The LC-3

Instruction Set Architecture

- ISA = All of the *programmer-visible* components and operations of the computer
  - memory organization
    - address space -- how may locations can be addressed?
    - addressability -- how many bits per location?
  - register set
    - how many? what size? how are they used?
  - instruction set
    - opcodes
    - data types
    - addressing modes
- ISA provides all information needed for someone that wants to write a program in machine language
  (or translate from a high-level language to machine language).

LC-3 Overview: Memory and Registers

- Memory
  - address space: 2^{16} locations (16-bit addresses)
  - addressability: 16 bits
- Registers
  - temporary storage, accessed in a single machine cycle
    - accessing memory generally takes longer than a single cycle
  - eight general-purpose registers: R0 - R7
    - each 16 bits wide
    - how many bits to uniquely identify a register?
  - other registers
    - not directly addressable, but used by (and affected by) instructions
    - PC (program counter), condition codes

LC-3 Overview: Instruction Set

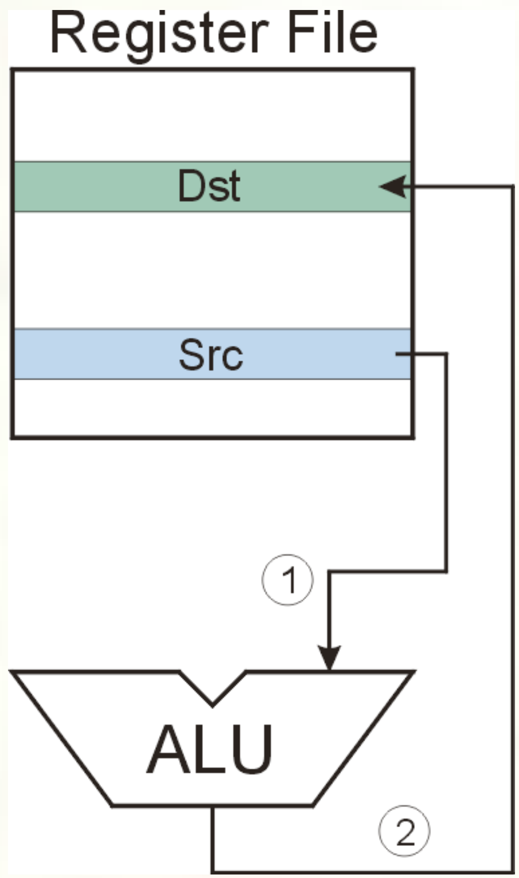
- Opcodes
  - 15 opcodes
  - ***Operate*** instructions: ADD, AND, NOT
  - ***Data movement*** instructions: LD, LDI, LDR, LEA, ST, STR, STI
  - ***Control*** instructions: BR, JSR/JSRR, JMP, RTI, TRAP
  - some opcodes set/clear *condition codes*, based on result:
    - N = negative, Z = zero, P = positive (> 0)
- Data Types
  - 16-bit 2's complement integer
- Addressing Modes
  - How is the location of an operand specified?
  - non-memory addresses: *immediate*, *register*
  - memory addresses: *PC-relative*, *indirect*, *base+offset*

Operate Instructions

- Only three operations: ADD, AND, NOT
- Source and destination operands are registers
  - These instructions *do not* reference memory.
  - ADD and AND can use "immediate" mode, where one operand is hard-wired into the instruction.
- Will show dataflow diagram with each instruction.
  - illustrates *when* and *where* data moves to accomplish the desired operation

NOT (Register)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
NOT	1	0	0	1	Dst			Src			1	1	1	1	1	1



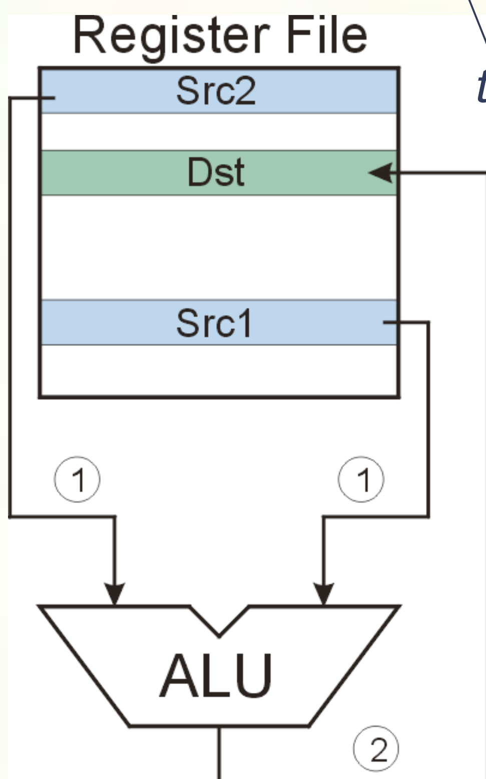
Note: Src and Dst could be the same register.

ADD/AND (Register)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
ADD	0	0	0	1	Dst			Src1			0	0	0	Src2		

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
AND	0	1	0	1	Dst			Src1			0	0	0	Src2		

this zero means "register mode"

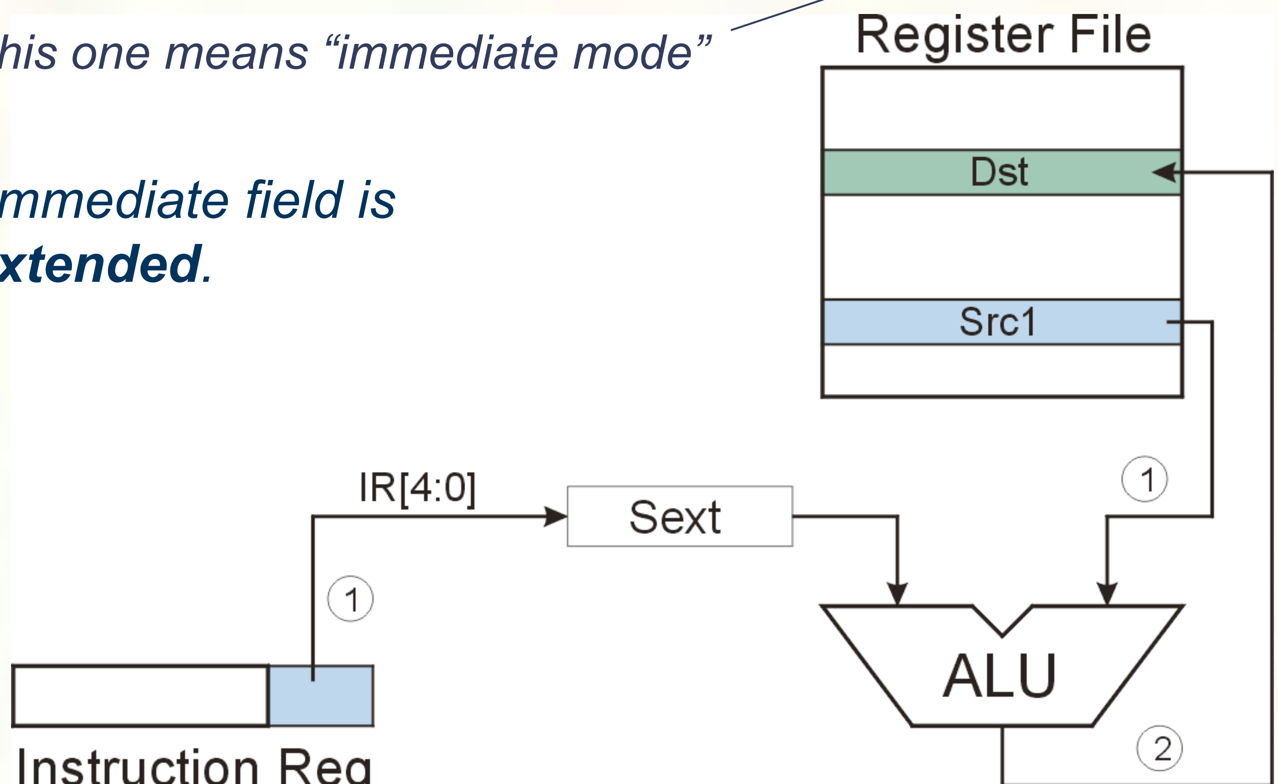


ADD/AND (Immediate)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
ADD	0	0	0	1	Dst			Src1			1	Imm5				
AND	0	1	0	1	Dst			Src1			1	Imm5				

this one means "immediate mode"

Note: Immediate field is ***sign-extended****.*



Using Operate Instructions

- With only ADD, AND, NOT…
  - How do we subtract?
  - How do we OR?
  - How do we copy from one register to another?
  - How do we initialize a register to zero?

Data Movement Instructions

- Load -- read data from memory to register
  - LD: PC-relative mode
  - LDR: base+offset mode
  - LDI: indirect mode

- Store -- write data from register to memory
  - ST: PC-relative mode
  - STR: base+offset mode
  - STI: indirect mode

- Load effective address -- compute address, save in register
  - LEA: immediate mode
  - *does not access memory*

PC-Relative Addressing Mode

- Want to specify address directly in the instruction
  - But an address is 16 bits, and so is an instruction!
  - After subtracting 4 bits for opcode
    and 3 bits for register, we have <u>9 bits</u> available for address.

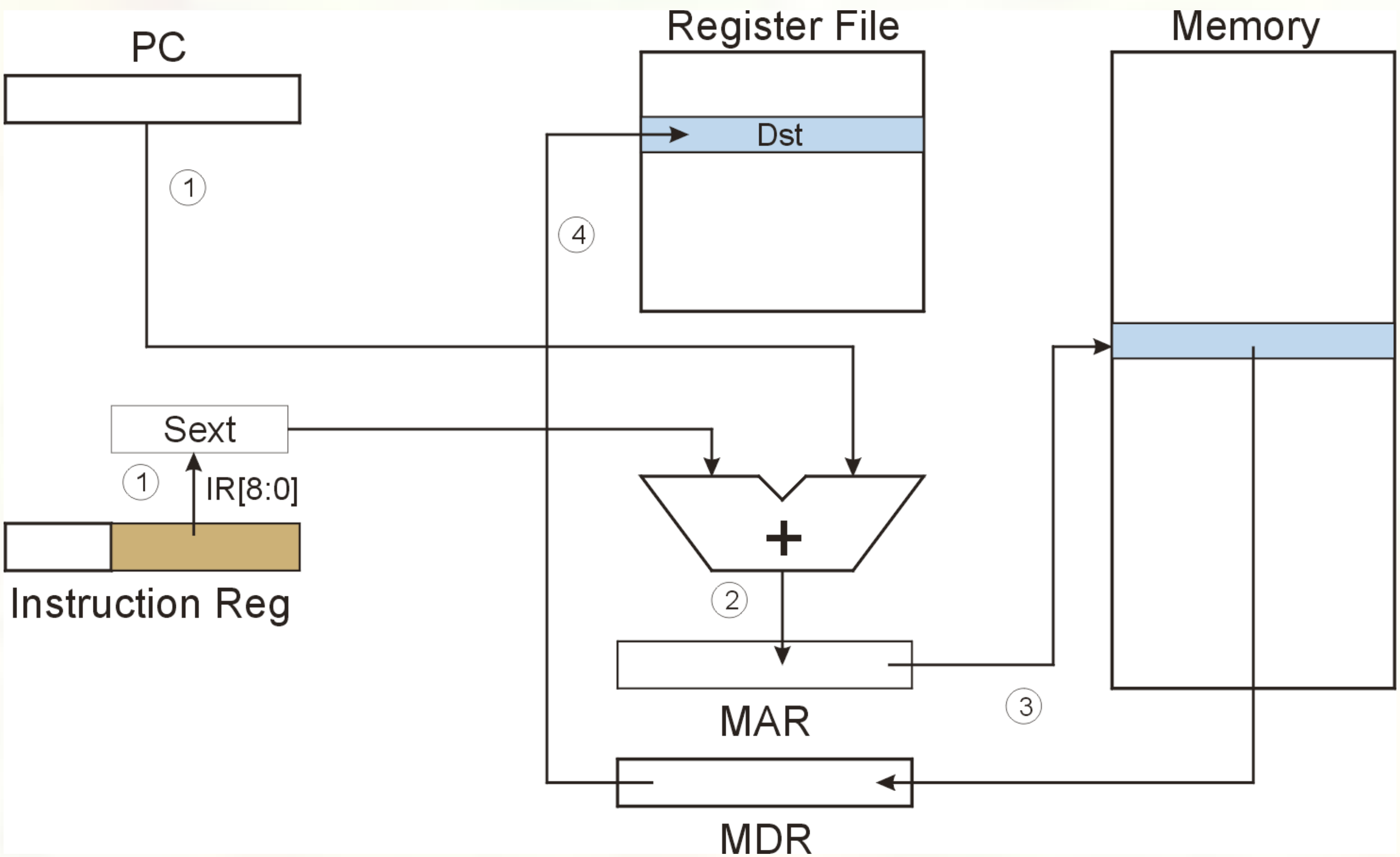
- Solution:
  - Use the 9 bits as a <u>*signed offset*</u> from the current PC.

- 9 bits: $-256 \leq \text{offset} \leq +255$
- Can form any address X, such that: $PC - 256 \leq X \leq PC + 255$

- Remember that PC is incremented as part of the FETCH phase;
- This is done <u>before</u> the EVALUATE ADDRESS stage.

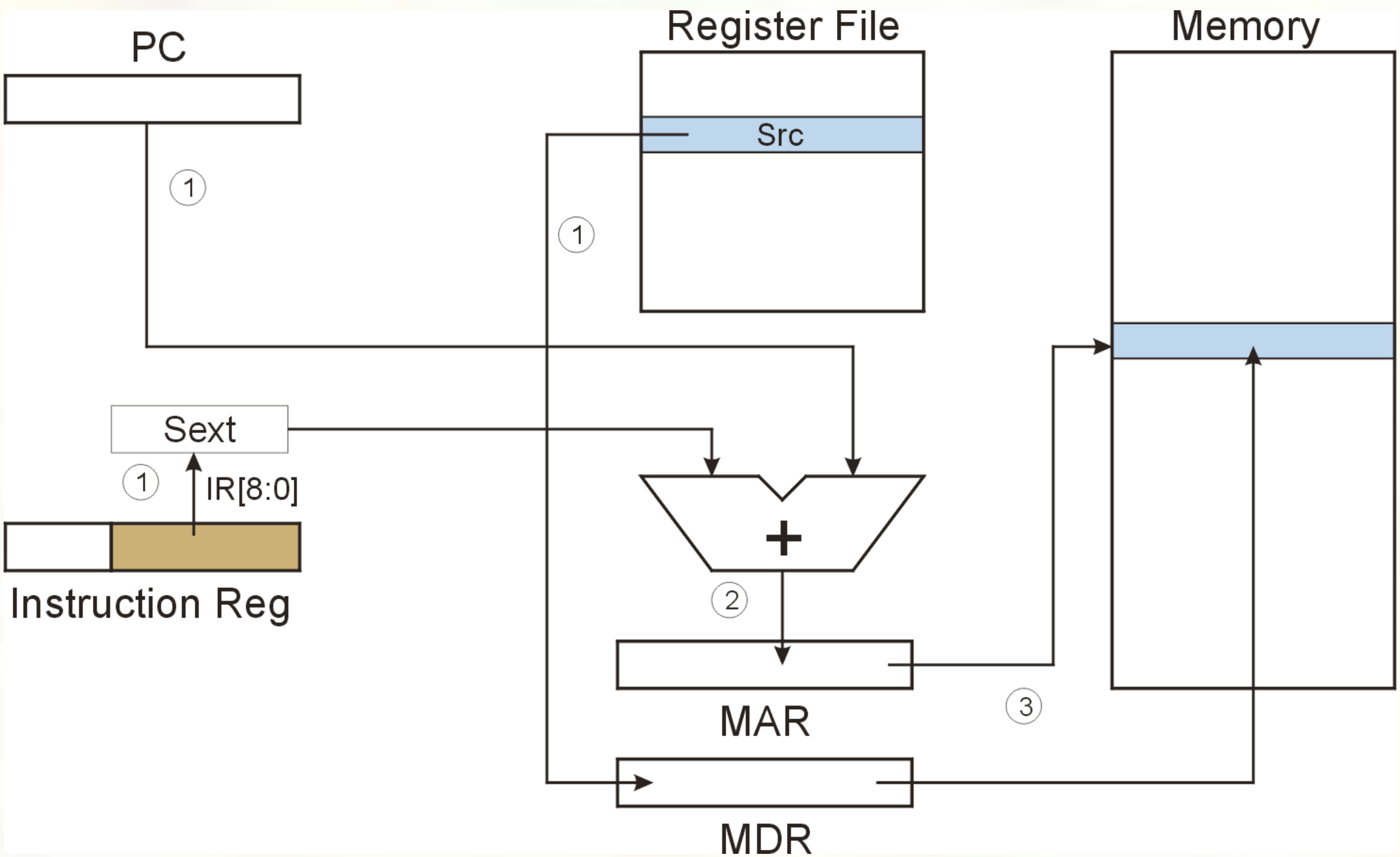
LD (PC-Relative)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
LD	0	0	1	0	Dst			PCoffset9								



ST (PC-Relative)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
ST	0	0	1	1	Src			PCoffset9								



Indirect Addressing Mode

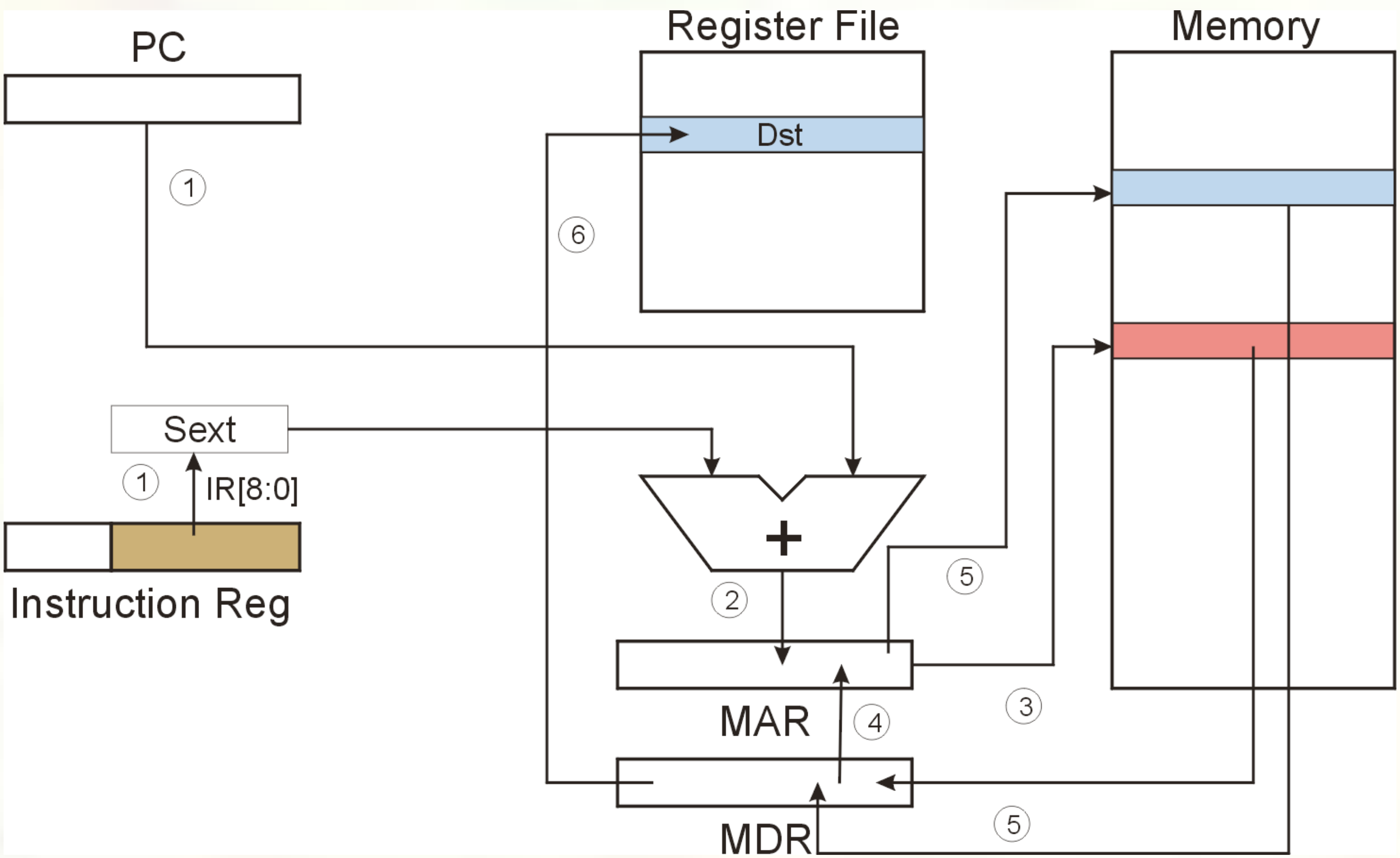
- With PC-relative mode, can only address data within 256 words of the instruction.
  - What about the rest of memory?

- Solution #1:
  - Read address from memory location, then load/store to that address.

- First address is generated from PC and IR (just like PC-relative addressing), then content of that address is used as target for load/store.

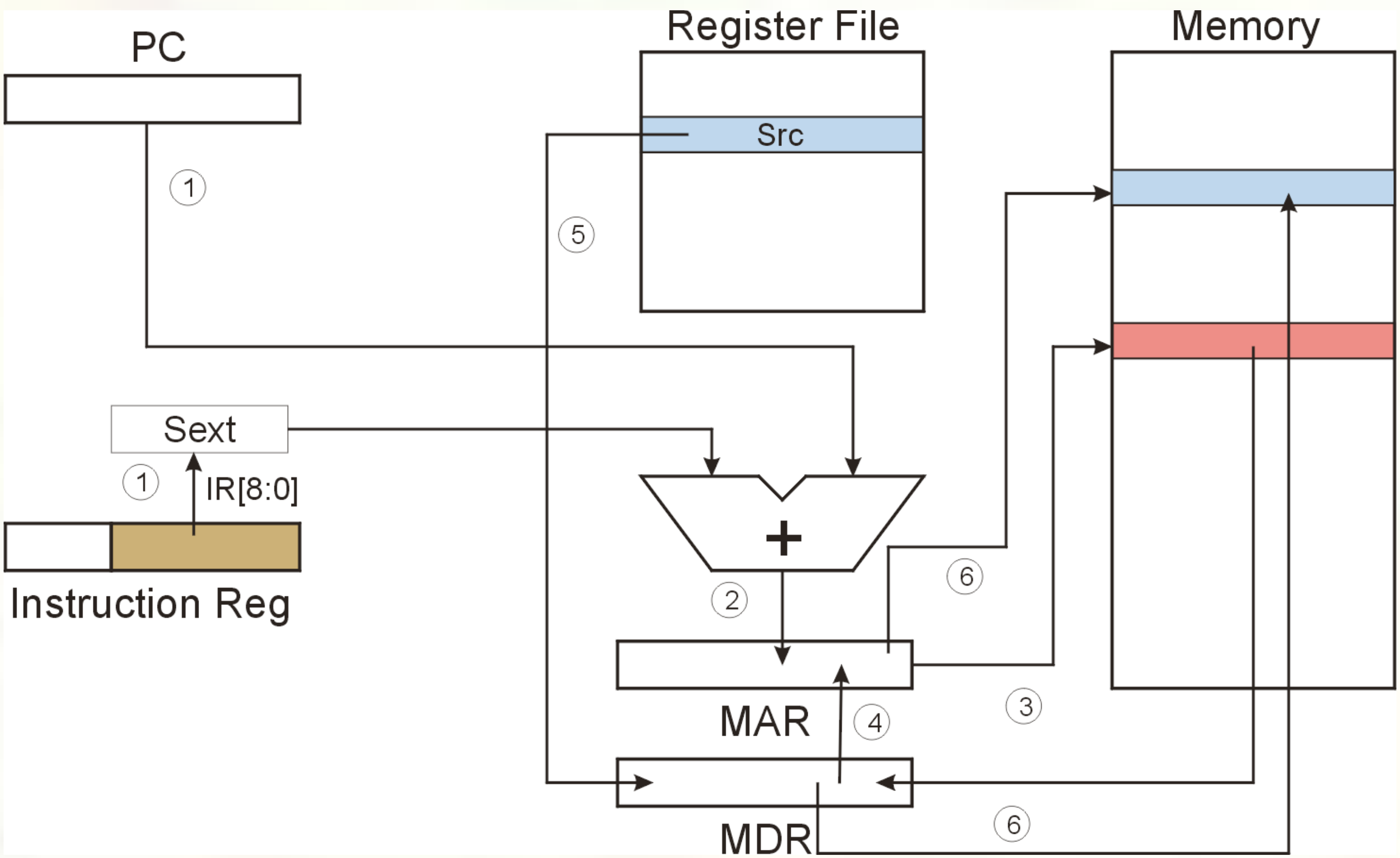
LDI (Indirect)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
LDI	1	0	1	0	Dst			PCoffset9								



STI (Indirect)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
STI	1	0	1	1	Src			PCoffset9								



Base + Offset Addressing Mode

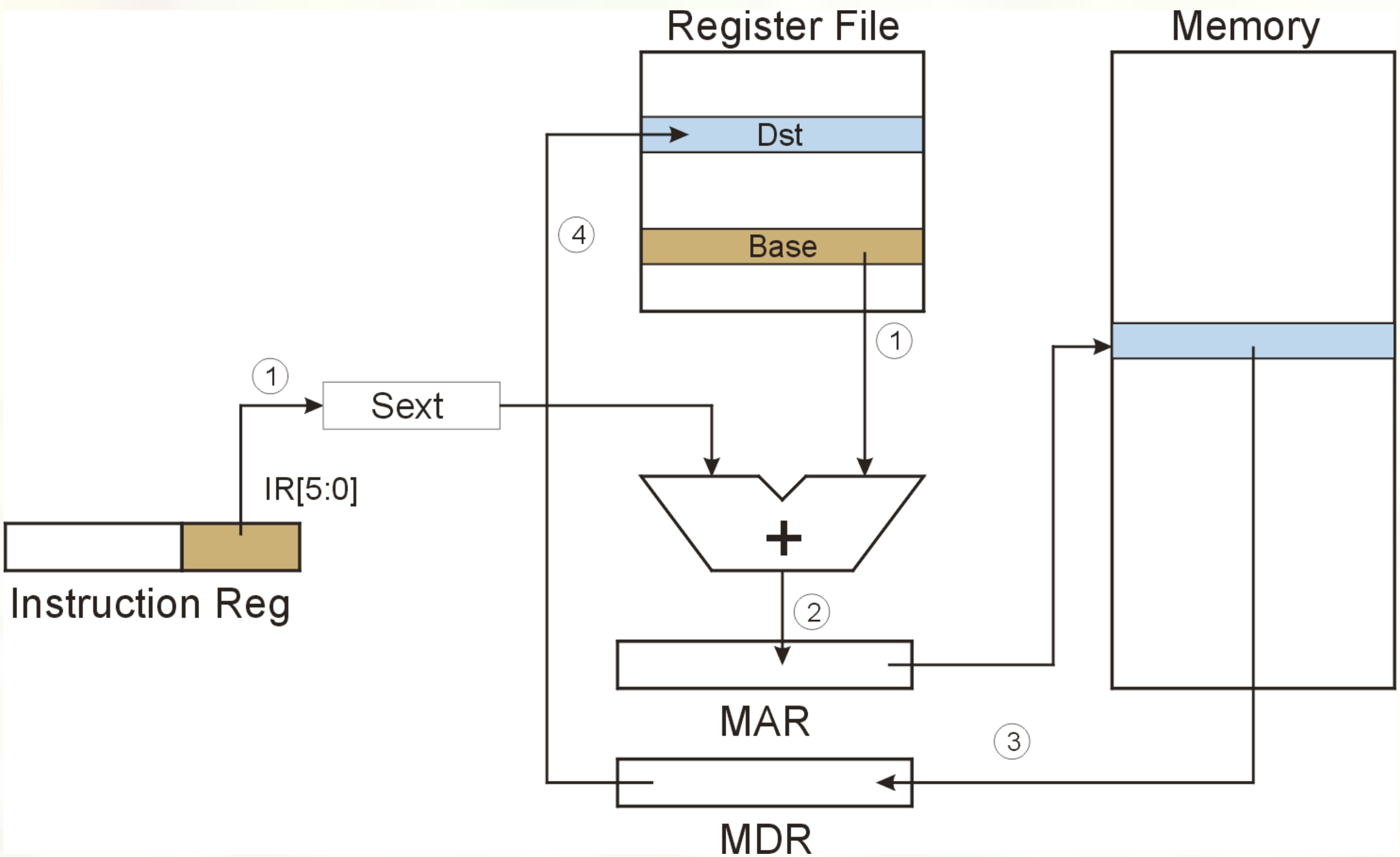
- With PC-relative mode, can only address data within 256 words of the instruction.
  - What about the rest of memory?

- Solution #2:
  - Use a register to generate a full 16-bit address.

- 4 bits for opcode, 3 for src/dest register, 3 bits for *base* register -- remaining 6 bits are used as a *signed offset*.
  - **Offset is *sign-extended* before adding to base register.**

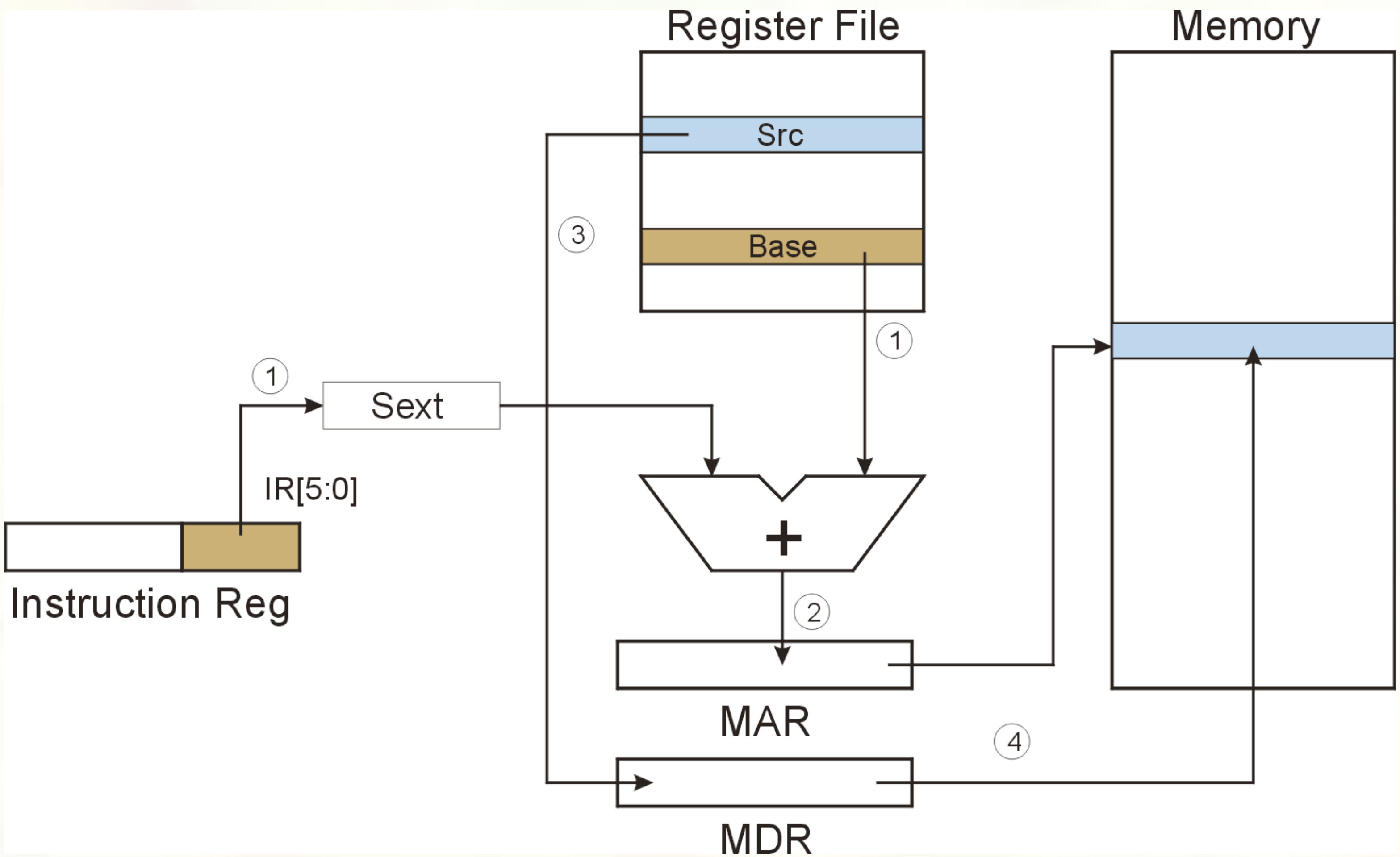
LDR (Base+Offset)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
LDR	0	1	1	0	Dst			Base			offset6					



STR (Base+Offset)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
STR	0	1	1	1	Src			Base			offset6					



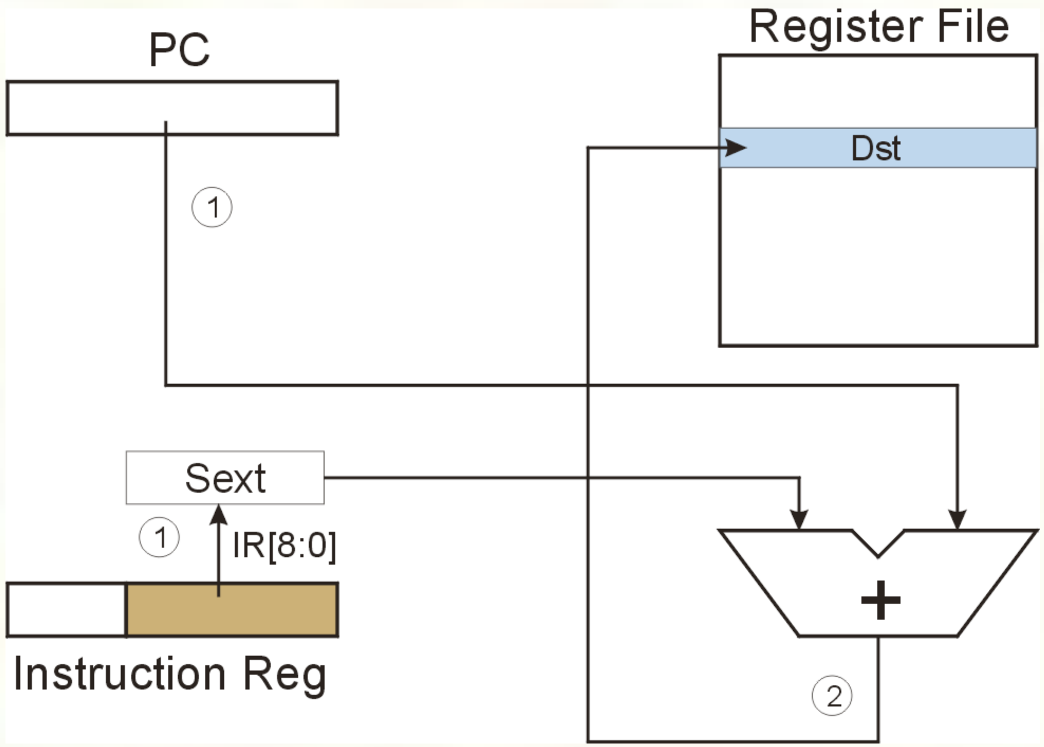
Load Effective Address

- Computes address like PC-relative (PC plus signed offset) and stores the result into a register.

- Note: The *address* is stored in the register, not the contents of the memory location.

LEA (Immediate)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
LEA	1	1	1	0	Dst			PCoffset9								



Example

Address	*Instruction*	*Comments*
x30F6	1 1 1 0 0 0 1 1 1 1 1 1 1 1 0 1	*R1 ← PC – 3 = x30F4*
x30F7	0 0 0 1 0 1 0 0 0 1 1 0 1 1 1 0	*R2 ← R1 + 14 = x3102*
x30F8	0 0 1 1 0 1 0 1 1 1 1 1 1 0 1 1	*M[PC - 5] ← R2* *M[x30F4] ← x3102*
x30F9	0 1 0 1 0 1 0 0 1 0 1 0 0 0 0 0	*R2 ← 0*
x30FA	0 0 0 1 0 1 0 0 1 0 1 0 0 1 0 1	*R2 ← R2 + 5 = 5*
x30FB	0 1 1 1 0 1 0 0 0 1 0 0 1 1 1 0	*M[R1+14] ← R2* *M[x3102] ← 5*
x30FC	1 0 1 0 0 1 1 1 1 1 1 1 0 1 1 1	*R3 ← M[M[x30F4]]* *R3 ← M[x3102]* *R3 ← 5*

opcode

Control Instructions

- Used to alter the sequence of instructions (by changing the Program Counter)

- Conditional Branch
  - branch is *taken* if a specified condition is true
    - signed offset is added to PC to yield new PC
  - else, the branch is *not taken*
    - PC is not changed, points to the next sequential instruction

- Unconditional Branch (or Jump)
  - always changes the PC

- TRAP
  - changes PC to the address of an OS "service routine"
  - routine will return control to the next instruction (after TRAP)

Condition Codes

- LC-3 has three condition code registers:
  N -- negative
  Z -- zero
  P -- positive (greater than zero)

- Set by any instruction that writes a value to a register (ADD, AND, NOT, LD, LDR, LDI, LEA)

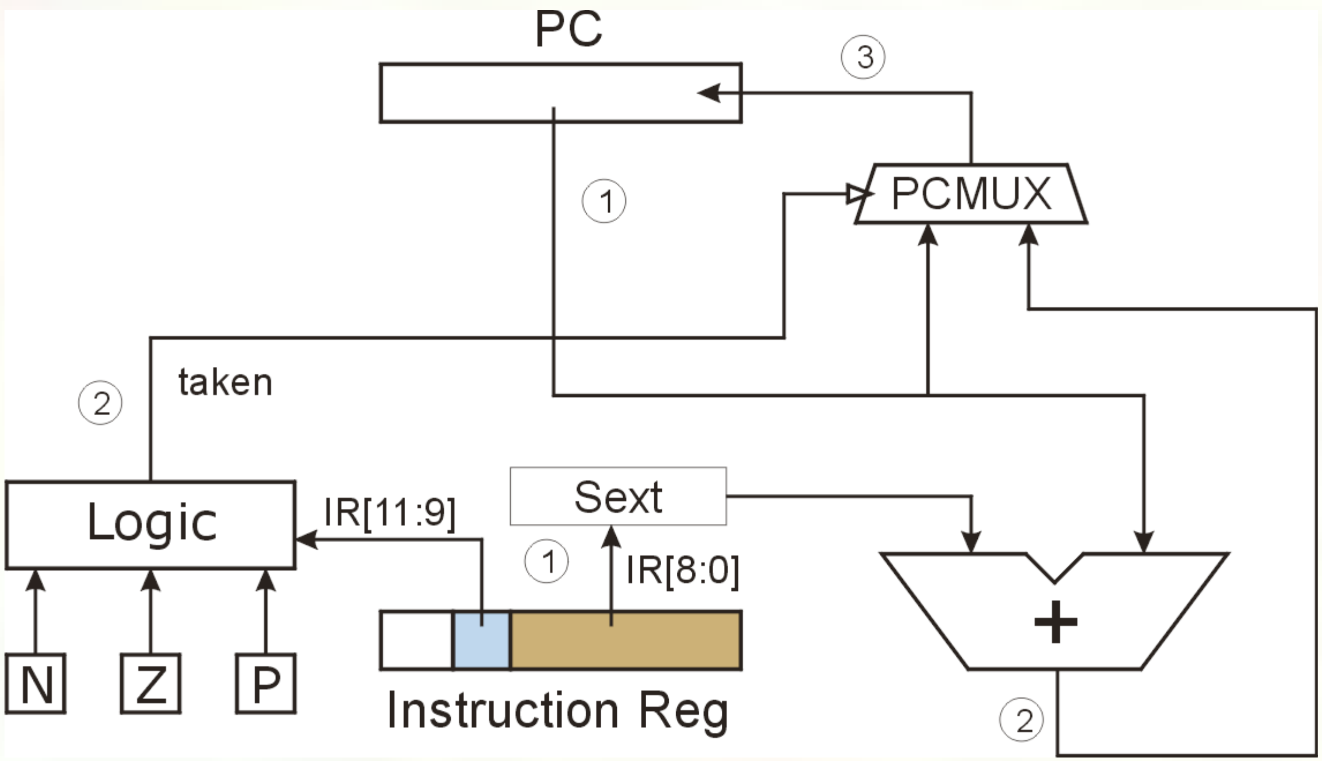
- Exactly <u>one</u> will be set at all times
  - Based on the last instruction that altered a register

Branch Instruction

- Branch specifies one or more condition codes.
- If the set bit is specified, the branch is taken.
  - PC-relative addressing:
    target address is made by adding signed offset (IR[8:0])
    to current PC.
  - Note: PC has already been incremented by FETCH stage.
  - Note: Target must be within 256 words of BR instruction.
- If the branch is not taken,
  the next sequential instruction is executed.

BR (PC-Relative)

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
BR	0	0	0	0	n	z	p	PCoffset9								

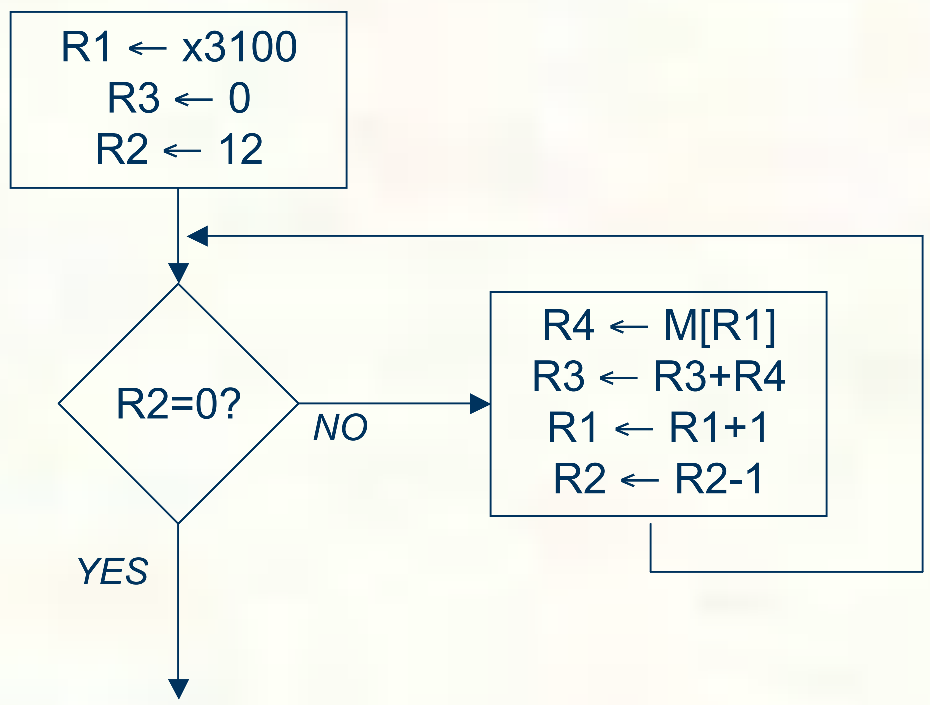


What happens if bits [11:9] are all zero? All one?

Using Branch Instructions

- Compute sum of 12 integers.

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



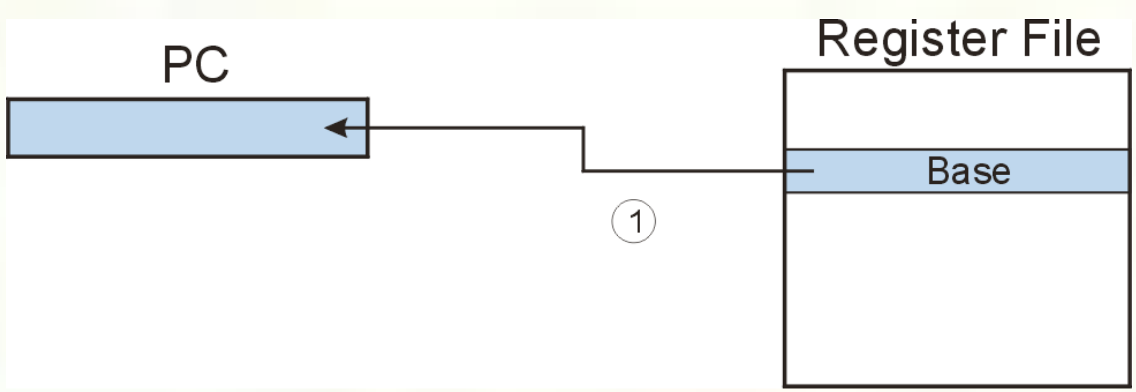
Sample Program

Address	*Instruction*	*Comments*
x3000	1 1 1 0 0 0 1 0 1 1 1 1 1 1 1 1	*R1 ← x3100 (PC+0xFF)*
x3001	0 1 0 1 0 1 1 0 1 1 1 0 0 0 0 0	*R3 ← 0*
x3002	0 1 0 1 0 1 0 0 1 0 1 0 0 0 0 0	*R2 ← 0*
x3003	0 0 0 1 0 1 0 0 1 0 1 0 1 1 0 0	*R2 ← 12*
x3004	0 0 0 0 0 1 0 0 0 0 0 0 0 1 0 1	*If Z, goto x300A (PC+5)*
x3005	0 1 1 0 1 0 0 0 0 1 0 0 0 0 0 0	*Load next value to R4*
x3006	0 0 0 1 0 1 1 0 1 1 0 0 0 0 0 1	*Add to R3*
x3007	0 0 0 1 0 0 1 0 0 1 1 0 0 0 0 1	*Increment R1 (pointer)*
X3008	0 0 0 1 0 1 0 0 1 0 1 1 1 1 1 1	*Decrement R2 (counter)*
x3009	0 0 0 0 1 1 1 1 1 1 1 1 1 0 1 0	*Goto x3004 (PC-6)*

JMP (Register)

- Jump is an unconditional branch -- *always* taken.
  - Target address is the contents of a register.
  - Allows any target address.

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



TRAP

	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

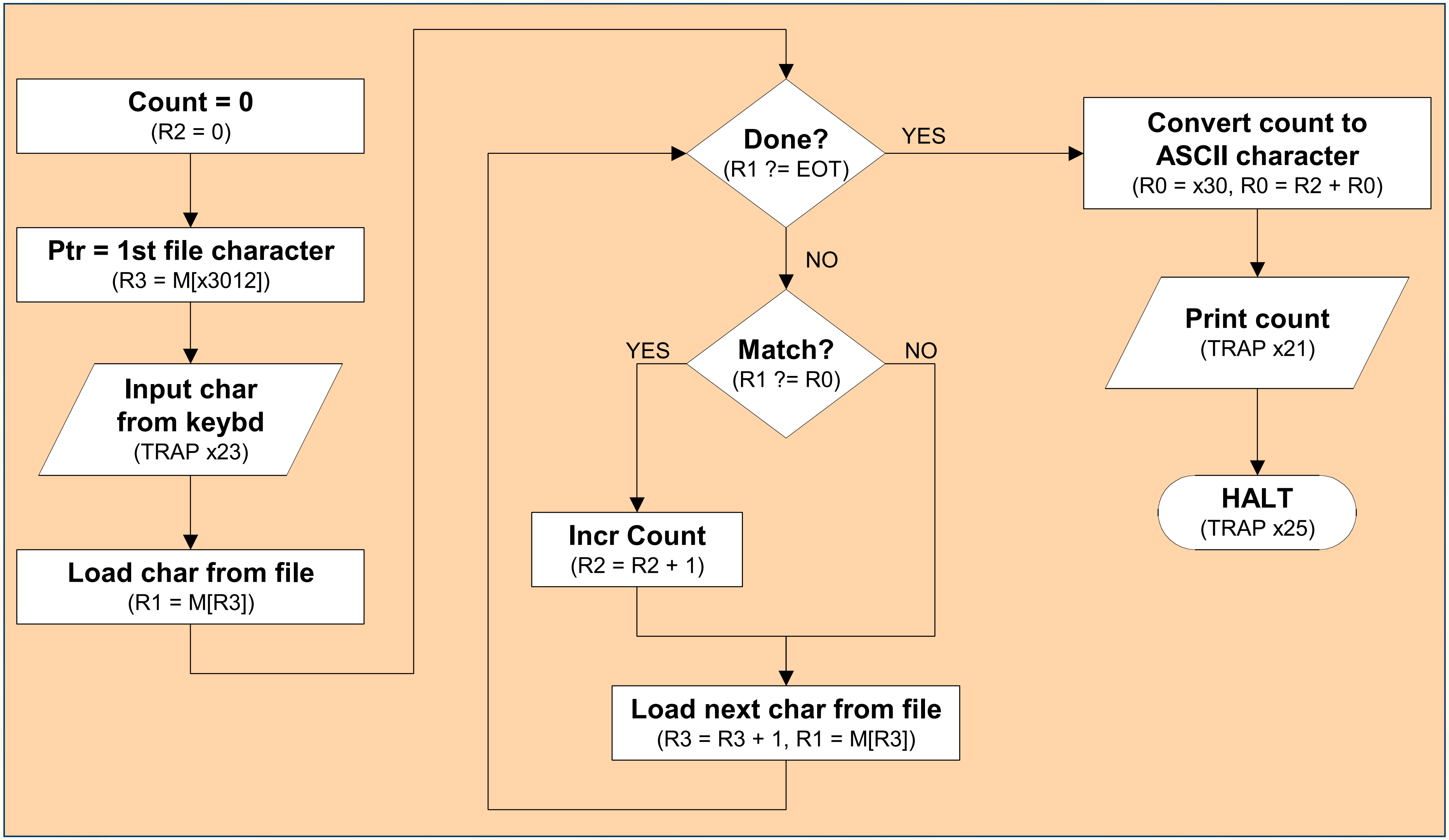
- When routine is done,
  PC is set to the instruction following TRAP.
- (We'll talk about how this works later.)

Another 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)
  - At the end, print the number of characters and halt **(assume there will be less than 10 occurrences of the character)**

- A special character used to indicate the end of a sequence is often called a sentinel.
  - **Useful when you don't know ahead of time how many times to execute a loop.**

Flow Chart



Count = 0
(R2 = 0)
Ptr = 1st file character
(R3 = M[x3012])
Input char
from keybd
(TRAP x23)
Load char from file
(R1 = M[R3])
Done?
(R1 ?= EOT)
YES
NO
Convert count to
ASCII character
(R0 = x30, R0 = R2 + R0)
Print count
(TRAP x21)
HALT
(TRAP x25)
Match?
(R1 ?= R0)
YES
NO
Incr Count
(R2 = R2 + 1)
Load next char from file
(R3 = R3 + 1, R1 = M[R3])

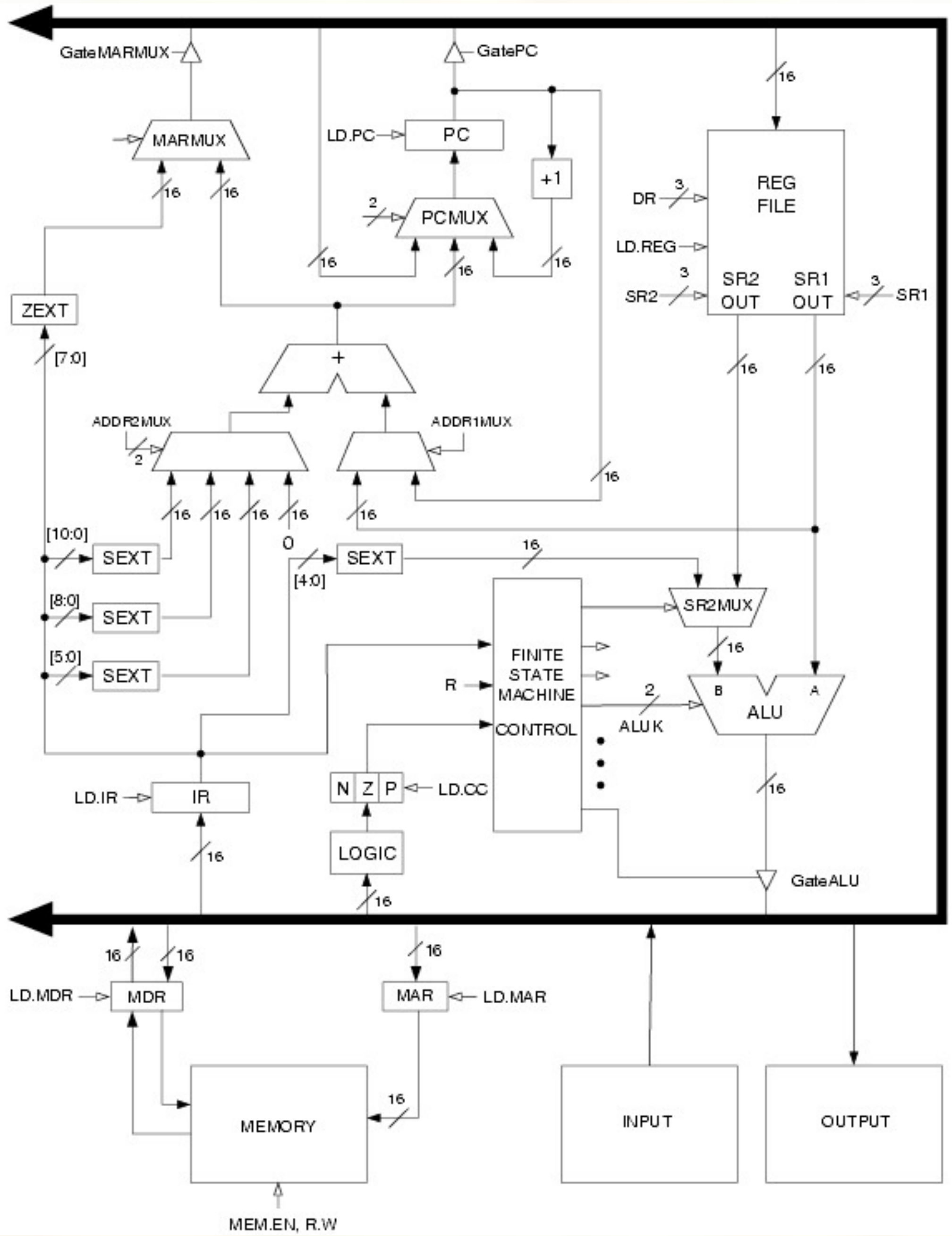
Program (1 of 2)

Address	*Instruction*					*Comments*
x3000	0 1 0 1	0 1 0	0 1 0	1	0 0 0 0 0	***R2 ← 0 (counter)***
x3001	0 0 1 0	0 1 1	0 0 0 0 1 0 0 0 0			***R3 ← M[x3012] (ptr)***
x3002	1 1 1 1	0 0 0 0	0 0 1 0 0 0 1 1			***Input to R0 (TRAP x23)***
x3003	0 1 1 0	0 0 1	0 1 1	0 0 0 0 0 0		***R1 ← M[R3]***
x3004	0 0 0 1	1 0 0	0 0 1	1	1 1 1 0 0	***R4 ← R1 – 4 (EOT)***
x3005	0 0 0 0	0 1 0	0 0 0 0 0 1 0 0 0			***If Z, goto x300E***
x3006	1 0 0 1	0 0 1	0 0 1	1	1 1 1 1 1	***R1 ← NOT R1***
x3007	0 0 0 1	0 0 1	0 0 1	1	0 0 0 0 1	***R1 ← R1 + 1***
X3008	0 0 0 1	0 0 1	0 0 1	0	0 0 0 0 0	***R1 ← R1 + R0***
x3009	0 0 0 0	1 0 1	0 0 0 0 0 0 0 0 1			***If N or P, goto x300B***

Program (2 of 2)

Address	*Instruction*					*Comments*
x300A	0 0 0 1	0 1 0	0 1 0	1	0 0 0 0 1	*R2 ← R2 + 1*
x300B	0 0 0 1	0 1 1	0 1 1	1	0 0 0 0 1	*R3 ← R3 + 1*
x300C	0 1 1 0	0 0 1	0 1 1		0 0 0 0 0 0	*R1 ← M[R3]*
x300D	0 0 0 0	1 1 1			1 1 1 1 1 0 1 1 0	*Goto x3004*
x300E	0 0 1 0	0 0 0			0 0 0 0 0 0 1 0 0	*R0 ← M[x3013]*
x300F	0 0 0 1	0 0 0	0 0 0	0	0 0 0 1 0	*R0 ← R0 + R2*
x3010	1 1 1 1	0 0 0 0			0 0 1 0 0 0 0 1	*Print R0 (TRAP x21)*
x3011	1 1 1 1	0 0 0 0			0 0 1 0 0 1 0 1	*HALT (TRAP x25)*
X3012	Starting Address of File					
x3013	0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0					*ASCII x30 ('0')*

LC-3 Data Path Revisited



Filled arrow

= info to be processed.

Unfilled arrow

= control signal.

Data Path Components

- Global bus
  - special set of wires that carry a 16-bit signal to many components
  - inputs to the bus are "tri-state devices," that only place a signal on the bus when they are enabled
  - only one (16-bit) signal should be enabled at any time
    - control unit decides which signal "drives" the bus
  - any number of components can read the bus
    - register only captures bus data if it is write-enabled by the control unit

- Memory
  - Control and data registers for memory and I/O devices
  - memory: MAR, MDR (also control signal for read/write)

Data Path Components

- ALU
  - Accepts inputs from register file
    and from sign-extended bits from IR (immediate field).
  - Output goes to bus.
    - used by condition code logic, register file, memory
- Register File
  - Two read addresses (SR1, SR2), one write address (DR)
  - Input from bus
    - result of ALU operation or memory read
  - Two 16-bit outputs
    - used by ALU, PC, memory address
    - data for store instructions passes through ALU

Data Path Components

PC and PCMUX

- Three inputs to PC, controlled by PCMUX
  - PC+1 – FETCH stage
  - Address adder – BR, JMP
  - bus – TRAP (discussed later)

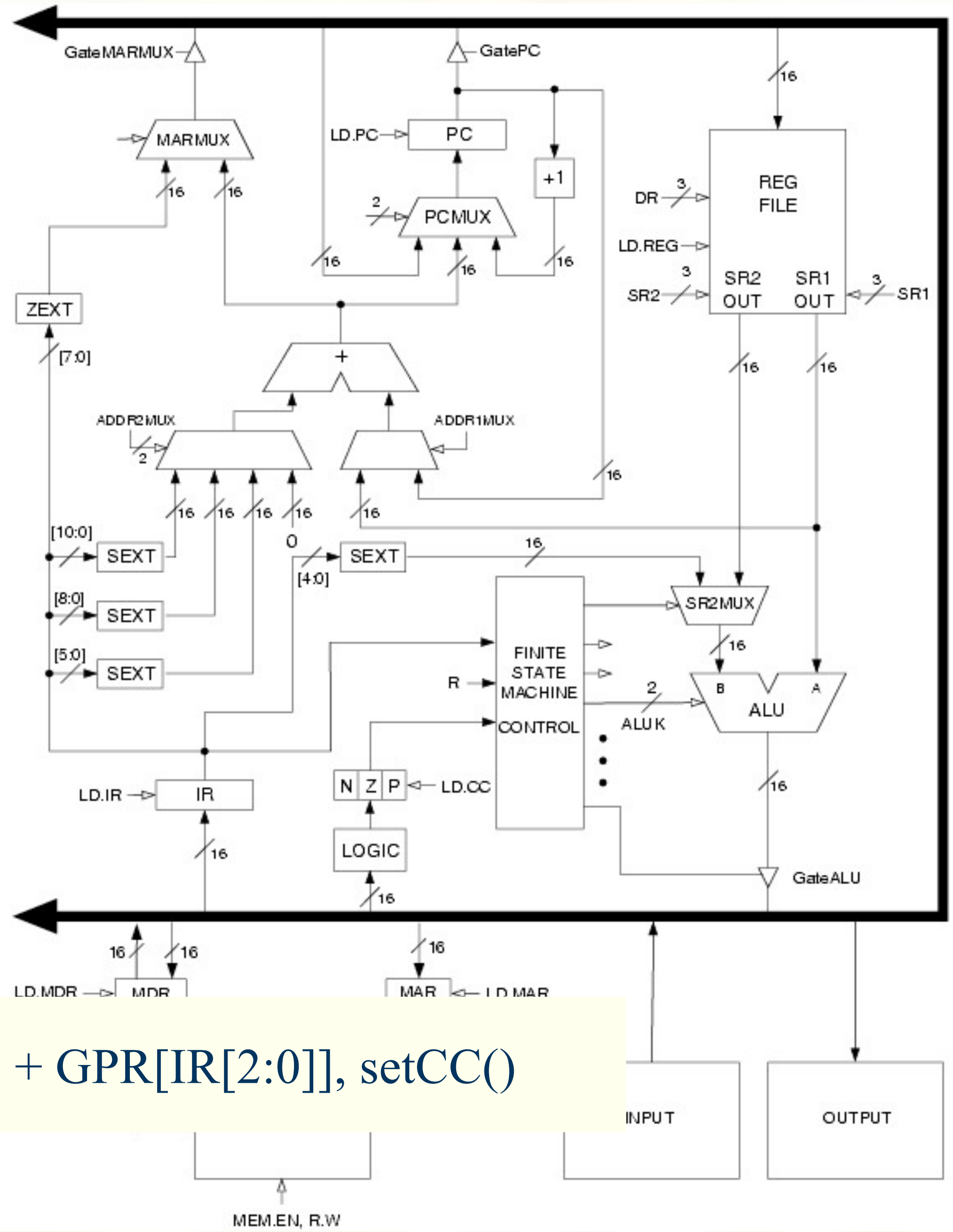
MAR and MARMUX

- Two inputs to MAR, controlled by MARMUX
  1. Address adder – LD/ST, LDR/STR
  2. Zero-extended IR[7:0] -- TRAP (discussed later)

Data Path Components

- Condition Code Logic
  - Looks at value on bus and generates N, Z, P signals
  - Registers set only when control unit enables them (LD.CC)
    - only certain instructions set the codes **(ADD, AND, NOT, LD, LDI, LDR, LEA)**
- Control Unit – Finite State Machine
  - On each machine cycle, changes control signals for next phase of instruction processing
    - who drives the bus? **(GatePC, GateALU, …)**
    - which registers are write enabled? **(LD.IR, LD.REG, …)**
    - which operation should ALU perform? **(ALUK)**
    - …
  - Logic includes decoder for opcode, etc.

Register Transfer Language (RTL)



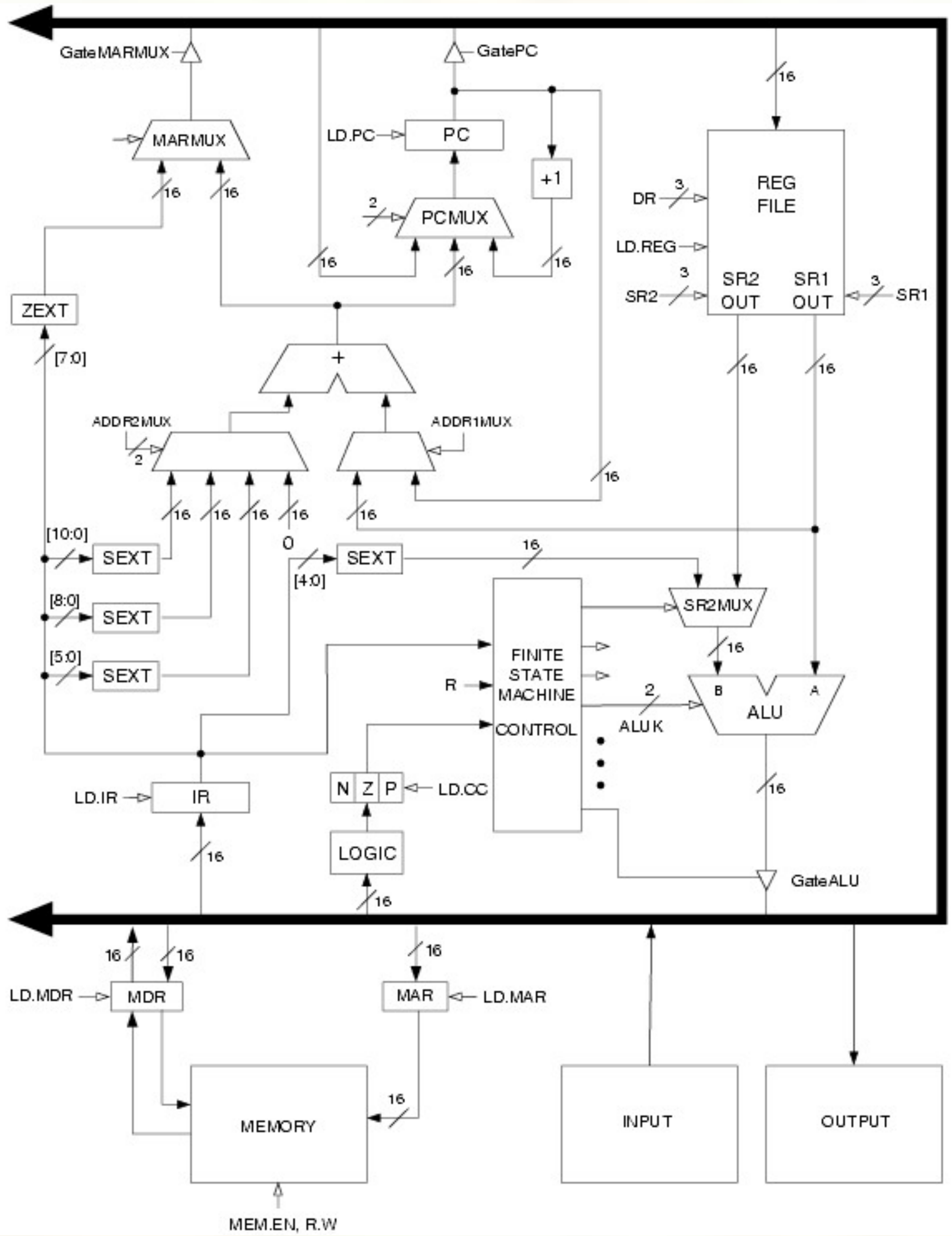
ADD:

MAR <- PC, PC <- PC+1
MDR <- MEM[MAR]
IR <- MDR
DECODE
GPR[IR[11:9]] <- GPR[IR[8:6]] + GPR[IR[2:0]], setCC()

Register Transfer Language (RTL)

LD:

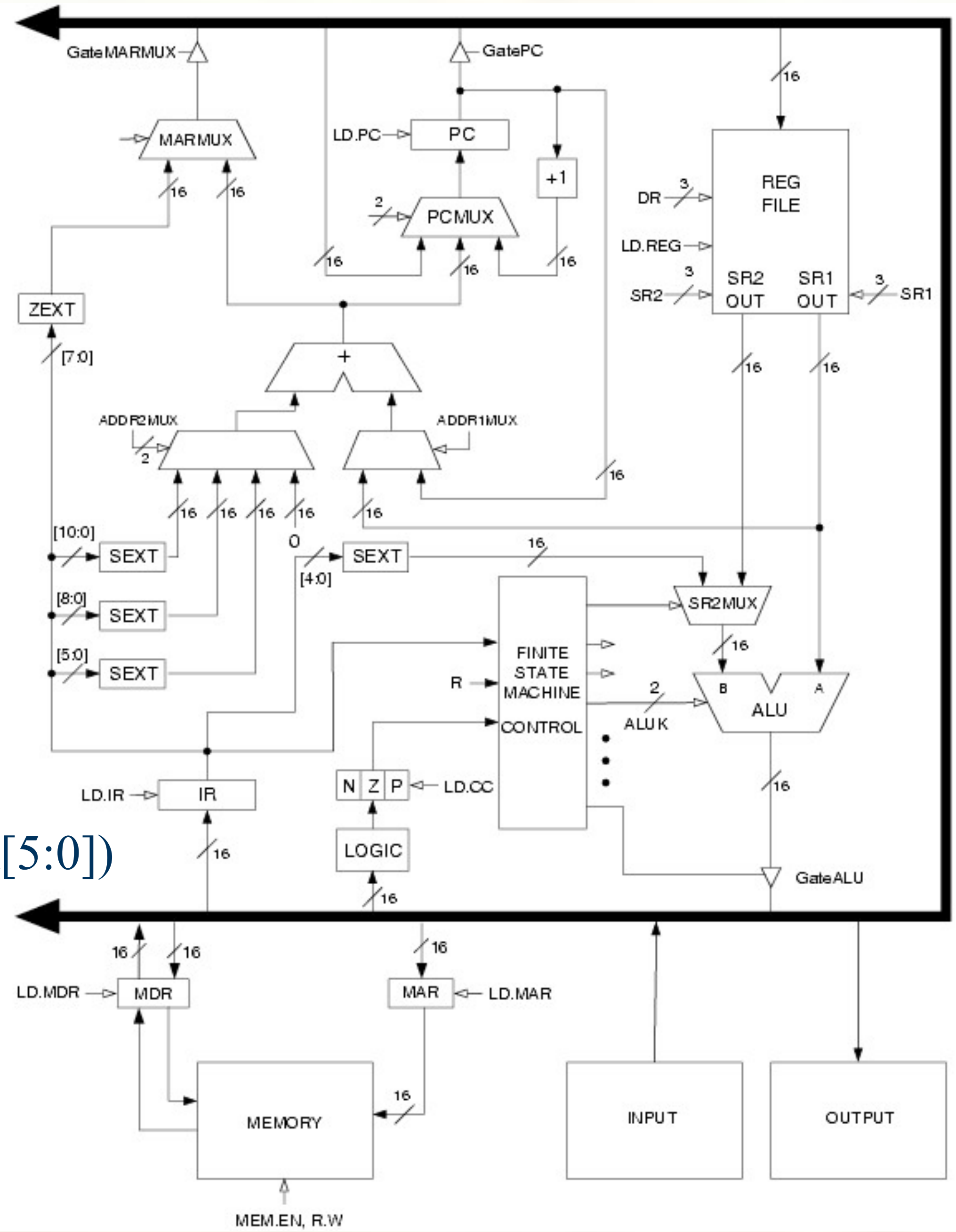
MAR <- PC, PC <- PC + 1
MDR <- MEM[MAR]
IR <- MDR
DECODE
MAR <- PC + sext(IR[8:0])
MDR <- MEM[MAR]
GPR[IR[11:9]] <- MDR, setCC()



Register Transfer Language (RTL)

STR:

- MAR <- PC, PC <- PC + 1
- MDR <- MEM[MAR]
- IR <- MDR
- DECODE
- MAR <- GPR[IR[8:6]] + sext(IR[5:0])
- MDR <- GPR[IR[11:9]]
- MEM[MAR] <- MDR



Register Transfer Language (RTL)

JSR:

- MAR <- PC, PC <- PC + 1
- MDR <- MEM[MAR]
- IR <- MDR
- DECODE
- R7 <- PC
- PC <- PC + sext(IR[10:0])