CS 61C:
Great Ideas in Computer Architecture

Lecture 22:
Operating Systems

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http://inst.eecs.berkeley.edu/~cs61c

CS61C so far…

C Programs

```
#include <stdlib.h>

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

HW 1

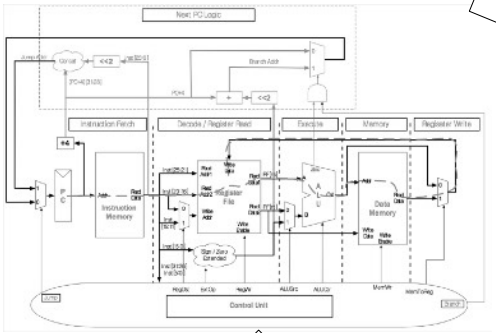
RISC-V Assembly

```
.foo
lw $t0, 4($r0)
addi $t1, $t0, 3
beq $t1, $t2, foo
nop
```

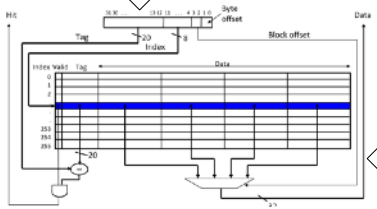
Project 1

Project 2

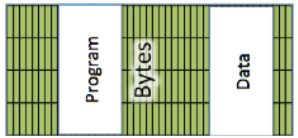
CPU



Caches

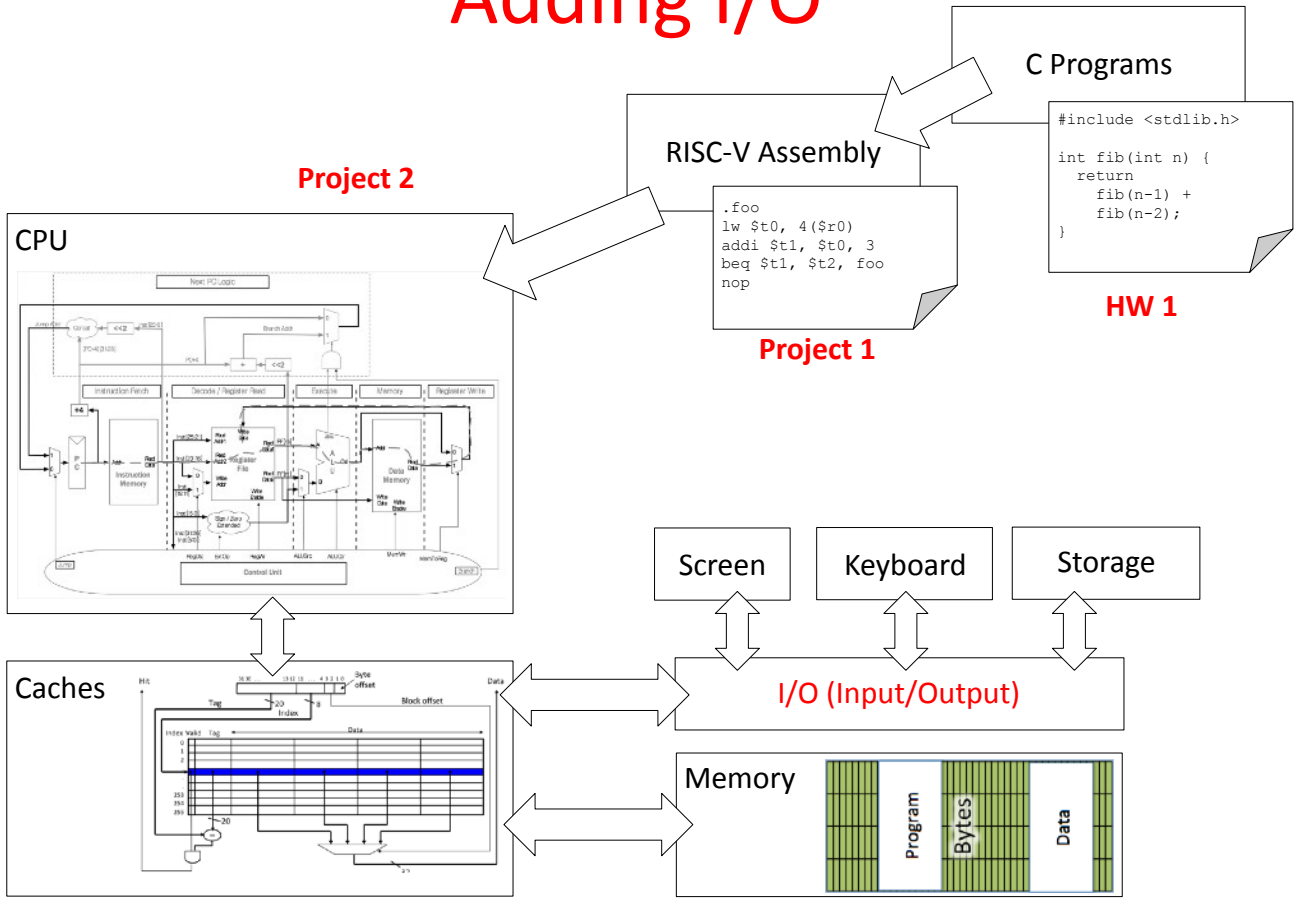


Memory



So How is a Laptop Any Different?

Adding I/O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RISC-V Assembly
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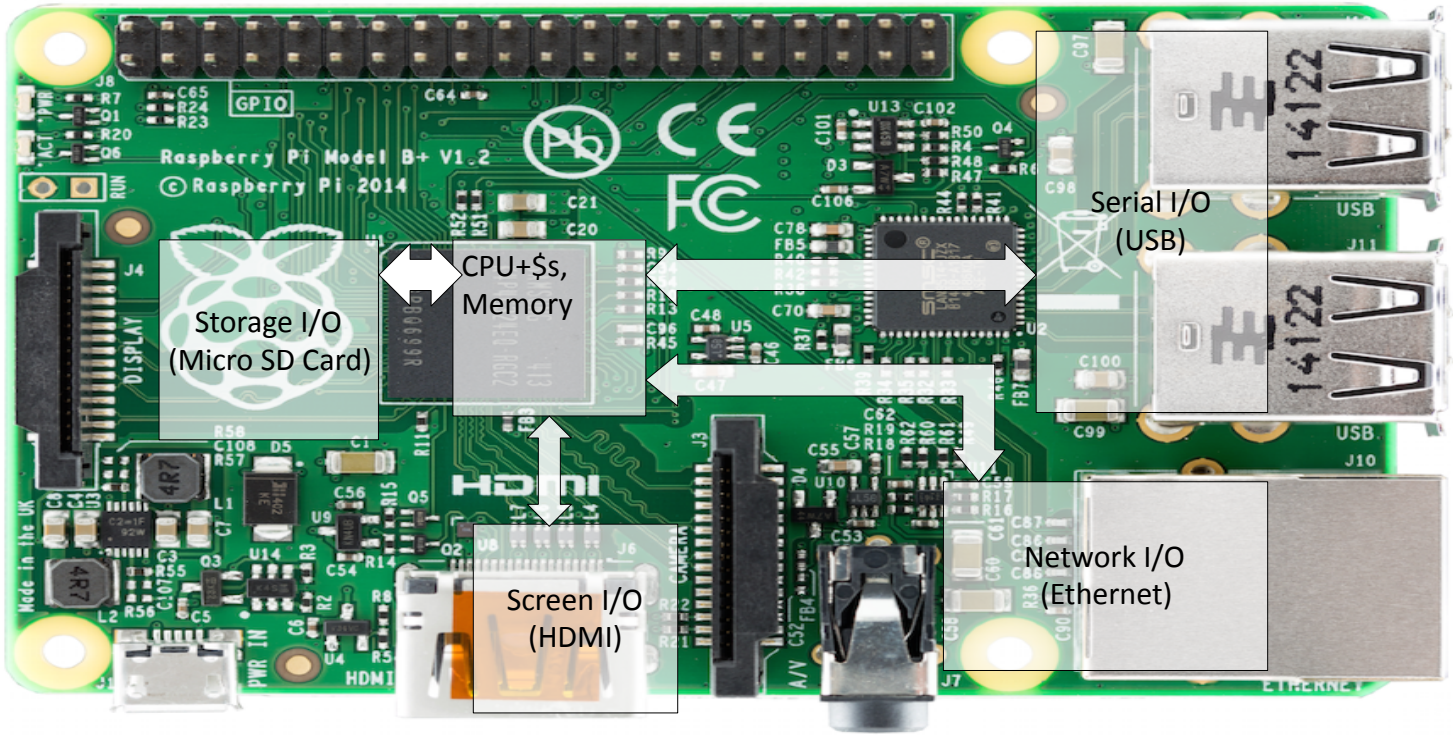
nop
Project 1
Project 2
CPU
Screen
Keyboard
Storage
I/O (Input/Output)
Caches
Memory
Program
Bytes
Data

Raspberry Pi (Less than $40 on Amazon in 2018)



It’s a Real Computer!

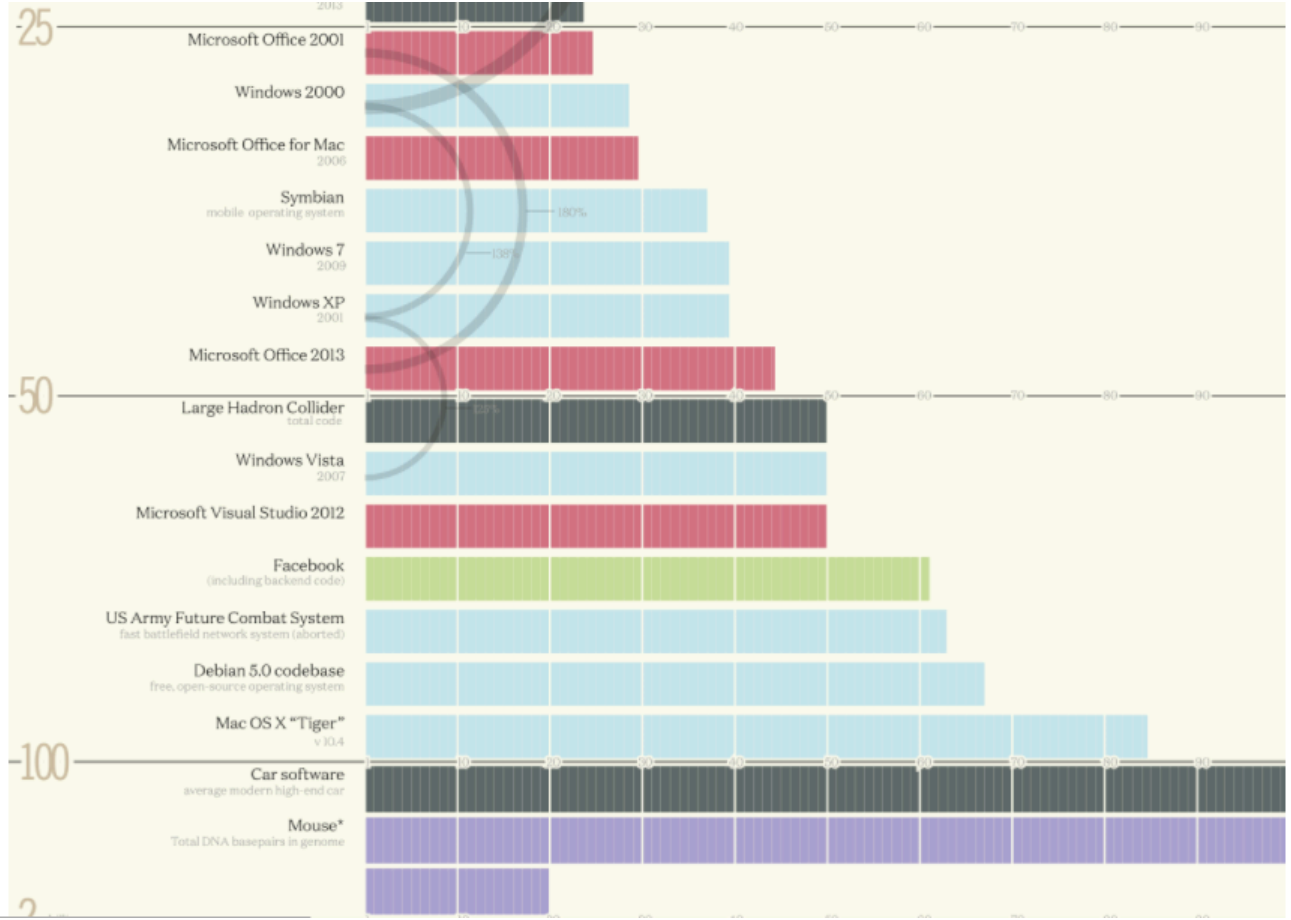
But Wait…

- That's not the same! Our 61c experience isn't like the real world. 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)

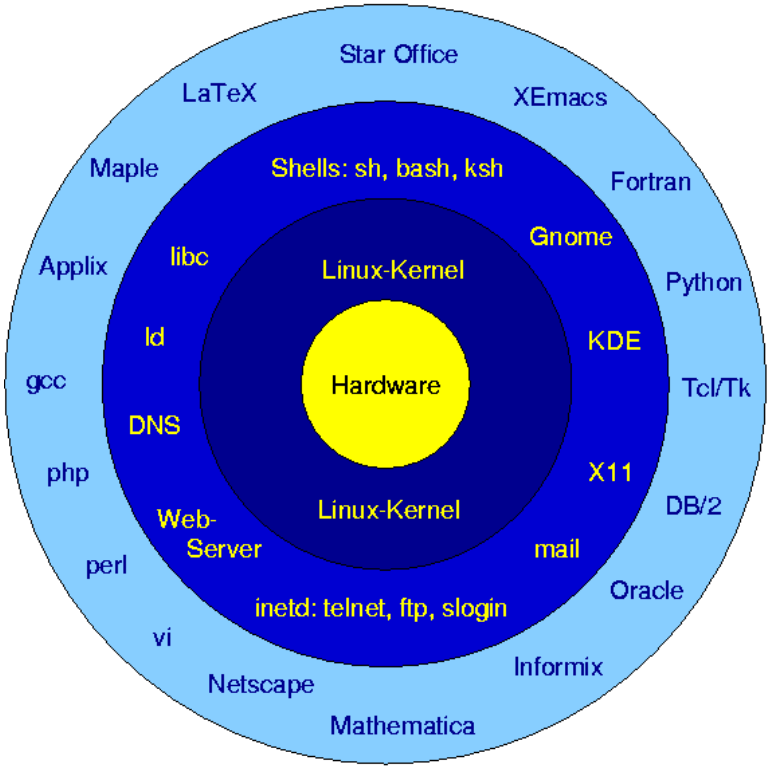
Well, “Just Software”

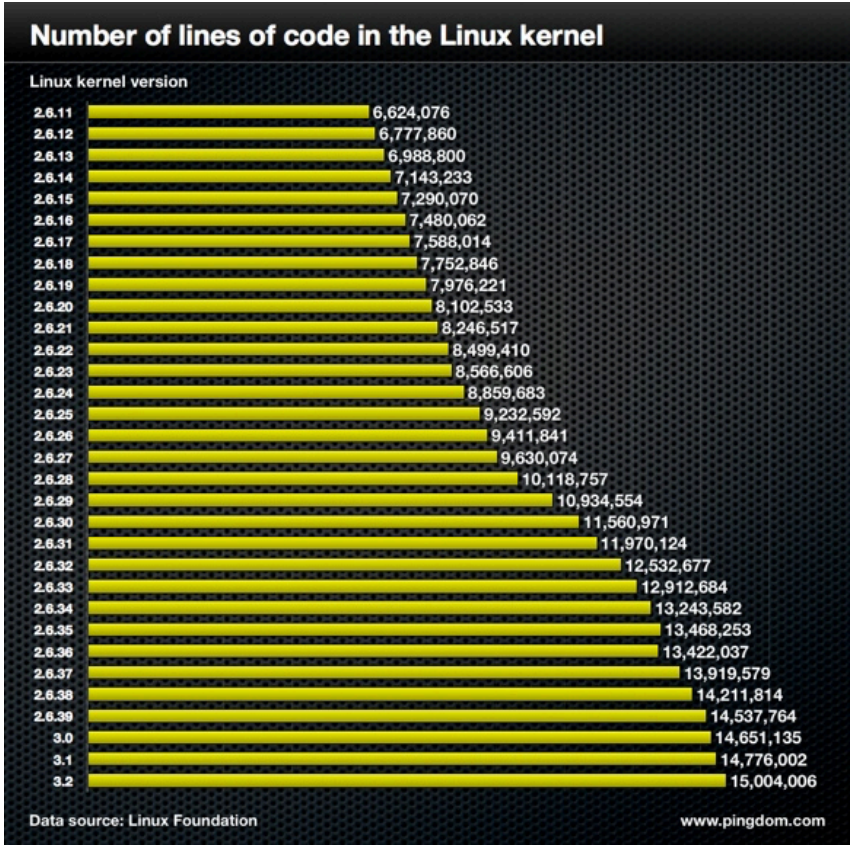
- The biggest piece of software on your machine?
- How many lines of code? These are guesstimates:



Codebases (in millions of lines of code). CC BY-NC 3.0 —
David McCandless © 2013
http://www.informationisbeautiful.net/visualizations/million-lines-of-code/

Operating System





What Does the OS do?

- OS is first thing that runs when computer starts (and intermittently runs as long as computer is on)
- Finds and controls all I/O devices in the machine in a general way
  - Relying on hardware specific “device drivers”
- Starts services (100+)
  - File system,
  - Network stack (Ethernet, WiFi, Bluetooth, …),
  - …
- 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)

Agenda

- Devices and I/O
- Polling
- Interrupts
- OS Boot Sequence
- Multiprogramming/time-sharing

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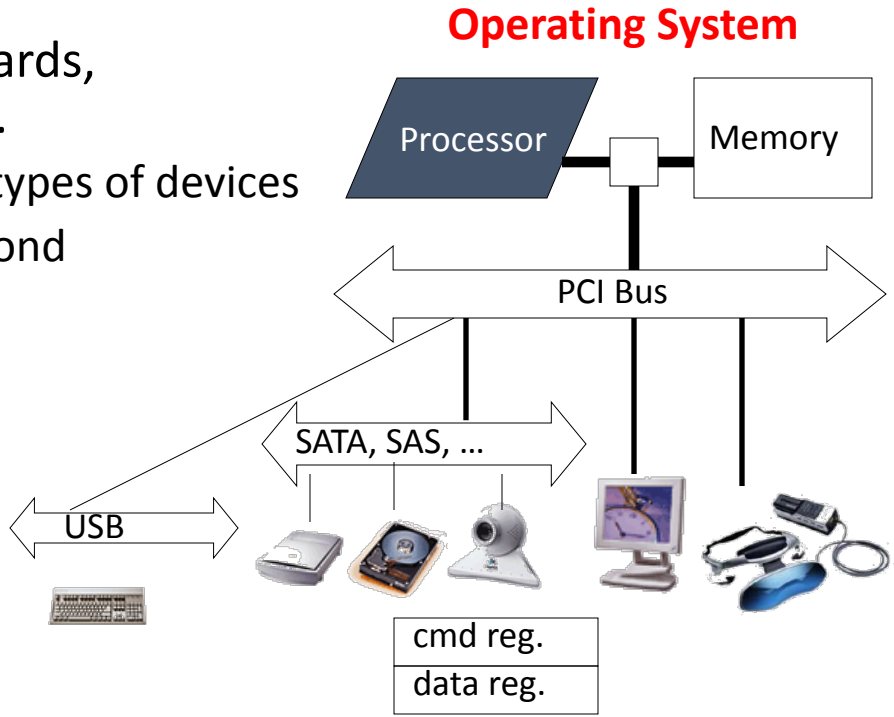
How to Interact with Devices?

- Assume a program running on a CPU. How does it interact with the "outside world"?
- Need I/O interface for Keyboards, Network, Mouse, Screen, etc.
  - Connect to many different types of devices
  - Control these devices, respond to them, and transfer data
  - Present them to user programs so they are useful

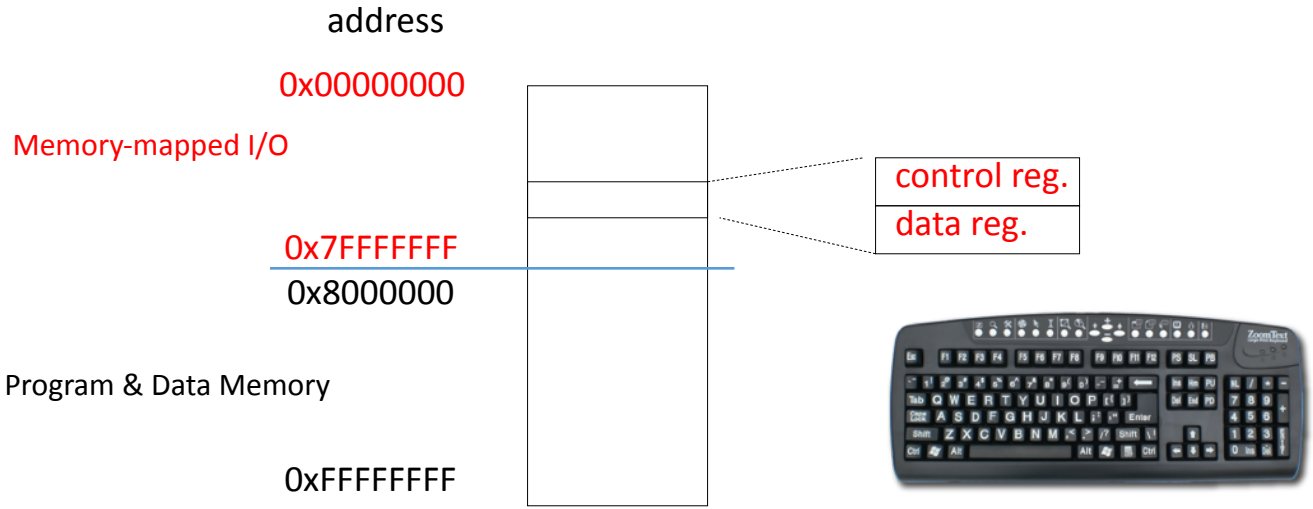


Instruction Set Architecture for I/O

- What must the processor do for I/O?
  - Input: read a sequence of bytes
  - Output: write a sequence of bytes
- Interface options
  a) Special input/output instructions & hardware
  b) Memory mapped I/O
     - Portion of address space dedicated to I/O
     - I/O device registers there (no memory)
     - Use normal load/store instructions, e.g. **`lw/sw`**
     - Very common, used by RISC-V

Memory Mapped I/O

- Certain addresses are not regular memory
- Instead, they correspond to registers in I/O devices



Processor-I/O Speed Mismatch

- 1 GHz microprocessor I/O throughput:
  - 4 Gi-B/s (**`lw/sw`**)
  - Typical I/O data rates:
    - 10 B/s (keyboard)
    - 100 Ki-B/s (Bluetooth)
    - 60 Mi-B/s (USB 2)
    - 100 Mi-B/s (Wifi, depends on standard)
    - 125 Mi-B/s (G-bit Ethernet)
    - 550 Mi-B/s (cutting edge SSD)
    - 1.25 Gi-B/s (USB 3.1 Gen 2)
    - 6.4 Gi-B/s (DDR3 DRAM)
  - These are peak rates – actual throughput is lower
- Common I/O devices neither deliver nor accept data matching processor speed


KEEP
CALM
IT'S
BREAK
TIME

Agenda

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- Polling
- Interrupts
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Processor Checks Status before Acting

- Device registers generally serve two functions:
  - Control Register, says it's OK to read/write (I/O ready)
    [think of a flagman on a road]
  - Data Register, contains data
- Processor reads from Control Register in loop
  - Waiting for device to set Ready bit in Control reg (0 → 1)
  - Indicates "data available" or "ready to accept data"
- Processor then loads from (input) or writes to (output) data register
  - I/O device resets control register bit (1 → 0)
- Procedure called "Polling"

I/O Example (Polling)

- Input: Read from keyboard into **a0**

```
            lui   t0,0x7ffff #7ffff000 (io addr)
Waitloop:   lw    t1,0(t0)   #read control
            andi  t1,t1,0x1  #ready bit
            beq   t1,zero,Waitloop
            lw    a0,4(t0)   #data
```

- Output: Write to display from **a1**

```
            lui   t0,0x7ffff #7ffff000
Waitloop:   lw    t1,8($t0)  #write control
            andi  t1,t1,0x1  #ready bit
            beq   t1,zero,Waitloop
            sw    a1,12(t0)  #data
```

Memory Map

.	
.	
.	
7ffff000	input control reg
7ffff004	input data reg
7ffff008	output control reg
7ffff00C	output data reg
.	
.	
.	

"Ready" bit is from processor's point of view!

Cost of Polling?

- Assume for a processor with
  - 1 GHz clock rate
  - Taking 400 clock cycles for a polling operation
    - Call polling routine
    - Check device (e.g., keyboard or wifi input available)
    - Return
  - What's the percentage of processor time spent polling?
- Example:
  - Mouse
  - Poll 30 times per second
    - Set by requirement not to miss any mouse motion
      (which would lead to choppy motion of the cursor on the screen)

% Processor time to poll

- Mouse Polling [clocks/sec]

  = 30 [polls/s] * 400 [clocks/poll] = 12K [clocks/s]

- % Processor for polling:

  $12*10^3$ [clocks/s] / $1*10^9$ [clocks/s] = 0.0012%

  => Polling mouse little impact on processor

Clicker Time

Hard disk: transfers data in 16-Byte chunks and can transfer at 16 MB/second. No transfer can be missed. What percentage of processor time is spent in polling (assume 1GHz clock)?

- A: 2%
- B: 4%
- C: 20%
- D: 40%
- E: 80%

% Processor time to poll hard disk

- Frequency of Polling Disk (rate at which chunks come could off disk)

  = 16 [MB/s] / 16 [B/poll] = 1M [polls/s]

- Disk Polling, Clocks/sec

  = 1M [polls/s] * 400 [clocks/poll]

  = 400M [clocks/s]

- % Processor for polling:

  $400*10^6$ [clocks/s] / $1*10^9$ [clocks/s] = 40%

  => Unacceptable

  (Polling is only part of the problem – main problem is that accessing in small chunks is inefficient)

What is the Alternative to Polling?

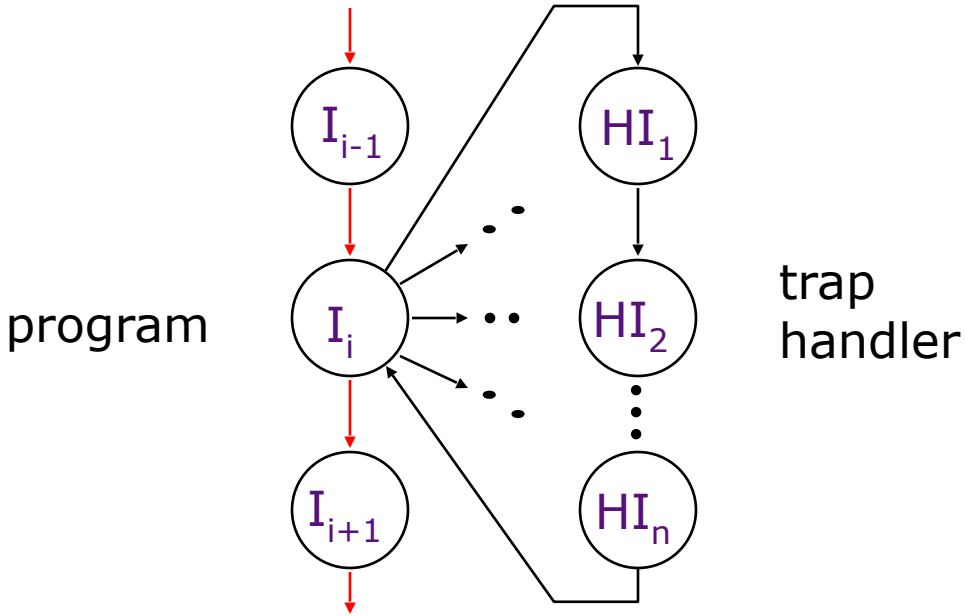
- Polling wastes processor resources
- Akin to waiting at the door for guests to show up
  - What about a bell?
- Computer lingo for bell:
  - Interrupt
  - Occurs when I/O is ready or needs attention
    - Interrupt current program
    - Transfer control to special code "interrupt handler"

Agenda

- Devices and I/O
- Polling
- Interrupts
- OS Boot Sequence
- Multiprogramming/time-sharing

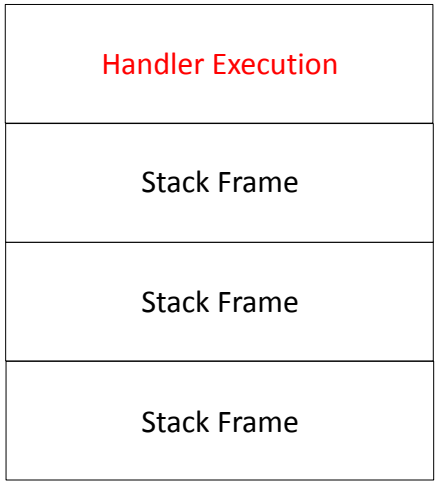
Traps/Interrupts/Exceptions:

altering the normal flow of control



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

Interrupt-Driven I/O



1. Incoming interrupt suspends instruction stream
2. Looks up the vector (function address) of a handler in an interrupt vector table stored within the CPU
3. Perform a jal to the handler (save PC in *special* MEPC* register)
4. Handler run on current stack and returns on finish (thread doesn't notice that a handler was run)

```
handler:  save registers
          decode interrupt cause
          handle interrupt
              clear interrupt
              restore registers
              mret
```

```
Label: sll  t1,s3,2
       add  t1,t1,s5
       lw   t1,0(t1)
       or   s1,s1,t1
       add  s3,s3,s4
       bne  s3,s2,Label
```

Interrupt(SPI0)

CPU Vector Interrupt Table	
SPI0	handler
…	…

*MEPC: Machine Exception Program Counter

Terminology

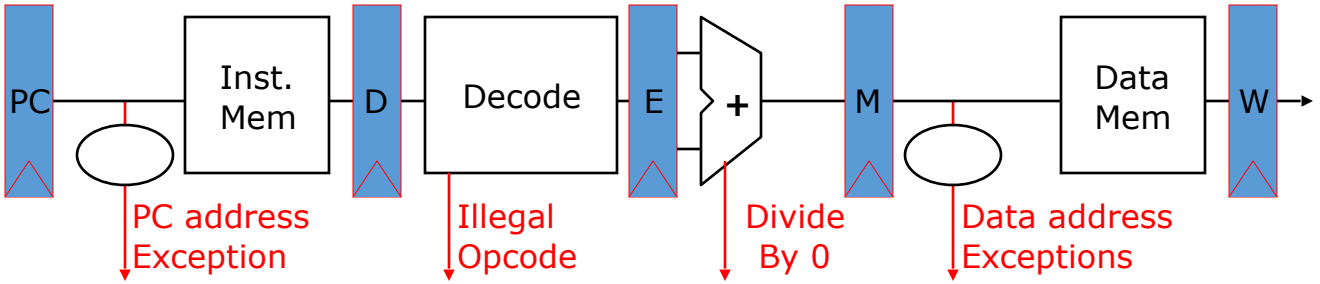
In CS61C (other definitions in use elsewhere):

- 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., divide by zero, bus error, illegal instruction
  - 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

Precise Traps

- *Trap handler's view of machine state is that every instruction prior to the trapped one (e.g., overflow) 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, e.g., for
    - Virtual memory to function properly (see next lecture)

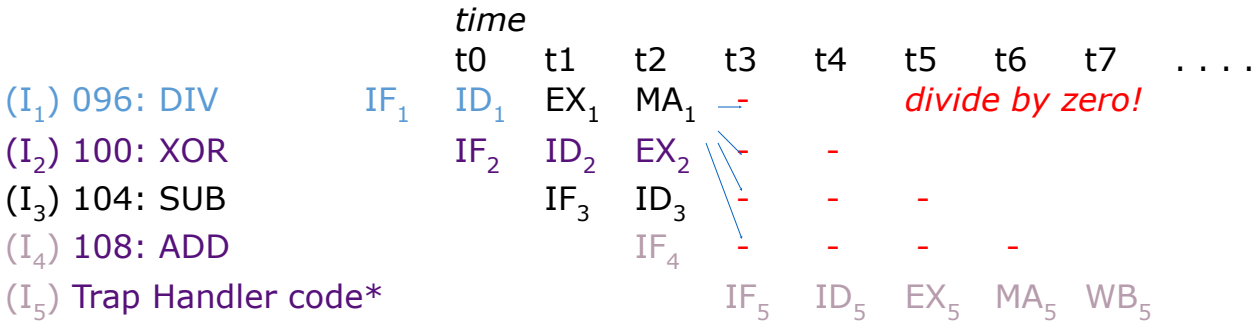
Trap Handling in 5-Stage Pipeline



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
   - Note: several exceptions can occur in a single clock cycle!
4) Transfer execution to trap handler
5) Optionally, return to original program and re-execute instruction

Trap Pipeline Diagram



*MEPC = 100 (instruction following offending ADD)


KEEP
CALM
IT'S
BREAK
TIME

Administrivia

- Only 2 more weeks to go!

- HW 4 due tomorrow evening
- HW 5 (final homework!) released next week due Friday of last week of classes

- Project 4: Performance Programming
  - Due Monday, Monday April 16 (this coming Monday)

- Guerrilla Session tonight in 7-9pm in Mulford 159
  - Topics covered: Parallelism & MapReduce
  - Second to last guerrilla session—come and get valuable exam practice!

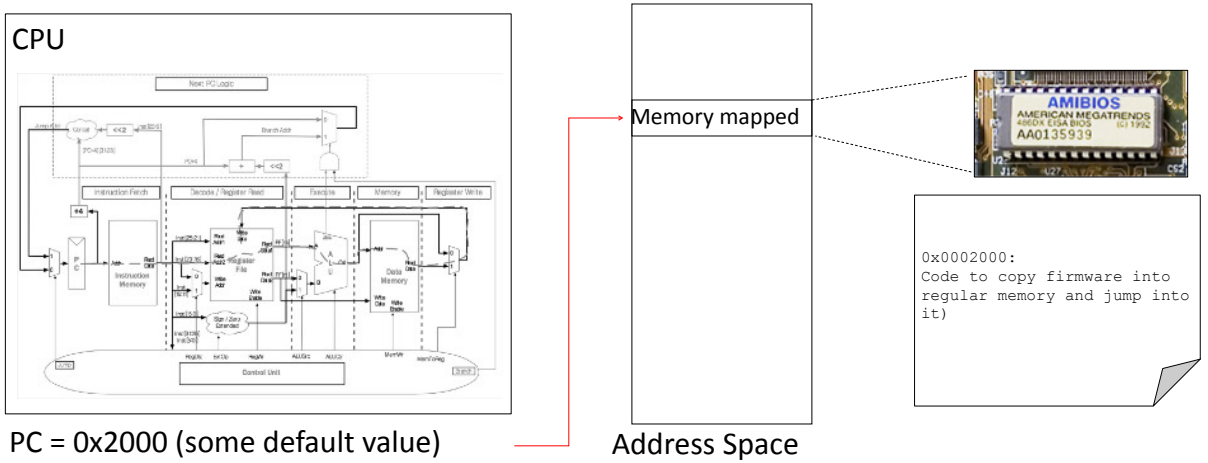
- Project 5 (WSC related) will be released by next week
  - You'll get at ~1.5 weeks to complete it - due Monday RRR week

Agenda

- Devices and I/O
- Polling
- Interrupts
- OS Boot Sequence
- Multiprogramming/time-sharing

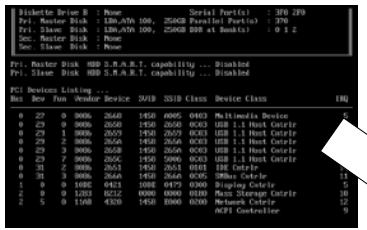
What Happens at Boot?

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



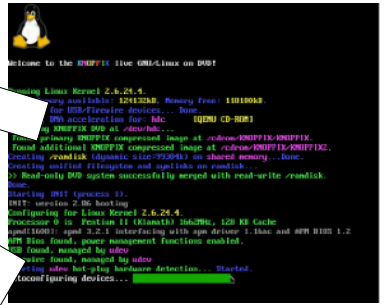
What Happens at Boot?

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

Launching Applications

- Applications are called “processes” in most OSs
  - Thread: shared memory
  - Process: separate memory
  - Both threads and processes run (pseudo) simultaneously
  - Many user applications actually comprise multiple threads and/or processes
- Apps are started by another process (e.g., shell) calling an OS routine (using a “syscall”)
  - Depends on OS, but 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 (“sbreak” used by 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

Agenda

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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 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

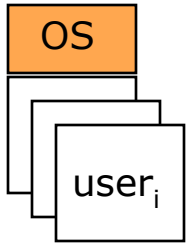
- Supervisor mode alone is not sufficient to fully isolate applications from each other or from the OS
  - Application could overwrite another application's memory.
  - Typically programs start at some fixed address, e.g. 0x8FFFFFFF
    - How can 100's of programs share memory at location 0x8FFFFFFF?
  - 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

Modern *Virtual Memory* Systems

Illusion of a large, private, uniform store

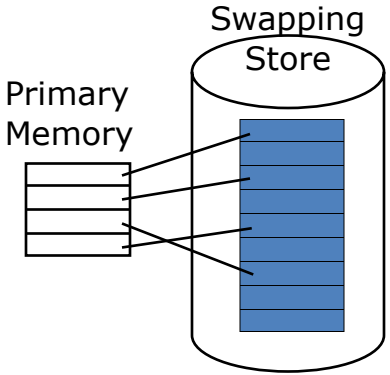
Protection

- several users (processes), each with their private address space and one or more shared address spaces

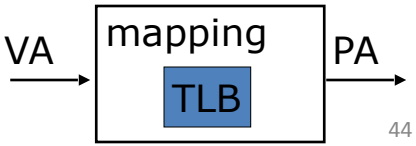


Demand Paging

- Provides the ability to run programs larger than the primary memory
- Hides differences in machine configurations



The price is address translation on each memory reference



Dynamic Address Translation

Motivation

Multiprogramming, multitasking: Desire to execute more than one process at a time (more than one process can reside in main memory at the same time).

Location-independent programs

Programming and storage management ease

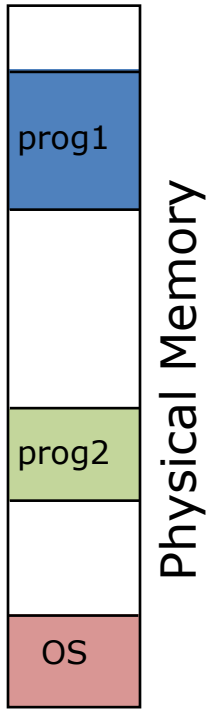
⇒ *base register – add offset to each address*

Protection

Independent programs should not affect each other inadvertently

⇒ *bound register – check range of access*

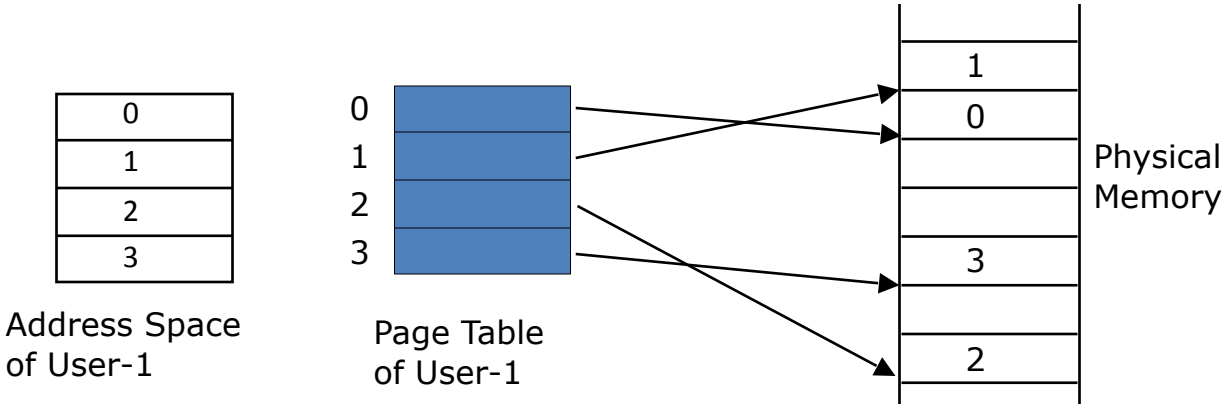
(Note: Multiprogramming drives requirement for resident *supervisor (OS)* software to manage context switches between multiple programs)



Paged Memory Systems

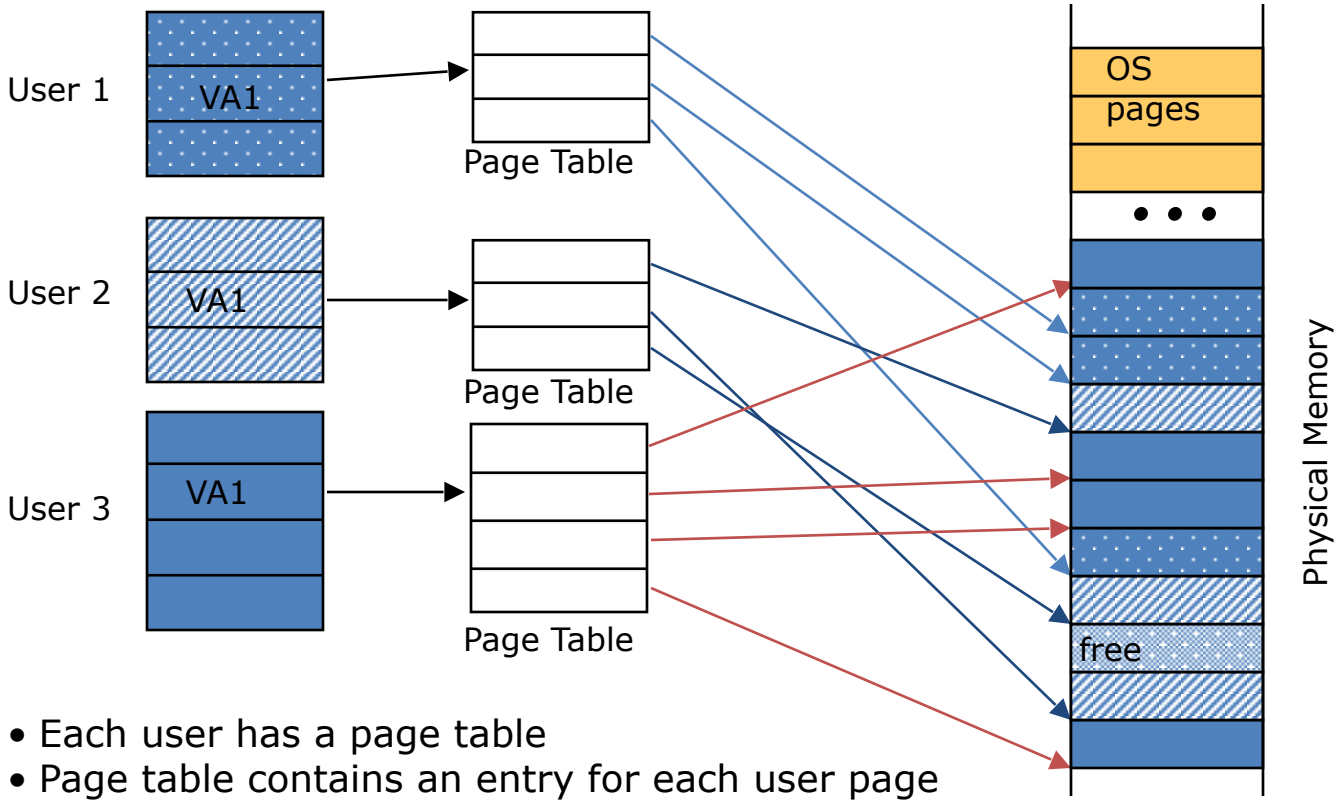
- Processor-generated address can be split into:

- A page table contains the physical address of the base of each page



Page tables make it possible to store the pages of a program non-contiguously.

Private Address Space per User



- Each user has a page table
- Page table contains an entry for each user page

Where Should Page Tables Reside?

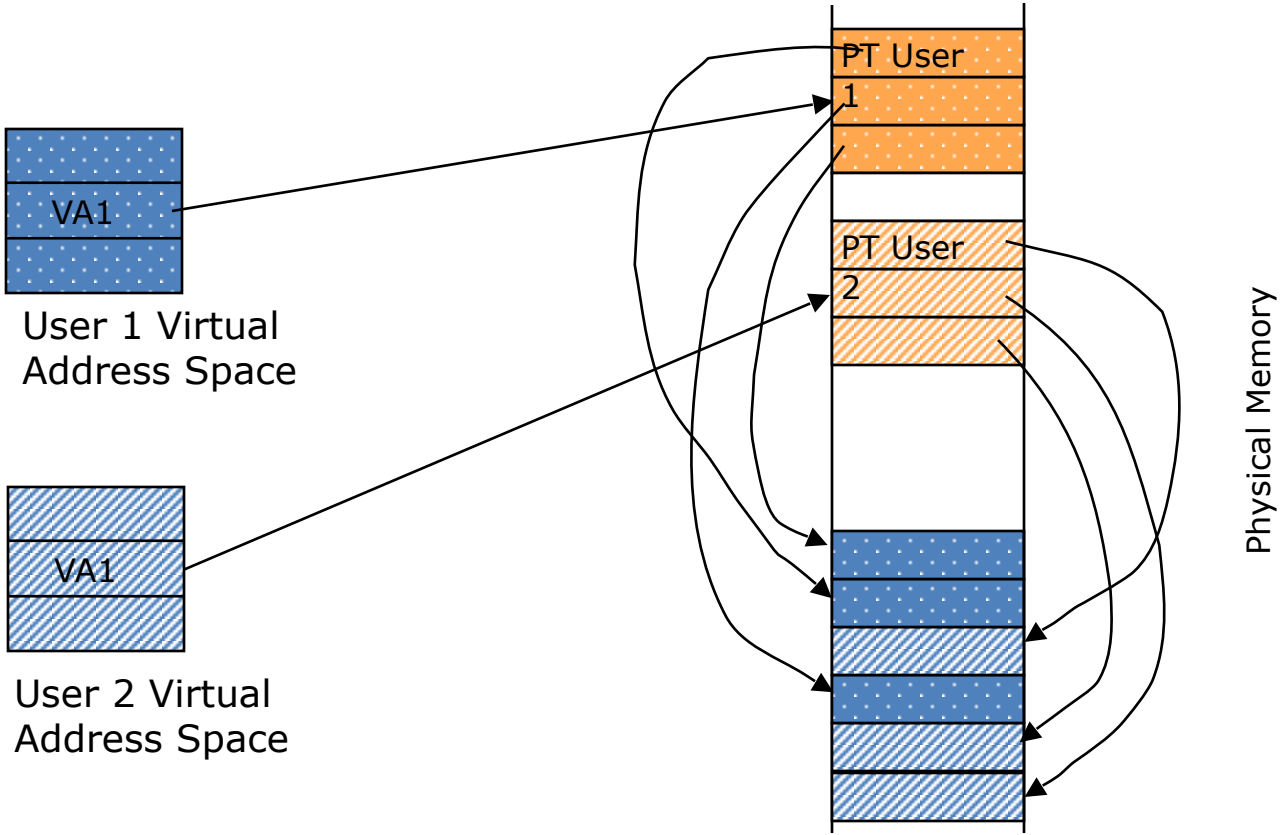
- Space required by the page tables (PT) is proportional to the address space, number of users, ...

  ⇒ *Too large to keep in cpu registers*

- Idea: Keep PTs in the main memory
  - Needs one reference to retrieve the page base address and another to access the data word

    ⇒ *doubles the number of memory references!*

Page Tables in Physical Memory



And, in Conclusion, …

- Input / output (I/O)
  - Memory mapped: appears like “special kind of memory”
  - Access with usual load/store instructions (e.g., **`lw,sw`**)
- Exceptions
  - Notify processor of special events, e.g. divide by 0, *page fault* (next lecture)
  - “Precise” handling: immediately at offending instruction
- Interrupts
  - Notification of external events, e.g., keyboard input, disk or Ethernet traffic
- Multiprogramming and supervisory mode
  - Enables and isolates multiple programs
- **Take CS162 to learn more about operating systems**