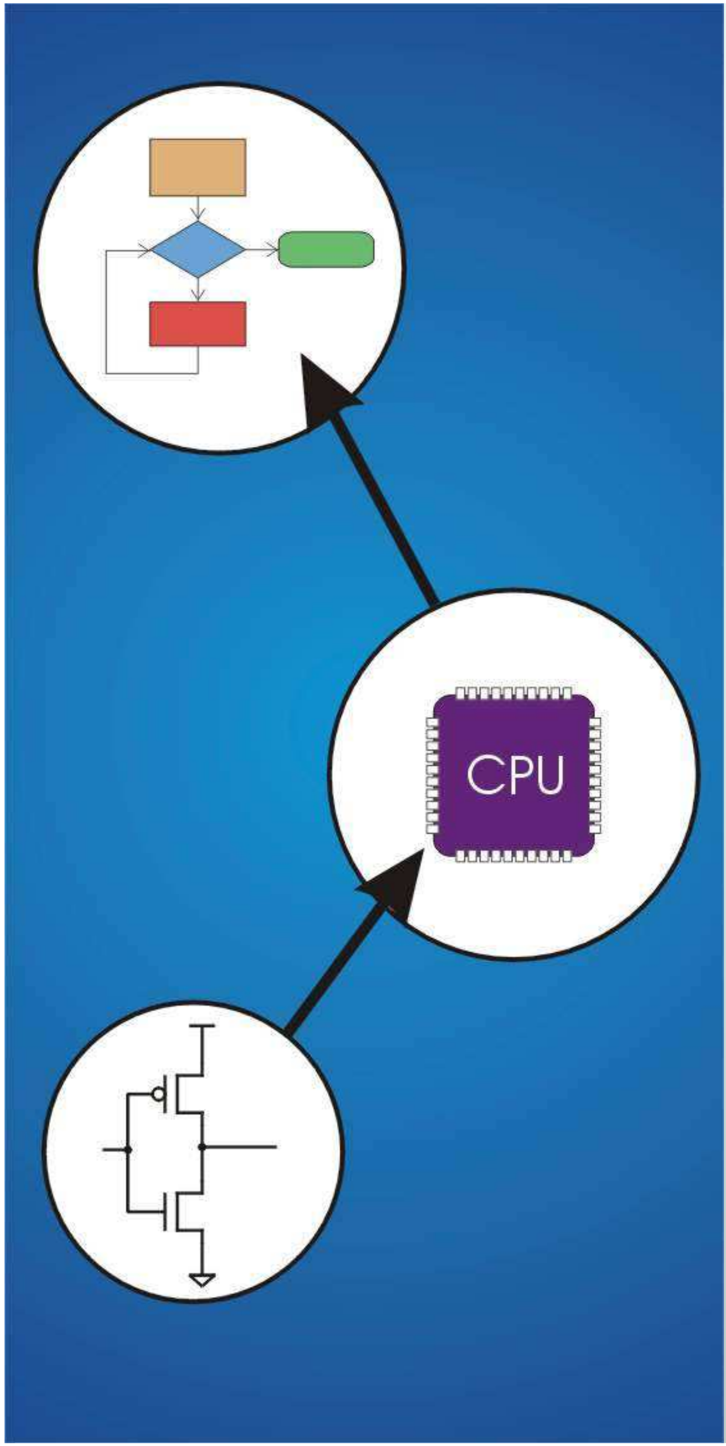

Chapter 9
TRAP Routines and Subroutines

TRAP: system routines
Subroutines: user routines
Difference: how control is transferred to routine

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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, <u>privileged</u> 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

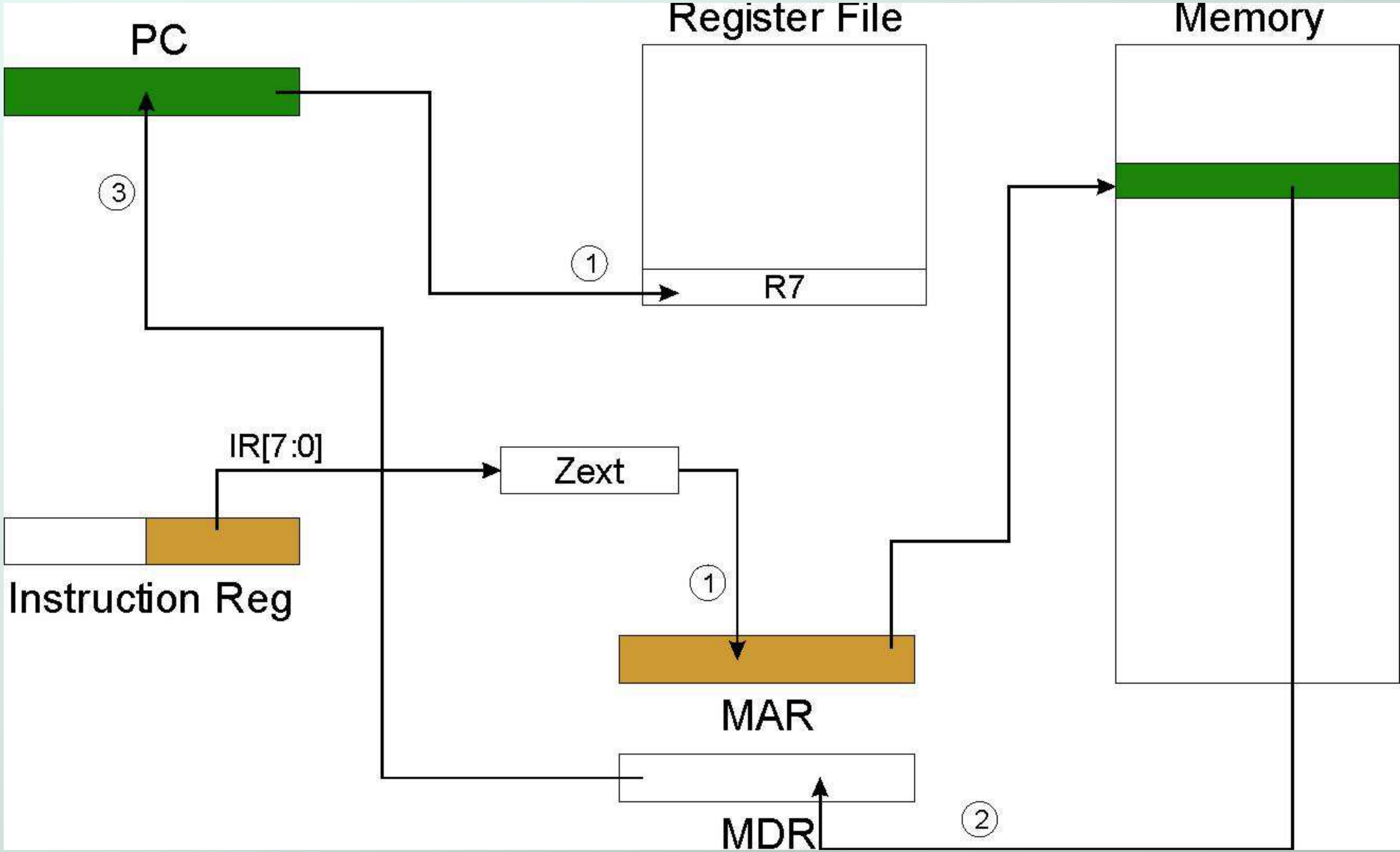
- *1. A set of service routines.*
  - part of operating system -- routines start at arbitrary addresses **(convention is that system code is below x3000)**
  - up to 256 routines
- *2. Table of starting addresses.*
  - stored at x0000 through x00FF in memory
  - called System Control Block in some architectures
- *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

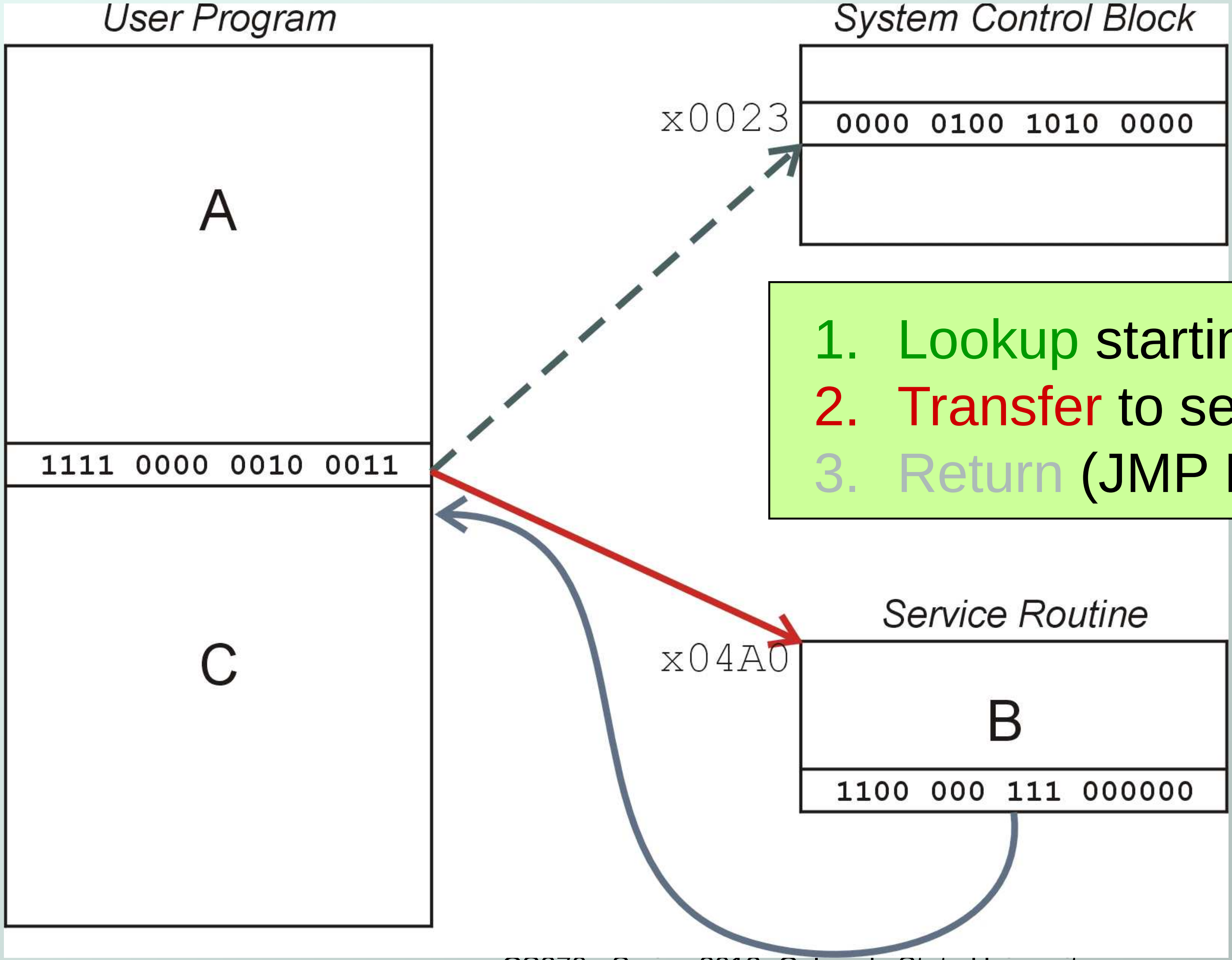


NOTE: PC has already been incremented during instruction fetch stage.

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: 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

Howard H. Aiken

- Harvard Mark I: 1943 (IBM support)
- : invented subroutines
- Aiken: 3rd from left

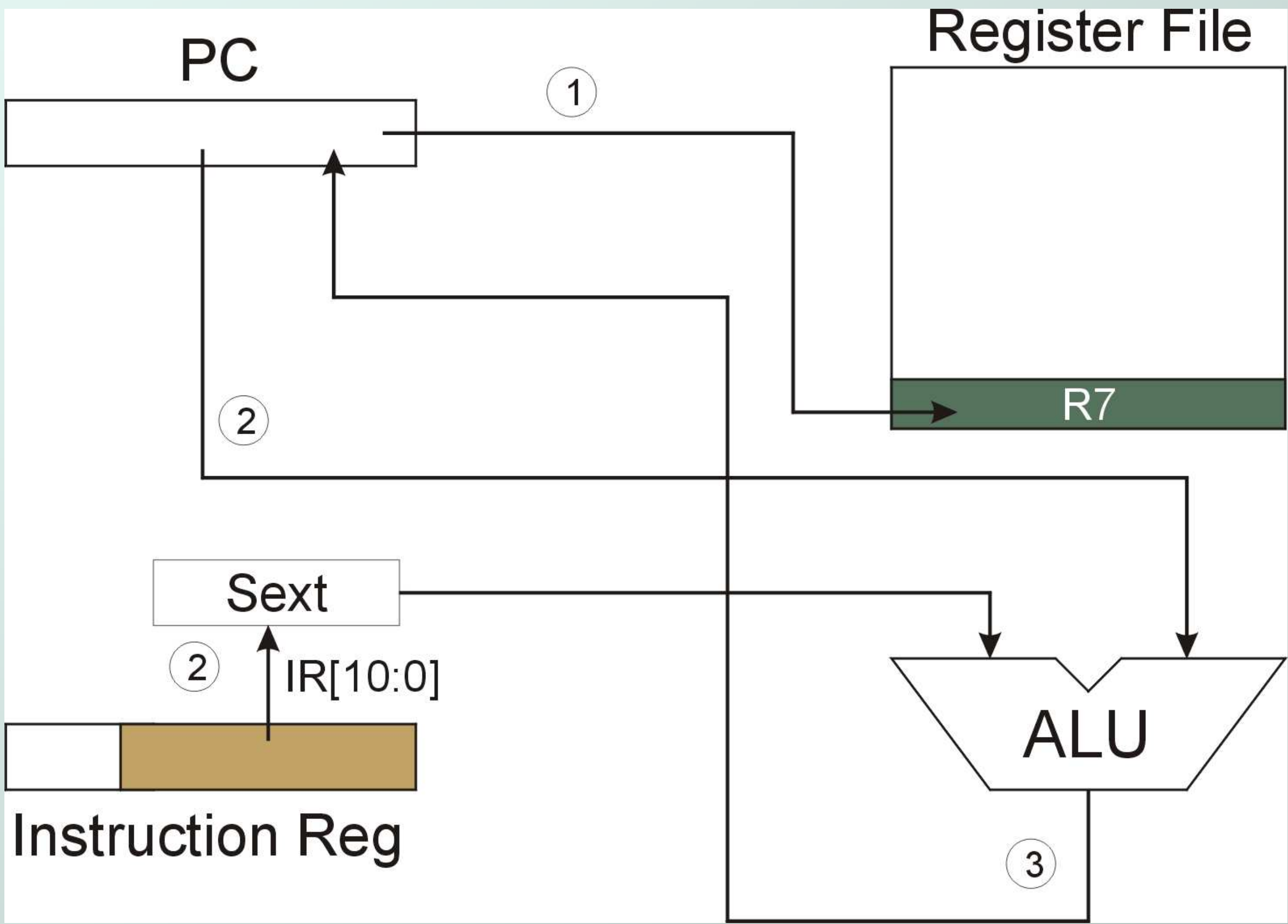
IBM required all workers to wear a tie until early 1980s.

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



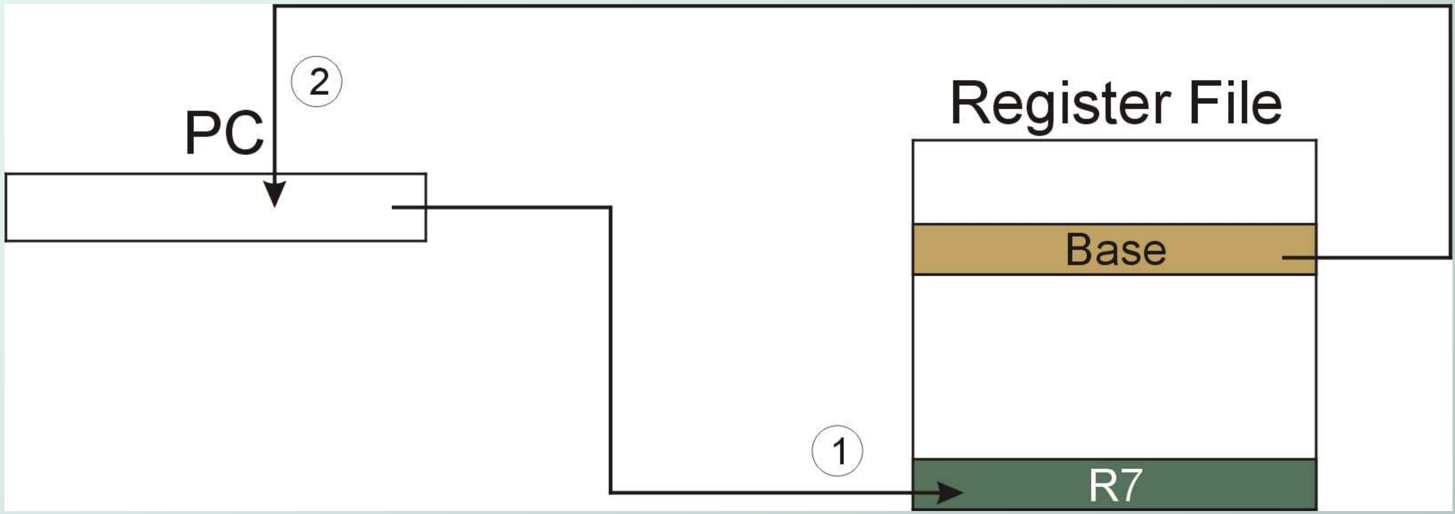
NOTE: PC has already been incremented during instruction fetch stage.

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.

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.

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)

Example: Subtract

```
;Main program load numbers and performs subtraction
; Num3<- Num1- Num2
;using subroutine SUB
            .ORIG x3000
            LD R1, Num1         ;subroutine argument
            LD R2, Num2         ;subroutine argument
            JSR SUBT
            ST R3, Num3         ;value returned by SUBT
            HALT
;   Data
Num1        .fill 23
Num2        .fill 8
Num3        .blkw 1

;Subtract subroutine: Performs R3 <- R1-R2
```

```
;Subtract subroutine: Performs R3 <- R1-R2
;
;Arguments: R1, R2, Returns value in R3
;
SUBT        NOT R3, R2
            ADD R3, R3, #1
            Add R3, R1, R3
            RET
            .END
```

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:

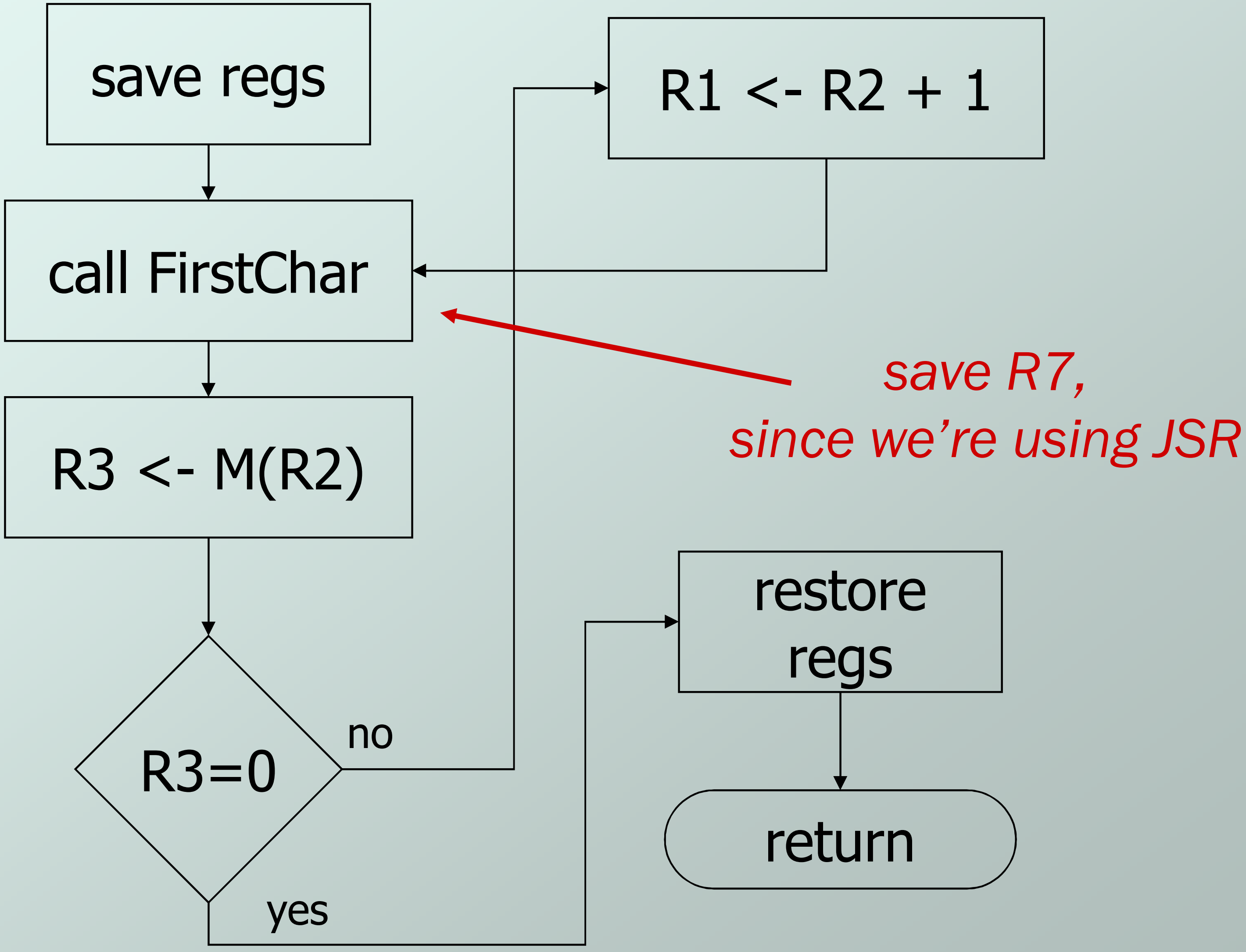
find the first occurrence
of a particular character (in R0)
in a string (pointed to by R1);
return pointer to character or to end of string (NULL) in R2.

(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!

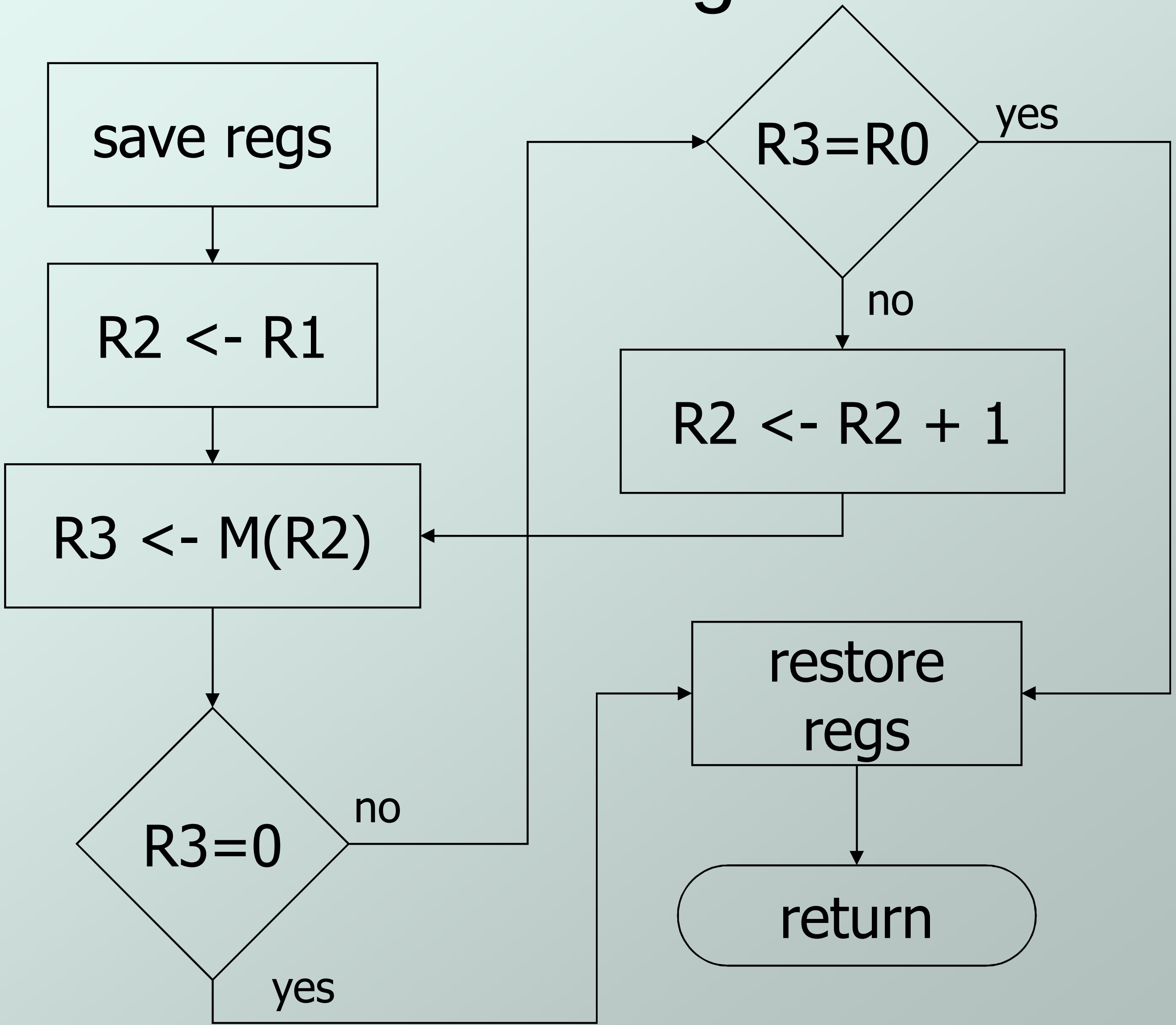
CountChar Algorithm (using FirstChar)



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
```