COMP-273
Input/Output:
Polling and Interrupts

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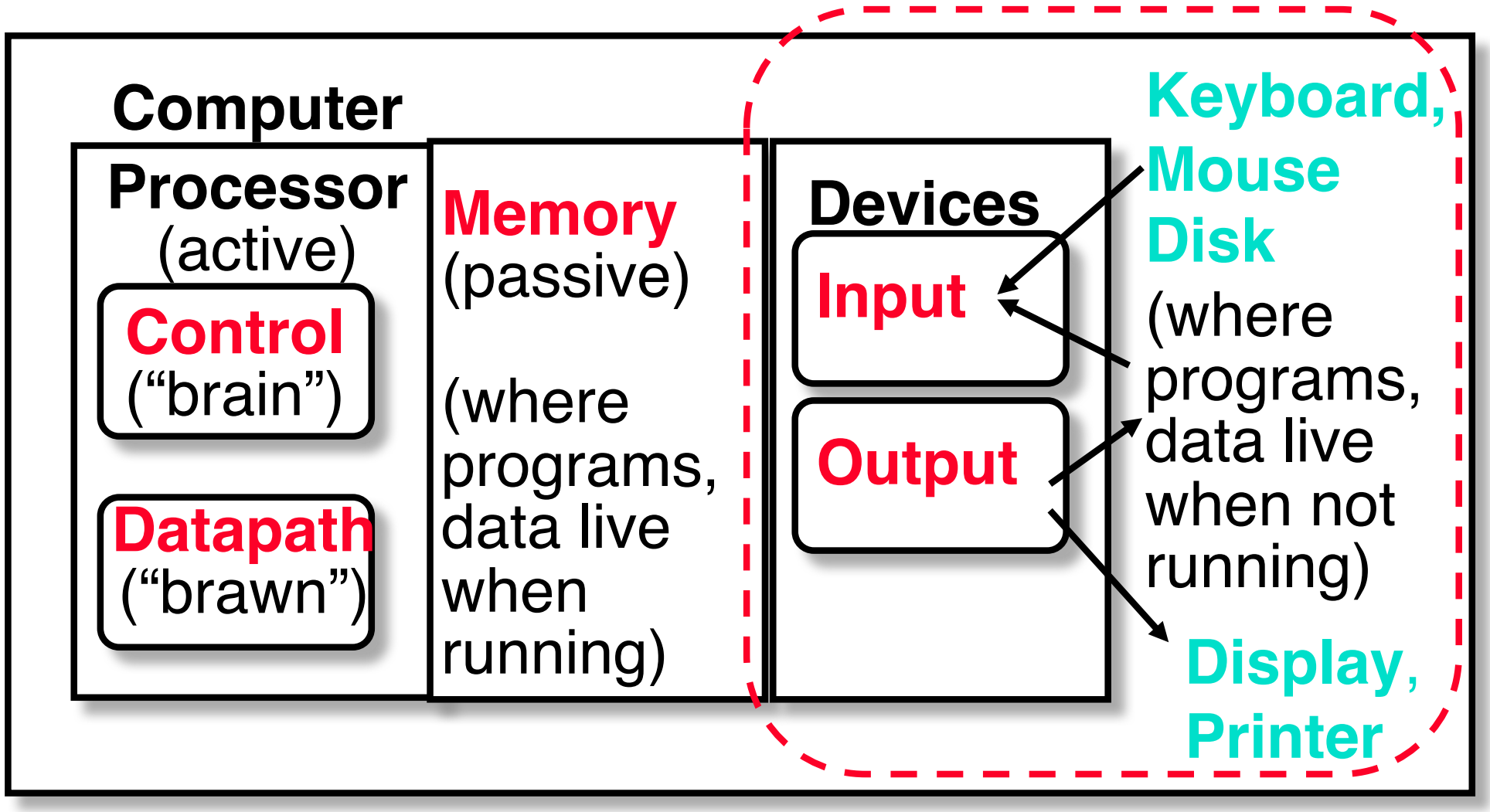
Outline

- I/O Background
- Polling
- Interrupts

Anatomy: 5 components of any Computer



Motivation for Input/Output

- I/O is how humans interact with computers
- I/O gives computers long-term memory.
- I/O lets computers do amazing things:

  - Read pressure of synthetic hand and control synthetic arm and hand of fireman
  - Display complex medical data
  - Computer without I/O like a car without wheels; great technology, but won't get you anywhere

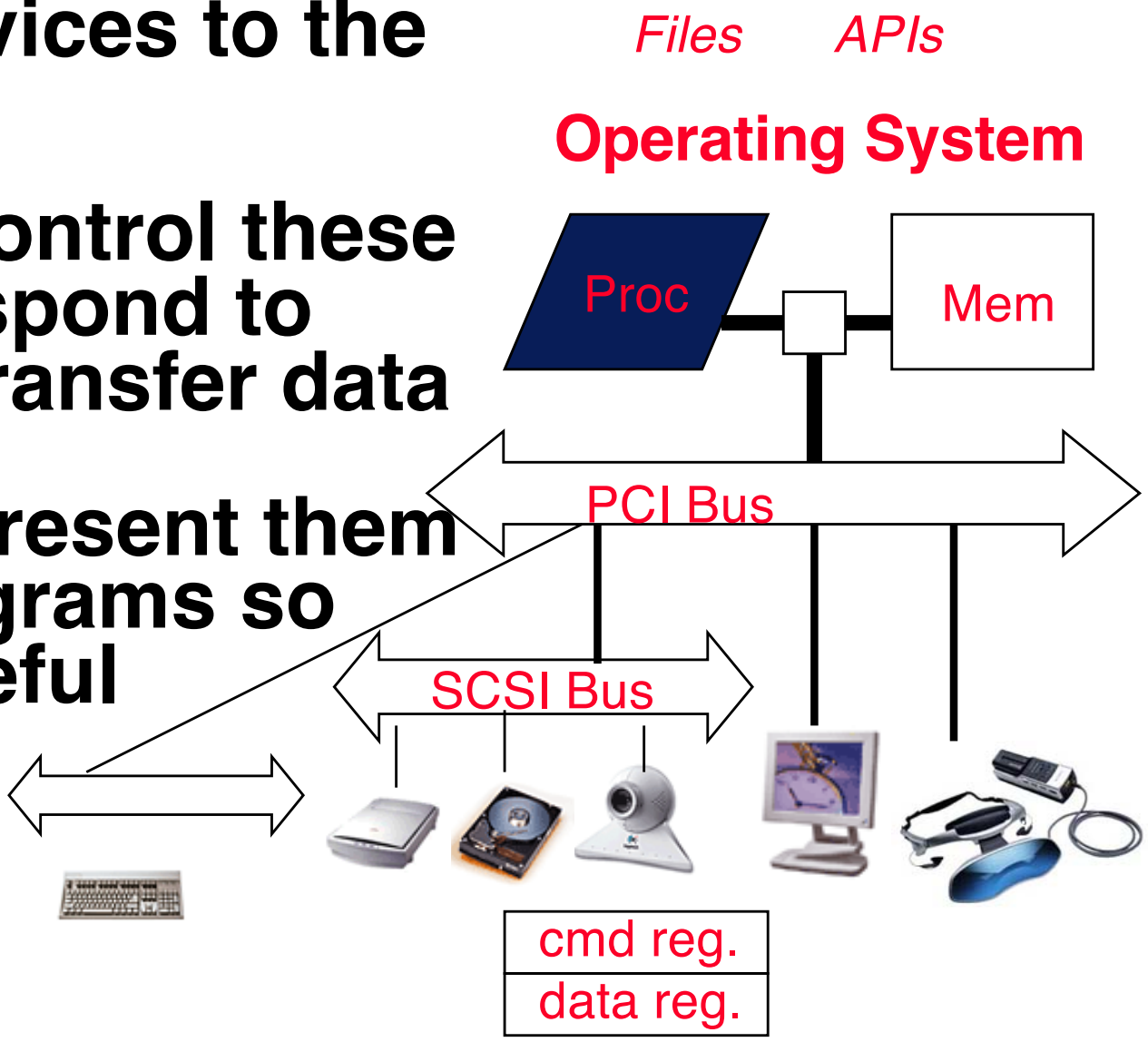
I/O Device Examples and Speeds

- ~~I/O Speed: bytes transferred per second~~

Device	Behavior	Partner	Data Rate (KBytes/s)
Keyboard	Input	Human	0.01
Mouse	Input	Human	0.02
Voice output	Output	Human	5.00
Floppy disk	Storage	Machine	50.00
Laser Printer	Output	Human	100.00
Magnetic Disk	Storage	Machine	10,000.00
Network-LAN	I or O	Machine	10,000.00
Graphics Display	Output	Human	30,000.00

What do we need to make I/O work?

- A way to connect many types of devices to the Proc-Mem
- A way to control these devices, respond to them, and transfer data
- A way to present them to user programs so they are useful



Current Bus Speeds

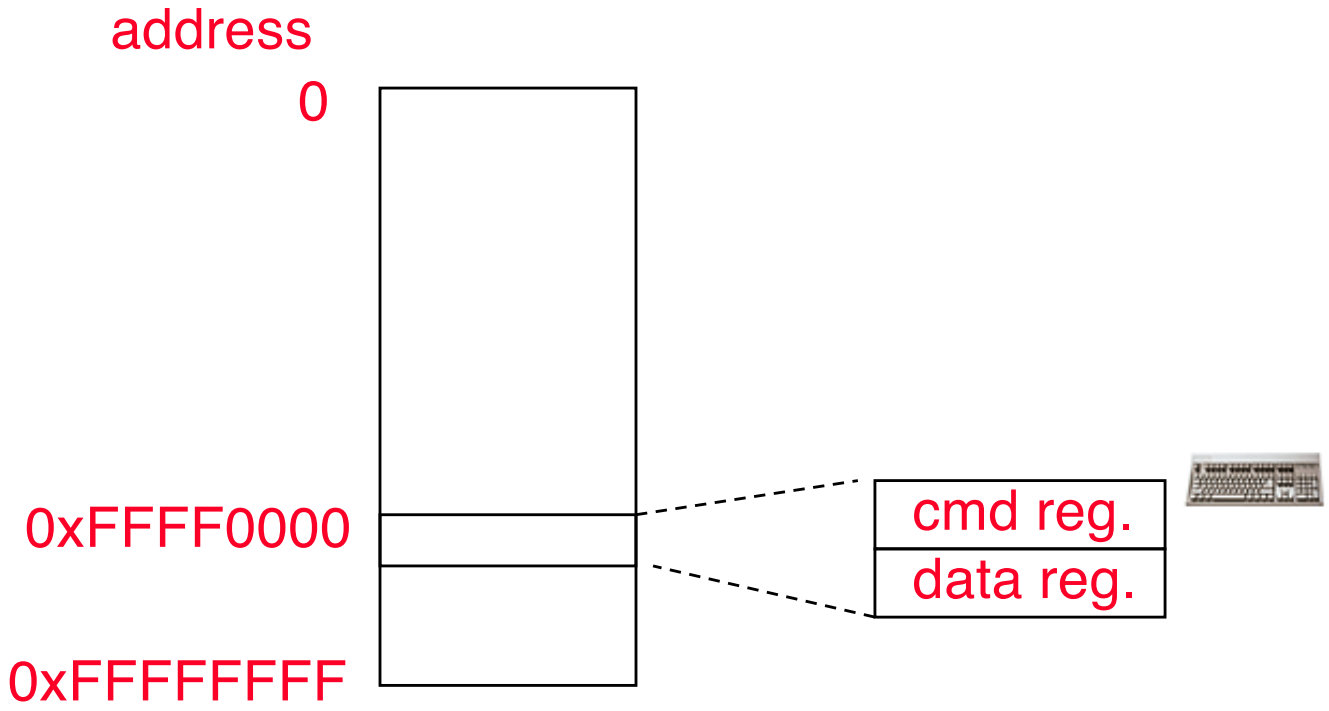
- **PCI (Peripheral Component Interconnect) bus:** PCI bus was created by Intel in 1993. PCI bus can transfer 32 or 64 bits at one time. PCI bus ran originally at 33 Mhz, with a data transfer of 250 Mbyte/s. PCI Express is used with modern graphics processor cards at 1 GByte/s (or more), also network cards.
- **SCSI (Small Computer System Interface) bus:** It is a high performance 16-bit bus which was used for fast disks, scanners, and for devices which require high bandwidth. It has a data rate of 640 MByte/s.
- **USB (Universal Serial Bus), a single bit bus:** It is used for connecting keyboard mouse and printer and other USB devices such as wireless network adapters to the computer. A USB bus has a connector with four wires. Two wires are used for supplying electrical power to the USB devices. USB 1.0 had a data rate of 1½ MByte/s and USB 2.0 has a data rate of 60 MByte/s. There is now a USB 3.0, that can travel at 640 MByte/s.
- **IEEE 1394 or FireWire:** IEEE 1394 is used for high speed data transfer. It was built by Apple, **though Apple have moved away from it**. It can transfer data at a rate of up to 400 MByte/s. It is a single bit serial bus which is used for connecting cameras, and other multimedia devices.

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
  - 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 (Polling)

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



Processor-I/O Speed Mismatch

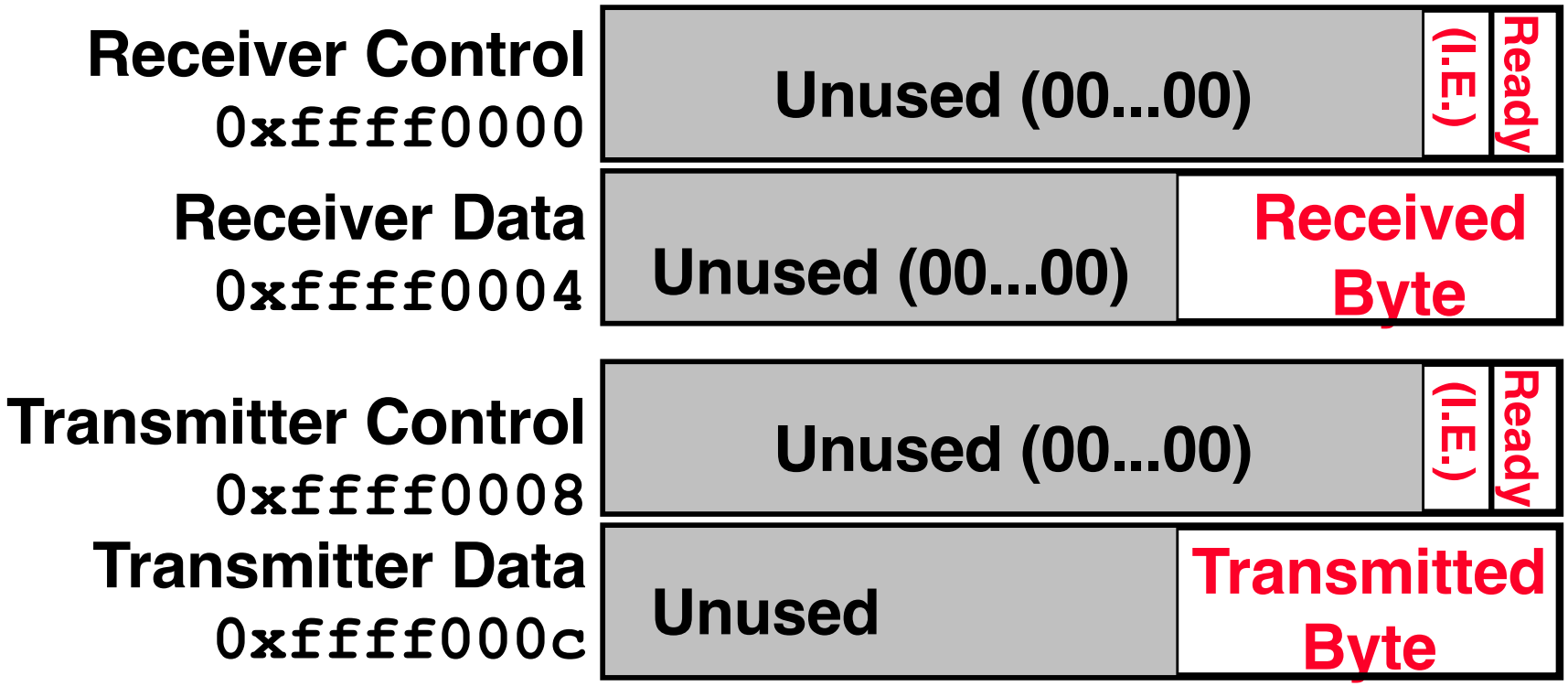
- 1GHz microprocessor can execute 1 billion load or store instructions per second, or 4,000,000 KB/s data rate
  - I/O devices data rates range from 0.01 KB/s to 30,000 KB/s
- Input: device may not be ready to send data as fast as the processor loads it
  - Also, might be waiting for human to act
- Output: device may not be ready to accept data as fast as processor stores it
- What to do?

Processor Checks Status before Acting

- Path to device generally has 2 registers:
  - Control Register, says it's OK to read/write (I/O ready)
  - 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 its 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

MARS I/O Simulation

- MARS simulates 1 I/O device: memory-mapped terminal (keyboard + display)
  - Read from keyboard (receiver); 2 device regs
  - Writes to terminal (transmitter); 2 device regs



SPIM I/O

- Control register rightmost bit (0): Ready
  - Receiver: Ready==1 means character in Data Register not yet been read;
    1 ⇒ 0 when data is read from Data Reg
  - Transmitter: Ready==1 means transmitter is ready to accept a new character;
    0 ⇒ Transmitter still busy writing last char
    - I.E. bit discussed later
- Data register rightmost byte has data
  - Receiver: last char from keyboard; rest = 0
  - Transmitter: when write rightmost byte, writes char to display

I/O Example

- Input: Read from keyboard into $v0

```
                lui  $t0, 0xffff #ffff0000
Waitloop:       lw   $t1, 0($t0) #control
                andi $t1,$t1,0x0001
                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 $t1,$t1,0x0001
                beq  $t1,$zero, Waitloop
                sw   $a0, 12($t0) #data
```

- Processor waiting for I/O called "Polling"

Cost of Polling?

- The following example used dated estimates, but it conveys the general idea. 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 used for polling
  - Mouse: polled 30 times/sec so as not to miss user movement
  - Floppy disk: transfers data in 2-Byte units and has 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.

% Processor time to poll mouse, floppy

- Mouse Polling, Clocks/sec

  = 30 * 400 = 12000 clocks/sec

- % Processor for polling:

  $12*10^3/1*10^9 = 0.0012\%$

  ⇒ Polling mouse little impact on processor

- Frequency of Polling Floppy

  = 50 KB/s /2B = 25K polls/sec

- Floppy Polling, Clocks/sec

  = 25K * 400 = 10,000,000 clocks/sec

- % Processor for polling:

  $10*10^6/1*10^9 = 1\%$

  ⇒ OK if not too many I/O devices

% Processor time to hard disk

- Frequency of Polling Disk

  = 16 MB/s /16B = 1M polls/sec

- Disk Polling, Clocks/sec

  = 1M * 400 = 400,000,000 clocks/sec

- % Processor for polling:

  $400*10^6/1*10^9 = 40\%$

  $\Rightarrow$ Unacceptable

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

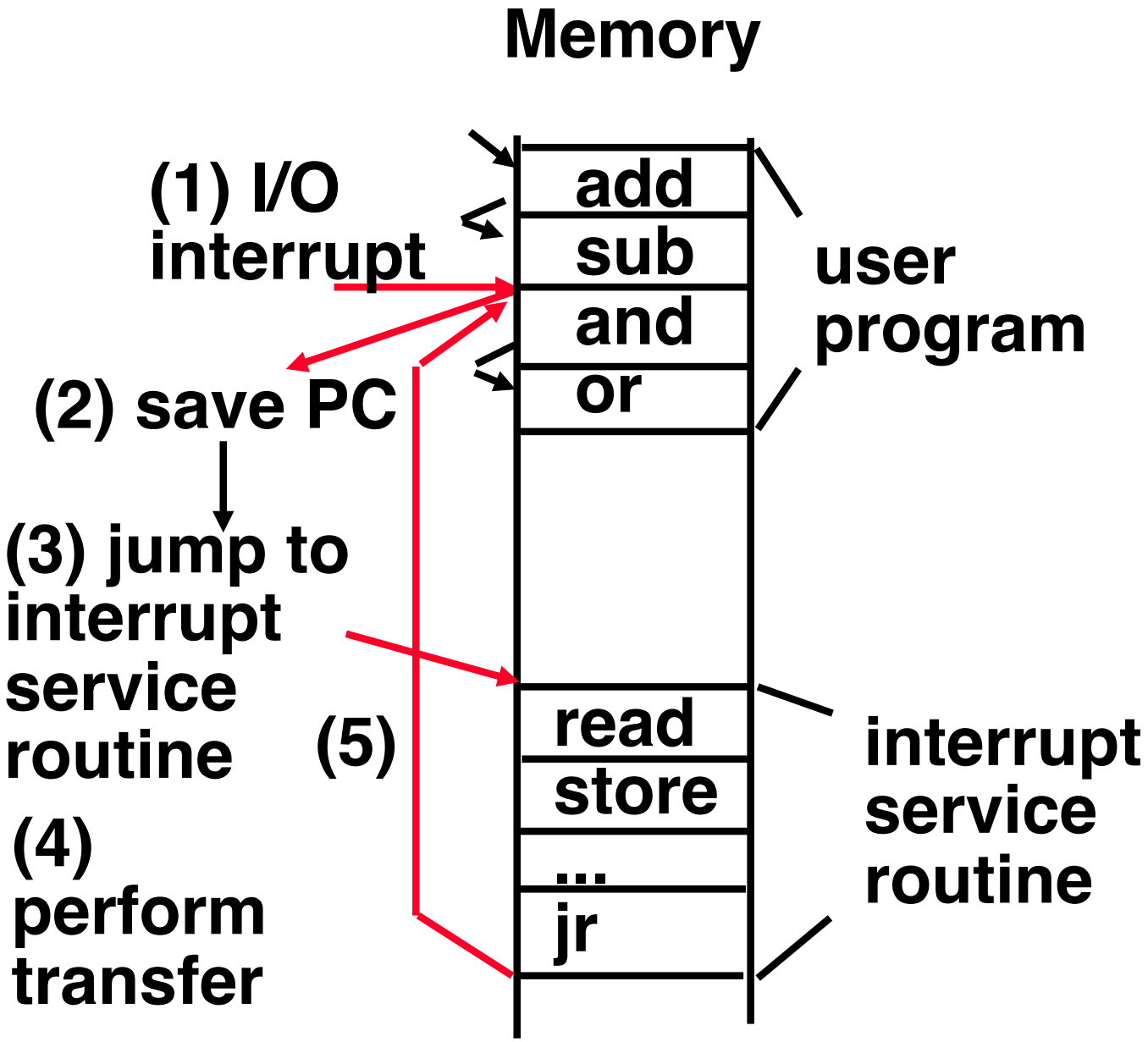
I/O Interrupt

- An I/O interrupt is like overflow exceptions except:
  - An I/O interrupt is “asynchronous”
  - More information needs to be conveyed
- An I/O interrupt is asynchronous with respect to instruction execution:
  - I/O interrupt is not associated with any instruction, but it can happen in the middle of any given instruction
  - I/O interrupt does not prevent any instruction from completion

Definitions for Clarification

- **Exception**: signal marking that something "out of the ordinary" has happened and needs to be handled
- **Interrupt**: asynchronous exception
- **Trap**: synchronous exception

Interrupt Driven Data Transfer



Instruction Set Support for I/O Interrupt

- Save the PC for return
  - But where?
- Where to go when interrupt occurs?
  - MIPS defines location: 0x80000080
- Determine cause of interrupt?
  - MIPS has Cause Register, 4-bit field (bits 5 to 2) gives cause of exception

Instruction Set Support for I/O Interrupt

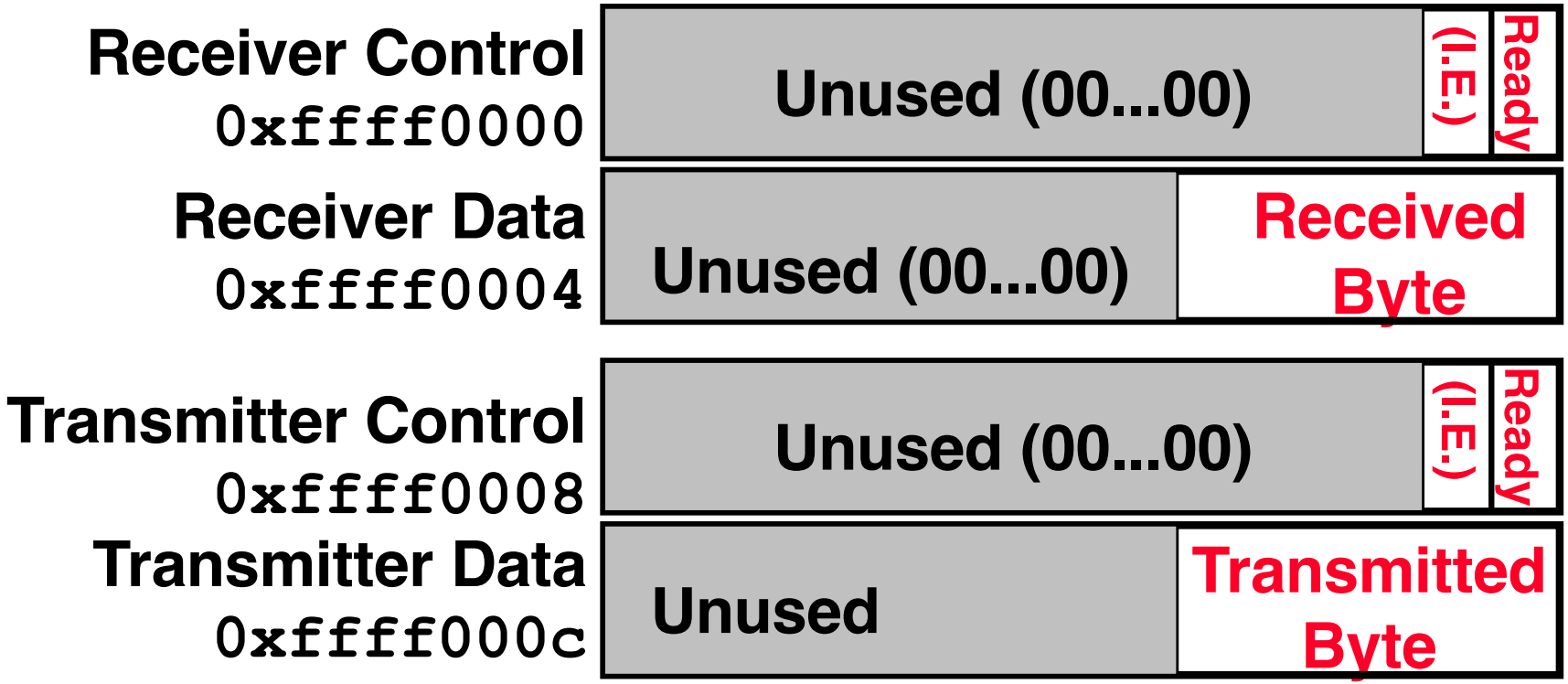
- Portion of MIPS architecture for interrupts called “coprocessor 0”
- Coprocessor 0 Instructions
  - Data transfer: lwc0, swc0
  - Move: mfc0, mtc0
- Coprocessor 0 Registers:

name	*number*	*usage*
Status	`$12`	Interrupt enable
Cause	`$13`	Exception type
EPC	`$14`	Return address

(details in appendix A.7)

SPIM I/O Simulation: Interrupt Driven I/O

- I.E. stands for Interrupt Enable
- Set Interrupt Enable bit to 1 have interrupt occur whenever Ready bit is set



Benefit of Interrupt-Driven I/O

- Find the % of processor consumed if the hard disk is only active 5% of the time. Assuming 500 clock cycle overhead for each transfer, including interrupt:
  - Disk Interrupts/sec = 16 MB/s /16B
    = 1M interrupts/sec
  - Disk Interrupts, Clocks/sec = 1M * 500
    = 500,000,000 clocks/sec
  - % Processor for during transfer:
    $500*10^6/1*10^9 = 50\%$
- Disk active 5% ⇒ 5% * 50% ⇒ 2.5% busy

Questions Raised about Interrupts

- Which I/O device caused exception?
  - Needs to convey the identity of the device generating the interrupt
- Can avoid interrupts during the interrupt routine?
  - What if more important interrupt occurs while servicing this interrupt?
  - Allow interrupt routine to be entered again?
- Who keeps track of status of all the devices, handle errors, know where to put/supply the I/O data?

4 Responsibilities leading to OS

- The I/O system is shared by multiple programs using the processor
- Low-level control of I/O device is complex because requires managing a set of concurrent events and because requirements for correct device control are often very detailed
- I/O systems often use interrupts to communicate information about I/O operations
- Would like I/O services for all user programs under safe control

4 Functions OS must provide

- OS: guarantees that user's program accesses only the portions of I/O device to which user has rights (e.g., file access)
- provides abstractions for accessing devices by supplying routines that handle low-level device operations
- handles the exceptions generated by I/O devices (and arithmetic exceptions generated by a program)
- tries to provide equitable access to the shared I/O resources, as well as schedule accesses to enhance system performance

Things to Remember

- I/O gives computers their 5 senses
- I/O speed range is a few million to one
- Processor speed means must synchronize with I/O devices before use
- Polling works, but expensive
  - processor repeatedly queries devices
- Interrupts works, more complex
  - devices causes an exception, causing OS to run and deal with the device
- I/O control leads to Operating Systems