CPS104 Computer Organization

Lecture 11

MIPS Assembly:
Functions, Subroutines, Methods

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Administratrivia

- **Homework 2 is Due: Today (11:59 PM)**
- **Homework 3 is posted. Due: October 7 (11:59 pm)**
- **Reading: Chapter 2.**
- **Reading: Appendix A**
  - **Available on:. . .** `cps104/Handouts/spim_appendix.pdf`

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Review: Assembly Examples: code fragments

- `If ( ... ) { ... };`

Example

The C++ code

```
a=b=c=0;
if (i < 5) {
a = 1;
b = 2;
c = 3;
}
d = 5;
```

The Assembler code

```
        move $a0,0   # a=0
        move $a1,0   # b=0
        move $a2,0   # c=0
        bge  $s0,5,flbl # if i >=5
                        # goto flbl
        move $a0,1   # a=1
        move $a1,2   # b=2
        move $a2,3   # c=3

flbl:   move $a3,5   # d=5
```


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Review: Assembly Examples: code fragments

- `If ( ... ){ ... } else { ...} ;` **Example**

The C++ code

```
a=b=c=0;
if (i < 5) {
a = 1;
b = 2;
c = 3;
}
else{
a = 4;
b = 5;
c = 6;
}
d = 5;
```

The Assembler code

```
       move $a0,0   # a=0
       move $a1,0   # b=0
       move $a2,0   # c=0
       bge  $s0,5,lbl1 # if i >=5
                       # goto lbl1
       move $a0,1   # a=1
       move $a1,2   # b=2
       move $a2,3   # c=3
       j    lbl2    # goto lbl2
lbl1:  move $a0,4   # a=4
       move $a1,5   # b=5
       move $a2,6   # c=6
lbl2:  move $a3,5   # d=5
```


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Review: Assembly Examples: code fragments

- `for(i=0; i<100; i++)sum=sum+A[i];` **Example-1:**

The C++ code

```
int a[100];
. . .
sum = 0;
for(i=0;i<100;i++)
  sum=sum+a[i];
```

The Assembler code

```
      la   $t0,a          # $t0 = &a[0]
      move $a0,0          # sum=0
      move $a1,0          # i=0
      move $a3,100        # $a3 = 100
loop: mult $a2,$a1,4      # $a2=i*4
      addu $t1,$t0,$a2    # $t1=&a[i]
      lw   $t2,0($t1)     # $t2=a[i]
      add  $a0,$a0,$t2    # sum=sum+a[i]
      addi $a1,$a1,1      # i++
      blt  $a1,$a3,loop   # if i<100
                          # goto loop
```


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Review: Assembly Examples: code fragments

- `for(i=0; i<100; i++)sum=sum+A[i];` Example-2:

The C++ code

```
int a[100];
int* p=&a[0];
sum = 0;
for(i=0;i<100;i++)
   {sum=sum+*p;
    p++;
   }
```

The Assembler code

```
      la    $t0,a           # p = &a[0]
      move  $a0,0           # sum=0
      move  $a1,0           # i=0
      move  $a3,100         # $a3 = 100
loop: lw    $t2,0($t0)      # $t2=a[i]
      add   $a0,$a0,$t2     # sum=sum+a[i]
      addi  $a1,$ai,1       # i++
      addui  $t0,4          # p++
      blt   $a1,$a3,loop    # if i<100
                            # goto loop
```


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Functions Subroutines & Methods

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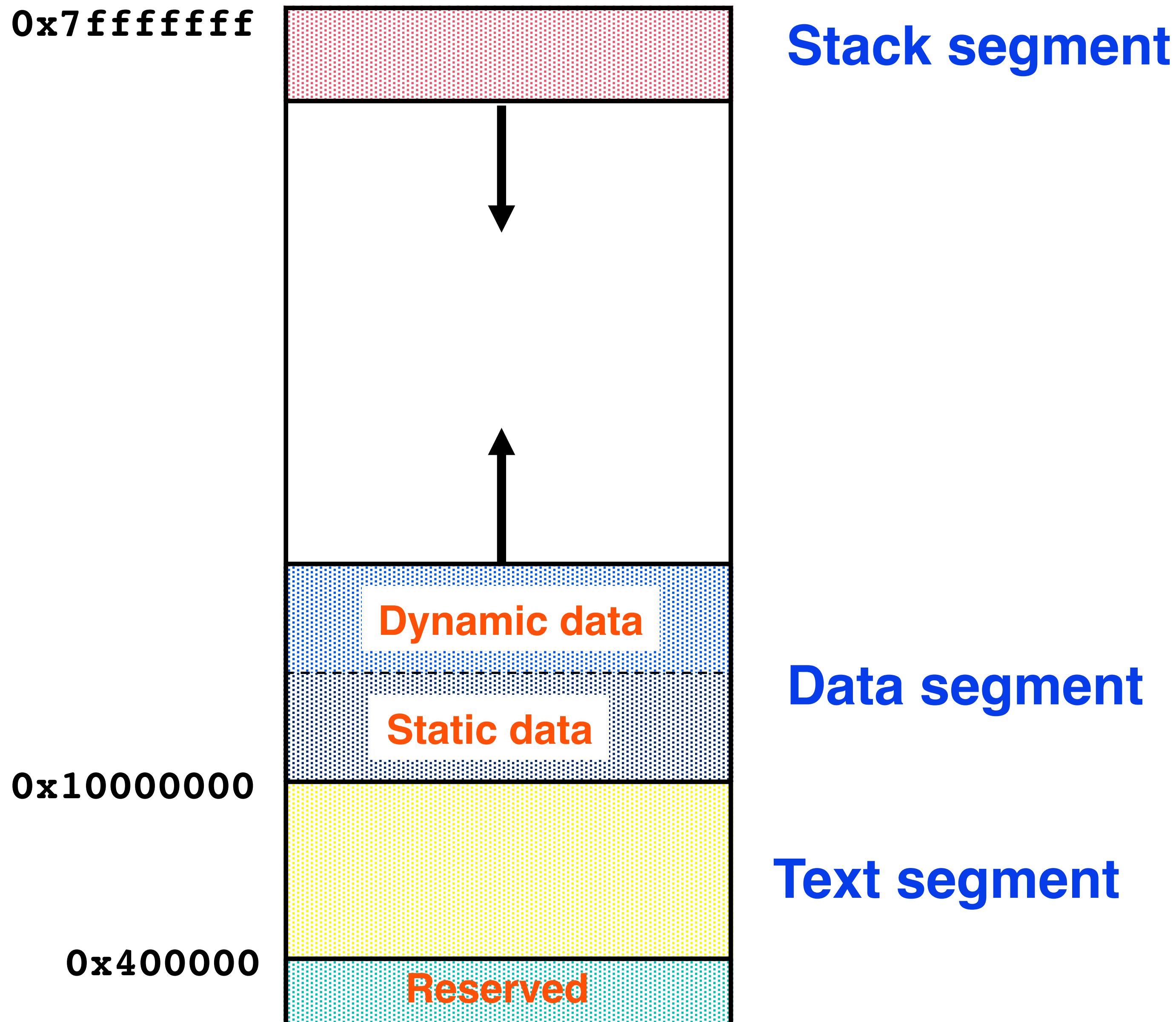
Review: Memory Layout



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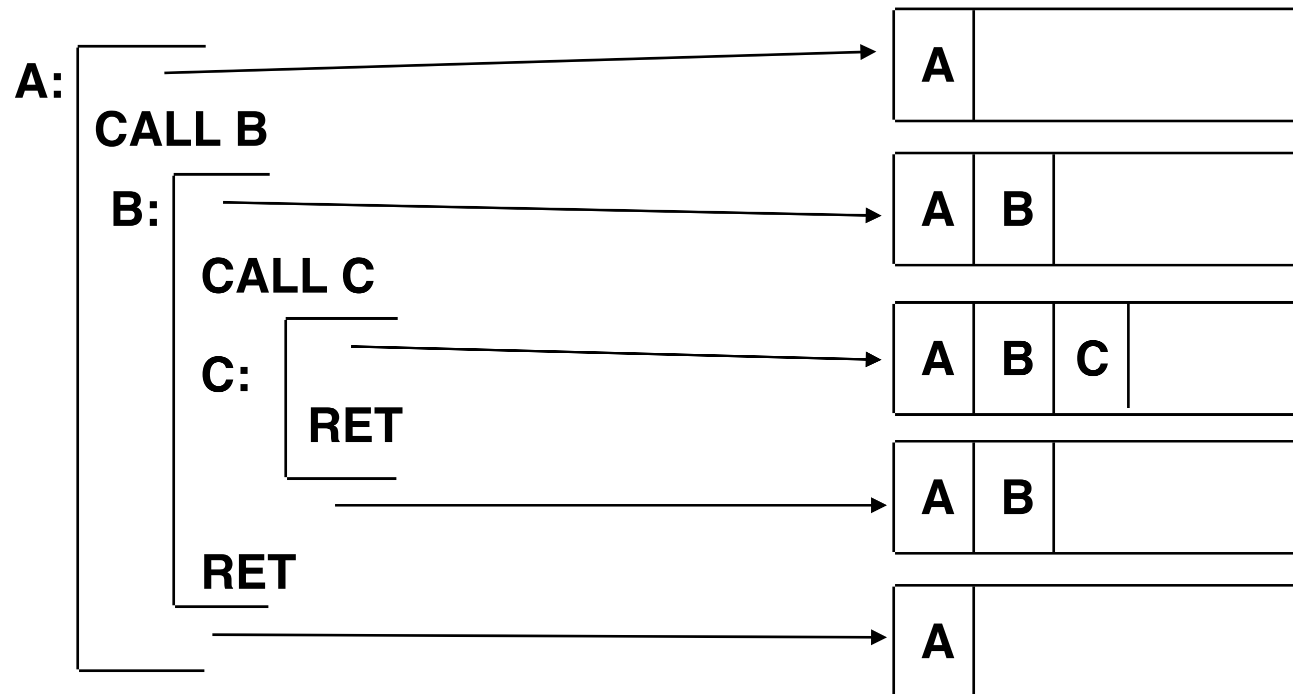
Calls: Why Are Stacks So Great?

Stacking of Subroutine Calls & Returns and Environments:



Some machines provide a memory stack as part of the architecture (e.g., VAX)

Sometimes stacks are implemented via software convention (e.g., MIPS)

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Procedure Call (Stack) Frame

- **Procedures use a frame in the stack to:**
  - **Hold values passed to procedures as arguments.**
  - **Save registers that a procedure may modify, but which the procedure's caller does not want changed. (ex: `$s0-$s7`)**
  - **Save the procedure return address (`$ra`),**
  - **provide space for local variables (variables with local scope)**
  - **Evaluate complex expressions.**

- **There is a special registers the `$sp` that are used as special data reference**
  - **The stack pointer $sp points to the top of the stack.**

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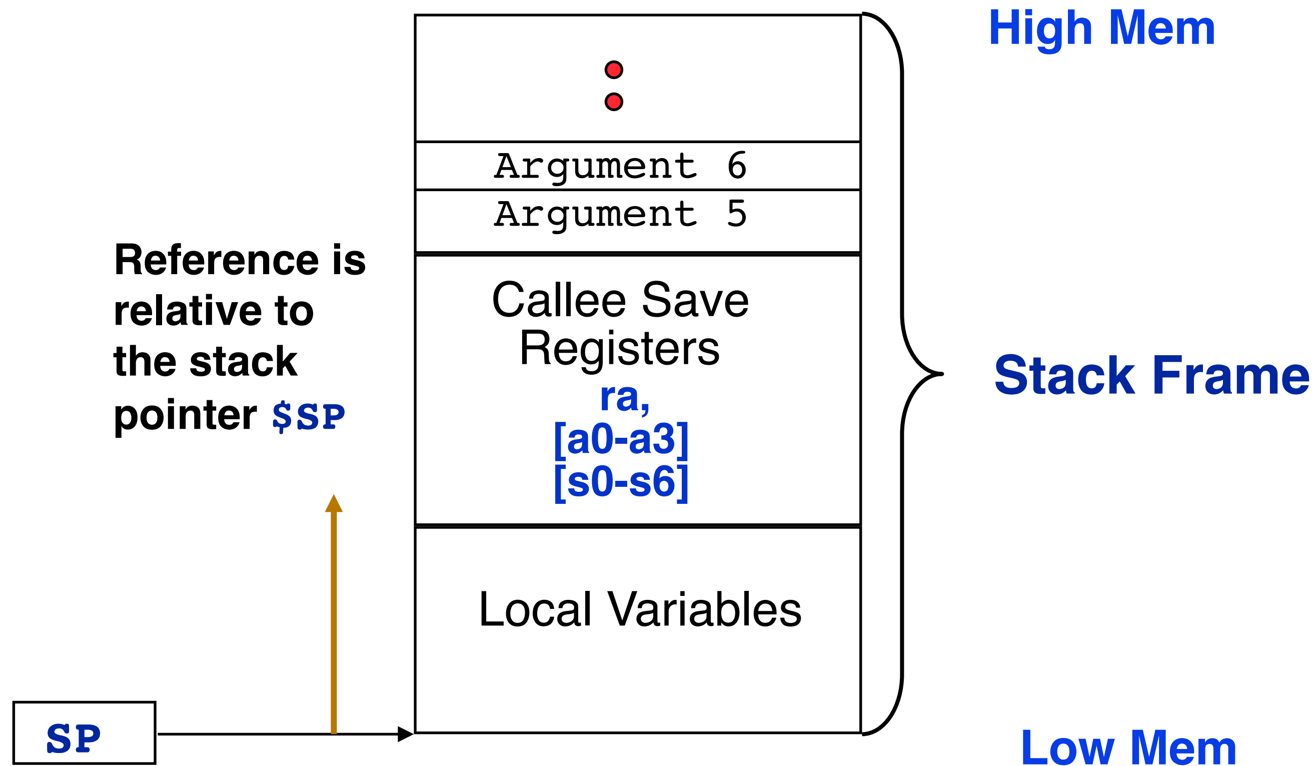
Call-Return Linkage: Stack Frames



- **Many variations on stacks possible (up/down, last pushed / next)**
- **Block structured languages contain link to lexically enclosing frame**
- **Compilers normally keep scalar variables in registers, not memory!**

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MIPS/GCC Procedure Calling Conventions

Calling Procedure:

- **Step-1: Save caller-saved registers**
  - **Save registers `$t0-$t9` if they contain live values at the call site.**
- **Step-2: Pass the arguments:**
  - **The first four arguments are passed in registers `$a0-$a3`**
  - **Remaining arguments are pushed into the stack**
    - **(in reversed order `arg5` is at the top of the stack).**
- **Step-3: Execute a `jal` instruction.**

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MIPS/GCC Procedure Calling Conventions (cont.)

Called Routine

- Step-1: Establish stack frame.
  - Subtract the frame size from the stack pointer.

```
    subiu $sp,  $sp,  <frame-size>
```

  - Typically, minimum frame size is 32 bytes (8 words).

- Step-2: Save callee saved registers in the frame.
  - Register `$ra` is saved if routine makes a call.
  - Registers `$a0-$a3` are saved if they are changed.
  - Registers `$s0-$s7` are saved if they are used.

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MIPS/GCC Procedure Calling Conventions (cont.)

On return from a call

- **Step-1: Put returned values in registers `$v0, [$v1].`**
  (if values are returned)
- **Step-2: Restore callee-saved registers.**
  - **Restore `$sp` and other saved registers.**

```
[$ra,$a0-$a3,$s0-$s7]
```

- **Step-3: Pop the stack**
  - **Add the frame size to `$sp`.**

```
addiu $sp, $sp, <frame-size>
```

- **Step-4: Return**
  - **Jump to the address in `$ra`.**

```
jr      $ra
```


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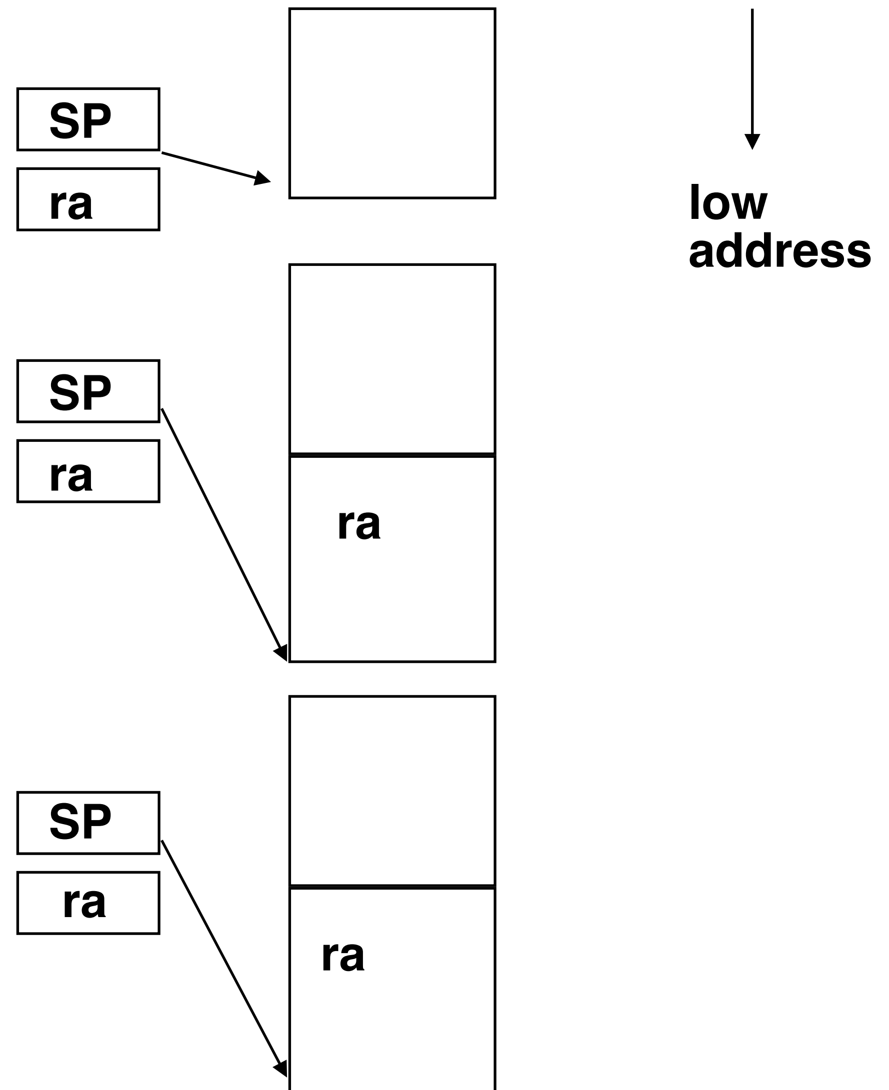
MIPS / GCC Calling Conventions

```
fact:
  subiu $sp, $sp, 32
  sw    $ra, 20($sp)
  addiu $fp,$sp,28
. . .
  sw    $a0, 0($fp)
...
  lw    $ra, 20($sp)
        addiu   $sp,$sp,32
  jr    $ra
```



First four arguments are passed in registers!

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Example2B

```
# Example for CPS 104
# Program to add together list of 9 numbers.

        .text                       # Code
        .align  2
        .globl  main
main:                               # MAIN procedure Entrance
        subu    $sp, 40             #\ Push the stack
        sw      $ra, 36($sp)        # \ Save return address
        sw      $s3, 32($sp)        #  \
        sw      $s2, 28($sp)        #   > Entry Housekeeping
        sw      $s1, 24($sp)        #  / save registers on stack
        sw      $s0, 20($sp)        # /
        move    $v0, $0             #/ initialize exit code to 0

        move    $s1, $0             #\
        la      $s0, list           # \ Initialization
        la      $s2, msg            # /
        la      $s3, list+36        #/
```


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Example2B (cont.)

```
#                      Main code segment

again:                                  #   Begin main loop
        lw      $t6, 0(s0)              #\
        add     $s1, $s1, $t6           #/  Actual "work"
                                        #    SPIM I/O
        li      $v0, 4                  #\
        move    $a0, $s2                # >  Print a string
        syscall                         #/
        li      $v0, 1                  #\
        move    $a0, $s1                # >  Print a number
        syscall                         #/
        li      $v0, 4                  #\
        la      $a0, nln                # > Print a string (eol)
        syscall                         #/

        addiu   $s0, $s0, 4               #\ index update and
        bne     $s0, $s3, again           #/  end of loop
```


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Example2B (cont.)

```
#                        Exit Code

      move     $v0, $0           #\
       lw      $s0, 20($sp)      # \
       lw      $s1, 24($sp)      #  \
       lw      $s2, 28($sp)      #   \ Closing Housekeeping
       lw      $s3, 32($sp)      #   /   restore registers
       lw      $ra, 36($sp)      #  / load return address
       addu    $sp, 40           # / Pop the stack
       jr      $ra               #/    exit(0) ;
       .end    main              #  end of program

#                Data Segment

        .data                    # Start of data segment
list:   .word   35, 16, 42, 19, 55, 91, 24, 61, 53
msg:    .asciiz "The sum is "
nln:    .asciiz "\n"
```


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Example: Factorial

```
main()
{
  printf("The factorial of 10 is %d\n",
 fact(10));
}


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


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```
.text
        .global main
main:
        subiu   $sp, $sp,32     #stack frame size is 32 bytes
        sw      $ra,20($sp)     #save return address

        li      $a0,10          # load argument (10) in $a0
        jal     fact            #call fact
        la      $a0 LC          #load string address in $a0
        move    $a1,$v0         #load fact result in $a1
        jal     printf          # call printf

        lw      $ra,20($sp)     # restore $ra
        addu    $sp, $sp,32     # pop the stack
        jr      $ra             # exit()


        .rdata
LC:
        .asciiz "The factorial of 10 is %d\n"
```


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```
.text
fact:
        subiu   $sp,$sp,32      # stack frame is 32 bytes
        sw      $ra,20($sp)     #save return address
        sw      $a0,28($sp)     # save argument(n)on stack

        lw      $v0,28($sp)     # load n from stack
        bgtz    $v0, L2         # if n>0 go to $L2
        li      $v0, 1          #
        j       L1              # return(1)
L2:
        lw      $v1,28($sp)     # load n
        sub     $v0,$v1,1       # compute n-1
        move    $a0,$v0         # load argument (n-1) into $a0
        jal     fact            # call fact
        lw      $v1,28($sp)     # load n
        mul     $v0,$v0,$v1     # fact(n-1)*n

L1:                             # return (result in $v0)
        lw      $ra,20($sp)     # restore $ra
        addiu   $sp,$sp,32      # pop the stack
        jr      $ra             #return
```


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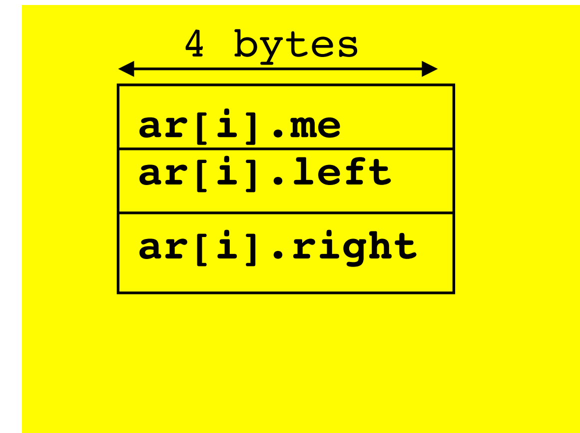
Example: Binary Tree

```
class Tree_node {
public:
  int me;                    // node number
  Tree_node *left;           // left sub-tree pointer
  Tree_node *right;          // right sub-tree pointer
} ;

main()
{
  Tree_node *ar = new Tree_node[31];   // The tree has 31 nodes.
  Tree_node *p = ar;                   //  p = <top of the array>.
  int k;
  for (k = 0; k < 31; k++){            // initialize all nodes.
      ar[k].me = k;
      if( (2*k+2) < 31 ) {             // if it is an interior node,
         ar[k].left = &ar[2*k+1];      // set left and right pointers
         ar[k].right = &ar[2*k+2];
      }
      else{                            // if it is a leaf node
         ar[k].left = NULL;            // set the left and right pointers
         ar[k].right = NULL;           // to NULL.
      }
  }
  print_tree(p);              // print the tree nodes in preorder.
}
```



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Example: Binary Tree

```
void print_tree(Tree_node * p)
{
// a recursive procedure to print a binary tree in preorder.

  if( p == NULL) return;         // if the tree is null, return

  cout <<  p << endl;            // print the node address

  print_tree(p->left);           // print the left subtree
  print_tree(p->right);          // print the right subtree
}
```


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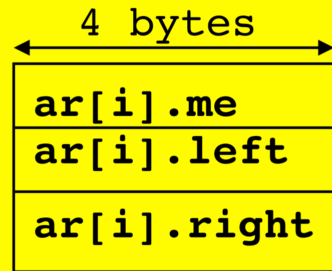
Example: Binary Tree

```
class Tree_node {
public:
  int me;
  Tree_node *left;
  Tree_node *right;
} ;
```




```
Tree_node ar[31] ;
```

```
&(ar[i].me)    = ?
&(ar[i].left   = ?
&(ar[i].right  = ?
```

```
.align 2
.text
.globl main
main:
        subiu  $sp, $sp, 32         # stack frame 32 bytes
        sw     $ra, 20($sp)         # save return address

        # allocate the tree node array:    ar = new Tree_node[31] ;

        li $a0 372                  #  31 nodes, 12 bytes each.
        li $v0 9                    #  get a block from sbrk
        syscall                     #  $v0 points to the root $v0=ar ;
```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Example: Binary Tree

```
#   for (k=0; k<31 ; k++) {
        move $t0 $0              #  k = 0;
LP:     mul  $t1, $t0, 12        #  $t1 = k*12
        addu $t2, $v0, $t1       #  $t2 = &ar[k]
        sw   $t0, 0($t2)         #  ar[k].me = k ;
        mul  $t3, $t0, 2         #
        addi $t3, $t3, 2         #  $t3 = 2*k+2
        mul  $t4, $t3, 12        #
        addu $t5, $v0, $t4       #  $t5 = &ar[2*k+2];
        bge  $t3, 32, L1         # if( (2*k+2) < 31 ) then{
        sw   $t5, 8($t2)         #     ar[k].right = &ar[2*k+2] ;
        subiu $t5, $t5, 12       #     $t5 = &ar[2*k+1] ;
        sw   $t5, 4($t2)         #     ar[k].left = &ar[2*k+1]}
        j    LD                  #     go to LD
L1:     sw   $0, 4($t2)          # else {  ar[k].left = NULL;
        sw   $0, 8($t2)          #         ar[k].right = NULL;}
LD:     addi $t0, $t0, 1         #  k++
        blt  $t0, 31 LP          #  if k < 31 go to LP
#                                 }       end of  for()  loop
```


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Example: Binary Tree

```
move    $a0, $v0            # $a points to root node
jal     print_tree          # go print it

li      $v0 ,0              #  do exit(0) ;
lw      $ra, 20($sp)        # restore return address
addiu   $sp, $sp, 32        # pop the stack frame
j       $ra
```


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Example (cont.)

```
.text
print_tree:
        subiu  $sp, $sp, 32  # stack frame 32 bytes
        sw     $ra, 20($sp)  # save return address
        sw     $a0, 12($sp)  # save node_ptr
        beqz   $a0, pr_done  # if null, return
        li     $v0, 1        # prepare to print int
        syscall                     # print it out
        li     $v0, 4
        la     $a0, mystr    #print end_of_line
        syscall
        lw     $a0, 12($sp)  # restore node_ptr
        lw     $a0, 4($a0)   # load left ptr
        jal    print_tree
        lw     $a0, 12($sp)  # restore node_ptr
        lw     $a0, 8($a0)   # load right ptr
        jal    print_tree
pr_done:                     #  return code
        lw     $ra, 20($sp)  # restore return address
        addu   $sp, $sp, 32  # remove frame
        j      $ra
.data
mystr: .asciiz "\n"
```


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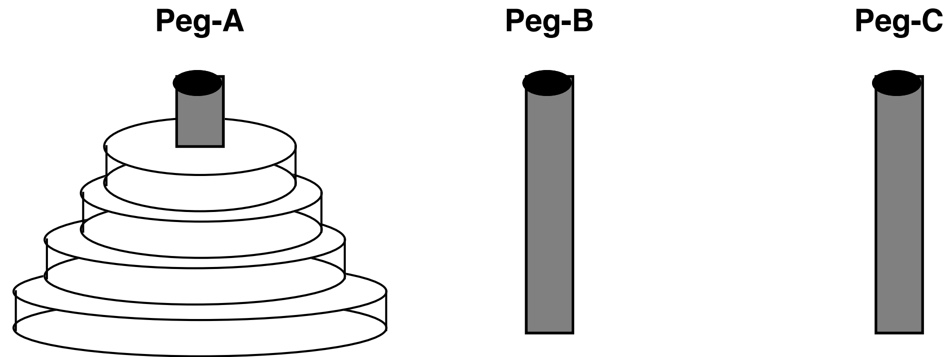
Example: Towers of Hanoi



The puzzle has the following recursive solution.

- `Move N-1 disks from` **`peg-a`** `to` **`peg-b`**
  (using **peg-c** as auxiliary peg);

- `Move the largest disk from` **`peg-a`** `to` **`peg-c`**`;`

- `Move N-1 disks from` **`peg-b`** `to` **`peg-c`**
  (using **peg-a** as auxiliary peg);

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Example: Towers of Hanoi

```
void hanoi (int n, char * a, char* b, char* c)
// Towers of Hanoi puzzle
// Move n disks from a to c using b as auxiliary peg
{
 if (n == 1) {// if one disk, move the disk from a to c
   cout << "move disk from " << a << " to " ;
   cout << c << endl ;
 }
 else{        // if n > 1
   hanoi(n-1, a, c, b) ;  // move n-1 disks from a to b
   // move the last disk from a to c
   cout << "move disk from " << a << " to " ;
   cout << c << endl ;
   hanoi(n-1, b, a, c);   // move n-1 disks from b to c
 }
}

main()
{    hanoi(10,"peg-A", "peg-B", "peg-C");}
```


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```
# Towers of Hanoi MIPS assembly program
.align 2
.data               #   Begin Data Segment
movedisk: .asciiz "Move disk from "
to: .asciiz " to "
nln: .asciiz "\n"
peg1: .asciiz "Peg-A"
peg2: .asciiz "Peg-B"
peg3: .asciiz "Peg-C"
.text               # Begin Text Segment
main:   subu  $sp,$sp,28        # Push a frame into stack
        sw $ra,24($sp)          # save return address
        li $a0,10               # set n=10
        la $a1,peg1             # pass to hanoi 4 variables
        la $a2,peg2             # n, #-of disks in $a0
        la $a3,peg3             # names of pegs in $a1-$a3
        jal hanoi               # call hanoi
        lw   $ra,24($sp)        # load return address
        addi  $sp,$sp,28        # Pop the stack frame
        jr $ra                  # exit
```


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```
hanoi:
  addi $sp,$sp,-20        # Push frame into stack
  sw $ra,0($sp)           # save the return address
  sw $a0,4($sp)           # save n
  sw $a1,8($sp)           # save peg A
  sw $a2,12($sp)          # save peg B
  sw $a3,16($sp)          # save peg C

  li $t0,1                # make $t0 = 1
  bne $t0,$a0,recurse     # if (n =/= 1) recurse

  li $v0,4                # print a string
  la $a0,movedisk         # "Move disk from "
  syscall                 #
  move $a0,$a1            # copy peg-A into a0
  syscall
  la $a0,to               # print " to "
  syscall
  move $a0,$a3            # copy peg-C into a0
  syscall
  la $a0,nln              # print end-of-line
  syscall

endcase:                  # exit code
  lw $ra,0($sp)           # load variables back
  lw $a0,4($sp)           # load n
  lw $a1,8($sp)           # load peg-A
  lw $a2,12($sp)          # load peg-B
  lw $a3,16($sp)          # load peg-C
  addi $sp,$sp,20         # Pop the stack frame
  jr $ra                  # return
```


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```
recurse:
    lw $a0,4($sp)           # Load n (num disks)
    addi $a0,$a0,-1         # n=(n-1)
    lw $a1,8($sp)           # load peg-A
    lw $a2,16($sp)          # load peg-C
    lw $a3,12($sp)          # load peg-B
    jal hanoi               # call hanoi

    li $v0,4                # print a string
    la $a0,movedisk         # "Move disk from "
    syscall                 #
    move $a0,$a1            # copy peg-A into a0
    syscall
    la $a0,to               # print " to "
    syscall
    move $a0,$a3            # copy peg-C into a0
    syscall
    la $a0,nln              # print end-of-line
    syscall

    lw $a0,4($sp)           # Load n (num disks)
    addi $a0,$a0,-1         # n=(n-1)
    lw $a1,12($sp)          # load peg-B
    lw $a2,8($sp)                   # load peg-A
    lw $a3,16($sp)          # load peg-C
    jal hanoi               # call hanoi

    j endcase               # goto exit code (return)
```


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Simple functions

If a function does not call other functions one can simplify!

```c
int min(int a, int b)
{
  if(a <= b) return(a) ;
  return(b);
}
```

```
min:    bgt  $a0, $a1, L1
        move $v0, $a0
        jr   $ra
L1:     move $v0, $a1
        jr   $ra
```


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