MIPS Assembly Language Programming

COE 308

Computer Architecture

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Presentation Outline

Assembly Language Statements

- Three types of statements in assembly language
  - Typically, one statement should appear on a line

1. Executable Instructions
   - Generate machine code for the processor to execute at runtime
   - Instructions tell the processor what to do
2. Pseudo-Instructions and Macros
   - Translated by the assembler into real instructions
   - Simplify the programmer task
3. Assembler Directives
   - Provide information to the assembler while translating a program
   - Used to define segments, allocate memory variables, etc.
   - Non-executable: directives are not part of the instruction set

Instructions

- Assembly language instructions have the format:

```
[label:]   mnemonic   [operands]   [#comment]
```

- Label: (optional)
  - Marks the address of a memory location, must have a colon
  - Typically appear in data and text segments
- Mnemonic
  - Identifies the operation (e.g. **add**, **sub**, etc.)
- Operands
  - Specify the data required by the operation
  - Operands can be registers, memory variables, or constants
  - Most instructions have three operands

```
L1:   addiu $t0, $t0, 1        #increment $t0
```

Comments

❖ Comments are very important!

- ✧ Explain the program's purpose
- ✧ When it was written, revised, and by whom
- ✧ Explain data used in the program, input, and output
- ✧ Explain instruction sequences and algorithms used
- ✧ Comments are also required at the beginning of every procedure
  - Indicate input parameters and results of a procedure
  - Describe what the procedure does

❖ Single-line comment

- ✧ Begins with a hash symbol **#** and terminates at end of line

Next . . .

- ❖ Assembly Language Statements
- ❖ Assembly Language Program Template
- ❖ Defining Data
- ❖ Memory Alignment and Byte Ordering
- ❖ System Calls
- ❖ Procedures
- ❖ Parameter Passing and the Runtime Stack

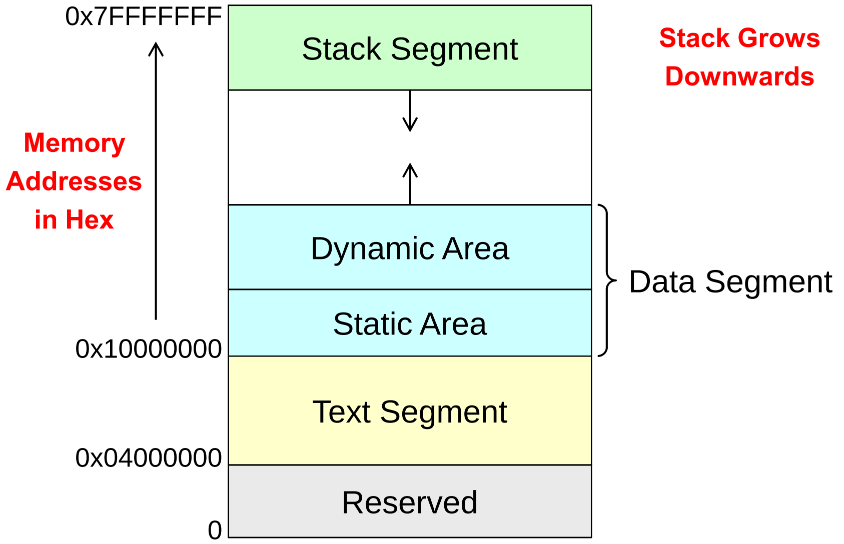
Program Template

```
# Title:                        Filename:
# Author:                       Date:
# Description:
# Input:
# Output:
################# Data segment #####################
.data
 . . .
################# Code segment #####################
.text
.globl main
main:                           # main program entry
 . . .
li $v0, 10                      # Exit program
syscall
```


.DATA, .TEXT, & .GLOBL Directives

- **.DATA** directive
  - Defines the data segment of a program containing data
  - The program's variables should be defined under this directive
  - Assembler will allocate and initialize the storage of variables
- **.TEXT** directive
  - Defines the code segment of a program containing instructions
- **.GLOBL** directive
  - Declares a symbol as global
  - Global symbols can be referenced from other files
  - We use this directive to declare *main* procedure of a program

Layout of a Program in Memory



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Data Definition Statement

- Sets aside storage in memory for a variable
- May optionally assign a name (label) to the data
- Syntax:

[*name*:] *directive* *initializer* [, *initializer*] . . .

```
var1: .WORD    10
```

- All initializers become binary data in memory

Data Directives

- **.BYTE** Directive
  - Stores the list of values as 8-bit bytes
- **.HALF** Directive
  - Stores the list as 16-bit values aligned on half-word boundary
- **.WORD** Directive
  - Stores the list as 32-bit values aligned on a word boundary
- **.FLOAT** Directive
  - Stores the listed values as single-precision floating point
- **.DOUBLE** Directive
  - Stores the listed values as double-precision floating point

String Directives

- **.ASCII** Directive
  - Allocates a sequence of bytes for an ASCII string
- **.ASCIIZ** Directive
  - Same as **.ASCII** directive, but adds a NULL char at end of string
  - Strings are null-terminated, as in the C programming language
- **.SPACE** Directive
  - Allocates space of *n* uninitialized bytes in the data segment

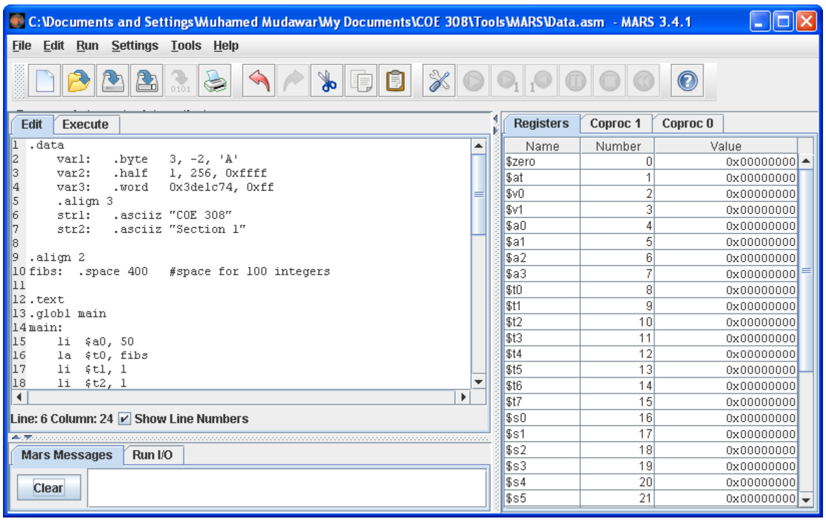
Examples of Data Definitions

```
.DATA
var1:  .BYTE     'A', 'E', 127, -1, '\n'
var2:  .HALF     -10, 0xffff
var3:  .WORD     0x12345678:100
var4:  .FLOAT    12.3, -0.1
var5:  .DOUBLE   1.5e-10
str1:  .ASCII    "A String\n"
str2:  .ASCIIZ   "NULL Terminated String"
array: .SPACE    100
```

Array of 100 words (var3)

100 bytes (not initialized) (array)

MARS Assembler and Simulator Tool



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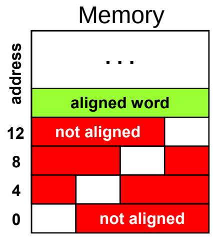
Memory Alignment

- ❖ Memory is viewed as an array of bytes with addresses
  - ✧ Byte Addressing: address points to a byte in memory
- ❖ Words occupy 4 consecutive bytes in memory
  - ✧ MIPS instructions and integers occupy 4 bytes
- ❖ Alignment: address is a multiple of size
  - ✧ Word address should be a multiple of **4**
    - ▪ Least significant 2 bits of address should be **00**
  - ✧ Halfword address should be a multiple of **2**
- ❖ **`.ALIGN n`** directive
  - ✧ Aligns the next data definition on a 2^n byte boundary



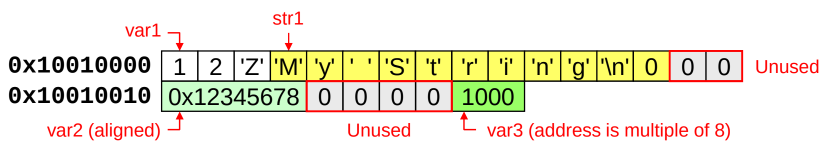
Symbol Table

- ❖ Assembler builds a symbol table for labels (variables)
  - ✧ Assembler computes the address of each label in data segment
- ❖ Example

```
.DATA
var1:   .BYTE   1, 2,'Z'
str1:   .ASCIIZ "My String\n"
var2:   .WORD   0x12345678
.ALIGN  3
var3:   .HALF   1000
```

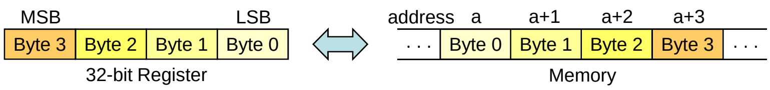
Symbol Table

Label	Address
var1	0x10010000
str1	0x10010003
var2	0x10010010
var3	0x10010018

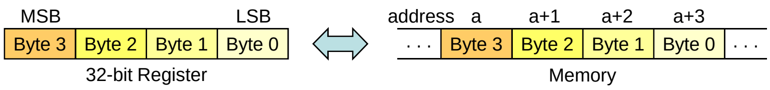


Byte Ordering and Endianness

- ❖ Processors can order bytes within a word in two ways
- ❖ Little Endian Byte Ordering
  - ✧ Memory address = Address of **least significant byte**
  - ✧ Example: Intel IA-32, Alpha



- ❖ Big Endian Byte Ordering
  - ✧ Memory address = Address of **most significant byte**
  - ✧ Example: SPARC, PA-RISC



- ❖ MIPS can operate with both byte orderings

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System Calls

- Programs do input/output through system calls
- MIPS provides a special **syscall** instruction
  - To obtain services from the operating system
  - Many services are provided in the SPIM and MARS simulators
- Using the **syscall** system services
  - Load the service number in register $v0
  - Load argument values, if any, in registers $a0, $a1, etc.
  - Issue the **syscall** instruction
  - Retrieve return values, if any, from result registers

Syscall Services

Service	$v0	Arguments / Result
Print Integer	1	$a0 = integer value to print
Print Float	2	$f12 = float value to print
Print Double	3	$f12 = double value to print
Print String	4	$a0 = address of null-terminated string
Read Integer	5	$v0 = integer read
Read Float	6	$f0 = float read
Read Double	7	$f0 = double read
Read String	8	$a0 = address of input buffer $a1 = maximum number of characters to read
Exit Program	10	
Print Char	11	$a0 = character to print
Read Char	12	$a0 = character read

Supported by MARS

Reading and Printing an Integer

```
################# Code segment #####################
.text
.globl main
main:                        # main program entry
   li    $v0, 5              # Read integer
   syscall                   # $v0 = value read

   move  $a0, $v0            # $a0 = value to print
   li    $v0, 1              # Print integer
   syscall

   li    $v0, 10             # Exit program
   syscall
```


Reading and Printing a String

```
################# Data segment #####################
.data
   str: .space  10         # array of 10 bytes
################# Code segment #####################
.text
.globl main
main:                      # main program entry
   la    $a0, str          # $a0 = address of str
   li    $a1, 10           # $a1 = max string length
   li    $v0, 8            # read string
   syscall
   li    $v0, 4            # Print string str
   syscall
   li    $v0, 10           # Exit program
   syscall
```

Program 1: Sum of Three Integers

```
# Sum of three integers
#
# Objective: Computes the sum of three integers.
#     Input: Requests three numbers.
#    Output: Outputs the sum.
################### Data segment ###################
.data
prompt:   .asciiz     "Please enter three numbers: \n"
sum_msg:  .asciiz     "The sum is: "
################### Code segment ###################
.text
.globl main
main:
      la    $a0,prompt          # display prompt string
      li    $v0,4
      syscall
      li    $v0,5               # read 1st integer into $t0
      syscall
      move  $t0,$v0
```


Sum of Three Integers – Slide 2 of 2

```
      li    $v0,5               # read 2nd integer into $t1
      syscall
      move  $t1,$v0

      li    $v0,5               # read 3rd integer into $t2
      syscall
      move  $t2,$v0

      addu  $t0,$t0,$t1         # accumulate the sum
      addu  $t0,$t0,$t2

      la    $a0,sum_msg         # write sum message
      li    $v0,4
      syscall

      move  $a0,$t0             # output sum
      li    $v0,1
      syscall

      li    $v0,10              # exit
      syscall
```

Program 2: Case Conversion

```
# Objective: Convert lowercase letters to uppercase
#      Input: Requests a character string from the user.
#     Output: Prints the input string in uppercase.
################### Data segment #####################
.data
name_prompt:  .asciiz         "Please type your name: "
out_msg:      .asciiz         "Your name in capitals is: "
in_name:      .space 31       # space for input string
################### Code segment #####################
.text
.globl main
main:
      la    $a0,name_prompt   # print prompt string
      li    $v0,4
      syscall
      la    $a0,in_name       # read the input string
      li    $a1,31            # at most 30 chars + 1 null char
      li    $v0,8
      syscall
```


Case Conversion - Slide 2 of 2

```
      la    $a0,out_msg       # write output message
      li    $v0,4
      syscall
      la    $t0,in_name
loop:
      lb    $t1,($t0)
      beqz  $t1,exit_loop     # if NULL, we are done
      blt   $t1,'a',no_change
      bgt   $t1,'z',no_change
      addiu $t1,$t1,-32       # convert to uppercase: 'A'-'a'=-32
      sb    $t1,($t0)
no_change:
      addiu $t0,$t0,1         # increment pointer
      j     loop
exit_loop:
      la    $a0,in_name       # output converted string
      li    $v0,4
      syscall
      li    $v0,10            # exit
      syscall
```

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Procedures

- ❖ Consider the following swap procedure (written in C)
- ❖ Translate this procedure to MIPS assembly language

```
void swap(int v[], int k)
{   int temp;
    temp = v[k]
    v[k] = v[k+1];
    v[k+1] = temp;
}
```

Parameters:

`$a0` = Address of `v[]`
`$a1` = `k`, and
Return address is in `$ra`

```
swap:
 sll $t0,$a1,2     # $t0=k*4
 add $t0,$t0,$a0   # $t0=v+k*4
 lw  $t1,0($t0)    # $t1=v[k]
 lw  $t2,4($t0)    # $t2=v[k+1]
 sw  $t2,0($t0)    # v[k]=$t2
 sw  $t1,4($t0)    # v[k+1]=$t1
 jr  $ra           # return
```

Call / Return Sequence

- Suppose we call procedure swap as: **swap(a,10)**
  - Pass **address** of array **a** and **10** as arguments
  - Call the procedure swap saving **return address** in **$31 = $ra**
  - Execute procedure swap
  - Return control to the point of origin (return address)

Registers

	. . .
$a0=$4	addr a
$a1=$5	10
	. . .
$ra=$31	ret addr

Caller

```
   la    $a0, a
   li    $a1, 10
   jal   swap
# return here
   . . .
```

```
swap:
 sll $t0,$a1,2
 add $t0,$t0,$a0
 lw  $t1,0($t0)
 lw  $t2,4($t0)
 sw  $t2,0($t0)
 sw  $t1,4($t0)
 jr  $ra
```


Details of JAL and JR

Address	Instructions	Assembly Language
00400020	lui $1, 0x1001	la $a0, a
00400024	ori $4, $1, 0	
00400028	ori $5, $0, 10	ori $a1,$0,10
0040002C	jal 0x10000f	jal swap
00400030	. . .	# return here
		swap:
0040003C	sll $8, $5, 2	sll $t0,$a1,2
00400040	add $8, $8, $4	add $t0,$t0,$a0
00400044	lw $9, 0($8)	lw $t1,0($t0)
00400048	lw $10,4($8)	lw $t2,4($t0)
0040004C	sw $10,0($8)	sw $t2,0($t0)
00400050	sw $9, 4($8)	sw $t1,4($t0)
00400054	jr $31	jr $ra

Pseudo-Direct Addressing

PC = imm26<<2

0x10000f << 2

= 0x0040003C

$31 = 0x00400030

Register $31 is the return address register

Instructions for Procedures

- JAL (Jump-and-Link) used as the call instruction
  - Save return address in **$ra = PC+4** and jump to procedure
  - Register **$ra = $31** is used by **JAL** as the **return address**
- JR (Jump Register) used to return from a procedure
  - Jump to instruction whose address is in register Rs (PC = Rs)
- JALR (Jump-and-Link Register)
  - Save return address in Rd = PC+4, and
  - Jump to procedure whose address is in register Rs (PC = Rs)
  - Can be used to call methods (addresses known only at runtime)

Instruction	Meaning	Format					
jal label	$31=PC+4, jump	$op^6 = 3$	imm^{26}				
jr Rs	PC = Rs	$op^6 = 0$	rs^5	0	0	0	8
jalr Rd, Rs	Rd=PC+4, PC=Rs	$op^6 = 0$	rs^5	0	rd^5	0	9

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Parameter Passing

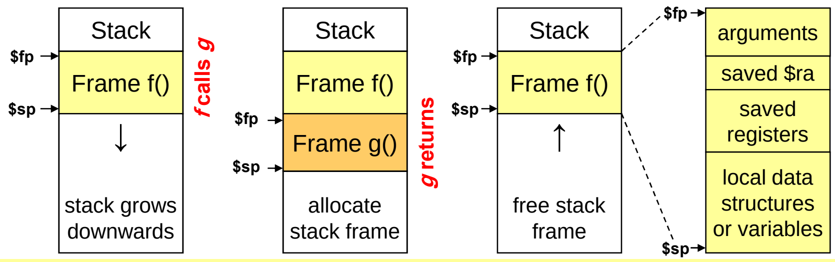
- ❖ Parameter passing in assembly language is different
  - ✧ More complicated than that used in a high-level language
- ❖ In assembly language
  - ✧ Place all required parameters in an accessible storage area
  - ✧ Then call the procedure
- ❖ Two types of storage areas used
  - ✧ Registers: general-purpose registers are used (register method)
  - ✧ Memory: stack is used (stack method)
- ❖ Two common mechanisms of parameter passing
  - ✧ Pass-by-value: parameter **value** is passed
  - ✧ Pass-by-reference: **address** of parameter is passed

Parameter Passing – cont'd

- ❖ By convention, register are used for parameter passing
  - ✧ `$a0 = $4 .. $a3 = $7` are used for **passing arguments**
  - ✧ `$v0 = $2 .. $v1 = $3` are used for **result values**
- ❖ Additional arguments/results can be placed on the stack
- ❖ Runtime stack is also needed to …
  - ✧ Store variables / data structures when they cannot fit in registers
  - ✧ Save and restore registers across procedure calls
  - ✧ Implement recursion
- ❖ Runtime stack is implemented via software convention
  - ✧ The **stack pointer** `$sp = $29` (points to top of stack)
  - ✧ The **frame pointer** `$fp = $30` (points to a procedure frame)

Stack Frame

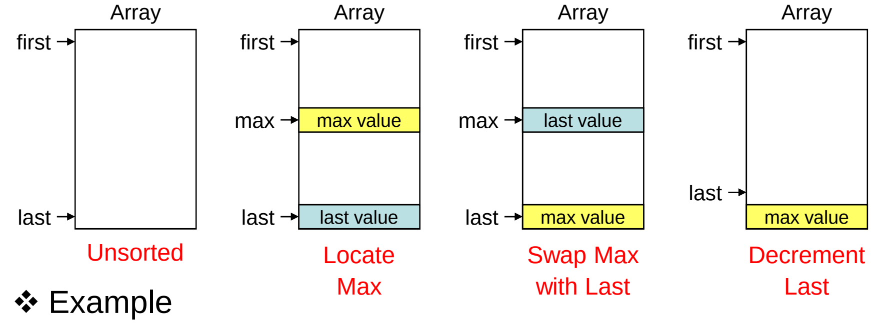
- Stack frame is the segment of the stack containing …
  - Saved arguments, registers, and local data structures (if any)
- Called also the activation frame or activation record
- Frames are pushed and popped by adjusting …
  - Stack pointer `$sp = $29` and Frame pointer `$fp = R30`
  - Decrement `$sp` to allocate stack frame, and increment to free



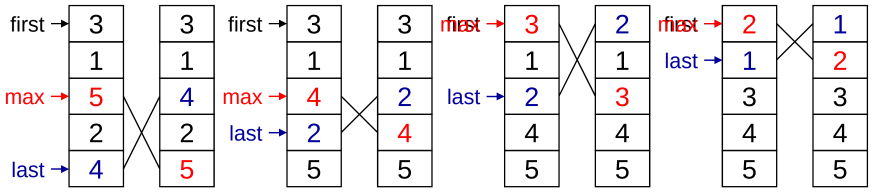
Preserving Registers

- Need to preserve registers across a procedure call
  - Stack can be used to preserve register values
- Which registers should be saved?
  - Registers modified by the called procedure, and
  - Still used by the calling procedure
- Who should preserve the registers?
  - **Called Procedure**: preferred method for modular code
    - Register preservation is done inside the called procedure
  - By convention, registers **$s0**, **$s1**, …, **$s7** should be preserved
  - Also, registers **$sp**, **$fp**, and **$ra** should also be preserved

Selection Sort



❖ Example



Selection Sort Procedure

```
# Objective: Sort array using selection sort algorithm
#      Input: $a0 = pointer to first, $a1 = pointer to last
#     Output: array is sorted in place
##########################################################
sort: addiu $sp, $sp, -4    # allocate one word on stack
      sw    $ra, 0($sp)     # save return address on stack
top:  jal   max             # call max procedure
      lw    $t0, 0($a1)     # $t0 = last value
      sw    $t0, 0($v0)     # swap last and max values
      sw    $v1, 0($a1)
      addiu $a1, $a1, -4    # decrement pointer to last
      bne   $a0, $a1, top   # more elements to sort
      lw    $ra, 0($sp)     # pop return address
      addiu $sp, $sp, 4
      jr    $ra             # return to caller
```

Max Procedure

```
# Objective: Find the address and value of maximum element
#      Input: $a0 = pointer to first, $a1 = pointer to last
#     Output: $v0 = pointer to max,    $v1 = value of max
##########################################################
max:  move   $v0, $a0        # max pointer = first pointer
      lw     $v1, 0($v0)     # $v1 = first value
      beq    $a0, $a1, ret   # if (first == last) return
      move   $t0, $a0        # $t0 = array pointer
loop: addi   $t0, $t0, 4     # point to next array element
      lw     $t1, 0($t0)     # $t1 = value of A[i]
      ble    $t1, $v1, skip  # if (A[i] <= max) then skip
      move   $v0, $t0        # found new maximum
      move   $v1, $t1
skip: bne    $t0, $a1, loop  # loop back if more elements
ret:  jr     $ra
```


Example of a Recursive Procedure

int fact(int n) { if (n<2) return 1; else return (n*fact(n-1)); }

```
fact:  slti    $t0,$a0,2      # (n<2)?
       beq     $t0,$0,else    # if false branch to else
       li      $v0,1          # $v0 = 1
       jr      $ra            # return to caller
else:  addiu   $sp,$sp,-8     # allocate 2 words on stack
       sw      $a0,4($sp)     # save argument n
       sw      $ra,0($sp)     # save return address
       addiu   $a0,$a0,-1     # argument = n-1
       jal     fact           # call fact(n-1)
       lw      $a0,4($sp)     # restore argument
       lw      $ra,0($sp)     # restore return address
       mul     $v0,$a0,$v0    # $v0 = n*fact(n-1)
       addi    $sp,$sp,8      # free stack frame
       jr      $ra            # return to caller
```