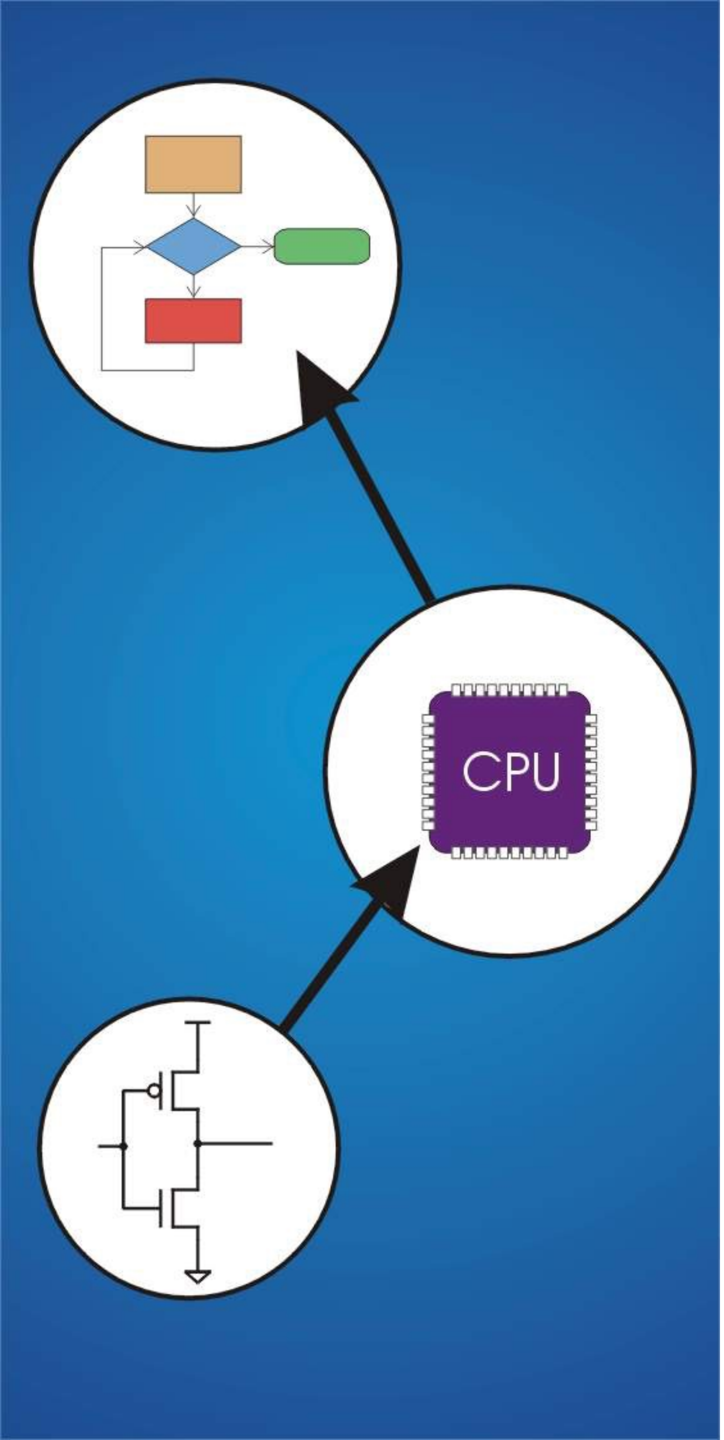
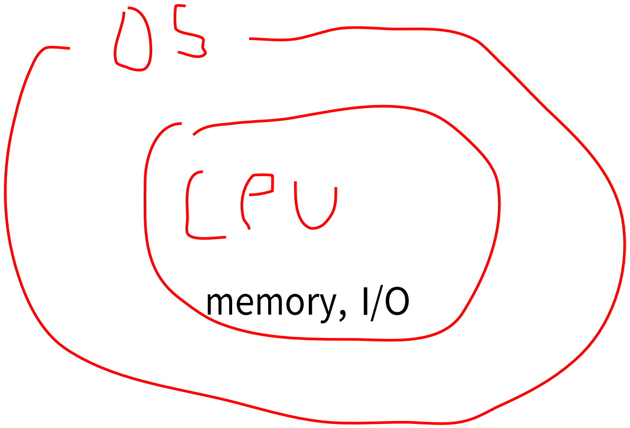




Chapter 9
TRAP Routines and Subroutines

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. 서비스 주소 (trapvect8)

- **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**

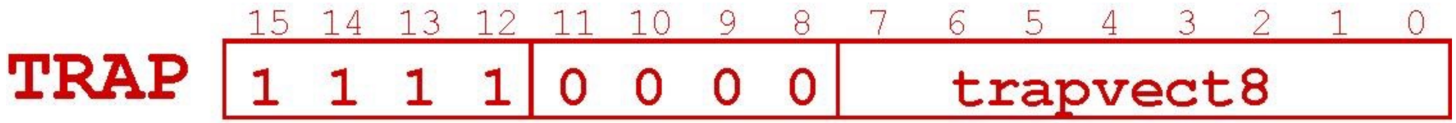
3. TRAP instruction.

- **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

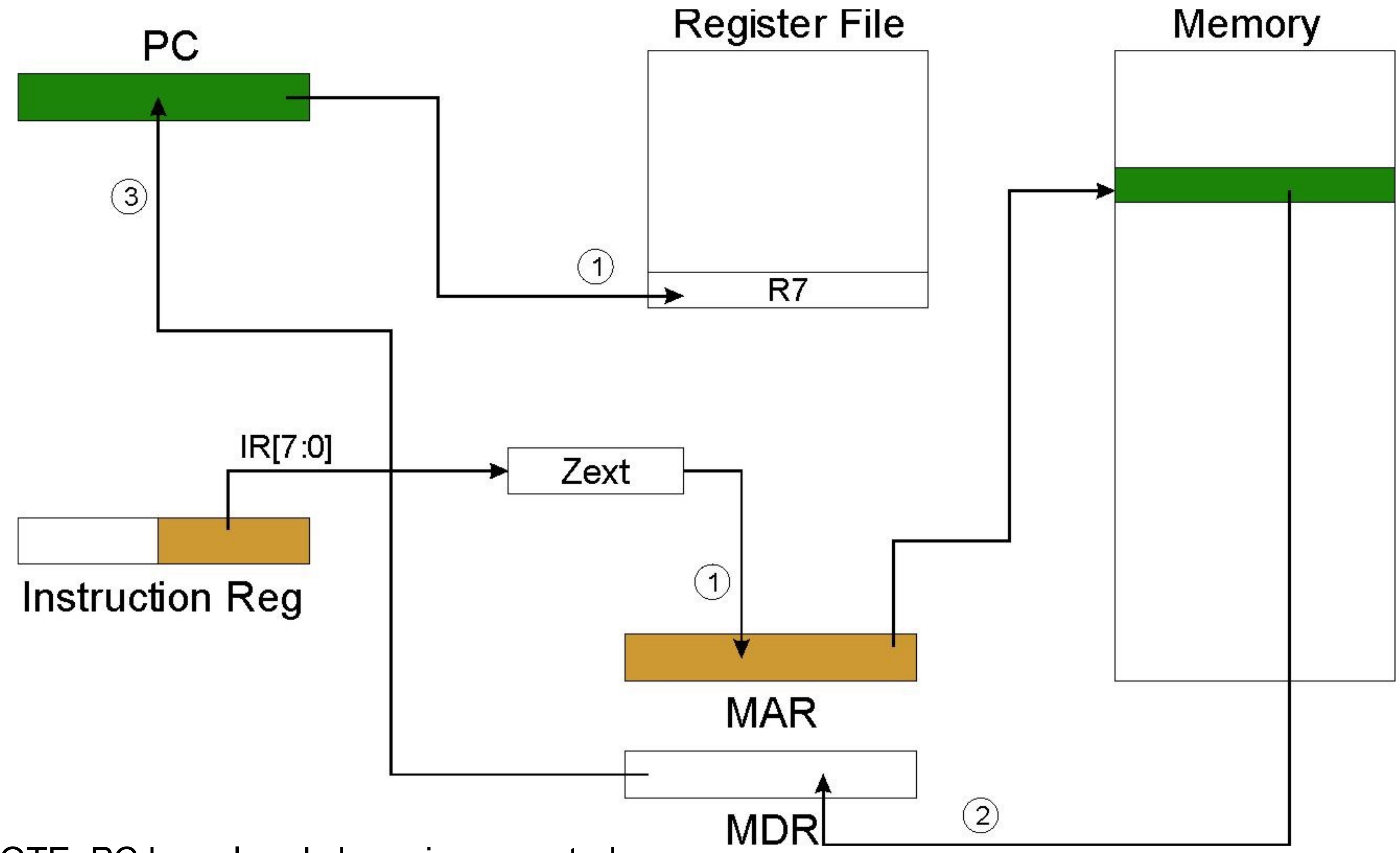
- lookup starting address from table; place in PC

How to get back

- save address of next instruction (current PC) in R7

TRAP이 끝나고 가야할 PC값을 R7에 미리 넣어둔다.

TRAP



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

RET (JMP R7)

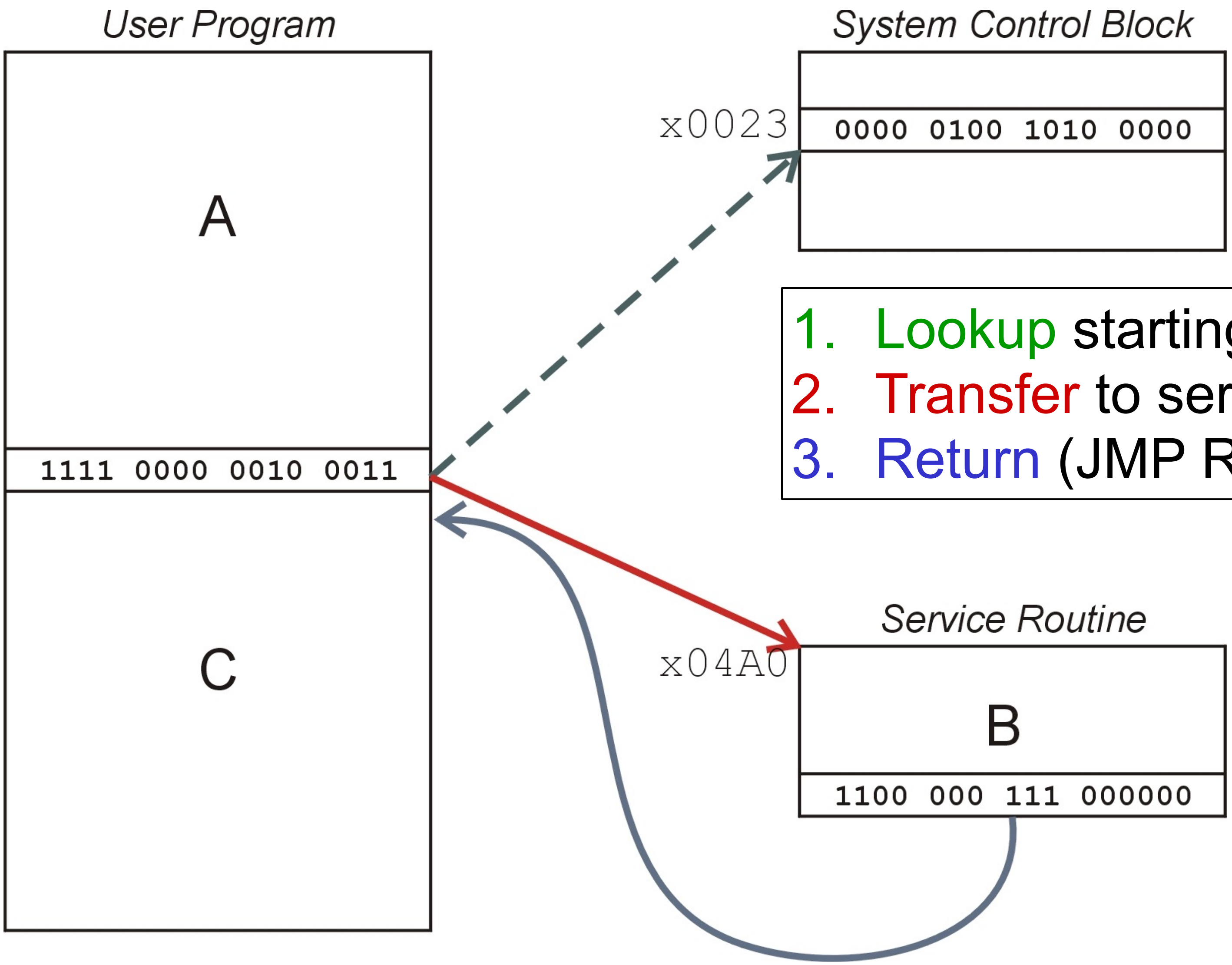
How do we transfer control back to instruction following the TRAP?

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
          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?

R7의 값이 망가지므로 TRAP전에 R7를 저장해놔야한다.

최적화방법

Saving and Restoring Registers

Called routine -- “callee-save” 함수안에서 보존?

- **Before start, save any registers that will be altered (unless altered value is desired by calling program!)**
- **Before return, restore those same registers**

바뀌는 것들만!

Calling routine -- “caller-save” 함수밖에서 보존?

- **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**

미래에 쓸것만!

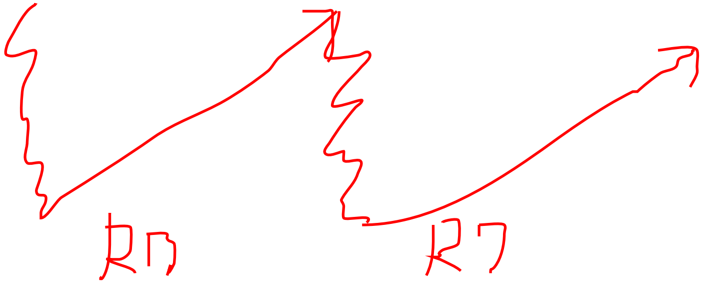
원칙적으로는 모두 저장해야한다.

Values are saved by storing them in memory.

Question

R7를 함수를 들어갈 때 마다 저장을 해야한다.

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

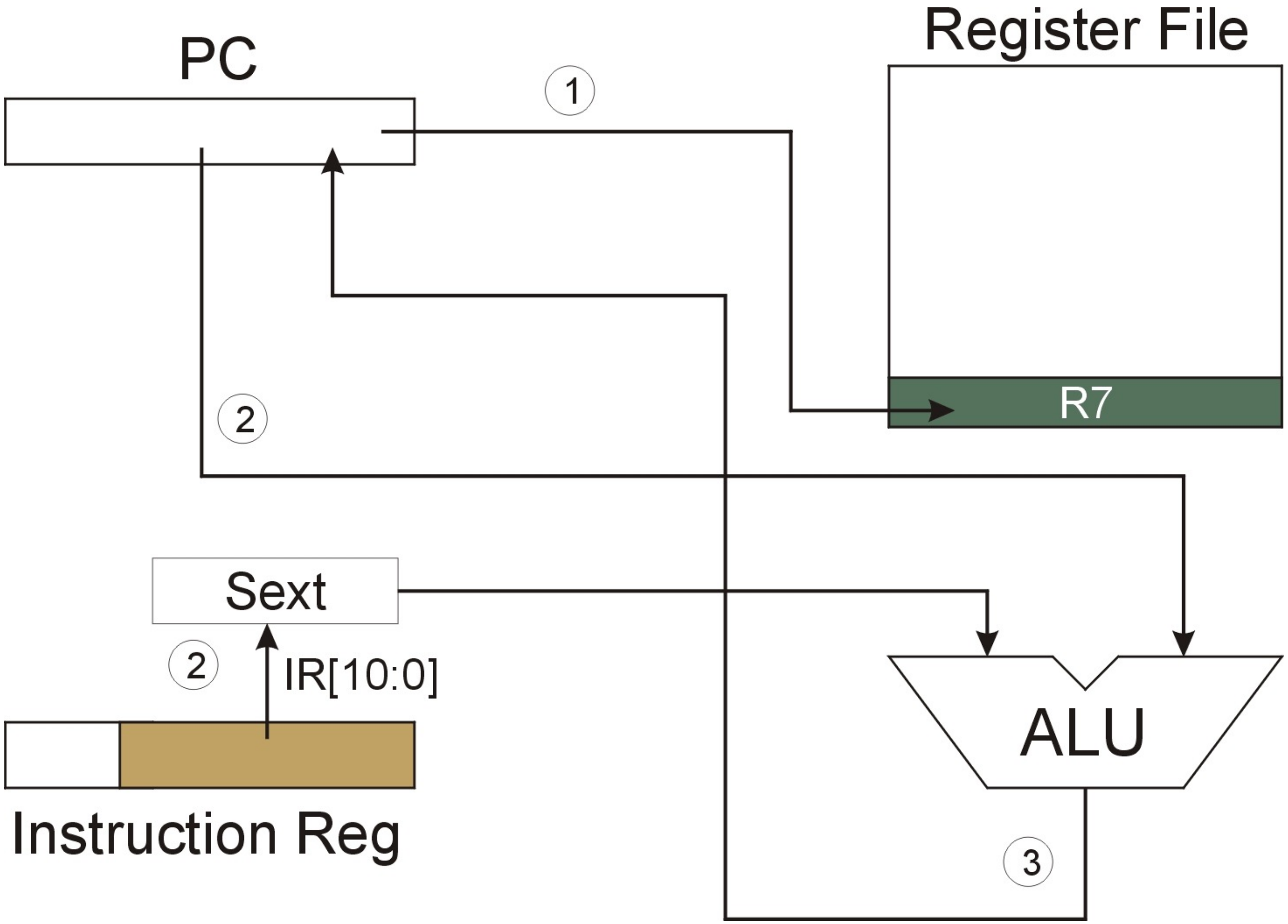
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
JSR	0	1	0	0	1	PCoffset11										

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]**

location으로 점프하고 R7에 현재 PC값을 저장한다.

JSR



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

JSRR Instruction

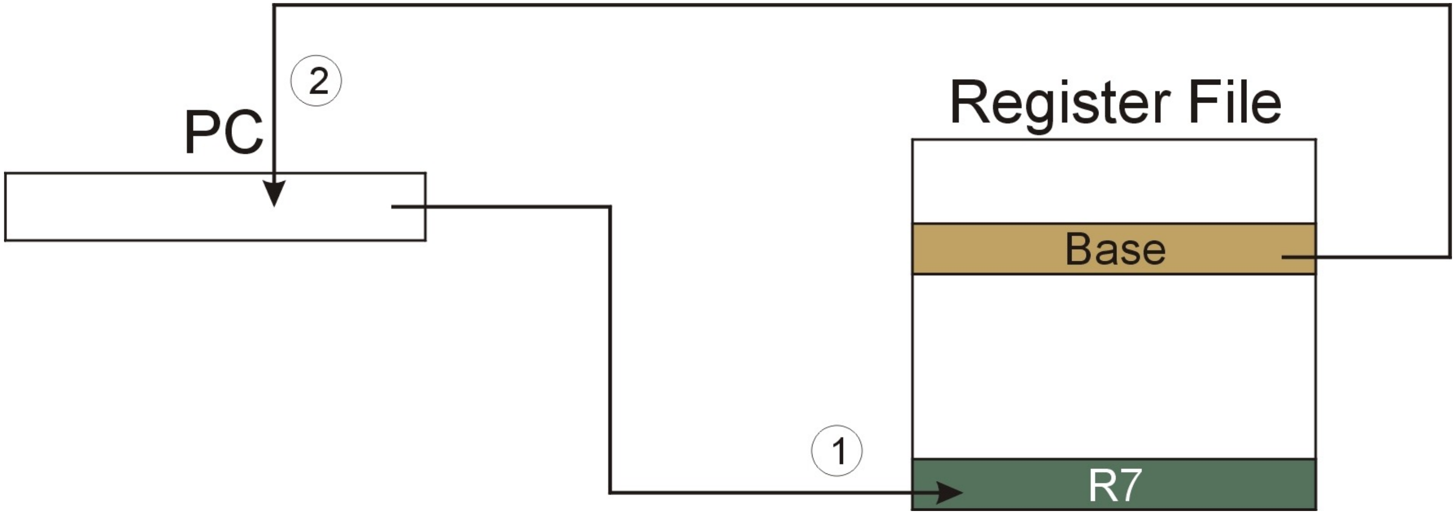
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
JSRR	0	1	0	0	0	0	0	Base			0	0	0	0	0	0

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

input parameters

- **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

output parameters

- **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: R1문자열에서 R0이 나오는 첫 위치

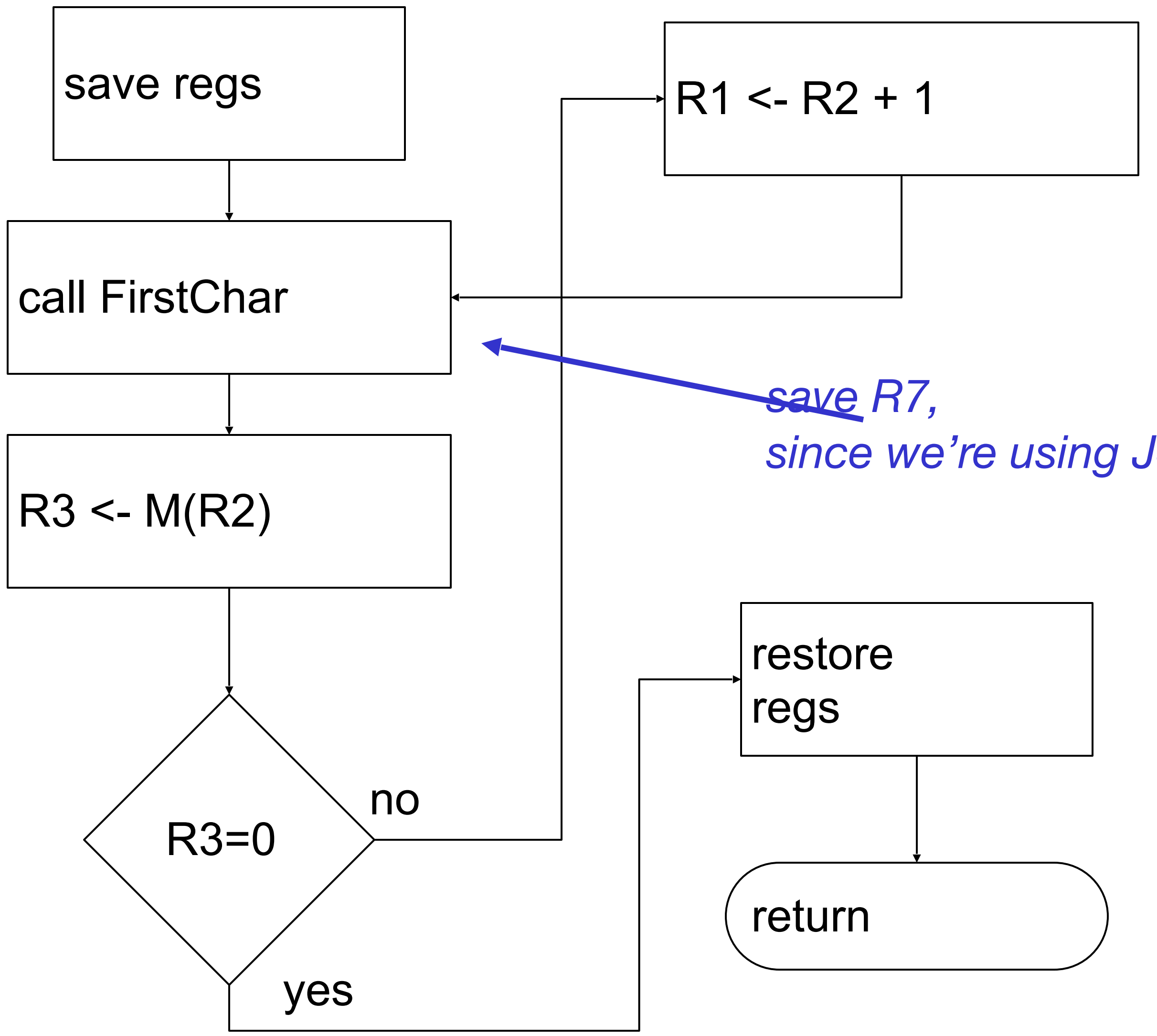
find the first occurrence
of a particular character (in R0)
in a string (pointed to by R1);
return pointer to character or to end of string (NULL) in R2.

(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)



save regs

call FirstChar

R3 <- M(R2)

R3=0

no

yes

R1 <- R2 + 1

restore regs

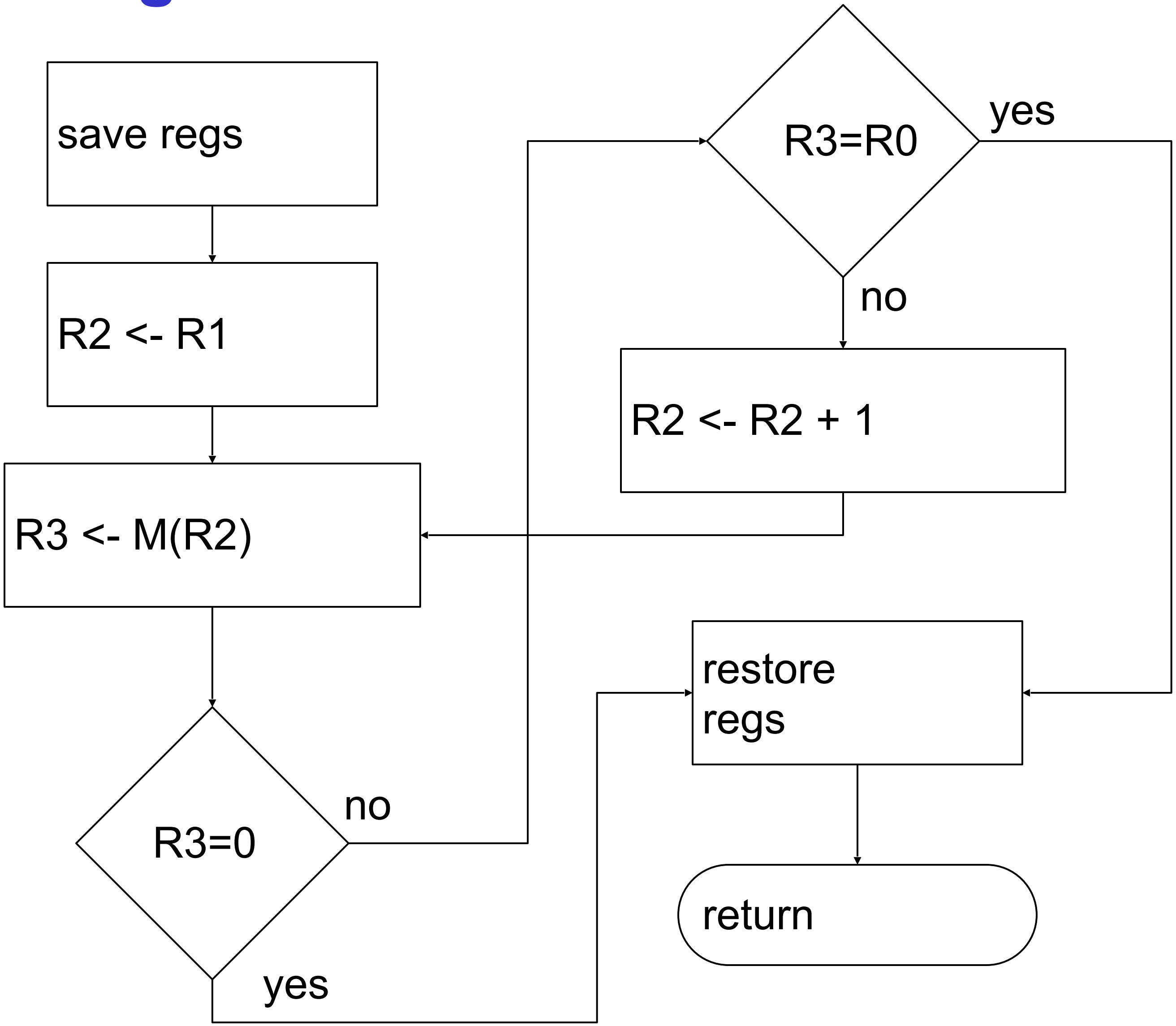
return

save R7,
since we're using JSR

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

지적 재산

- **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.