Introduction to Computer Architecture

Lecture 8: Assembly Programming

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[Slides are primarily based on those of Onur Mutlu for the Computer Architecture Course at CMU]

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

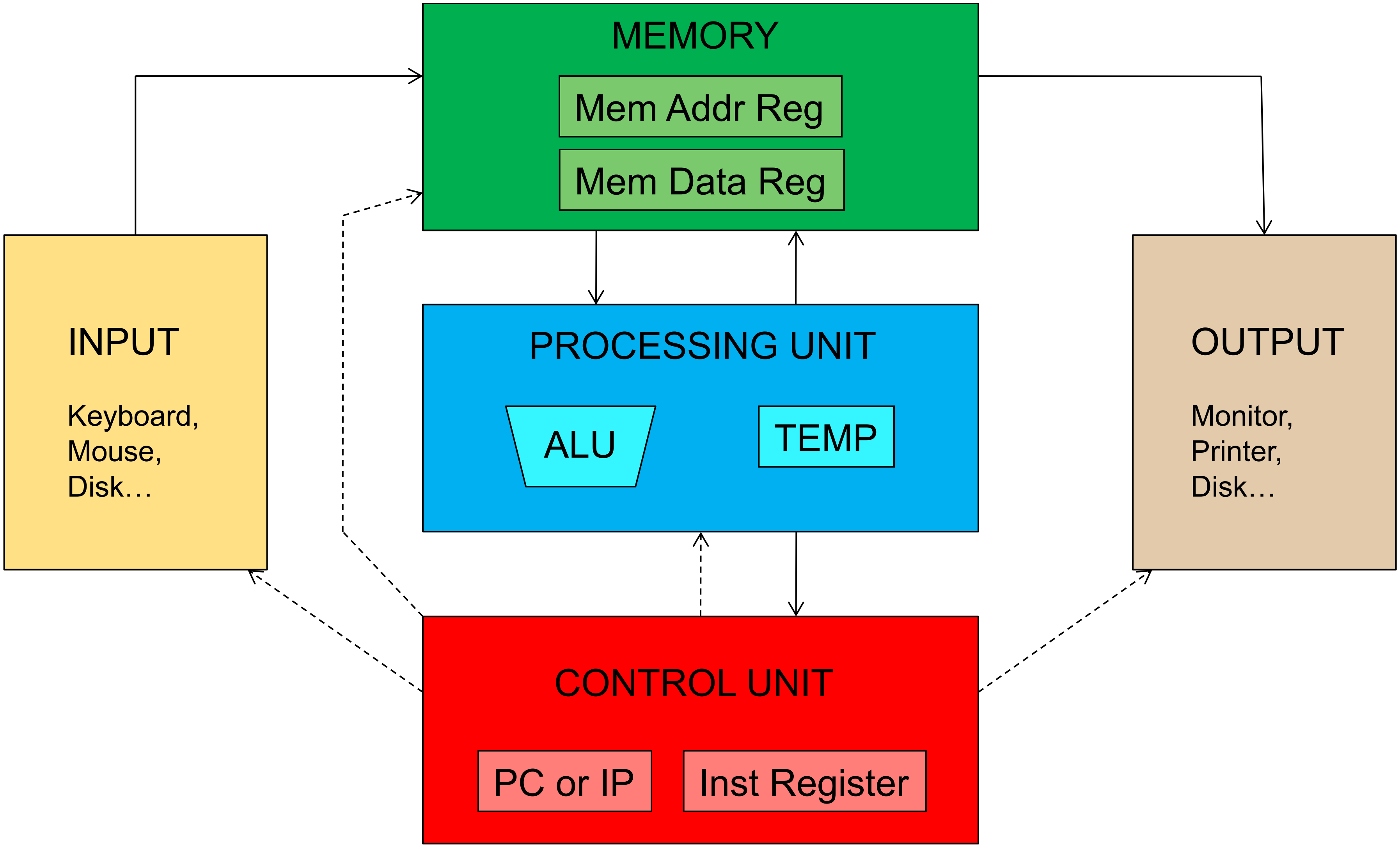
- This week
  - Von Neumann Model, LC-3, and MIPS
    - P&P, Chapters 4, 5
    - H&H, Chapter 6
    - P&P, Appendices A and C (ISA and microarchitecture of LC-3)
    - H&H, Appendix B (MIPS instructions)
  - Programming
    - P&P, Chapter 6
  - **Recommended:** H&H Chapter 5, especially 5.1, 5.2, 5.4,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



Recall: LC-3: A Von Neumann Machine

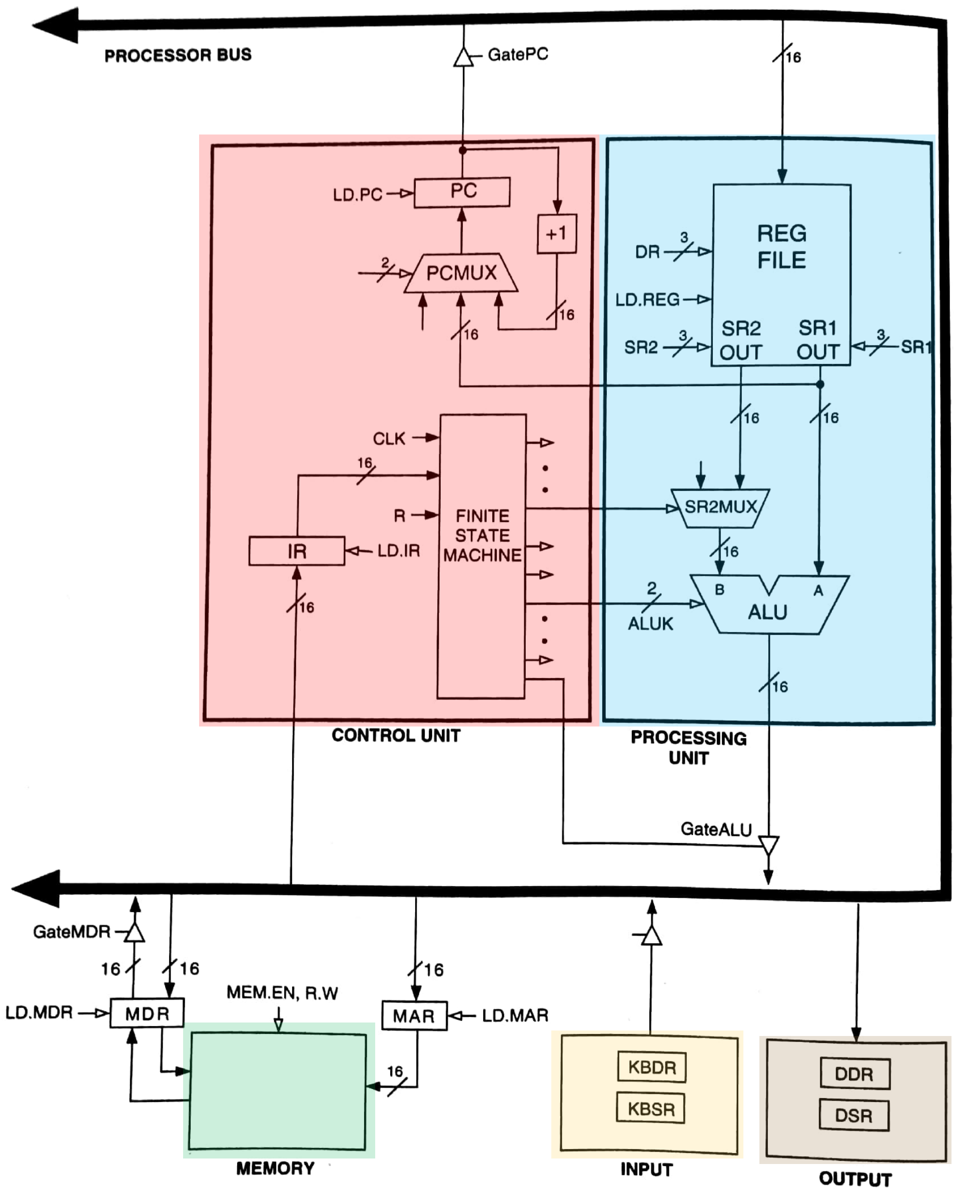


Figure 4.3 The LC-3 as an example of the von Neumann model

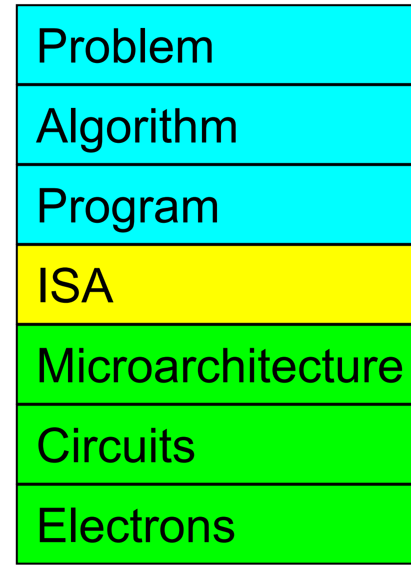
Recall: The Instruction Cycle

- 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

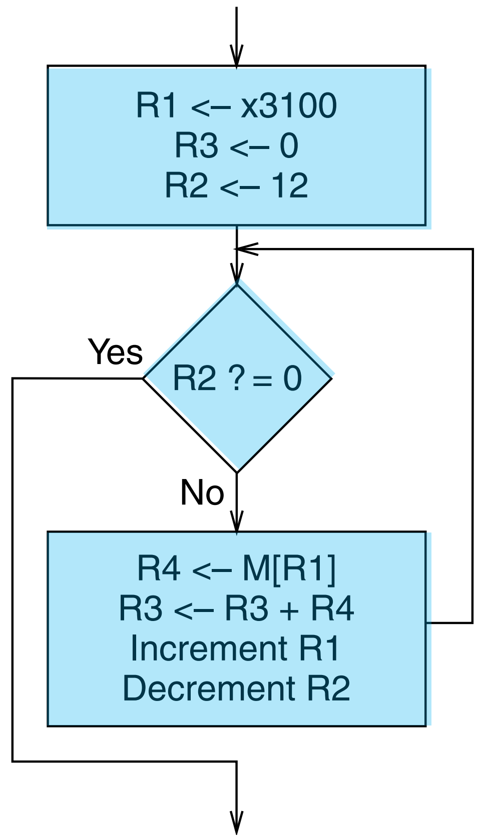
- The ISA specifies
  - The memory organization
    - Address space (LC-3: 2^{16}, MIPS: 2^{32})
    - Addressability (LC-3: 16 bits, MIPS: 32 bits)
    - Word- or Byte-addressable
  - The register set
    - R0 to R7 in LC-3
    - 32 registers in MIPS
  - The instruction set
    - Opcodes
    - Data 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: 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

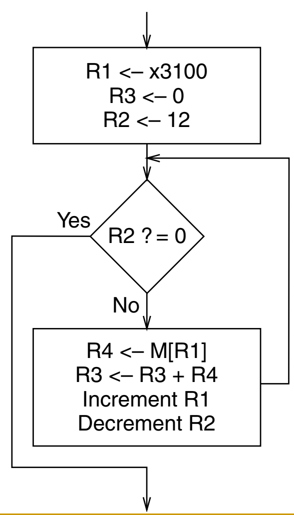
Accumulate integer value in R3

Increment address R1
Decrement R2

A Program for Adding Integers in LC-3

- We use conditional branch instructions to create a loop

Address	Instr.	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x3000	LEA	1	1	1	0	0	0	1	0	1	1	1	1	1	1	1	1	R1 = PC † + 0x00FF = 3100 // load address (0x00FF)
x3001	AND	0	1	0	1	0	1	1	0	1	1	1	0	0	0	0	0	R3 = 0 // reset register
x3002	AND	0	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	R2 = 0 // reset register
x3003	ADD	0	0	0	1	0	1	0	0	1	0	1	0	1	1	0	0	R2 = R2 + 12 // initialize counter
x3004	BR	0	0	0	0	0	1 (z)	0	0 (5)	0	0	0	0	0	1	0	1	BRz (PC † + 5) = BRz 0x300A // check condition
x3005	LDR	0	1	1	0	1	0	0	0	0	1	0 (0)	0	0	0	0	0	R4 = M[R1 + 0] // load value
x3006	ADD	0	0	0	1	0	1	1	0	1	1	0	0	0	1	0	0	R3 = R3 + R4 // accumulate
x3007	ADD	0	0	0	1	0	0	1	0	0	1	1	0 (1)	0	0	0	1	R1 = R1 + 1 // increment address
x3008	ADD	0	0	0	1	0	1	0	0	1	0	1	1 (-1)	1	1	1	1	R2 = R2 – 1 // decrement counter
x3009	BR	0	0	0	0	1 (n)	1 (z)	1 (p)	1 (-6)	1	1	1	1	1	0	1	0	BRnzp (PC † – 6) = BRnzp 0x3004 // jump



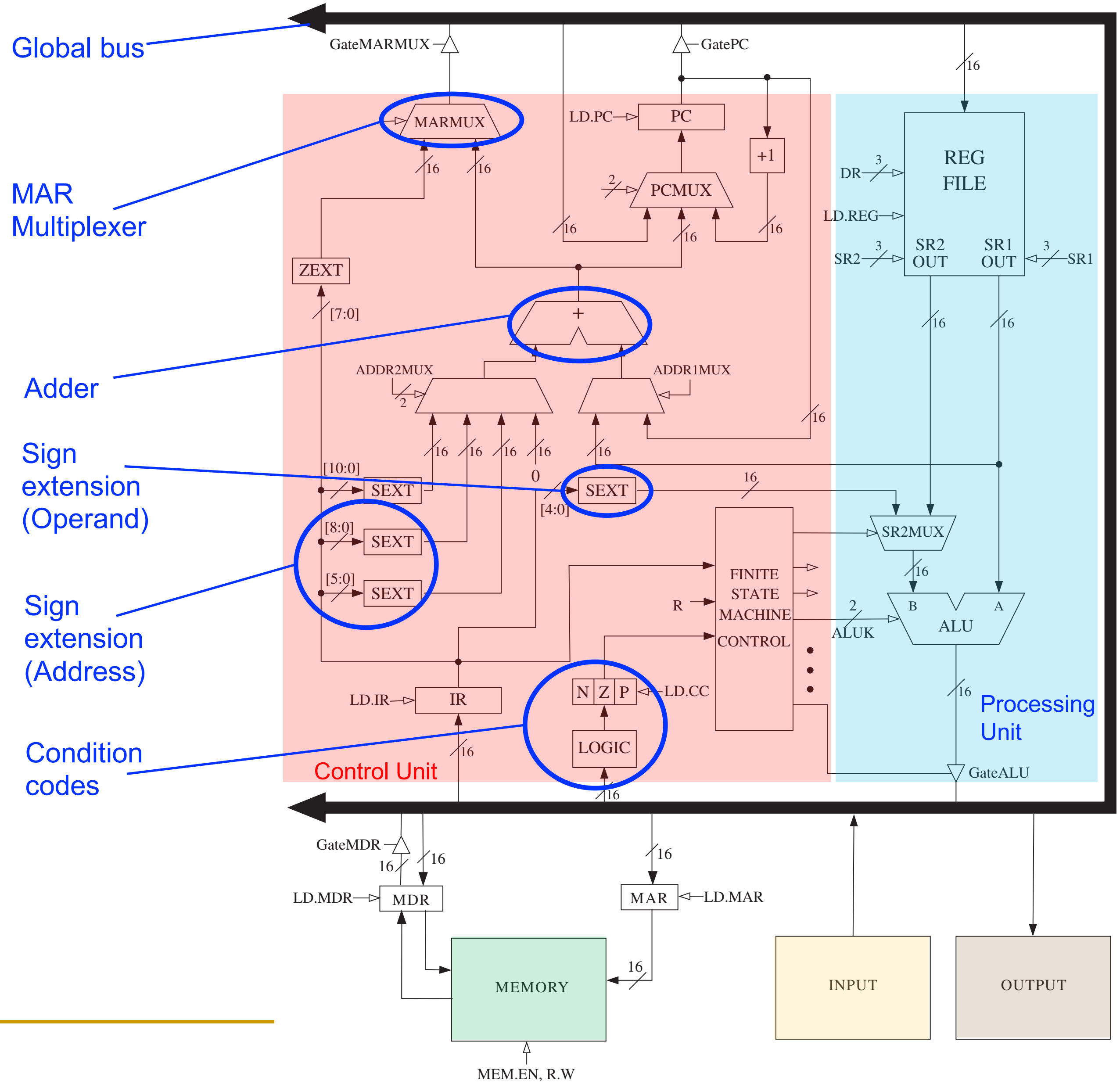
Bit 5 to differentiate both ADD instructions

† 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)



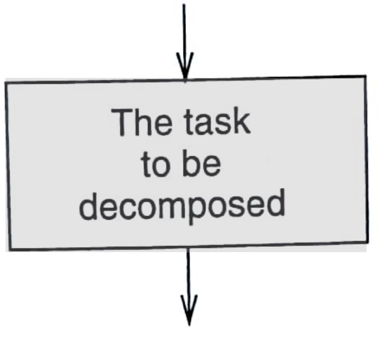
(Assembly) Programming

Programming Constructs

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

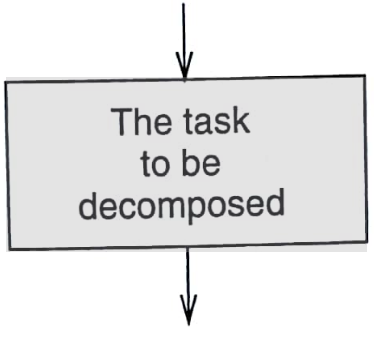
- The goal is to replace the units of work with programming constructs that represent that part of the task

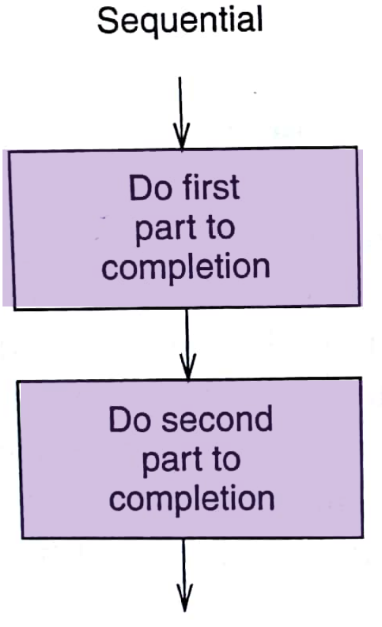
- There are three basic programming constructs
  - Sequential construct
  - Conditional construct
  - Iterative construct



Sequential Construct

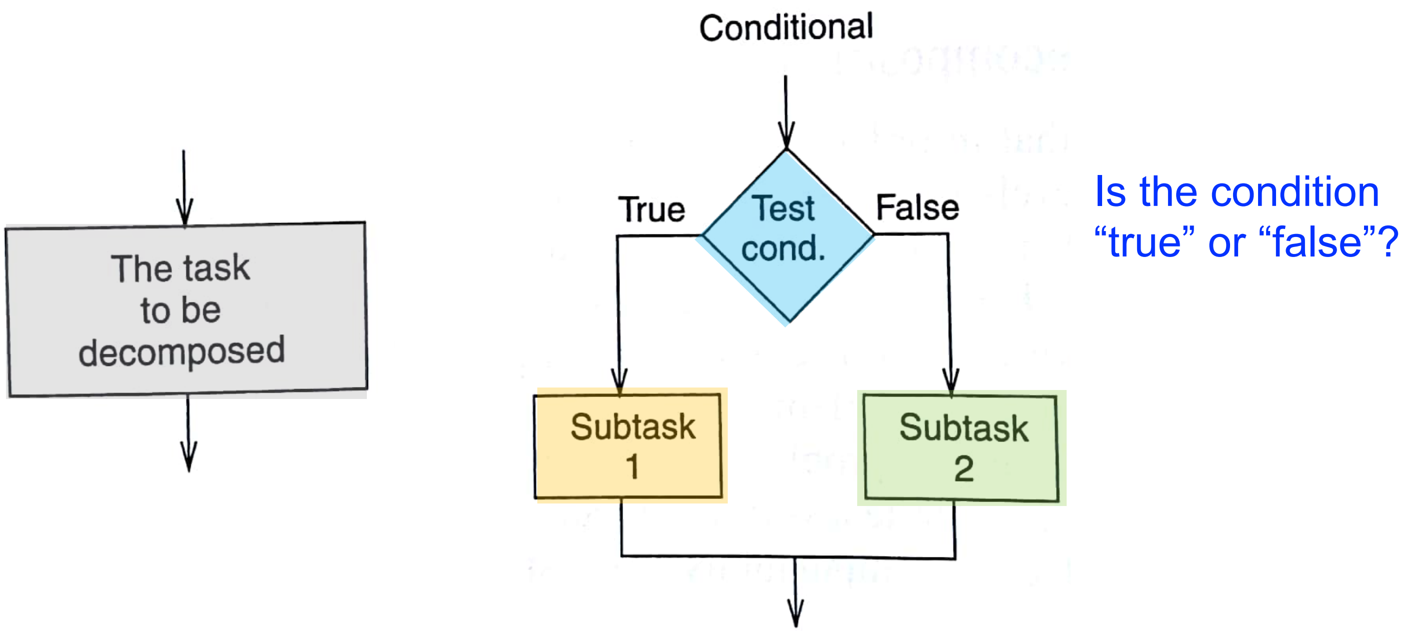
- The sequential construct is used if the designated task can be broken down into two subtasks, one following the other





Conditional Construct

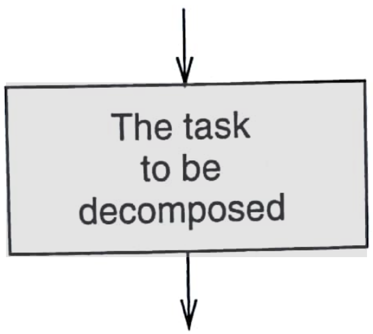
- The conditional construct is used if the designated task consists of doing one of two subtasks, but not both

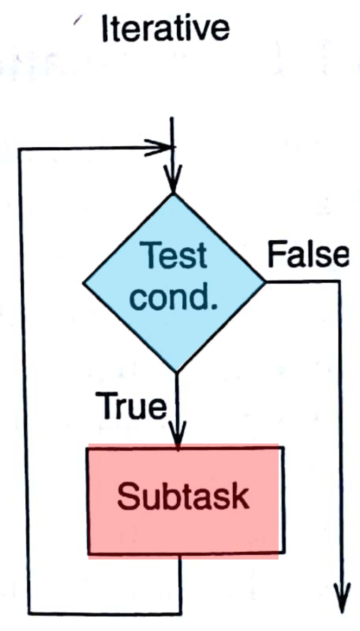


  - Either subtask may be "do nothing"
  - After the correct subtask is completed, the program moves onward
- E.g., if-else statement, switch-case statement

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





Is the condition still "true"?

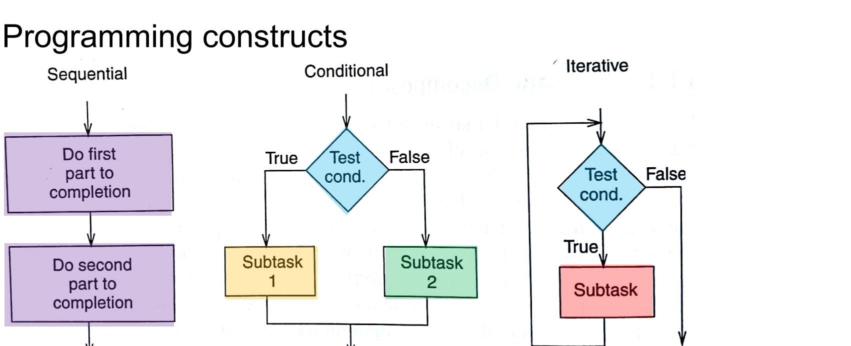
- E.g., for loop, while loop, do-while loop

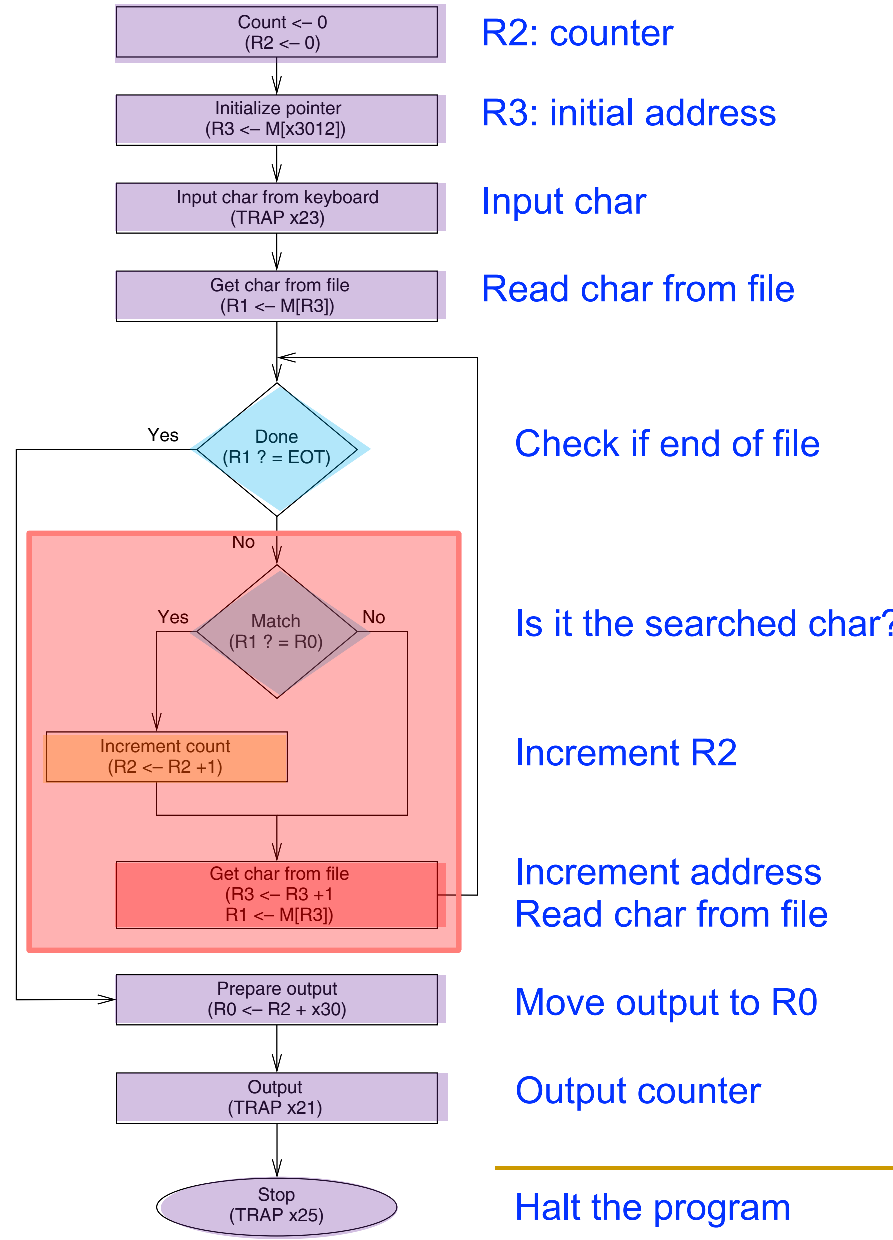
Constructs in an Example Program

- 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
  - Character 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
  - Result to the monitor (TRAP instr.)





TRAP Instruction

- TRAP invokes an OS service call

LC-3 assembly

```
TRAP 0x23;
```

Machine Code

15 14 13 12	11 10 9 8	7 6 5 4 3 2 1 0
OP	0 0 0 0	trapvect8
4 bits		8 bits

  - 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 a loops and if statements

Address	Opcode	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x3000	AND	0	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	R2 = 0 // initialize counter
x3001	LD	0	0	1	0	0	1	1	0	0	0	0	1	0	0	0	0	R3 = M[0x3012] // initial address
x3002	TRAP	1	1	1	1	0	0	0	0	0	0	1	0	0	0	1	1	TRAP 0x23 // input char to R0
x3003	LDR	0	1	1	0	0	0	1	0	1	1	0	0	0	0	0	0	R1 = M[R3] // char from file
x3004	ADD	0	0	0	1	1	0	0	0	0	1	1	1	1	1	0	0	R4 = R1 – 4 // char – EOT
x3005	BR	0	0	0	0	0	z	0	0	0	0	0	0	1	0	0	0	BRz 0x300E // check if end of file
x3006	NOT	1	0	0	1	0	0	1	0	0	1	1	1	1	1	1	1	R1 = NOT(R1)
x3007	ADD	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0	1	R1 = R1 + 1
x3008	ADD	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	R1 = R1 + R0
x3009	BR	0	0	0	0	n	0	p	0	0	0	0	0	0	0	0	1	BRnp 0x300B
x300A	ADD	0	0	0	1	0	1	0	0	1	0	1	0	0	0	0	1	R2 = R2 + 1 // increment the counter
x300B	ADD	0	0	0	1	0	1	1	0	1	1	1	0	0	0	0	1	R3 = R3 + 1 // increment address
x300C	LDR	0	1	1	0	0	0	1	0	1	1	0	0	0	0	0	0	R1 = M[R3] // char from file
x300D	BR	0	0	0	0	n	z	p	1	1	1	1	1	0	1	1	0	BRnzp 0x3004
x300E	LD	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	R0 = M[0x3013]
x300F	ADD	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	R0 = R0 + R2
x3010	TRAP	1	1	1	1	0	0	0	0	0	0	1	0	0	0	0	1	TRAP 0x21
x3011	AND	1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	TRAP 0x25
x3012		Starting address of file																
x3013	ASCII TEMPLATE	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	

// subtract char from file from input char for comparison (x3006–x3008)

// output counter to monitor with TRAP (x300E–x3011)

?

?

Programming Constructs in LC-3

- Let us do some reverse engineering to identify conditional constructs and iterative constructs

Address	Op	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x3000	AND	0	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	
x3001	LD	0	0	1	0	0	1	1	0	0	0	0	1	0	0	0	0	
x3002	TRAP	1	1	1	1	0	0	0	0	0	0	1	0	0	0	1	1	
x3003	LDR	0	1	1	0	0	0	1	0	1	1	0	0	0	0	0	0	
x3004	ADD	0	0	0	1	1	0	0	0	0	1	1	1	1	1	0	0	R4 = R1 – 4 // char – EOT
x3005	BR	0	0	0	0	0	1 (z)	0	0	0	0	0	0	1	0	0	0	BRz 0x300E // check if end of file
x3006	NOT	1	0	0	1	0	0	1	0	0	1	1	1	1	1	1	1	R1 = NOT(R1)
x3007	ADD	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0	1	R1 = R1 + 1
x3008	ADD	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	R1 = R1 + R0
x3009	BR	0	0	0	0	1 (n)	0	1 (p)	0	0	0	0	0	0	0	0	1	BRnp 0x300B
x300A	ADD	0	0	0	1	0	1	0	0	1	0	1	0	0	0	0	1	R2 = R2 + 1 // increment the counter
x300B	ADD	0	0	0	1	0	1	1	0	1	1	1	0	0	0	0	1	
x300C	LDR	0	1	1	0	0	0	1	0	1	1	0	0	0	0	0	0	
x300D	BR	0	0	0	0	1 (n)	1 (z)	1 (p)	1	1	1	1	1	0	1	1	0	BRnzp 0x3004
x300E	LD	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	
x300F	ADD	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	
x3010	TRAP	1	1	1	1	0	0	0	0	0	0	1	0	0	0	0	1	
x3011	AND	1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	
x3012		Starting address of file																
x3013		0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	

// subtract char from file from input char for comparison (x3006–x3008)

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

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

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

Address		15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x3200	AND	0	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	R2 = 0 // initialize register
x3201	ADD	0	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0	R2 = R2 + R4
x3202	ADD	0	0	0	1	1	0	1	1	0	1	1	1	1	1	1	1	R5 = R5 – 1
x3203	BR	0	0	0	0	0	1 z	1 p	1	1	1	1	1	1	1	0	1	BRzp 0x3201 ?
x3204	HALT	1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	HALT // end program

Debugging the Multiply Program

Address	Instruction	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Comment
x3200	AND	0	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	R2 = 0 // initialize register
x3201	ADD	0	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0	R2 = R2 + R4
x3202	ADD	0	0	0	1	1	0	1	1	0	1	1	1	1	1	1	1	R5 = R5 – 1
x3203	BR	0	0	0	0	0	z 1	p 1	1	1	1	1	1	1	1	0	1	BRzp 0x3201 ?
x3204	HALT	1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	HALT // end program

- We examine the contents of all registers after the execution of each instruction

PC	R2	R4	R5	
x3201	0	10	3	
x3202	10	10	3	
x3203	10	10	2	
x3201	10	10	2	
x3202	20	10	2	
x3203	20	10	1	
x3201	20	10	1	
x3202	30	10	1	← Correct result
x3203	30	10	0	← BR should not be taken if R5 = 0
x3201	30	10	0	
x3202	40	10	0	
x3203	40	10	−1	
x3204	40	10	−1	
	40	10	−1	

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

Correct instruction:

```
BRp #-3    // BRp 0x3201
```

Easier Debugging with Breakpoints

Address	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
x3200	AND 0	1	0	1	0	1	0	0	1	0	1	0	0	0	0	0	R2 = 0 // initialize register
x3201	ADD 0	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0	R2 = R2 + R4
x3202	ADD 0	0	0	1	1	0	1	1	0	1	1	1	1	1	1	1	R5 = R5 – 1
x3203	BR 0	0	0	0	0	z 1	p 1	1	1	1	1	1	1	1	0	1	BRzp 0x3201 ?
x3204	HALT 1	1	1	1	0	0	0	0	0	0	1	0	0	1	0	1	HALT // end program

- 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

PC	R2	R4	R5	
x3203	10	10	2	
x3203	20	10	1	
x3203	30	10	0	← BR should not be taken if R5 = 0
x3203	40	10	−1	

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

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

f = f - i;
```

MIPS assembly

```
# $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

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

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

MIPS assembly

```
# $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

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

```
// 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

```
# $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

For Loop

- The implementation of the "for" loop is similar to the "while" loop

High-level code

```
// 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

```
# $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
       addi $t0, $0, 101
loop:  slt  $t1, $s0, $t0
       beq  $t1, $0, done
       add  $s1, $s1, $s0
       sll  $s0, $s0, 1
       j    loop
done:
```

Initialize sum and i

Set less than

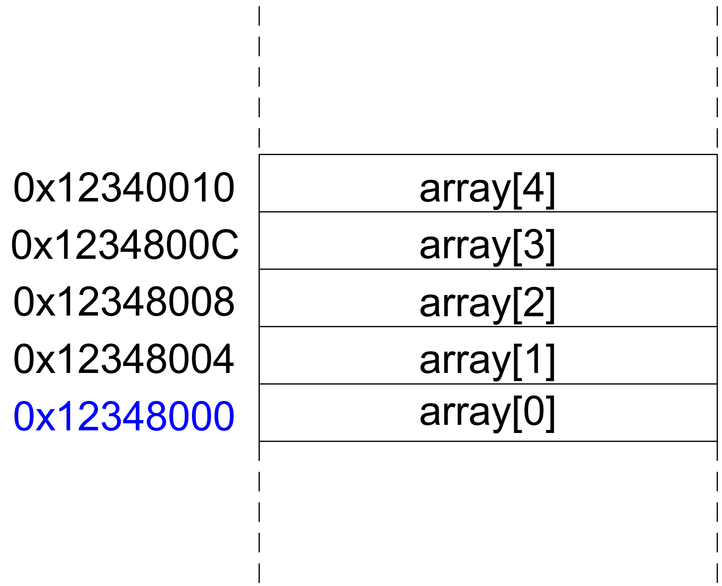
$t1 = $s0 < $t0 ? 1:0

Shift left logical

Arrays in MIPS

Arrays

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



- 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

```
int array[5];

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

array[1] = array[1] * 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

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()

```
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

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

void simple() {
  return;
}
```

MIPS 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

```
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

Argument values

Return value

```
# $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
```

Return address

Function Calls: Need for the Stack

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
```

- 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

Address	Data	
7FFFFFFC	12345678	← $sp
7FFFFFF8		
7FFFFFF4		
7FFFFFF0		
⋮	⋮	

Address	Data	
7FFFFFFC	12345678	
7FFFFFF8	AABBCCDD	
7FFFFFF4	11223344	← $sp
7FFFFFF0		
⋮	⋮	

Two words pushed on the stack

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
```

- 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:
  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