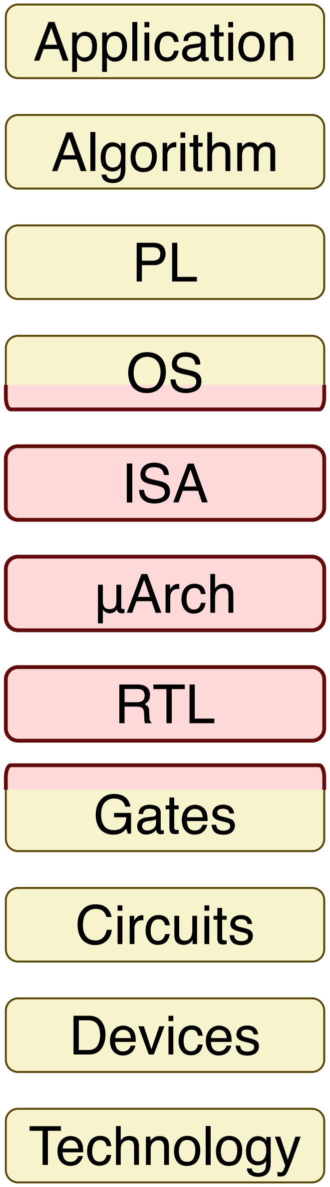
Intel Sandy Bridge E:
2.27 Billion transistors

- **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, implemented at the register-transfer-level and capable running real parallel programs



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