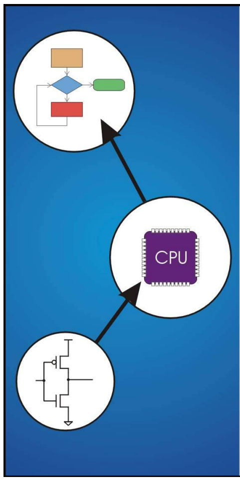


Chapter 9
TRAP Routines and Subroutines

Original slides from Gregory Byrd, North Carolina State University

Modified slides by Chris Wilcox, Colorado State University

System Calls

- Certain operations require **specialized knowledge** and **protection**:
  - specific knowledge of I/O device registers and the sequence of operations needed to use them
  - I/O resources shared among multiple users/programs; a mistake could affect lots of other users!
- Not every programmer knows (or wants to know) this level of detail
- Solution: provide ***service routines*** or ***system calls*** (in operating system) to safely and conveniently perform low-level, privileged operations

System Call

- 1. User program invokes system call.
- 2. Operating system code performs operation.
- 3. Returns control to user program.

In LC-3, this is done through the *TRAP mechanism*.

LC-3 TRAP Mechanism

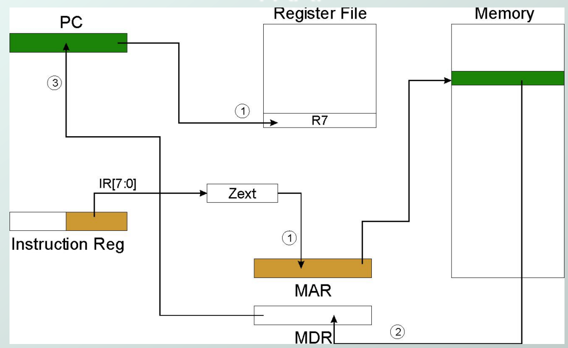
- *1. A set of service routines.*
  - part of operating system -- routines start at arbitrary addresses **(convention is that system code is below x3000)**
  - up to 256 routines
- *2. Table of starting addresses.*
  - stored at **x0000** through **x00FF** in memory
  - called **System Control Block** in some architectures
- *3. TRAP instruction.*
  - used by program to transfer control to operating system
  - 8-bit trap vector names one of the 256 service routines
- *4. A linkage back to the user program.*
  - want execution to resume immediately after the TRAP instruction

TRAP Instruction

	15	14	13	12	11	10	9	8	7–0
TRAP	1	1	1	1	0	0	0	0	trapvect8

- Trap vector
  - identifies which system call to invoke
  - 8-bit index into table of service routine addresses
    - in LC-3, this table is stored in memory at 0x0000 – 0x00FF
    - 8-bit trap vector is zero-extended into 16-bit memory address
- Where to go
  - lookup starting address from table; place in PC
- How to get back
  - save address of next instruction (current PC) in R7

TRAP

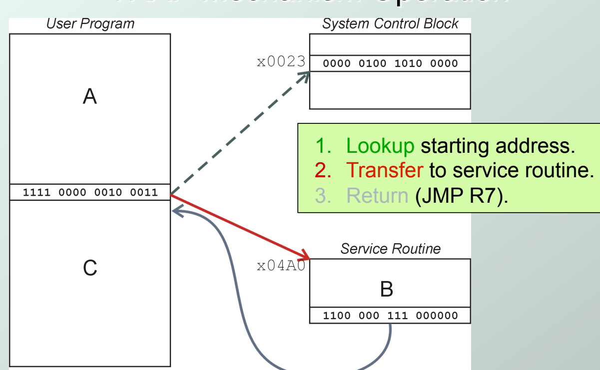


NOTE: PC has already been incremented during instruction fetch stage.

RET (JMP R7)

- How do we transfer control back to instruction following the TRAP?
- We saved old PC in R7.
  - JMP R7 gets us back to the user program at the right spot.
  - LC-3 assembly language lets us use RET (return) in place of "JMP R7".
- Must make sure that service routine does not change R7, or we won't know where to return.

TRAP Mechanism Operation



Example: Using the TRAP Instruction

```
        .ORIG x3000
        LD   R2, TERM      ; Load negative ASCII '7'
        LD   R3, ASCII     ; Load ASCII difference
AGAIN   TRAP x23           ; input character
        ADD R1, R2, R0     ; Test for terminate
        BRz EXIT           ; Exit if done
        ADD R0, R0, R3     ; Change to lowercase
        TRAP x21           ; Output to monitor...
        BRnzp  AGAIN       ; ... again and again...
TERM    .FILL xFFC9        ; -'7'
ASCII   .FILL x0020        ; lowercase bit
EXIT    TRAP x25           ; halt
        .END
```


Example: Output Service Routine

```
   .ORIG x0430                 ; syscall address
          ST R7, SaveR7        ; save R7 & R1
          ST R1, SaveR1
; ----- Write character
TryWrite  LDI  R1, CRTSR       ; get status
          BRzp TryWrite        ; look for bit 15 on
WriteIt   STI  R0, CRTDR       ; write char
; ----- Return from TRAP
Return    LD   R1, SaveR1      ; restore R1 & R7
          LD   R7, SaveR7
          RET                  ; back to user
CRTSR     .FILL xF3FC
CRTDR     .FILL xF3FF
SaveR1    .FILL 0
SaveR7    .FILL 0
          .END
```

stored in table, location x21

TRAP Routines and their Assembler Names

vector	symbol	routine
x20	GETC	read a single character (no echo)
x21	OUT	output a character to the monitor
x22	PUTS	write a string to the console
x23	IN	print prompt to console, read and echo character from keyboard
x25	HALT	halt the program

Saving and Restoring Registers

- Must save the value of a register if:
  - Its value will be destroyed by service routine

  and
  - We will need to use the value after that action.
- Who saves?
  - caller of service routine?
    - knows what it needs later, but may not know what gets altered by called routine
  - called service routine?
    - knows what it alters, but does not know what will be needed later by calling routine

Example

```
       LEA R3, Binary    ; load pointer
       LD  R6, ASCII     ; char to digit
       LD  R7, COUNT     ; initialize to 10
AGAIN  TRAP x23          ; get character
       ADD R0, R0, R6    ; convert to number
       STR R0, R3, #0    ; store number
       ADD R3, R3, #1    ; increment pointer
       ADD R7, R7, -1    ; decrement counter
       BRp AGAIN         ; more?
       BRnzp NEXT
ASCII  .FILL xFFD0
COUNT  .FILL #10
Binary .BLKW #10
```

What's wrong with this routine?
What happens to R7?

Saving and Restoring Registers

- Called routine -- ***"callee-save"***
  - Before start, save any registers that will be altered (unless altered value is desired by calling program!)
  - Before return, restore those same registers
- Calling routine -- ***"caller-save"***
  - Save registers destroyed by own instructions or by called routines (if known), if values needed later
    - save R7 before TRAP
    - save R0 before TRAP x23 (input character)
  - Or avoid using those registers altogether
- ***Values are saved by storing them in memory.***

Question

- Can a service routine call another service routine?
- If so, is there anything special the calling service routine must do?

What about User Code?

- Service routines provide three main functions:
  1. Shield programmers from system-specific details.
  2. Write frequently-used code just once.
  3. Protect system resources from malicious/clumsy programmers.
- Are there any reasons to provide the same functions for non-system (user) code?

Subroutines

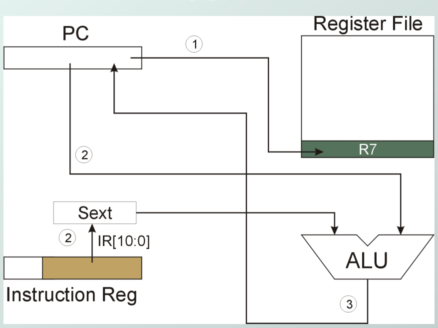
- A **subroutine** is a program fragment that:
  - lives in user space
  - performs a well-defined task
  - is invoked (called) by another user program
  - returns control to the calling program when finished
- Like a service routine, but not part of the OS
  - not concerned with protecting hardware resources
  - no special privilege required
- Reasons for subroutines:
  - reuse useful (and debugged!) code without having to keep typing it in
  - divide task among multiple programmers
  - use vendor-supplied ***library*** of useful routines

JSR Instruction

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
JSR	0	1	0	0	1	PCoffset11										

- Jumps to a location (like a branch but unconditional), and saves current PC (addr of next instruction) in R7.
  - saving the return address is called "linking"
  - target address is PC-relative **(PC + Sext(IR[10:0]))**
  - bit 11 specifies addressing mode
    - if =1, PC-relative: target address = PC + Sext(IR[10:0])
    - if =0, register: target address = contents of register IR[8:6]

JSR



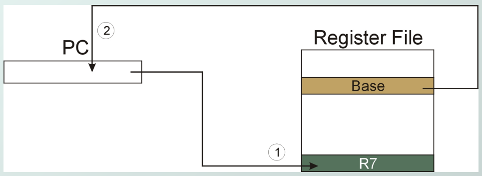
NOTE: PC has already been incremented during instruction fetch stage.

JSRR Instruction

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
JSRR	0	1	0	0	0	0	0	Base			0	0	0	0	0	0

- Just like JSR, except Register addressing mode.
  - target address is Base Register
  - bit 11 specifies addressing mode
- What important feature does JSRR provide that JSR does not?

JSRR



NOTE: PC has already been incremented during instruction fetch stage.

Returning from a Subroutine

- RET (JMP R7) gets us back to the calling routine.
  - just like TRAP

Example: Negate the value in R0

```
2sComp   NOT  R0, R0      ; flip bits
         ADD  R0, R0, #1  ; add one
         RET              ; return to caller
```

To call from a program (within 1024 instructions):

```
; need to compute R4 = R1 - R3
         ADD  R0, R3, #0  ; copy R3 to R0
         JSR  2sComp      ; negate
         ADD  R4, R1, R0  ; add to R1
         ...
```

Note: Caller should save R0 if we'll need it later!

Passing Information to/from Subroutines

- Arguments
  - A value passed in to a subroutine is an argument.
  - This is a value needed by the subroutine to do its job.
  - Examples:
    - In 2sComp routine, R0 is the number to be negated
    - In OUT service routine, R0 is the character to be printed.
    - In PUTS routine, R0 is *address* of string to be printed.
- Return Values
  - A value passed out of a subroutine is a return value.
  - You called the subroutine to compute this value!
  - Examples:
    - In 2sComp routine, negated value is returned in R0.
    - GETC service routine returns char from the keyboard in R0.

Using Subroutines

- In order to use a subroutine, a programmer must know:
  - its address (or at least a label that will be bound to its address)
  - its function (what does it do?)
    - NOTE: The programmer does not need to know *how* the subroutine works, but what changes are visible in the machine's state after the routine has run.
  - its arguments (where to pass data in, if any)
  - its return values (where to get computed data, if any)

Saving and Restore Registers

- Since subroutines are just like service routines, we also need to save and restore registers, if needed.
- Generally use "callee-save" strategy, except for return values.
  - Save anything that the subroutine will alter internally that shouldn't be visible when the subroutine returns.
  - It's good practice to restore incoming arguments to their original values (unless overwritten by return value).
- *Remember*: You MUST save R7 if you call any other subroutine or service routine (TRAP).
  - Otherwise, you won't be able to return to caller.

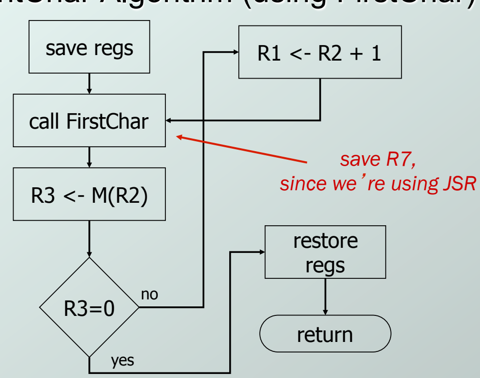
Example

(1) Write a subroutine FirstChar to:
find the first occurrence
of a particular character (in R0)
in a string (pointed to by R1);
return pointer to character or to end of string (NULL) in R2.

(2) Use FirstChar to write CountChar, which:
counts the number of occurrences
of a particular character (in R0)
in a string (pointed to by R1);
return count in R2.

- Can write the second subroutine first, without knowing the implementation of FirstChar!

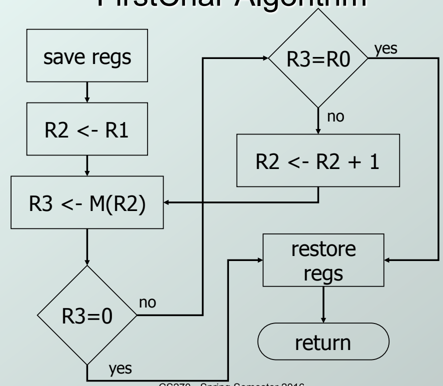
CountChar Algorithm (using FirstChar)



CountChar Implementation

```
; subroutine to count occurrences of a char
CountChar
      ST     R3, CCR3    ; save registers
      ST     R4, CCR4
      ST     R7, CCR7    ; JSR alters R7
      ST     R1, CCR1    ; save original pointer
      AND    R4, R4, #0  ; count = 0
CC1   JSR    FirstChar   ; find next occurrence
      LDR    R3, R2, #0  ; null?
      BRz    CC2         ; done if null
      ADD    R4, R4, #1  ; increment count
      ADD    R1, R2, #1  ; increment pointer
      BRnzp       CC1
CC2   ADD    R2, R4, #0  ; return value to R2
      LD     R3, CCR3    ; restore regs
      LD     R4, CCR4
      LD     R1, CCR1
      LD     R7, CCR7
      RET
```


FirstChar Algorithm



FirstChar Implementation

```
; subroutine to find first occurrence of a char
FirstChar
      ST     R3, FCR3    ; save registers
      ST     R4, FCR4    ; save original char
      NOT    R4, R0      ; negate for comparisons
      ADD    R4, R4, #1
      ADD    R2, R1, #0  ; initialize pointer
FC1   LDR    R3, R2, #0  ; read character
      BRz    FC2         ; if null, we're done
      ADD    R3, R3, R4  ; see if matches input
      BRz    FC2         ; if yes, we're done
      ADD    R2, R2, #1  ; increment pointer
      BRnzp  FC1
FC2   LD     R3, FCR3    ; restore registers
      LD     R4, FCR4
      RET
```


Library Routines

- Vendor may provide object files containing useful subroutines
  - don't want to provide source code -- intellectual property
  - assembler/linker must support EXTERNAL symbols (or starting address of routine must be supplied to user)

```
      .EXTERNAL SQRT
...
      LD    R2, SQAddr   ; load SQRT addr
      JSRR  R2
...
SQAddr .FILL    SQRT
```

- Using JSRR, because we don't know whether SQRT is within 1024 instructions.