UC Berkeley
Teaching Professor
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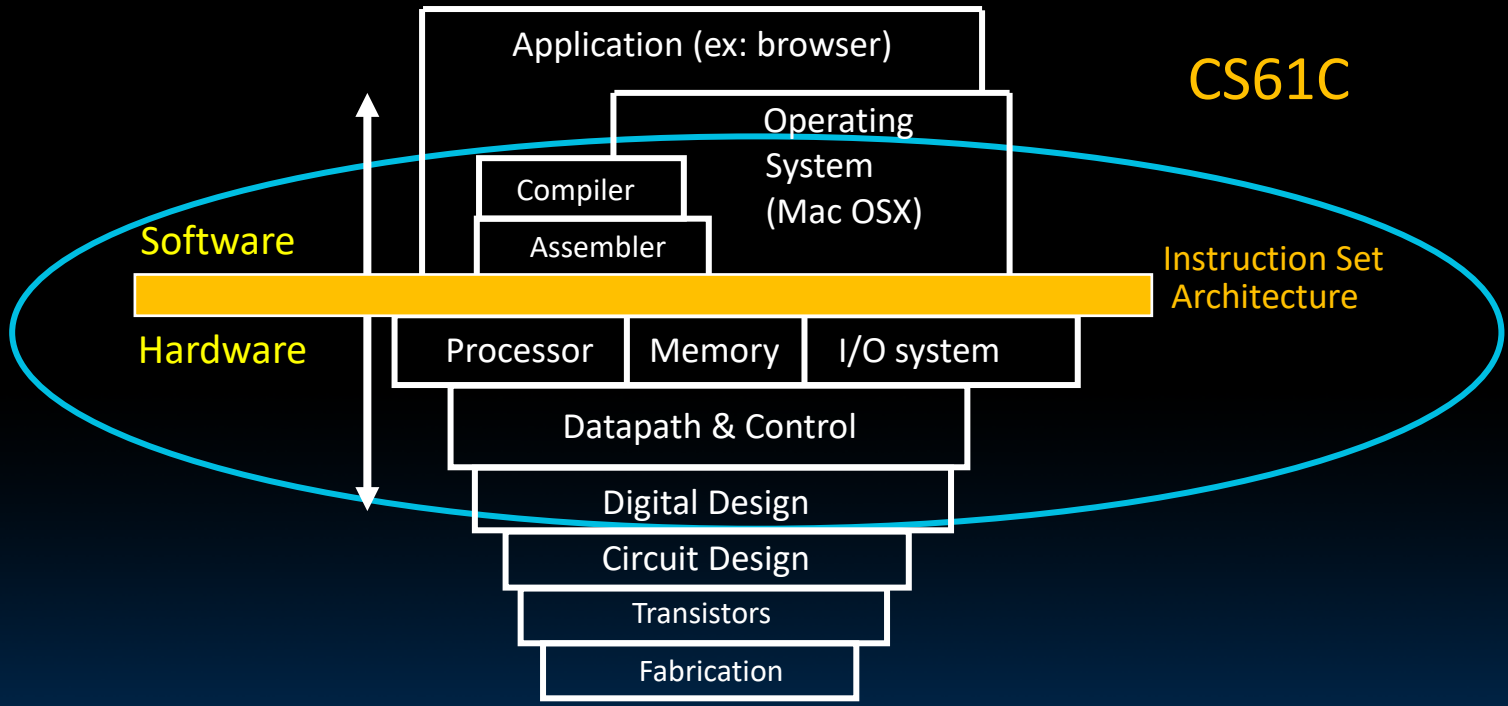
CS61C

Great Ideas in Computer Architecture (a.k.a. Machine Structures)

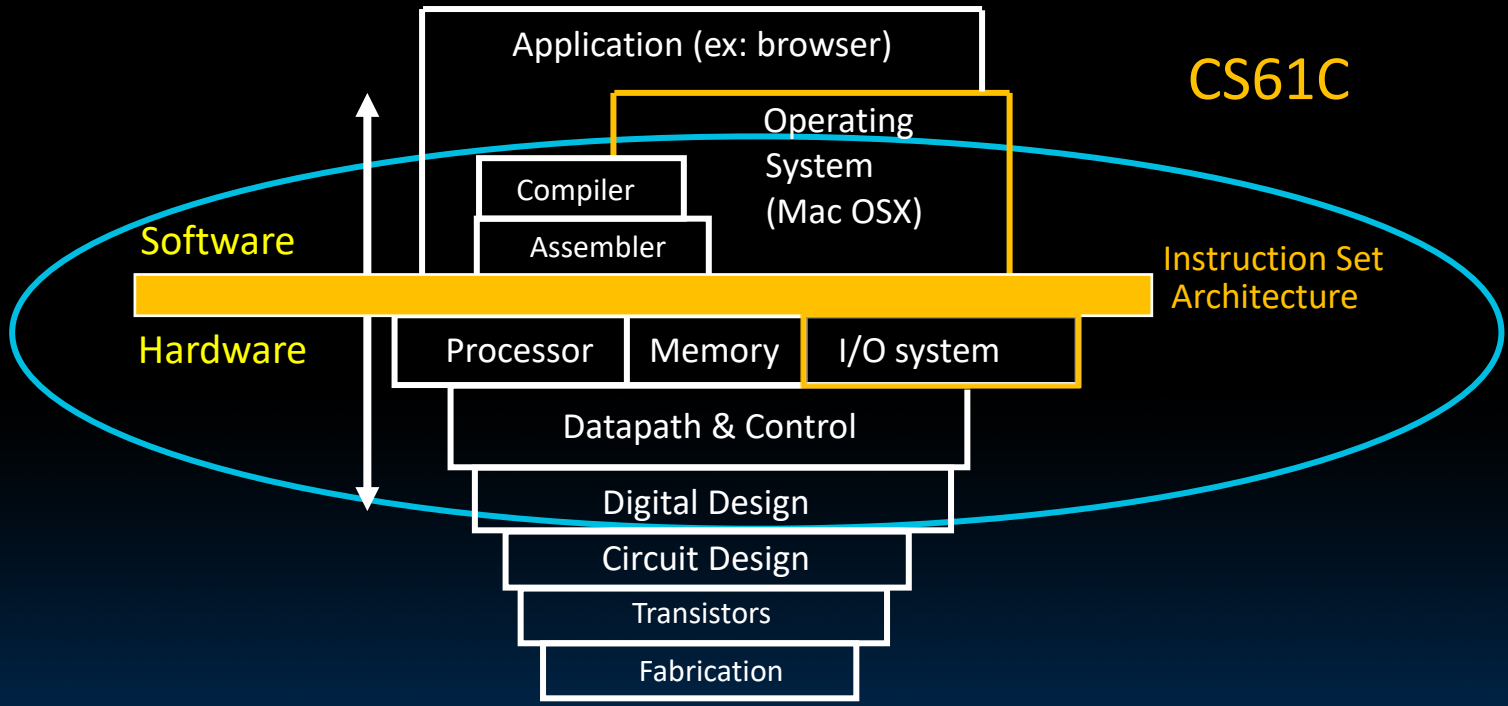
UC Berkeley
Professor
Bora Nikolić

Operating Systems and Virtual Memory

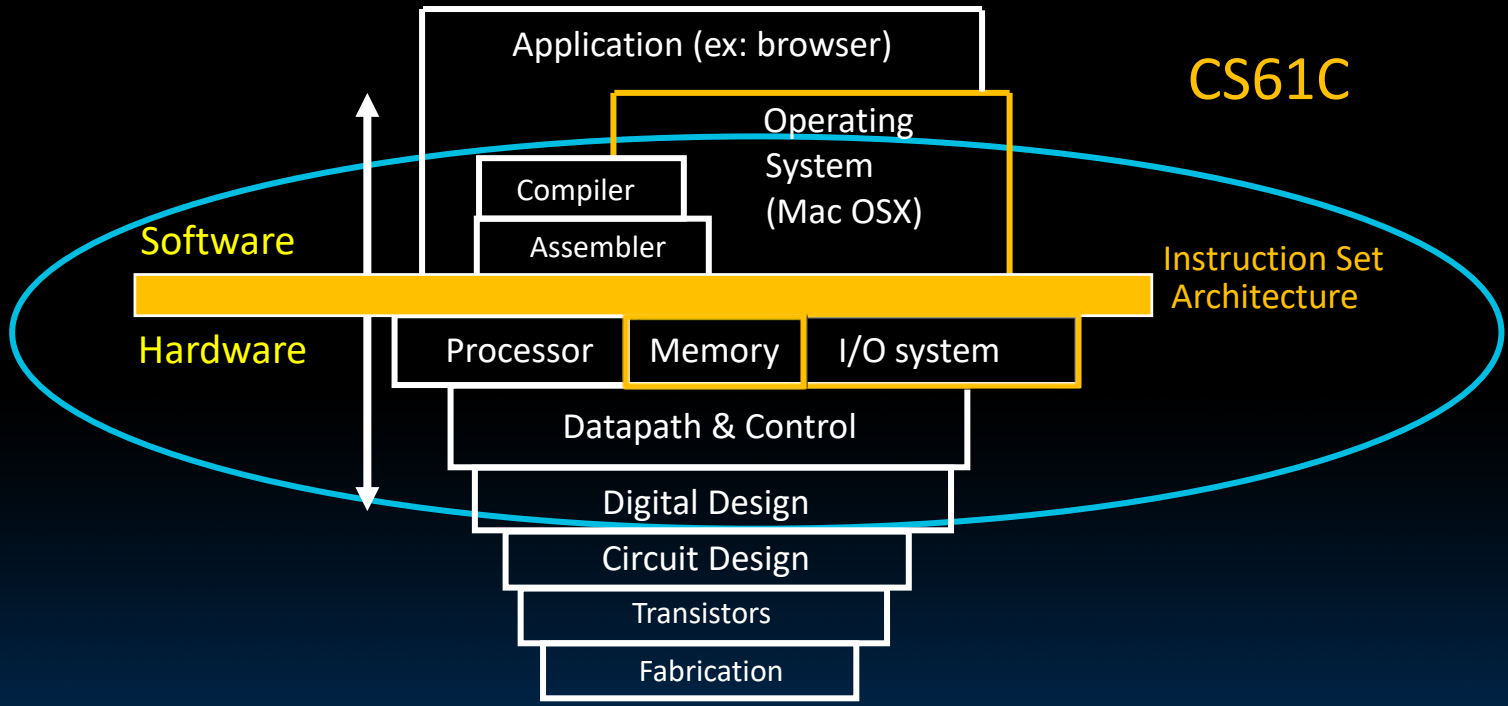
Machine Structures



Machine Structures



Machine Structures



New-School Machine Structures

Software

Parallel Requests
Assigned to computer
e.g., Search "Cats"

Parallel Threads
Assigned to core e.g., Lookup, Ads

Parallel Instructions
>1 instruction @ one time
e.g., 5 pipelined instructions

Parallel Data
>1 data item @ one time
e.g., Add of 4 pairs of words

Hardware descriptions
All gates work in parallel at same time

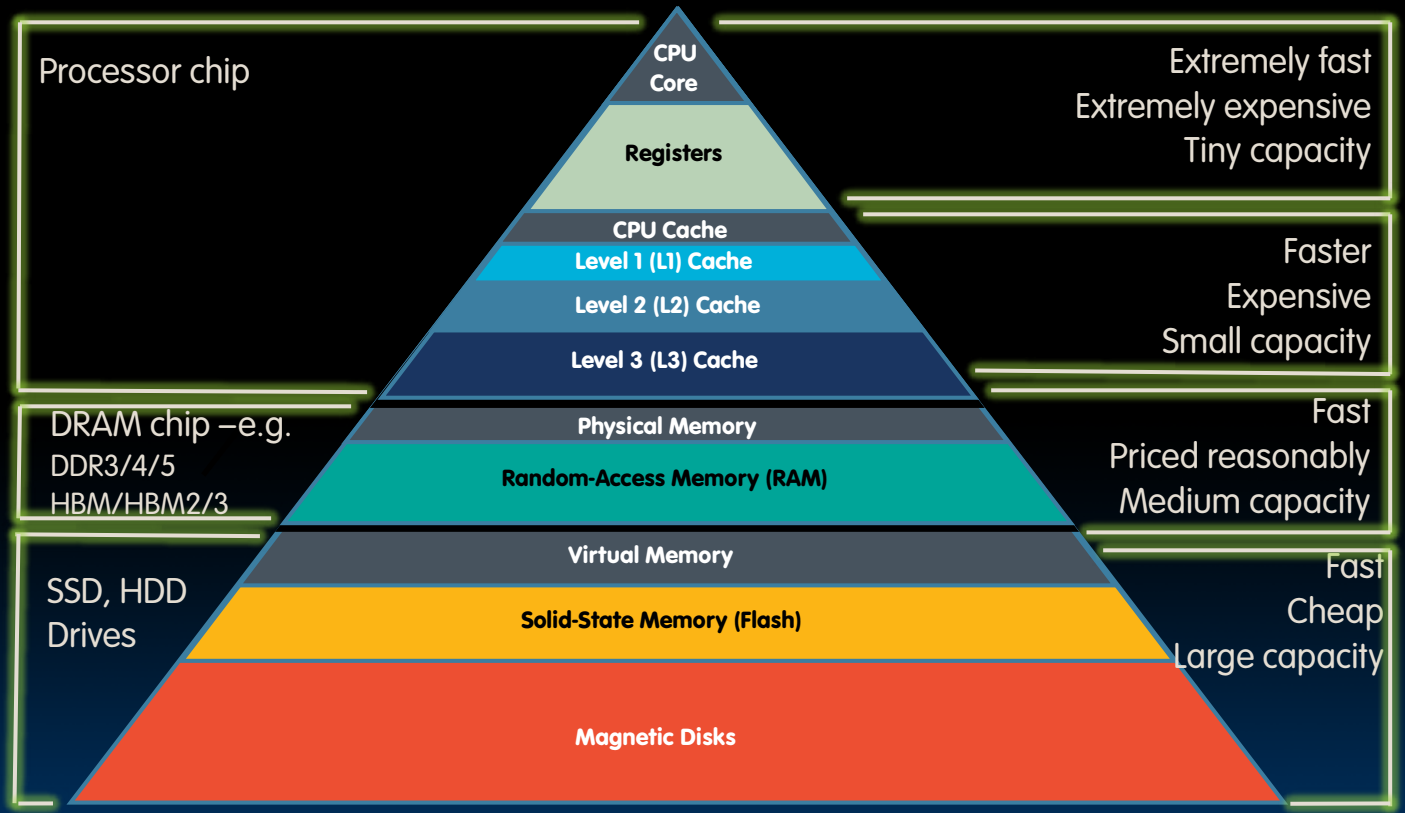
Harness Parallelism & Achieve High Performance

Hardware

Warehouse Scale Computer

Smart Phone

Great Idea #3: Principle of Locality / Memory Hierarchy



CS61C so far...

C Programs

```
#include <stdlib.h>

int fib(int n) {
  return
    fib(n-1) +
    fib(n-2);
}
```

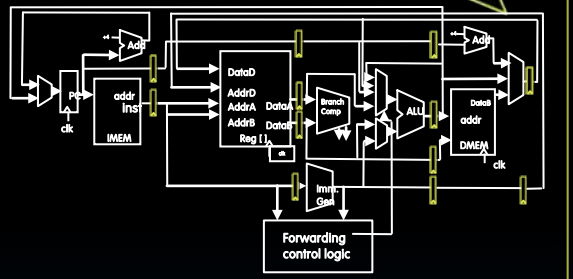
Project 1

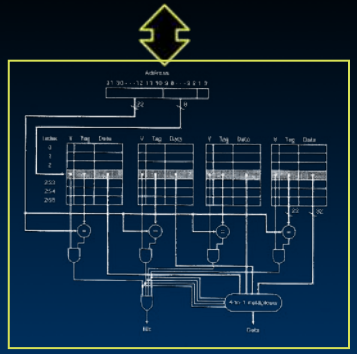
RISC-V Assembly

```
.foo
lw t0, 4(a0)
addi t1, t0, 3
beq t1, t2, foo
nop
```

Project 2

Project 3





So How is a Laptop Any Different?

Adding I/O

C Programs

```
#include <stdlib.h>

int fib(int n) {
  return
    fib(n-1) +
    fib(n-2);
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Project 1

RISC-V Assembly

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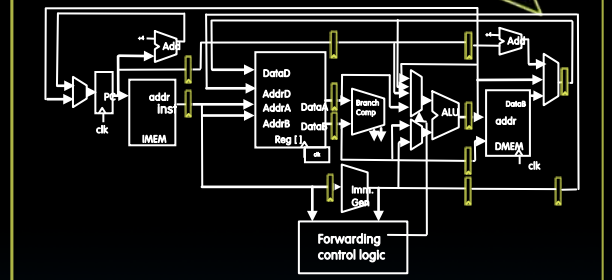
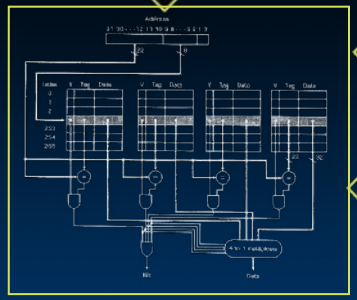
Project 2

Project 3



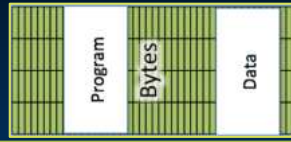
This module: Memory (DRAM) Storage (Disk) and I/O

Screen | Keyboard | Storage

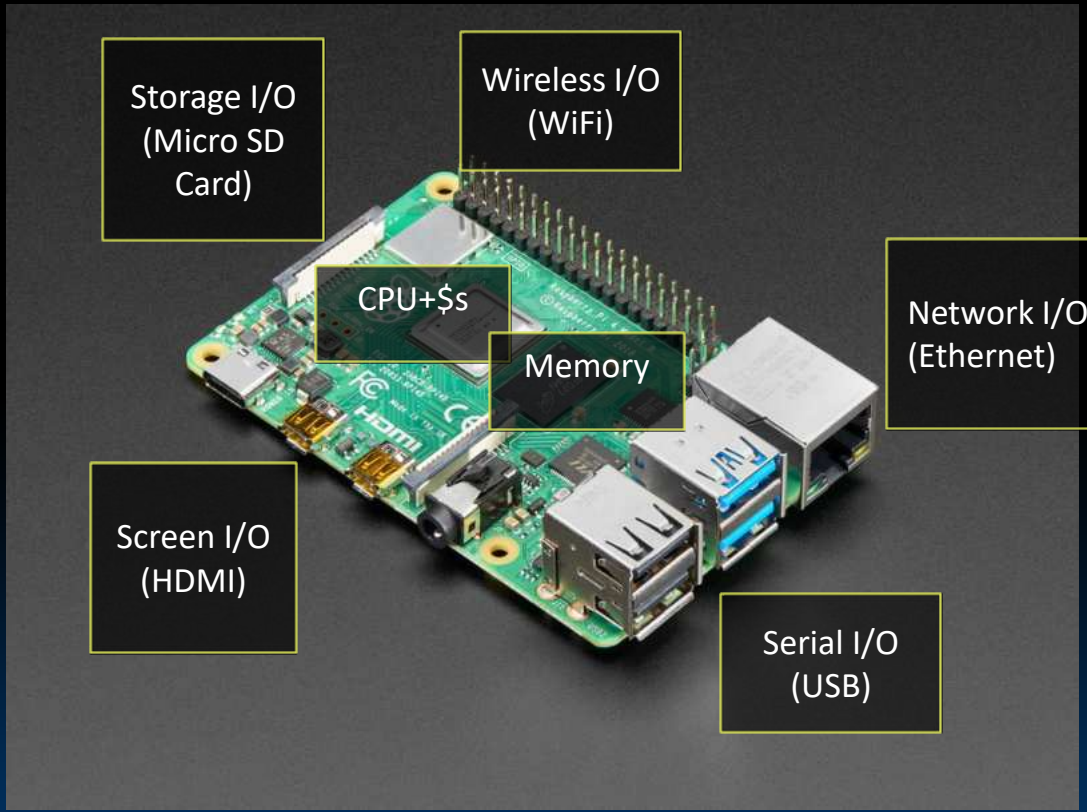


I/O (Input/Output)

Memory



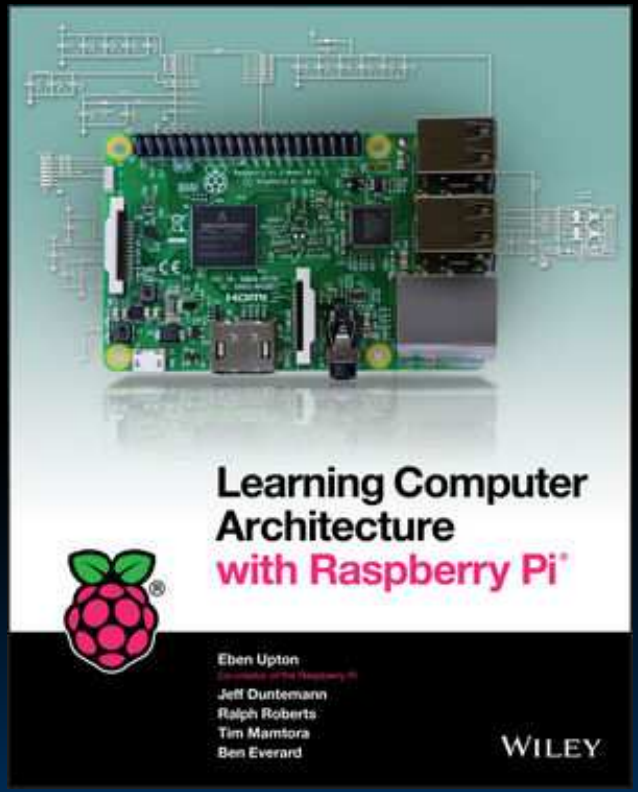
Raspberry Pi ($35)



It's a Real Computer!

CS61C with Raspberry PI?

- Lot's of concepts from 61C covered in a book, with Raspberry Pi exercises



(and it is free to download if you are a Cal student:

https://onlinelibrary.wiley.com/doi/book/10.1002/9781119415534)

But Wait...

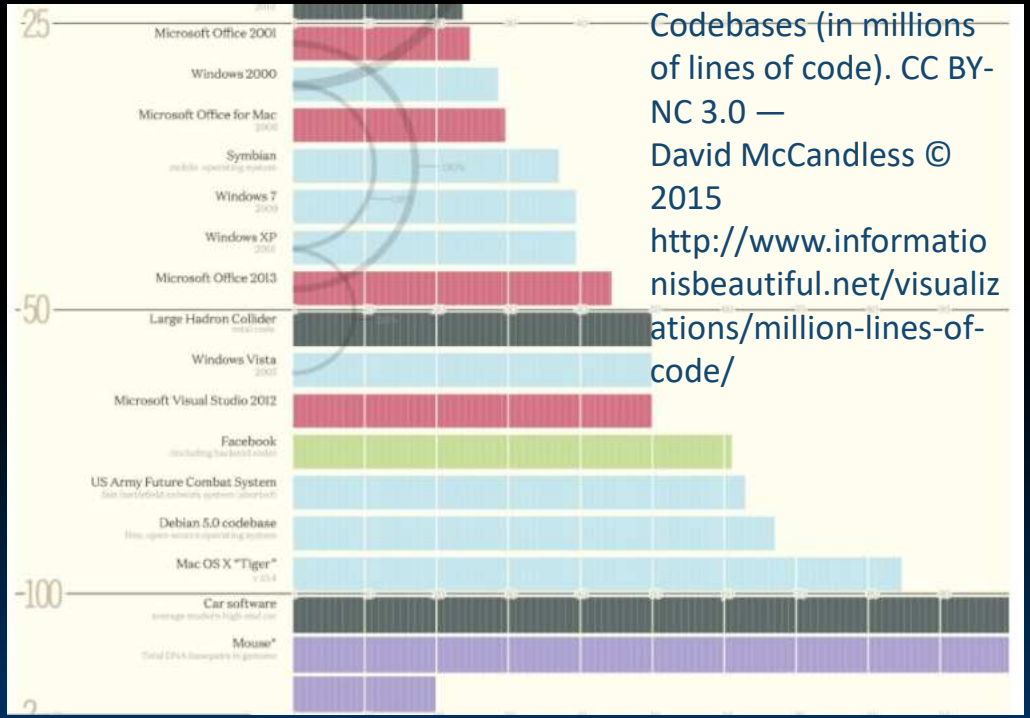
- That's not the same! When we run VENUS, it only executes one program and then stops.
- When I switch on my computer, I get this:

Yes, but that's *just* software! The Operating System (OS)

Operating System Basics

Well, "Just Software"

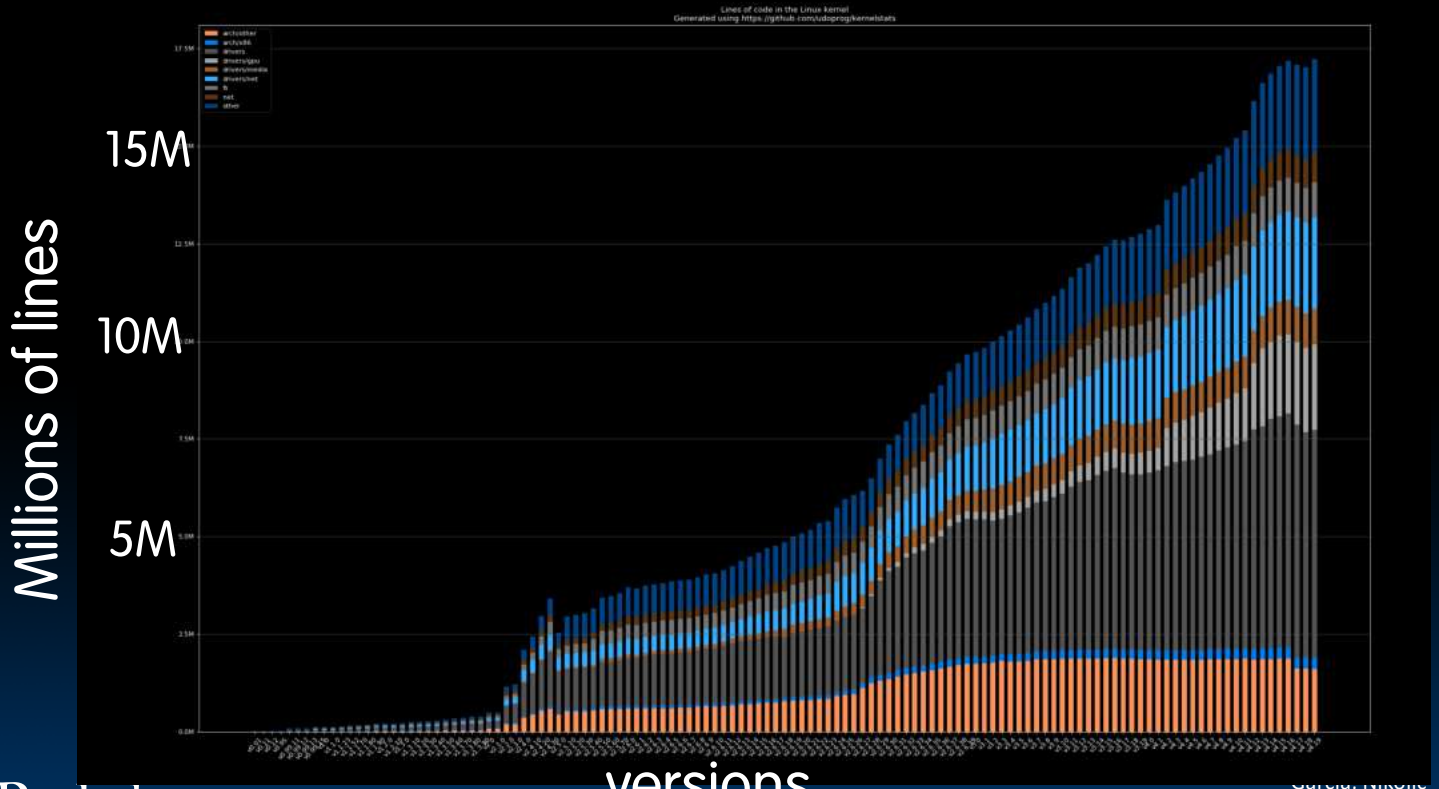
- The biggest piece of software on your machine?
- How many lines of code? These are guesstimates:



Codebases (in millions of lines of code). CC BY-NC 3.0 — David McCandless © 2015 http://www.informationisbeautiful.net/visualizations/million-lines-of-code/

Operating System

Lines of code in Linux kernel



What Does the OS do?

- OS is the (first) thing that runs when computer starts
- Finds and controls all devices in the machine in a general way
  - Relying on hardware specific "device drivers"
- Starts services (100+)
  - File system,
  - Network stack (Ethernet, WiFi, Bluetooth, …),
  - TTY (keyboard),
  - …
- Loads, runs and manages programs:
  - Multiple programs at the same time (time-sharing)
  - Isolate programs from each other (isolation)
  - Multiplex resources between applications (e.g., devices)

What Does the Core of the OS Do?

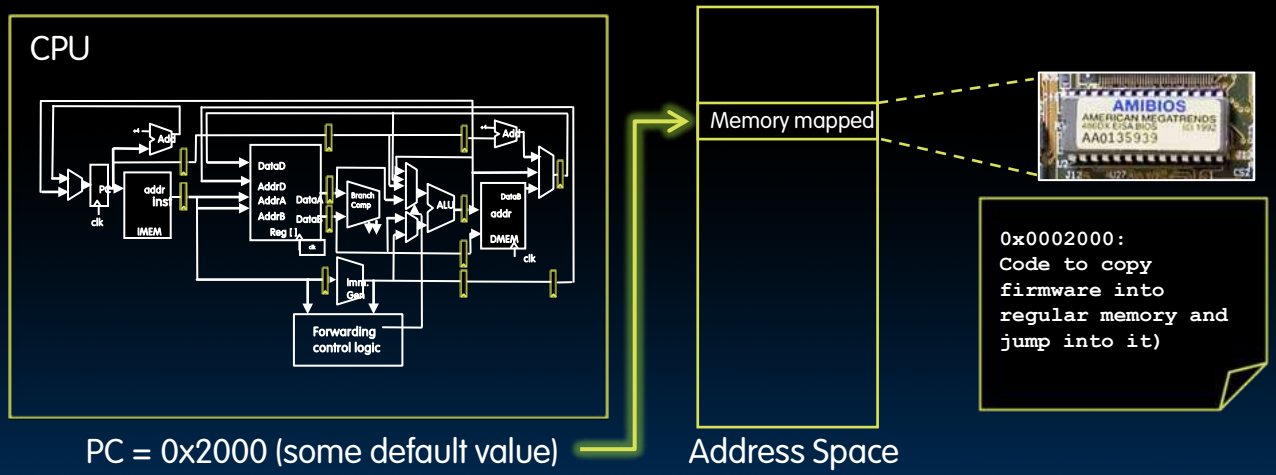
- Provide ***isolation*** between running processes
  - Each program runs in its own little world •
- Provide ***interaction*** with the outside world
  - Interact with "devices": Disk, display, network, etc... 11

What Does OS Need from Hardware?

- Memory translation
  - Each running process has a mapping from "virtual" to "physical" addresses that are different for each process
  - When you do a load or a store, the program issues a virtual address... But the actual memory accessed is a physical address
- Protection and privilege
  - Split the processor into at least two running modes: "User" and "Supervisor"
    - RISC-V also has "Machine" below "Supervisor"
  - Lesser privilege ***can not*** change its memory mapping
    - But "Supervisor" ***can*** change the mapping for any given program
    - And supervisor has its own set of mapping of virtual->physical
- Traps & Interrupts
  - A way of going into Supervisor mode on demand

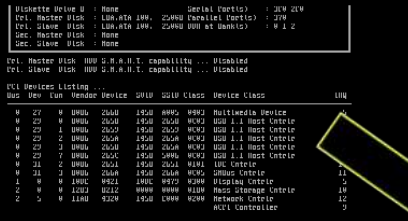
What Happens at Boot?

- When the computer switches on, it does the same as VENUS: the CPU executes instructions from some start address (stored in Flash ROM)



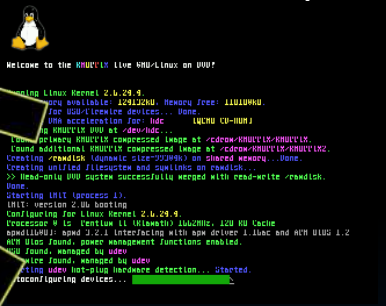
What Happens at Boot?

1. BIOS*: Find a storage device and load first sector (block of data)



2. Bootloader (stored on, e.g., disk): Load the OS *kernel* from disk into a location in memory and jump into it

4. Init: Launch an application that waits for input in loop (e.g., Terminal/Desktop/...



3. OS Boot: Initialize services, drivers, etc.

*BIOS: Basic Input Output System

Operating System Functions

Launching Applications

- Applications are called “processes” in most OSs
  - Thread: shared memory
  - Process: separate memory
  - Both threads and processes run (pseudo) simultaneously
- Apps are started by another process (e.g., shell) calling an OS routine (using a “syscall”)
  - Depends on OS; Linux uses fork to create a new process, and execve (execute file command) to load application
- Loads executable file from disk (using the file system service) and puts instructions & data into memory (.text, .data sections), prepares stack and heap
- Set argc and argv, jump to start of main
- Shell waits for main to return (join)

Supervisor Mode

- If something goes wrong in an application, it could crash the entire machine. And what about malware, etc.?
- The OS enforces resource constraints to applications (e.g., access to memory, devices)
- To help protect the OS from the application, CPUs have a supervisor mode (e.g., set by a status bit in a special register)
  - A process can only access a subset of instructions and (physical) memory when not in supervisor mode (user mode)
  - Process can change out of supervisor mode using a special instruction, but not into it directly – only using an interrupt
  - Supervisory mode is a bit like "superuser"
    - But used much more sparingly (most of OS code does *not* run in supervisory mode)
    - Errors in supervisory mode often catastrophic (blue "screen of death", or "I just corrupted your disk")

Syscalls

- What if we want to call an OS routine? E.g.,
  - to read a file,
  - launch a new process,
  - ask for more memory (malloc),
  - send data, etc.
- Need to perform a syscall:
  - Set up function arguments in registers,
  - Raise software interrupt (with special assembly instruction)
- OS will perform the operation and return to user mode
- This way, the OS can mediate access to all resources, and devices

Interrupts, Exceptions

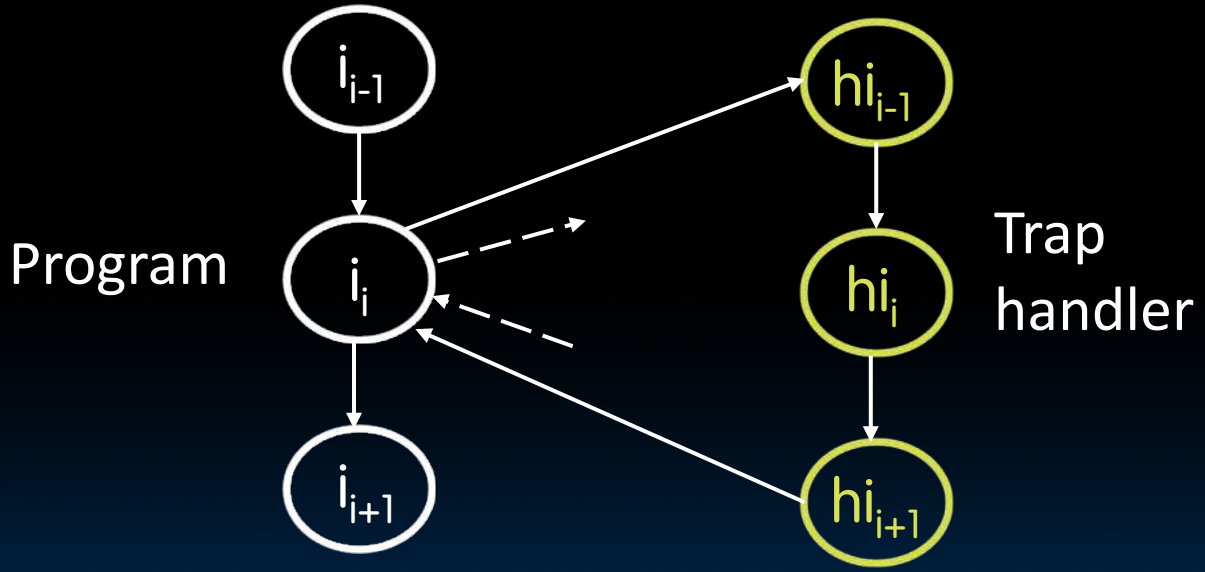
- We need to transition into Supervisor mode when "something" happens
- Interrupt: Something external to the running program
  - Something happens from the outside world
- Exception: Something done by the running program
  - Accessing memory it isn't "supposed" to, executing an illegal instruction, reading a csr not supposed at that privilege
- **ECALL**: Trigger an exception to the higher privilege
  - How you communicate with the operating system: Used to implement "syscalls"
- **EBREAK**: Trigger an exception within the current privilege

Terminology (In 61C)

- Interrupt – caused by an event *external* to current running program
  - E.g., key press, disk I/O
  - Asynchronous to current program
    - Can handle interrupt on any convenient instruction
    - "Whenever it's convenient, just don't wait too long"
- Exception – caused by some event *during* execution of one instruction of current running program
  - E.g., memory error, bus error, illegal instruction, raised exception
  - Synchronous
    - Must handle exception *precisely* on instruction that causes exception
    - "Drop whatever you are doing and act now"
- Trap – action of servicing interrupt or exception by hardware jump to "interrupt or trap handler" code

Trap Handling

- Altering the regular execution flow

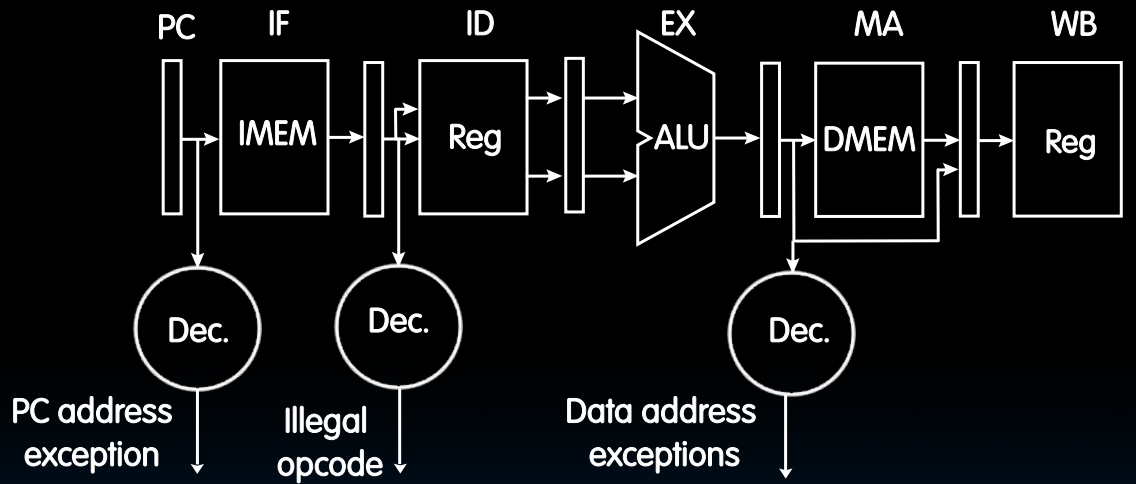


An *external or internal event* that needs to be processed - by another program; often handled by OS. The event is often unexpected from original program's point of view.

Precise Traps

- *Trap handler's view of machine state is that every instruction prior to the trapped one (e.g., memory error) has completed, and no instruction after the trap has executed.*
- Implies that handler can return from an interrupt by restoring user registers and jumping back to interrupted instruction
  - Interrupt handler software doesn't need to understand the pipeline of the machine, or what program was doing!
  - More complex to handle trap caused by an exception than interrupt
- Providing precise traps is tricky in a pipelined superscalar out-of-order processor!
  - But a requirement for things to actually work right!

Exceptions in a 5-Stage Pipeline



Trap Handling

- Exceptions are handled *like pipeline hazards*
  1) Complete execution of instructions before exception occurred
  2) Flush instructions currently in pipeline (i.e., convert to `nop`s or "bubbles")
  3) Optionally store exception cause in status register
     - Indicate type of exception
- 4) Transfer execution to trap handler
- 5) Optionally, return to original program and re-execute instruction

Multiprogramming

- The OS runs multiple applications at the same time
- But not really (unless you have a core per process)
- Switches between processes very quickly (on human time scale) – this is called a “context switch”
- When jumping into process, set timer (we will call this ‘interrupt’)
  - When it expires, store PC, registers, etc. (process state)
  - Pick a different process to run and load its state
  - Set timer, change to user mode, jump to the new PC
- Deciding what process to run is called scheduling

Protection, Translation, Paging

- Supervisor mode alone is not sufficient to fully isolate applications from each other or from the OS
  - Application could overwrite another application's memory.
  - Typically programs start at some fixed address, e.g. 0x8FFFFFFF
    - How can 100's of programs share memory at location 0x8FFFFFFF?
  - Also, may want to address more memory than we actually have (e.g., for sparse data structures)
- Solution: Virtual Memory
  - Gives each process the *illusion* of a full memory address space that it has completely for itself