ECE 220

Lecture x0002 - 01/22
TRAPs & Subroutines

Slides based on material by: Yuting Chen, Yih-Chun Hu & Ujjal Bhowmik

Recap

- Wrote a program to display “ECE 220 is fun!” to the console. We used the pseudo-op `.STRINGZ` to store string to memory. Avoided using `TRAP` codes.

```
.ORIG x3000
; Load start address of string
LEA R2, MY_STRING

; Set up loop to load char into R0
CHRLOOP LDR R0, R2, #0

;Break if all done
BRz ALLDONE

;Loop to poll display until ready
DPOLL
     LDI R1, DSR
     BRzp DPOLL
;Store value in R0 to DDR
STI R0, DDR

;Move onto next char
ADD R2, R2, #1

BRnzp CHRLOOP

ALLDONE HALT

DSR .FILL xFE04
DDR .FILL xFE06

MY_STRING .STRINGZ "ECE 220 IS FUN"
.END
```

Recap from last time

- Consider “echo” routine:

```
KPOLL   LDI     R1, KBSR
        BRzp    KPOLL
        LDI     R0, KBDR
```

```
DPOLL   LDI     R1, DSR
        BRzp    DPOLL
        STI     R0, DDR
```

```
        BRnzp   NEXT_TASK
KBSR    .FILL   xFE00
KBDR    .FILL   xFE02
DSR     .FILL   xFE04
DDR     .FILL   xFE06
```

- Reading & writing from keyboard or display is common task
  - Inefficient to keep repeating this code
- Need to free up `R1` and `R0` for use whenever blocks run
  - Save/restore current values before/after these blocks run

Recap from last time

- Consider “echo” routine:

```
;SAVE R0, R1
KPOLL   LDI     R1, KBSR
        BRzp    KPOLL
        LDI     R0, KBDR
;RESTORE R0, R1
```

```
;SAVE R0, R1
DPOLL   LDI     R1, DSR
        BRzp    DPOLL
        STI     R0, DDR
;RESTORE R0, R1
```

```
        BRnzp   NEXT_TASK
KBSR    .FILL   xFE00
KBDR    .FILL   xFE02
DSR     .FILL   xFE04
DDR     .FILL   xFE06
```

- Reading & writing from keyboard or display is common task
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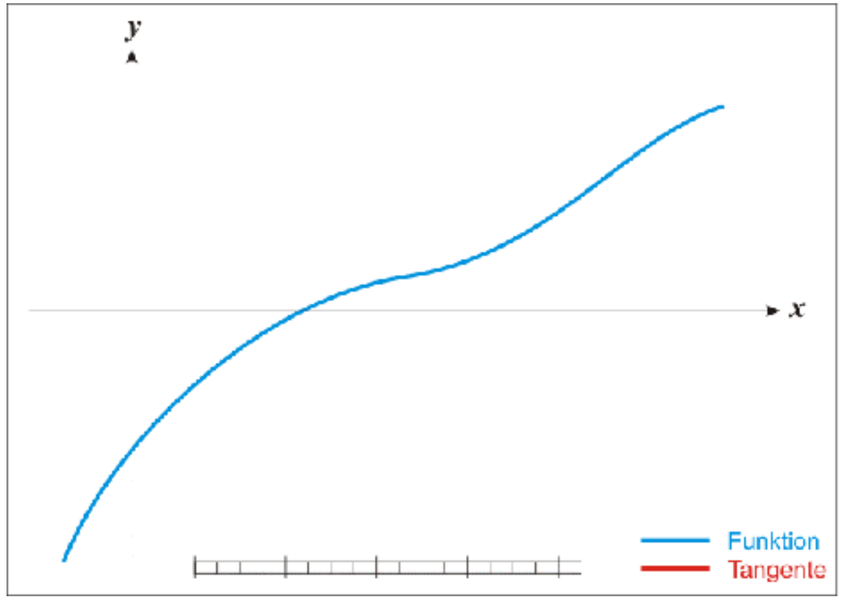
Repeating code

- Consider $f(x) = x^4 + 4x^3 + 3x^2 + 2x + 1$
- Evaluate $f(2)$
  - How many multiplications?



- Suppose we wish to evaluate $f(x)$ for many values of x
  - Why? E.g. Newton-Raphson method for finding roots of $f(x)$

Aside: NR method

Suppose $f(x)$ such that $x, f(x) \in \mathbb{R}$ and $f'(x)$ is well defined. Let x_0 be an initial guess for some root $\bar{x}$ of $f(x)$. Then the iterates x_n

More multiplications!

$$x_1 = x_0 - \frac{f(x)}{f'(x_0)} \text{ and } x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}$$

successively improve on the guess x_0 as an approximation to $\bar{x}$ (roughly doubling the number of correct digits at each step).

Lesson objectives

- Understand and articulate need for subroutines (or functions)
- Understand callee-save and caller-save notions for saving registers
- Be able to write subroutines in LC3 assembly
- Understand return-linkage mechanism
- Understand difference between user-written subroutines and TRAPs

Subroutines

- Subroutines are blocks/pieces of code that do something specific. Examples:
  - Multiply two numbers
  - Sort a list of integers
  - Read keyboard press into a register
- Often called functions, methods, procedures, service calls, etc.
  - Different from *functions* in mathematics or functional programming languages!

Functions vs. subroutines

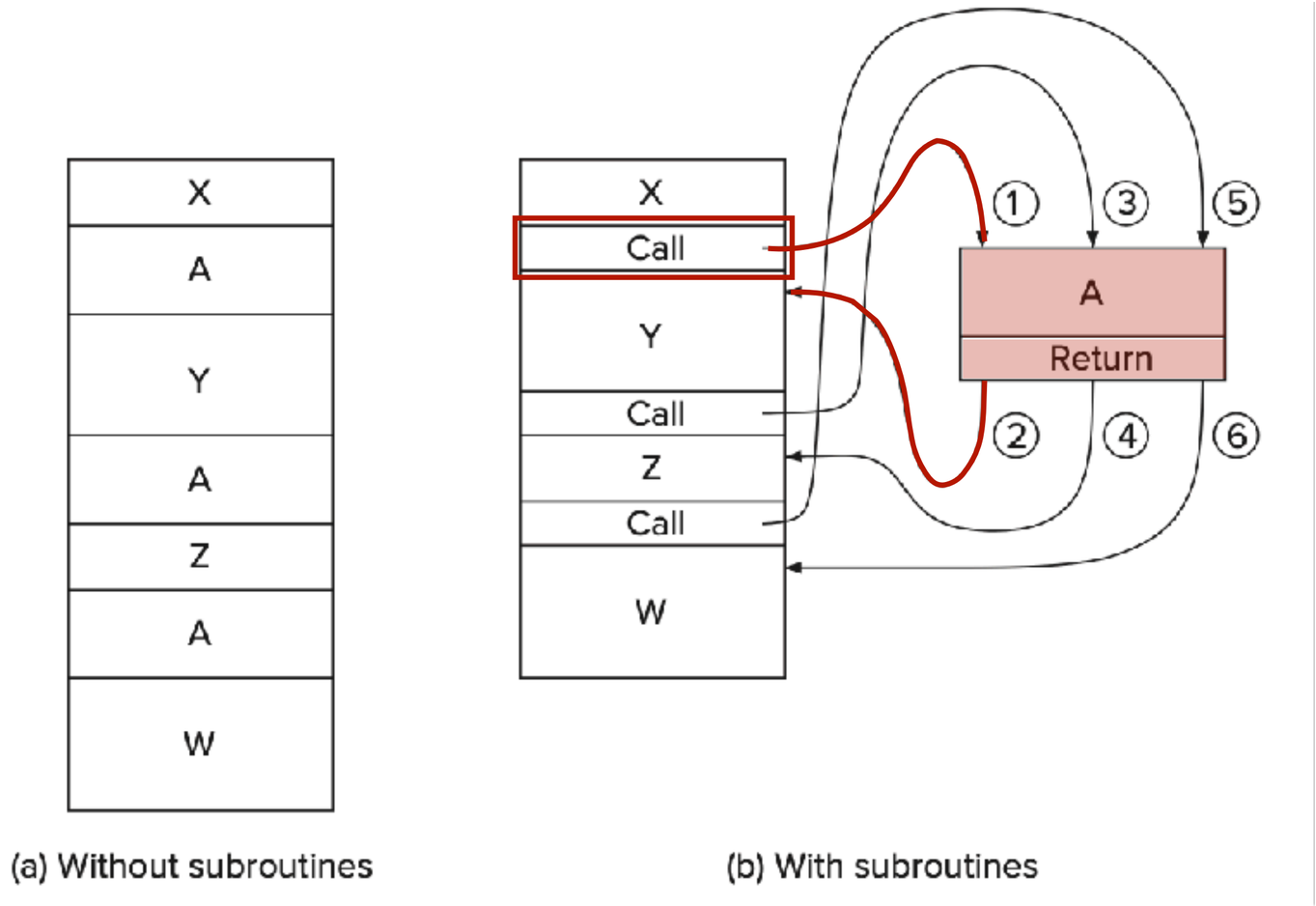
- In mathematics, a function $f(x)$ takes a value from a *set* and returns a value in a(nother) *set.* If you call f with some particular value x_0 then it *always* returns $f(x_0)$.

- In CS/programming, a function `foo` is a piece of code that can be called, *perhaps* with inputs, and does *some* stuff and *maybe* returns something.

  - In *functional* languages (in theory at least), you can replace a function call with its return value and nothing *should* break.

Subroutines

- User invokes or calls subroutine
- Subroutine code performs operation / task
- Returns control to user program with no other unexpected changes



(a) Without subroutines

(b) With subroutines

Figure 8.2 - P&P 3rd Ed.

Subroutines in LC3

- Recall instructions that change program flow

- Subroutines make use of the `JSR(R)` and `RET` commands.

- What is/are the difference(s) between `BR/JMP` and `JSR/JSRR`?

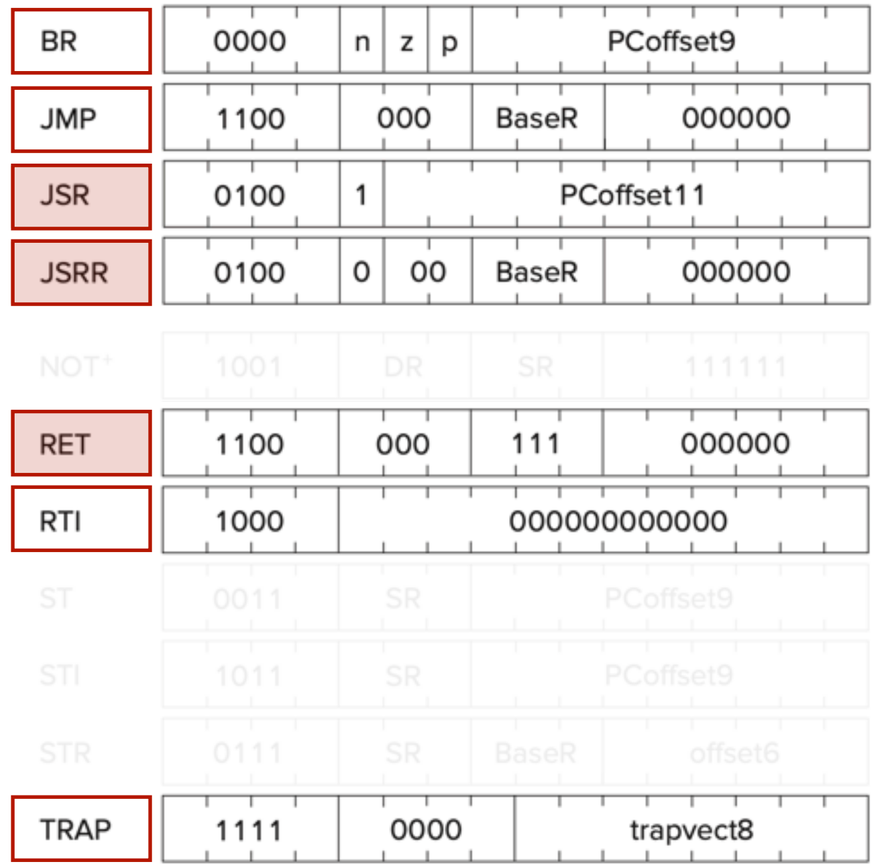
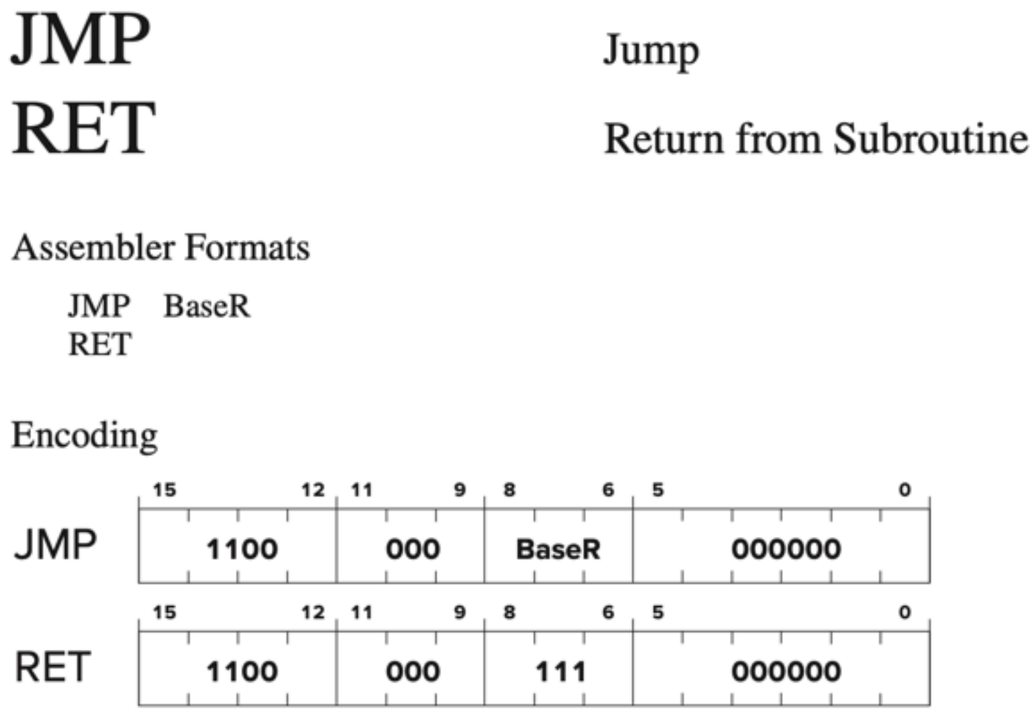


Figure “A.2” - P&P 3rd Ed.

RET & JMP

- `JMP` & `RET` are relatives; op-code is the same
  - `JMP: PC ← BaseR`
  - `RET: PC ← R7`



JMP — Jump

RET — Return from Subroutine

Assembler Formats

JMP BaseR

RET

Encoding

JSR & JSRR

- When `JSR(R)` is encountered **`R7`** is loaded with `PC`+ and then `PC` is set in one of two ways:

- `JSR` and `JSRR` differ in addressing modes (signified by bit #11).
  - `PC ← PC + SEXT(PCoffset11)`
  - `PC ← BaseR`

- After subroutine ends, `RET` is used to return to caller

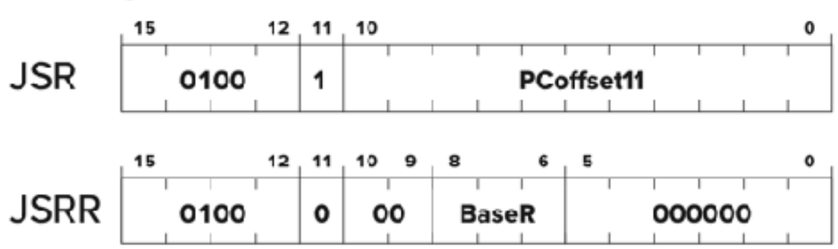
JSR
JSRR

Jump to Subroutine

Assembler Formats

```
JSR    LABEL
JSRR   BaseR
```

Encoding



Appendix A, P&P 3rd Ed.

+ Recall PC is incremented after FETCH.

Using subroutines

Saving & restoring registers

- To use a subroutine the user must know:
  - It's address (or label)
  - It's *arguments* (where to pass in data, if any)
  - It's *return values* (where to *put* computed data, if any)
  - What it does 🙄
    - Maybe not all the gory details but definitely registers it may use or overwrite!

Using subroutines

Saving & restoring registers

Generally we have two strategies depending on **who** saves/restores registers:

- **Caller-saved:** Onus on user to save/restore registers that will be needed later; may not know what registers subroutine will use
  - User saves/restore registers they will need (or know could get destroyed)

- **Callee-saved:** Subroutine knows registers it will alter/use, but cannot know what the user will need later
  - Subroutine saves/restores registers it will use

Using subroutines

Saving & restoring registers

Good practices:

- Keep `R7` unused, especially for *nested* subroutines
- Use callee-save, except for return values (should be caller saved)
- Restore incoming *arguments* to their original values unless intended to be overwritten by return value

Example

Multiplication

Try to complete `MULTIPLY` subroutine by filling in the missing piece.

Driver code is on Github. This snippet doesn't show `.ORIG`, `.END` or label definitions!

```
; LC3 subroutine to multiply two numbers
; Inputs: R0 (multiplicand), R1 (multiplier)
; Output:  R2 (result)

MULTIPLY:
    ST R0, MulSaveR0          ; Callee save registers
    ST R1, MulSaveR1
    AND R2, R2, #0            ; Clear R2 to be used as result
    ADD R2, R0, #0            ; Load multiplicand into R2
    ADD R1, R1, #-1           ; Use R1 as counter

MUL_LOOP:
    _

MUL_DONE:
    LD R0, MulSaveR0          ; Restore registers
    LD R1, MulSaveR1
    RET                       ; Return from the subroutine
```

Exercise

Exponentiation

Use the `MULTIPLY` subroutine in the previous slide to write an LC3 subroutine that performs exponentiation.

```
; LC3 subroutine to multiply two numbers
; Inputs: R0 (multiplicand), R1 (multiplier)
; Output:  R2 (result)

MULTIPLY:
```

```
; LC3 subroutine to that performs exponentiation
; Inputs: R0 (base), R1 (exponent)
; Loop counter: R2
; Output: R2 (result)
; POW knows it should call MULTIPLY and it knows
; MULTIPLY overwrites the value in R2

POW:



POW_LOOP:
    BRz POW_DONE          ; If R2==0, loop complete
    ST R2, PowSaveR2      ; Caller save
    JSR MULTIPLY          ; Result in R2
    ADD R1, R2, #0        ; Copy result for next multiply
    LD R2, PowSaveR2      ; Caller restore
    ADD R2, R2, #-1       ; Decrement counter
    BR POW_LOOP

POW_DONE:
```

Exercise

Exponentiation

Use the `MULTIPLY` subroutine in the previous slide to write an LC3 subroutine that performs exponentiation.

Will this program halt? Why? Why not?

```
; LC3 subroutine to that performs exponentiation
; Inputs: R0 (base), R1 (exponent)
; Loop counter: R2
; Output: R2 (result)
; POW knows it should call MULTIPLY and it knows
; MULTIPLY overwrites the value in R2

POW:
    ST R0, PowSaveR0     ; Callee save registers
    ST R1, PowSaveR1
    ADD R2, R1, #-1      ; Initialize counter
                         ; Why can't we use R1 as counter?
    ADD R1, R0, #0       ; Set up to call MULTIPLY

POW_LOOP:
    BRz POW_DONE         ; If R2==0, loop complete
    ST R2, PowSaveR2     ; Caller save
    JSR MULTIPLY         ; Result in R2
    ADD R1, R2, #0       ; Copy result for JSR to multiply
    LD R2, PowSaveR2     ; Caller restore
    ADD R2, R2, #-1      ; Decrement counter
    BR POW_LOOP

POW_DONE:
    ADD R2, R1, #0       ; Move result to R2
    LD R0, PowSaveR0     ; Callee restore
    LD R1, PowSaveR1
    RET
```

User routine vs. service routine

- Consider keyboard input:
  - It's used often and has too many specific details for most programmers
  - Improper usage could breach security of the system or mess up keyboard usage for other users/programs
- Solution: make this part of the OS
  - User program → invokes service routine (a.k.a OS call) → OS performs operation → returns control to user program

TRAP mechanism

System calls in LC3 are achieved using the `TRAP` mechanism

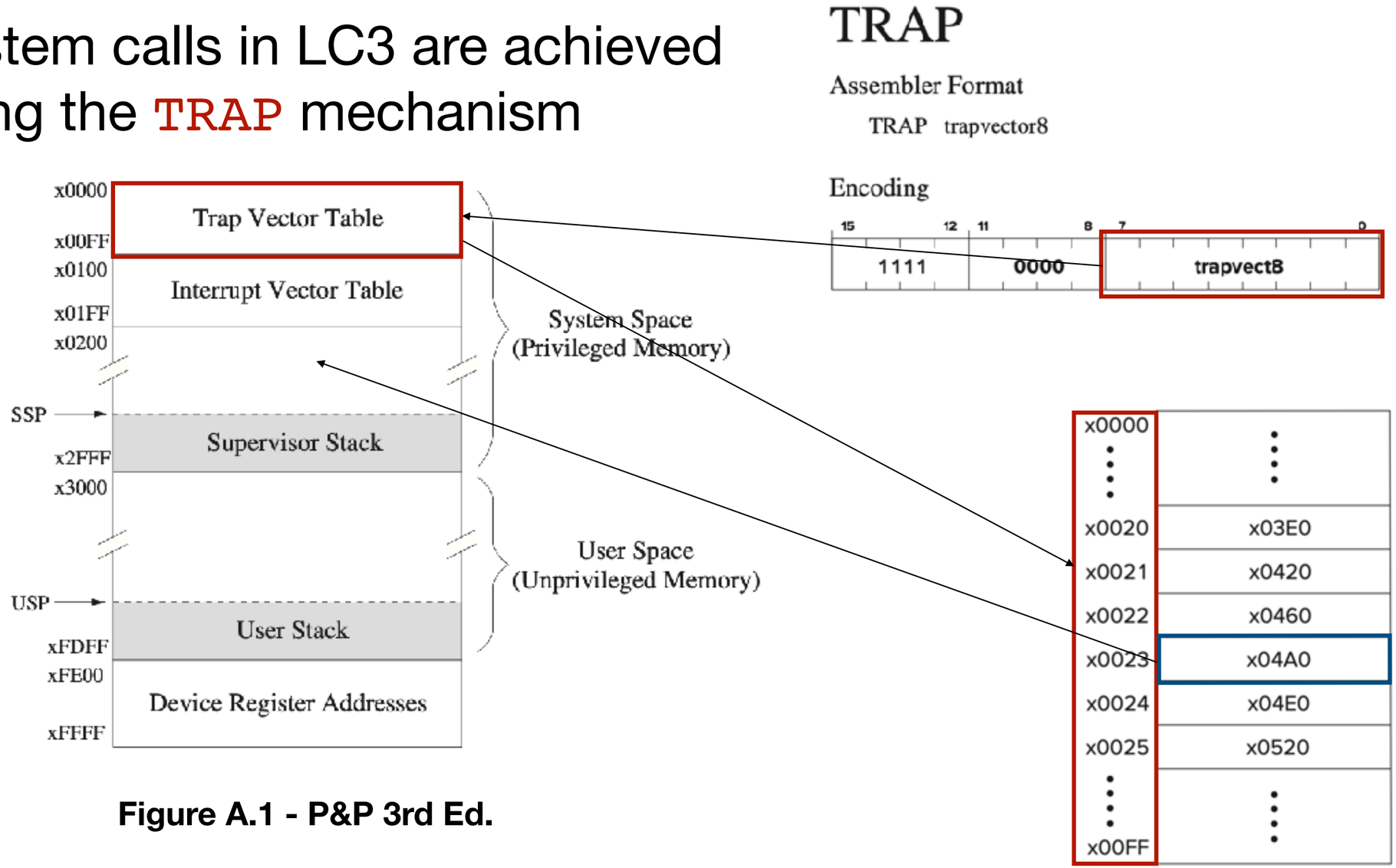


Figure A.1 - P&P 3rd Ed.

TRAP mechanism

Table A.3 of P&P 3rd Ed.

Vector	Symbol	Routine
x20	GETC	Read a single character (no echo)
x21	OUT	Output character to monitor
x22	PUTS	Write a string to monitor
x23	IN	Print prompt to monitor, read and echo character from keyboard
x24	PUTSP	Write a string to monitor, two characters per memory location
x25	HALT	Halt program
x26		Write a number to monitor (undocumented)

Exercise at home: Try using each of these!

TRAP: Flow Control

- Slight difference between editions of the textbook

- **Edition 2**: Last statement in `TRAP` is `JMP R7` (i.e. `RET`)

- **Edition 3**: Last statement is `RTI`

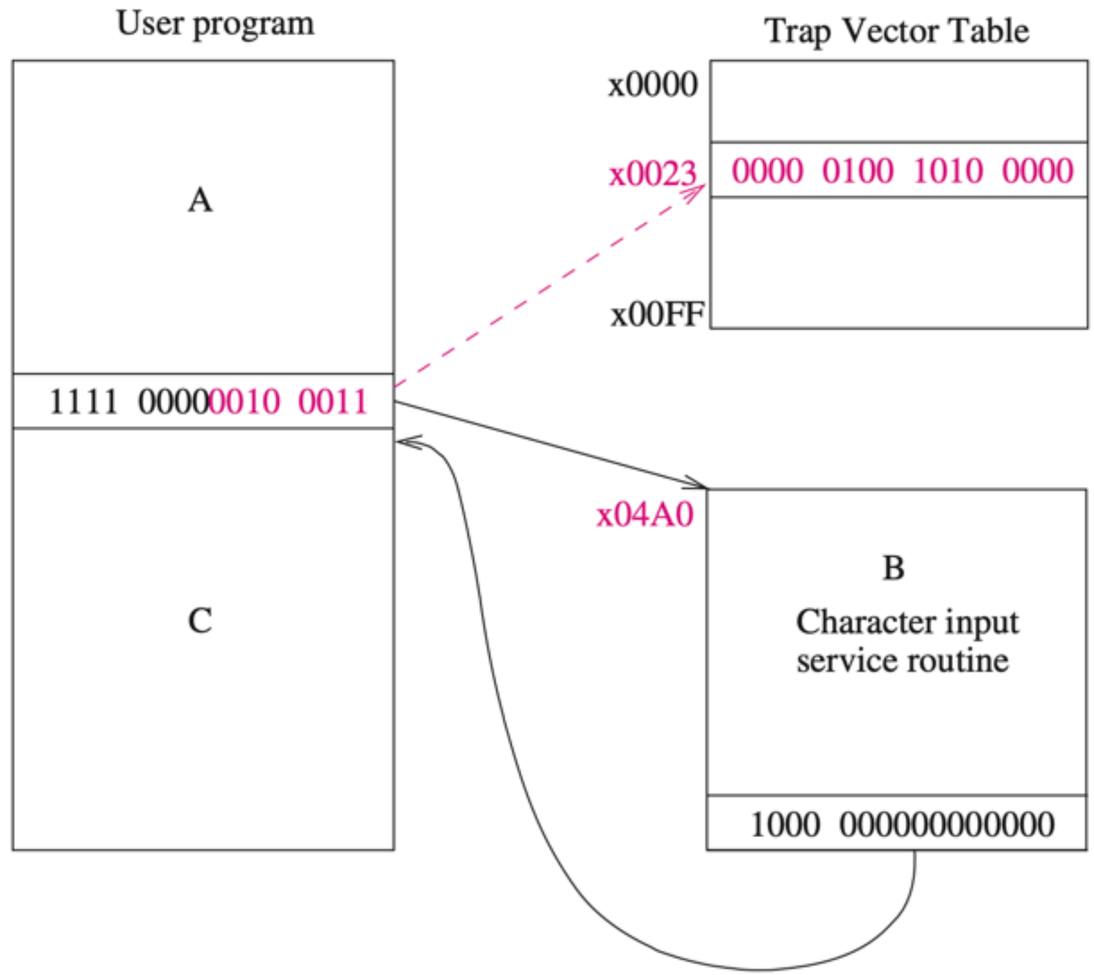
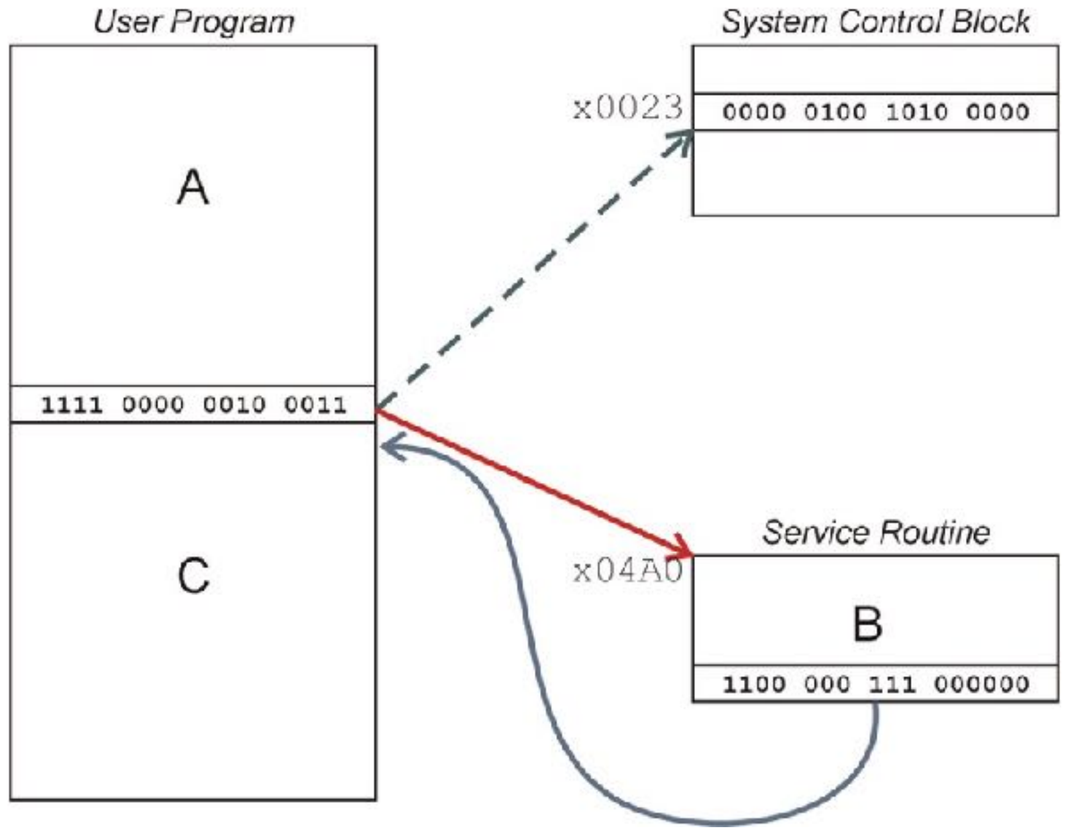


Figure 9.11 In P&P 3rd Ed.

TRAP Mechanism: 2nd Ed.

- `MAR ← ZEXT(trapvect8)`
- `MDR ← MEM[MAR]`
- `R7 ← PC`
- `PC ← MDR`
- `....`
- `JMP R7`



TRAP example

- What are the values in `R0` and `R7` right before `IN`?
- How about right before `HALT`?

```
.ORIG x3000


AND R0, R0, #0          ;init R0
ADD R0, R0, #3          ;set R0 to 3
ADD R7, R0, #4          ;set R7 to 7
ADD R0, R0, #1          ;increment R0
ADD R7, R7, #1          ;increment R7

IN                      ;same as ‘TRAP x23’

ADD R0, R0, #1          ;increment R0
ADD R7, R7, #0          ;increment R7

HALT
.END
```

RTI: Return from TRAP/Interrupt

- 2nd edition: LC3 will overwrite `R7`
- 3rd edition: `R7` will be left unchanged.
  - Mechanism? **Uses *stacks* → next lecture.**

Which one does EWS use?

BR	0000	n	z	p	PCoffset9	
JMP	1100	000		BaseR	000000	
JSR	0100	1	PCoffset11			
JSRR	0100	0	00	BaseR	000000	
NOT*	1001	DR		SR	111111	
RET	1100	000		111	000000	
RTI	1000	000000000000				
ST	0011	SR	PCoffset9			
STI	1011	SR	PCoffset9			
STR	0111	SR	BaseR	offset6		
TRAP	1111	0000	trapvect8			

Figure "A.2" - P&P 3rd Ed.

TRAP vs. subroutines

- Service routines (`TRAP`) provide 3 main functions
  - Shield programmers from system-specific details (`KBDR`, `KBSR`, etc.)
  - Write frequently-used code just once
  - Protect system recourses from malicious/clumsy programmers
- Subroutines provide the same functions for non-system (user) code
  - Lives in user space
  - Performs a well-defined task
  - Is invoked (called) by another user program
  - Returns control to the calling program when finished