Agenda for Today & Next Few Lectures

- The von Neumann model
- LC-3: An example of von Neumann machine

- LC-3 and MIPS Instruction Set Architectures

- LC-3 and MIPS assembly and programming

- Introduction to microarchitecture and single-cycle microarchitecture

- Multi-cycle microarchitecture
Readings

- **This week**
  - Von Neumann Model, ISA, LC-3, and MIPS
    - P&P, Chapters 4, 5 (we will follow these today)
    - 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 (we will follow this today)
  - **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…

OUTPUT
- Monitor,
- Printer,
- Disk…

MEMORY
- Mem Addr Reg
- Mem Data Reg

PROCESSING UNIT
- ALU
- TEMP

CONTROL UNIT
- PC or IP
- Inst Register
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: 8 bits)
      - Word- or Byte-addressable
  - The register set:
    - 8 registers (R0 to R7) in LC-3
    - 32 registers in MIPS
  - The instruction set:
    - Opcodes
    - Data types
    - Addressing modes
    - Length and format of instructions

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<table>
<thead>
<tr>
<th>Problem</th>
<th>ISA</th>
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<tbody>
<tr>
<td>Algorithm</td>
<td>Microarchitecture</td>
</tr>
<tr>
<td>Program</td>
<td>Circuits</td>
</tr>
<tr>
<td>Electrons</td>
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</tbody>
</table>
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

![Flowchart of the algorithm](image)

- **R1**: initial address of integers
- **R3**: final result of addition
- **R2**: number of integers left to be added

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

- Load integer in R4
- Accumulate integer value in R3
- Increment address R1
- Decrement R2
A Program for Adding Integers in LC-3

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

### Table: Program Instructions and Variables

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x3000</td>
<td>LEA 1 1 0</td>
<td>R1 = PC + 0x00FF = 3100 // load address</td>
</tr>
<tr>
<td>x3001</td>
<td>AND 1 0 1</td>
<td>R3 = 0 // reset register</td>
</tr>
<tr>
<td>x3002</td>
<td>AND 1 0 1</td>
<td>R2 = 0 // reset register</td>
</tr>
<tr>
<td>x3003</td>
<td>ADD 0 0 1</td>
<td>R2 = R2 + 12 // initialize counter</td>
</tr>
<tr>
<td>x3004</td>
<td>BR 0 0 0 0 0 z 0 0 0 0 0 0 1 0 1</td>
<td>BRz (PC + 5) = BRz 0x300A // check condition</td>
</tr>
<tr>
<td>x3005</td>
<td>LDR 1 1 0</td>
<td>R4 = M[R1 + 0] // load value</td>
</tr>
<tr>
<td>x3006</td>
<td>ADD 0 0 1</td>
<td>R3 = R3 + R4 // accumulate</td>
</tr>
<tr>
<td>x3007</td>
<td>ADD 0 0 1</td>
<td>R1 = R1 + 1 // increment address</td>
</tr>
<tr>
<td>x3008</td>
<td>ADD 0 0 1</td>
<td>R2 = R2 – 1 // decrement counter</td>
</tr>
<tr>
<td>x3009</td>
<td>BR 0 0 0 n z p 1 1 1 1 1 1 0 1 0</td>
<td>BRnzp (PC – 6) = BRnzp 0x3004 // jump</td>
</tr>
</tbody>
</table>

### Diagram:

1. **Start** with R1 <- x3100, R3 <- 0, R2 <- 12.
2. Check if R2 = 0. If yes, proceed. If no, decrement R2 and continue.
3. Load value R4 <- M[R1].
4. Increment R1.
5. Add R3 <- R3 + R4 and R2 becomes R2 - 1.
6. If R2 = 0, end. Otherwise, repeat the process.

**Note:** Bit 5 to differentiate the two ADD instructions.

✝ This is the incremented PC.
The LC-3 Data Path Revisited
The LC-3 Data Path

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
Sequential Construct

- The sequential construct is used if the designated task can be broken down into two subtasks, one following the other.
Conditional Construct

- 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
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

Sequential
- Do first part to completion
- Do second part to completion

Conditional
- Test cond. True
- Test cond. False

Iterative
- Test cond. True
- Test cond. False

Figure 5.16 An algorithm to count occurrences of a character

<table>
<thead>
<tr>
<th>R2: counter</th>
<th>R3: initial address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input char</td>
<td>Read char from file</td>
</tr>
<tr>
<td>Check if end of file</td>
<td>Is it the searched char?</td>
</tr>
<tr>
<td>Increment R2</td>
<td>Increment address</td>
</tr>
<tr>
<td>Move output to R0</td>
<td>Output counter</td>
</tr>
<tr>
<td>Halt the program</td>
<td>Stop (TRAP x25)</td>
</tr>
</tbody>
</table>
TRAP Instruction

- TRAP invokes an OS service call

LC-3 assembly

```assembly
TRAP 0x23;
```

Machine Code

```
<table>
<thead>
<tr>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
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</tr>
<tr>
<td>OP</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>trapvect8</td>
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</tbody>
</table>
```

- OP = 1111
- trapvect8 = service call
  - 0x23 = Input a character from the keyboard
  - 0x21 = Output a character to the monitor
  - 0x25 = Halt the program
Counting Occurrences of a Char in LC-3

- We use **conditional branch instructions** to create **loops** and **if statements**

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<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>x3000</td>
<td>AND</td>
<td>0 1</td>
<td>0 1 0 0 1 0 1 0 0 0 0 0 0 0 0 0</td>
<td>R2 = 0 // initialize counter</td>
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</tr>
<tr>
<td>x3001</td>
<td>LD</td>
<td>0 1 0 0 1 1 0 0 0 0 0 1 0 0 0 0</td>
<td>R3 = M[0x3012] // initial address</td>
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</tr>
<tr>
<td>x3002</td>
<td>TRAP</td>
<td>1 1 0 0 0 0 0 0 0 1 0 0 0 0 1 1</td>
<td>TRAP 0x23 // input char to R0</td>
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</tr>
<tr>
<td>x3003</td>
<td>LDR</td>
<td>1 0 0 0 1 0 1 1 0 0 0 0 0 0 0 0</td>
<td>R1 = M[R3] // char from file</td>
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</tr>
<tr>
<td>x3004</td>
<td>ADD</td>
<td>0 1 1 0 0 0 0 1 1 1 1 1 0 0 0 0</td>
<td>R4 = R1 - 4 // char – EOT</td>
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</tr>
<tr>
<td>x3005</td>
<td>BR</td>
<td>0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0</td>
<td>BRz 0x300E // check if end of file</td>
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<tr>
<td>x3006</td>
<td>NOT</td>
<td>0 1 0 0 1 0 0 1 1 1 1 1 1 1 1 1</td>
<td>R1 = NOT(R1)</td>
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<tr>
<td>x3007</td>
<td>ADD</td>
<td>0 1 0 0 1 0 0 1 1 0 0 0 0 0 1</td>
<td>R1 = R1 + 1</td>
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<tr>
<td>x3008</td>
<td>ADD</td>
<td>0 1 0 0 1 0 0 1 0 0 0 0 0 0 0 0</td>
<td>R1 = R1 + R0</td>
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<tr>
<td>x3009</td>
<td>BR</td>
<td>0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1</td>
<td>BRnp 0x300B</td>
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<tr>
<td>x300A</td>
<td>ADD</td>
<td>0 1 0 1 0 0 1 0 1 0 0 0 0 0 0 1</td>
<td>R2 = R2 + 1 // increment the counter</td>
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<tr>
<td>x300B</td>
<td>ADD</td>
<td>0 1 0 1 1 0 1 1 1 1 0 0 0 0 0 0</td>
<td>R3 = R3 + 1 // increment address</td>
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<td>x300C</td>
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<td>1 0 0 0 1 0 1 1 0 0 0 0 0 0 0 0</td>
<td>R1 = M[R3] // char from file</td>
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<td>x300D</td>
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<td>0 0 0 1 0 0 1 1 1 1 1 0 1 1 0 0</td>
<td>BRnzp 0x3004</td>
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<tr>
<td>x300E</td>
<td>LD</td>
<td>0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1</td>
<td>R0 = M[0x3013]</td>
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<td>x300F</td>
<td>ADD</td>
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<td>R0 = R0 + R2</td>
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<td>1 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1</td>
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<td>x3011</td>
<td>AND</td>
<td>1 1 0 0 0 0 0 0 0 1 0 0 1 0 0 0</td>
<td>TRAP 0x25</td>
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<tr>
<td>x3012</td>
<td>ASCII TEMPLATE</td>
<td>0 0 0 0 0 1 1 0 0 0 0</td>
<td>// output counter to monitor with TRAP</td>
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</tbody>
</table>

Starting address of file
Let us do some reverse engineering to identify **conditional constructs** and **iterative constructs**.

### Programming Constructs in LC-3

<table>
<thead>
<tr>
<th>Address</th>
<th>15</th>
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<th>13</th>
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</table>

*Starting address of file*

R4 = R1 – 4 // char – EOT
BRz 0x300E // check if end of file

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</tr>
</tbody>
</table>

*Starting address of file*

if (R1 == R0) {
  ...
} // increment the counter

while (R1 != EOT) {
  ...
}
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

- Machine code debugging: **Elementary interactive debugging operations**
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>Address</th>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
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<tbody>
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</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: \( \text{BRp} \ #-3 \) // BRp 0x3201
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.

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
If Statement

- In MIPS, we create **conditional constructs with conditional branches** (e.g., beq, bne...)

**High-level code**

```plaintext
if (i == j)
    f = g + h;

f = f - i;
```

**MIPS assembly**

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

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

**Branch not equal**

Compares two values ($s3=i$, $s4=j$) and jumps if they are different.
We use the **unconditional branch** (i.e., \( j \)) to skip the "**else**" subtask if the "**if**" subtask is the correct one.

### High-level code

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

### MIPS assembly

```plaintext
# $s0 = f, $s1 = g, $s2 = h
# $s3 = i, $s4 = j
bne $s3, $s4, L1
add $s0, $s1, $s2
j done
L1: sub $s0, $s0, $s3
done:
```

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.
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**

```asm
# $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

```mips
# $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.
For Loop Using SLT

- We use `slt` (i.e., set less than) for the "less than" comparison

**High-level code**

```
// 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;
}
```

**MIPS assembly**

```
# $s0 = i, $s1 = sum

addi $s1, $0, 0
addi $s0, $0, 1
add $t0, $0, 101

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

done:
```

- **Set less than**
  
  $t1 = $s0 < $t0 ? 1:0

- **Shift left logical**
Arrays in MIPS
**Arrays**

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

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x12340010</td>
<td>array[4]</td>
</tr>
<tr>
<td>0x1234800C</td>
<td>array[3]</td>
</tr>
<tr>
<td>0x12348008</td>
<td>array[2]</td>
</tr>
<tr>
<td>0x12348004</td>
<td>array[1]</td>
</tr>
<tr>
<td>0x12348000</td>
<td>array[0]</td>
</tr>
</tbody>
</table>

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

- **Load upper immediate + OR immediate**

```assembly
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 \texttt{lui} and \texttt{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**

<table>
<thead>
<tr>
<th>High-level code</th>
<th>MIPS assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>int main() {</code></td>
<td><code>0x00400200  main: jal simple</code></td>
</tr>
<tr>
<td><code>simple();</code></td>
<td><code>0x00400204  add $s0,$s1,$s2</code></td>
</tr>
<tr>
<td><code>a = b + c;</code></td>
<td>...</td>
</tr>
<tr>
<td><code>}</code></td>
<td><code>0x00401020  simple: jr $ra</code></td>
</tr>
<tr>
<td><code>void simple() {</code></td>
<td></td>
</tr>
<tr>
<td><code>return;</code></td>
<td></td>
</tr>
<tr>
<td><code>}</code></td>
<td></td>
</tr>
</tbody>
</table>

- **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

```assembly
# $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

MIPS assembly

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
# 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>
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<td></td>
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</tr>
</tbody>
</table>

Two words pushed on the stack

---

46
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.
MIPS Stack: Register Saving Convention

MIPS assembly

diffofsums:

```mips
addi $sp, $sp, -4   # allocate space on stack to store 1 register
sw  $s0, 0($sp)   # save $s0 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  $s0, 0($sp)   # restore $s0 from stack
addi $sp, $sp, 4  # 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