

ECE 350

Real-time

Operating

Systems



Lecture I: Introduction

Prof. Seyed Majid Zahedi

<https://ece.uwaterloo.ca/~smzahedi>

Outline

- How do things work in ECE 350?
- What is a real-time system?
- What is an operating system?
- What makes operating systems so exciting?

Useful Links

- Course webpage

<https://ece.uwaterloo.ca/~smzahedi/crs/ece350>

- Course on Piazza

<https://piazza.com/uwaterloo.ca/winter2022/ece350>

- Anonymous feedback form

<https://forms.gle/c5kK1twHfRejuwMv9>

Class is Entirely Online!

- Lectures will be delivered on Teams
 - Links are provided on course webpage
 - Recordings will be available afterwards
- Office hours will be on Teams
 - Links are provided on course webpage
 - There will be no recordings
 - No office hours during week 1 and reading week
- Lab tutorials will be delivered on Teams
 - Links are provided on course webpage



Who Are We?



Instructor: Prof. Seyed Majid Zahedi
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ECE 350 GTAs



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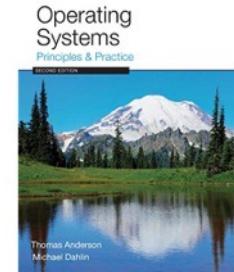
Maizi Liao
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Readings

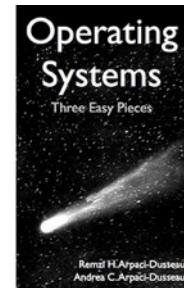
- Main textbook

[Operating Systems: Principles and Practice \(2nd Edition\)](#)

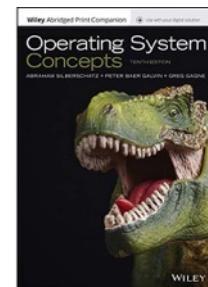


- Optional references

[Operating Systems: Three Easy Pieces \(Freely Available\)](#)



[Operating System Concepts \(10th Edition\)](#)



Prerequisite: ECE 252

- It is assumed that you know
 - File system API
 - File operations, directory structure
 - Processes and threads
 - PCB, TCB, process/thread life cycle, fork and exec, signals
 - Inter-process communication
 - File sharing, memory sharing, message passing, pipes
 - Networking
 - Sockets, ports, client and server programs
 - Concurrency
 - Mutual exclusion, mutex, semaphores, locks, condition variables, monitors
 - Deadlock
 - Avoidance, detection, recovery, Banker's algorithm

ECE 350 is a Class About...

- Design of key systems abstractions that have emerged over time
 - Processes, threads, events, address spaces, file systems, sockets, transactions, key-value stores, etc.
- Tradeoffs surrounding these designs
- Their efficient implementation
 - Including hardware support that makes them possible and practical
- And how to use them effectively

Why Take ECE 350? Why Learn About OS?

- Some of you will design and build parts of (real-time) operating systems
- Many of you will create systems that use OS concepts
 - Whether you build hardware or software
 - Concepts and design patterns appear at many levels
- All of you will write programs that use OS abstractions
 - The better you understand them, the better you use them

PAY ATTENTION!

**THIS IS THE IMPORTANT STUFF.
SERIOUSLY GUYS.**

Evaluation

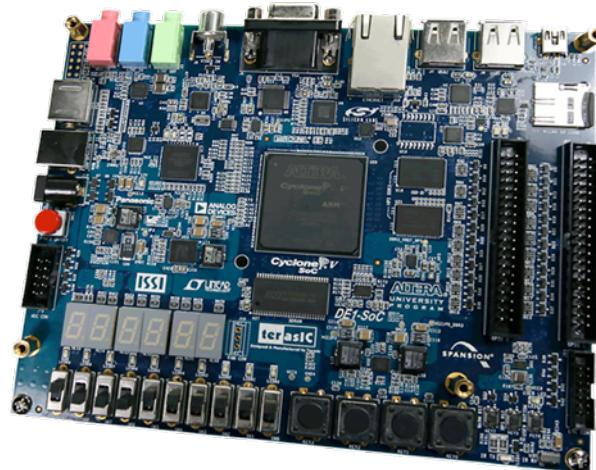
- In-person final: 30%
- Lab projects: 50%
 - 3 projects (more on this later)
- Quizzes: 20%
 - 9 quizzes (highest 7 will be considered)
 - All online on LEARN
 - Quizzes are open book
 - You may consult your textbook, course notes, and materials posted on course webpage
 - Use of any other resource (including online services such as stackexchange.com) is prohibited
 - You may not communicate directly or indirectly with any person except course instructors (you can email course instructors if you have any questions or need any clarification)
 - You may not discuss nor disclose quiz questions with anyone

Contingency Proviso

- Course outline presents intended weights, and due dates
- As best as possible, we will keep to the outline
- We reserve the right to modify topics and/or assessments and/or weight and/or deadlines with due and fair notice
- In the event of such challenges, we will work with the Department/Faculty to find reasonable and fair solutions

Lab Project

- You will design, implement, and test
real-time executive (RTX) on DE1-SoC boards



Groups

- Groups should have 4 members
 - Never 5! 3 requires serious justification
 - Sign up on LEARN by 23:00 on Jan. 11th EST
- Only one split-up is allowed
 - One-week notice in writing before nearest deadline
 - All students involved lose their group sign-up points

Milestones

Project	Weight	Due Date
Group sing-up	3%	23:00 Jan 11
Memory management (P1)	27%	23:00 Feb 1
Task management (P2)	35%	23:00 Mar 8
Inter-task communication and I/O (P3)	35%	23:00 Mar 29

All times are Eastern Standard Time

Start Early!

- Time/work estimation is hard
 - Programmers are eternal optimists (it will only take two days)!
 - This is why we bug you about starting the project early
- Can a project be efficiently partitioned?
 - Partitionable task decreases in time as you add people
 - But ... what about communication?
 - Time reaches a minimum bound
 - With complex interactions, time increases!



Techniques for Partitioning Tasks

- Functional
 - Person A implements threads, Person B implements semaphores, Person C implements locks...
 - Problem: Lots of communication across APIs
 - If B changes the API, A may need to make changes
- Task
 - Person A designs, Person B writes code, Person C tests
 - May be difficult to find right balance, but can focus on each person's strengths (Theory vs systems hacker)
 - Since debugging is hard, Microsoft has two testers for each programmer

Communication

- More people means more communication
 - Changes have to be propagated to more people
 - Think about person writing code for most fundamental component of system: everyone depends on them!
- Miscommunication is common
 - “***Index starts at 0? I thought you said 1!***”
- Who makes decisions?
 - Individual decisions are fast but trouble
 - Group decisions take time
 - Centralized decisions require a big picture view (someone who can be the “system architect”)
- Often designating someone as system architect can be a good thing
 - Better not be clueless
 - Better have good people skills
 - Better let other people do work



Coordination

- Many are in different time zones ⇒ some cannot make all meetings!
 - They miss decisions and associated discussion
 - Why do we limit groups to 4 people?
 - You would never be able to schedule meetings otherwise
 - Why do we require 3 people minimum?
 - You need to experience groups to get ready for real world
- People have **different work styles**
 - Some people work in the morning, some at night
 - How do you decide when to meet or work together?
- What about project slippage?
 - Everyone busy but not talking, one is way behind, but no one will know until very end!
- Hard to add people to existing group
 - Members have already figured out how to work together



How to Make it Work?

- People are human ... get over it!
 - People will make mistakes, miss meetings, miss deadlines, etc.
 - You need to live with it and adapt
 - It is better to anticipate problems than clean up afterwards
- Document, document, document
 - Why Document?
 - Expose decisions and communicate to others
 - Easier to spot mistakes early
 - Easier to estimate progress
 - What to document?
 - Everything (but don't overwhelm people or no one will read)



Suggested Documents for You to Maintain

- Project objectives: goals, constraints, and priorities
- Specifications
 - This should be the first document generated and the last one finished
- Meeting notes
 - Document all decisions
- Schedule
 - This document is critical!
- Organizational chart
 - Who is responsible for what task?



Use Software Tools



- Source revision control software (CVS, SVN, git)
 - Easy to go back and see history
 - Figure out where and why bugs got introduced
 - Communicates changes to everyone
(use RCS's features)
- Use automated testing tools
 - Write scripts for non-interactive software
- Use E-mail and instant messaging consistently to leave history trail

Test Continuously



- Integration tests all the time, not at 8pm on due date!
 - Write dummy stubs with simple functionality
 - Schedule periodic integration tests
 - Get everyone code, build, and test ... don't wait until it is too late!
- Testing types
 - Unit tests: white-/black-box check each module in isolation
 - Daemons: subject code to exceptional cases
 - Random testing: subject code to random timing changes
- Test early, test later, test again
 - What if something changes in some other part of code?

Late Submissions

- 3 grace days (including weekends) without penalty
- 15% per day late submission penalty afterwards
 - 1-hour-late submission = 15-hour-late submission
- Late submissions are not accepted after three days

Collaboration Policy

- Explaining concepts to someone in another group
 - Discussing algorithms/testing strategies with other groups
 - Helping debug someone else's code (in another group)
 - Searching online for generic algorithms (e.g., hash table)
-
- Sharing code or test cases with another group
 - Open-sourcing code (e.g., on GitHub) even after this term
 - Copying OR reading another group's code or test cases
 - Copying OR reading online code or test cases from prior years
-
- Zero tolerance policy for plagiarism
 - We use [Moss](#) and follow [UW Policy 71](#) for any single incident



Seeking Help

- Lab Q&A on Piazza discussion forum
 - Looking for group partners
 - Lab/Project administration
 - ARM DS Q&A
 - Project Q&A
 - Target response time: one business day
 - **Do not wait till the last minute to ask questions**
- Individual emails
 - Only for questions containing confidential information
- Office hours
- Appointment

Important Near-term Task

Sign up for project groups on LEARN by
23:00 on January 11th, 2022 EST

WORK HARD



RELAX HARDER

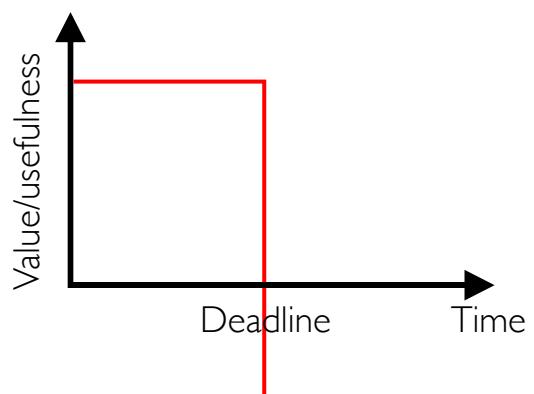
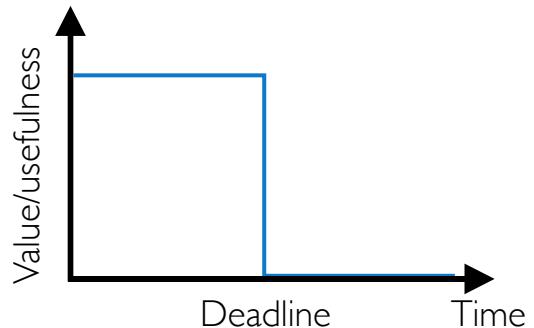
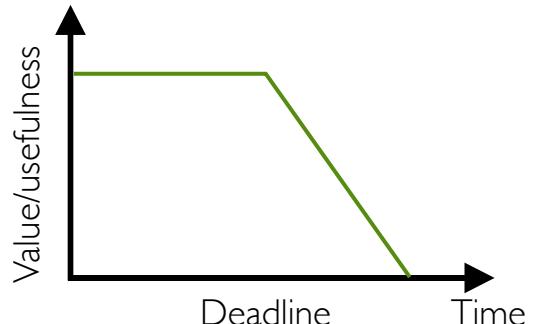
makeameme.org

What is a Real-time System?

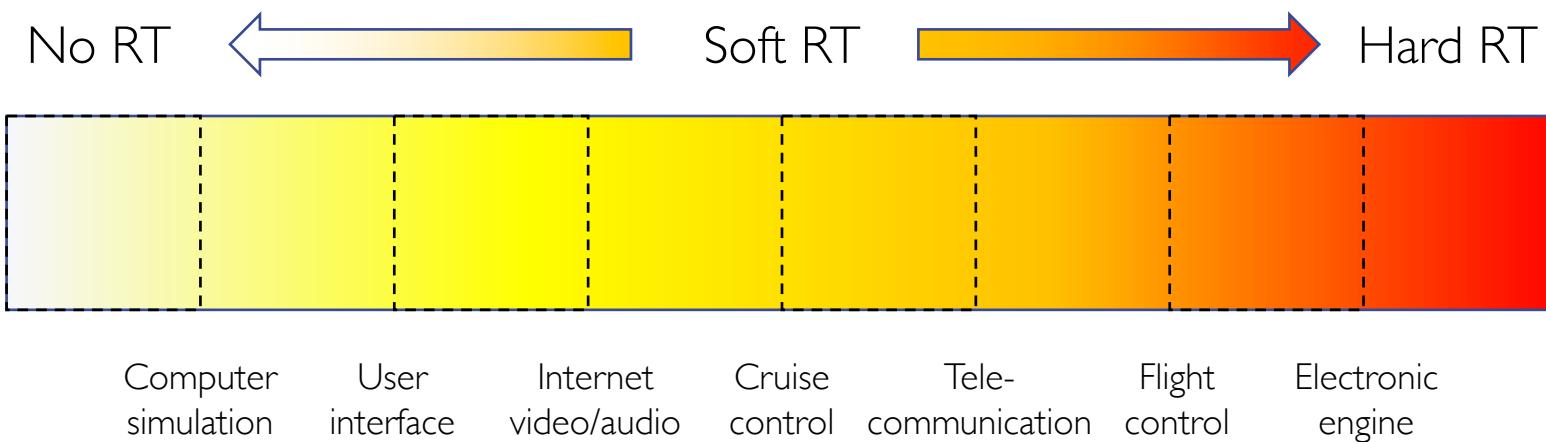
- Systems whose correctness depends on both their **temporal** aspects as well as their **functional** aspects
- Temporal aspects are typically specified through **deadline**
 - Results must be produced before deadline
 - Correct result produced too late is considered failure
- Real-time systems are typically embedded control systems
 - E.g., safety-critical systems
- OS must be carefully designed to support temporal properties

Types of Real-time Systems

- **Soft**: must try to meet all deadlines
 - System does not fail if a few deadlines are missed
- **Firm**: result has no use outside deadline window
 - Tasks that fail are discarded
- **Hard**: must always meet all deadlines
 - System fails if deadline window is missed



Real-time Spectrum

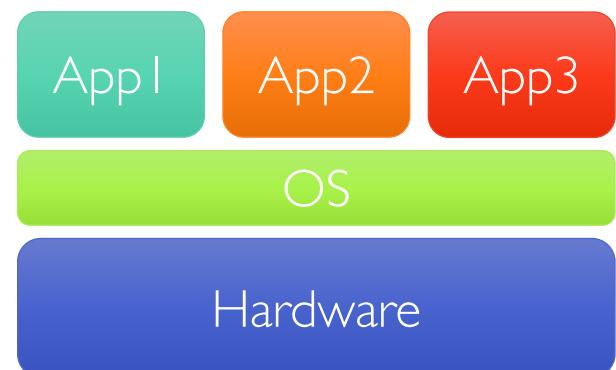


What is an Operating System?

- No universally accepted definition
- “Everything vendors ship when you order OS” is good approximation, but varies wildly
- “The one program running at all times on computer” is kernel
 - Everything else is either system program (ships with OS) or application program

What is an Operating System? (cont.)

- Special layer of software that provides applications access to hardware resources
 - **Abstract** view of complex hardware devices
 - **Protected** access to shared resources
 - Security and authentication
 - Communication amongst logical entities

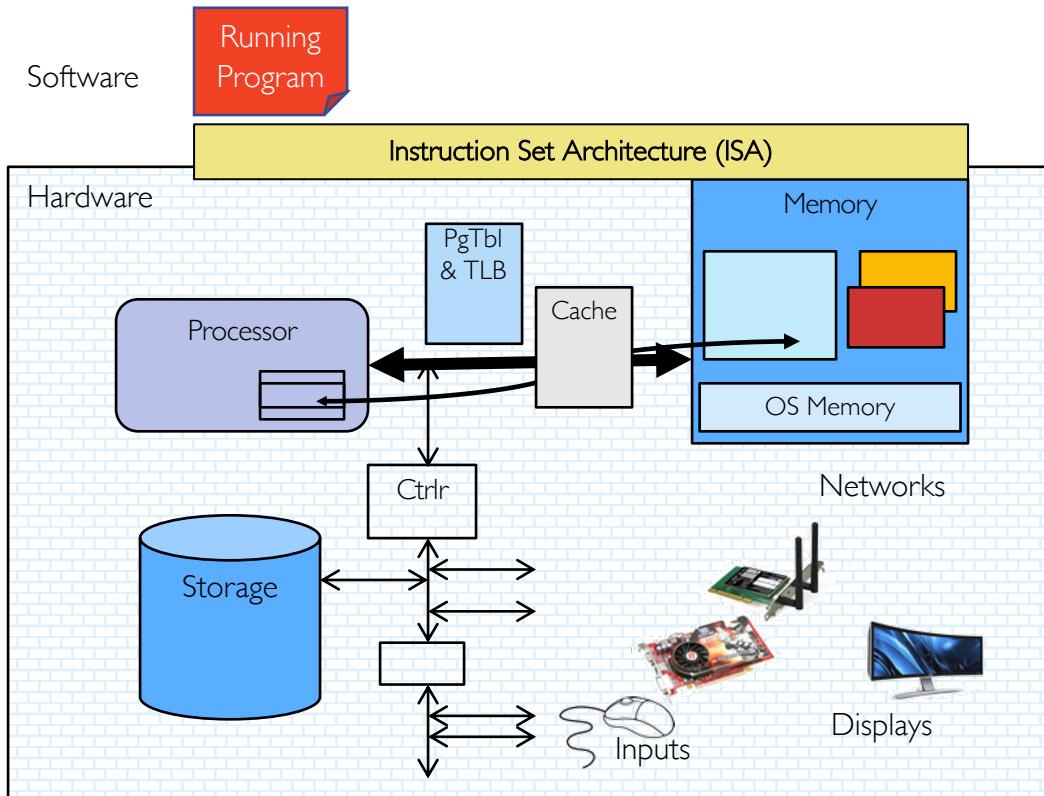


What is an Operating System? (cont.)

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

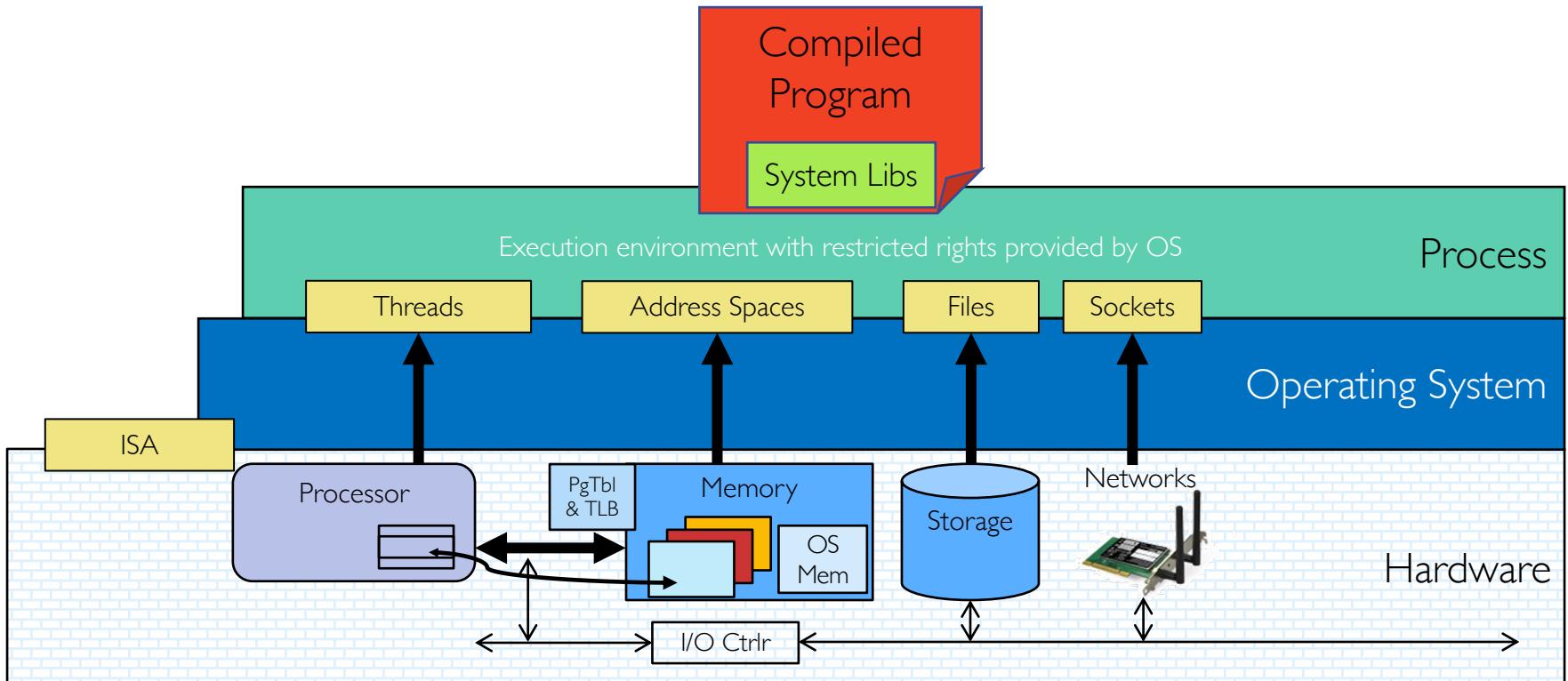


Hardware/Software Interface



- ECE 222 and ECE 320: Machine structures (and C)
- OS *abstracts* these hardware details from the application

OS Basics: Virtualizing Hardware

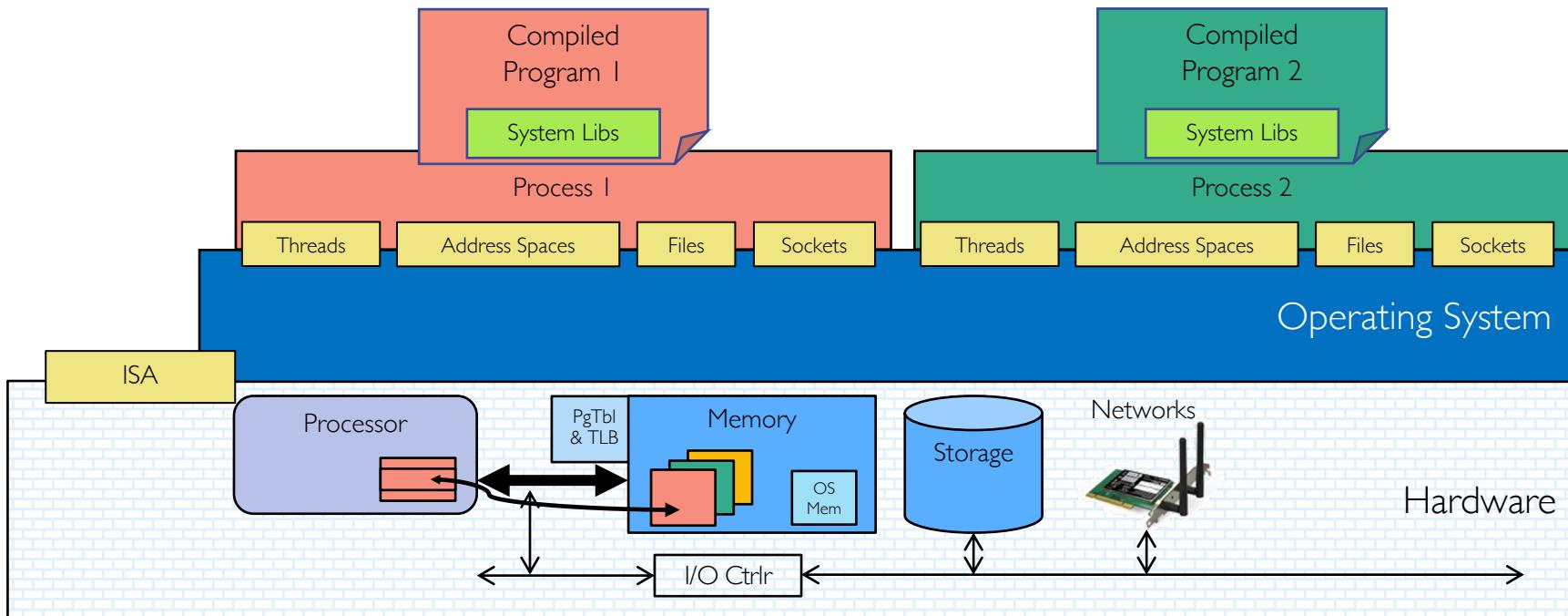


What is an Operating System? (cont.)

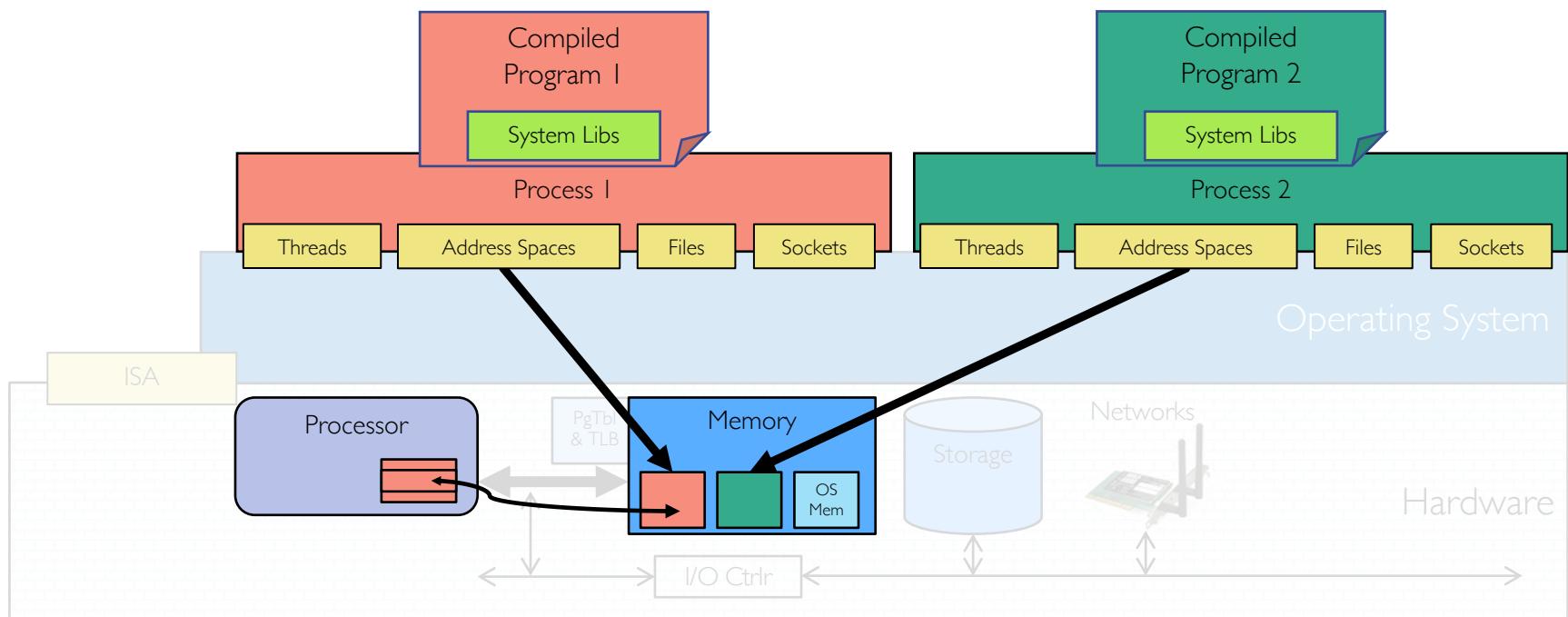
- Illusionist
 - Provide clean, easy-to-use abstractions of physical resources
 - Infinite memory, dedicated machine
 - Higher level objects: files, users, messages
 - Masking limitations, virtualization
- Referee
 - Provide protection, isolation, and sharing of resources
 - Resource allocation and communication



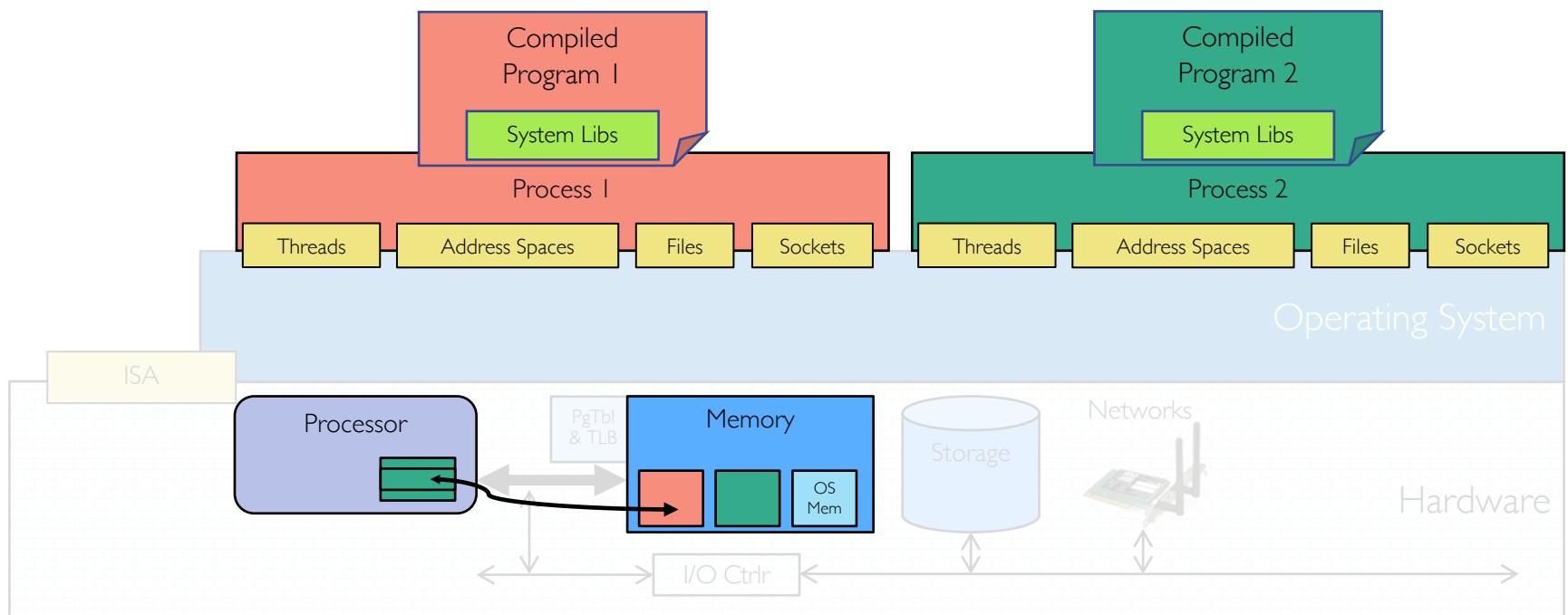
OS Basics: Switching Processes



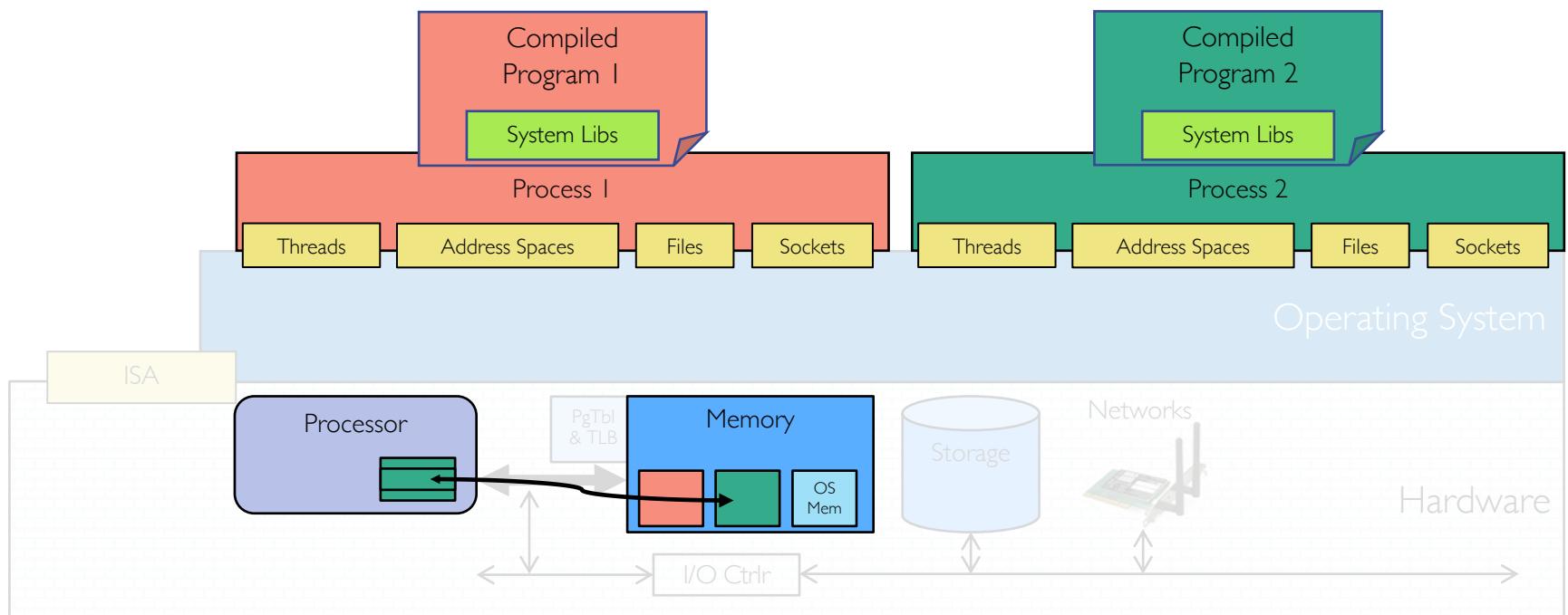
OS Basics: Switching Processes



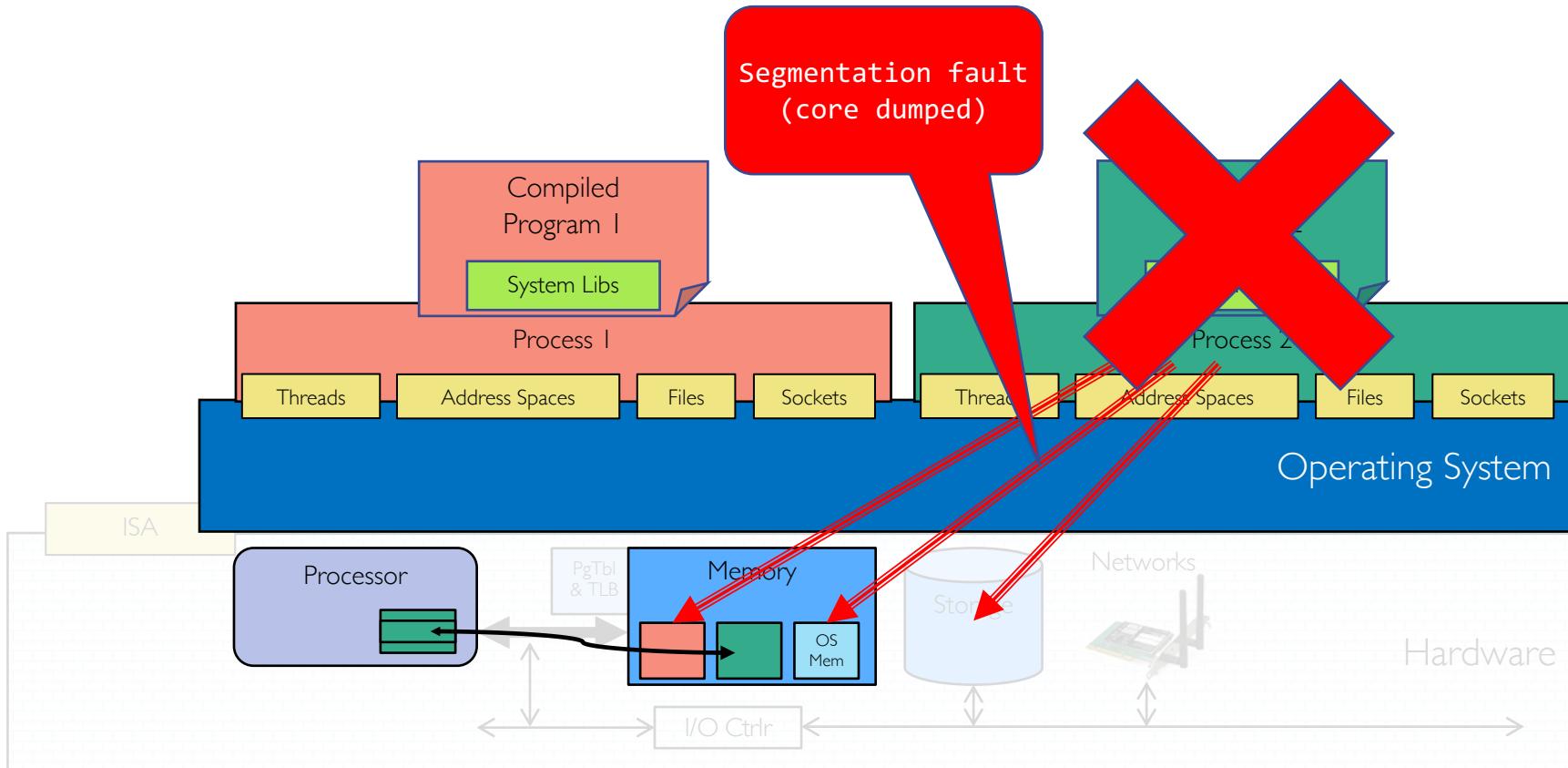
OS Basics: Switching Processes (cont.)



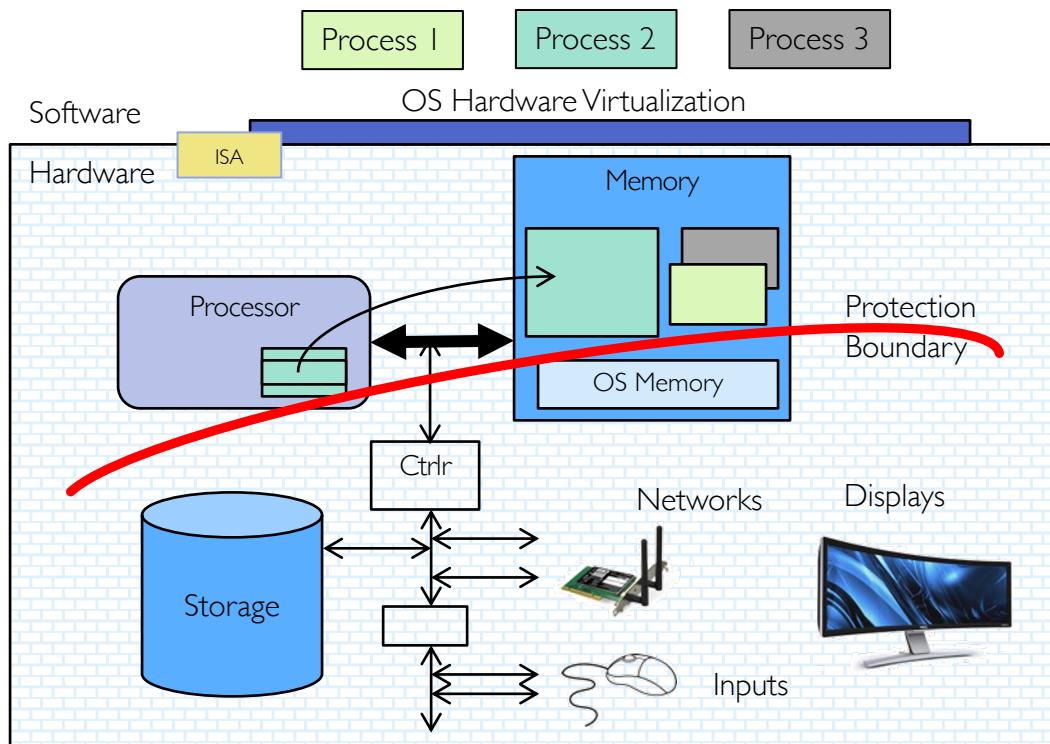
OS Basics: Switching Processes (cont.)



OS Basics: Protection



OS Basics: Protection (cont.)



- OS isolates processes from each other
- OS isolates itself from other processes
- ... even though they run on the same HW!

What is an Operating System? (cont.)

- Illusionist



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

- Referee



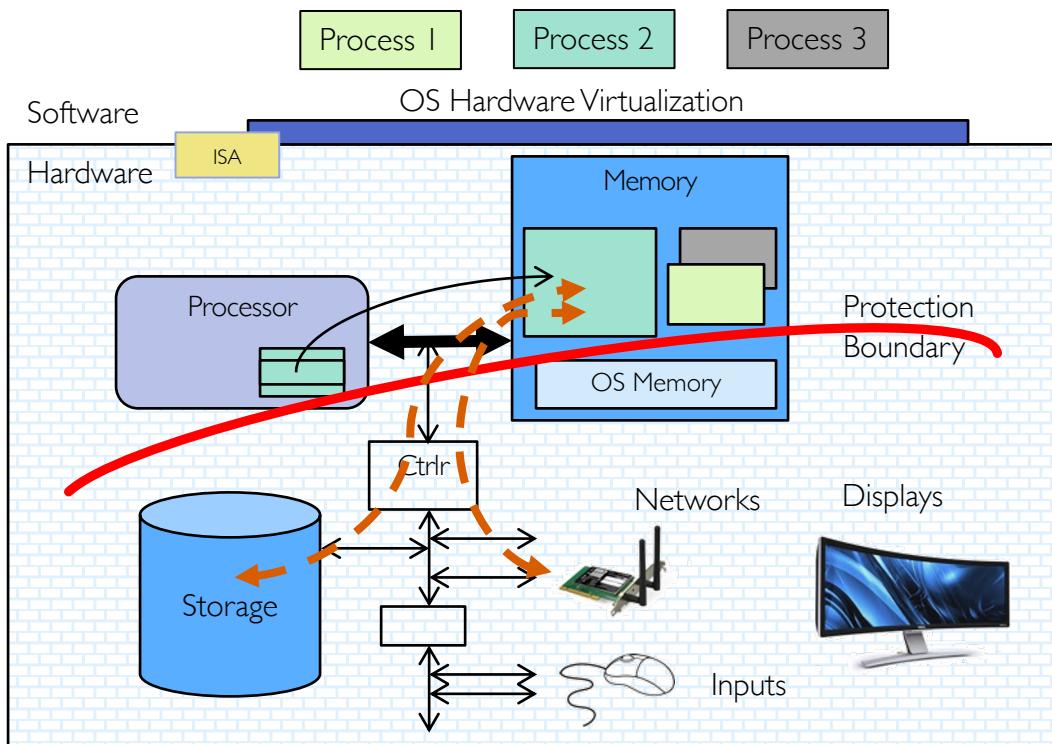
- Provide protection, isolation, and sharing of resources
 - Resource allocation and communication

- Glue



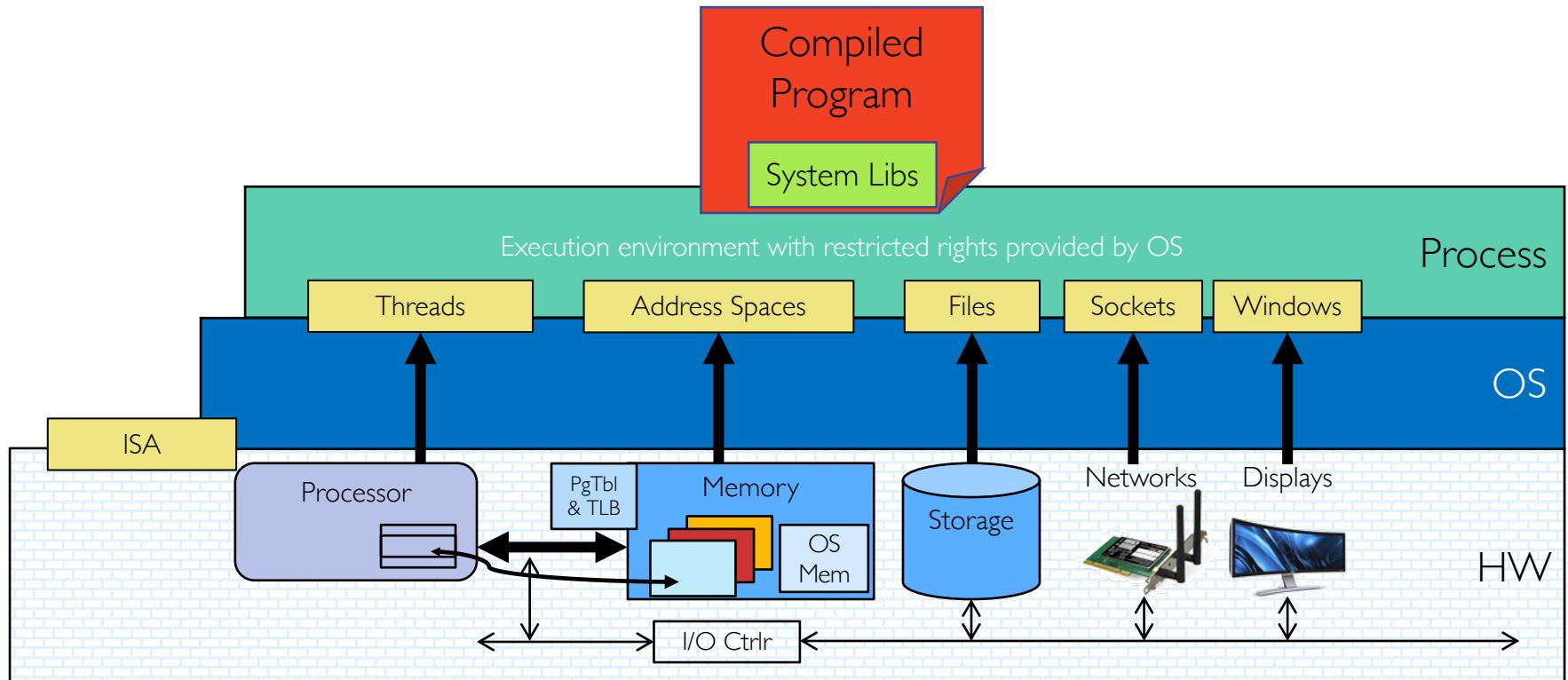
- Provide common services
 - Storage, window system, networking, sharing, authorization
 - Look and feel

OS Basics: I/O

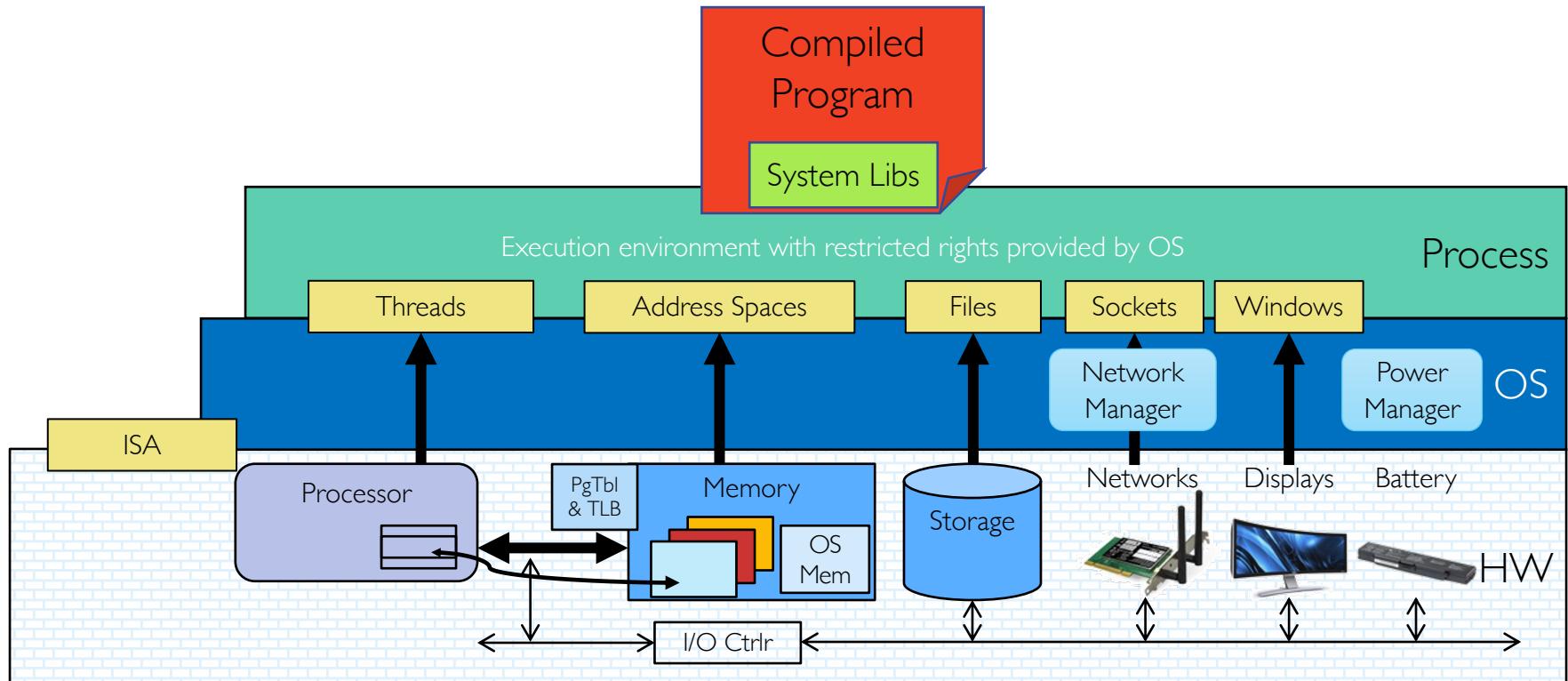


- OS provides common services in the form of I/O

OS Basics: Look and Feel



OS Basics: Background Management

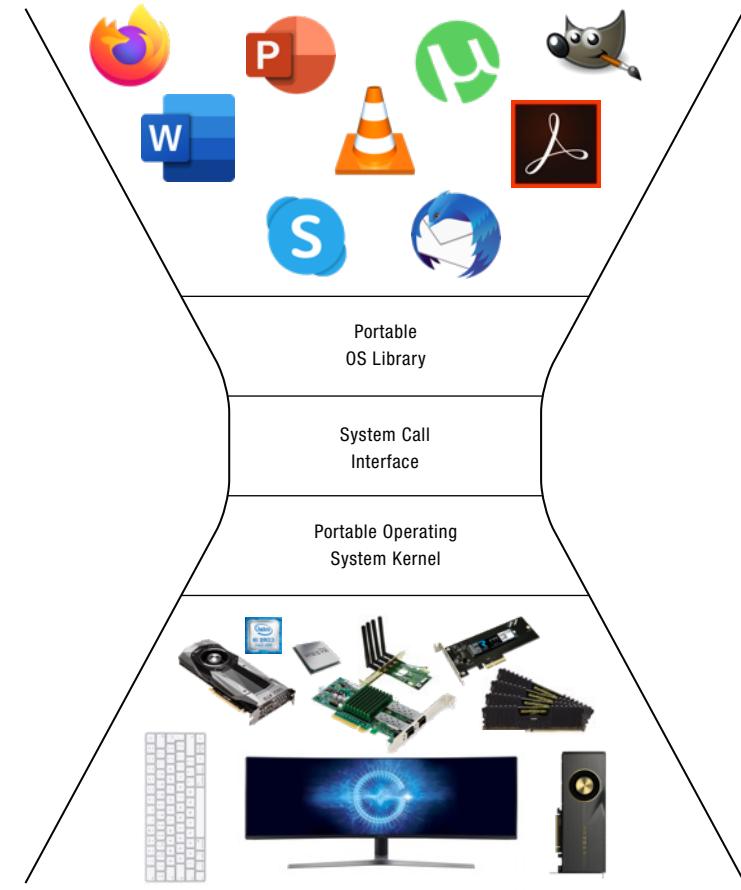


OS Basics: Hardware Support

- OS bottom line is to support applications!
 - OS itself is **incidental**
 - Ideally, OS should have very low performance overhead over raw hardware
- OS relies on HW support to provide abstractions **efficiently**
 - Dual-mode operation, interrupts, traps, precise exceptions, memory management unit, translation lookaside buffer, etc.
- HW support and OS design continue to co-evolve...
 - ... as hardware performance improves (e.g., faster storage/network), ...
 - ... and application requirements change
 - What we study in this class is result of decades of co-evolution!

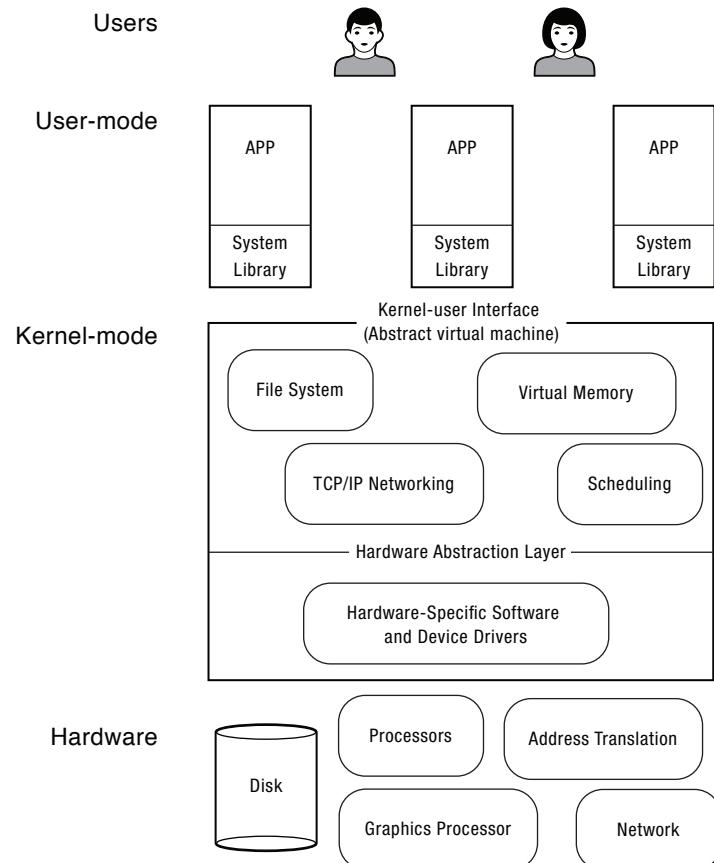
What Do Operating Systems Do?

- Provide abstractions to applications
 - File systems
 - Processes, threads
 - Virtual memory
 - Naming system, ...
- Manage diverse resources
 - Memory, CPU, storage, ...
- Achieves above by implementing specific algorithms and techniques
 - Scheduling
 - Concurrency
 - Transactions
 - Security, ...



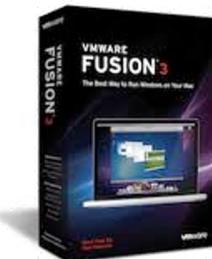
What Do Operating Systems Do? (cont.)

- Manage hardware resources for users and applications
- Convert what hardware gives into something that application programmers want
- For any OS component, begin by asking two questions
 - What is hardware interface? (physical reality)
 - What is application interface? (virtual machine)



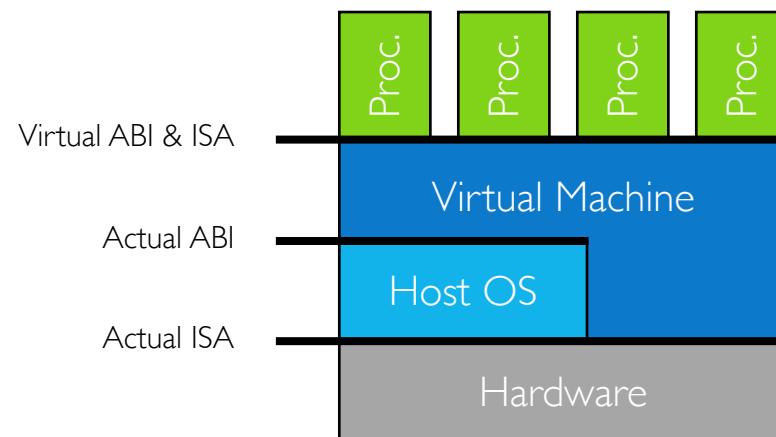
Virtual Machines (VMs)

- Software that emulates physical machine
 - Gives programs **illusion** that they run on physical machine
 - Provides platform that is independent of actual underlying hardware
 - Makes it look like hardware has features programs want
- Two types of virtual machines
 - Process VM: supports execution of single program (e.g., Java)
 - System VM: supports execution of entire OS (e.g., VMWare Fusion, Virtual box, Parallels Desktop, Xen)



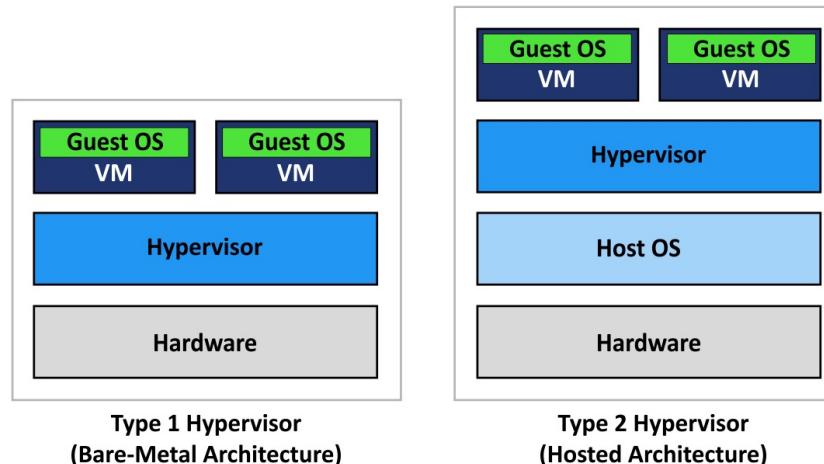
Process VMs

- Runs processes
 - Abstracts underlying OS and hardware
 - Provides platform-independent environment
 - E.g., Java virtual machine, .NET framework



System Virtual Machines: Layers of OSes

- Runs OSes
 - Useful for OS development and testing programs on other OSes
- Hypervisors create and run virtual machines
- **Type-I** hypervisors allocate HW to VMs in addition to managing them
 - E.g., Xen, VMWare ESXi
- **Type-II** hypervisors rely on host OS for HW management
 - E.g., Virtual Box, VMWare Workstation, KVM

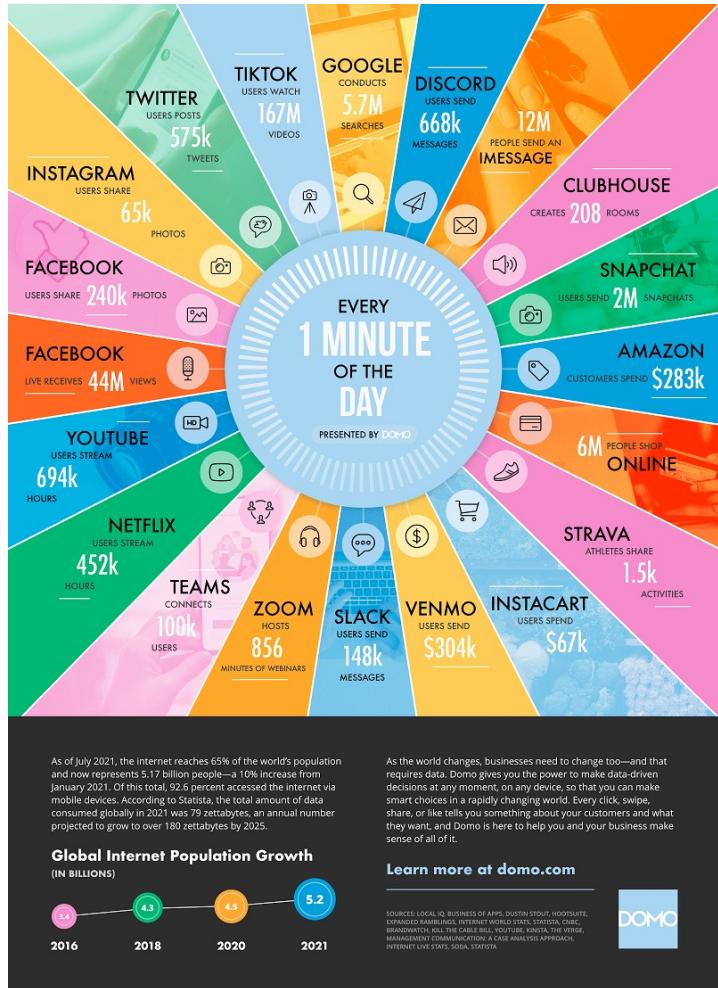


Containers: Low-weight Alternatives to Full-system Virtualization

- Provide OS virtualization above single shared kernel
 - Do not provide *full-machine* virtualization
 - Each VM has illusion of running on isolated machine
 - Each container has illusion of running on isolated OS
- Use OS constructs to provide *sand boxes* for execution
 - E.g., Linux cgroups, namespaces, etc.
- Can run on bare metal OS, or atop of OS running in VM
- **OS containers:** multiple applications run in same container
 - E.g., LXC, OpenVZ, FreeBSD Jail
- **Application containers:** each application has its own container
 - E.g., Docker, rkt



What Makes Operating Systems so Exciting and Challenging?

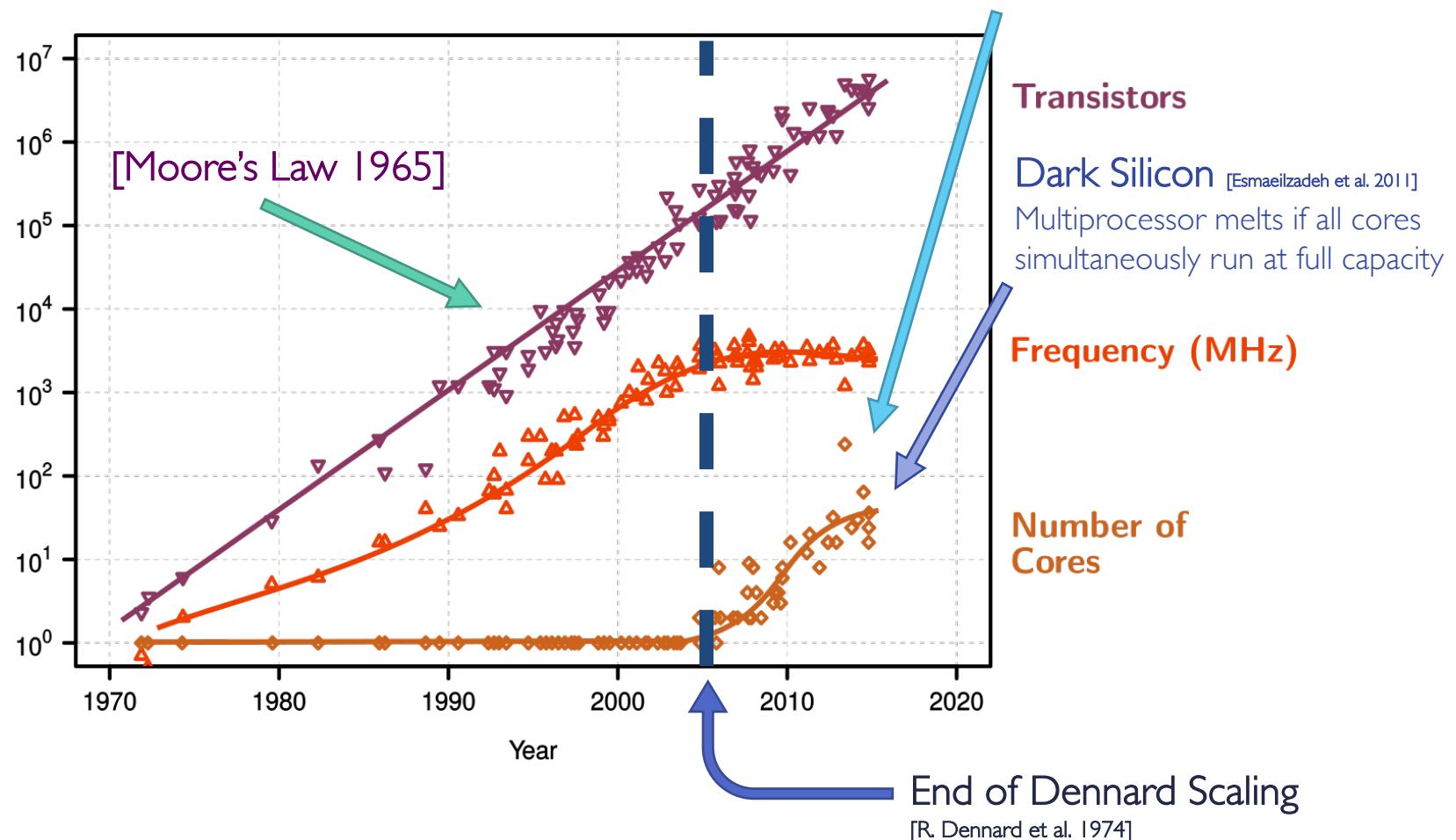


Operating systems are at the heart of it all ...

- Challenges
 - Keeping up with evolving HW
 - Managing ever-growing complexity of SW

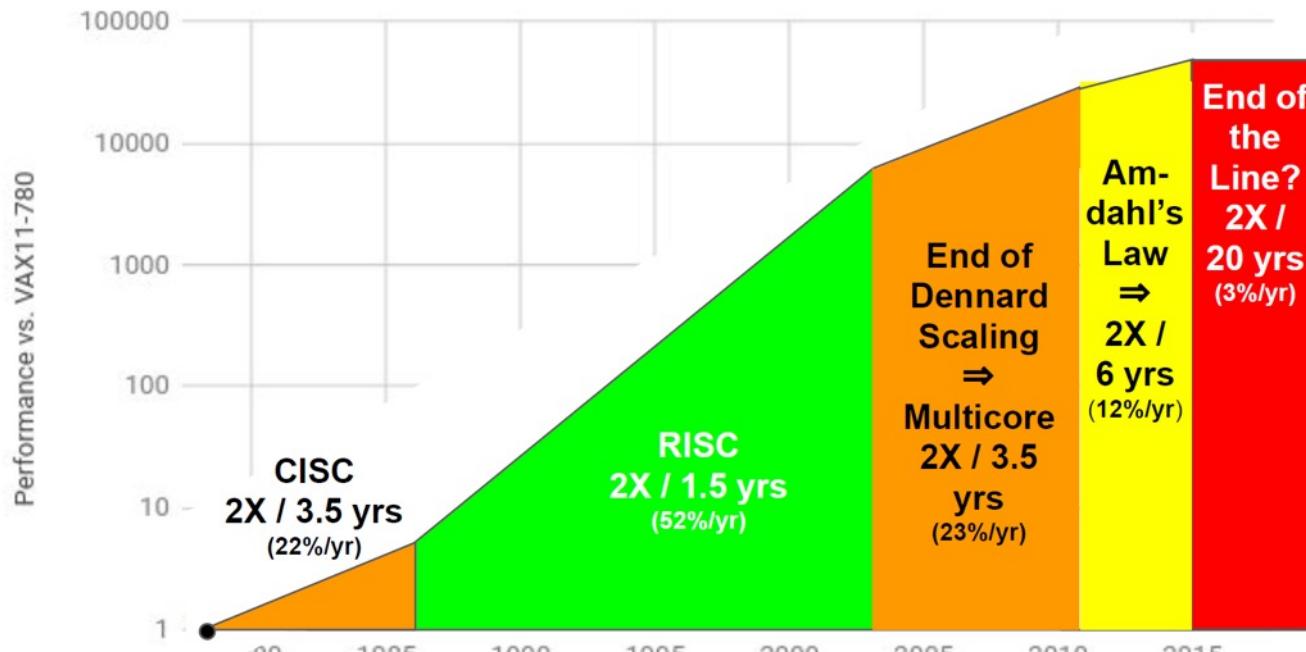
Technology Trends

How do we program these?
Parallelism must be exploited at all levels



End of Growth of Single Program Speed

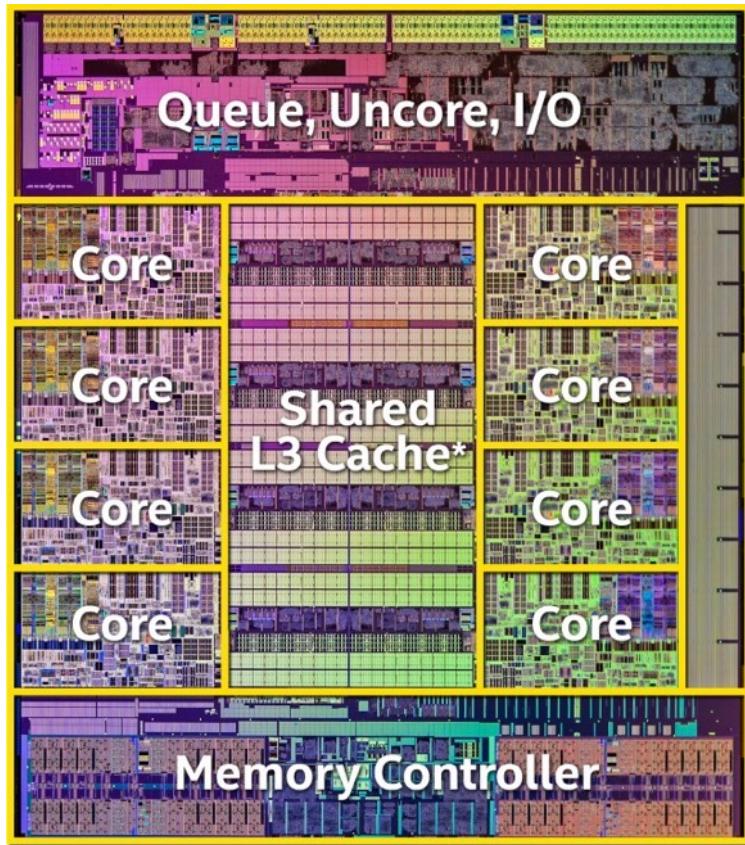
40 years of Processor Performance



Based on SPECintCPU. Source: John Hennessy and David Patterson, Computer Architecture: A Quantitative Approach, 6/e. 2018

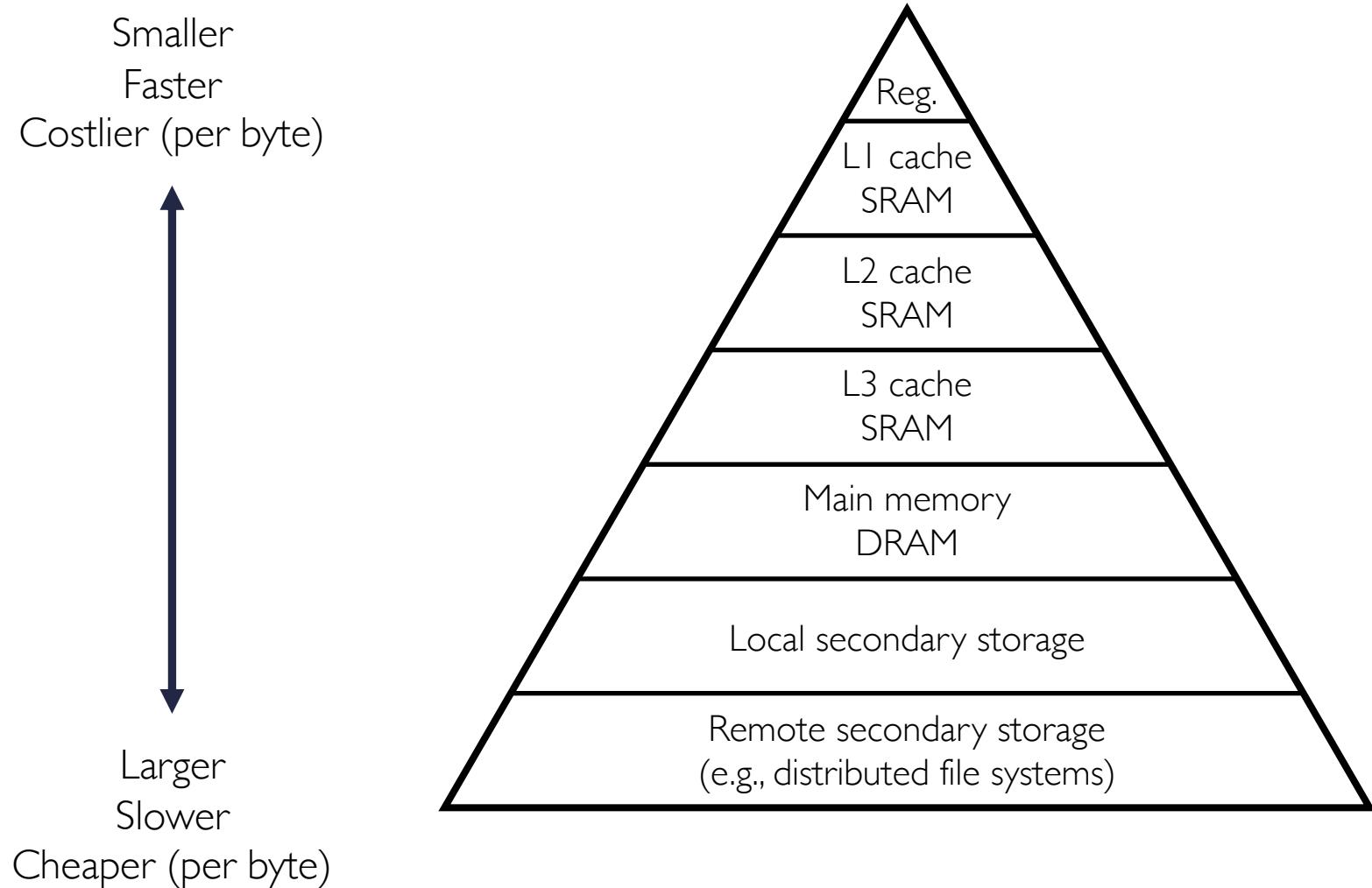
Modern Processors

Intel Haswell E



- Intel Xeon Platinum 9282
 - 14nm processor
 - 56 cores, 112 threads
 - 1.75MB data and ins. L1 cache
 - 56MB L2 cache
 - 77MB shared L3 cache
 - 8B transistors
- AMD EPYC 7H12
 - 7nm processor
 - 64 cores, 128 threads
 - 2MB data and ins. L1 cache
 - 32MB L2 cache
 - 256MB shared L3 cache
 - 4.8B transistors

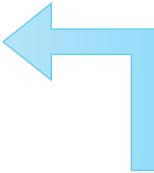
Memory Hierarchy



Numbers Everyone Should Know

[Jeff Dean, 2009]

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



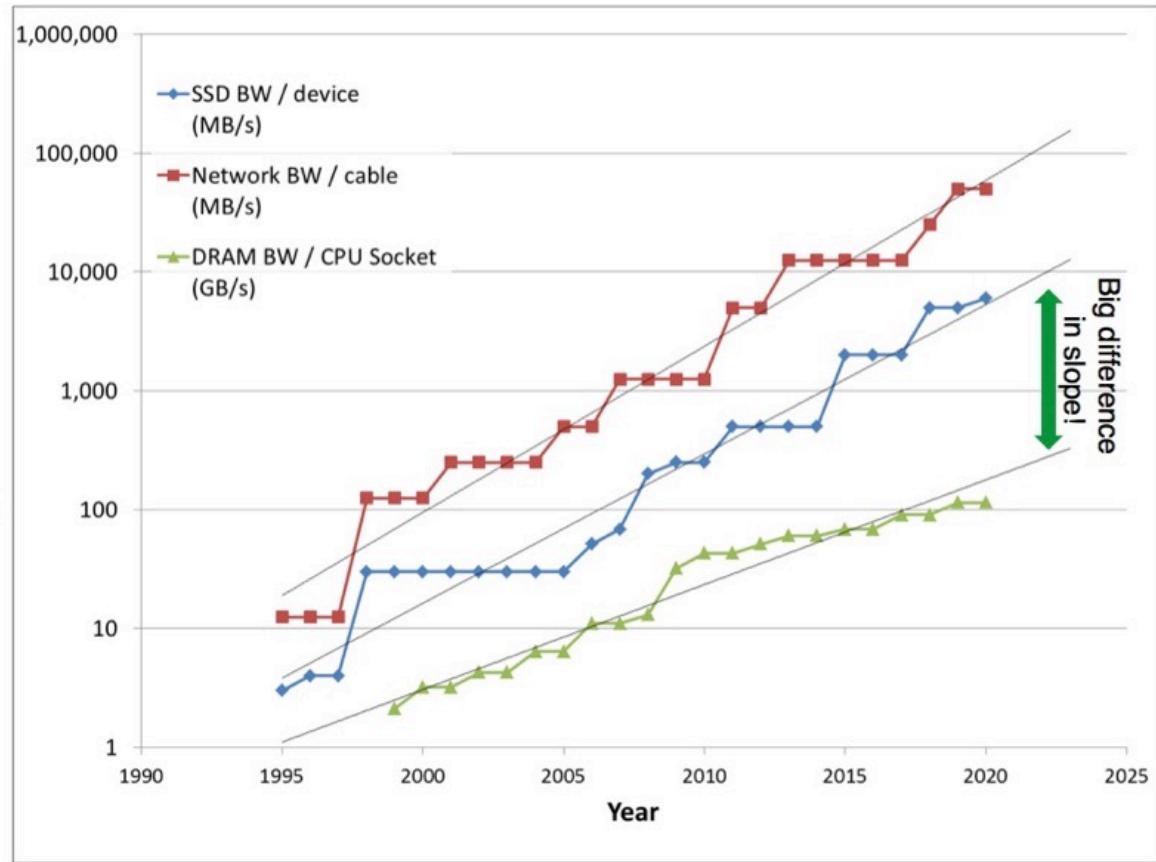
Key stroke ~100 ms

Network, IO, and Memory Bandwidth Trends

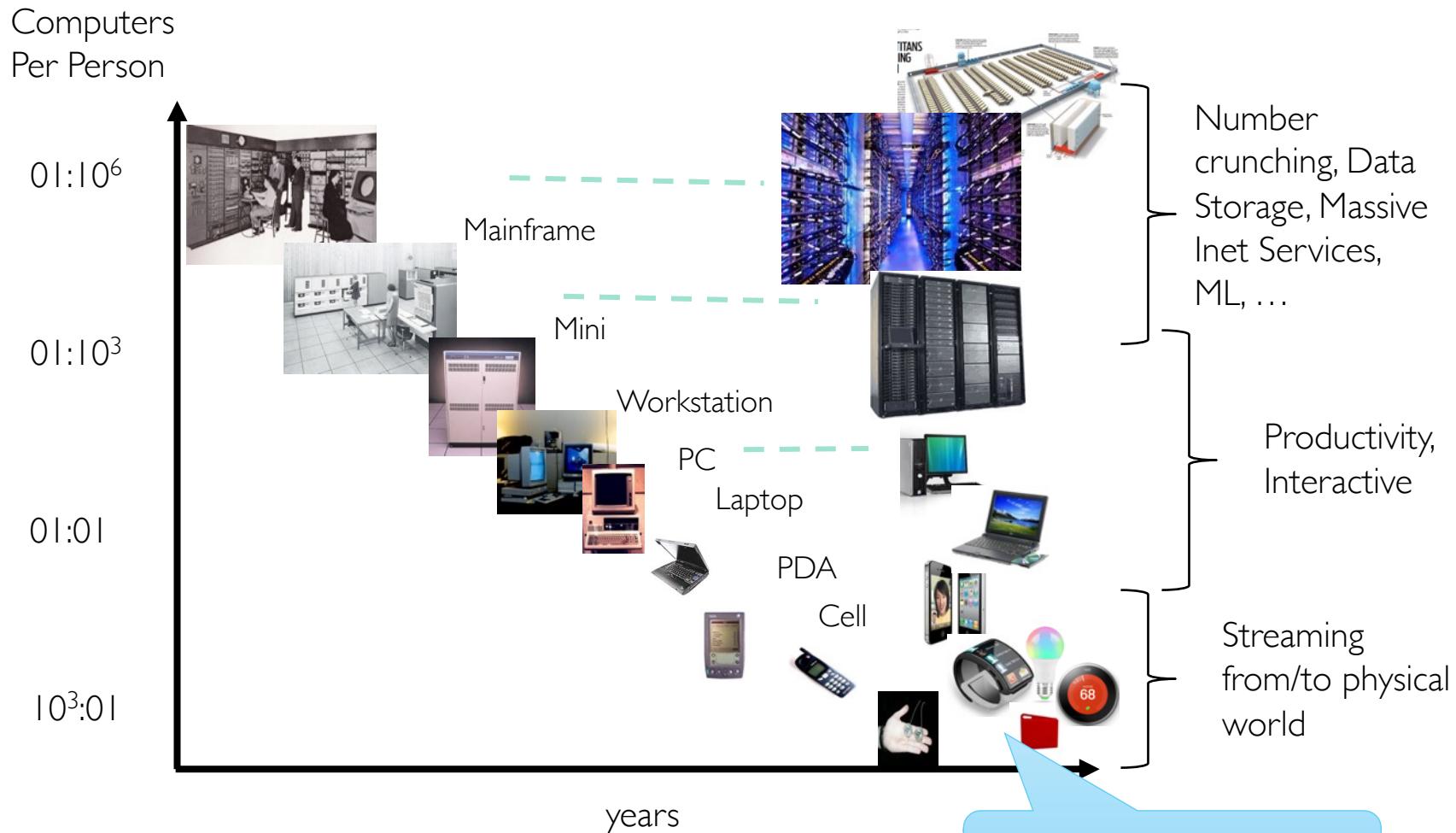
Network, Storage, & DRAM trends

Log scale

- Use DRAM Bandwidth as a proxy for CPU throughput
- Reasonable approximation for DMA and poor cache performance workloads (e.g. Storage)



People to Computer Ratio Trend



Bell's Law: new computer class per 10 years

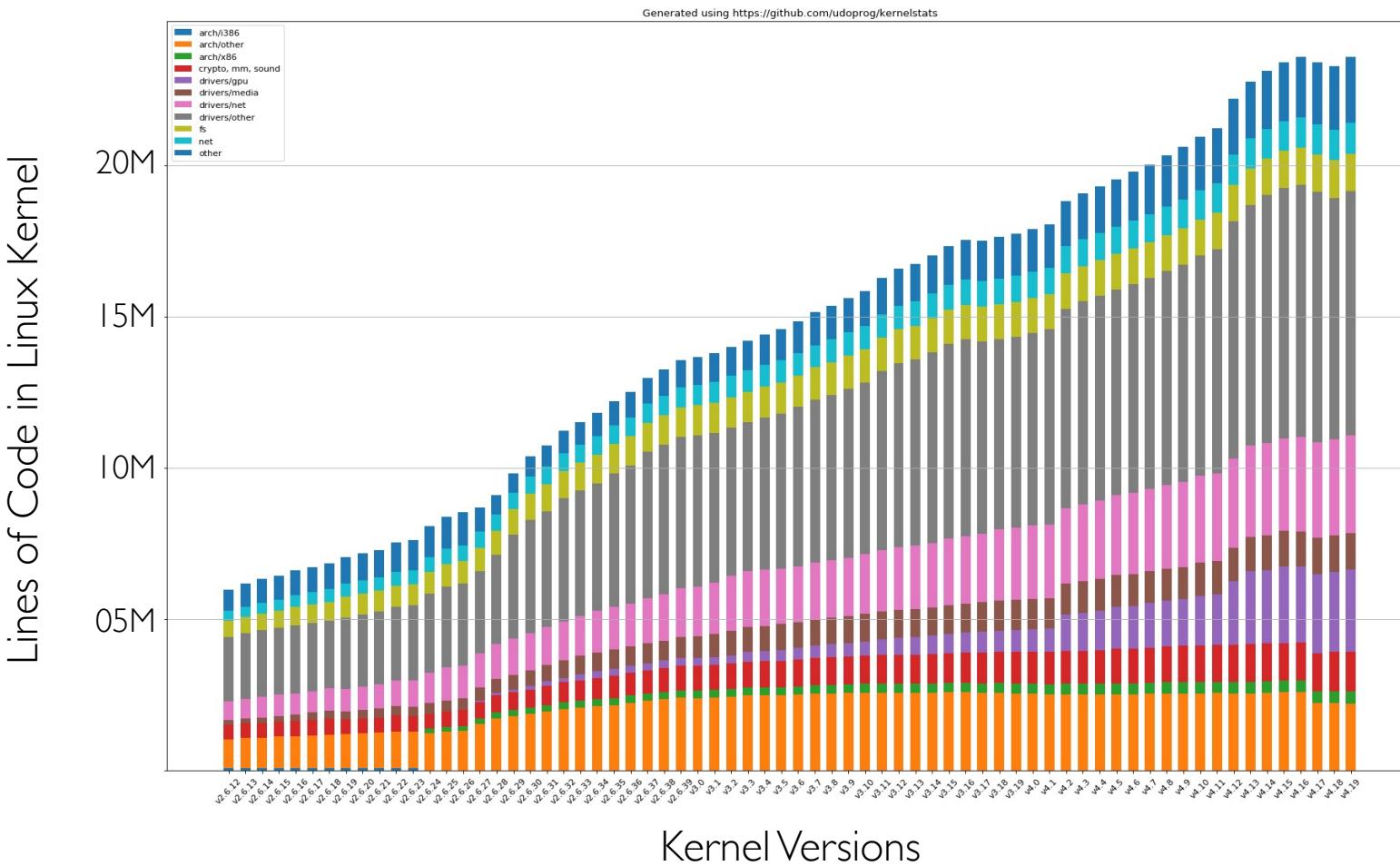
Early vs. Current Operating Systems

- One user/application at any given time
 - Had complete control of hardware
 - OS was runtime library
 - Users would stand in line to use the computer
- *Batch systems*
 - Keep CPU busy by having a queue of jobs
 - OS would load next job while current one runs
 - Users would submit jobs, and wait, and wait, and wait ...
- Multiple users on computer at the same time
 - Multiprogramming: run multiple programs at the same time
 - Interactive performance: try to complete everyone's tasks quickly
 - As computers became cheaper, more important to optimize for user time, not computer time

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
 - Question is not whether there are bugs but how serious are bugs!

Kernel Complexity



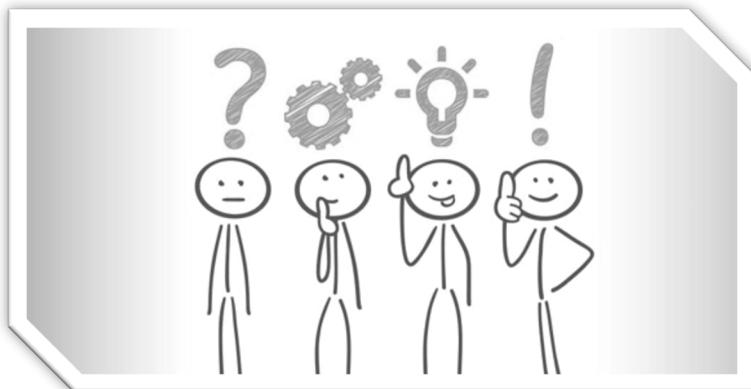
How do We Tame Complexity?

- Every piece of computer hardware different
 - Different CPUs
 - Pentium, ARM, PowerPC, ColdFire
 - Different amounts of memory, disk, ...
 - Different types of devices
 - Mice, keyboards, sensors, cameras, fingerprint readers, touch screen
 - Different networking environment
 - Cable, DSL, Wireless, ...
- Questions
 - Does programmer need to write single program that performs many independent activities?
 - Does every program have to be altered for every piece of hardware?
 - Does one faulty program crash everything?
 - Does every program have access to all hardware?

Summary

- OS provides VM abstraction to handle diverse HW
 - OS simplifies application development by providing standard services
- OS coordinates resources and protect users from each other
 - OS can provide fault containment, fault tolerance, and fault recovery
- ECE 350 combines ideas and concepts from many other areas of computer science and engineering
 - Languages, data structures, hardware, and algorithms

Questions?



Acknowledgment

- Slides by courtesy of Anderson, Culler, Stoica, Silberschatz, Joseph, Canny, and Kumar (Sam)