Introduction to Computer Engineering

CS/ECE 252
Prof. Mark D. Hill
Computer Sciences Department
University of Wisconsin – Madison
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)

\[
\begin{array}{cccccccccccccc}
15 & 14 & 13 & 12 & 11 & 10 & 9 & 8 & 7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 \\
\end{array}
\]

\[
\begin{array}{cccccccccc}
1 & 0 & 0 & 1 & & & & & & \text{Dst} & & & & & & & \text{Src} & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{array}
\]

Register File

- **Src**
- **Dst**

\[
\begin{array}{cccccccccc}
\]

**Note:** **Src** and **Dst** could be the same register.
ADD/AND (Register)

**ADD**

<table>
<thead>
<tr>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Dst</td>
<td>Src1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Src2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

**AND**

<table>
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<tr>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Dst</td>
<td>Src1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Src2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*This zero means “register mode”*
## ADD/AND (Immediate)

### ADD

<table>
<thead>
<tr>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Imm5</td>
</tr>
</tbody>
</table>

### AND

<table>
<thead>
<tr>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Imm5</td>
</tr>
</tbody>
</table>

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

---

*This one means “immediate mode”*
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: $-256 \leq \text{offset} \leq +255$

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

Remember that PC is incremented as part of the FETCH phase; This is done before the EVALUATE ADDRESS stage.
LD (PC-Relative)

LD  0 0 1 0 | Dst | PC offset 9

1. Instruction Reg
2. Sext
3. IR[8:0]
4. Register File

PC
Register File
Memory

Sext
IR[8:0]
PC offset 9
ST (PC-Relative)

ST 0 0 1 1 | Src | PC offset 9

PC

Register File

Memory

Instruction Reg

IR[8:0]

Sext

MAR

MDR

+
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)

LDI

1 0 1 0 | Dst | PCoffset9

Diagram:
- PC
- Register File
- Memory
- Sext
- Instruction Reg
- IR[8:0]
- MAR
- MDR

Steps:
1. IR[8:0] → Sext
2. Sext → Dst
3. Dst → Memory
4. Memory → MAR
5. MAR → MDR
6. MDR → Register File
STI (Indirect)

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)

\[
\begin{array}{cccccccccccccc}
15 & 14 & 13 & 12 & 11 & 10 & 9 & 8 & 7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 \\
\end{array}
\]

LDR \hspace{1cm} 0 \hspace{0.5cm} 1 \hspace{0.5cm} 1 \hspace{0.5cm} 0 \hspace{1cm} Dst \hspace{1cm} Base \hspace{1cm} offset6

Diagram:

- Instruction Reg
- IR[5:0]
- Sext
- +
- MAR
- MDR
- Memory

Process:
1. Sext
2. Base
3. MDR
4. Register File
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

Diagram:
- Instruction Reg
- Sext
- IR[5:0]
- Register File
  - Src
  - Base
- Memory
- MAR
- MDR

Steps:
1. Sext
2. Base
3. Src
4. Memory
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)

LEA 1 1 1 0 Dst PCoffset9
### Example

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>x30F6</td>
<td>1 1 1 0 0 0 1 1 1 1 1 1 1 1 0 1</td>
<td>( R1 \leftarrow PC - 3 = x30F4 )</td>
</tr>
<tr>
<td>x30F7</td>
<td>0 0 0 1 0 1 0 0 0 1 1 0 1 1 1 0</td>
<td>( R2 \leftarrow R1 + 14 = x3102 )</td>
</tr>
<tr>
<td>x30F8</td>
<td>0 0 1 1 0 1 0 1 1 1 1 1 1 1 0 1</td>
<td>( M[PC - 5] \leftarrow R2 ) ( M[x30F4] \leftarrow x3102 )</td>
</tr>
<tr>
<td>x30F9</td>
<td>0 1 0 1 0 1 0 0 1 0 1 0 0 0 0 0</td>
<td>( R2 \leftarrow 0 )</td>
</tr>
<tr>
<td>x30FA</td>
<td>0 0 0 1 0 1 0 0 1 0 1 0 0 1 0 1</td>
<td>( R2 \leftarrow R2 + 5 = 5 )</td>
</tr>
<tr>
<td>x30FB</td>
<td>0 1 1 1 0 1 0 0 0 1 0 0 1 1 1 0</td>
<td>( M[R1+14] \leftarrow R2 ) ( M[x3102] \leftarrow 5 )</td>
</tr>
<tr>
<td>x30FC</td>
<td>1 0 1 0 0 1 1 1 1 1 1 1 1 0 1 1</td>
<td>( R3 \leftarrow M[M[x30F4]] ) ( R3 \leftarrow M[x3102] ) ( R3 \leftarrow 5 )</td>
</tr>
</tbody>
</table>

*opcodes*
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.

```
R1 ← x3100
R3 ← 0
R2 ← 12

R2=0?

NO
R4 ← M[R1]
R3 ← R3+R4
R1 ← R1+1
R2 ← R2-1

YES
```
## Sample Program

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>x3000</td>
<td>0 0 1 0 1 1 1 1 1 1 1 1 1 1 1 1</td>
<td>R1 ← x3100 (PC+0xFF)</td>
</tr>
<tr>
<td>x3001</td>
<td>0 1 0 1 0 1 1 0 1 1 1 0 0 0 0 0</td>
<td>R3 ← 0</td>
</tr>
<tr>
<td>x3002</td>
<td>0 1 0 1 0 1 0 0 1 0 1 0 1 0 0 0 0 0</td>
<td>R2 ← 0</td>
</tr>
<tr>
<td>x3003</td>
<td>0 0 0 1 0 1 0 0 1 0 1 0 1 0 1 1 0 0</td>
<td>R2 ← 12</td>
</tr>
<tr>
<td>x3004</td>
<td>0 0 0 0 0 1 0 0 0 0 0 0 0 1 0 1</td>
<td>If Z, goto x300A (PC+5)</td>
</tr>
<tr>
<td>x3005</td>
<td>0 1 1 0 1 0 0 0 0 1 0 0 0 0 0 0 0</td>
<td>Load next value to R4</td>
</tr>
<tr>
<td>x3006</td>
<td>0 0 0 1 0 1 1 0 1 1 0 0 0 0 0 1</td>
<td>Add to R3</td>
</tr>
<tr>
<td>x3007</td>
<td>0 0 0 1 0 0 1 0 0 1 1 0 0 0 0 1</td>
<td>Increment R1 (pointer)</td>
</tr>
<tr>
<td>x3008</td>
<td>0 0 0 1 0 1 0 0 1 0 1 1 1 1 1 1</td>
<td>Decrement R2 (counter)</td>
</tr>
<tr>
<td>x3009</td>
<td>0 0 0 0 1 1 1 1 1 1 1 1 1 1 0 1 0</td>
<td>Goto x3004 (PC-6)</td>
</tr>
</tbody>
</table>
JMP (Register)

Jump is an unconditional branch -- *always* taken.
- Target address is the contents of a register.
- Allows any target address.
Calls a service routine, identified by 8-bit “trap vector.”

<table>
<thead>
<tr>
<th>vector</th>
<th>routine</th>
</tr>
</thead>
<tbody>
<tr>
<td>x23</td>
<td>input a character from the keyboard</td>
</tr>
<tr>
<td>x21</td>
<td>output a character to the monitor</td>
</tr>
<tr>
<td>x25</td>
<td>halt the program</td>
</tr>
</tbody>
</table>

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)

Match?  
(R1 ?= R0)

Incr Count  
(R2 = R2 + 1)

Load next char from file  
(R3 = R3 + 1, R1 = M[R3])

Convert count to ASCII character  
(R0 = x30, R0 = R2 + R0)

Print count  
(TRAP x21)

HALT  
(TRAP x25)
# Program (1 of 2)

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>x3000</td>
<td>0 1 0 1 0 1 0 1 0 1 0 1 0 0 0 0 0</td>
<td>( R2 \leftarrow 0 ) (counter)</td>
</tr>
<tr>
<td>x3001</td>
<td>0 0 1 0 0 1 1 0 0 0 0 1 0 0 0 0 0</td>
<td>( R3 \leftarrow M[x3102] ) (ptr)</td>
</tr>
<tr>
<td>x3002</td>
<td>1 1 1 1 0 0 0 0 0 0 1 0 0 0 1 1 1</td>
<td>Input to ( R0 ) (TRAP x23)</td>
</tr>
<tr>
<td>x3003</td>
<td>0 1 1 0 0 0 1 0 1 1 0 0 0 0 0 0 0</td>
<td>( R1 \leftarrow M[R3] )</td>
</tr>
<tr>
<td>x3004</td>
<td>0 0 0 1 1 0 0 0 0 1 1 1 1 1 1 0 0</td>
<td>( R4 \leftarrow R1 - 4 ) (EOT)</td>
</tr>
<tr>
<td>x3005</td>
<td>0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0</td>
<td>If Z, goto x300E</td>
</tr>
<tr>
<td>x3006</td>
<td>1 0 0 1 0 0 1 0 0 1 1 1 1 1 1 1 1</td>
<td>( R1 \leftarrow \text{NOT} R1 )</td>
</tr>
<tr>
<td>x3007</td>
<td>0 0 0 1 0 0 1 0 0 1 1 0 0 0 0 1</td>
<td>( R1 \leftarrow R1 + 1 )</td>
</tr>
<tr>
<td>x3008</td>
<td>0 0 0 1 0 0 1 0 0 1 0 0 0 0 0 0 0</td>
<td>( R1 \leftarrow R1 + R0 )</td>
</tr>
<tr>
<td>x3009</td>
<td>0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 1</td>
<td>If N or P, goto x300B</td>
</tr>
</tbody>
</table>
# Program (2 of 2)

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>x300A</td>
<td>0 0 0 1 0 1 0 0 1 0 1 0 0 0 0 1</td>
<td>R2 ← R2 + 1</td>
</tr>
<tr>
<td>x300B</td>
<td>0 0 0 1 0 1 1 0 1 1 1 1 0 0 0 0 1</td>
<td>R3 ← R3 + 1</td>
</tr>
<tr>
<td>x300C</td>
<td>0 1 1 0 0 0 1 0 1 1 0 0 0 0 0 0 0</td>
<td>R1 ← M[R3]</td>
</tr>
<tr>
<td>x300D</td>
<td>0 0 0 0 1 1 1 1 1 1 1 1 0 1 1 0</td>
<td>Goto x3004</td>
</tr>
<tr>
<td>x300E</td>
<td>0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0</td>
<td>R0 ← M[x3013]</td>
</tr>
<tr>
<td>x300F</td>
<td>0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 1 0</td>
<td>R0 ← R0 + R2</td>
</tr>
<tr>
<td>x3010</td>
<td>1 1 1 1 0 0 0 0 0 0 0 1 0 0 0 0 1</td>
<td>Print R0 (TRAP x21)</td>
</tr>
<tr>
<td>x3011</td>
<td>1 1 1 1 0 0 0 0 0 0 1 0 0 1 0 1</td>
<td>HALT (TRAP x25)</td>
</tr>
<tr>
<td>X3012</td>
<td>Starting Address of File</td>
<td></td>
</tr>
<tr>
<td>x3013</td>
<td>0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0</td>
<td>ASCII ‘0’</td>
</tr>
</tbody>
</table>
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.