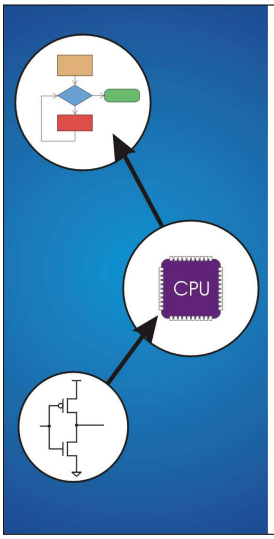


Chapter 5
The LC-3

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?
  - addressibility -- 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

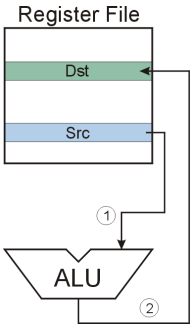
Source and destination operands are registers

- 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

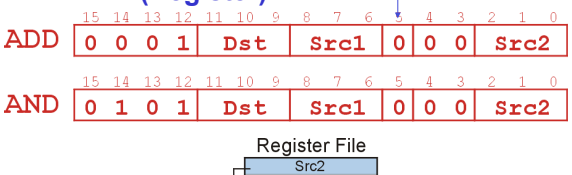
NOT (Register)

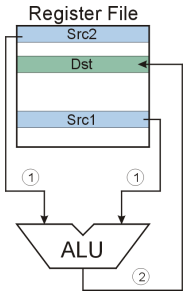


Note: Src and Dst could be the same register.

ADD/AND (Register)

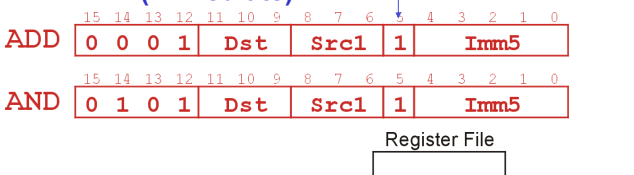
this zero means "register mode"



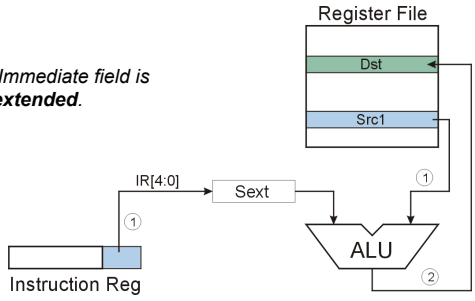


ADD/AND (Immediate)

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 9 bits available for address.**

Solution:

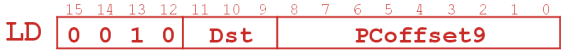
- **Use the 9 bits as a *signed offset* from the current PC.**

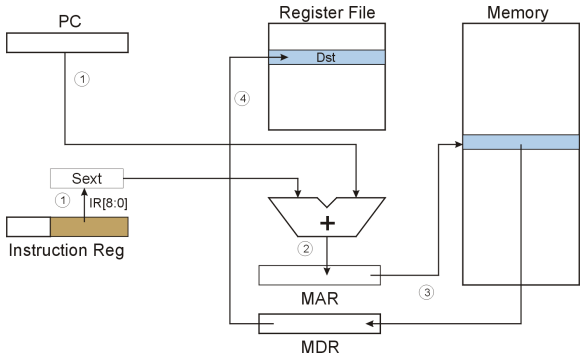
9 bits: $-256 \le \text{offset} \le +255$

Can form any address X, such that: $PC - 256 \le X \le PC + 255$

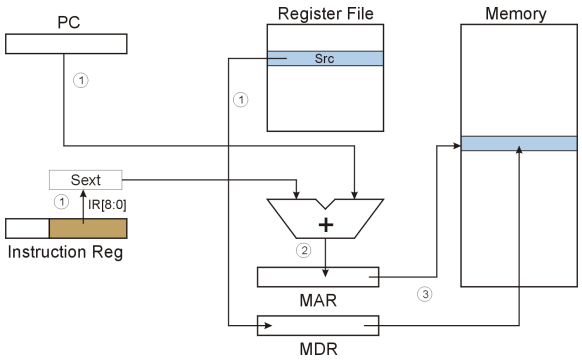
Remember that PC is incremented as part of the FETCH phase; This is done before the EVALUATE ADDRESS stage.

LD (PC-Relative)





ST (PC-Relative)



Indirect Addressing Mode

With PC-relative mode, can only address data within 256 words of the instruction.

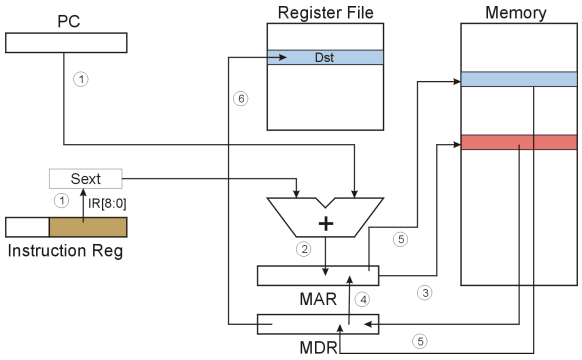
- **What about the rest of memory?**

Solution #1:

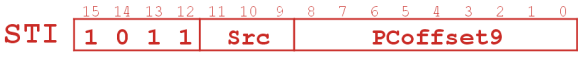
- **Read address from memory location, then load/store to that address.**

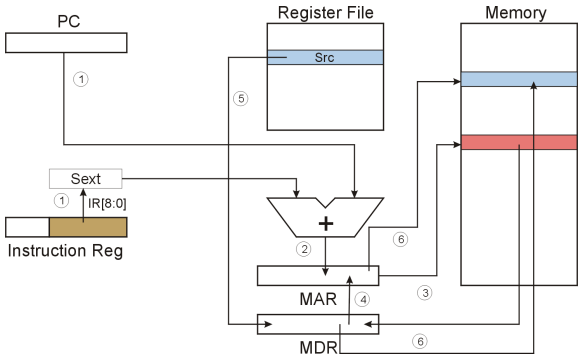
First address is generated from PC and IR (just like PC-relative addressing), then content of that address is used as target for load/store.

LDI (Indirect)



STI (Indirect)





Base + Offset Addressing Mode

With PC-relative mode, can only address data within 256 words of the instruction.

- **What about the rest of memory?**

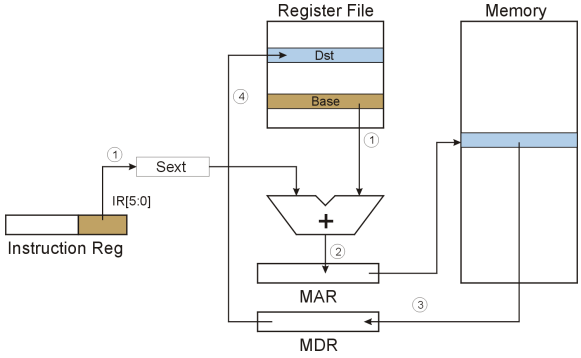
Solution #2:

- **Use a register to generate a full 16-bit address.**

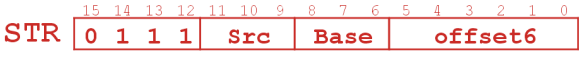
4 bits for opcode, 3 for src/dest register, 3 bits for *base* register -- remaining 6 bits are used as a *signed offset*.

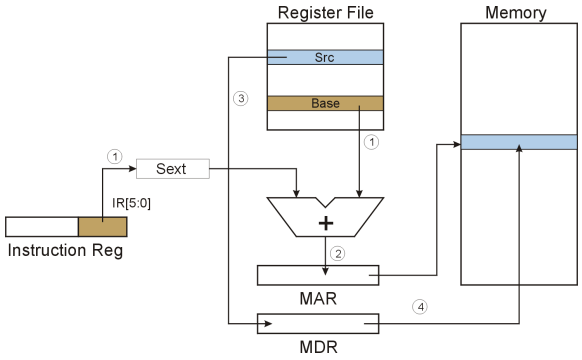
- Offset is *sign-extended* before adding to base register.

LDR (Base+Offset)



STR (Base+Offset)



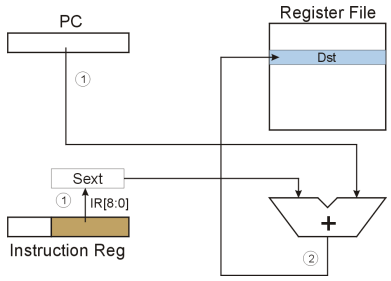


Load Effective Address

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)



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 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 one will be set at all times

- Based on the last instruction that altered a register

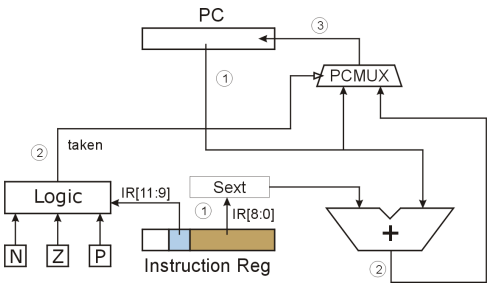
Branch Instruction

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.

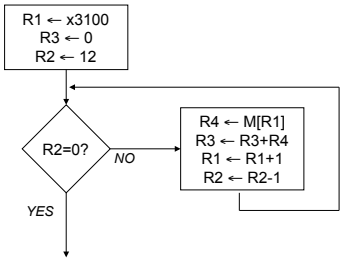
BR (PC-Relative)



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.



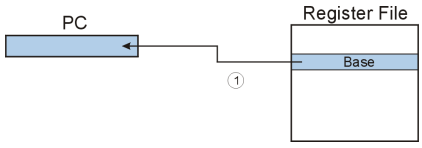
Sample Program

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 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.**



TRAP

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

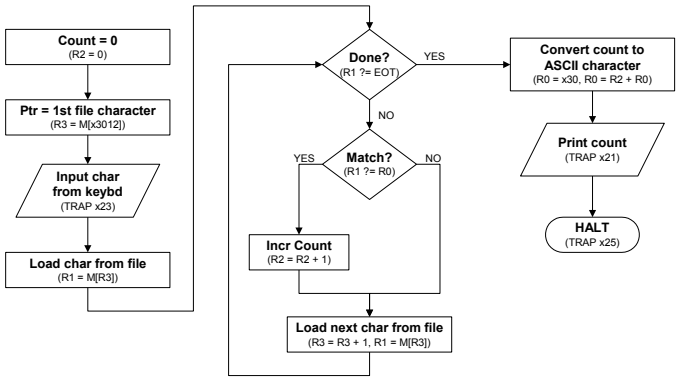
Count the occurrences of a character in a file

- **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



Program (1 of 2)

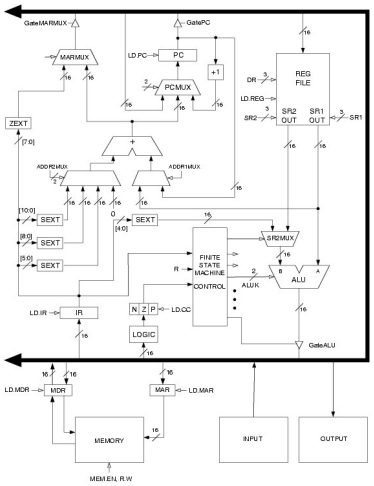
Address	*Instruction*	*Comments*
x3000	0 1 0 1 0 1 0 0 1 0 1 0 0 0 0 0	*R2 ← 0 (counter)*
x3001	0 0 1 0 0 1 1 0 0 0 0 1 0 0 0 0	*R3 ← M[x3102] (ptr)*
x3002	1 1 1 1 0 0 0 0 0 0 1 0 0 0 1 1	*Input to R0 (TRAP x23)*
x3003	0 1 1 0 0 0 1 0 1 1 0 0 0 0 0 0	*R1 ← M[R3]*
x3004	0 0 0 1 1 0 0 0 0 1 1 1 1 1 0 0	*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 1 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 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
  1. PC+1 – FETCH stage
  2. Address adder – BR, JMP
  3. 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.