

# **ECE 350**

## **Real-time**

## **Operating**

## **Systems**



# Lecture I: Introduction

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Prof. Seyed Majid Zahedi

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

# Outline

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- 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

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- 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!

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- 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?

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Instructor: Prof. Seyed Majid Zahedi  
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Lab instructor: Aravind Vellora Vayalapra  
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# ECE 350 GTAs

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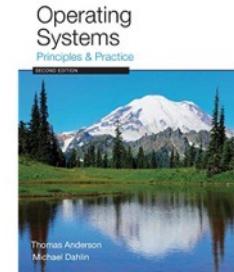


# Readings

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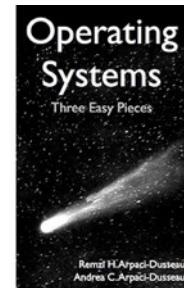
- Main textbook

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

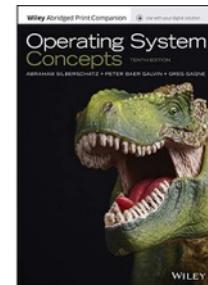


- Optional references

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



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



# Prerequisite: ECE 252

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- 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...

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- 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?

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- 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

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- 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

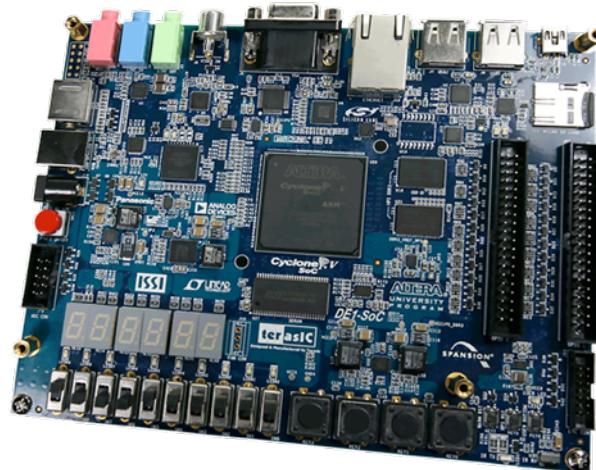
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- Course outline presents intended weights, and due dates
- As best as possible, we will keep to the outline
- We reserve the right to modify topics and/or assessments and/or weight and/or deadlines with due and fair notice
- In the event of such challenges,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

# Lab Project

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



# Groups

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- Groups should have 4 members
  - Never 5! 3 requires serious justification
  - Sign up on LEARN by 23:00 on Jan. 11<sup>th</sup> 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

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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!

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- 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

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- 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

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- 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

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- 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?

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- 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

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- 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

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- 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

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- 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

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- 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

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- 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)
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- 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

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- 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

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

**WORK HARD**

**RELAX HARDER**

makeameme.org

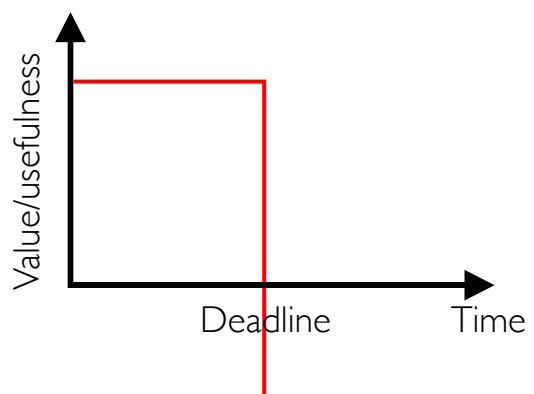
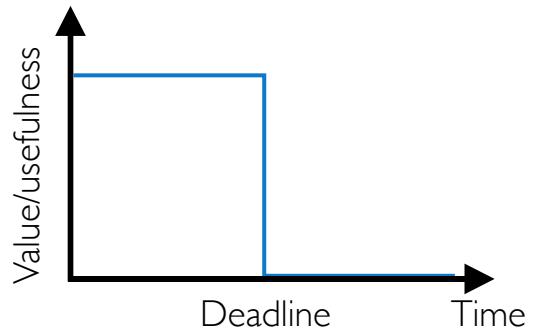
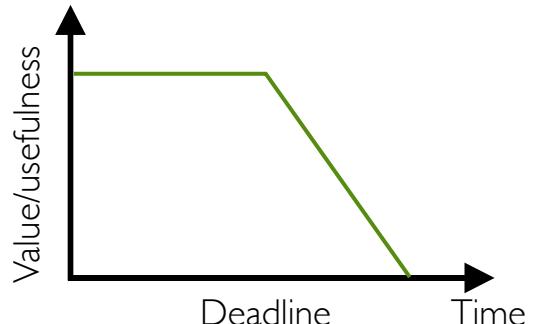
# What is a Real-time System?

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- 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

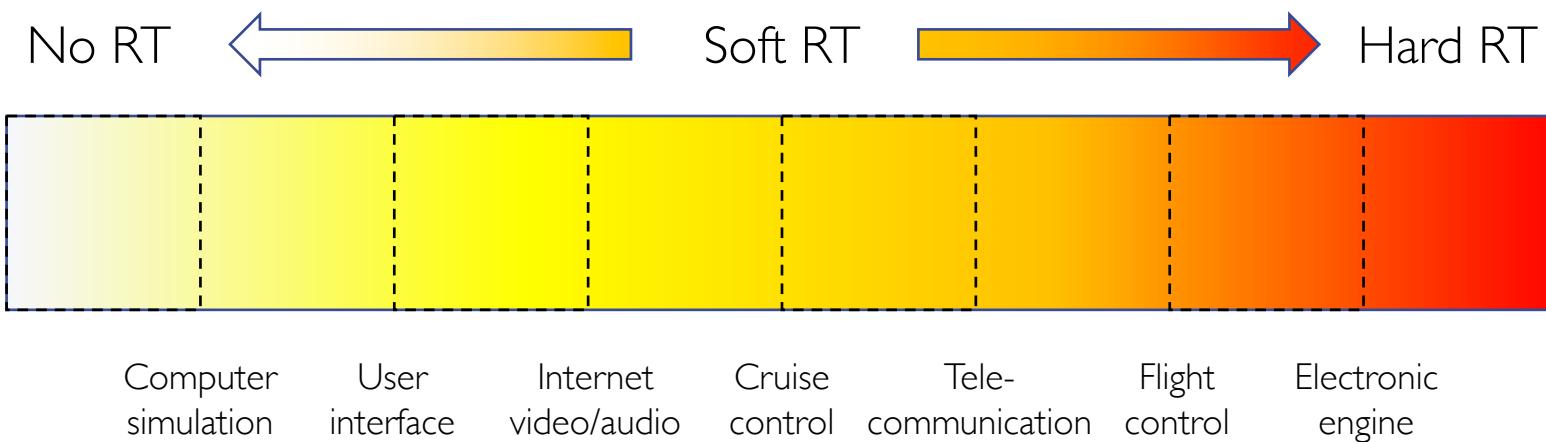
# Types of Real-time Systems

- **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

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# What is an Operating System?

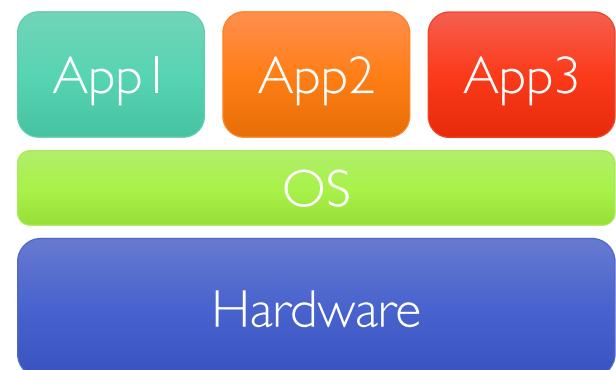
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- No universally accepted definition
- “Everything vendors ship when you order OS” is good approximation, but varies wildly
- “The one program running at all times on computer” is kernel
  - Everything else is either system program (ships with OS)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

# What is an Operating System? (cont.)

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- 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



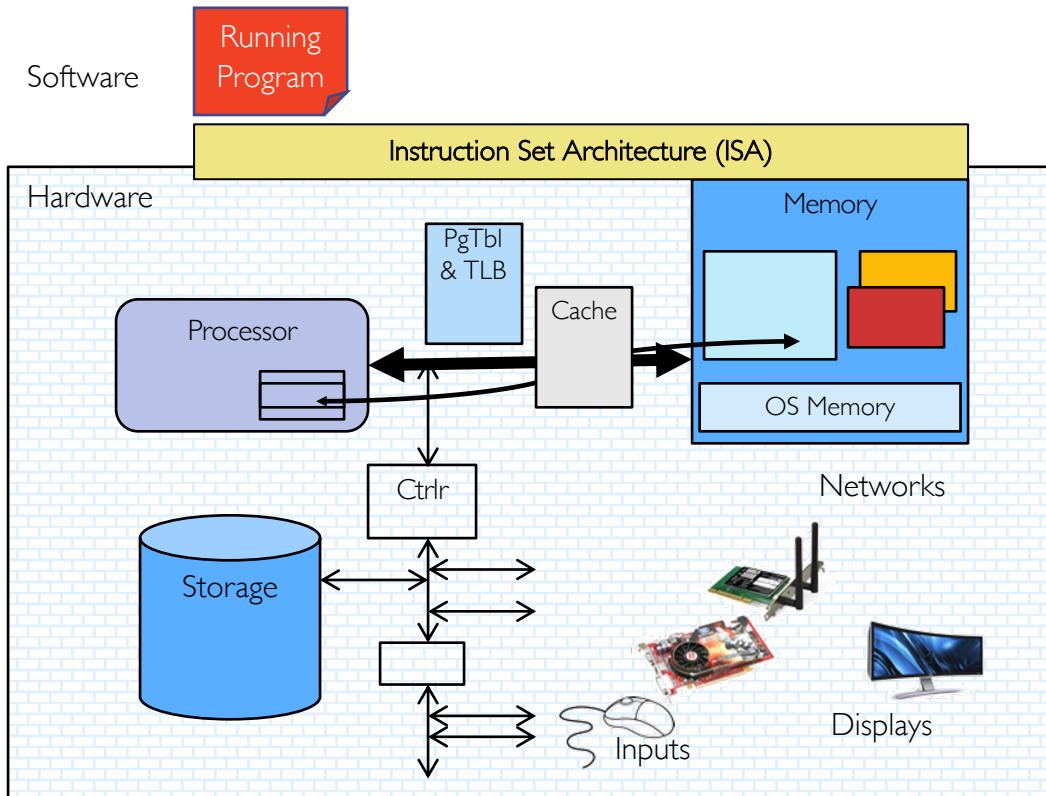
# What is an Operating System? (cont.)

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

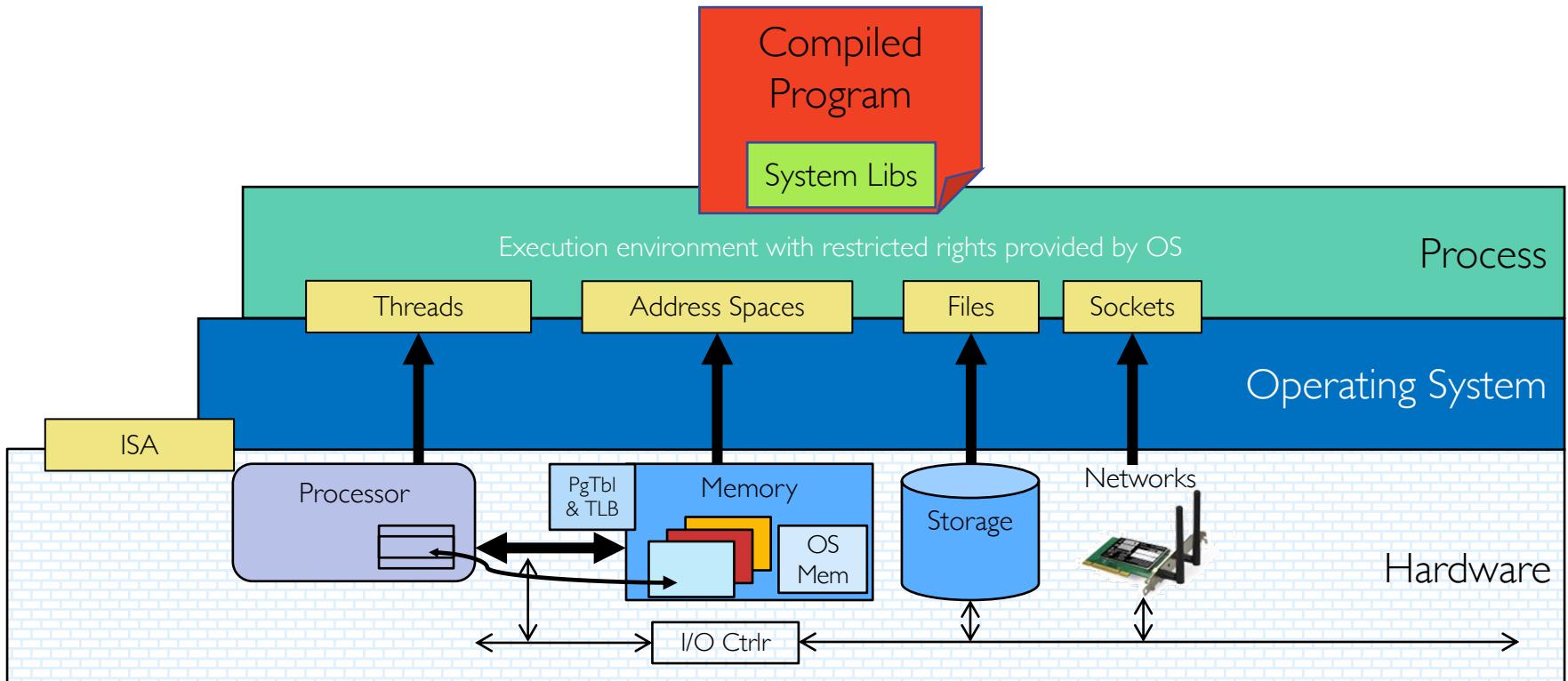


# Hardware/Software Interface



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

# OS Basics: Virtualizing Hardware



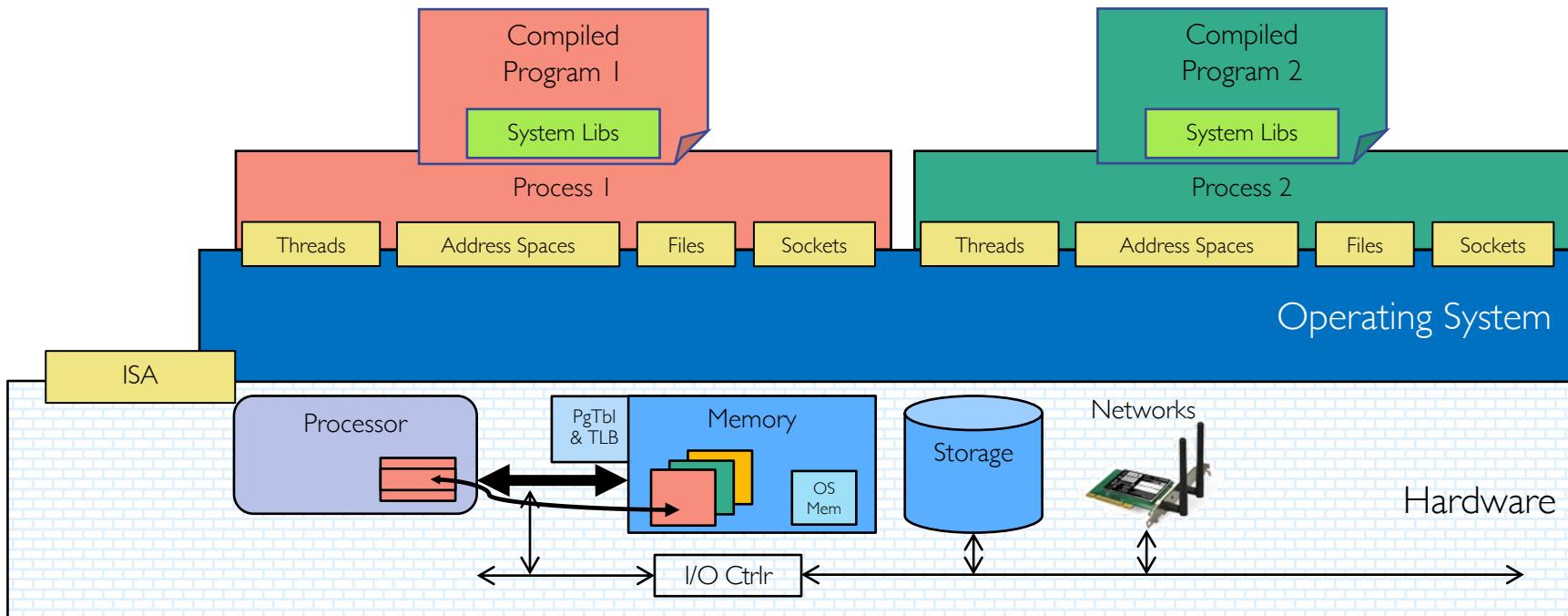
# What is an Operating System? (cont.)

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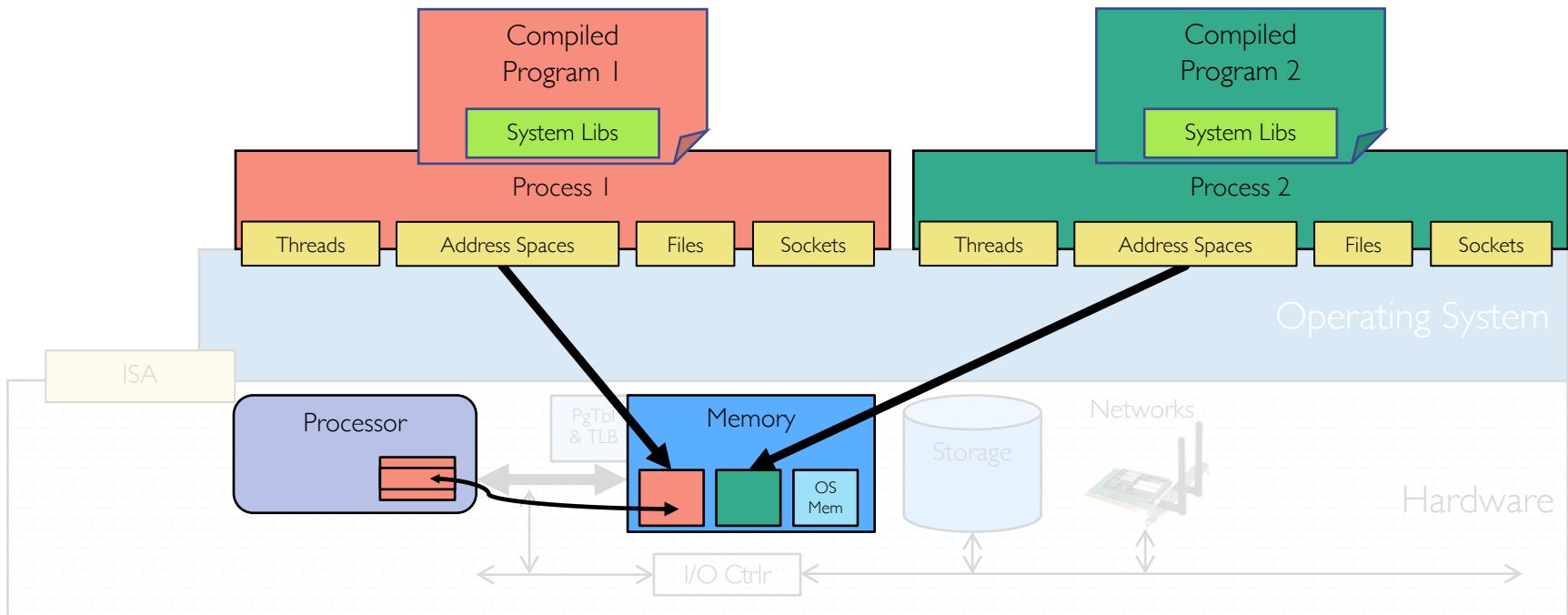
- Illusionist
  - Provide clean, easy-to-use abstractions of physical resources
    - Infinite memory, dedicated machine
    - Higher level objects: files, users, messages
    - Masking limitations, virtualization
- Referee
  - Provide protection, isolation, and sharing of resources
    - Resource allocation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



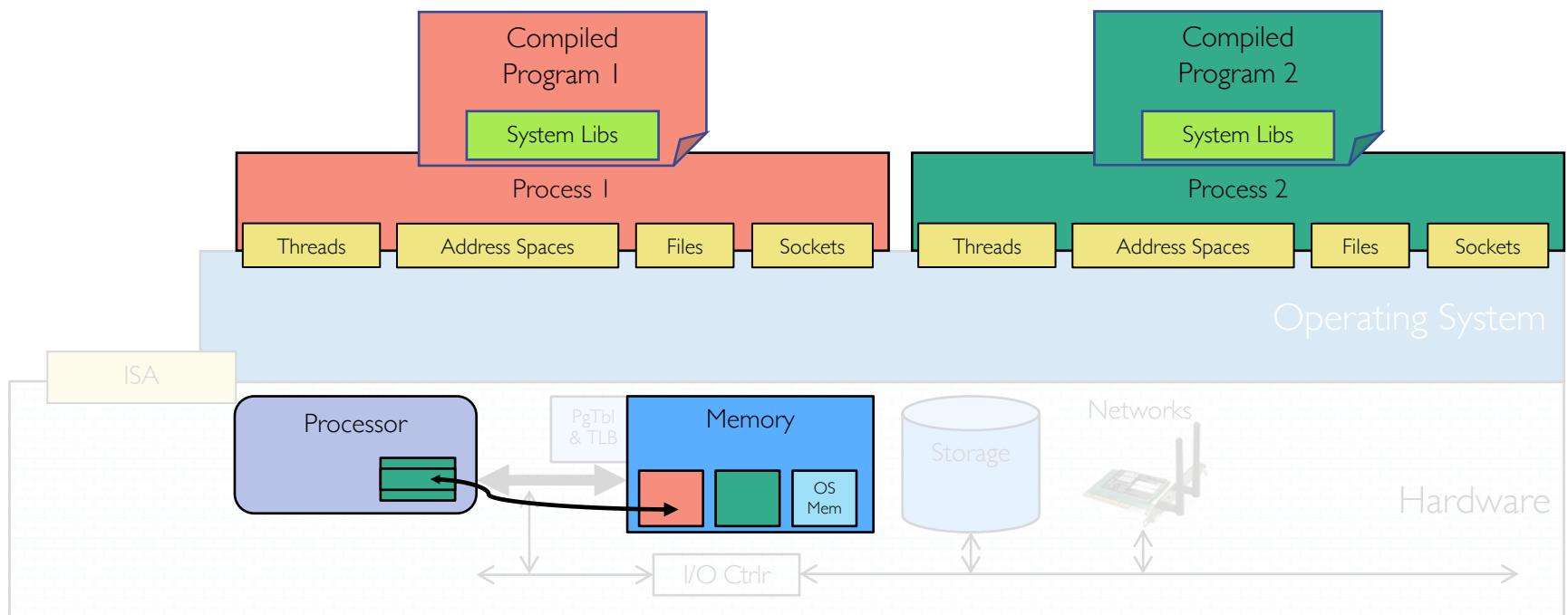
# OS Basics: Switching Processes



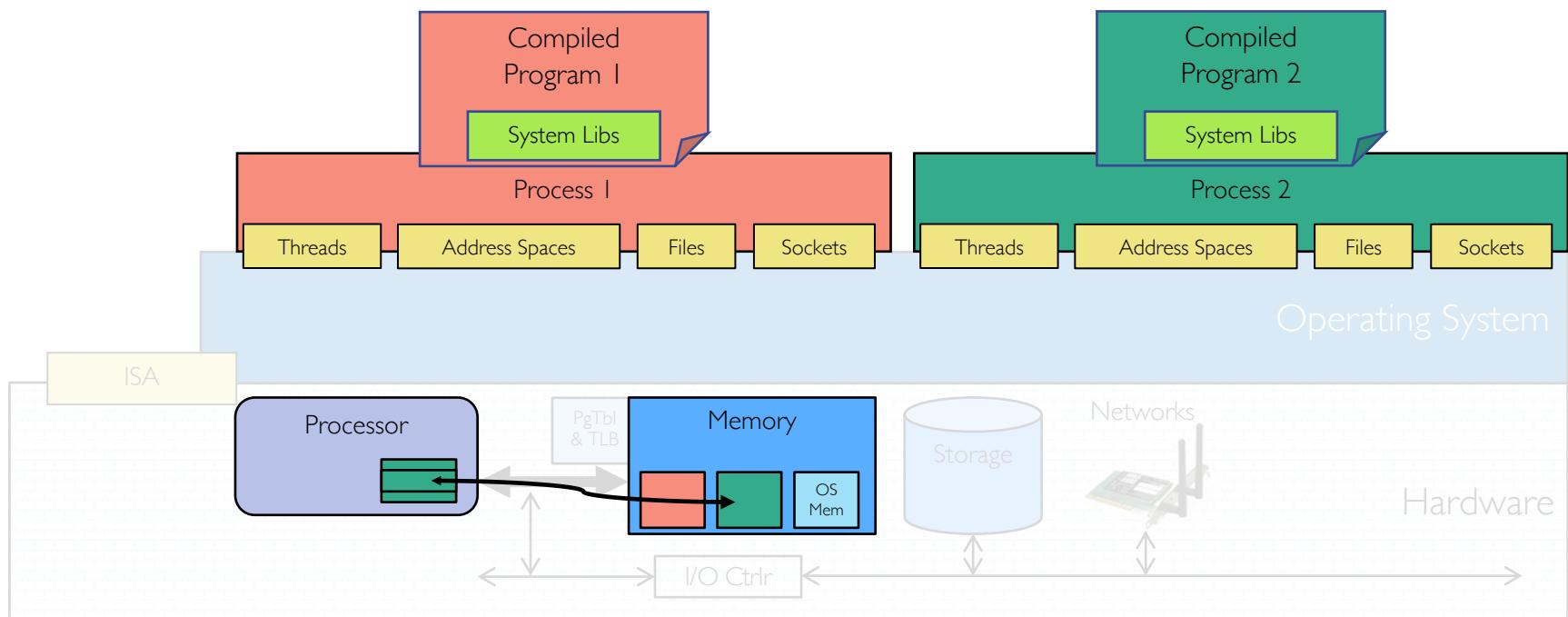
# OS Basics: Switching Processes



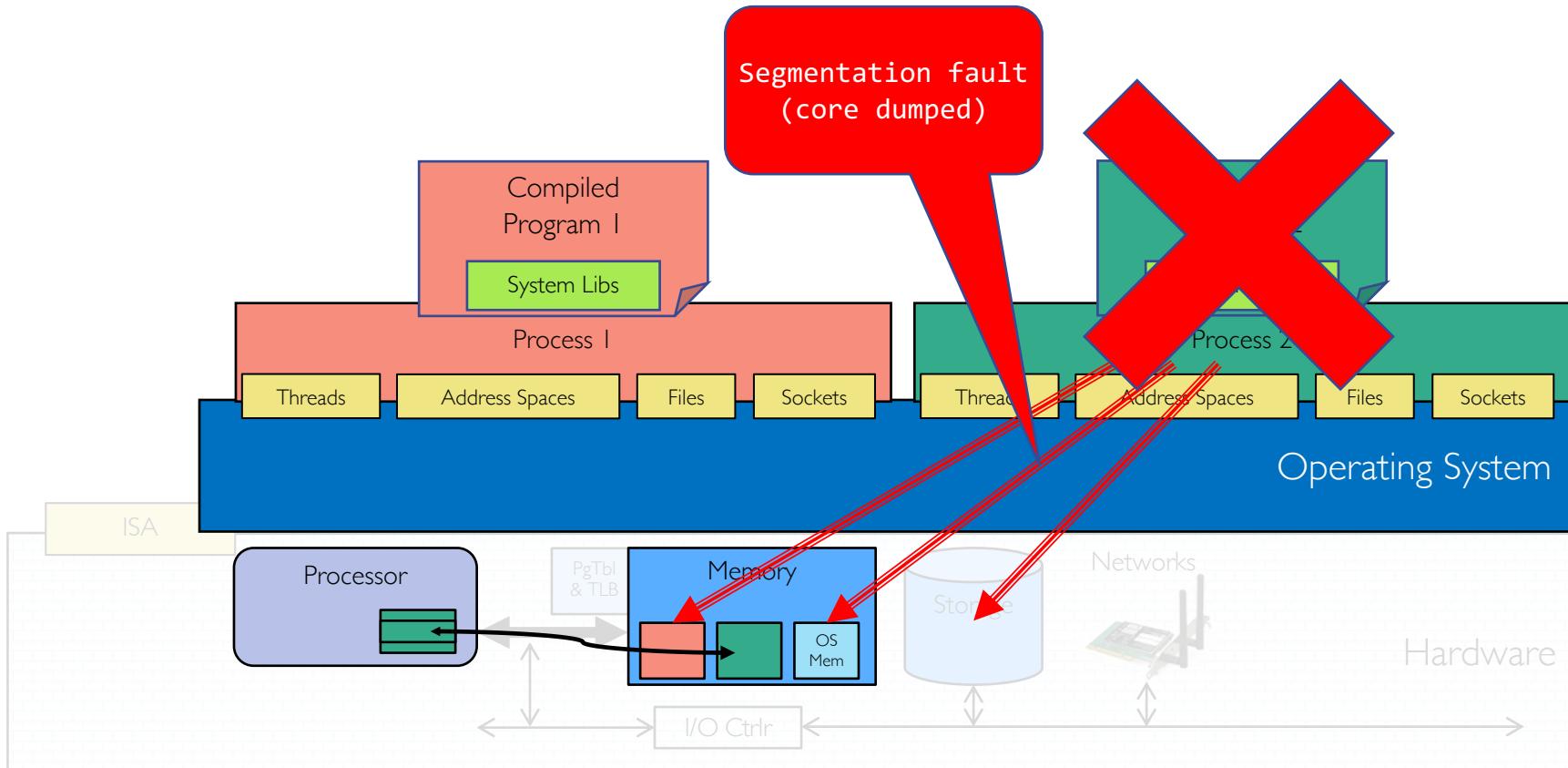
# OS Basics: Switching Processes (cont.)



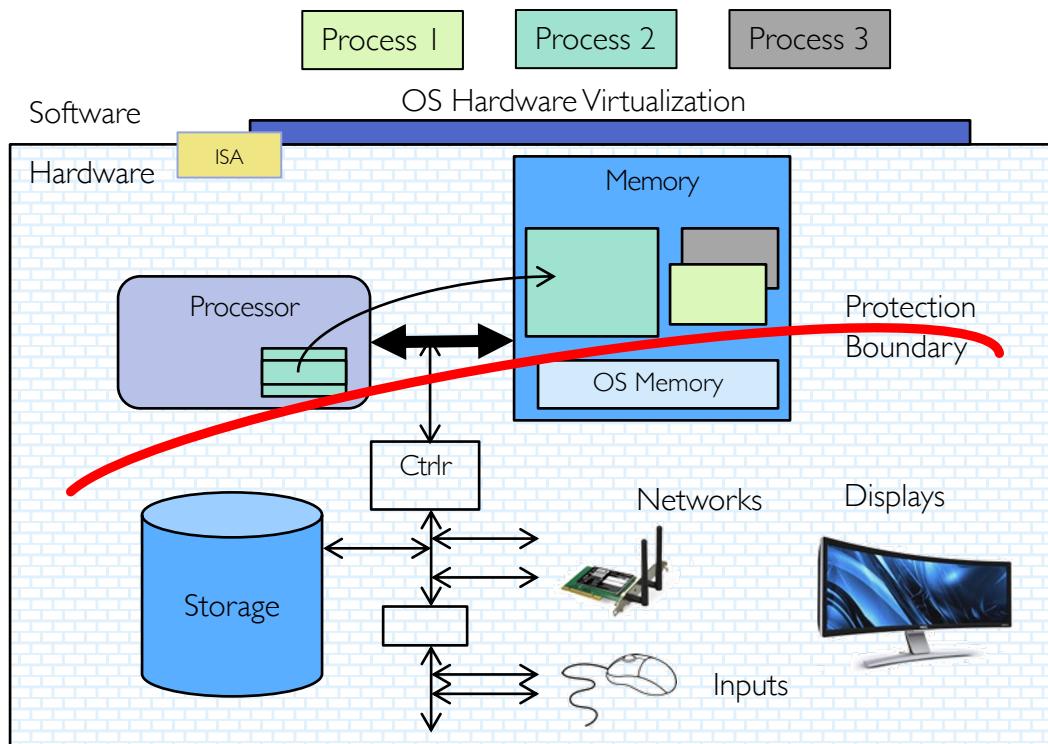
# OS Basics: Switching Processes (cont.)



# 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.)

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- Illusionist



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

- Referee



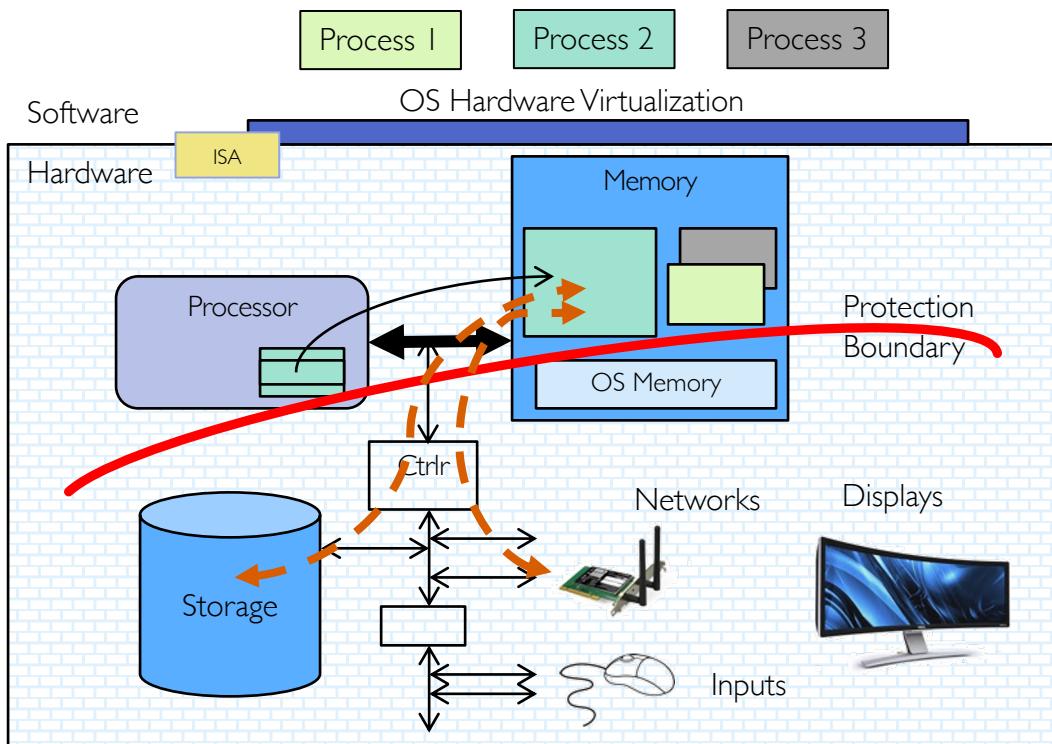
- Provide protection, isolation, and sharing of resources
  - Resource allocation and communication

- Glue



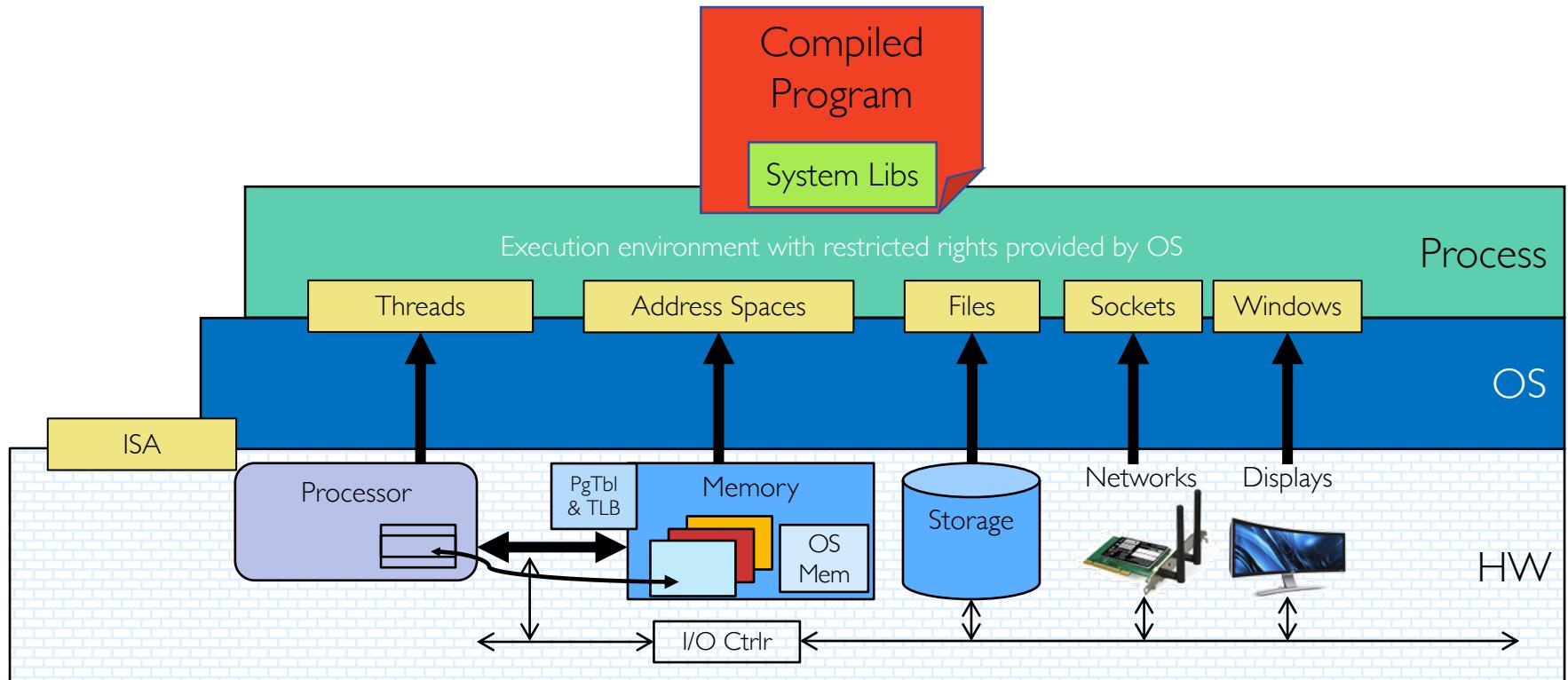
- Provide common services
  - Storage, window system, networking, sharing, authorization
  - Look and feel

# OS Basics: I/O

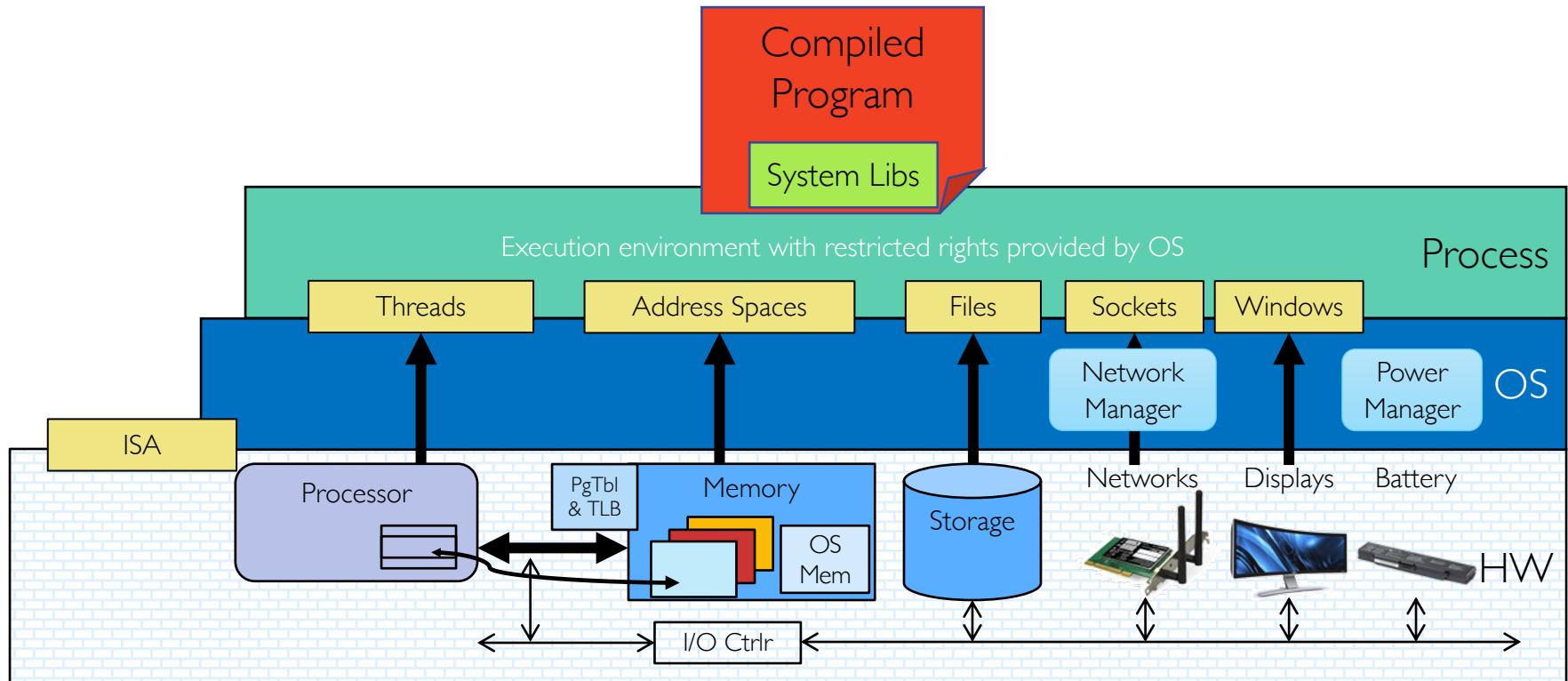


- OS provides common services in the form of I/O

# OS Basics: Look and Feel



# OS Basics: Background Management



# OS Basics: Hardware Support

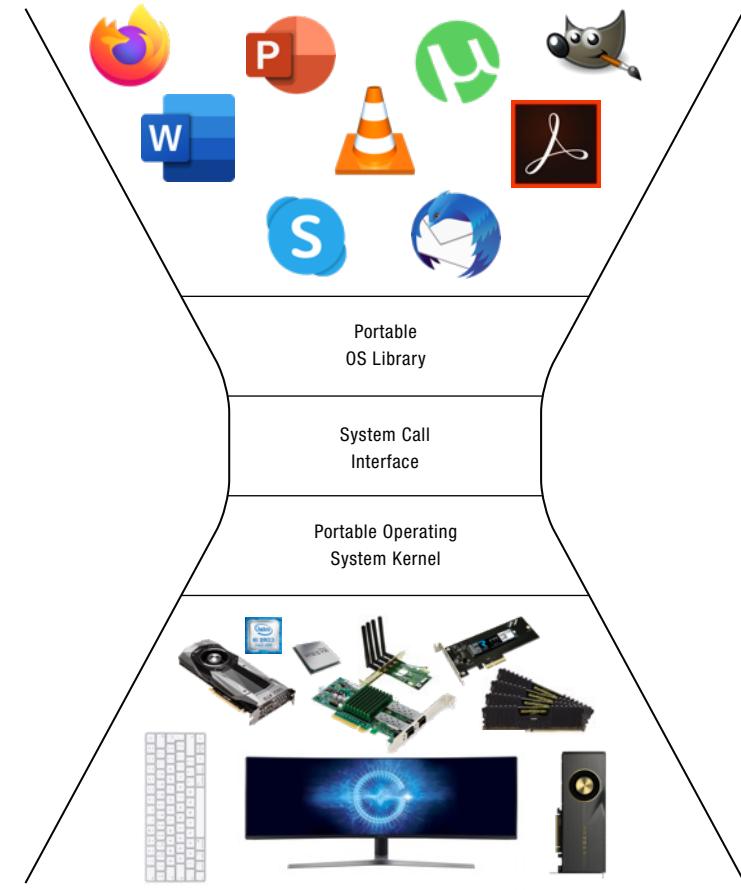
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- OS bottom line is to support applications!
  - OS itself is **incidental**
  - Ideally, OS should have very low performance overhead over raw hardware
- OS relies on HW support to provide abstractions **efficiently**
  - Dual-mode operation, interrupts, 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?

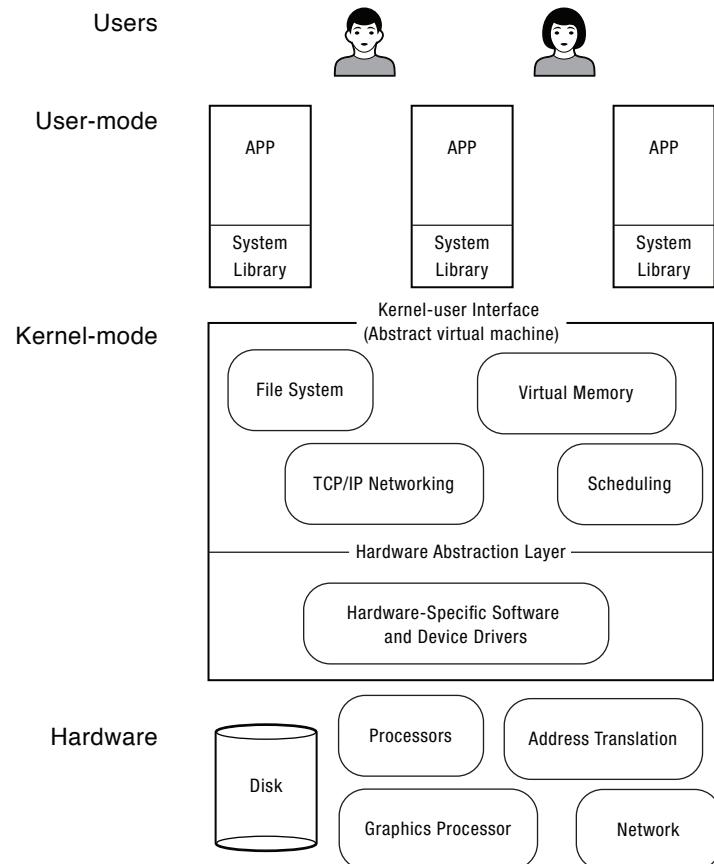
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- Provide abstractions to applications
  - File systems
  - Processes, threads
  - Virtual memory
  - Naming system, ...
- Manage diverse resources
  - Memory, CPU, storage, ...
- Achieves above by implementing specific algorithms and techniques
 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



# What do Operating Systems do? (cont.)

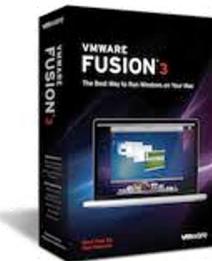
- Manage hardware resources for users and applications
- Convert what hardware gives into something that application programmers want
- For any OS component, begin by asking two questions
  - What is hardware interface? (physical reality)
  - What is application interface? (virtual machine)



# Virtual Machines (VMs)

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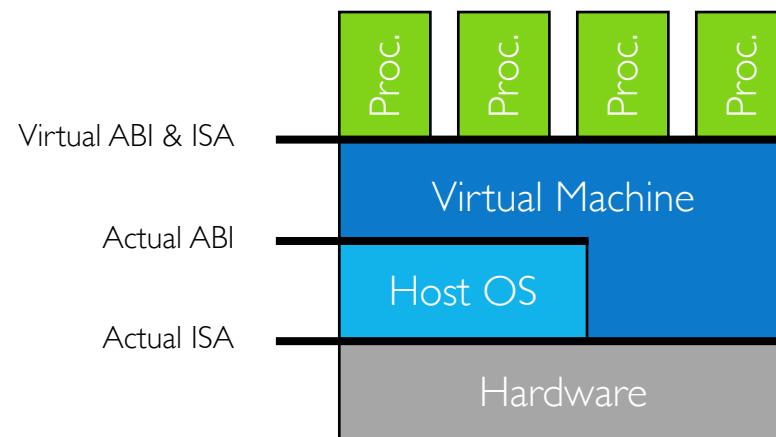
- Software that emulates physical machine
  - Gives programs **illusion** that they run on physical machine
  - Provides platform that is independent of actual underlying hardware
  - Makes it look like hardware has features programs want
- Two types of virtual machines
  - Process VM: supports execution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



# Process VMs

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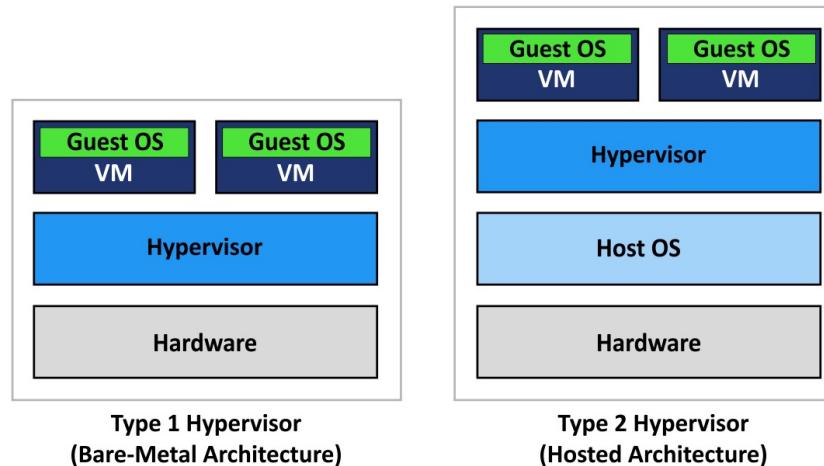
- Runs processes
  - Abstracts underlying OS and hardware
  - Provides platform-independent environment
  - E.g., Java virtual machine, .NET framework



# System Virtual Machines: Layers of OSes

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- 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



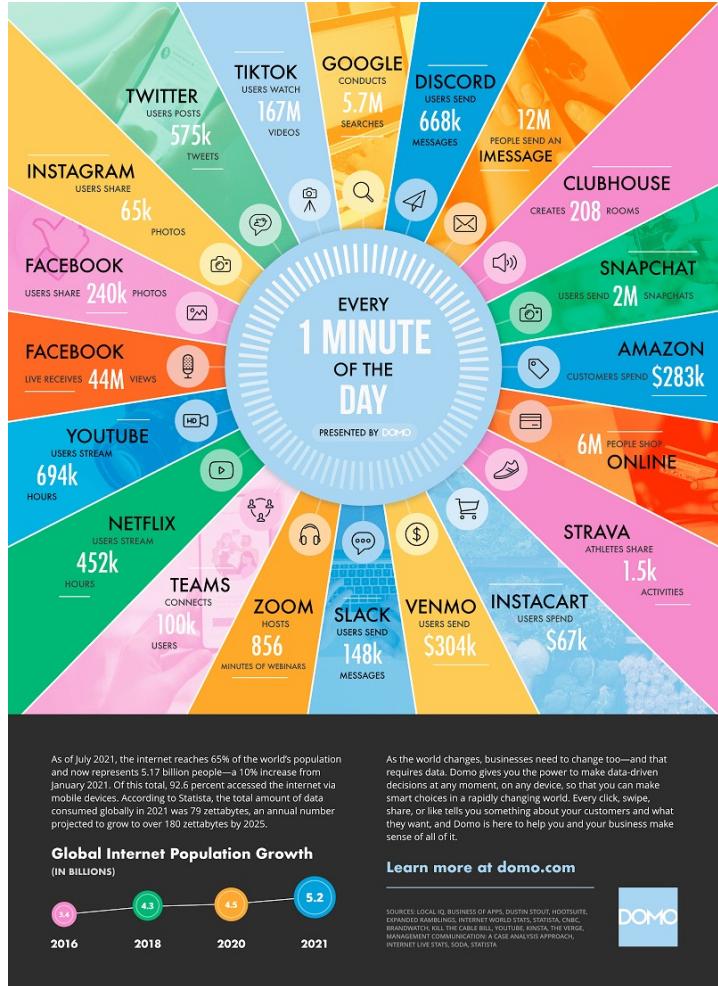
# Containers: Low-weight Alternatives to Full-system Virtualization

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- 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?

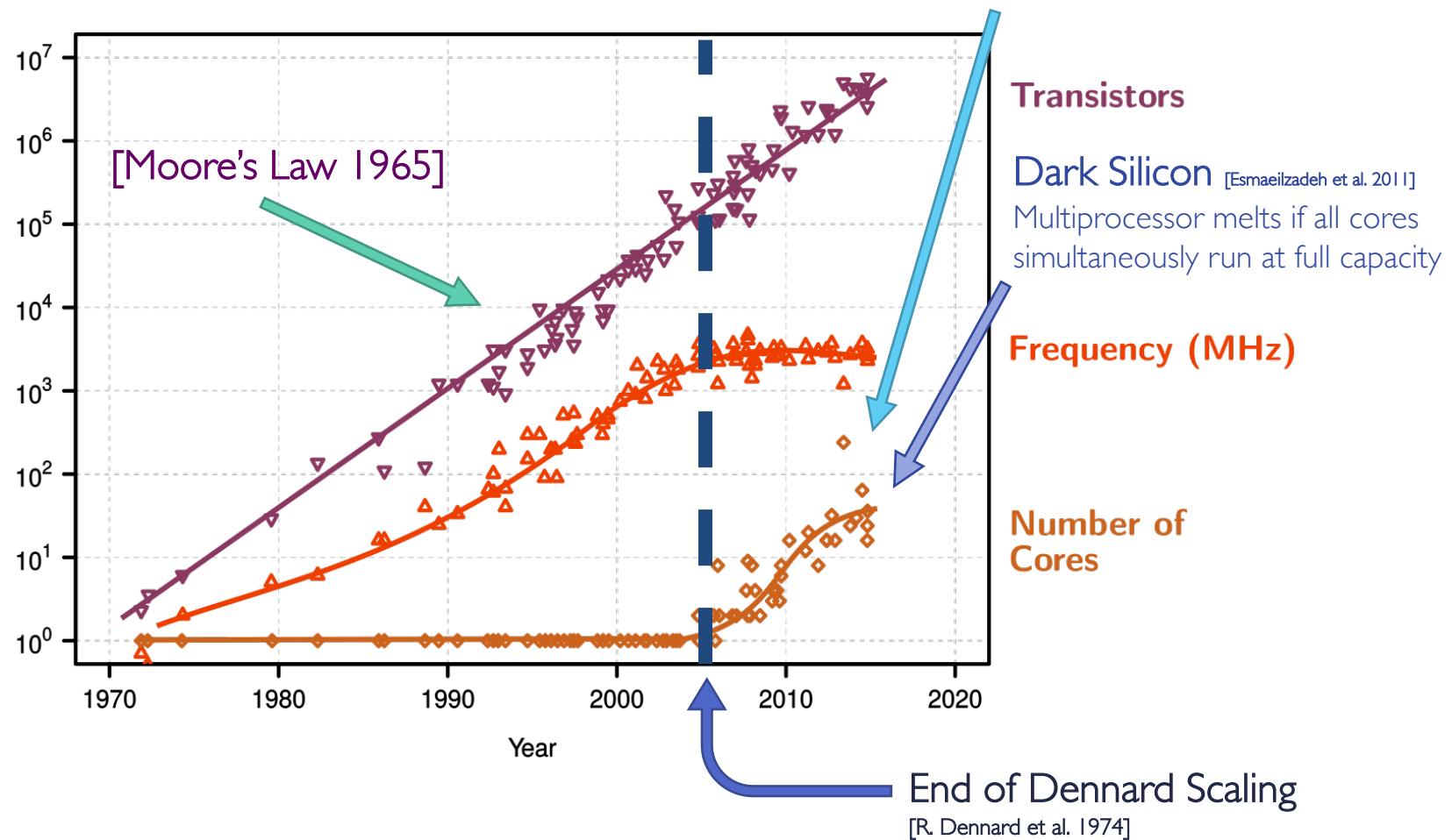


Operating systems are at the heart of it all ...

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

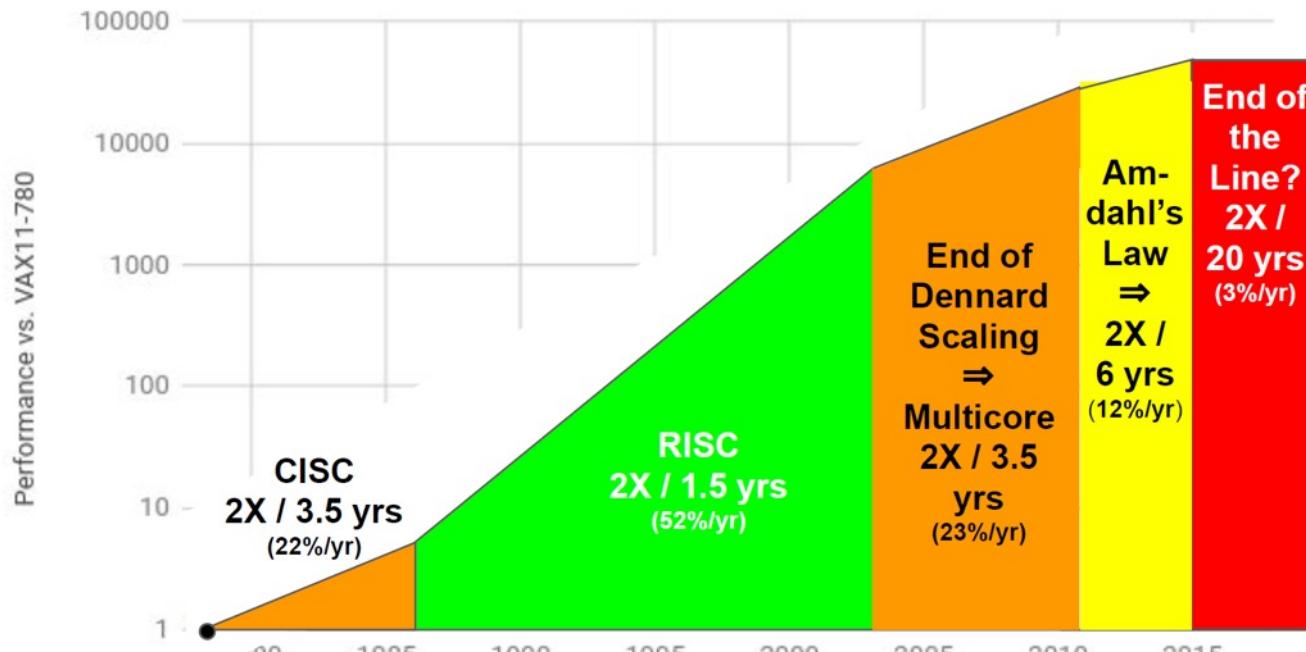
# Technology Trends

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



# End of Growth of Single Program Speed

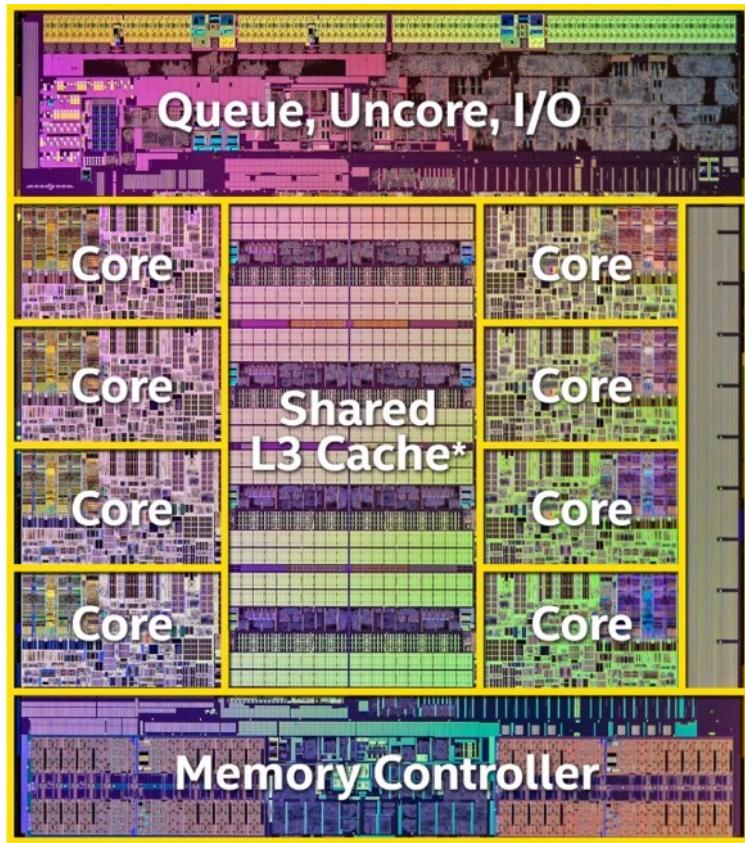
## 40 years of Processor Performance



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

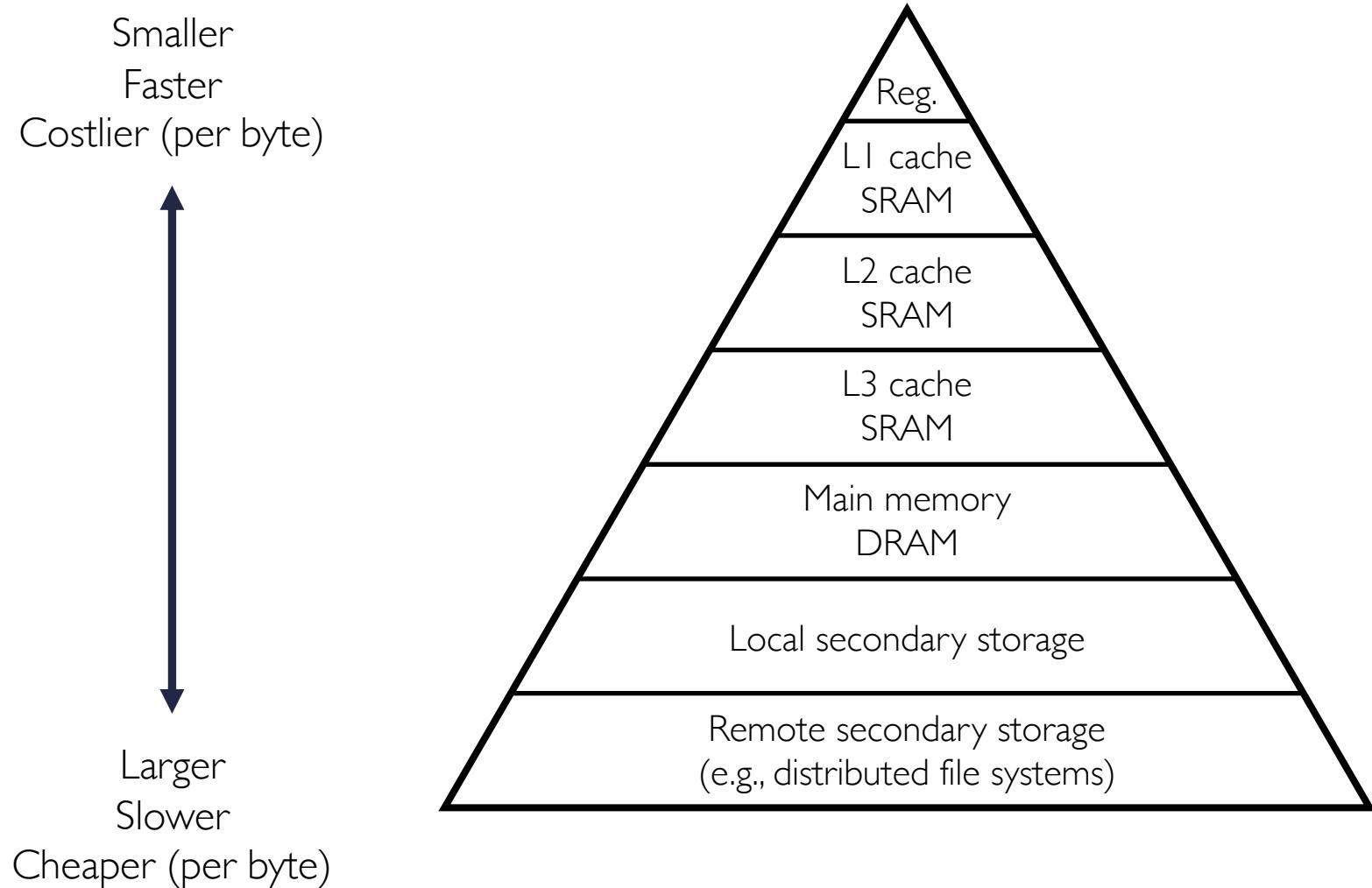
# Modern Processors

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

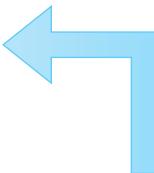
# Memory Hierarchy



# 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



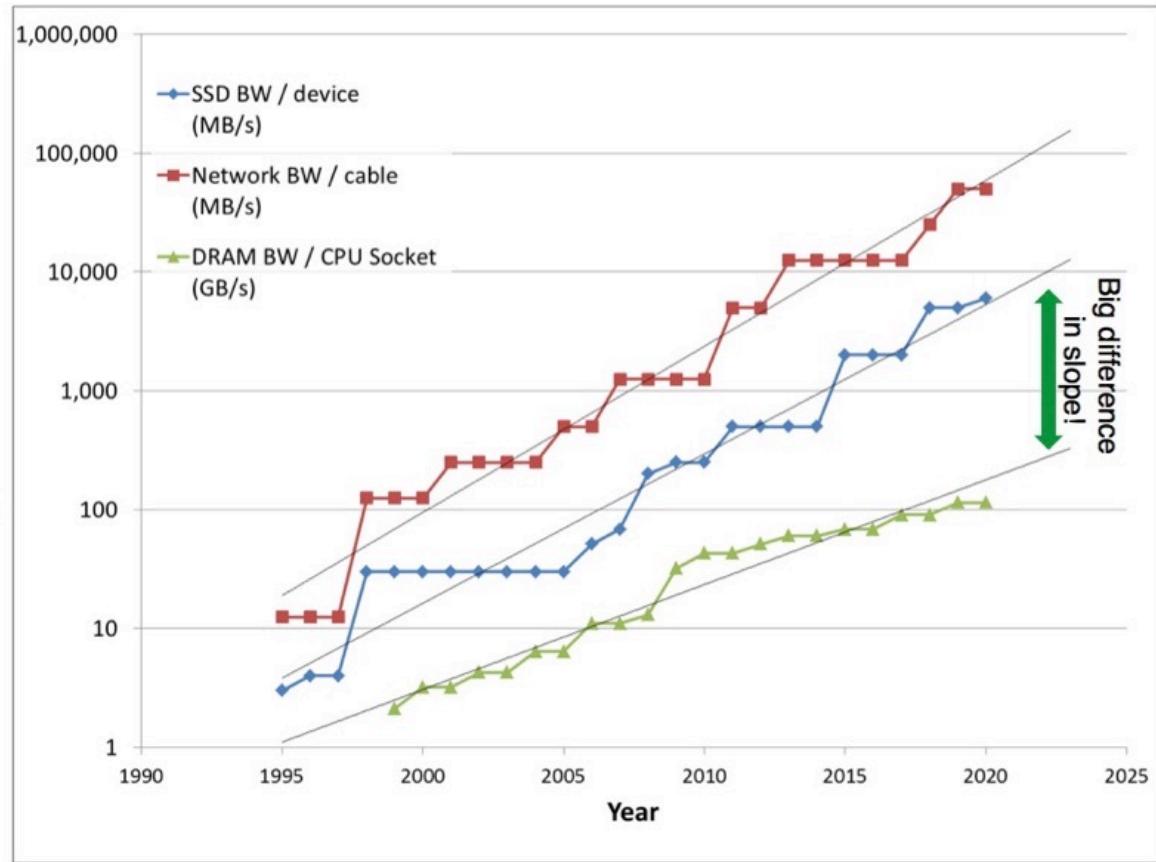
Key stroke ~100 ms

# Network, IO, and Memory Bandwidth Trends

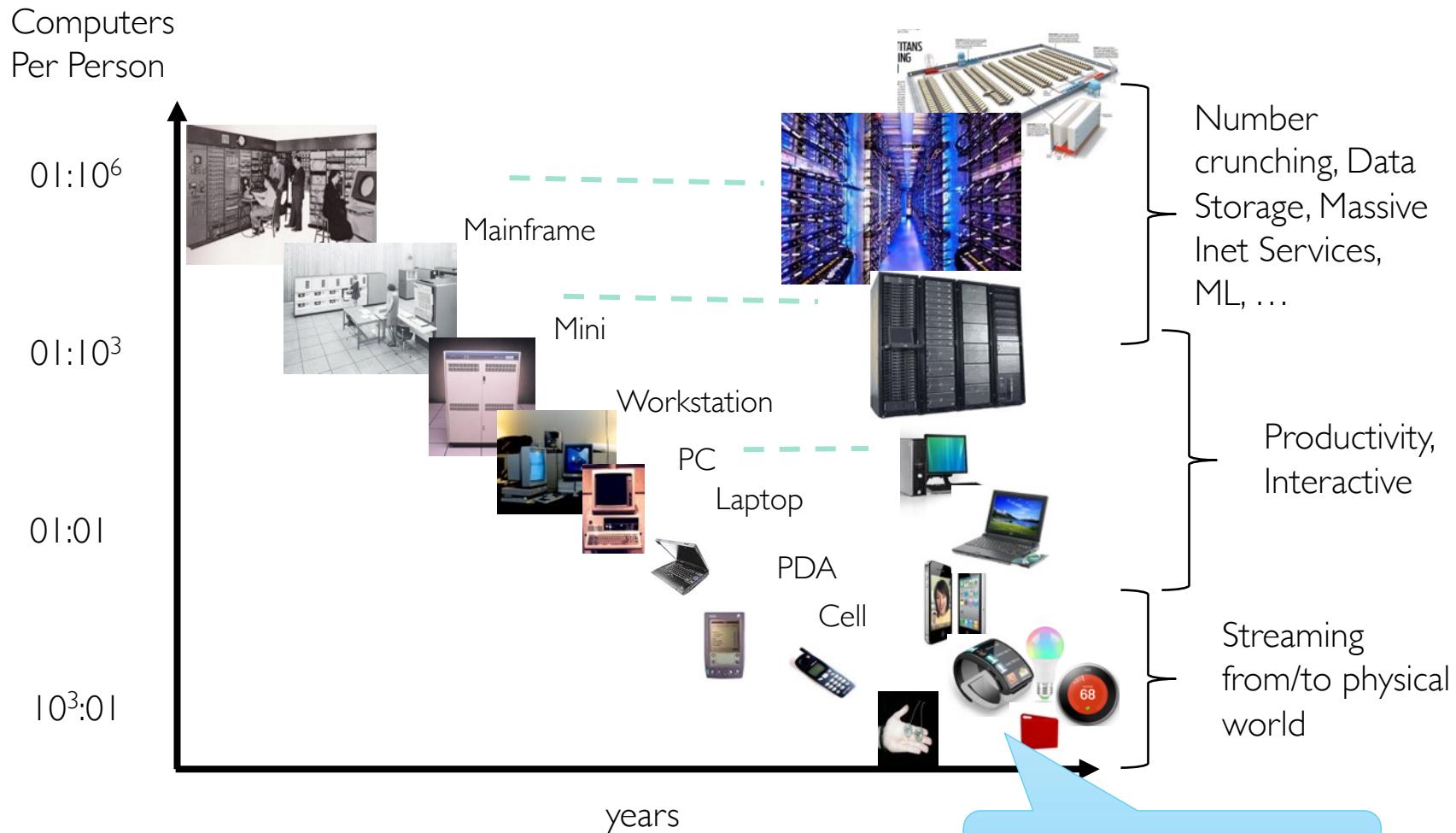
## Network, Storage, & DRAM trends

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



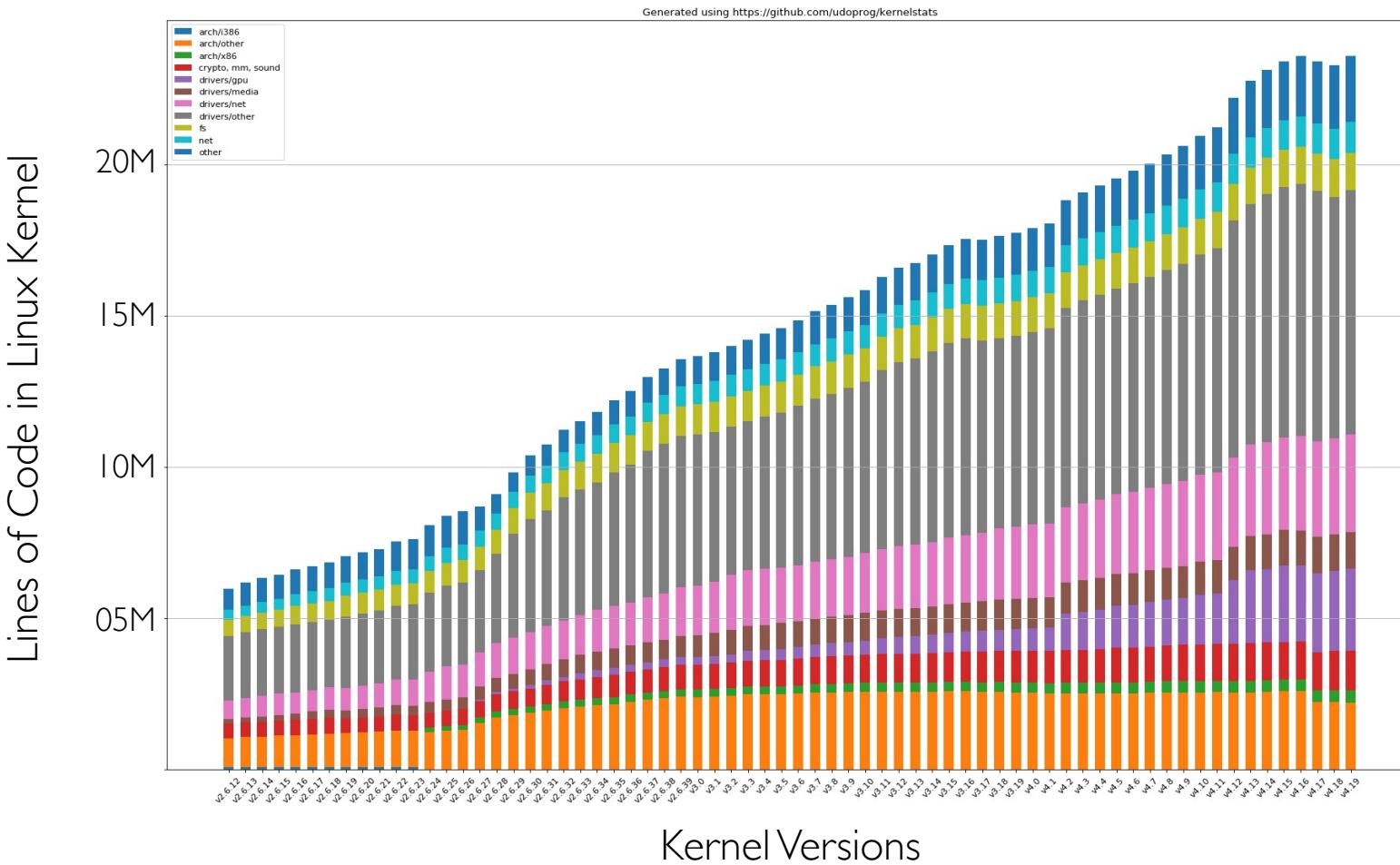
Bell's Law: new computer class per 10 years

# Complexity

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- 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?

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- 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?

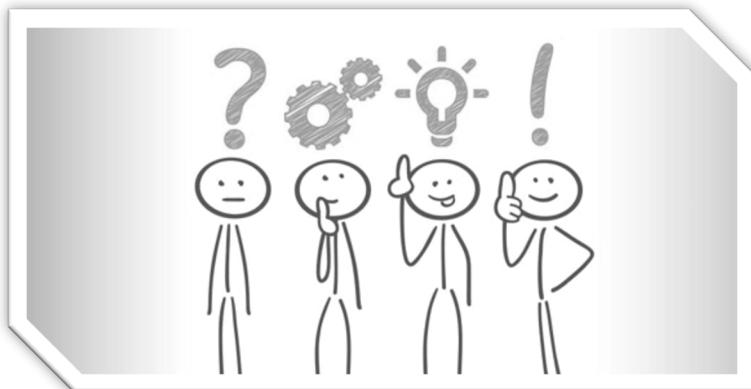
# Summary

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- 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?

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# Acknowledgment

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