Introduction to Assembly Language Programming

COE 301

Computer Organization

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Presentation Outline

- **The MIPS Instruction Set Architecture**
- Introduction to Assembly Language
- Defining Data
- Memory Alignment and Byte Ordering
- System Calls

Instruction Set Architecture (ISA)

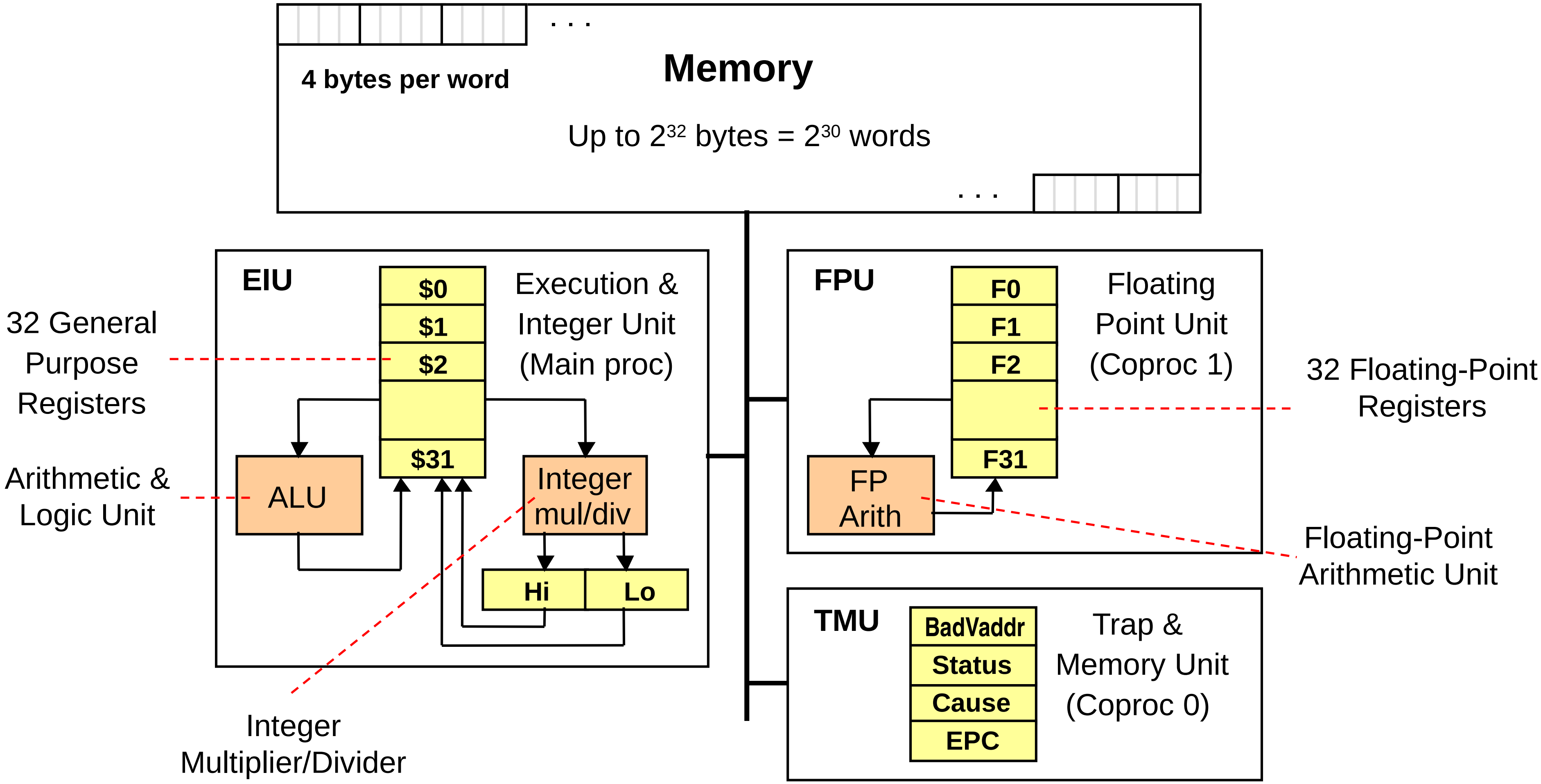
- Critical Interface between software and hardware
- An ISA includes the following …
  - Instructions and Instruction Formats
  - Data Types, Encodings, and Representations
  - Programmable Storage: Registers and Memory
  - Addressing Modes: to address Instructions and Data
  - Handling Exceptional Conditions (like overflow)
- Examples (Versions) Introduced in

Examples	(Versions)	Introduced in
Intel	(8086, 80386, Pentium, Core, ...)	1978
MIPS	(MIPS I, II, …, MIPS32, MIPS64)	1986
ARM	(version 1, 2, …)	1985

Instructions

- Instructions are the language of the machine
- We will study the MIPS instruction set architecture
  - Known as **Reduced Instruction Set Computer (RISC)**
  - Elegant and relatively simple design
  - Similar to RISC architectures developed in mid-1980's and 90's
  - Popular, used in many products
    - Silicon Graphics, ATI, Cisco, Sony, etc.
- Alternative to: Intel x86 architecture
  - Known as **Complex Instruction Set Computer (CISC)**

Overview of the MIPS Architecture



MIPS General-Purpose Registers

- 32 General Purpose Registers (GPRs)
  - All registers are 32-bit wide in the MIPS 32-bit architecture
  - Software defines names for registers to standardize their use
  - Assembler can refer to registers by name or by number ($ notation)

Name	Register	Usage
$zero	$0	Always 0 (forced by hardware)
$at	$1	Reserved for assembler use
$v0 – $v1	$2 – $3	Result values of a function
$a0 – $a3	$4 – $7	Arguments of a function
$t0 – $t7	$8 – $15	Temporary Values
$s0 – $s7	$16 – $23	Saved registers (preserved across call)
$t8 – $t9	$24 – $25	More temporaries
$k0 – $k1	$26 – $27	Reserved for OS kernel
$gp	$28	Global pointer (points to global data)
$sp	$29	Stack pointer (points to top of stack)
$fp	$30	Frame pointer (points to stack frame)
$ra	$31	Return address (used by jal for function call)

Instruction Formats

- All instructions are 32-bit wide, Three instruction formats:
- Register (R-Type)
  - Register-to-register instructions
  - Op: operation code specifies the format of the instruction

Op^6	Rs^5	Rt^5	Rd^5	sa^5	$funct^6$

- Immediate (I-Type)
  - 16-bit immediate constant is part in the instruction

Op^6	Rs^5	Rt^5	$immediate^{16}$

- Jump (J-Type)
  - Used by jump instructions

Op^6	$immediate^{26}$

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What is Assembly Language?

- Low-level programming language for a computer
- One-to-one correspondence with the machine instructions
- Assembly language is specific to a given processor
- Assembler: converts assembly program into machine code
- Assembly language uses:
  - Mnemonics: to represent the names of low-level machine instructions
  - Labels: to represent the names of variables or memory addresses
  - Directives: to define data and constants
  - Macros: to facilitate the inline expansion of text into other code

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

Assembly Language 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

- Single-line comment
  - Begins with a hash symbol # and terminates at end of line
- 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

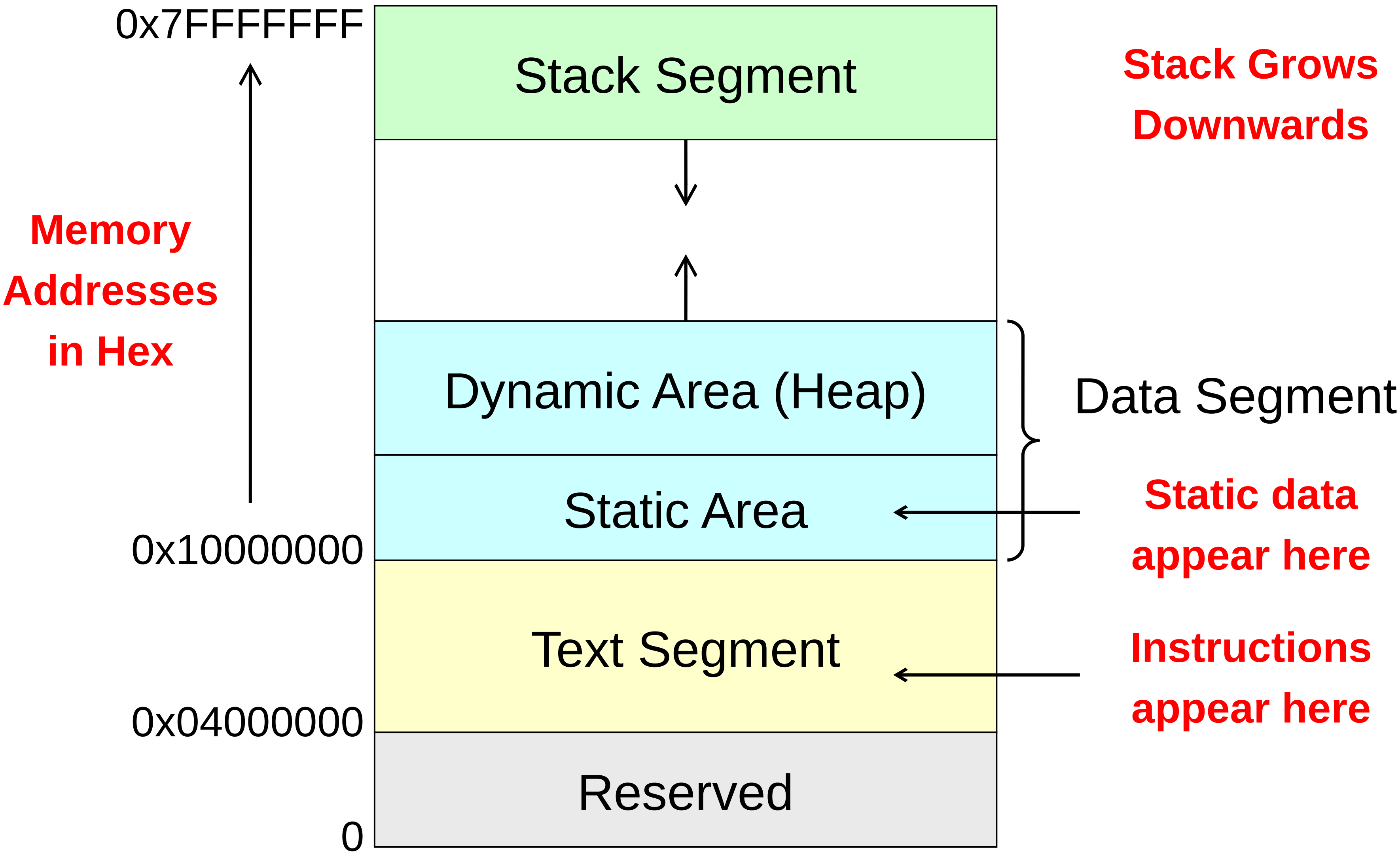
Program Template

```
# 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* function of a program

Layout of a Program in Memory



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Data Definition Statement

- The assembler uses directives to define data
- It allocates storage in the static data segment 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 Initialized with the same value

100 bytes (not initialized)

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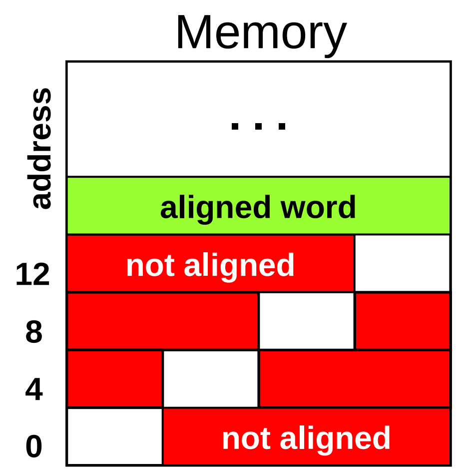
Memory Alignment

- Memory is viewed as an **addressable array of bytes**
- **Byte Addressing**: address points to a byte in memory
- However, words occupy 4 consecutive bytes in memory
  - MIPS instructions and integers occupy 4 bytes
- **Memory Alignment**:
  - Address must be multiple of size
  - Word address should be a multiple of **4**
  - Double-word address should be a multiple of **8**



- `.ALIGN n` directive
  - Aligns the next data definition on a 2^n byte boundary
  - Forces the address of next data definition to be multiple of 2^n

Byte Ordering (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

MSB			LSB
Byte 3	Byte 2	Byte 1	Byte 0

32-bit Register

address	a	a+1	a+2	a+3	
. . .	Byte 0	Byte 1	Byte 2	Byte 3	. . .

Memory

- Big Endian Byte Ordering
  - Memory address = Address of **most significant byte**
  - Example: SPARC architecture

MSB			LSB
Byte 3	Byte 2	Byte 1	Byte 0

32-bit Register

address	a	a+1	a+2	a+3	
. . .	Byte 3	Byte 2	Byte 1	Byte 0	. . .

Memory

- MIPS can operate with both byte orderings

Symbol Table

- Assembler builds a **symbol table** for labels
  - 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

var1 str1

0x10010000	1	2	'Z'	'M'	'y'	' '	'S'	't'	'r'	'i'	'n'	'g'	'\n'	0	0	0	Unused
0x10010010	0x12345678				0	0	0	0	1000								

var2 (aligned) Unused var3 (address is multiple of 8)

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System Calls

- Programs do input/output through system calls
- The MIPS architecture provides a `syscall` instruction
  - To obtain services from the operating system
  - The operating system handles all system calls requested by program
- Since MARS is a simulator, it simulates the `syscall` services
- To use the `syscall` 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	Return integer value in $v0
Read Float	6	Return float value in $f0
Read Double	7	Return double value in $f0
Read String	8	$a0 = address of input buffer $a1 = maximum number of characters to read
Allocate Heap memory	9	$a0 = number of bytes to allocate Return address of allocated memory in $v0
Exit Program	10	

Syscall Services – Cont'd

Print Char	11	$a0 = character to print
Read Char	12	Return character read in $v0
Open File	13	$a0 = address of null-terminated filename string $a1 = flags (0 = read-only, 1 = write-only) $a2 = mode (ignored) Return file descriptor in $v0 (negative if error)
Read from File	14	$a0 = File descriptor $a1 = address of input buffer $a2 = maximum number of characters to read Return number of characters read in $v0
Write to File	15	$a0 = File descriptor $a1 = address of buffer $a2 = number of characters to write Return number of characters written in $v0
Close File	16	$a0 = File descriptor

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
```

Sum of Three Integers

```
# Sum of three integers
# Objective: Computes the sum of three integers.
# Input: Requests three numbers, Output: 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 – (cont'd)

```
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
```