TRAPs and Subroutines

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
- Provide *service routines* or *system calls* (part of 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.

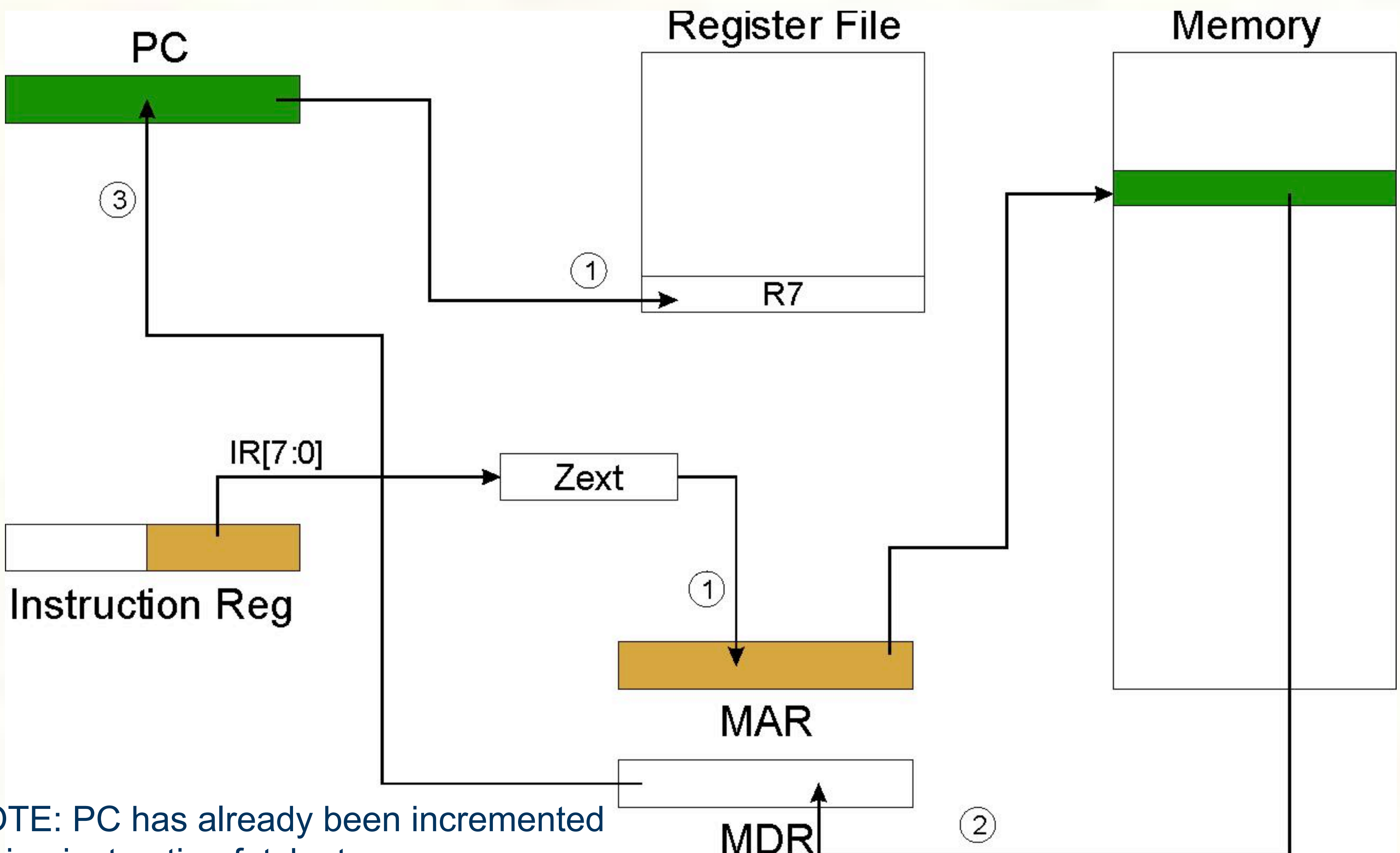
- want execution to resume
  immediately after the TRAP instruction

TRAP Instruction

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	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.

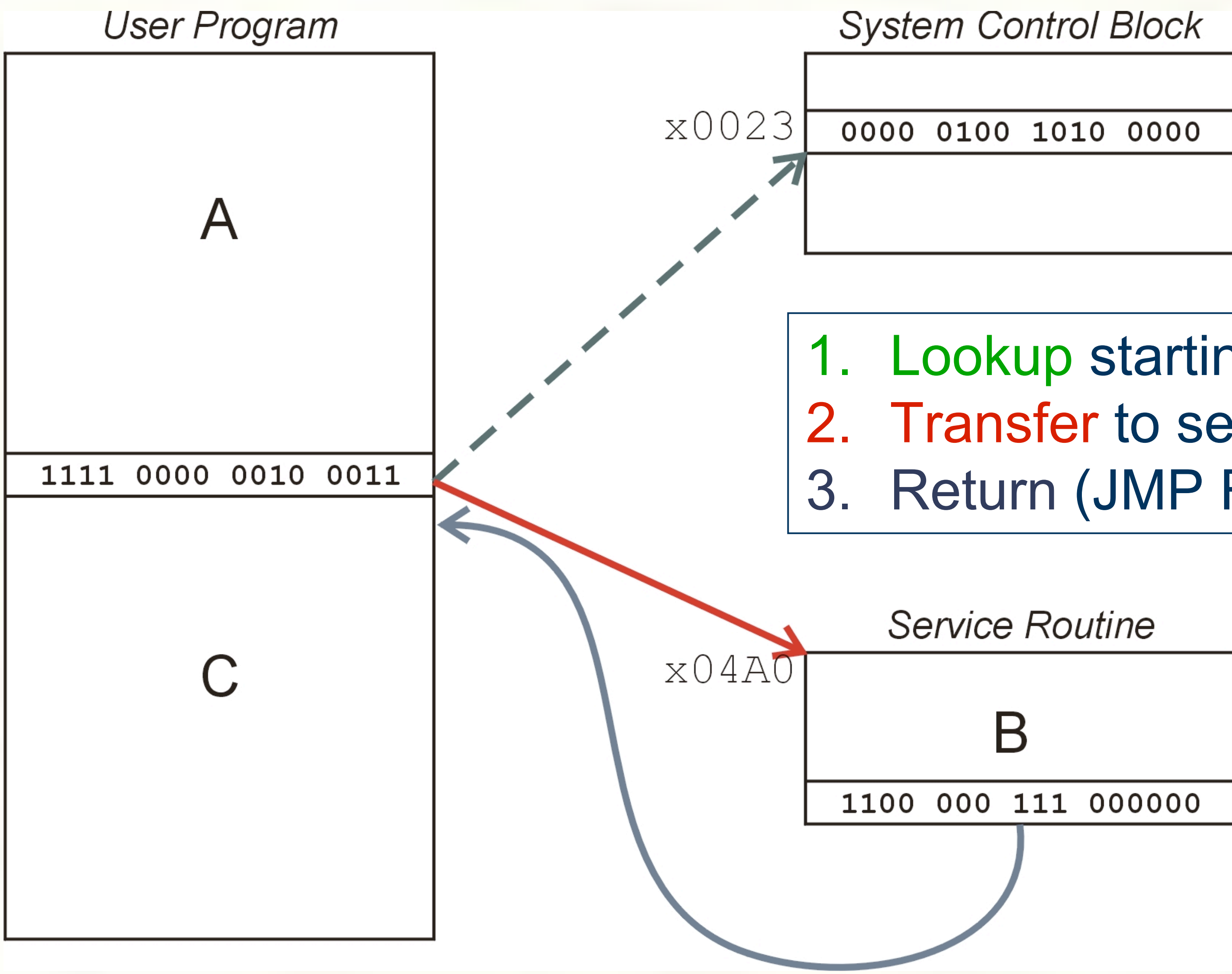
RET (JMP R7)

- 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



1. Lookup starting address.
2. Transfer to service routine.
3. Return (JMP R7).

Example: 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 Routine 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

```
LEAR3, Binary
          LD    R6, ASCII    ; char->digit template
          LD    R7, COUNT    ; initialize to 10
AGAIN           TRAP x23          ; Get char
          ADD   R0, R0, R6        ; convert to number
          STR   R0, R3, #0        ; store number
          ADD   R3, R3, #1        ; incr pointer
          ADD   R7, R7, -1        ; decr 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

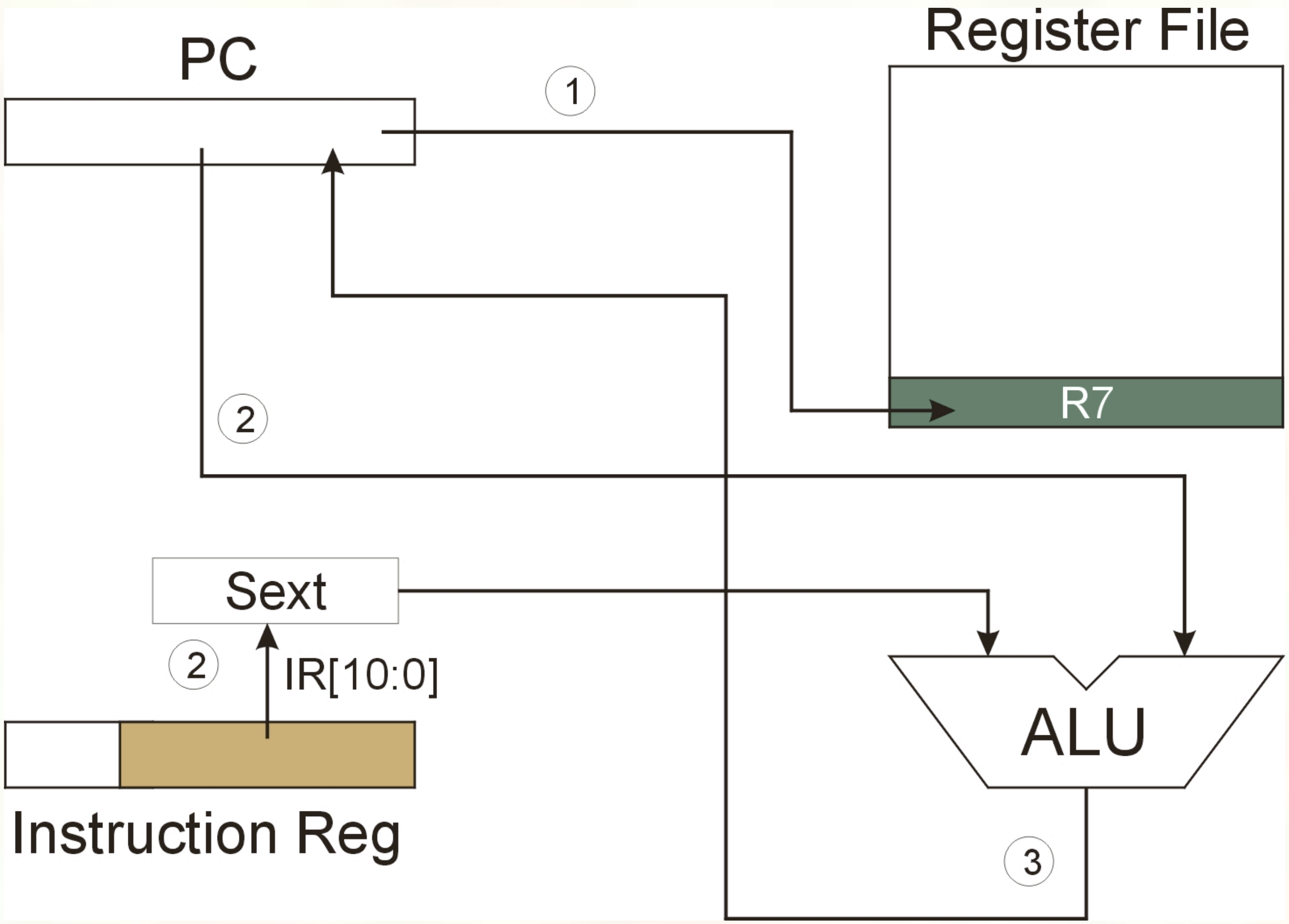
- A subroutine is a program fragment that:
  - lives in user space
  - performs a well-defined task
  - is invoked (called) by another user program
  - returns control to the calling program when finished
- Like a service routine, but not part of the OS
  - not concerned with protecting hardware resources
  - 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



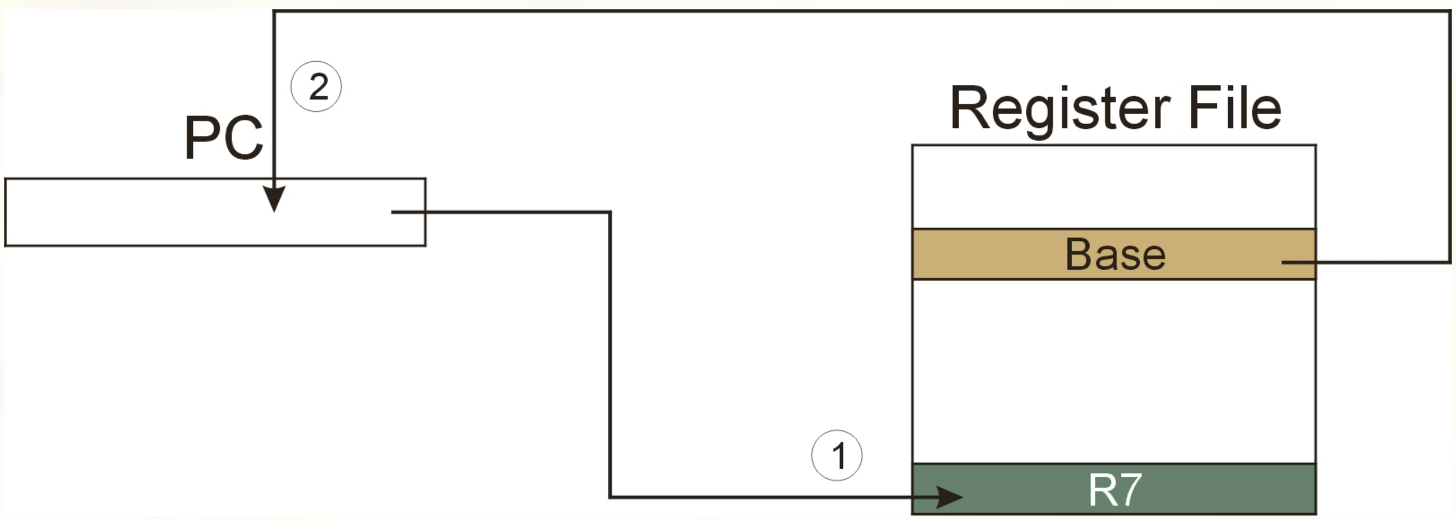
NOTE: PC has already been incremented during instruction fetch stage.

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 called 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 called a return value.
  - This is the value that you called the subroutine to compute.
  - Examples:
    - In 2sComp routine, negated value is returned in R0.
    - In GETC service routine, character read from the keyboard is returned 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);

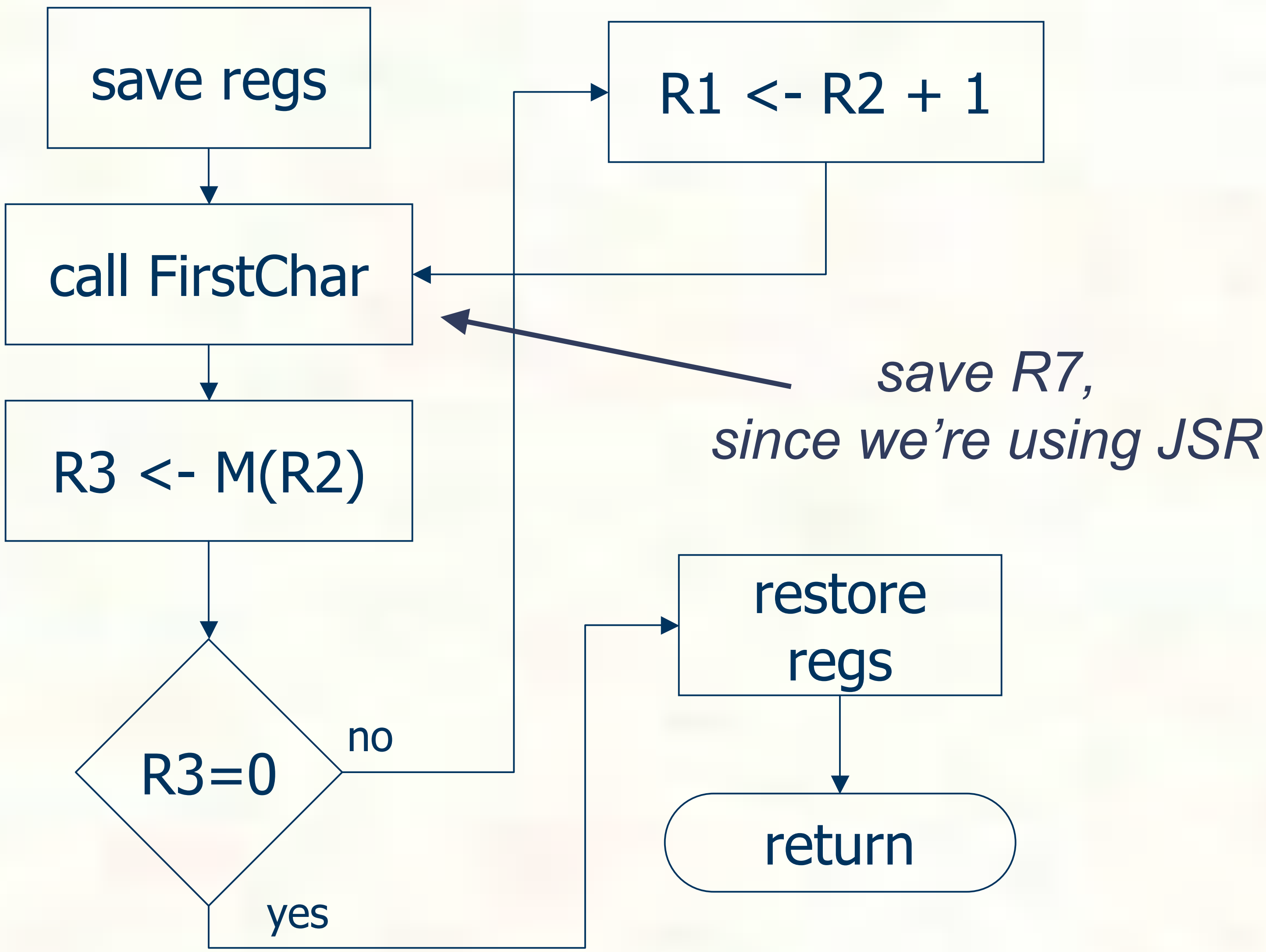
   return pointer to character or to end of string (NULL) in R2.

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!

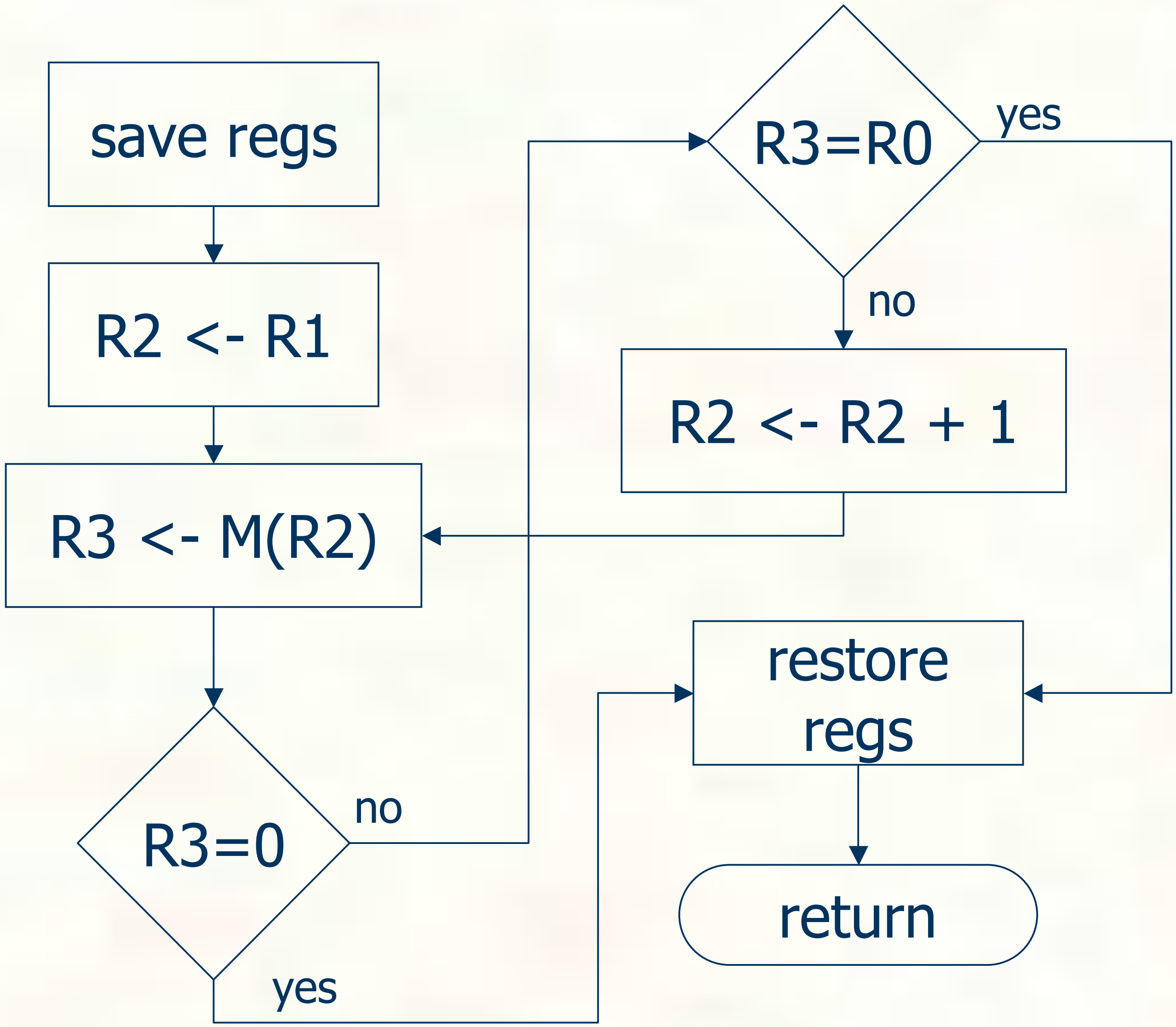
CountChar Algorithm (using FirstChar)



CountChar Implementation

```
;  CountChar: 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 string ptr
    AND   R4, R4, #0      ;  initialize count to zero
CC1 JSR   FirstChar       ;  find next occurrence (ptr in R2)
    LDR   R3, R2, #0      ;  see if char or null
    BRz   CC2             ;  if null, no more chars
    ADD   R4, R4, #1      ;  increment count
    ADD   R1, R2, #1      ;  point to next char in string
BRnzp     CC1
CC2 ADD   R2, R4, #0      ;  move return val (count) to R2
    LD    R3, CCR3        ;  restore regs
    LD    R4, CCR4
    LD    R1, CCR1
    LD    R7, CCR7
    RET                   ;  and return
```

FirstChar Algorithm



FirstChar Implementation

```
;   FirstChar: subroutine to find first occurrence of a char
FirstChar
    ST    R3, FCR3      ; save registers
    ST    R4, FCR4      ; save original char
    NOT   R4, R0        ; negate R0 for comparisons
    ADD   R4, R4, #1
    ADD   R2, R1, #0    ; initialize ptr to beginning of string
FC1 LDR   R3, R2, #0    ; read character
    BRz   FC2           ; if null, we're done
    ADD   R3, R3, R4    ; see if matches input char
    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                 ; and return
```

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.