1) Assign variables to registers and then translate the following high-level language code segment to MIPS assembly language.

```
if X < Y then
   min = X
else
   min = Y
end if
```

2. Translate the following high-level language code segment to MIPS assembly language. Use the registers indicated in the code.

a)
```
for $4 = 0 to 100 by steps of size 10 do
    if ($3 < $4) AND ($2 >= 50) then
        $2 = $2 + $3
    end if
end for
```

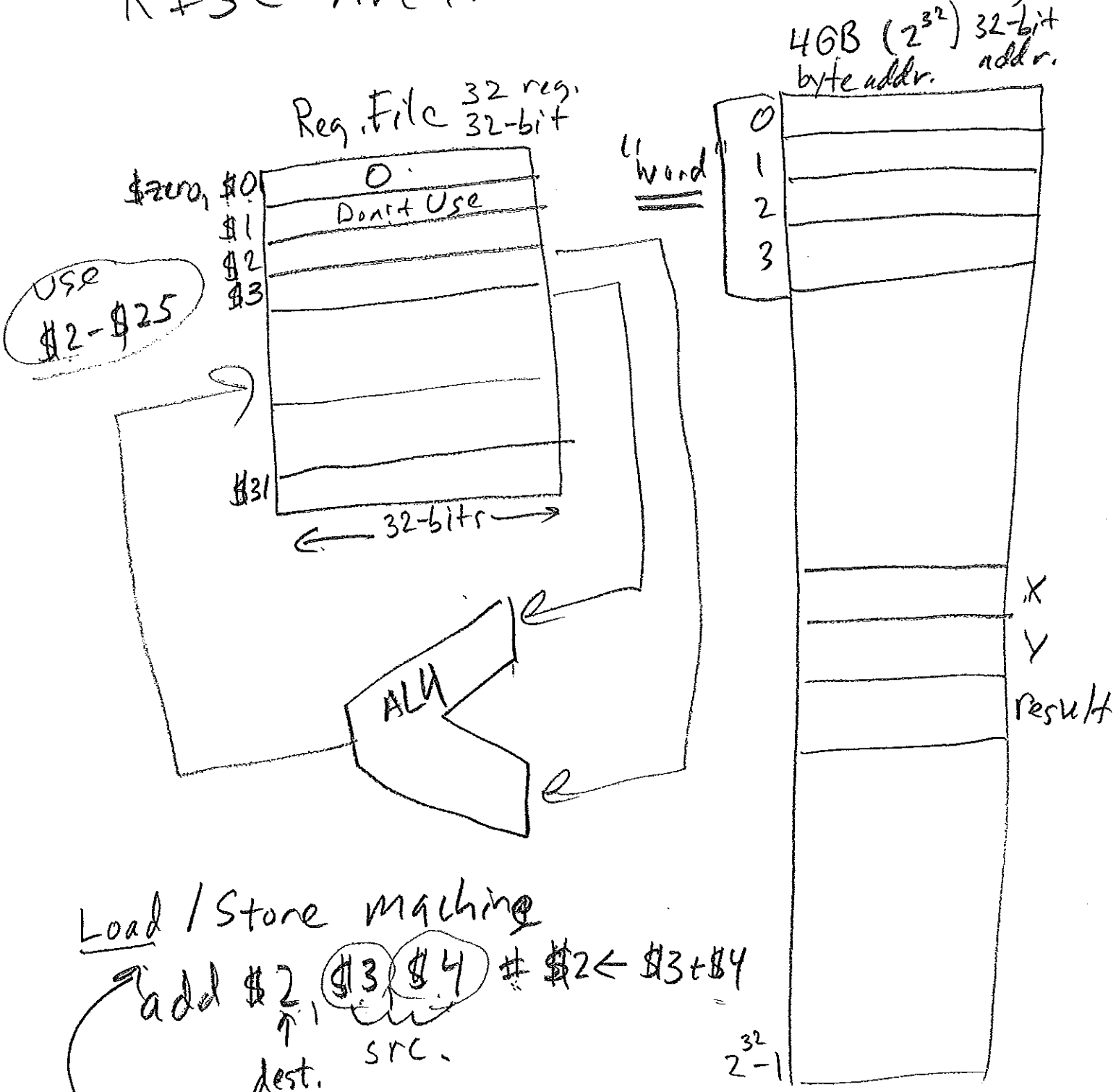
b)
```
while ($8 > 20) do
    if ($8 < 100)  OR ($8 > 200) then
        $7 = $8
        $8 = $8 - 10
    else
        $8 = $8 - $7
    end if
    $7 =  $6 + 4
end while
```

3) Use a laptop and MIPS simulator (PCSpim, QtSpim, MARS, etc.) to enter and run the following MIPS program.

```
      .data
x:          .word -3
y:          .word 5
product:    .word 0
sum:        .word 0

      .text
      .globl main
# High-level language program
#       product = x * y
#       sum = x + y

# Register usage
#     x is in $2
#     y is in $3
#     product is in $4
#     sum is in $5
main:
      lw $2, x
      lw $3, y
      mul $4,$2,$3
      add $5,$2,$3
      sw $4, product
      sw $5, sum

      li $v0, 10      # system call code to exit program
      syscall
```

Lecture 16 MIPS Introduction

RISC Arch. (CISC - Intel x86)



Load / Store machine

add $2, $3, $4 # $2 ← $3+$4

dest. src.

lw $3, X
~~load~~
lw $4, Y
~~load~~
add $2, $3, $4
~~store~~ $2, result

HLL:

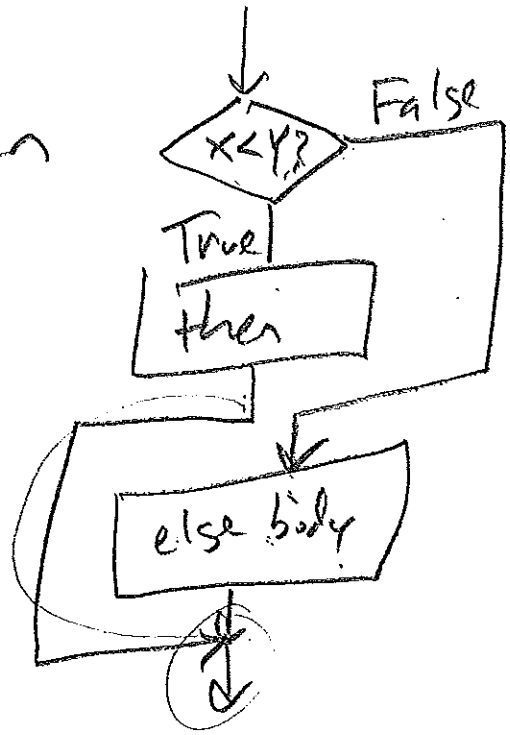
if $\overset{\$2}{X} < \overset{\$3}{Y}$ then

"then body

else

else body

endif

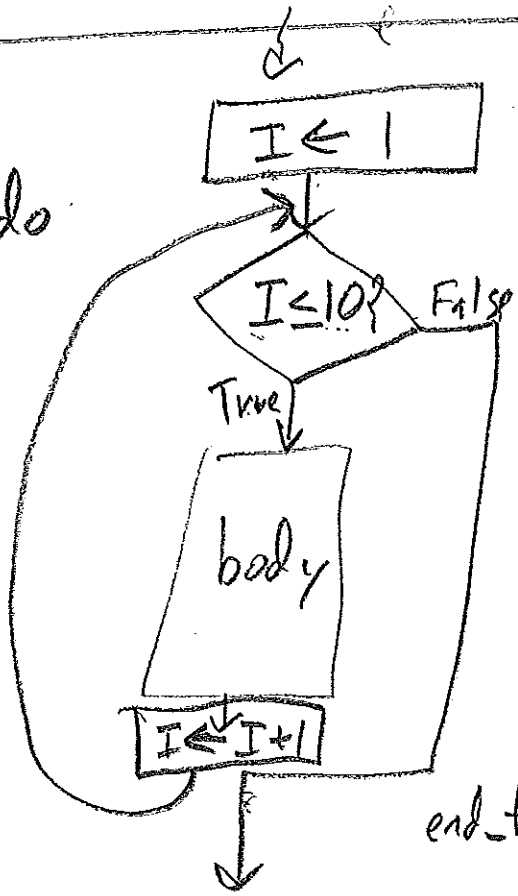



```
lw $2, X
lw $3, Y
bge $2,$3,else
    #then body
    j end_if
else:
    #else body
end_if:
```

HLL:

for $\overset{\$5}{I}$ = 1 to 10 do

end_for




```
for_init: li $5, 1
for_compare:
    bgt $5, 10, end_for
    #for body
    addi $5,$5,1
    j for_compare
end_for:
```

MIPS Assembly Language Guide

MIPS is an example of a Reduced Instruction Set Computer (RISC) which was designed for easy instruction pipelining. MIPS has a "Load/Store" architecture since all instructions (other than the load and store instructions) must use register operands. MIPS has 32 32-bit "general purpose" registers ($0, $1, $2, ... , $31), but some of these have special uses (see MIPS Register Conventions table).

Common MIPS Instructions (and **psuedo-instructions**)		
Type of Instruction	**MIPS Assembly Language**	**Register Transfer Language Description**
Memory Access (Load and Store)	lw $4, Mem	$4← [Mem]
	sw $4, Mem	Mem←$4
	lw $4, 16($3)	$4← [Mem at address in $3 + 16]
	sw $4, 16($3)	[Mem at address in $3 + 16]← $4
Move	**move** $4, $2	$4← $2
	li $4, 100	$4← 100
Load Address	**la** $5, mem	$4← load address of mem
Arithmetic Instruction (reg. operands only)	add $4, $2, $3	$4← $2 + $3
	mul $10, $12, $8	$10← $12 * $8 (32-bit product)
	sub $4, $2, $3	$4← $2 - $3
Arithmetic with Immediates (last operand must be an integer)	addi $4, $2, 100	$4← $2 + 100
	mul $4, $2, 100	$4← $2 * 100 (32-bit product)
Conditional Branch	**bgt** $4, $2, LABEL **(bge, blt, ble, beq, bne)**	Branch to LABEL if $4 > $2
Unconditional Branch	j LABEL	Always Branch to LABEL

A simple MIPS assembly language program to sum the elements in an array is given below:

```
        .data
array:      .word 5, 10, 20, 25, 30, 40, 60
length:     .word 7
sum:        .word 0

# Algorithm being implemented to sum an array
#       sum = 0                         (use $8 for sum)
#       for i := 0 to length-1 do       (use $9 for i)
#               sum := sum + array[i]   (use $10 for length-1)
#       end for                         (use $11 for base addr. of array)

        .text
        .globl main
main:
        li      $8, 0               # load immediate 0 in reg. $8 (sum)
        la      $11, array          # load base addr. of array into $11
for:
        lw      $10, length         # load length in reg. $10
        addi    $10, $10, -1        # $10 = length - 1
        li      $9, 0               # initialize i in $9 to 0
for_compare:
        bgt     $9, $10, end_for    # drop out of loop when i > (length-1)
        mul     $12, $9, 4          # mult. i by 4 to get offset within array
        add     $12, $11, $12       # add base addr. of array to $12 to get addr. of array[i]
        lw      $12, 0($12)         # load value of array[i] from memory into $12
        add     $8, $8, $12         # update sum
        addi    $9, $9, 1           # increment i
        j       for_compare
end_for:

        sw      $8, sum

        li      $v0, 10             # system code for exit

        syscall
```

MIPS Logical Instructions	
and $4, $5, $6	$4←$5 (bit-wise AND) $6
andi $4, $5, 0x5f	$4←$5 (bit-wise AND) $5f_{16}$
or $4, $5, $6	$4←$5 (bit-wise OR) $6
ori $4, $5, 0x5f	$4←$5 (bit-wise OR) $5f_{16}$
xor $4, $5, $6	$4←$5 (bit-wise Exclusive-OR) $6
xori $4, $5, 0x5f	$4←$5 (bit-wise Exclusive-OR) $5f_{16}$
nor $4, $5, $6	$4←$5 (bit-wise NOR) $6
not $4, $5	$4←NOT $5 #inverts all the bits

MIPS Shift and Rotate Instructions	
sll $4, $5, 3	$4←shift left $5 by 3 positions. Shift in zeros (only least significant 5-bits of immediate value are used to shift)
sllv $4, $5, $6	Similar to sll, but least significant 5-bits of $6 determine the amount to shift.
srl $4, $5, 3	$4← shift right $5 by 3 positions. Shift in zeros
srlv $4, $5, $6	Similar to srl, but least significant 5-bits of $6 determine the amount to shift.
sra $4, $5, 3	$4←shift right $5 by 3 positions. Sign-extend (shift in sign bit)
srav $4, $5, $6	Similar to sra, but least significant 5-bits of $6 determine the amount to shift.
rol $4, $5, 3	$4←rotate left $5 by 3 positions
rol $4, $5, $6	Similar to above, but least significant 5-bits of $6 determine the amount to rotate.
ror $4, $5, 3	$4←rotate right $5 by 3 positions
ror $4, $5, $6	Similar to above, but least significant 5-bits of $6 determine the amount to rotate.

Common usages for shift/rotate and logical instructions include:

1. To calculate the address of element array[i], we calculate (base address of array) + i * 4 for an array of words. Since multiplication is a slow operation, we can shift the value left two bit positions. For example:

```
la $3, array            # load base address of array into $3
sll $10, $2, 2          # logical shift i's value in $2 by 2 to multiply its value by 4
add  $10, $3, $10       # finish calculation of the address of element array[i]
lw  $4, 0($10)          # load the value of array[i] into $4
```

2. Sometimes you want to manipulate individual bits in a "string of bits". For example, you can represent a set of letters using a bit-string. Each bit in the bit-string is associated with a letter: bit position 0 with 'A', bit position 1 with 'B', ..., bit position 25 with 'Z'. Bit-string bits are set to '1' to indicate that their corresponding letters are in the set. For example, the set { 'A', 'B', 'D', 'Y' } would be represented as:

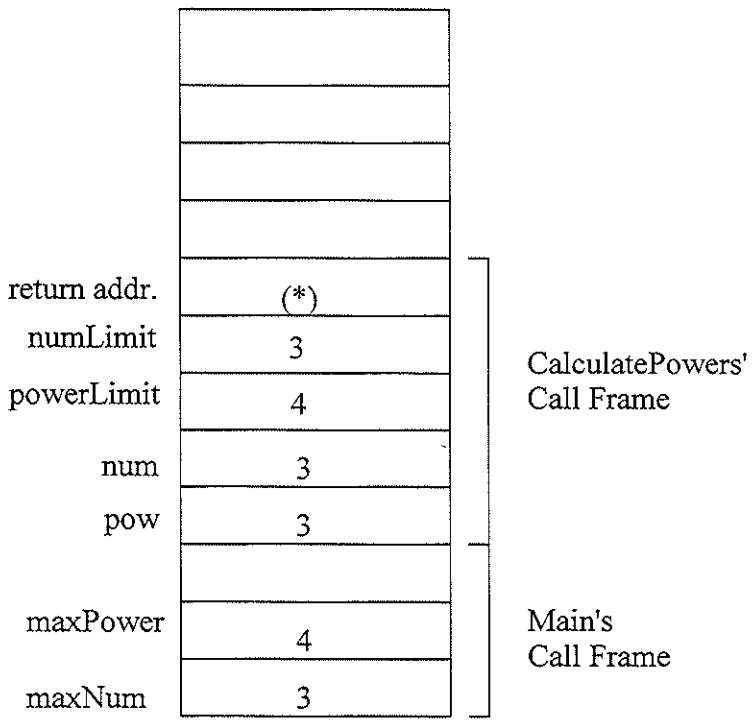
	unused	'Z'	'Y'	'X'	. . .	'E'	'D'	'C'	'B'	'A'
{ 'A', 'B', 'D', 'Y' } is	0 0 0 0 0 0	0	1	0		0	1	0	1	1
bit position:		25	24	23		4	3	2	1	0

To determine if a specific ASCII character, say 'C' (67_{10}) is in the set, you would need to build a "mask" containing a single "1" in bit position 2. The sequence of instructions "li $3, 1" followed by "sll $3, $3, 2" would build the needed mask in $3. If the bit-string set of letters is in register $5, then we can check for the character 'C' using the mask in $3 and the instruction "and $6, $5, $3". If the bit-string set in $5 contained a 'C', then $6 will be non-zero; otherwise $6 will be zero.

High-level Language Programmer's View

main:
 	
maxNum = 3
maxPower = 4
 	
CalculatePowers(maxNum, maxPower)
(*)
. . .
end main
	CalculatePowers(In: integer numLimit,
	integer powerLimit)
	
	integer num, pow
	
	for num := 1 to numLimit do
	for pow := 1 to powerLimit do
	
	print num " raised to " pow " power is "
	Power(num, pow)
	end for pow
	end for num
		integer **Power(In:** integer n, integer e)
		
		integer result
		if e = 0 then
		result = 1
		else if e = 1 then
		result = n
		else
		result = Power(n, e - 1)* n
		end if
		return result
		end Power

HLL View of Run-time Stack



Compiler uses registers to avoid accessing the run-time stack in memory as much as possible. Registers can be used for local variables, parameters, return address, function-return value.

```
AL code for subprogram "caller"

  <code using some registers>

 call subprogram

  <wants used registers to be unchanged>
```

When a subprogram is called, some of the register values might need to be saved ("spilled") on the stack to free up some registers for the subprogram to use.

Standard conventions for spilling registers:
1) caller save - before the call, caller saves the register values it needs after execution returns from the subprogram
2) callee save - subprogram saves and restores any register it uses in its code
3) some combination of caller and callee saved (USED BY MIPS)

MIPS Register Conventions			
Reg. #	**Convention Name**	**Role in Procedure Calls**	**Comments**
$0	$zero	constant value zero	Cannot be changed
$1	$at	Used by assembler to implement psuedoinstructions	DON'T USE
$2, $3	$v0, $v1	Results of a function	
$4 - $7	$a0 - $a3	First 4 arguments to a procedure	
$8 - $15, $24, $25	$t0 - $t9	Temporary registers (not preserved across call)	Caller-saved registers - subprogram can use them as scratch registers, but it must also save any needed values before calling another subprogram.
$16 - $23	$s0 - $s7	Saved temporary (preserved across call)	Callee-saved registers - it can rely on an subprogram it calls not to change them (so a subprogram wishing to use these registers must save them on entry and restore them before it exits)
$26, $27	$k0, $k1	Reserved for the Operating System Kernel	DON'T USE
$28	$gp	Pointer to global area	
$29	$sp	Stack pointer	Points to first free memory location above stack
$30	$fp/$s8	Frame pointer (if needed) or another saved register	$fp not used so use as $s8
$31	$ra	Return address (used by a procedure call)	Receives return addr. on *jal* call to procedure

Using MIPS Calling Convention	
Caller Code	**Callee Code**
. . . 1) save on stack any $t0 - $t9 and $a0 - $a3 that are needed upon return 2) place arguments to be passed in $a0 - $a3 with additional parameters pushed onto the stack 3) jal ProcName # saves return address in $ra 4) restore any saved registers $t0 - $t9 and $a0 - $a3 from stack	. . . 1) allocate memory for frame by subtracting frame size from $sp 2) save callee-saved registers ($s0 - $s7) if more registers than $t0 - $t9 and $a0 - $a3 are needed 3) save $ra if another procedure is to be called **. . . code for the callee** 4) for functions, place result to be returned in $v0 - $v1 5) restore any callee-saved registers ($s0 - $s7) from step (2) above 6) restore $ra if it was saved on the stack in step (3) 7) pop stack frame by adding frame size to $sp 8) return to caller by "jr $ra" instruction

main:	**CalculatePowers(In:** integer numLimit, integer powerLimit)	integer **Power(In:** integer n, integer e)
maxNum = 3		integer result
maxPower = 4	integer num, pow	if e = 0 then
		result = 1
CalculatePowers(maxNum, maxPower)	for num := 1 to numLimit do	else if e = 1 then
(*)	for pow := 1 to powerLimit do	result = n
. . .		else
end main	print num " raised to " pow " power is "	result = Power(n, e - 1)* n
	Power(num, pow)	end if
	end for pow	return result
	end for num	**end Power**
	end CalculatePowers	

a) Using the MIPS register conventions, what registers would be used to pass each of the following parameters to CalculatePowers:

maxNum	maxPower

b) Using the MIPS register conventions, which of these parameters ("numLimit", "powerLimit", or both of them) should be moved into s-registers?
(NOTE: Use an s-register for any value you still need after you come back from a subprogram/function/procedure call, e.g., call to "Power")

c) Using the MIPS register conventions, what registers should be used for each of the local variables:

num	pow

d) Using the MIPS register conventions, what registers would be used to pass each of the following parameters to Power:

num	pow

e) Using the MIPS register conventions, which of these parameters ("n", "e", or both of them) should be moved into s-registers?

f) Using the MIPS register conventions, what register should be used for the local variable:

result

g) Write the code for main, CalculatePowers, and Power in MIPS assembly language.

```
main:

integer scores [100];
integer n;  // # of elements

InsertionSort(scores, n)

(*)
...

end main
```

```
InsertionSort(numbers - address to integer array,
              length - integer)

   integer firstUnsortedIndex
   for firstUnsortedIndex = 1 to (length-1) do
      Insert(numbers, numbers[firstUnsortedIndex],
             firstUnsortedIndex-1);
   end for

end InsertionSort
```

```
Insert(numbers - address to integer array,
       elementToInsert - integer,
       lastSortedIndex - integer) {
    integer testIndex;
    testIndex = lastSortedIndex;
    while (testIndex >=0) AND
          (numbers[testIndex] > elementToInsert ) do
       numbers[ testIndex+1 ] = numbers[ testIndex ];

       testIndex =  testIndex - 1;
    end while
    numbers[ testIndex + 1 ] = elementToInsert;
end Insert
```

a) Using the MIPS register conventions, what registers would be used to pass each of the following parameters to InsertionSort:

scores	n

b) Using the MIPS register conventions, which of these parameters ("numbers", "length", or both of them) should be moved into s-registers?

c) Using the MIPS register conventions, what registers should be used for the local variable "firstUnsortedIndex"?

d) Using the MIPS register conventions, what registers would be used to pass each of the following parameter values to Insert:

numbers	numbers[firstUnsortedIndex]	firstUnsortedIndex-1

e) Using the MIPS register conventions, which of these parameters ("numbers", "elementToInsert", or "lastSortedIndex") should be moved into s-registers?

f) Using the MIPS register conventions, what registers should be used for the local variable "testIndex"?

g) Write the code for main, InsertionSort, and Insert in MIPS assembly language.

PCSpim I/O Support

Access to Input/Output (I/O) devices within a computer system is generally restricted to prevent user programs from directly accessing them. This prevents a user program from accidentally or maliciously doing things like:

- reading someone else's data file from a disk
- writing to someone else's data file on a disk
- etc.

However, user programs need to perform I/O (e.g., read and write information to files, write to the console, read from the keyboard, etc.) if they are to be useful. Therefore, most computer systems require a user program to request I/O by asking the operating system to perform it on their behalf.

PCSpim uses the "syscall" (short for "system call") instruction to submit requests for I/O to the operating system. The register $v0 is used to indicate the type of I/O being requested with $a0, $a1, $f12 registers being used to pass additional parameters to the operating system. Integer results and addresses are returned in the $v0 register, and floating point results being returned in the $f0 register. The following table provides details of the PCSpim syscall usage.

Service Requested	**System call code passed in $v0**	**Registers used to pass additional arguments**	**Registers used to return results**
print_int	1	$a0 contains the integer value to print	
print_float	2	$f12 contains the 32-bit float to print	
print_double	3	$f12 (and $f13) contains the 64-bit double to print	
print_string	4	$a0 contains the address of the .asciiz string to print	
read_int	5		$v0 returns the integer value read
read_float	6		$f0 returns the 32-bit floating-point value read
read_double	7		$f0 and $f1 returns the 64-bit floating-point value read
read_string	8	$a0 contains the address of the buffer to store the string $a1 contains the maximum length of the buffer	
sbrk - request a memory block	9	$a0 contains the number of bytes in the requested block	$v0 returns the starting address of the block of memory
exit	10		

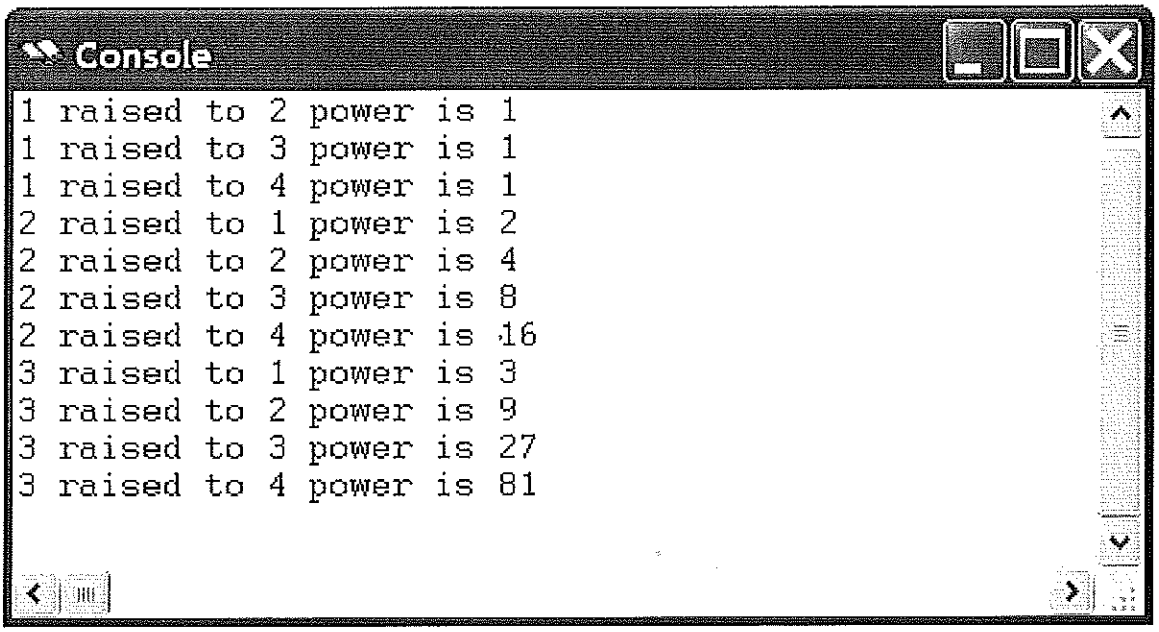
CalculatePowers subprogram example using MIPS register conventions and PCSpim syscalls

```
                .data
maxNum:         .word 3
maxPower:       .word 4
str1:           .asciiz " raised to "
str2:           .asciiz " power is "
str3:           .asciiz  "\n"                   # newline character

                .text
                .globl main
main:
                lw      $a0, maxNum             # $a0 contains maxNum
                lw      $a1, maxPower           # $a1 contains maxPower
                jal     CalculatePower

                li      $v0, 10                 # system code for exit
                syscall


##############################################################################
CalculatePower:                                 # $a0 contains value of numLimit
                                                # $a1 contains value of powerLimit

                addi    $sp, $sp, -20           # save room for the return address
                sw      $ra, 4($sp)             # push return address onto stack
                sw      $s0, 8($sp)
                sw      $s1, 12($sp)
                sw      $s2, 16($sp)
                sw      $s3, 20($sp)

                move    $s0, $a0                # save numLimit in $s0
                move    $s1, $a1                # save powerLimit in $s1

for_1:
                li      $s2, 1                  # $s2 contains num
for_compare_1:
                bgt     $s2, $s0, end_for_1
for_body_1:

for_2:
                li      $s3, 1                  # $s3 contains pow
for_compare_2:
                bgt     $s3, $s1, end_for_2
for_body_2:
                move    $a0, $s2                # print num
                li      $v0, 1
                syscall
```

```
        la      $a0, str1           # print " raised to "
        li      $v0, 4
        syscall

        move    $a0, $s3            # print pow
        li      $v0, 1
        syscall

        la      $a0, str2           # print " power is "
        li      $v0, 4
        syscall

        move    $a0, $s2            # call Power(num, pow)
        move    $a1, $s3
        jal     Power

        move    $a0, $v0            # print result

        li      $v0, 1
        syscall

        la      $a0, str3           # print new-line character
        li      $v0, 4
        syscall

        addi    $s3, $s3, 1
        j       for_compare_2
end_for_2:

        addi    $s2, $s2, 1
        j       for_compare_1
end_for_1:

        lw      $ra, 4($sp)         # restore return addr. to $ra
        lw      $s0, 8($sp)         # restore saved $s registers
        lw      $s1, 12($sp)
        lw      $s2, 16($sp)
        lw      $s3, 20($sp)

        addi    $sp, $sp, 20        # pop call frame from stack
        jr      $ra
end_CalculatePowers:
```

```
##############################################################################
Power:                                  # $a0 contains n (we never change it during the
                                        #       recursive calls so we don't need to save it)
                                        # $a1 contains e
            addi    $sp, $sp, -4
            sw      $ra, 4($sp)         # save $ra on stack

if:
            bne     $a1, $zero, else_if
            li      $v0, 1              # $v0 contains result
            j       end_if
else_if:
            bne     $a1, 1, else
            move    $v0, $a0
            j       end_if
else:                                   # first parameter is still n in $a0
            addi    $a1, $a1, -1        # put second parameter, e-1, in $a1
            jal     Power               # returns with value of Power(n, e-1) in $v0
            mul     $v0, $v0, $a0       # result = Power(n, e-1) * n
end_if:
            lw      $ra, 4($sp)         # restore return addr. to $ra
            addi    $sp, $sp, 4         # pop call frame from stack
            jr      $ra
end_Power:
```

Snap-shot of the Console window after the program executes:



1) Consider the following array scores:

	0	1	2	3	4	5	6	7	8
scores:	10	30	45	20	80	20	70	30	50

length 9

a) What MIPS instruction would load the base (starting) address of scores into register $12?

b) If register $5 contained the index i's value, what MIPS instructions would calculate the address of scores[i] into register $13?

c) What MIPS instruction would load the value of scores[i] into register $14

2) Complete the MIPS sequential search program that finds the <u>index location</u> of the first occurrence of targetValue in the array scores. If the targetValue is not in the array, then foundIndex should be set to -1.

```
# MIPS sequential search program -- High-level algorithm:
# foundIndex = -1
# for i = 0 to (length-1) do
#     if scores[i] == targetValue then
#          foundIndex = i
#          break out of loop
#     end if
# end for
      .data
scores:           .word 10, 30, 45, 20, 80, 20, 70, 30, 50
length:           .word 9
targetValue:      .word 20
foundIndex: .word 0

      .text
      .globl main
main:
```

```
integer firstUnsortedIndex, testIndex, elementToInsert;
for firstUnsortedIndex = 1 to (length-1) do
    testIndex = firstUnsortedIndex-1;
    elementToInsert = numbers[firstUnsortedIndex];
    while (testIndex >=0) AND (numbers[testIndex] > elementToInsert ) do
        numbers[ testIndex + 1 ] = numbers[ testIndex ];
        testIndex =  testIndex - 1;
    end while
    numbers[ testIndex + 1 ] = elementToInsert;
end for
```

3. Write MIPS Assembly Language code for the above insertion sort algorithm

```
          .data
numbers:      .word 20, 30, 10, 40, 50, 60, 30, 25, 10, 5
length:       .word 10

          .text
          .globl main
main:
```

```
li    $v0, 10            # system call to exit
syscall
```

Lecture 17 1-D array MIPS Examples

1-D arrays

array:

0	1	2	3	4	5	6
5	10	20	~~25~~ 23	30	40	60

HLL:

X = array[3]

array[3] = 23

RAM access O(1) "constant time"

"n" items in array

memory

addr. of array[i] = (base addr. of array) + (i * (elt. size))

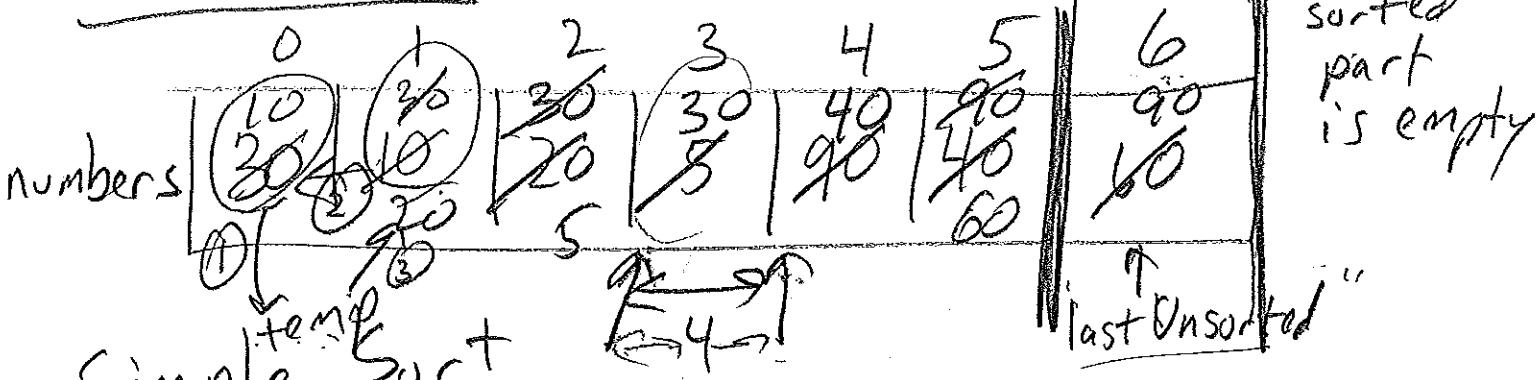
$12 $9 4 elements

addr.	memory	
400	5	array[0]
404	10	[1]
408	20	[2]
412	25	[3]
416	30	
420	40	
	60	

```
la $11, array
#i is $9
mul $12, $9, 4
add $12, $11 $12
lw  $14, 0($12)
```

Bubble Sort

ascending sort smaller → larger



Simple Sort

outer loop - track the dividing line between the sorted and unsorted part of the array

inner loop - extend the sorted by one item

HLL:

```
for lastUnsorted = (length - 1) downto 1 do
    for test = 0 to (lastUnsorted - 1) do
        if numbers[test] > numbers[test+1] then
            temp = numbers[test]
            numbers[test] = numbers[test+1]
            numbers[test+1] = temp
        end if
    end for
end for
```

$8 $9 $10 $11 $12 $13 $14 $15

(base of numbers $12)

(addr. of numbers[test] $13)

```
                la $12, numbers
for_init_1:     lw $9, length
                addi $8, $9, -1

for_compare_1:  blt $8, 1, end_for_1

for_init_2:     li $10, 0
                addi $11, $8, -1

for_compare_2:  bgt $10, $11, end_for_2
if:             mul $13, $10, 4
                add $13, $12, $13   #addr. numbers[test]
                lw $14, 0($13)      #value numbers[test]
                lw $15, 4($13)      #value numbers[test+1]
                ble $14, $15, end_if
                sw $14, 4($13)
                sw $15, 0($13)
end_if:
                addi $10, $10, 1
                j for_compare_2
end_for_2:
                addi $8, $8, -1
                j for_compare_1
end_for_1:
```

```
# Bubble sort code in MIPS
# HLL:
# for lastUnsorted = (length-1) downto 1 do
#     for test = 0 to (lastUnsorted -1) do
#         if numbers[test] > numbers[test + 1] then
#             temp = numbers[test]
#             numbers[test] = numbers[test + 1]
#             numbers[test + 1] = temp
#         end if
#     end for
# end for
#
# Register Usage:
# $8 is lastUnsorted
# $10 is test
# $11 is (lastUnsorted - 1)
# $12 is base address of array numbers
# $13 is address of numbers[test]
# $14 is value of numbers[test]
# $15 is value of numbers[test + 1]

        .data
numbers:        .word 30, 10, 20, 5, 90, 40, 60
length:         .word 7

        .text
        .globl main
main:
        la $12, numbers
for_init_1:
        lw $9, length
        addi $8, $9, -1
for_compare_1:
        blt $8, 1, end_for_1

for_init_2:
        li $10, 0
        addi $11, $8, -1
for_compare_2:
        bgt $10, $11, end_for_2

if:     mul $13, $10, 4
        add $13, $12, $13       # addr. of numbers[test]
        lw $14, 0($13)          # value of numbers[test]
        lw $15, 4($13)          # value of numbers[test+1]
        ble $14, $15, end_if
        sw $14, 4($13)
        sw $15, 0($13)
end_if:

        addi $10, $10, 1
```

```
        j for_compare_2
end_for_2:

        addi $8, $8, -1
        j for_compare_1
end_for_1:

        li $v0, 10      # system call code for exit program
        syscall
```

MIPS Assembly Language Supplement (Section 4.14 of the textbook)

Section 4.14 does a good job emphasizing that MARIE is a toy architecture that lacks key feature of real-world computer architectures. Most noticable, MARIE only supports a limited subroutine call, but it lacks a run-time stack to support more powerful subprograms: procedure, function, or method calls. Additionally, MARIE has only one "general-purpose" register, the ACcummulator, for temporary storage within the CPU, so it is difficult and inefficient to program with lots of LOADs and STOREs for intermediate results while processing. Real-world computers have many (10s or 100s) general-purpose registers to store temporary results while calculating. Both the Intel and MIPS architectures discussed in the textbook support subprograms and have multiple registers, but Intel is a Complex Instruction Set Computer (CISC) architecture while MIPS is a Reduced Instruction Set Computer (RISC) architecture.

A CISC approach to instruction set design was the traditional approach through the early 1980's. The main philosophy was to make assembly language (AL) as much like a high-level language (HLL) as possible to reduce the "*semantic gap*" between AL and HLL. The rational for CISC at the time was to:

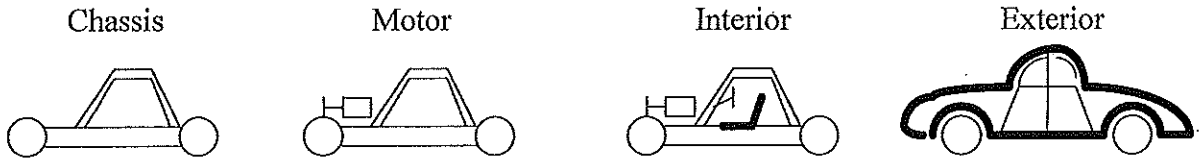
- reduce compiler complexity and aid assembly language programming. Compilers were not too good during the 50's to 70's, (e.g., they made poor use of general purpose registers so code was inefficient) so some programs were written in assembly language.
- reduce the program size. More powerful/complex instructions reduced the number of instructions necessary in a program. Memory during the 50's to 70's was limited and expensive.
- improve code efficiency by allowing complex sequence of instructions to be implemented in microcode. For example, the Digital Equipment Corporation (DEC) VAX computer had an assembly-language instruction "MATCHC *substrLength, substr, strLength, str*" that looks for a substring within a string.

The architectural characteristics of CISC machines include:

- complex, high-level like AL instructions
- variable format machine-language instructions that execute using a variable number of clock cycles
- many addressing modes (e.g., the DEC VAX had 22 addressing modes)

By the early 1980's, some computer engineers were seeing some problems with the CISC approach:

- complex CPU hardware, including a microprogrammed control unit, was needed to implement more and complex instructions which slows the execution of simpler instructions
- high-level language compilers could rarely figure out when to use complex instructions. Assembly-language programmer could may use of complex instructions, but compilers had become more efficient with respect to register usage, and programs were larger and harder to write in assembly language. Thus, fewer programs were written in assembly language.
- variability in instruction format and instruction execution time made CISC hard to pipeline. *Instruction pipelining* through the CPU speeds up program execution like an assembly-line speeds up manufacturing of a car. A car assembly line might split up building a car into four stages: chassis, motor, interior, and exterior.



Assume that the whole car assembly process takes 4 hours. If you divide the process into four equal stages of an hour each, then ideally we can complete a car every hour. Problems occur if the stages are not equally balanced for all cars. If someone ordered the deluxe interior package that takes two hours to install, then the chassis, motor, and exterior workers get an hour break during the second hour of the deluxe interior package installation.

MIPS Assembly Language Supplement (Section 4.14 of the textbook)

The main RISC philosophy (mid-80's and after) is to design the assembly language (AL) to optimize the instruction pipeline to speed program execution. One possible break down of an instruction execution into stages would be:

Stage	Actions
Fetch	Read next instruction into CPU and increment PC to next instruction
Decode	Determine opcode, and read register operands from the register file
Execution	Calculate using register operands read in the Decode stage. The ALU calculation depends on the type instruction being performed: ▪ memory reference (load/store): calculate the *effective memory* address of the operand ▪ arithmetic operation (add, sub, etc.) with two register operands ▪ arithmetic operation with a register and an immediate constant
Memory access	▪ load: read memory from effective address into a temporary pipeline register ▪ store: write register value from Decode stage to memory at effective address
Write-back	▪ ALU or load instruction: write result into register file

The architectural characteristics of RISC machines include:

- one instruction completion per clock cycle. This means that each stage needs fit in one clock cycle.
- large number of registers with register-to-register operations (e.g., "ADD R2, R3, R4," where R2 gets the results of R3 + R4). Register operands are already in the CPU so they are fast to access.
- simple addressing modes because complex address calculations might take longer that one clock cycle
- simple, fixed-length instruction formats. Fixed-length instructions require a fixed amount of time to fetch. Simple instruction formats can be decoded in a clock cycle. MIPS instruction formats are all 32-bits, and are as follows:

Arithmetic: add R1, R2, R3

opcode	dest reg	operand 1 reg	operand 2 reg	unused

Unconditional Branch/"jump": j someLabel

opcode	large offset from PC or absolute address

Arithmetic with immediate: addi R1, R2, 8

opcode	operand 1 reg	operand 2 reg	immediate value

Conditional Branch: beq R1, R2, end_if

opcode	operand 1 reg	operand 2 reg	PC-relative offset to label

Load/Store: lw R1, 16(R2)

opcode	operand reg	base reg	offset from base reg

- hardwired control unit. The simple instructions can be performed using hardwired control unit that allows for a fast clock cycle

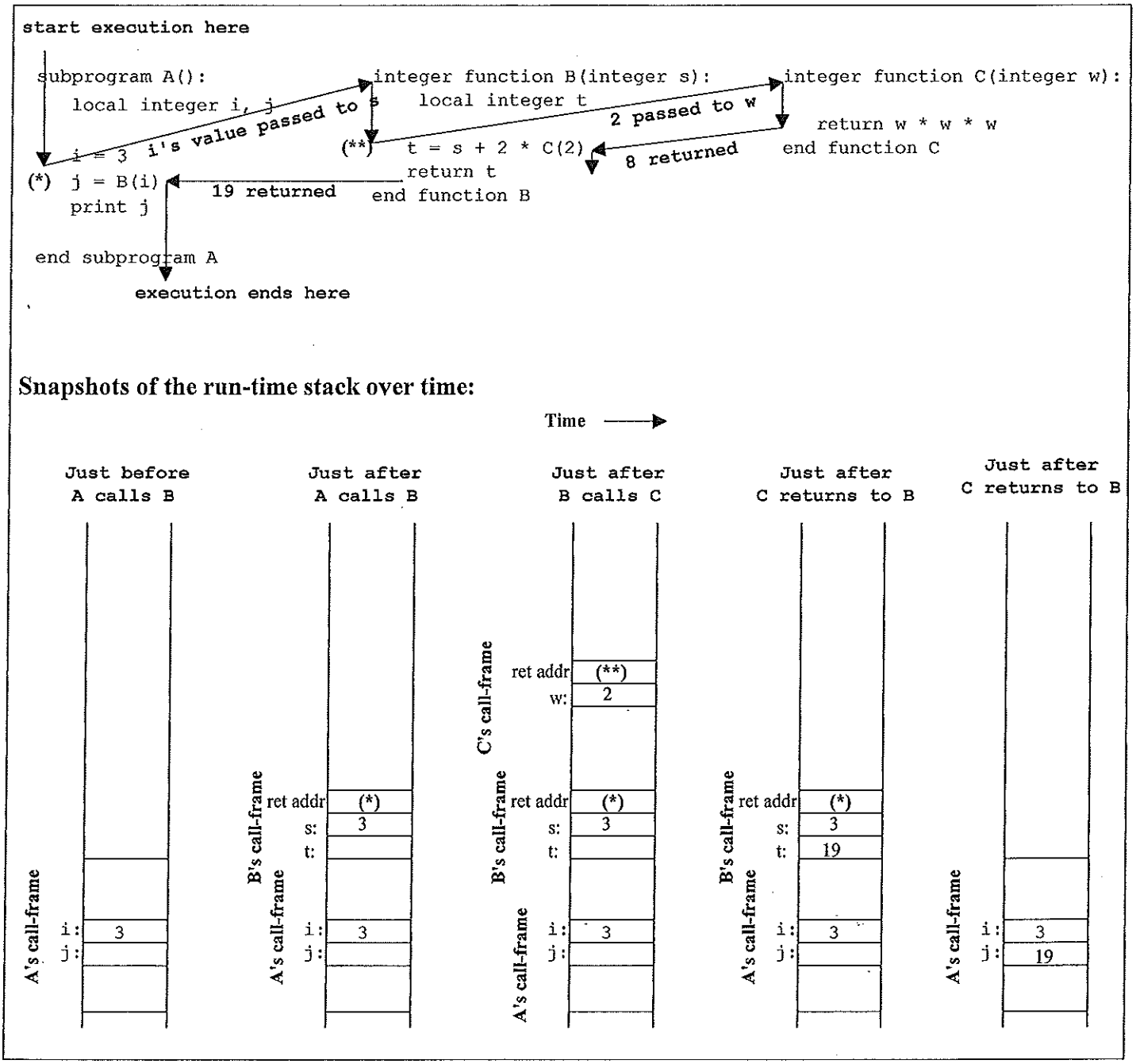
Most high-level programming languages (C, C++, Ada, Cobol, Java, Python, etc.) enable programs to be written in small reusable sections of code call subprograms that perform a specific task. A subprogram can be invoked using different *actual parameters* to allow them to perform their task on different data values. When writing the subprogram, *formal parameters* are used to describe the task. When a subprogram is called, the actual parameter values are passed to the formal parameters. This is called parameter passing.

MIPS Assembly Language Supplement (Section 4.14 of the textbook)

To help manage memory for subprograms, a run-time stack is used to provide memory space for a subprogram when it is called and delete it when it completes/returns. Specifically, when a subprogram is called, a call-frame (/activation record) is pushed on top of the run-time stack which contains:

- the return address - where to return execution after the the subprogram returns
- space for the formal parameters - these get initialized to the value of their corresponding actual parameter from the subprogram call
- space for local variables - temporary variables allocated within the subprogram

After the call-frame is setup, the execution begins at the beginning of the subprogram. When the subprogram completes/returns, its call-frame is popped off the run-time stack and execution resumes at the return address. If the subprogram is a function, then a return value will be returned to the return address. Consider the scenario of subprogram A calling subprogram B, then subprogram B calling subprogram C.



MIPS Assembly Language Supplement (Section 4.14 of the textbook)

Consider the more realistic program that calculates the values:

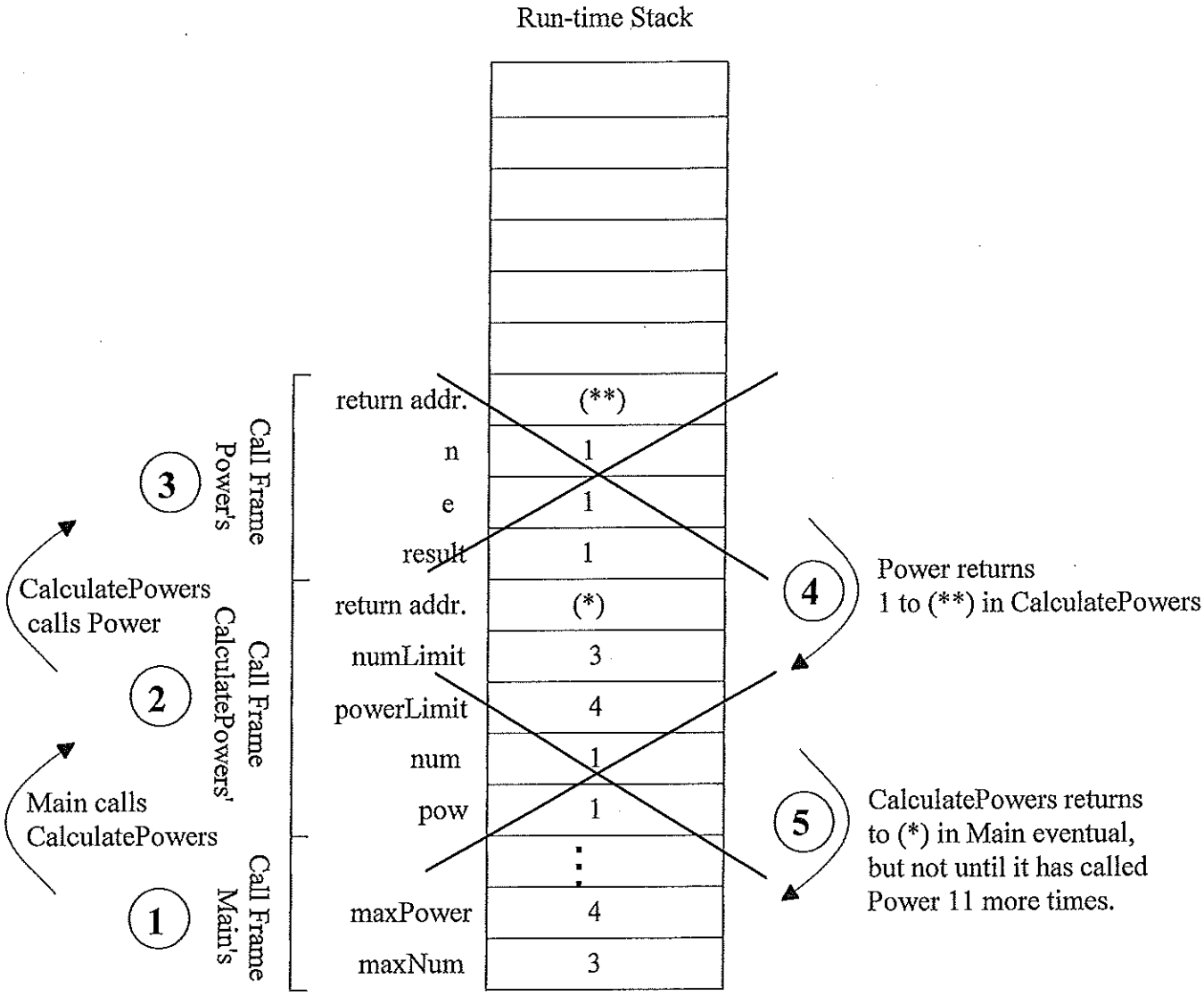
$$\begin{array}{cccc} 1^1 & 1^2 & 1^3 & 1^4 \\ 2^1 & 2^2 & 2^3 & 2^4 \\ 3^1 & 3^2 & 3^3 & 3^4 \end{array}$$

where the number and exponent ranges start at 1, but their upper bound are parameters to CalculatePowers. CalculatePowers uses a recursive function Power to calculate a number raised to an exponent. Recursion plays by the same rules as any other subprogram.

```
main:
   maxNum = 3
   maxPower = 4

   CalculatePowers(maxNum, maxPower)
   (*)
   . . .
end main


CalculatePowers( integer numLimit,
                 integer powerLimit)
   integer num, pow

   for num := 1 to numLimit do
       for pow := 1 to powerLimit do
          print num " raised to " pow " power is "
(**)                Power(num, pow)

       end for pow
   end for num

end CalculatePowers


integer function Power( integer n, integer e)

   integer result
   if e = 0 then
       result = 1
   else if e = 1 then
       result = n
   else
      result = Power(n, e - 1) * n        (***)
   end if
   return result
end Power
```

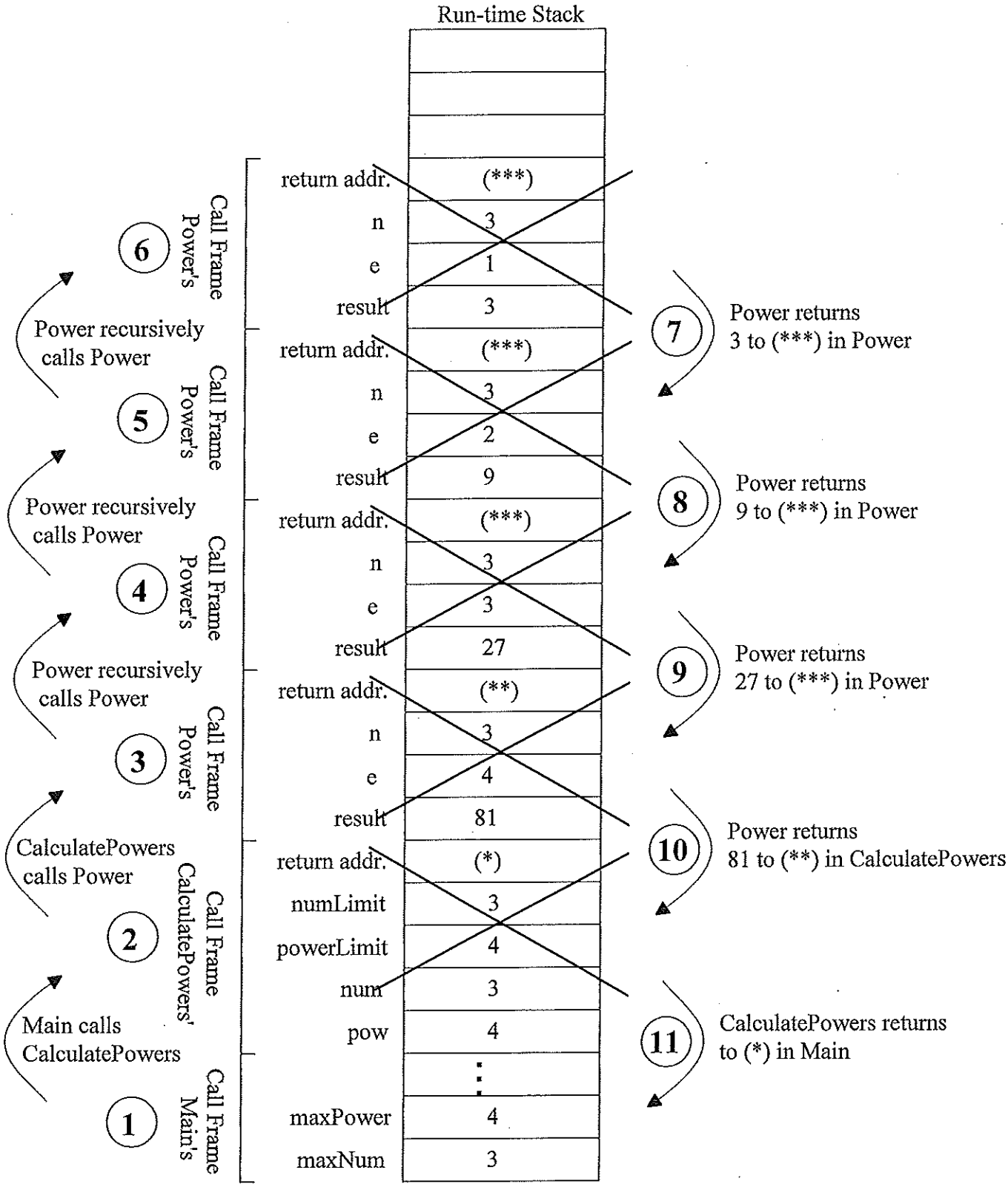
MIPS Assembly Language Supplement (Section 4.14 of the textbook)

The figure below shows a trace of the run-time stack after CalculatePowers called Power when num = 1 and pow = 1. When Power is called with n = 1 and e = 1, a base case of the recursion assigns result to 1 and then returns. The circled numbers indicate the order of events in the trace.



The figure below shows a trace of the run-time stack after CalculatePowers called Power when num = 3 and pow = 4. Notice that Power follows the same rules as any other subprogram with respect to parameter passing and the run-time stack. The circled numbers indicate the order of events in the trace.

MIPS Assembly Language Supplement (Section 4.14 of the textbook)



MIPS Assembly Language Supplement (Section 4.14 of the textbook)

One of the main goals of the course is for you to learn how to program in assembly language. MARIE was a good introduction, and simple enough to discuss its control unit's implementation. However, its simplicity made it very difficult to actually write useful assembly-language programs in MARIE, so the next three assignments will focus on MIPS assembly-language programming.

Today very few people actually write code in assembly language, but knowing how is necessary to understanding how high-level language programming languages are implemented with respect to the run-time stack and built-in data structures such as arrays and records. In the past, people wrote in assembly-language for several reasons:

- to improve the speed of there program
- to decrease the amount of memory used to store the program
- to gain access to low-level features of the machine that are difficulty from a high-level programming language (you might be writing a device driver for a new peripheral and need to fiddle with individual bits of data)

Fortunately, today's compilers generate extremely efficient machine-language code, so it is unlikely that the first two reasons apply. Plus, programs are generally much larger than in the past, so writing them all in assembly language would be difficult.

If you did want to speed up a high-level program by using assembly language, you would compile the program with a profiling option, and then run the program with real data. Having profiling turned on causes the program to track where it spends its execution time, and generates a report of the program's profile. Usually, over 85% of a program's time is spent executing a single subprogram. Thus, you can write just this subprogram in assembly language and leave the rest of the program in the high-level language (HLL). To correctly have the HLL program call your assembly-language subprogram, your assembly-language subprogram must follow the run-time stack and *register conventions* established for the processor. The register conventions are the rules about how the registers should be used. Before looking at the MIPS subprograms and its register convention, we must first learn to write simple main programs.

MIPS Assembly Language Guide:

As discussed earlier, MIPS is an example of a Reduced Instruction Set Computer (RISC) which was designed for easy instruction pipelining. MIPS has a "Load/Store" architecture since all instructions (other than the load and store instructions) must use register operands. MIPS has 32 32-bit "general purpose" registers ($0, $1, $2, ... , $31), but some of these have special uses (see MIPS Register Conventions table). For now it's enough to know that register $0 always contains the value 0, $1 should never be used, and registers $2 to $25 can be used for writing simple main programs. (MIPS also has floating point registers and instruction, but we'll only focus on integer instructions)

Memory is *byte* addressable, but your can also access a 16-bit *halfword*, or a 32-bit *word*. The *load word* instruction, lw, reads a 32-bit word from memory into a register. An example might be "lw $4, X" where X is a label for a variable in memory. We'll mostly deal with signed 32-bit word data, but some times 8-bit byte data with be used for ASCII characters. The load byte, lb, instruction will be used to read character data. Store instructions are used to write a register value back to memory. For example, "sw $5, Y" would store register $5 to the label Y in memory.

The MIPS assembler is fairly helpful and provides the program with not only assembly instructions, but also psuedo-instructions that can be implemented by the assembler with a couple actual assembler instructions. The following table is list of common MIPS instructions and psuedo-instructions.

MIPS Assembly Language Supplement (Section 4.14 of the textbook)

Common MIPS Instructions (and **psuedo-instructions**)		
Type of Instruction	**MIPS Assembly Language**	**Register Transfer Language Description**
Memory Access (Load and Store)	lw $4, Mem	$4 ← [Mem]
	sw $4, Mem	Mem ← $4
	lw $4, 16($3)	$4 ← [Mem at address in $3 + 16]
	sw $4, 16($3)	[Mem at address in $3 + 16] ← $4
Move	**move** $4, $2	$4 ← $2
	li $4, 100	$4 ← 100
Load Address	**la** $5, Mem	$4 ← load address of Mem
Arithmetic Instruction (reg. operands only)	add $4, $2, $3	$4 ← $2 + $3
	mul $10, $12, $8	$10 ← $12 * $8 (32-bit product)
	sub $4, $2, $3	$4 ← $2 - $3
Arithmetic with Immediates (last operand must be an integer)	addi $4, $2, 100	$4 ← $2 + 100
	mul $4, $2, 100	$4 ← $2 * 100 (32-bit product)
Conditional Branch	**bgt** $4, $2, LABEL (**bge, blt, ble**, beq, bne)	Branch to LABEL if $4 > $2
Unconditional Branch	j LABEL	Always Branch to LABEL

Lets look at a simple, complete MIPS program to calculate: result = (x + y) * (10 - z), where x is 1, y is 2, and z is 3.

```
# Simple program to calculate:  result = (x + y) * (10 - z).
     .data                    # Data segment used to global variables
x:        .word 1             # variable x initialized to 1 before program starts to execute
y:        .word 2             # variable y initialized to 2 before program starts to execute
z:        .word 3             # variable z initialized to 3 before program starts to execute
result:   .word 0             # variable result initialized to 0 before program starts to execute

     .text                    # Text segment used to store the program
     .globl main              # main is global so it can be found at start
main:
       lw $2, x               # load values into registers
       lw $3, y
       lw $4, z
       add $5, $2, $3         # $5 gets the value of (x + y)
       li $6, 10              # load the value 10 into register $6
       sub $6, $6, $4         # $6 gets the value of (10 - z)
       mul $6, $5, $6         # $6 gets the result
       sw $6, result          # save the result to memory

       li $v0, 10             # system code for exit
       syscall                # call the operating system
```

A MIPS program needs a data segment (started with ".data") and a text segment (started with ".text") for the program. Execution of the program starts at the global "main" label and terminates with a system call to the operating system in the last two lines of the program. Notice that labels (named spots in memory) for variables and in the code (e.g., "main") end with a colon, ":".

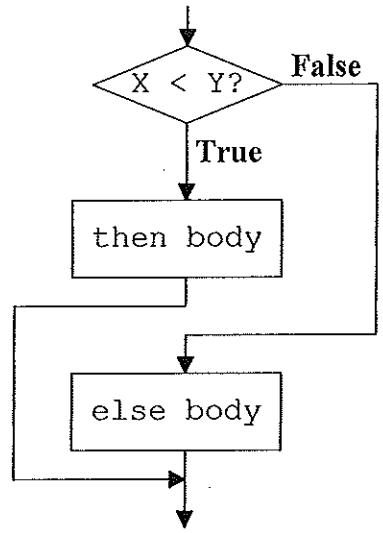
MIPS Assembly Language Supplement (Section 4.14 of the textbook)

Lets look at how MIPS can be used to implement various HLL control structures. For example, consider the following IF-THEN-ELSE statement and corresponding flow-chart:

HLL statement

```
if X < Y then
    ...
else
    ...
end if
```

Flow chart



Assembly Language

```
    lw $8, X
    lw $9, Y
    bge $8,$9,ELSE
THEN:

    J END_IF
ELSE:

END_IF:
```

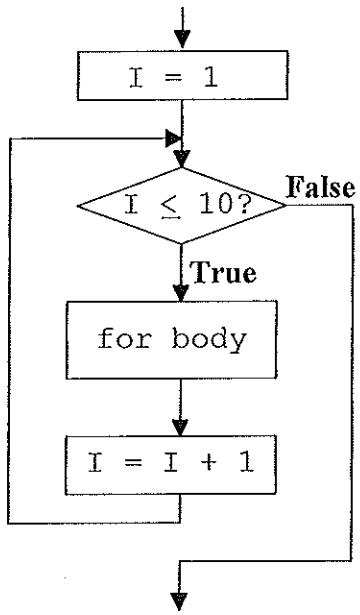
Since we want to conditionally jump over the THEN part when X < Y is False, the branch condition we check is the opposite of less-than, i.e., greater-than-or-equal (bge). If the THEN part is executed, then we jump to the END_IF.

For a loop example, consider the following FOR-loop and corresponding flow-chart:

HLL statement

```
for I = 1 to 10 do
    ...
end for
```

Flow chart



Assembly Language

```
FOR_INIT: li $5,1
FOR_COND: bgt $5,10,END_FOR
FOR_BODY:

    addi $5,$5,1
    j FOR_COND
END_FOR:
```

Register $5 is used to store I in this example. We can initialize $5 to 1 by using the "load immediate" instruction:
`li $5, 1`. If I ≤ 10 is False, then we want to drop out of the loop. Since I ≤ 10 is False when I > 10, use the conditional branch instruction: `bgt $5,10,END_FOR` to drop out of the FOR loop. After the for-body executes and the loop-control variable I is incremented, the j FOR_COND loops back to recheck the loop control variable.

MIPS Assembly Language Supplement (Section 4.14 of the textbook)

Most high-level programming languages have an array data structure for storing a collection of same type elements. We generally view an array as a rectangle divide into smaller cells that can be access by specifying an index. Consider an array scores with room for 15 element, but only containing 7 items.

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
scores:	5	10	20	25	30	40	60								

In most HLL you use square-brackets, [ ], to access individual elements in the array. For example, scores[3] has the value 25. If we want to change the element at index 3, would assign "scores[3] = 23." Arrays are implemented as a contiguous block of memory with a known starting location, called the *base address*. Because array elements are all the same size, we can calculate the address of some index "i" by:

address of array[i] = base address + (i * element size in bytes)

In a HLL the compiler generates code to perform this addressing calculation, but in assembly language its the programmer's job. The MIPS code looks something like:

```
            .data
array:      .word 5, 10, 20, 25, 30, 40, 60, 0, 0 , 0, 0 , 0, 0 , 0, 0
      .
      .
      .
# code to access array[i], where i's value is in register $5
      la $4, array            # load the base address of the array in register $4


      mul $6, $5, 4           # calculates i * the element size of 4 bytes
      add $7, $4, $6          # $7 contains the complete address of array[i]
      lw  $8, 0($7)           # load the value of element array[i] to register $8
```

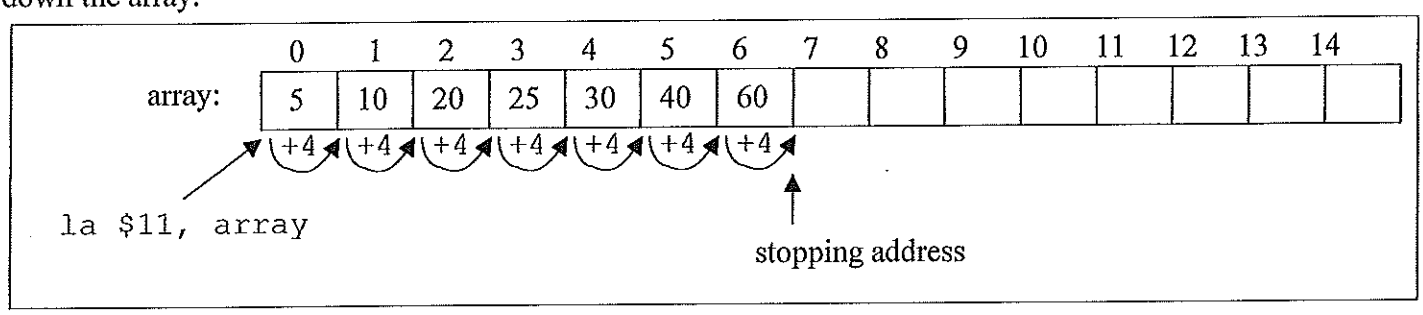
The above load instruction "`lw $8, 0($7)`" loads register $8 with the address specified by `0($7)` where 0 is a displacement added to the address in $7. Since we calculated the exact address of array[i] in $7, adding 0 is what we want to do. A displacement is useful in an array if you are accessing nearby elements. For example, if we want to perform the assignment: array[i+1] = array[i], we could use the above code which reads the value of array[i] into $8, and then store $8 to at 4 bytes from where $7 points in memory, i.e., `sw $8, 4($7)`.

MIPS Assembly Language Supplement (Section 4.14 of the textbook)

A simple MIPS assembly language program to sum the elements in an array is given below:

```
        .data
array:      .word 5, 10, 20, 25, 30, 40, 60, 0, 0, 0, 0, 0, 0, 0, 0
length:     .word 7
sum:        .word 0

# Algorithm being implemented to sum an array
#       sum = 0                         (use $8 for sum)
#       for i := 0 to length-1 do       (use $9 for i)
#             sum := sum + array[i]     (use $10 for length-1)
#       end for                         (use $11 for base addr. of array)

        .text
        .globl main
main:
        li      $8, 0               # load immediate 0 in reg. $8 (sum)
        la      $11, array          # load base addr. of array into $11
for:
        lw      $10, length         # load length in reg. $10
        addi    $10, $10, -1        # $10 = length - 1
        li      $9, 0               # initialize i in $9 to 0
for_compare:
        bgt     $9, $10, end_for    # drop out of loop when i > (length-1)
        mul     $12, $9, 4          # mult. i by 4 to get offset within array
        add     $12, $11, $12       # add base addr. of array to $12 to get addr. of array[i]
        lw      $12, 0($12)         # load value of array[i] from memory into $12
        add     $8, $8, $12         # update sum
        addi    $9, $9, 1           # increment i
        j       for_compare
end_for:

        sw      $8, sum

        li      $v0, 10             # system code for exit
        syscall
```

In the above code each array element access involves one addition and one multiplication. One way to speed up this code is by *walking pointers*. Because of the regular access pattern of the array element, i.e., start at the beginning and move down the array sequentially on each iteration of the loop. Since the elements are words and each that up 4 bytes, we can just add 4 to the pointer register $11 on each iteration. Plus, we can eliminate the loop-control variable `i` if we calculate the stopping address and use it to compare to register $11 as we "walk" it down the array.



The following program is the walking-pointer version. Walking a pointer reduces the number of calculations per iteration of the loop by one addition and one multiplication.

```
        .data
array:      .word 5, 10, 20, 25, 30, 40, 60, 0, 0, 0, 0, 0, 0, 0, 0
length:     .word 7
sum:        .word 0

# Algorithm being implemented to sum an array, but we are walking $11 down the array
#     sum = 0                        (use $8 for sum).
#     for i := 0 to length-1 do      (use $11 for the address of array[i])
#           sum := sum + array[i]    (use $10 for the stopping address,i.e, addr. of
#                                                                  array[length])
#     end for

        .text
        .globl main
main:
        li    $8, 0              # load immediate 0 in reg. $8 (sum)
        la    $11, array         # load base addr. of array into $11, i.e., addr. of array[0]
for:
        lw    $10, length        # load length in reg. $10
        mul   $10, $10, 4        # calculate the stopping address of array[length] in $10
        add   $10, $11, $10      #
for_compare:
        bge   $11, $10, end_for  # drop out of loop when $11 gets to stopping address in $10
        lw    $12, 0($11)        # load value of array[i] from memory into $12
        add   $8, $8, $12        # update sum
        addi  $11, $11, 4        # walk the pointer $11 to the next array element
        j     for_compare
end_for:

        sw    $8, sum

        li    $v0, 10            # system code for exit
        syscall
```

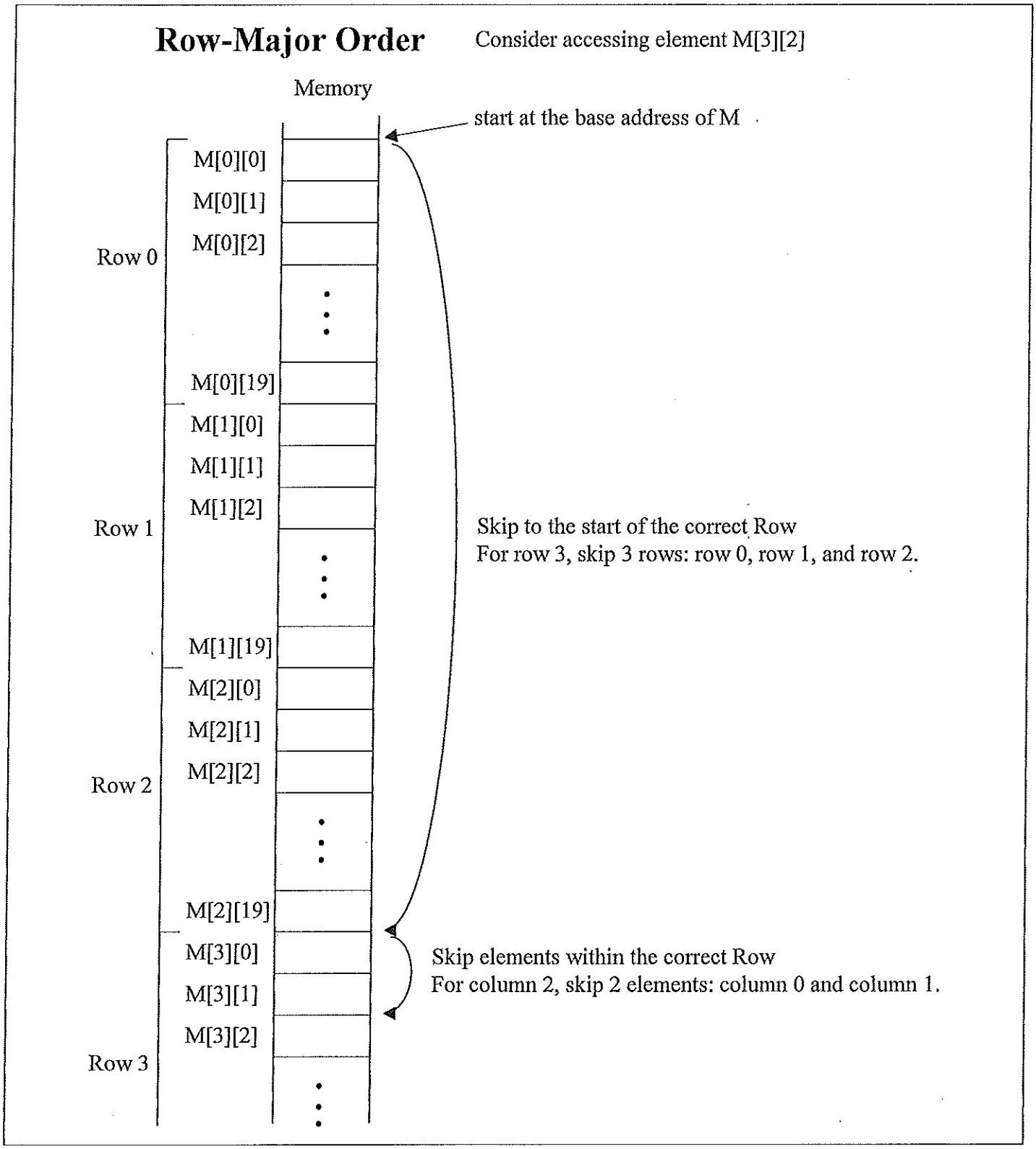
Multi-dimensional Arrays:

Consider a two-dimensional array M with 10 rows x 20 columns, we need to "unfold" this two-dimensional array into the one-dimensional memory. Two possible approaches could be taken:

- *column-major order* (see diagram below) where column 0 is followed by column 1 in memory, and column 1 is followed by column 2, etc.
- *row-major order* (see diagram below) where row 0 is followed by row 1 in memory, and row 1 is followed by row 2, etc.

Some high-level languages use one approach and some use the other. The choice is somewhat arbitary, since access to an element requires the same type of calculations.

Lets examine how row-major order would be packed into memory to develop the address calculation for an element M[r][c], i.e., row r and column c.



To calculate the address of some element M[r][c], we perform the calculation:

address of M[r][c] = base address + r * size in a row + c * size of an element

address of M[r][c] = base address + r * # of columns * size of an element + c * size of an element

address of M[r][c] = base address + (r * # of columns + c) * size of an element

MIPS Assembly Language Supplement (Section 4.14 of the textbook)

The MIPS code to access M[r][c] where M has 10 rows and 20 columns and is stored in row-major order:

```
        .
        .
        .
# code to access M[r][c], where r's value is in register $5  and c's is in $6
      la $4, M                # load the base address of the array in register $4


      mul $7, $5, 20          # calculates r * # of columns
      add $7, $7, $6          # calculates r * # of columns + c
      mul $7, $7, 4           # calculates (r * # of columns + c)* size of an element
      add $7, $4, $7          # complete address calculation for M[r][c]

      lw  $8, 0($7)           # load the value of element M[r][c] to register $8
```

For a two-dimensional array, the address calculation takes 2 additions and 2 multiplications.

If we wanted to "walk" a pointer down a single column, say column 2, then we would just need to perform one addition to increment the pointer by the size of a row to move it from one element to the next, i.e., M[0][2], M[1][2], M[2][2], M[3][2], etc. Thus, a pointer would eliminate one addition and 2 multiplications per element access.

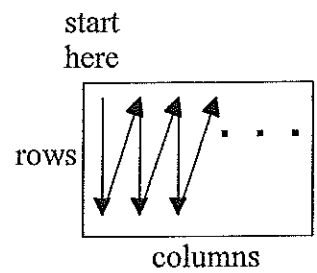
1) Using the idea of "<u>walking pointers</u>" re-do the MIPS sequential search program that finds the <u>index location</u> of the first occurrence of targetValue in the array scores. If the targetValue is not in the array, then foundIndex should be set to -1.

```
# MIPS sequential search program -- High-level algorithm:
# foundIndex = -1
# for i = 0 to (length-1) do
#     if scores[i] == targetValue then
#          foundIndex = i
#          break out of loop
#     end if
# end for
      .data
scores:           .word 10, 30, 45, 20, 80, 20, 70, 30, 50, 0, 0, 0, 0
length:           .word 9
targetValue:      .word 20
foundIndex: .word 0

      .text
      .globl main
main:
```

2) For a 2D array M stored using column-major order, complete the formula to calculate the address of some element M[r][c]:

address of M[r][c] = base address +

<u>Column-major order</u>



```
integer firstUnsortedIndex, testIndex, elementToInsert;
for firstUnsortedIndex = 1 to (length-1) do
    testIndex = firstUnsortedIndex-1;
    elementToInsert = numbers[firstUnsortedIndex];
    while (testIndex >=0) AND (numbers[testIndex] > elementToInsert ) do
        numbers[ testIndex + 1 ] = numbers[ testIndex ];
        testIndex =  testIndex - 1;
    end while
    numbers[ testIndex + 1 ] = elementToInsert;
end for
```

3. Write MIPS Assembly Language code for the above insertion sort algorithm <u>by walking pointers</u>.

```
          .data
numbers:      .word 20, 30, 10, 40, 50, 60, 30, 25, 10, 5
length:       .word 10

          .text
          .globl main
main:
```

```
    li    $v0, 10            # system call to exit
    syscall
```

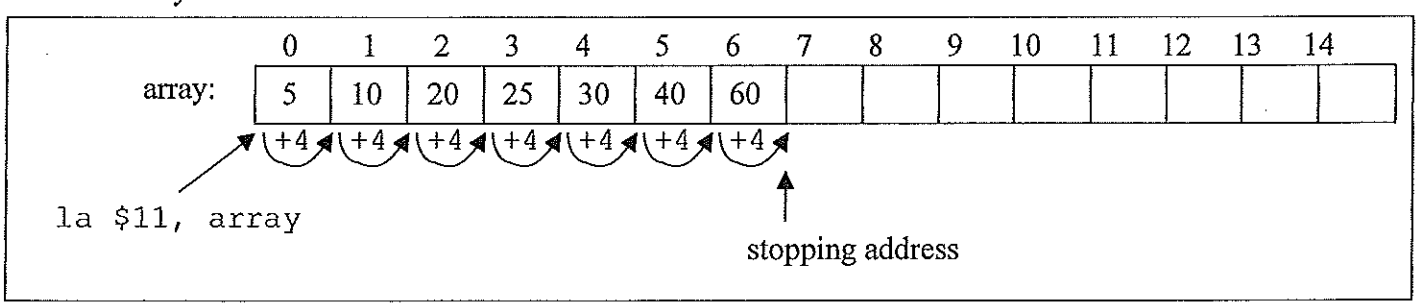
Lecture 18 "walking pointers" in an array and 2D arrays

MIPS Assembly Language Supplement (Section 4.14 of the textbook) (p. 11)

A simple MIPS assembly language program to sum the elements in an array is given below:

```
        .data
array:      .word 5, 10, 20, 25, 30, 40, 60, 0, 0, 0, 0, 0, 0, 0, 0
length:     .word 7
sum:        .word 0

# Algorithm being implemented to sum an array
#     sum = 0                          (use $8 for sum)
#     for i := 0 to length-1 do        (use $9 for i)
#           sum := sum + array[i]      (use $10 for length-1)
#     end for                          (use $11 for base addr. of array)

        .text
        .globl main
main:
        li    $8, 0              # load immediate 0 in reg. $8 (sum)
        la    $11, array         # load base addr. of array into $11
for:
        lw    $10, length        # load length in reg. $10
        addi  $10, $10, -1       # $10 = length - 1
        li    $9, 0              # initialize i in $9 to 0
for_compare:
        bgt   $9, $10, end_for   # drop out of loop when i > (length-1)
        mul   $12, $9, 4         # mult. i by 4 to get offset within array
        add   $12, $11, $12      # add base addr. of array to $12 to get addr. of array[i]
        lw    $12, 0($12)        # load value of array[i] from memory into $12
        add   $8, $8, $12        # update sum
        addi  $9, $9, 1          # increment i
        j     for_compare
end_for:

        sw    $8, sum

        li    $v0, 10            # system code for exit
        syscall
```

In the above code each array element access involves one addition and one multiplication. One way to speed up this code is by *walking pointers*. Because of the regular access pattern of the array element, i.e., start at the beginning and move down the array sequentially on each iteration of the loop. Since the elements are words and each that up 4 bytes, we can just add 4 to the pointer register $11 on each iteration. Plus, we can eliminate the loop-control variable i if we calculate the stopping address and use it to compare to register $11 as we "walk" it down the array.



The following program is the walking-pointer version. Walking a pointer reduces the number of calculations per iteration of the loop by one addition and one multiplication.

MIPS Assembly Language Supplement (Section 4.14 of the textbook)

```
        .data
array:      .word 5, 10, 20, 25, 30, 40, 60, 0, 0, 0, 0, 0, 0, 0, 0
length:     .word 7
sum:        .word 0

# Algorithm being implemented to sum an array, but we are walking $11 down the array
#       sum = 0                         (use $8 for sum)
#       for i := 0 to length-1 do       (use $11 for the address of array[i])
#             sum := sum + array[i]     (use $10 for the stopping address,i.e, addr. of
#                                                                   array[length])
#       end for

        .text
        .globl main
main:
        li      $8, 0               # load immediate 0 in reg. $8 (sum)
        la      $11, array          # load base addr. of array into $11, i.e., addr. of array[0]
for:
        lw      $10, length         # load length in reg. $10
        mul     $10, $10, 4         # calculate the stopping address of array[length] in $10
        add     $10, $11, $10       #
for_compare:
        bge     $11, $10, end_for # drop out of loop when $11 gets to stopping address in $10
        lw      $12, 0($11)         # load value of array[i] from memory into $12
        add     $8, $8, $12         # update sum
        addi    $11, $11, 4         # walk the pointer $11 to the next array element
        j       for_compare
end_for:

        sw      $8, sum

        li      $v0, 10             # system code for exit
        syscall
```

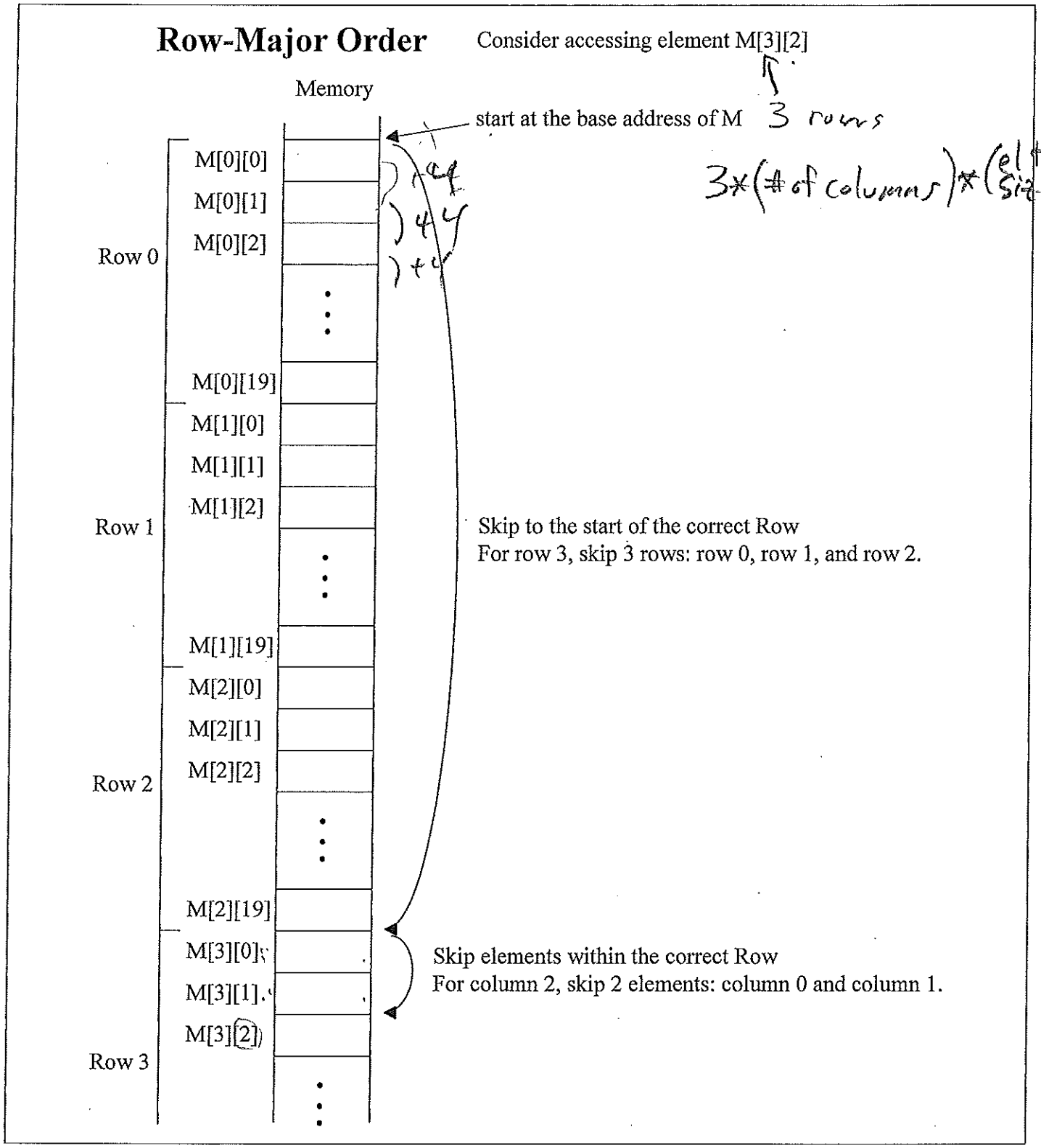
Multi-dimensional Arrays:

Consider a two-dimensional array M with 10 rows x 20 columns, we need to "unfold" this two-dimensional array into the one-dimensional memory. Two possible approaches could be taken:

- *column-major order* (see diagram below) where column 0 is followed by column 1 in memory, and column 1 is followed by column 2, etc.
- *row-major order* (see diagram below) where row 0 is followed by row 1 in memory, and row 1 is followed by row 2, etc.

Some high-level languages use one approach and some use the other. The choice is somewhat arbitary, since access to an element requires the same type of calculations.

Lets examine how row-major order would be packed into memory to develop the address calculation for an element M[r][c], i.e., row r and column c.



To calculate the address of some element M[r][c], we perform the calculation:

address of M[r][c] = base address + r * size in a row + c * size of an element

address of M[r][c] = base address + r * # of columns * size of an element + c * size of an element

address of M[r][c] = base address + (r * # of columns + c) * size of an element

2 * 2 +

MIPS Assembly Language Supplement (Section 4.14 of the textbook)

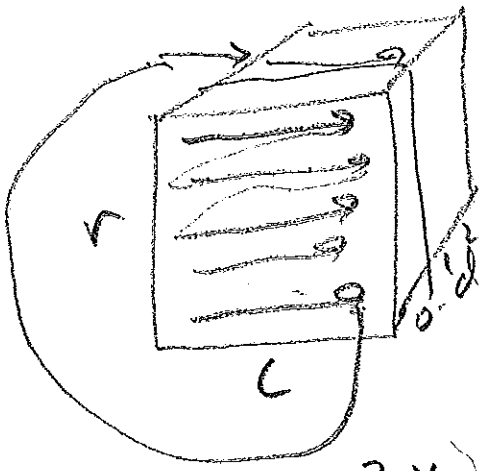
The MIPS code to access M[r][c] where M has 10 rows and 20 columns and is stored in row-major order:

```
        .
        .
        .
# code to access M[r][c], where r's value is in register $5  and c's is in $6
      la $4, M                # load the base address of the array in register $4


      mul $7, $5, 20          # calculates r * # of columns
      add $7, $7, $6          # calculates r * # of columns + c
      mul $7, $7, 4           # calculates (r * # of columns + c)* size of an element
      add $7, $4, $7          # complete address calculation for M[r][c]

      lw  $8, 0($7)           # load the value of element M[r][c] to register $8
```

For a two-dimensional array, the address calculation takes 2 additions and 2 multiplications.

If we wanted to "walk" a pointer down a single column, say column 2, then we would just need to perform one addition to increment the pointer by the size of a row to move it from one element to the next, i.e., M[0][2], M[1][2], M[2][2], M[3][2], etc. Thus, a pointer would eliminate one addition and 2 multiplications per element access.

sum = 0
for r = 0 to 9 do ++
  for c = 0 to 19 do ++
    sum = sum + M[r][c] 2×, 2+



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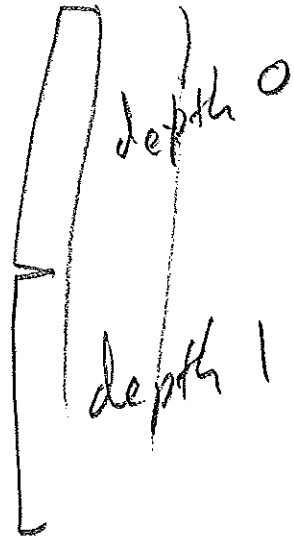
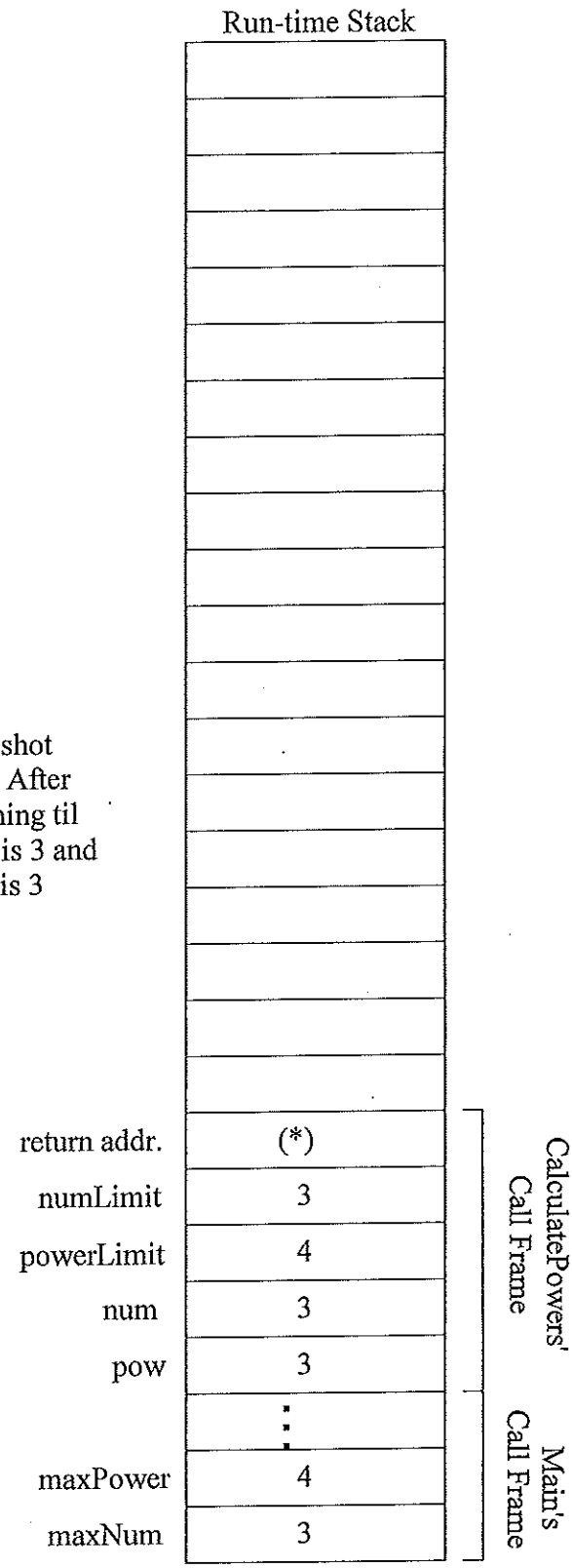
3+



High-level Language Programmer's View

```
main:
   maxNum = 3
   maxPower = 4

   CalculatePowers(maxNum, maxPower)
   (*)
   . . .
end main


CalculatePowers(In: integer numLimit,
                    integer powerLimit)
   integer num, pow

   for num := 1 to numLimit do
       for pow := 1 to powerLimit do
          print num " raised to " pow " power is "
(**)                Power(num, pow)

       end for pow
   end for num

end CalculatePowers


integer Power( In:  integer n, integer e)

   integer result
   if e = 0 then
       result = 1
   else if e = 1 then
       result = n
   else
      result = Power(n, e - 1) * n        (***)
   end if
   return result
end Power
```

Snapshot Here After Running til num is 3 and pow is 3



1) Trace the next execution (e.g., num is 3 and pow is 3) of the recursive function Power by showing the run-time stack.

2) What is the most number of call frames on the stack at any one time for the <u>whole</u> program?

main:	**CalculatePowers(In:** integer numLimit, integer powerLimit)	integer **Power(In:** integer n, integer e)
maxNum = 3		integer result
maxPower = 4	integer num, pow	if e = 0 then
		result = 1
CalculatePowers(maxNum, maxPower)	for num := 1 to numLimit do	else if e = 1 then
(*)	for pow := 1 to powerLimit do	result = n
. . .		else
end main	print num " raised to " pow " power is "	result = Power(n, e - 1)* n
	Power(num, pow)	end if
	end for pow	return result
	end for num	**end Power**
	end CalculatePowers	

a) Using the MIPS register conventions, what registers would be used to pass each of the following parameters to CalculatePowers:

maxNum	maxPower

b) Using the MIPS register conventions, which of these parameters ("numLimit", "powerLimit", or both of them) should be moved into s-registers?
(NOTE: Use an s-register for any value you still need after you come back from a subprogram/function/procedure call, e.g., call to "Power")

c) Using the MIPS register conventions, what registers should be used for each of the local variables:

num	pow

d) Using the MIPS register conventions, what registers would be used to pass each of the following parameters to Power:

num	pow

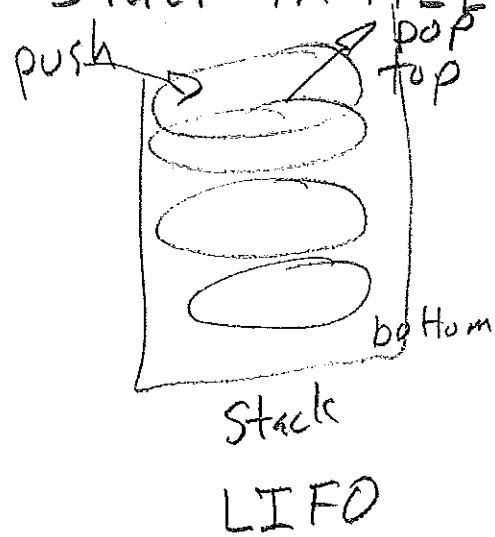
e) Using the MIPS register conventions, which of these parameters ("n", "e", or both of them) should be moved into s-registers?

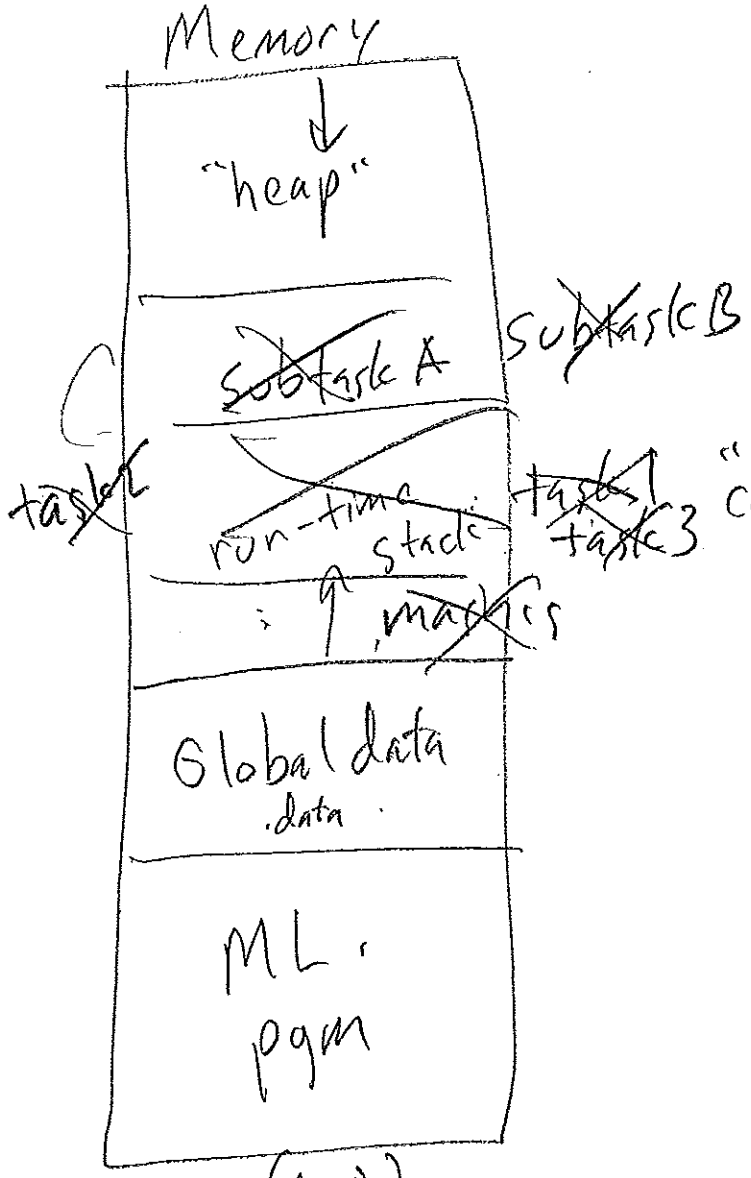
f) Using the MIPS register conventions, what register should be used for the local variable:

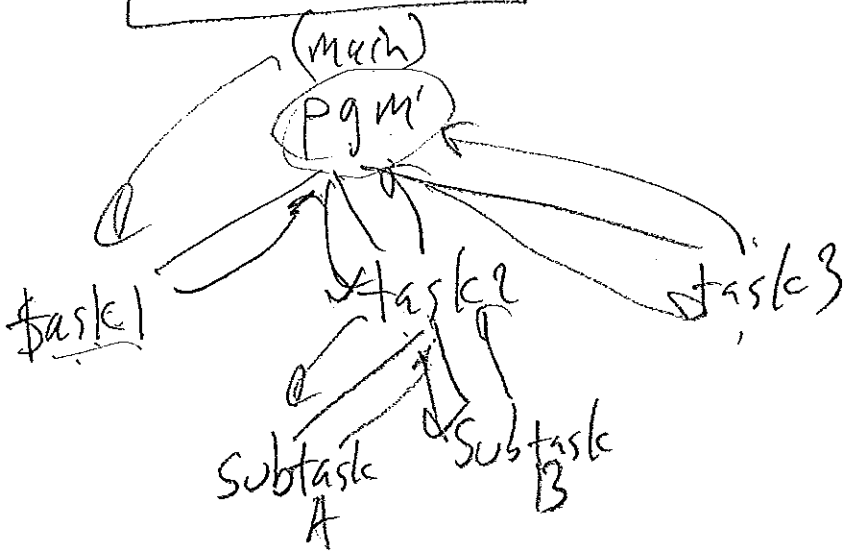
result

g) Write the code for main, CalculatePowers, and Power in MIPS assembly language.

Lecture 19 Run-time stack in HLL





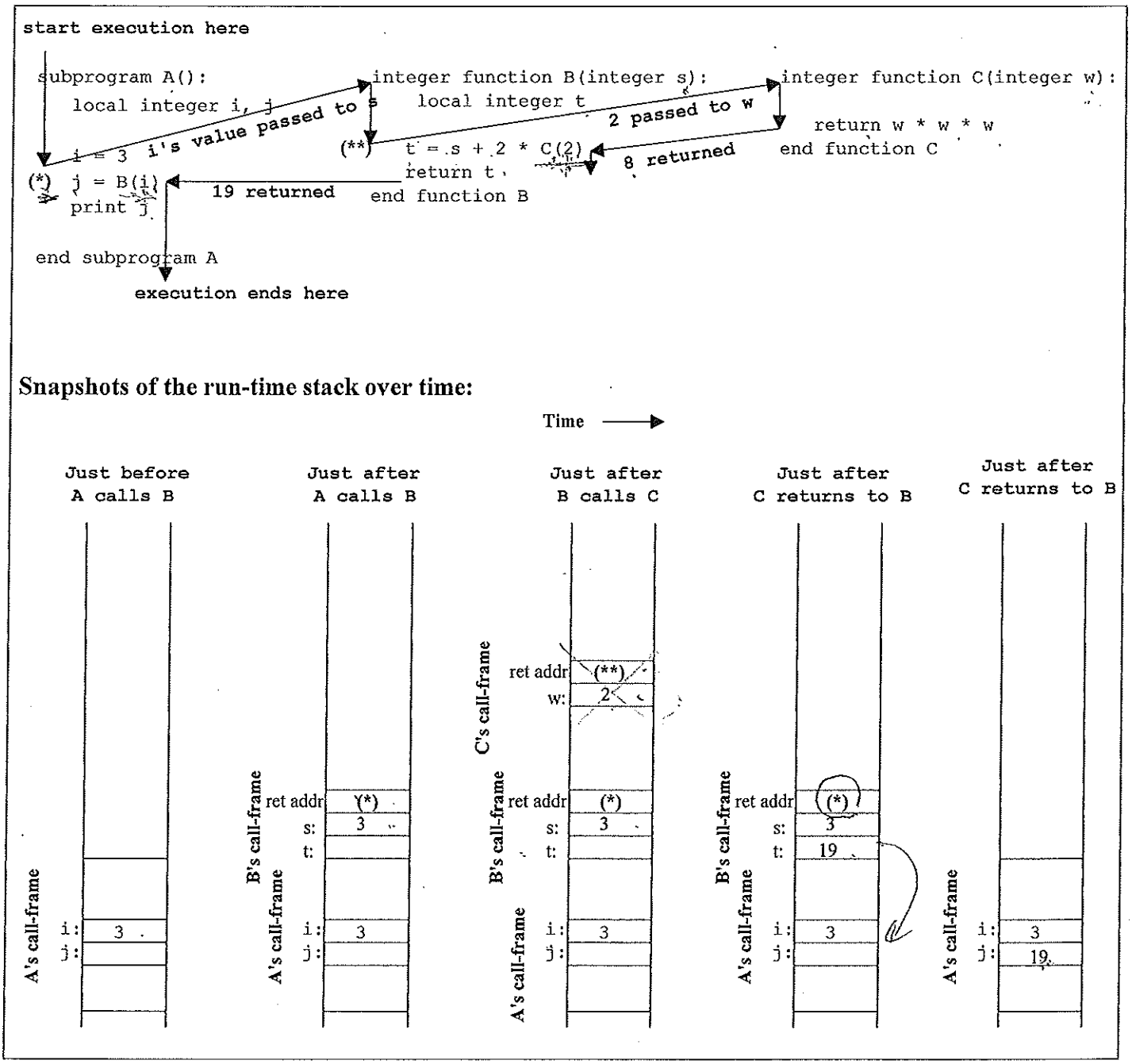


MIPS Assembly Language Supplement (Section 4.14 of the textbook) (p. 3)

To help manage memory for subprograms, a run-time stack is used to provide memory space for a subprogram when it is called and delete it when it completes/returns. Specifically, when a subprogram is called, a call-frame (/activation record) is pushed on top of the run-time stack which contains:

- the return address - where to return execution after the the subprogram returns
- space for the formal parameters - these get initialized to the value of their corresponding actual parameter from the subprogram call
- space for local variables - temporary variables allocated within the subprogram

After the call-frame is setup, the execution begins at the beginning of the subprogram. When the subprogram completes/returns, its call-frame is popped off the run-time stack and execution resumes at the return address. If the subprogram is a function, then a return value will be returned to the return address. Consider the scenario of subprogram A calling subprogram B, then subprogram B calling subprogram C.



MIPS Assembly Language Supplement (Section 4.14 of the textbook)

Consider the more realistic program that calculates the values:

$$\begin{array}{cccc} 1^1 & 1^2 & 1^3 & 1^4 \\ 2^1 & 2^2 & 2^3 & 2^4 \\ 3^1 & 3^2 & 3^3 & 3^4 \end{array}$$

where the number and exponent ranges start at 1, but their upper bound are parameters to CalculatePowers. CalculatePowers uses a recursive function Power to calculate a number raised to an exponent. Recursion plays by the same rules as any other subprogram.

```
main:
   maxNum = 3
   maxPower = 4

   CalculatePowers(maxNum, maxPower)
   (*)                  3          4
   . . .
end main


CalculatePowers( integer numLimit,
                 integer powerLimit)
   integer num, pow

   for num := 1 to numLimit do
       for pow := 1 to powerLimit do
          print num " raised to " pow " power is "
(**)                Power(num, pow)

       end for pow
   end for num

end CalculatePowers

integer function Power( integer n, integer e)

   integer result
   if e = 0 then
       result = 1
   else if e = 1 then
       result = n
   else
      result = Power(n, e - 1) * n        (***)
   end if
   return result
end Power
```

n^e

$3^4 = 3 * 3 * 3 * 3$

$3^4 = 3 * 3^3$

$3 * 3^2$

$3 * 3^1$

$3^1 = 3$

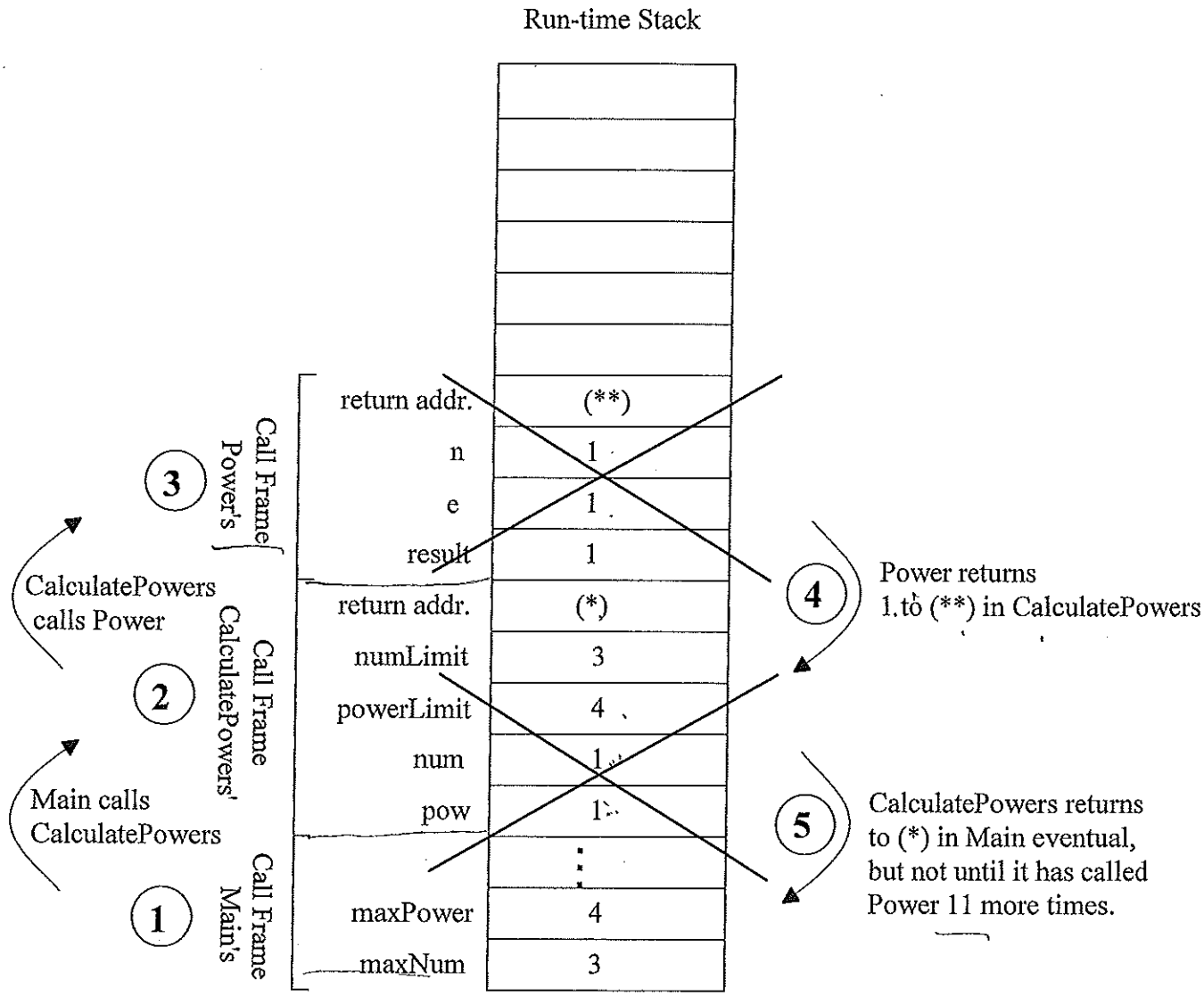
$n^e = n * n^{(e-1)}$

$\begin{cases} e=1 & n^1 = n \\ e=0 & n^0 = 1. \end{cases}$

base cases

MIPS Assembly Language Supplement (Section 4.14 of the textbook)

The figure below shows a trace of the run-time stack after CalculatePowers called Power when num = 1 and pow = 1. When Power is called with n = 1 and e = 1, a base case of the recursion assigns result to 1 and then returns. The circled numbers indicate the order of events in the trace.



The figure below shows a trace of the run-time stack after CalculatePowers called Power when num = 3 and pow = 4. Notice that Power follows the same rules as any other subprogram with respect to parameter passing and the run-time stack. The circled numbers indicate the order of events in the trace.

MIP Calling-Conventions Supplement 2 for Section 4.14 of the textbook

If you did want to speed up a high-level program by using assembly language, you would compile the program with a profiling option, and then run the program with real data. Having profiling turned on causes the program to track where it spends its execution time, and generates a report of the program's profile. Usually, over 85% of a program's time is spent executing a single subprogram. Thus, you can write just this subprogram in assembly language and leave the rest of the program in the high-level language (HLL). To correctly have the HLL program call your assembly-language subprogram, your assembly-language subprogram must follow the run-time stack and *register conventions* established for the processor. The register conventions are the rules about how the registers should be used.

Compiler uses registers to avoid accessing the run-time stack in memory as much as possible. Registers can be used for local variables, parameters, the return address, and the function-return value. Unfortunately, the number of registers is limited. When a subprogram is called, some of the register values might need to be saved ("spilled") on the stack to free up some registers for the subprogram to use.

Different machines use one of several standard conventions for spilling registers:
1) caller save - before the call, caller saves the register values it needs after execution returns from the subprogram
2) callee save - subprogram saves and restores any register it uses in its code
3) some combination of caller and callee saved (USED BY MIPS)

The following table shows the MIPS register conventions. Each register can be referenced to by its number or its convention name, e.g., $4 as $a0 for an "argument"/parameter register. The caller of the subprogram would place the parameter value in $a0 and call the subprogram. The subprogram has the parameter value since it is in the register. Thus, avoiding pushing it on the run-time stack in the slow memory.

MIPS Register Conventions

Reg. #	Convention Name	Role in Procedure Calls	Comments
$0	$zero	constant value zero	Cannot be changed
$1	$at	Used by assembler to implement psuedoinstructions	DON'T USE
$2, $3	$v0, $v1	Results of a function	
$4 - $7	$a0 - $a3	First 4 arguments to a procedure	
$8 - $15, $24, $25	$t0 - $t9	Temporary registers (not preserved across call)	Caller-saved registers - subprogram can use them as scratch registers, but it must also save any needed values before calling another subprogram.
$16 - $23	$s0 - $s7	Saved temporary (preserved across call)	Callee-saved registers - it can rely on an subprogram it calls not to change them (so a subprogram wishing to use these registers must save them on entry and restore them before it exits)
$26, $27	$k0, $k1	Reserved for the Operating System Kernel	DON'T USE
$28	$gp	Pointer to global area	
$29	$sp	Stack pointer	Points to first free memory location above stack
$30	$fp/$s8	Frame pointer (if needed) or another saved register	$fp not used so use as $s8
$31	$ra	Return address (used by a procedure call)	Receives return addr. on *jal* call to procedure

MIP Calling-Conventions Supplement 2 for Section 4.14 of the textbook

The general steps for using the MIPS register conventions are listed below.

Using MIPS Calling Convention	
Caller Code (caller of the subprogram)	**Callee Code (the subprogram itself)**
. . . 1) save on stack any $t0 - $t9 and $a0 - $a3 that are needed upon return 2) place arguments to be passed in $a0 - $a3 with additional parameters pushed onto the stack 3) jal ProcName # saves return address in $ra 4) restore any saved registers $t0 - $t9 and $a0 - $a3 from stack	. . . 1) allocate memory for frame by subtracting frame size from $sp 2) save callee-saved registers ($s0 - $s7) if more registers than $t0 - $t9 and $a0 - $a3 are needed 3) save $ra if another procedure is to be called **. . . code for the callee** 4) for functions, place result to be returned in $v0 - $v1 5) restore any callee-saved registers ($s0 - $s7) from step (2) above 6) restore $ra if it was saved on the stack in step (3) 7) pop stack frame by adding frame size to $sp 8) return to caller by "jr $ra" instruction

Lets reconsider the CalculatePowers program and examine how to apply the MIPS register conventions:

High-level Language Programmer's View of CalculatePowers

main:
 	
maxNum = 3
maxPower = 4
 	
CalculatePowers(maxNum, maxPower)
(*)
. . .
end main
	CalculatePowers(integer numLimit,
	integer powerLimit)
	
	integer num, pow
	
	for num := 1 to numLimit do
	for pow := 1 to powerLimit do
	
	print num " raised to " pow " power is "
	Power(num, pow)
	end for pow
	end for num
		integer function **Power**(integer n, integer e)
		
		integer result
		if e = 0 then
		result = 1
		else if e = 1 then
		result = n
		else
		result = Power(n, e - 1)* n
		end if
		return result
		end Power

I would recommend asking your self the following questions to determine which registers to use when applying the register conventions.

1) Using the MIPS register conventions, what registers would be used to pass the parameters (maxNum and maxPower) to CalculatePowers?

The first parameter is always passed in $a0, the second parameter in $a1, etc. If there are more than four parameters, then additional parameters

are pushed onto the run-time stack. Thus, we'll use the following register allocation:

maxNum	maxPower
$a0	$a1

The main program code that calls CalculatePowers would be:

```
main:
        ...
        lw   $a0, maxNum          # $a0 contains maxNum
        lw   $a1, maxPower        # $a1 contains maxPower
        jal  CalculatePowers
```

The jump-and-link (`jal`) instruction acts an unconditional jump instruction, but it also saves the address of the instruction after the jal to register $ra so execution can return there when CalculatePowers returns. Having the return-address saved to a register avoids the need to save it to the run-time stack.

When CalculatePowers starts execution its formal parameters, numLimit and powerLimit, will be in registers $a0 and $a1, respectively. Since CalculatePowers calls the Power function which takes two parameters, both register $a0 and $a1 must eventually be used for this purpose. You want to decide if either numLimit or powerLimit is needed across the call to Power. If so, we must save their value(s) before calling Power. One way to save their value is to move them into an s-register which is maintained across the call to a subprogram (i.e., the subprogram will not change the s-registers if it is following the register conventions). In writing the code for a subprogram, the second question I ask myself is:

2) Using the MIPS register conventions, which of these parameters ("numLimit", "powerLimit", or both of them) should be moved into s-registers?
(NOTE: Use an s-register for any value you still need after you come back from a subprogram/function/procedure call, e.g., call to "Power")

The call to Power is part of the inner-for-loop body with numLimit and powerLimit both being needed after the call (so they can be compared to the loop control variables). Thus, both should be saved to s-registers: $a0 can be moved to $s0 and $a1 can be moved to $s1.

For the local variables, num and pow, we need to ask ourself a similar question:
3) Using the MIPS register conventions, what registers should be used for each of the local variables?

Since both variables are used as loop-control variables with Power being called as part of the inner-for-loop body, both variable must maintain their value across the call to Power. Thus, s-registers should be used for both. Since $s0 and $s1 are already being used for numLimit and powerLimit, we can use $s2 and $s3 as:

num	pow
$s2	$s3

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Before we can use $s0 to $s3 in CalculatePowers, we need to save their values to the run-time stack. After all, "main" might be storing something in these s-registers, and by convention CalculatePowers should not be allowed to change "main's" values in s-registers. The code that starts the CalculatePowers subprogram would be:

```
CalculatePowers:     # parameters:    $a0 contains numLimit, and $a1 contains powerLimit

          sub  $sp, $sp, -20        # move stack pointer, $sp, "up" to make room for the call-frame
          sw   $ra, 4($sp)          # push return address onto stack
          sw   $s0, 8($sp)          # push the caller's s-register values onto the stack
          sw   $s1, 12($sp)
          sw   $s2, 16($sp)
          sw   $s3, 20($sp)
                                # save a-registers to s-registers so they don't get wiped out
          move $s0, $a0         # save numLimit in $s0
          move $s1, $a1         # save powerLimit in $s1
...
```

To create room on the run-time stack for CalculatePowers' call-frame, we subtract 20 bytes from the stack-pointer, $sp register, which is enough for 5 registers. The registers saved are the s-registers $s0 to $s3 and the $ra register which contains the return address back in the "main." We save the $ra on the stack since the "`jal Power`" instructions in the subprogram body would wipe it out.

Since CalculatePowers calls Power, we start over with the same set of questions for the call to Power and the code for Power.

1) Using the MIPS register conventions, what registers would be used to pass each of the following parameters to Power:

num	pow
$a0	$a1

The CalculatePowers' code that calls Power would be:

```
CalculatePowers:
          ...
          move $a0, $s2         # call Power(num, pow), where num is in $s2 and pow is in $s3
          move $a1, $s3
          jal  Power
          ...
```

Writing the Power function is a little trick. Since it is recursive and it only calls itself, we can "bend the register conventions" alittle bit to improve efficiency.

2) Using the MIPS register conventions, which of these parameters ("n", "e", or both of them) should be moved into s-registers?

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Normally, I'd look at the recursive call "result = Power(n, e - 1)* n", and think that parameter n is needed after we return from Power so we can multiple it. Thus, I'd want to move the original parameter n in $a0 to an s-register, so the call to Power does not wipe it out. However, the first parameter in the recursive call is the value of n, so we can just leave $a0 as the value of n throughout subprogram Power. If this is confusing, you might look at the HLL run-time stack diagram on page 6 of the "MIPS Supplement". Notice that n's value is unchanged in each call-frame.

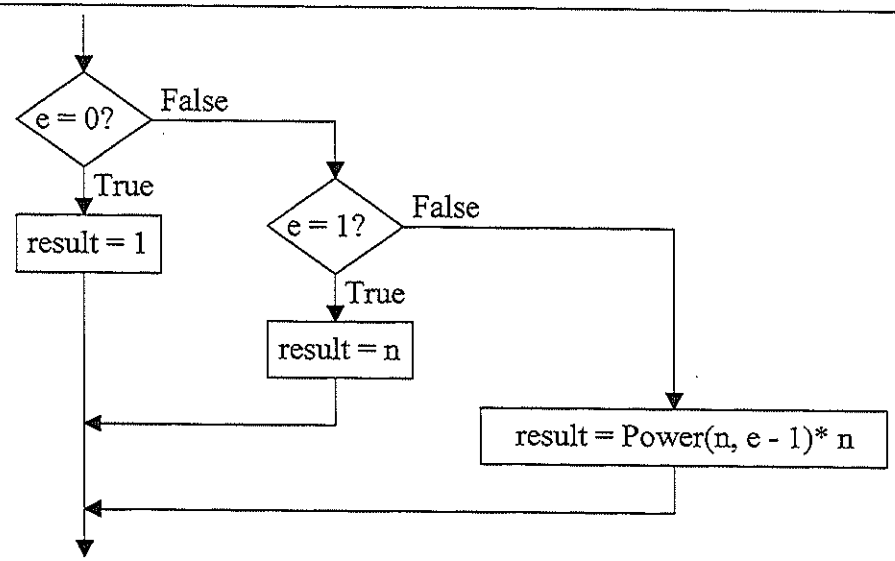
The parameter e is initially in $a1. Since e's value is not needed after the recursive call to Power, it does not need to be saved to an s-register.

3) Using the MIPS register conventions, what register should be used for the local variable "result"?

Since "result" has no value before the recursive call to Power, we don't need to use a s-register. The value of "result" is returned as the function value so using $v0 makes the most sense. The flow-chart of the Power function clearly shows that "result" does not have a value before the recursive call. Suppose e = 1, then the "result = n" assignment statement would be executed, but the recursive call would not be performed.

HLL Power code:

```
integer function Power( integer n, integer e)
integer result
   if e = 0 then
      result = 1
   else if e = 1 then
      result = n
   else
      result = Power(n, e - 1)* n
   end if
   return result
end Power
```



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The Power function in MIPS assembly language using the above decisions is given below. Since neither parameter nor the local variable "result" needs to be saved to an s-register, the only thing to save on the run-time stack is the return-address register, $ra.

```
Power:                              # $a0 contains n (we never change it during the
                                    #        recursive calls so we don't need to save it)
                                    # $a1 contains e
          sub  $sp, $sp, -4         # make room for the call-frame
          sw   $ra, 4($sp)          # save $ra on stack

if:
          bne  $a1, $zero, else_if
          li   $v0, 1               # $v0 contains result
          j    end_if
else_if:
          bne  $a1, 1, else
          move $v0, $a0
          j    end_if
else:                               # first parameter is still n in $a0
          addi $a1, $a1, -1         # put second parameter, e-1, in $a1
          jal  Power                # returns with value of Power(n, e-1) in $v0
          mul  $v0, $v0, $a0        # result = Power(n, e-1) * n
end_if:
          lw   $ra, 4($sp)          # restore return addr. to $ra
          addi $sp, $sp, 4          # pop call frame from stack
          jr   $ra
end_Power:
```

Notice at the end of Power, we must

- restore the saved register(s) (here only the $ra register),
- restore the stack pointer to its original position before the call, and
- jump-register (`jr $ra`) back to the return address in register $ra.

Complete code for the above example, including printing of the output, is included at the end of this Supplement. Before we look at this code, lets practice using the register conventions on the following Insertion sort example.

Insertion sort is a *simple sort*. All simple sorts consist of two nested loops where:

- the outer loop keeps track of the dividing line between the sorted and unsorted part with the sorted part growing by one in size each iteration of the outer loop.
- the inner loop's job is to do the work to extend the sorted part's size by one.

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After several iterations of the outer loop, an array might look like:

Sorted Part						Unsorted Part						
0	1	2	3	4	5	6	7	8				
10	20	35	40	45	60	25	50	90	• • •			

Insertion sort takes the "first unsorted element" (25 at index 6 in the above example) and "inserts" it into the sorted part of the list "at the correct spot." After 25 is inserted into the sorted part, the array would look like:

Sorted Part							Unsorted Part					
0	1	2	3	4	5	6	7	8				
10	20	25	35	40	45	60	50	90	• • •			

The below code, splits off the inner-loop into its own Insert subprogram. The array is passed by sending its starting/base address as a parameter.

```
main:

integer scores [100];
integer n;  // # of elements

InsertionSort(scores, n)

(*)
...

end main
```

```
InsertionSort(numbers - address to integer array,
              length - integer)

   integer firstUnsortedIndex
   for firstUnsortedIndex = 1 to (length-1) do
      Insert(numbers, numbers[firstUnsortedIndex],
             firstUnsortedIndex-1);
   end for

end InsertionSort
```

```
Insert(numbers - address to integer array,
       elementToInsert - integer,
       lastSortedIndex - integer) {
      integer testIndex;
      testIndex = lastSortedIndex;
      while (testIndex >=0) AND
            (numbers[testIndex] > elementToInsert ) do
         numbers[ testIndex+1 ] = numbers[ testIndex ];

         testIndex =  testIndex - 1;
      end while
      numbers[ testIndex + 1 ] = elementToInsert;
end Insert
```

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Try to apply the MIPS register conventions by answering the "standard" questions. On the next page, I'll supply my answers to these questions.

1) Using the MIPS register conventions, what registers would be used to pass each of the following parameters from main to InsertionSort:

scores	n

2) Using the MIPS register conventions, which of these parameters ("numbers", "length", or both of them) should be moved into s-registers?

3) Using the MIPS register conventions, what registers should be used for the local variable "firstUnsortedIndex"?

1) Using the MIPS register conventions, what registers would be used to pass each of the following parameter values to Insert:

numbers	numbers[firstUnsortedIndex]	firstUnsortedIndex-1

2) Using the MIPS register conventions, which of these parameters ("numbers", "elementToInsert", or "lastSortedIndex") should be moved into s-registers?

3) Using the MIPS register conventions, what registers should be used for the local variable "testIndex"?

Try to write the code for main, InsertionSort, and Insert in MIPS assembly language.

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My answers to these questions:

1) Using the MIPS register conventions, what registers would be used to pass each of the following parameters from main to InsertionSort:

scores	n
$a0	$a1

Because the first parameter always is passed in $a0, and the second parameter is always passed in $a1. The array scores is passed by sending the base address in $a0.

2) Using the MIPS register conventions, which of these parameters ("numbers", "length", or both of them) should be moved into s-registers?

Both numbers and (length-1) need to be stored in s-registers since their values are needed each iteration of the for-loop, i.e., their values are needed across the call to Insert. We'll use $s0 for "numbers" and $s1 for the value of (length-1).

3) Using the MIPS register conventions, what registers should be used for the local variable "firstUnsortedIndex"?

The local variable firstUnsortedIndex needs to be stored in an s-register since its value is needed each iteration of the for-loop, i.e., its value is needed across the call to Insert. We'll use $s2 for "firstUnsortedIndex".

1) Using the MIPS register conventions, what registers would be used to pass each of the following parameter values to Insert:

numbers	numbers[firstUnsortedIndex]	firstUnsortedIndex-1
$a0	$a1	$a2

2) Using the MIPS register conventions, which of these parameters ("numbers", "elementToInsert", or "lastSortedIndex") should be moved into s-registers?

Since Insert does not call any subprograms, we can leave the parameters in the a-registers.

3) Using the MIPS register conventions, what registers should be used for the local variable "testIndex"?

Since Insert does not call any subprograms, we can use a "temporary" register, say $t0 for testIndex. Thus, Insert does not need to store anything on the run-time stack making it very efficient. The beauty of a combined caller-saved with callee-saved register convention.

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main:	InsertionSort(numbers - address to integer array, length - integer)	Insert(numbers - address to integer array, elementToInsert - integer, lastSortedIndex - integer) {

integer scores [100];
integer n; // # of elements
 	
InsertionSort(scores, n)
 	
(*)
...
 	
end main
	integer firstUnsortedIndex
	for firstUnsortedIndex = 1 to (length-1) do
	Insert(numbers, numbers[firstUnsortedIndex],
	firstUnsortedIndex-1);
	end for
	
	end InsertionSort
		integer testIndex;
		testIndex = lastSortedIndex;
		while (testIndex >=0) AND
		(numbers[testIndex] > elementToInsert) do
		numbers[testIndex+1] = numbers[testIndex];
		
		testIndex = testIndex - 1;
		end while
		numbers[testIndex + 1] = elementToInsert;
		end Insert

The code for main, InsertionSort, and Insert in MIPS assembly language is given below.

```
            .data
scores:     .word 20, 30, 10, 40, 50, 60, 30, 25, 10, 50
n:          .word 10

            .text
            .globl main
main:
            la $a0, scores
            lw $a1, n
            jal insertionSort

            li $v0, 10
            syscall
end_main:

##########################################################################################

insertionSort:
            sub $sp, $sp, 16        # setup call-frame
            sw $ra, 4($sp)          # save the return addr to get back to main
            sw $s0, 8($sp)          # save main's s-registers if it is
            sw $s1, 12($sp)         # using any
            sw $s2, 16($sp)

            move $s0, $a0           # save address of numbers in $s0
            sub $s1, $a1, 1         # save (length-1) in $s1
for_init:
            li $s2, 1               # save firstUnsortedIndex in $s2
for_loop:   bgt $s2, $s1, end_for
            move $a0, $s0           # fill actual parameters
```

```
            mul $t0, $s2, 4
            add $t0, $s0, $t0
            lw $a1, 0($t0)
            sub $a2, $s2, 1
            jal insert              # call insert subpgm
            addi $s2, $s2, 1
            j for_loop
end_for:
            lw $ra, 4($sp)          # restore return addr. and
            lw $s0, 8($sp)          # restore main's s-registers
            lw $s1, 12($sp)
            lw $s2, 16($sp)
            addi $sp, $sp, 16       # remove call-frame
            jr $ra                  # 'jump register' back to main
end_insertionSort:

##########################################################################################

insert:  # insert does not call any subpgms so we'll use $a and $t registers
         # nothing to save on the run-time stack
            move $t0, $a2           # use $t0 for testIndex
while:      blt $t0, 0, end_while
            mul $t1, $t0, 4
            add $t1, $a0, $t1
            lw $t2, 0($t1)
            ble $t2, $a1, end_while
            sw $t2, 4($t1)
            sub $t0, $t0, 1
            j while
end_while:
            mul $t1, $t0, 4
            add $t1, $a0, $t1
            sw $a1, 4($t1)
            jr $ra                  # 'jump register' back to insertionSort
end_insert:
```

PCSpim I/O Support

Access to Input/Output (I/O) devices within a computer system is generally restricted to prevent user programs from directly accessing them. This prevents a user program from accidentally or maliciously doing things like:

- reading someone else's data file from a disk
- writing to someone else's data file on a disk
- etc.

However, user programs need to perform I/O (e.g., read and write information to files, write to the console, read from the keyboard, etc.) if they are to be useful. Therefore, most computer systems require a user program to request I/O by asking the operating system to perform it on their behalf.

PCSpim uses the "syscall" (short for "system call") instruction to submit requests for I/O to the operating system. The register $v0 is used to indicate the type of I/O being requested with $a0, $a1, $f12 registers being used to pass additional parameters to the operating system. Integer results and addresses are returned in the $v0 register, and floating point results being returned in the $f0 register. The following table provides details of the PCSpim syscall usage.

Service Requested	**System call code passed in $v0**	**Registers used to pass additional arguments**	**Registers used to return results**
print_int	1	$a0 contains the integer value to print	
print_float	2	$f12 contains the 32-bit float to print	
print_double	3	$f12 (and $f13) contains the 64-bit double to print	
print_string	4	$a0 contains the address of the .asciiz string to print	
read_int	5		$v0 returns the integer value read
read_float	6		$f0 returns the 32-bit floating-point value read
read_double	7		$f0 and $f1 returns the 64-bit floating-point value read
read_string	8	$a0 contains the address of the buffer to store the string $a1 contains the maximum length of the buffer	
sbrk - request a memory block	9	$a0 contains the number of bytes in the requested block	$v0 returns the starting address of the block of memory
exit	10		

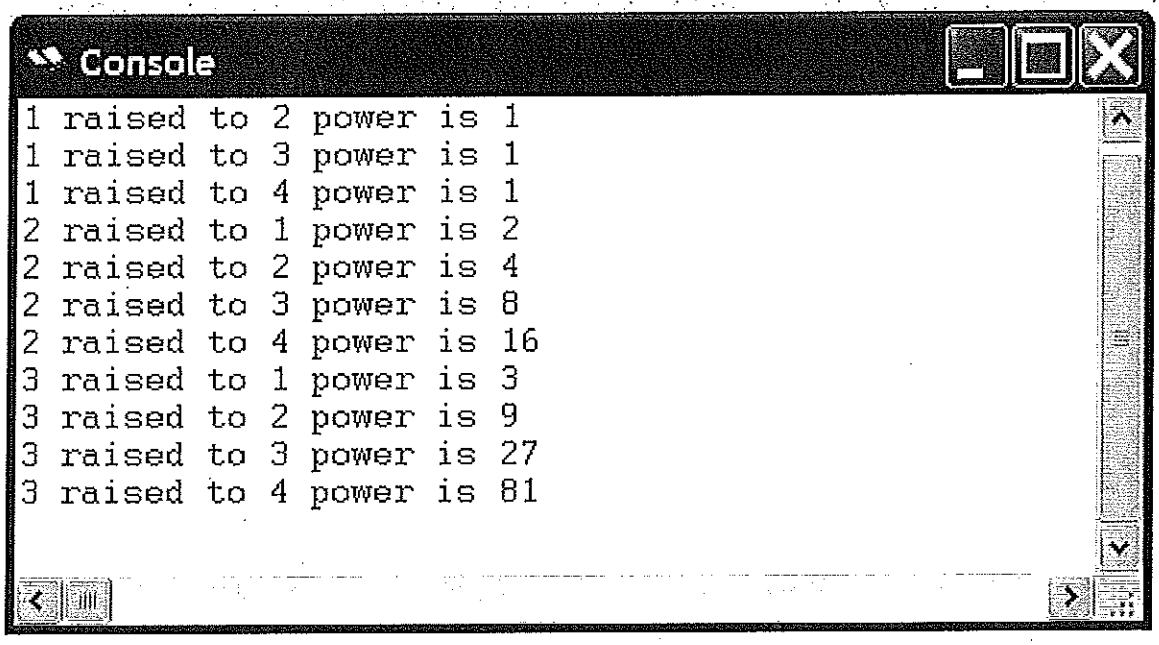
Below is the complete CalculatePowers program example using MIPS register conventions and PCSpim syscalls. Notice that strings use the ".asciiz" assembler directive to generate an array of ASCII characters that are "null" terminated (ASCII value 0).

```
# CalculatePowers subprogram example using MIPS register conventions and PCSpim syscalls

            .data
maxNum:     .word 3
maxPower:   .word 4
str1:       .asciiz " raised to "
str2:       .asciiz " power is "
str3:       .asciiz "\n"                # newline character

            .text
            .globl main
main:
            lw      $a0, maxNum         # $a0 contains maxNum
            lw      $a1, maxPower       # $a1 contains maxPower
            jal     CalculatePowers

            li      $v0, 10             # system code for exit
            syscall


##########################################################################
CalculatePowers:                        # $a0 contains value of numLimit
                                        # $a1 contains value of powerLimit

            sub     $sp, $sp, -20       # save room for the return address
            sw      $ra, 4($sp)         # push return address onto stack
            sw      $s0, 8($sp)
            sw      $s1, 12($sp)
            sw      $s2, 16($sp)
            sw      $s3, 20($sp)

            move    $s0, $a0            # save numLimit in $s0
            move    $s1, $a1            # save powerLimit in $s1

for_1:
            li      $s2, 1              # $s2 contains num
for_compare_1:
            bgt     $s2, $s0, end_for_1
for_body_1:

for_2:
            li      $s3, 1              # $s3 contains pow
for_compare_2:
            bgt     $s3, $s1, end_for_2
for_body_2:
            move    $a0, $s2            # print num
            li      $v0, 1
            syscall
```

```
        la      $a0, str1           # print " raised to "
        li      $v0, 4
        syscall

        move    $a0, $s3            # print pow
        li      $v0, 1
        syscall

        la      $a0, str2           # print " power is "
        li      $v0, 4
        syscall

        move    $a0, $s2            # call Power(num, pow)
        move    $a1, $s3
        jal     Power

        move    $a0, $v0            # print result

        li      $v0, 1
        syscall

        la      $a0, str3           # print new-line character
        li      $v0, 4
        syscall

        addi    $s3, $s3, 1
        j       for_compare_2
end_for_2:

        addi    $s2, $s2, 1
        j       for_compare_1
end_for_1:

        lw      $ra, 4($sp)         # restore return addr. to $ra
        lw      $s0, 8($sp)         # restore saved $s registers
        lw      $s1, 12($sp)
        lw      $s2, 16($sp)
        lw      $s3, 20($sp)

        addi    $sp, $sp, 20        # pop call frame from stack
        jr      $ra
end_CalculatePowers:
```

```
##############################################################################
Power:                                  # $a0 contains n (we never change it during the
                                        #      recursive calls so we don't need to save it)
                                        # $a1 contains e
            sub     $sp, $sp, -4
            sw      $ra, 4($sp)         # save $ra on stack

if:
            bne     $a1, $zero, else_if
            li      $v0, 1              # $v0 contains result
            j       end_if
else_if:
            bne     $a1, 1, else
            move    $v0, $a0
            j       end_if
else:                                   # first parameter is still n in $a0
            addi    $a1, $a1, -1        # put second parameter, e-1, in $a1
            jal     Power               # returns with value of Power(n, e-1) in $v0
            mul     $v0, $v0, $a0       # result = Power(n, e-1) * n
end_if:
            lw      $ra, 4($sp)         # restore return addr. to $ra
            addi    $sp, $sp, 4         # pop call frame from stack
            jr      $ra
end_Power:
```

Snap-shot of the Console window after the program executes:



```
main:

integer scores [100];
integer n;  // # of elements

InsertionSort(scores, n)

(*)
...

end main
```

```
InsertionSort(numbers - address to integer array,
              length - integer)

   integer firstUnsortedIndex
   for firstUnsortedIndex = 1 to (length-1) do
      Insert(numbers, numbers[firstUnsortedIndex],
             firstUnsortedIndex-1);
   end for

end InsertionSort
```

```
Insert(numbers - address to integer array,
       elementToInsert - integer,
       lastSortedIndex - integer) {
      integer testIndex;
      testIndex = lastSortedIndex;
      while (testIndex >=0) AND
            (numbers[testIndex] > elementToInsert ) do
         numbers[ testIndex+1 ] = numbers[ testIndex ];

         testIndex =  testIndex - 1;
      end while
      numbers[ testIndex + 1 ] = elementToInsert;
end Insert
```

a) Using the MIPS register conventions, what registers would be used to pass each of the following parameters to InsertionSort:

scores	n

b) Using the MIPS register conventions, which of these parameters ("numbers", "length", or both of them) should be moved into s-registers?

c) Using the MIPS register conventions, what registers should be used for the local variable "firstUnsortedIndex"?

d) Using the MIPS register conventions, what registers would be used to pass each of the following parameter values to Insert:

numbers	numbers[firstUnsortedIndex]	firstUnsortedIndex-1

e) Using the MIPS register conventions, which of these parameters ("numbers", "elementToInsert", or "lastSortedIndex") should be moved into s-registers?

f) Using the MIPS register conventions, what registers should be used for the local variable "testIndex"?

g) Write the code for main, InsertionSort, and Insert in MIPS assembly language.

Lecture 20 Practice MIPS calling Conventions

n →	0	1	2	3	4	5	6
fibonacci	0,	1,	1,	2,	3,	5,	8, 13, 21, ..

Main:

result = fib(5) $a0 jal fib

$ra $a0 ← addr. of next instr. in main in $ra

def fib(n) = { 0 if n==0 ; 1 if n==1 } "base cases"

fib(n-1) + fib(n-2) if n ≥ 2

if n==0 then

return 0 → $v0 // $v0,0 jr $ra

else if n==1 then

return 1 // $v0,1 jr $ra

else

return fib(n-1) + fib(n-2)

$a0 → $s0 (n)

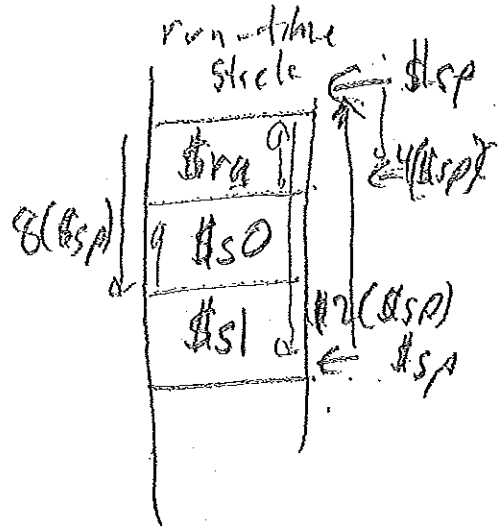
$a0 → $v0 → $s1

$a0 → $v0

```
        .data
result:  .word 0

        .text
        .globl main

main:
        li $a0, 5    # n is 5
        jal fib
        sw $v0, result

        li $v0, 10
        syscall

fib:    # $a0 is n
if:     bne $a0, 0, else_if
        li $v0, 0
        jr $ra
else_if:
        bne $a0, 1, else
        li $v0, 1
        jr $ra
else:
```

else:

```
addi $sp, $sp, -12
sw $ra, 4($sp)
sw $s0, 8($sp)
sw $s1, 12($sp)
move $s0, $a0
addi $a0, $s0, -1
jal fib
move $s1, $v0
addi $a0, $s0, -2
jal fib
add $v0, $s1, $v0

lw $ra, 4($sp)
lw $s0, 8($sp)
lw $s1, 12($sp)
addi $sp, $sp, 12
jr $ra
```



```
# Recursive fibonacci example

        .data
result:         .word 0

        .text
        .globl main
main:                                   # Fibonacci seq.:  0, 1, 1, 2, 3, 5, 8, 13, 21, ...

        li      $a0, 7                  # fib(7) is 13 in decimal or D in hex.
        jal  fib
        sw      $v0, result

        li $v0, 10
        syscall


fib:            # $a0 is n

if:
        bne     $a0, 0, else_if
        li      $v0, 0
        jr      $ra
else_if:
        bne     $a0, 1, else
        li      $v0, 1
        jr      $ra
else:
        addi    $sp, $sp, -12
        sw      $ra, 4($sp)     # save return addr.
        sw      $s0, 8($sp)     # save n in $s0
        sw      $s1, 12($sp)    # save result of fib(n-1) in $s1
        move    $s0, $a0

        addi    $a0, $s0, -1
        jal     fib
        move    $s1, $v0

        addi    $a0, $s0, -2
        jal     fib
        add     $v0, $s1, $v0   # calculate fib(n-1) + fib(n-2)

        lw      $ra, 4($sp)     # restore return addr.
        lw      $s0, 8($sp)     # restore $s0
        lw      $s1, 12($sp)    # restore $s1
        addi    $sp, $sp, 12    # "pop" call frame
        jr      $ra
```

1. If $5 contains 0xAF000A5D and $6 contained 0x6, what hexadecimal value would be in $4 after each of the following?

a) sll $4, $5, 3

b) sllv $4, $5, $6

c) sra $4, $5, 3

d) ror $4, $5, $6

2. If $5 contains 0xA5D and $6 contained 0x63C, what hexadecimal value would be in $4 after each of the following?

a) and $4, $5, $6

b) ori $4, $5, 0xBF

c) xor $4, $5, $6

d) nor $4, $5, $6

e) not $4, $5

3. Sometimes you want to manipulate individual bits in a "string of bits". For example, you can represent a set of letters using a bit-string. Each bit in the bit-string is associated with a letter: bit position 0 with 'A', bit position 1 with 'B', ..., bit position 25 with 'Z'. Bit-string bits are set to '1' to indicate that their corresponding letters are in the set. For example, the set { 'A', 'B', 'D', 'Y' } would be represented as:

	unused	'Z'	'Y'	'X'	. . .	'E'	'D'	'C'	'B'	'A'	
{ 'A', 'B', 'D', 'Y' } is	0 0 0 0 0 0	0	1	0		0	1	0	1	1	in $5
bit position:		25	24	23		4	3	2	1	0	

To determine if a specific ASCII character, say 'C' (67_{10}) is in the set, you would need to build a "mask" containing a single "1" in bit position 2.

a) What instruction(s) could we use to build the mask needed for 'C' in $3?

b) If a bit-string set of letters is in register $5, then what instruction(s) can be used to check if the character 'C' (using the mask in $3) is in the set contained in $5?

c) If a bit-string set of letters is in register $5 and another bit-string set of letters is in $6, then what instruction(s) can be used to calculate in $7 the union of sets in $5 and $6? (i.e., all elements in either set)

d) If a bit-string set of letters is in register $5 and another bit-string set of letters is in $6, then what instruction(s) can be used to calculate in $7 the intersection of sets in $5 and $6? (i.e., all elements in both sets)

e) If a bit-string set of letters is in register $5 and another bit-string set of letters is in $6, then what instruction(s) can be used to calculate in $7 the set difference: set in $5 - set in $6? (i.e., all elements in the left-hand set that are not in the right-hand set)

4. Write MIPS code for the set-of-letters abstract-data type (ADT) using a bit string. The bit string representation for the set of letters can use a 32-bit word with the least-significant bit associated with the letter 'A', etc.

	unused	'Z'	'Y'	'X'	. . .	'E'	'D'	'C'	'B'	'A'
{ 'A', 'B', 'D', 'Y' } is	000000	0	1	0		0	1	0	1	1
bit position:		25	24	23		4	3	2	1	0

The set of letters ADT should have the following operations as subprograms, so use appropriate register conventions:

Subprogram Name	**Parameters**	**Description**
bitString	▪ pass in a pointer to the an .ASCIIZ string ▪ returns a word containing the set of letters as a bitString	Returns a bit string corresponding to the set of letters in the .ASCIIZ string. Non-letter characters are ignored, and both upper and lower-case letters should be represented as letters in the set.
union	▪ passed two set bitStrings ▪ returns the set union of the two sets	The resulting set should contain the elements that are in one or both of the input sets.
intersection	▪ passed two set bitStrings ▪ returns the set intersection of the two sets	The resulting set should contain the elements that are in both of the input sets.
difference	▪ passed two set bitStrings ▪ returns the set difference of the first set - second set	The resulting set should contain the elements that are in the first set, but not also in the second set.
contains	▪ passed an .ASCII character and a set bitString ▪ returns a Boolean (0 for false or 1 for true)	Returns 1 (true) if the .ASCII character is in the bitString set; otherwise return 0 (false).
print	▪ passed an set bitString	Prints the bitString to the console using print_string system calls. The set should be printed in the conventional format, i.e., "{ E, G, T, Y }"

Lecture ~~24~~ 23 PC Spim I/O + MIPS Logical + Shift Instructions

A_{16} B C D E F_{16}
10_{10} 11 12 13 14 15_{10}

8 4 2 1 8 4 2 1

li $4, 0xB9 #$4 000 . . . 0 1011 1001
li $5, 0x35 #$5 0 0011 0101

and $6, $4, $5 #$6 0 0011 0001

0x3 1_{16}

or $7 $4 $5 00 . . . 0 1011 1101

logical - fill with 0's

left

shift

0xB D_{16}

8 4 2 1

sll $8, $4, 2 00 . . . 0010 1110 0100

2 E 4_{16}

rol $8, $4, 2

8 4 2 1

ror $9, $4, 2 0100 00 . 0010 1110

0x 4000002E$_{16}$

PCSpim I/O Support

Access to Input/Output (I/O) devices within a computer system is generally restricted to prevent user programs from directly accessing them. This prevents a user program from accidentally or maliciously doing things like:

- reading someone else's data file from a disk
- writing to someone else's data file on a disk
- etc.

However, user programs need to perform I/O (e.g., read and write information to files, write to the console, read from the keyboard, etc.) if they are to be useful. Therefore, most computer systems require a user program to request I/O by asking the operating system to perform it on their behalf.

PCSpim uses the "syscall" (short for "system call") instruction to submit requests for I/O to the operating system. The register $v0 is used to indicate the type of I/O being requested with $a0, $a1, $f12 registers being used to pass additional parameters to the operating system. Integer results and addresses are returned in the $v0 register, and floating point results being returned in the $f0 register. The following table provides details of the PCSpim syscall usage.

Service Requested	**System call code passed in $v0**	**Registers used to pass additional arguments**	**Registers used to return results**
print_int	1	$a0 contains the integer value to print	
print_float	2	$f12 contains the 32-bit float to print	
print_double	3	$f12 (and $f13) contains the 64-bit double to print	
print_string	4	$a0 contains the address of the .asciiz string to print	
read_int	5		$v0 returns the integer value read
read_float	6		$f0 returns the 32-bit floating-point value read
read_double	7		$f0 and $f1 returns the 64-bit floating-point value read
read_string	8	$a0 contains the address of the buffer to store the string $a1 contains the maximum length of the buffer	
sbrk - request a memory block	9	$a0 contains the number of bytes in the requested block	$v0 returns the starting address of the block of memory
exit	10		

main:	**CalculatePowers(In:** integer numLimit, integer powerLimit)	integer **Power(In:** integer n, integer e)
maxNum = 3		integer result
maxPower = 4	integer num, pow	if e = 0 then
		result = 1
CalculatePowers(maxNum, maxPower)	for num := 1 to numLimit do	else if e = 1 then
(*)	for pow := 1 to powerLimit do	result = n
. . .		else
end main	print(num " raised to " pow " power is "	result = Power(n, e - 1)* n
	Power(num, pow)	end if
	end for pow	return result
	end for num	**end Power**
	end CalculatePowers	

a) Using the MIPS register conventions, what registers would be used to pass each of the following parameters to CalculatePowers:

maxNum	maxPower

b) Using the MIPS register conventions, which of these parameters ("numLimit", "powerLimit", or both of them) should be moved into s-registers?
(NOTE: Use an s-register for any value you still need after you come back from a subprogram/function/procedure call, e.g., call to "Power")

c) Using the MIPS register conventions, what registers should be used for each of the local variables:

num	pow

d) Using the MIPS register conventions, what registers would be used to pass each of the following parameters to Power:

num	pow

e) Using the MIPS register conventions, which of these parameters ("n", "e", or both of them) should be moved into s-registers?

f) Using the MIPS register conventions, what register should be used for the local variable:

result

g) Write the code for main, CalculatePowers, and Power in MIPS assembly language.

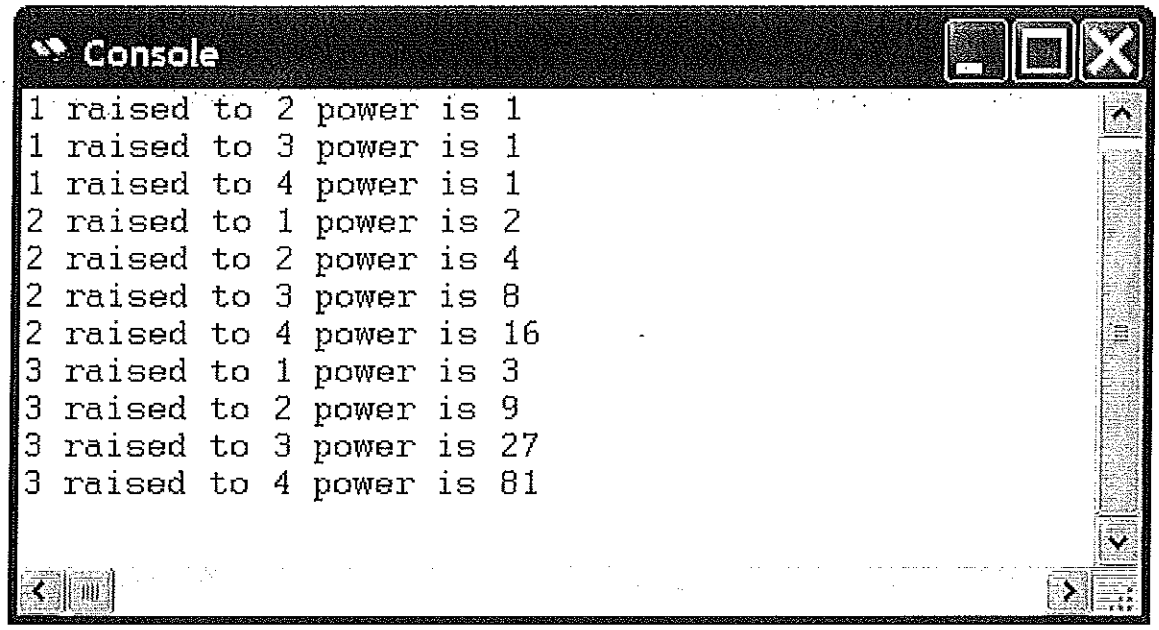
CalculatePowers subprogram example using MIPS register conventions and PCSpim syscalls

```
                .data
maxNum:         .word 3
maxPower:       .word 4
str1:           .asciiz " raised to "
str2:           .asciiz " power is "
str3:           .asciiz "\n"                    # newline character

                .text
                .globl main
main:
                lw      $a0, maxNum             # $a0 contains maxNum
                lw      $a1, maxPower           # $a1 contains maxPower
                jal     CalculatePower

                li      $v0, 10                 # system code for exit
                syscall


##############################################################################
CalculatePower:                                 # $a0 contains value of numLimit
                                                # $a1 contains value of powerLimit

                addi    $sp, $sp, -20           # save room for the return address
                sw      $ra, 4($sp)             # push return address onto stack
                sw      $s0, 8($sp)
                sw      $s1, 12($sp)
                sw      $s2, 16($sp)
                sw      $s3, 20($sp)

                move    $s0, $a0                # save numLimit in $s0
                move    $s1, $a1                # save powerLimit in $s1

for_1:
                li      $s2, 1                  # $s2 contains num
for_compare_1:
                bgt     $s2, $s0, end_for_1
for_body_1:

for_2:
                li      $s3, 1                  # $s3 contains pow
for_compare_2:
                bgt     $s3, $s1, end_for_2
for_body_2:
                move    $a0, $s2                # print num
                li      $v0, 1
                syscall
```

```
            la      $a0, str1           # print " raised to "
            li      $v0, 4
            syscall

            move    $a0, $s3            # print pow
            li      $v0, 1
            syscall

            la      $a0, str2           # print " power is "
            li      $v0, 4
            syscall

            move    $a0, $s2            # call Power(num, pow)
            move    $a1, $s3
            jal     Power

            move    $a0, $v0            # print result

            li      $v0, 1
            syscall

            la      $a0, str3           # print new-line character
            li      $v0, 4
            syscall

            addi    $s3, $s3, 1
            j       for_compare_2
end_for_2:

            addi    $s2, $s2, 1
            j       for_compare_1
end_for_1:

            lw      $ra, 4($sp)         # restore return addr. to $ra
            lw      $s0, 8($sp)         # restore saved $s registers
            lw      $s1, 12($sp)
            lw      $s2, 16($sp)
            lw      $s3, 20($sp)

            addi    $sp, $sp, 20        # pop call frame from stack
            jr      $ra
end_CalculatePowers:
```

```
##############################################################################
Power:                                  # $a0 contains n (we never change it during the
                                        #       recursive calls so we don't need to save it)
                                        # $a1 contains e
            addi    $sp, $sp, -4
            sw      $ra, 4($sp)         # save $ra on stack

if:
            bne     $a1, $zero, else_if
            li      $v0, 1              # $v0 contains result
            j       end_if
else_if:
            bne     $a1, 1, else
            move    $v0, $a0
            j       end_if
else:                                   # first parameter is still n in $a0
            addi    $a1, $a1, -1        # put second parameter, e-1, in $a1
            jal     Power               # returns with value of Power(n, e-1) in $v0
            mul     $v0, $v0, $a0       # result = Power(n, e-1) * n
end_if:
            lw      $ra, 4($sp)         # restore return addr. to $ra
            addi    $sp, $sp, 4         # pop call frame from stack
            jr      $ra
end_Power:
```

Snap-shot of the Console window after the program executes:



Lecture 23

MIPS Logical Instructions	
and $4, $5, $6	$4←$5 (bit-wise AND) $6
andi $4, $5, 0x5f	$4←$5 (bit-wise AND) $5f_{16}$
or $4, $5, $6	$4←$5 (bit-wise OR) $6
ori $4, $5, 0x5f	$4←$5 (bit-wise OR) $5f_{16}$
xor $4, $5, $6	$4←$5 (bit-wise Exclusive-OR) $6
xori $4, $5, 0x5f	$4←$5 (bit-wise Exclusive-OR) $5f_{16}$
nor $4, $5, $6	$4←$5 (bit-wise NOR) $6
not $4, $5	$4←NOT $5 #inverts all the bits

MIPS Shift and Rotate Instructions	
sll $4, $5, 3	$4←shift left $5 by 3 positions. Shift in zeros (only least significant 5-bits of immediate value are used to shift)
sllv $4, $5, $6	Similar to sll, but least significant 5-bits of $6 determine the amount to shift.
srl $4, $5, 3	$4← shift right $5 by 3 positions. Shift in zeros
srlv $4, $5, $6	Similar to srl, but least significant 5-bits of $6 determine the amount to shift.
sra $4, $5, 3	$4←shift right $5 by 3 positions. Sign-extend (shift in sign bit)
srav $4, $5, $6	Similar to sra, but least significant 5-bits of $6 determine the amount to shift.
rol $4, $5, 3	$4←rotate left $5 by 3 positions
rol $4, $5, $6	Similar to above, but least significant 5-bits of $6 determine the amount to rotate.
ror $4, $5, 3	$4←rotate right $5 by 3 positions
ror $4, $5, $6	Similar to above, but least significant 5-bits of $6 determine the amount to rotate.

Common usages for shift/rotate and logical instructions include:

1. To calculate the address of element array[i], we calculate (base address of array) + i * 4 for an array of words. Since multiplication is a slow operation, we can shift the value left two bit positions. For example:

```
la $3, array            # load base address of array into $3
sll $10, $2, 2          # logical shift i's value in $2 by 2 to multiply its value by 4
add  $10, $3, $10       # finish calculation of the address of element array[i]
lw  $4, 0($10)          # load the value of array[i] into $4
```

2. Sometimes you want to manipulate individual bits in a "string of bits". For example, you can represent a set of letters using a bit-string. Each bit in the bit-string is associated with a letter: bit position 0 with 'A', bit position 1 with 'B', ..., bit position 25 with 'Z'. Bit-string bits are set to '1' to indicate that their corresponding letters are in the set. For example, the set { 'A', 'B', 'D', 'Y' } would be represented as:

	unused	'Z'	'Y'	'X'	. . .	'E'	'D'	'C'	'B'	'A'
{ 'A', 'B', 'D', 'Y' } is	0 0 0 0 0 0	0	1	0		0	1	0	1	1
bit position:		25	24	23		4	3	2	1	0

'C' = 67
67 - 65
2

To determine if a specific ASCII character, say 'C' (67_{10}) is in the set, you would need to build a "mask" containing a single "1" in bit position 2. The sequence of instructions "li $3, 1" followed by "sll $3, $3, 2" would build the needed mask in $3. If the bit-string set of letters is in register $5, then we can check for the character 'C' using the mask in $3 and the instruction "and $6, $5, $3". If the bit-string set in $5 contained a 'C', then $6 will be non-zero; otherwise $6 will be zero.

and $3 | 0 | 0 1 0 0 | mask

2 1 0

0 | 0 0 0 ← zero, 'C' ∉ set
← mask

0