Agenda for Today & Next Few Lectures

- LC-3 and MIPS Instruction Set Architectures

- LC-3 and MIPS assembly and programming

- Introduction to microarchitecture and single-cycle microarchitecture

- Multi-cycle microarchitecture
Required Readings

- **This week**
  - Von Neumann Model, ISA, LC-3, and MIPS
    - P&P, Chapters 4, 5
    - H&H, Chapter 6 (until 6.5)
    - P&P, Appendices A and C (ISA and microarchitecture of LC-3)
    - H&H, Appendix B (MIPS instructions)
  - Programming
    - P&P, Chapter 6
  - **Recommended**: H&H Chapter 5, especially 5.1, 5.2, 5.4, 5.5

- **Next week**
  - Introduction to microarchitecture and single-cycle microarchitecture
    - H&H, Chapter 7.1-7.3
    - P&P, Appendices A and C
  - Multi-cycle microarchitecture
    - H&H, Chapter 7.4
    - P&P, Appendices A and C
What Will We Learn Today?

- Assembly Programming
  - Programming constructs
  - Debugging
  - Conditional statements and loops in MIPS assembly
  - Arrays in MIPS assembly
  - Function calls
    - The stack
Recall: The Von Neumann Model

INPUT
Keyboard, Mouse, Disk...

PROCESSING UNIT
ALU
TEMP

MEMORY
Mem Addr Reg
Mem Data Reg

CONTROL UNIT
PC or IP
Inst Register

OUTPUT
Monitor, Printer, Disk...
Recall: LC-3: A Von Neumann Machine

Figure 4.3 The LC-3 as an example of the von Neumann model
Recall: The Instruction Cycle

- FETCH
- DECODE
- EVALUATE ADDRESS
- FETCH OPERANDS
- EXECUTE
- STORE RESULT
Recall: The Instruction Set Architecture

- The ISA is the **interface between** what the **software** commands and what the **hardware** carries out.

- The ISA specifies:
  - The **memory organization**
    - Address space (LC-3: $2^{16}$, MIPS: $2^{32}$)
    - Addressability (LC-3: 16 bits, MIPS: 32 bits)
    - Word- or Byte-addressable
  - The **register set**
    - R0 to R7 in LC-3
    - 32 registers in MIPS
  - The **instruction set**
    - Opcodes
    - Data types
    - Addressing modes
Our First LC-3 Program:
Use of Conditional Branches for Looping
An Algorithm for Adding Integers

- We want to write a program that adds 12 integers
  - They are stored in addresses 0x3100 to 0x310B
  - Let us take a look at the flowchart of the algorithm

```
R1 ← x3100
R3 ← 0
R2 ← 12

R4 ← M[R1]
R3 ← R3 + R4
Increment R1
Decrement R2

Yes

No

R2 ?= 0

Check if R2
becomes 0
(done with all
integers?)

Load integer in R4
Accumulate integer value in R3
Increment address R1
Decrement R2

R1: initial address of integers
R3: final result of addition
R2: number of integers left to be added
```
A Program for Adding Integers in LC-3

We use **conditional branch instructions** to create a **loop**

### Address Table

| Address | 15 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---------|----|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|---|
| x3000   | LEA| 1  | 1  | 0  | 0  | 0  | 1  |     | 0x00FF | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  |
| x3001   | AND| 0  | 1  | 0  | 1  | 1  | 0  | 1  | 1  | 1  | 1  | 0  | 0  | 0  | 0  | 0  | 0  |
| x3002   | AND| 0  | 1  | 0  | 1  | 0  | 1  | 0  | 1  | 0  | 1  | 0  | 0  | 0  | 0  | 0  | 0  |
| x3003   | ADD | 0  | 1  | 0  | 1  | 0  | 1  | 0  | 1  | 0  | 1  | 1  | 0  | 0  | 0  | 0  | 0  |
| x3004   | BR  | 0  | 0  | 0  | 0  | 0  | 0  | 1  | 0  | 5  | 0  | 0  | 0  | 0  | 0  | 1  | 0  |
| x3005   | LDR | 1  | 1  | 0  | 1  | 0  | 0  | 0  | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| x3006   | ADD | 0  | 1  | 0  | 1  | 1  | 0  | 1  | 1  | 0  | 0  | 0  | 1  | 0  | 0  | 0  | 0  |
| x3007   | ADD | 0  | 1  | 0  | 0  | 1  | 0  | 1  | 1  | 1  | 0  | 0  | 0  | 0  | 0  | 1  | 0  |
| x3008   | ADD | 0  | 1  | 0  | 1  | 0  | 1  | 0  | 1  | 0  | 1  | 1  | 1  | 1  | 1  | 1  | 1  |
| x3009   | BR  | 0  | 0  | 1  | n  | z  | p  | -6 | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 0  |

- **R1 = PC† + 0x00FF = 3100** // load address
- **R3 = 0** // reset register
- **R2 = 0** // reset register
- **R2 = R2 + 12** // initialize counter
- **BRz (PC† + 5) = BRz 0x300A** // check condition
- **R4 = M[R1 + 0]** // load value
- **R3 = R3 + R4** // accumulate
- **R1 = R1 + 1** // increment address
- **R2 = R2 – 1** // decrement counter
- **BRnzp (PC† – 6) = BRnzp 0x3004** // jump

---

Bit 5 to differentiate the two ADD instructions

† This is the incremented PC
The LC-3 Data Path Revisited
We highlight some data path components used in the execution of the instructions in the previous slides (not shown in the simplified data path).
(Assembly) Programming
Programming Constructs

- Programming requires **dividing a task**, i.e., a unit of work into **smaller units of work**

- The goal is to replace the units of work with **programming constructs** that represent that part of the task

- There are **three basic programming constructs**
  - **Sequential construct**
  - **Conditional construct**
  - **Iterative construct**
The sequential construct is used if the designated task can be broken down into two subtasks, one following the other.
The conditional construct is used if the designated task consists of **doing one of two subtasks**, but not both.

- Either subtask may be "do nothing"
- After the correct subtask is completed, the program moves onward
- E.g., if-else statement, switch-case statement

Is the condition “true” or “false”?
Iterative Construct

- The iterative construct is used if the designated task consists of doing a subtask a number of times, but only as long as some condition is true.

- E.g., for loop, while loop, do-while loop
Constructs in an Example Program

- Let us see how to use the **programming constructs in an example program**

- The example program **counts the number of occurrences of a character** in a text file

- It uses **sequential, conditional, and iterative constructs**

- We will see how to write **conditional and iterative constructs with conditional branches**
Counting Occurrences of a Character

- We want to write a program that counts the occurrences of a character in a file
  - Get character-to-search from the keyboard (TRAP instr.)
  - The file finishes with the character EOT (End Of Text)
    - That is called a sentinel
    - In this example, EOT = 4
  - Output result to the monitor (TRAP instr.)

Programming constructs:

(a) The task to be decomposed

(b) Sequential

(c) Conditional

(d) Iterative

```
R2: counter
R3: initial address

Increment address
Read char from file
Check if end of file
Is it the searched char?
Increment R2
Increment address
Move output to R0
Output counter
Halt the program
```
TRAP Instruction

- TRAP invokes an **OS service call**

### LC-3 assembly

```
TRAP 0x23;
```

### Machine Code

- **OP = 1111**
- **trapvect8 = service call**
  - 0x23 = **Input a character** from the keyboard
  - 0x21 = **Output a character** to the monitor
  - 0x25 = **Halt** the program
We use conditional branch instructions to create loops and if statements.
Let us do some reverse engineering to identify **conditional constructs** and **iterative constructs**.
Debugging
Debugging

- Debugging is the process of removing errors in programs.

- It consists of tracing the program, i.e., keeping track of the sequence of instructions that have been executed and the results produced by each instruction.

- A useful technique is to partition the program into parts, often referred to as modules, and examine the results computed in each module.

- High-level language (e.g., C programming language) debuggers: dbx, gdb, Visual Studio debugger.

Interactive Debugging

- When debugging interactively, it is important to be able to
  
  1. Deposit values in memory and in registers, in order to test the execution of a part of a program in isolation
  
  2. Execute instruction sequences in a program by using
     - RUN command: execute until HALT instruction or a breakpoint
     - STEP N command: execute a fixed number (N) of instructions
  
  3. Stop execution when desired
     - SET BREAKPOINT command: stop execution at a specific instruction in a program
  
  4. Examine what is in memory and registers at any point in the program
Example: Multiplying in LC-3 (Buggy)

- A program is necessary to multiply, since LC-3 does not have multiply instruction
  - The following program multiplies R4 and R5
  - Initially, \( R4 = 10 \) and \( R5 = 3 \)
  - The program produces 40. What went wrong?
  - It is useful to annotate each instruction

<table>
<thead>
<tr>
<th>PC</th>
<th>R2</th>
<th>R4</th>
<th>R5</th>
</tr>
</thead>
<tbody>
<tr>
<td>x3201</td>
<td>10</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>x3202</td>
<td>20</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>x3203</td>
<td>10</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>x3204</td>
<td>20</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

R2 = 0 // initialize register
R2 = R2 + R4
R5 = R5 - 1
BRzp 0x3201
HALT // end program
We examine the contents of all registers after the execution of each instruction.

The branch condition codes were set wrong. The conditional branch should only be taken if R5 is positive.

Correct instruction: 

BRzp 0x3201
Easier Debugging with Breakpoints

- We could use a **breakpoint** to save some work.
- Setting a breakpoint in 0x3203 (BR) allows us to examine the results of each iteration of the loop.

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**One last question:**

Does this program work if the initial value of R5 is 0?

---

A good test should also consider the **corner cases**, i.e., unusual values that the programmer might fail to consider.
Conditional Statements and Loops in MIPS Assembly
In MIPS, we create **conditional constructs** with **conditional branches** (e.g., `beq`, `bne`...)

<table>
<thead>
<tr>
<th>High-level code</th>
<th>MIPS assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>if (i == j)</td>
<td># $s0 = f, $s1 = g</td>
</tr>
<tr>
<td></td>
<td># $s2 = h</td>
</tr>
<tr>
<td></td>
<td># $s3 = i, $s4 = j</td>
</tr>
<tr>
<td>f = g + h;</td>
<td>bne $s3, $s4, L1</td>
</tr>
<tr>
<td>f = f - i;</td>
<td>add $s0, $s1, $s2</td>
</tr>
<tr>
<td></td>
<td>L1: sub $s0, $s0, $s3</td>
</tr>
</tbody>
</table>

**Branch not equal**

Compares two values ($s3=i$, $s4=j$) and jumps if they are different
If-Else Statement

- We use the unconditional branch (i.e., \( j \)) to skip the "else" subtask if the "if" subtask is the correct one.

**High-level code**

```java
if (i == j) 
  f = g + h;
else 
  f = f - i;
```

**MIPS assembly**

```mips
# $s0 = f, $s1 = g, # $s2 = h 
# $s3 = i, $s4 = j 

bne $s3, $s4, L1 
add $s0, $s1, $s2 
add $s0, $s0, $s3 
```

1. Compare two values ($s3=i, \( s4=j \)) and, if they are different, jump to L1, to execute the "else" subtask.
2. Jump to done, after executing the "if" subtask.
While Loop

- As in LC-3, the conditional branch (i.e., beq) checks the condition and the unconditional branch (i.e., j) jumps to the beginning of the loop.

High-level code

```c
// determines the power of 2 equal to 128
int pow = 1;
int x = 0;

while (pow != 128) {
    pow = pow * 2;
    x = x + 1;
}
```

MIPS assembly

```mips
# $s0 = pow, $s1 = x
addi $s0, $0, 1
add $s1, $0, $0
addi $t0, $0, 128
while: beq $s0, $t0, done
sll $s0, $s0, 1
addi $s1, $s1, 1
j while
done:
```

1. Conditional branch to check if the condition still holds
2. Unconditional branch to the beginning of the loop
The implementation of the "for" loop is similar to the "while" loop.

High-level code:
```c
// add the numbers from 0 to 9
int sum = 0;
int i;
for (i = 0; i != 10; i = i+1)
{
    sum = sum + i;
}
```

MIPS assembly:
```assembly
# $s0 = i, $s1 = sum
    addi $s1, $0, 0
    add $s0, $0, $0
    addi $t0, $0, 10
for:   beq $s0, $t0, done
    add $s1, $s1, $s0
    addi $s0, $s0, 1
    j for
done:
```

1. Conditional branch to check if the condition still holds.
2. Unconditional branch to the beginning of the loop.
We use \texttt{slt} (i.e., set less than) for the "less than" comparison.

\begin{itemize}
\item \textbf{High-level code:}
\begin{verbatim}
// add the powers of 2 from 1 to 100
int sum = 0;
int i;

for (i = 1; i < 101; i = i*2)
{
    sum = sum + i;
}
\end{verbatim}
\end{itemize}

\begin{itemize}
\item \textbf{MIPS assembly:}
\begin{verbatim}
# $s0 = i, $s1 = sum
addi $s1, $0, 0
addi $s0, $0, 1
addi $t0, $0, 101

loop: slt $t1, $s0, $t0
beq $t1, $0, done
add $s1, $s1, $s0
sll $s0, $s0, 1
j    loop

done:
\end{verbatim}
\end{itemize}

- \textbf{Set less than:}
  \[ \texttt{$t1 = $s0 < $t0 \ ? 1:0} \]

- \textbf{Shift left logical:}
Arrays in MIPS
Arrays

- Accessing an array requires **loading the base address into a register**

  - In MIPS, this is something we **cannot do with one single immediate operation**

- **Load upper immediate + OR immediate**

  ```
  lui $s0, 0x1234
  ori $s0, $s0, 0x8000
  ```
Arrays: Code Example

- We first load the **base address of the array** into a register (e.g., $s0) using **lui** and **ori**

High-level code

```c
int array[5];

array[0] = array[0] * 2;

```

MIPS assembly

```
# array base address = $s0
# Initialize $s0 to 0x12348000
lui $s0, 0x1234
ori $s0, $s0, 0x8000

lw $t1, 0($s0)
sll $t1, $t1, 1
sw $t1, 0($s0)
lw $t1, 4($s0)
sll $t1, $t1, 1
sw $t1, 4($s0)
```
Function Calls
Why functions (i.e., procedures)?
- Frequently accessed code
- Make a program more modular and readable

Functions have **arguments and return value**

**Caller**: calling function
- main()

**Callee**: called function
- sum()

```c
void main()
{
    int y;
    y = sum(42, 7);
    ...
}

int sum(int a, int b)
{
    return (a + b);
}
```
Function Calls: Conventions

- Conventions
  - **Caller**
    - passes arguments
    - jumps to **callee**
  - **Callee**
    - performs the procedure
    - returns the result to caller
    - returns to the point of call
    - must not overwrite registers or memory needed by the caller
Function Calls in MIPS and LC-3

- Conventions in MIPS and LC-3

- **Call procedure**
  - MIPS: Jump and link (jal)
  - LC-3: Jump to Subroutine (JSR, JSRR)

- **Return from procedure**
  - MIPS: Jump register (jr)
  - LC-3: Return from Subroutine (RET)

- **Argument values**
  - MIPS: $a0 - $a3

- **Return value**
  - MIPS: $v0
Function Calls: Simple Example

High-level code

```c
int main() {
    simple();
    a = b + c;
}

void simple() {
    return;
}
```

MIPS assembly

```assembly
0x00400200 main: jal simple
0x00400204 add $s0,$s1,$s2

...  
0x00401020 simple: jr $ra
```

- **jal** jumps to **simple()** and saves PC+4 in the **return address register** ($ra)
  - $ra = 0x00400204

- In LC-3, **JSR(R)** put the return address in **R7**

- **jr $ra** jumps to address in $ra (LC-3 uses **RET** instruction)
Function Calls: Code Example

High-level code

```c
int main()
{
    int y;
    ...
    // 4 arguments
    y = diffofsums(2, 3, 4, 5);
    ...
}

int diffofsums(int f, int g, int h, int i)
{
    int result;
    result = (f + g) - (h + i);
    // return value
    return result;
}
```

MIPS assembly

```mips
# $s0 = y
main:
...
addi $a0, $0, 2  # argument 0 = 2
addi $a1, $0, 3  # argument 1 = 3
addi $a2, $0, 4  # argument 2 = 4
addi $a3, $0, 5  # argument 3 = 5
jal diffofsums   # call procedure
add $s0, $v0, $0 # y = returned value
...

# $s0 = result
diffofsums:
add $t0, $a0, $a1 # $t0 = f + g
add $t1, $a2, $a3 # $t1 = h + i
sub $s0, $t0, $t1 # result=(f + g) - (h + i)
add $v0, $s0, $0 # put return value in $v0
jr $ra            # return to caller
```

Argument values
Return value
Return address
What if the main function was using some of those registers?

- $t0$, $t1$, $s0$

- They could be overwritten by the function

- We can use the stack to temporarily store registers
The Stack

- The stack is a memory area used to **save local variables**

- It is a **Last-In-First-Out (LIFO)** queue

- The **stack pointer ($sp$)** points to the top of the stack
  - It grows down in MIPS

<table>
<thead>
<tr>
<th>Address</th>
<th>Data</th>
<th>Address</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>7FFFFFFFC</td>
<td>12345678</td>
<td>7FFFFFFFC</td>
<td>12345678</td>
</tr>
<tr>
<td>7FFFFFF8</td>
<td></td>
<td>7FFFFFF8</td>
<td>AABBCDD</td>
</tr>
<tr>
<td>7FFFFFF4</td>
<td></td>
<td>7FFFFFF4</td>
<td>11223344</td>
</tr>
<tr>
<td>7FFFFFF0</td>
<td></td>
<td>7FFFFFF0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Two words pushed on the stack
Saving and restoring all registers requires a lot of effort

In MIPS, there is a convention about temporary registers (i.e., $t0-$t9): There is no need to save them

- Programmers can use them for temporary/partial results

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**The Stack: Code Example**

**MIPS assembly**

```
diffofsums:
    addi $sp, $sp, -12  # allocate space on stack to store 3 registers
    sw  $s0, 8($sp)     # save $s0 on stack
    sw  $t0, 4($sp)     # save $t0 on stack
    sw  $t1, 0($sp)     # save $t1 on stack
    add  $t0, $a0, $a1  # $t0 = f + g
    add  $t1, $a2, $a3  # $t1 = h + i
    sub  $s0, $t0, $t1  # result=(f + g) - (h + i)
    add  $v0, $s0, $0    # put return value in $v0
    lw   $t1, 0($sp)    # restore $t1 from stack
    lw   $t0, 4($sp)    # restore $t0 from stack
    lw   $s0, 8($sp)    # restore $s0 from stack
    addi $sp, $sp, 12   # deallocate stack space
    jr   $ra            # return to caller
```
Temporary registers $t0$-$t9$ are nonpreserved registers. They are not saved, thus, they can be overwritten by the function.

Registers $s0$-$s7$ are preserved (saved; callee-saved) registers.
Lecture Summary

- Assembly Programming
  - Programming constructs
  - Debugging
  - Conditional statements and loops in MIPS assembly
  - Arrays in MIPS assembly
  - Function calls
    - The stack
Digital Design & Computer Arch.
Lecture 10b: Assembly Programming

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ETH Zürich
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