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CS110 Computer Architecture

Introduction to OS

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Review: OpenMP and Multi-threading

- Architectural support for synchronization
  - Load reserved/store conditional
  - Atomic memory operation (AMO)
- OpenMP
  - An approach for programming with multi-threads
  - Shared memory
  - Language extension
    - Pragma, directives, reduction, etc. for multi-threading programs

CA so far…

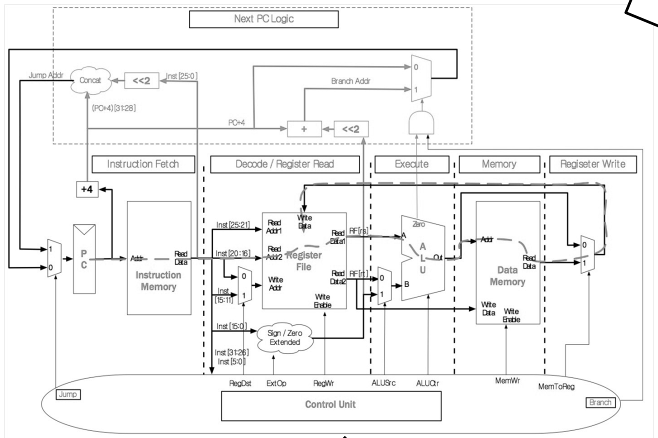
C Programs

```
#include <stdlib.h>

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

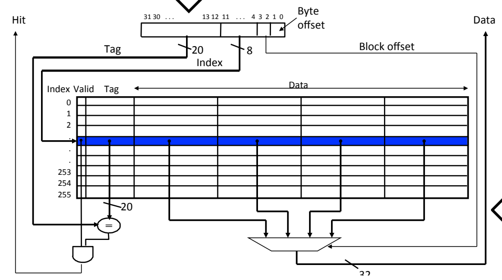
RISC-V Assembly

```
.foo
lw   t0, 4(s1)
addi t1, t0, 3
beq  t1, t2, foo
nop
```

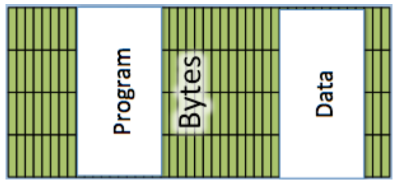
CPU

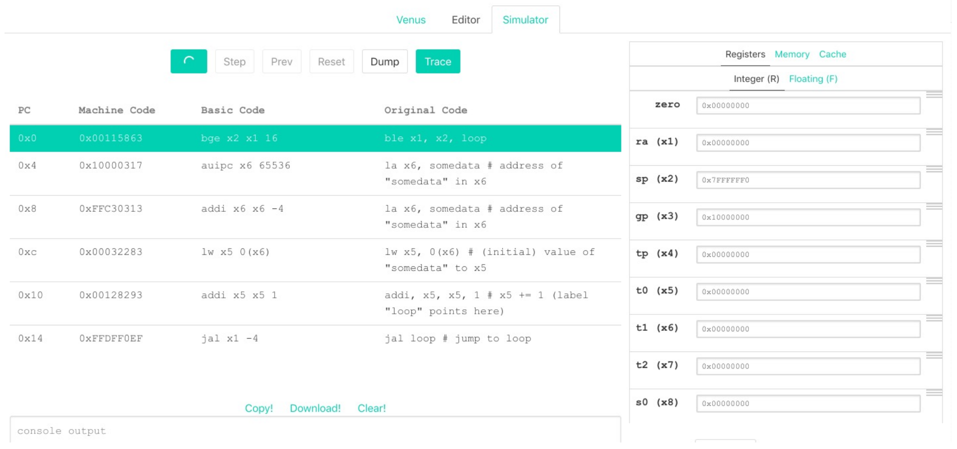


Caches



Memory

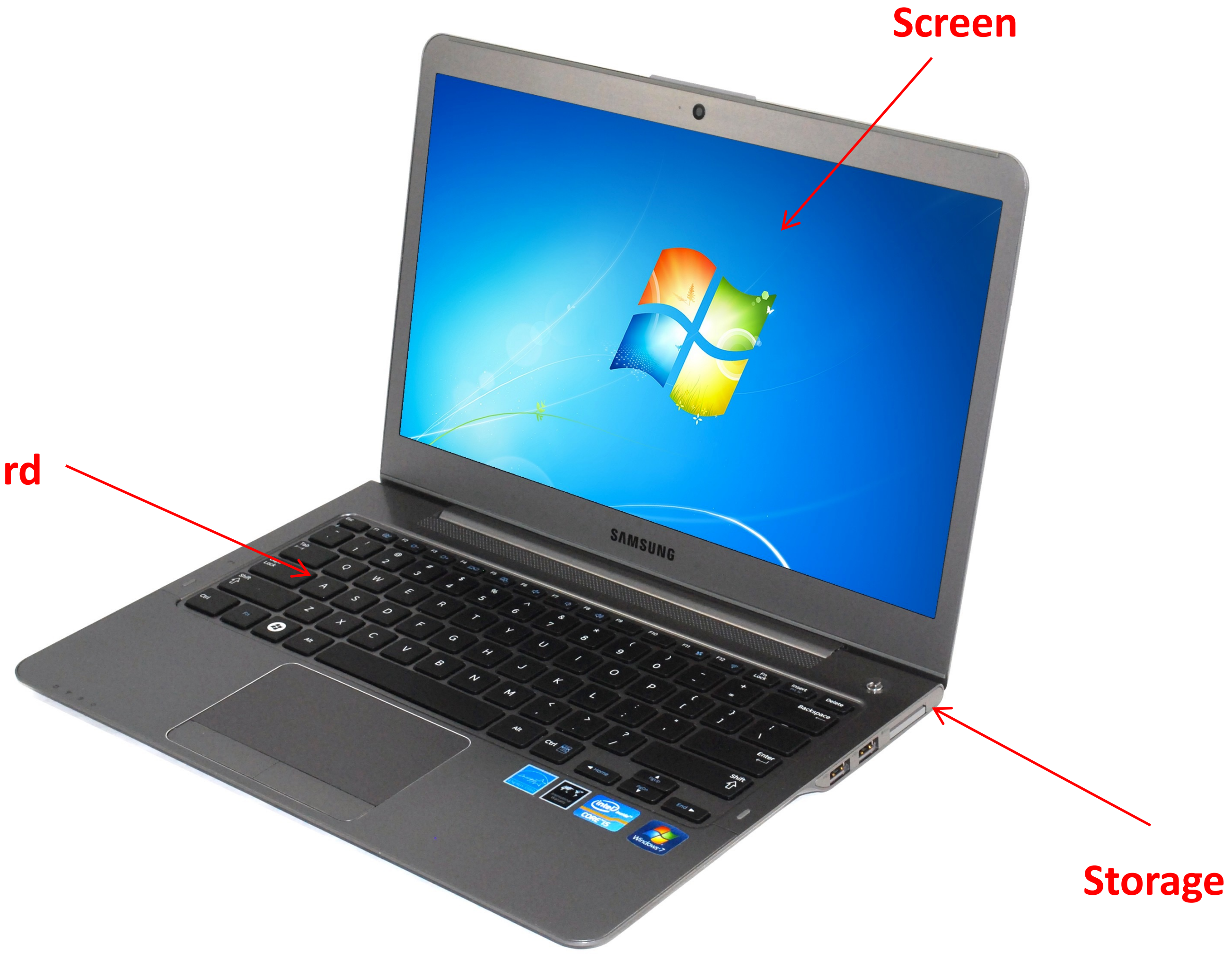




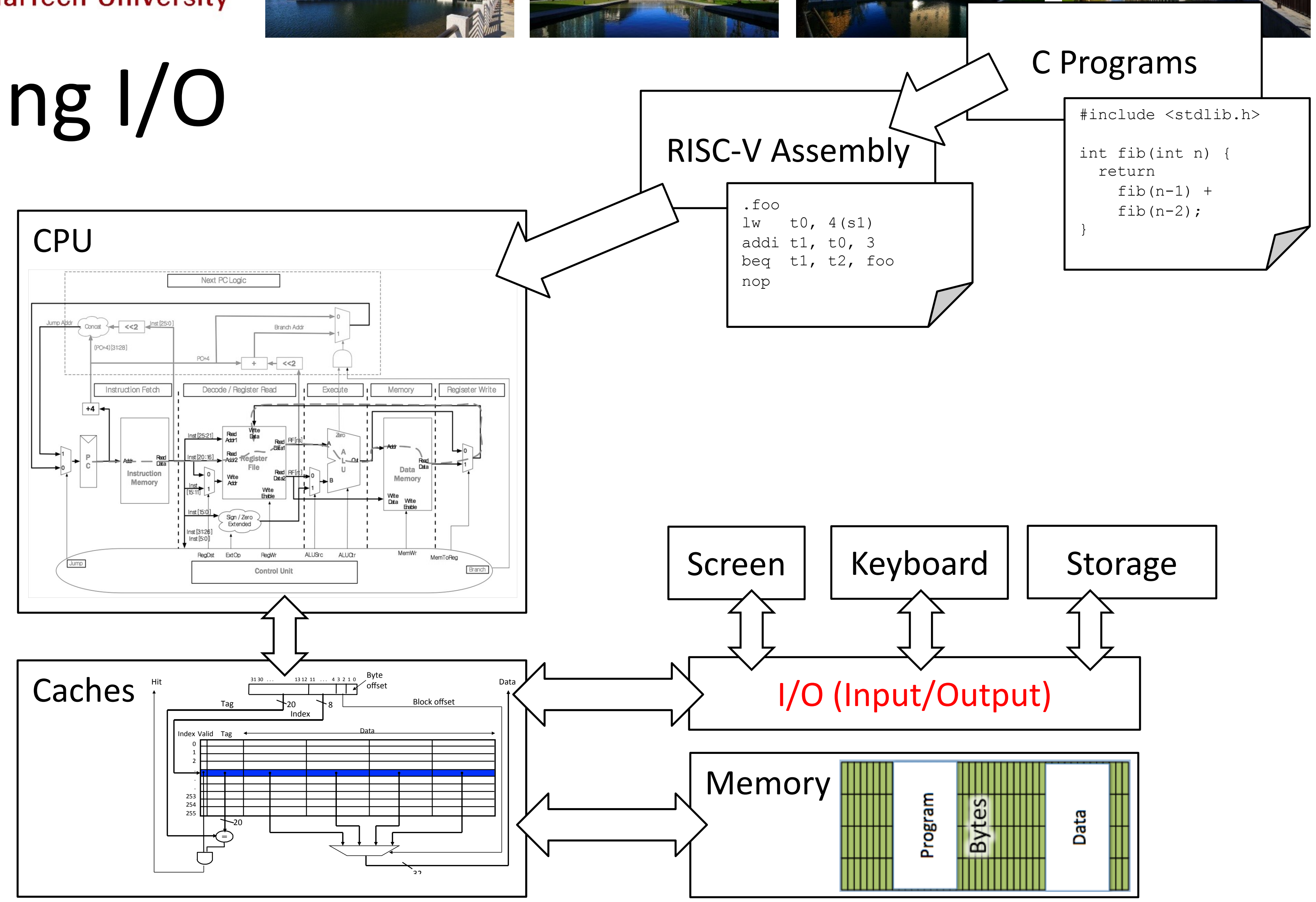
PC	Machine Code	Basic Code	Original Code
0x0	0x00115863	bge x2 x1 16	ble x1, x2, loop
0x4	0x10000317	auipc x6 65536	la x6, somedata # address of "somedata" in x6
0x8	0xFFC30313	addi x6 x6 -4	la x6, somedata # address of "somedata" in x6
0xc	0x00032283	lw x5 0(x6)	lw x5, 0(x6) # (initial) value of "somedata" to x5
0x10	0x00128293	addi x5 x5 1	addi, x5, x5, 1 # x5 += 1 (label "loop" points here)
0x14	0xFFDFF0EF	jal x1 -4	jal loop # jump to loop

zero	0x00000000
ra (x1)	0x00000000
sp (x2)	0x7FFFFFF0
gp (x3)	0x10000000
tp (x4)	0x00000000
t0 (x5)	0x00000000
t1 (x6)	0x00000000
t2 (x7)	0x00000000
s0 (x8)	0x00000000

So how is this any different?



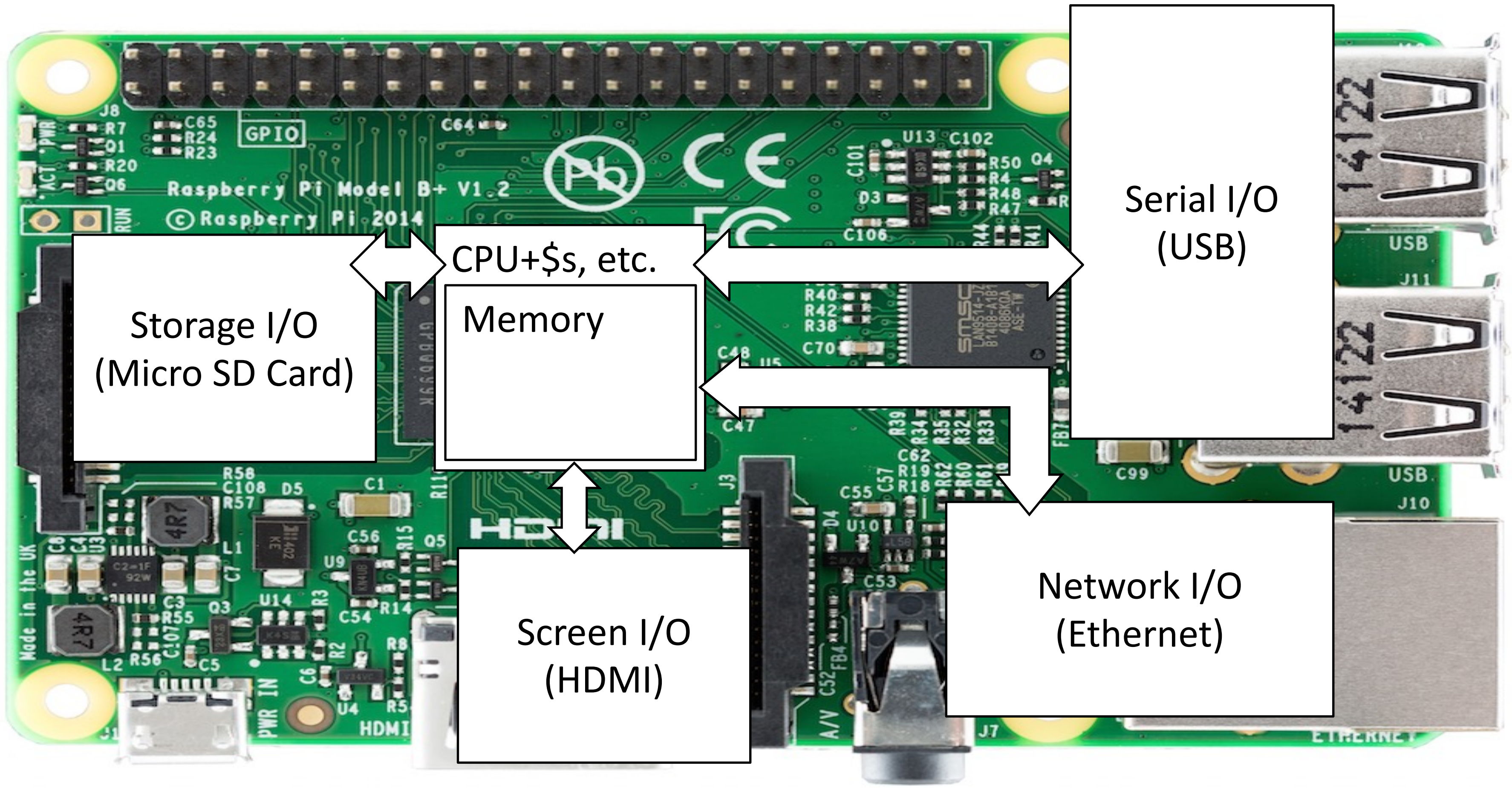
Adding I/O



```
#include <stdlib.h>

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

```
.foo
lw   t0, 4(s1)
addi t1, t0, 3
beq  t1, t2, foo
nop
```

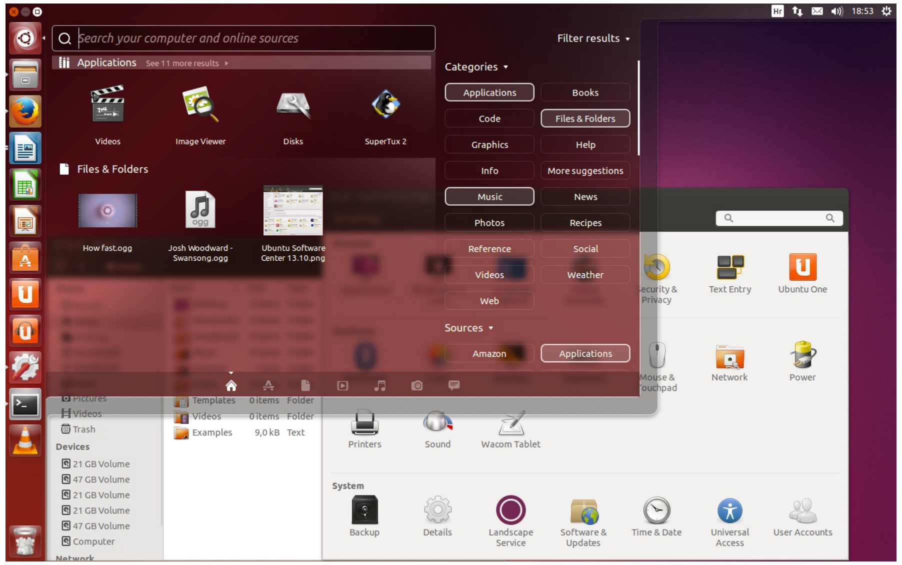
Raspberry Pi



It’s a real computer!

But wait…

- That’s not the same! Our CS 110 experience isn’t like the real world.
- 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 so e?
- How many lines of cod tes:

All 7 fictions in txt format zipped to be **2.5MB**

Say No to Pirated Products (拒绝盗版)

5MB

Year		ize of zipped file
1994		1MB
1996		6MB
2001		23MB
2003		40MB
2		92MB
201		118MB
2019		155MB
Apr 2020		166MB
May 2021		179MB
May 2022	linux-5.17.5.tar.gz	189MB

What does the OS do?

- One of the first things that runs when your computer starts (right after firmware/ bootloader)
- 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)
- Services: File System, Network stack, printer, etc.
- Finds and controls all the devices in the machine in a general way (using “device drivers”)

What does the core of OS need to do?

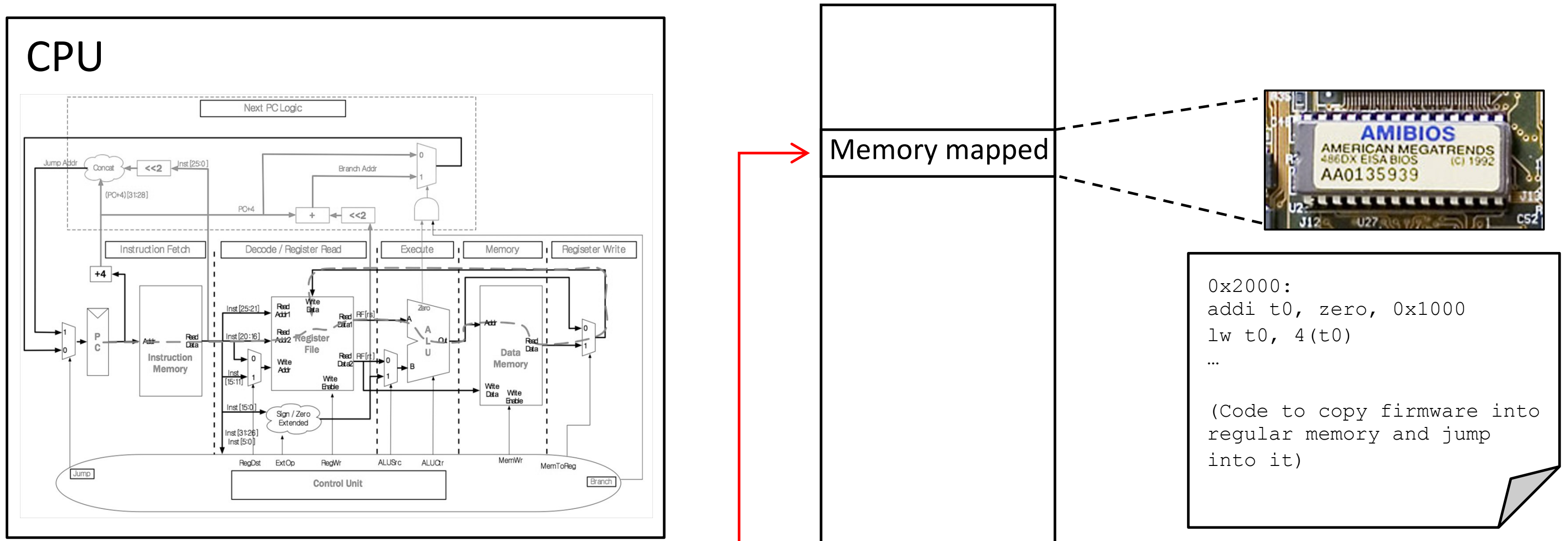
- Provide **interaction** with the outside world
  - Interact with “devices”
    - Disk, screen, keyboard, mouse, network, etc.
- Provide **isolation** between running programs (processes)
  - Each program runs in its own little world
    - Virtual memory

Agenda

- OS Boot Sequence and Operation
- Devices and I/O, interrupt and traps
- Application, Multiprogramming/time-sharing

What happens at boot?

- When the computer switches on, the CPU executes instructions from some start address (stored in Flash ROM)



```
0x2000:
addi t0, zero, 0x1000
lw t0, 4(t0)
…

(Code to copy firmware into
regular memory and jump
into it)
```

PC = 0x2000 (some default value)

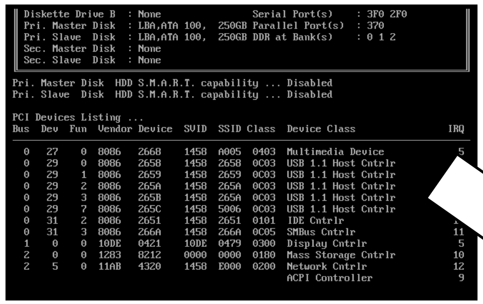
Address Space

- Bootstrapping: https://en.wikipedia.org/wiki/Bootstrapping

What happens at boot?

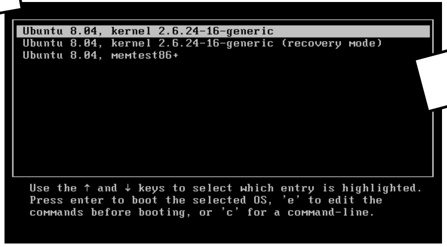
- When the computer switches on, the CPU executes instructions from some start address (stored in Flash ROM)

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



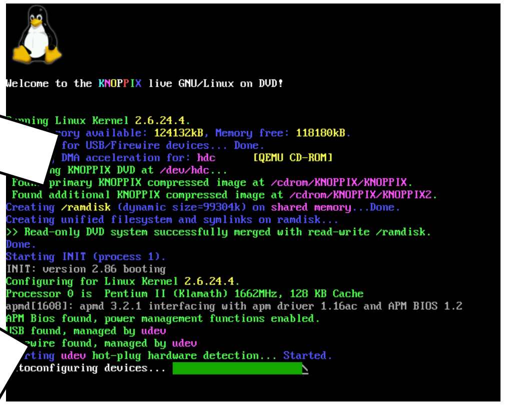
```
 Diskette Drive B  : None                  Serial Port(s)    : 3F0 2F0
 Pri. Master Disk  : LBA,ATA 100,  250GB Parallel Port(s)  : 370
 Pri. Slave  Disk  : LBA,ATA 100,  250GB DDR at Bank(s)    : 0 1 2
 Sec. Master Disk  : None
 Sec. Slave  Disk  : None

Pri. Master Disk  HDD S.M.A.R.T. capability ... Disabled
Pri. Slave  Disk  HDD S.M.A.R.T. capability ... Disabled

PCI Devices Listing ...
Bus  Dev  Fun  Vendor Device  SVID  SSID Class  Device Class                IRQ

  0   27    0  8086   2668    1458  A005  0403  Multimedia Device             5
  0   29    0  8086   2658    1458  2658  0C03  USB 1.1 Host Cntrlr
  0   29    1  8086   2659    1458  2659  0C03  USB 1.1 Host Cntrlr
  0   29    2  8086   265A    1458  265A  0C03  USB 1.1 Host Cntrlr
  0   29    3  8086   265B    1458  265A  0C03  USB 1.1 Host Cntrlr
  0   29    7  8086   265C    1458  5006  0C03  USB 1.1 Host Cntrlr
  0   31    2  8086   2651    1458  2651  0101  IDE Cntrlr
  0   31    3  8086   266A    1458  266A  0C05  SMBus Cntrlr                 11
  1    0    0  10DE   0421    10DE  0479  0300  Display Cntrlr                5
  2    0    0  1283   8212    0000  0000  0180  Mass Storage Cntrlr          10
  2    5    0  11AB   4320    1458  E000  0200  Network Cntrlr               12
                                                ACPI Controller               9
```

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



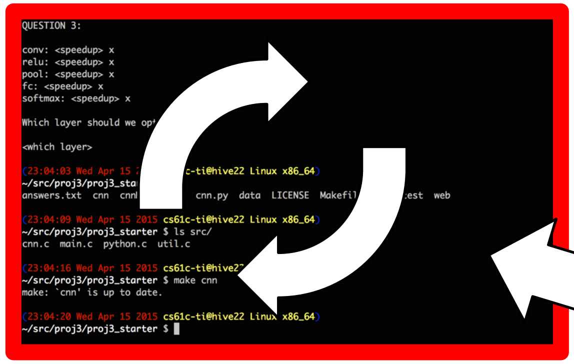
```
 Ubuntu 8.04, kernel 2.6.24-16-generic
 Ubuntu 8.04, kernel 2.6.24-16-generic (recovery mode)
 Ubuntu 8.04, memtest86+

   Use the ↑ and ↓ keys to select which entry is highlighted.
   Press enter to boot the selected OS, 'e' to edit the
   commands before booting, or 'c' for a command-line.
```

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



```
Welcome to the KNOPPIX live GNU/Linux on DVD!

nning Linux Kernel 2.6.24.4.
   ory available: 124132kB, Memory free: 118180kB.
    for USB/Firewire devices... Done.
    DMA acceleration for: hdc       [QEMU CD-ROM]
    ng KNOPPIX DVD at /dev/hdc...
 Fou   primary KNOPPIX compressed image at /cdrom/KNOPPIX/KNOPPIX.
 Found additional KNOPPIX compressed image at /cdrom/KNOPPIX/KNOPPIX2.
Creating /ramdisk (dynamic size=99304k) on shared memory...Done.
Creating unified filesystem and symlinks on ramdisk...
>> Read-only DVD system successfully merged with read-write /ramdisk.
Done.
Starting INIT (process 1).
INIT: version 2.86 booting
Configuring for Linux Kernel 2.6.24.4.
Processor 0 is  Pentium II (Klamath) 1662MHz, 128 KB Cache
apmd[1608]: apmd 3.2.1 interfacing with apm driver 1.16ac and APM BIOS 1.2
APM Bios found, power management functions enabled.
USB found, managed by udev
 ewire found, managed by udev
 rting udev hot-plug hardware detection... Started.
 toconfiguring devices...
```

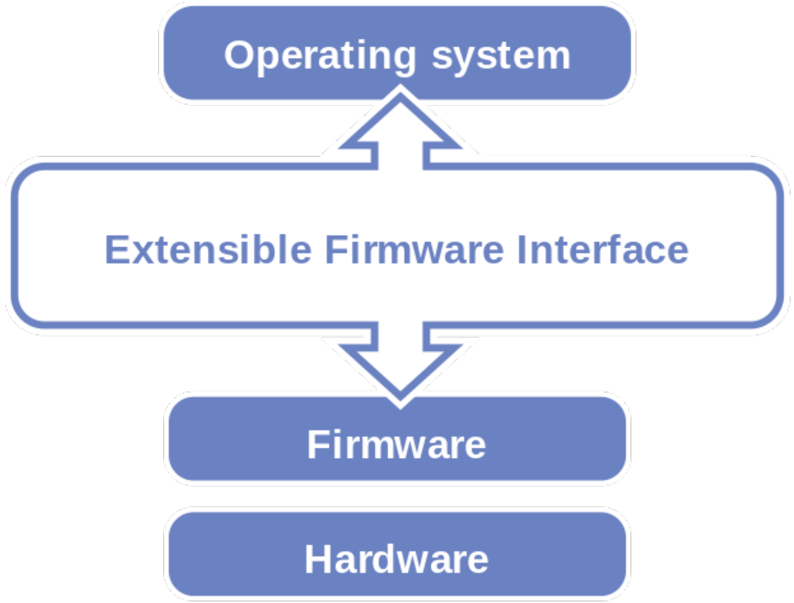
4. Init: Launch an application that waits for input in loop (e.g., Terminal/Desktop/...



```
QUESTION 3:

conv: <speedup> x
relu: <speedup> x
pool: <speedup> x
fc: <speedup> x
softmax: <speedup> x

Which layer should we op

<which layer>

(23:04:03 Wed Apr 15             c-ti@hive22 Linux x86_64)
~/src/proj3/proj3_sta
answers.txt  cnn  cnn         cnn.py  data  LICENSE  Makefil        est  web

(23:04:09 Wed Apr 15 2015 cs61c-ti@hive22 Linux x86_64)
~/src/proj3/proj3_starter $ ls src/
cnn.c  main.c  python.c  util.c

(23:04:16 Wed Apr 15 2015 cs61c-ti@hive22
~/src/proj3/proj3_starter $ make cnn
make: `cnn' is up to date.

(23:04:20 Wed Apr 15 2015 cs61c-ti@hive22 Linux x86_64)
~/src/proj3/proj3_starter $ █
```

UEFI: Unified Extensible Firmware Interface

- Successor of BIOS
- Much more powerful and complex
- E.g. graphics menu; networking; browsers
- All modern Intel & AMD based computer use UEFI

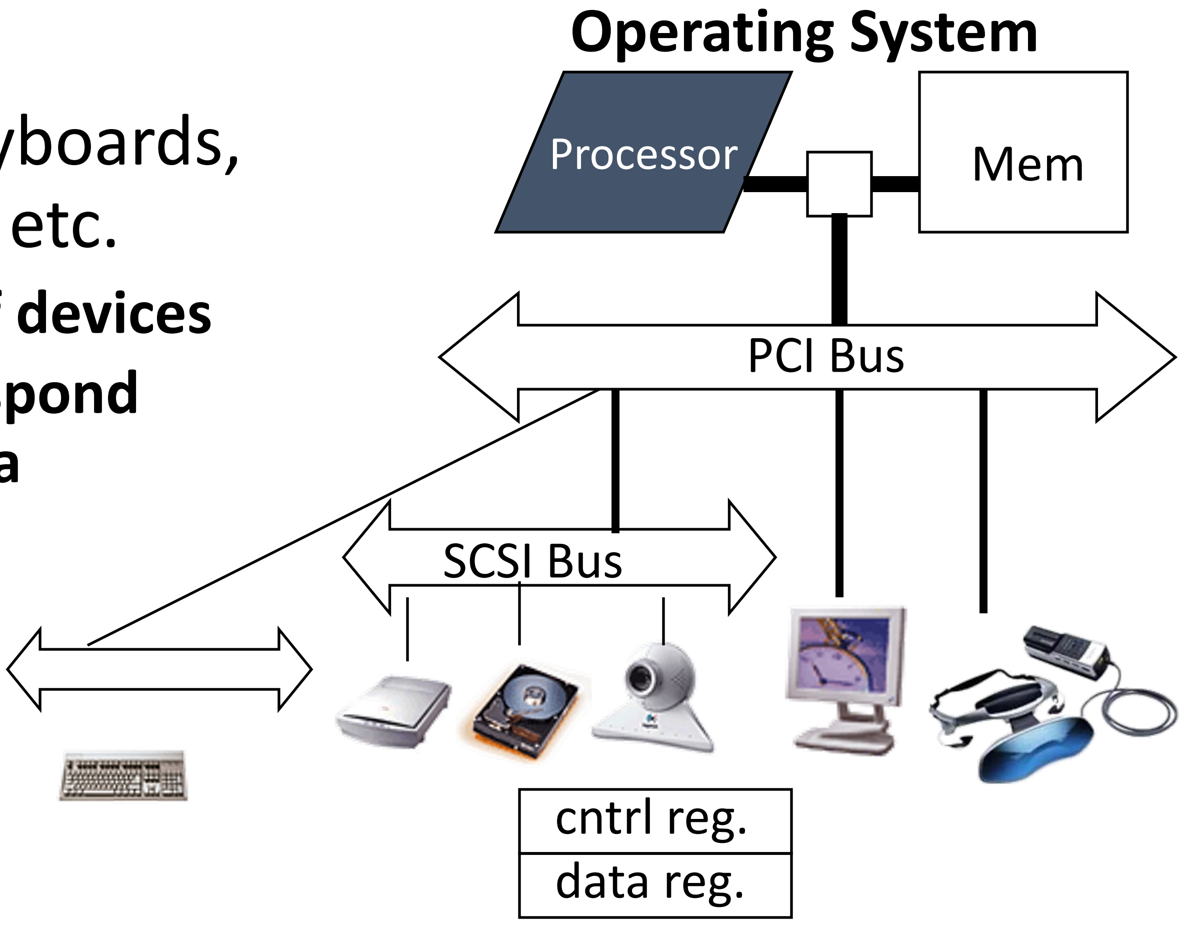


Agenda

- OS Boot Sequence and Operation
- Devices and I/O, interrupt and traps
- Application, Multiprogramming/time-sharing

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 types of devices**
  - **Control these devices, respond to them, and transfer data**
  - **Present them to user programs so they are useful**

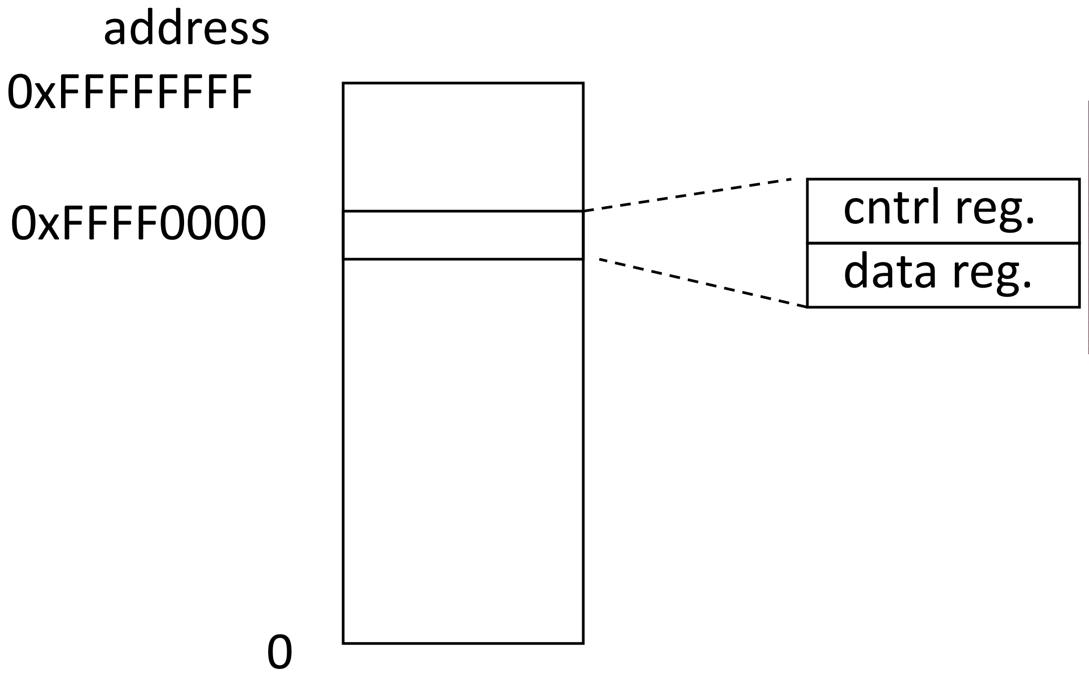


Instruction Set Architecture for I/O

- What must the processor do for I/O?
  - Input: reads a sequence of bytes
  - Output: writes a sequence of bytes
- Interface options
  - Some processors have special input/output instructions
  - Memory Mapped Input/Output (used by RISC-V):
    - Use normal load/store instructions, e.g., lw/sw, for input/output
      - In small pieces
    - A portion of the address space dedicated to IO
    - I/O device registers there (no memory there)

Memory Mapped I/O

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



Processor-I/O Speed Mismatch

- 1GHz microprocessor can execute 1 billion load or store instructions per second, or 4,000,000 KB/s data rate
  - I/O data rates range from 0.01 KB/s to 1,250,000 KB/s
- Input: device may not be ready to send data as fast as the processor loads it
  - Also, might be waiting for human to act
- Output: device not be ready to accept data as fast as processor stores it
- What to do?

Processor Checks Status before Acting

- Path to a device generally has 2 registers:
  - 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) to say it's OK
- Processor then loads from (input), or writes to (output) data register
  - Load from or Store into Data Register resets Ready bit
    (1 => 0) of Control Register
- This is called "Polling"

I/O Example (polling)

- Input: Read from keyboard into a0

```
Waitloop:      li    t0, 0xffff0000 #ffff0000
               lw    t1, 0(t0)      #control
               andi  t1, t1,0x1
               beq   t1, zero, Waitloop
               lw    a0, 4(t0)      #data
```

- Output: Write to display from **a0**

```
Waitloop:      li    t0, 0xffff0000 #ffff0000
               lw    t1, 8(t0)      #control
               andi  t1, t1,0x1
               beq   t1, zero, Waitloop
               sw    a0, 12(t0)     #data
```

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

Cost of Polling?

- Assume for a processor with a 1GHz clock it takes 400 clock cycles for a polling operation (call polling routine, accessing the device, and returning). Determine % of processor time for polling
    - Mouse: polled 30 times/sec so as not to miss user movement

% 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%

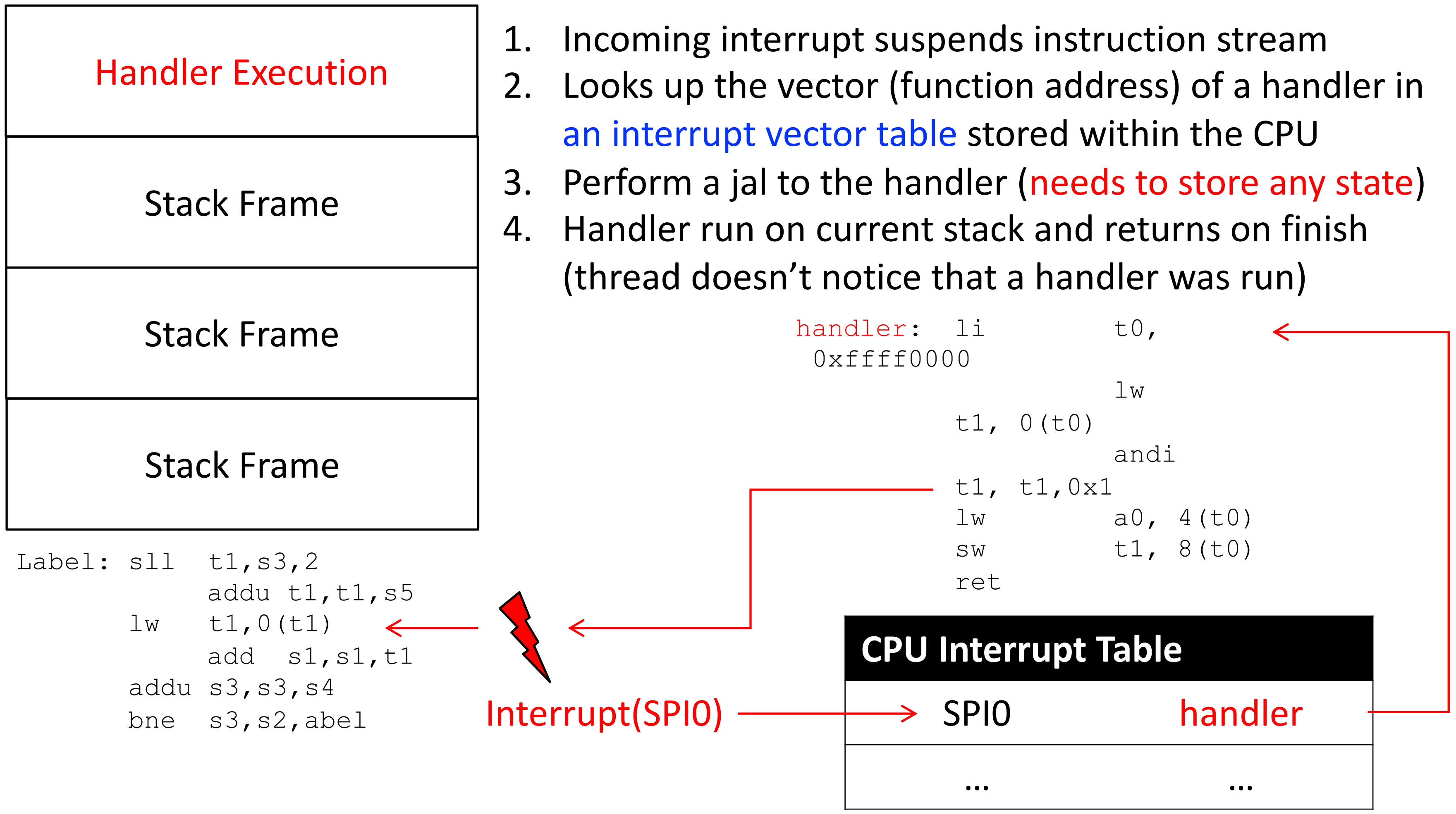
  => Polling mouse little impact on processor

What is the alternative to polling?

- Wasteful to have processor spend most of its time “spin-waiting” for I/O to be ready
- Would like an unplanned procedure call that would be invoked only when I/O device is ready
- Solution: use exception mechanism to help I/O.
  - Interrupt program when I/O ready, return when done with data transfer
- Allow to register (post) interrupt handlers: functions that are called when an interrupt is triggered

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 (needs to store any state)
4. Handler run on current stack and returns on finish (thread doesn’t notice that a handler was run)



```
handler:  li          t0,
 0xffff0000
                      lw
          t1,  0(t0)
                      andi
          t1,  t1,0x1
          lw          a0,  4(t0)
          sw          t1,  8(t0)
          ret
```

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

CPU Interrupt Table	
SPI0	handler
…	…

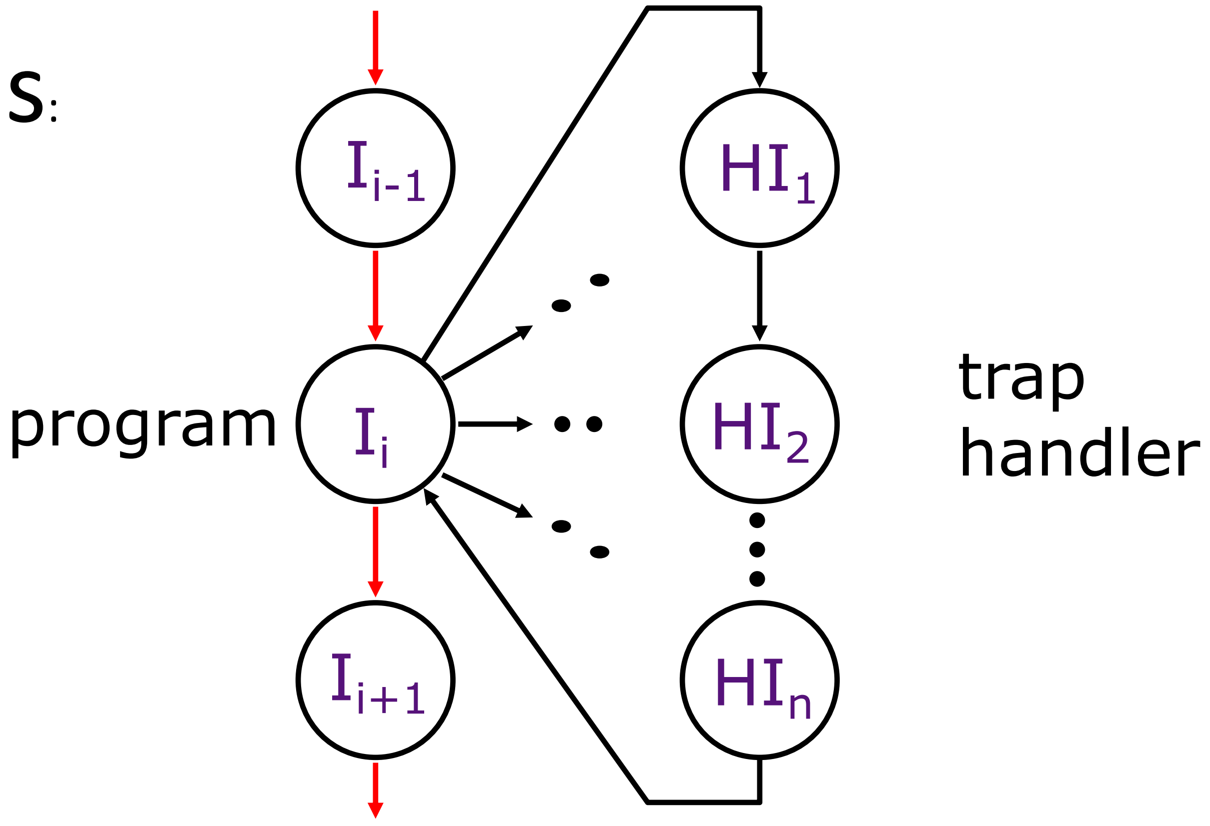
Terminology

In CA (you’ll see other definitions in use elsewhere):

- Interrupt – caused by an event *external* to current running program (e.g. key press, mouse activity)
  - Asynchronous to current program, can handle interrupt on any convenient instruction
- Exception – caused by some event during execution of one instruction of current running program (e.g., page fault, bus error, illegal instruction)
  - Synchronous, must handle exception on instruction that causes exception
- Trap – action of servicing interrupt or exception by hardware jump to “trap handler” code

Traps/Interrupts/Exceptions:

altering the normal flow of control



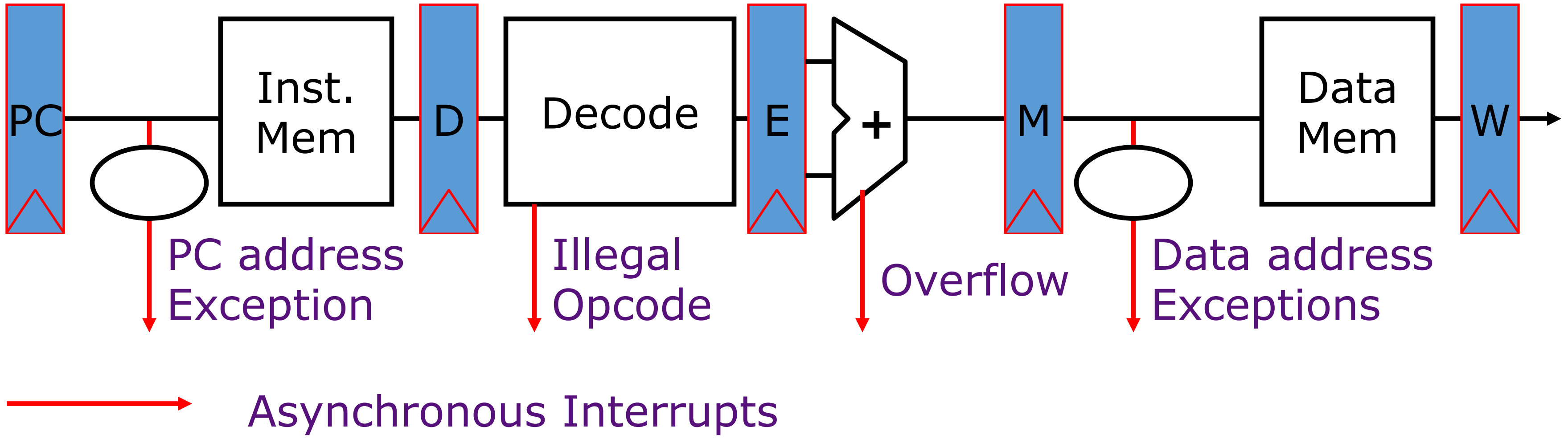
An *external or internal event* that needs to be processed - by another program – the OS. The event is often unexpected from original program’s point of view.

Supervisor exception program counter

Precise Traps

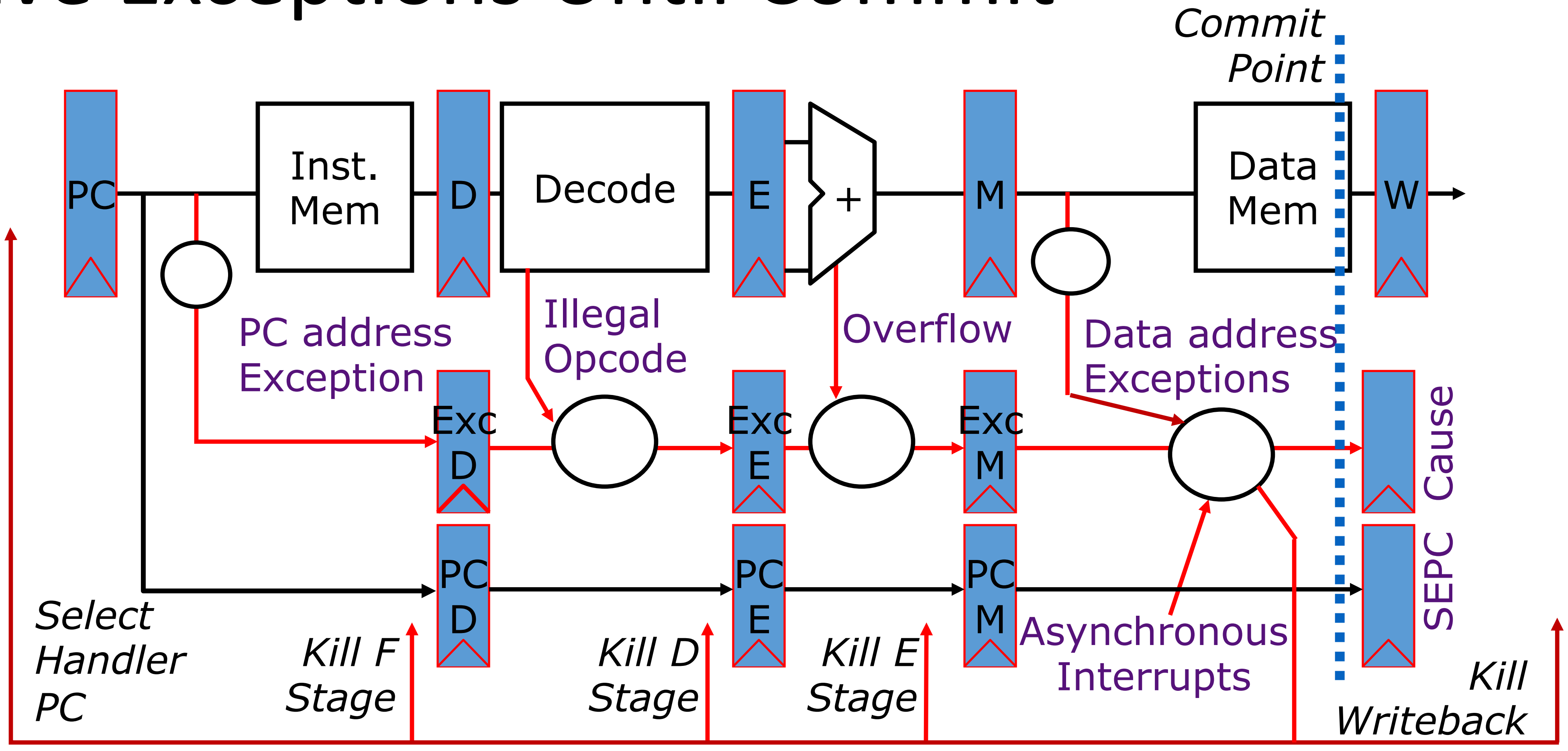
- *Trap handler's view of machine state is that every instruction prior to the trapped one has completed, and no instruction after the trap has executed.*
- Implies that handler can return from an interrupt by restoring user registers and jumping back to interrupted instruction (SEPC register will hold the instruction address)
  - 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 handling imprecise interrupts in software is even worse.

Trap Handling in 5-Stage Pipeline



- How to handle multiple simultaneous exceptions in different pipeline stages?
- How and where to handle external asynchronous interrupts?

Save Exceptions Until Commit



Handling Traps in In-Order Pipeline

- Hold exception flags in pipeline until commit point (M stage)
- Exceptions in earlier instructions override exceptions in later instructions
- Exceptions in earlier pipe stages override later exceptions *for a given instruction*
- Inject external interrupts at commit point
- If exception/interrupt at commit: update Cause and SEPC registers, kill all stages, inject handler PC into fetch stage

Trap Pipeline Diagram

time

	t0	t1	t2	t3	t4	t5	t6	t7	. . . .
(I_1) 096: ADD	IF_1	ID_1	EX_1	MA_1 →	-		*overflow!*		
(I_2) 100: XOR		IF_2	ID_2	EX_2	-	-			
(I_3) 104: SUB			IF_3	ID_3	-	-	-		
(I_4) 108: ADD				IF_4	-	-	-	-	
(I_5) Trap Handler code					IF_5	ID_5	EX_5	MA_5	WB_5

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Launching Applications

- Applications are called “processes” in most OSs.
  - Process: separate memory;
  - Thread: shared memory
- Created by another process calling into an OS routine (using a “syscall”, more details later).
  - Depends on OS, but Linux uses fork to create a new process, and execve to load application.
- Loads executable file from disk (using the file system service) and puts instructions & data into memory (.text, .data sections), prepare stack and heap.
- Set argc and argv, jump into the main function.

Supervisor Mode

- If something goes wrong in an application, it could crash the entire machine.
  - And what about malware, etc.?
- The OS may need to enforce resource constraints to applications (e.g., access to devices).
- To help protect the OS from the application, CPUs have a supervisor mode bit.
  - When not in supervisor mode (user mode), a process can only access a subset of instructions and (physical) memory.
  - Process can enter the supervisor mode by using an interrupt, and change out of supervisor mode using a special instruction.

Syscalls

- What if we want to call into an OS routine? (e.g., to read a file, launch a new process, send data, etc.)
  - Need to perform a syscall: set up function arguments in registers, and then raise software interrupt
  - OS will perform the operation and return to user mode
- This way, the OS can mediate access to all resources, including devices and the CPU itself.

Multiprogramming

- The OS runs multiple applications at the same time.
- But not really (unless you have a core per process)
  - Time-sharing processor
- 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.
- Switches between processes very quickly. This is called a “context switch”.
- Deciding what process to run is called scheduling.

Protection, Translation, Paging

- Supervisor mode does not fully isolate applications from each other or from the OS.
  - Application could overwrite another application’s memory.
  - 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.

In Conclusion

- Once we have a basic machine, it’s mostly up to the OS to use it and define application interfaces.
- I/O
  - Polling
  - Interrupt
- Exception, interrupt, trap
  - Precise trap