
Interrupts & Input/Output

Chapter 12
S. Dandamudi

Interrupts and Input/Output

- What are interrupts?
- Types of interrupts
 - * Software interrupts
 - * Hardware interrupts
 - * Exceptions
- Interrupt processing
 - * Protected mode
 - * Real mode
- Software interrupts
 - * Keyboard services
 - » int 21H DOS services
 - » int 16H BIOS services
- Exceptions
 - * Single-step example
- Hardware interrupts
 - * Accessing I/O
 - * Peripheral support chips
- Writing user ISRs

What Are Interrupts?

- Interrupts alter a program's flow of control
 - * Behaviour is similar to a procedure call
 - » Some significant differences between the two
- Interrupt causes transfer of control to an *interrupt service routine (ISR)*
 - » ISR is also called a *handler*
- When the ISR is completed, the original program resumes execution
- Interrupts provide an efficient way to handle unanticipated events

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Interrupts versus Procedures

Interrupts

- Initiated by both *software* and *hardware*
- Can handle *anticipated* and *unanticipated* internal as well as external events
- ISRs or interrupt handlers are memory resident
- Use numbers to identify an interrupt service
- (E)FLAGS register is saved automatically

Procedures

- Can only be initiated by *software*
- Can handle *anticipated* events that are coded into the program
- Typically loaded along with the program
- Use meaningful names to indicate their function
- Do not save the (E)FLAGS register

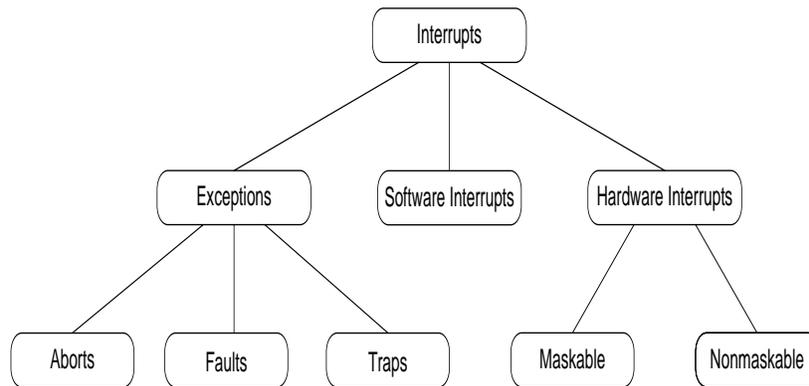
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A Taxonomy of Pentium Interrupts



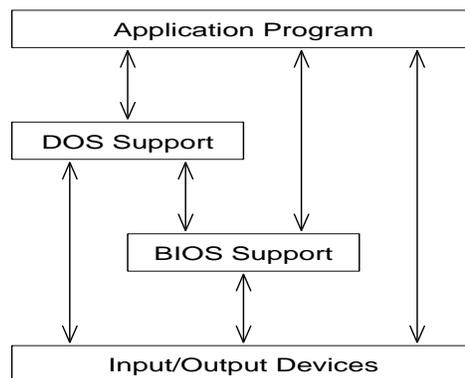
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Various Ways of Interacting with I/O Devices



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Protected Mode Interrupt Processing

- Up to 256 interrupts are supported (0 to 255)
 - » Same number in both real and protected modes
 - » Some significant differences between real and protected mode interrupt processing
- Interrupt number is used as an index into the *Interrupt Descriptor Table (IDT)*
 - * This table stores the addresses of all ISRs
 - * Each descriptor entry is 8 bytes long
 - » Interrupt number is multiplied by 8 to get byte offset into IDT
 - * IDT can be stored anywhere in memory
 - » In contrast, real mode interrupt table has to start at address 0

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Protected Mode Interrupt Processing (cont'd)

- * Location of IDT is maintained by IDT register IDTR
- * IDTR is a 48-bit register
 - » 32 bits for IDT base address
 - » 16 bits for IDT limit value
 - IDT requires only 2048 (11 bits)
 - A system may have smaller number of descriptors
 - Set the IDT limit to indicate the size in bytes
 - » If a descriptor outside the limit is referenced
 - Processor enters shutdown mode
- * Two special instructions to load (**lidt**) and store (**sidt**) IDT
 - » Both take the address of a 6-byte memory as the operand

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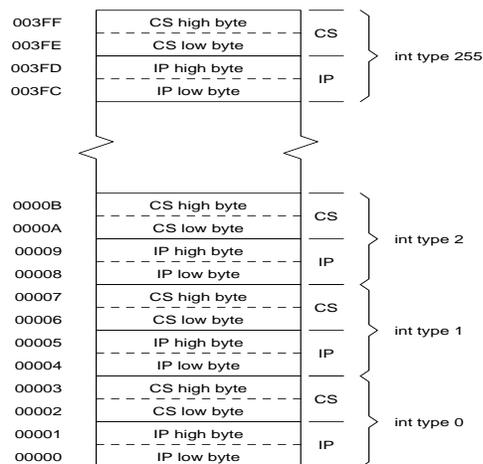
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Interrupt Processing in Real Mode

- Uses an interrupt vector table that stores pointers to the associated interrupt handlers.
- This table is located at base address zero.
- Each entry in this table consists of a CS:IP pointer to the associated ISRs
- Each entry or vector requires four bytes:
 - * Two bytes for specifying CS
 - * Two bytes for the offset
- Up to 256 interrupts are supported (0 to 255).

Interrupt Vector Table

Memory address (in Hex)



Interrupt Number to Vector Translation

- Interrupt numbers range from 0 to 255
 - Interrupt number acts as an index into the interrupt vector table
 - Since each vector takes 4 bytes, interrupt number is multiplied by 4 to get the corresponding ISR pointer
- Example**
- For interrupt 2, the memory address is
 $2 * 4 = 8H$
 - The first two bytes at 8H are taken as the offset value
 - The next two bytes (i.e., at address AH) are used as the CS value

A Typical ISR Structure

- Just like procedures, ISRs should end with a return statement to return control back
- The interrupt return (**iret**) is used of this purpose

```
;save the registers used in the ISR
sti      ;enable further interrupts
. . .
ISR body
. . .
;restore the saved registers
iret    ;return to interrupted program
```

What Happens When An Interrupt Occurs?

- Push flags register onto the stack
- Clear interrupt enable and trap flags
 - * This disables further interrupts
 - * Use **sti** to enable interrupts
- Push CS and IP registers onto the stack
- Load CS with the 16-bit data at memory address
interrupt-type * 4 + 2
- Load IP with the 16-bit data at memory address
interrupt-type * 4

Interrupt Enable Flag Instructions

- Interrupt enable flag controls whether the processor should be interrupted or not
- Clearing this flag disables all further interrupts until it is set
 - * Use **ccli** (clear interrupt) instruction for this purpose
 - * It is cleared as part interrupt processing
- Unless there is special reason to block further interrupts, enable interrupts in your ISR
 - * Use **sti** (set interrupt) instruction for this purpose

Returning From An ISR

- As in procedures, the last instruction in an ISR should be **iret**
- The actions taken on **iret** are:
 - * pop the 16-bit value on top of the stack into IP register
 - * pop the 16-bit value on top of the stack into CS register
 - * pop the 16-bit value on top of the stack into the flags register
- As in procedures, make sure that your ISR does not leave any data on the stack (i.e., match your push and pop operations within the ISR)

Software Interrupts

- Initiated by executing an interrupt instruction
int interrupt-type
interrupt-type is an integer in the range 0 to 255
- Each interrupt type can be parameterized to provide several services.
- For example, DOS interrupt service **int 21H** provides more than 80 different services
 - * AH register is used to identify the required service under **int 21H**.

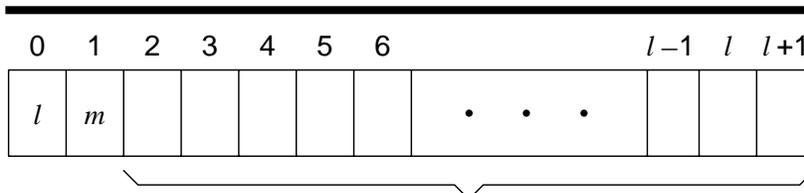
Example DOS Service: Keyboard

- DOS provides several interrupt services to interact with the keyboard
- AH register should be loaded with the desired function under int 21H.
- Seven functions are provided by DOS to read a character or get the status of the keyboard
 - » See Section 12.5.2 for details
- We look at one function to read a string of characters from the keyboard.

A DOS Keyboard Function

- Function 0AH --- Buffered Keyboard Input
 - Inputs:** AH = 0AH
 - DS:DX = pointer to the input buffer
(first byte should be buffer size)
 - Returns:** character string in the input buffer
- Input string is terminated by CR
- Input string starts at the third byte of the buffer
- Second byte gives the actual number of characters read (excluding the CR)

Input Buffer Details



l = maximum number of characters (given as input to the function)

m = actual number of characters in the buffer excluding CR (returned by the function)

A Keyboard Example

- **GetStr** procedure to read a string from the keyboard (see io.mac)
- Expects buffer pointer in AX and buffer length in CX
- Uses DOScall macro:

```

DOScall  MACRO  fun_num
mov     AH, fun_num
int     21H
ENDM
    
```

```

Proc_GetStr ()
Save registers used in proc.
if (CX < 2) then CX := 2
if (CX > 81) then CX := 81
Use function 0AH to read
input string into temp.
buffer str_buffer
Copy input string from
str_buffer to user
buffer and append NULL
Restore registers
    
```

BIOS Keyboard Services

- BIOS provides keyboard services under int 16H
- We focus on three functions provided by int 16H
 - * Function 00H --- To read a character
 - * Function 01H --- To check keyboard buffer
 - * Function 02H --- To check keyboard status
- As with DOS functions, AH is used to identify the required service
- DOS services are flexible in that the keyboard input can be redirected (BIOS does not allow it)

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BIOS Character Read Function

- Function 00H --- Read a char. from the keyboard
 - Inputs:** AH = 00H
 - Returns:** if AL is not zero
 - AL = ASCII code of the key
 - AH = Scan code of the key
 - if AL is zero
 - AH = Scan code of the extended key
- If keyboard buffer is empty, this function waits for a key to be entered

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BIOS Keyboard Buffer Check Function

- Function 01H --- Check keyboard buffer
 - Inputs:** AH = 01H
 - Returns:** ZF = 1 if keyboard buffer is empty
ZF = 0 if not empty
 - ASCII and Scan codes
are placed in AL and AH
as in Function 00H
- The character is **not** removed from the keyboard buffer

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BIOS Keyboard Status Check Function

- Function 02H --- Check keyboard status
 - Inputs:** AH = 02H
 - Returns:**
AL = status of shift
and toggle keys
 - Bit assignment is shown on the right
- | Bit# | Key assignment |
|------|------------------|
| 0 | Right SHIFT down |
| 1 | Left SHIFT down |
| 2 | CONTROL down |
| 3 | ALT down |
| 4 | SCROLL LOCK down |
| 5 | NUMBER LOCK down |
| 6 | CAPS LOCK down |
| 7 | INS LOCK down |

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A BIOS Keyboard Example

- BIOS, being a lower-level service, provides more flexibility
- FUNNYSTR.ASM reads a character string from the keyboard and displays it along with its length
- The input string can be terminated either by pressing both SHIFT keys simultaneously, or by entering 80 characters, whichever occurs first.
- We use BIOS function 02H to detect the first termination condition.

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Display and Printer Support

- Both DOS and BIOS provide support for Printer and Display screen
- An example DOS int 21H character display function

Function 02H --- Display a char. to screen

Inputs: AH = 02H

DL = ASCII code of the character
to be displayed

Returns: nothing

- See proc_nwln procedure for usage

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Exceptions

- Three types of exceptions
 - * Depending on the way they are reported
 - * Whether or not the interrupted instruction is restarted
 - » Faults
 - » Traps
 - » Aborts
- Faults and traps are reported at instruction boundaries
- Aborts report severe errors
 - * Hardware errors
 - * Inconsistent values in system tables

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Faults and Traps

- Faults
 - » Instruction boundary before the instruction during which the exception was detected
 - » Restarts the instruction
 - » Divide error (detected during `div/ldiv` instruction)
 - » Segment-not-found fault
- Traps
 - » Instruction boundary immediately after the instruction during which the exception was detected
 - » No instruction restart
 - » Overflow exception (interrupt 4) is a trap
 - » User defined interrupts are also examples of traps

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Dedicated Interrupts

- Several Pentium predefined interrupts --- called dedicated interrupts
- These include the first five interrupts:

interrupt type	Purpose
0	Divide error
1	Single-step
2	Nonmaskable interrupt (NMI)
3	Breakpoint
4	Overflow

Dedicated Interrupts (cont'd)

- **Divide Error Interrupt**
 - * CPU generates a type 0 interrupt whenever the div/idiv instructions result in a quotient that is larger than the destination specified
- **Single-Step Interrupt**
 - * Useful in debugging
 - * To single step, Trap Flag (TF) should be set
 - * CPU automatically generates a type 1 interrupt after executing each instruction if TF is set
 - * Type 1 ISR can be used to present the system state to the user

Dedicated Interrupts (cont'd)

- Breakpoint Interrupt
 - * Useful in debugging
 - * CPU generates a type 3 interrupt
 - * Generated by executing a special single-byte version of int 3 instruction (opcode CCH)
- Overflow Interrupt
 - * Two ways of generating this type 4 interrupt
 - » int 4 (unconditionally generates a type 4 interrupt)
 - » into (interrupt is generated only if the overflow flag is set)
 - * We do not normally use **into** as we can use **jo/jno** conditional jumps to take care of overflow

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A Single-Step Interrupt Example

- Objectives:
 - * To demonstrate how ISRs can be defined and installed (i.e., user defined ISRs)
 - * How trap flag can be manipulated
 - » There are no instruction to set/clear the trap flag unlike the interrupt enable flag sti/cli
- We write our own type 1 ISR that displays the contents of AX and BX registers after each instruction has been executed

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Two Services of int 21H

- Function 35H --- Get interrupt vector
 - Inputs:** AH = 35H
AL = interrupt type number
 - Returns:** ES:BX = address of the specified ISR
- Function 25H --- Set interrupt vector
 - Inputs:** AH = 25H
AL = interrupt type number
DS:DX = address of the ISR
 - Returns:** nothing

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Hardware Interrupts

- Software interrupts are synchronous events (caused by executing the int instruction)
- Hardware interrupts are of hardware origin and asynchronous in nature
 - * Typically caused by applying an electrical signal to the processor chip
- Hardware interrupts can be
 - * Maskable
 - * Non-maskable
 - » Causes a type 2 interrupt

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How Are Hardware Interrupts Triggered?

- Non-maskable interrupt is triggered by applying an electrical signal to the MNI pin of Pentium
 - * Processor always responds to this signal
 - * Cannot be disabled under program control
- Maskable interrupt is triggered by applying an electrical signal to the INTR (INTerrupt Request) pin of Pentium
 - * Pentium recognizes this interrupt only if IF (interrupt enable flag) is set
 - * Interrupts can be masked or disabled by clearing IF

How Does the CPU Know the Interrupt Type?

- Interrupt invocation process is common to all interrupts -- whether originated in software or hardware
- For hardware interrupts, CPU initiates an interrupt acknowledge sequence
 - * CPU sends out interrupt acknowledge (INTA) signal
 - * In response, interrupting device places interrupt type number on the data bus
 - * CPU uses this number to invoke the ISR that should service the device (as in software interrupts)

How can More Than One Device Interrupt?

- Processor has only one INTR pin to receive interrupt signal
- Typical system has more than one device that can interrupt --- keyboard, hard disk, floppy, etc.
- Use a special chip to prioritize the interrupts and forward only one interrupt to the CPU
- 8259 Programmable Interrupt Controller chip performs this function (more details later)

Direct Control of I/O Devices

- Two ways of mapping I/O ports:
 - * Memory-mapped I/O (e.g., Motorola 68000)
 - » I/O port is treated as a memory address (I/O port is mapped to a location in memory address space (MAS))
 - » Accessing an I/O port (read/write) is similar to accessing a memory location (all memory access instructions can be used)
 - * Isolated I/O (e.g., Pentium)
 - » I/O address space is separate from the memory address space
 - leaves the complete MAS for memory
 - » Separate I/O instructions and I/O signals are needed
 - » Can't use memory access instructions
 - » Can also use memory-mapped I/O and use all memory access instructions

Pentium I/O Address Space

- Pentium provides 64 KB of I/O address space
 - * Can be used for 8-, 16-, and 32-bit I/O ports
- Combination cannot exceed the total I/O space
 - * 64K 8-bit I/O ports
 - » Used for 8-bit devices, which transfer 8-bit data
 - » Can be located anywhere in the I/O space
 - * 32K 16-bit I/O ports (used for 16-bit devices)
 - » 16-bit ports should be aligned to an even address
 - * 16K 32-bit I/O ports (used for 32-bit devices)
 - » Should be aligned to addresses that are multiples of four
 - » Pentium supports unaligned ports, but with performance penalty
 - * A combination of these for a total of 64 KB

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Pentium I/O Instructions

- Pentium provides two types of I/O instructions:
 - * Register I/O instructions
 - » used to transfer data between a register (accumulator) and an I/O port
 - » `in` - to read from an I/O port
 - » `out` - to write to an I/O port
 - * Block I/O instructions
 - » used to transfer a block of data between memory and an I/O port
 - » `ins` - to read from an I/O port
 - » `outs` - to write to an I/O port

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Register I/O Instructions

- Can take one of two forms depending on whether a port is directly addressable or not
 - A port is said to be directly addressable if it is within the first 256 ports (so that one byte can be used specify it)
- To read from an I/O port
 - in accumulator, port8** -- direct addressing format
port8 is 8-bit port number
 - in accumulator, DX** -- indirect addressing format
port number should be loaded into DX
 - accumulator** can be AL, AX, or EAX (depending on I/O port)
- To write to an I/O port
 - out port8, accumulator** -- direct addressing format
 - out DX, accumulator** -- indirect addressing format

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Block I/O Instructions

- Similar to string instructions
- **ins** and **outs** do not take any operands
- I/O port address should be in **DX**
 - * No direct addressing format is allowed
- **ins** instruction to read from an I/O port
 - » ES:(E)DI should point to memory buffer
- **outs** instruction to write to an I/O port
 - » DS:(E)SI should point to memory buffer
- **rep** prefix can be used for block transfer of data as in the string instructions

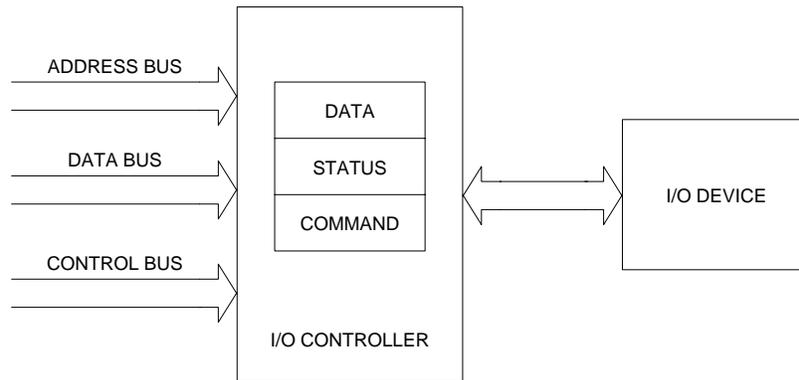
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I/O Device Interface



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8259 Programmable Interrupt Controller

- 8259 can service up to eight hardware devices
 - * Interrupts are received on IRQ0 through IRQ7
- 8259 can be programmed to assign priorities in several ways
 - * Fixed priority scheme is used in the PC
 - » IRQ0 has the highest priority and IRQ7 lowest
- 8259 has two registers
 - * Interrupt Command Register (ICR)
 - » Used to program 8259
 - * Interrupt Mask Register (IMR)

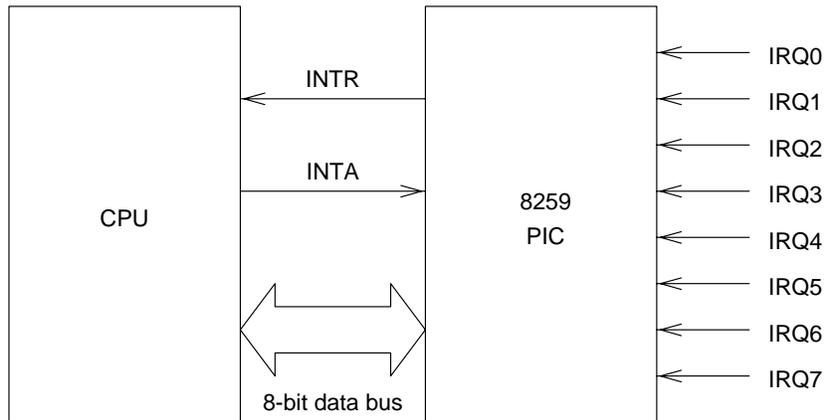
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8259 PIC (cont'd)



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8259 PIC (cont'd)

- Mapping in a single 8259 PIC systems

IRQ#	Interrupt type	Device
0	08H	System timer
1	09H	Keyboard
2	0AH	reserved (2nd 8259)
3	0BH	Serial port (COM1)
4	0CH	Serial port (COM2)
5	0DH	Hard disk
6	0EH	Floppy disk
7	0FH	Printer (LPT1)

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8259 PIC (cont'd)

- Interrupt Mask Register (IMR) is an 8-bit register
 - * Used to enable or disable individual interrupts on lines IRQ0 through IRQ7
 - » Bit 0 is associated with IRQ0, bit 1 to IRQ1, . . .
 - » A bit value of 0 enables the corresponding interrupt (1 disables)
- Processor recognizes external interrupts only when the IF is set
- Port addresses:
 - * ICR: 20H
 - * IMR: 21H

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8259 PIC (cont'd)

Example: Disable all 8259 interrupts except the system timer

```
mov    AL, 0FEH
out    21H, AL
```

- 8259 needs to know when an ISR is done (so that it can forward other pending interrupt requests)
 - * End-of-interrupt (EOI) is signaled to 8259 by writing 20H into ICR
- ```
mov AL, 20H
out 20H, AL
```
- \* This code fragment should be used before **iret**

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## 8255 Programmable Peripheral Interface Chip

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- Provides three 8-bit registers (PA, PB, PC) that can be used to interface with I/O devices
- These three ports are configured as follows:
  - PA -- Input port
  - PB -- Output port
  - PC -- Input port
- 8255 also has a command register
- 8255 port address mapping

|                  |         |
|------------------|---------|
| PA               | --- 60H |
| PB               | --- 61H |
| PC               | --- 62H |
| Command register | --- 63H |

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## Keyboard Interface

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- PA and PB7 are used for keyboard interface
  - \* PA0 -- PA6 = key scan code
  - \* PA7 = 0 if a key is depressed
  - \* PA7 = 1 if a key is released
- Keyboard provides the scan code on PA and waits for an acknowledgement
  - \* Scan code read acknowledge signal is provided by momentarily setting and clearing PB7
    - » Normal state of PB7 is 0
- Keyboard generates IRQ1
  - » IRQ1 generates a type 9 interrupt

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## Polling Versus Interrupts

- Using interrupts to service I/O requests is called *interrupt-driven I/O*
- An alternative is *programmed I/O*
  - \* Repeatedly checks the status of an I/O device (through a status register of the associated I/O controller) until the desired condition is indicated
  - \* This process is called *polling*
- Interrupt-driven I/O is efficient
  - » Can be used to handle unanticipated events
- Polling involves overhead
  - » Can be used to handle only anticipated event

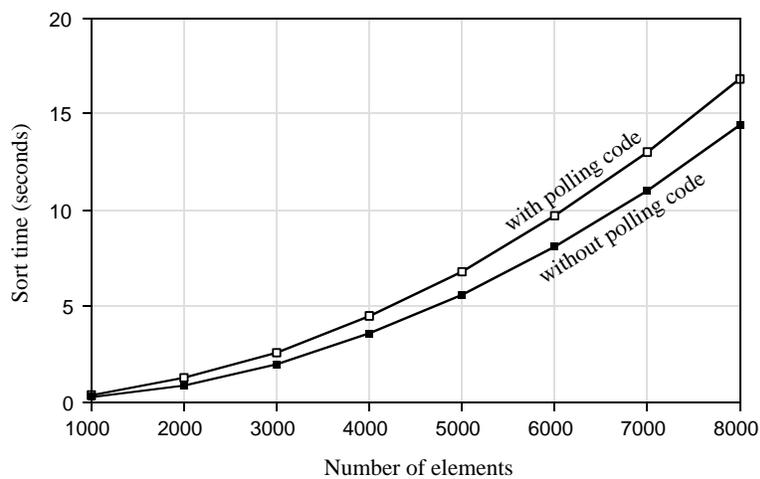
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## Polling Overhead for Bubble Sort Example



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