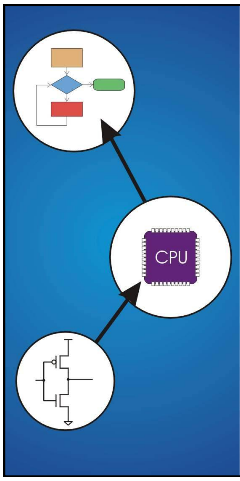
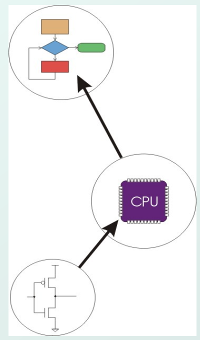


Chapter 8
I/O

Original slides from Gregory Byrd, North Carolina State University

Modified slides by Chris Wilcox, Colorado State University

Computing Layers



Problems

Algorithms

Language

Instruction Set Architecture

Microarchitecture

Circuits

Devices

I/O: Connecting to Outside World

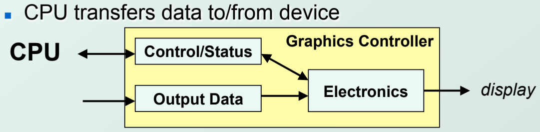
- So far, we've learned how to:
  - compute with values in registers
  - load data from memory to registers
  - store data from registers to memory
- But where does data in memory come from?
- And how does data get out of the system so that humans can use it?

I/O: Connecting to the Outside World

- Types of I/O devices characterized by:
  - behavior: input, output, storage
    - input: keyboard, motion detector, network interface
    - output: monitor, printer, network interface
    - storage: disk, CD-ROM
  - data rate: how fast can data be transferred?
    - keyboard: 100 bytes/sec
    - disk: 30 MB/s
    - network: 1 Mb/s - 1 Gb/s

I/O Controller

- Control/Status Registers
  - CPU tells device what to do -- write to control register
  - CPU checks if task is done -- read status register
- Data Registers
  - CPU transfers data to/from device



- Device electronics
  - performs actual operation
    - pixels to screen, bits to disk, chars from keyboard

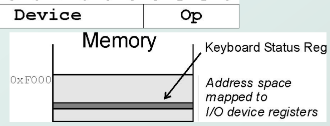
Programming Interface

- How are device registers identified?
  - Memory-mapped vs. special instructions
- How is timing of transfer managed?
  - Asynchronous vs. synchronous
- Who controls transfer?
  - CPU (polling) vs. device (interrupts)

Memory-Mapped vs. I/O Instructions

- Instructions
  - designate opcode(s) for I/O
  - register and operation encoded in instruction

15 14 13 12	11 10 9 8 7 6 5 4 3 2	1 0
IO	Device	Op



- Memory-mapped
  - assign a memory address to each device register
  - use data movement instructions (LD/ST) for control and data transfer

Transfer Timing

- I/O events generally happen much slower than CPU cycles.
- Synchronous
  - data supplied at a fixed, predictable rate
  - CPU reads/writes every X cycles
- Asynchronous
  - data rate less predictable
  - CPU must *synchronize* with device, so that it doesn't miss data or write too quickly

Transfer Control

- Who determines when the next data transfer occurs?
- **Polling**
  - CPU keeps checking status register until *new data* arrives OR *device ready* for next data
  - "Are we there yet? Are we there yet? Are we …
- **Interrupts**
  - Device sends a special signal to CPU when *new data* arrives OR *device ready* for next data
  - CPU can be performing other tasks instead of polling device.
  - "Wake me when we get there."

LC-3

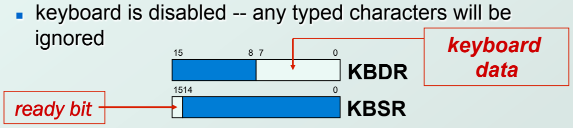
- **Memory-mapped I/O** (Table A.3)

Location	*I/O Register*	*Function*
`xFE00`	**Keyboard Status (KBSR)**	**Bit [15] is one when keyboard has received a new character.**
`xFE02`	**Keyboard Data (KBDR)**	**Bits [7:0] contain the last character typed on keyboard.**
`xFE04`	**Display Status (DSR)**	**Bit [15] is one when device ready to display char on screen.**
`xFE06`	**Display Data (DDR)**	**Character written to bits [7:0] will be displayed on screen.**

- **Asynchronous devices**
  - synchronized through status registers
- **Polling** and **Interrupts**
  - Interrupt details will be discussed in Chapter 10

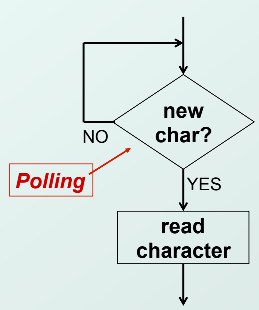
Input from Keyboard

- When a character is typed:
  - its ASCII code is placed in bits [7:0] of KBDR (bits [15:8] are always zero)
  - the "ready bit" (KBSR[15]) is set to one
  - keyboard is disabled -- any typed characters will be ignored



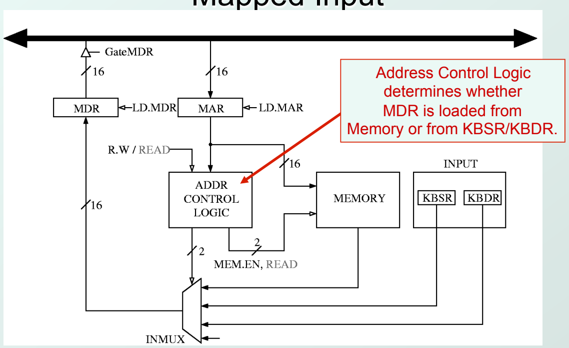
- When KBDR is read:
  - KBSR[15] is set to zero
  - keyboard is enabled

Basic Input Routine



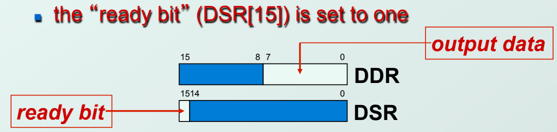

```
POLL     LDI   R0, KBSRPtr
         BRzp  POLL
         LDI   R0, KBDRPtr

         ...

KBSRPtr .FILL xFE00
KBDRPtr .FILL xFE02
```

Simple Implementation: Memory-Mapped Input



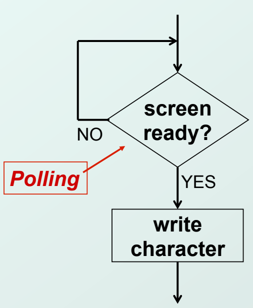
Output to Monitor

- When Monitor is ready to display another character:
  - the “ready bit” (DSR[15]) is set to one



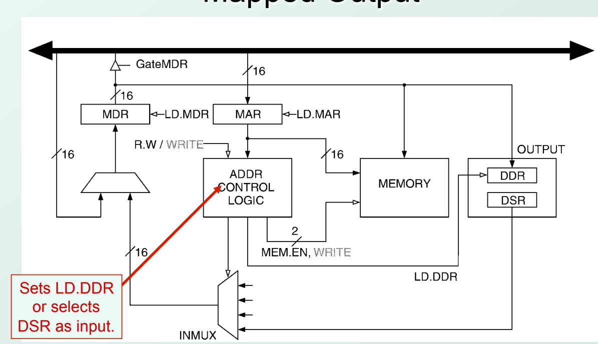
- When data is written to Display Data Register:
  - DSR[15] is set to zero
  - character in DDR[7:0] is displayed
  - any other character data written to DDR is ignored

Basic Output Routine




```
POLL    LDI  R1, DSRPtr
        BRzp POLL
        STI  R0, DDRPtr
        ...
DSRPtr .FILL xFE04
DDRPtr .FILL xFE06
```

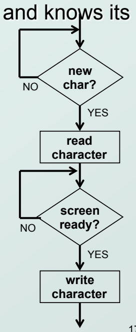

Simple Implementation: Memory-Mapped Output



Keyboard Echo Routine

- Usually, input character is also printed to screen.
  - User gets feedback on character typed and knows its ok to type the next character.

```
POLL1    LDI  R0, KBSRPtr
         BRzp POLL1
         LDI  R0, KBDRPtr
POLL2    LDI  R1, DSRPtr
         BRzp POLL2
         STI  R0, DDRPtr

         ...

KBSRPtr  .FILL xFE00
KBDRPtr  .FILL xFE02
DSRPtr   .FILL xFE04
DDRPtr   .FILL xFE06
```



Interrupt-Driven I/O

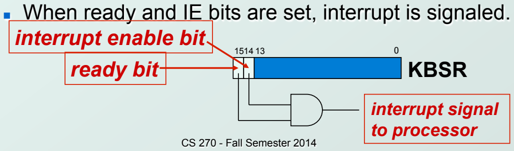
- External device can:

(1) Force currently executing program to stop.
(2) Have the processor satisfy the device needs.
(3) Resume the program as if nothing happened.

- Why?
  - Polling consumes a lot of cycles, especially for rare events – these cycles can be used for more computation.
  - Example: Process previous input while collecting current input. (See Example 8.1 in text.)

Interrupt-Driven I/O

- To implement an interrupt mechanism, we need:
  - A way for the I/O device to **signal** the CPU that an interesting event has occurred.
  - A way for the CPU to **test** if the **interrupt signal is set** and if its **priority is higher** than current program.
- **Generating Signal**
  - Software sets "interrupt enable" bit in device register.
  - When ready and IE bits are set, interrupt is signaled.

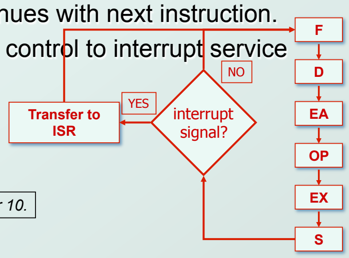


Priority

- Every instruction executes at a stated level of urgency.
- **LC-3: 8 priority levels (PL0-PL7)**
  - Example:
    - Payroll program runs at PL0.
    - Nuclear power correction program runs at PL6.
  - It's OK for PL6 device to interrupt PL0 program, but not the other way around.
- **Priority encoder** selects highest-priority device, compares to current processor priority level, and generates interrupt signal if appropriate.

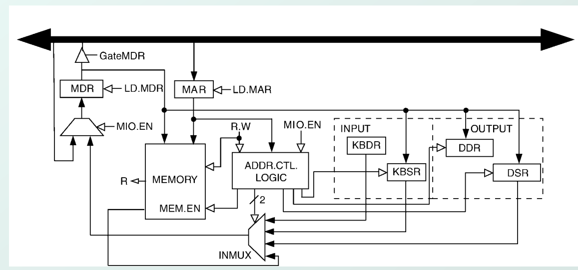
Testing for Interrupt Signal

- CPU looks at signal between STORE and FETCH phases.
- If not set, continues with next instruction.
- If set, transfers control to interrupt service routine.



More details in Chapter 10.

Full Implementation of LC-3 Memory-Mapped I/O



Because of interrupt enable bits, status registers (KBSR/DSR) must be written, as well as read.

Review Questions

- What is the danger of not testing the DSR before writing data to the screen?
- What is the danger of not testing the KBSR before reading data from the keyboard?
- What if the Monitor were a synchronous device, e.g., we know that it will be ready 1 microsecond after character is written.
  - Can we avoid polling? How?
  - What are advantages and disadvantages?

Review Questions

- Do you think polling is a good approach for other devices, such as a disk or a network interface?
- What is the advantage of using LDI/STI for accessing device registers?