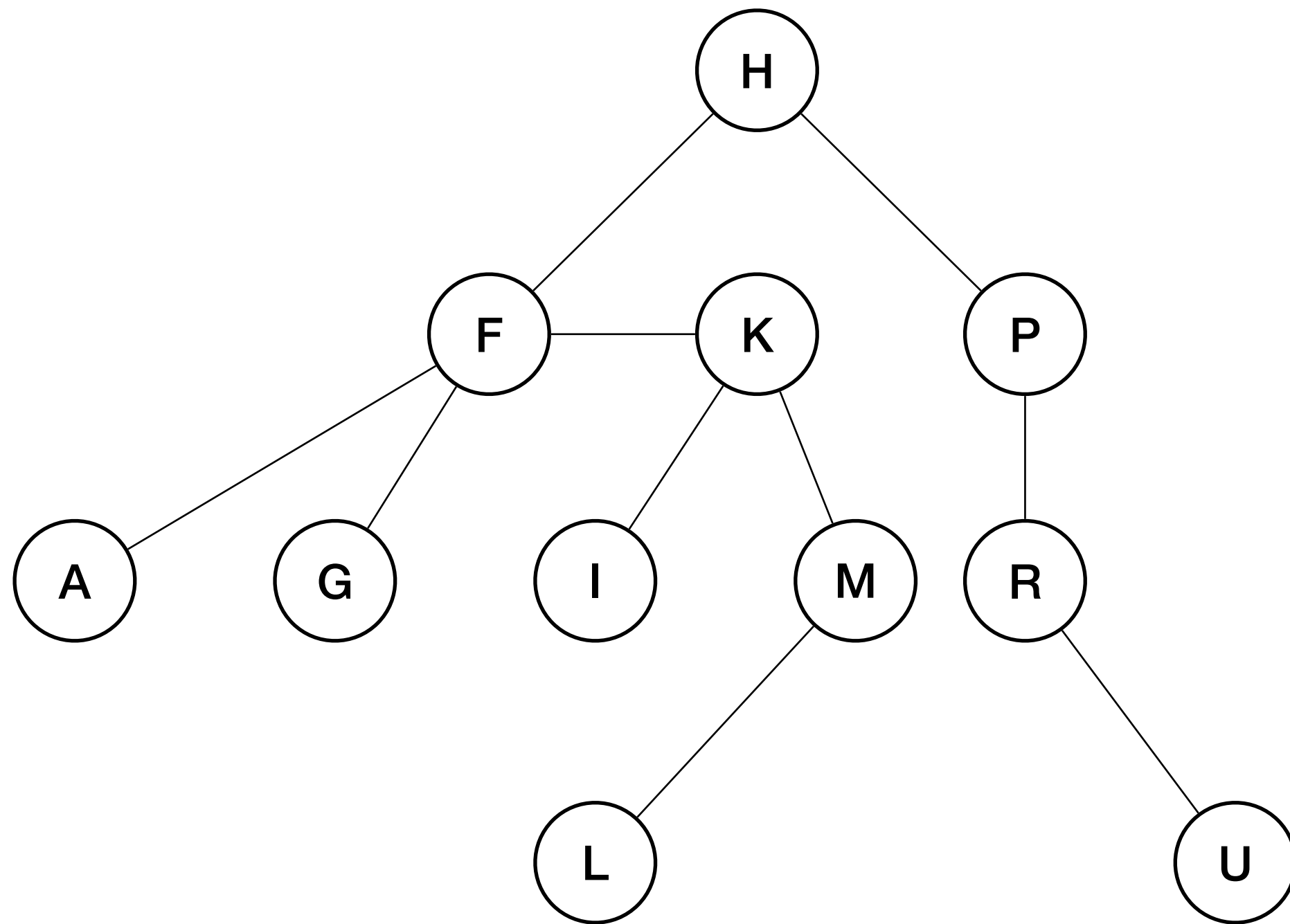


ECE 220

Lecture x0019 - 12/03
Recap & Interrupts in LC3

Post-break recall



Recap + reminders

- Trees
 - Concepts & properties
 - Traversals: preorder/inorder/postorder
 - Binary search trees
 - C to LC3 (structs, trees, linked lists)
 - Code posted
- Reminders
 - Extra credit quiz
 - Programming competition
 - ICES forms available

Today

- Change gears & talk about *interrupts* in LC3
- Recall: KBSR/KBDR & DSR/DDR?
 - When did we see these acronyms?
 - How did we implement I/O in LC3 before?

LC3 - Input/Output (IO)

Pressed key ASCII code

Ready bit

KBDR

KBSR

Data to be output

Ready bit

DDR

DSR

Address	I/O Register Name	I/O Register Function
xFE00	Keyboard status register (KBSR)	The ready bit (bit 15) indicates if the keyboard has received a new character
xFE02	Keyboard data register (KBDR)	Bits [7:0] contain the last character typed on the keyboard
xFE04	Display status register (DSR)	The ready bit (bit 15) indicates if the display device is ready to receive another character to print on the screen
xFE06	Display data register (DDR)	A character written in bits [7:0] will be displayed (displayed) on the screen

LC3 - Input from keyboard
Basic routine
Handshaking is performed using KBSR & KBDR

- When user presses a key
 - Its ASCII code is placed in KBDR[0:7]
 - KBSR[15] is set to 1 (*ready bit*)
 - Keyboard is disabled, i.e., any further keypress is ignored
- When KBDR is read by CPU
 - KBSR[15] is set to 0
 - Keyboard is enabled

LC3 - Input from keyboard
Basic routine

```
.ORIG x3000
;Create a loop to
;check KBSR
;If ready bit unset
;loop again
;If ready bit set,
;read KBSR into R0
;Other instructions
; --
; --
KBSR .FILL xFE00
KBDR .FILL xFE02
.END
```

```
.ORIG x1000
KPOLL LDI R1, KBSR
BZP KPOLL
LDI R0, KBDR
; --
; --
RALT
KBSR .FILL xFE00
KBDR .FILL xFE02
.END
```

LC3 - Display to console
Basic routine
Handshaking is performed using DSR & DDR

- When display is ready to present a character
 - DSR[15] is set to 1 (*ready bit*)
- When a new character is written to DDR
 - DSR[15] is set to 0
 - Any other chars written to DDR are ignored
 - DDR[7:0] is displayed

Slides from Lecture #1

Previously - I/O using Polling or TRAPs

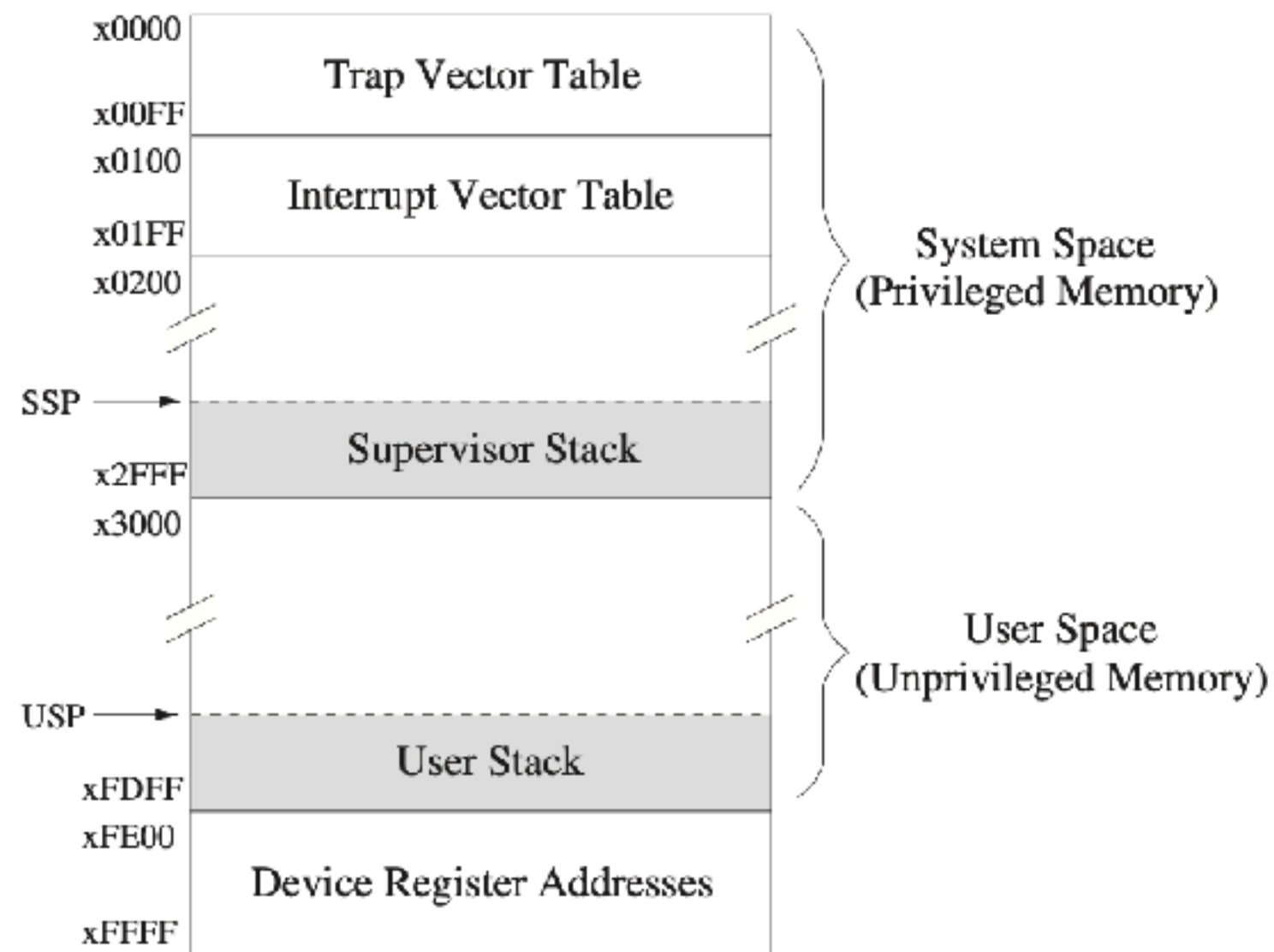
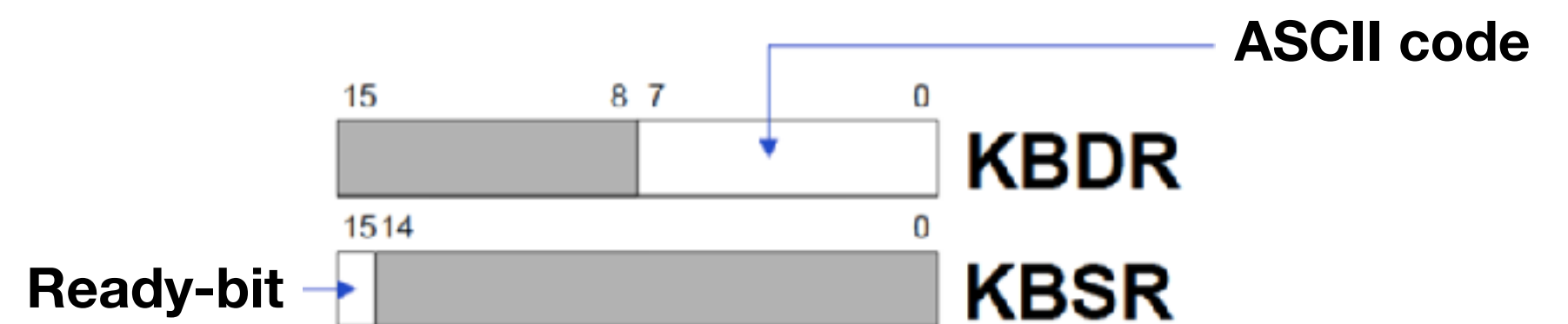
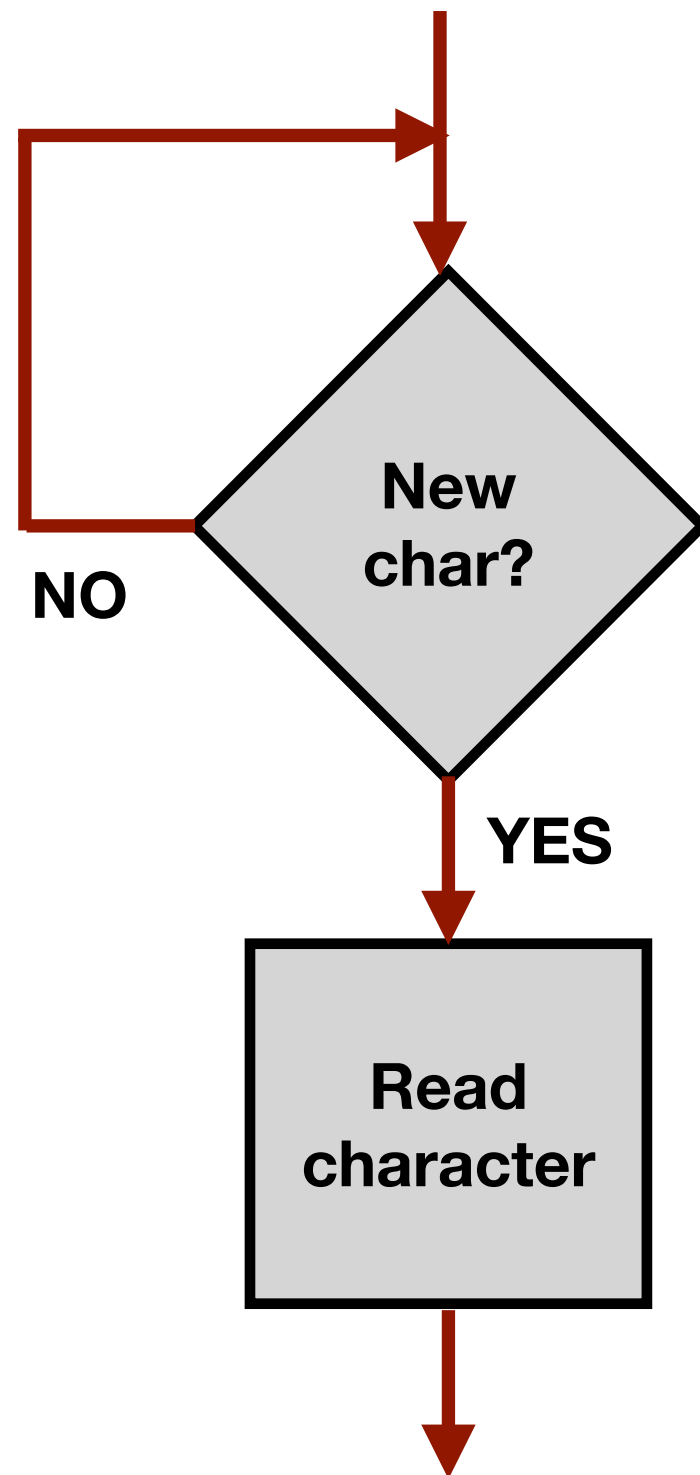


Figure A.1 - P&P 3rd Ed.

Address	I/O Register Name	I/O Register Function
xFE00	Keyboard status register (KBSR)	The ready bit (bit[15]) indicates if the keyboard has received a new character
xFE02	Keyboard data register (KBDR)	Bits [7:0] contain the last character typed on the keyboard



Any problems with polled I/O?



- Suppose we want to type 100 characters:
 - User can input at speed of 60 WPM, assume, eight characters/word:
 - How long to type 100 characters?
- Processor cannot do anything else while it waits on *next* character!
 - 12.5 seconds spend just polling!
- How can we free up the processor to do other tasks?

Interrupt driven I/O

- Key idea: An I/O device can
 - force running program to stop
 - have processor execute different program that carries out needs of I/O device, and *then*
 - resume execution of stopped program as if nothing had happened

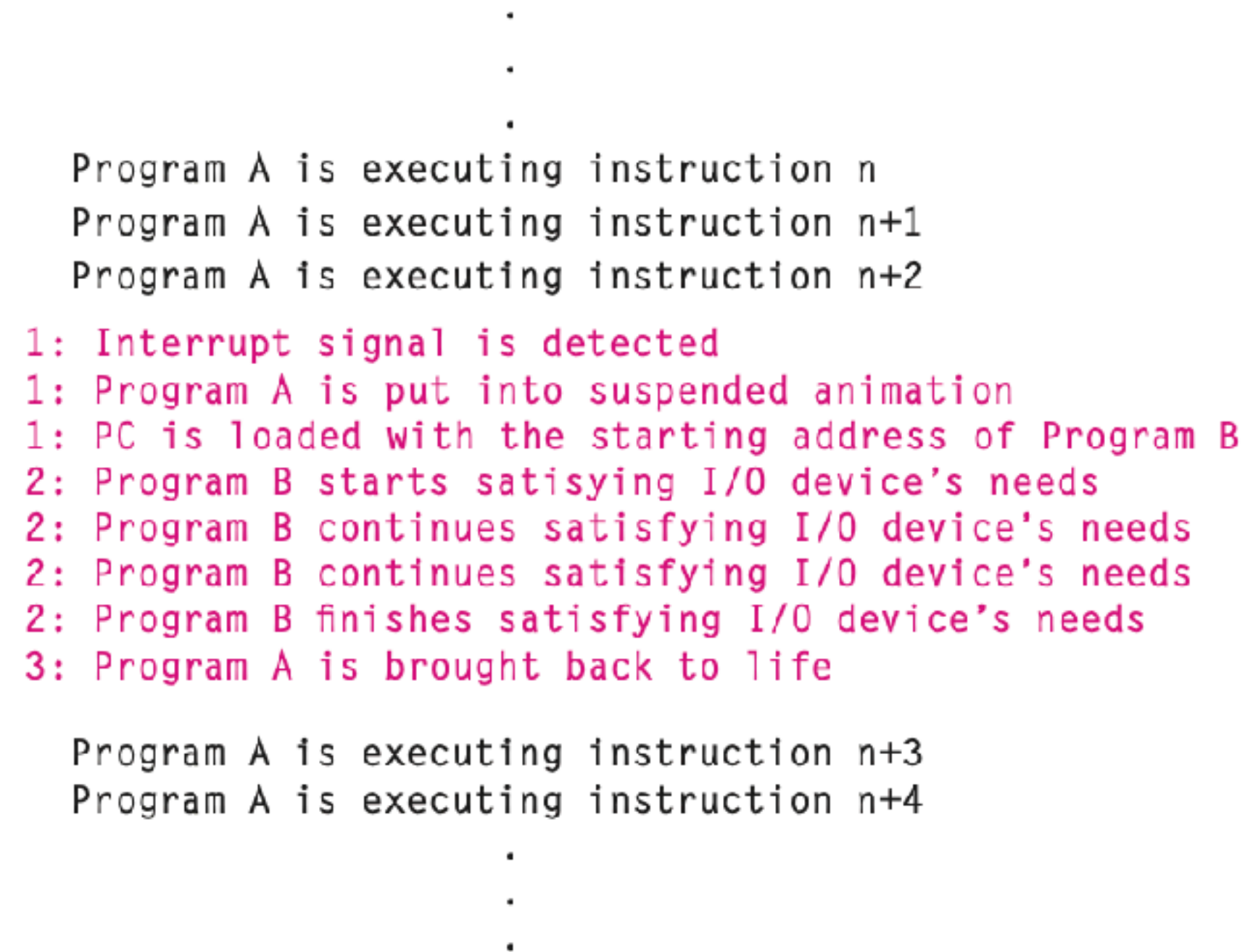


Figure 9.17 Instruction execution flow for interrupt-driven I/O.

Now - I/O using interrupts

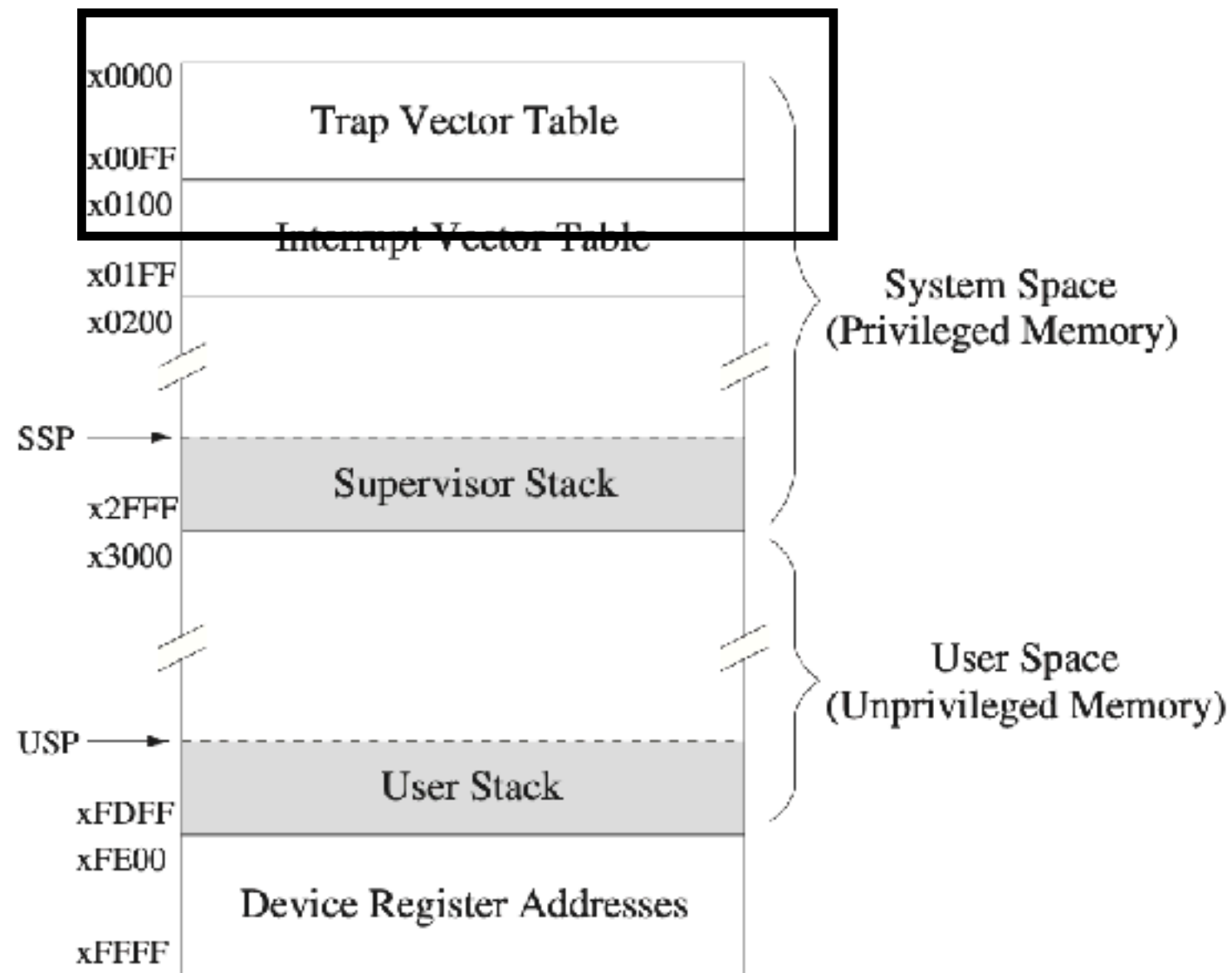
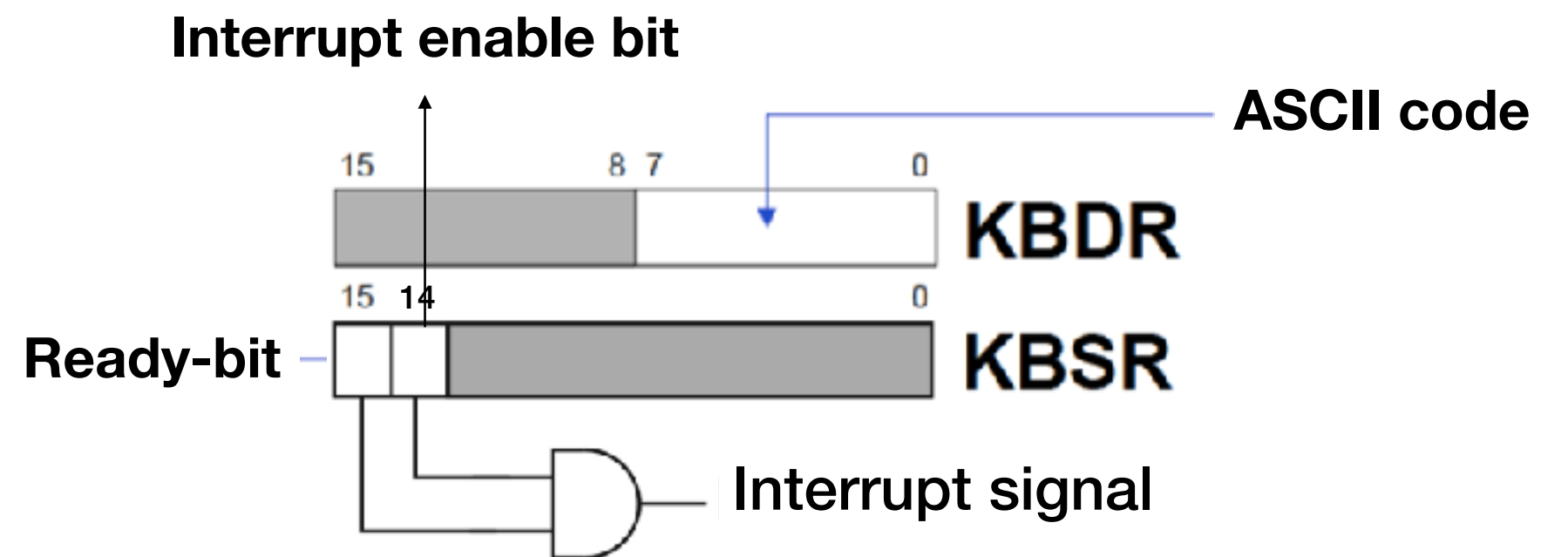


Figure A.1 - P&P 3rd Ed.

Address	I/O Register Name	I/O Register Function
xFE00	Keyboard status register (KBSR)	The ready bit (bit[15]) indicates if the keyboard has received a new character
		The IE bit (bit[14]) specifies if the I/O device has permission to generate interrupt signal



What needs to happen?

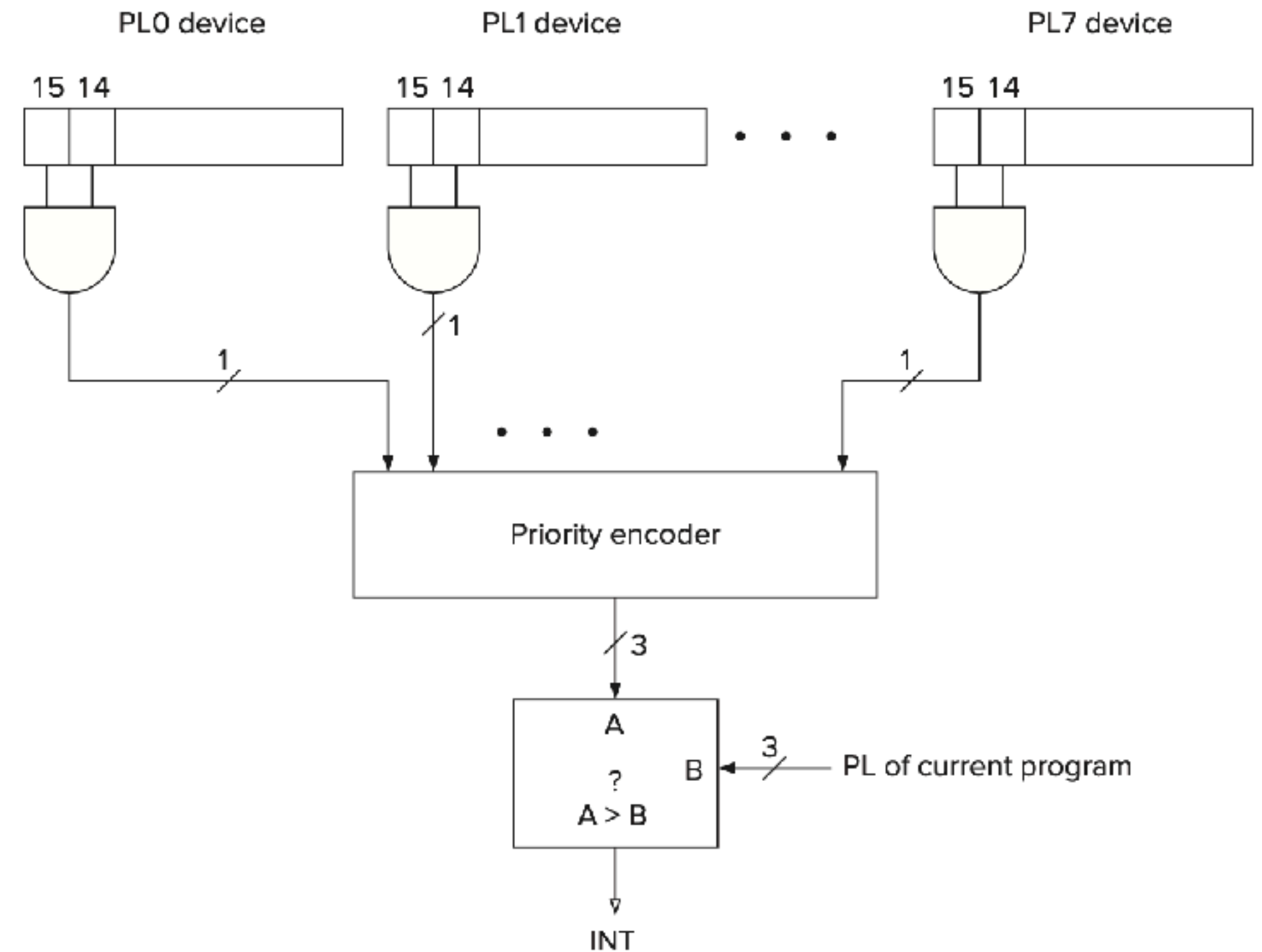
For interrupt driven I/O to work:

1. The I/O device **must want service.**
 - Ready bit
2. The device must have the **right to request** the service.
 - Interrupt enable bit

3. The device request must be **more urgent** than what the processor is currently doing.
 - **Priority levels:** $PL0 < PL1 < \dots < PL6$

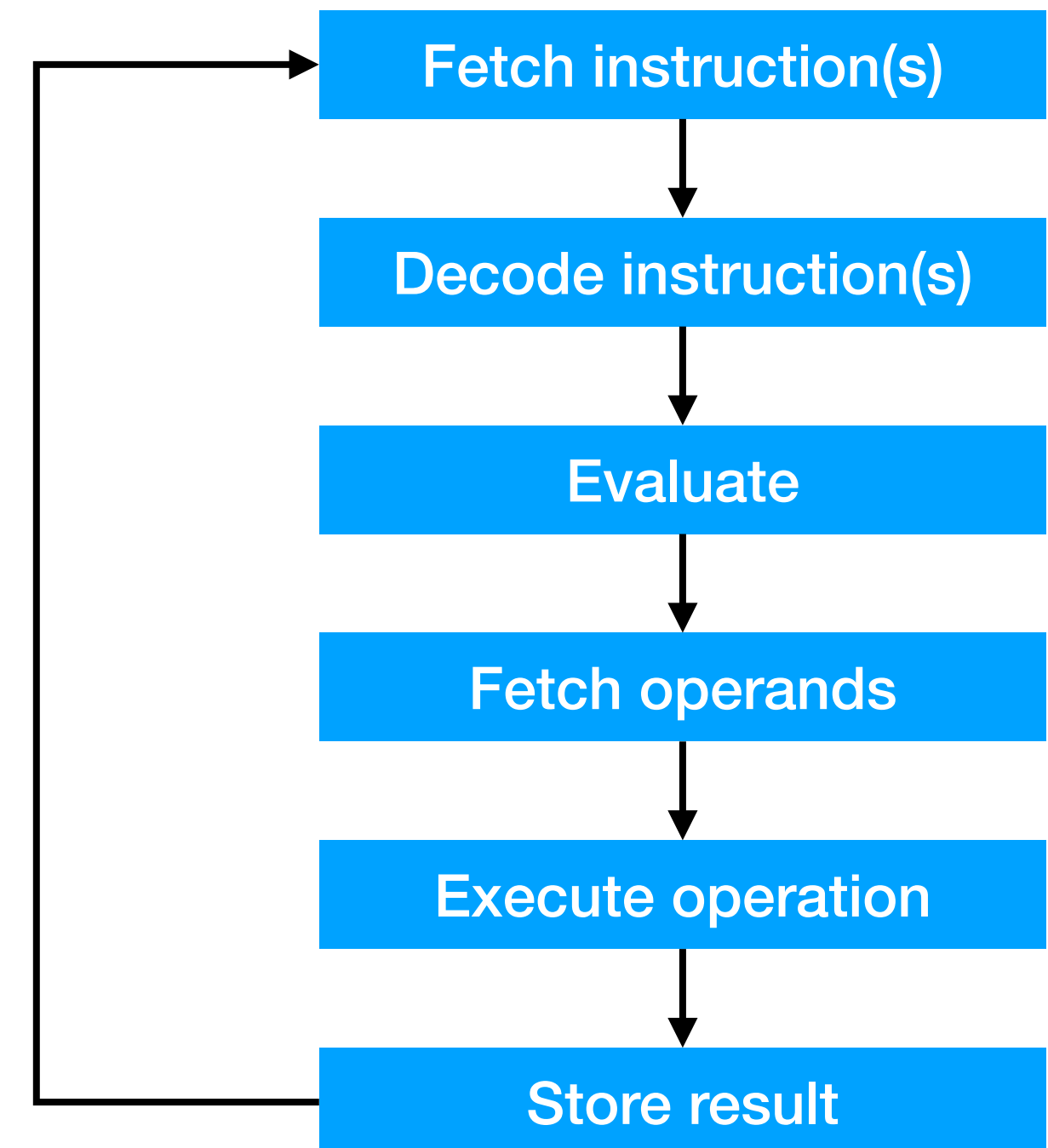
Generating an INTerrupt

- All devices asserting an interrupt signal are compared
- Highest PL request is compared to current program's PL
 - Interrupt is initiated.



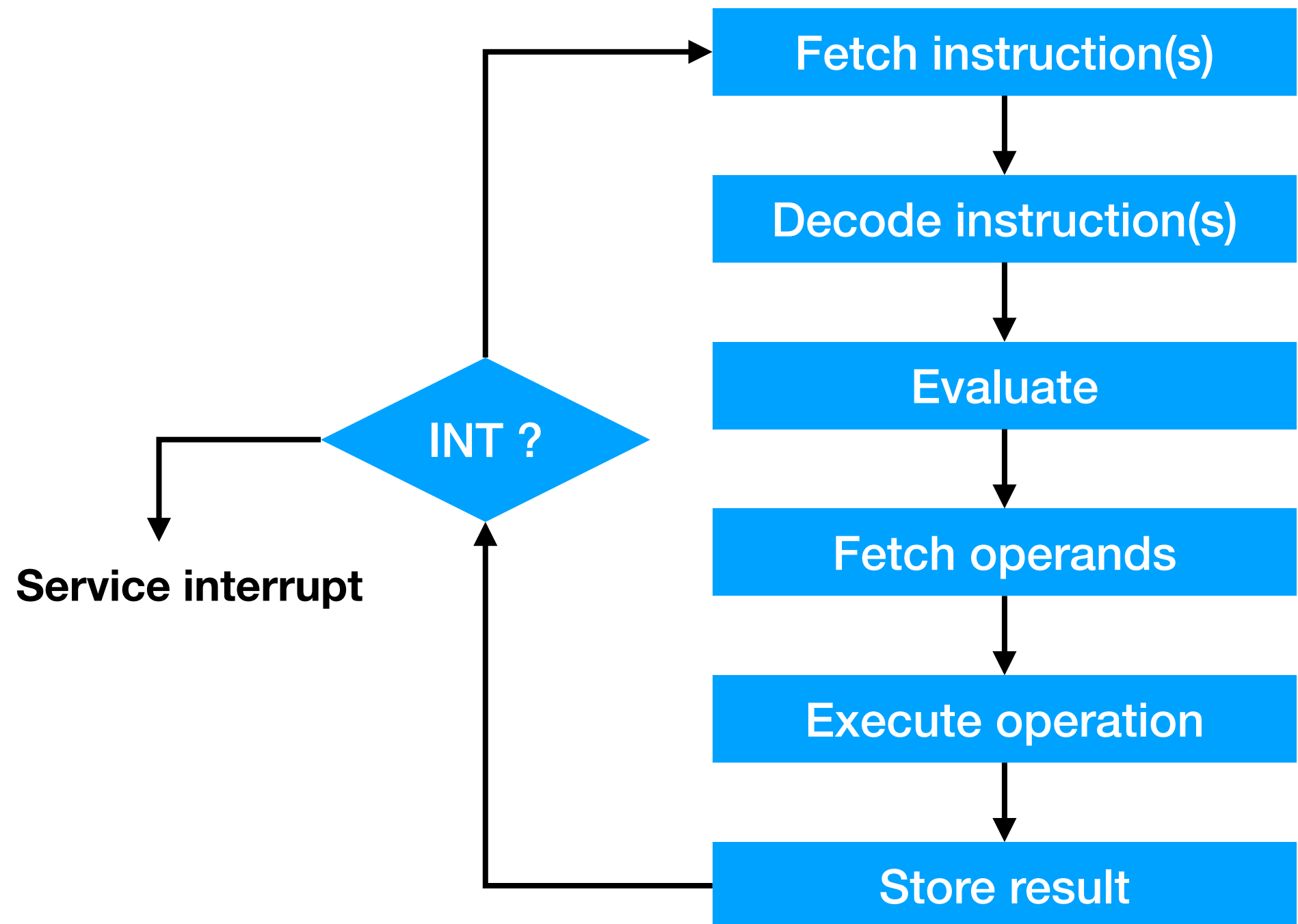
How processor detects INTerrupts

- Recall instruction cycle.
- Processor will check if INT is asserted at the end of each instruction cycle before starting a new FETCH



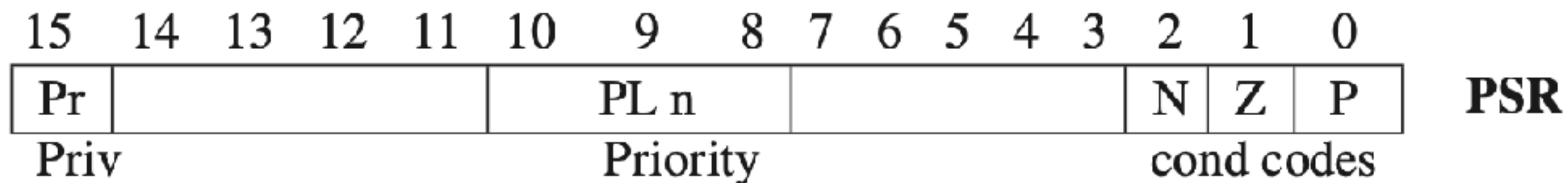
How processor detects INTerrupts

- Control unit needs to:
 - save state information to be able to resume interrupted program
 - load PC with the starting address of ISR (interrupt service routine)
 - resume old process on RTI (coming later)



Handling the INTerrupt

- What should be saved for program to resume?
 - PC (Program Counter)
 - Processor Status Register (PSR)
 - What about GPRs?
 - Callee saved



Privilege vs. priority

- Privilege
 - Privilege is all about the right to do something, such as execute a particular instruction or access a particular memory location.
- Priority
 - Priority is all about the urgency of a program to execute. Every program is assigned a priority, specifying its urgency as compared to all other programs.

User stack vs. supervisor stack

- Portion of privileged memory reserved for stack in supervisor mode (why?)
- R6 is used to denote active TOS always.
 - Can only run in user or supervisor mode at a time.
 - Save R6 on switching modes using (built-in) registers, Saved_SSP and Saved_USP

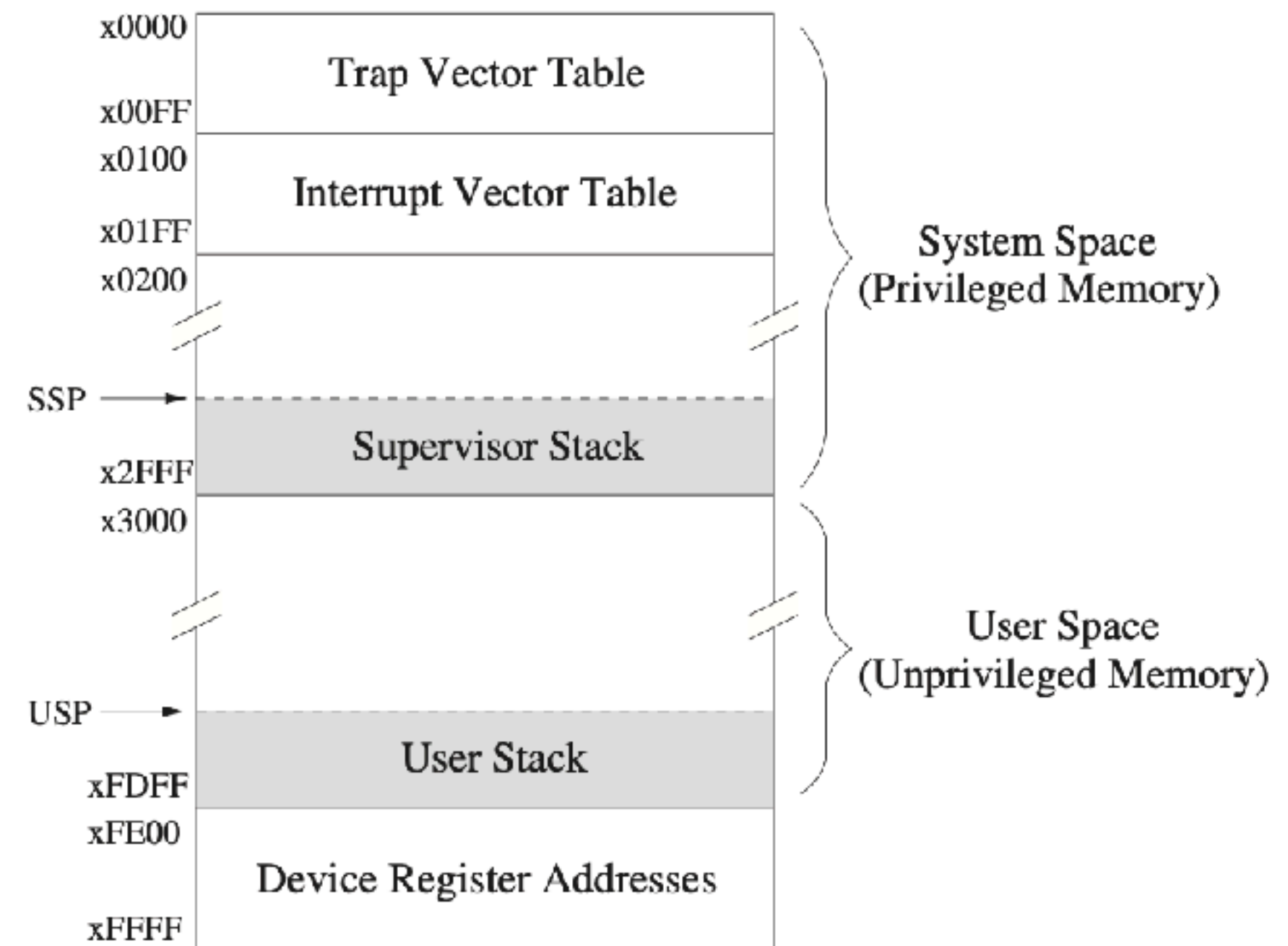


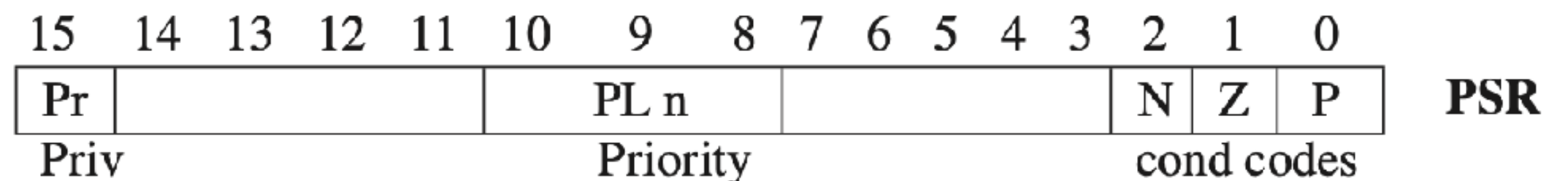
Figure A.1 - P&P 3rd Ed.

Handling the INTerrupt

- The I/O device generating the `INT` signal also provides an 8-bit *interrupt vector* `INTV` which identifies the device
- `INTV` will determine which `ISR` to be executed to service the interrupt
 - Similar to `TRAP` vector table we have seen previously

Summary of steps

1. Processor detects asserted **INT** along with **INTV**
2. Save **R6** to **Saved_USP**. Set **R6** to **Saved_SSP**.
3. Push **PSR** & **PC** to supervisor stack
4. Set **PSR[15]=0** and set **PSR[10:8]** = priority of ISR
 1. Set **PSR[2:0]=010** (arbitrarily sets condition codes) \longrightarrow 3rd Ed.
5. Load **MAR** with **x01vv**, where **vv**= 8-bit interrupt vector, then load **MDR**
6. Set **PC=MDR**



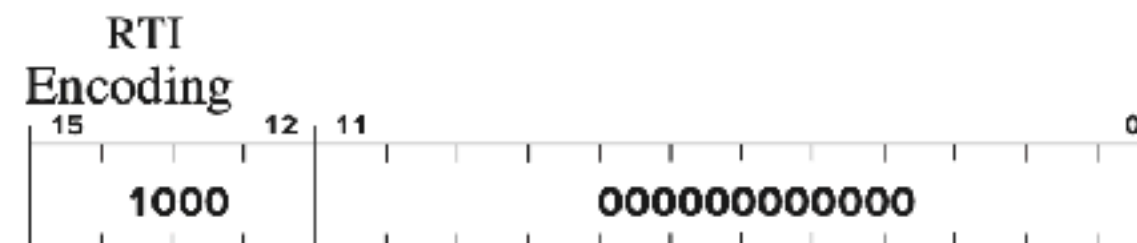
Returning from (TRAP or) INTerrupt: RTI

- Both **TRAP** routines and **INT**errupt routines end with the **RTI** instruction.
- Pop **PC** & **PSR** from supervisor stack
- If **PSR[15]=1**,
R6=Saved.USP
- **RTI** is *privileged*

RTI

Return from Trap or Interrupt

Assembler Format



Operation

```
if (PSR[15] == 1)
    Initiate a privilege mode exception;
else
    PC=mem[R6]; R6 is the SSP, PC is restored
    R6=R6+1;
    TEMP=mem[R6];
    R6=R6+1; system stack completes POP before saved PSR is restored
    PSR=TEMP; PSR is restored
    if (PSR[15] == 1)
        Saved_SSP=R6 and R6=Saved_USP;
```

Description

If the processor is running in User mode, a privilege mode exception occurs. If in Supervisor mode, the top two elements on the system stack are popped and loaded into PC, PSR. After PSR is restored, if the processor is running in User mode, the SSP is saved in Saved_SSP, and R6 is loaded with Saved_USP.

Example

RTI ; PC, PSR ← top two values popped off stack.

Interrupt example

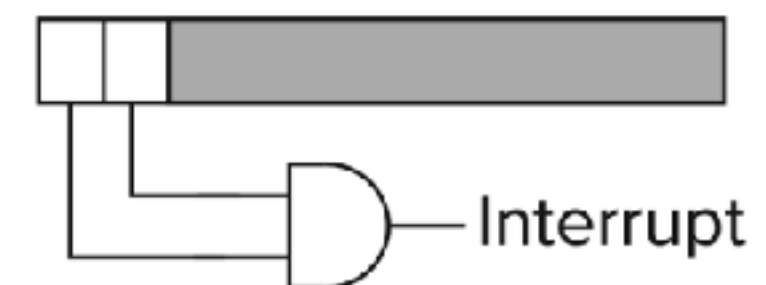
```

.ORG    x3000
LEA     R0, ISR_KB
STI     R0, KBINTV ; load ISR address to INTV
LD      R3, EN_IE
STI     R3, KBSR   ; set IE bit of KBSR
AGAIN  LD      R0, NUM2
        OUT
        BRnzp  AGAIN
ISR_KB ST      R0, SaveR0 ; callee-save R0
        LDI     R0, KBDR  ; read a char from KB and clear ready bit
        OUT
        LD      R0, SaveR0 ; callee-restore R0
        HALT

;
EN_IE   .FILL   x4000 ; To enable the IE bit
NUM2    .FILL   x0032 ; ASCII Code for '2'
KBSR    .FILL   xFE00
KBDR    .FILL   xFE02
KBINTV  .FILL   x0180 ; INT vector table address for keyboard
SaveR0  .BLKW   #1
.END

```

What does this program do?



Exceptions

- Exceptions happen when something ... well *unexpected* happens within the processor.
 - **Examples:** Privilege mode violation (PMV), illegal/invalid opcodes, accessing privileged memory (ACV)
 - Exception services routines occupy memory locations `x0100` to `x017F`, mechanism exactly like INTerrupts except ...
 - Priority level is **not changed**.

Next lecture(s)

- Examples
- Course review: <https://surveys.illinois.edu/sec/1742038613>
 - So far only C++ and recursion
- Exam preparation tips
- ICES forms