Computer Organization

Lab4 MIPS(3)

Subroutines, Memory,Assembler(Directive),Machine Code

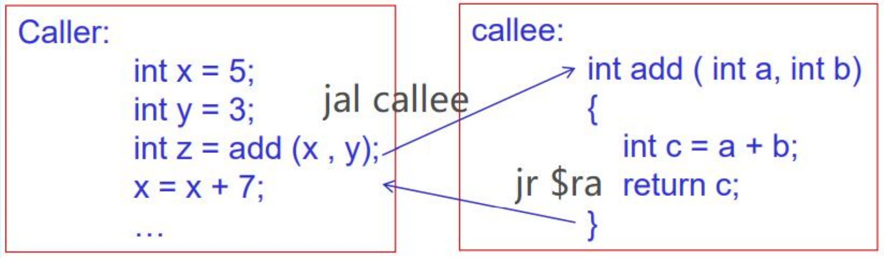
Topics

- Subroutines
  - Caller , Callee
  - jal , jr , $ra (P1-1:Page6)
  - Stack
  - Recursion (P1-2:Pge7)
- Memory
  - Static vs Dynamic
  - Dynamic Storage
    - Stack vs Heap (P1-3:Page9)
- Assembler - Directives
  - .data, .text
  - .macro, .endmacro (optional)
    - Procedure call vs Assembler replace
  - .align (0,1,2)
    - why, how (P2-1:Page15)
  - .globl vs .extern
    - .globl main
    - (P2-2:Page18)
- Machine Code and Addressing

(P3-1,P3-2: Page21)

Subroutines

- **jal** function_lable #jump and link
  - **Save** the address of the next instruction in **register $ra**
  - **Unconditionally jump** to the instruction at function_lable.
  - Used in **caller** while calling the function
- **jr $ra**
  - **Read** the value in **register $ra**
  - **Unconditionally jump** to the instruction according the value in register $ra
  - Used in **callee** while returning to the caller
- **lw / sw** with $sp
  - Protects register data by using **stack** in memory



```
Caller:
        int x = 5;
        int y = 3;
        int z = add (x , y);
        x = x + 7;
        …
```

```
callee:
        int add ( int a, int b)
        {
            int c = a + b;
            return c;
        }
```

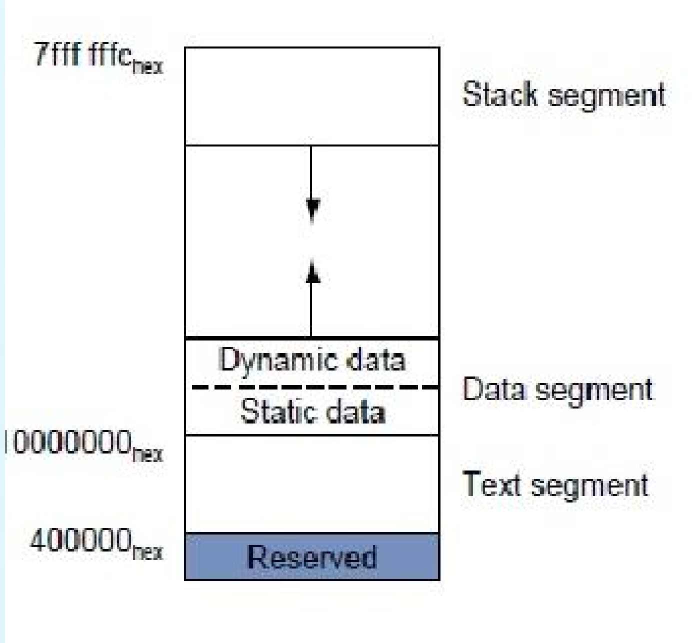
Stack Segment

Stack segment: The portion of memory used by a program to hold procedure call frames.

The program ***stack segment***, resides **at the top of the virtual address space** (starting at address 7fffffff $_{hex}$).

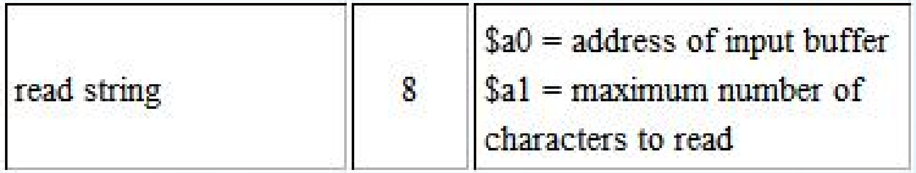
Like dynamic data, the maximum size of a program's stack is not known in advance.

As the program **pushes values on the stack**, the operating system **expands** the stack segment **down, toward the data segment**.



Demo #1(1)

```
.data                                   #piece 1/3
        tdata: .space 6
        str1:  .asciiz "the orignal string is: "
        str2:  .asciiz "\nthe last two character of the string is: "
.text
        la $a0,tdata
        addi $a1,$zero,6
        addi $v0,$zero,8
        syscall
```



read string	8	$a0 = address of input buffer $a1 = maximum number of characters to read

```
la $a0,str1    #piece 2/3
jal print_string

    la $a0,tdata
    jal print_string

    la $a0,str2
    jal print_string

    la $a0,tdata+3
    jal print_string

    addi $v0,$zero,10
    syscall
```

```
print_string:    #piece 3/3
        addi $sp,$sp,-8
        sw $a0,4($sp)
        sw $v0,0($sp)
        addi $v0,$zero,4
        syscall
        lw $v0,0($sp)
        lw $a0,4($sp)
        addi $sp,$sp,8
        jr $ra
```

1.可以
2.可以

*Q1. Is it ok to remove the push and pop processing of **$a0** on the stack in "print_string" ?*

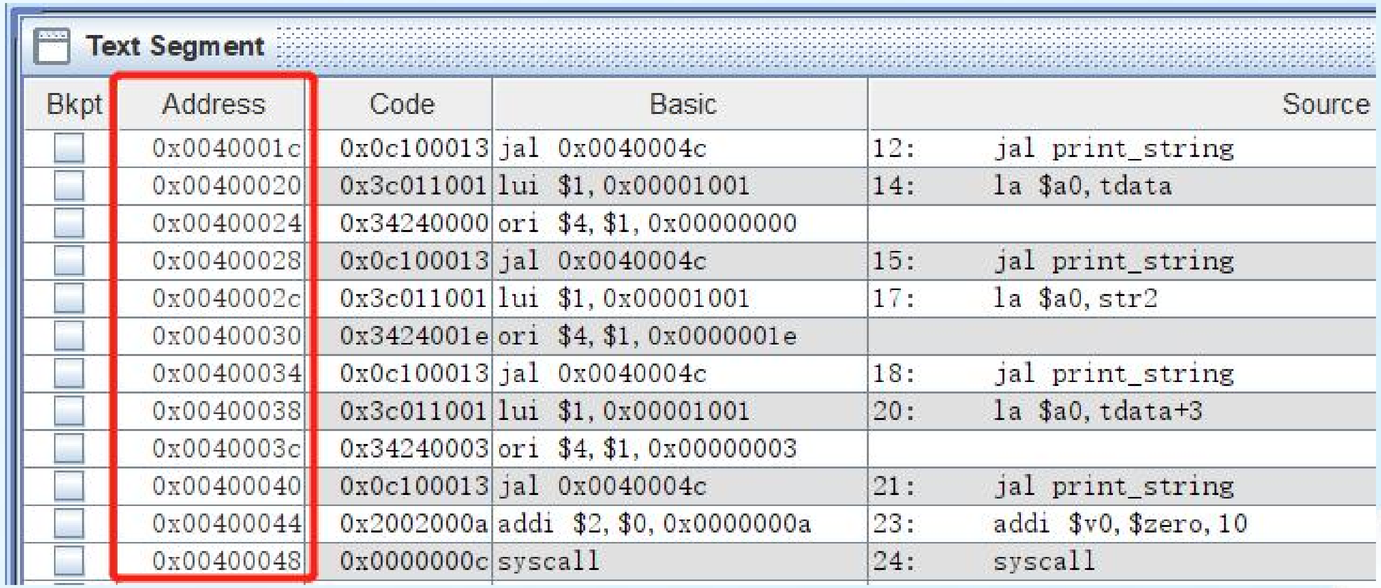
*Q2.   Is it ok to remove the push and pop processing of **$v0** on the stack in "print_string" ?*

Demo #1(2)

0x0040020
0x004002c
0x0040038
0x0040044

P1-1: What's the value of $ra while jumping and linking to the print_string (at line 12,15,18,21)?

```
print_string:
        addi $sp,$sp,-8
        sw $a0,4($sp)
        sw $v0,0($sp)

        addi $v0,$zero,4
        syscall

        lw $v0,0($sp)
        lw $a0,4($sp)
        addi $sp,$sp,8

        jr $ra
```



Text Segment

Bkpt	Address	Code	Basic	Source
□	0x0040001c	0x0c100013	jal 0x0040004c	12: jal print_string
□	0x00400020	0x3c011001	lui $1, 0x00001001	14: la $a0, tdata
□	0x00400024	0x34240000	ori $4, $1, 0x00000000	
□	0x00400028	0x0c100013	jal 0x0040004c	15: jal print_string
□	0x0040002c	0x3c011001	lui $1, 0x00001001	17: la $a0, str2
□	0x00400030	0x3424001e	ori $4, $1, 0x0000001e	
□	0x00400034	0x0c100013	jal 0x0040004c	18: jal print_string
□	0x00400038	0x3c011001	lui $1, 0x00001001	20: la $a0, tdata+3
□	0x0040003c	0x34240003	ori $4, $1, 0x00000003	
□	0x00400040	0x0c100013	jal 0x0040004c	21: jal print_string
□	0x00400044	0x2002000a	addi $2, $0, 0x0000000a	23: addi $v0, $zero, 10
□	0x00400048	0x0000000c	syscall	24: syscall

pay attention to the value of $pc

Recursion

"fact" is a function to calculate the Calculate the factorial.

Code in C:

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

*P1-2. While calculate **fact(6)**, how many times does push and pop processing on stack happend? How does the value of $a0 change when calculate **fact(6)**?*

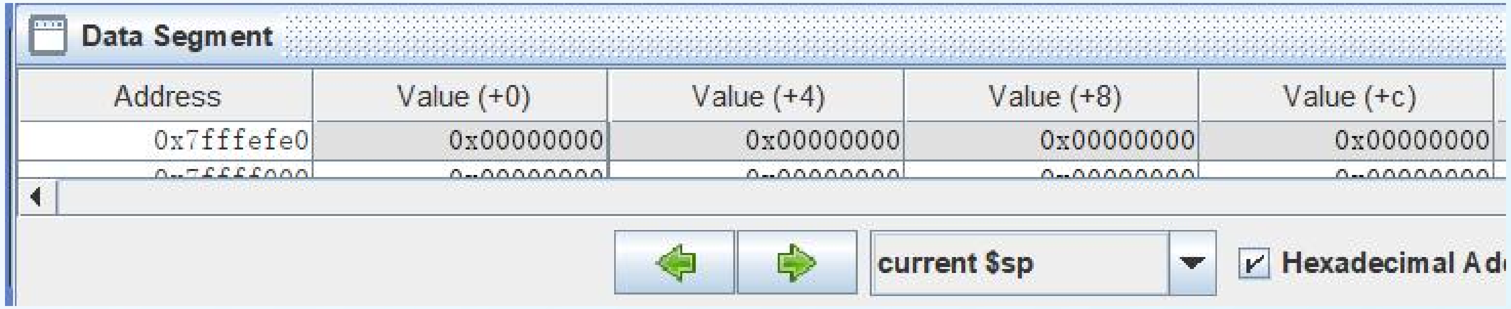
```
14, 6-5-4-3-2-1-0-1-2-3-4-5-6
```

Code in MIPS:

```
fact:
        addi   $sp,$sp,-8           #adjust stack for 2 items
        sw     $ra, 4($sp)          #save the return address
        sw     $a0, 0($sp)          #save the argument n

        slti   $t0,$a0,1            #test for n<1
        beq    $t0,$zero,L1         #if n>=1,go to L1

        addi  $v0,$zero,1           #return 1
        addi  $sp,$sp,8             #pop 2 items off stack
        jr          $ra             #return to caller

L1:     addi  $a0,$a0,-1            #n>=1; argument gets(n-1)
        jal         fact            #call fact with(n-1)

lw      $a0,0($sp)                  #return from jal: restore argument n
lw   $ra,4($sp)                     #restore the return address
addi    $sp,$sp,8                   #adjust stack pointer to pop 2 items

mul     $v0,$a0,$v0                 #return n*fact(n-1)

jr      $ra                         #return to the caller
```

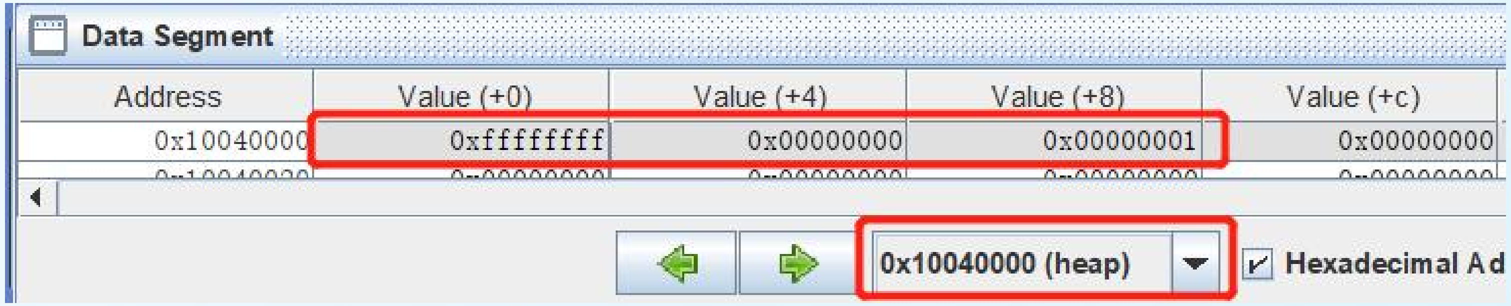
Memory: Stack vs Heap

- **Stack**: used to store the local variable, usually used in calle.
- **Heap**: The heap is reserved for **sbrk** and **break** system calls, and it not always present.



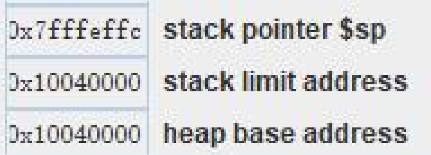
Data Segment

Address	Value (+0)	Value (+4)	Value (+8)	Value (+c)
0x7fffefe0	0x00000000	0x00000000	0x00000000	0x00000000

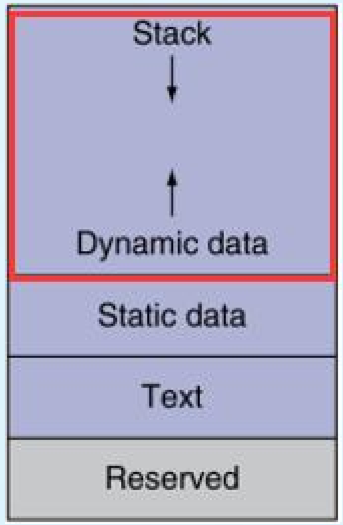


Data Segment

Address	Value (+0)	Value (+4)	Value (+8)	Value (+c)
0x10040000	0xffffffff	0x00000000	0x00000001	0x00000000



0x7fffeffc	stack pointer $sp
0x10040000	stack limit address
0x10040000	heap base address



Demo #2-1

The following demo(composed of 4 pieces on this page and the next) is supposed to get and store the data from input device, get the minimal value among the data, the number of input data is determined by user.

```
.include "macro_print_str.asm"          #piece 1/4
.data
        min_value: .word 0
.text
        print_string("please input the number:")

        li $v0,5            #read an integer
        syscall
        move $s0,$v0        #s0 is the number of integers

        sll $a0,$s0,2       #new a heap with 4*$s0
        li $v0,9
        syscall
        move $s1,$v0        #$s1 is the start of the heap
        move $s2,$v0        #$s2 is the point
```

```
print_string("please input the array\n")     #piece 2/4

add $t0,$0,$0

loop_read:

        li $v0,5        #read the array
        syscall
        sw $v0,($s2)

        addi $s2,$s2,4
        addi $t0,$t0,1
        bne $t0,$s0,loop_read
```

P1-3: What' s the value of $v0 after finish executing the syscall with yellow background ? Is it same with the value of $sp ?

0x10040000(即heap base address),No

While the 1st input number is 0 or 1,what will happen? why?

1:死循环，因为一次操作后$t0就大于数组长度了，满足bne $t0,$s0 loop_find_min所以会不断执行loop_find_min模块
0：死循环，因为在第一次读入一个数之后$t0的值就大于0了，满足bne $t0,$s0,loop_read所以会不断执行loop_read模块

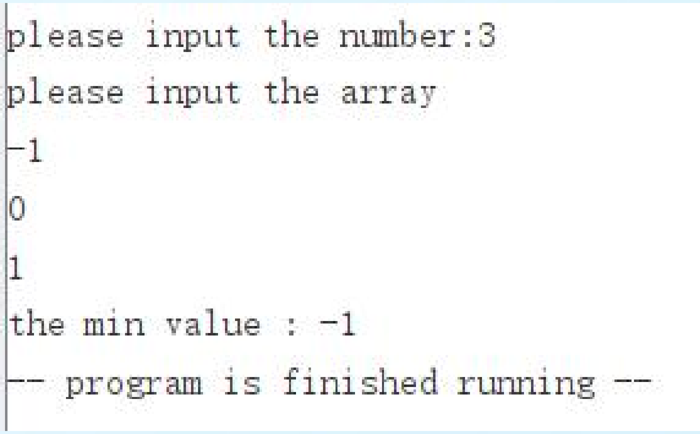
Modify this demo to make it better

bne->blt

Demo #2-2

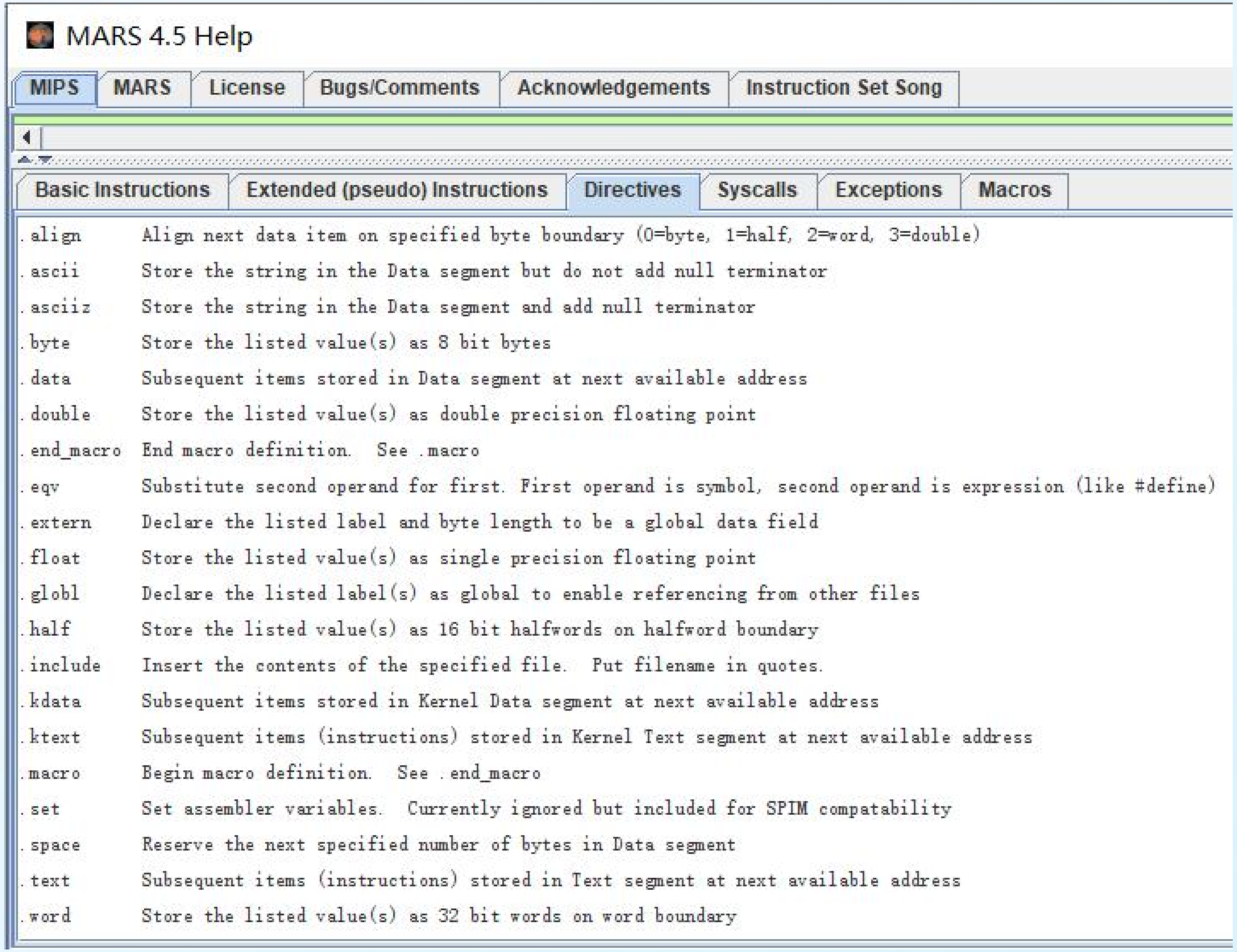
```
#piece 3/4
        lw $t0,($s1)        #initialize the min_value
        sw $t0,min_value
        li $t0,1
        addi $s2,$s1,4      #$s1 is the start of the heap

loop_find_min:
        lw $a0,min_value
        lw $a1,($s2)
        jal find_min
        sw $v0,min_value
        addi $s2,$s2,4                #$s2 is the point
        addi $t0,$t0,1
        bne $t0,$s0 loop_find_min     #s0 is the number of integers

        print_string("the min value : ")
        li $v0,1
        lw $a0,min_value
        syscall

        end        #end is defined in the file is macro_print_str.asm
```

```
#piece 4/4
find_min:

        move $v0,$a0
        blt $a0,$a1,not_update
        move $v0,$a1

not_update:

        jr $ra
```



```
please input the number:3
please input the array
-1
0
1
the min value : -1
-- program is finished running --
```

Derectives in Mars



.align	Align next data item on specified byte boundary (0=byte, 1=half, 2=word, 3=double)
.ascii	Store the string in the Data segment but do not add null terminator
.asciiz	Store the string in the Data segment and add null terminator
.byte	Store the listed value(s) as 8 bit bytes
.data	Subsequent items stored in Data segment at next available address
.double	Store the listed value(s) as double precision floating point
.end_macro	End macro definition. See .macro
.eqv	Substitute second operand for first. First operand is symbol, second operand is expression (like #define)
.extern	Declare the listed label and byte length to be a global data field
.float	Store the listed value(s) as single precision floating point
.globl	Declare the listed label(s) as global to enable referencing from other files
.half	Store the listed value(s) as 16 bit halfwords on halfword boundary
.include	Insert the contents of the specified file. Put filename in quotes.
.kdata	Subsequent items stored in Kernel Data segment at next available address
.ktext	Subsequent items (instructions) stored in Kernel Text segment at next available address
.macro	Begin macro definition. See .end_macro
.set	Set assembler variables. Currently ignored but included for SPIM compatability
.space	Reserve the next specified number of bytes in Data segment
.text	Subsequent items (instructions) stored in Text segment at next available address
.word	Store the listed value(s) as 32 bit words on word boundary

Derective: .macro, .endmacro

Macros:

A **pattern-matching** and **replacement** facility that provide a simple mechanism to name a frequently used sequence of instructions.

- **Programmer invokes** the macro.
- **Assembler replaces** the macro call with the corresponding sequence of instructions.

Macros vs Subroutines:

- **Same:** permit a programmer to create and name a new abstraction for a common operation.
- **Difference:** Unlike subroutines, macros do not cause a subroutine call and return when the program runs since a macro call is replaced by the macro’ s body when the program is assembled.

Demo #3

```
.text
print_string:
        addi $sp,$sp,-4
        sw $v0,($sp)

        li $v0,4
        syscall

        lw $v0,($sp)
        addi $sp,$sp,4

        jr $ra
```

Assembler replaces the macro call with the corresponding sequence of instructions.

Q1: What's the **difference** between macro and procedue?

Q2: While save the macro's defination(on the right hand in this slides) in an asm file, and assamble it,
what's the assembly result?
Is the macro's defination file runable?

Q3: While save the procedure's defination(on the left hand in this slides) in an asm file, and assemble it,
what's the assembly result?
Is the procedure defination file runable?

```
.macro print_string(%str)
.data
        pstr:   .asciiz   %str
.text
        addi $sp,$sp,-8
        sw $a0,4($sp)
        sw $v0,($sp)


        la $a0,pstr
        li $v0,4
        syscall


        lw $v0,($sp)
        lw $a0,4($sp)
        addi $sp,$sp,8
.end_macro
```

Derective: .align(Demo #4-1)

```
.data              #A
str1:  .ascii  "Welcome"
str2:  .ascii  "to"
str3:  .asciiz  "MIPS32World"
.text
la $t0, str2
lb $t1,($t0)
addi $t1,$t1,-32
sw $t1,($t0)

la $a0,str1
li $v0,4
syscall

li $v0,10
syscall
```

```
.data           #B
str1:  .ascii  "Welcome"
str2:  .ascii  "to"
str3:  .asciiz  "MIPS32World"
.text
la $t0, str2
lw  $t1,($t0)
addi $t1,$t1,-32
sb $t1,($t0)

la $a0,str1
li $v0,4
syscall

li $v0,10
syscall
```

Which demo(s) would invoke an exception “fetch address not aligned on word boundary 0x10010007” ?

Which instruction would invoke the exception? lb, sw, lw, sb?

Tips:
While transfering data, the address of data in memory is required to be aligned according to the bit width of data.

Derective: .align(Demo #4-2)

.align : align next data item on specified byte boundary(0=byte, 1=half, 2=word, 3=double)

P2-1: Which demo(s) would run without exception?
Which demo(s) would get the output “WelcomeToMIPS32World” ?

1.B D
2.D

```
.data          #A
str1:  .ascii  "Welcome"
str2:  .ascii  "to"
str3:  .asciiz  "MIPS32World"

.text
la $t0, str2
lh $t1,($t0)
addi $t1,$t1,-32
sh $t1,($t0)

la $a0,str1
li $v0,4
syscall
li $v0,10
syscall
```

```
.data          #B
str1:  .ascii  "Welcome"
.align 2
str2:  .ascii  "to"
str3:  .asciiz  "MIPS32World"

.text
la $t0, str2
lw $t1,($t0)
addi $t1,$t1,-32
sw $t1,($t0)

la $a0,str1
li $v0,4
syscall
li $v0,10
syscall
```

```
.data          #C
.align 2
str1:  .ascii  "Welcome"
str2:  .ascii  "to"
str3:  .asciiz  "MIPS32World"

.text
la $t0, str2
lw $t1,($t0)
addi $t1,$t1,-32
sw $t1,($t0)

la $a0,str1
li $v0,4
syscall
li $v0,10
syscall
```

```
.data          #D
str1:  .ascii  "Welcome"
str2:  .ascii  "to"
str3:  .asciiz  "MIPS32World"

.text
la $t0, str2
lb $t1,($t0)
addi $t1,$t1,-32
sb $t1,($t0)

la $a0,str1
li $v0,4
syscall
li $v0,10
syscall
```

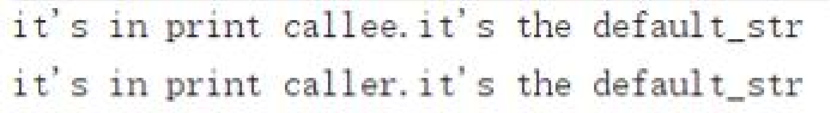
Derective: .globl vs .extern

- **.include :** insert the contents of the specified **file**, put filename in quotes
- **.globl :** declare the listed **label**(s) as global to enable referencing from other files
- **.extern :** declare the listed **label** and byte length to be a global **data** field

- **Local label**
  - A label referring to an object that **can be used ONLY within the FILE in which it is defined**.
- **External label**
  - A label referring to an object that **can be referenced from FILE other than the one in which it is defined**.

Find the usage of ".extern" and ".globl" on Demo 5-1 and 5-2
What's the relationship between globl main and the entrance of program?
What will happen if an external data have the same name with a local data?

Demo #5-1



```
it's in print callee.it's the default_str
it's in print caller.it's the default_str
```

Q1. Is the running result same as the sample snap?
Q2. How many “default_str” are defined in “lab5_print_callee.asm” ?
Q3. While executing the instruction “la $a0,default_str” in these two files, which “default_str” is used?

```
## "print_caller.asm" ##
.include "print_callee.asm"
.data
   str_caller:      .asciiz "it's in print caller."
.text
.globl main
main:
        jal print_callee

        addi $v0,$zero,4
        la  $a0,str_caller
        syscall
        la $a0,default_str    ###which one?
        syscall

        li $v0,10
        syscall
```

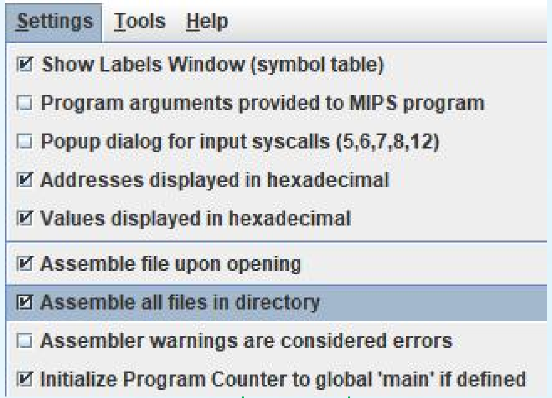
```
## "print_callee.asm" ##
.extern default_str 20
.data
        default_str:      .asciiz  "it's the default_str\n”
        str_callee:       .asciiz  "it's in print callee."
.text
print_callee:    addi $sp,$sp,-4
                 sw $v0,($sp)

                 addi $v0,$zero,4
                 la  $a0,str_callee
                 syscall
                 la $a0,default_str    ###which one?
                 syscall

                 lw $v0,($sp)
                 addi $sp,$sp,4
                 jr $ra
```

Demo #5-2

In Mars, set “Assemble all files in directory” , put the following files in the same directory, then run it.
Answer the questions on last page again.
Find the value of globl lable “main” , “print_callee” and the initial value of $PC

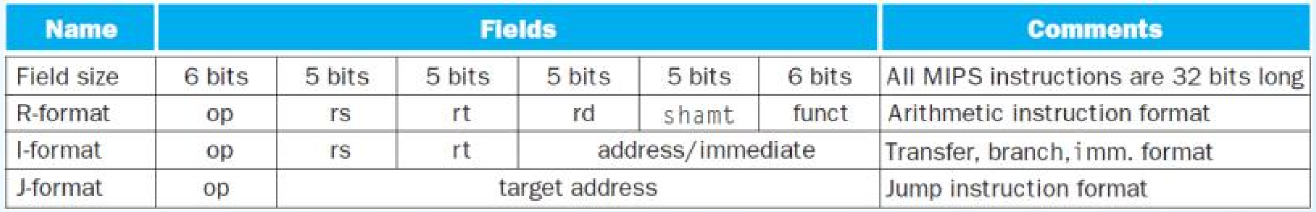
```
.data
    str_caller:     .asciiz      "it's in print caller."
.text
.globl  main
main:
        jal print_callee

        addi $v0,$0,0x0a636261
        sw $v0,defaulte_str

        addi $v0,$zero,4
        la  $a0,str_caller
        syscall
        la $a0,defaulte_str
        syscall

        li $v0,10
        syscall
```

```
.data
        .extern     defaulte_str   20
        str_callee:        .asciiz      "it's in print callee."
        defaulte_str:      .asciiz      "ABC\n"
.text
.globl  print_callee
print_callee:      addi $sp,$sp,-4
                   sw $v0,($sp)

                   addi $v0,$zero,4
                   la  $a0,str_callee
                   syscall
                   la $a0,defaulte_str
                   syscall

                   lw $v0,($sp)
                   addi $sp,$sp,4
                   jr $ra
```



☑ Show Labels Window (symbol table)
☐ Program arguments provided to MIPS program
☐ Popup dialog for input syscalls (5,6,7,8,12)
☑ Addresses displayed in hexadecimal
☑ Values displayed in hexadecimal
☑ Assemble file upon opening
☑ Assemble all files in directory
☐ Assembler warnings are considered errors
☑ Initialize Program Counter to global 'main' if defined

Practice3-1



Name	Fields						Comments
Field size	6 bits	5 bits	5 bits	5 bits	5 bits	6 bits	All MIPS instructions are 32 bits long
R-format	op	rs	rt	rd	shamt	funct	Arithmetic instruction format
I-format	op	rs	rt	address/immediate			Transfer, branch, imm. format
J-format	op	target address					Jump instruction format

Assember the MIPS code bellow, find three instructions which belong to **R, I and J** in the following code, what are the **opcode** of them? what’ s the **index of register** in the **R** type instruction? what’ s the **immediate** in the **I** type instruction? what’ s the value of **“target address”** field of the **J** type instruction?

#piece 1/4

```
.include
"macro_print_str.asm"
.data
        min_value: .word 0
.text
        print_string("please
input the number:")

        li $v0,5
        syscall
        move $s0,$v0

        sll $a0,$s0,2
        li $v0,9
        syscall
        move $s1,$v0
        move $s2,$v0
```

#piece 2/4

```
print_string("please input
the array\n")

add $t0,$0,$0

loop_read:

        li $v0,5        #read the
array
        syscall
        sw $v0,($s2)

        addi $s2,$s2,4
        addi $t0,$t0,1
        bne $t0,$s0,loop_read
```

#piece 3/4

```
        lw $t0,($s1)
        sw $t0,min_value
        li $t0,1
        addi $s2,$s1,4

loop_find_min:
        lw $a0,min_value
        lw $a1,($s2)
        jal find_min
        sw $v0,min_value
        addi $s2,$s2,4
        addi $t0,$t0,1
        bne $t0,$s0 loop_find_min

        print_string("the min value : ")
        li $v0,1
        lw $a0,min_value
        syscall

        end
```

#piece 4/4

```
find_min:

        move $v0,$a0
        blt $a0,$a1,not_update
        move $v0,$a1

not_update:

        jr $ra
```

Practice3-2

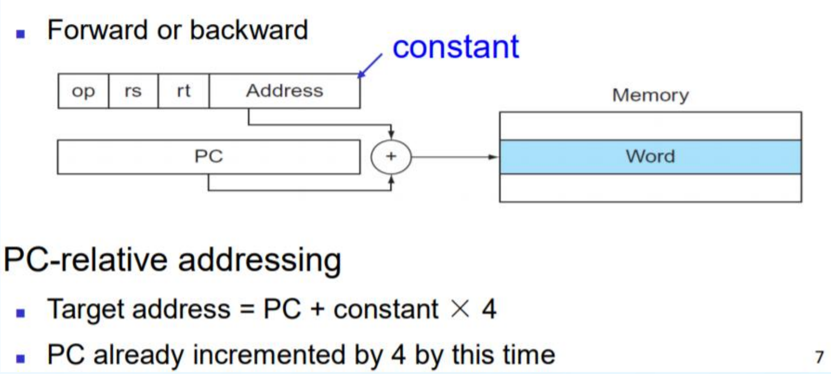
Assember the MIPS code on last page, Find the relationship between the binary part of the branch and jump instruction code and the address of the jumping destination:

step1: The value of two lables: **loop_find_min**, **find_min**

step2: What' s the "address" in the machine code of instruction:

"jal find_min" and "bne $t0,$s0 loop_find_min"

calculate the jumping destination based on the "address" got from step2, are the jumping destinations same with the value got from step1?

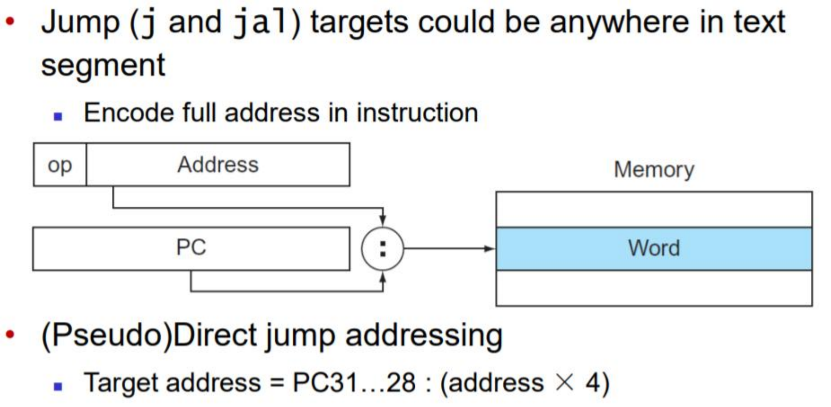


- Forward or backward

PC-relative addressing

- Target address = PC + constant × 4
- PC already incremented by 4 by this time

7



- Jump (`j` and `jal`) targets could be anywhere in text segment
  - Encode full address in instruction

- (Pseudo)Direct jump addressing
  - Target address = PC31…28 : (address × 4)

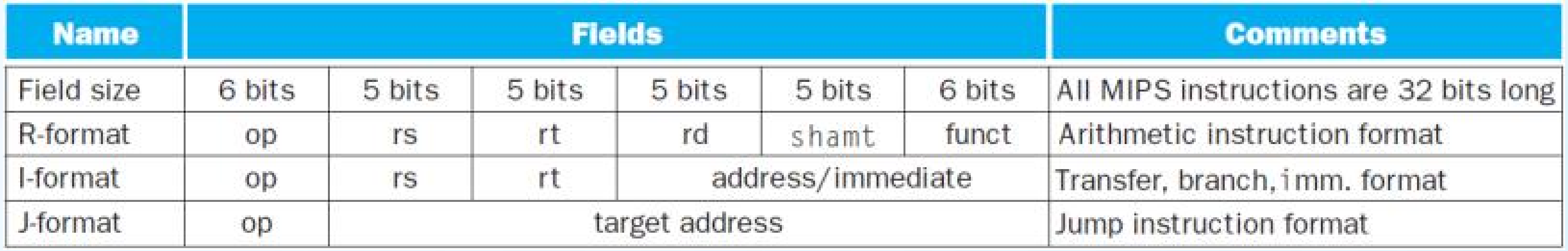
#piece 3/4

```
        lw $t0,($s1)
        sw $t0,min_value
        li $t0,1
        addi $s2,$s1,4

loop_find_min:
        lw $a0,min_value
        lw $a1,($s2)
        jal find_min
        sw $v0,min_value
        addi $s2,$s2,4
        addi $t0,$t0,1
        bne $t0,$s0 loop_find_min

        print_string("the min value : ")
        li $v0,1
        lw $a0,min_value
        syscall

        end
```

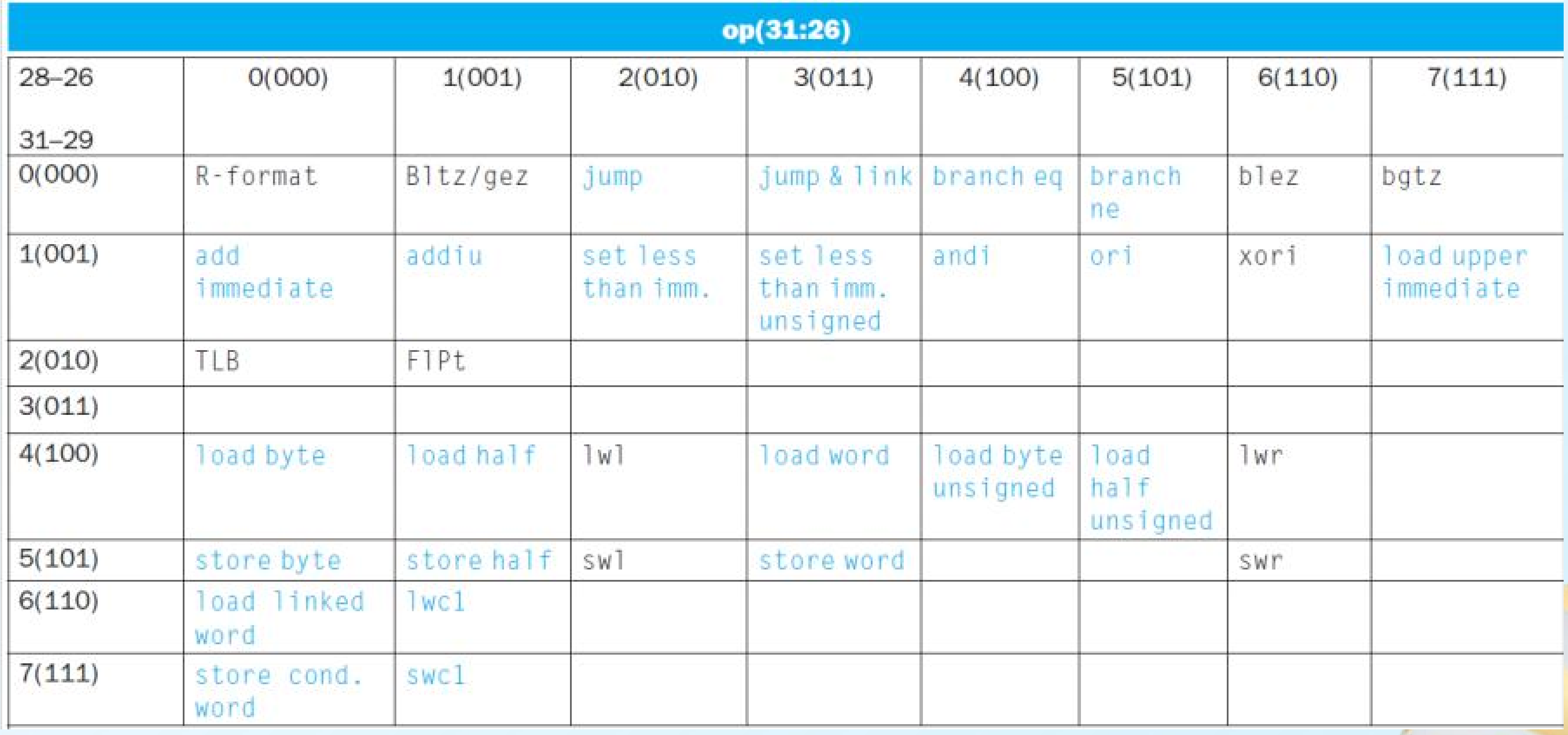
#piece 4/4

```
find_min:

        move $v0,$a0
        blt $a0,$a1,not_update
        move $v0,$a1

not_update:

        jr $ra
```

Tips: Machine Code of MIPS(1)

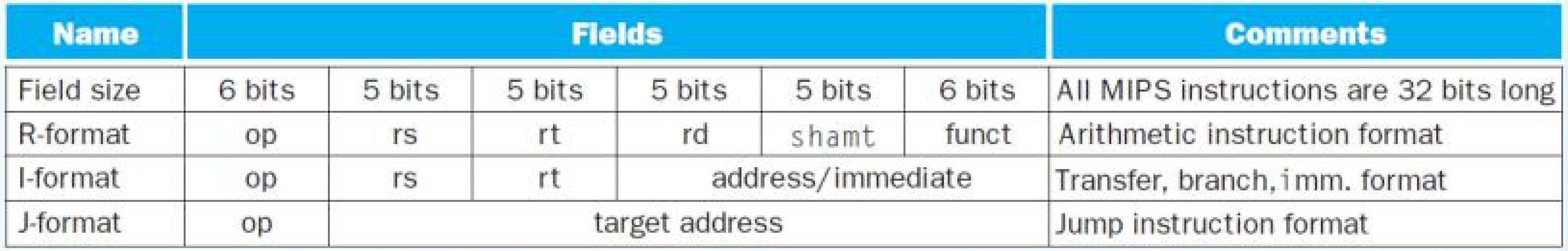


Name	Fields						Comments
Field size	6 bits	5 bits	5 bits	5 bits	5 bits	6 bits	All MIPS instructions are 32 bits long
R-format	op	rs	rt	rd	shamt	funct	Arithmetic instruction format
I-format	op	rs	rt	address/immediate			Transfer, branch, imm. format
J-format	op	target address					Jump instruction format

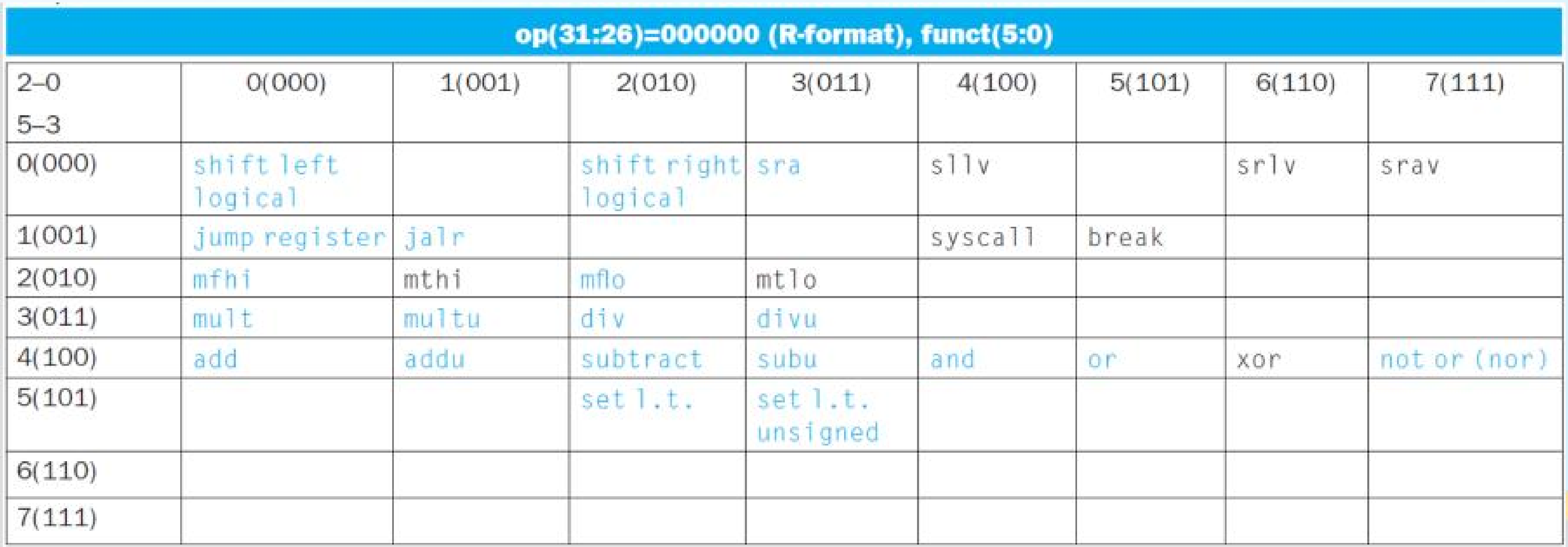


op(31:26)								
28–26 31–29	0(000)	1(001)	2(010)	3(011)	4(100)	5(101)	6(110)	7(111)
0(000)	R-format	Bltz/gez	jump	jump & link	branch eq	branch ne	blez	bgtz
1(001)	add immediate	addiu	set less than imm.	set less than imm. unsigned	andi	ori	xori	load upper immediate
2(010)	TLB	FlPt						
3(011)								
4(100)	load byte	load half	lwl	load word	load byte unsigned	load half unsigned	lwr	
5(101)	store byte	store half	swl	store word			swr	
6(110)	load linked word	lwc1						
7(111)	store cond. word	swc1						

Tips: Machine Code of MIPS(2)



Name	Fields						Comments
Field size	6 bits	5 bits	5 bits	5 bits	5 bits	6 bits	All MIPS instructions are 32 bits long
R-format	op	rs	rt	rd	shamt	funct	Arithmetic instruction format
I-format	op	rs	rt	address/immediate			Transfer, branch, imm. format
J-format	op	target address					Jump instruction format



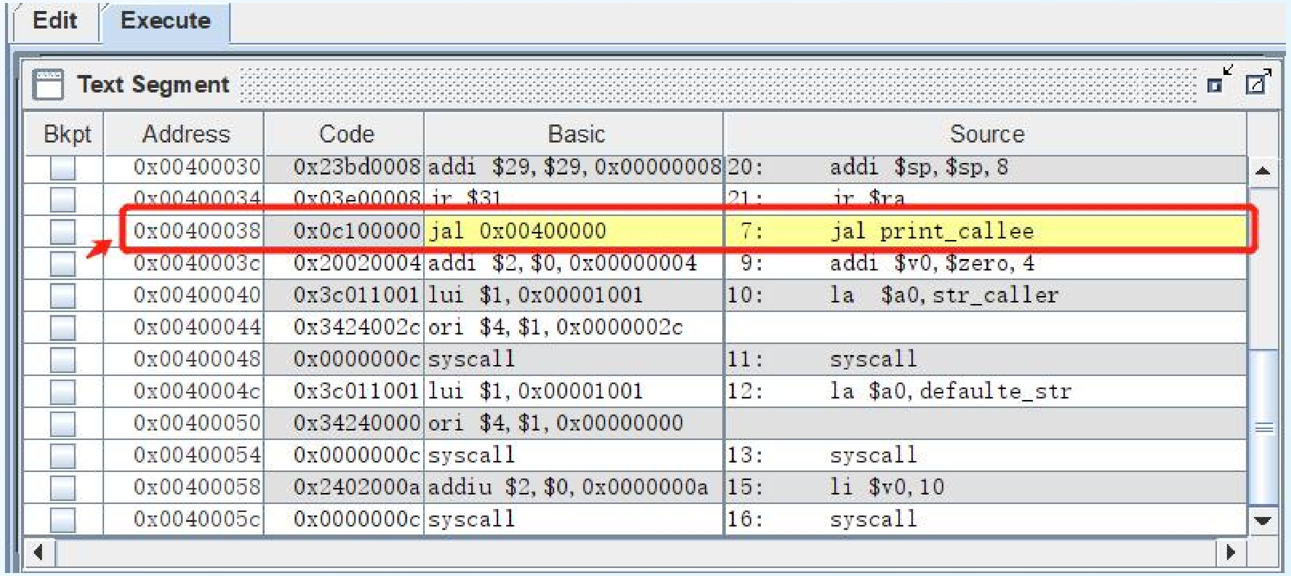
op(31:26)=000000 (R-format), funct(5:0)

2–0 5–3	0(000)	1(001)	2(010)	3(011)	4(100)	5(101)	6(110)	7(111)
0(000)	shift left logical		shift right logical	sra	sllv		srlv	srav
1(001)	jump register	jalr			syscall	break		
2(010)	mfhi	mthi	mflo	mtlo				
3(011)	mult	multu	div	divu				
4(100)	add	addu	subtract	subu	and	or	xor	not or (nor)
5(101)			set l.t.	set l.t. unsigned				
6(110)								
7(111)								

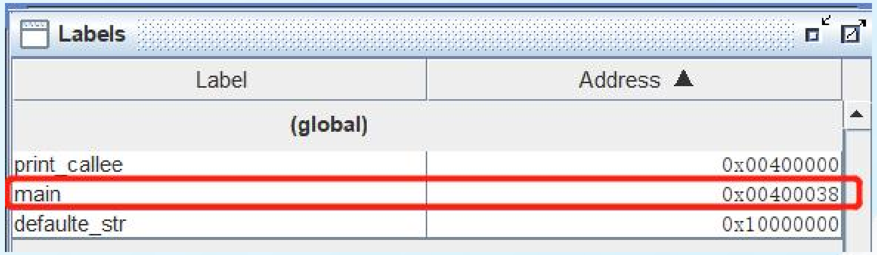
Tips on Mars

To make the instruction labled by ‘global main’ as the 1st instruction to run, do the following settings.

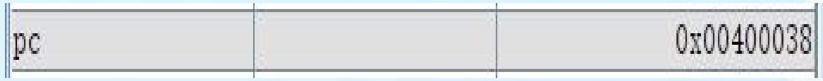
In **Mars**’ manual：
Settings -》Initialize Program Counter to global ‘main’ if defined



Bkpt	Address	Code	Basic	Source
☐	0x00400030	0x23bd0008	addi $29, $29, 0x00000008	20: addi $sp, $sp, 8
☐	0x00400034	0x03e00008	jr $31	21: jr $ra
☐	0x00400038	0x0c100000	jal 0x00400000	7: jal print_callee
☐	0x0040003c	0x20020004	addi $2, $0, 0x00000004	9: addi $v0, $zero, 4
☐	0x00400040	0x3c011001	lui $1, 0x00001001	10: la $a0, str_caller
☐	0x00400044	0x3424002c	ori $4, $1, 0x0000002c	
☐	0x00400048	0x0000000c	syscall	11: syscall
☐	0x0040004c	0x3c011001	lui $1, 0x00001001	12: la $a0, defaulte_str
☐	0x00400050	0x34240000	ori $4, $1, 0x00000000	
☐	0x00400054	0x0000000c	syscall	13: syscall
☐	0x00400058	0x2402000a	addiu $2, $0, 0x0000000a	15: li $v0, 10
☐	0x0040005c	0x0000000c	syscall	16: syscall



Label	Address ▲
(global)	
print_callee	0x00400000
main	0x00400038
defaulte_str	0x10000000



pc		0x00400038

Tips： macro_print_str.asm

```
.macro print_string(%str)
	.data
	pstr: .asciiz %str
	.text
	la $a0,pstr
	li $v0,4
	syscall
.end_macro


.macro end
	li $v0,10
	syscall
.end_macro
```

Define and use macro, get help form help page of Mars