# ECE 350 Real-time Operating Systems

# Lecture 1: 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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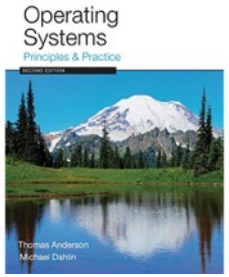
# Readings

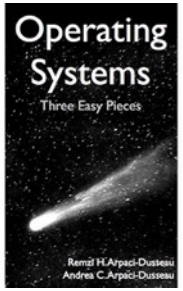
- Main textbook

  Operating Systems: Principles and Practice (2nd Edition)

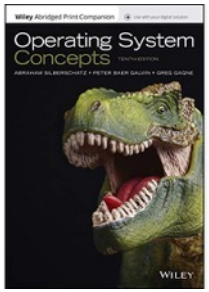



- Optional references

  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.
memegenerator.net

# Evaluation

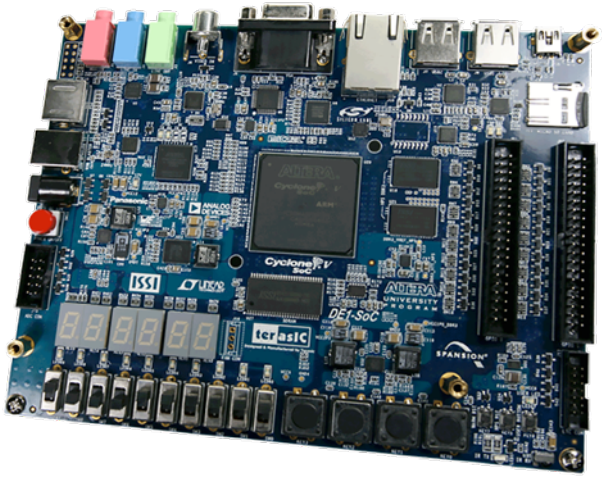
- In-person final: 40%
- Lab project: 35%
  - 3 deliverables (more on this later)
- Quizzes: 25%
  - 9 quizzes (highest 7 will be considered)
  - All online on LEARN
  - Quizzes are open book
    - You may consult your textbook, course notes, and materials posted on course webpage
    - Use of any other 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 in LEARN by 23:00 on Jan. 11th EST
- Each group must have a project manager
  - Responsible for coordinating group
  - Can rotate between teammates
  - For L1, report project manager by sign-up deadline
  - For L2 and L3, report project manager by L1 and L2 submissions
- Only one split-up is allowed
  - One-week notice in writing before nearest deadline
  - All students involved lose one grace day

# Milestones

| Deliverable | Weight | Due Date |
|---|---|---|
| Group sing-up | 2% | 23:00 Jan 11 |
| L1 | 28% | 23:00 Feb 3 |
| L2 | 35% | 23:00 Mar 10 |
| L3 | 35% | 23:00 Mar 31 |

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
- Lat 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

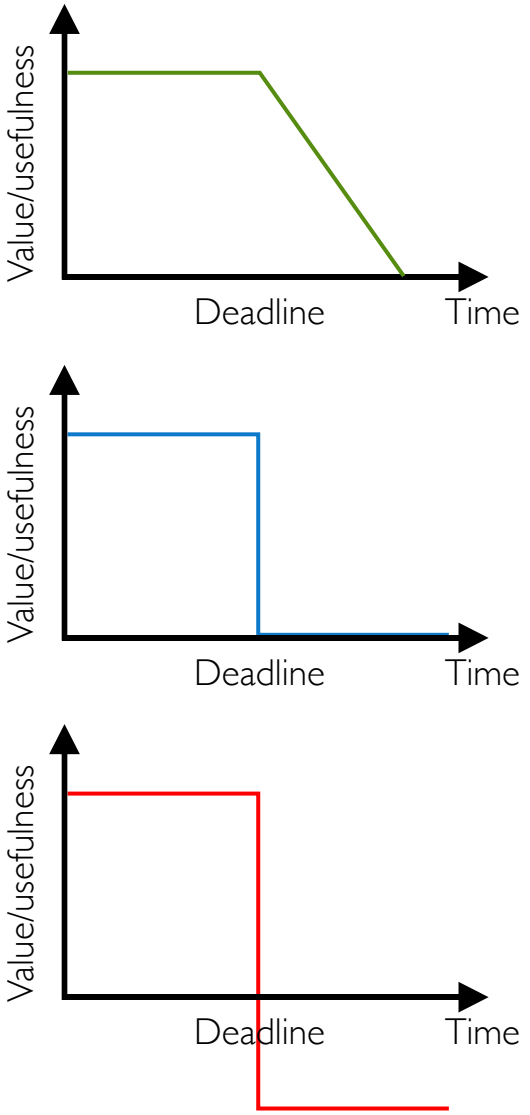

WORK HARD
RELAX HARDER
makeameme.org

# What is a Real-time System?

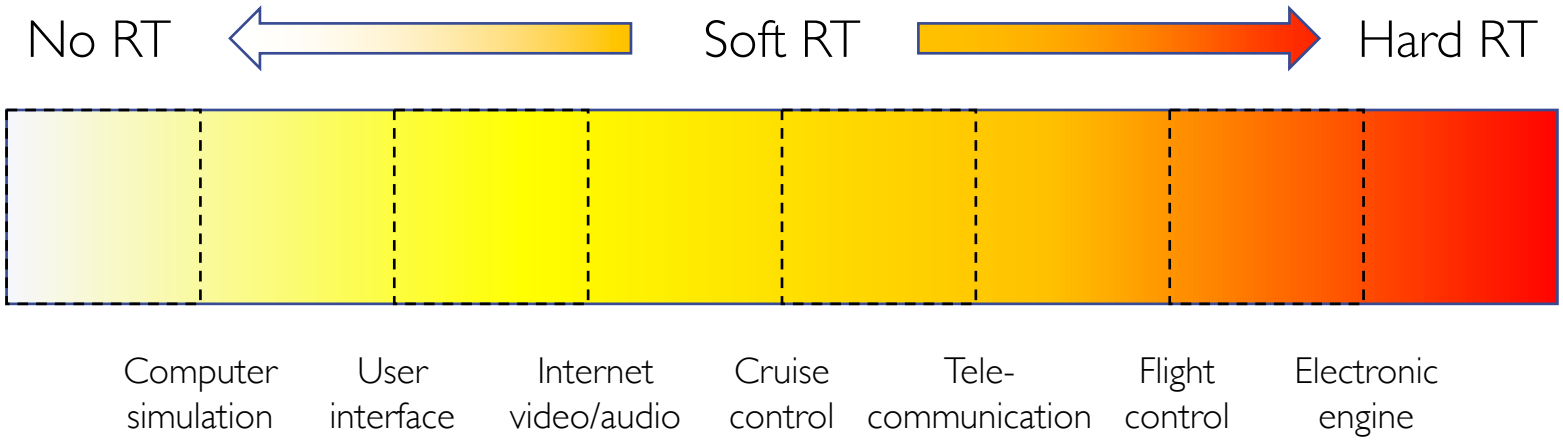
- Systems whose correctness depends on both their temporal aspects as well as their functional aspects
- Temporal aspects are typically specified through deadline
  - Results must be produced before deadline
  - Correct result produced too late is considered failure
- Real-time systems are typically 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

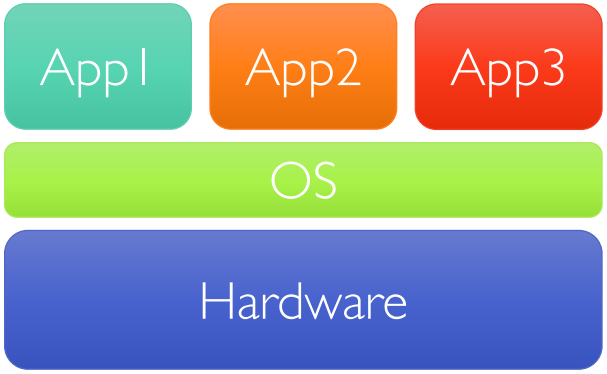


# What is an Operating System?

- 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.)

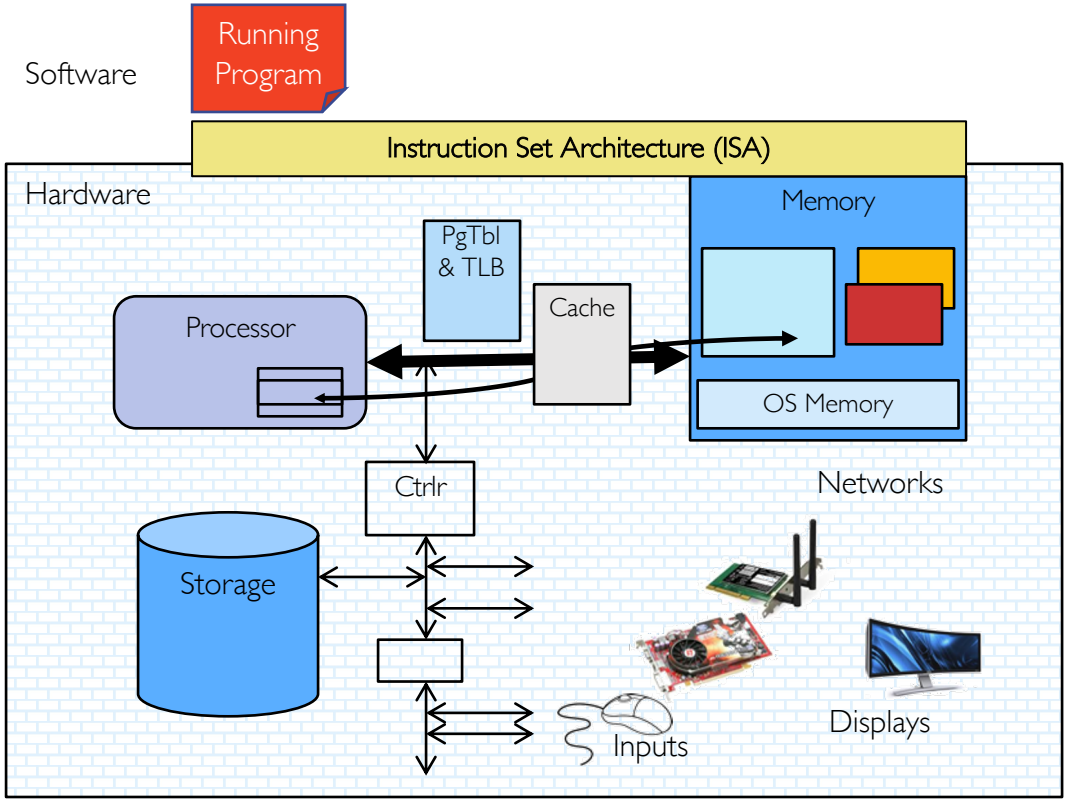
- Special layer of software that provides applications access to hardware resources
  - Abstract view of complex hardware devices
  - Protected access to shared resources
  - Security and authentication
  - Communication amongst logical entities



# What is an Operating System? (cont.)

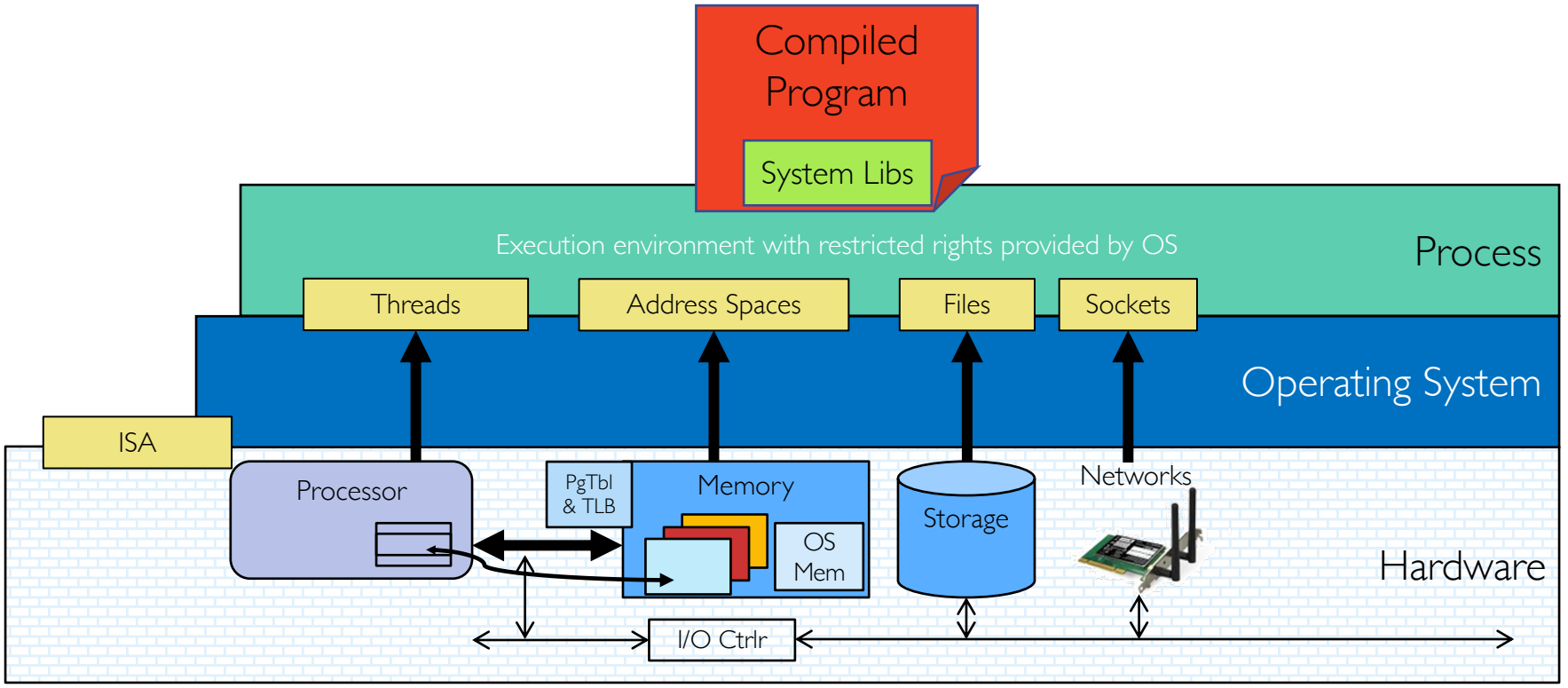
- Illusionist
  - Provide clean, easy-to-use abstractions of physical resources
    - Infinite memory, dedicated machine
    - Higher level objects: files, users, messages
    - Masking limitations, virtualization

# Hardware/Software Interface




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

# OS Basics: Virtualizing Hardware

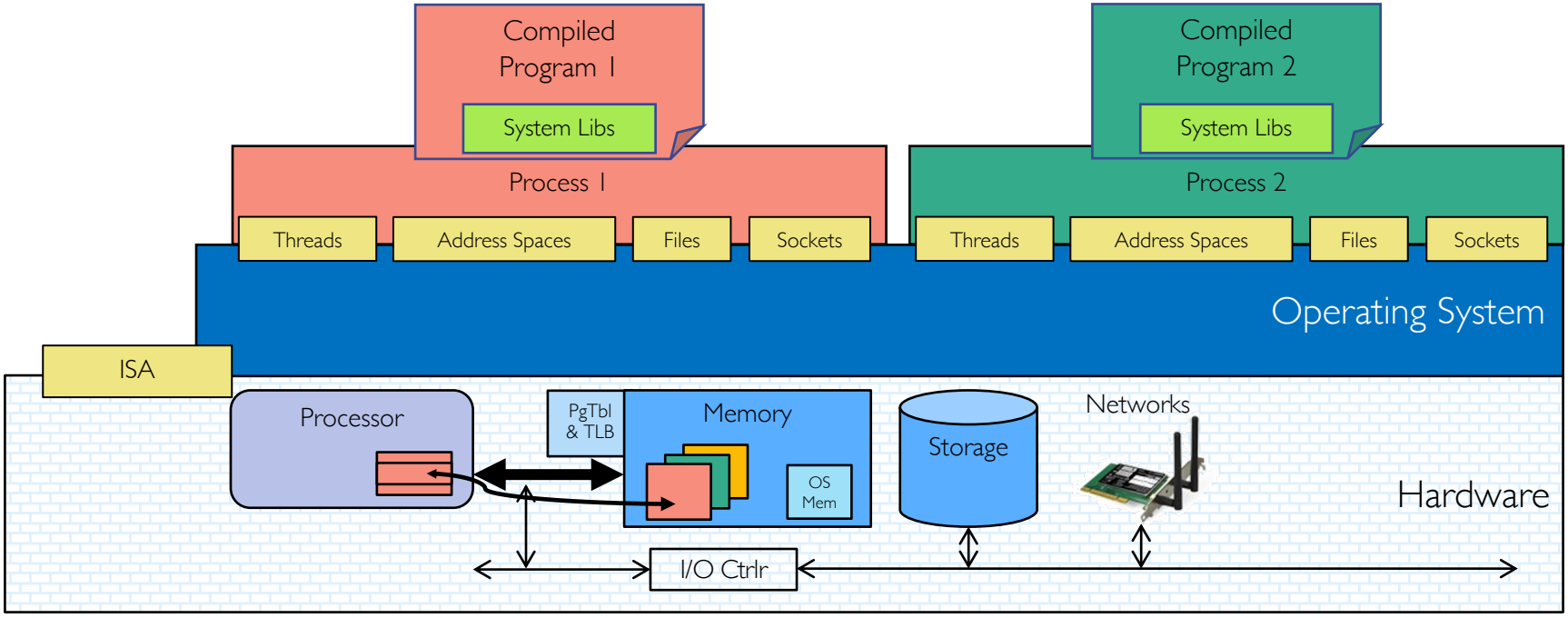


# What is an Operating System? (cont.)

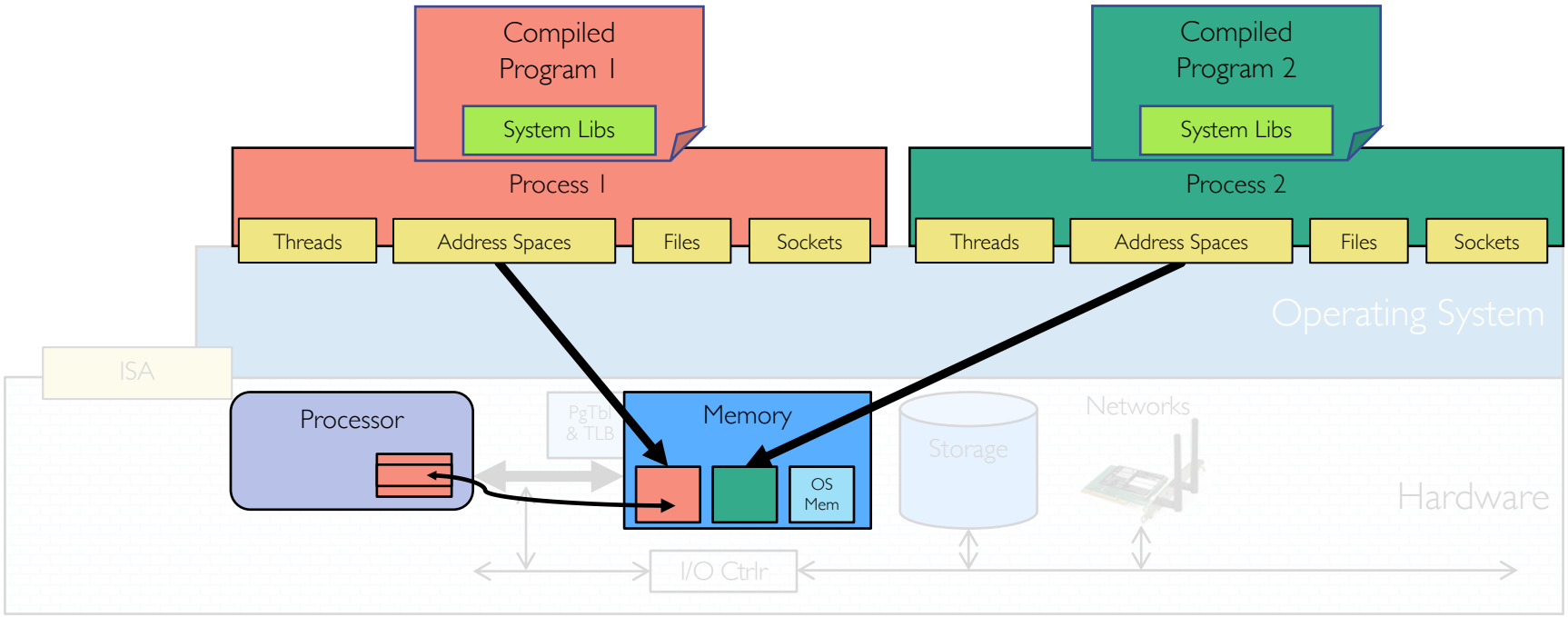
- Illusionist
  - Provide clean, easy-to-use abstractions of physical resources
    - Infinite memory, dedicated machine
    - Higher level objects: files, users, messages
    - Masking limitations, virtualization

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

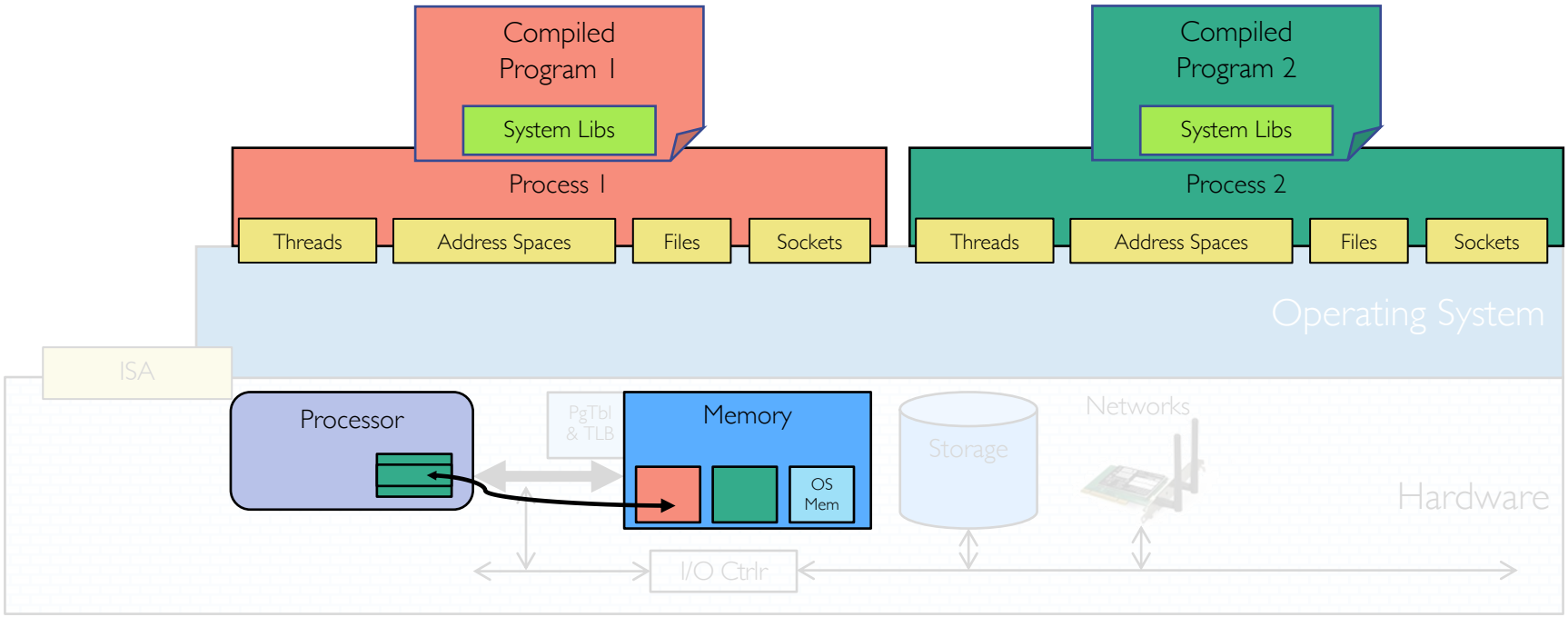
# OS Basics: Switching Processes



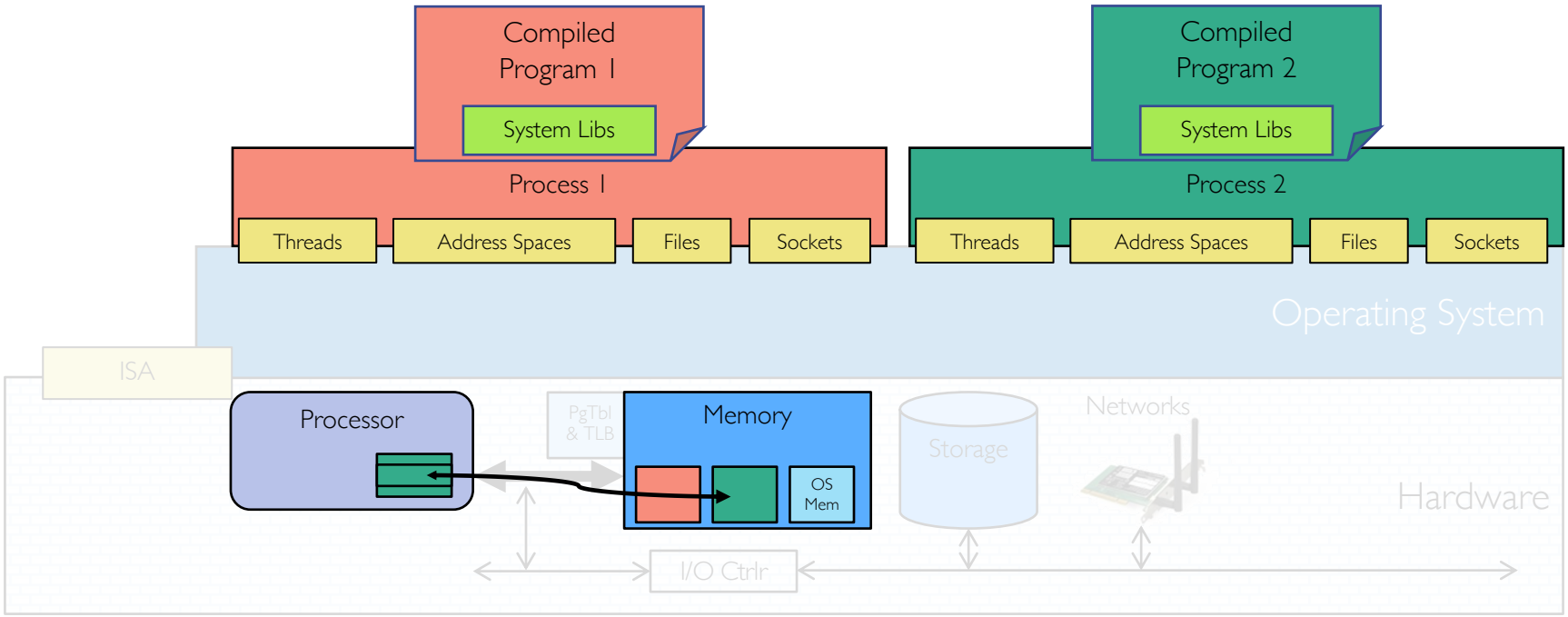
# OS Basics: Switching Processes



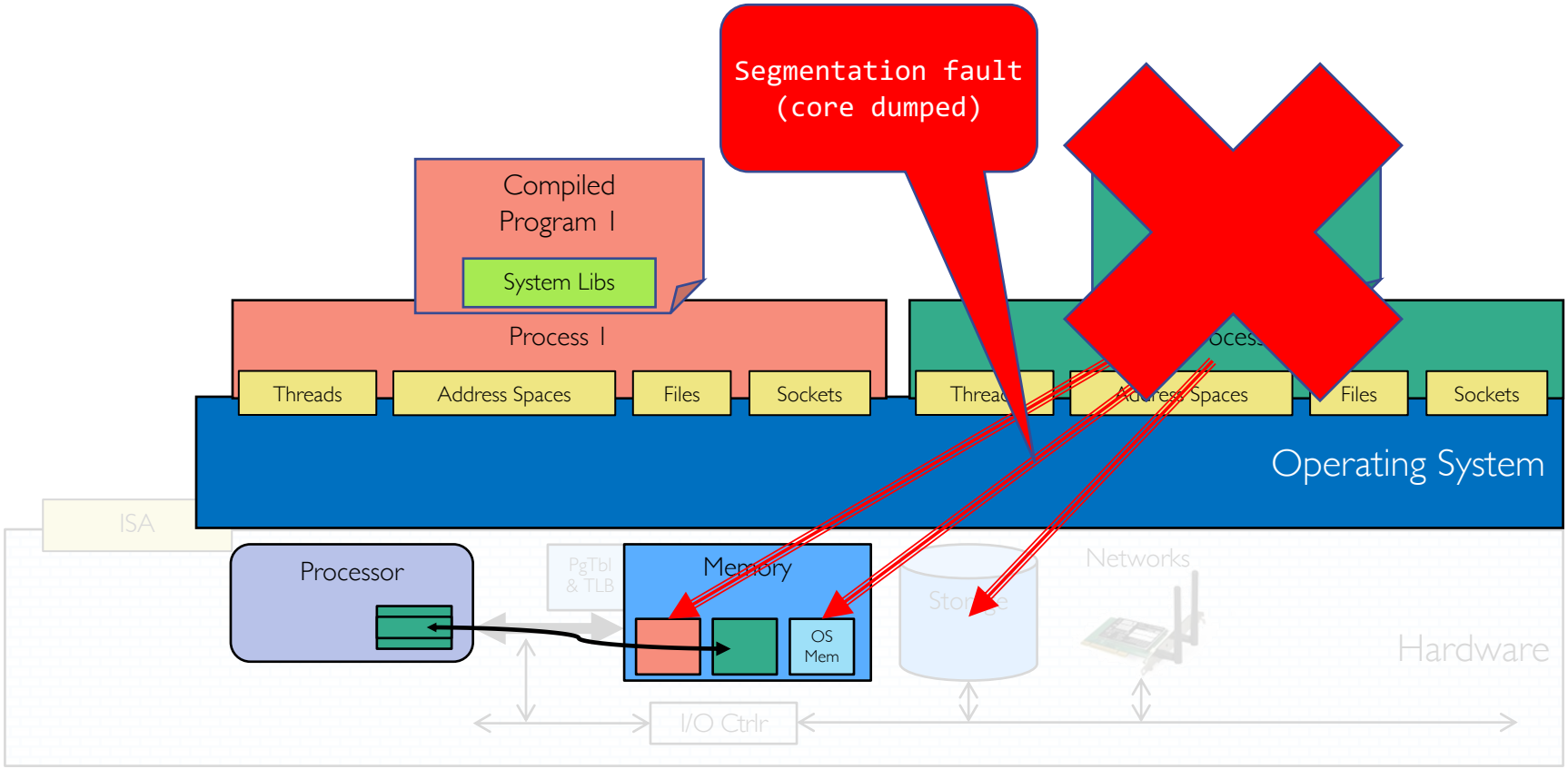
# OS Basics: Switching Processes (cont.)



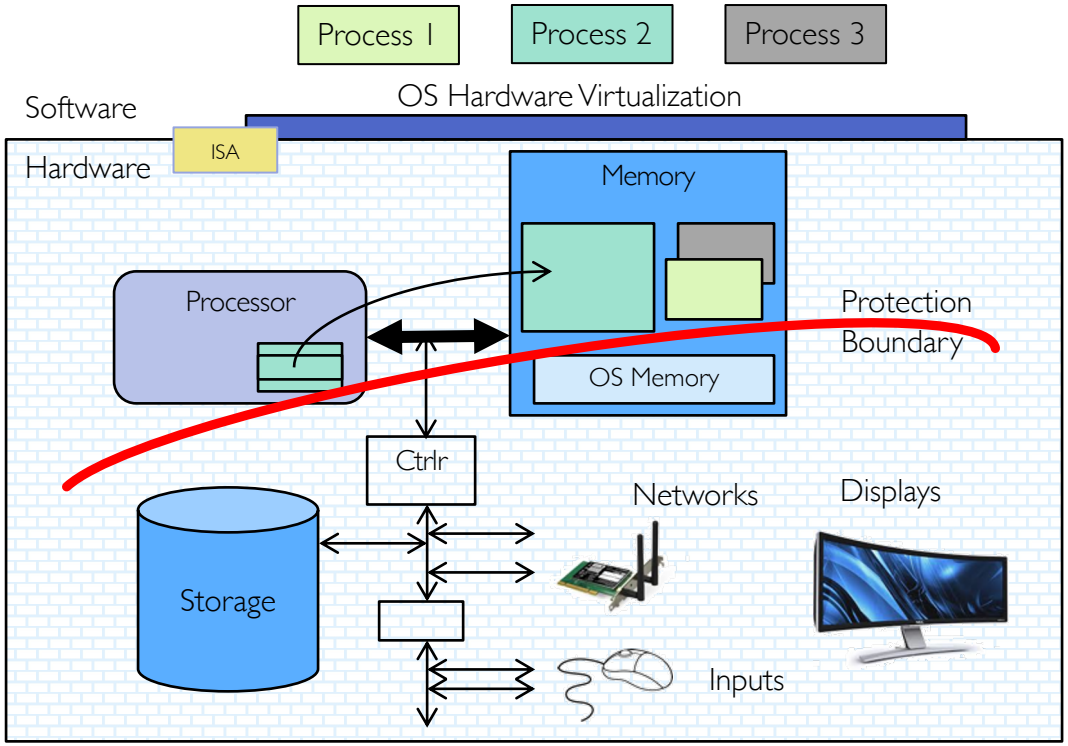
# OS Basics: Switching Processes (cont.)



# OS Basics: Protection



# OS Basics: Protection (cont.)



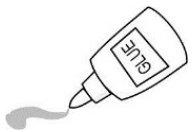

- OS isolates processes from each other
- OS isolates itself from other processes
- … even though they run on the same HW!

# What is an Operating System? (cont.)

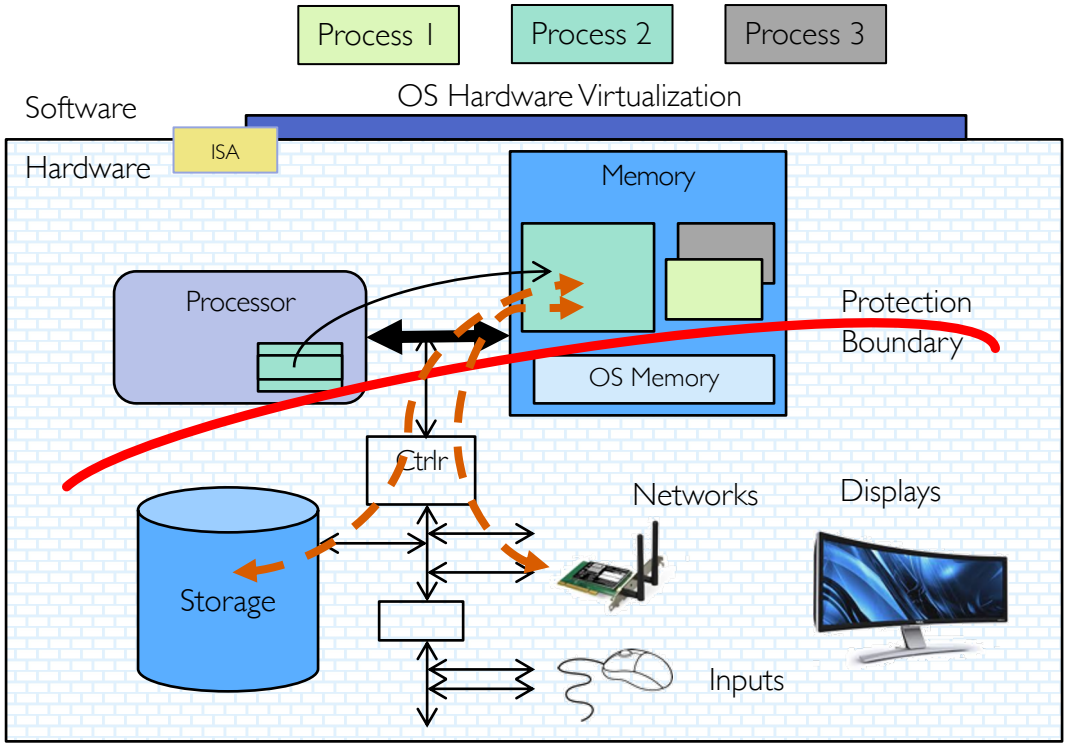
- Illusionist
  - Provide clean, easy-to-use abstractions of physical resources
    - Infinite memory, dedicated machine
    - Higher level objects: files, users, messages
    - Masking limitations, virtualization

- 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

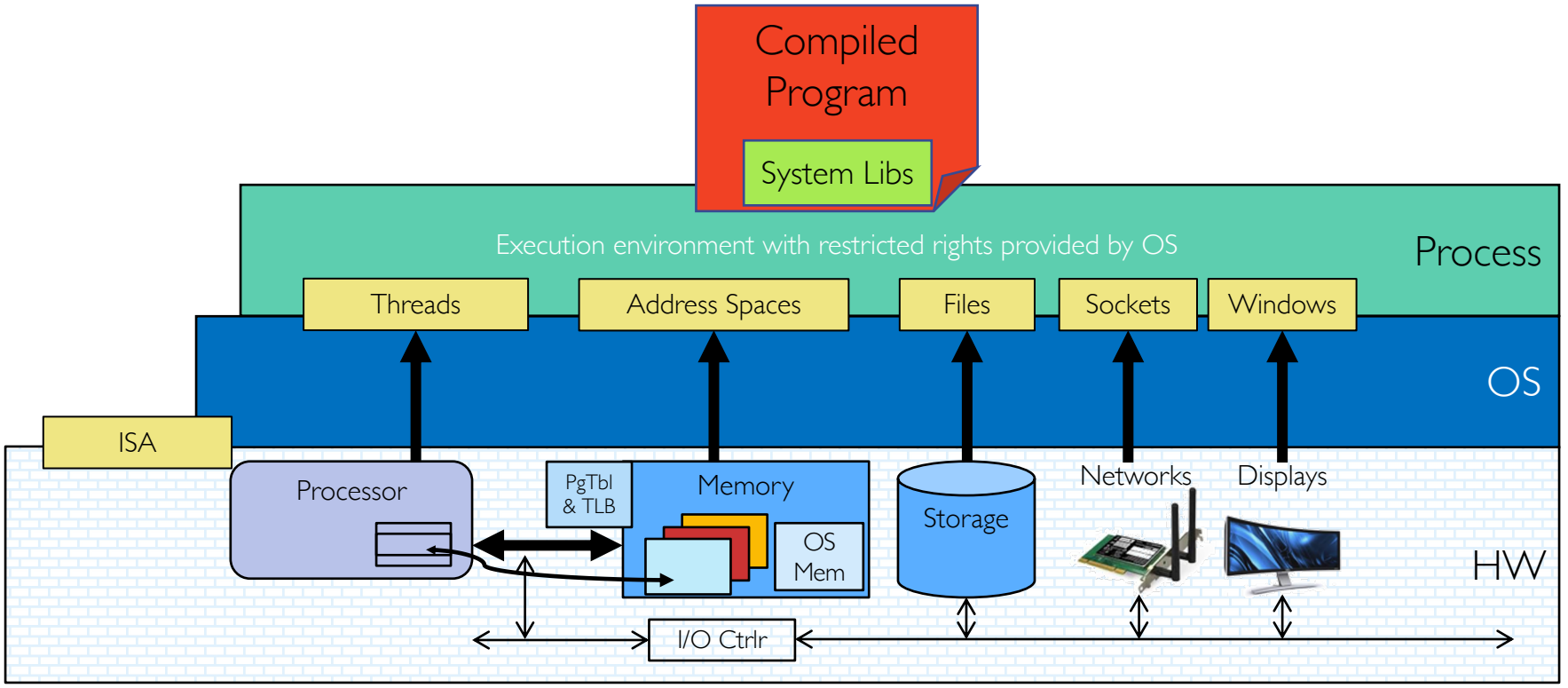


# OS Basics: I/O

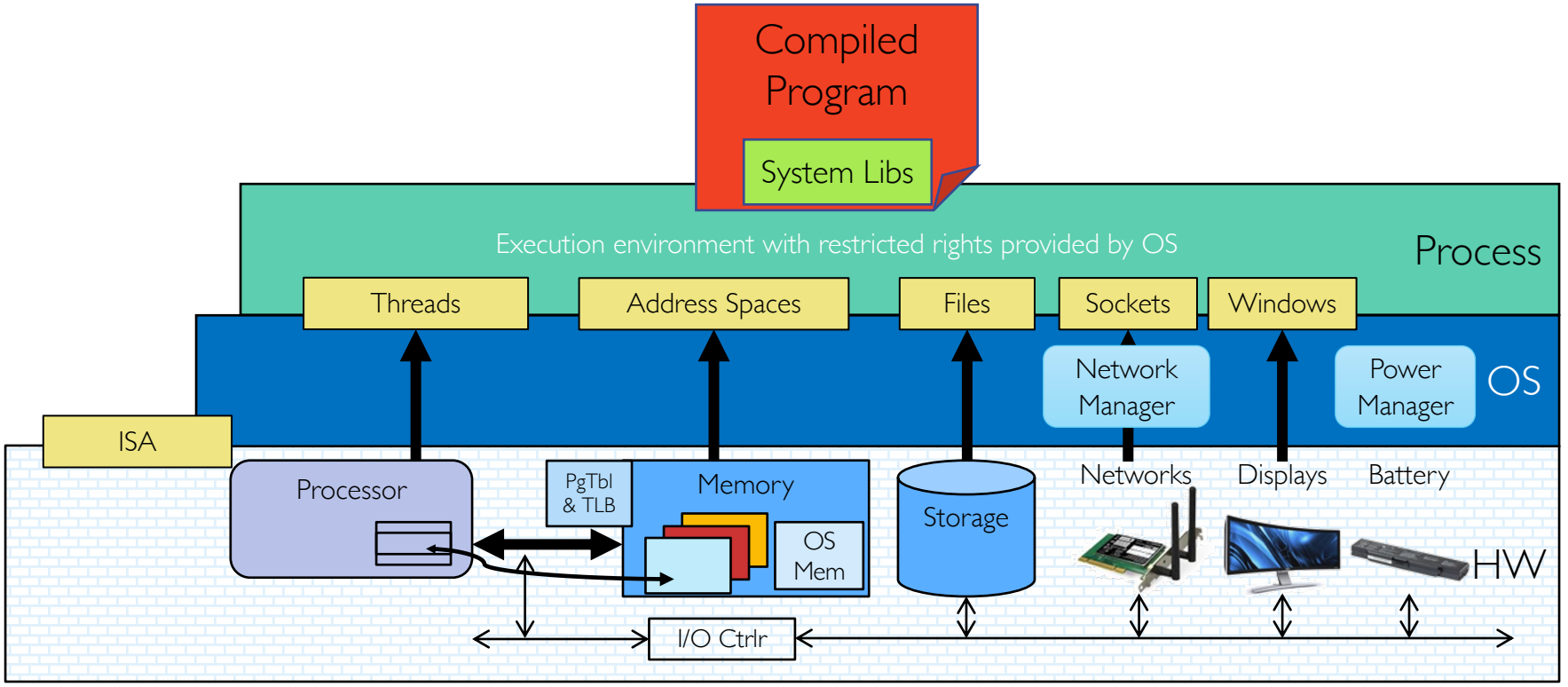



- OS provides common services in the form of I/O

# OS Basics: Look and Feel



# OS Basics: Background Management

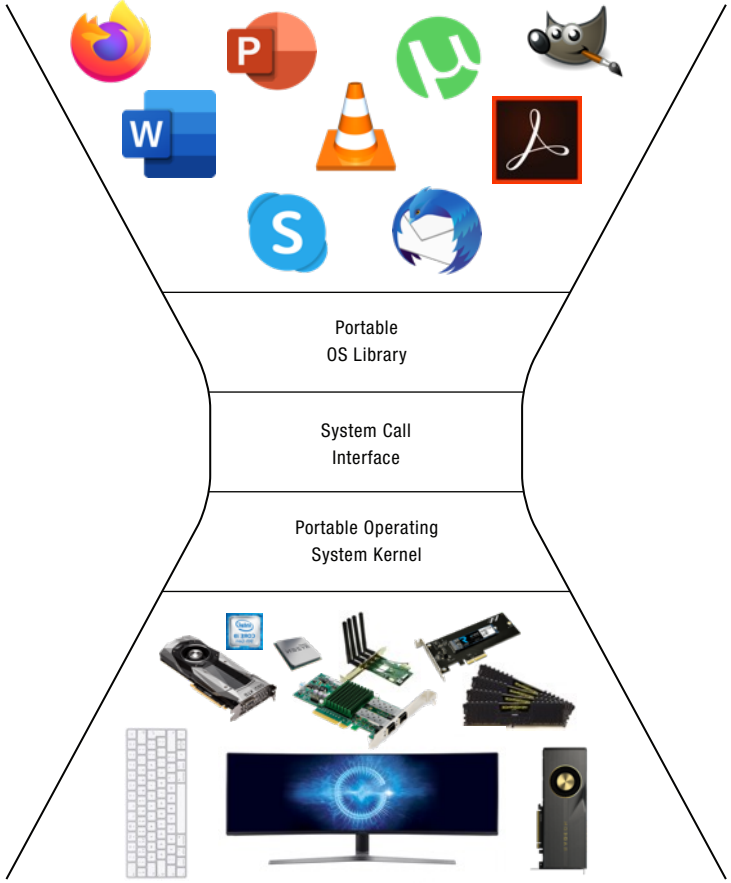


# OS Basics: Hardware Support

- 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!

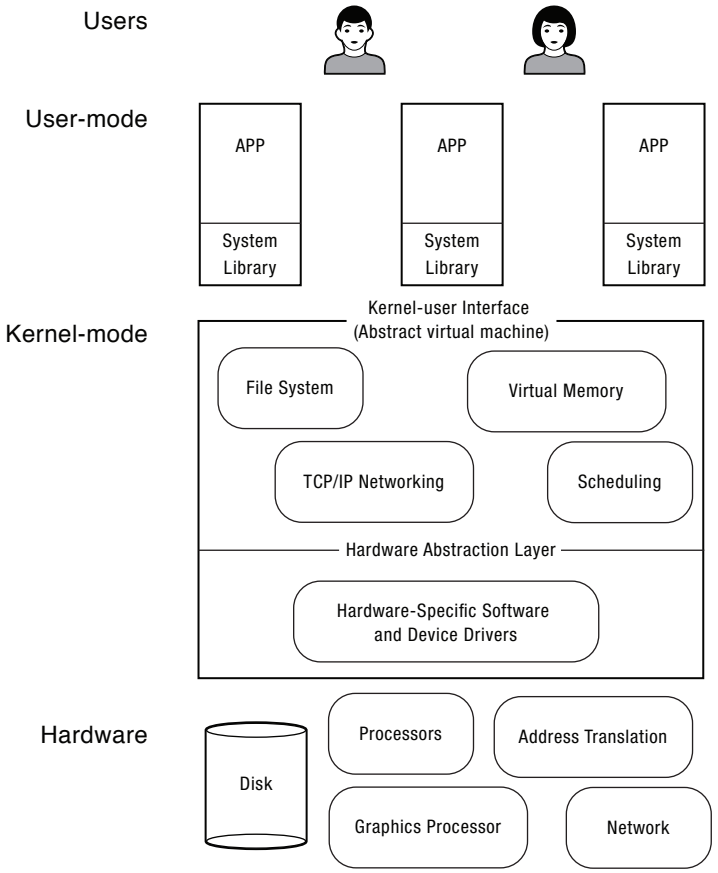
# What Do Operating Systems Do?

- 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)

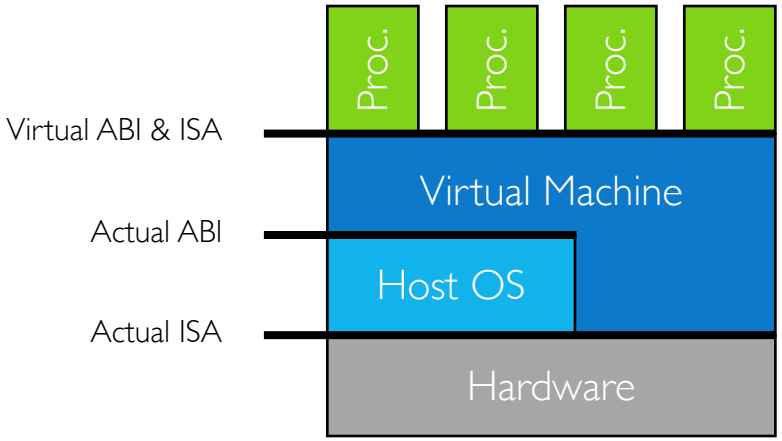


# Virtual Machines (VMs)

- 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)

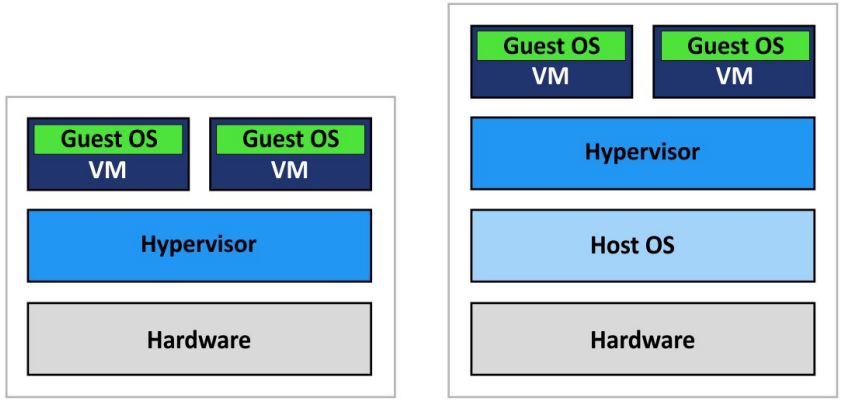
# Process VMs

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



# System Virtual Machines: Layers of OSes

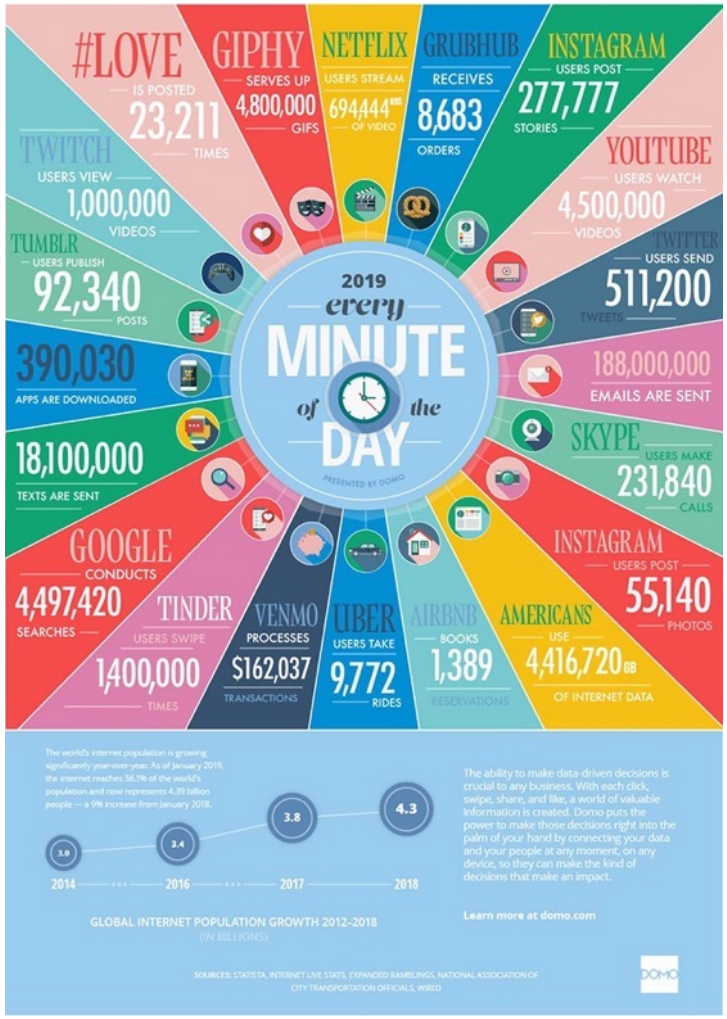
- Runs OSes
  - Useful for OS development and testing programs on other OSes
- Hypervisors create and run virtual machines
- Type-I hypervisors allocate HW to VMs in addition to managing them
  - E.g., Xen, VMWare ESXi
- Type-II hypervisors rely on host OS for HW management
  - E.g., Virtual Box, VMWare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



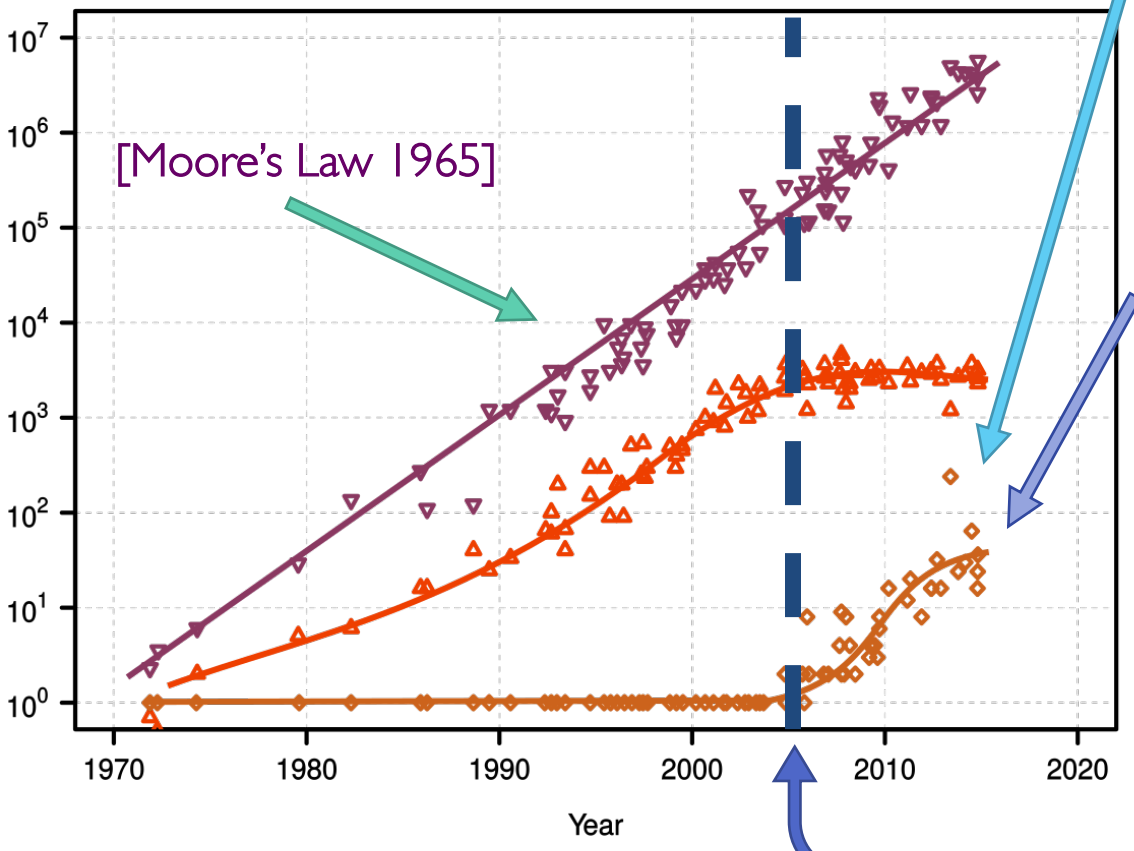

Operating systems are at the heart of it all …

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

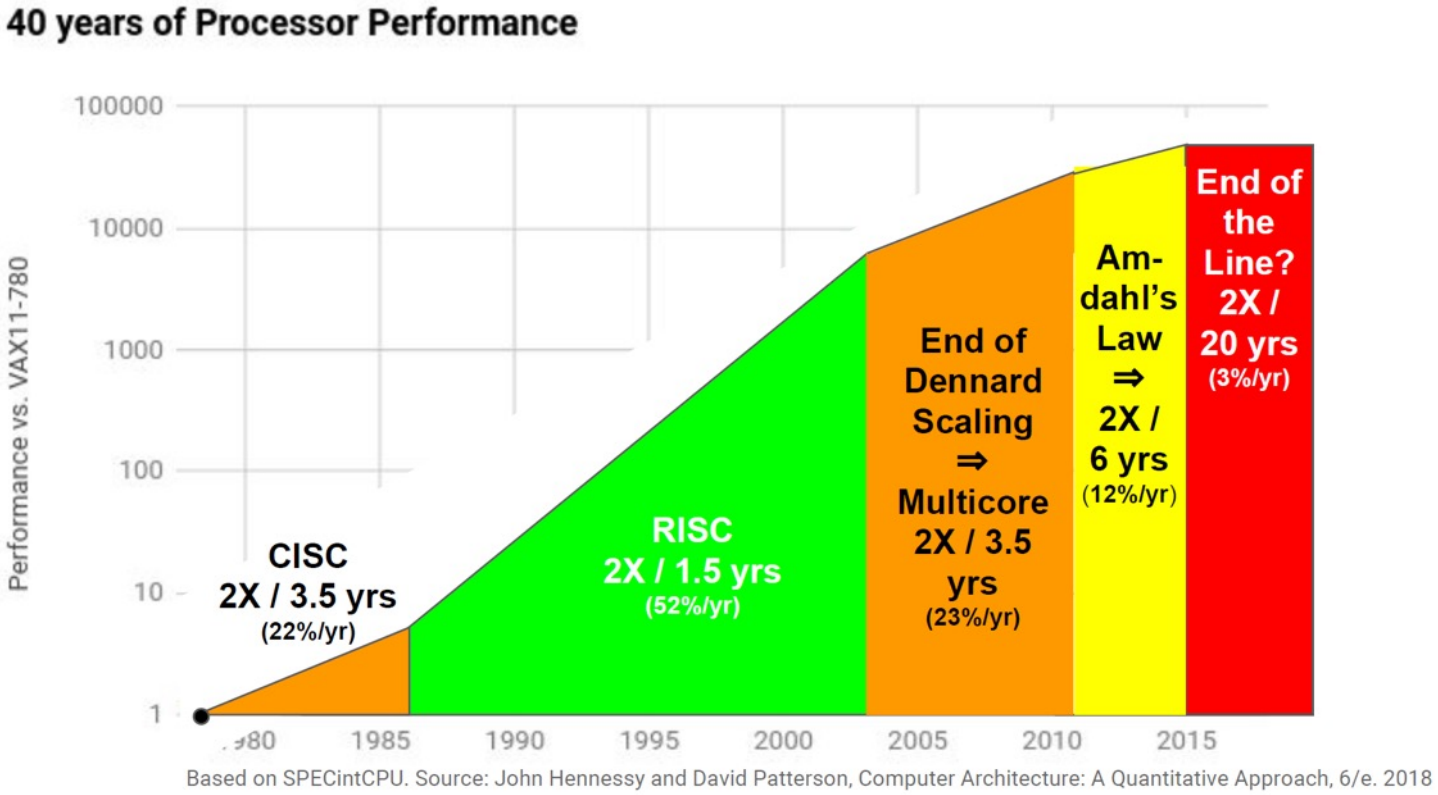
# Technology Trends

How do we program these?

Parallelism must be exploited at all levels



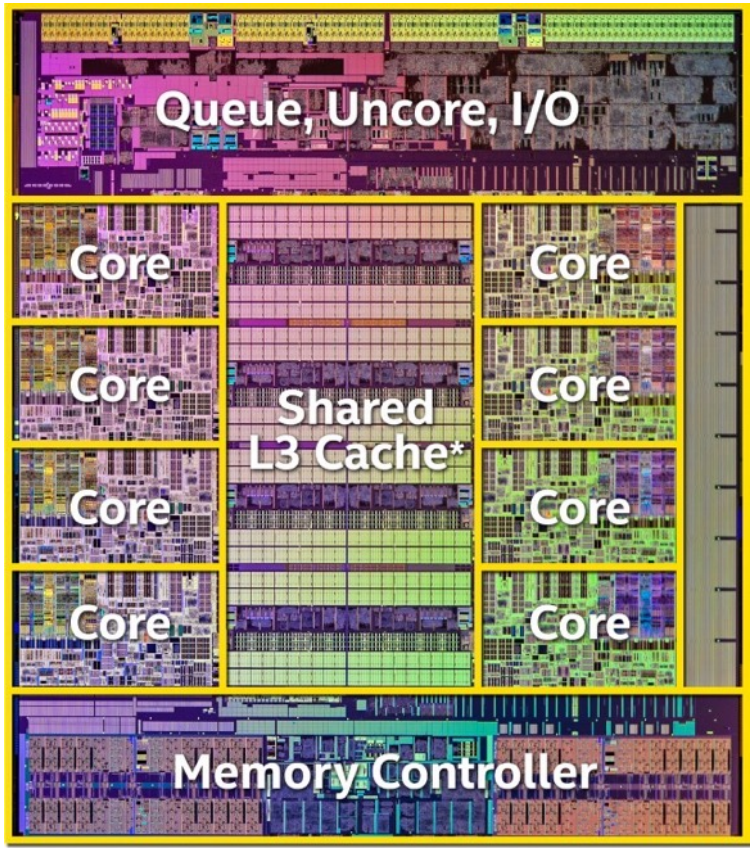
# End of Growth of Single Program Speed




From John Hennessy and David Patterson's 2017 ACM A.M. Turing Award Lecture

# Modern Processors

Intel Haswell E

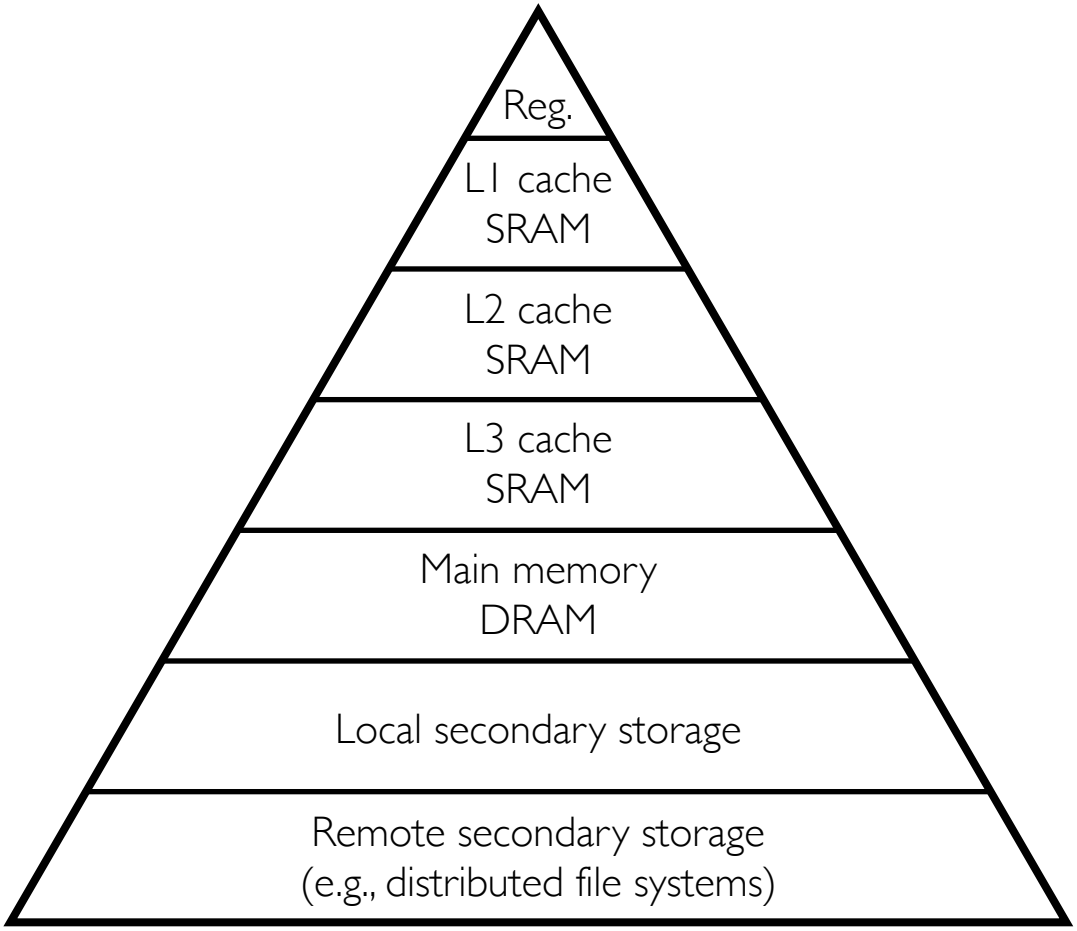



- Intel Xeon Platinum 9282
  - 14nm processor
  - 56 cores, 112 threads
  - 1.75MB data and ins. L1 cache
  - 56MB L2 cache
  - 77MB shared L3 cache
  - 8B transistors
- AMD EPYC 7H12
  - 7nm processor
  - 64 cores, 128 threads
  - 2MB data and ins. L1 cache
  - 32MB L2 cache
  - 256MB shared L3 cache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

# Memory Hierarchy

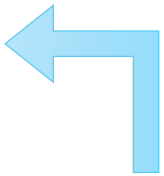
Smaller
Faster
Costlier (per byte)

Larger
Slower
Cheaper (per byte)



# 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 |



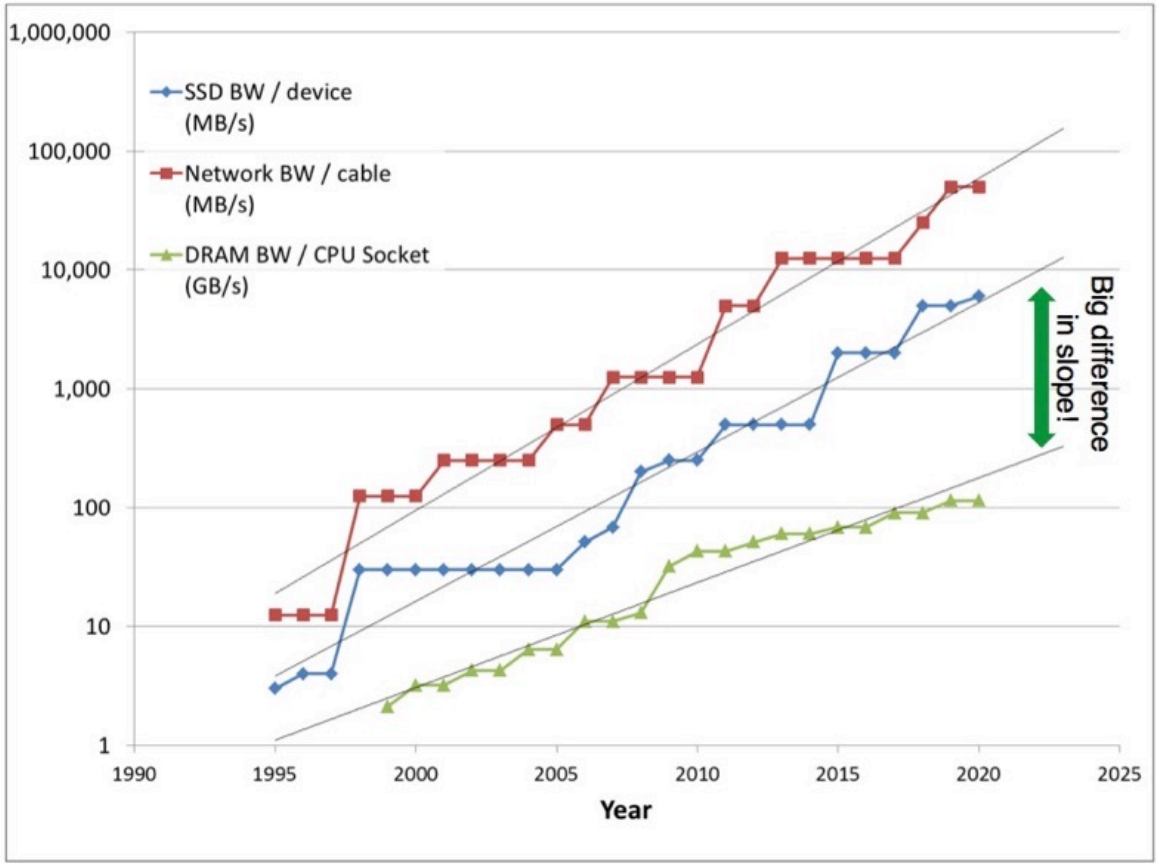
Key stroke ~100 ms

# Network, IO, and Memory Bandwidth Trends

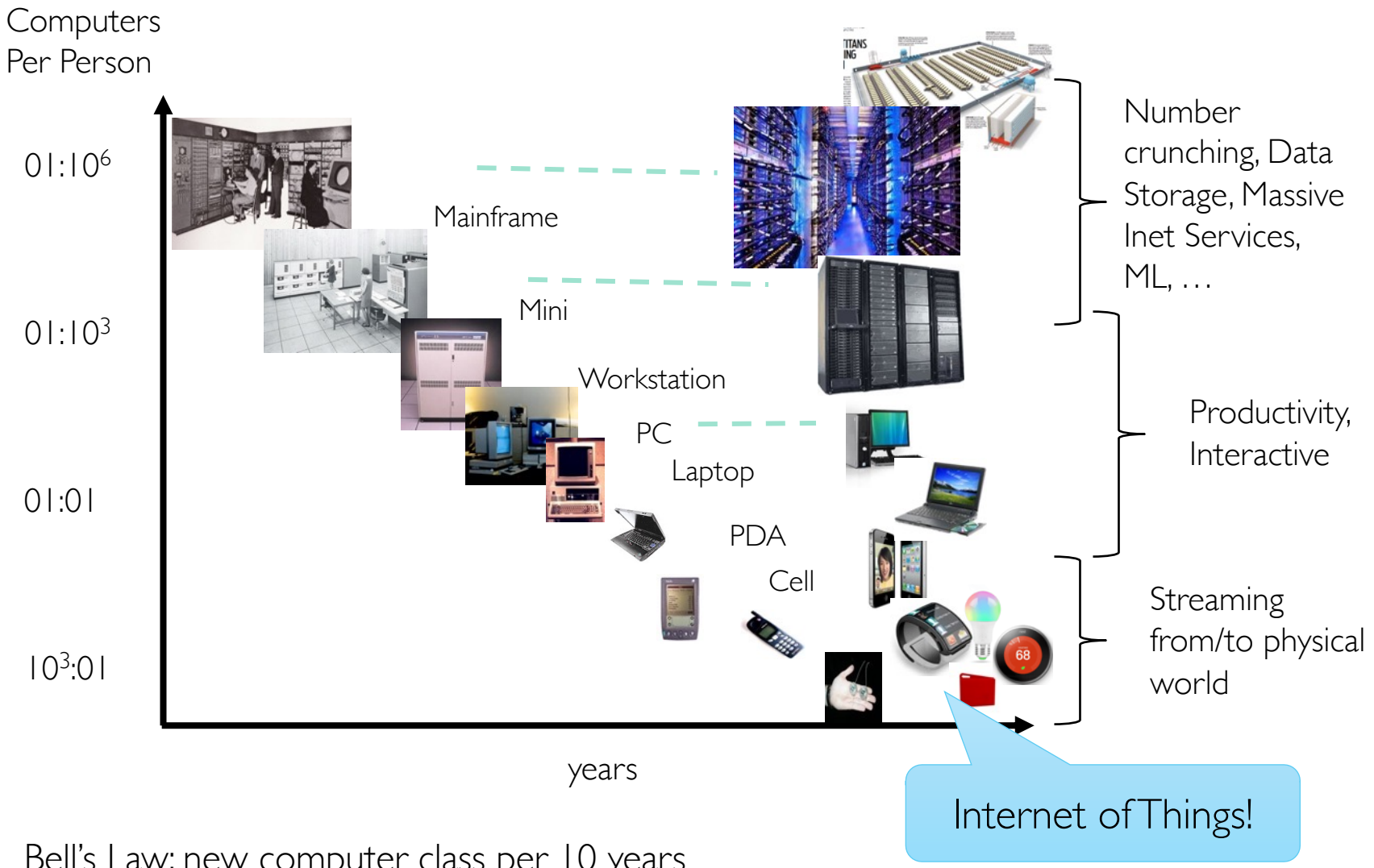
## Network, Storage, & DRAM trends

### 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 …

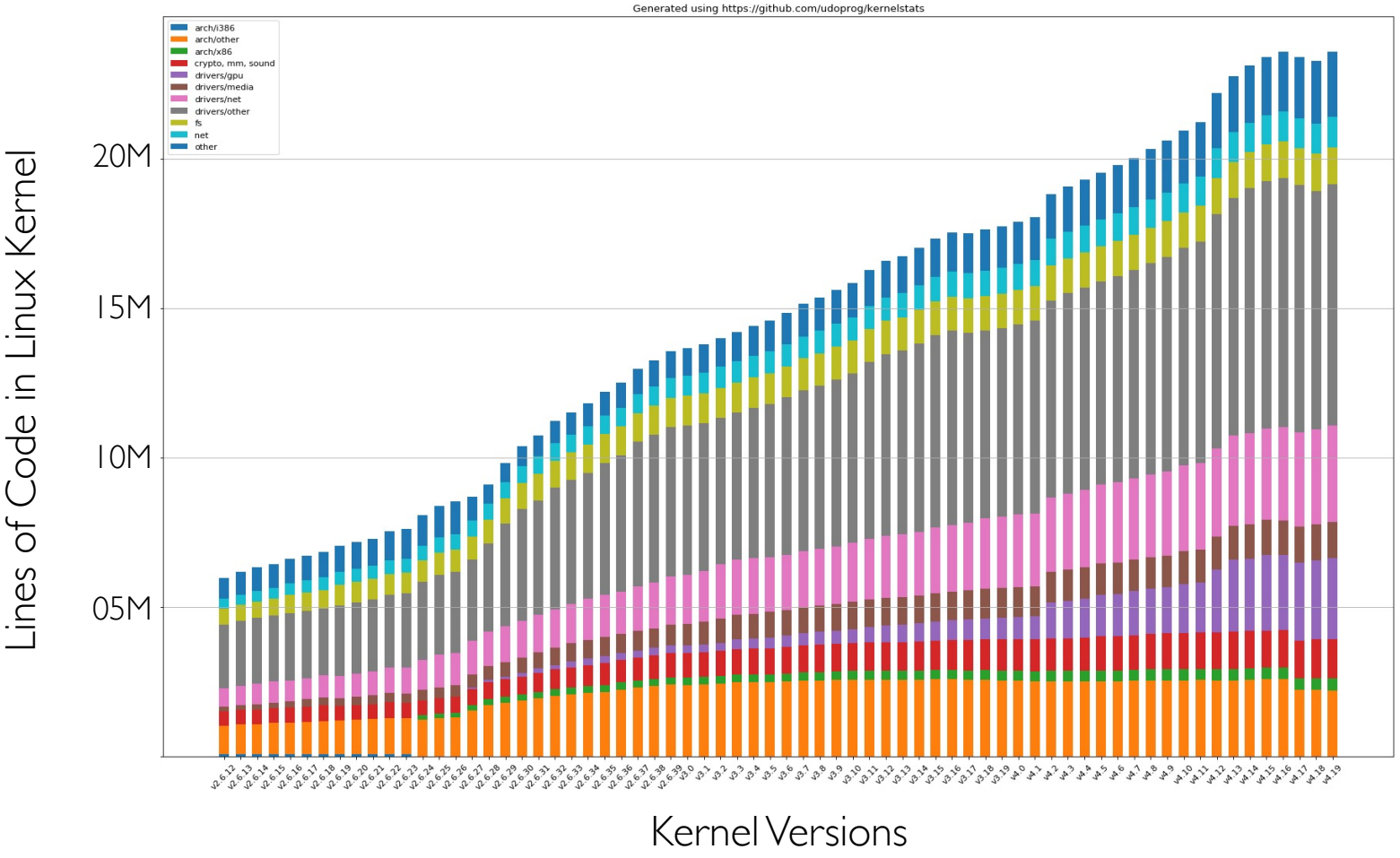
- Multiple users on computer at the same time
  - Multiprogramming: run multiple programs at the same time
  - Interactive performance: try to complete everyone's tasks quickly
  - As computers became cheaper, more important to optimize for user time, not computer time

# 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



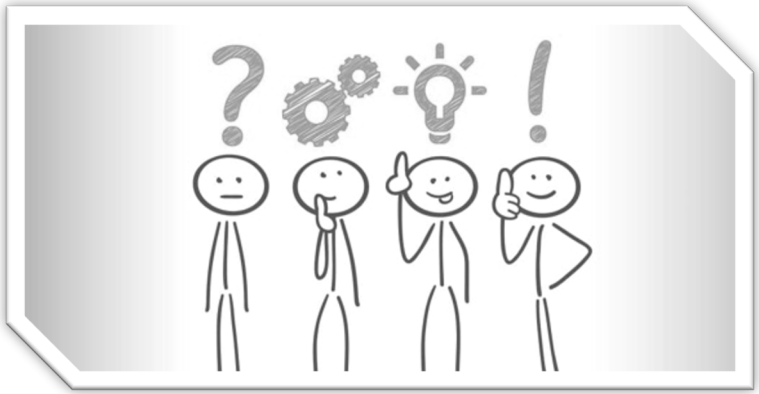
# How do We Tame Complexity?

- 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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