CSCI 210: Computer Architecture
Lecture 12: Procedures & The Stack

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CS History: IBM System 360

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- Family of mainframes developed in 1964
- Introduced:
  - 8-bit byte
  - Byte-addressable memory
  - 32-bit words
- Featured BAL (Branch and Link) and BR (Branch Register) instructions
- IBM’s current System z mainframes will still run code written for the 360 series

Register values across function calls

- “Preserved” registers
  - You can trust them to persist past function calls
    - Functions must ensure not to change them or to restore them if they do

- Not “Preserved” registers
  - Contents can be changed when you call a function
    - If you need the value, you need to put it somewhere else

Aside: MIPS Register Convention

Name	Register Number	Usage	Preserve on call?
$zero	0	constant 0 (hardware)	n.a.
$at	1	reserved for assembler	n.a.
$v0 - $v1	2-3	returned values	no
$a0 - $a3	4-7	arguments	no
$t0 - $t7	8-15	temporaries	no
$s0 - $s7	16-23	saved values	yes
$t8 - $t9	24-25	temporaries	no
$gp	28	global pointer	yes
$sp	29	stack pointer	yes
$fp	30	frame pointer	yes
$ra	31	return addr (hardware)	yes

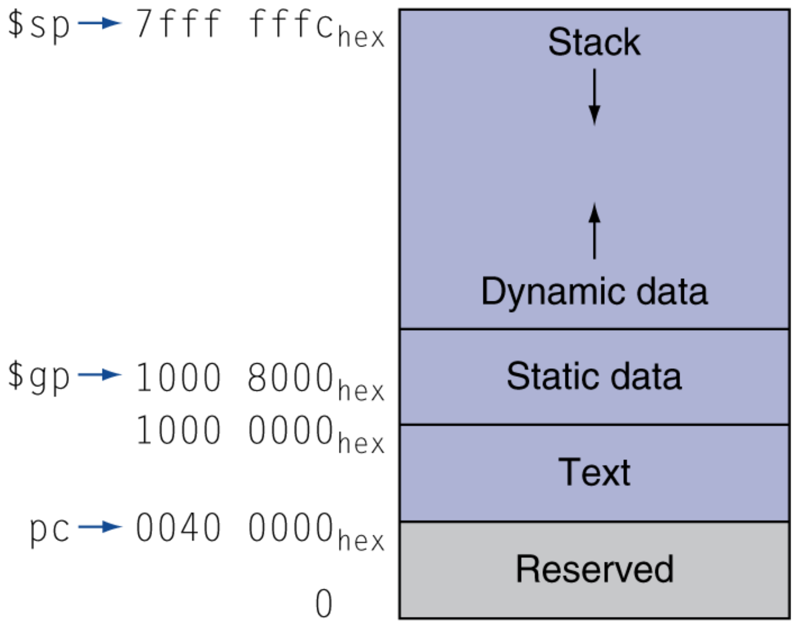
Programmer’s responsibility

“Spill” and “Fill”

- Spill register to memory
  - Whenever you have too many variables to keep in registers
  - Whenever you call a method and need values in non-preserved registers
  - Whenever you want to use a preserved register and need to keep a copy
- Fill registers from memory
  - To restore previously spilled registers

Memory Layout

- Text: program code
- Static data: global variables
  - e.g., static variables in C, constant arrays and strings
- Dynamic data: heap
  - E.g., malloc in C, new in Java
- Stack: "automatic" storage for procedures



Before and after a function

Assembly Code

```
sw   $t0, 4($sp)
jal  myFunction
lw   $t0, 4($sp)
```

Which register is being spilled and filled?

A. $ra

B. $t0

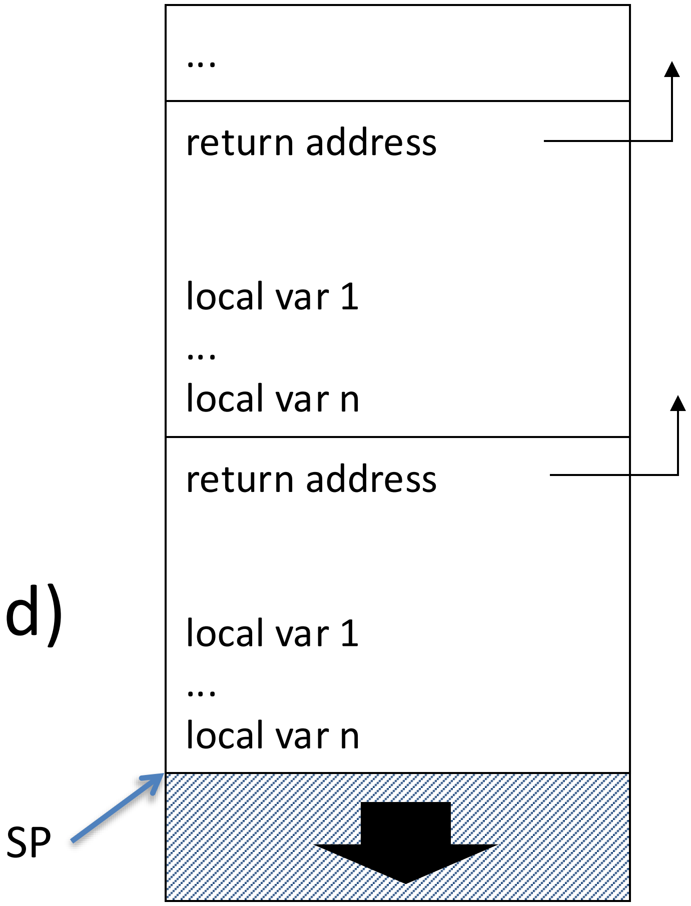
C. $sp

D. No register is spilled/filled

E. No need to spill/fill any registers

Stack

- Stack of stack frames
  - One per pending procedure
- Each stack frame stores
  - Where to return to
  - Local variables
  - Arguments for called functions (if needed)
- Stack pointer points to last record

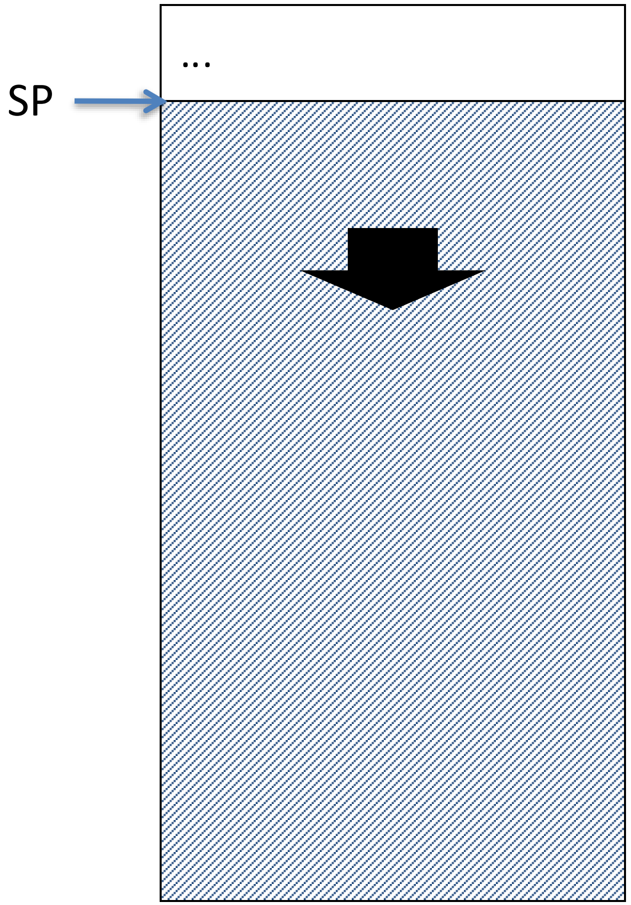


Process Stack

```
main () {
   int i = foo();
   print(i);
   return 0;
}

foo () {
  int n = 10;
  n = bar(n);
  return n;
}

bar(int n) {
   return n + 2;
}
```



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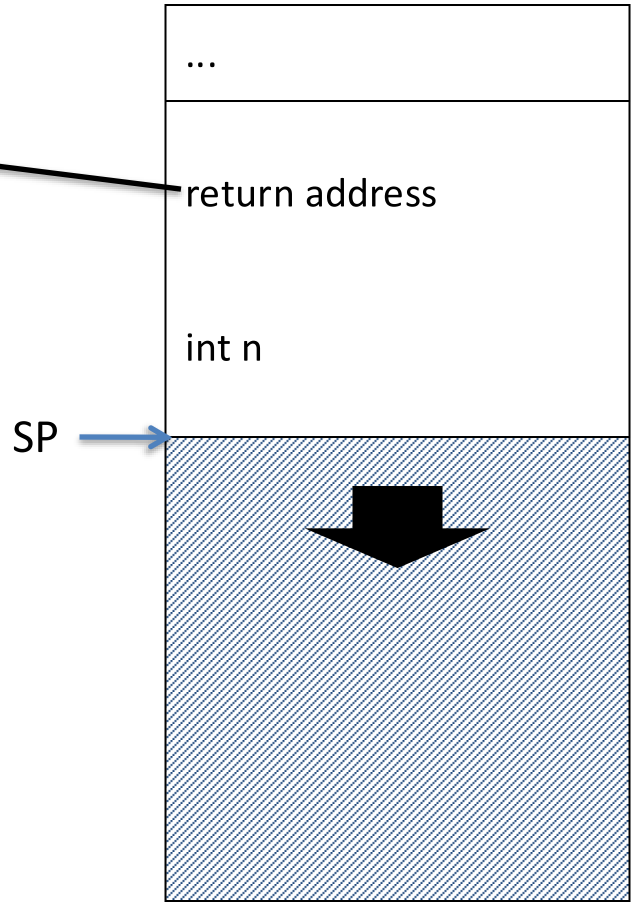

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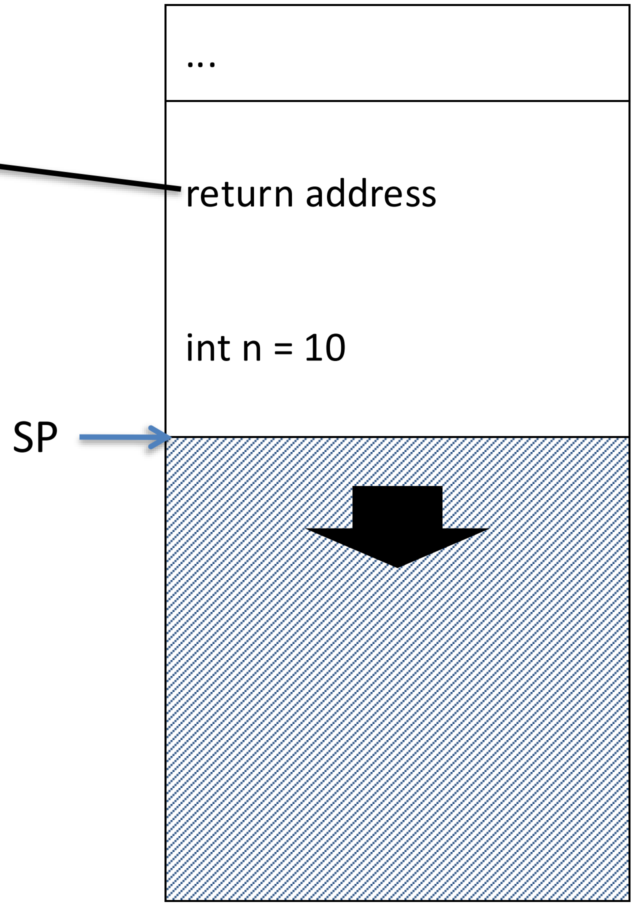

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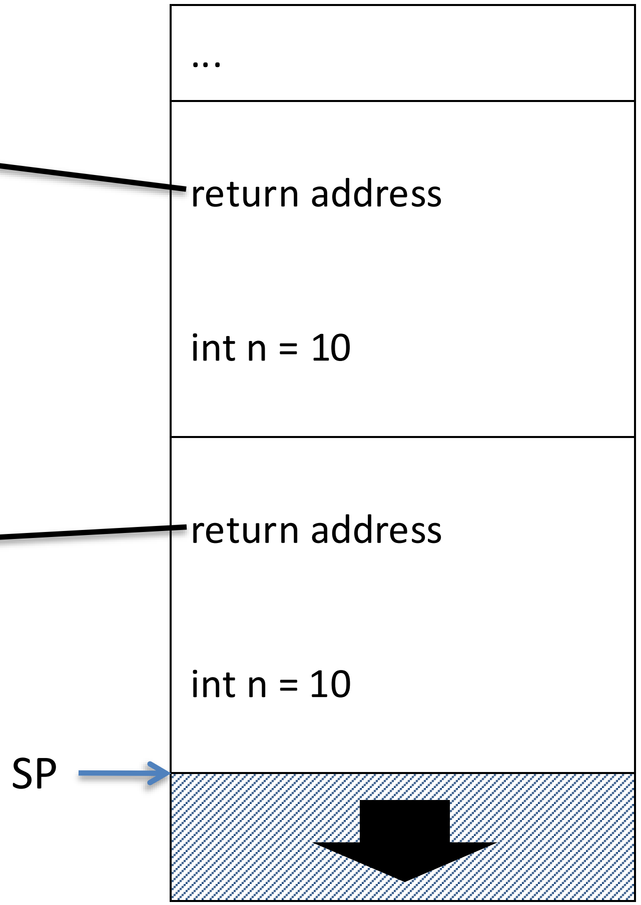

Process Stack

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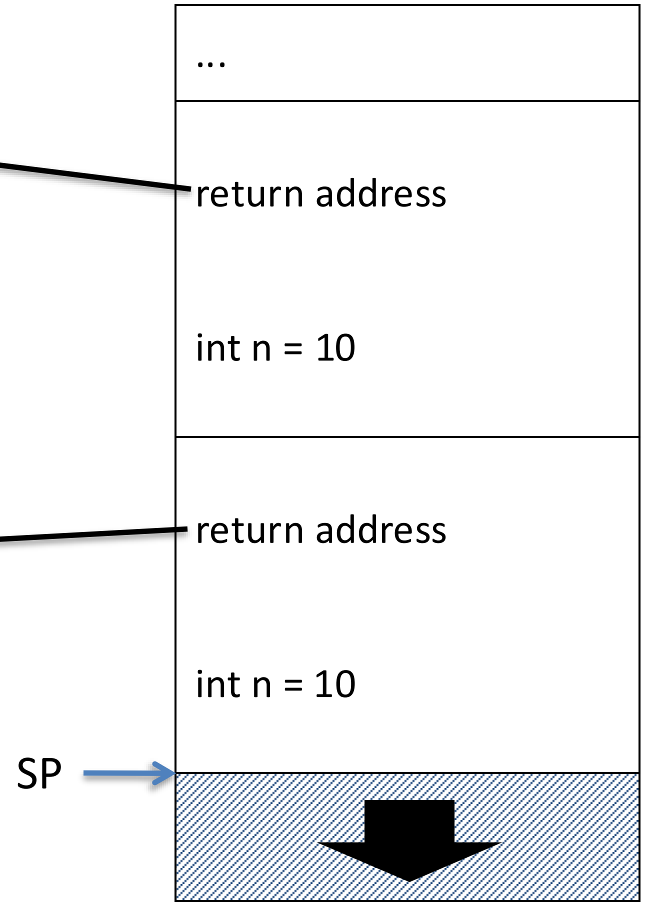
   return n + 2;
}
```



...

return address

int n = 10

return address

int n = 10

SP

Process Stack

```
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   print(i);
   return 0;
}

foo () {
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  return n;
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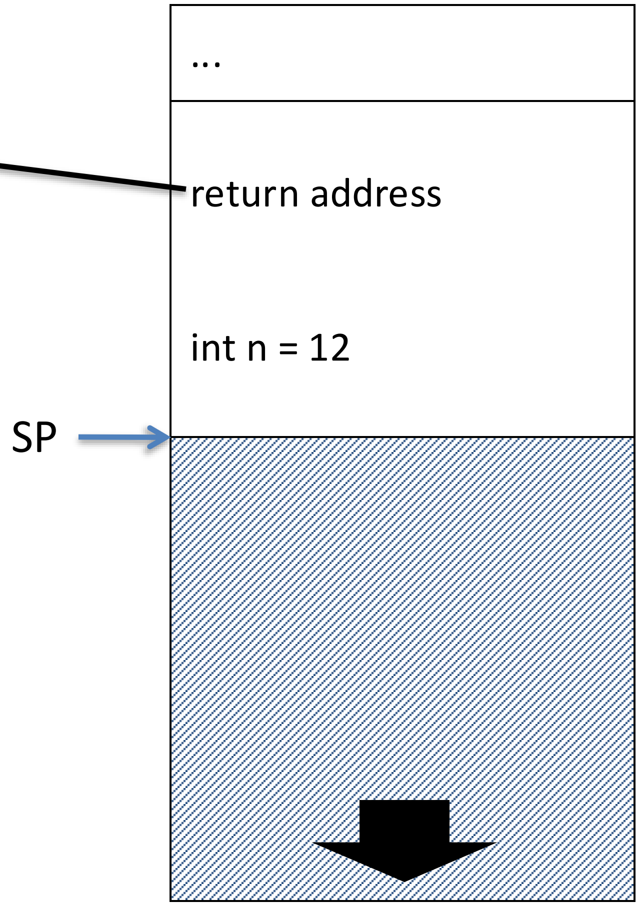

Process Stack

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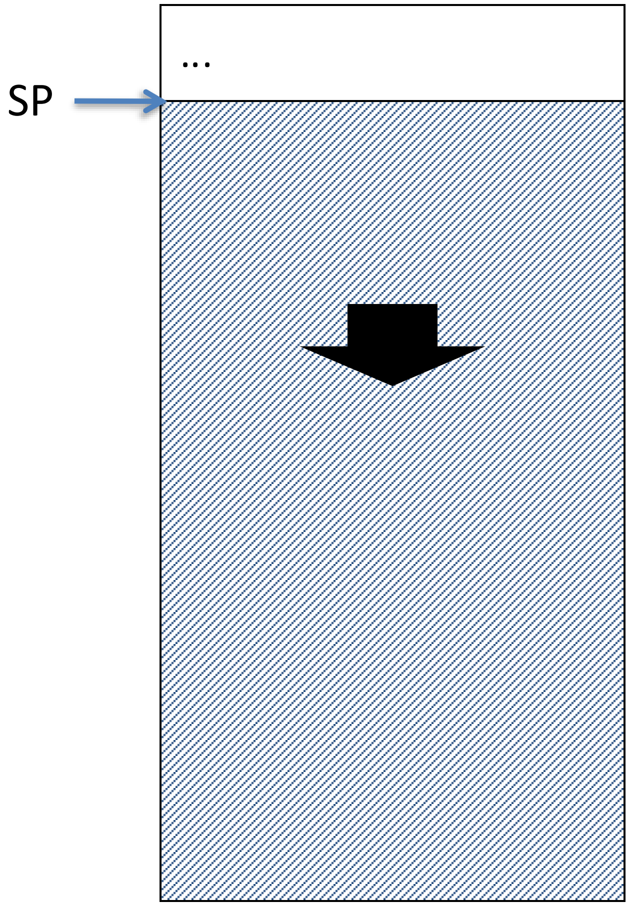


To add a variable to the stack in MIPS

- Change the stack pointer $sp to create room on the stack for the variable

- Use sw to store the variable on the stack

- The stack pointer in MIPS points after the last stack slot so the valid slots to access are 4($sp), 8($sp), 12($sp), etc.

Stack

If you wish to push an integer variable to the top of the stack, which of the following is true:

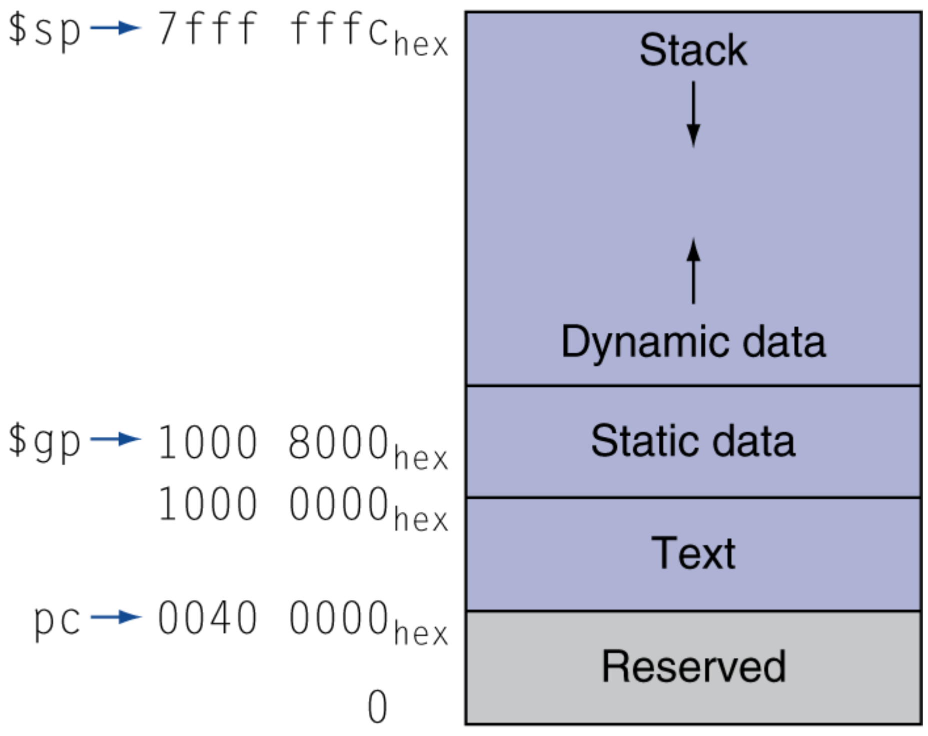
A. You should decrement the stack pointer ($sp) by 1

B. You should decrement $sp by 4

C. You should increment $sp by 1

D. You should increment $sp by 4

E. None of the above



Manipulating the Stack

- To add the contents of $s0 to the stack

  ```
  – addi      $sp,  $sp,  -4
    sw        $s0,  4($sp)        ; The stack pointer points after the last stack slot
  ```

- To get the value back from the stack

  ```
  – lw        $s0,  4($sp)
  ```

- To “erase” the value from the stack

  ```
  – addi      $sp,  $sp,  4
  ```

Think-Pair-Share: Why do we spill and fill the return address when we call a function from inside another function?

```
func1:
   . . .
   addi  $sp, $sp, -4
   sw    $ra, 4($sp)
   jal   func2
   lw    $ra, 4($sp)
   addi  $sp, $sp, 4
   . . .
   jr $ra
```

A better approach

- In the function “prologue,” reserve space on the stack for all of the variables and saved registers you’ll need

- Use sw/lw to spill and fill as needed to the space reserved in the prologue

- In the function “epilogue,” restore any saved registers you need and update the stack pointer

Complete example

```
foo:
      addi     $sp, $sp, -12  # Reserve space for 3 vars
      sw       $ra, 12($sp)   # Stores (spills) $ra, return address
      sw       $s0, 8($sp)    # Stores (spills) s0, callee-saved reg
      …
      li       $s0, 25        # Set s0 to 25
      sw       $t3, 4($sp)    # Stores (spills) t3, caller-saved reg
      add      $a0, $t1, $t3
      jal      myFunction
      lw       $t3, 4($sp)    # Restores (fills) t3
      …
      lw       $s0,  8($sp)   # Restores (fills) s0, must restore
      lw       $ra,  12($sp)  # Restores (fills) $ra, return address
      addi     $sp, $sp, 12   # Restore the stack pointer
      jr       $ra            # Return
```

Leaf function

- If the function doesn’t call any other functions, it’s a “leaf”
- If a leaf function doesn’t need to use any of the callee-saved registers (e.g., $s0–$s7), then it doesn’t need to change the stack pointer or spill/fill $ra
- Example:

```
# myFunction(int a0, int a1, int a2)
myFunction:
     add    $t0, $a0, $a2
     sub    $v0, $t0, $a1
     jr     $ra
```

Leaf Procedure Example

```
int leaf_example(
  int g, int h, int i, int j
) {
    int f = (g + h) - (i + j);
    return f;
  }
```

- Arguments g, …, j in $a0, …, $a3
- Result in $v0

```
leaf_example:
    add  $t0, $a0, $a1
    add  $t1, $a2, $a3
    sub  $v0, $t0, $t1
    jr   $ra
```

Non-Leaf Procedures

- Procedures that call other procedures
- For nested call, caller needs to save on the stack:
  - Its return address
  - Any arguments and temporaries needed after the call
- Restore from the stack after the call

Non-Leaf Procedure Example

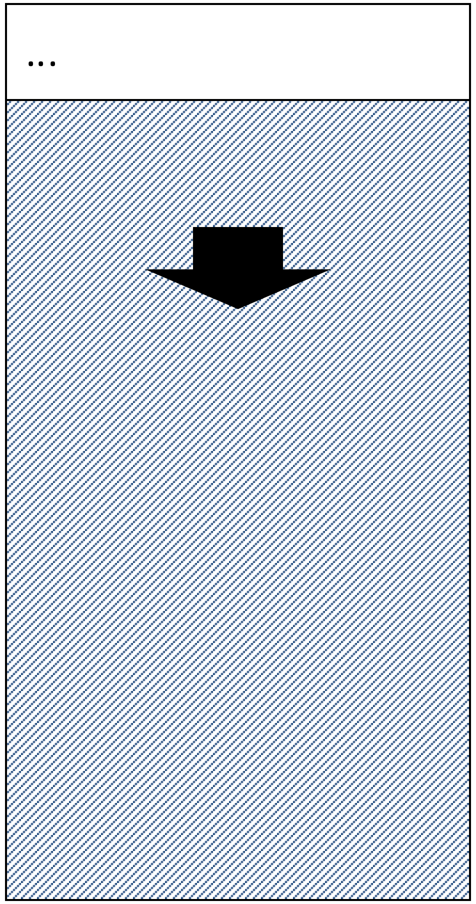
- C code:

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

  - Argument n in $a0
  - Result in $v0

Process Stack

```
int main ()
{
   int x;
   x = fact(3);
}
int fact (int n)
{
   if (n < 2)
        return 1;
   else
        return n * fact(n - 1);
}
```



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   int x;
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}
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}
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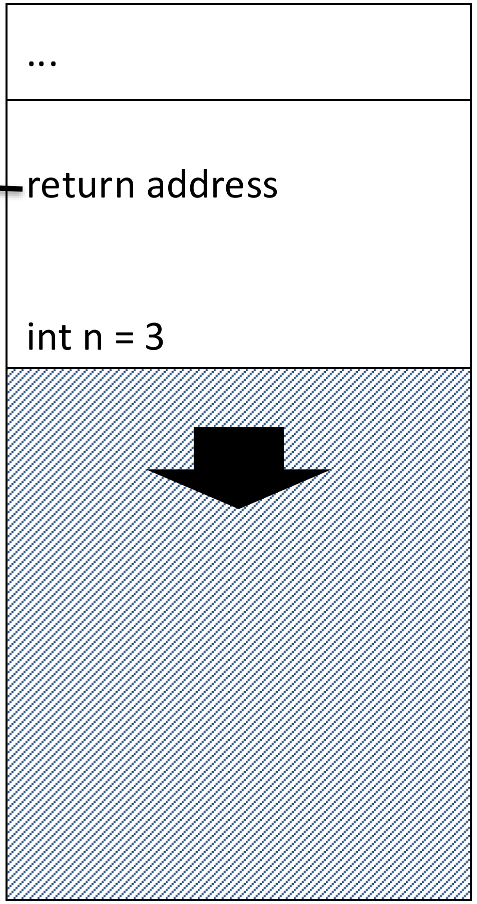

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int fact (int n)
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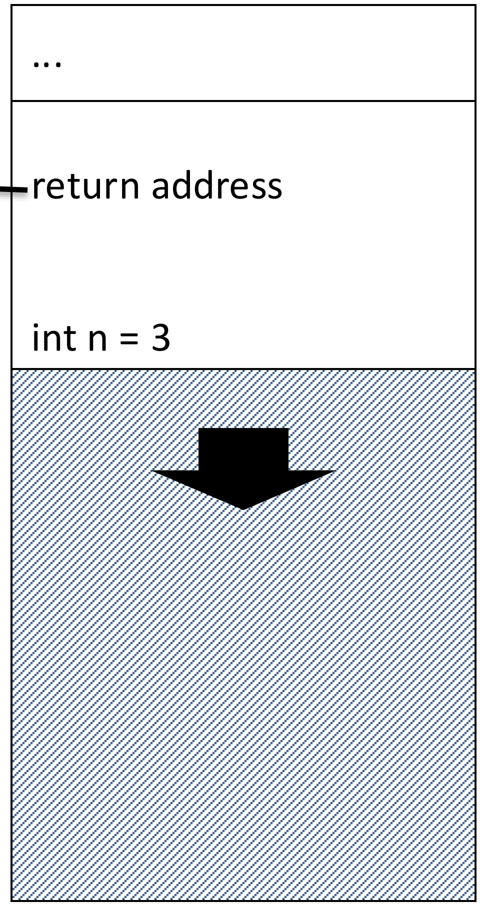

...

return address

int n = 3

Process Stack

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int main ()
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   int x;
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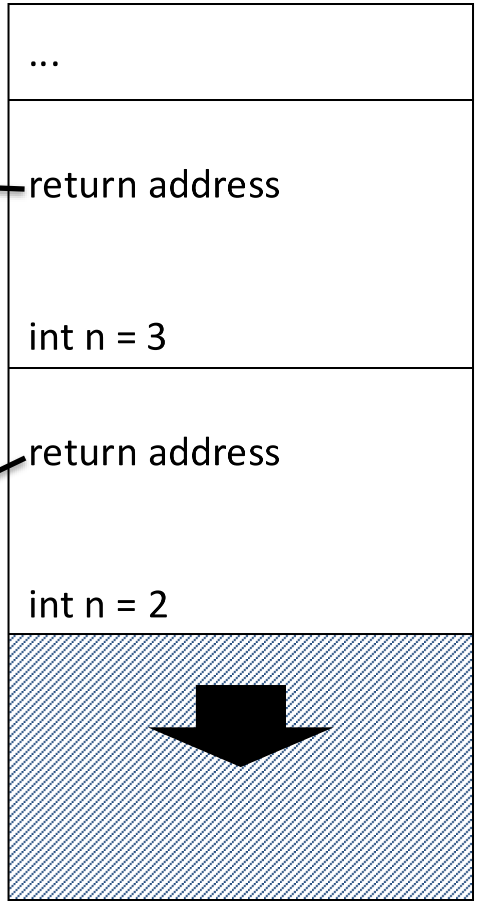

…

return address

int n = 3

return address

int n = 2

Process Stack

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int main ()
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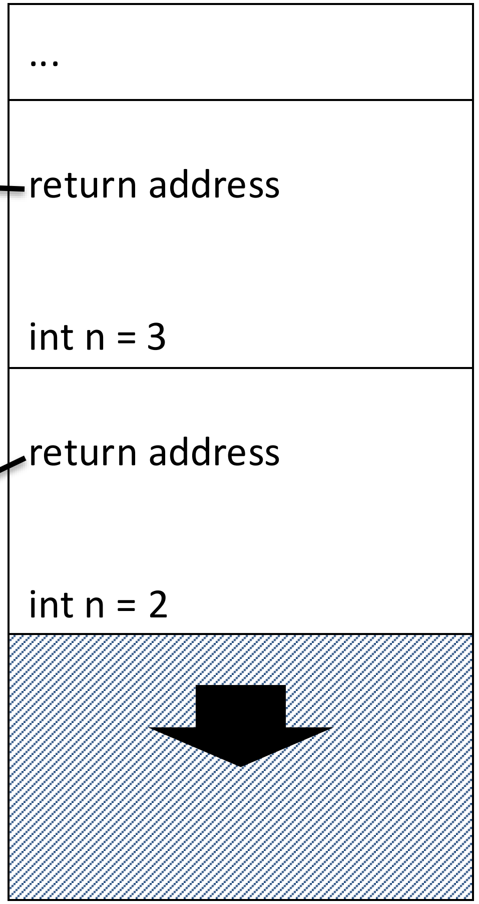


…

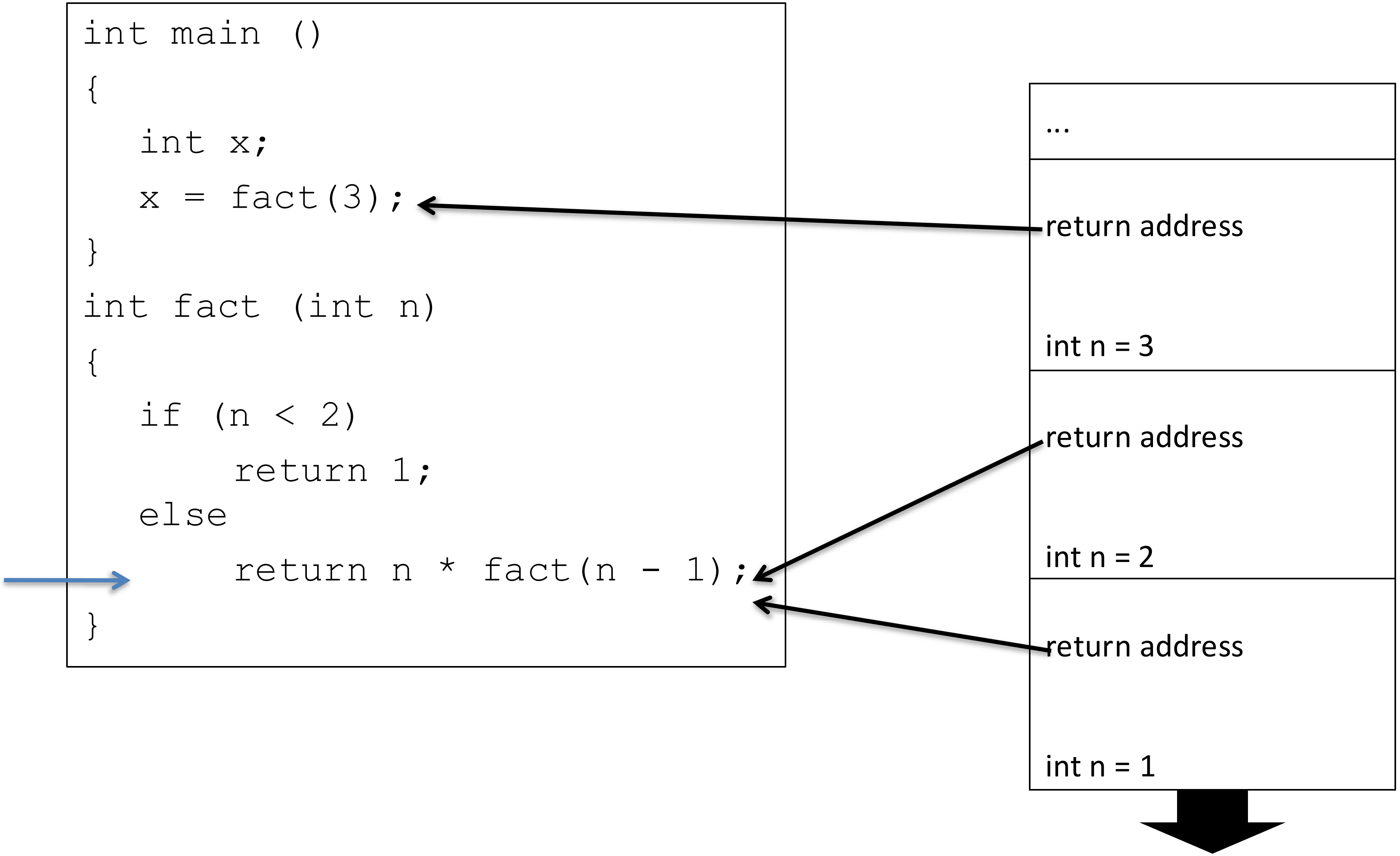
return address

int n = 3

return address

int n = 2

Process Stack



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   x = fact(3);
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int fact (int n)
{
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        return 1;
   else
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}
```

…

return address

int n = 3

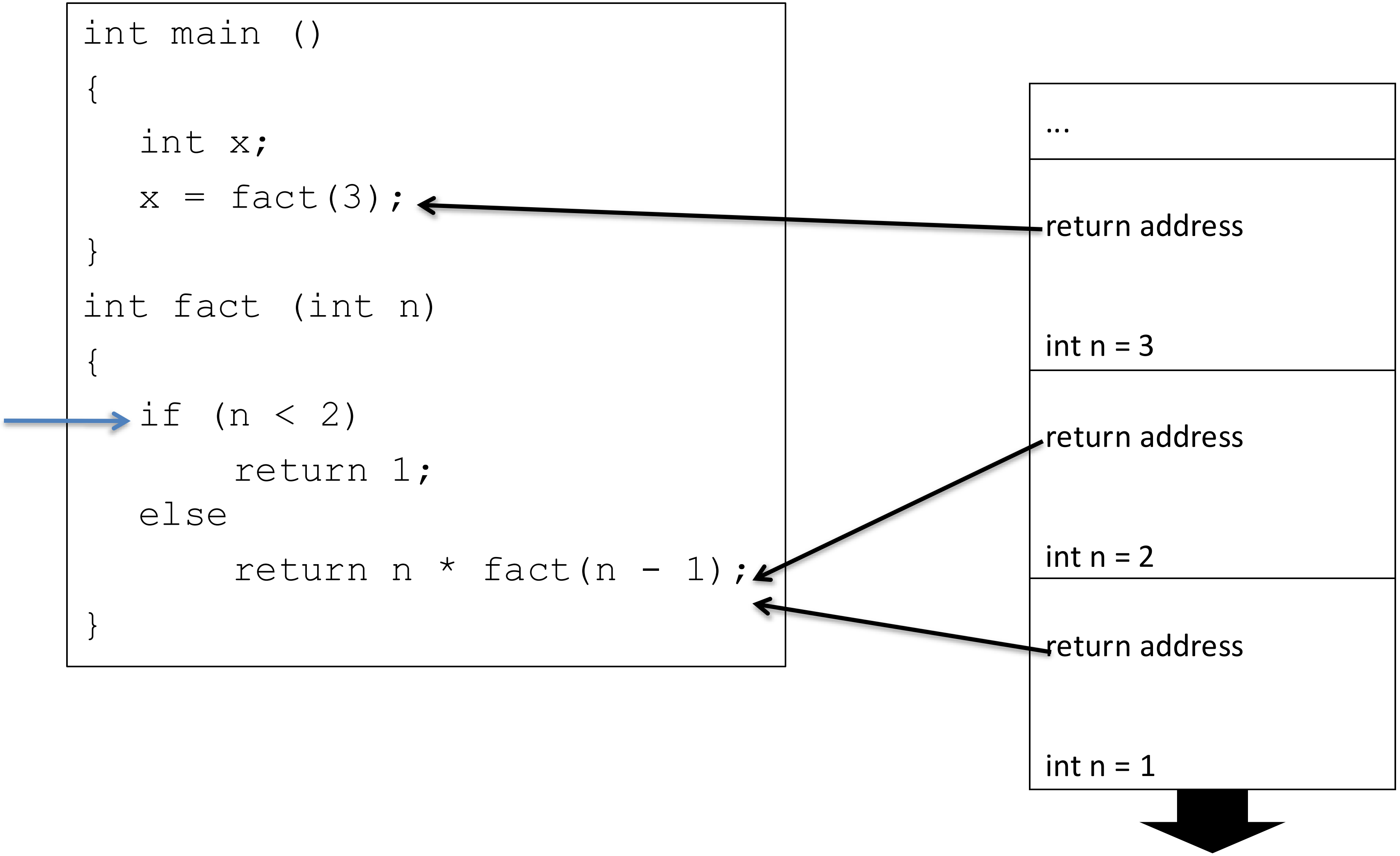
return address

int n = 2

return address

int n = 1

Process Stack



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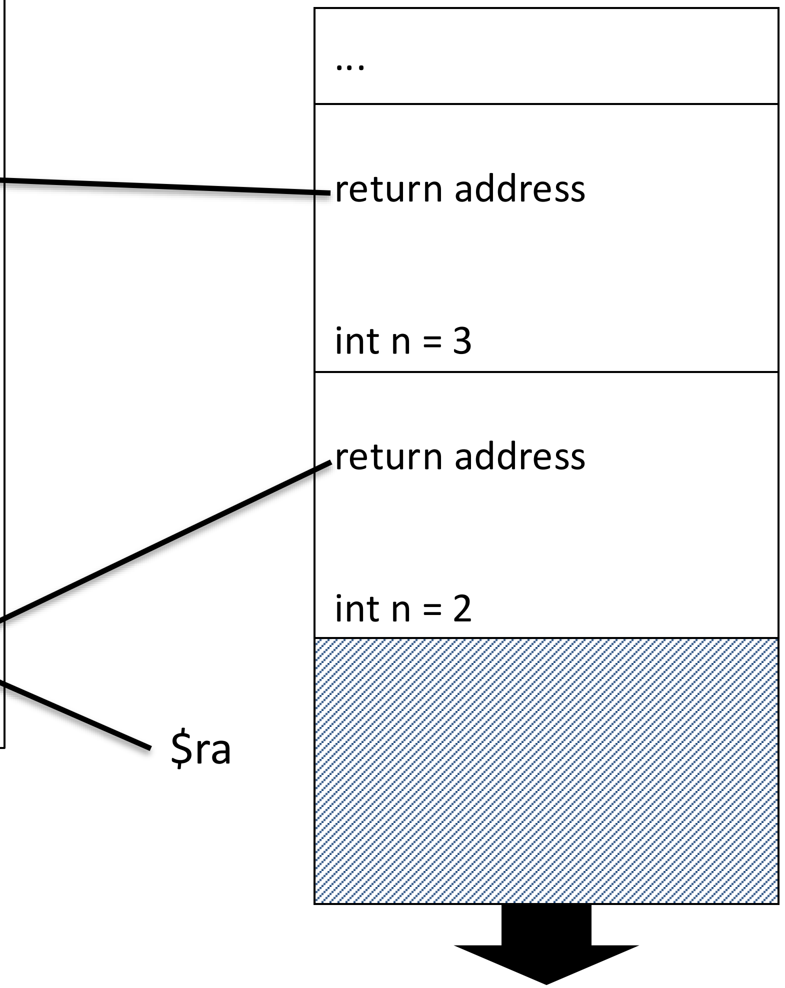
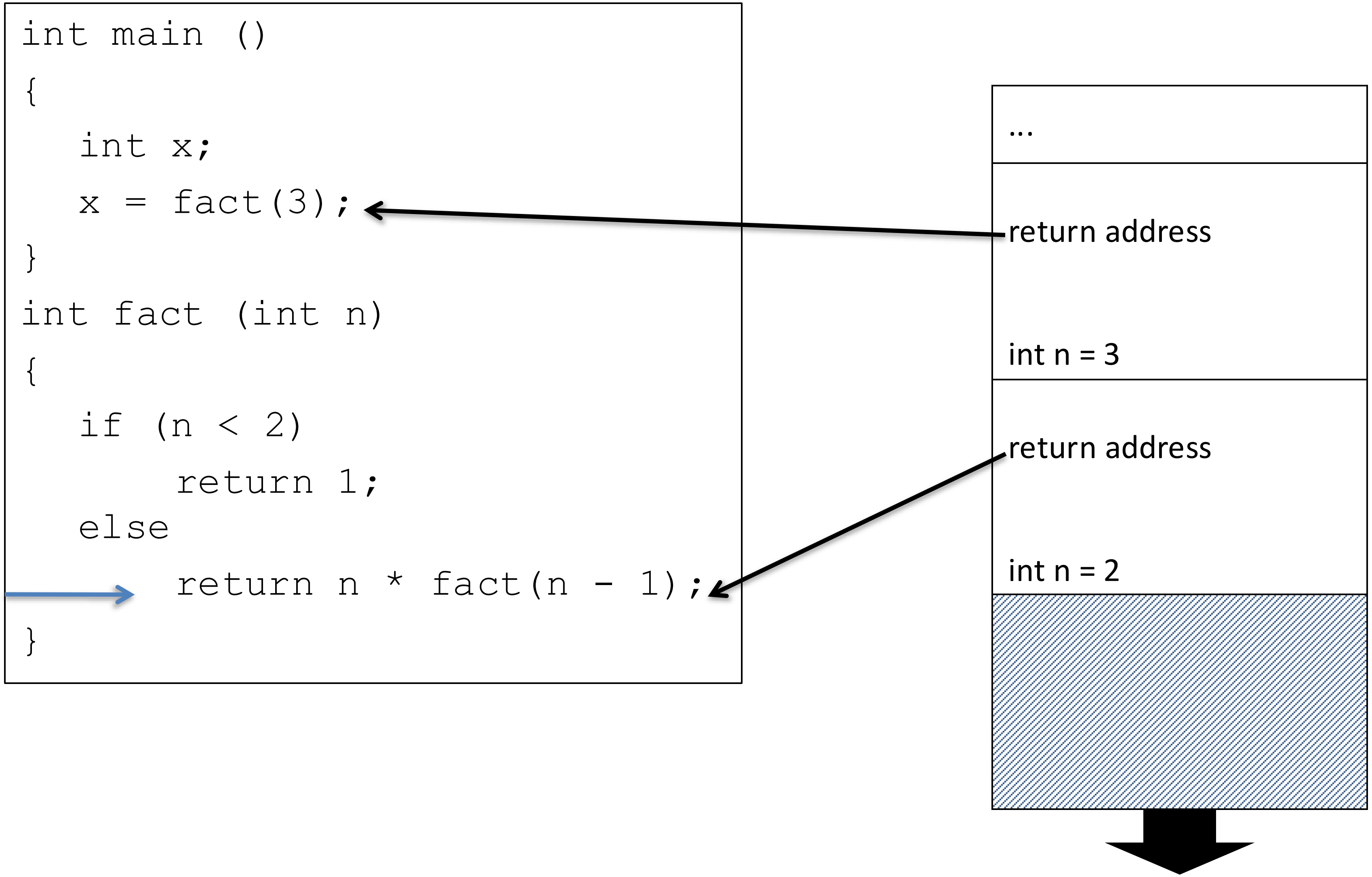


Process Stack



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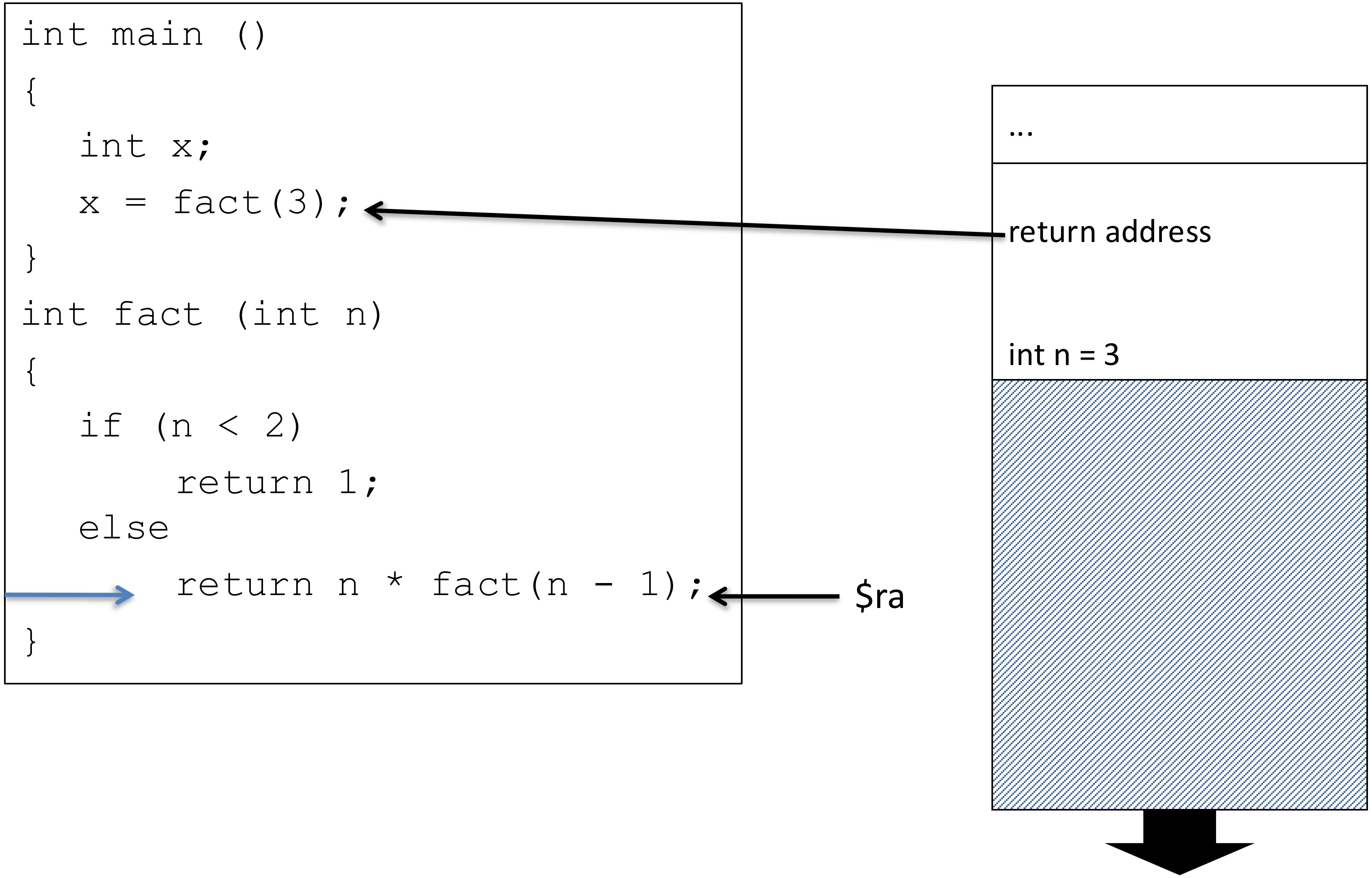

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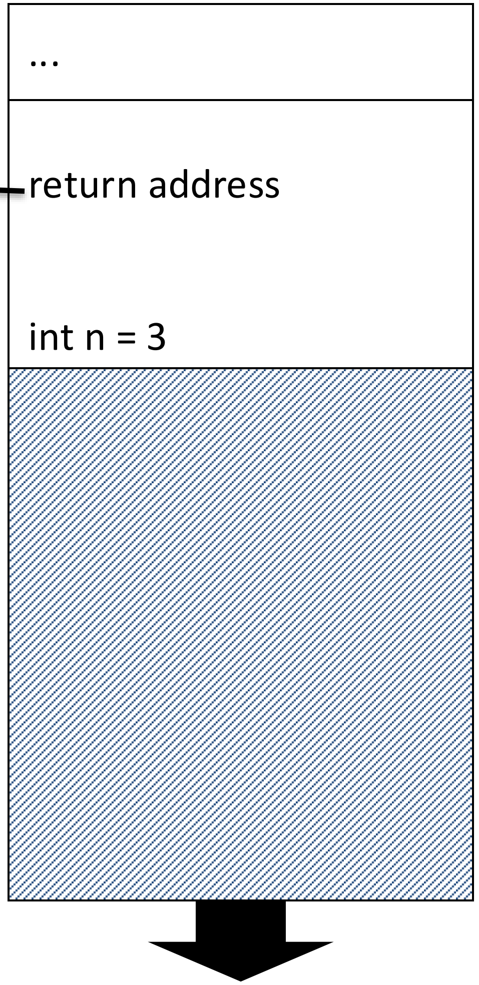

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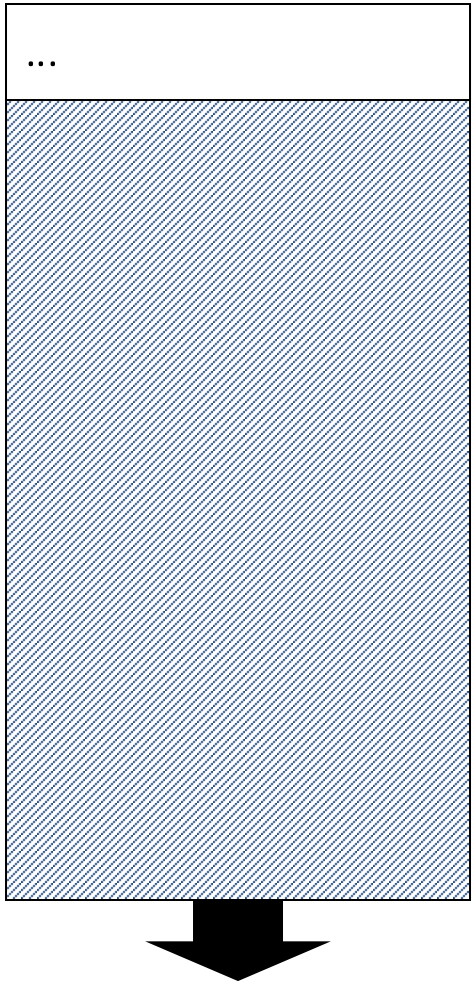
$ra



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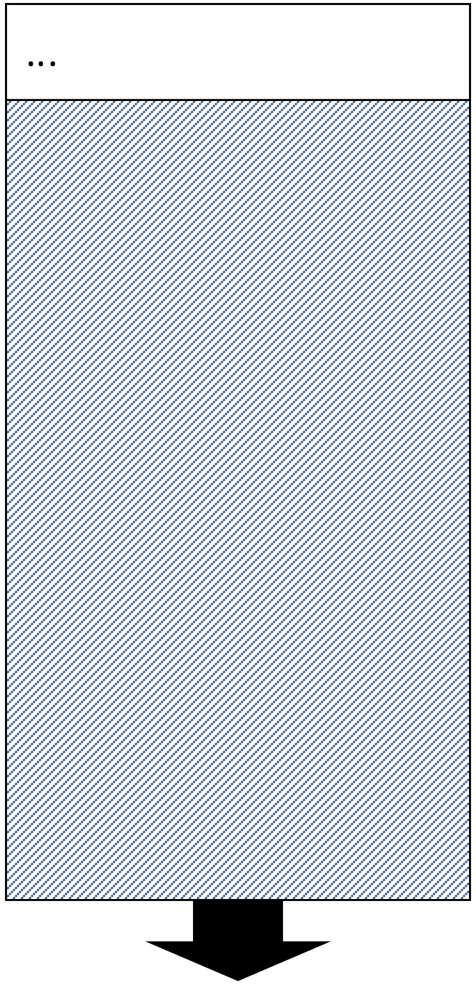

Questions?

Non-Leaf Procedure Example

- MIPS code:

```
fact:
    addi $sp, $sp, -8     # adjust stack for 2 items
    sw   $ra, 8($sp)      # save return address
    sw   $a0, 4($sp)      # save argument
    slti $t0, $a0, 2      # test for n < 2
    beq  $t0, $zero, L1
    addi $v0, $zero, 1    # if so, result is 1
    addi $sp, $sp, 8      #   pop 2 items from stack
    jr   $ra              #   and return
L1: addi $a0, $a0, -1     # else decrement n
    jal  fact             # recursive call
    lw   $a0, 4($sp)      # restore original n
    lw   $ra, 8($sp)      #   and return address
    addi $sp, $sp, 8      # pop 2 items from stack
    mul  $v0, $a0, $v0    # multiply to get result
    jr   $ra              # and return
```

fact(3)

$ra = 0x864
$a0 = 3
$v0 =
$t0 =

PC

```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
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        jr   $ra              #   and return
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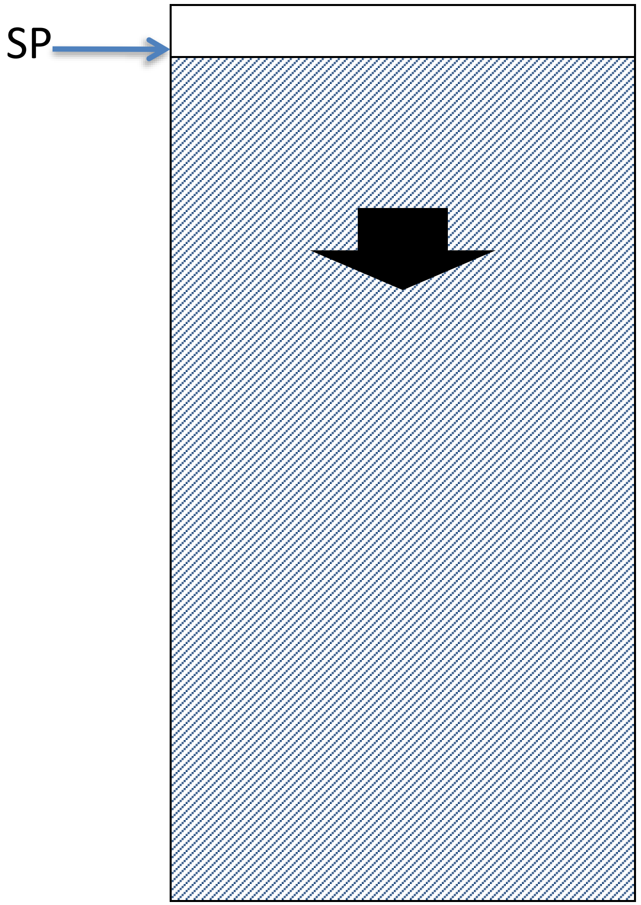

fact

$ra = 0x864
$a0 = 3
$v0 =
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```
   fact:
PC →   addi $sp, $sp, -8     # adjust stack for 2 items
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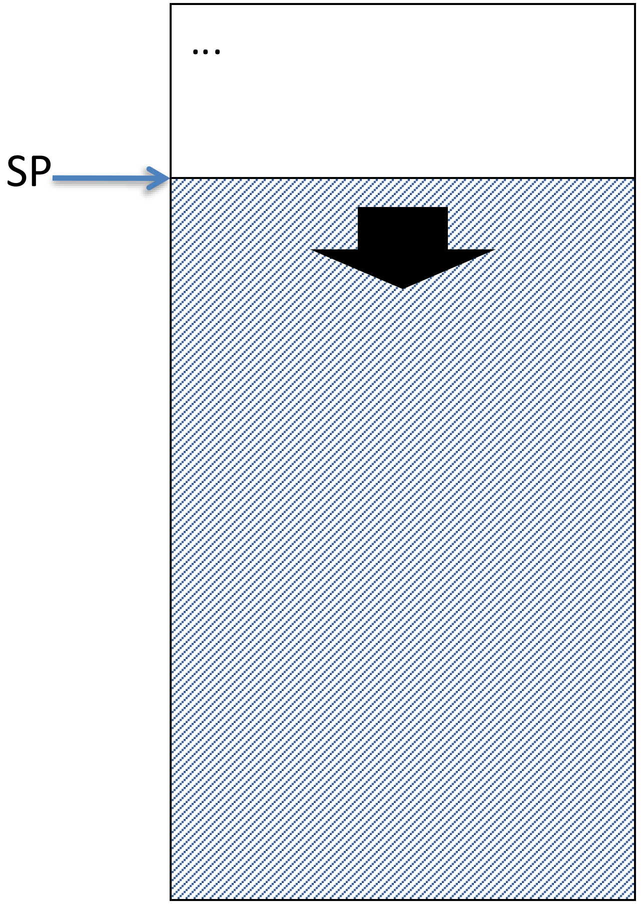

fact

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  fact:
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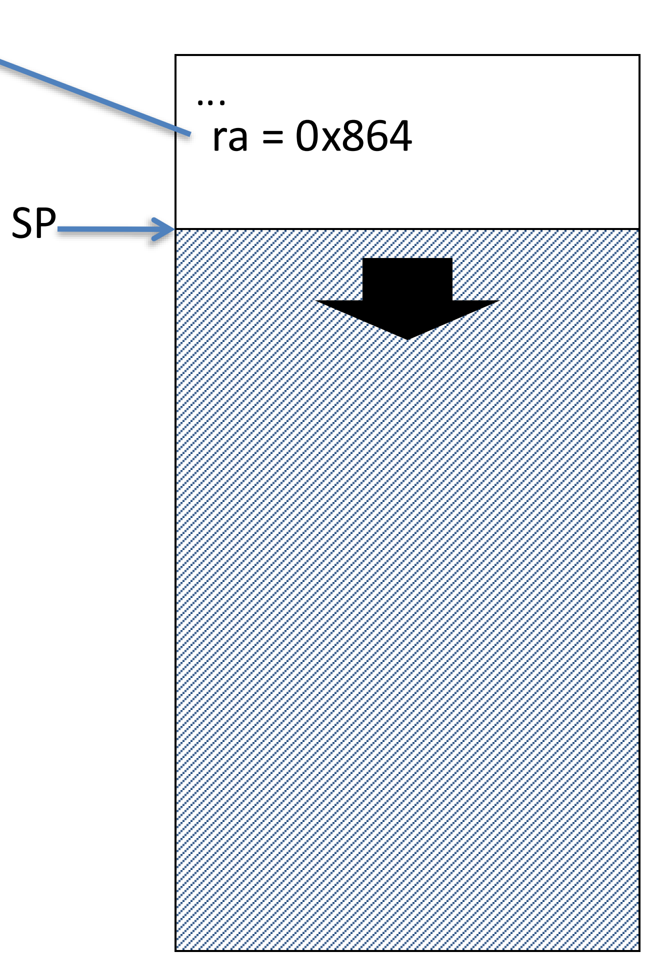

fact

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$a0 = 3
$v0 =
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```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
PC----> sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
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        addi $v0, $zero, 1    # if so, result is 1
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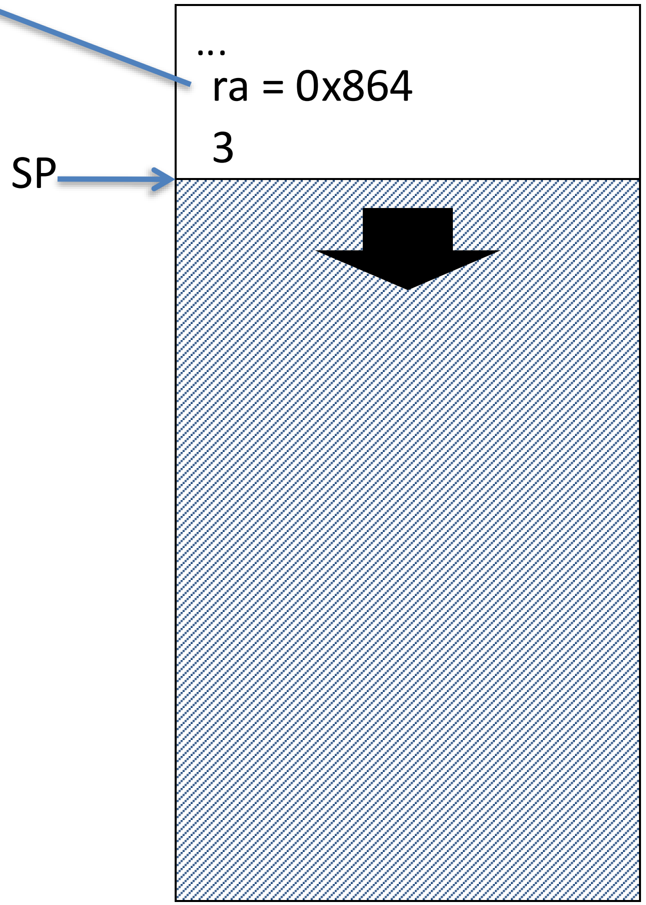
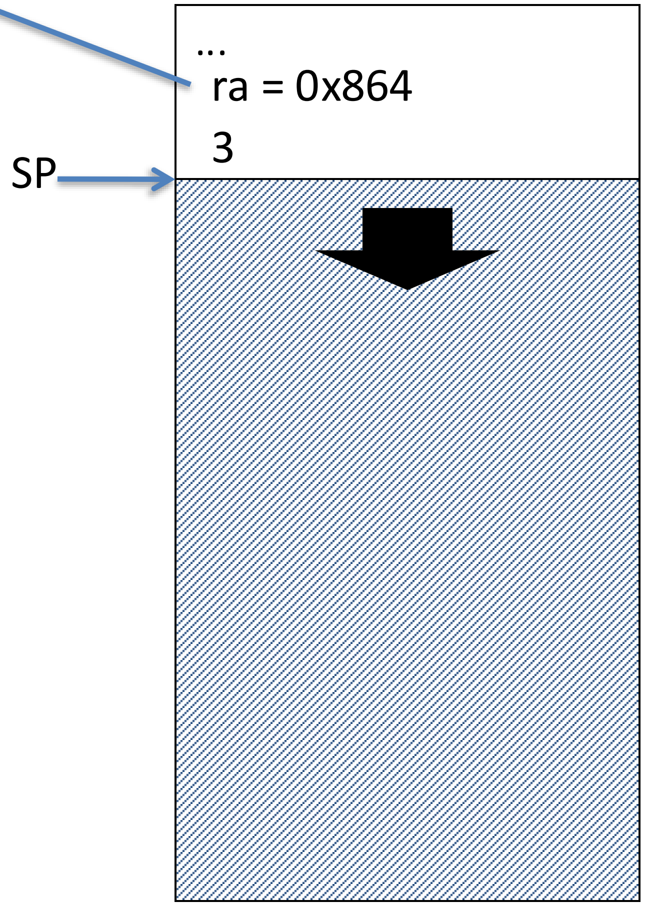


fact

$ra = 0x864
$a0 = 3
$v0 =
$t0 = 0

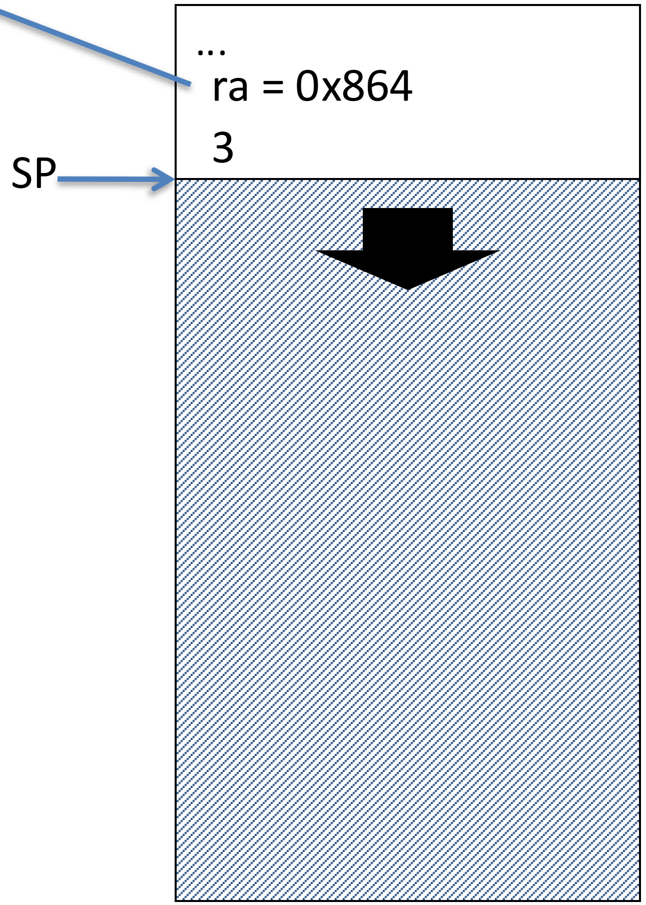
```
fact:
         addi $sp, $sp, -8     # adjust stack for 2 items
         sw   $ra, 8($sp)      # save return address
         sw   $a0, 4($sp)      # save argument
PC →     slti $t0, $a0, 2      # test for n < 2
         beq  $t0, $zero, L1
         addi $v0, $zero, 1    # if so, result is 1
         addi $sp, $sp, 8      #   pop 2 items from stack
         jr   $ra              #   and return
     L1: addi $a0, $a0, -1     # else decrement n
         jal  fact             # recursive call
         lw   $a0, 4($sp)      # restore original n
         lw   $ra, 8($sp)      #   and return address
         addi $sp, $sp, 8      # pop 2 items from stack
         mul  $v0, $a0, $v0    # multiply to get result
         jr   $ra              # and return
```



$ra = 0x864
$a0 = 3
$v0 =
$t0 = 0

fact

```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
PC      beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```

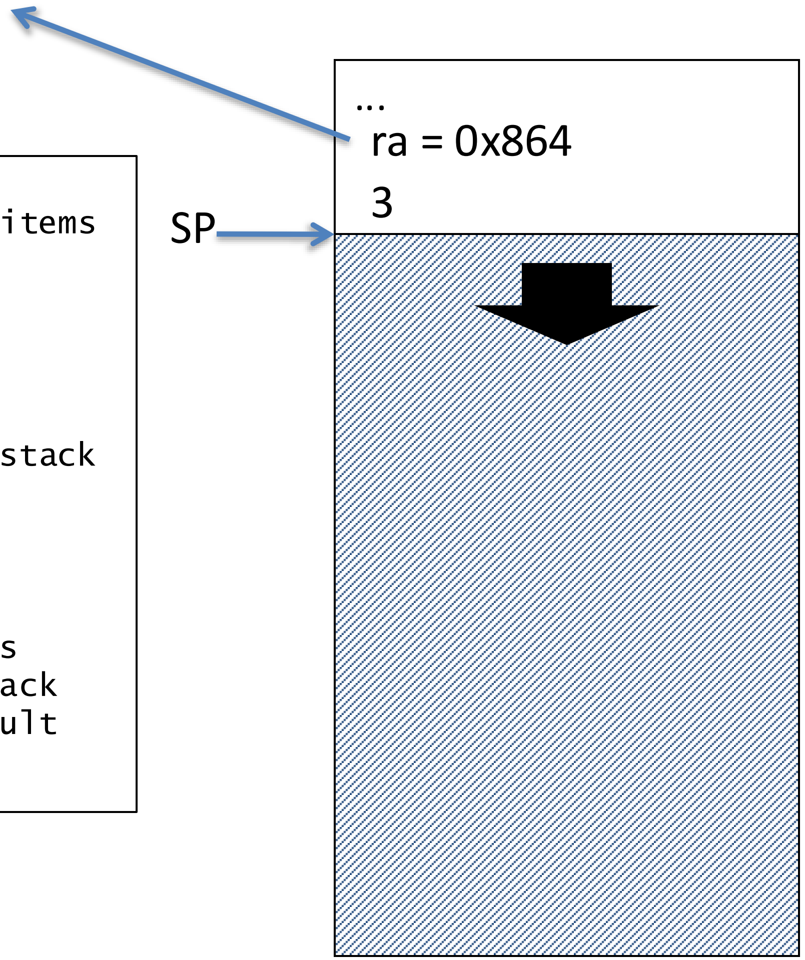


fact

$ra = 0x864
$a0 = 2
$v0 =
$t0 = 0

PC

```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



After this line of code, the next line of code we run will be

```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
PC →    jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```

A. `lw $a0, 4($sp)`

B. `addi $a0, $a0, -1`

C. `addi $sp, $sp, -8`

D. `jr $ra`

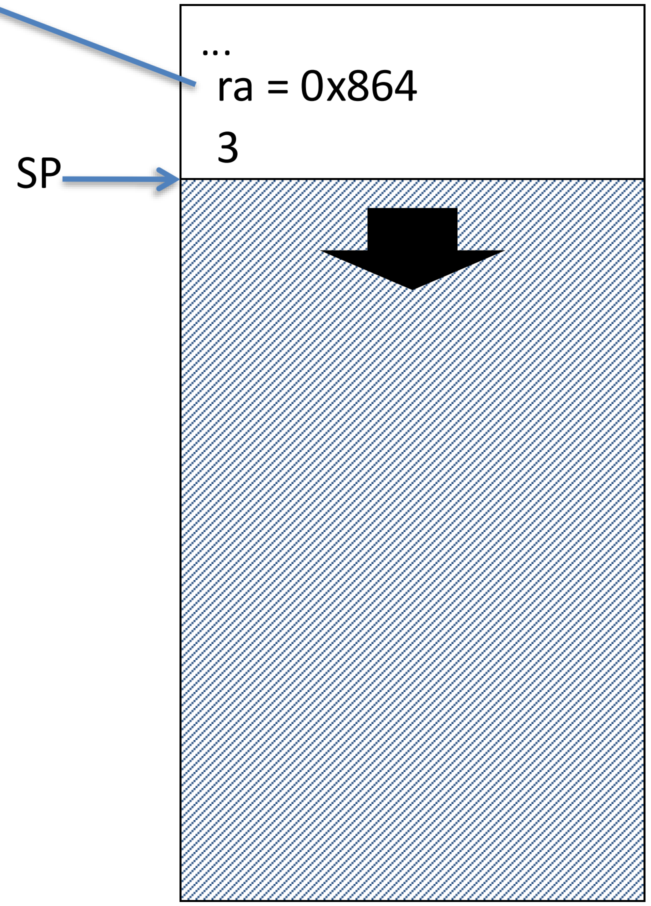
E. None of the above

$ra = 0x864
$a0 = 2
$v0 =
$t0 = 0

fact

$ra = L1 + 8
$a0 = 2
$v0 =
$t0 = 0

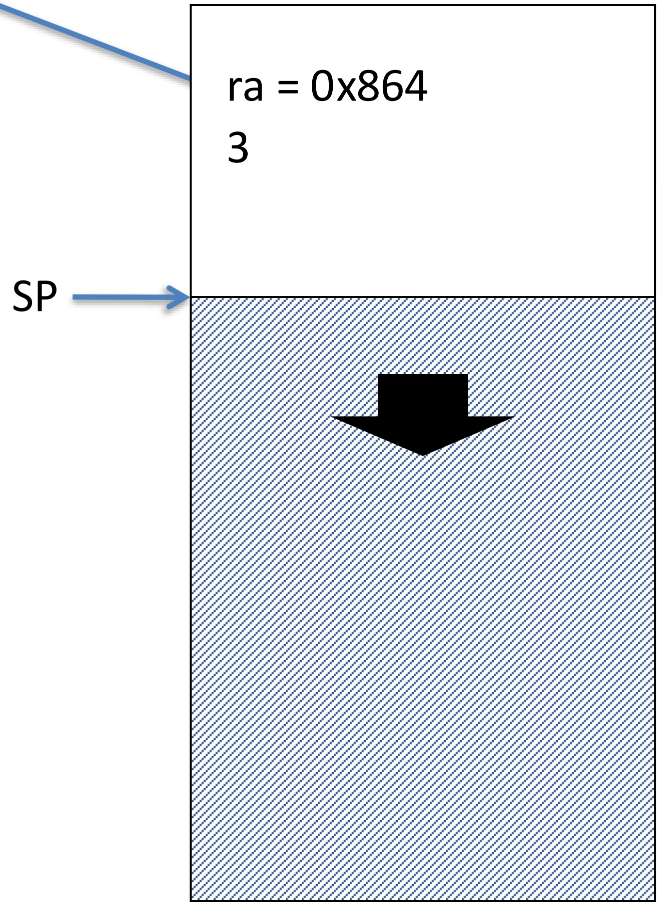
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
PC      jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 2
$v0 =
$t0 =

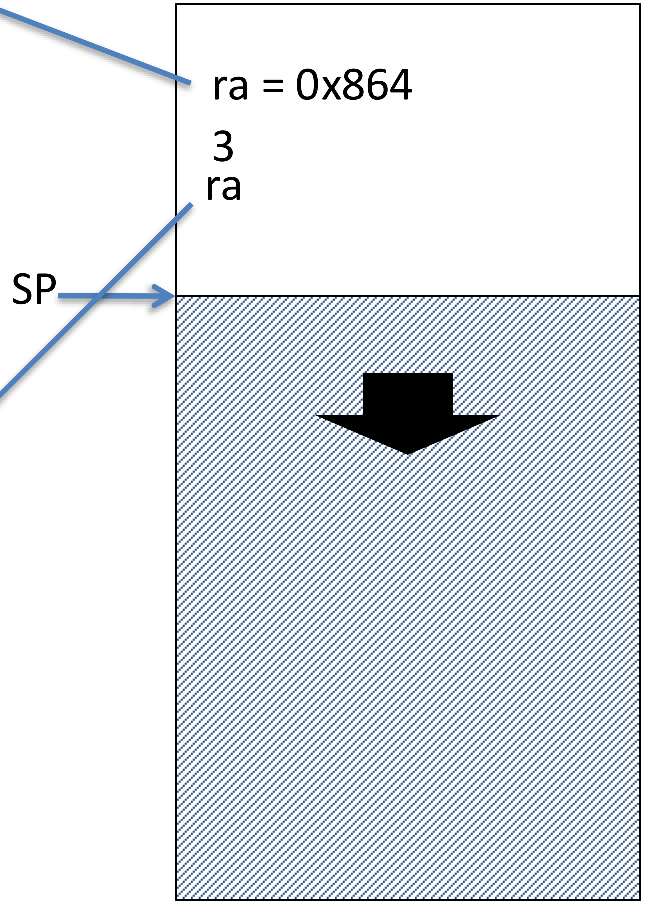
```
 fact:
PC      addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 2
$v0 =
$t0 = 0

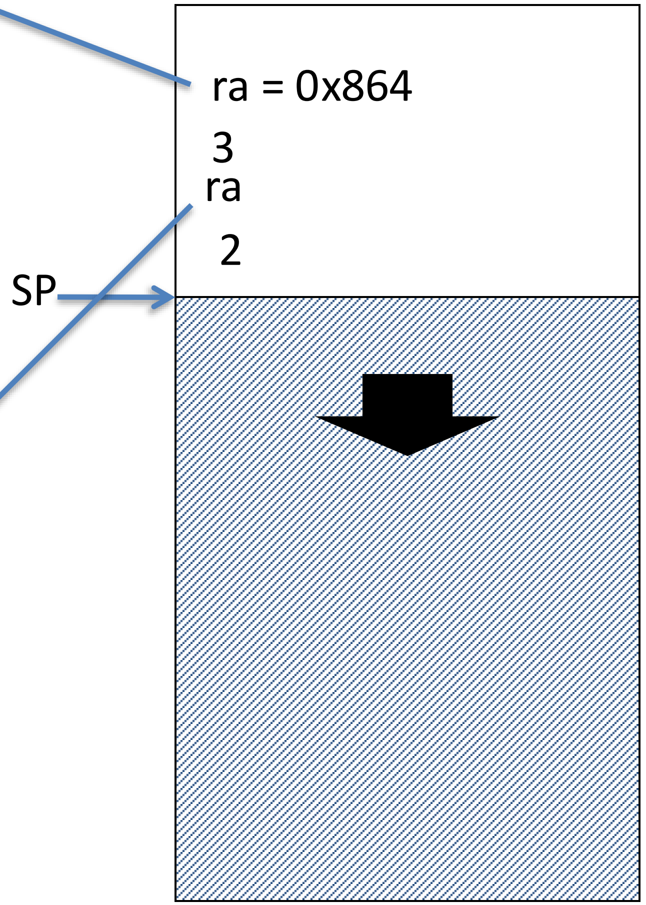
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
PC      sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 2
$v0 =
$t0 = 0

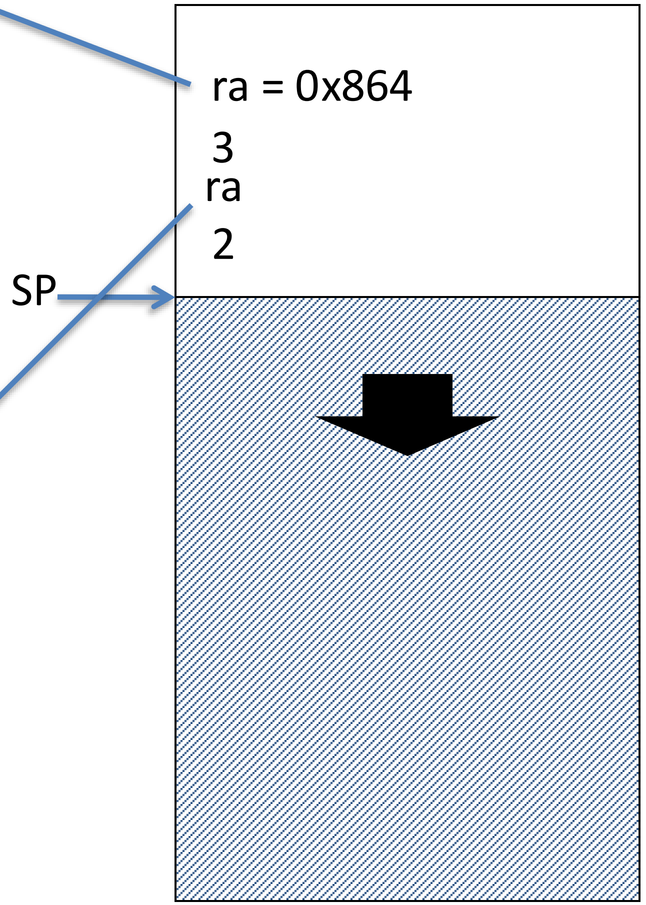
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
PC      sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 2
$v0 =
$t0 = 0

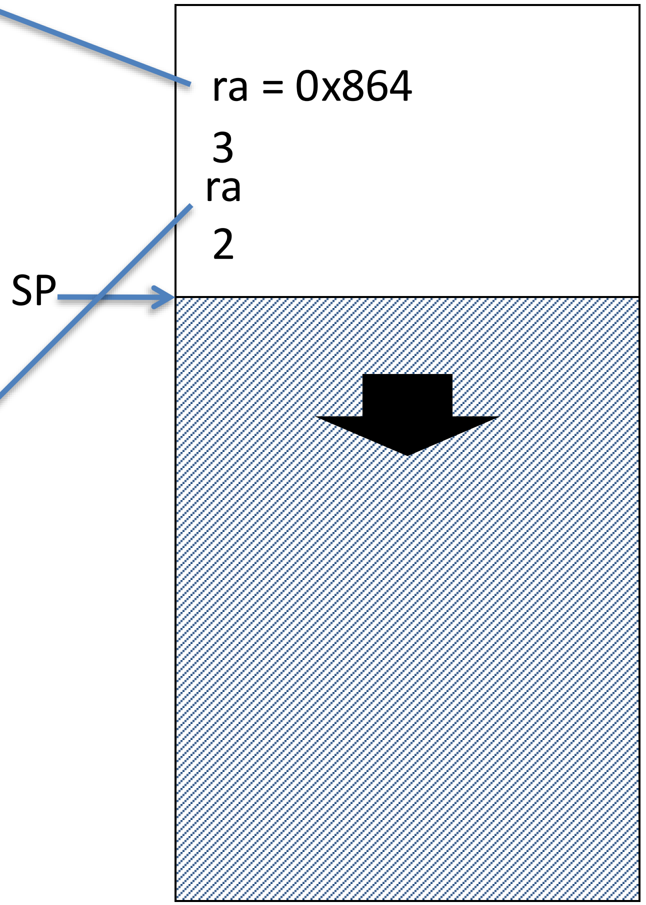
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
PC ->   slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 2
$v0 =
$t0 = 0

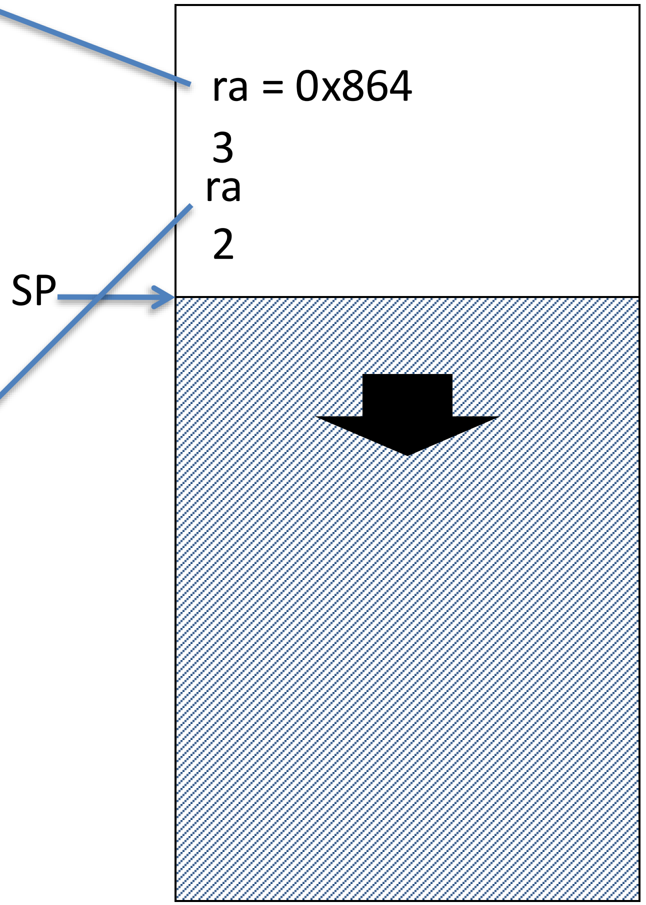
```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
        sw   $ra, 8($sp)       # save return address
        sw   $a0, 4($sp)       # save argument
        slti $t0, $a0, 2       # test for n < 2
PC      beq  $t0, $zero, L1
        addi $v0, $zero, 1     # if so, result is 1
        addi $sp, $sp, 8       #   pop 2 items from stack
        jr   $ra               #   and return
    L1: addi $a0, $a0, -1      # else decrement n
        jal  fact              # recursive call
        lw   $a0, 4($sp)       # restore original n
        lw   $ra, 8($sp)       #   and return address
        addi $sp, $sp, 8       # pop 2 items from stack
        mul  $v0, $a0, $v0     # multiply to get result
        jr   $ra               # and return
```



fact

$ra = L1 + 8
$a0 = 1
$v0 =
$t0 = 0

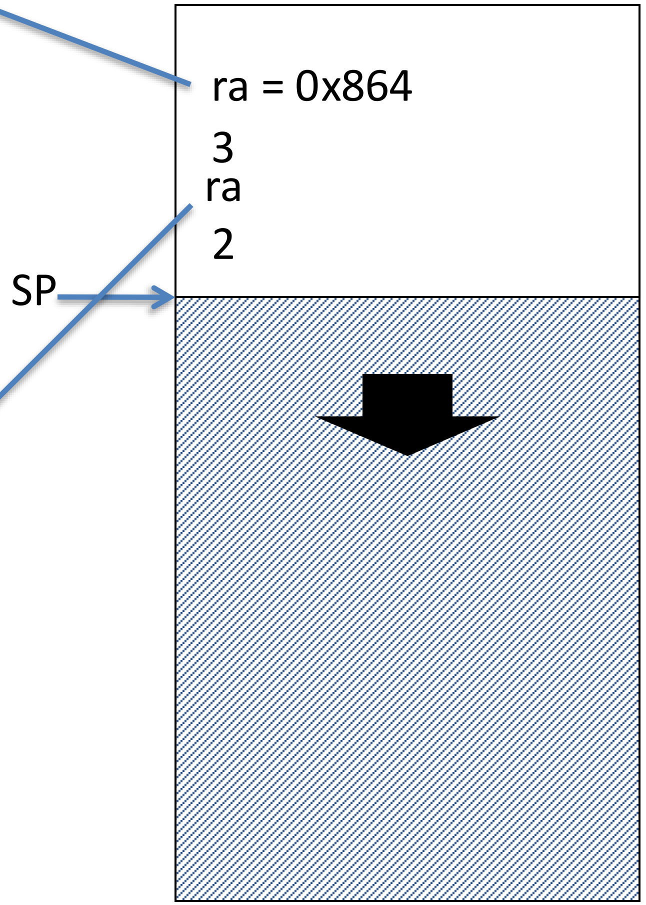
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
PC   L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 1
$v0 =
$t0 = 0

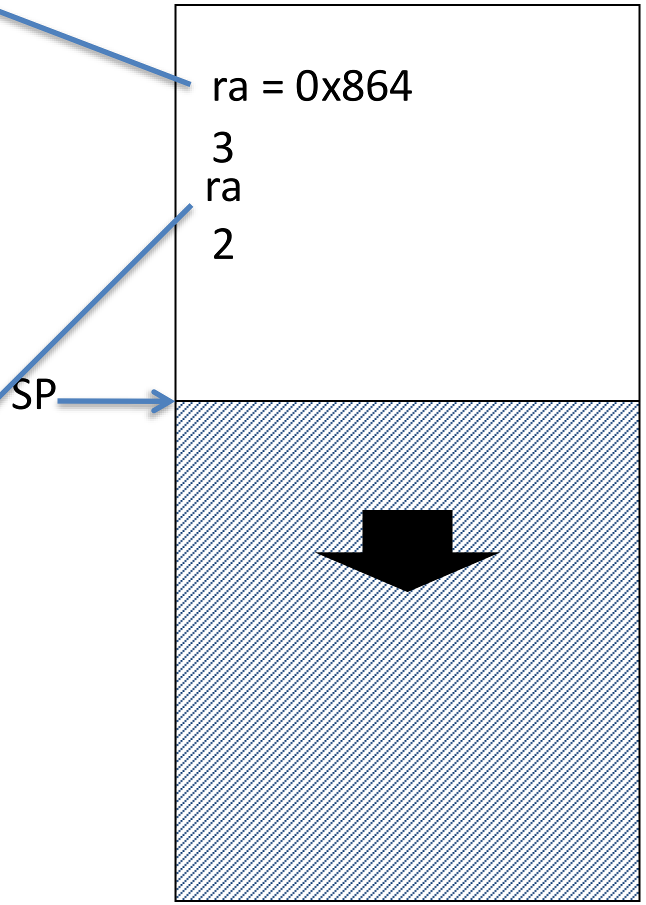
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
PC      jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 1
$v0 =
$t0 = 0

```
fact:
PC      addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```

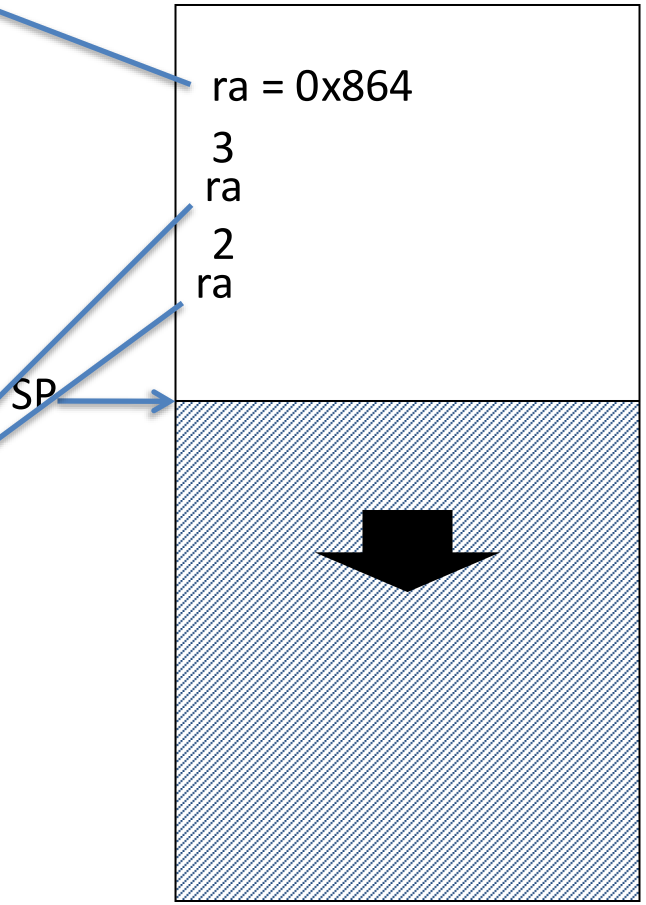


fact

$ra = L1 + 8
$a0 = 1
$v0 =
$t0 = 0

PC

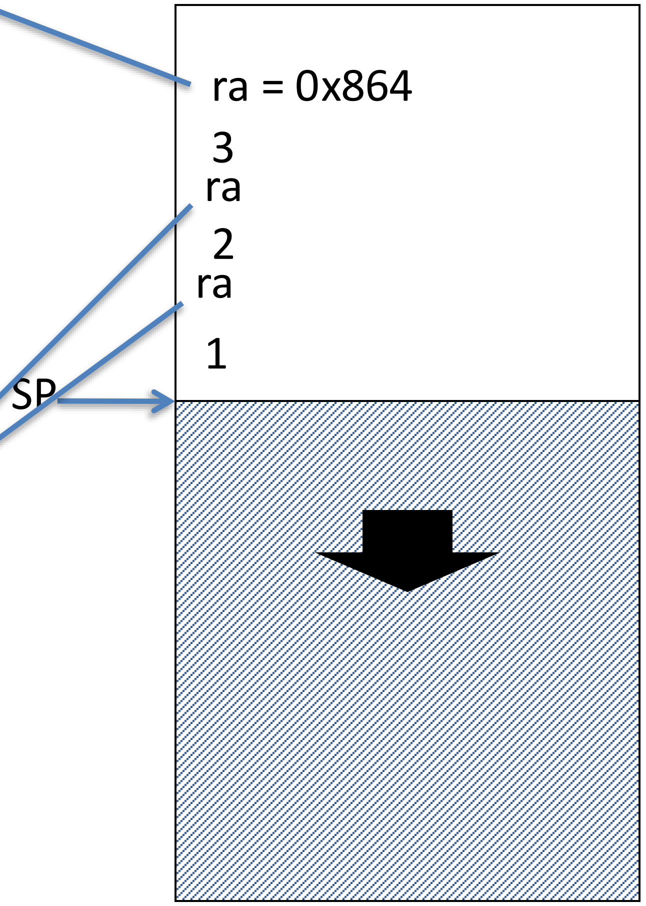
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 1
$v0 =
$t0 = 0

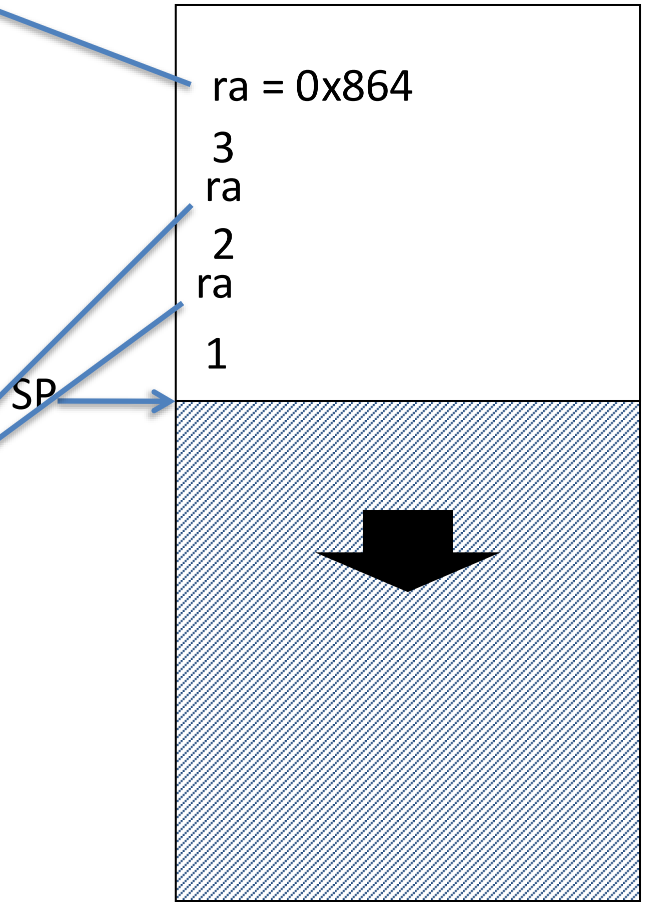
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
PC      sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 1
$v0 =
$t0 = 1

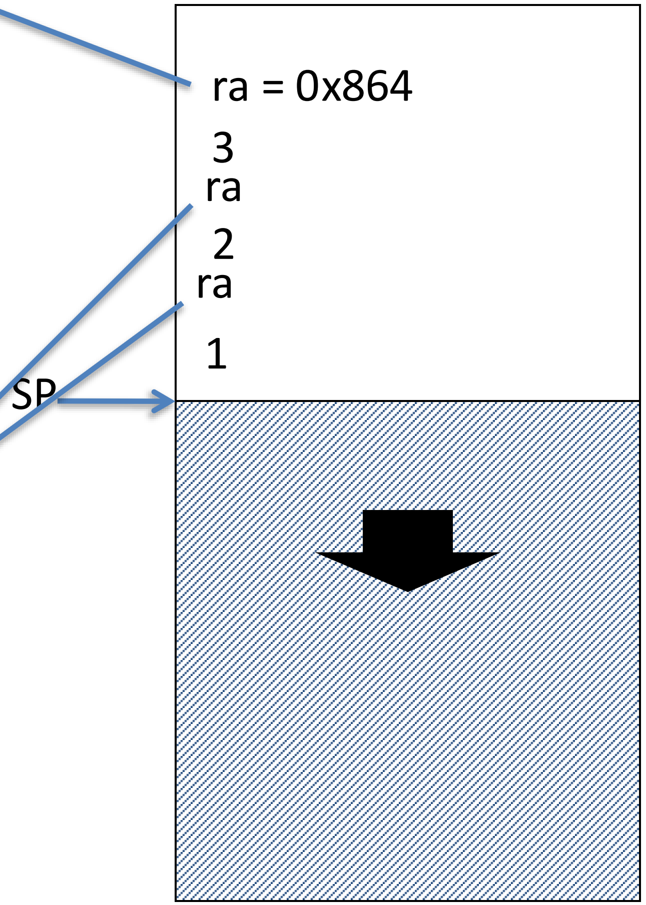
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
PC      slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 1
$v0 =
$t0 = 1

```
fact:
       addi $sp, $sp, -8     # adjust stack for 2 items
       sw   $ra, 8($sp)      # save return address
       sw   $a0, 4($sp)      # save argument
       slti $t0, $a0, 2      # test for n < 2
PC     beq  $t0, $zero, L1
       addi $v0, $zero, 1    # if so, result is 1
       addi $sp, $sp, 8      #   pop 2 items from stack
       jr   $ra              #   and return
   L1: addi $a0, $a0, -1     # else decrement n
       jal  fact             # recursive call
       lw   $a0, 4($sp)      # restore original n
       lw   $ra, 8($sp)      #   and return address
       addi $sp, $sp, 8      # pop 2 items from stack
       mul  $v0, $a0, $v0    # multiply to get result
       jr   $ra              # and return
```

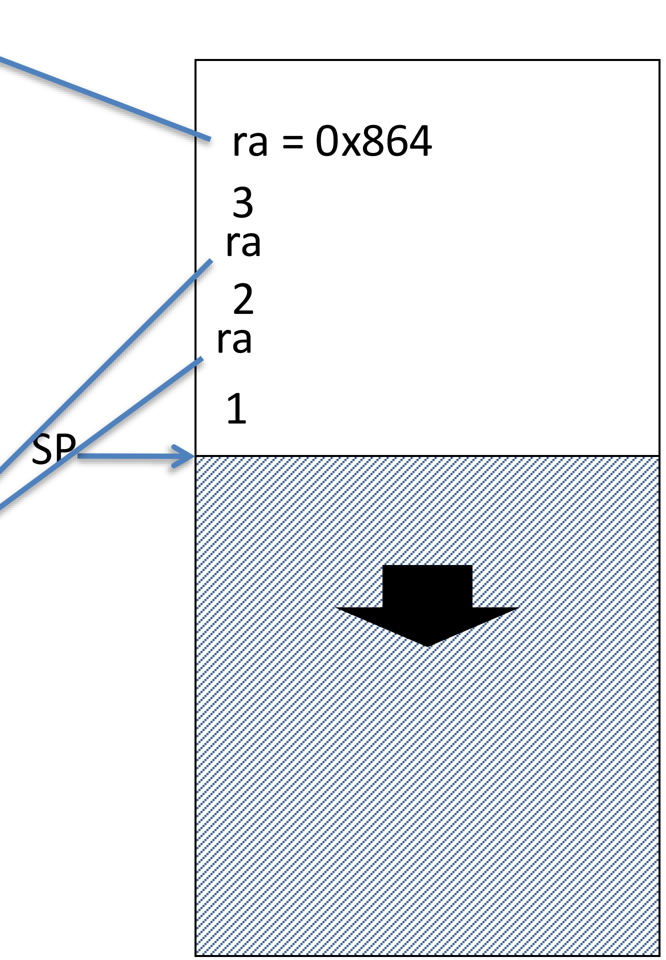


fact

$ra = L1 + 8
$a0 = 1
$v0 = 1
$t0 = 1

PC

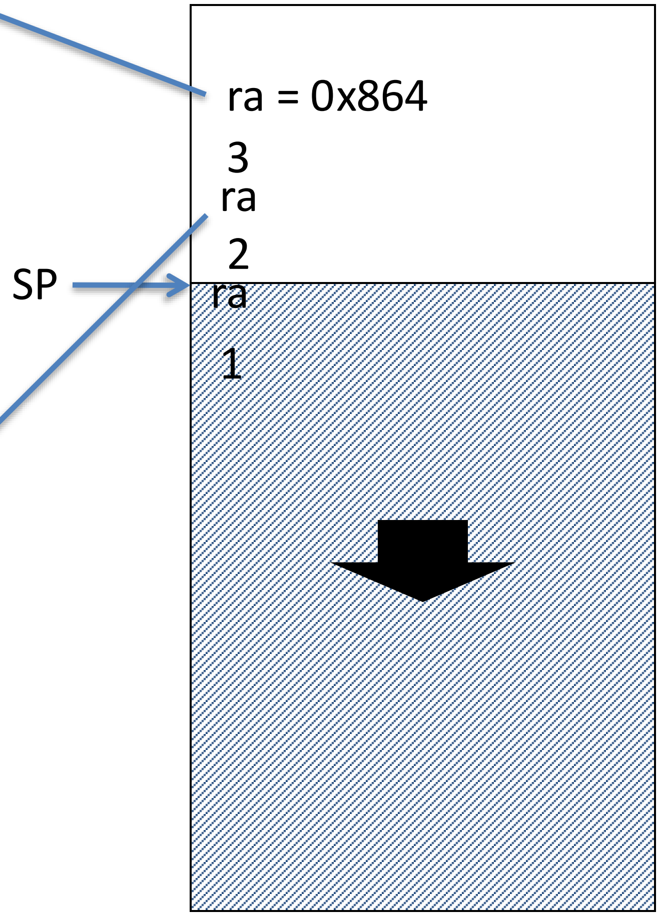
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 1
$v0 = 1
$t0 = 1

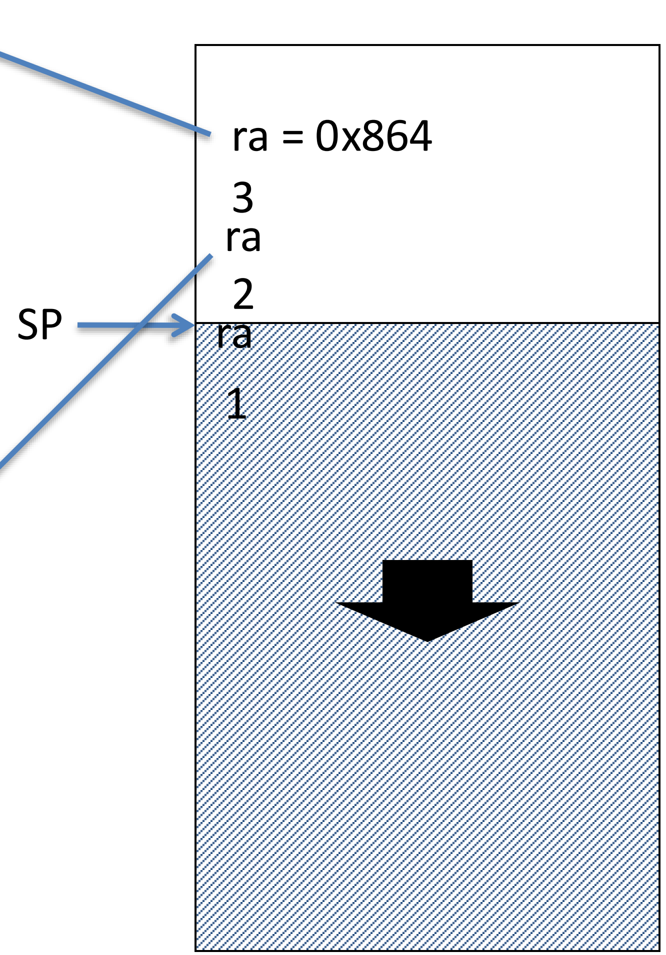
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
PC →    addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 1
$v0 = 1
$t0 = 1

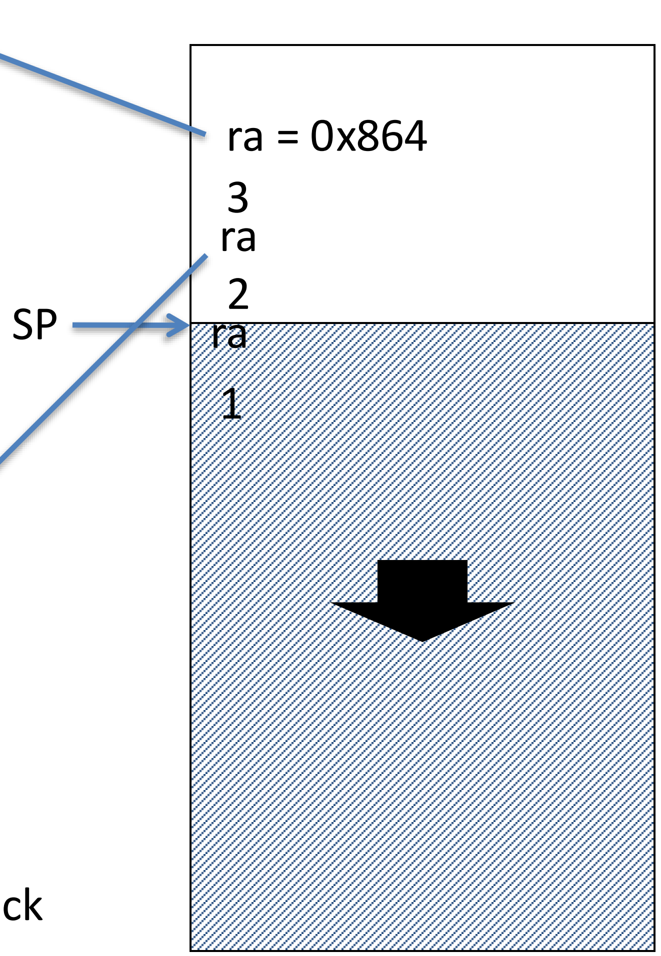
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
PC →    jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



We will return to

$ra = L1 + 8
$a0 = 1
$v0 = 1
$t0 = 1

```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
PC ->   jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```

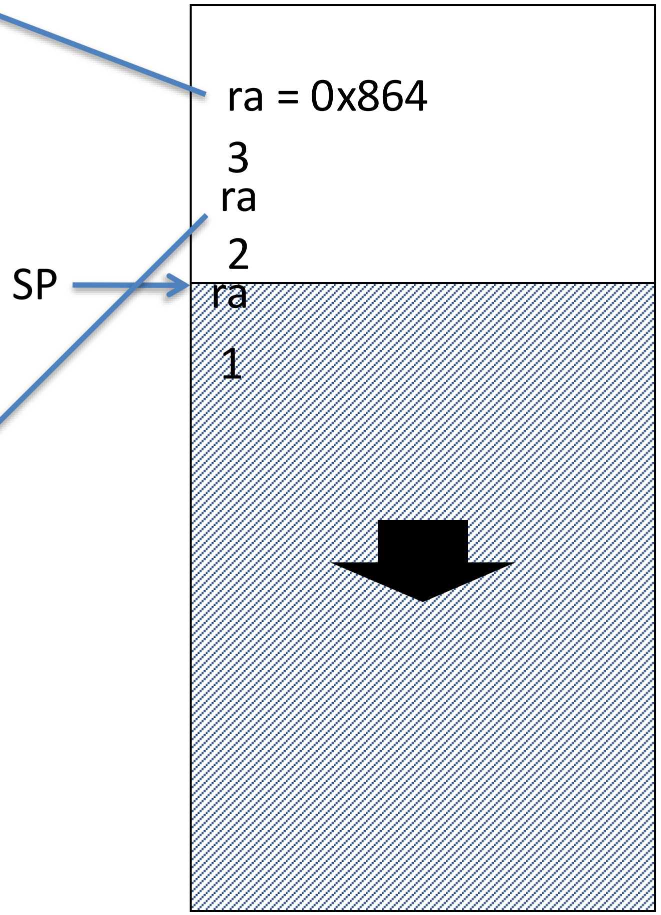


A. L1 + 8, because it in $ra
B. L1 + 8, because it’s the most recent value on the stack
C. 0x864, because it’s the top value on the stack
D. fact, because it’s the procedure call
E. None of the above

fact

$ra = L1 + 8
$a0 = 2
$v0 = 1
$t0 = 1

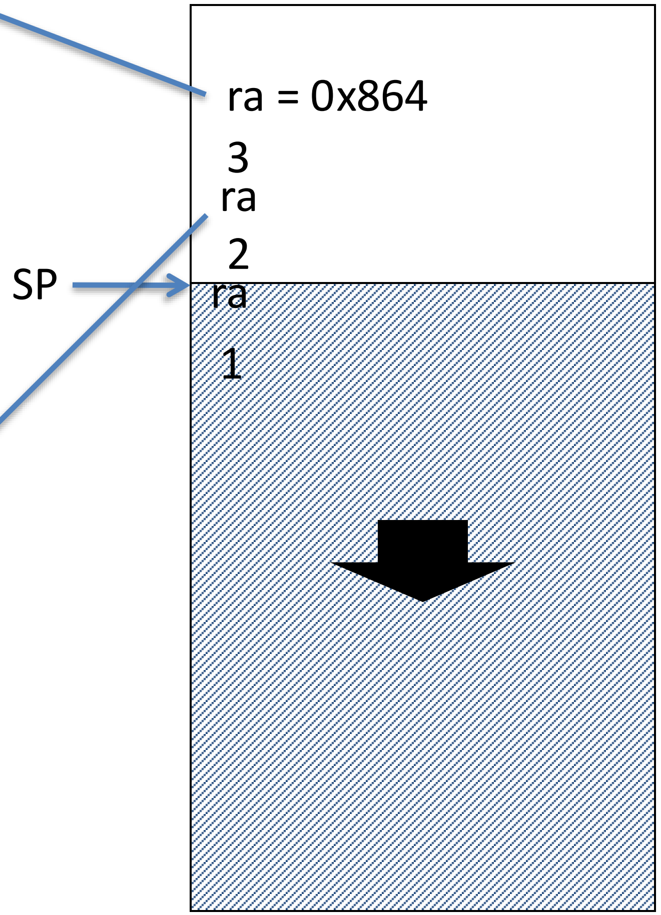
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
PC  →   lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 2
$v0 = 1
$t0 = 1

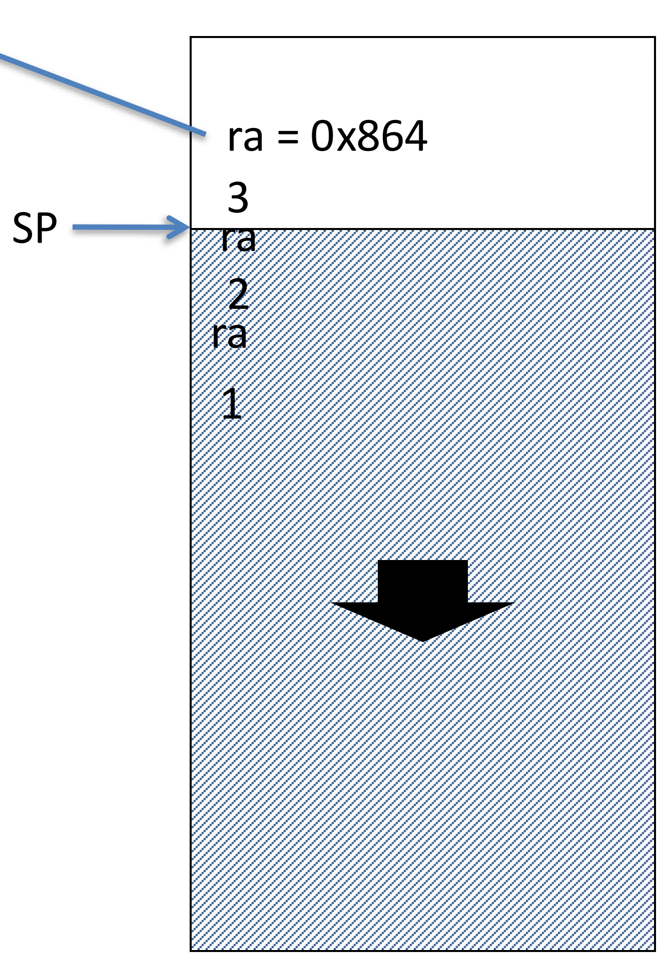
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
PC →    lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 2
$v0 = 1
$t0 = 1

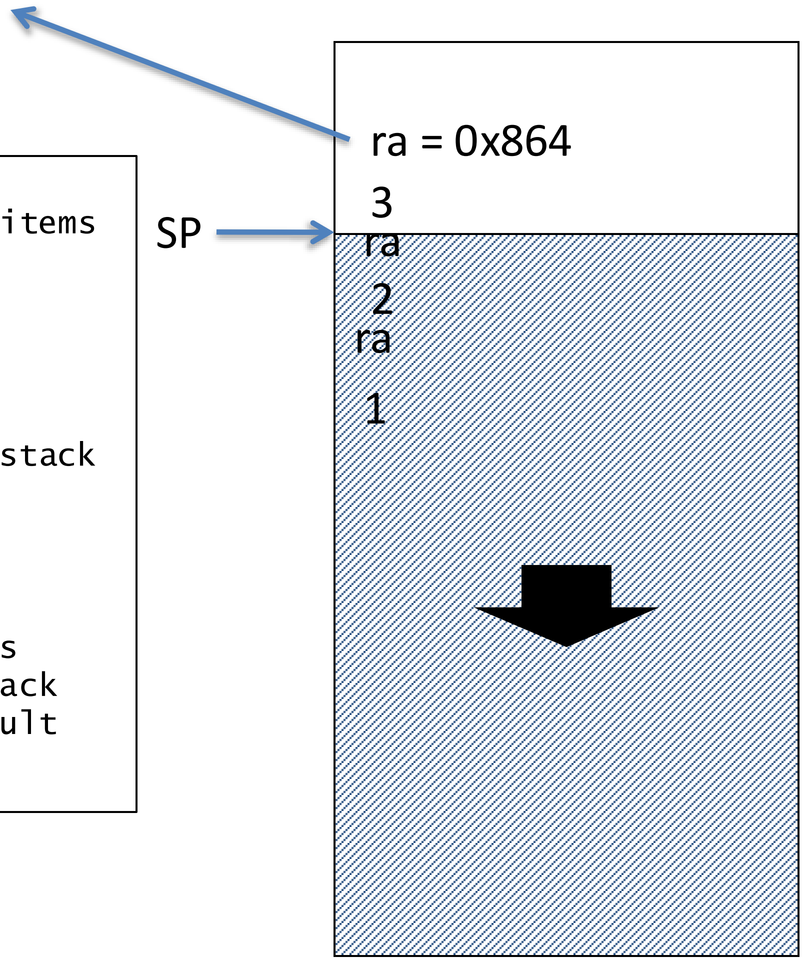
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
PC      addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 2
$v0 = 2
$t0 = 1

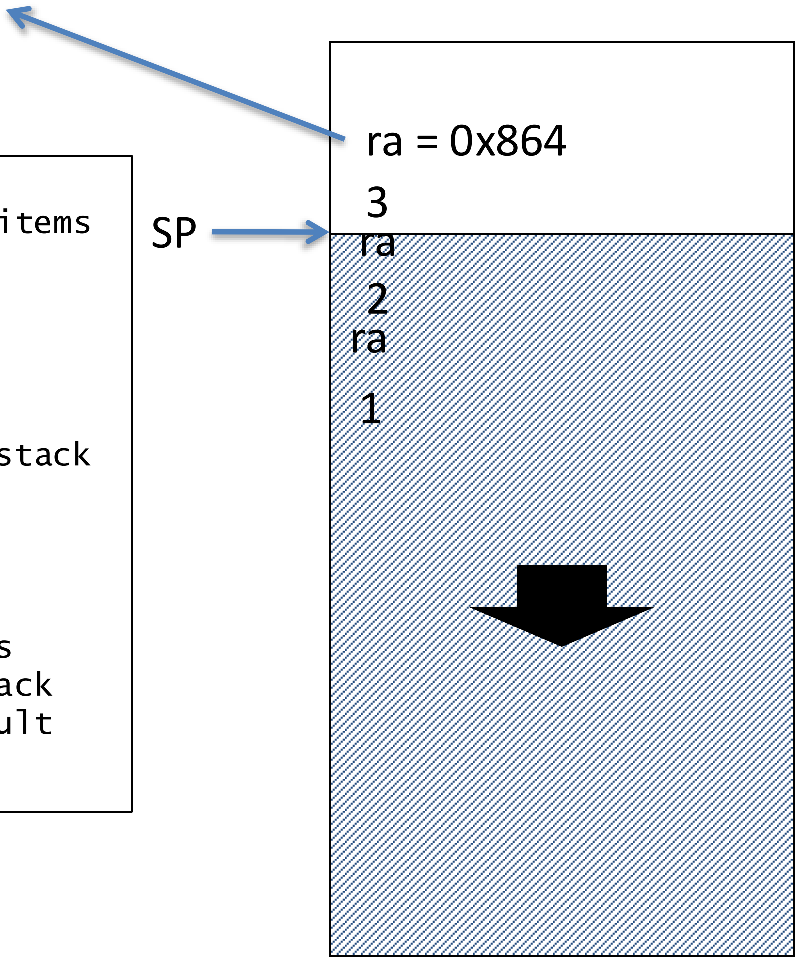
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
PC →    mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = L1 + 8
$a0 = 2
$v0 = 2
$t0 = 1

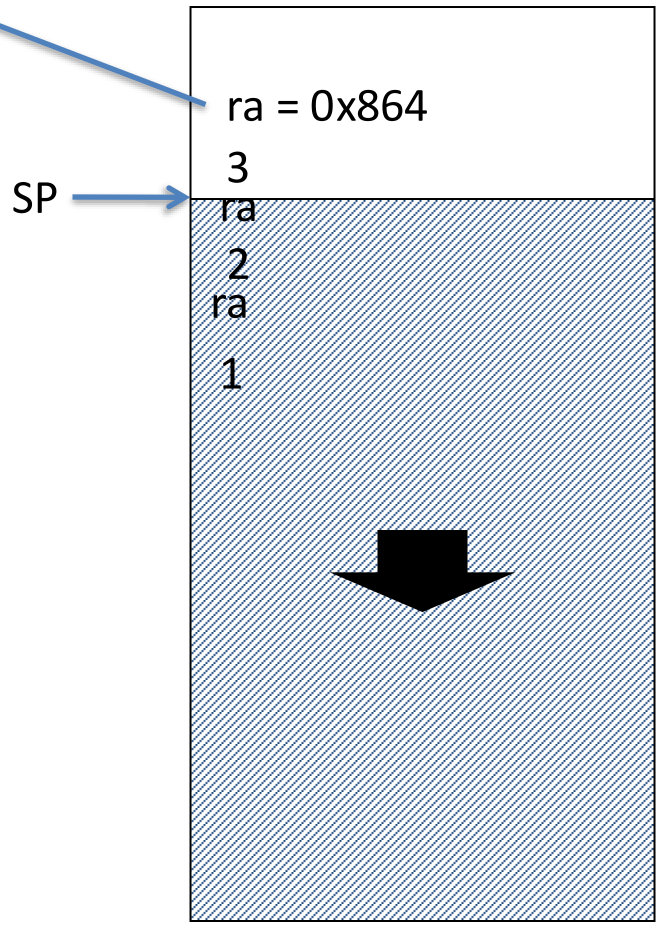
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
PC      jr   $ra              # and return
```



$ra = L1 + 8
$a0 = 3
$v0 = 2
$t0 = 1

fact

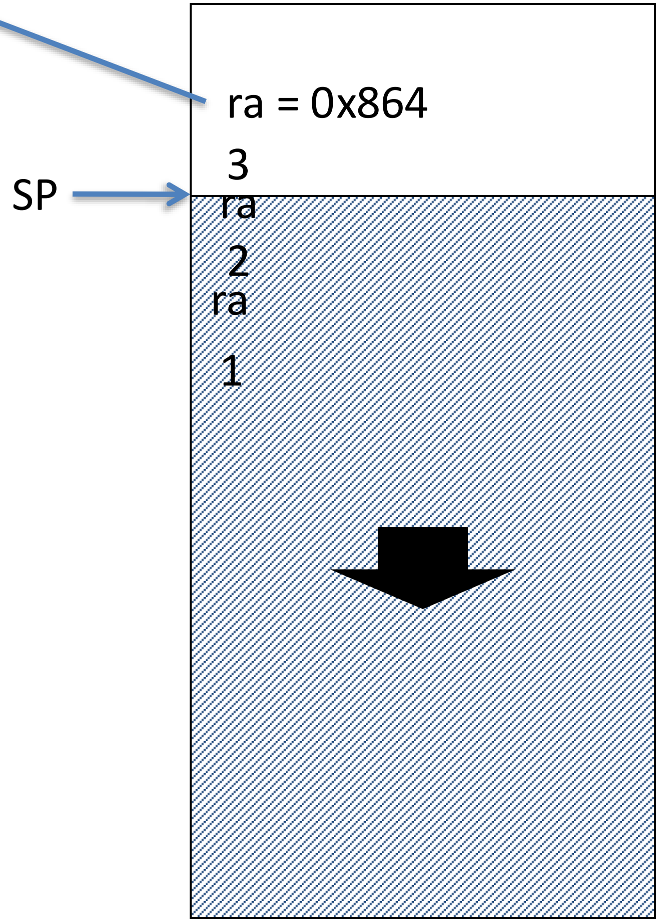
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
PC→     lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



fact

$ra = 0x864
$a0 = 3
$v0 = 2
$t0 = 1

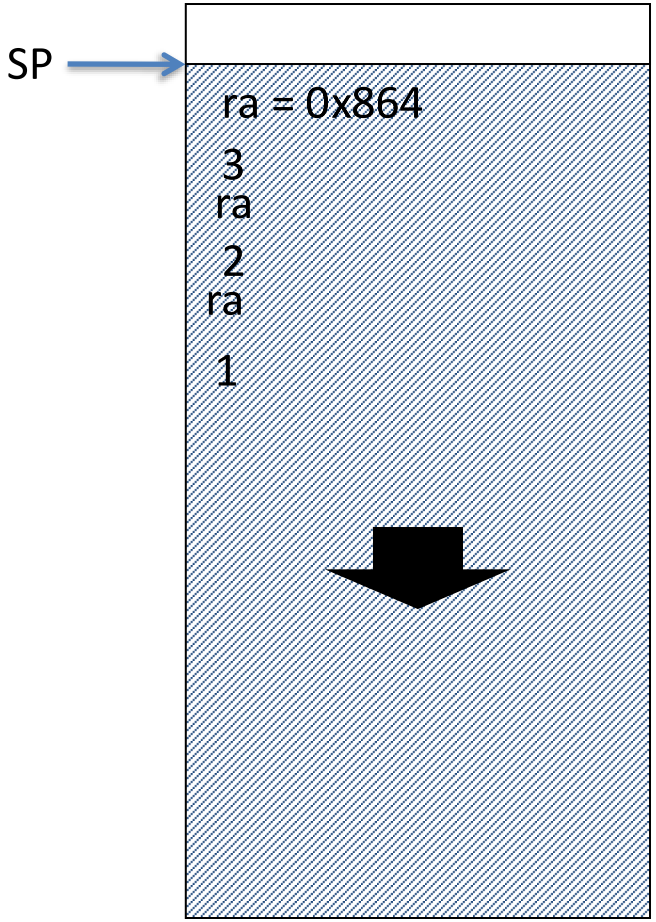
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
PC      lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



$ra = 0x864
$a0 = 3
$v0 = 2
$t0 = 1

fact

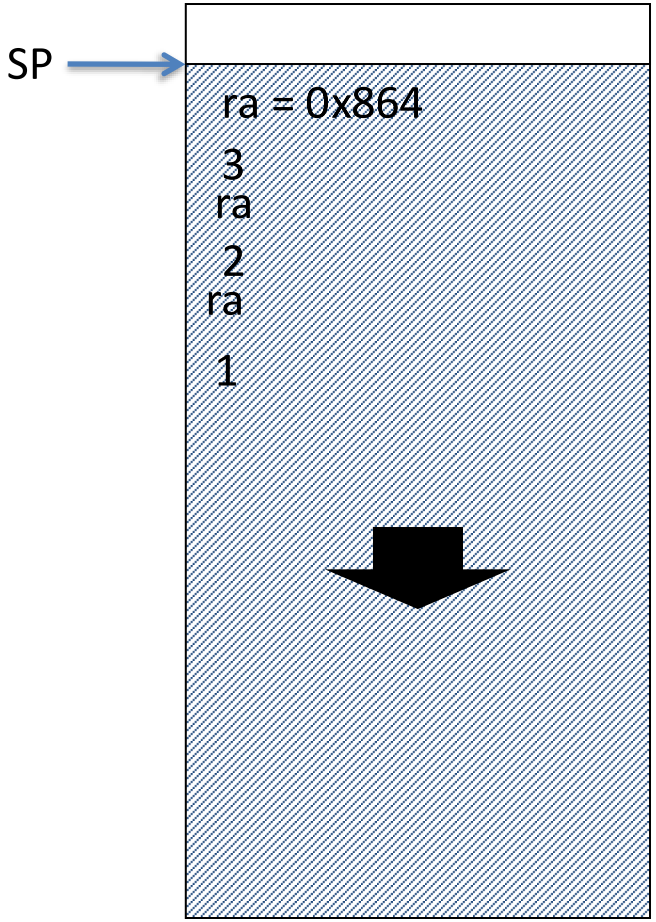
```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
        sw   $ra, 8($sp)       # save return address
        sw   $a0, 4($sp)       # save argument
        slti $t0, $a0, 2       # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1     # if so, result is 1
        addi $sp, $sp, 8       #   pop 2 items from stack
        jr   $ra               #   and return
    L1: addi $a0, $a0, -1      # else decrement n
        jal  fact              # recursive call
        lw   $a0, 4($sp)       # restore original n
        lw   $ra, 8($sp)       #   and return address
PC →    addi $sp, $sp, 8       # pop 2 items from stack
        mul  $v0, $a0, $v0     # multiply to get result
        jr   $ra               # and return
```



fact

$ra = 0x864
$a0 = 3
$v0 = 6
$t0 = 1

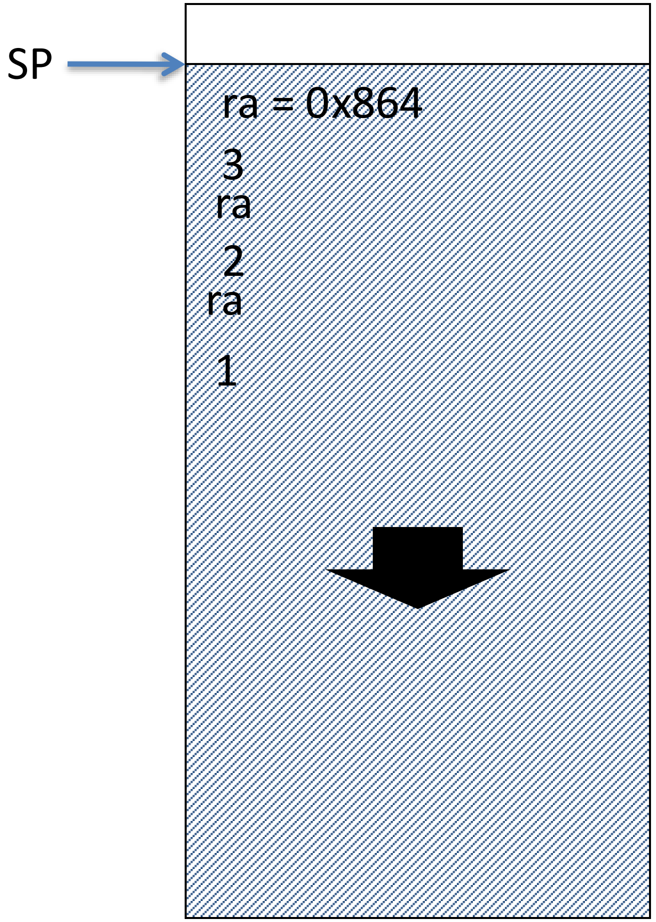
```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
PC →    mul  $v0, $a0, $v0    # multiply to get result
        jr   $ra              # and return
```



$ra = 0x864
$a0 = 3
$v0 = 6
$t0 = 1

fact

```
fact:
        addi $sp, $sp, -8     # adjust stack for 2 items
        sw   $ra, 8($sp)      # save return address
        sw   $a0, 4($sp)      # save argument
        slti $t0, $a0, 2      # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1    # if so, result is 1
        addi $sp, $sp, 8      #   pop 2 items from stack
        jr   $ra              #   and return
    L1: addi $a0, $a0, -1     # else decrement n
        jal  fact             # recursive call
        lw   $a0, 4($sp)      # restore original n
        lw   $ra, 8($sp)      #   and return address
        addi $sp, $sp, 8      # pop 2 items from stack
        mul  $v0, $a0, $v0    # multiply to get result
PC      jr   $ra              # and return
```



Why store registers relative to the stack pointer, rather than at some set memory location?

A. Saves space.

B. Easier to figure out where we stored things.

C. Functions won’t overwrite each other’s saves.

D. None of the above

Assembler directives

- Instructions to the assembler
  - .data / .text / .rodata / .bss are used to switch between global (mutable) data, executable code, read-only data, and uninitialized data in the output
  - .word x allocates space for 4 bytes with value x
  - .space n allocates n bytes of space
  - .asciiz “string” writes a 0-terminated string at that location

Review: Arrays!

- How do we declare a 10-word array in our data section?

- Could do

```
.data
 x1:    .word 0
 x2:    .word 0
 x3:    .word 0
 ...
 x10:   .word 0
```

Review: Declaring an Array

- Instead, just declare a big chunk of memory

```
.data
arr:  .space  40
```

```
.data
arr:    .space 40

.text
    li      $t0, 0
    addi    $t1, $t0, 10
    la      $s0, arr
loop:
    beq         $t0, $t1, end
    What goes here?
    addi    $t0, $t0, 1
    j           loop
end:
```

```
int i;
for (i = 0; i < 10; i++){
        arr[i] = i;
}
```

```
sw      $t0, $t1($s0)
```

A

```
add     $t2, $s0, $t1
sw      $t0, 0($t2)
```

B

```
sw      $t0, 0($s0)
addi    $s0, $s0, 4
```

C

D. More than one of the above

E. None of the above

But what if we don’t know how big the array will be before runtime?

sbrk system call

- Allocates memory and returns its address in $v0
- Amount of memory is specified in bytes in $a0
- Used by malloc, new

System Calls

- Syscalls (when we need OS intervention)
  - I/O (print/read stdout/file)
  - Exit (terminate)
  - Get system time
  - Random values

System Calls Review

- How to use:
  - Put syscall number into register $v0
  - Load arguments into argument registers
  - Issue syscall instruction
  - Retrieve return values
- Example (allocate $t4 bytes of memory with sbrk):

```
li      $v0, 9     # sbrk system call number
move    $a0, $t4# allocate $t4 bytes of mem
syscall
move    $s0, $v0# $s0 holds a pointer to mem
```

sbrk allocates memory from which region?

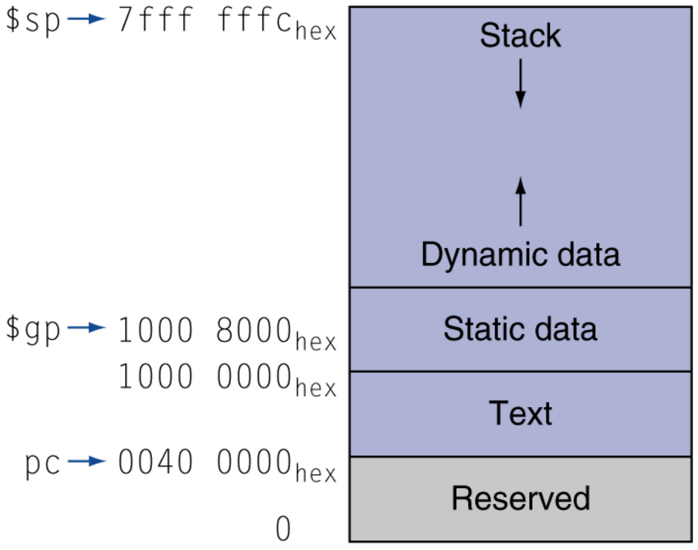
A. Stack

B. Dynamic data

C. Static data

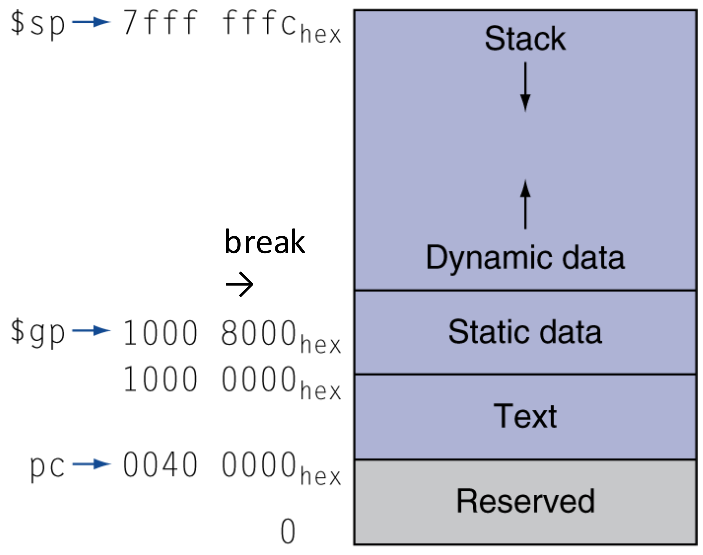
D. Text

E. Reserved



What about freeing memory?

- Some operating systems maintain a “program break” which controls the size of the dynamic data
- sbrk requests the OS increment/decrement the break
- malloc()/free() carve the dynamic data up into chunks which the application can use and maintain lists of free chunks
- Freeing memory adds the chunk to a “free list”
- When more memory is needed, the break is changed



Reading

- Next lecture: More Stack

- Problem set 3 due Today

- Lab 2 due Sunday