CS 110
Computer Architecture
Lecture 22:
Operating Systems, Interrupts, Virtual Memory

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http://shtech.org/courses/ca/

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Slides based on UC Berkley's CS61C

CA so far…

C Programs

```
#include <stdlib.h>

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

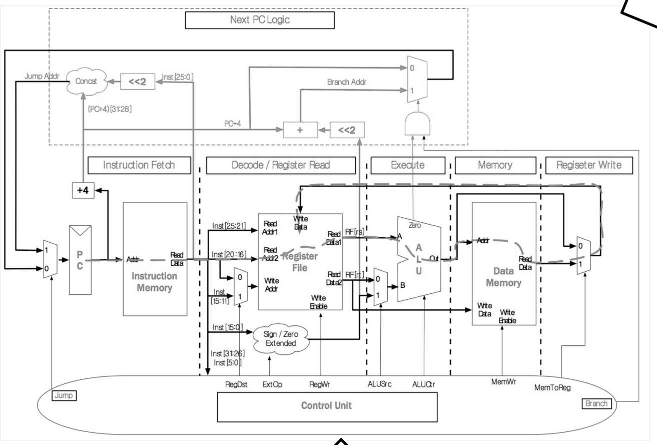
Project 1

MIPS Assembly

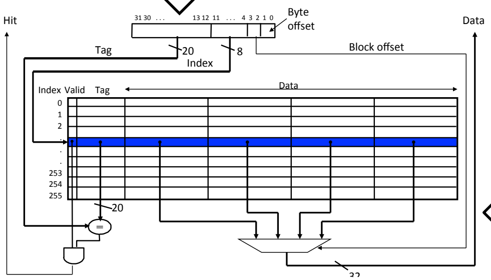
```
.foo
lw $t0, 4($r0)
addi $t1, $t0, 3
beq $t1, $t2, foo
nop
```

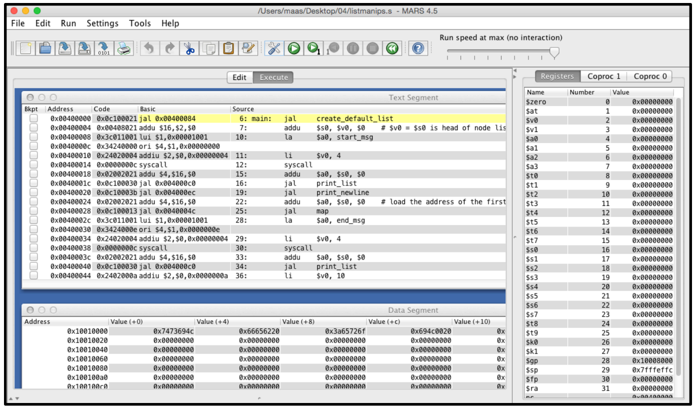
Project 2

CPU



Caches



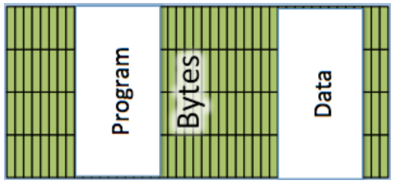


```
Bkpt Address    Code       Basic                     Source
     0x00400000 0x0c100021 jal 0x00400084             6: main:  jal    create_default_list
     0x00400004 0x00408021 addu $16,$2,$0             7:        addu   $s0, $v0, $0    # $v0 = $s0 is head of node lis
     0x00400008 0x3c011001 lui $1,0x00001001         10:        la     $a0, start_msg
     0x0040000c 0x34240000 ori $4,$1,0x00000000
     0x00400010 0x24020004 addiu $2,$0,0x00000004    11:        li     $v0, 4
     0x00400014 0x0000000c syscall                   12:        syscall
     0x00400018 0x02002021 addu $4,$16,$0            15:        addu   $a0, $s0, $0
     0x0040001c 0x0c100030 jal 0x004000c0            16:        jal    print_list
     0x00400020 0x0c10003b jal 0x004000ec            19:        jal    print_newline
     0x00400024 0x02002021 addu $4,$16,$0            22:        addu   $a0, $s0, $0    # load the address of the first
     0x00400028 0x0c100013 jal 0x0040004c            25:        jal    map
     0x0040002c 0x3c011001 lui $1,0x00001001         28:        la     $a0, end_msg
     0x00400030 0x3424000e ori $4,$1,0x0000000e
     0x00400034 0x24020004 addiu $2,$0,0x00000004    29:        li     $v0, 4
     0x00400038 0x0000000c syscall                   30:        syscall
     0x0040003c 0x02002021 addu $4,$16,$0            33:        addu   $a0, $s0, $0
     0x00400040 0x0c100030 jal 0x004000c0            34:        jal    print_list
     0x00400044 0x2402000a addiu $2,$0,0x0000000a    36:        li     $v0, 10
```

```
Address        Value (+0)    Value (+4)    Value (+8)    Value (+c)    Value (+10)
  0x10010000   0x7473694c    0x66656220    0x3a65726f    0x694c0020    0x
  0x10010020   0x00000000    0x00000000    0x00000000    0x00000000    0x
  0x10010040   0x00000000    0x00000000    0x00000000    0x00000000    0x
  0x10010060   0x00000000    0x00000000    0x00000000    0x00000000    0x
  0x10010080   0x00000000    0x00000000    0x00000000    0x00000000    0x
  0x100100a0   0x00000000    0x00000000    0x00000000    0x00000000    0x
  0x100100c0   0x00000000    0x00000000    0x00000000    0x00000000    0x
```

Name	Number	Value
$zero	0	0x00000000
$at	1	0x00000000
$v0	2	0x00000000
$v1	3	0x00000000
$a0	4	0x00000000
$a1	5	0x00000000
$a2	6	0x00000000
$a3	7	0x00000000
$t0	8	0x00000000
$t1	9	0x00000000
$t2	10	0x00000000
$t3	11	0x00000000
$t4	12	0x00000000
$t5	13	0x00000000
$t6	14	0x00000000
$t7	15	0x00000000
$s0	16	0x00000000
$s1	17	0x00000000
$s2	18	0x00000000
$s3	19	0x00000000
$s4	20	0x00000000
$s5	21	0x00000000
$s6	22	0x00000000
$s7	23	0x00000000
$t8	24	0x00000000
$t9	25	0x00000000
$k0	26	0x00000000
$k1	27	0x00000000
$gp	28	0x10008000
$sp	29	0x7fffeffc
$fp	30	0x00000000
$ra	31	0x00000000
pc		0x00400000

Memory



So how is this any different?

Adding I/O

C Programs

```
#include <stdlib.h>

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

Project 1

MIPS Assembly

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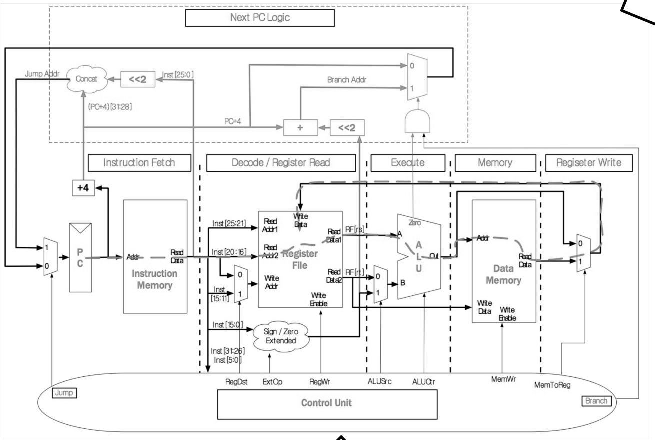
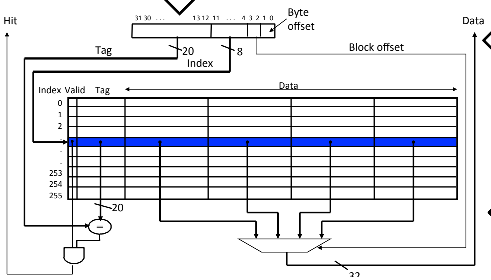
Project 2

CPU



Caches



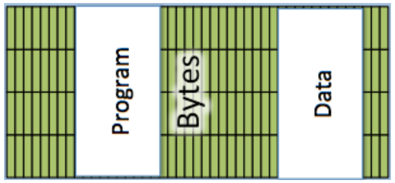
I/O (Input/Output)

Screen

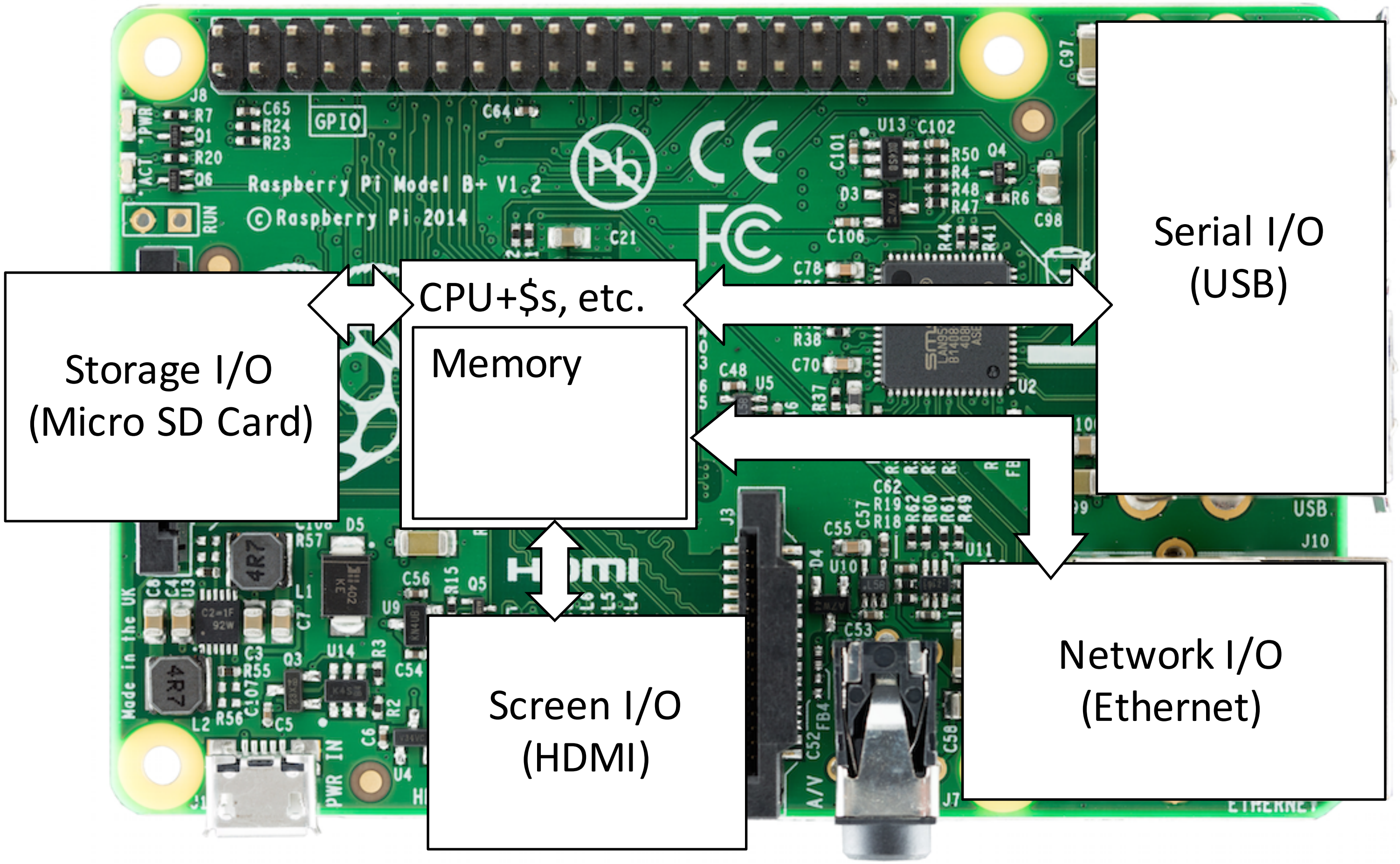
Keyboard

Storage

Memory



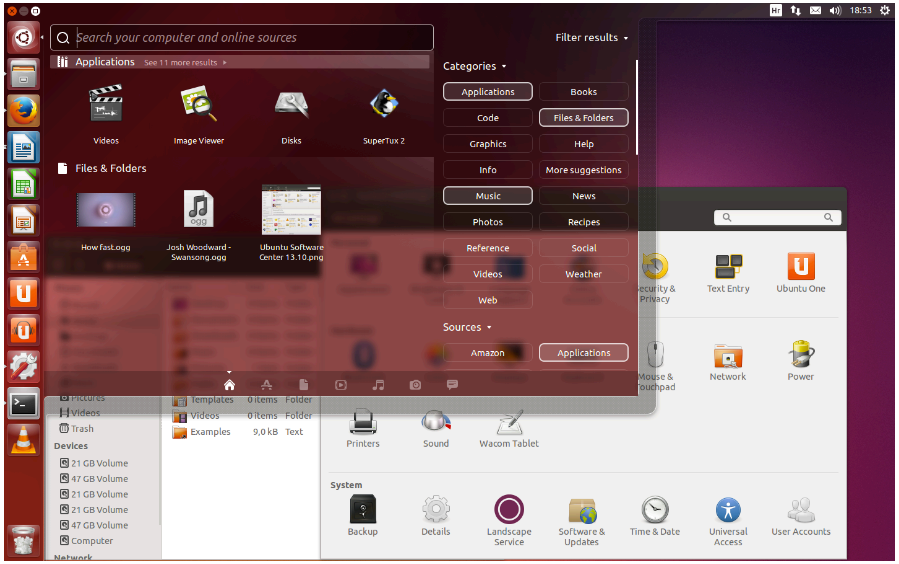
Raspberry Pi (< 300RMB on jd.com)



It’s a real computer!

But wait…

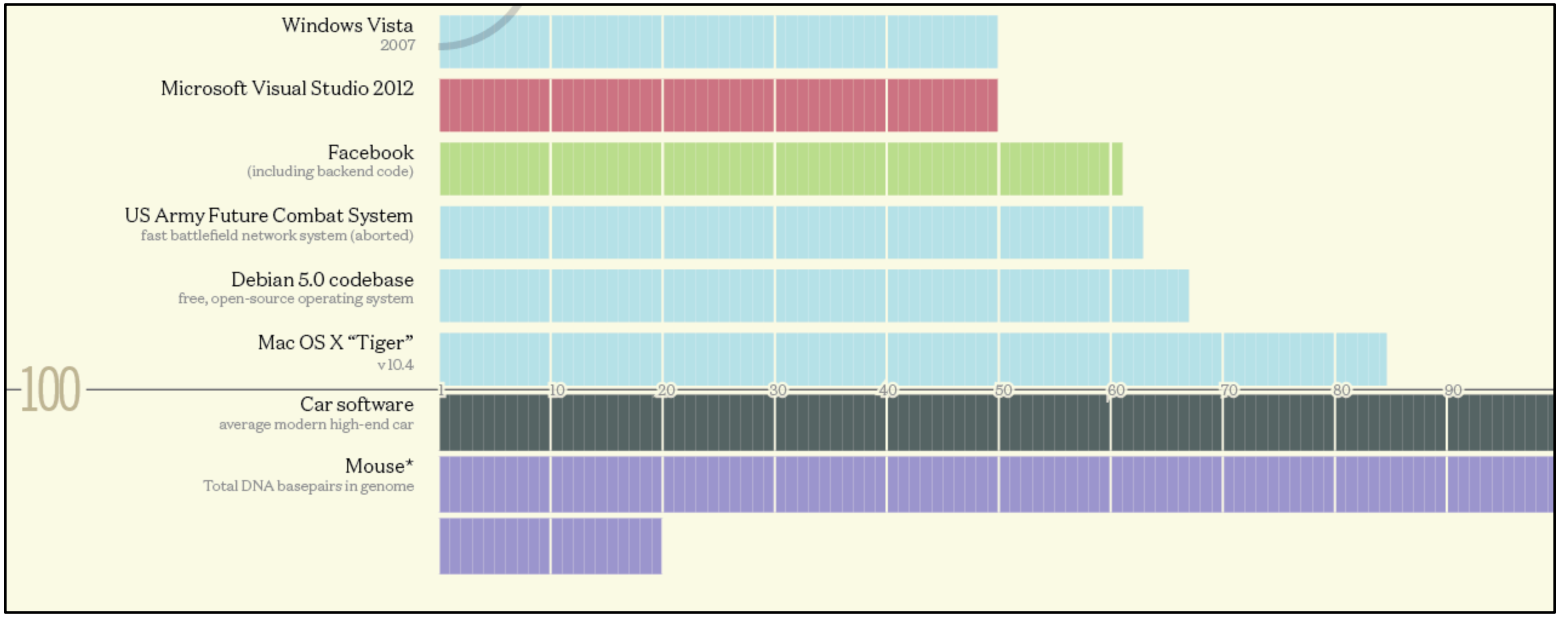
- That’s not the same! When we run MARS, it only executes one program and then stops.
- When I switch on my computer, I get this:



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/

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, etc.
- Finds and controls all the devices in the machine in a general way (using "device drivers")

Agenda

- Devices and I/O
- OS Boot Sequence and Operation
- Multiprogramming/time-sharing
- Introduction to Virtual Memory

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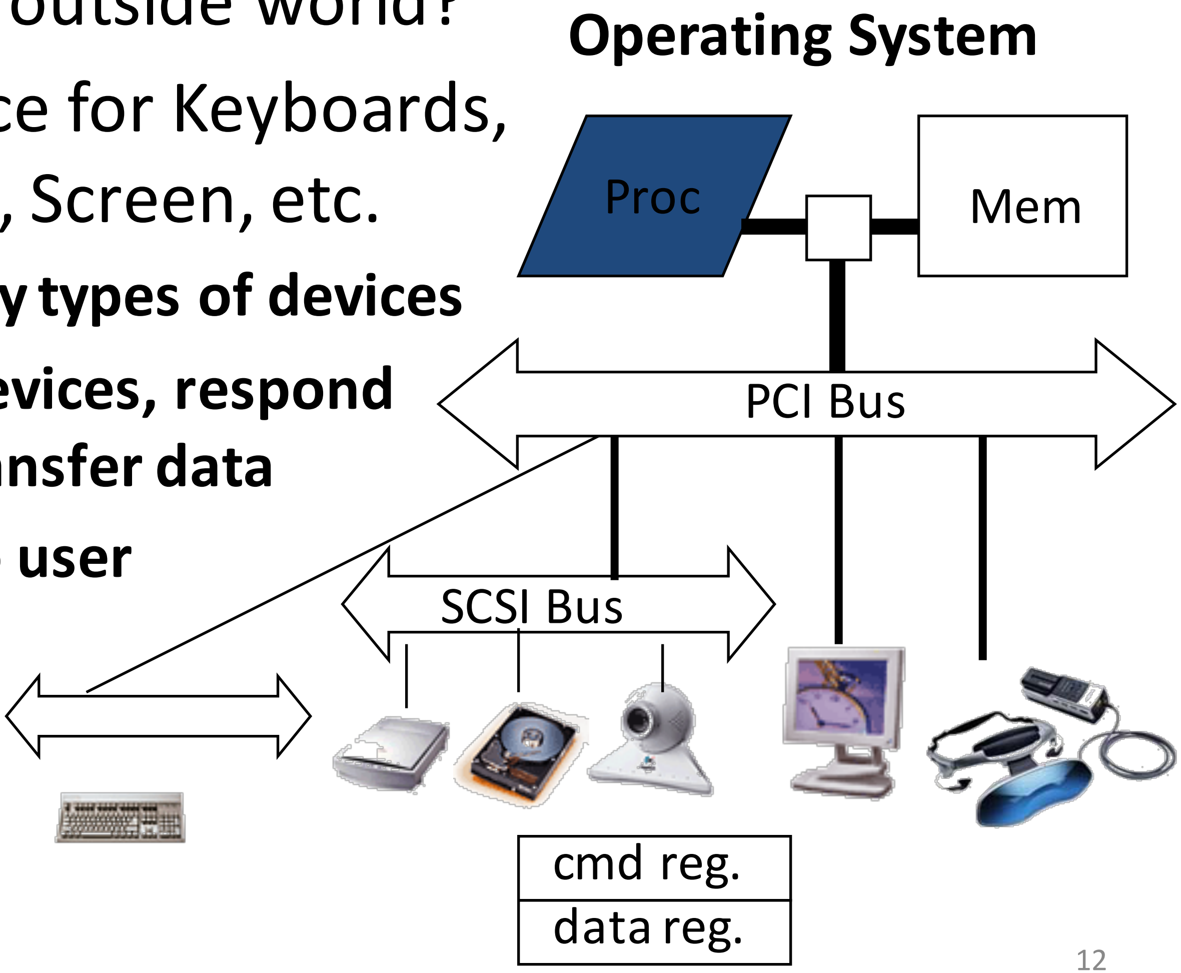
How to interact with devices?

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

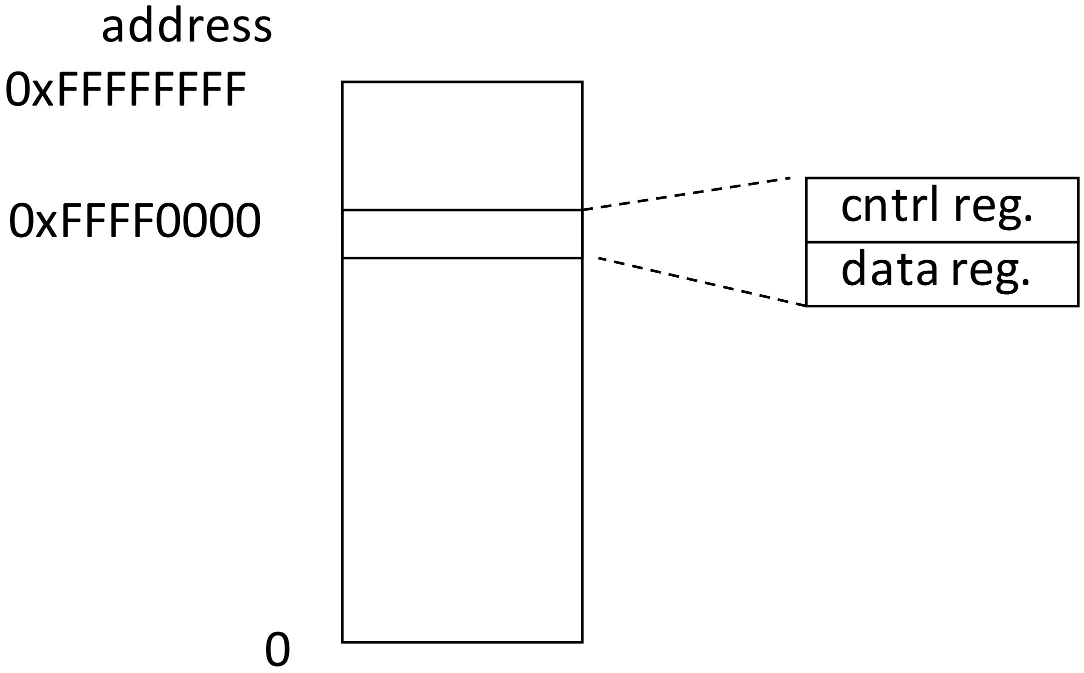


Instruction Set Architecture for I/O

- What must the processor do for I/O?
  - Input: reads a sequence of bytes
  - Output: writes a sequence of bytes
- Some processors have special input and output instructions
- Alternative model (used by MIPS):
  - Use loads for input, stores for output (in small pieces)
  - Called Memory Mapped Input/Output
  - A portion of the address space dedicated to communication paths to Input or Output devices (no memory there)

Memory Mapped I/O

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



address

0xFFFFFFFF

0xFFFF0000

0

cntrl reg.

data reg.

Processor-I/O Speed Mismatch

- 1GHz microprocessor can execute 1B 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 **$v0**

```
            lui   $t0, 0xffff #ffff0000
Waitloop:   lw    $t1, 0($t0) #control
            andi  $t1,$t1,0x1
            beq   $t1,$zero, Waitloop
            lw    $v0, 4($t0) #data
```

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

```
            lui   $t0, 0xffff #ffff0000
Waitloop:   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
  - Hard disk: assume transfers data in 16-Byte chunks and can transfer at 16 MB/second. Again, no transfer can be missed. (we'll come up with a better way to do this)

% 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

  = 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

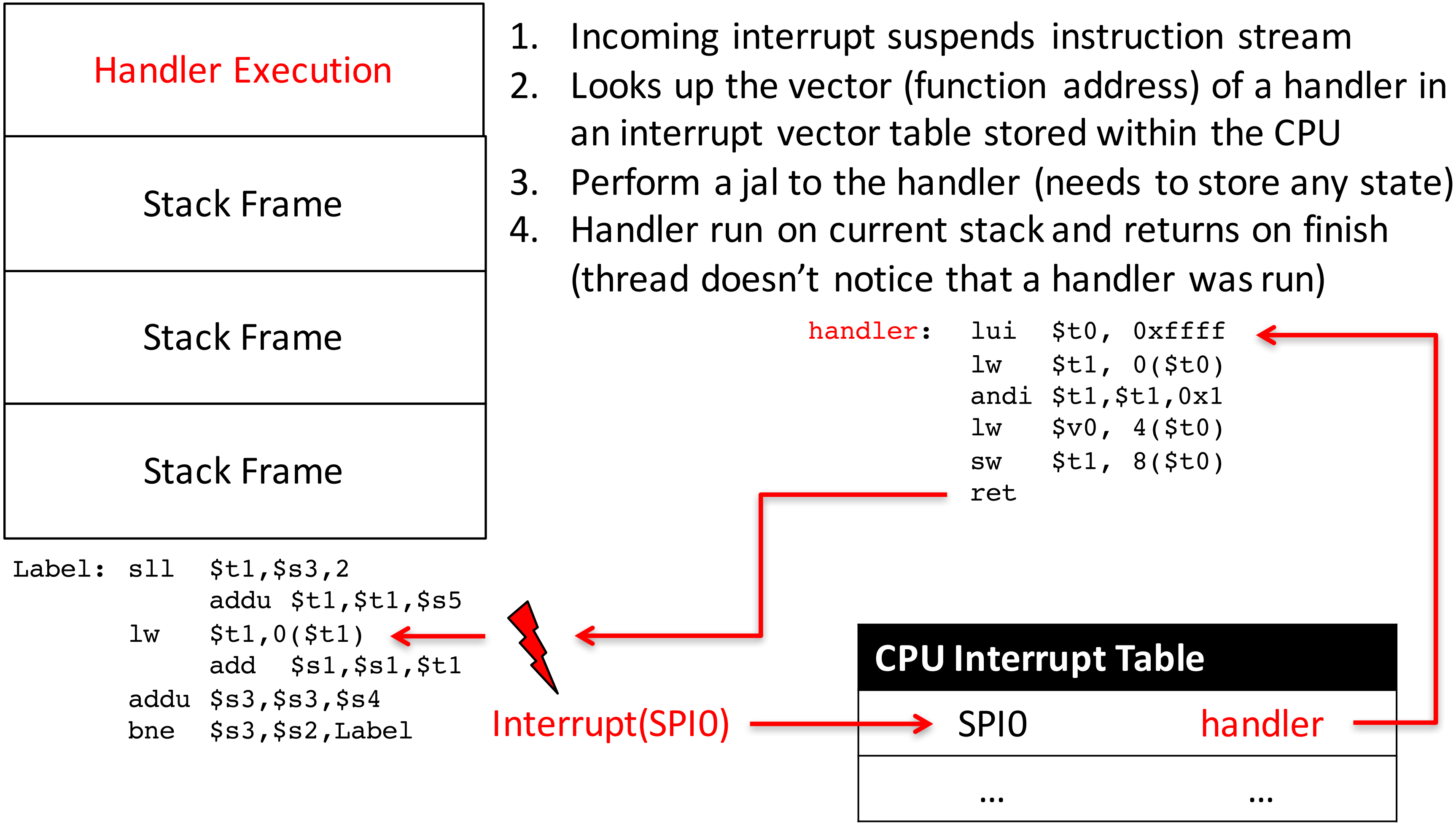
  (Polling is only part of the problem – main problem is that accessing in small chunks is inefficient)

What is the alternative to polling?

- 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: lui  $t0, 0xffff
         lw   $t1, 0($t0)
         andi $t1,$t1,0x1
         lw   $v0, 4($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,Label
```

CPU Interrupt Table	
SPI0	handler
…	…

Agenda

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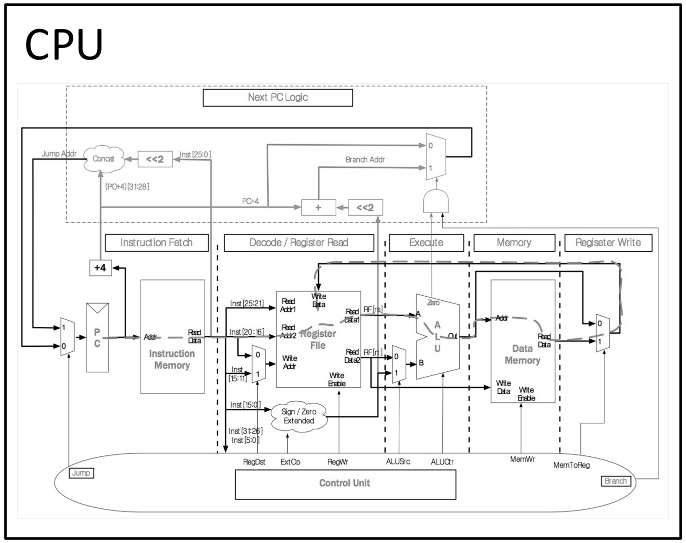
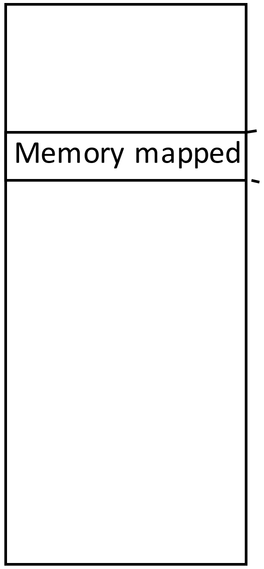
What happens at boot?

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



PC = 0x2000 (some default value)



Address Space

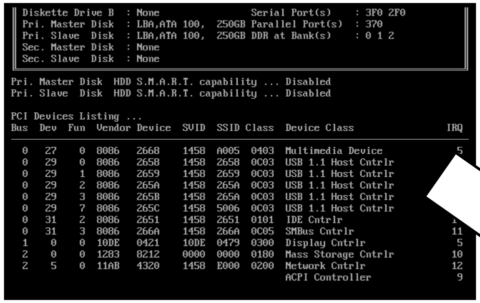
```
0x2000:
addi $t0, $zero, 0x1000
lw $t0, 4($r0)
…

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

What happens at boot?

- When the computer switches on, it does the same as MARS: 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)



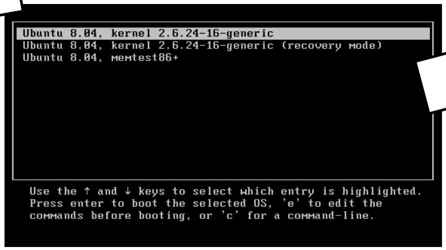
```
 Diskette Drive B  : None                    Serial Port(s)    : 3F0 2F0
 Pri. Master Disk  : LBA,ATA 100,  250GB Parallel Port(s)  : 370
 Pri. Slave  Disk  : LBA,ATA 100,  250GB DDR at Bank(s)    : 0 1 2
 Sec. Master Disk  : None
 Sec. Slave  Disk  : None

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
```

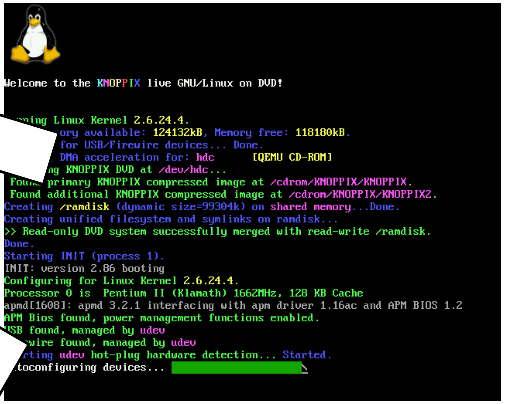
2. Bootloader (stored on, e.g., disk): Load the OS *kernel* from disk into a location in memory and jump into it.



```
 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.
```

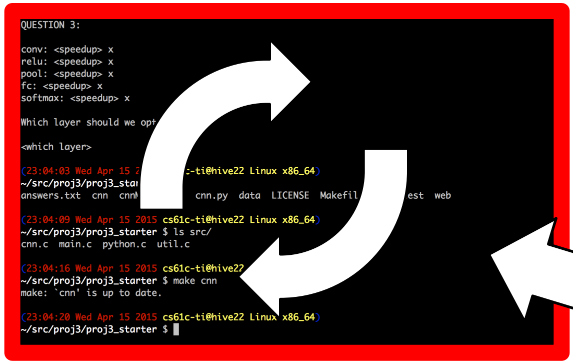
3. OS Boot: Initialize services, drivers, etc.



```
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...
 Foun  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.
SB found, managed by udev
  wire 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 opt

<which layer>

(23:04:03 Wed Apr 15 2        c-ti@hive22 Linux x86_64)
~/src/proj3/proj3_star
answers.txt  cnn  cnnM        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 $ 
```

Launching Applications

- Applications are called “processes” in most OSs.
- 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.
  - 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.

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
- Also, OS uses interrupts for scheduling process execution:
  - OS sets scheduler timer interrupt then drops to user mode and start executing a user task, when interrupts triggers, switch into supervisor mode, select next task to execute (& set timer) and drop back to user mode.
- This way, the OS can mediate access to all resources, including devices and the CPU itself.

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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. 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 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.

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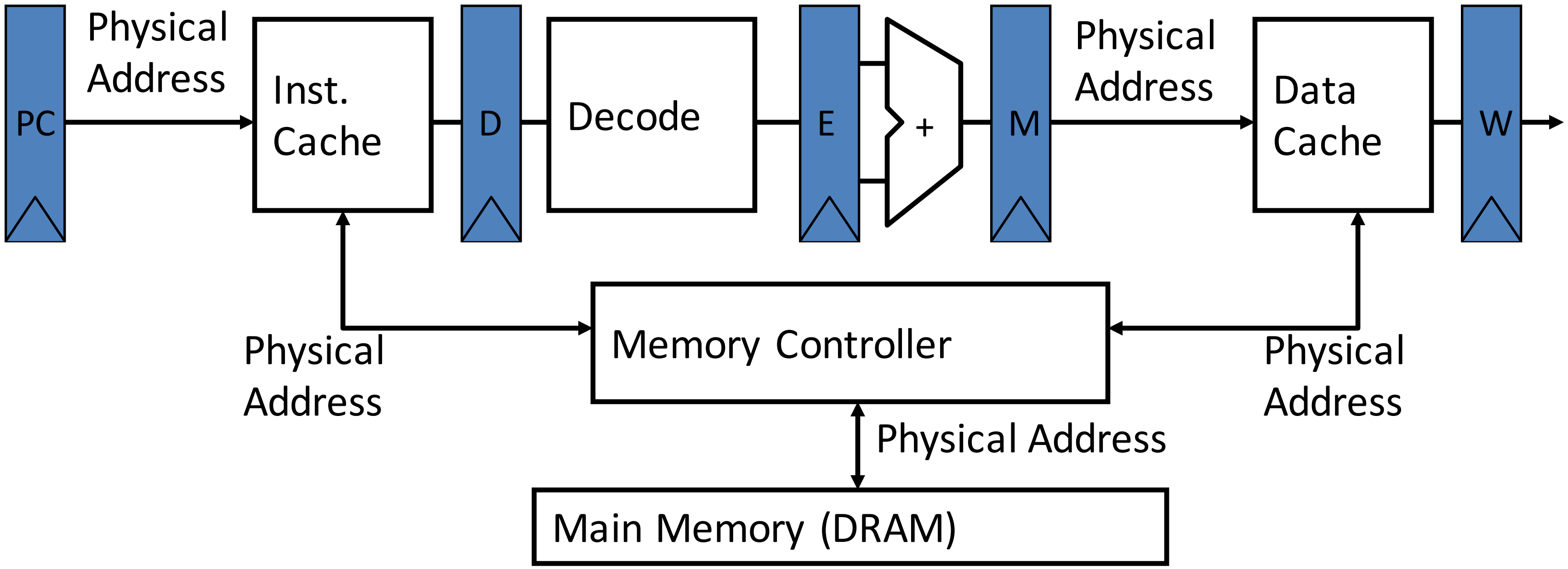
“Bare” 5-Stage Pipeline



- In a bare machine, the only kind of address is a physical address

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).

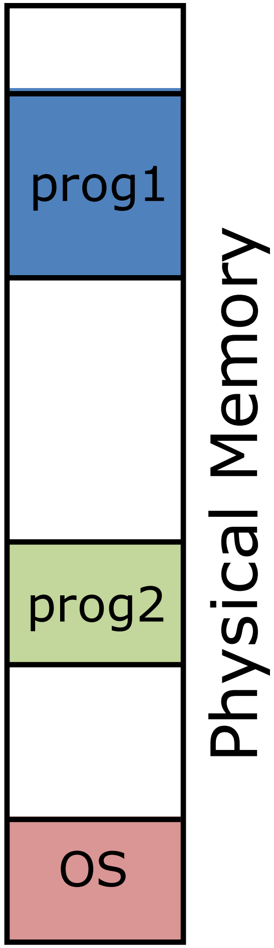
Location-independent programs

Programming and storage management ease
=> *base register – add offset to each address*

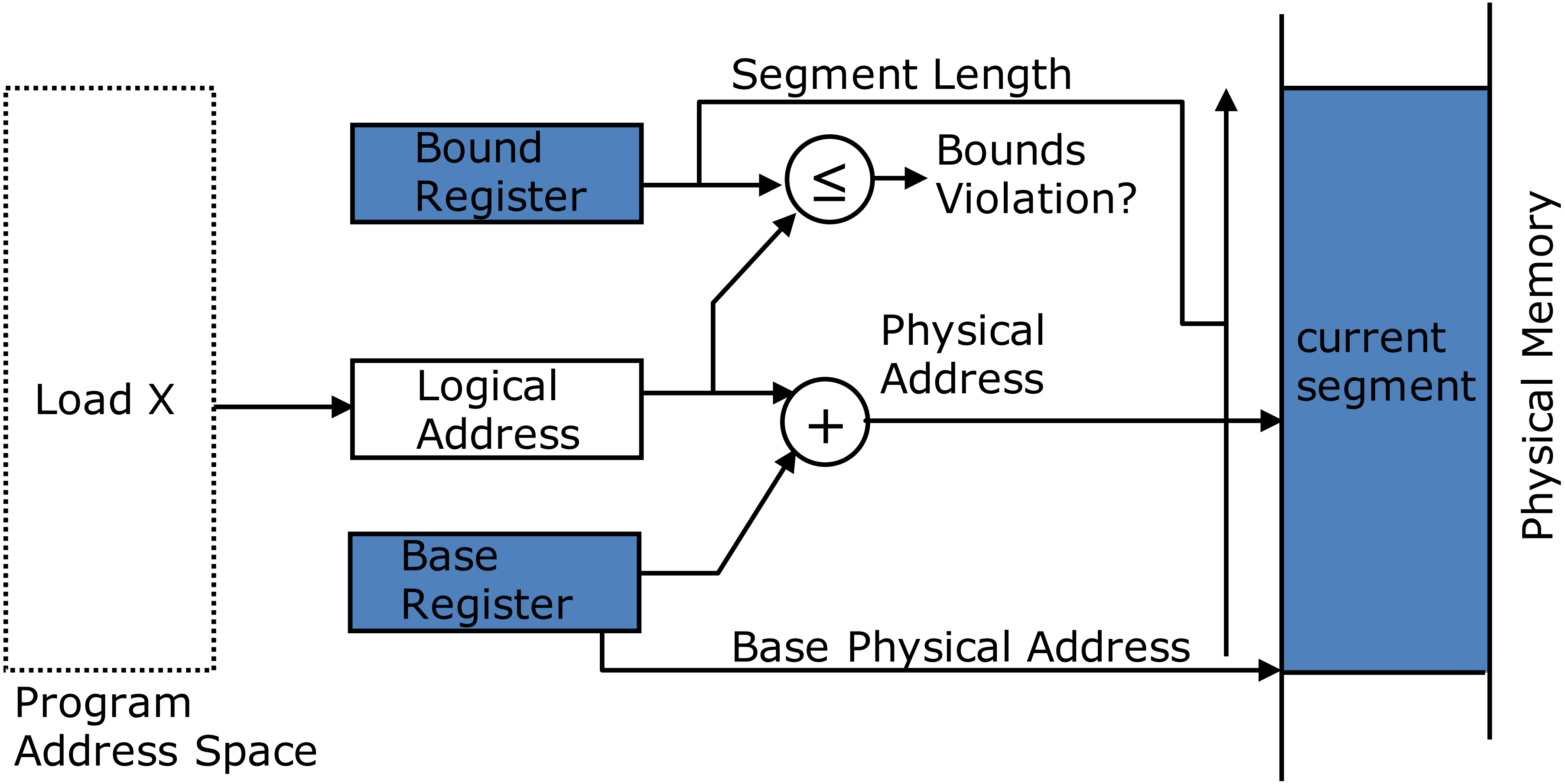
Protection

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)

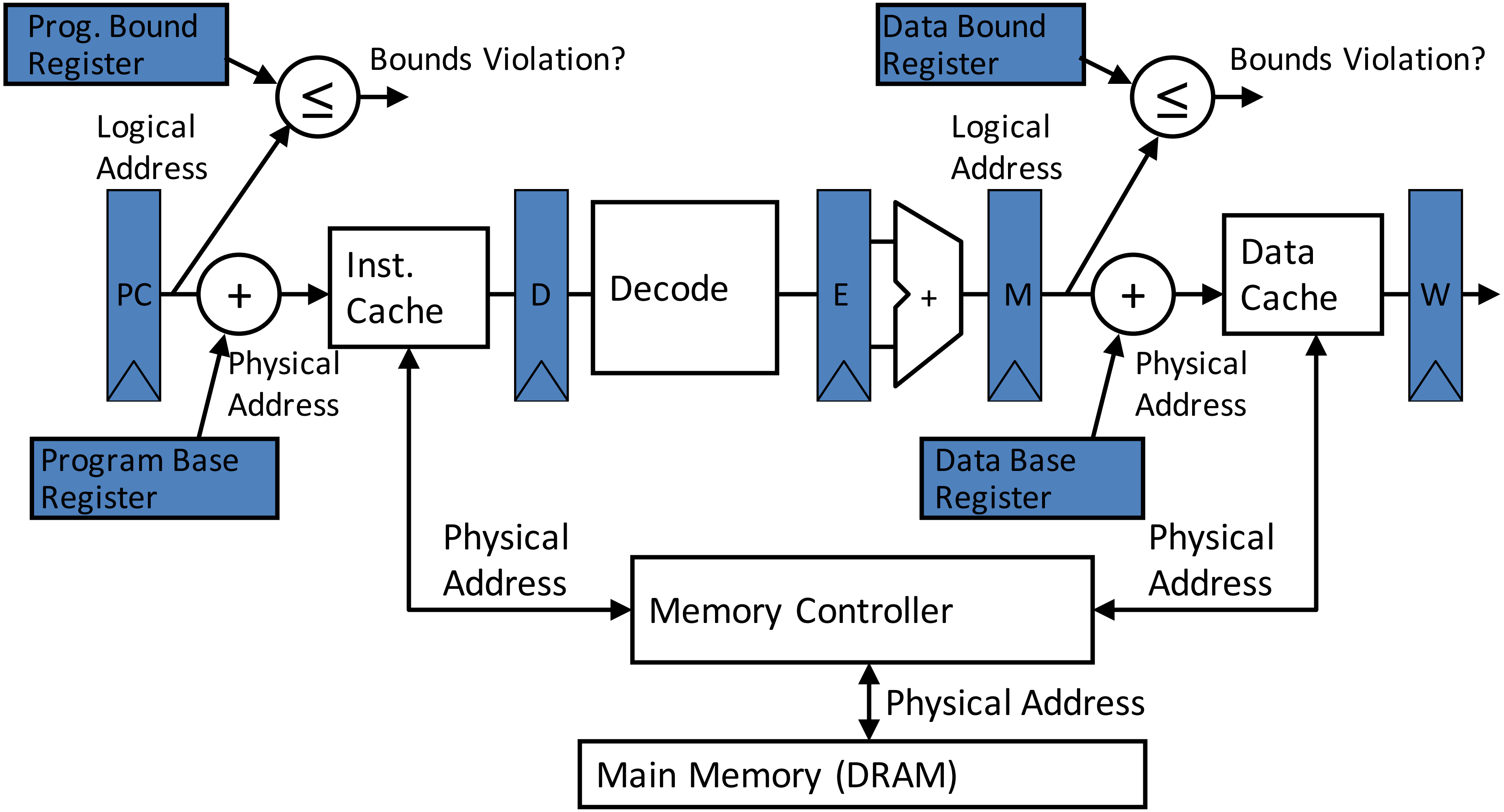


Simple Base and Bound Translation



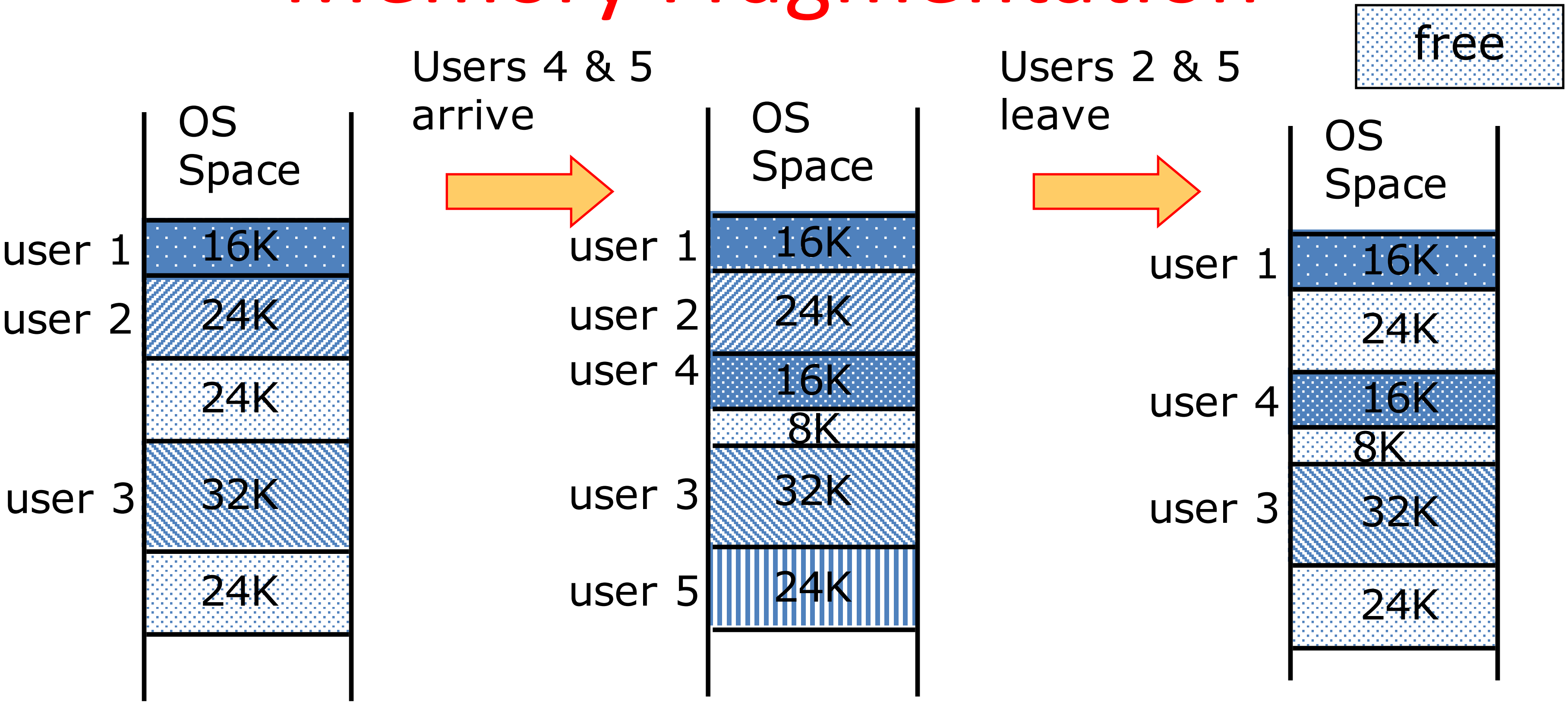
Base and bounds registers are visible/accessible only when processor is running in *supervisor mode*

Base and Bound Machine



[Can fold addition of base register into (register+immediate) address calculation using a carry-save adder (sums three numbers with only a few gate delays more than adding two numbers)]

Memory Fragmentation



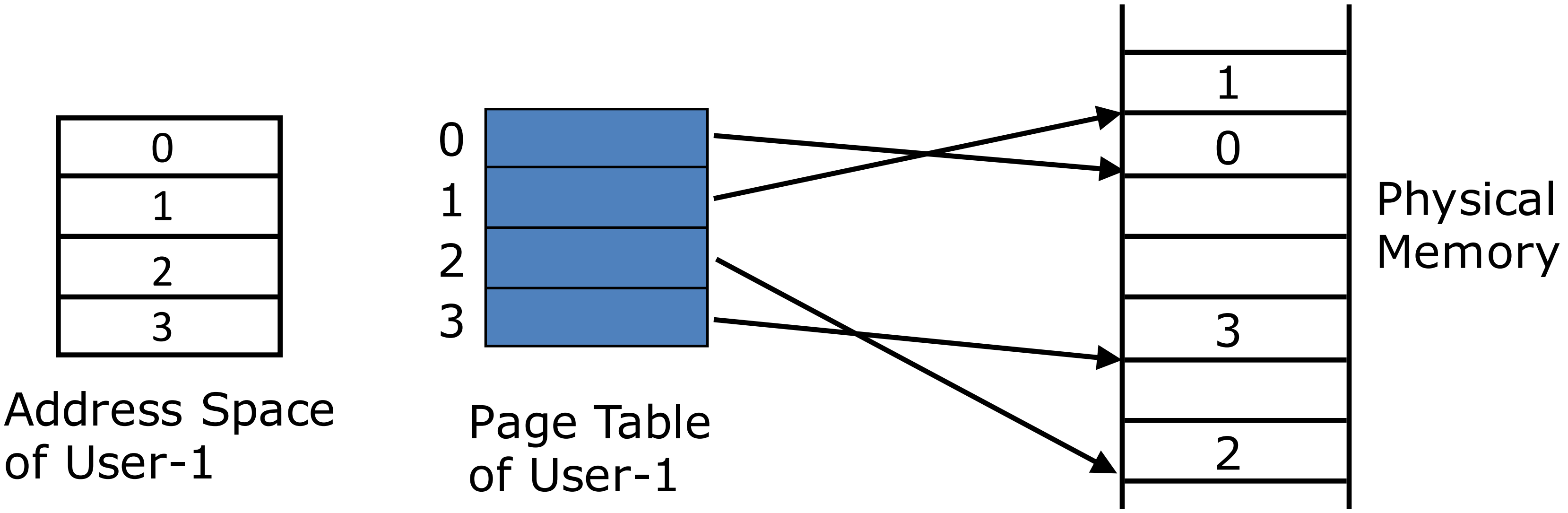
As users come and go, the storage is "fragmented". Therefore, at some stage programs have to be moved around to compact the storage.

Paged Memory Systems

- Processor-generated address can be split into:

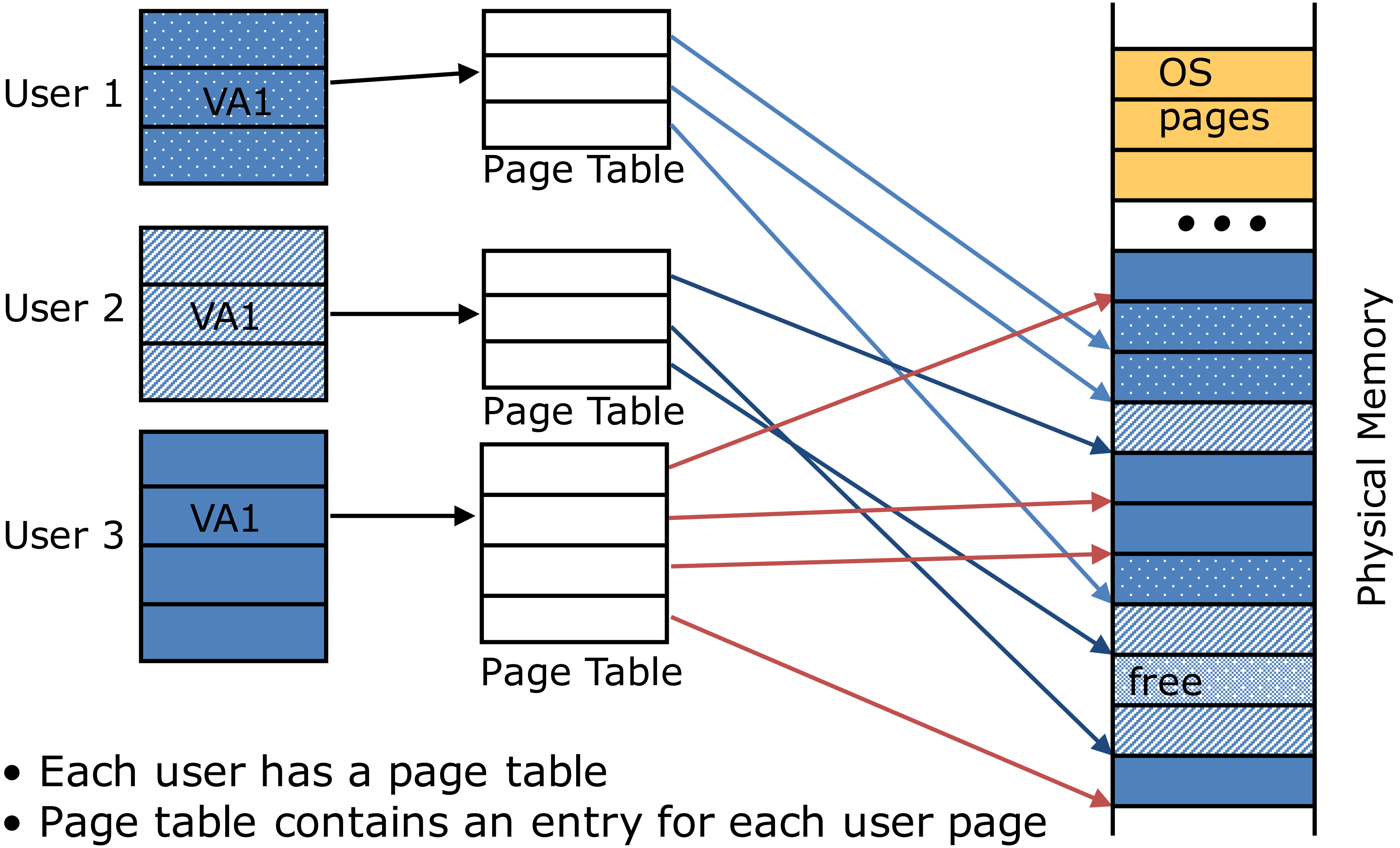
page number	offset

- 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

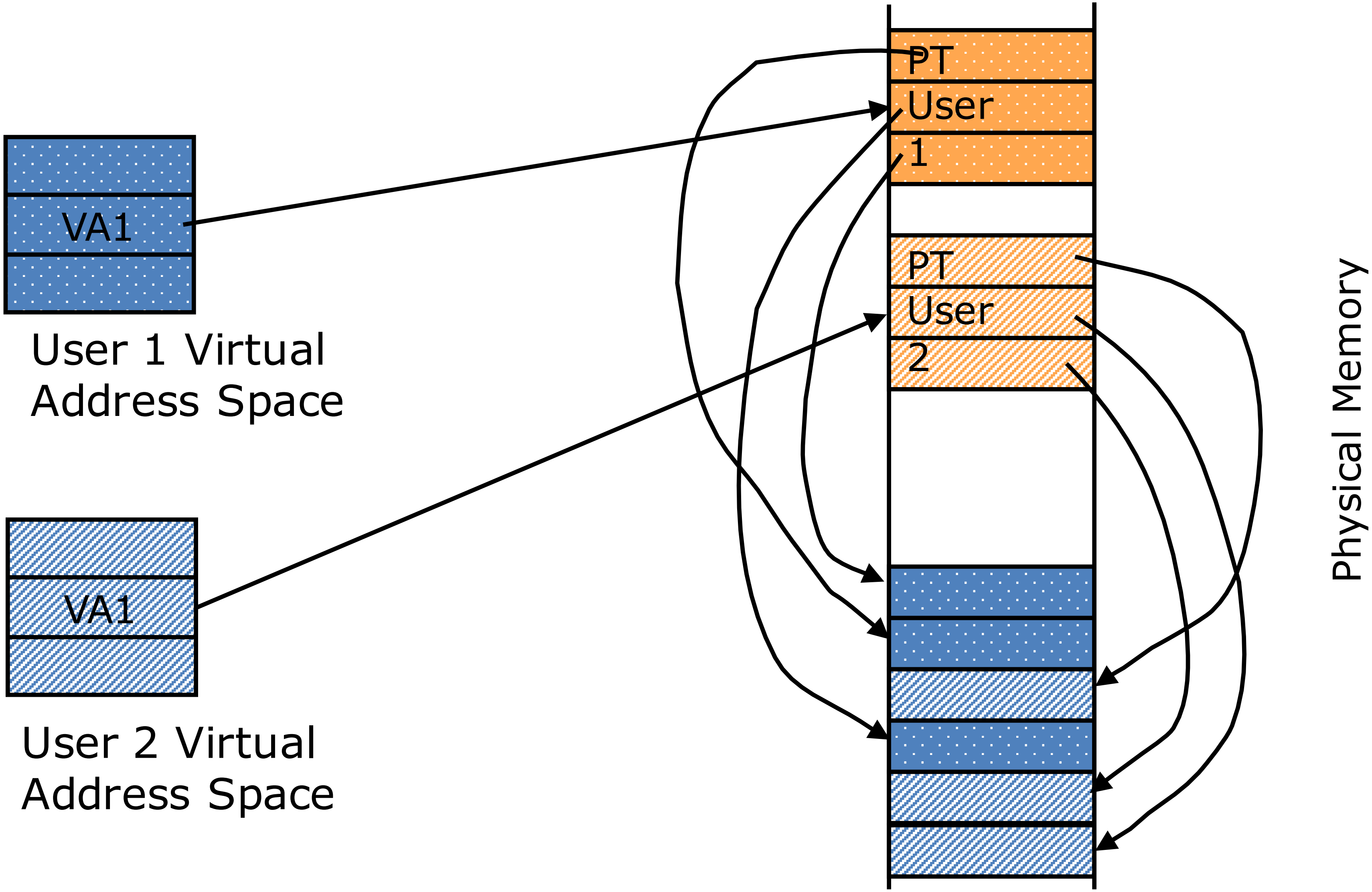
Where Should Page Tables Reside?

- 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



In Conclusion

- Once we have a basic machine, it’s mostly up to the OS to use it and define application interfaces.
- Hardware helps by providing the right abstractions and features (e.g., Virtual Memory, I/O).