CS162
Operating Systems and Systems Programming
Lecture 1

What is an Operating System?

August 29th, 2024

Prof. Ion Stoica

http://cs162.eecs.Berkeley.edu

Instructor: Ion Stoica

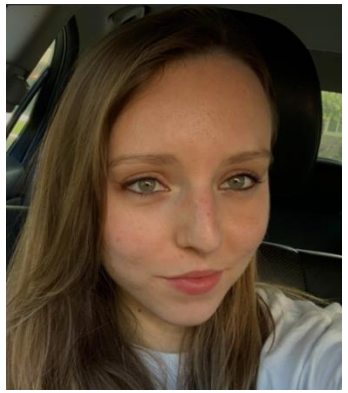
- Web: http://www.cs.berkeley.edu/~istoica/
  - 465 Soda Hall (Sky Computing Lab)
  - Office hour: Tuesdays, 11-12pm
- Research areas:
  - ML/LLM systems (vLLM, Ray, ChatBot Arena, Alpa, …)
  - Cloud computing (SkyPilot. SkyStorage)
  - Previous: Cluster computing (Apache Mesos, Apache Spark, Alluxio), Peer-to-Peer networking (Chord), Networking QoS
- Industry experience: co-founded
  - Conviva (2006 -): Video distribution and analytics
  - Databricks (2013 -): Company behind Apache Spark
  - Ray (2019 -): Company behind Ray

CONVIVA

databricks

anyscale

CS162 TAs: Sections TBA



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(Head TA)

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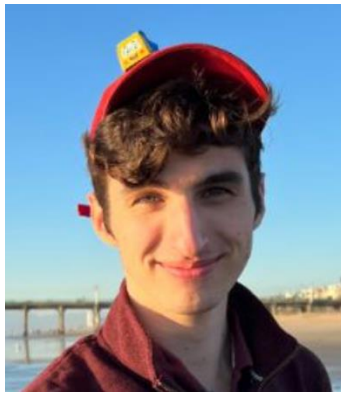
(Head TA)

Sean Yang



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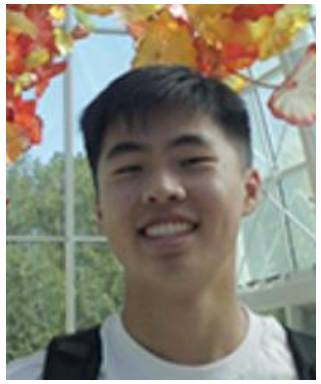

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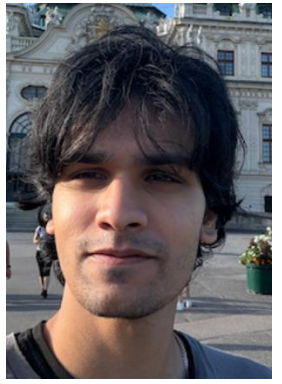


Ashwin Chugh

CS162 Readers

Aditya Balasubramanian

Rohan Penmatcha

Jason Guo

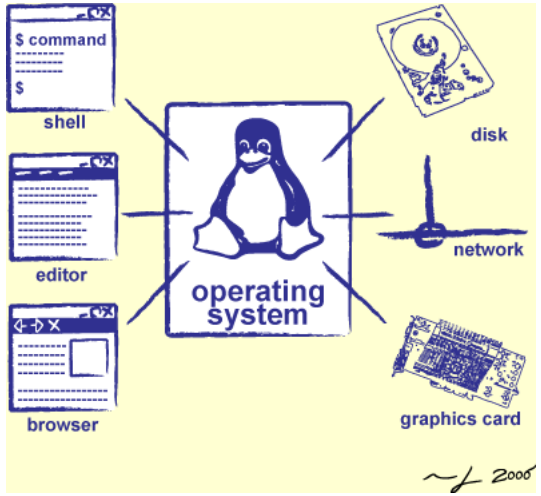
Enrollment

- This is an Early Drop Deadline course (September 6th)
  - If you are not serious about taking, please drop early
  - Department will continue to admit students as other students drop
  - Really hard to drop afterwards!
    - » Don't forget to keep up with work if you are still on the waitlist!

- On the waitlist/Concurrent enrollment ?
  - All decisions concerning appeals for enrolling in the course are made by CS departmental staff; the course staff have no say in the matter. Se please do not e-mail us about waitlist or concurrent enrollment.
  - If people drop, others will be moved off the waitlist

Goals for Today

- What is an Operating System?
  - And – what is it not?
- What makes Operating Systems so exciting?
- "How does this class operate?"



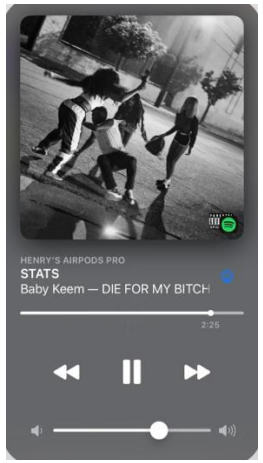
Interactive is important!

Ask Questions!

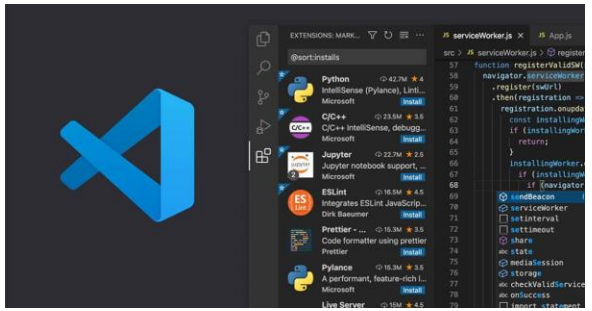
Slides courtesy of David Culler, Natacha Crooks, Anthony D. Joseph, John Kubiatowicz, AJ Shankar, Alex Aiken, Eric Brewer, Ras Bodik, Doug Tygar, and David Wagner.

What is an operating system?

Apps



OS (e.g., iOS, Android)



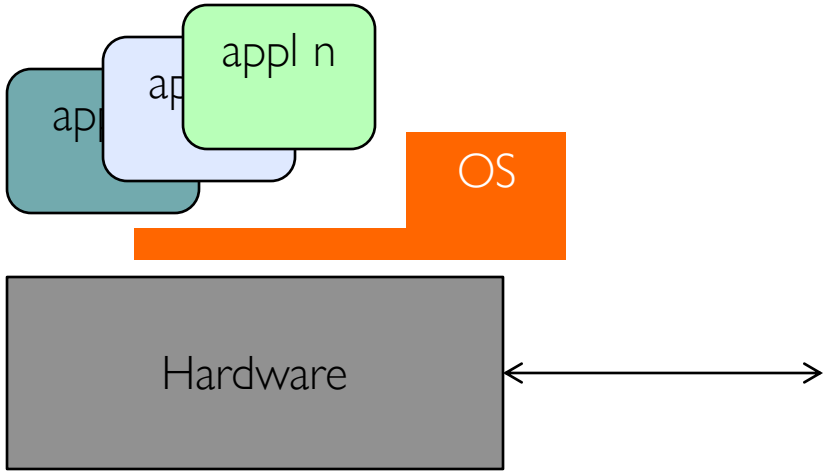
OS (e.g., MacOS, Linux, Windows)

Hardware

What is an operating system?

Special layer of software that provides application software access to hardware resources

- Convenient abstraction of complex hardware devices
- Protected access to shared resources
- Security and authentication
- Communication amongst logical entities

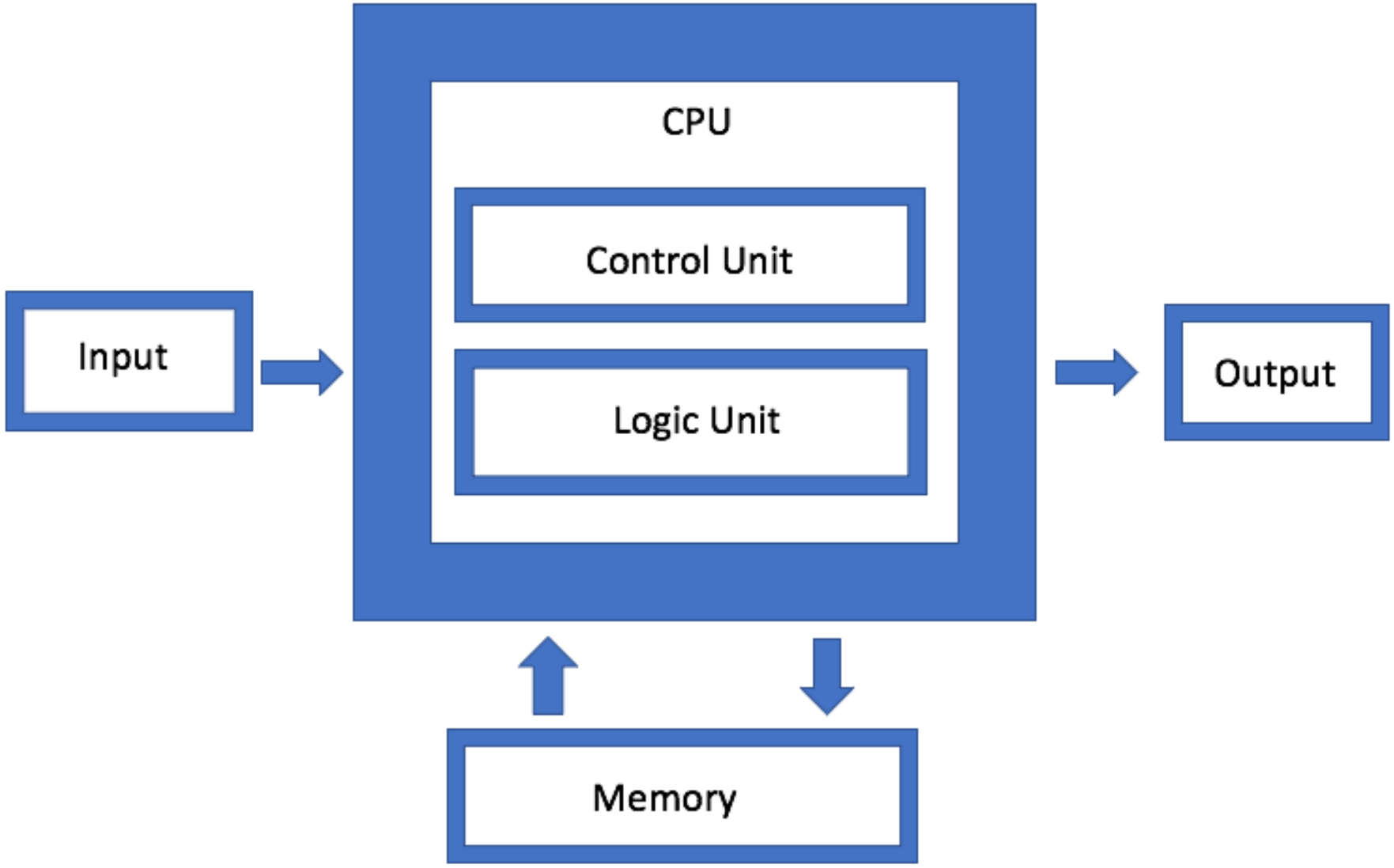


What Does an OS do?

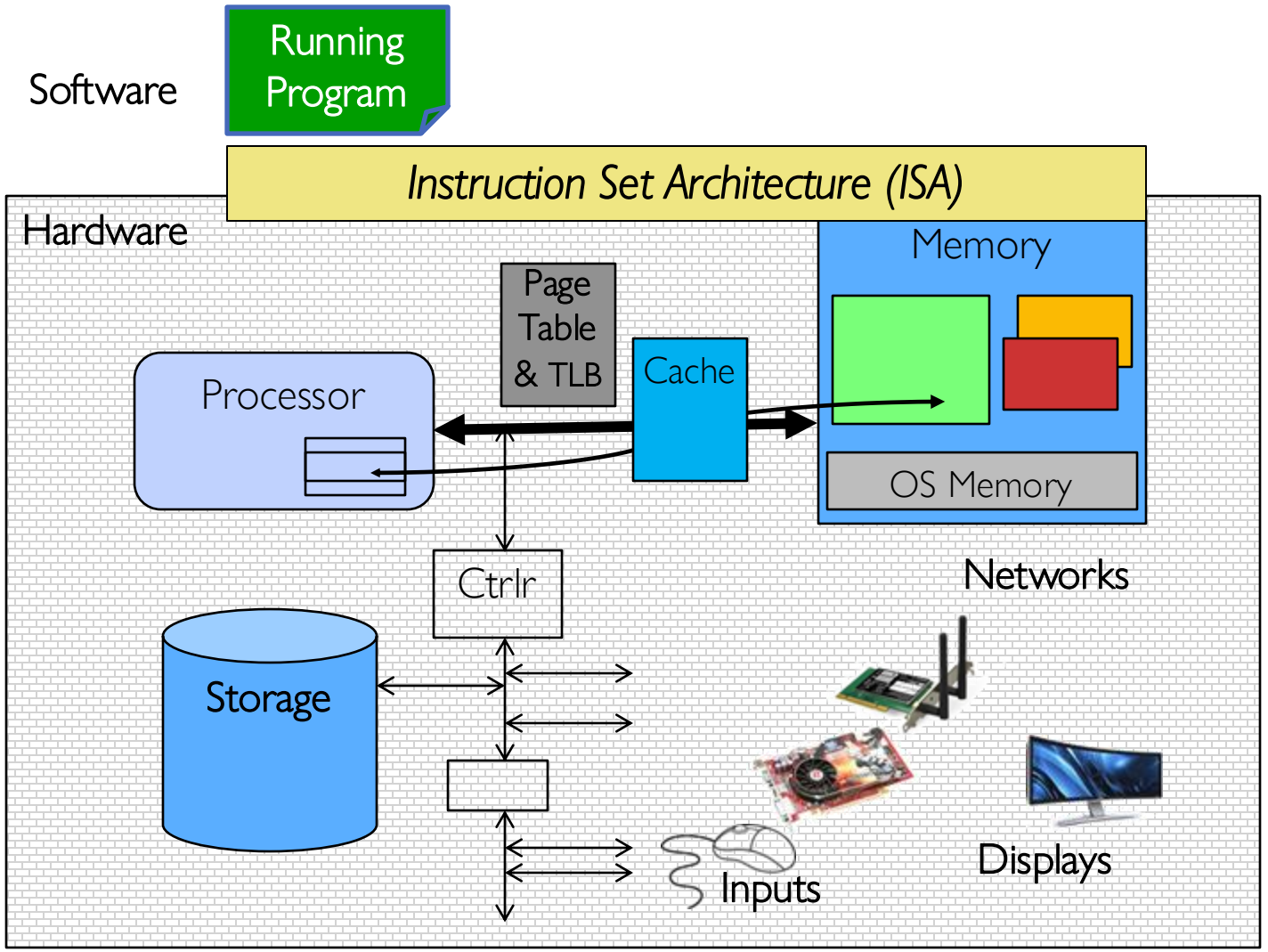
- Provide abstractions to **apps**
  - File systems
  - Processes, threads
  - VM, containers
  - Naming system
  - …
- Manage resources:
  - Memory, CPU, storage, …
- Achieves the above by implementing specific algos and techniques:
  - Scheduling
  - Concurrency
  - Transactions
  - Security
  - …..

Von Neumann Architecture

John von Neumann
(1903 – 1957)



Hardware/Software Interface



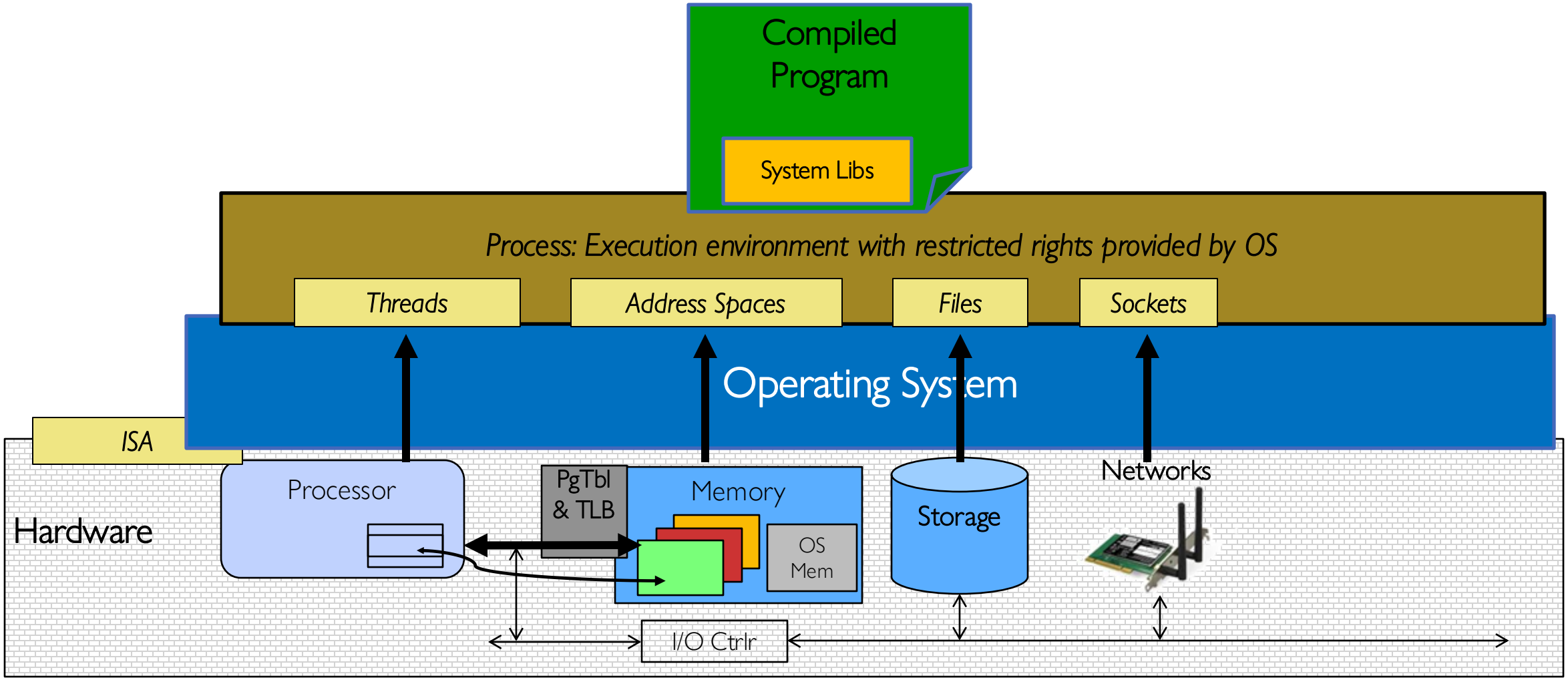
What you learned in CS 61C – Machine Structures (and C)

The OS *abstracts* these hardware details from the application

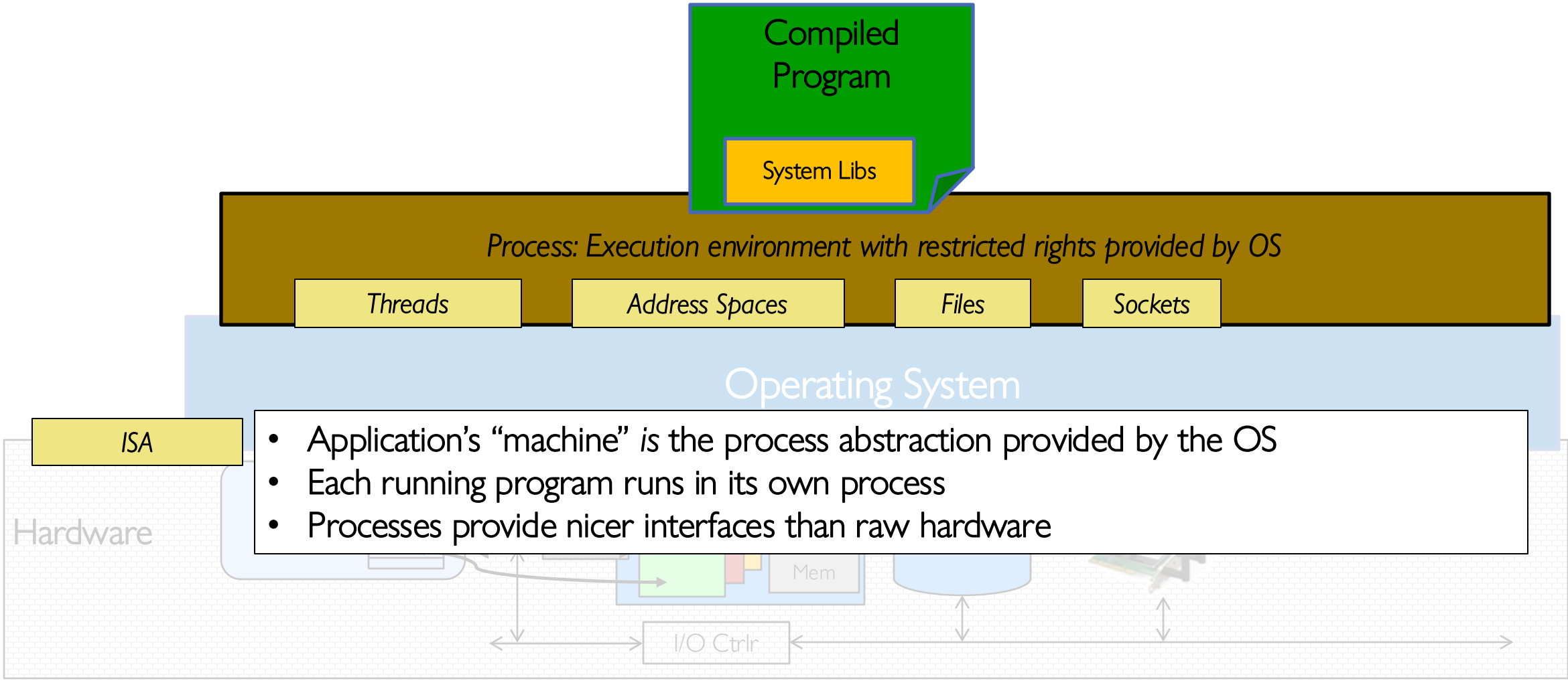
What is an Operating System?

- Illusionist
  - Provide clean, easy-to-use abstractions of physical resources
    - » Infinite memory, dedicated machine
    - » Higher level objects: files, users, messages
    - » Masking limitations, virtualization

OS Basics: Virtualizing the Machine

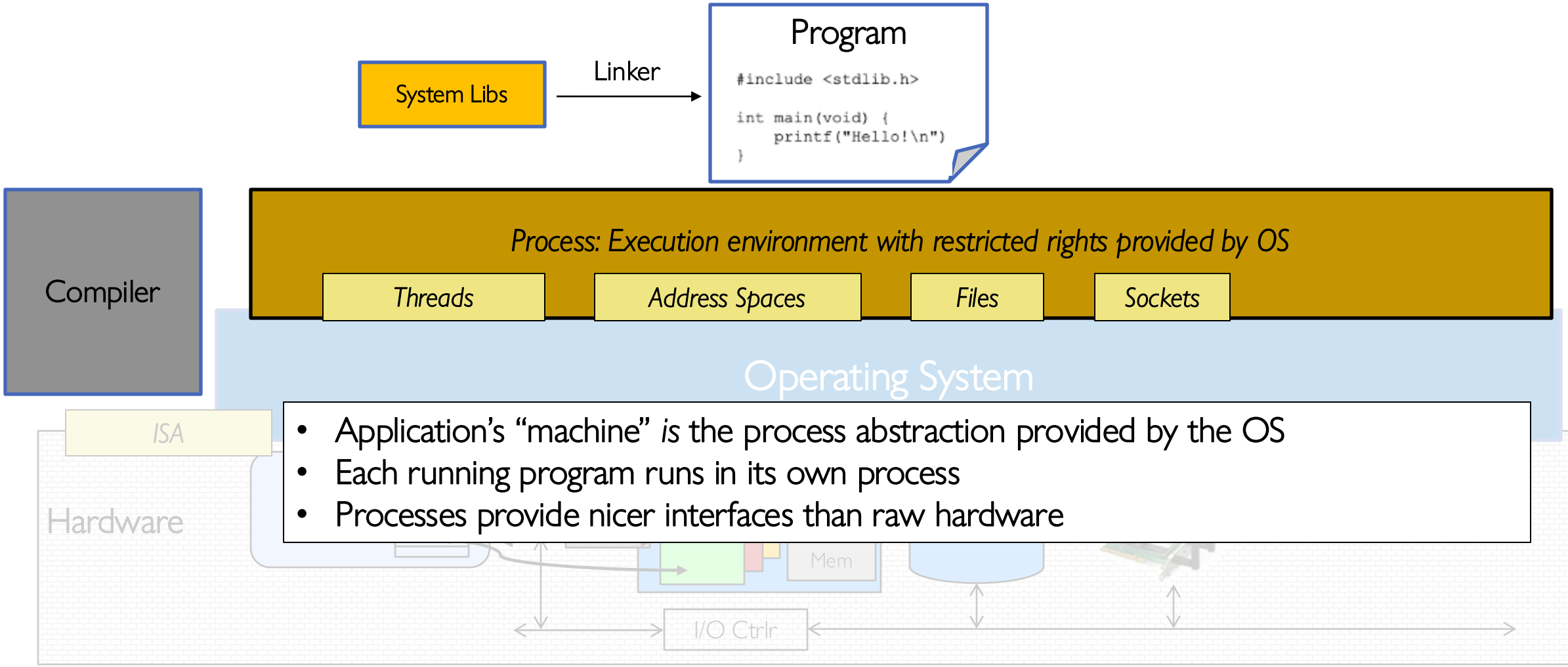


Compiled Program's View of the World



- Application's "machine" *is* the process abstraction provided by the OS
- Each running program runs in its own process
- Processes provide nicer interfaces than raw hardware

System Programmer's View of the World



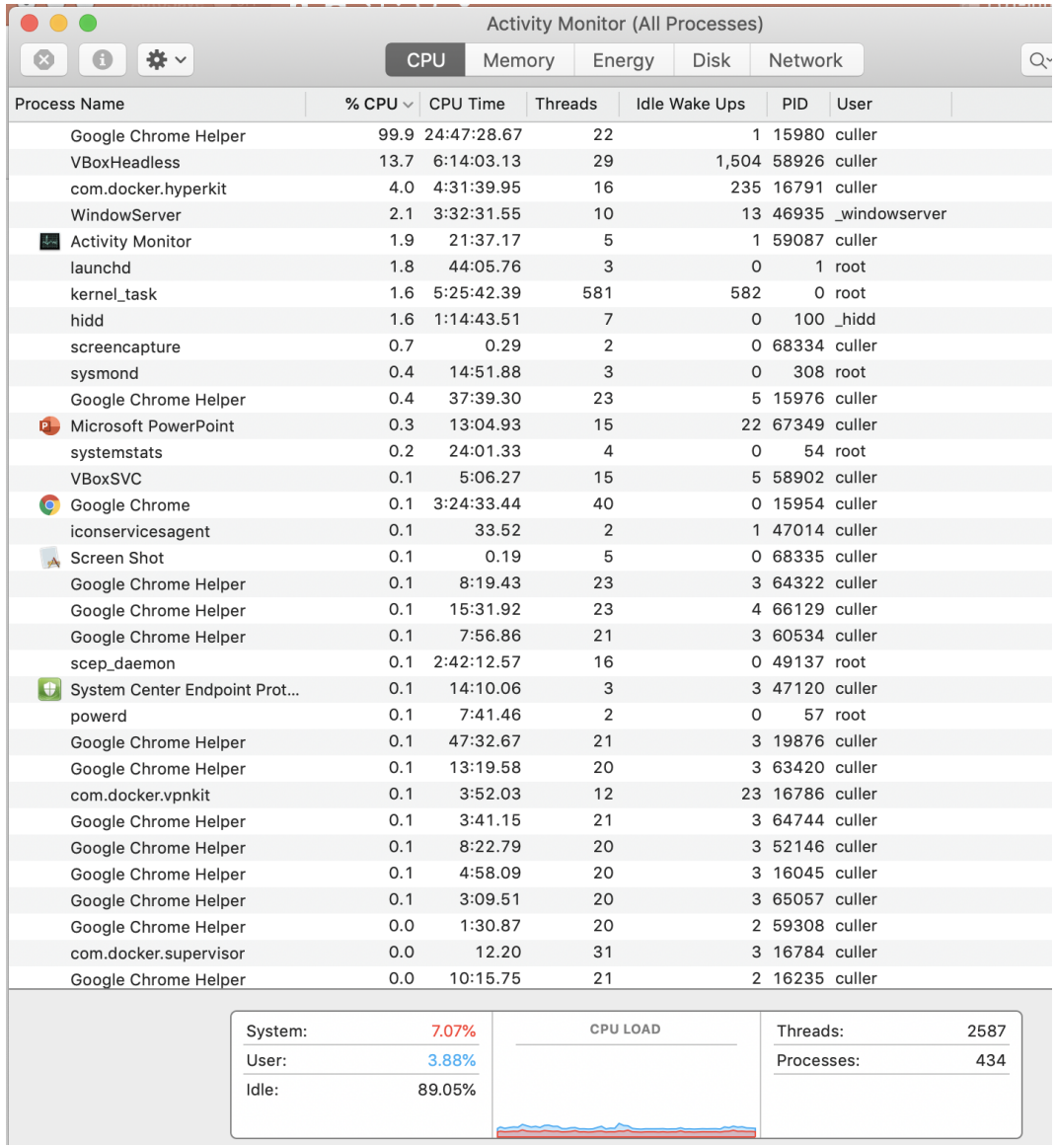
- Application's "machine" *is* the process abstraction provided by the OS
- Each running program runs in its own process
- Processes provide nicer interfaces than raw hardware

What's in a Process?

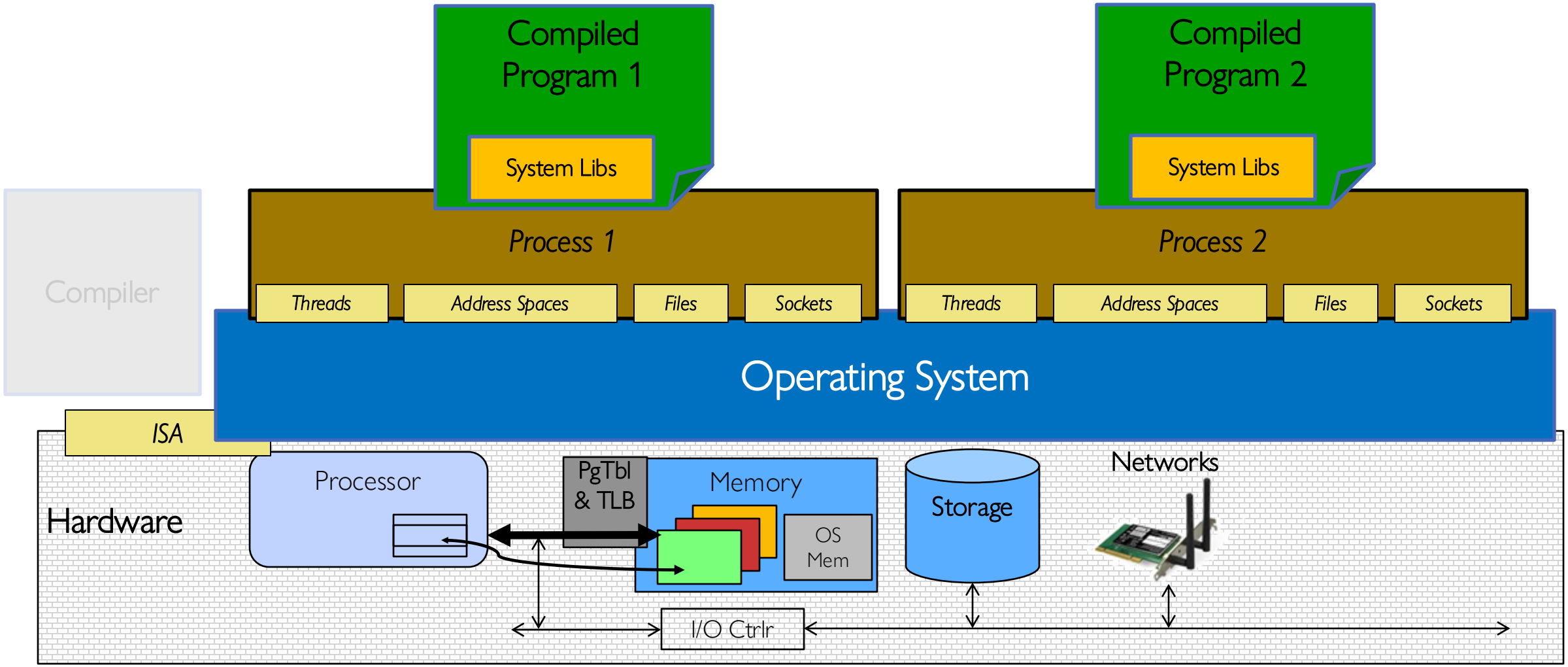
A process consists of:

- Address Space
- One or more threads of control executing in that address space
- Additional system state associated with it
  - Open files
  - Open sockets (network connections)
  - …

For Example…

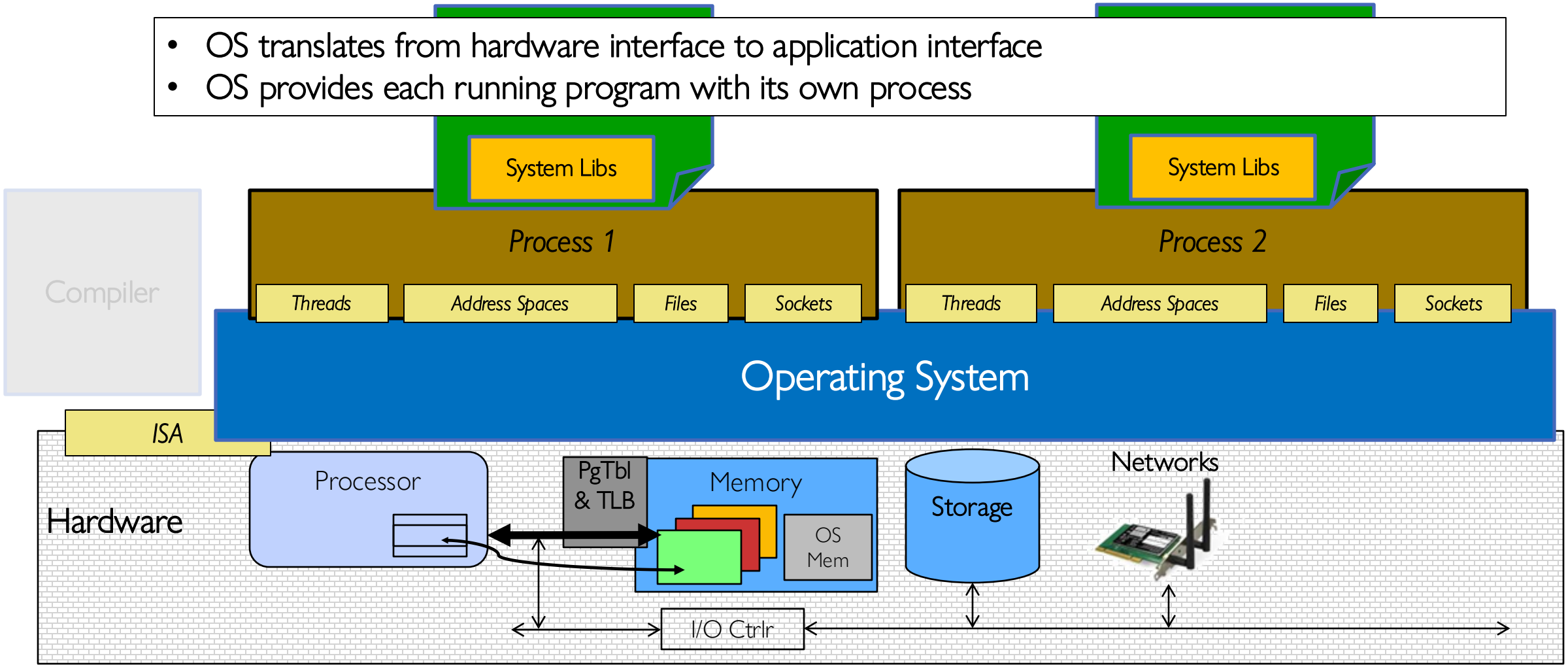

Activity Monitor (All Processes)
CPU
Memory
Energy
Disk
Network
Process Name % CPU CPU Time Threads Idle Wake Ups PID User
Google Chrome Helper 99.9 24:47:28.67 22 1 15980 culler
VBoxHeadless 13.7 6:14:03.13 29 1,504 58926 culler
com.docker.hyperkit 4.0 4:31:39.95 16 235 16791 culler
WindowServer 2.1 3:32:31.55 10 13 46935 _windowserver
Activity Monitor 1.9 21:37.17 5 1 59087 culler
launchd 1.8 44:05.76 3 0 1 root
kernel_task 1.6 5:25:42.39 581 582 0 root
hidd 1.6 1:14:43.51 7 0 100 _hidd
screencapture 0.7 0.29 2 0 68334 culler
sysmond 0.4 14:51.88 3 0 308 root
Google Chrome Helper 0.4 37:39.30 23 5 15976 culler
Microsoft PowerPoint 0.3 13:04.93 15 22 67349 culler
systemstats 0.2 24:01.33 4 0 54 root
VBoxSVC 0.1 5:06.27 15 5 58902 culler
Google Chrome 0.1 3:24:33.44 40 0 15954 culler
iconservicesagent 0.1 33.52 2 1 47014 culler
Screen Shot 0.1 0.19 5 0 68335 culler
Google Chrome Helper 0.1 8:19.43 23 3 64322 culler
Google Chrome Helper 0.1 15:31.92 23 4 66129 culler
Google Chrome Helper 0.1 7:56.86 21 3 60534 culler
scep_daemon 0.1 2:42:12.57 16 0 49137 root
System Center Endpoint Prot… 0.1 14:10.06 3 3 47120 culler
powerd 0.1 7:41.46 2 0 57 root
Google Chrome Helper 0.1 47:32.67 21 3 19876 culler
Google Chrome Helper 0.1 13:19.58 20 3 63420 culler
com.docker.vpnkit 0.1 3:52.03 12 23 16786 culler
Google Chrome Helper 0.1 3:41.15 21 3 64744 culler
Google Chrome Helper 0.1 8:22.79 20 3 52146 culler
Google Chrome Helper 0.1 4:58.09 20 3 16045 culler
Google Chrome Helper 0.1 3:09.51 20 3 65057 culler
Google Chrome Helper 0.0 1:30.87 20 2 59308 culler
com.docker.supervisor 0.0 12.20 31 3 16784 culler
Google Chrome Helper 0.0 10:15.75 21 2 16235 culler
System: 7.07%
User: 3.88%
Idle: 89.05%
CPU LOAD
Threads: 2587
Processes: 434

Operating System's View of the World



Operating System's View of the World

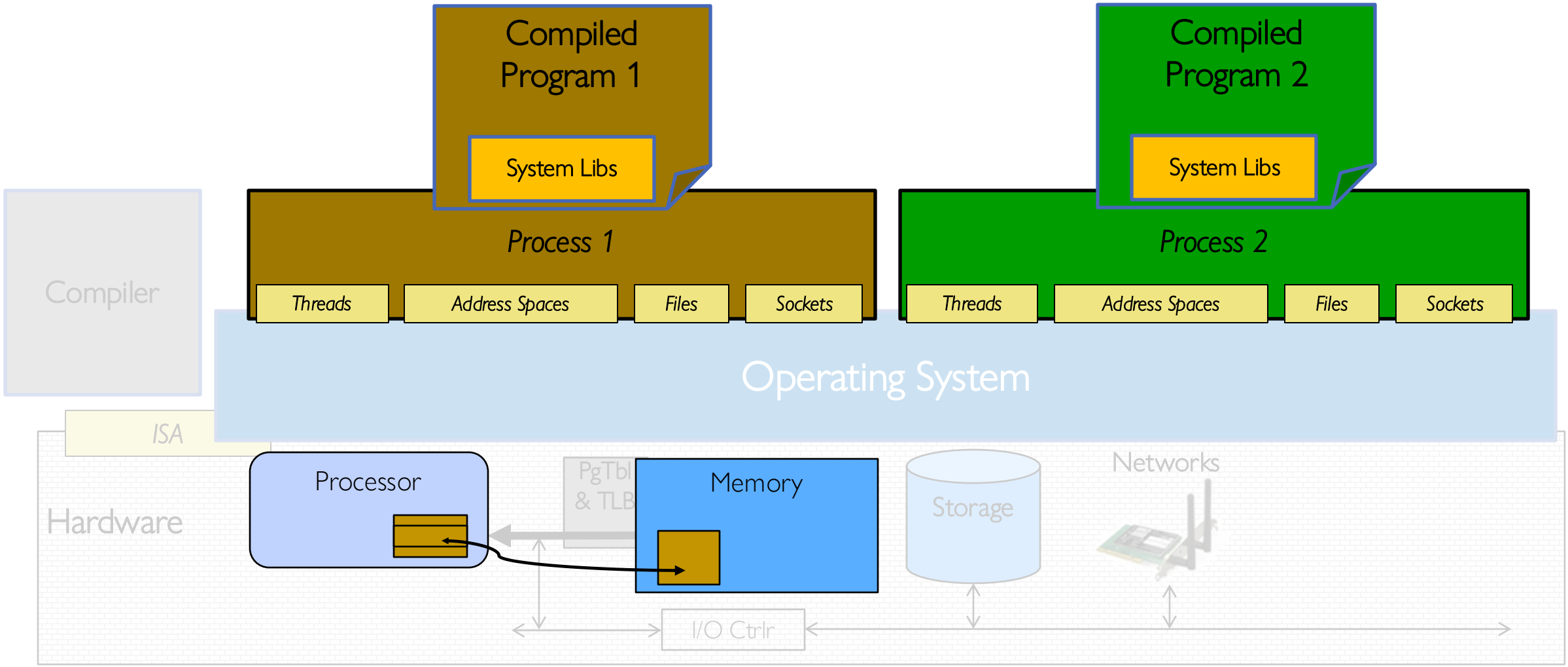
- OS translates from hardware interface to application interface
- OS provides each running program with its own process



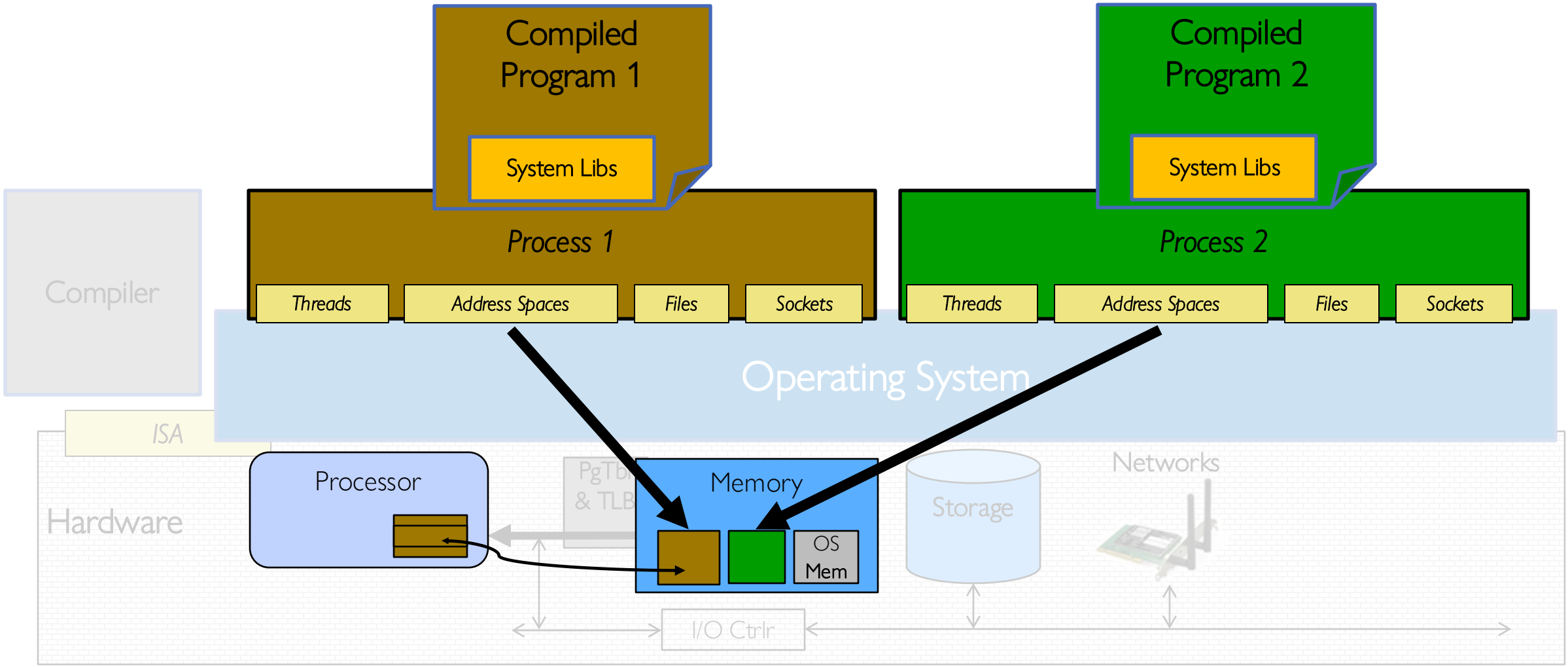
What is an Operating System?

- Referee
  - Manage protection, isolation, and sharing of resources
    - » Resource allocation and communication
- Illusionist
  - Provide clean, easy-to-use abstractions of physical resources
    - » Infinite memory, dedicated machine
    - » Higher level objects: files, users, messages
    - » Masking limitations, virtualization

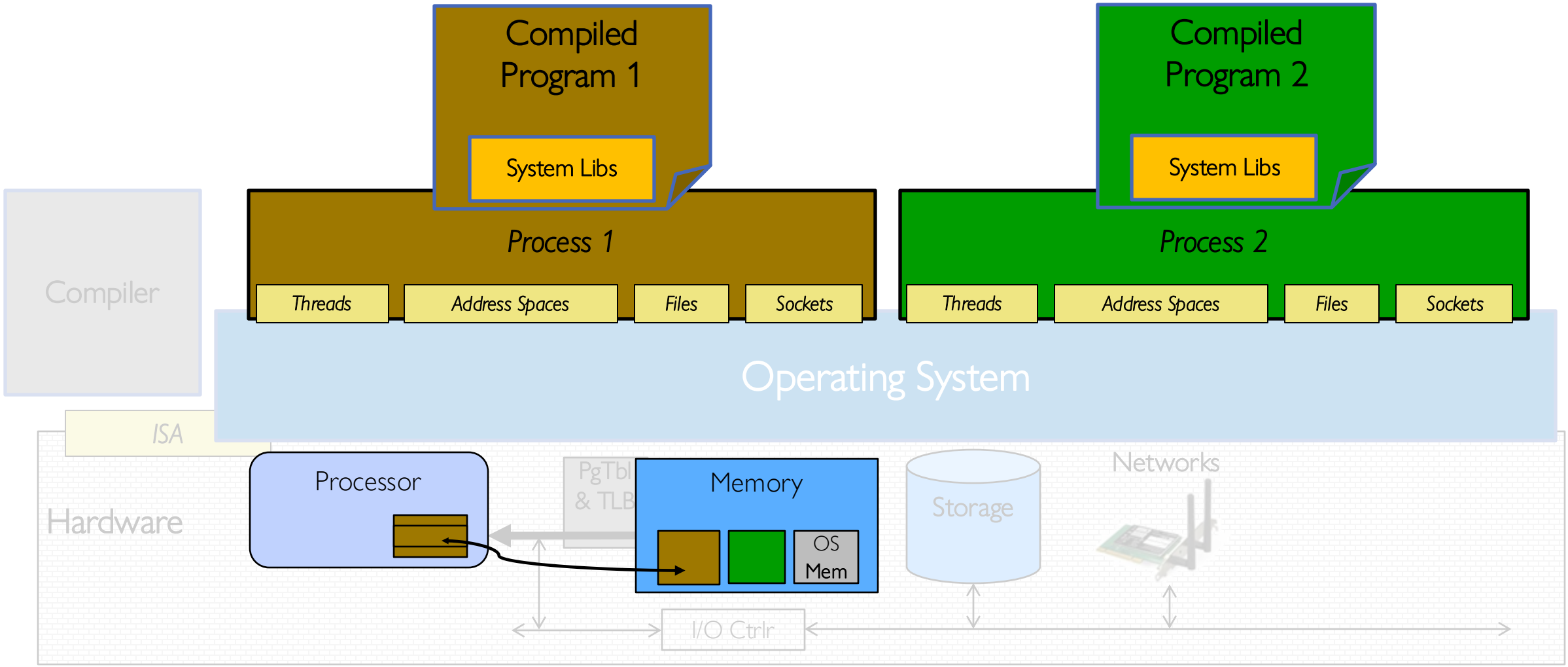
OS Basics: Running a Process



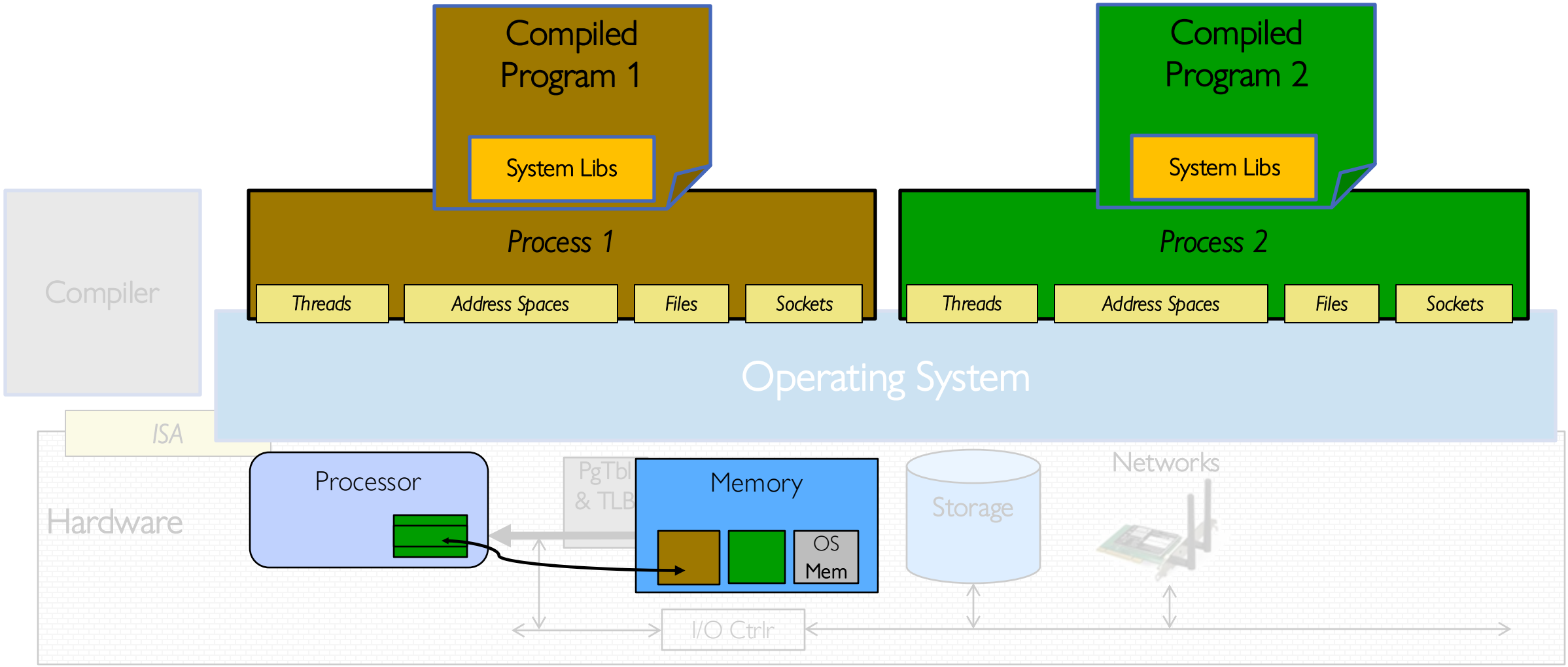
OS Basics: Switching Processes



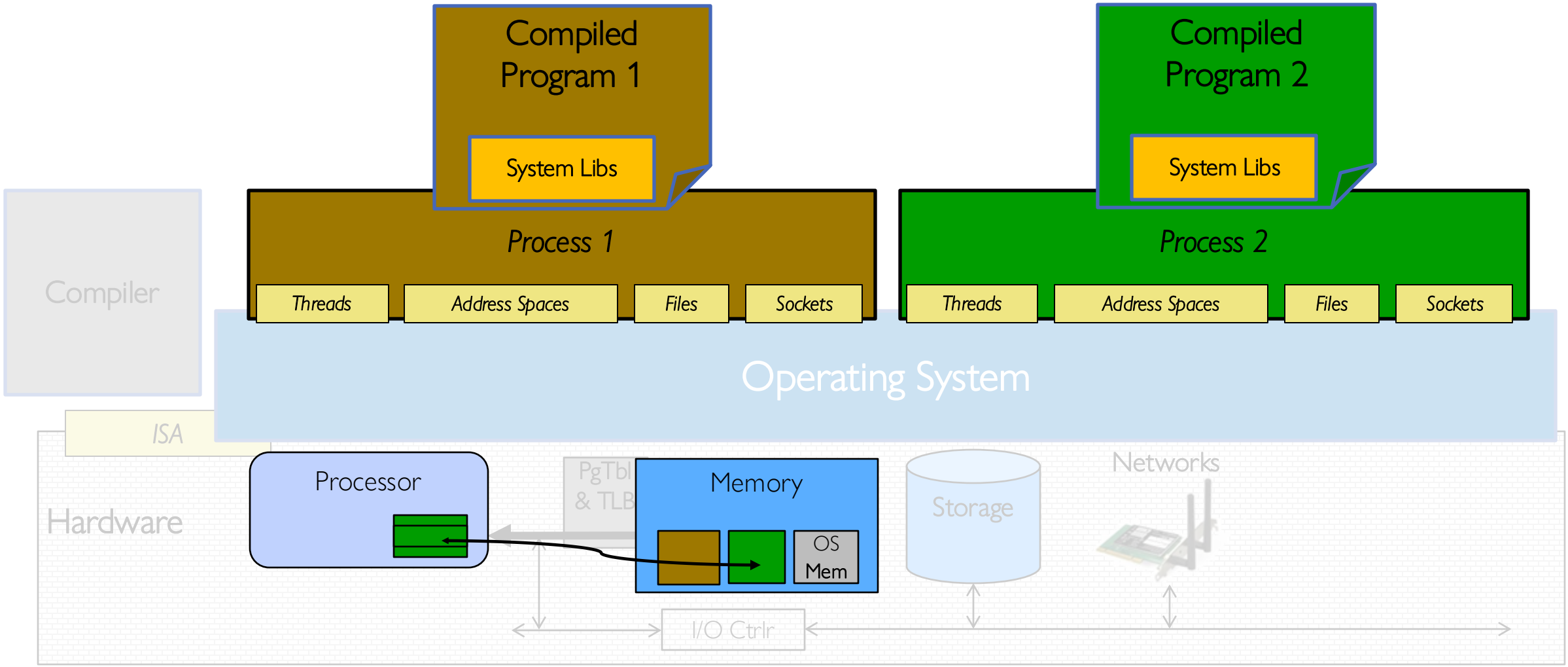
OS Basics: Switching Processes



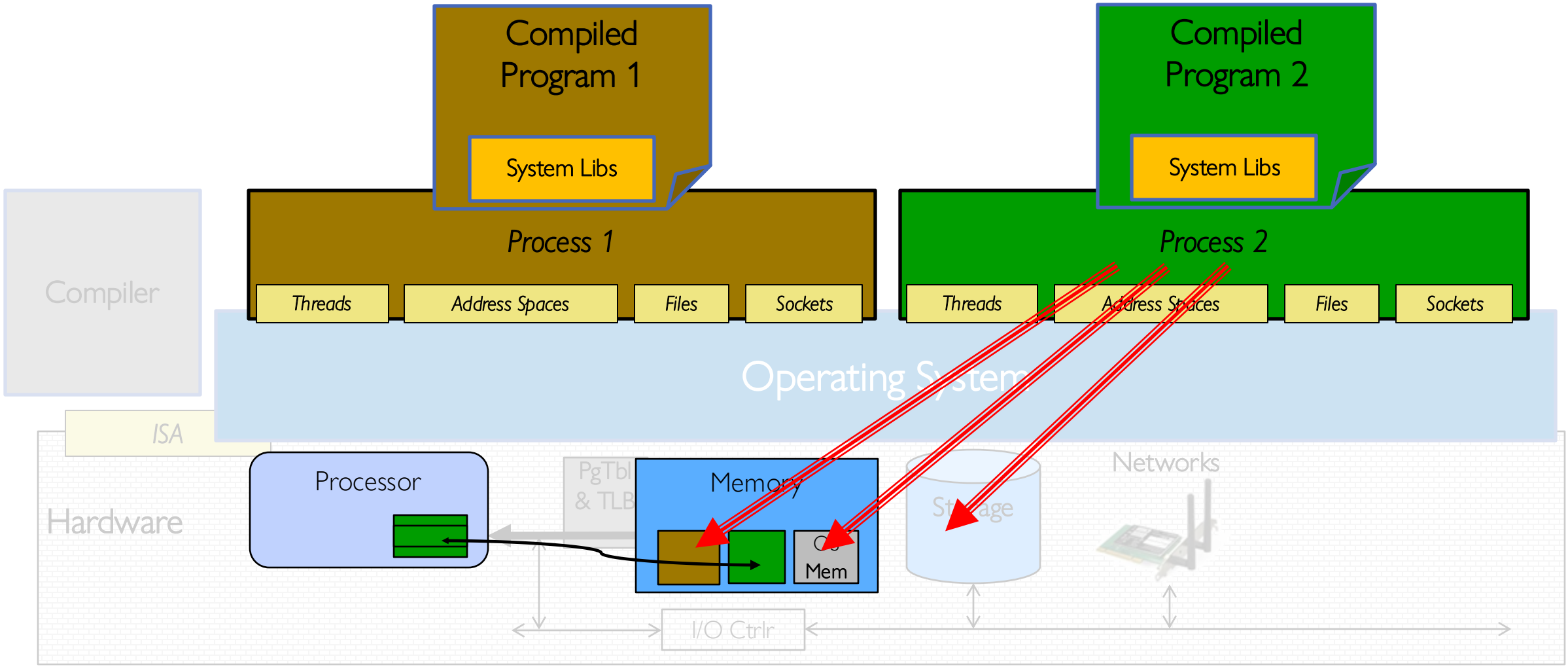
OS Basics: Switching Processes



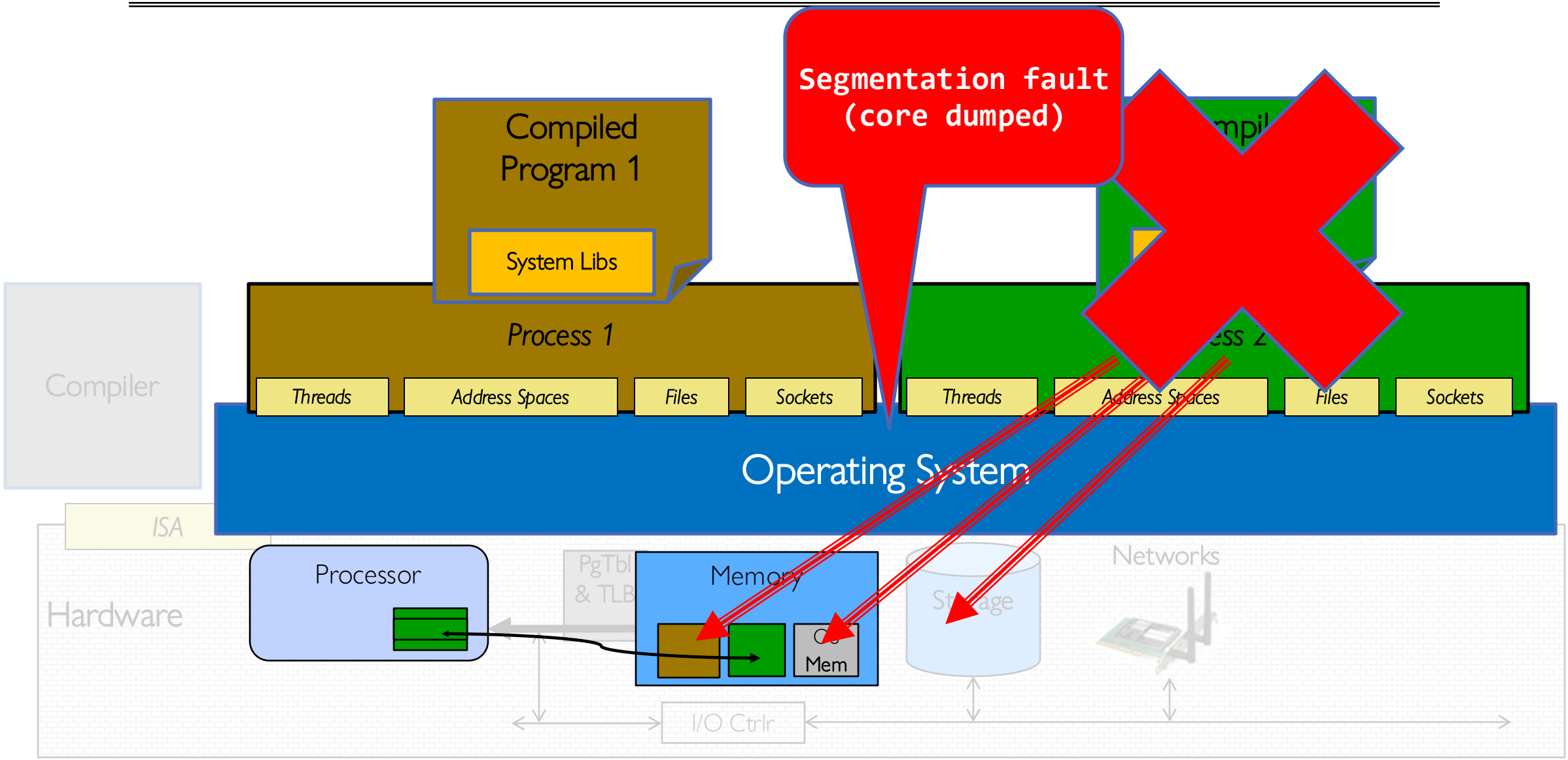
OS Basics: Switching Processes



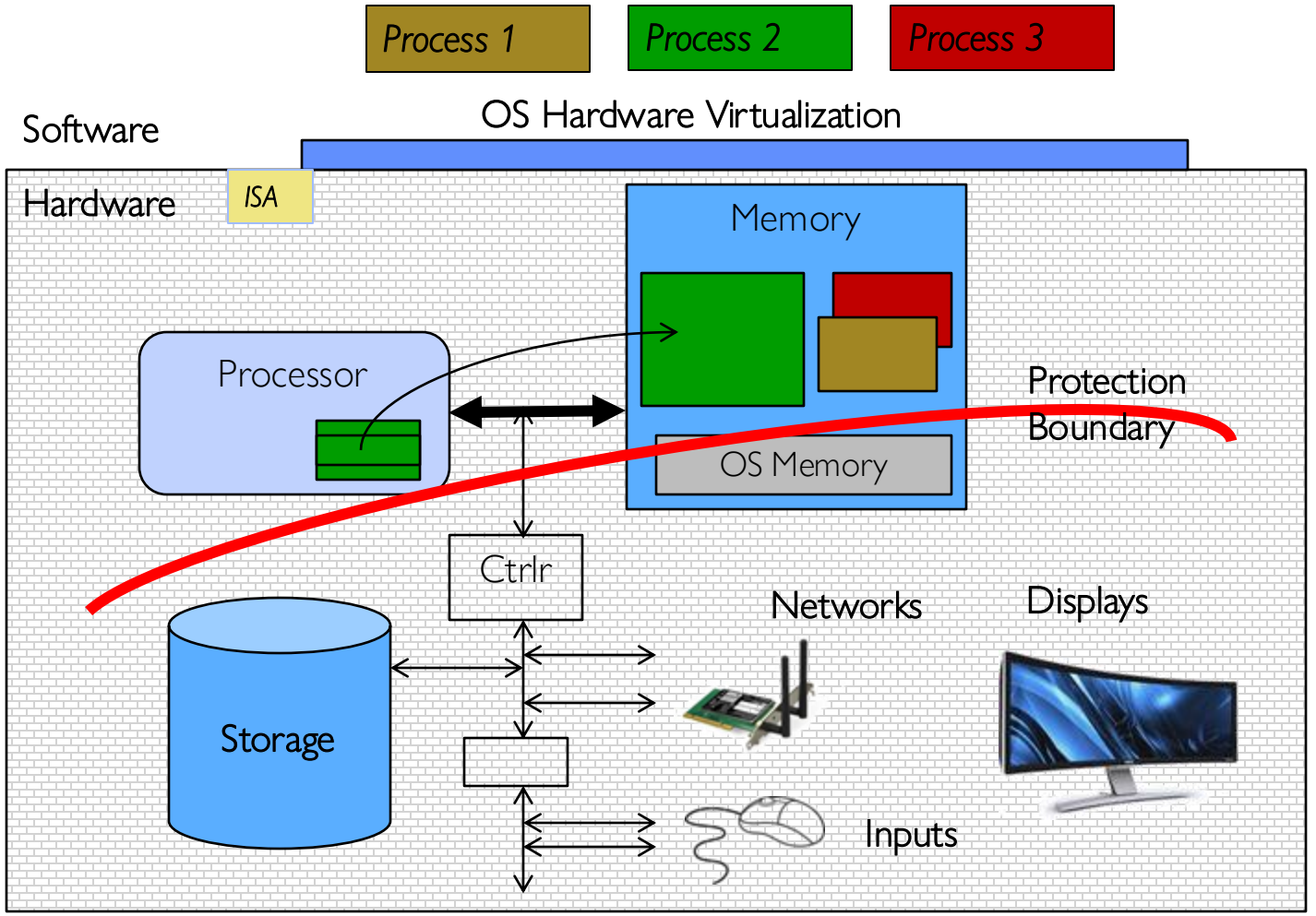
OS Basics: Protection



OS Basics: Protection

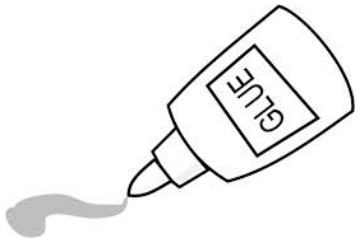


OS Basics: Protection



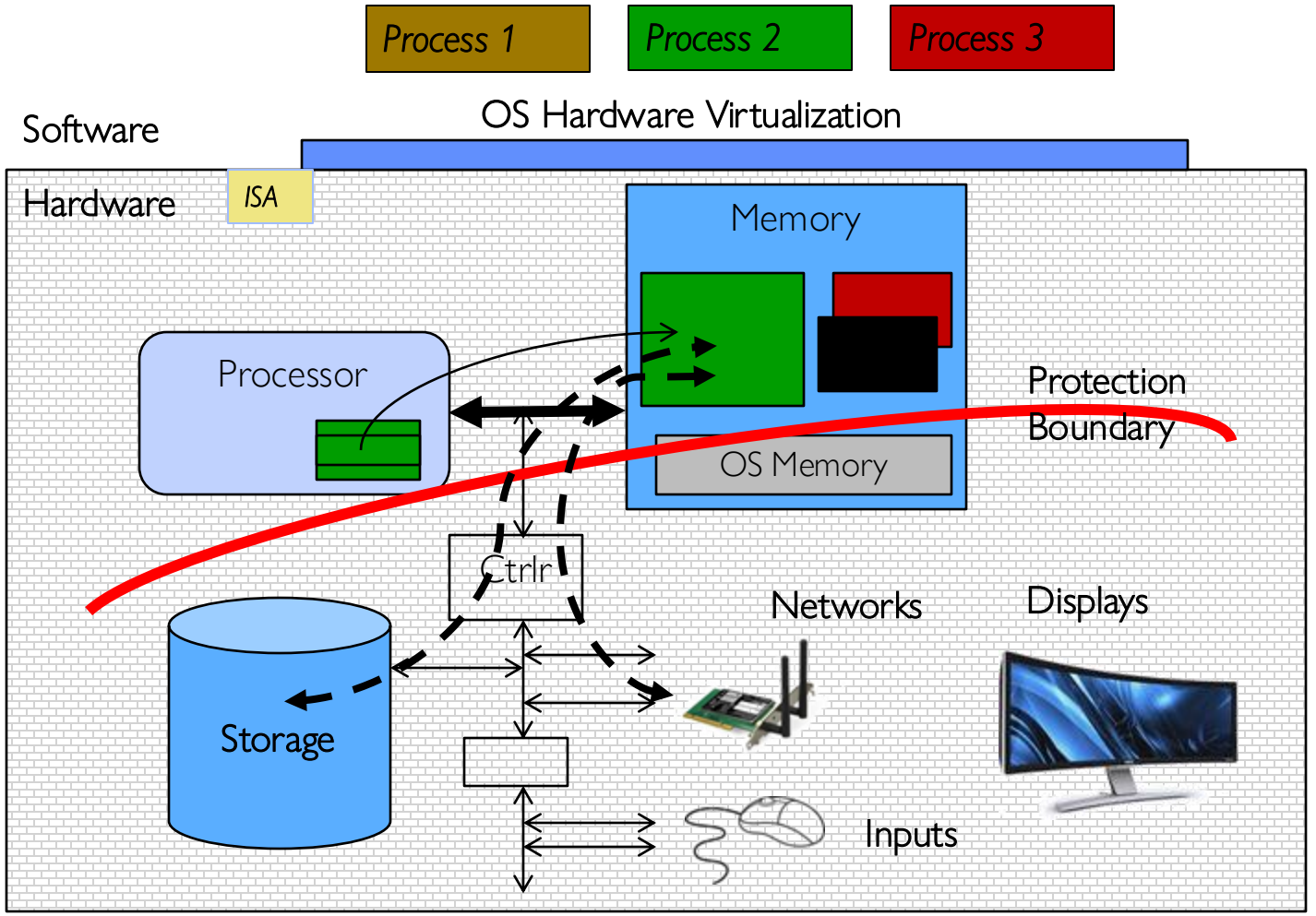
- OS *isolates* processes from each other
- OS *isolates* itself from other processes
- … even though they are actually running on the same hardware!

What is an Operating System?



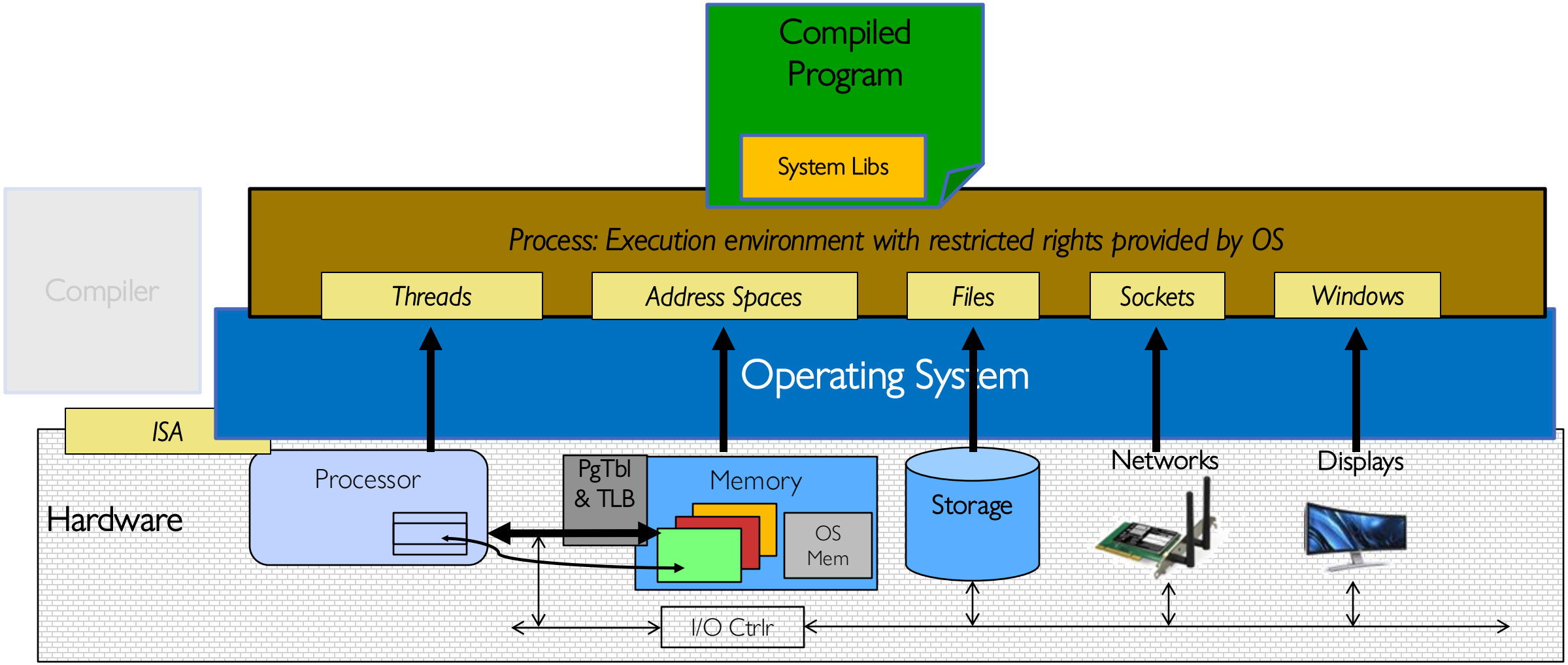
- Referee
  - Manage protection, isolation, and sharing of resources
    - » Resource allocation and communication
- Illusionist
  - Provide clean, easy-to-use abstractions of physical resources
    - » Infinite memory, dedicated machine
    - » Higher level objects: files, users, messages
    - » Masking limitations, virtualization
- Glue
  - Common services
    - » Storage, Window system, Networking
    - » Sharing, Authorization
    - » Look and feel

OS Basics: I/O

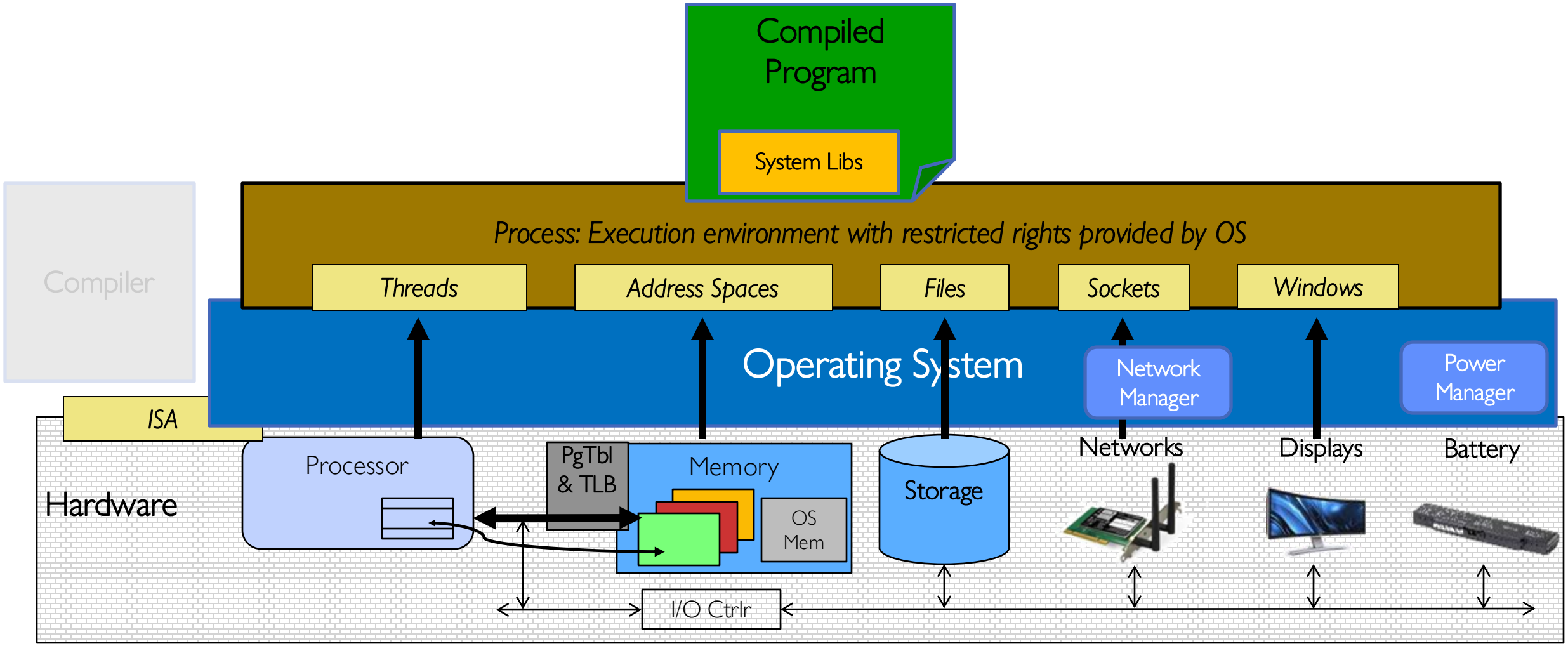


- OS provides common services in the form of I/O

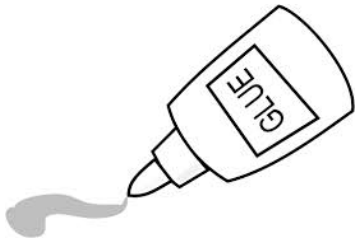
OS Basics: Look and Feel



OS Basics: Background Management



What is an Operating System?



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  - Common services
    - » Storage, Window system, Networking
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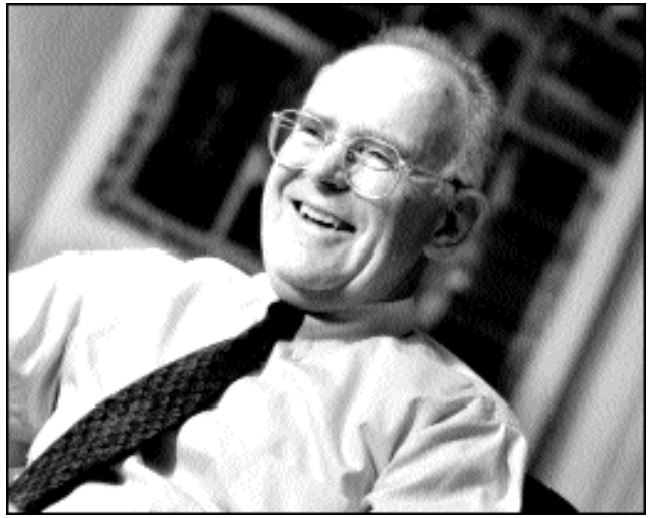
    - » Look and feel

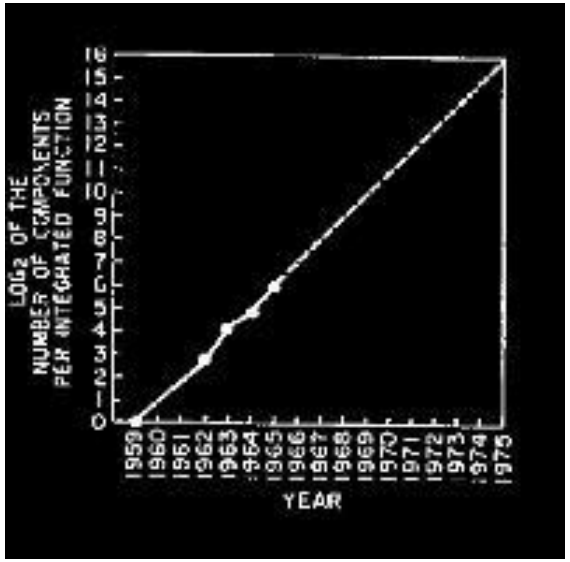
Why take CS162?

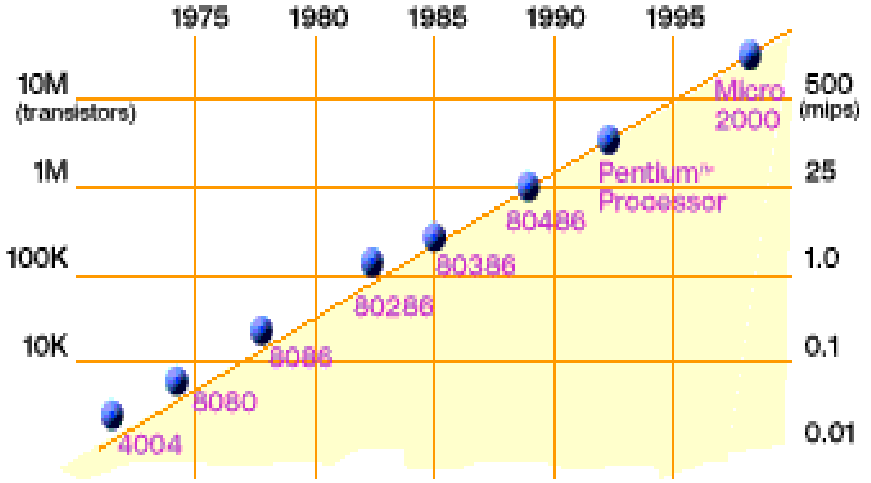
- Some of you will actually design and build operating systems or components of them
- Many of you will create systems that utilize the core concepts in operating systems.
  - Whether you build software or hardware
  - The concepts and design patterns appear at many levels
- All of you will build applications, etc. that utilize operating systems
  - The better you understand their design and implementation, the better use you'll make of them.

What makes Operating Systems Exciting and Challenging?

Technology Trends: Moore's Law







2X transistors/Chip Every 2 years

Called "Moore's Law"

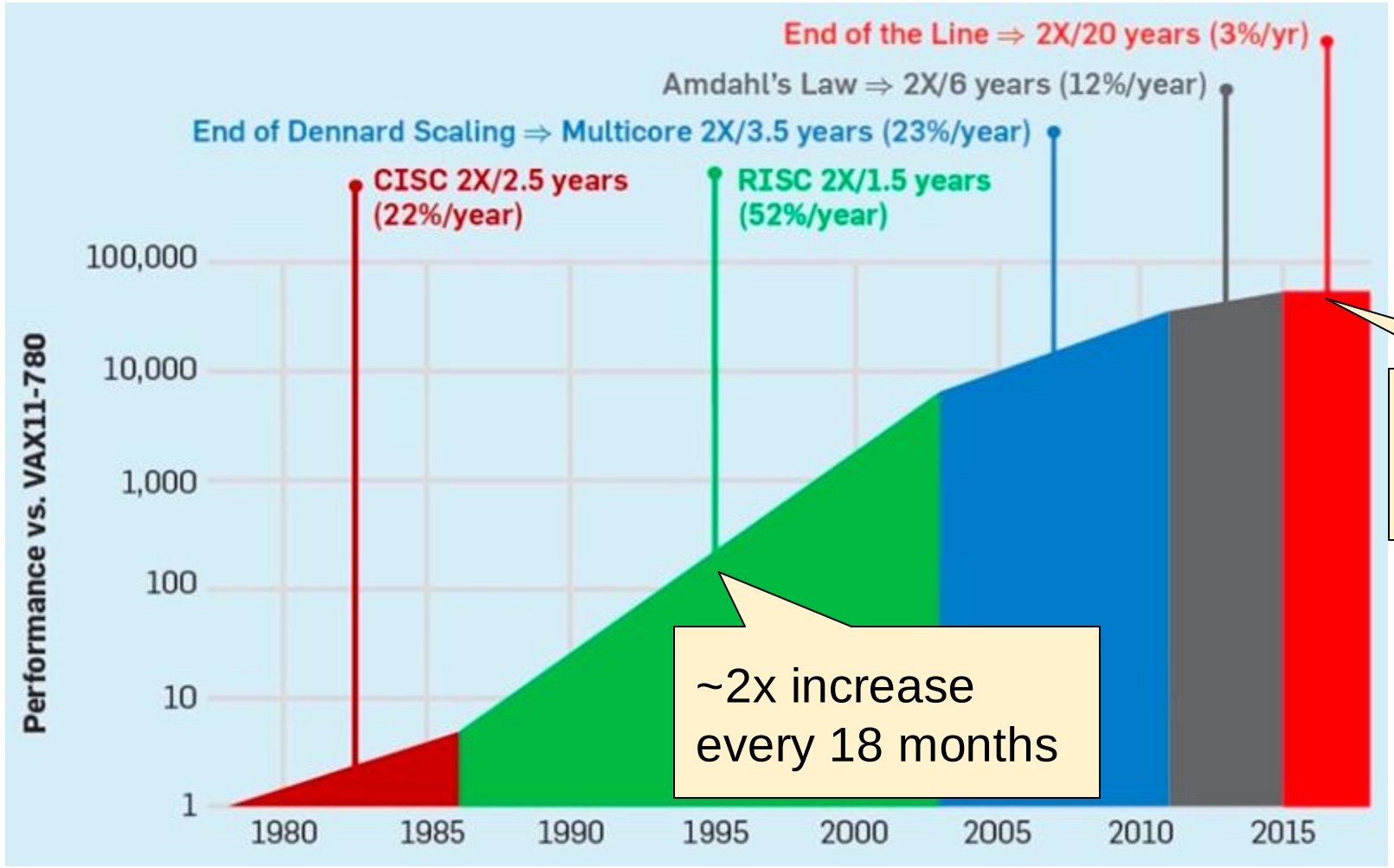
Gordon Moore (co-founder of Intel) predicted in 1965 that the transistor density of semiconductor chips would double roughly every 2 years

- Microprocessors have become smaller, denser, and more powerful

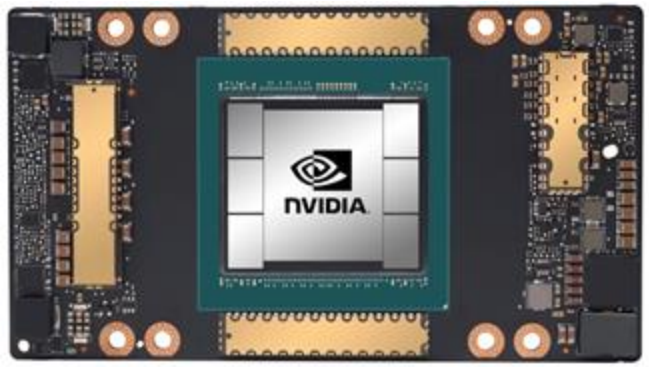
Corollary: Performance double roughly every 1.5 years (18 months)

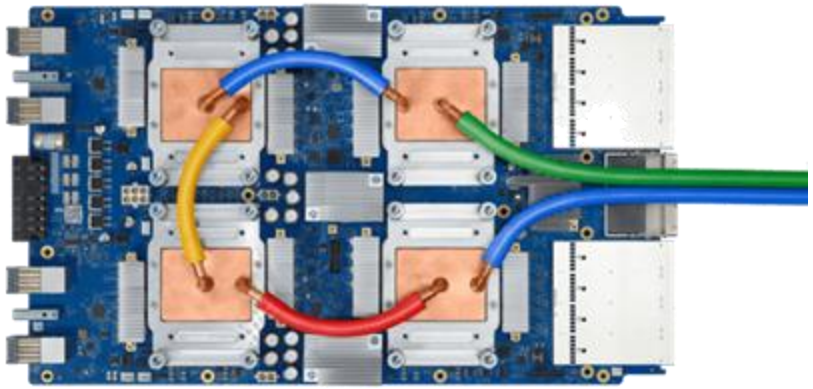
- Faster growth because transistors are closer to each other so electrical signals travel faster

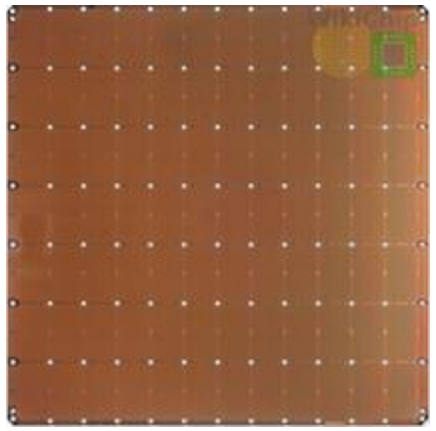
Moore's Law coming to an end



Specialized processors to the rescue



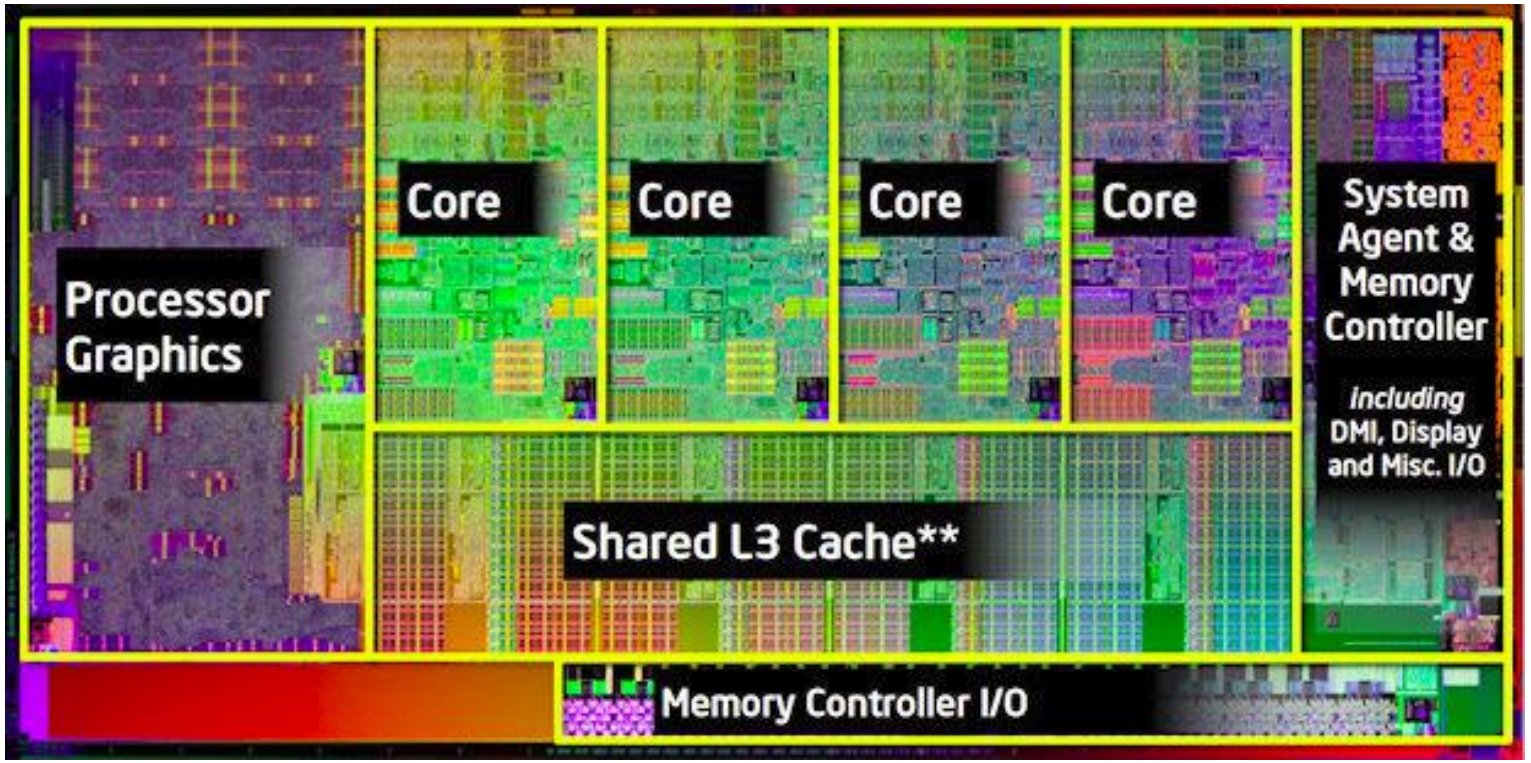




Not only specialized processors …

- Multi-core processors
  - Intel Xeon Sierra Forest:
    144 cores; planned 288
  - AMD Epyc
    128 cores; planned 192

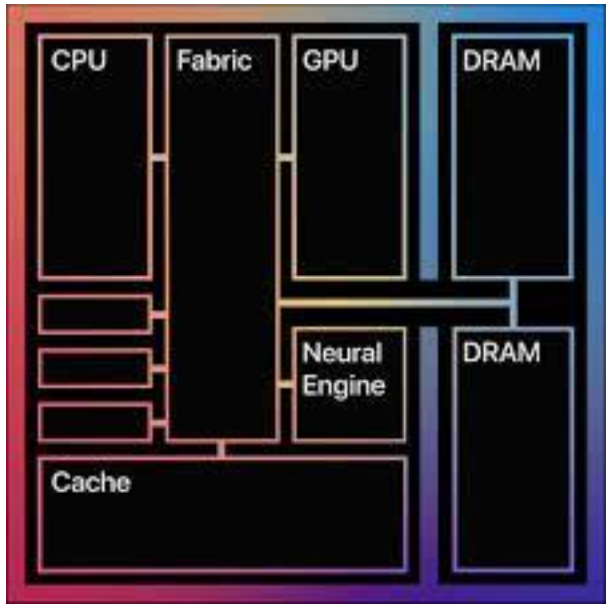
A Modern Processor: Intel Sandy Bridge



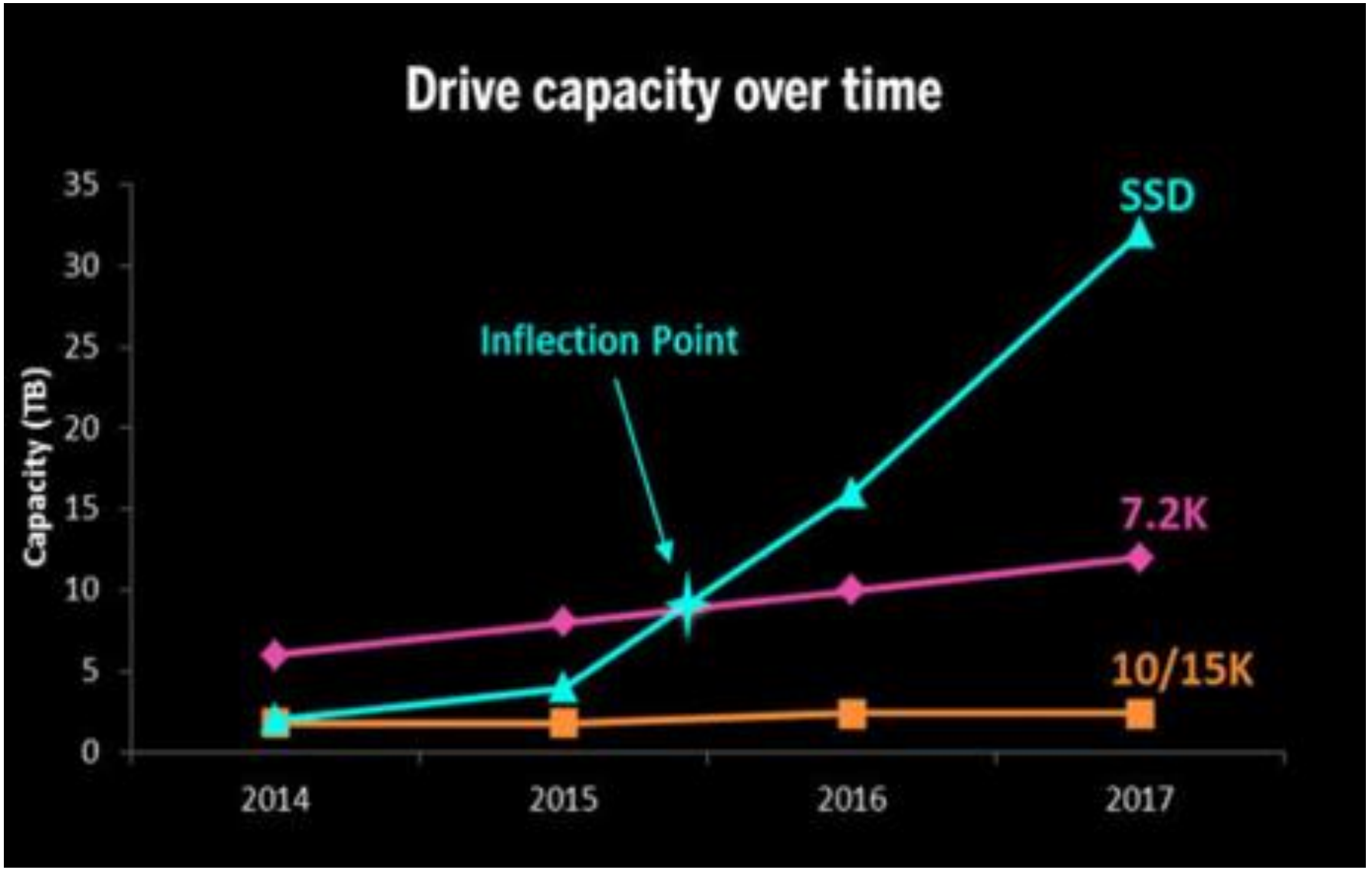
- Package: LGA 1155
  - 1155 pins
  - 95W design envelope
- Cache:
  - L1: 32K Inst, 32K Data (3 clock access)
  - L2: 256K (8 clock access)
  - Shared L3: 3MB – 20MB
- Transistor count:
  - 504 Million (2 cores, 3MB L3)
  - 2.27 Billion (8 cores, 20MB L3)
- Note that ring bus is on high metal layers – above the Shared L3 Cache

Not only specialized processors…

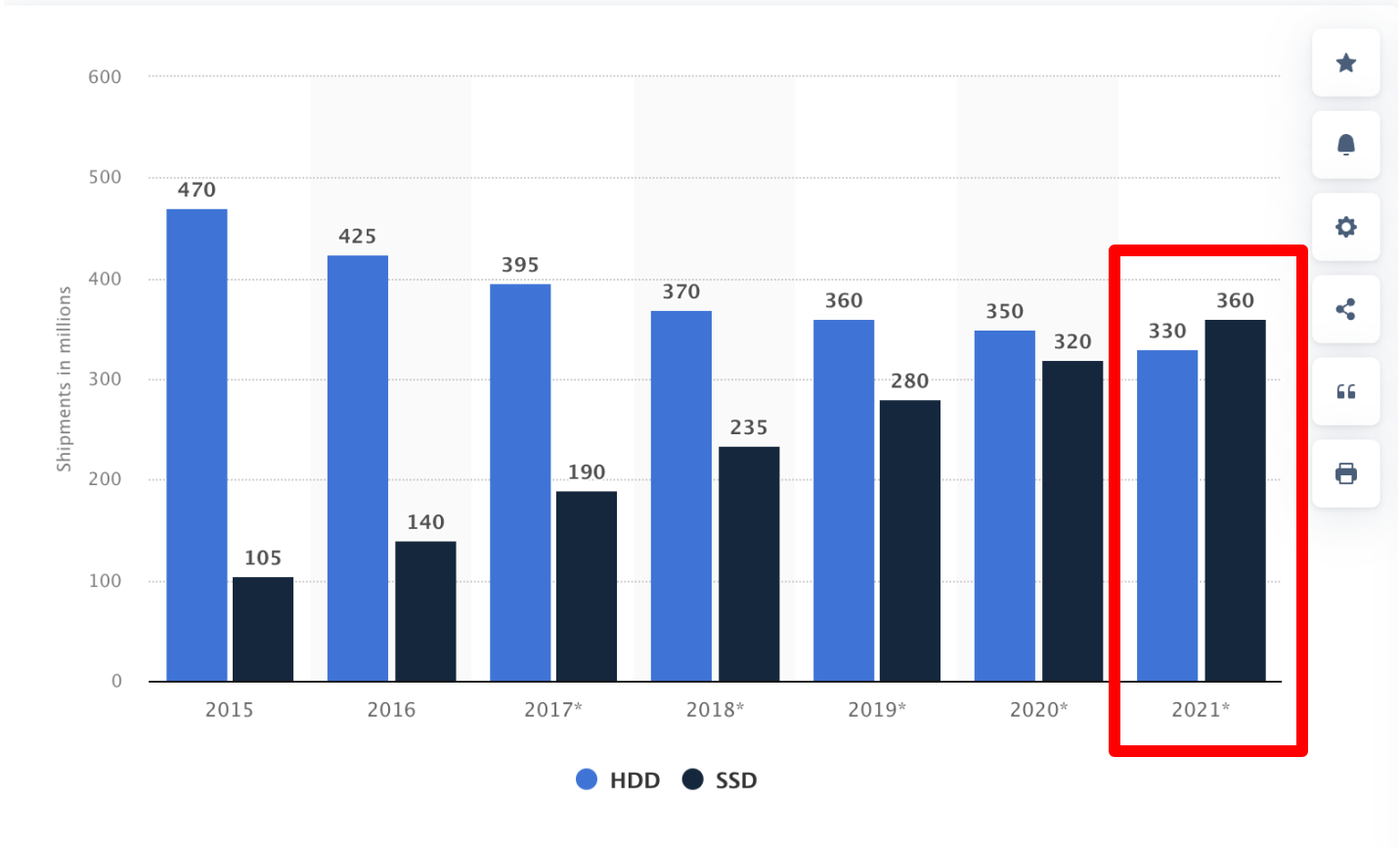
- Multi-core processors
  - Intel Xeon Sierra Forest:
    144 cores; planned 288
  - AMD Epyc
    128 cores; planned 192
- System On a Chip (SOC):
  accelerating trend

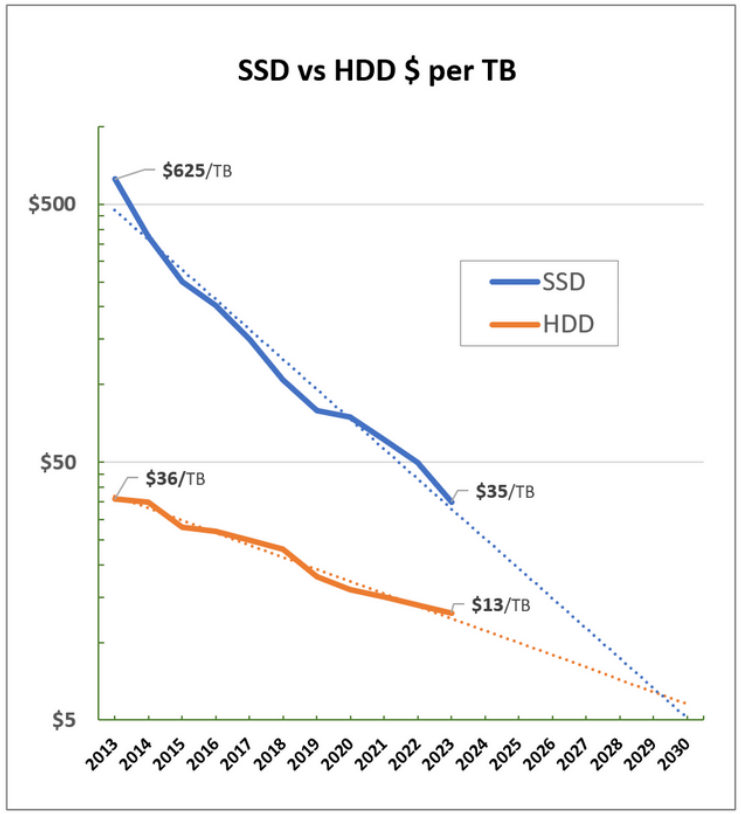


SSD overtaking HDD



SSD/Flash Dominating





Storage Capacity

Largest SSD 3.5-inch drive:
100 TB @ $40K ($400/TB)

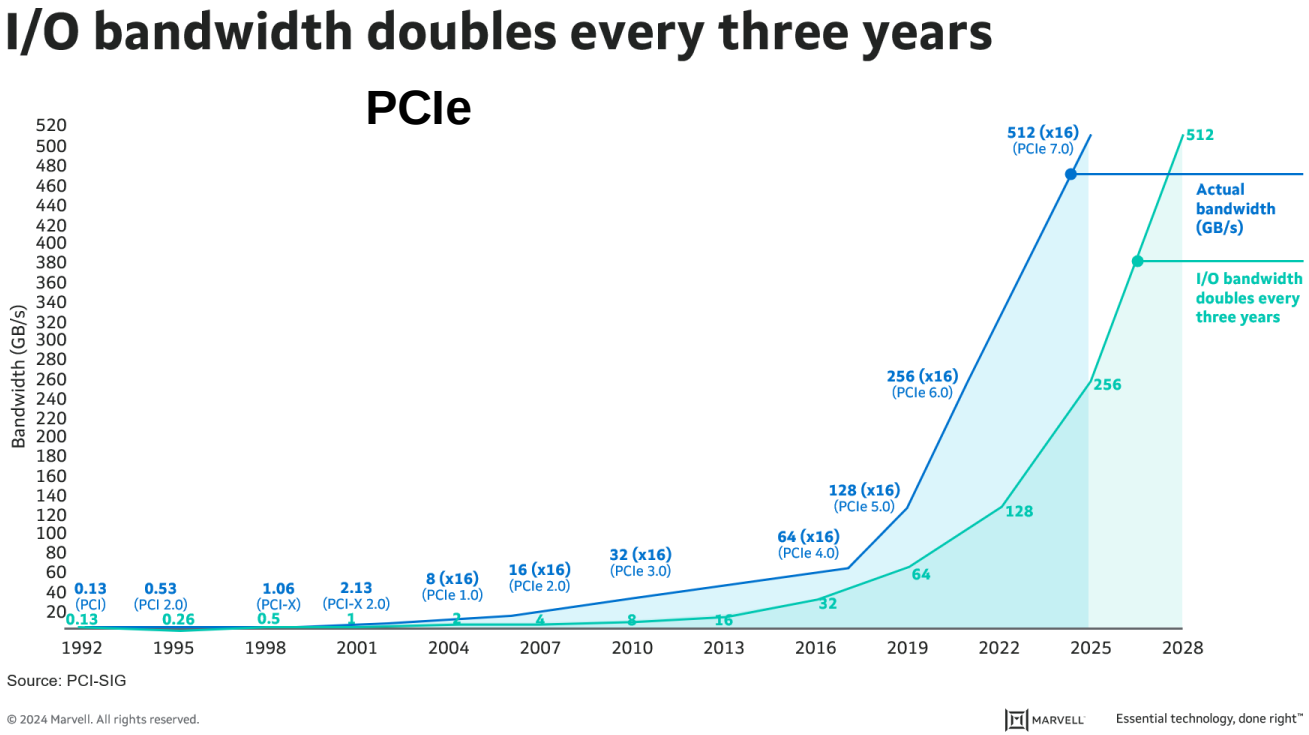
Leven SSD 2.5-inch drive:
4 TB @ $180 ($45/TB)

Largest HDD 3.5-inch drive:
24 TB @ $480 ($20/TB)

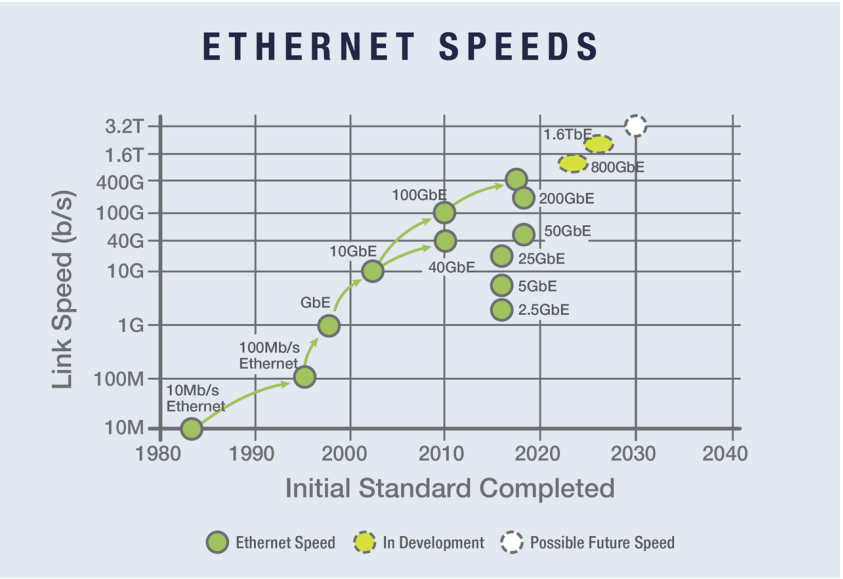
Cheaper, but

- Slower (10x-100x)
- Consumes more power
- Less reliable

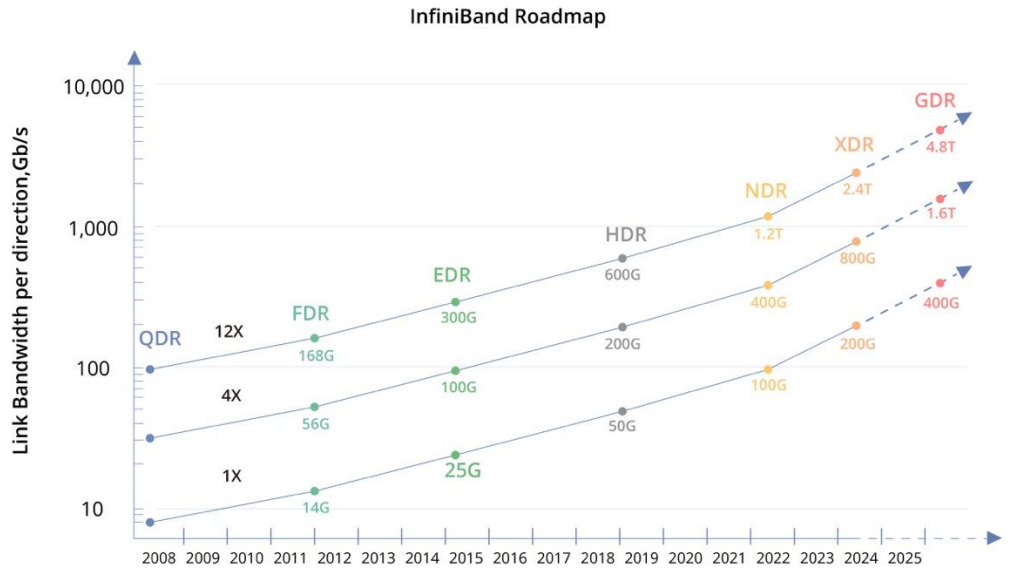
Network Capacity



(source: https://www.marvell.com/blogs/how-pcie-interconnect-is-critical-for-the-emerging-ai-era.html)

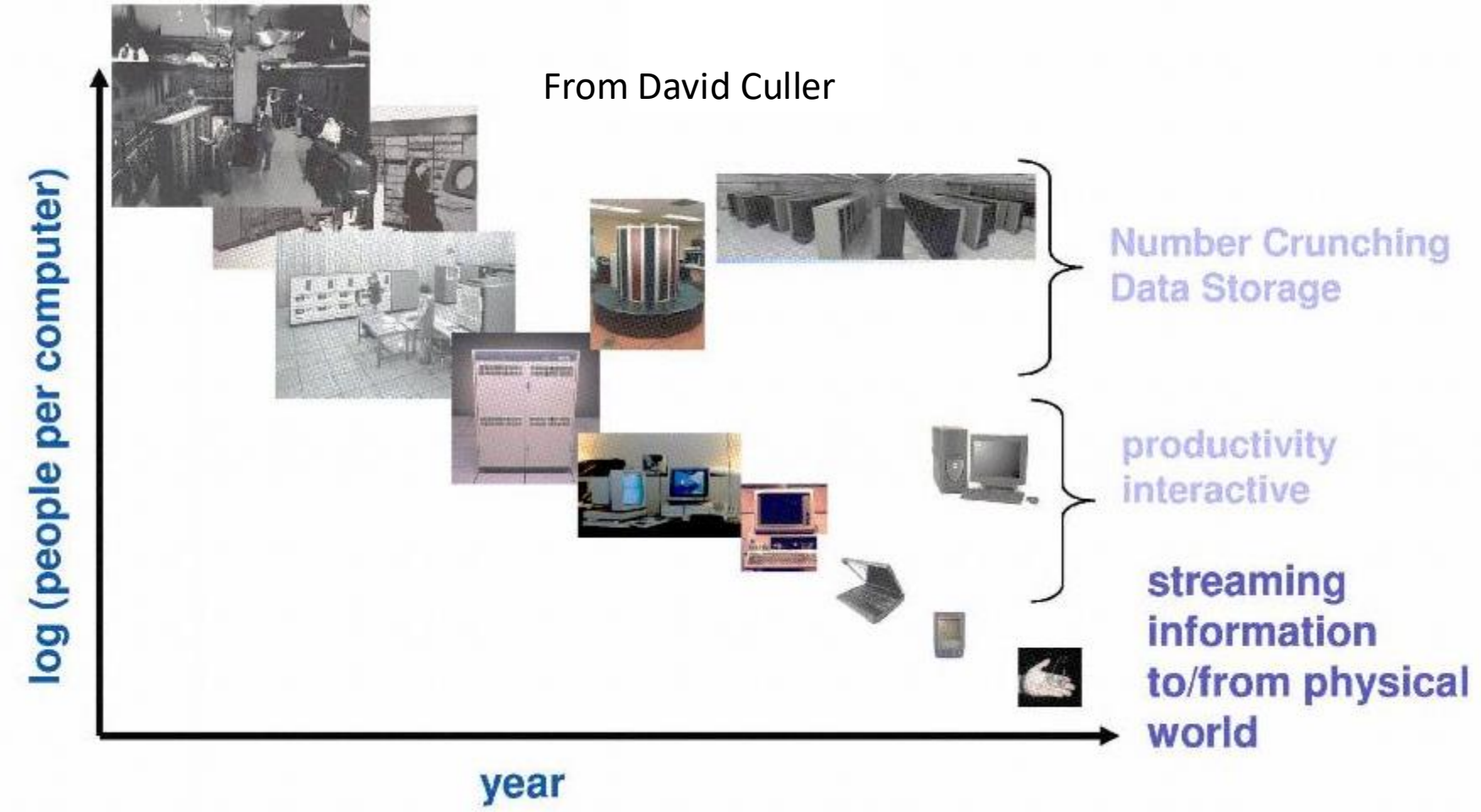


(source: https://iebmedia.com/technology/industrial-ethernet/ethernet-celebrates-50-years-with-2023-roadmap-and-demo/)



(source: https://community.fs.com/article/need-for-speed-%E2%80%93-infiniband-network-bandwidth-evolution.html)

People-to-Computer Ratio Over Time



- Today: multiple CPUs/person!
  - Approaching 100s?

And Range of Timescales

Jeff Dean: "Numbers Everyone Should Know"

L1 cache reference	0.5 ns
Branch mispredict	5 ns
L2 cache reference	7 ns
Mutex lock/unlock	25 ns
Main memory reference	100 ns
Compress 1K bytes with Zippy	3,000 ns
Send 2K bytes over 1 Gbps network	20,000 ns
Read 1 MB sequentially from memory	250,000 ns
Round trip within same datacenter	500,000 ns
Disk seek	10,000,000 ns
Read 1 MB sequentially from disk	20,000,000 ns
Send packet CA->Netherlands->CA	150,000,000 ns

Challenge: Complexity

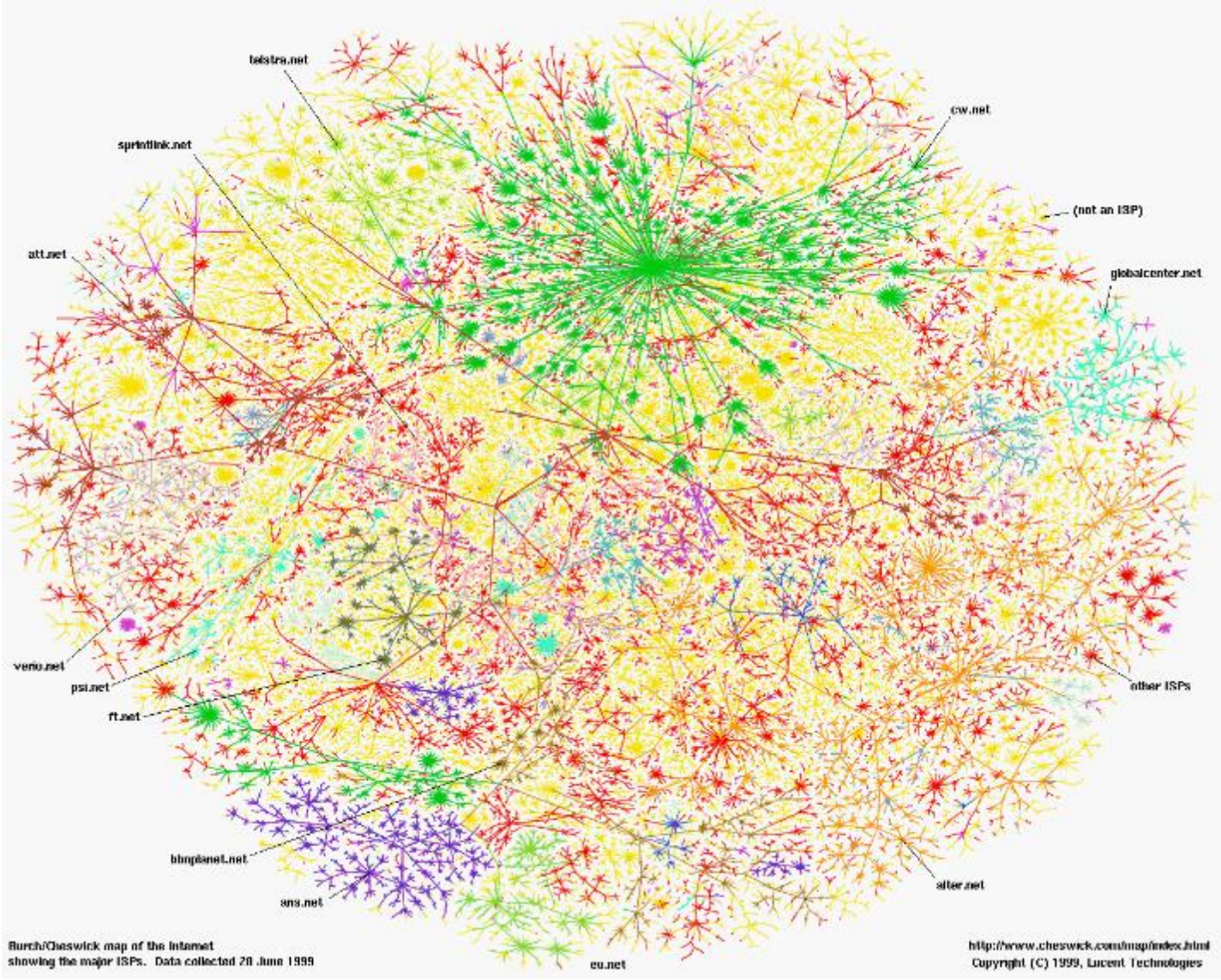
- Applications consisting of…
  - … a variety of software modules that …
  - … run on a variety of devices (machines) that
    - » … implement different hardware architectures
    - » … run competing applications
    - » … fail in unexpected ways
    - » … can be under a variety of attacks

- Not feasible to test software for all possible environments and combinations of components and devices
  - The question is not whether there are bugs but how serious are the bugs!

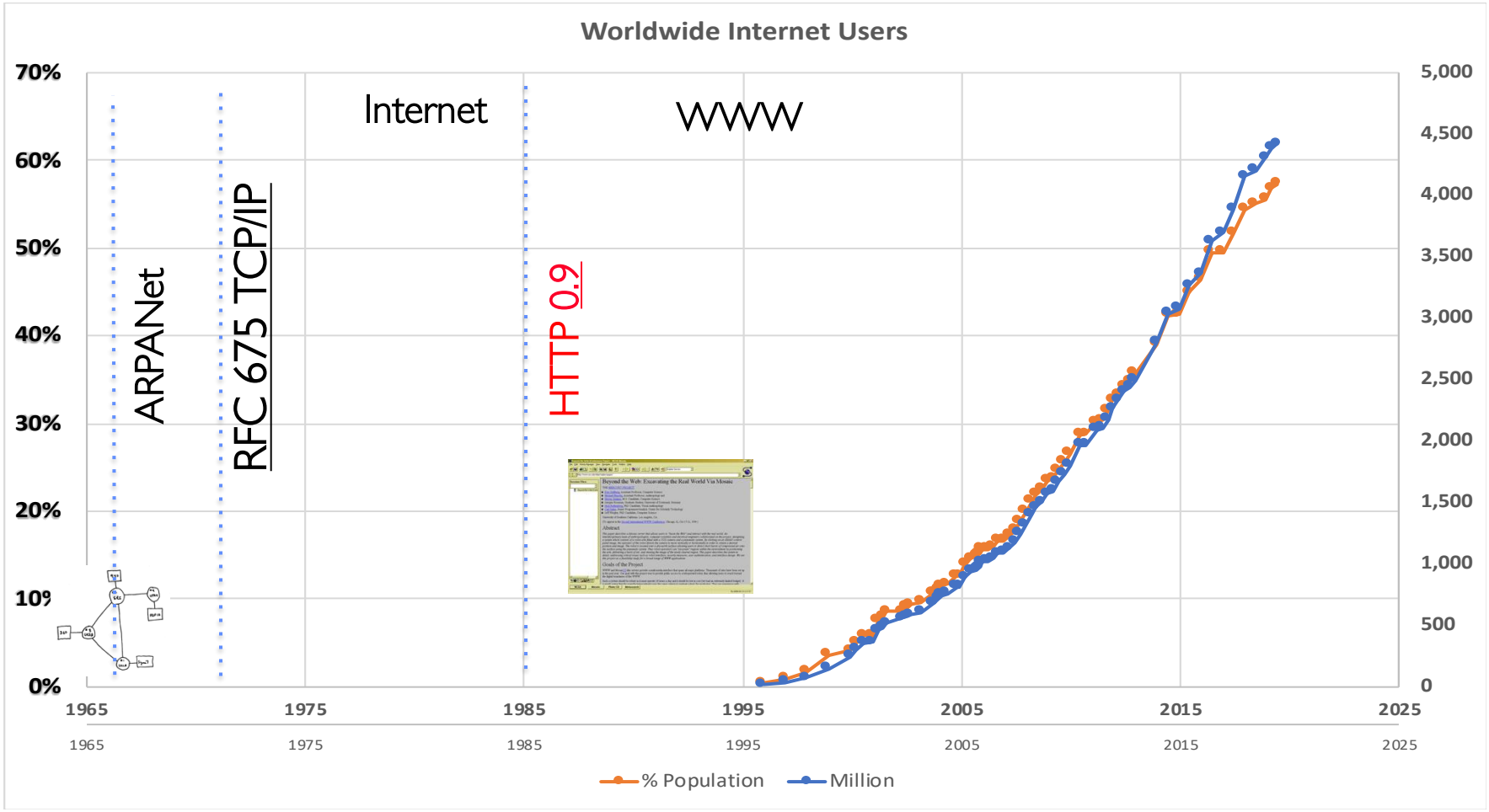
Everything going distributed and heterogeneous

- Need to scale
  - Machine learning (AI) workloads
  - Big Data analytics
  - Scientific computing
  - …
- Everything is connected!

Greatest Artifact of Human Civilization…



Running Systems at Internet Scale



1969 1974 1990

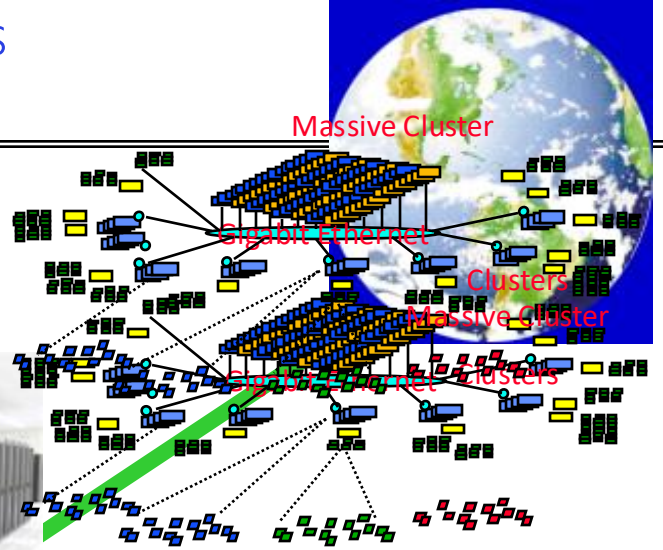
Not Only PCs connected to the Internet

- Smartphone shipments exceed PC shipments in 2012!
- 2011 shipments:
  - 487M smartphones
  - 414M PC clients
    - » 210M notebooks
    - » 112M desktops
    - » 63M tablets
  - 25M smart TVs

- Now 7 billion smartphone in the world

Societal Scale Information Systems (Or the "Internet of Things"?)

- The world is a large distributed system
  - Microprocessors in everything
  - Vast infrastructure behind them



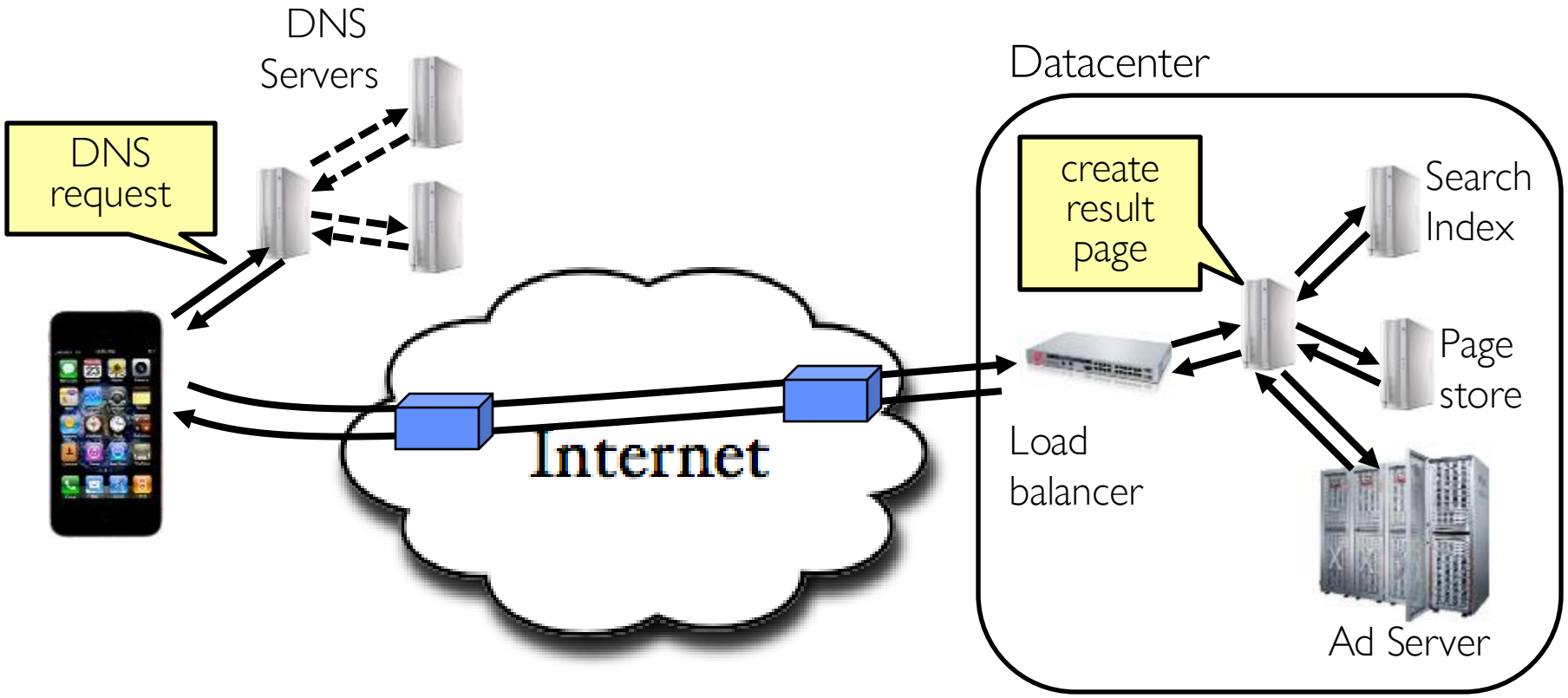
Scalable, Reliable, Secure Services

Internet Connectivity

Databases
Information Collection
Remote Storage
Online Games
Commerce
…

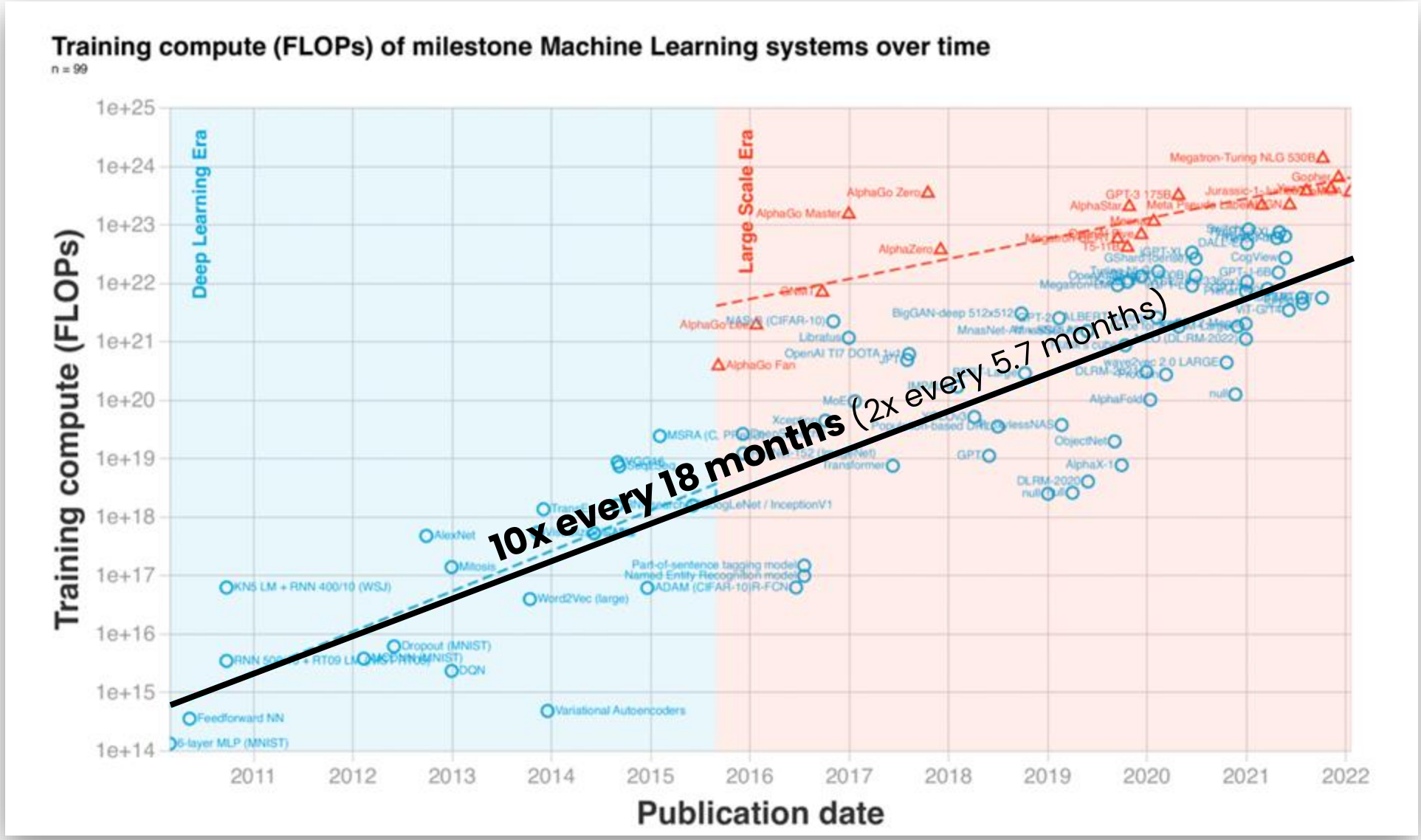
MEMS for Sensor Nets

Example: What's in a Search Query?



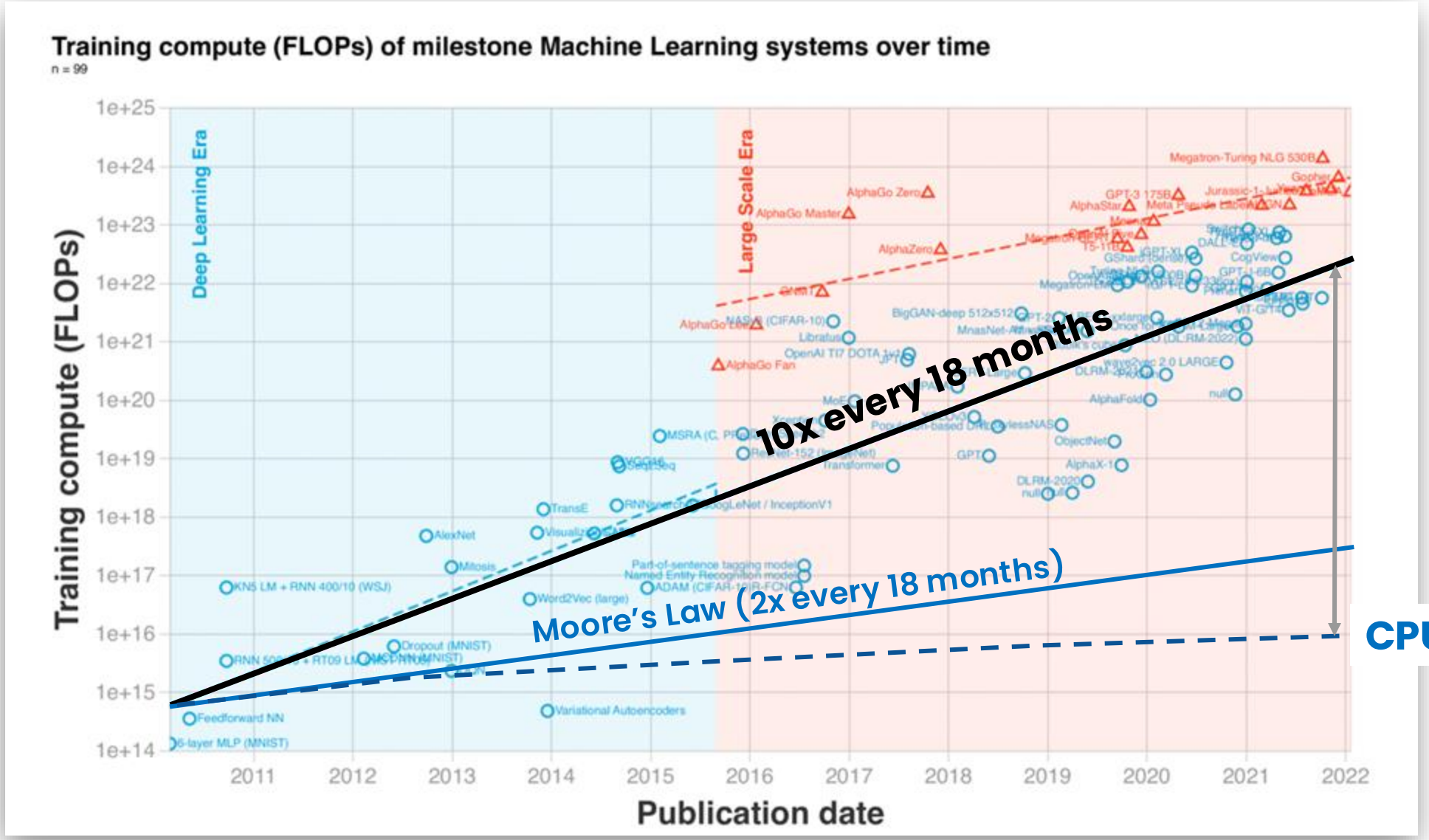
- Complex interaction of multiple components in multiple administrative domains
  - Systems, services, protocols, …

AI demands are exploding



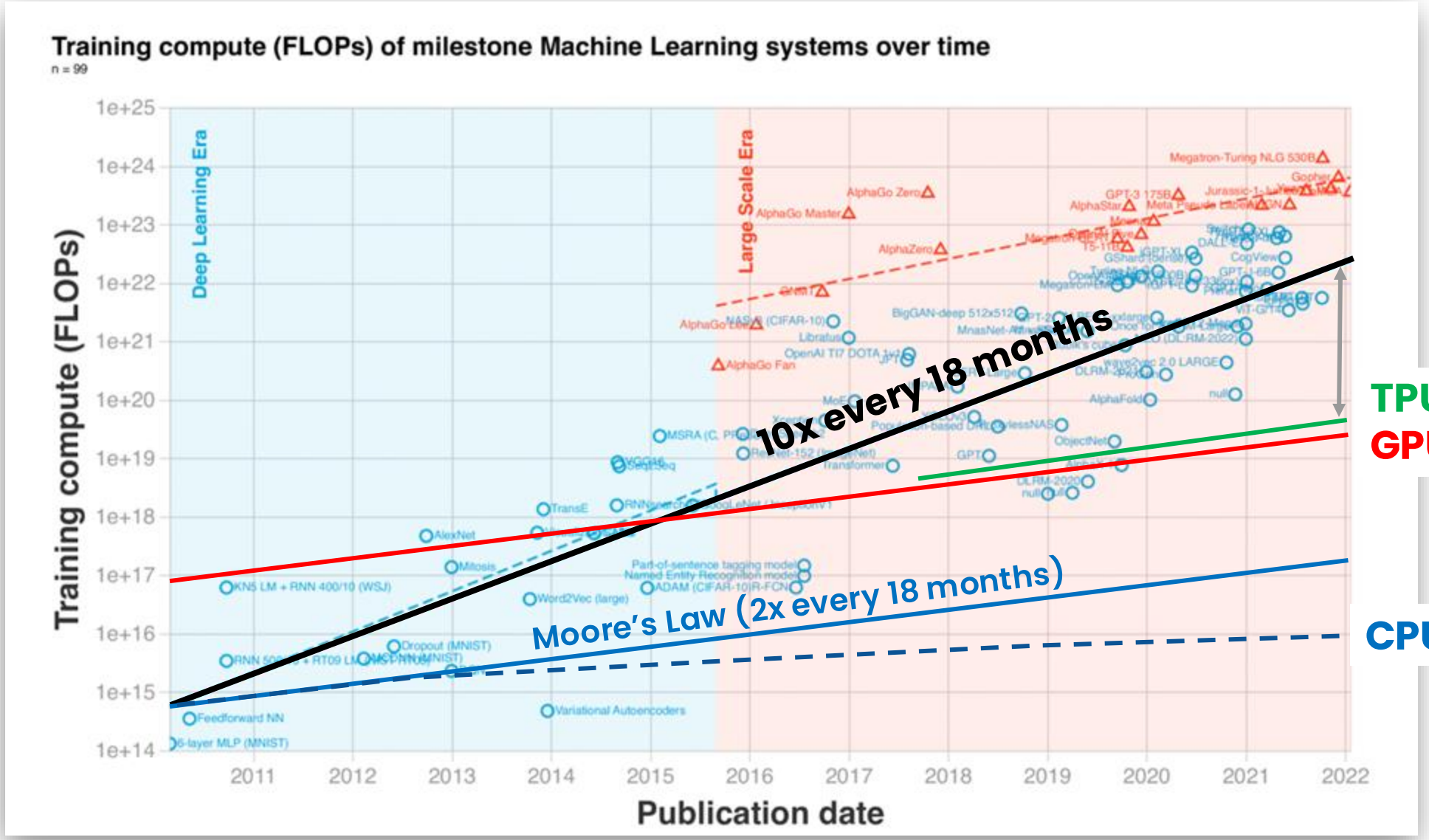
"Compute trends across three eras of machine learning", J. Sevilla, https://ar5iv.labs.arxiv.org/html/2202.05924

Growing gap between demand and supply



"Compute trends across three eras of machine learning", J. Sevilla, https://ar5iv.labs.arxiv.org/html/2202.05924

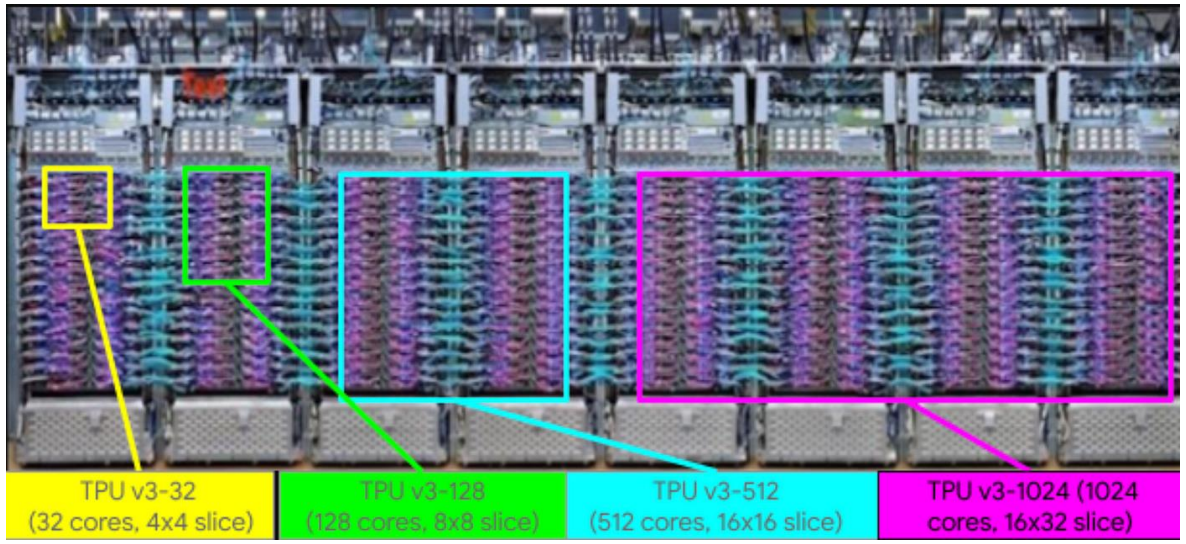
Specialized hardware not enough



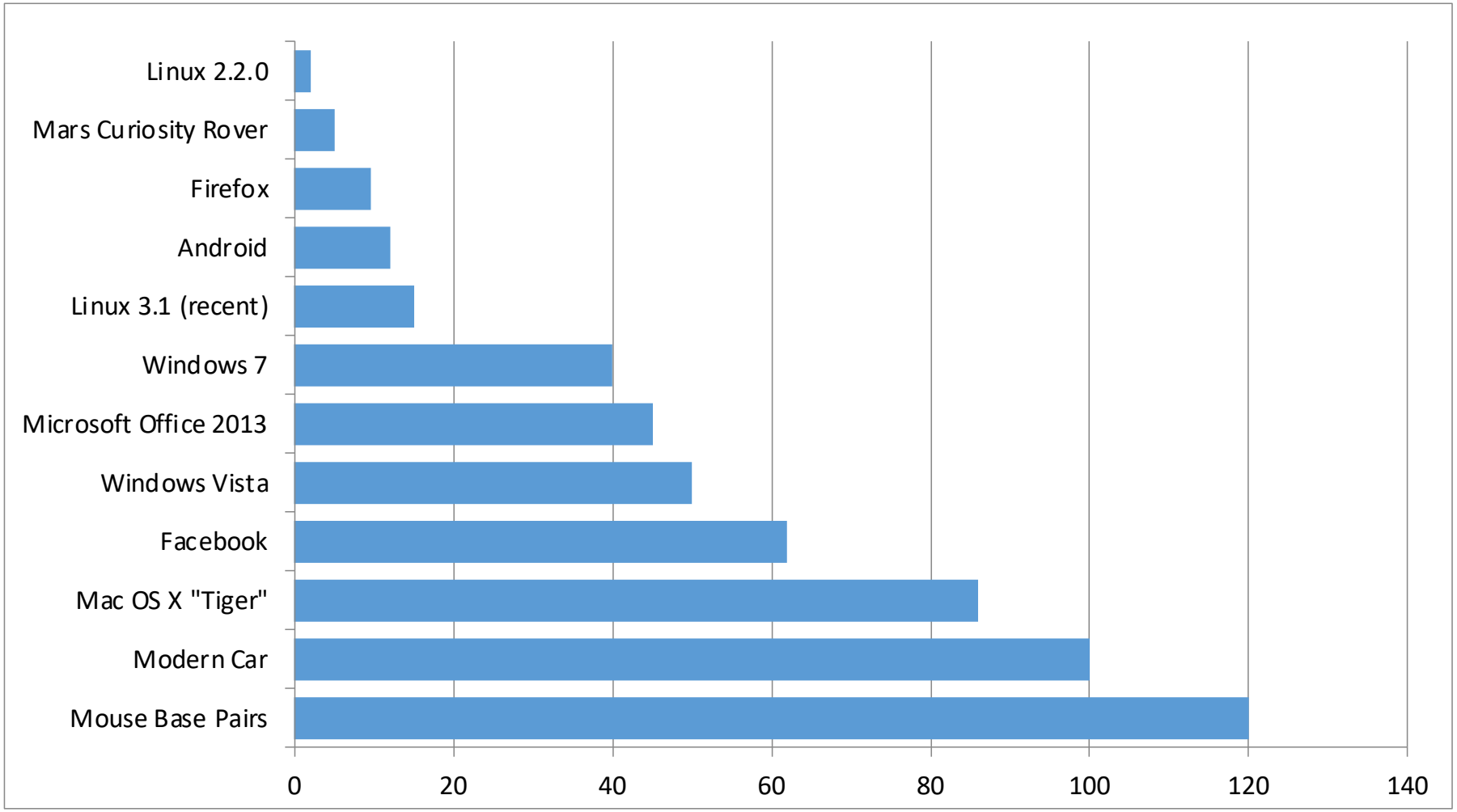
"Compute trends across three eras of machine learning", J. Sevilla, https://ar5iv.labs.arxiv.org/html/2202.05924

From Servers to Pods

From servers to Pods (hundreds of thousands of GPUs tightly connected by high-speed networks, i.e., supercomputers)



Increasing Software Complexity



Millions of Lines of Code

(source https://informationisbeautiful.net/visualizations/million-lines-of-code/)

How do we tame complexity?

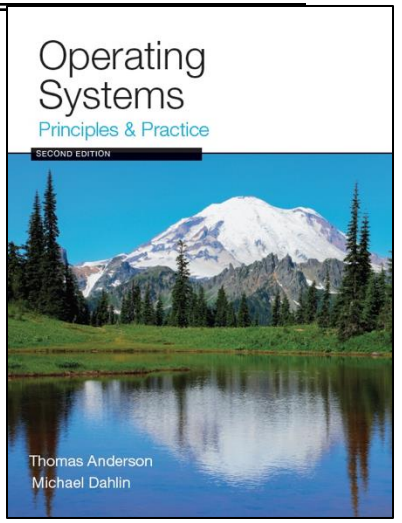
- Every piece of computer hardware different
  - Different CPU
    - » Intel, ARM, AMD, RISC-V
  - Different specialized hardware
    - » Nvidia GPUs, TPUs, Intel Gaudi, AWS Trainium/Inferentia, …
  - Different amounts of memory, disk, …
  - Different types of devices
    - » Mice, Keyboards, Sensors, Cameras, Fingerprint readers, Face recognition
  - Different networking environment
    - » Fiber, Cable, DSL, Wireless, Firewalls,…
- Questions:
  - Does the programmer need to write a single program that performs many independent activities?
  - Does every program have to be altered for every piece of hardware?
  - Does a faulty program crash everything?
  - Does every program have access to all hardware?

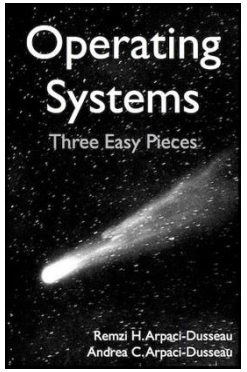
Syllabus

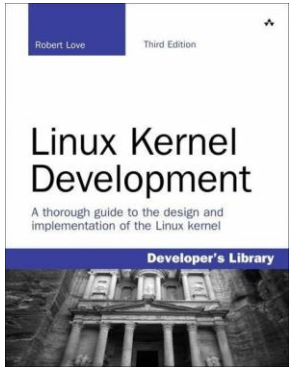
- OS Concepts: How to Navigate as a Systems Programmer!
  - Process, I/O, Networks and Virtual Machines
- Concurrency
  - Threads, scheduling, locks, deadlock, scalability, fairness
- Address Space
  - Virtual memory, address translation, protection, sharing
- File Systems
  - I/O devices, file objects, storage, naming, caching, performance, paging, transactions, databases
- Distributed Systems
  - Protocols, N-Tiers, RPC, NFS, DHTs, Consistency, Scalability, multicast
- Reliability & Security
  - Fault tolerance, protection, security
- Cloud Infrastructure

Infrastructure, Textbook & Readings

- Infrastructure
  - Website: **https://cs162.org**
- Textbook: Operating Systems: Principles and Practice (2nd Edition) Anderson and Dahlin
  - Suggested readings posted along with lectures
  - Try to keep up with material in book as well as lectures
- Supplementary Material
  - Operating Systems: Three Easy Pieces, by Remzi and Andrea Arpaci-Dusseau, available for free online
  - Linux Kernel Development, 3rd edition, by Robert Love
- Online supplements
  - See course website
  - Includes Appendices, sample problems, etc.
  - Networking, Databases, Software Eng, Security
  - Some Research Papers!







Learning by Doing

- Individual Homeworks (2-3 weeks) - preliminary
  - 0. Tools & Environment, Autograding, recall C, executable
  - 1. Lists in C
  - 2. BYOS – build your own shell
  - 3. Sockets & Threads in HTTP server
  - 4. Memory mapping and management
  - 5. Map Reduce
- Three (and ½) Group Projects
  - 0. Getting Started (Individual, before you have a group)
  - 1. User-programs (exec & syscall)
  - 2. Threads & Scheduling
  - 3. File Systems

Group Projects

- Project teams have 4 members!
  - never 5, 3 requires serious justification
  - Must work in groups in "the real world"
  - Same section (at least same TA)
- Communication and cooperation will be essential
  - Regular in-person meetings very important!
  - Joint work on Design Documents
  - Slack/Messenger/whatever doesn't replace face-to-face!
- Everyone should do work and have clear responsibilities
  - You will evaluate your teammates at the end of each project
  - Dividing up by Task is the worst approach. Work as a team.
- Communicate with supervisor (TAs)
  - What is the team's plan?
  - What is each member's responsibility?
  - Short progress reports are required
  - Design Documents: High-level description for a manager!

Getting started

- EVERYONE (even if you are on the waitlist!):
  Start homework 0 right away (hopefully Today!), project 0 next week
  - Github account
  - VM environment for the course
    - » Consistent, managed environment on your machine
  - Get familiar with all the cs162 tools
  - Submit to autograder via git
- First two weeks, attend any section you want
  - We'll assign permanent sections after forming project groups
  - Section attendance will be mandatory after we form groups
  - These section times will be adjusted after we have a better idea where people are

Preparing Yourself for this Class

- The projects will require you to be very comfortable with programming and debugging C
  - Pointers (including function pointers, void*)
  - Memory Management (malloc, free, stack vs heap)
  - Debugging with GDB
- You will be working on a larger, more sophisticated code base than anything you've likely seen in 61C!
- Review Session on the C language
  - Time and logistics TBA, but soon!
- "Resources" page on course website
  - Ebooks on “git” and “C”
- C programming reference
  - https://cs162.org/ladder/
- First two sections are also dedicated to programming and debugging review:
  - Attend ANY sections in first two weeks

Grading (Tentative breakdown)

- 36% three midterms (12% each)
  - Thursday, 10/3 (7-9pm or 8-10pm), No class on day of Midterm
  - Tuesday, 11/05 (7-9pm or 8-10pm), No class on day of Midterm
  - Thursday, 12/05 (7-9pm or 8-10pm), No class on day of Midterm
  - These will be IN-PERSON!
- 36% projects
- 18% homework
- 10% participation (Sections, Lecture, …)
- *No final exam*
- Projects
  - Initial design document, Design review, Code, Final design
  - Submission via *git push* triggers autograder

CS 162 Collaboration Policy

Explaining a concept to someone in another group

Discussing algorithms/testing strategies with other groups

Discussing debugging approaches with other groups

Searching online for generic algorithms (e.g., hash table)

Sharing code or test cases with another group

Copying OR reading another group's code or test cases

Copying OR reading online code or test cases from prior years

Helping someone in another group to debug their code

- We compare all project submissions against prior year submissions and online solutions and will take actions (described on the course overview page) against offenders
- Don't put a friend in a bad position by asking for help that they shouldn't give!

Lecture Goal

Interactive!!!

Ask Questions in Chat