CS 61C: Great Ideas in Computer Architecture (Machine Structures) *Operating Systems, Interrupts, Virtual Memory*

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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);
}
```

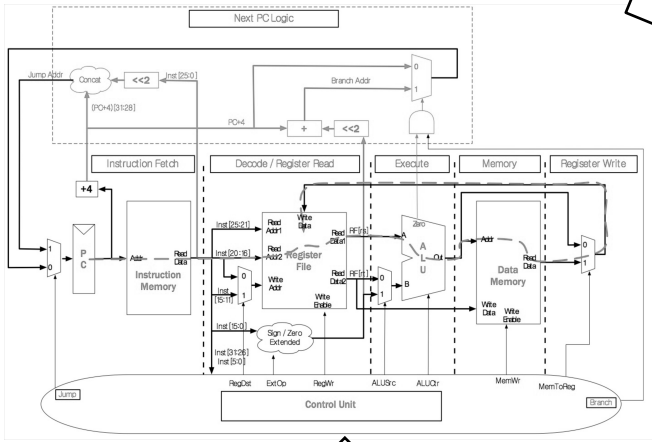
MIPS Assembly

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

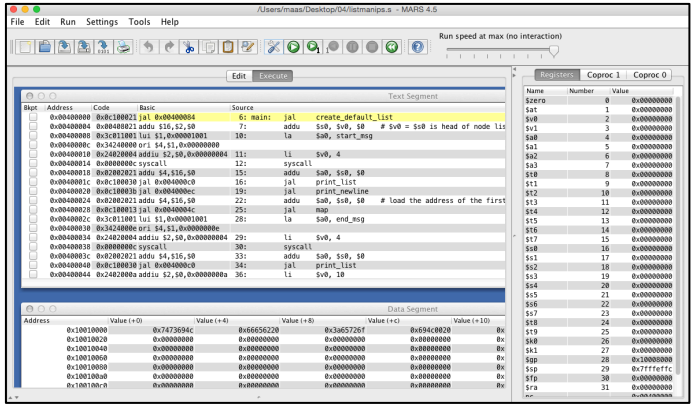
Project 1

Project 2

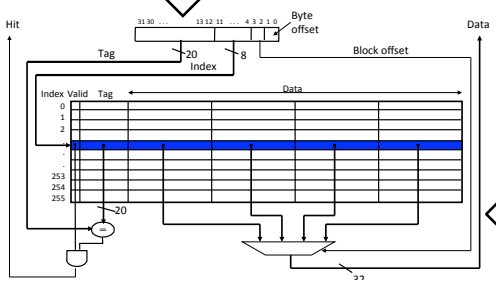
CPU



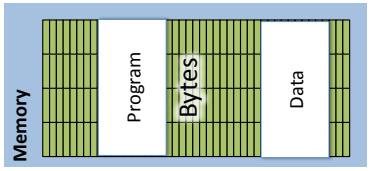
Labs



Caches



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);
}
```

MIPS Assembly

```
.foo
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addi $t1, $t0, 3
beq $t1, $t2, foo
nop
```
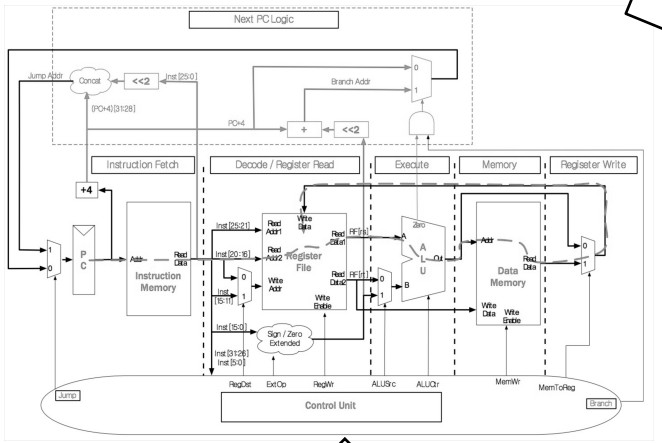

Project 2

Project 1

CPU

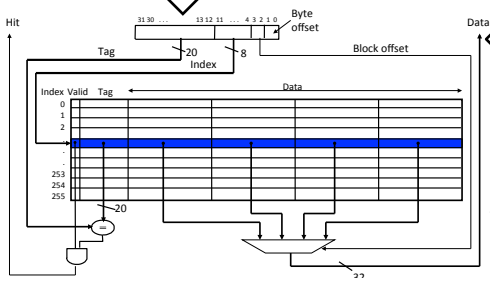


Screen

Keyboard

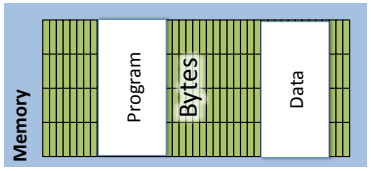
Storage

Caches

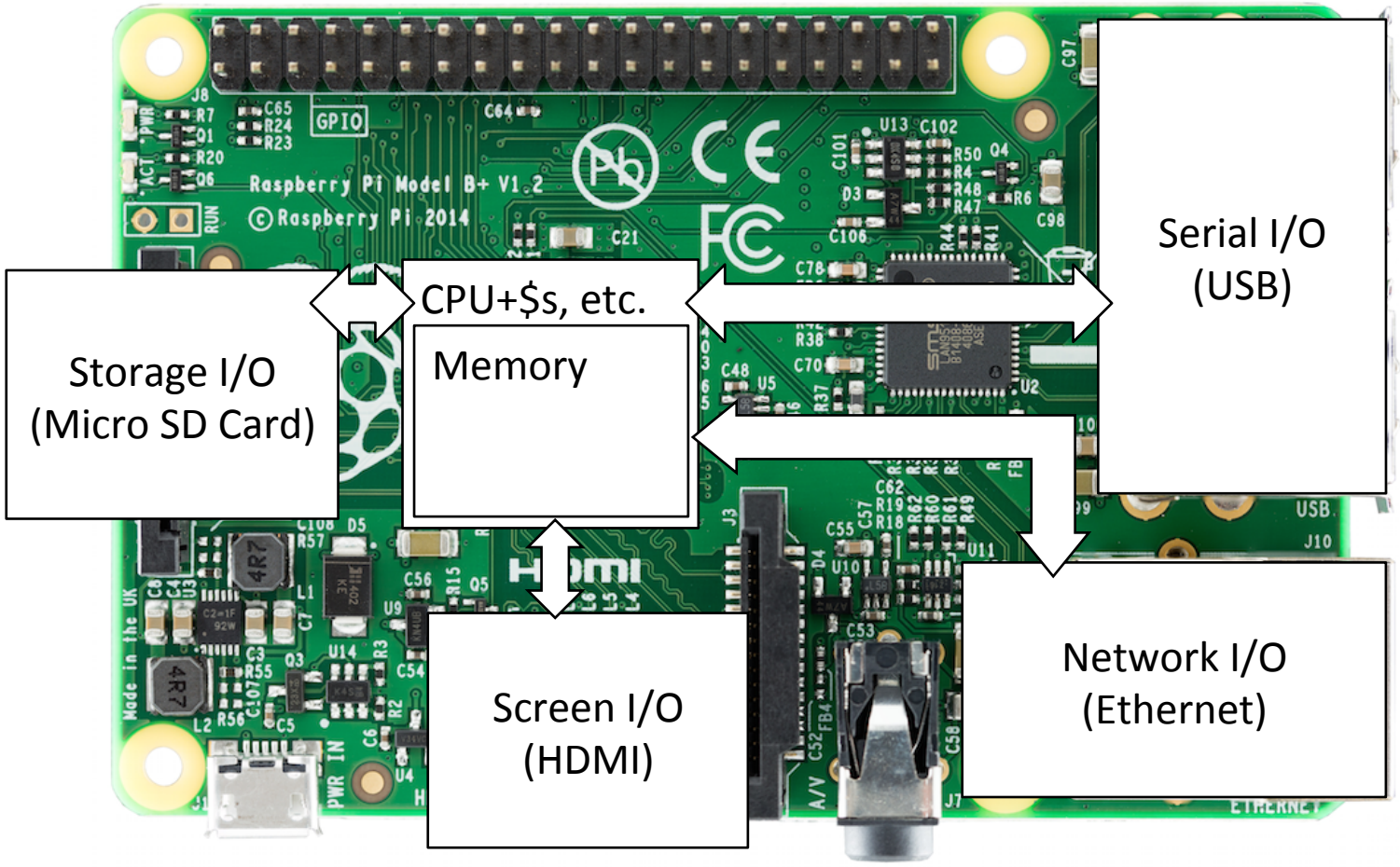


I/O (Input/Output)

Memory



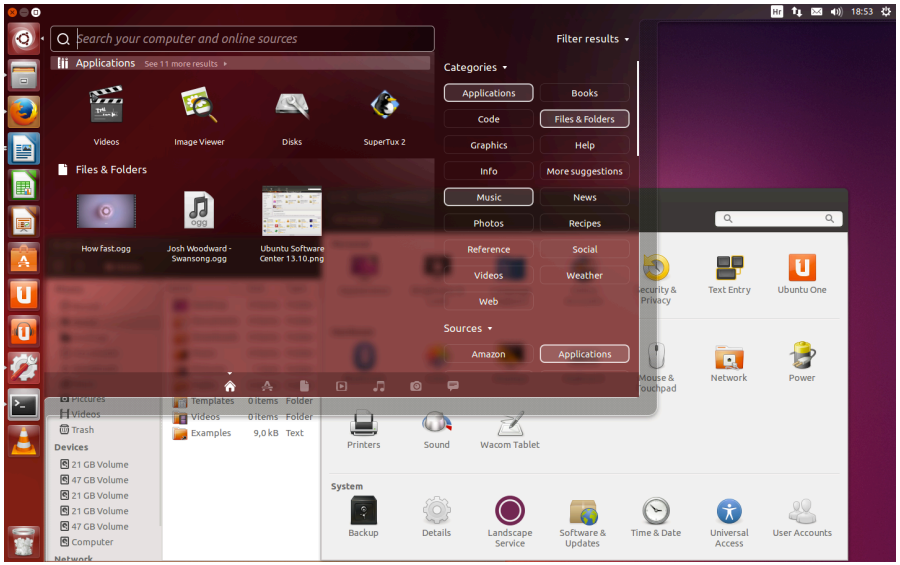
Raspberry Pi ($40 on Amazon)



It’s a real computer!

But wait…

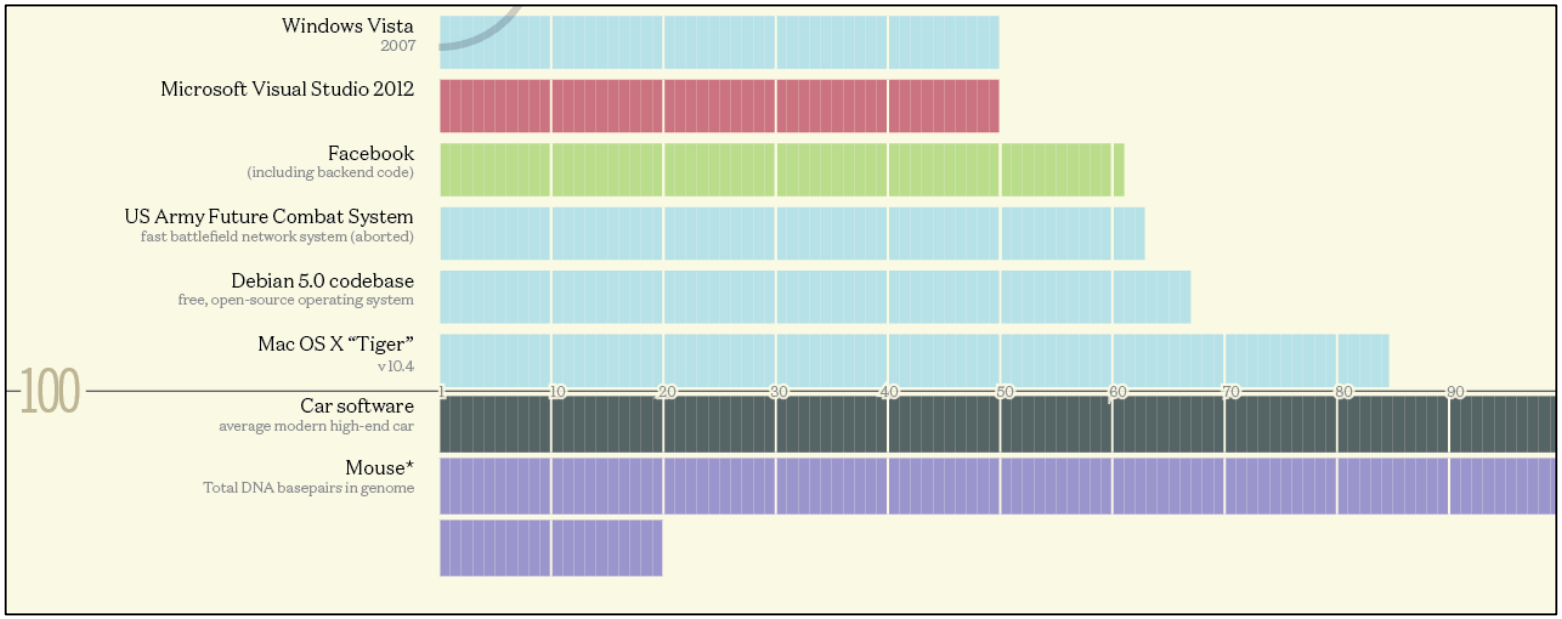
- That's not the same! When we run MARS, it only executes one program and then stops.
- When I switch on my computer, I get this:



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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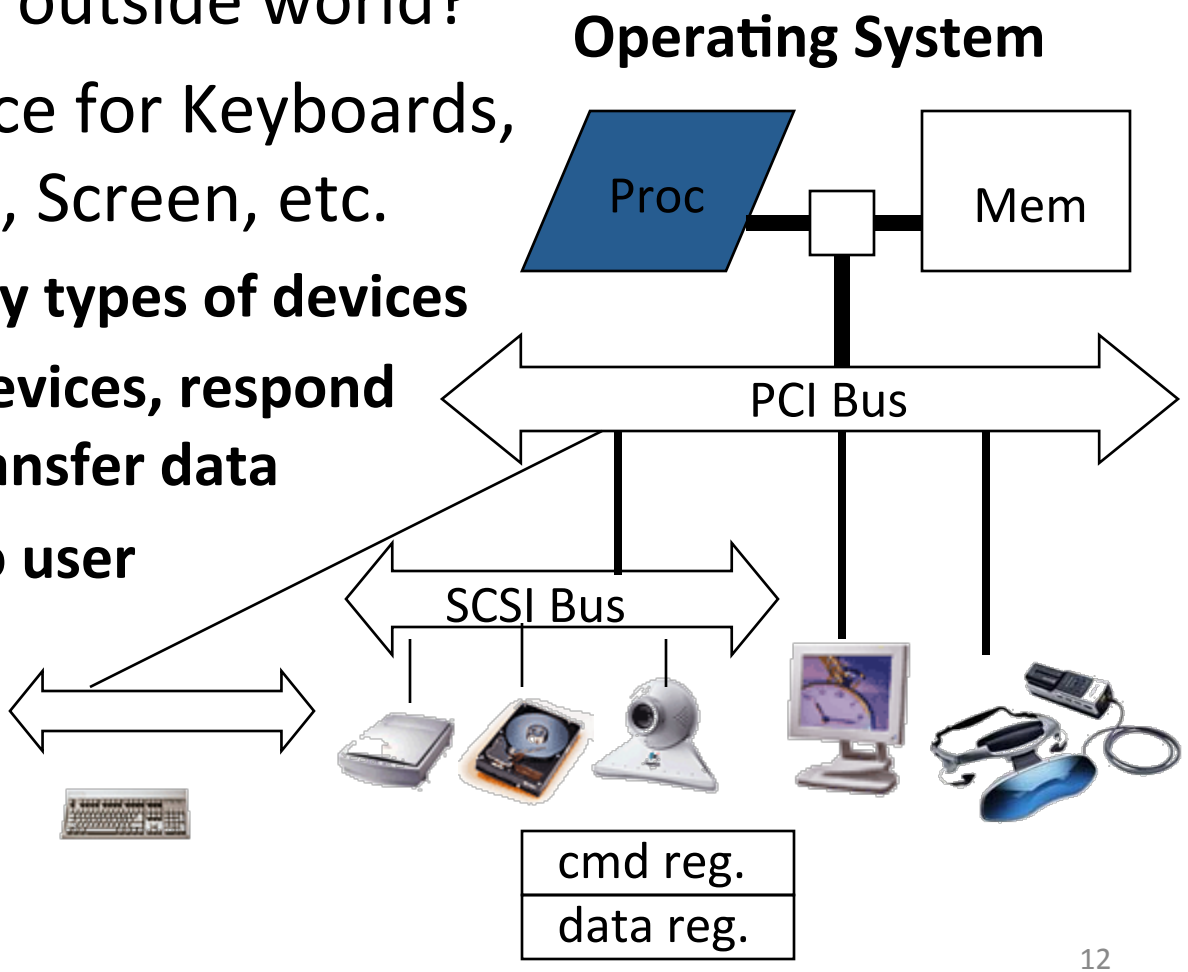
How to interact with devices?

- 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**

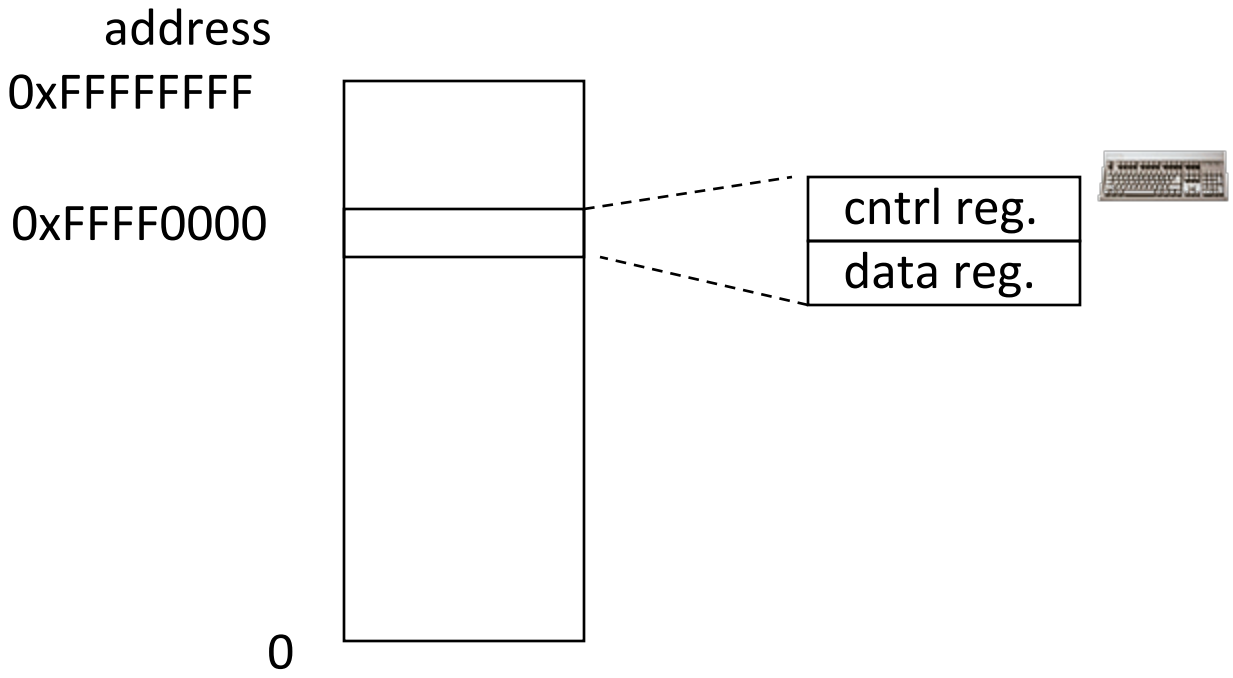


Instruction Set Architecture for I/O

- 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



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
  - Floppy disk (Remember those?): transferred data in 2-Byte units and had a data rate of 50 KB/second. No data transfer can be missed.
  - Hard disk: 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%

  $\Rightarrow$ 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?

- 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%

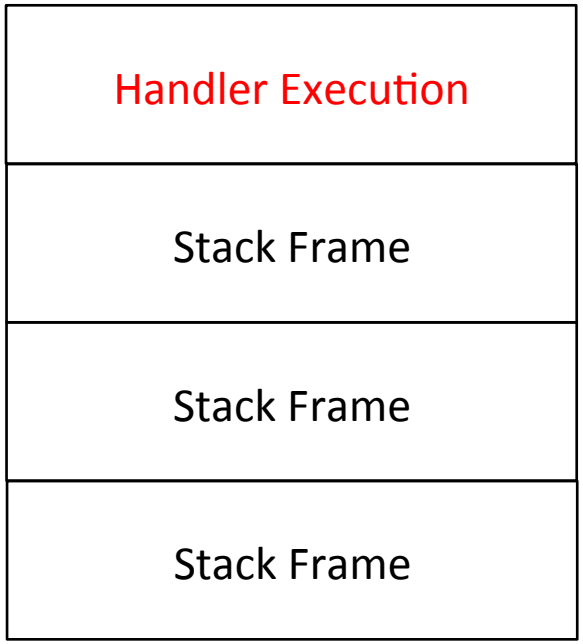
  $\Rightarrow$ Unacceptable

  (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 interrupt handlers: functions that are called when an interrupt is triggered

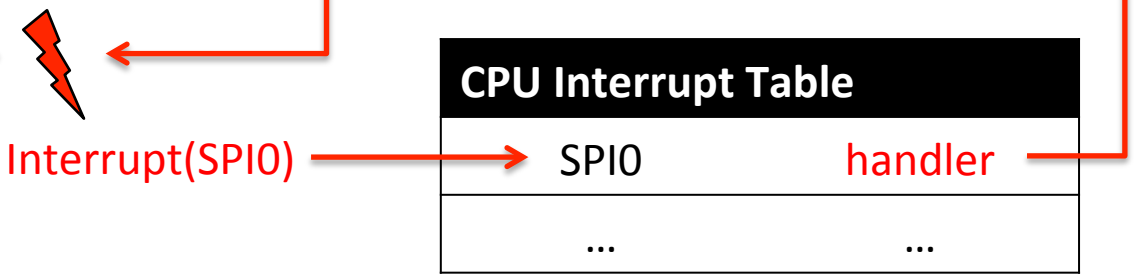
Interrupt-driven I/O



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
```



Administrivia

- **Project 3 is due on Sunday, 19 April, 23:59pm**
  - Try to get it to run at 3 KCat/s
  - Make sure it passes all tests!
- You can make it much faster than that – **take part in the competition!!!**
- Glory (and a small amount of extra credit) awaits for the most successful teams!

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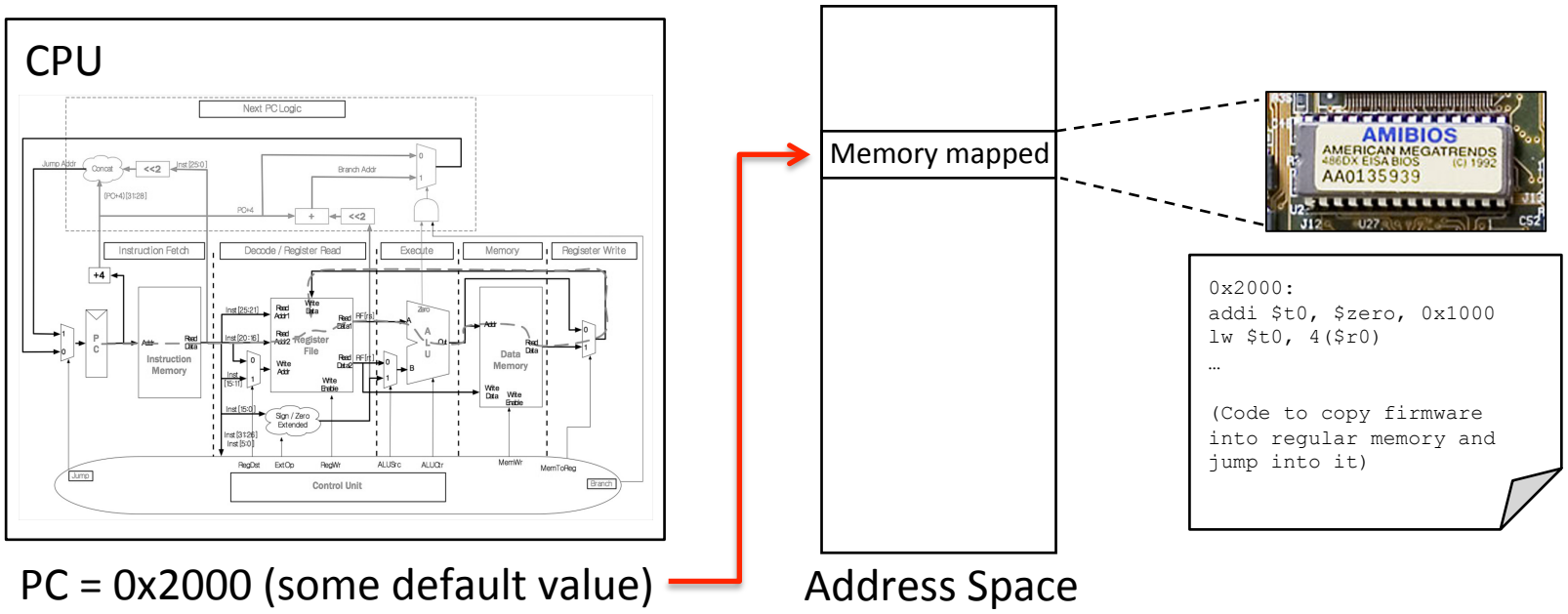
What happens at boot?

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



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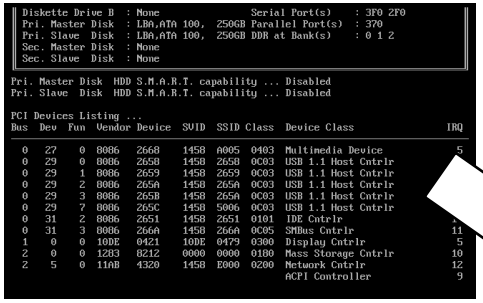
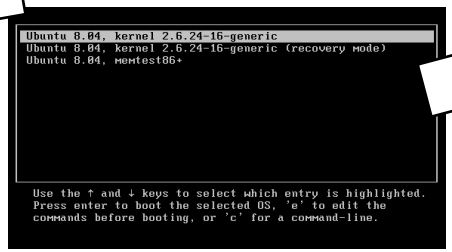
- When the computer switches on, it does the same as MARS: the CPU executes instructions from some start address (stored in Flash ROM)

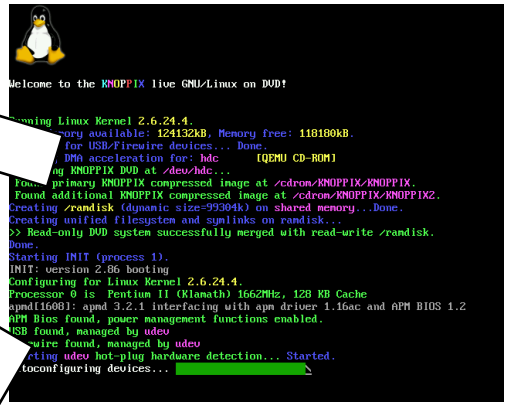
1. BIOS: Find a storage device and load first sector (block of data)



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



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



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

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 (see OpenMP threads) 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 can crash the entire machine. What about malware, etc.?
- The OS may need to enforce resource constraints to applications (e.g., access to devices).
- To protect the OS from the application, CPUs have a supervisor mode bit (also need isolation, more later).
  - You can only access a subset of instructions and (physical) memory when not in supervisor mode (user mode).
  - You can change out of supervisor mode using a special instruction, but not into it (unless there is an interrupt).

Syscalls

- How to switch back to OS? OS sets timer interrupt, when interrupts trigger, drop into supervisor mode.
- 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, the CPU itself, etc.

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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.
  - Remember your Project 1 linker: application assumes that code is in certain location. How to prevent overlaps?
  - 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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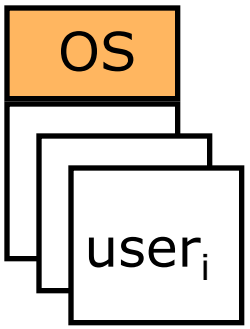
Modern Virtual Memory Systems

Illusion of a large, private, uniform store

Protection

several users, each with their private address space and one or more shared address spaces

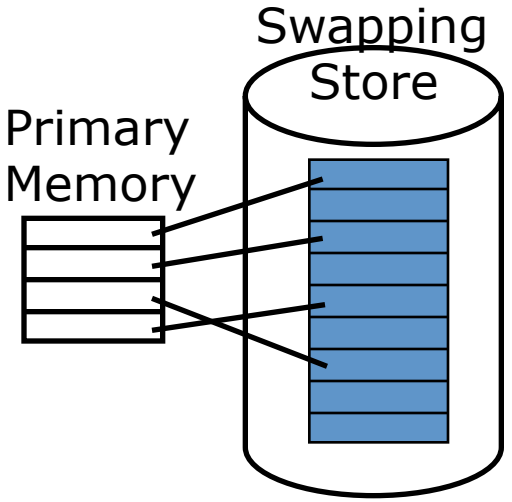
page table ≡ name space



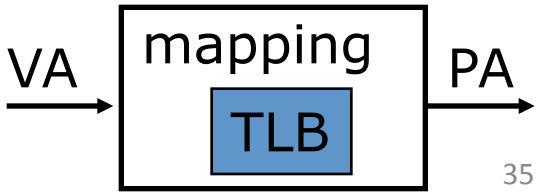
Demand Paging

Provides the ability to run programs larger than the primary memory

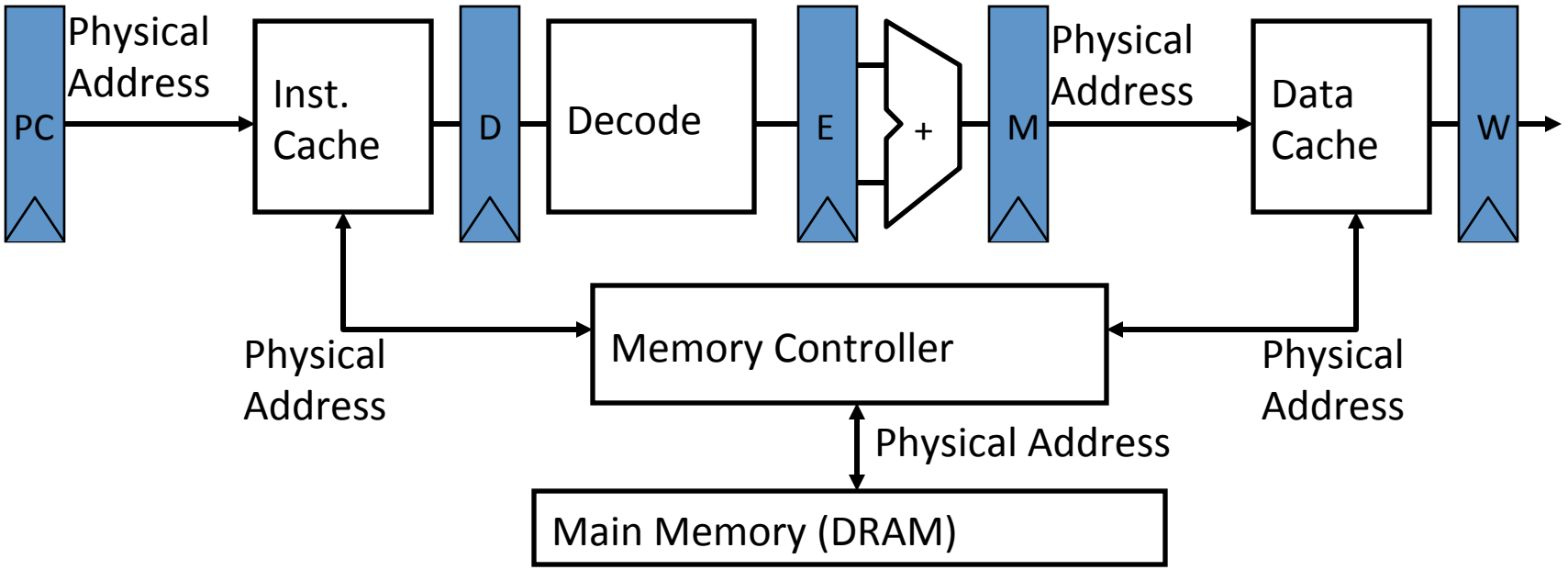
Hides differences in machine configurations



The price is address translation on each memory reference



“Bare” 5-Stage Pipeline



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

Dynamic Address Translation

Motivation

In early machines, I/O operations were slow and each word transferred involved the CPU
Higher throughput if CPU and I/O of 2 or more programs were overlapped.

Location-independent programs

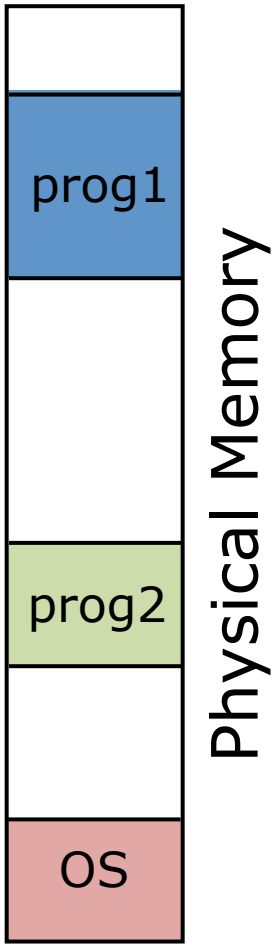
Programming and storage management ease
⇒ need for a *base register*

Protection

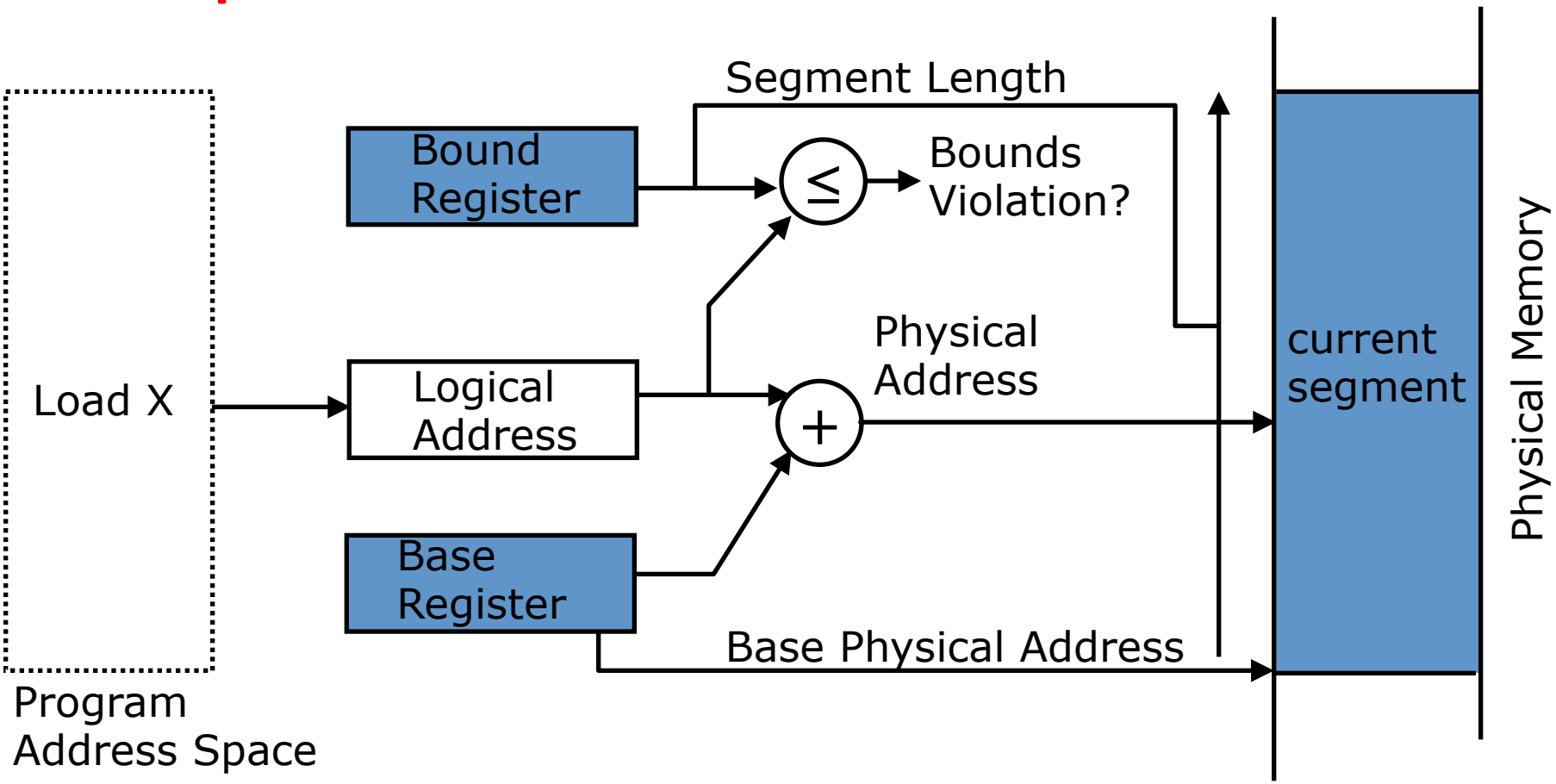
Independent programs should not affect each other inadvertently

⇒ need for a *bound register*

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



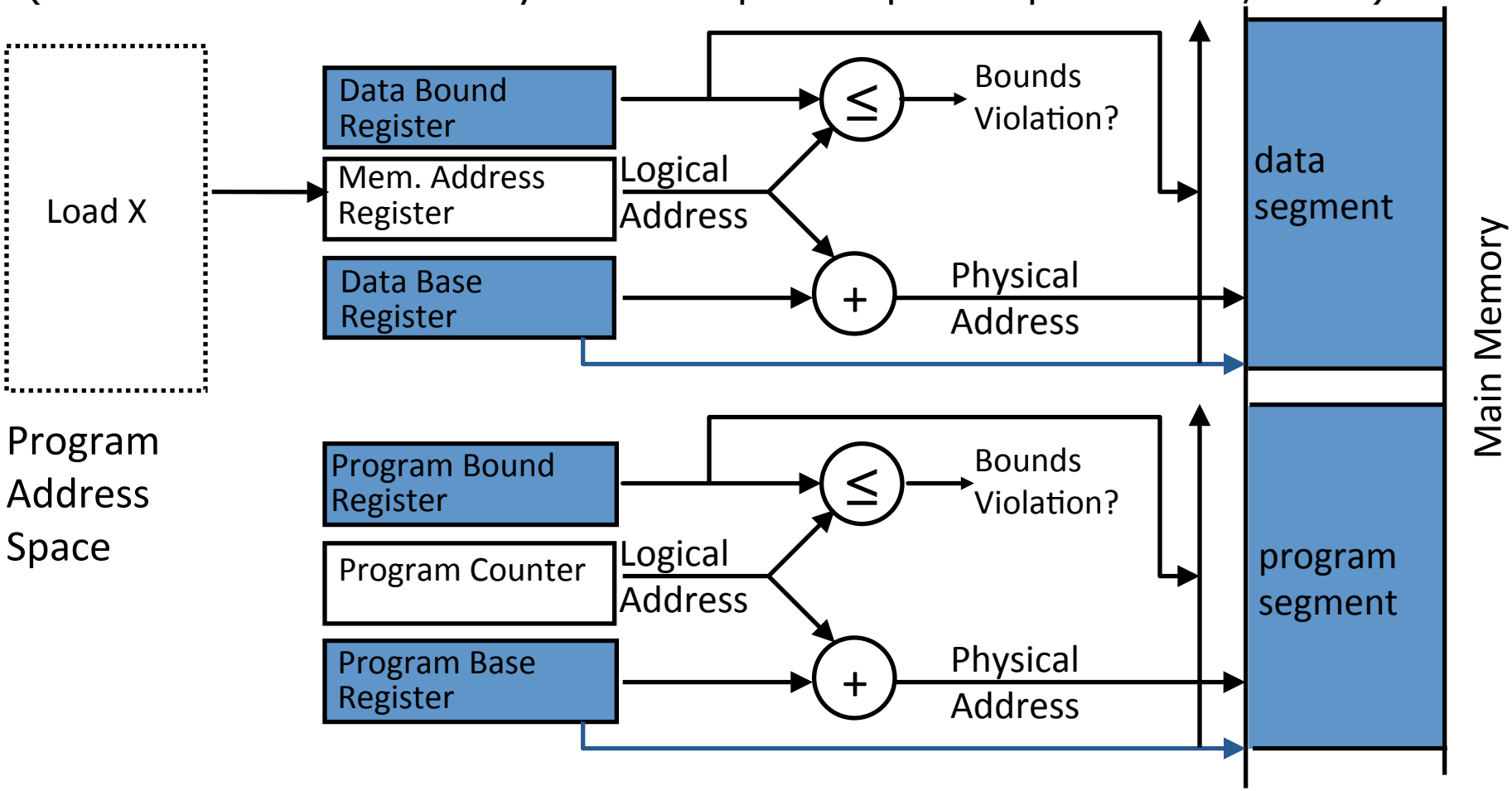
Simple Base and Bound Translation



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

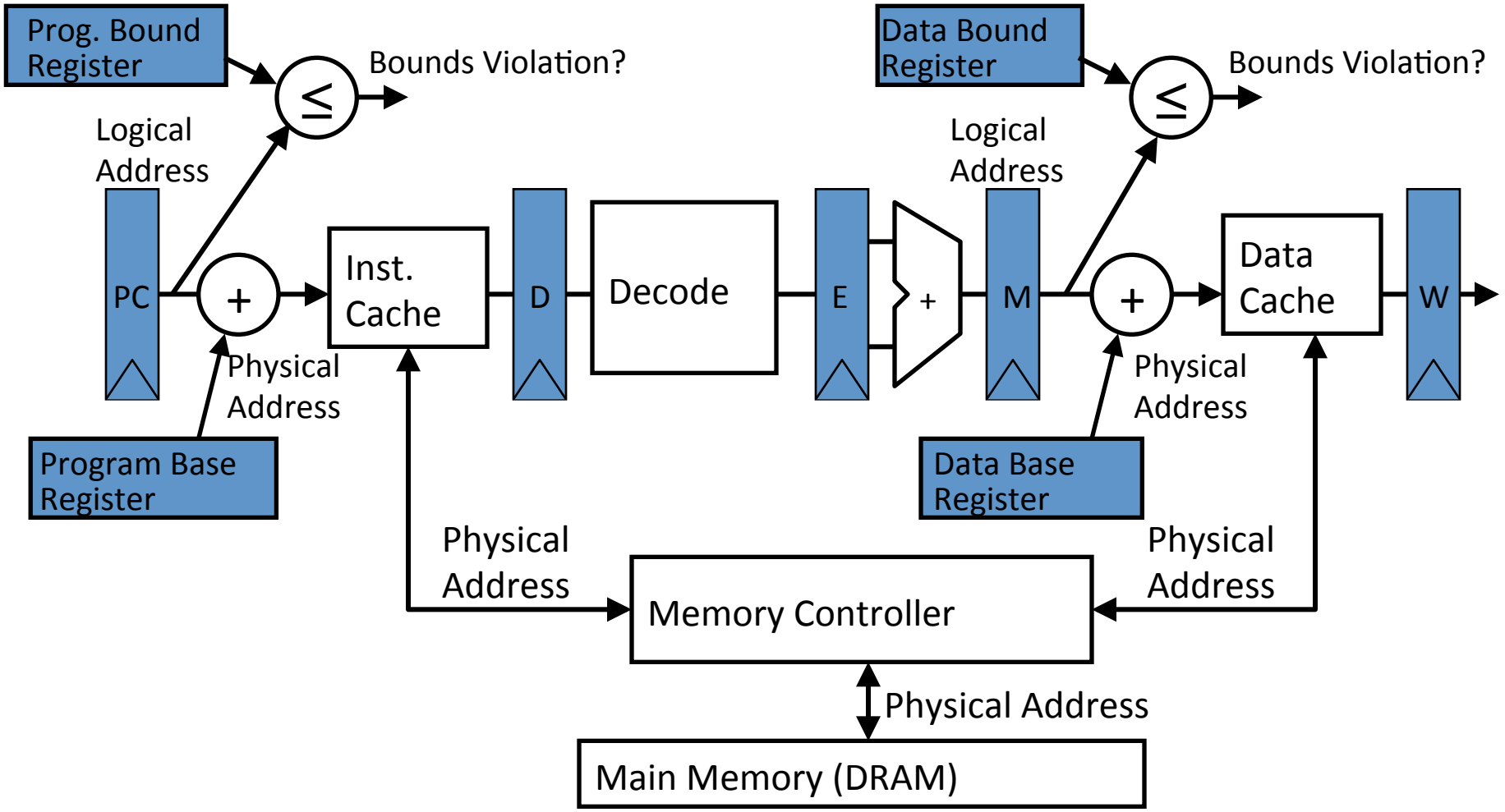
Separate Areas for Program and Data

(Scheme used on all Cray vector supercomputers prior to X1, 2002)



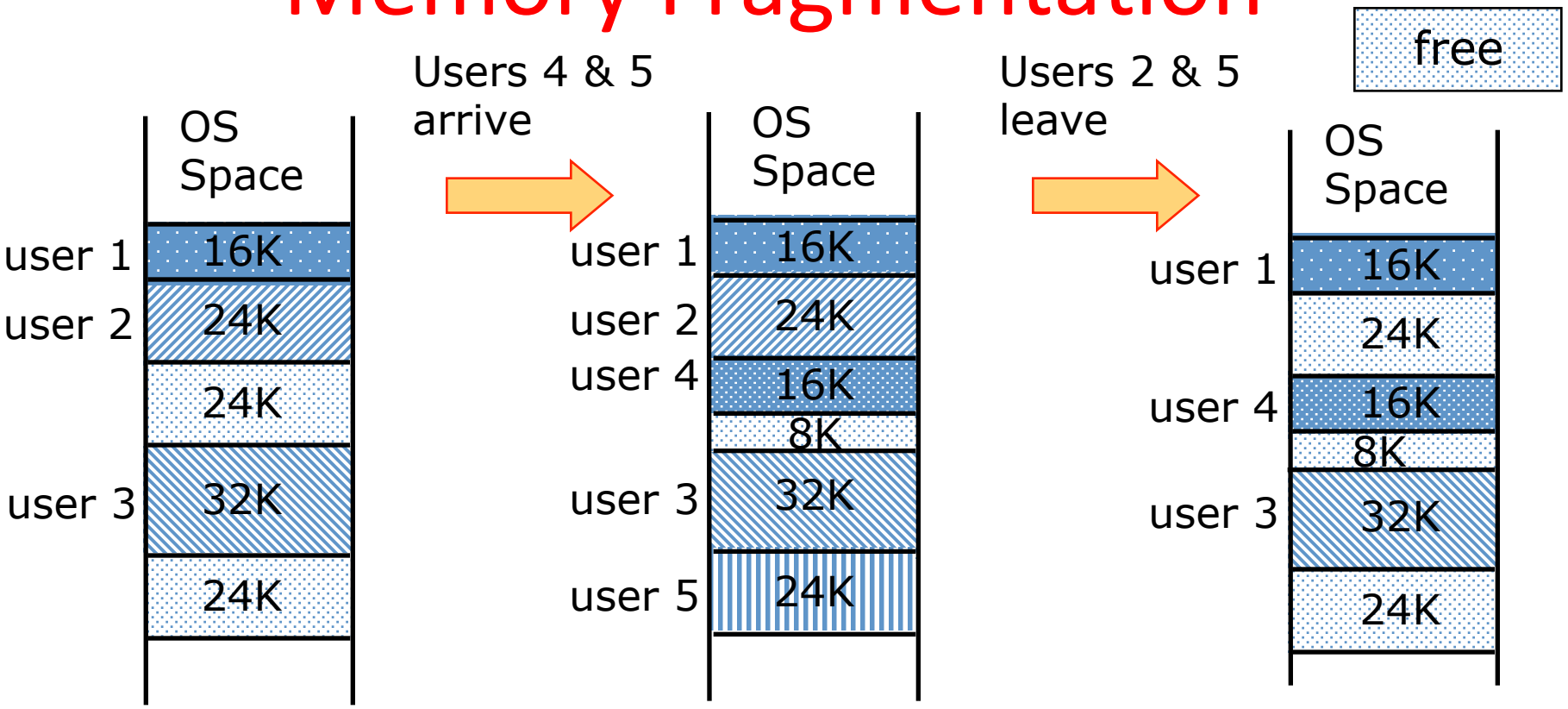
What is an advantage of this separation?

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



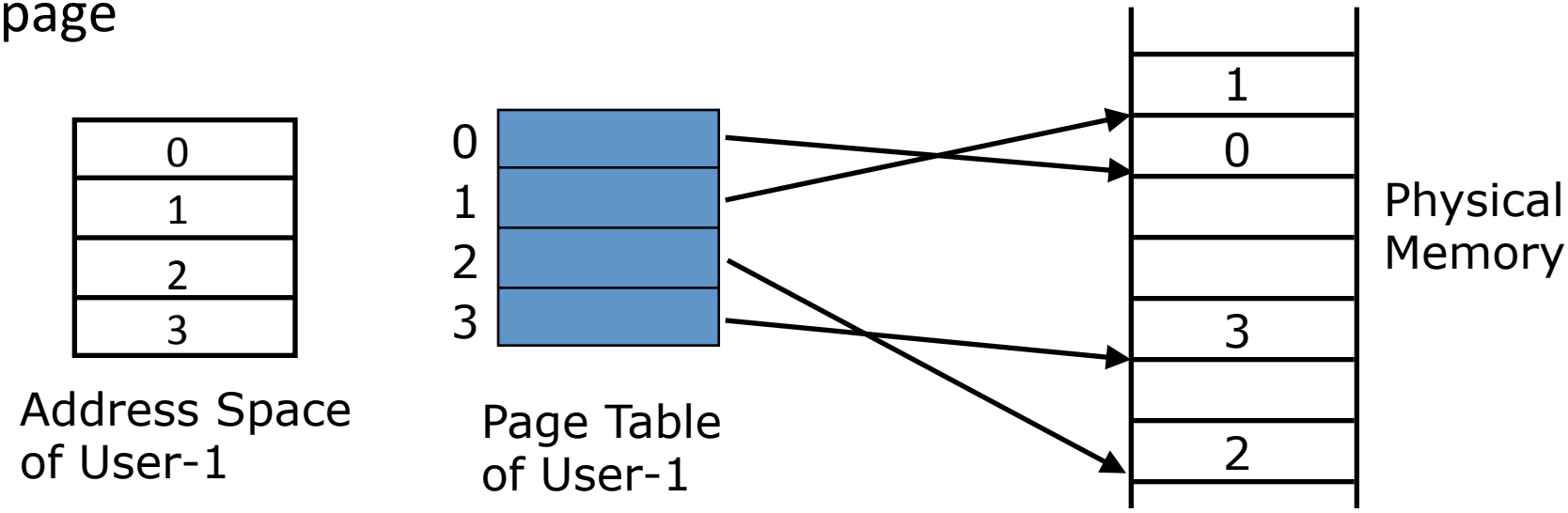
As users come and go, the storage is "fragmented". Therefore, at some stage programs have to be moved around to compact the storage.

Paged Memory Systems

- Processor-generated address can be split into:

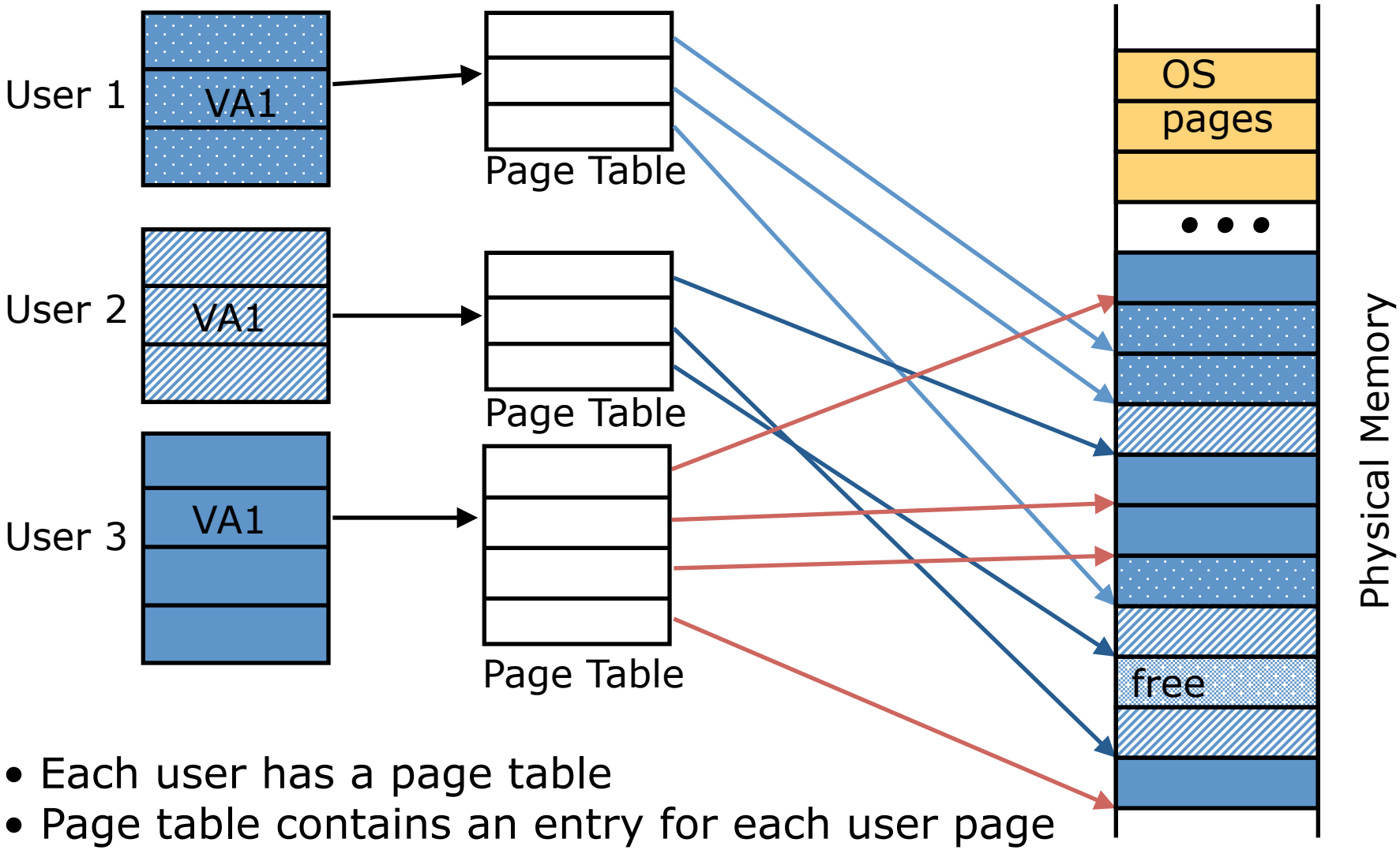
page number	offset

- 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?

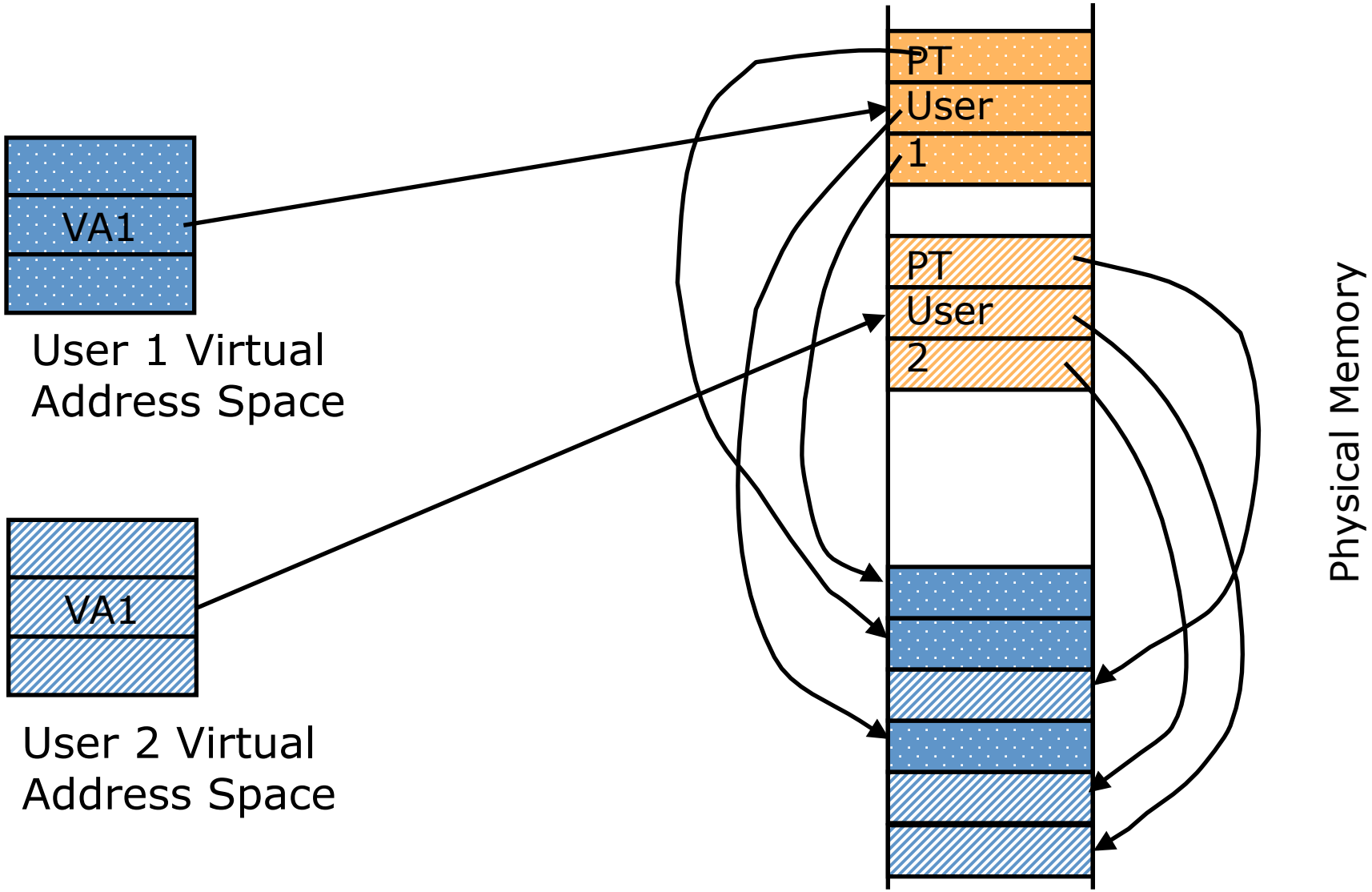
- Space required by the page tables (PT) is proportional to the address space, number of users, ...

  ⇒ *Too large to keep in 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).
- If you want to learn more about operating systems, you should take CS162!
- What's next in CS61C?
  - More details on I/O
  - More about Virtual Memory