CPSC 213

Introduction to Computer Systems

Unit 2a

I/O Devices, Interrupts and DMA

Reading

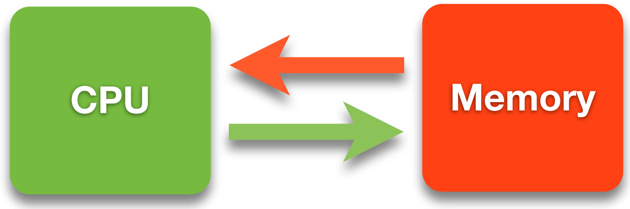
- Text
  - *Exceptions, Logical Control Flow, Signal Terminology, Sending Signals, Receiving Signals*
  - 8.1, 8.2.1, 8.5.1-8.5.3

Big Ideas: Second Half

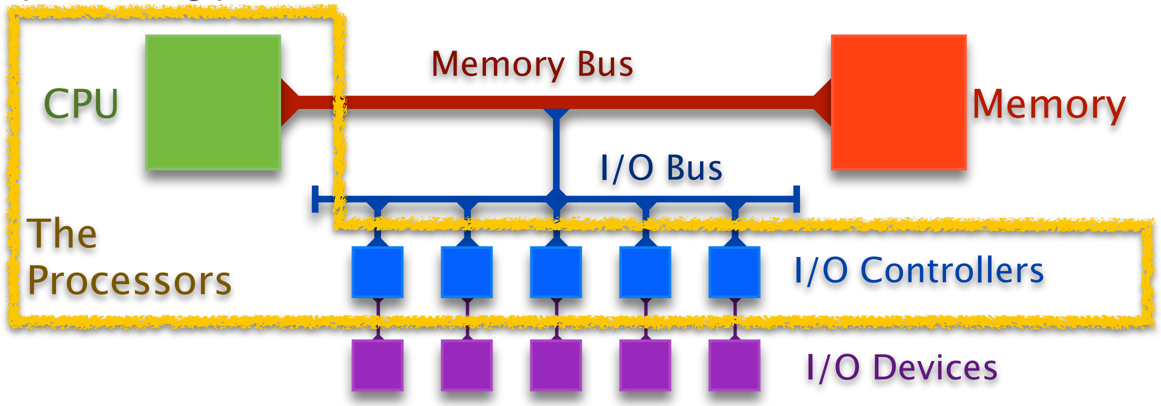
- Memory hierarchy
  - progression from small/fast to large/slow
    - registers (same speed as ALU instruction execution, roughly: 1 ns clock tick)
    - memory (over 100x slower: 100ns)
    - disk (over 1,000,000x slower: 10 millisec)
    - network (even worse: 200+ millisec RT to other side of world just from speed of light in fiber)
  - implications
    - don't make ALU wait for memory
      - ALU input only from registers, not memory
    - don't make CPU wait for disk
      - interrupts, threads, asynchrony
- Clean abstraction for programmer
  - ignore asynchronous reality via threads and virtual memory (mostly)
  - explicit synchronization as needed

Adding I/O to Simple Machine

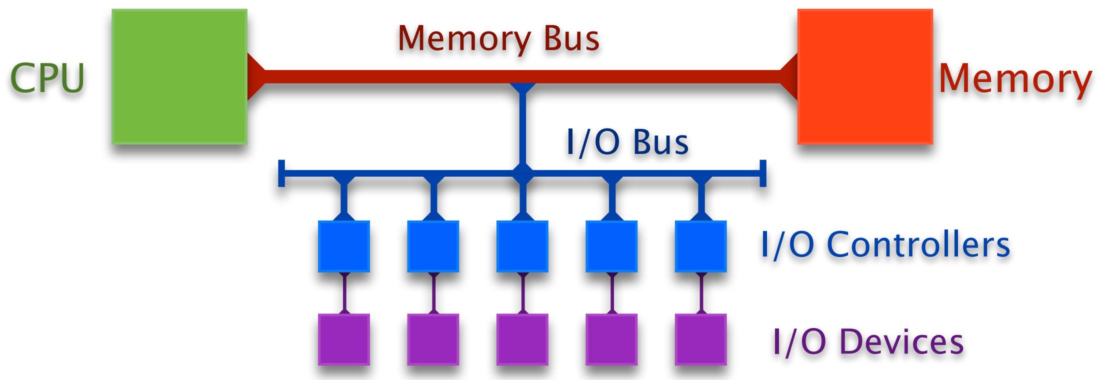
- Beyond CPU/memory
  - CPU: ALU and registers



- I/O devices have small processors: I/O controllers
  - processing power available outside CPU



Looking Beyond the CPU and Memory



- Memory Bus
  - data/control path connecting CPU, Main Memory, and I/O Bus
- I/O Bus
  - data/control path connecting Memory Bus and I/O Controllers
  - e.g. PCI
- I/O Controller
  - a processor running software (firmware)
  - connects I/O Device to I/O Bus
  - e.g. SCSI, SATA, Ethernet, ...
- I/O Device
  - I/O mechanism that generates or consumes data
  - e.g. disk, radio, keyboard, mouse, ...

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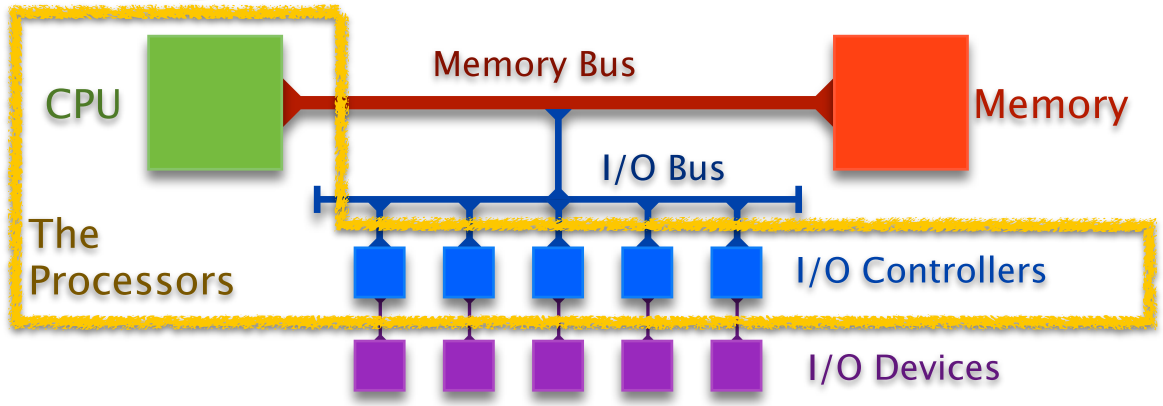

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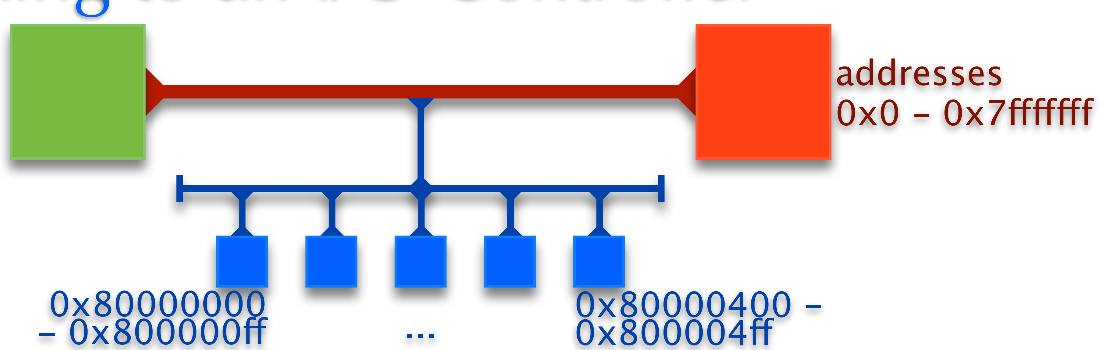
Talking to an I/O Controller



- Programmed I/O (PIO)
  - CPU transfers a word at a time between CPU and I/O controller
  - typically use standard load/store instructions, but to I/O-mapped memory
- I/O-Mapped Memory
  - memory addresses beyond the end of main memory
  - used to name I/O controllers (usually configured at boot time)
  - loads and stores are translated into I/O-bus messages to controller
- Example
  - to read/write to controller at address 0x80000000

```
ld  $0x80000000, r0
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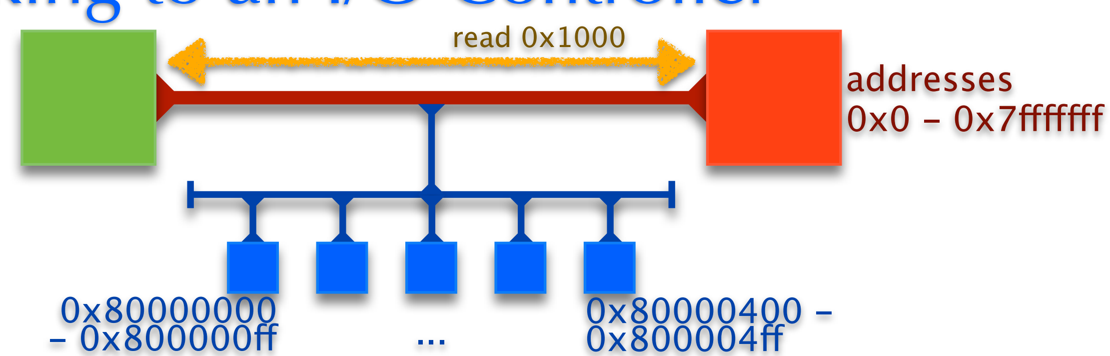
Talking to an I/O Controller



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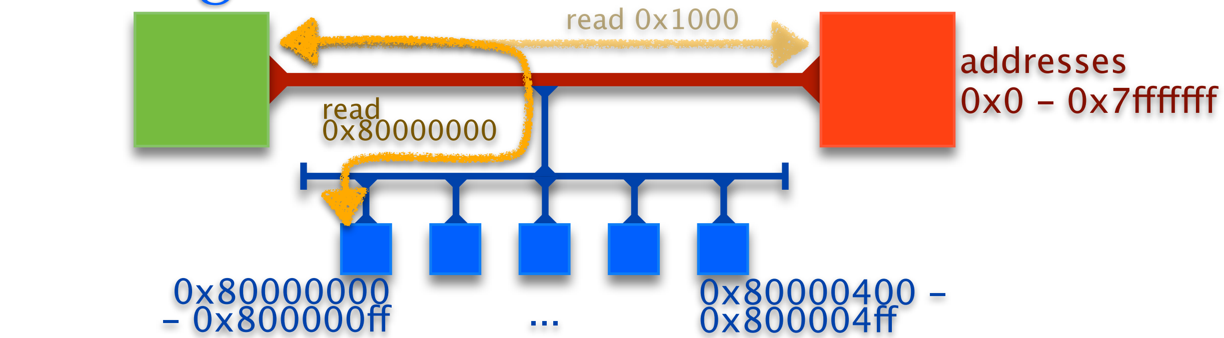

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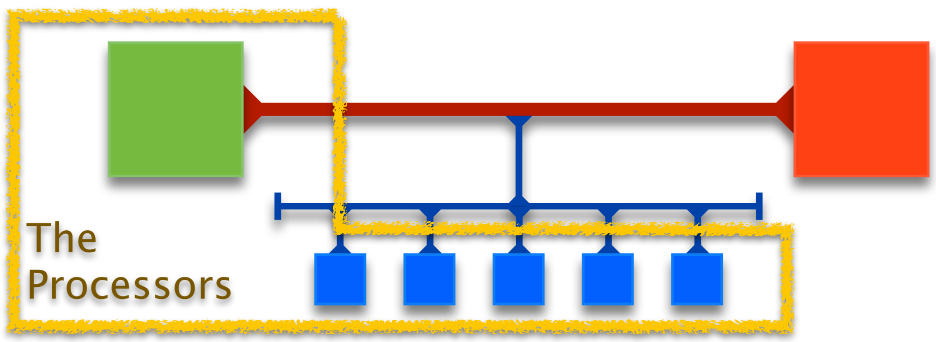
Limitations of PIO

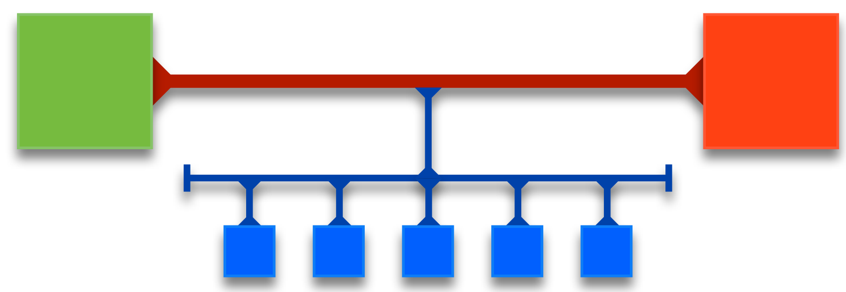
- Reading or writing large amounts of data slows CPU
  - requires CPU to transfer one word at a time
  - controller/device is (often) much slower than CPU
  - and so, CPU runs at controller/device speed, mostly waiting for controller
- IO Controller can not initiate communication
  - sometimes the CPU asks for for data
  - but, sometimes controller receives data for the CPU, without CPU asking
    - e.g., mouse click or network packet reception (everything is like this really as we will see)
  - how does controller notify CPU that it has data the CPU should want?
- One not-so-good idea
  - what is it? ____
  - what are drawbacks? ___________________________________
  - when is it okay? ______________________________________

Key Observation



- CPU and I/O Controller are independent processors
  - they should be permitted to work in parallel
  - either should be able to initiate data transfer to/from memory
  - either should be able to signal the other to get the other's attention

Autonomous Controller Operation



- Direct Memory Access (DMA)
  - controller can send/read data from/to any main memory address
  - the CPU is oblivious to these transfers
  - DMA addresses and sizes are *programmed* by CPU using PIO
- CPU Interrupts
  - controller can signal the CPU
  - CPU checks for interrupts on every cycle (it's like a really fast, clock-speed poll)
  - CPU jumps to controller's *Interrupt Service Routine* if it is interrupting

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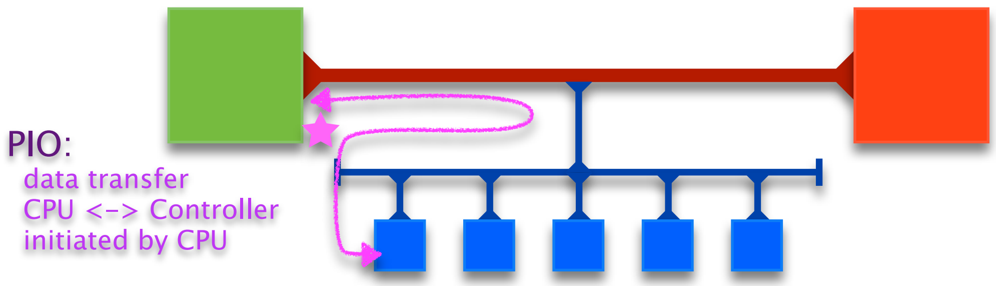

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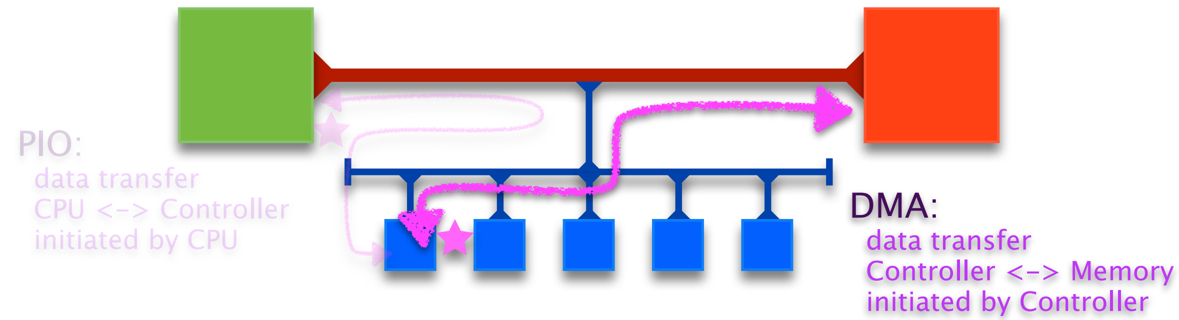

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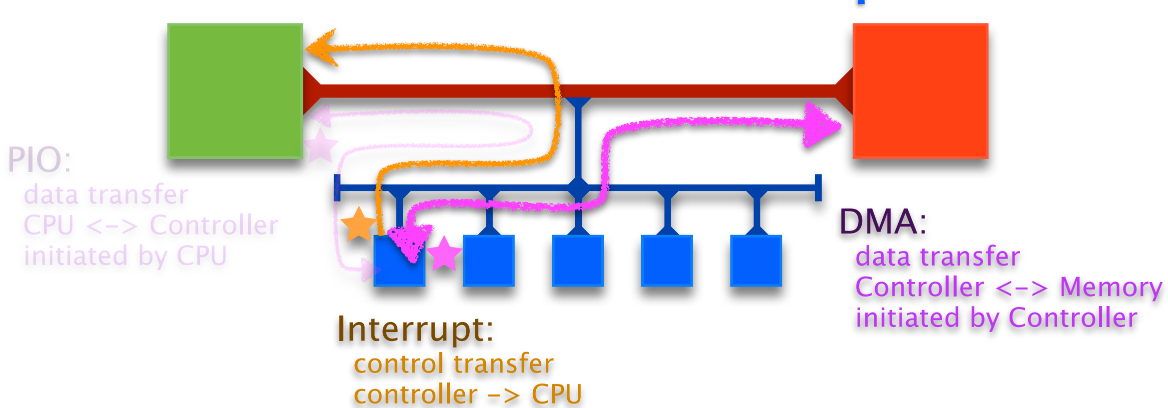

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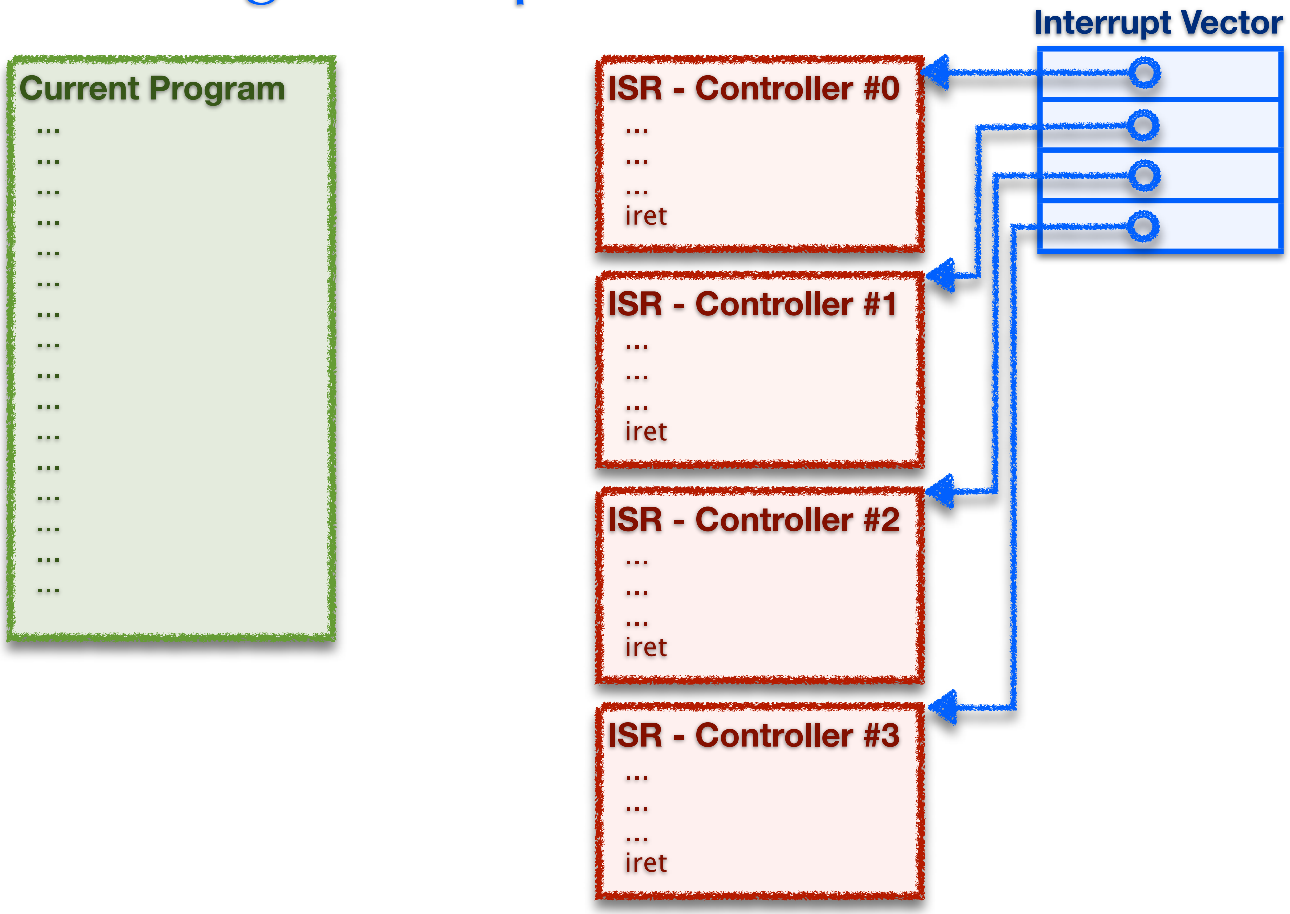
Adding Interrupts to Simple CPU

- New special-purpose CPU registers
  - **isDeviceInterrupting** set by I/O Controller to signal interrupt
  - **interruptControllerID** set by I/O Controller to identify interrupting device
  - **interruptVectorBase** interrupt-handler jump table, initialized at boot time
- Modified fetch-execute cycle

```
while (true) {
  if (isDeviceInterrupting) {
    m[r[5]-4] ← r[6];
    r[5]      ← r[5]-4;
    r[6]      ← pc;
    pc        ← interruptVectorBase [interruptControllerID];
  }
  fetch ();
  execute ();
}
```

Sketching Interrupt Control Flow



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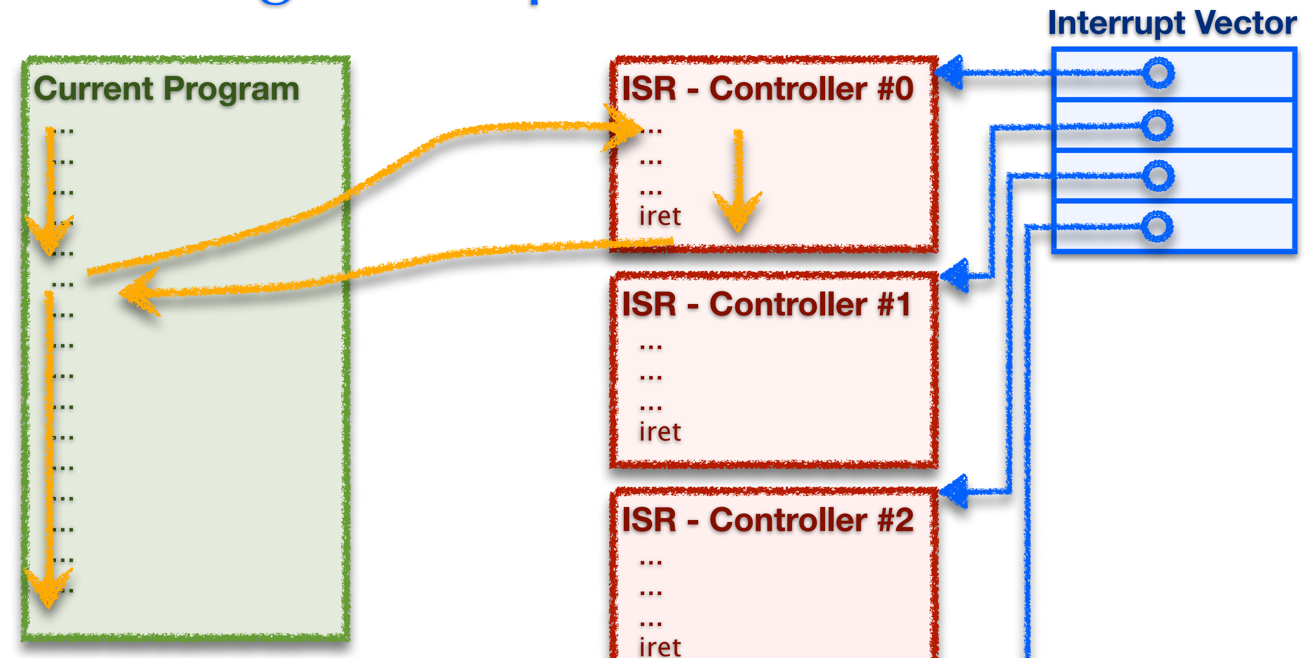
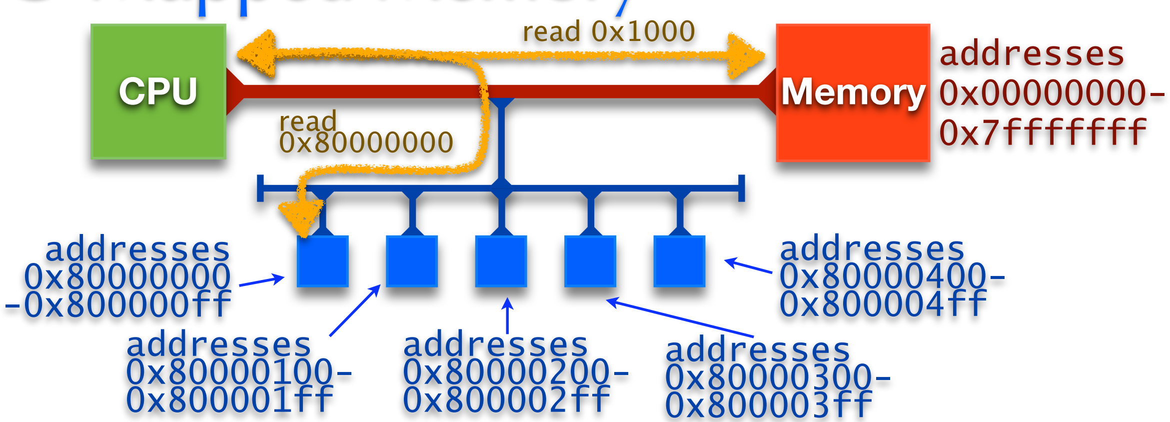


1. Controller #0 Interrupts
2. CPU jumps to its ISR
3. ISR returns to program

I/O-Mapped Memory



- I/O-Mapped Memory
  - use familiar syntax for load/store for both memory and I/O
  - memory addresses beyond the end of main memory handled by I/O controllers
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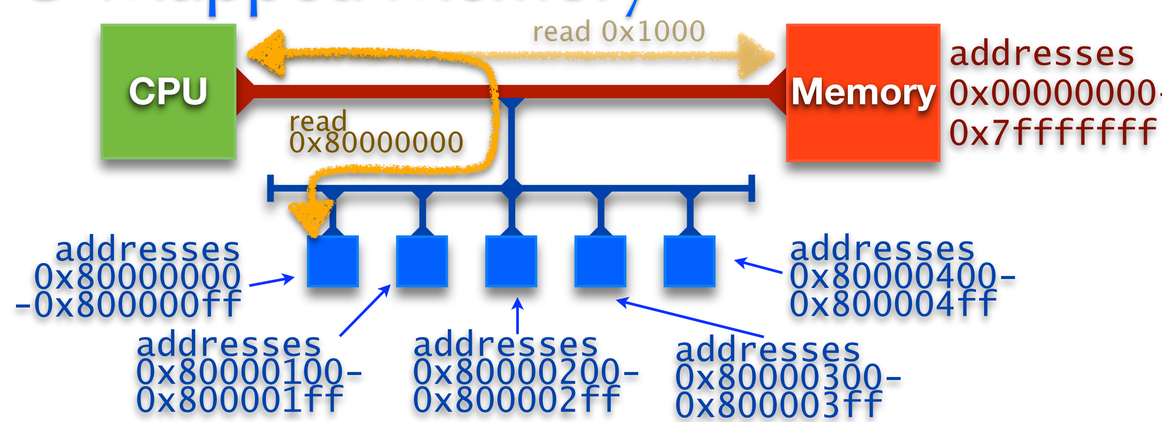

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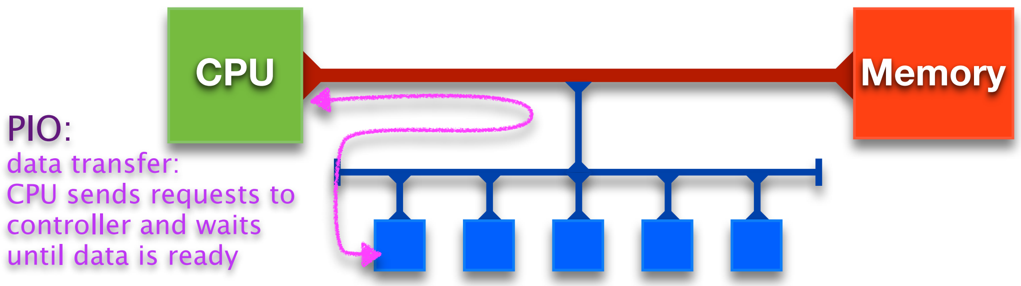
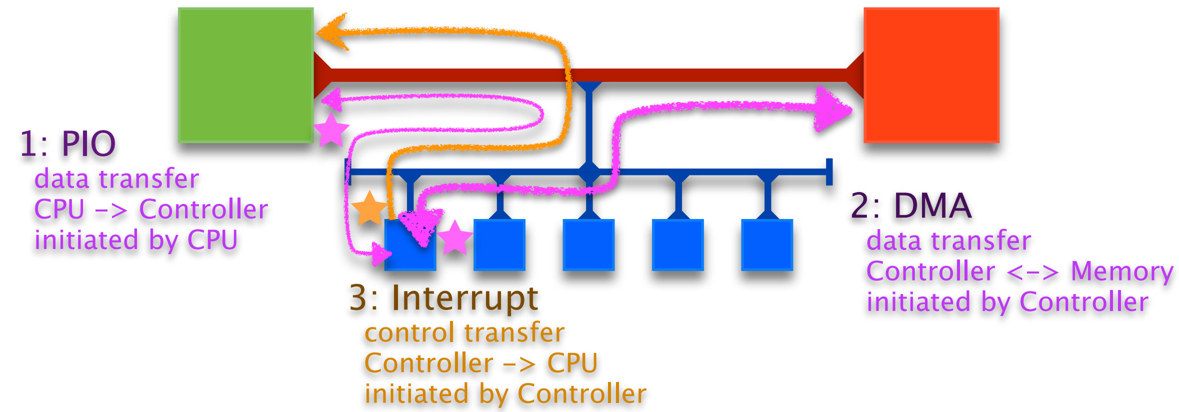
Programmed IO (PIO)



- CPU requests one word at a time and waits for I/O controller
  - CPU must wait until data is available
    - but I/O devices may be **much** slower than CPU (disks millions of times slower)
  - large transfers slow since must be done one word at a time
  - CPU must check back with I/O controller (for instance by polling)
    - poll too often means high overhead
    - poll too seldom means high latency
  - no way for I/O controller to initiate communication
    - for some devices CPU has no idea when to poll (network traffic, mouse click)

Direct Memory Access (DMA)



- I/O controller transfers data to/from main memory independently of CPU
  - process initiated by CPU using PIO
    - send request to controller with addresses and sizes
  - data transferred to memory without CPU involvement
  - controller signals CPU with interrupt when transfer complete
- can transfer large amounts of data with one request
  - not limited to one word at a time

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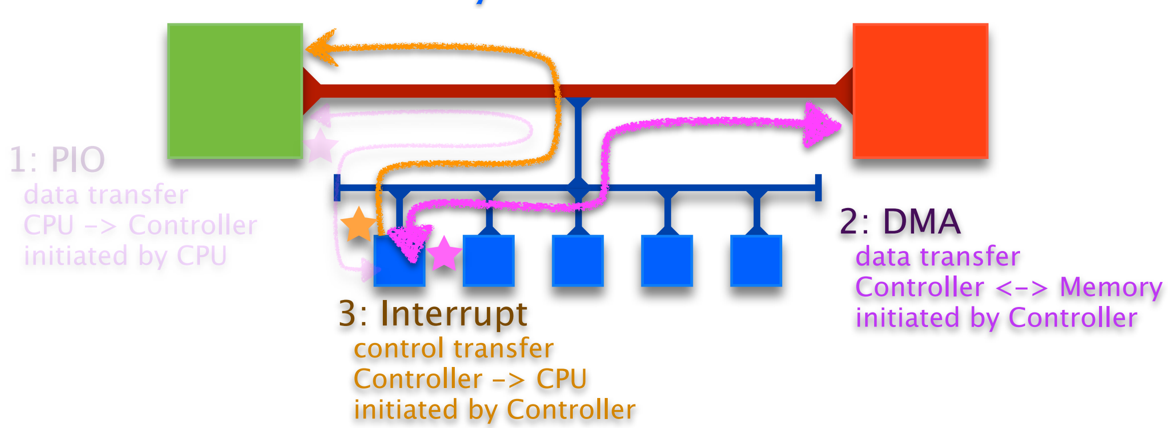

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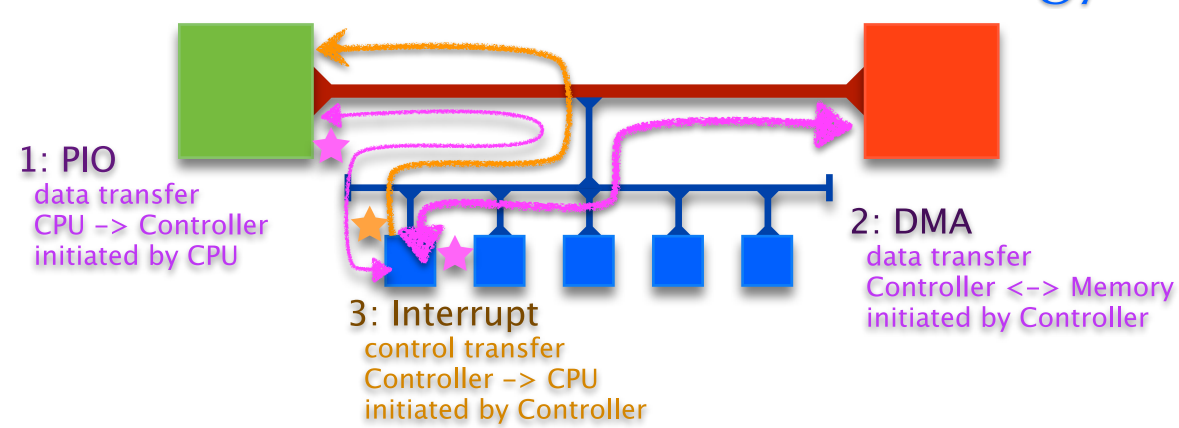
PIO vs DMA: Phone Call Analogy



- PIO: only CPU can make a phone call
  - must stay on the line a looooong time waiting for controller to finish
- PIO/DMA/Interrupt combination: sequence of phone calls
  - PIO: CPU calls controller to make request, then hangs up
  - DMA: controller calls memory to deliver data
  - Interrupt: controller calls CPU to inform that data is ready
    - leaves voicemail that CPU picks up on the next fetch/execute cycle

Programming with I/O

Reading from Disk (a Timeline)

CPU	I/O Controller
1. PIO to request read	
	2. PIO Received, start read
	... wait for read to complete ...
... do other things ...	
	3. Read completes
	4. Transfer data to memory (DMA)
	5. Interrupt CPU
6. Interrupt Received Call readComplete	

First Cut at Disk Read

- Tell disk controller what block to read and where to put data

```
struct Ctrl {
  int   op;
  char* buf;
  int   siz;
  int   blkNo;
};
void scheduleRead (char* aBuf, int aSiz, int aBlkNo) {
  // use PIO to instruct disk controller to read
  struct Ctrl* ctrl = (struct Ctrl*) 0x80000000;
  ctrl->op    = 1;
  ctrl->buf   = aBuf;
  ctrl->siz   = aSiz;
  ctrl->blkNo = aBlkNo;
}
```

```
char buf[4096]
scheduleRead (buf, sizeof(buf), 1234);
// do some other things ... LOTS of other things
```

- Read is finished when disk controller interrupts CPU

```
interruptVector [DISK_ID] = readComplete;
void readComplete () {
  // content of disk block 1234 is now in buf
}
```

What is wrong?

Generalized Disk Read

- Completion Queue
  - stores a completion routine (and other info) for all pending operations
  - organized as a circular queue: add to head, consume from tail

```
struct Comp {
  void (*handler) (char*, int);
  char* buf;
  int   siz;
};

struct Comp compQueue[1000];
int        compHead = 0;
int        compTail = 0;

void asyncRead (char* aBuf, int aSiz, int aBlkNo,
                void (*aCompHandler) (char*, int)) {
  // store completion record in main memory
  compHead = (compHead + 1) % 1000;
  compQueue [compHead].handler = aCompHandler;
  compQueue [compHead].buf     = aBuf;
  compQueue [compHead].siz     = aSiz;
  // use PIO to instruct disk controller to read
  scheduleRead (aBuf, aSiz, aBlkNo);
}
```

- Your code to request a disk read
  - call asynchronous read
  - specify your own completion routine

```
char buf[4096];
void askForBlock (int aBlkNo) {
  asyncRead (buf, sizeof(buf), aBlkNo, nowHaveBlock);
}

void nowHaveBlock (char* aBuf, int aSiz) {
  // aBuf now stores the requested disk data
}
```

- Generalized interrupt service routine
  - consumes next completion record, calling specified completion routine
  - assumes I/O operations complete in order

```
interruptVector [DISK_ID] = diskInterruptServiceRoutine;

void diskInterruptServiceRoutine () {
  struct Comp comp = compQueue[compTail];
  compTail = (compTail + 1) % 1000;
  comp.handler (comp.buf, comp.siz);
  asm ("iret"); // return from interrupt
}
```


Timeline of Asynchronous Disk Read

- Your program schedules the read
  - call asyncRead, register a completion routine
  - enqueue completion routine
  - use PIO to tell controller which block to read and where to put the data
- The disk controller performs the read
  - gets data from disk surface
  - uses DMA to transfer data to memory
  - interrupts CPU to signal completion
- Interrupt Service Routine
  - dequeue next completion routine
  - call completion routine so that your program can consume data ...
  - return from interrupt

What is wrong now?

Synchronous vs Asynchronous

- Consider reading a block and then using its data
  - *read* must complete before data can be read (by *nowHaveBlock*)
- A synchronous approach

```
read         (buf, siz, blkNo);  // read siz bytes at blkNo into buf
nowHaveBlock (buf, siz);         // now do something with the block
```

  - *nowHaveBlock starts only after read* completes and block is in memory
  - the execution of consecutive statements in a program is ***synchronized***
- An asynchronous approach

```
asyncRead (buf, siz, blkNo, nowHaveBlock);
```

  - *asyncRead* returns immediately; the next statement executes before *nowHaveBlock*
  - the execution of request and response is ***not synchronized***
  - when *nowHaveBlock* runs, it does not have the context of its calling procedure

Sync vs Async a Closer look

- Call graphs

Synchronous | Asynchronous

- Runtime stack when nowHaveBlock runs

Synchronous	Asynchronous
nowHaveBlock	nowHaveBlock
main	disk ISR

Happy System, Sad Programmer

- Humans like synchrony
  - we expect each step of a program to complete before the next one starts
  - we use the result of previous steps as input to subsequent steps
  - with disks, for example,
    - we read from a file in one step and then usually use the data we've read in the next step
- Computer systems are asynchronous
  - the disk controller takes 10-20 milliseconds (10^{-3}s) to read a block
    - CPU can execute 60 million instructions while waiting for the disk
    - we must allow the CPU to do other work while waiting for I/O completion
  - many devices send unsolicited data at unpredictable times
    - e.g., incoming network packets, mouse clicks, keyboard-key presses
    - we must allow programs to be interrupted many, many times a second to handle these things
- Asynchrony makes programmers sad
  - it makes programs more difficult to write and much more difficult to debug

Possible Solutions

- Accept the inevitable
  - use an event-driven programming model
    - event triggering and handling are de-coupled
  - a common idiom in many Java programs
    - GUI programming follows this model
  - *CSP* is a language boosts this idea to first-class status
    - no procedures or procedure calls
    - program code is decomposed into a set of sequential/synchronous processes
    - processes can fire events, which can cause other processes to run in parallel
    - each process has a guard predicate that lists events that will cause it to run
- Invent a new abstraction
  - an abstraction that provides programs the illusion of synchrony
  - but, what happens when
    - a program does something asynchronous, like disk read?
    - an unanticipated device event occurs?
- What's the right solution?
  - we still don't know — this is one of the most pressing questions we currently face