10. Example Program, Debugging (Chapters 5, 6.1, 6.2) October 3, 2018

- Review: LC3 data path and control state machine
  - Steps during instruction execution

- Example programs

- LC3 Tools (Edit, Simulate)

- Introduction to debugging

CONTROL INSTRUCTIONS

ALTERS SEQUENCE OF INSTRUCTIONS

$\Rightarrow$ CHANGES PC

JUMP - UNCONDITIONAL

BRANCH - CONDITIONAL

LC3: CONDITION CODE REGISTERS (1-BIT)

SET BY ANY INSTR. WHICH WRITES A VALUE INTO A REGISTER

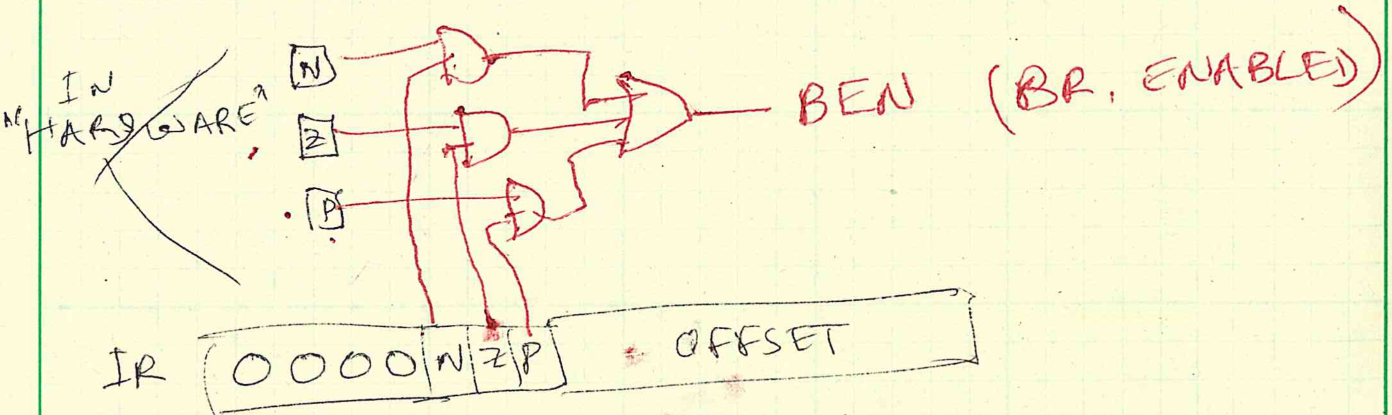
(ADD, AND, NOT, LDR, LD, LDI, LEA)

n - NEGATIVE

z - ZERO

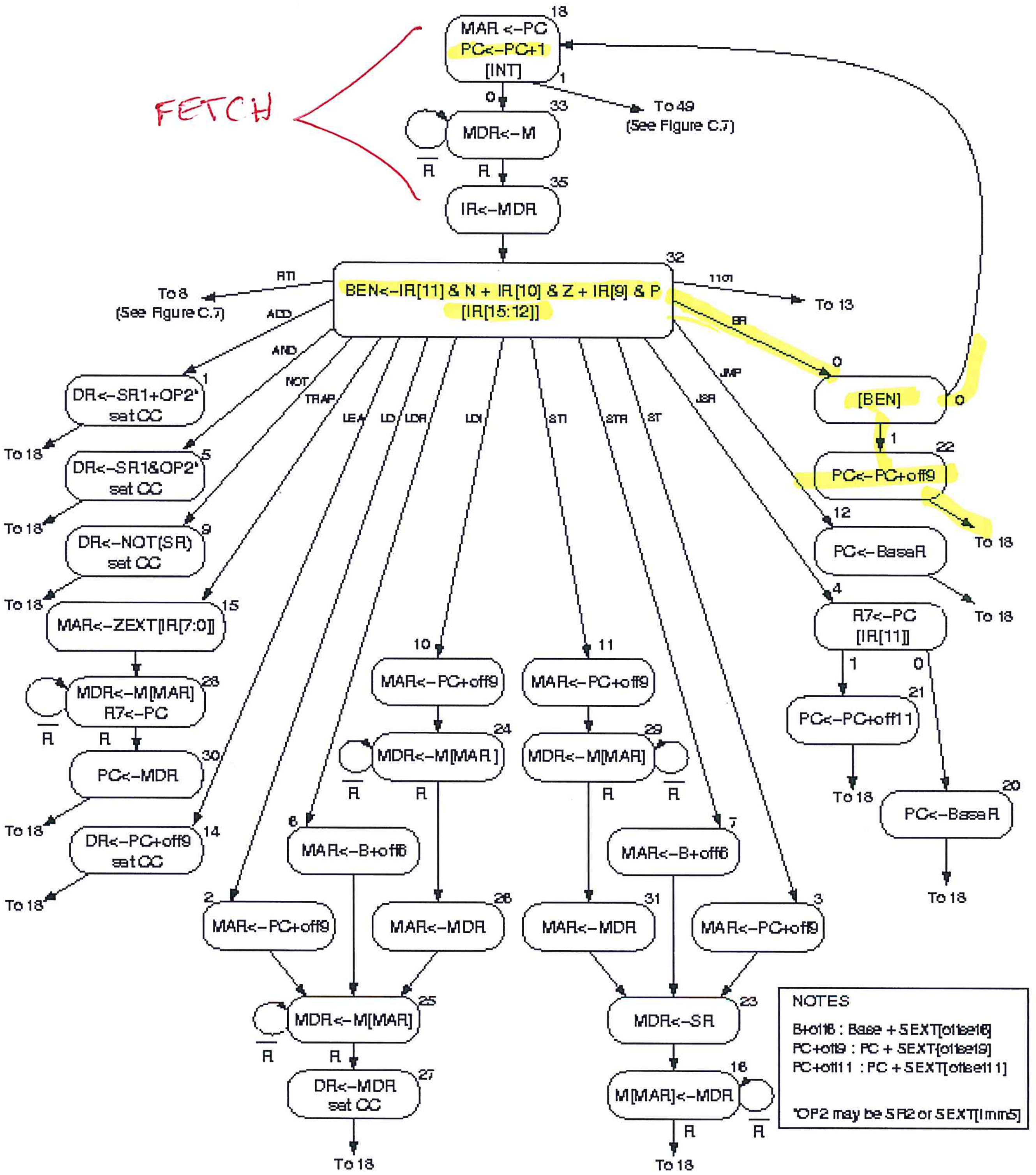
p - POSITIVE

IN A PROGRAM, BR IS TAKEN, OR NOT TAKEN DEPENDING ON WHAT IS SPECIFIED



WHAT IS THE X0000 INSTRUCTION

= NOP (NO OPERATION)

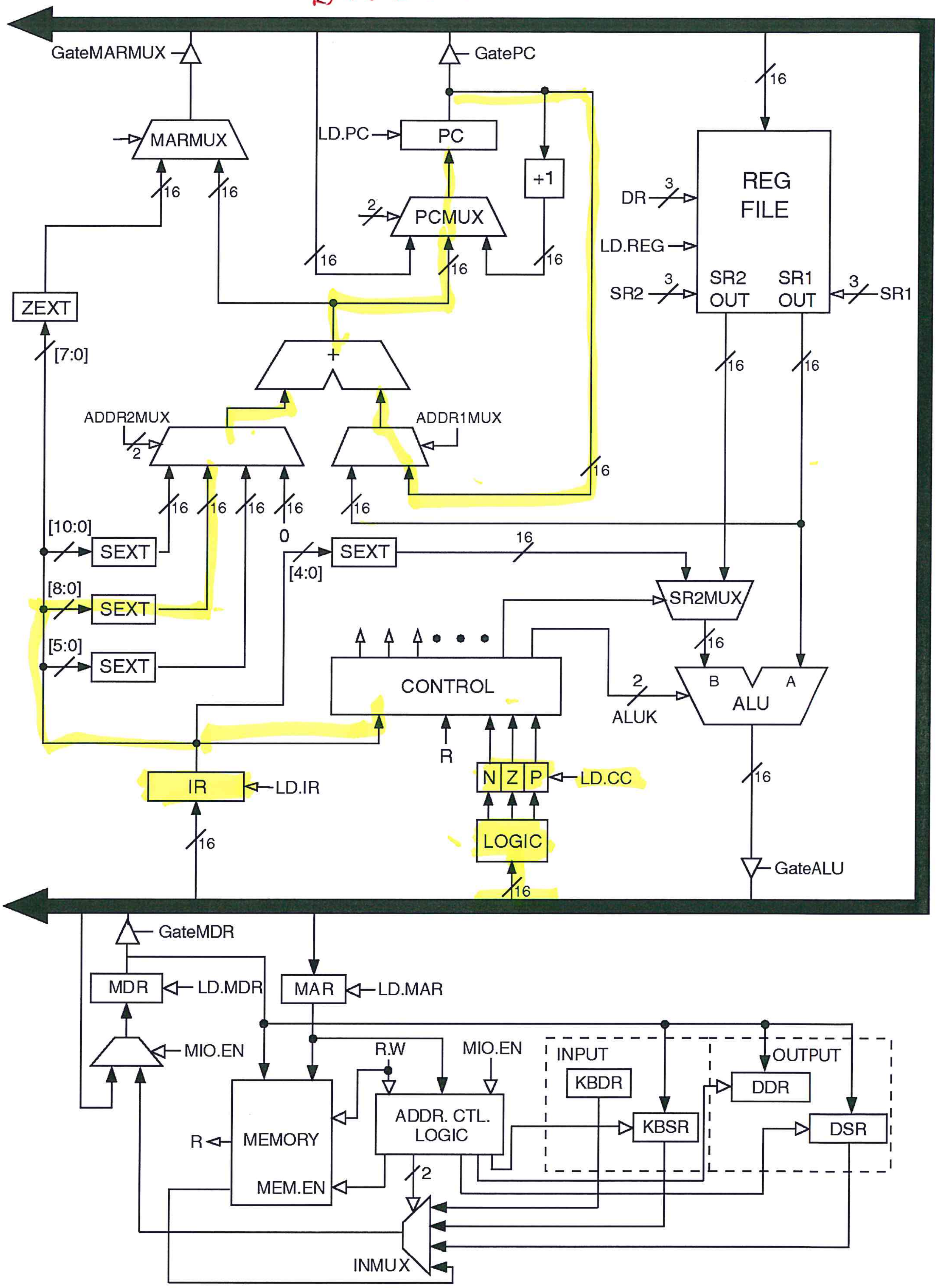


NOTES

B+off6 : Base + SEXT[offset6]
PC+off9 : PC + SEXT[offset9]
PC+off11 : PC + SEXT[offset11]

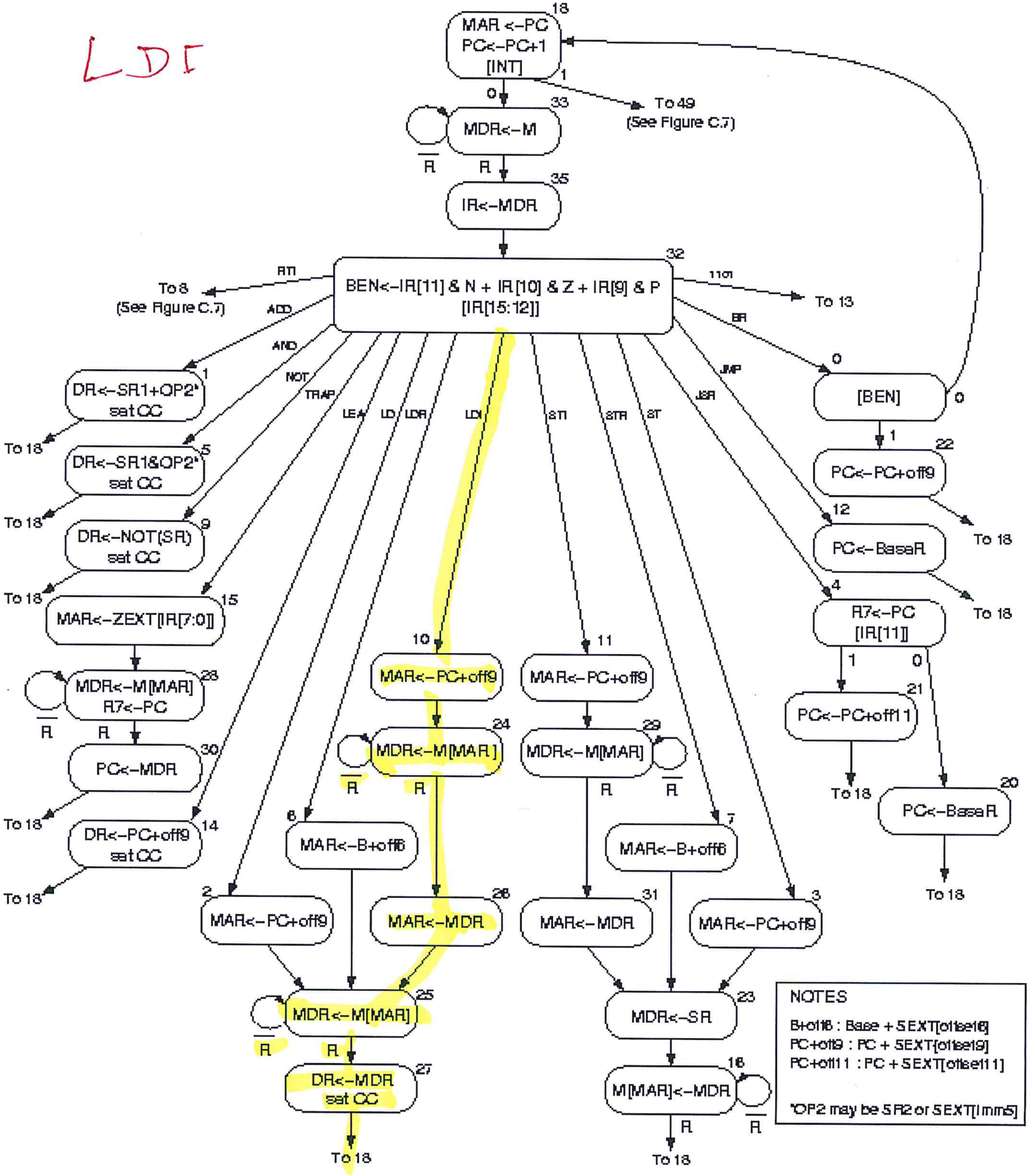
*OP2 may be SR2 or SEXT[imm5]

BR



GateMARMUX
GatePC
MARMUX
LD.PC
PC
+1
16
PCMUX
2
REG
FILE
DR
3
LD.REG
SR2
SR1
SR2
OUT
SR1
OUT
ZEXT
[7:0]
+
ADDR2MUX
ADDR1MUX
[10:0]
SEXT
[8:0]
SEXT
[5:0]
SEXT
0
[4:0]
SEXT
SR2MUX
CONTROL
2
ALUK
B
A
ALU
R
IR
LD.IR
N
Z
P
LD.CC
LOGIC
GateALU
GateMDR
MDR
LD.MDR
MAR
LD.MAR
MIO.EN
R.W
MIO.EN
INPUT
OUTPUT
KBDR
DDR
KBSR
DSR
MEMORY
ADDR. CTL.
LOGIC
R
MEM.EN
INMUX

LDI



NOTES

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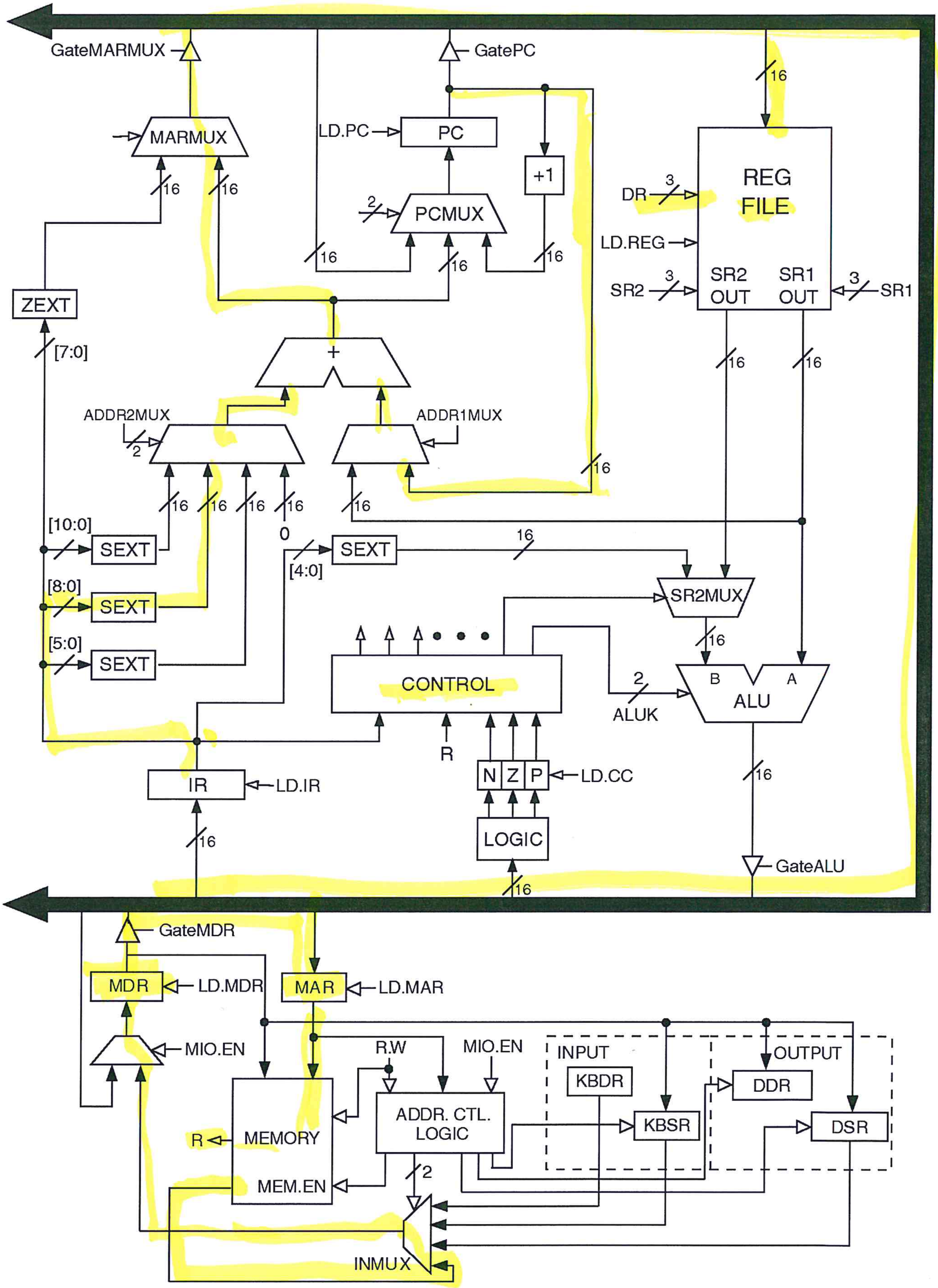
PC+off9 : PC + SEXT[offset9]
PC+off11 : PC + SEXT[offset11]

*OP2 may be SR2 or SEXT[imm5]


GateMARMUX
GatePC
MARMUX
LD.PC
PC
+1
PCMUX
REG
FILE
DR
LD.REG
SR2
SR2
OUT
SR1
OUT
SR1
ZEXT
[7:0]
ADDR2MUX
ADDR1MUX
[10:0]
SEXT
[8:0]
SEXT
[5:0]
SEXT
0
[4:0]
SEXT
SR2MUX
CONTROL
ALUK
B
A
ALU
R
IR
LD.IR
N
Z
P
LD.CC
LOGIC
GateALU
GateMDR
MDR
LD.MDR
MAR
LD.MAR
MIO.EN
R.W
MIO.EN
INPUT
OUTPUT
KBDR
DDR
MEMORY
R
MEM.EN
ADDR. CTL.
LOGIC
KBSR
DSR
INMUX
16
3
2

TRAP

(CONTROL)

	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							

Calls a service routine, identified by 8-bit "trap vector."

vector	*routine*
x23	input a character from the keyboard
x21	output a character to the monitor
x25	halt the program

When routine is done,
PC is set to the instruction following TRAP.

(We'll talk about how this works later.)

Using Branch Instructions

Compute sum of 12 integers.

Numbers start at location x3100. Program starts at location x3000.

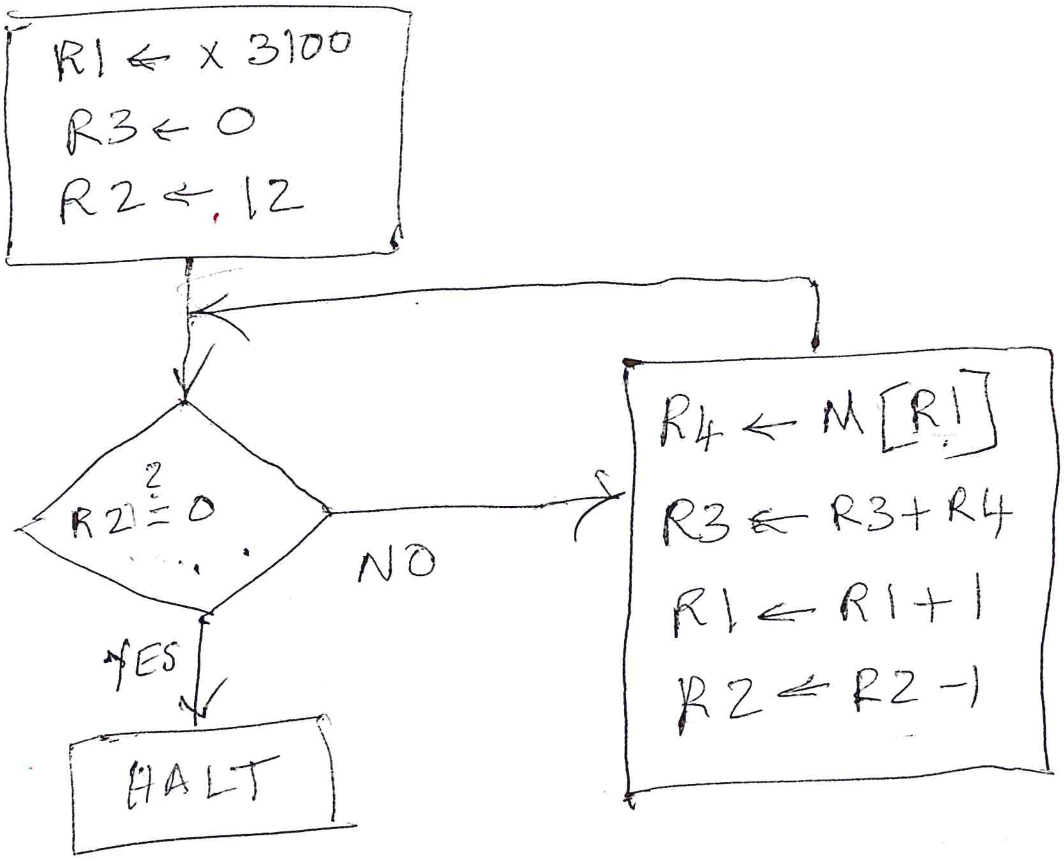
ADDRESS

R1: POINTS TO MEM. LOCATION WHERE NEXT NUMBER IS STORED

R2: NEXT INTEGER TO BE ADDED (OF 12)

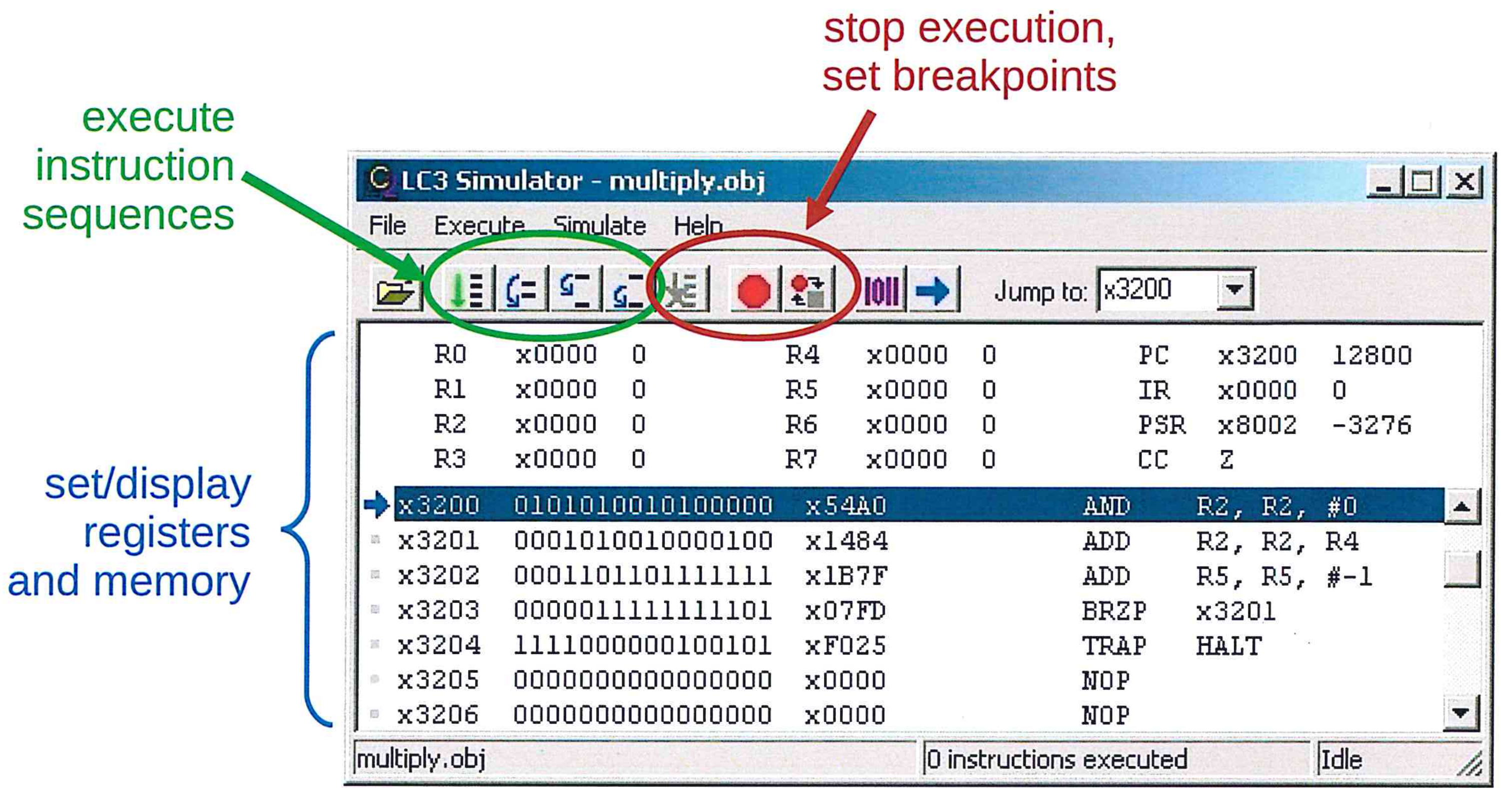
⇒ R3: SUM

R4: LOADS CURRENT INTEGER (FROM MEMORY)



Address	Instruction	Comments
LEA x3000	1110 001 011 111111	R1 ← x3100 (PC+OFFSET)
AND x3001	0101 011 011 100000	R3 ← 0.
AND X3002	0101 010 010 100000	R2 ← 0
ADD X3003	0001 010 010 101100	R2 ← 12
BR X3004	0000 010 000 000101	IF Z, GO TO HALT (PC+5)
LDR X3005	0110 100 001 000000	LOAD NEXT VALUE INTO R4
ADD X3006	0001 011 011 000100	ADD TO R3 (R3 ← R3+R4)
ADD X 3007	0001 001 001 100001	R1 ← R1+1
ADD X3008	0001 010 010 111111	R2 ← R2−1
BR X 3009	0000 111 111 111010	GO TO X 3004 (−6 OFFSET)
HALT, X 300A	1111 000 000 100101	HALT

LC-3 Simulator



stop execution,
set breakpoints

execute
instruction
sequences

set/display
registers
and memory

```
R0   x0000  0        R4   x0000  0        PC   x3200  12800
R1   x0000  0        R5   x0000  0        IR   x0000  0
R2   x0000  0        R6   x0000  0        PSR  x8002  -3276
R3   x0000  0        R7   x0000  0        CC   Z

x3200  0101010010100000  x54A0   AND   R2, R2, #0
x3201  0001010010000100  x1484   ADD   R2, R2, R4
x3202  0001101101111111  x1B7F   ADD   R5, R5, #-1
x3203  0000011111111101  x07FD   BRZP  x3201
x3204  1111000000100101  xF025   TRAP  HALT
x3205  0000000000000000  x0000   NOP
x3206  0000000000000000  x0000   NOP
```

multiply.obj | 0 instructions executed | Idle

Using “Sentinel”

Compute sum of 12 integers.

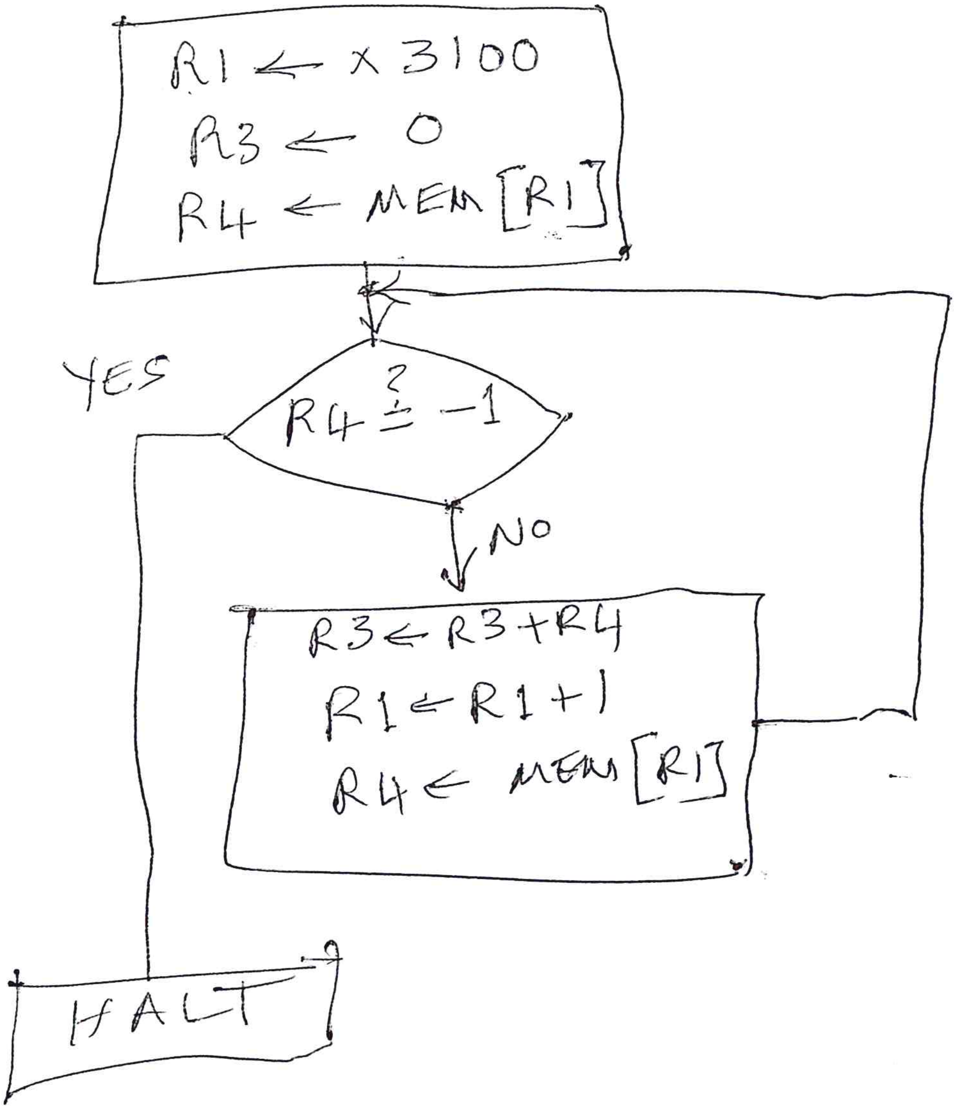
Numbers start at location x3100. Program starts at location x3000.

Sentinel stored in x310C is -1

R1: LOCATIONS WHERE NUMBERS ARE STORED

R3 : SUM

R4 : CURRENT INTEGER



Program Using “Sentinel” for Loop Control

Address	Instruction	Comments
x3000	1 1 1 0 0 0 1 0 1 1 1 1 1 1 1 1	R1 ← x3100 (PC+0xFF) LEA R1, 0x0FF
x3001	0 1 0 1 0 1 1 0 1 1 1 0 0 0 0 0	R3 ← 0 AND R3, R3, 0x00
x3002	0 1 1 0 1 0 0 0 0 1 0 0 0 0 0 0	R4 ← M[R1] LDR R4, R1 0x00
x3003	0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 0	BRn x3008 (0x04)
x3004	0 0 0 1 0 1 1 0 1 1 0 0 0 1 0 0	R3 ← R3 + R4 ADD R3, R3, R4
x3005	0 0 0 1 0 0 1 0 0 1 1 0 0 0 0 1	R1 ← R1 + 1 ADD R1. R1. 0x01
x3006	0 1 1 0 1 0 0 0 0 1 0 0 0 0 0 0	R4 ← M[R1] LDR R4, R1 0x00
x3007	0 0 0 0 1 1 1 1 1 1 1 1 1 0 1 0	BRnzp (goto) x3003 (#-6)
x3008	1 1 1 1 0 0 0 0 0 0 1 0 0 1 0 1	HALT

Solving Problems using a Computer

Methodologies for creating computer programs that perform a desired function.

Problem Solving

- How do we figure out what to tell the computer to do?
- Convert problem statement into algorithm, using *stepwise refinement*.
- Convert algorithm into LC-3 machine instructions.

Debugging

- How do we figure out why it didn't work?
- Examining registers and memory, setting breakpoints, etc.

Time spent on the first can reduce time spent on the second!

Stepwise Refinement

Also known as systematic decomposition.

Start with problem statement:

> "We wish to count the number of occurrences of a character in a file. The character in question is to be input from the keyboard; the result is to be displayed on the monitor."

Decompose task into a few simpler subtasks.

Decompose each subtask into smaller subtasks,
and these into even smaller subtasks, etc....
until you get to the machine instruction level.

Text: ASCII Characters

ASCII: Maps 128 characters to 7-bit code.

- both printable and non-printable (ESC, DEL, …) characters

00	nul	10	dle	20	sp	30	0	40	@	50	P	60	`	70	p
01	soh	11	dc1	21	!	31	1	41	A	51	Q	61	a	71	q
02	stx	12	dc2	22	"	32	2	42	B	52	R	62	b	72	r
03	etx	13	dc3	23	#	33	3	43	C	53	S	63	c	73	s
04	eot	14	dc4	24	$	34	4	44	D	54	T	64	d	74	t
05	enq	15	nak	25	%	35	5	45	E	55	U	65	e	75	u
06	ack	16	syn	26	&	36	6	46	F	56	V	66	f	76	v
07	bel	17	etb	27	'	37	7	47	G	57	W	67	g	77	w
08	bs	18	can	28	(	38	8	48	H	58	X	68	h	78	x
09	ht	19	em	29	)	39	9	49	I	59	Y	69	i	79	y
0a	nl	1a	sub	2a	*	3a	:	4a	J	5a	Z	6a	j	7a	z
0b	vt	1b	esc	2b	+	3b	;	4b	K	5b	[	6b	k	7b	{
0c	np	1c	fs	2c	,	3c	<	4c	L	5c	\	6c	l	7c	|
0d	cr	1d	gs	2d	-	3d	=	4d	M	5d	]	6d	m	7d	}
0e	so	1e	rs	2e	.	3e	>	4e	N	5e	^	6e	n	7e	~
0f	si	1f	us	2f	/	3f	?	4f	O	5f	_	6f	o	7f	del

Problem Statement

Because problem statements are written in English, they are sometimes ambiguous and/or incomplete.

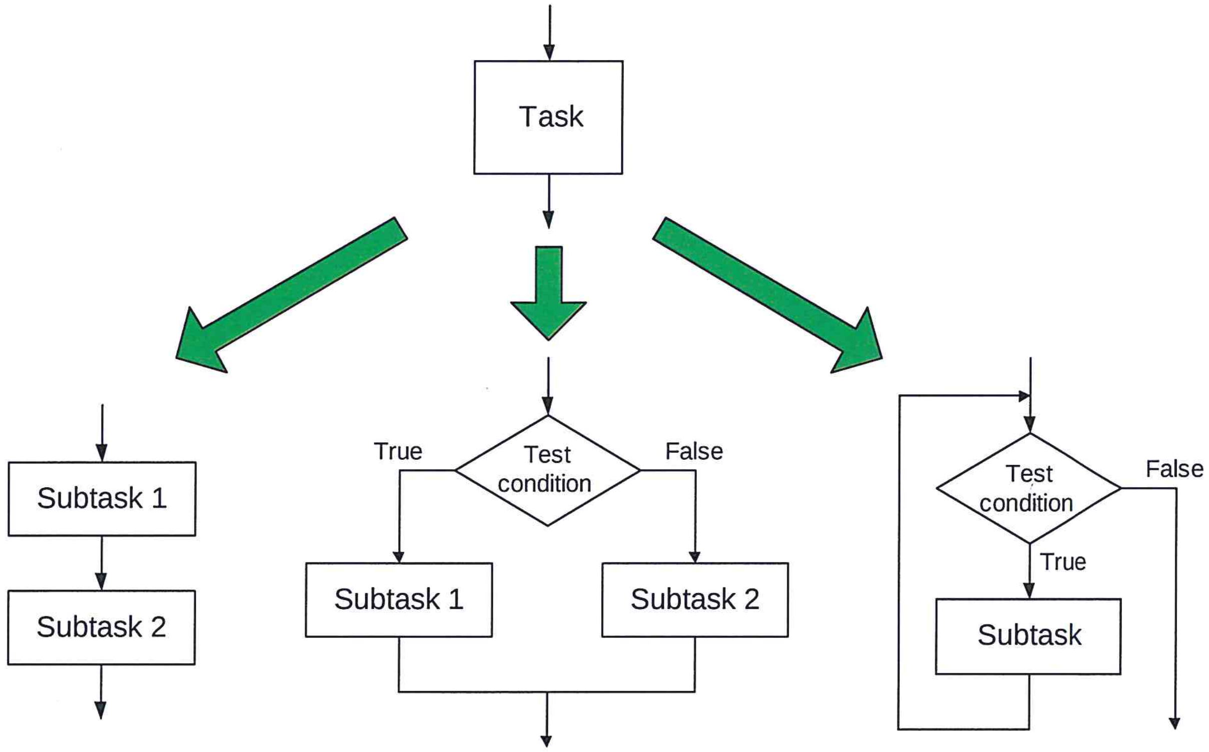
- Where is "file" located? How big is it, or how do I know when I've reached the end?
- How should final count be printed? A decimal number?
- If the character is a letter, should I count both upper-case and lower-case occurrences?

How do you resolve these issues?

- Ask the person who wants the problem solved, or
- Make a decision and document it.

Three Basic Constructs

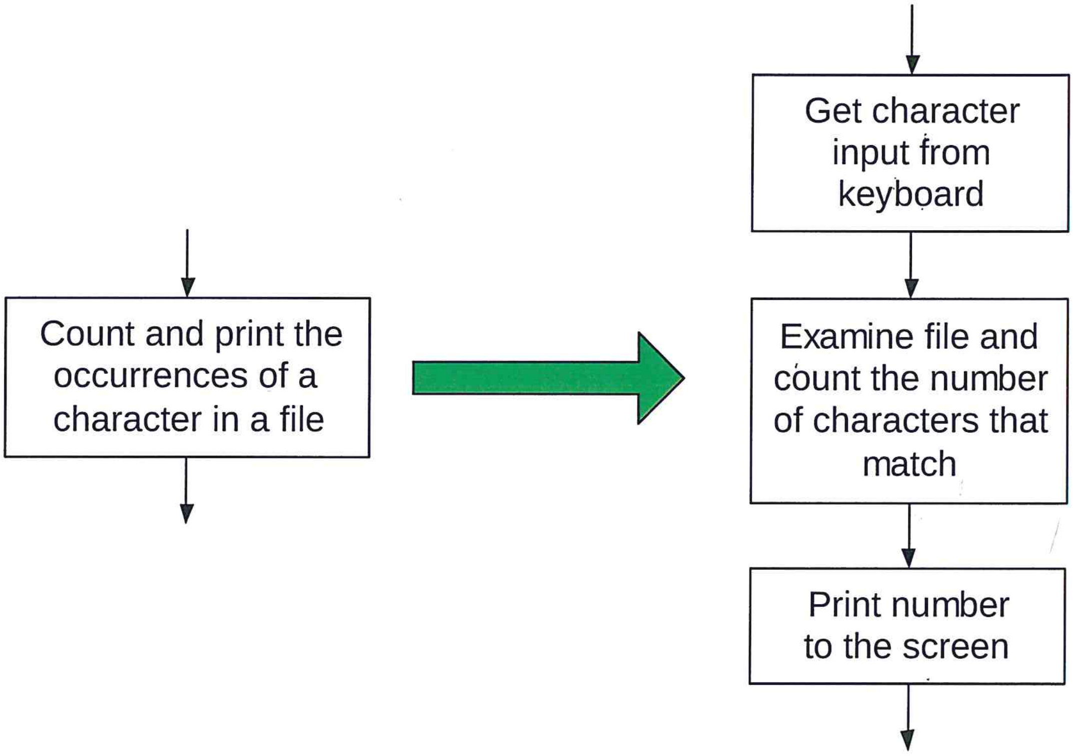
There are three basic ways to decompose a task:



Sequential *Conditional* *Iterative*

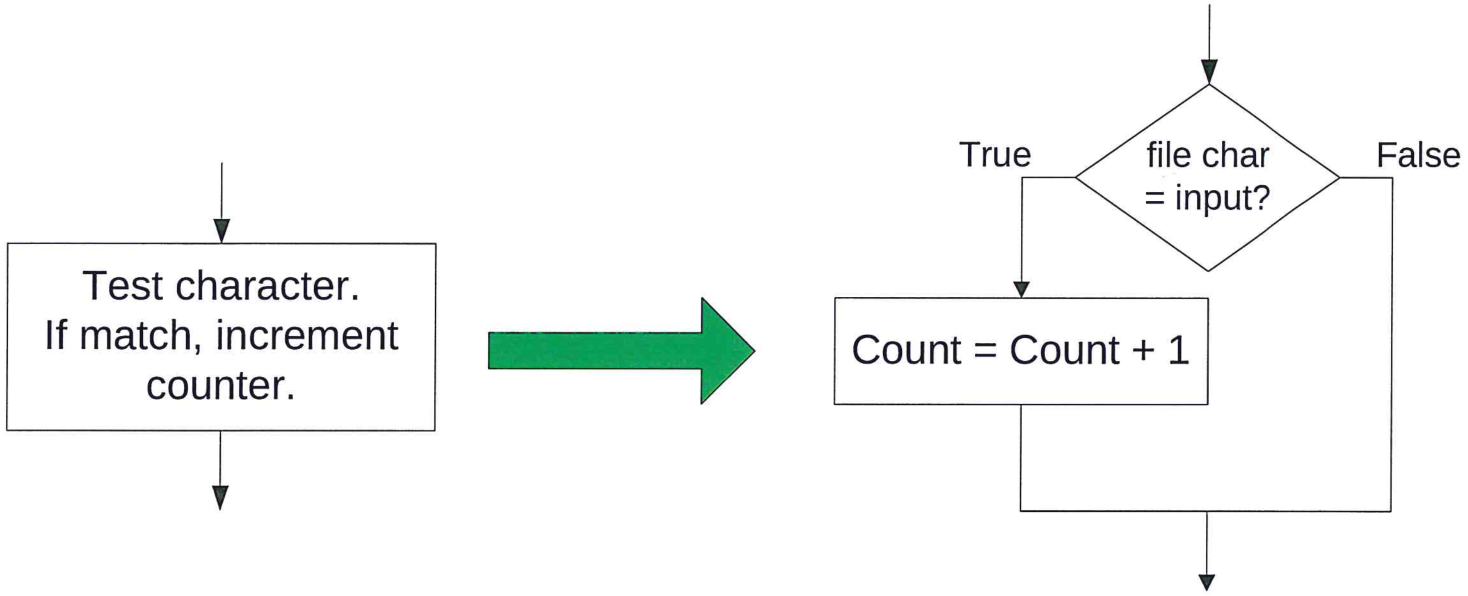
Sequential

Do Subtask 1 to completion, then do Subtask 2 to completion, etc.


Count and print the occurrences of a character in a file
Get character input from keyboard
Examine file and count the number of characters that match
Print number to the screen

Conditional

If condition is true, do Subtask 1;
else, do Subtask 2.



Test character.
If match, increment counter.

True

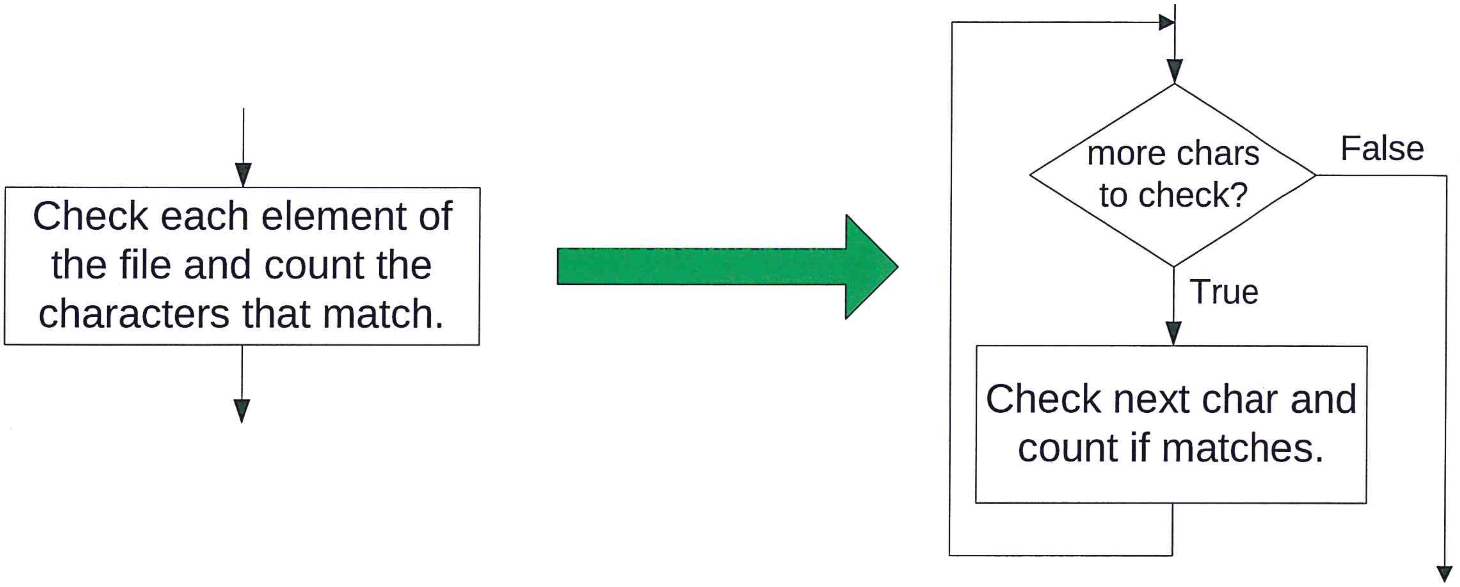
file char = input?

False

Count = Count + 1

Iterative

Do Subtask over and over,
as long as the test condition is true.



Check each element of the file and count the characters that match.

more chars to check?

False

True

Check next char and count if matches.

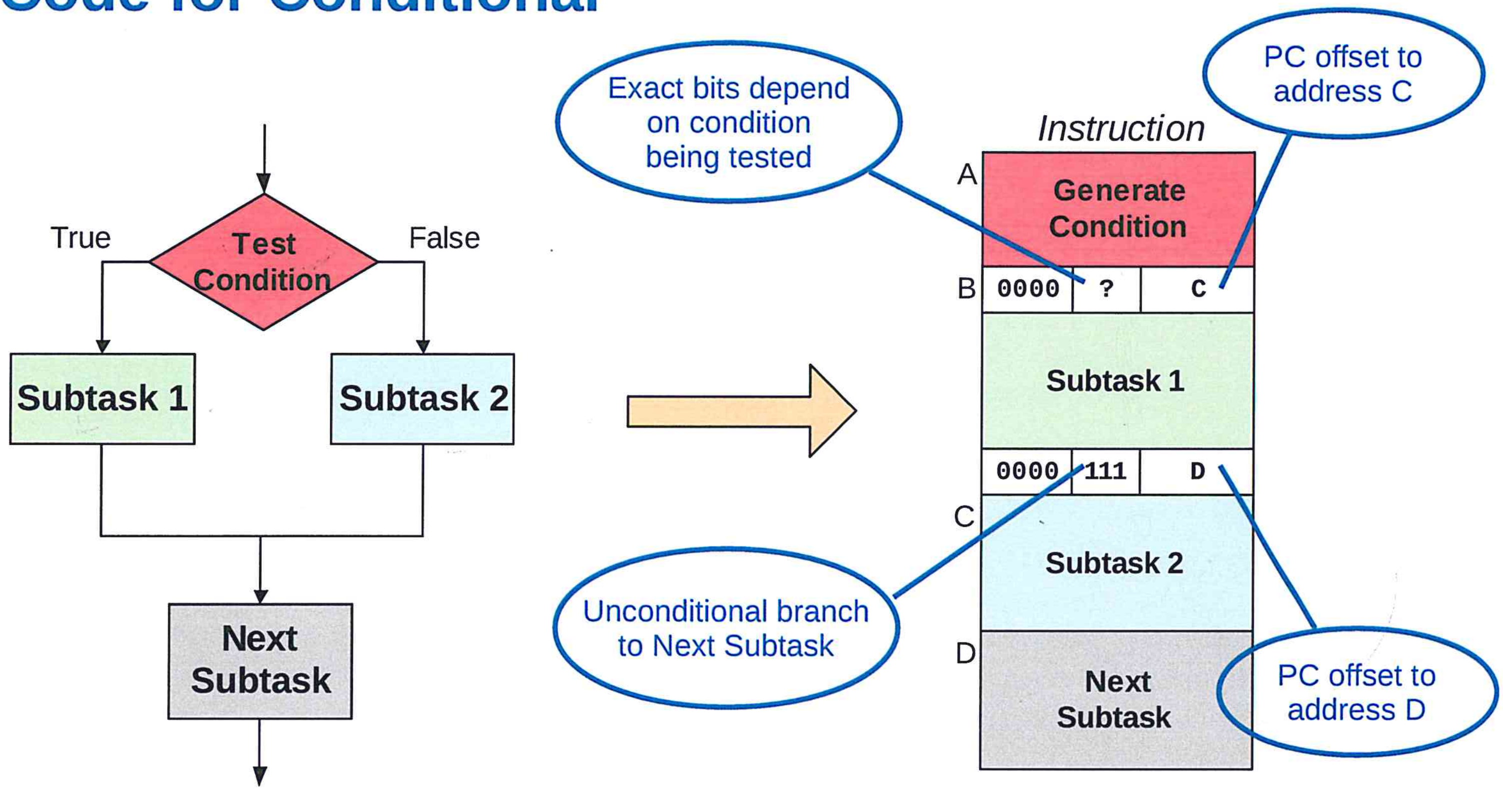
Problem Solving Skills

Learn to convert problem statement into step-by-step description of subtasks.

- Like a puzzle, or a “word problem” from grammar school math.
  - ➢ What is the starting state of the system?
  - ➢ What is the desired ending state?
  - ➢ How do we move from one state to another?

- Recognize English words that correlate to three basic constructs:
  - ➢ “do A then do B” ⇒ sequential
  - ➢ “if G, then do H” ⇒ conditional
  - ➢ “for each X, do Y” ⇒ iterative
  - ➢ “do Z until W” ⇒ iterative

Code for Conditional



Exact bits depend on condition being tested

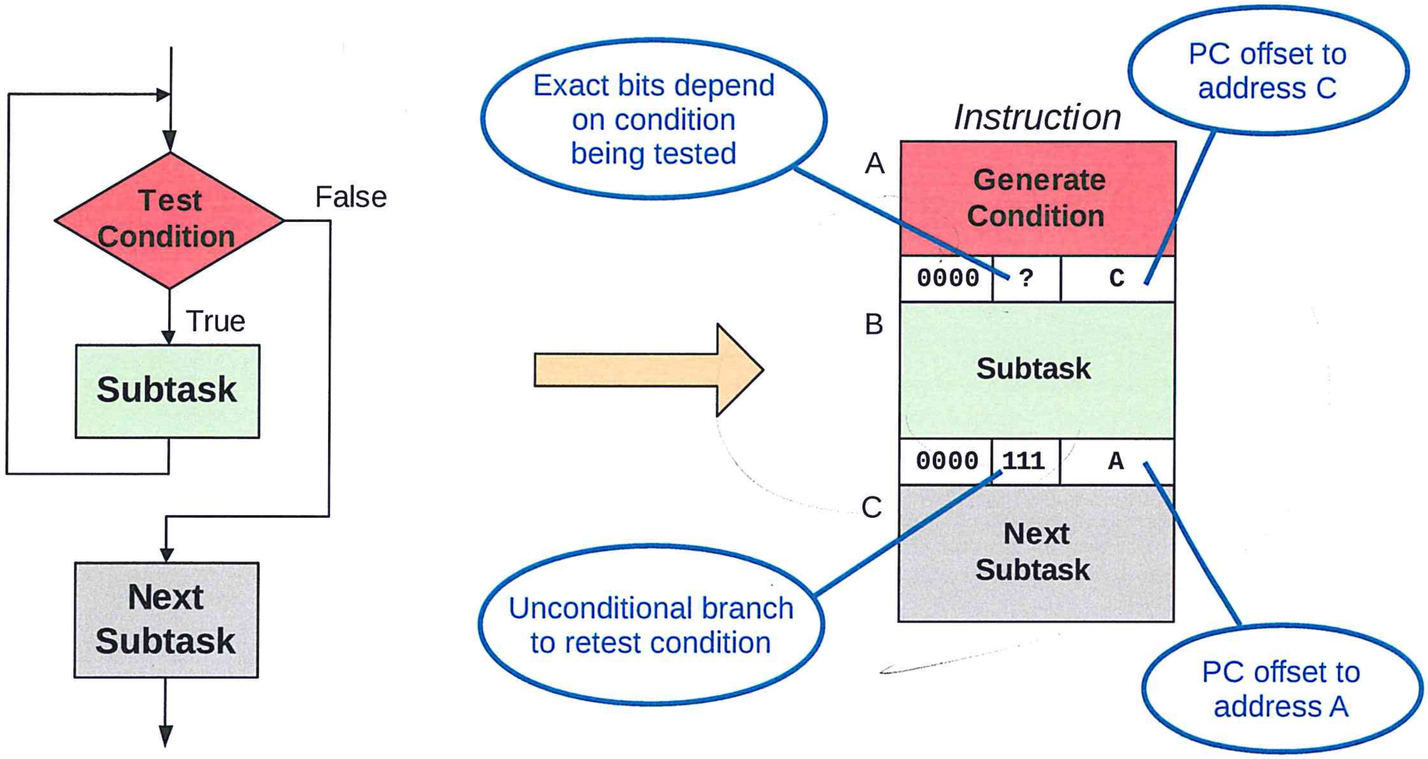
PC offset to address C

Unconditional branch to Next Subtask

PC offset to address D

Assuming all addresses are close enough that PC-relative branch can be used.

Code for Iteration



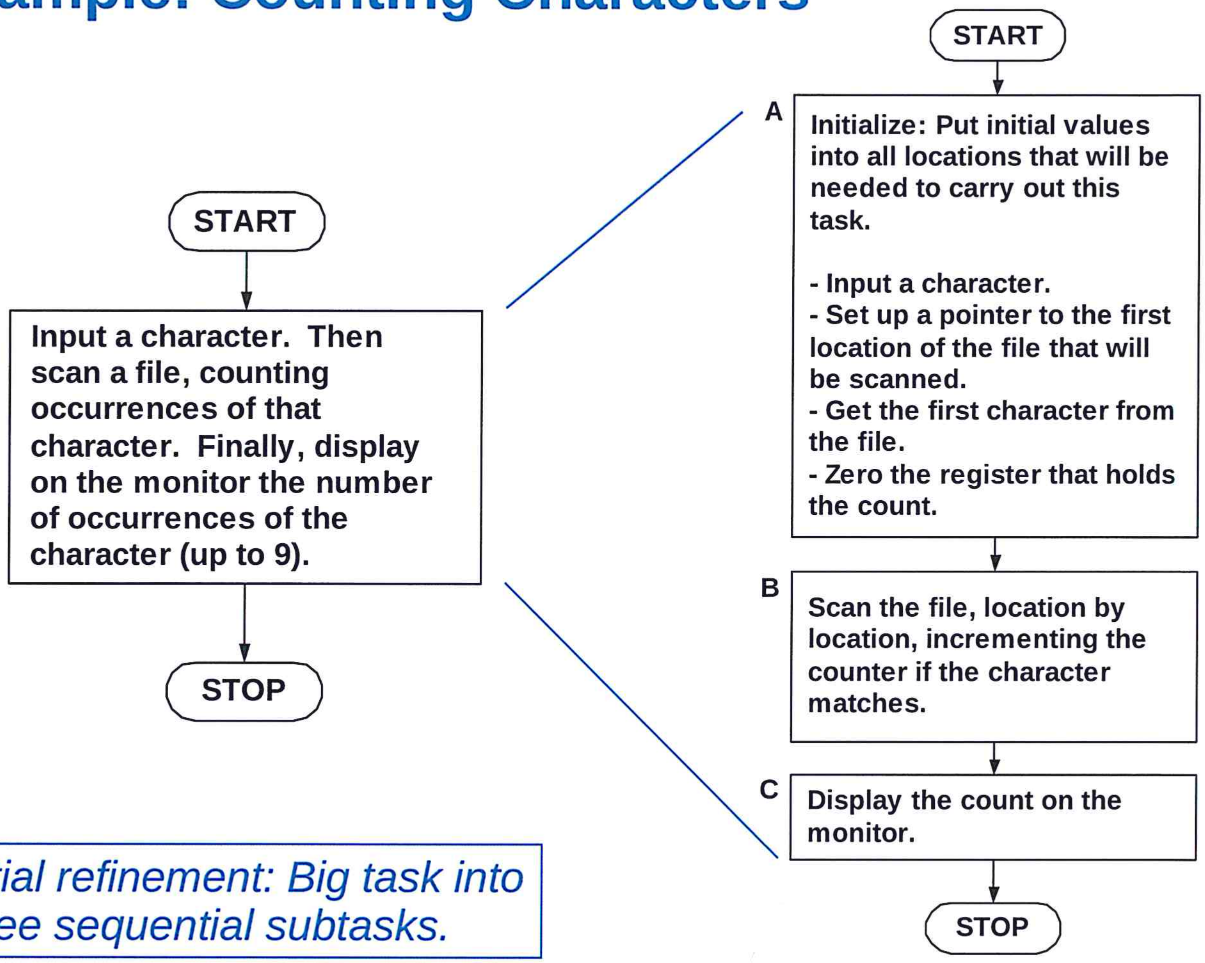
Assuming all addresses are on the same page.

Detailed Example

Count the occurrences of a character in a file

- **Program begins at location x3000**
- **Read character from keyboard**
- **Load each character from a "file"**
  - ➢ File is a sequence of memory locations
  - ➢ Starting address of file is stored in the memory location immediately after the program
- **If file character equals input character, increment counter**
- **End of file is indicated by a special ASCII value: EOT (x04)**
  - ➢ **Sentinal**
- **At the end, print the number of characters and halt**
  (assume there will be less than 10 occurrences of the character)

Example: Counting Characters



START

Input a character. Then scan a file, counting occurrences of that character. Finally, display on the monitor the number of occurrences of the character (up to 9).

STOP

START

A

Initialize: Put initial values into all locations that will be needed to carry out this task.

- Input a character.
- Set up a pointer to the first location of the file that will be scanned.
- Get the first character from the file.
- Zero the register that holds the count.

B

Scan the file, location by location, incrementing the counter if the character matches.

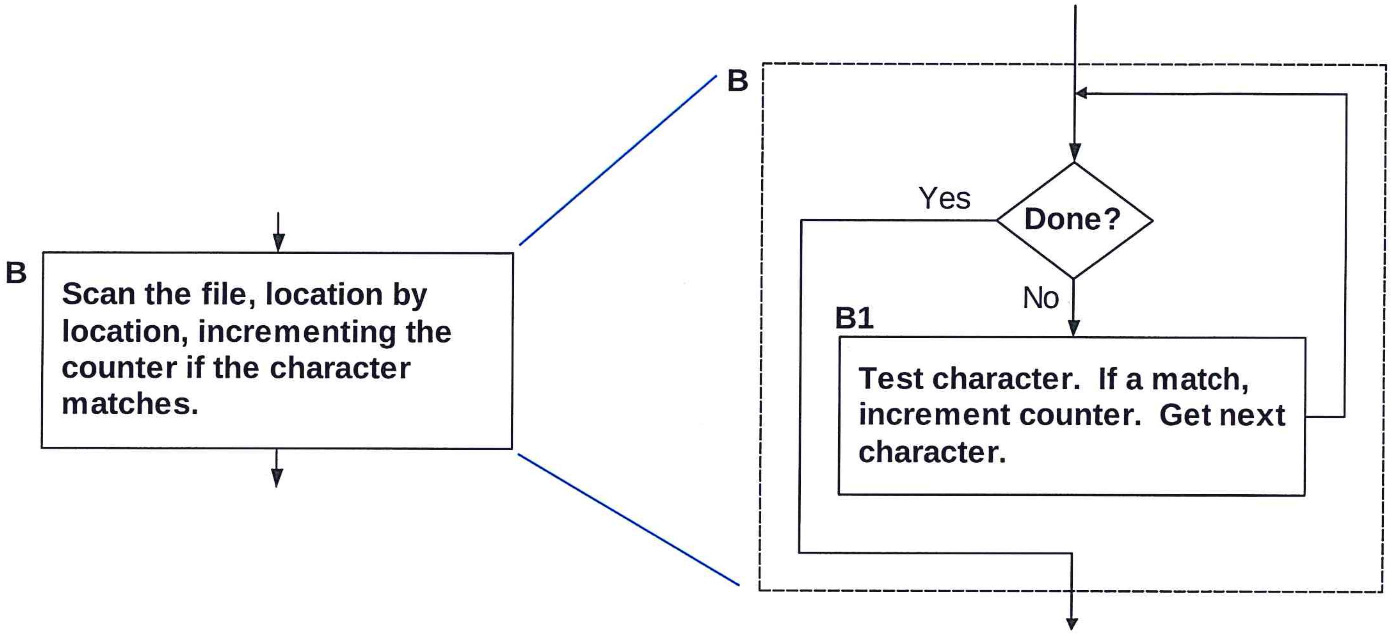
C

Display the count on the monitor.

STOP

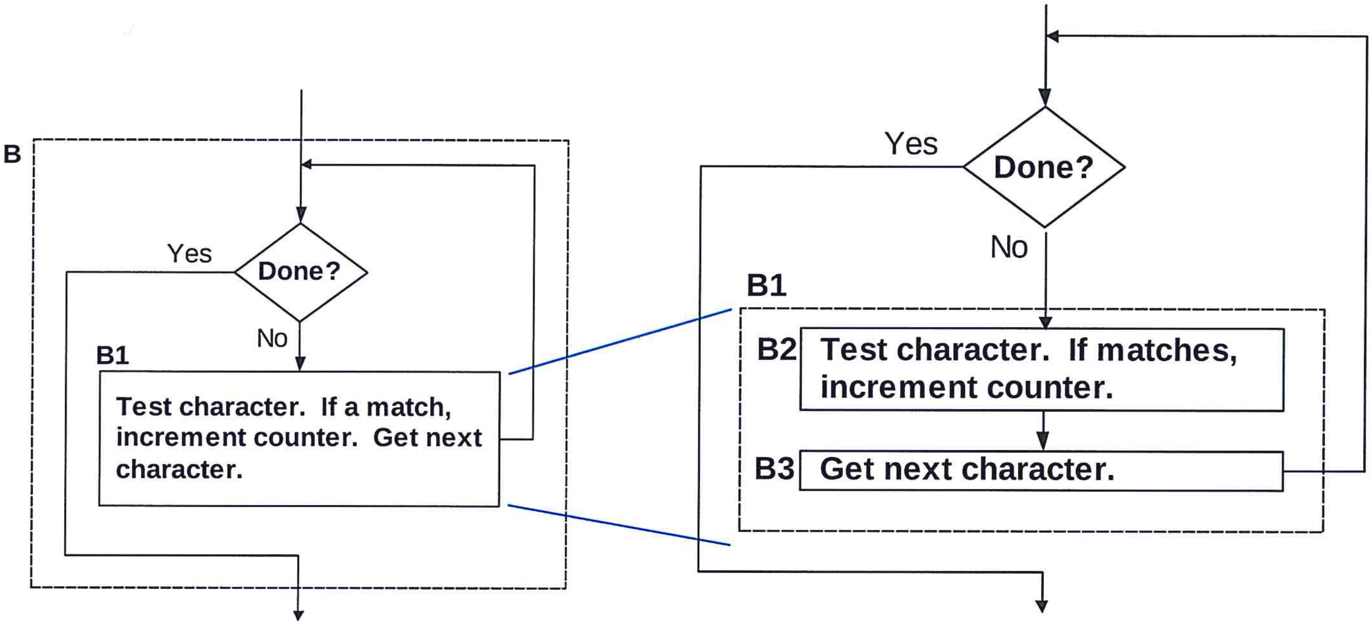
Initial refinement: Big task into three sequential subtasks.

Refining B


B
Scan the file, location by location, incrementing the counter if the character matches.
B
Yes
Done?
No
B1
Test character. If a match, increment counter. Get next character.

Refining B into iterative construct.

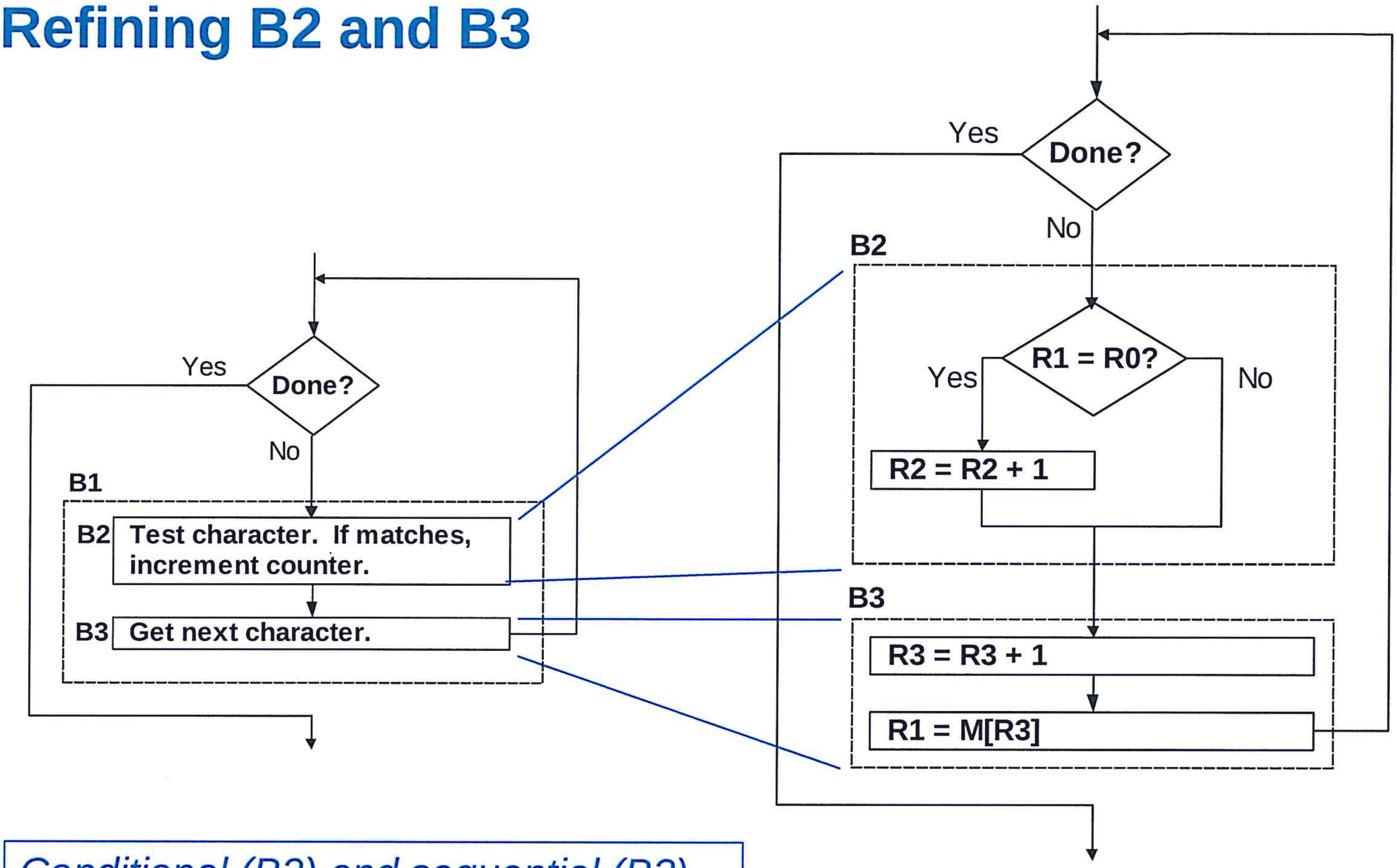
Refining B1



B
Yes
Done?
No
B1
Test character. If a match, increment counter. Get next character.
Yes
Done?
No
B1
B2
Test character. If matches, increment counter.
B3
Get next character.

Refining B1 into sequential subtasks.

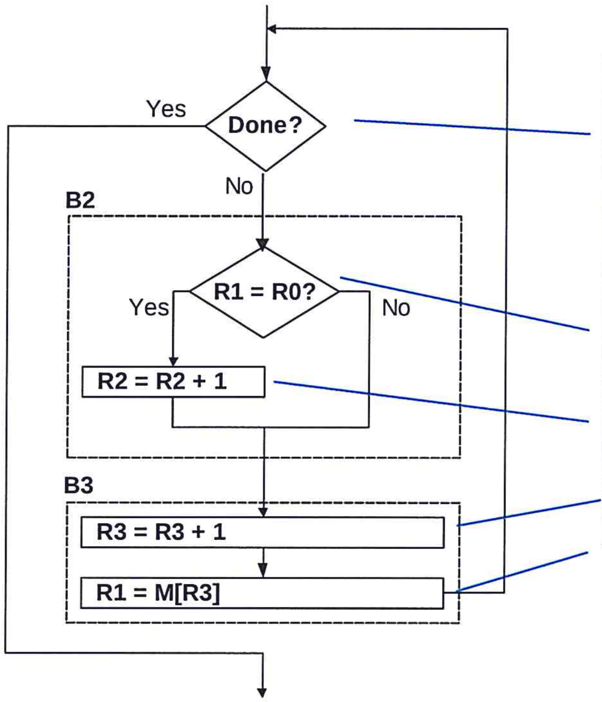
Refining B2 and B3



Conditional (B2) and sequential (B3).
Use of LC-2 registers and instructions.

The Last Step: LC-3 Instructions

Use comments to separate into modules and to document your code.



```
; Look at each char in file.
0001100001111100  ; is R1 = EOT?
0000010xxxxxxxxx  ; if so, exit loop
; Check for match with R0.
1001001001111111  ; R1 = -char
0001001001100001
0001001000000001  ; R1 = R0 – char
0000101xxxxxxxxx  ; no match, skip incr
0001010010100001  ; R2 = R2 + 1
; Incr file ptr and get next char
0001011011100001  ; R3 = R3 + 1
0110001011000000  ; R1 = M[R3]
```

Don't know PCoffset bits until all the code is done

Debugging

You've written your program and it doesn't work.

Now what?

What do you do when you're lost in a city?

- ✗ **Drive around randomly and hope you find it?**
- ✓ **Return to a known point and look at a map?**

In debugging, the equivalent to looking at a map is *tracing* your program.

- **Examine the sequence of instructions being executed.**
- **Keep track of results being produced.**
- **Compare result from each instruction to the *expected* result.**