CSCI 210: Computer Architecture
Lecture 13: Procedures & The Stack

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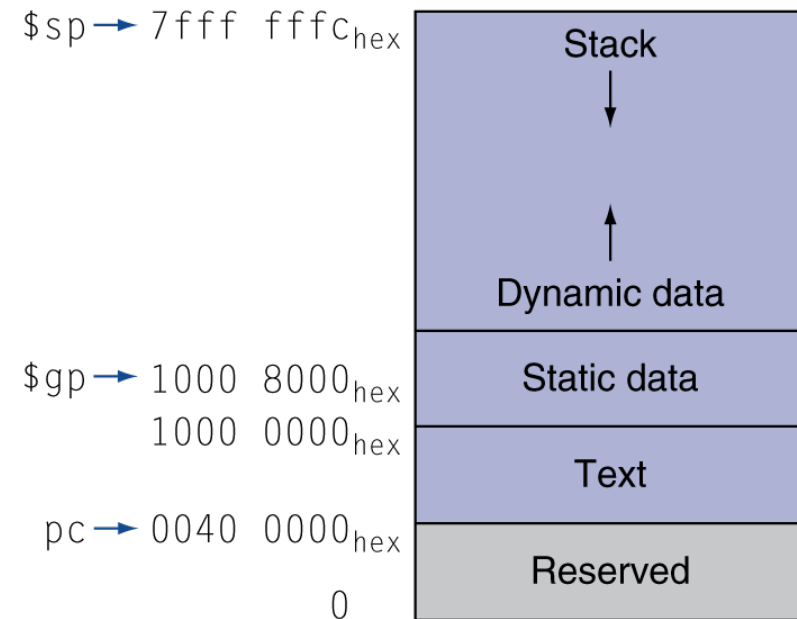
Slides from Cynthia Taylor

Announcements

- Problem Set 4 due Friday
- Lab 3 due Sunday
- Office hours: Tuesday 13:30–14:30

Last Class

- Spill and fill registers whose values we need to preserve
  - Return address $ra
  - Any saved registers $s0–$s7
  - Any temporary registers over function calls
  - Any time we have more variables than fit in registers

Leaf function Example

- C code:

```
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

  – f in $s0 (hence, need to save $s0 on stack)

  – Result in $v0

Leaf Procedure Example

- MIPS code:
- leaf_example:
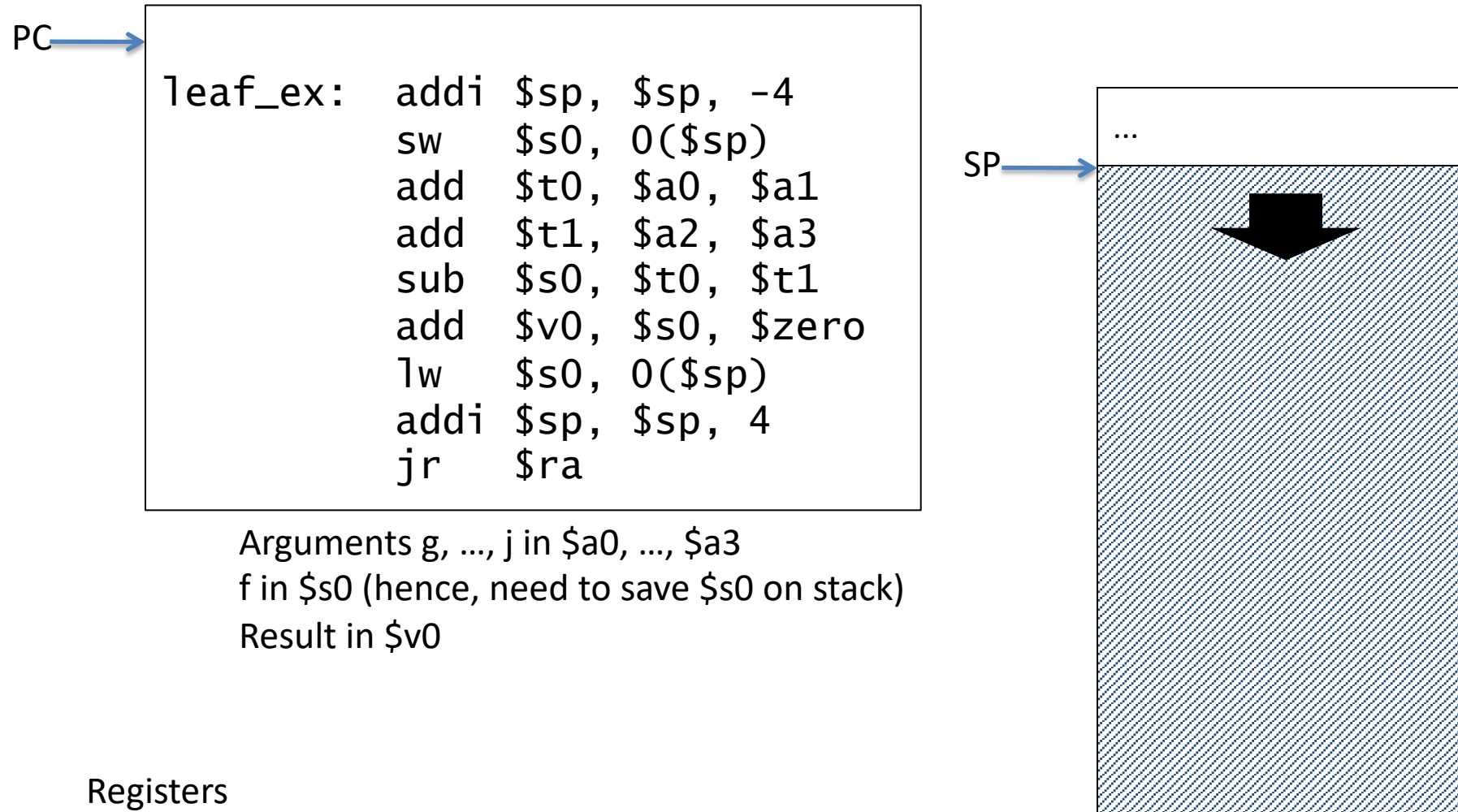
```
leaf_example:
    addi $sp, $sp, -4
    sw   $s0, 0($sp)

    add  $t0, $a0, $a1
    add  $t1, $a2, $a3
    sub  $s0, $t0, $t1
    move $v0, $s0

    lw   $s0, 0($sp)
    addi $sp, $sp, 4
    jr   $ra
```

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

Process Stack

PC

```
leaf_ex:   addi $sp, $sp, -4
           sw   $s0, 0($sp)
           add  $t0, $a0, $a1
           add  $t1, $a2, $a3
           sub  $s0, $t0, $t1
           add  $v0, $s0, $zero
           lw   $s0, 0($sp)
           addi $sp, $sp, 4
           jr   $ra
```

Arguments g, …, j in $a0, …, $a3
f in $s0 (hence, need to save $s0 on stack)
Result in $v0

SP

...

Registers
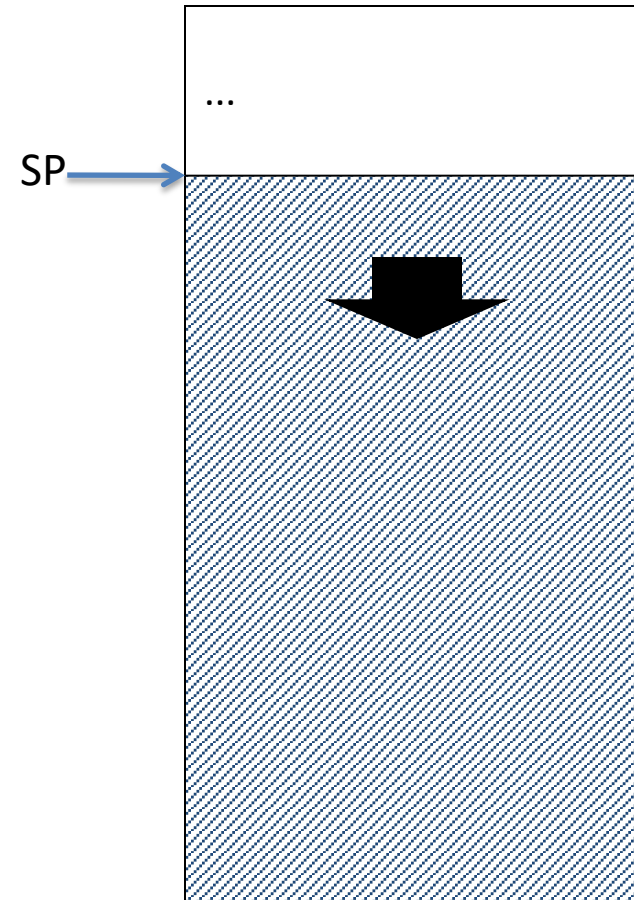$s0: 25 $a0: 5 $a1: 2 $a2: 3 $a3: 1
$t0: $t1: $v0:

Process Stack


```
PC ──▶ leaf_ex:   addi  $sp, $sp, -4
                  sw    $s0, 0($sp)
                  add   $t0, $a0, $a1
                  add   $t1, $a2, $a3
                  sub   $s0, $t0, $t1
                  add   $v0, $s0, $zero
                  lw    $s0, 0($sp)
                  addi  $sp, $sp, 4
                  jr    $ra
```

Arguments g, …, j in $a0, …, $a3
f in $s0 (hence, need to save $s0 on stack)
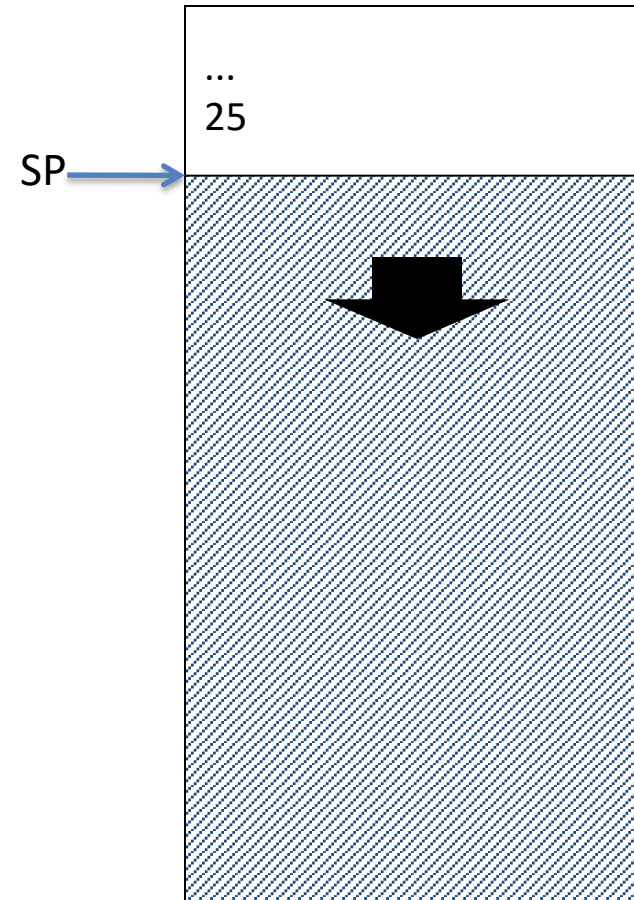Result in $v0

Registers
$s0: 25 $a0: 5 $a1: 2 $a2: 3 $a3: 1
$t0: $t1: $v0:

Process Stack

```
leaf_ex:    addi  $sp, $sp, -4
PC→         sw    $s0, 0($sp)
            add   $t0, $a0, $a1
            add   $t1, $a2, $a3
            sub   $s0, $t0, $t1
            add   $v0, $s0, $zero
            lw    $s0, 0($sp)
            addi  $sp, $sp, 4
            jr    $ra
```

Arguments g, …, j in $a0, …, $a3
f in $s0 (hence, need to save $s0 on stack)
Result in $v0

Registers
$s0: 25 $a0: 5 $a1: 2 $a2: 3 $a3: 1
$t0: $t1: $v0:

SP→

...
25

Process Stack

```
leaf_ex:   addi $sp, $sp, -4
           sw   $s0, 0($sp)
PC →       add  $t0, $a0, $a1
           add  $t1, $a2, $a3
           sub  $s0, $t0, $t1
           add  $v0, $s0, $zero
           lw   $s0, 0($sp)
           addi $sp, $sp, 4
           jr   $ra
```
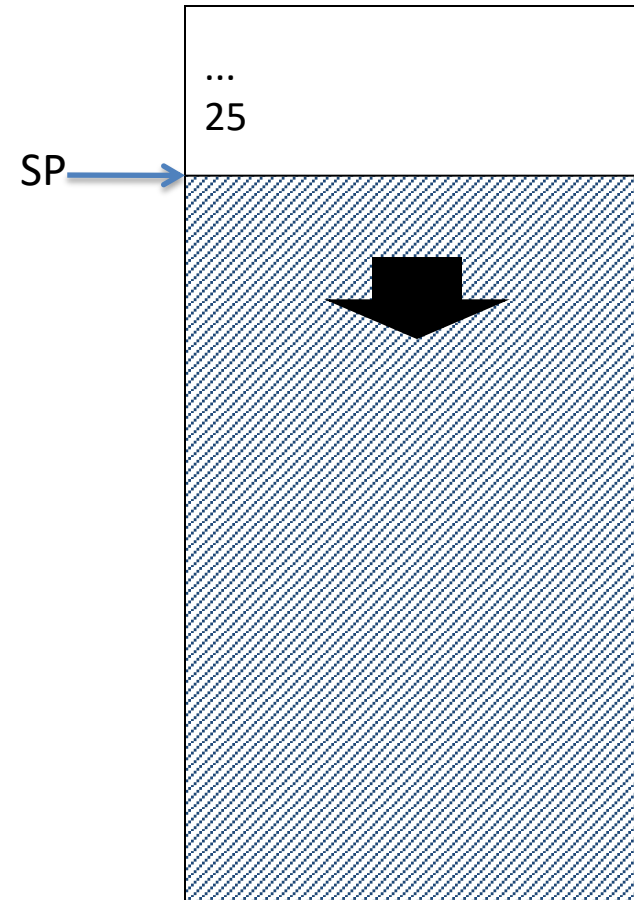
| ... |
| 25 |

SP →

Arguments g, …, j in $a0, …, $a3
f in $s0 (hence, need to save $s0 on stack)
Result in $v0

Registers
$s0: 25 $a0: 5 $a1: 2 $a2: 3 $a3: 1
$t0: 7 $t1: $v0:

Process Stack

```
leaf_ex:    addi $sp, $sp, -4
            sw   $s0, 0($sp)
            add  $t0, $a0, $a1
PC ->       add  $t1, $a2, $a3
            sub  $s0, $t0, $t1
            add  $v0, $s0, $zero
            lw   $s0, 0($sp)
            addi $sp, $sp, 4
            jr   $ra
```
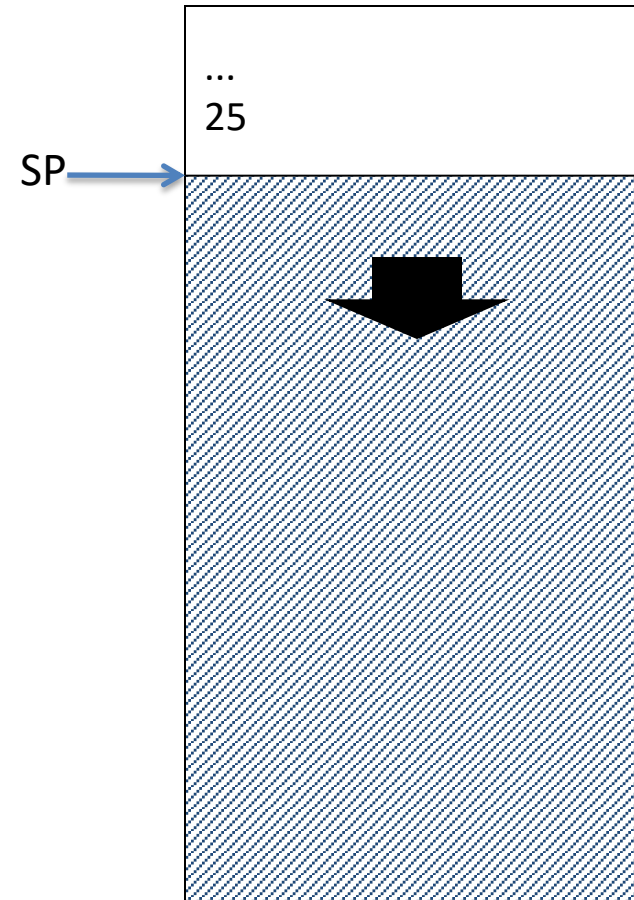
Arguments g, …, j in $a0, …, $a3
f in $s0 (hence, need to save $s0 on stack)
Result in $v0

Registers
$s0: 25 $a0: 5 $a1: 2 $a2: 3 $a3: 1
$t0: 7 $t1: 4 $v0:

...
25

SP

Process Stack

```
leaf_ex:   addi  $sp, $sp, -4
           sw    $s0, 0($sp)
           add   $t0, $a0, $a1
           add   $t1, $a2, $a3
PC →       sub   $s0, $t0, $t1
           add   $v0, $s0, $zero
           lw    $s0, 0($sp)
           addi  $sp, $sp, 4
           jr    $ra
```
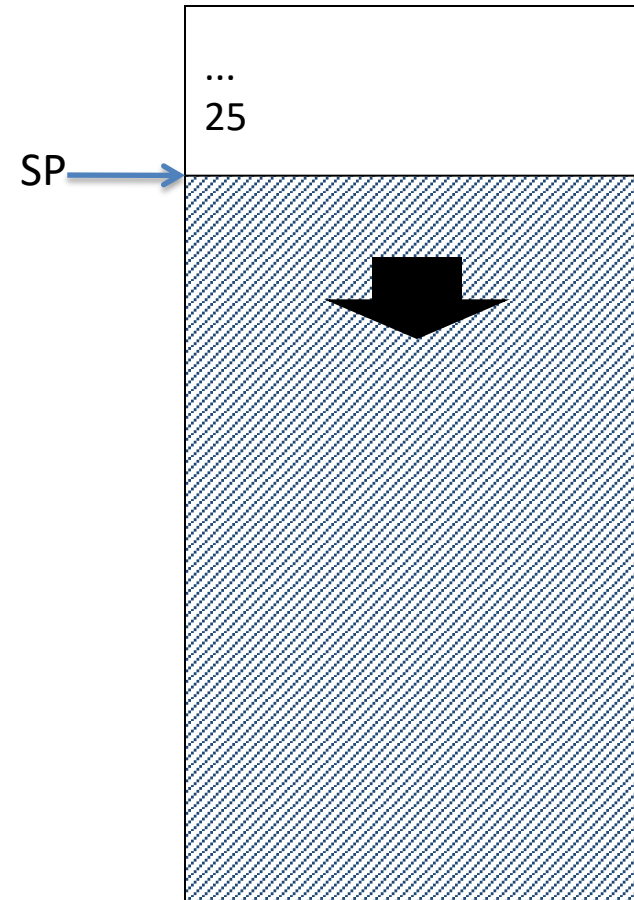
SP →

```
...
25
```

Arguments g, …, j in $a0, …, $a3
f in $s0 (hence, need to save $s0 on stack)
Result in $v0

Registers
$s0: 3 $a0: 5 $a1: 2 $a2: 3 $a3: 1
$t0: 7 $t1: 4 $v0:

Process Stack

```
leaf_ex:   addi  $sp, $sp, -4
           sw    $s0, 0($sp)
           add   $t0, $a0, $a1
           add   $t1, $a2, $a3
           sub   $s0, $t0, $t1
     PC →  add   $v0, $s0, $zero
           lw    $s0, 0($sp)
           addi  $sp, $sp, 4
           jr    $ra
```
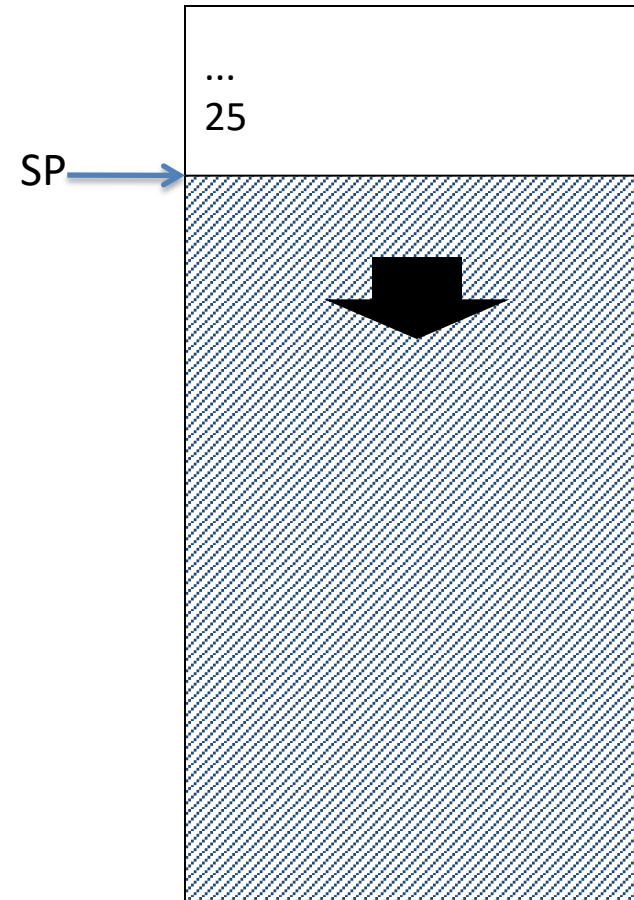
...
25

SP →

Arguments g, …, j in $a0, …, $a3
f in $s0 (hence, need to save $s0 on stack)
Result in $v0

Registers
$s0: 3 $a0: 5 $a1: 2 $a2: 3 $a3: 1
$t0: 7 $t1: 4 $v0: 3

Process Stack

```
leaf_ex:   addi $sp, $sp, -4
           sw   $s0, 0($sp)
           add  $t0, $a0, $a1
           add  $t1, $a2, $a3
           sub  $s0, $t0, $t1
           add  $v0, $s0, $zero
PC ──▶     lw   $s0, 0($sp)
           addi $sp, $sp, 4
           jr   $ra
```

Arguments g, …, j in $a0, …, $a3
f in $s0 (hence, need to save $s0 on stack)
Result in $v0

Registers
$s0: 25 $a0: 5 $a1: 2 $a2: 3 $a3: 1
$t0: 7 $t1: 4 $v0: 3

...
25

SP

Process Stack

```
leaf_ex:   addi $sp, $sp, -4
           sw   $s0, 0($sp)
           add  $t0, $a0, $a1
           add  $t1, $a2, $a3
           sub  $s0, $t0, $t1
           add  $v0, $s0, $zero
           lw   $s0, 0($sp)
PC  →      addi $sp, $sp, 4
           jr   $ra
```
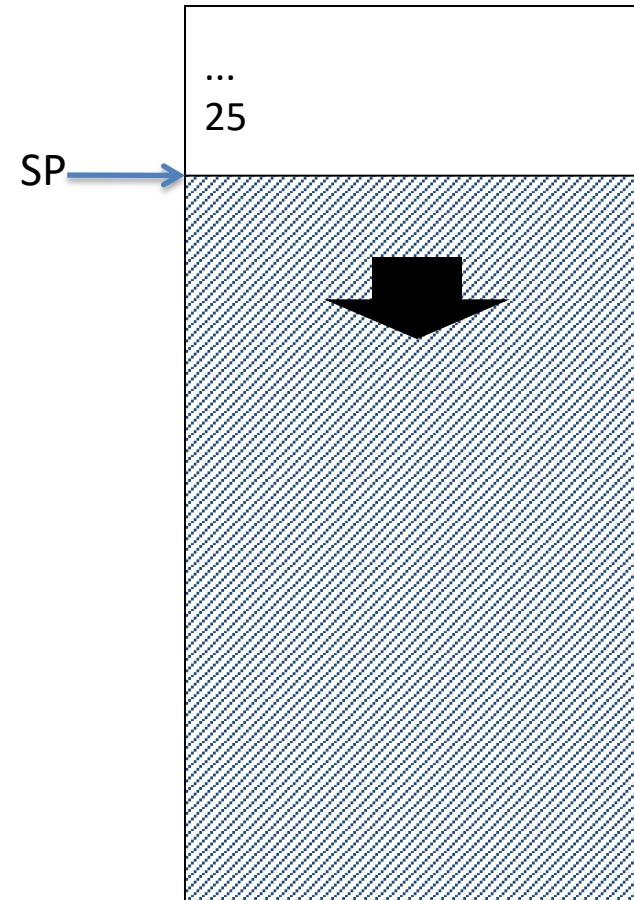
Arguments g, …, j in $a0, …, $a3
f in $s0 (hence, need to save $s0 on stack)
Result in $v0

SP →

...

25

Registers
$s0: 25 $a0: 5 $a1: 2 $a2: 3 $a3: 1
$t0: 7 $t1: 4 $v0: 3

Process Stack

```
leaf_ex:   addi $sp, $sp, -4
           sw   $s0, 0($sp)
           add  $t0, $a0, $a1
           add  $t1, $a2, $a3
           sub  $s0, $t0, $t1
           add  $v0, $s0, $zero
           lw   $s0, 0($sp)
           addi $sp, $sp, 4
PC ─────▶  jr   $ra
```
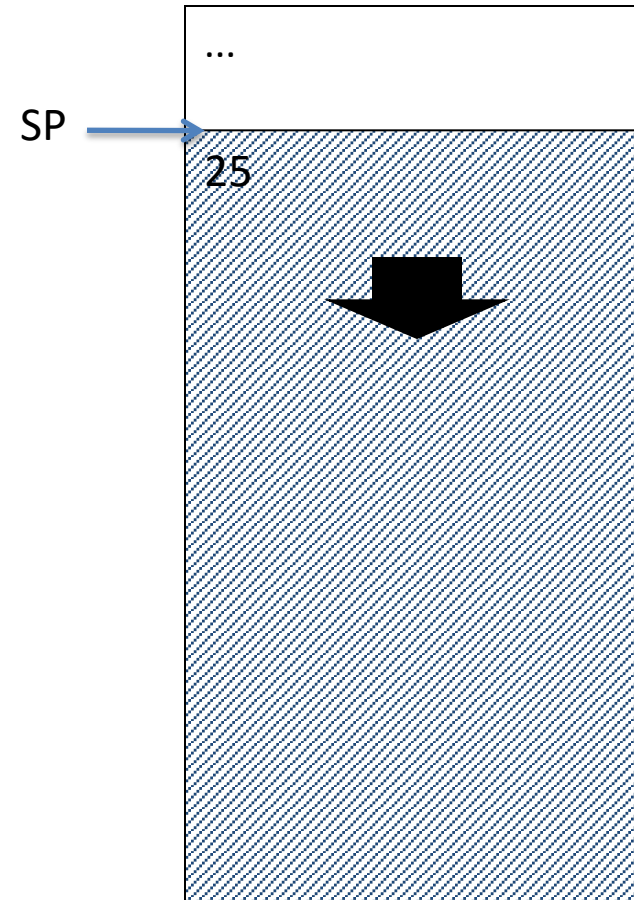
Arguments g, …, j in $a0, …, $a3
f in $s0 (hence, need to save $s0 on stack)
Result in $v0

Registers
$s0: 25 $a0: 5 $a1: 2 $a2: 3 $a3: 1
$t0: 7 $t1: 4 $v0: 3
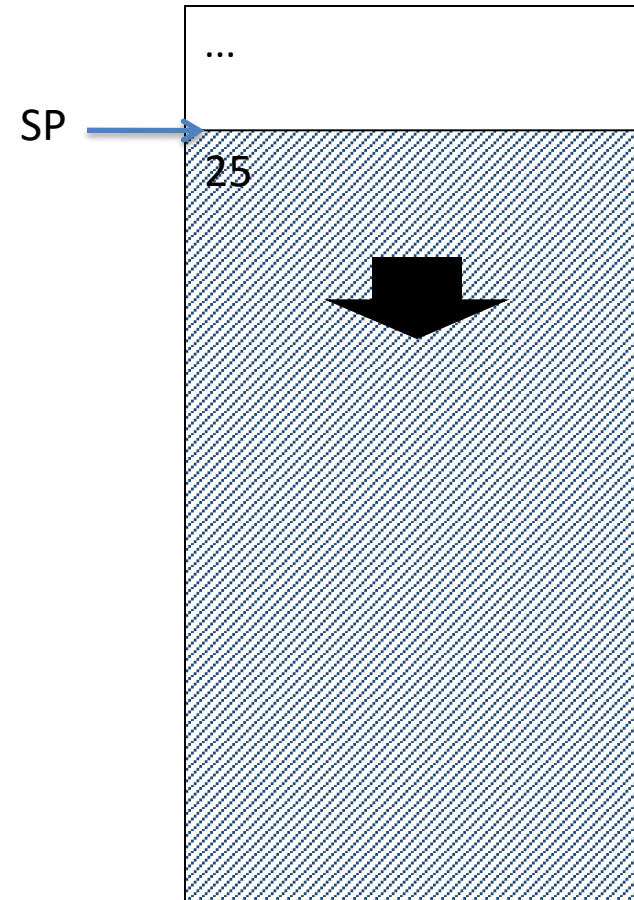
...

SP ────▶

25

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

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

...

Process Stack

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

...

return address

int n = 3

Process Stack

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

...

return address

int n = 3

Process Stack

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

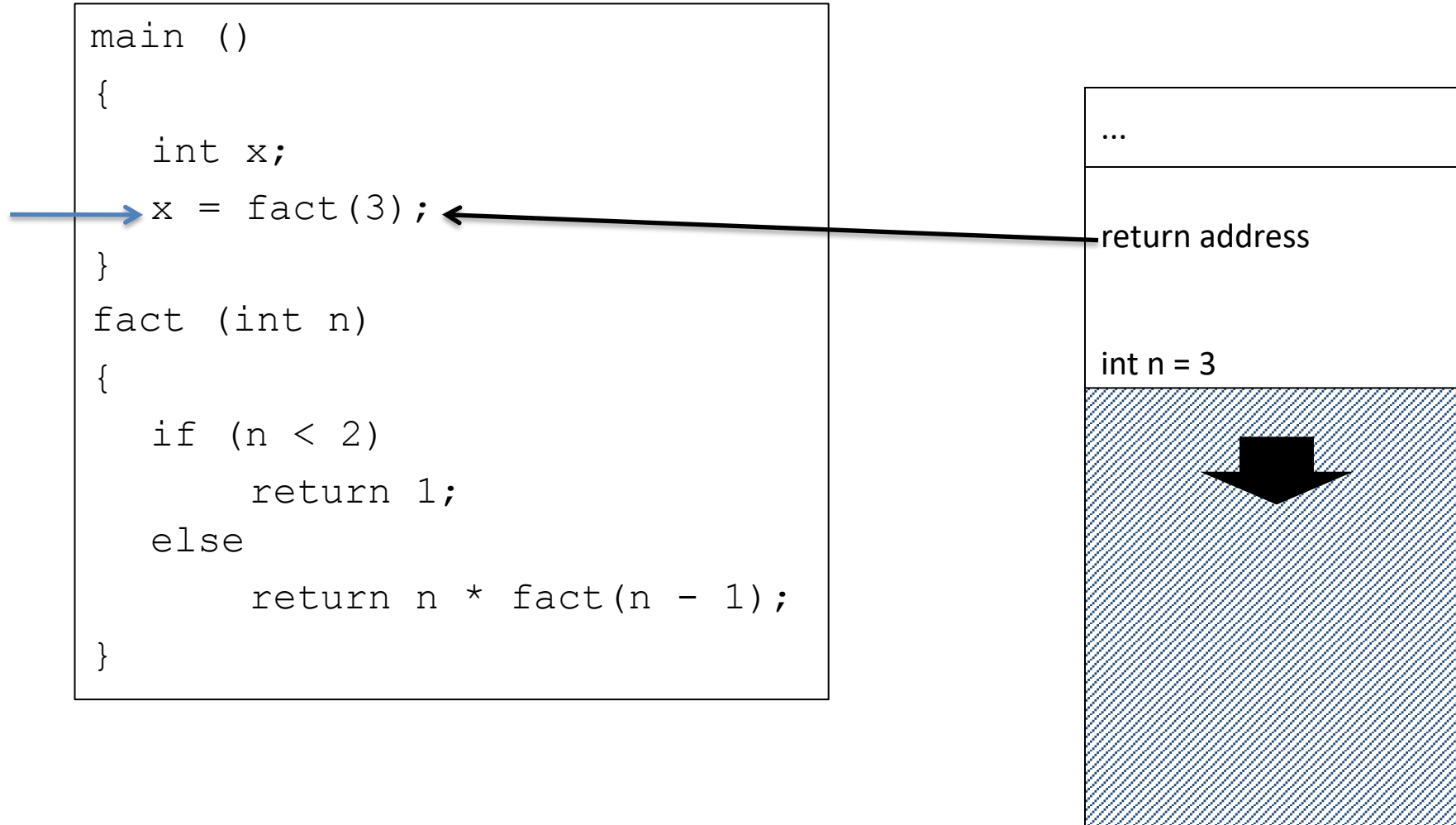| |
|---|
| ... |
| return address |
| int n = 3 |
| return address |
| int n = 2 |
| |

Process Stack

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

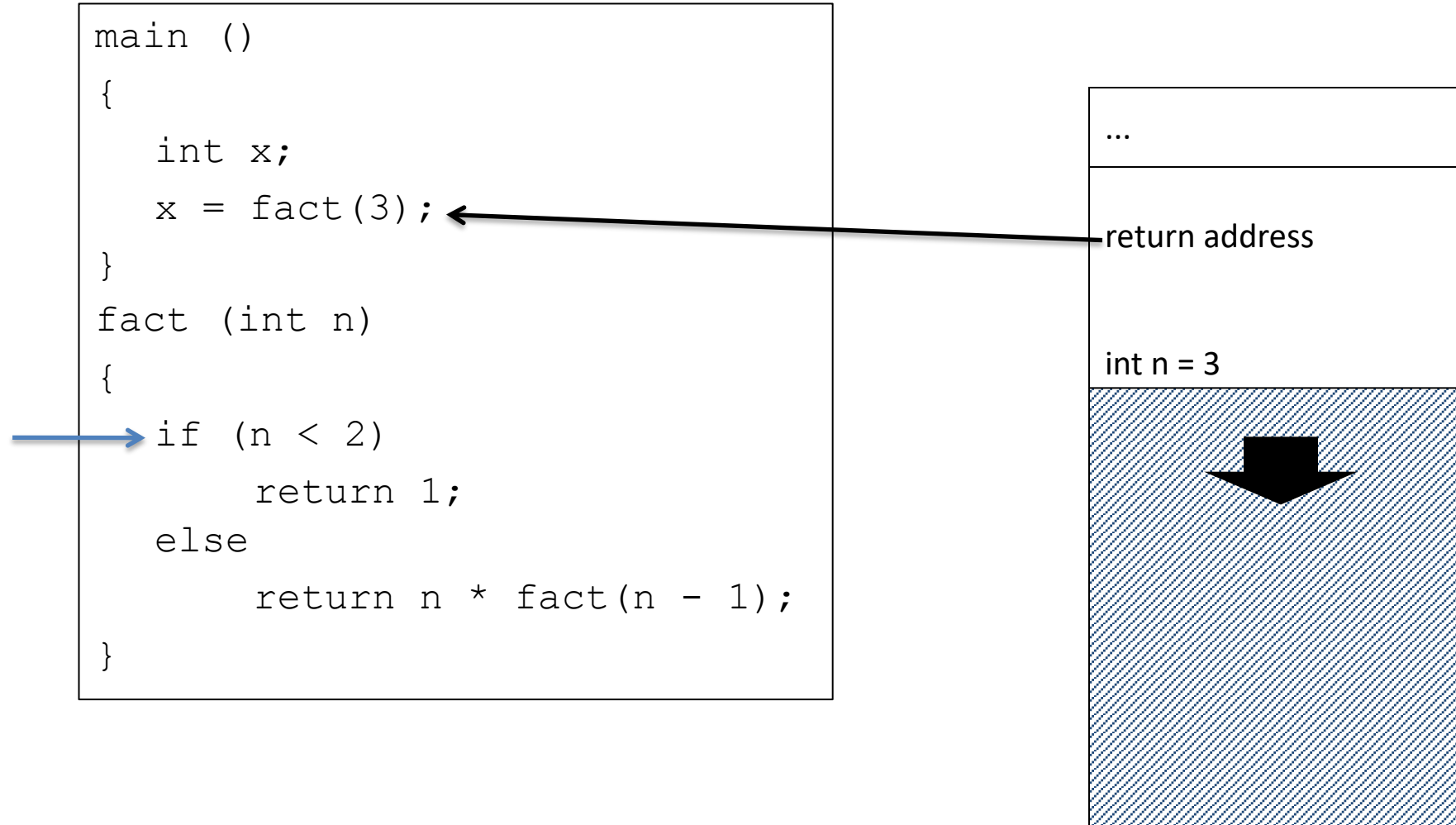| |
|---|
| ... |
| return address |
| int n = 3 |
| return address |
| int n = 2 |
| |

Process Stack

Process Stack

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

...
return address int n = 3
return address int n = 2
return address int n = 1

Process Stack

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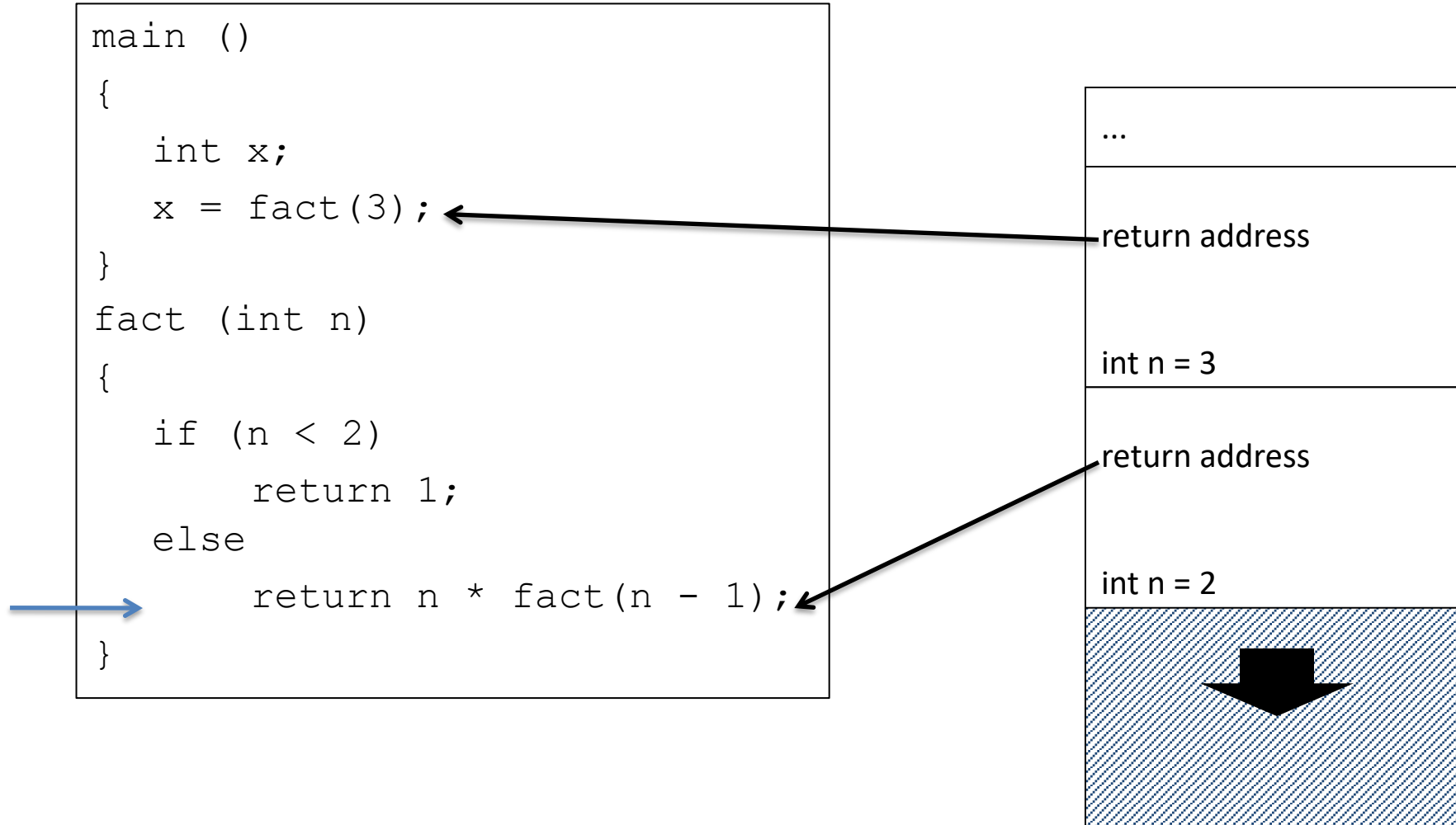
...

return address

int n = 3

return address

int n = 2

$ra

Process Stack

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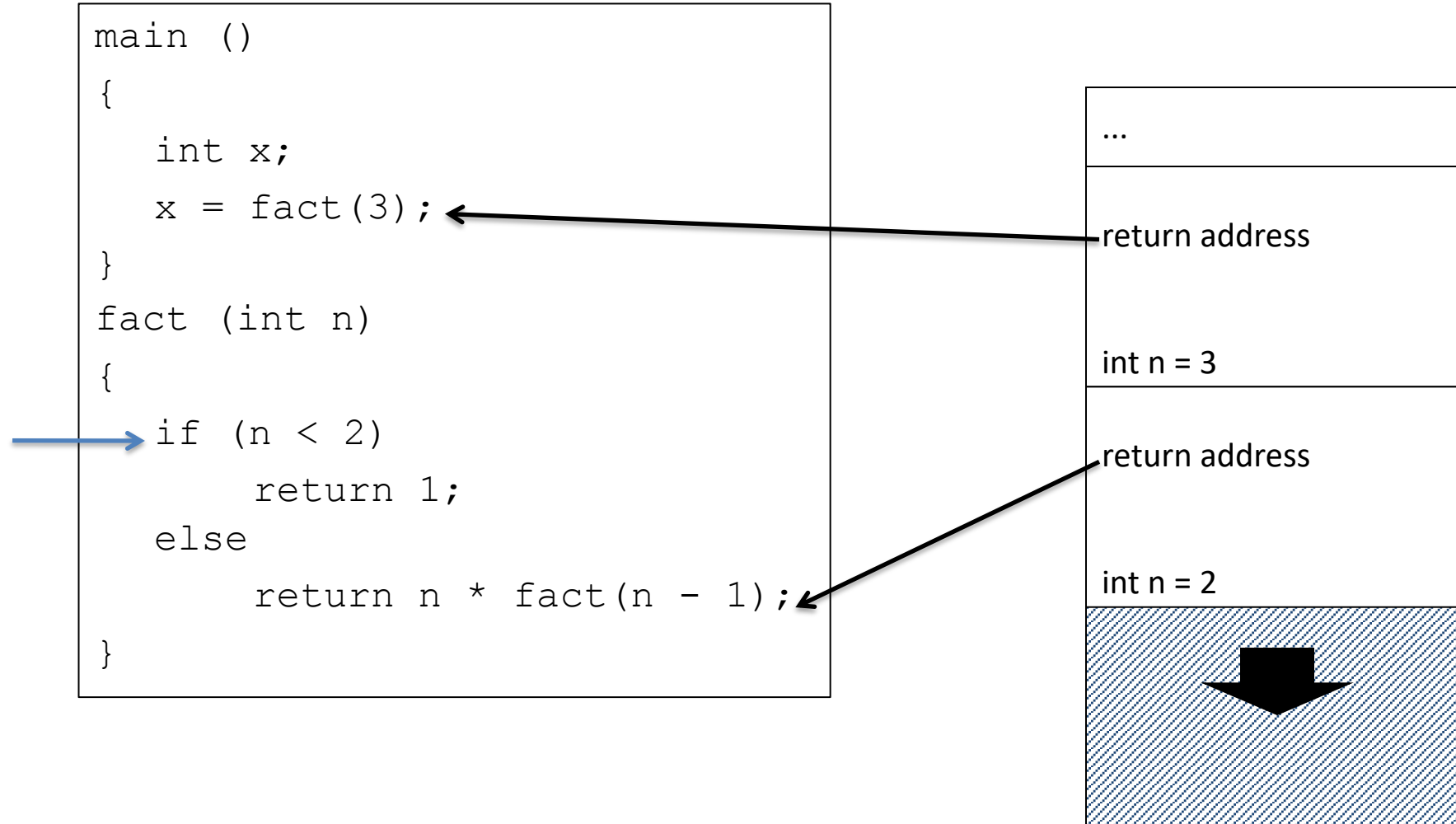
...
return address
int n = 3
return address
int n = 2

Process Stack

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

...
return address
int n = 3

$ra

Process Stack

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

...

return address

int n = 3

Process Stack

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

...
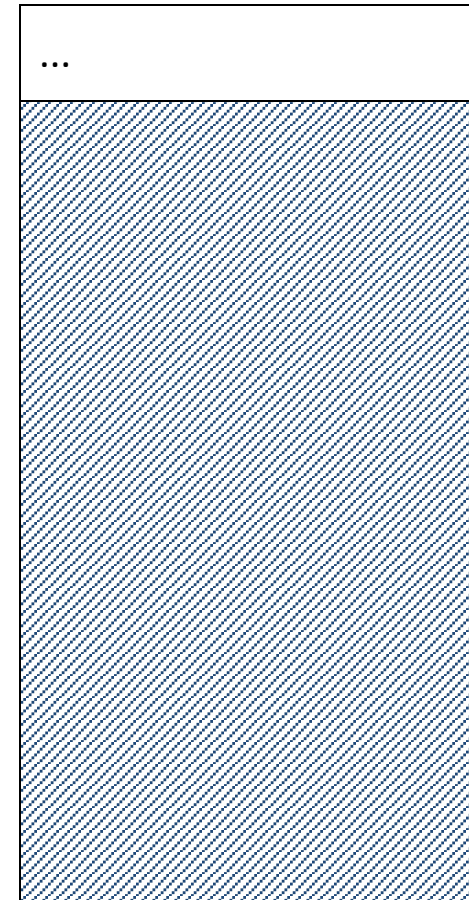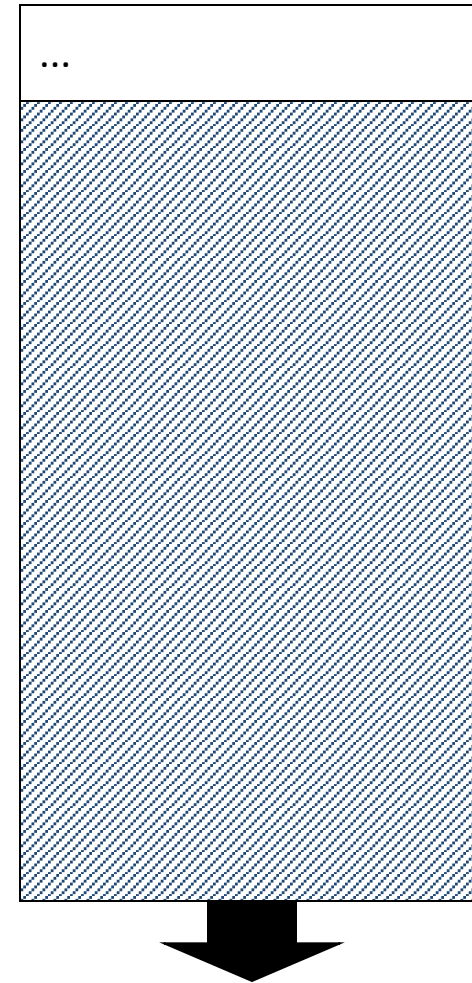
Process Stack

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

...

Non-Leaf Procedure Example

- MIPS code:

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

SP →

fact

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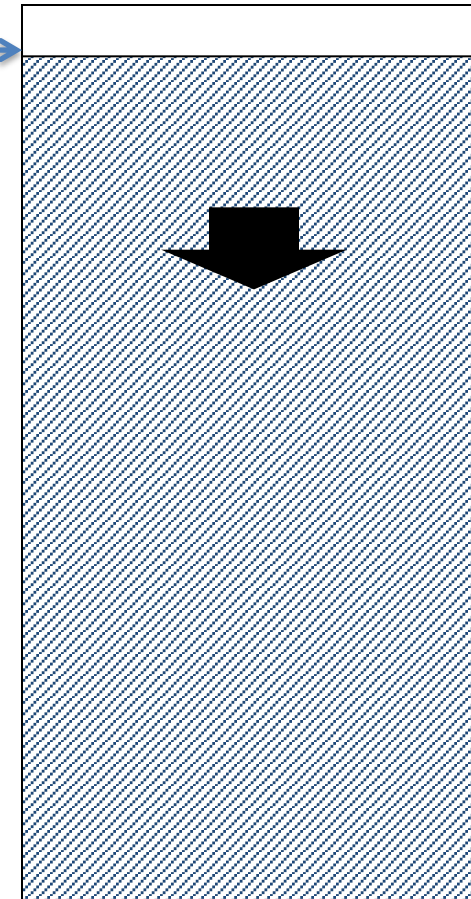$v0 =
$t0 =

...

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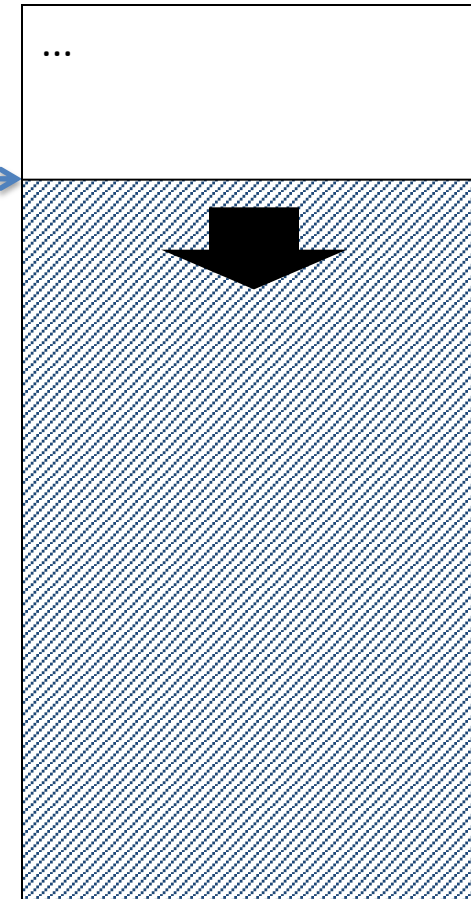
PC

SP

fact

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

...
ra = 0x864

SP

```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
PC →    sw   $ra, 4($sp)       # save return address
        sw   $a0, 0($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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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
```
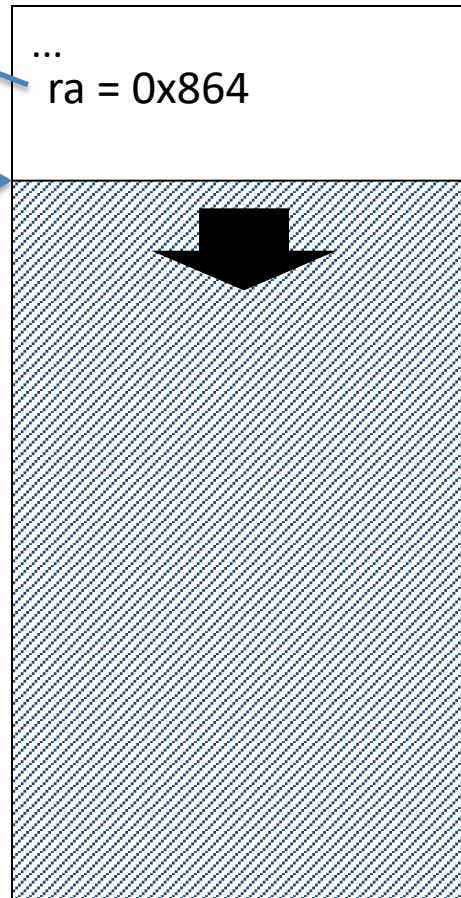
fact

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

... ra = 0x864

3

SP

PC

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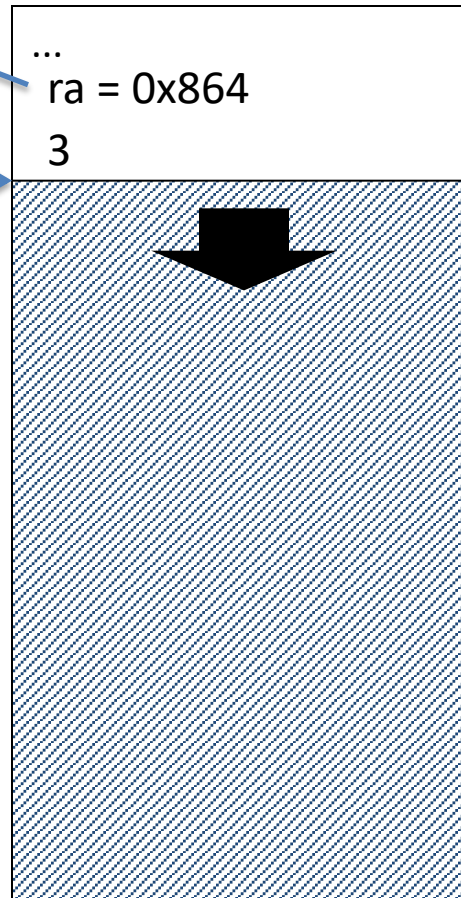
fact

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

...
ra = 0x864
3

SP

```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
        sw   $ra, 4($sp)       # save return address
        sw   $a0, 0($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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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
```
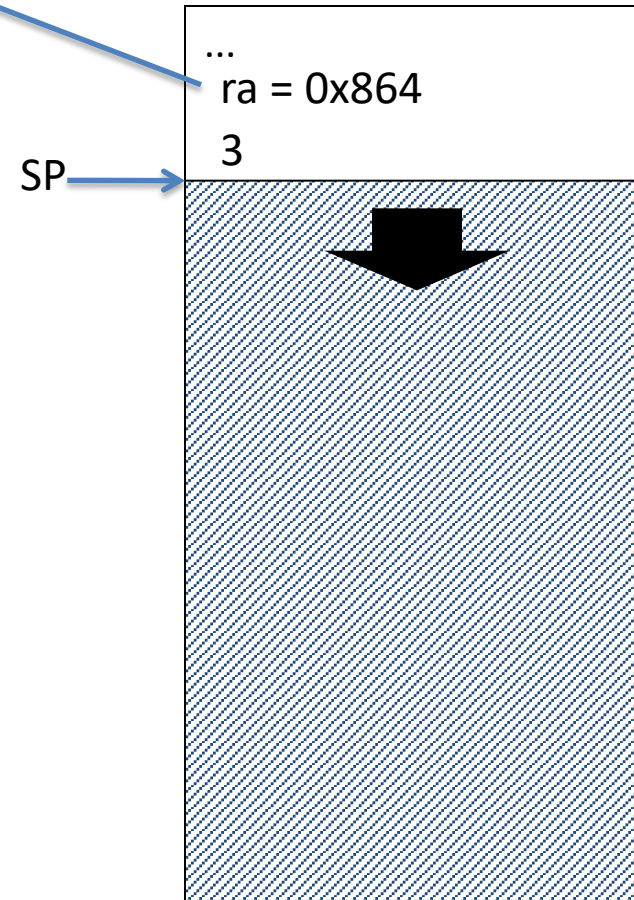
37

fact

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

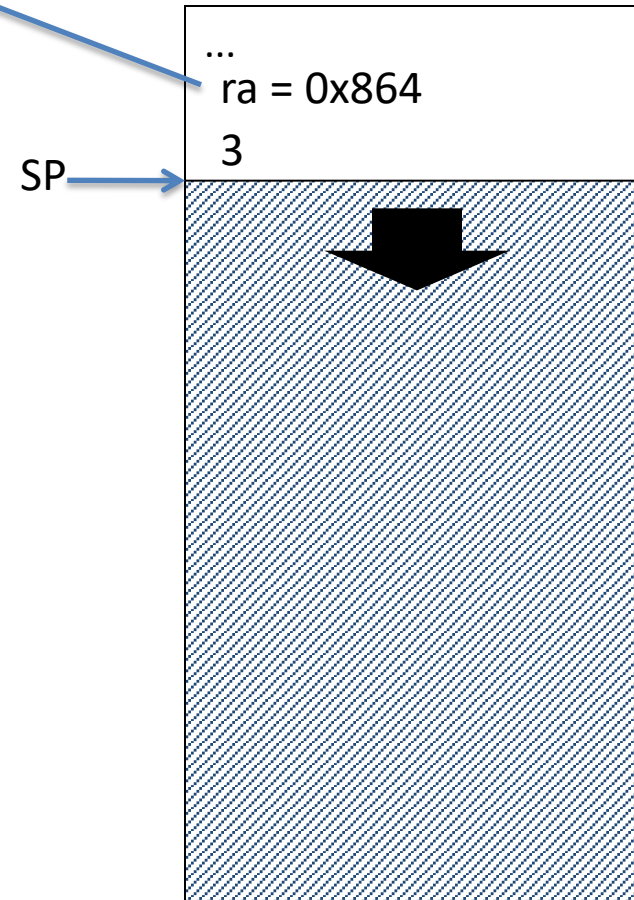```
fact:
        addi $sp, $sp, -8   # adjust stack for 2 items
        sw $ra, 4($sp)   # save return address
        sw $a0, 0($sp)   # save argument
        slti $t0, $a0, 2   # test for n < 2
PC   beq $t0, $zero, L1
        addi $v0, $zero, 1   # if so, result is 1
        addi $sp, $sp, 8   #   pop 2 items from stack
        jr $ra   #   and return
    L1: addi $a0, $a0, -1   # else decrement n
        jal fact   # recursive call
        lw $a0, 0($sp)   # restore original n
        lw $ra, 4($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
3

SP

# fact

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

...
ra = 0x864
3

SP

```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
        sw   $ra, 4($sp)       # save return address
        sw   $a0, 0($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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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
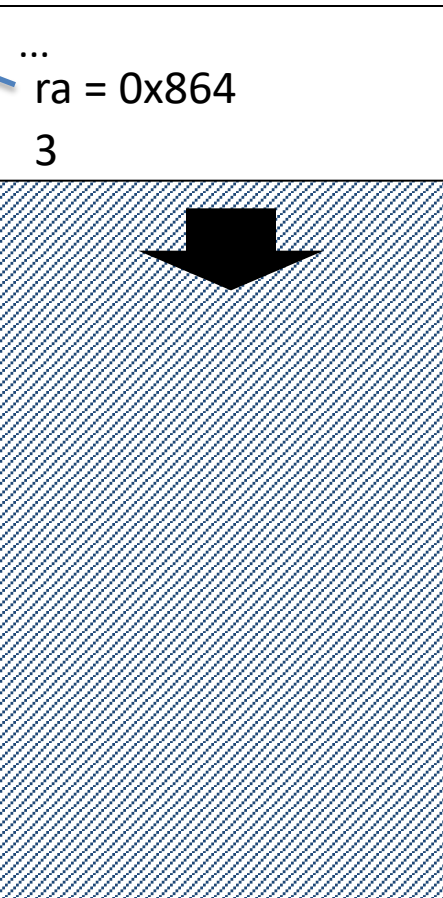
```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
        sw   $ra, 4($sp)       # save return address
        sw   $a0, 0($sp)       # save argument
        slti $t0, $a0, 2       # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1     # if so, result is 1
        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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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 $a0, 0($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   $ra, 4($sp)        # save return address
        sw   $a0, 0($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   $a0, 0($sp)        # restore original n
        lw   $ra, 4($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
```

PC

...
ra = 0x864
3

SP

fact

$ra = L1 + 8
$a0 = 2
$v0 =
$t0 =
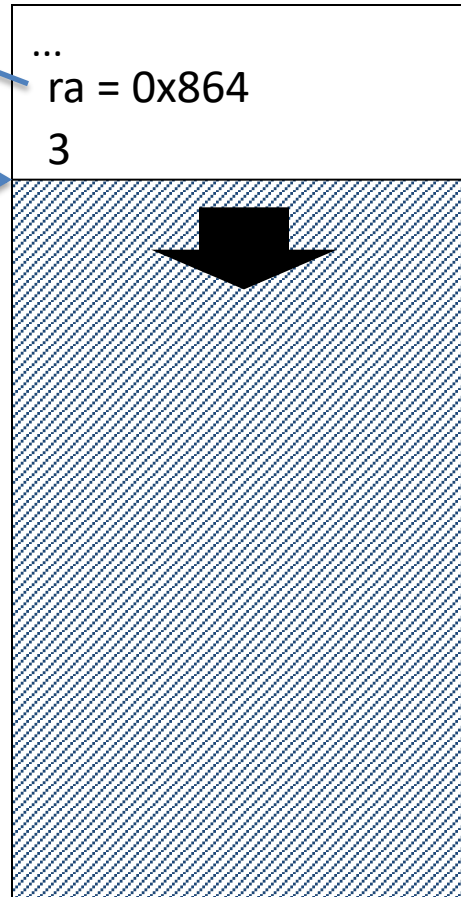
ra = 0x864
3

SP

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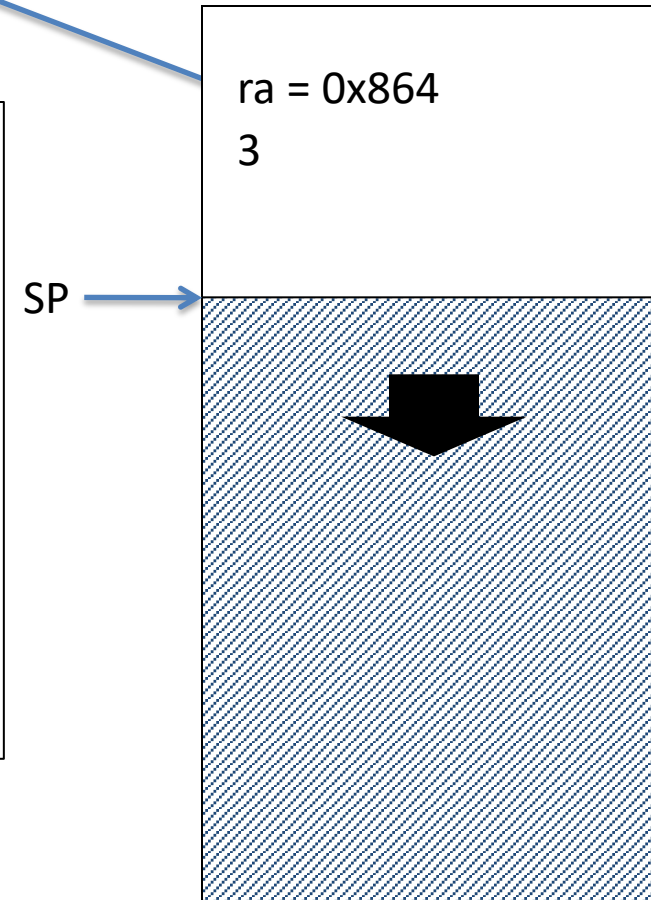
fact

$ra = L1 + 8
$a0 = 2
$v0 =
$t0 = 0
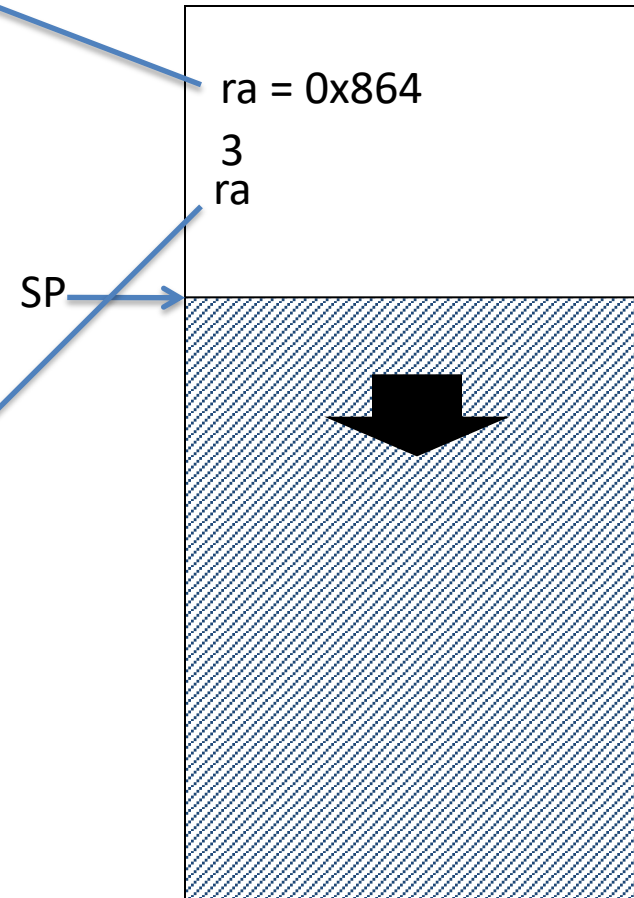
```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
PC →    sw   $ra, 4($sp)       # save return address
        sw   $a0, 0($sp)       # save argument
        slti $t0, $a0, 2       # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1     # if so, result is 1
        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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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

3
ra

SP →

fact

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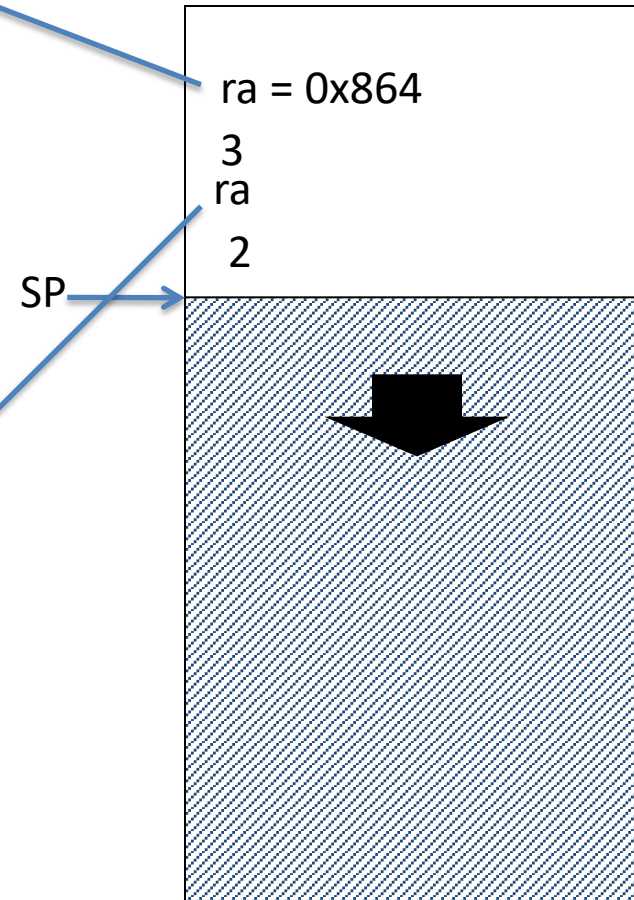$v0 =
$t0 = 0

```
fact:
        addi $sp, $sp, -8    # adjust stack for 2 items
        sw   $ra, 4($sp)     # save return address
PC →    sw   $a0, 0($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   $a0, 0($sp)     # restore original n
        lw   $ra, 4($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

3
ra

2

SP

fact

$ra = L1 + 8
$a0 = 2
$v0 =
$t0 = 0
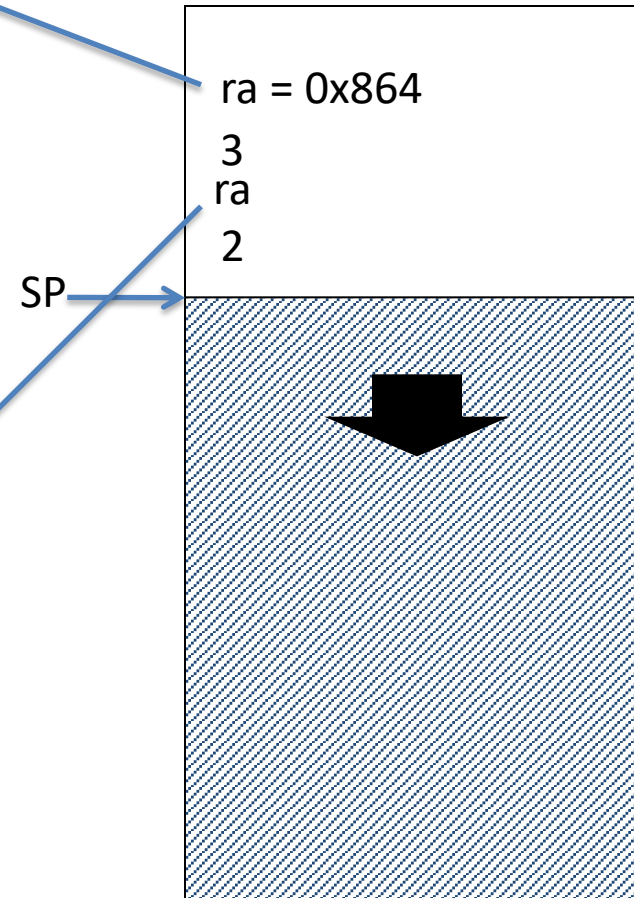
```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
        sw   $ra, 4($sp)       # save return address
        sw   $a0, 0($sp)       # save argument
PC →    slti $t0, $a0, 2       # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1     # if so, result is 1
        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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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
3
ra
2

SP →

45

fact

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

```
fact:
        addi $sp, $sp, -8       # adjust stack for 2 items
        sw   $ra, 4($sp)        # save return address
        sw   $a0, 0($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   $a0, 0($sp)        # restore original n
        lw   $ra, 4($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
```
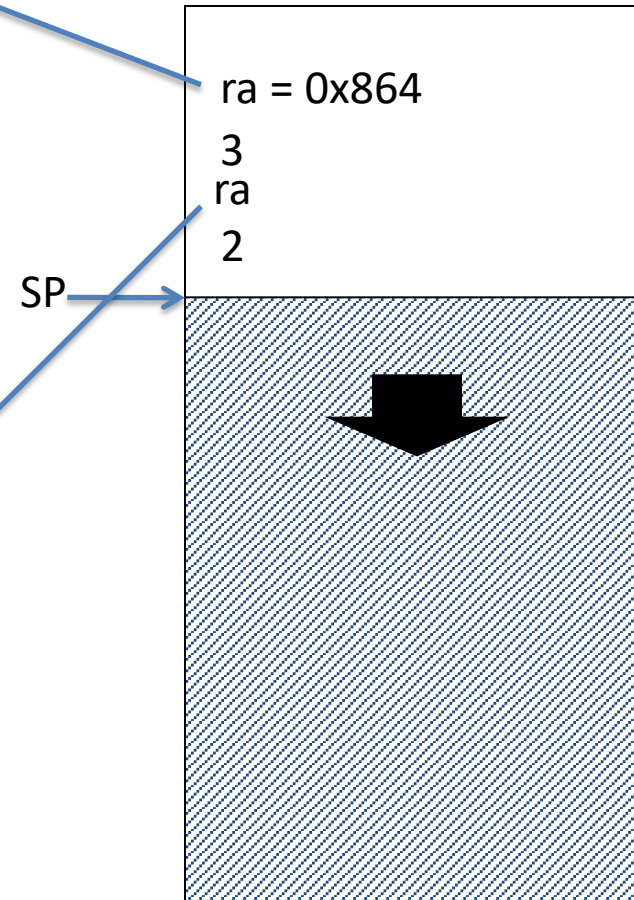
ra = 0x864

3
ra
2

SP

fact

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

```
fact:
        addi $sp, $sp, -8       # adjust stack for 2 items
        sw   $ra, 4($sp)        # save return address
        sw   $a0, 0($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   $a0, 0($sp)        # restore original n
        lw   $ra, 4($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
```
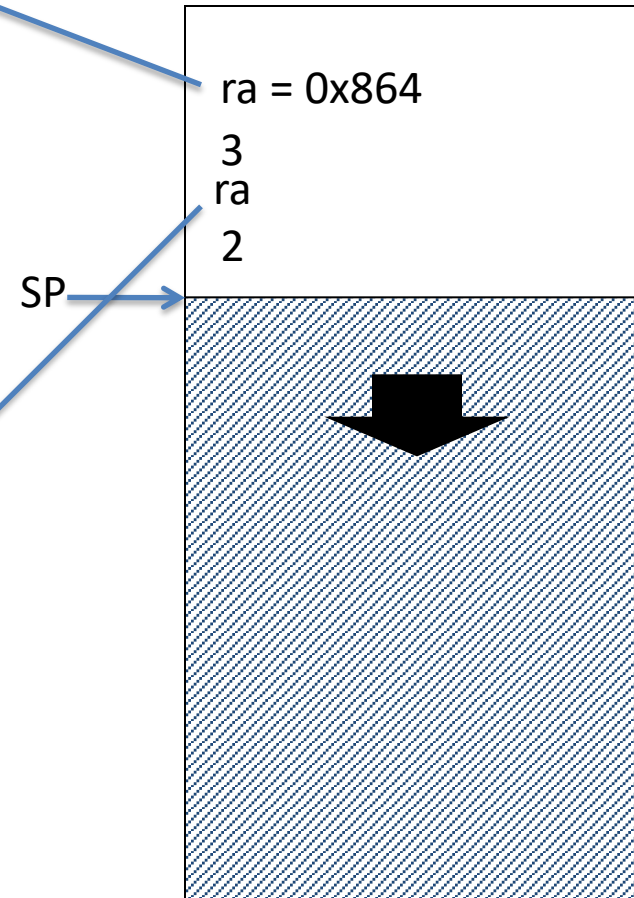
ra = 0x864

3
ra
2

SP

47

fact

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

ra = 0x864
3
ra
2

SP

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

PC

fact

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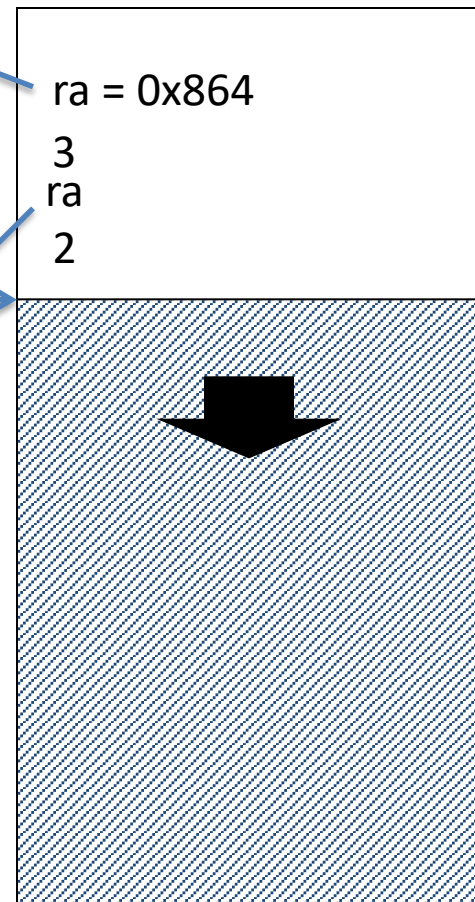$t0 = 0

```
fact:
PC →    addi  $sp, $sp, -8    # adjust stack for 2 items
        sw    $ra, 4($sp)     # save return address
        sw    $a0, 0($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    $a0, 0($sp)     # restore original n
        lw    $ra, 4($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
```
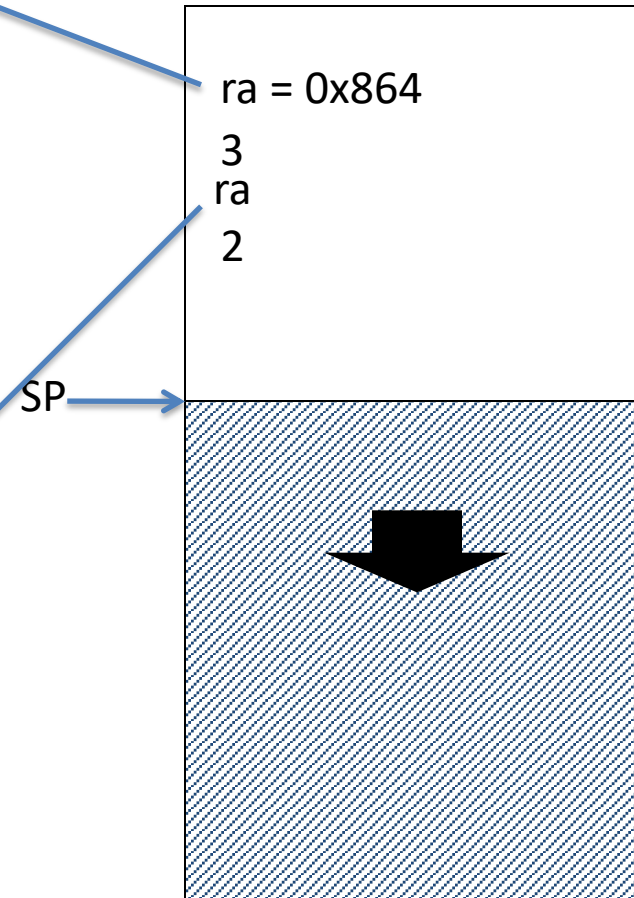
ra = 0x864

3
ra
2

SP

fact

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

```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
  PC    sw   $ra, 4($sp)       # save return address
        sw   $a0, 0($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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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
```
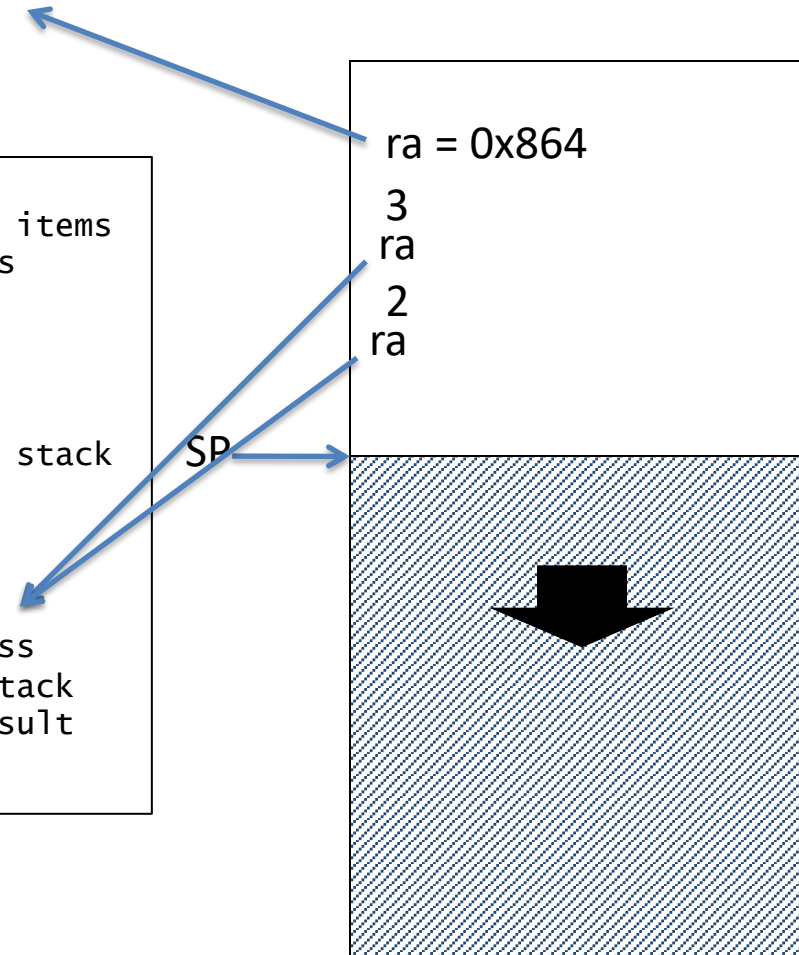
ra = 0x864
3
ra
2
ra

SP

fact

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

```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
        sw   $ra, 4($sp)       # save return address
PC →    sw   $a0, 0($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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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
```
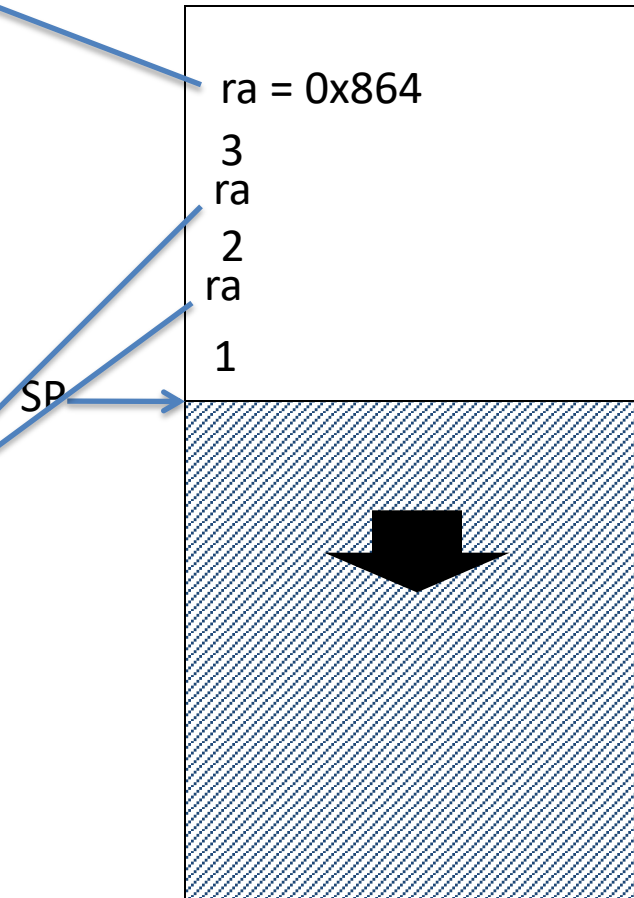
ra = 0x864

3
ra

2
ra

1

SP

fact

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

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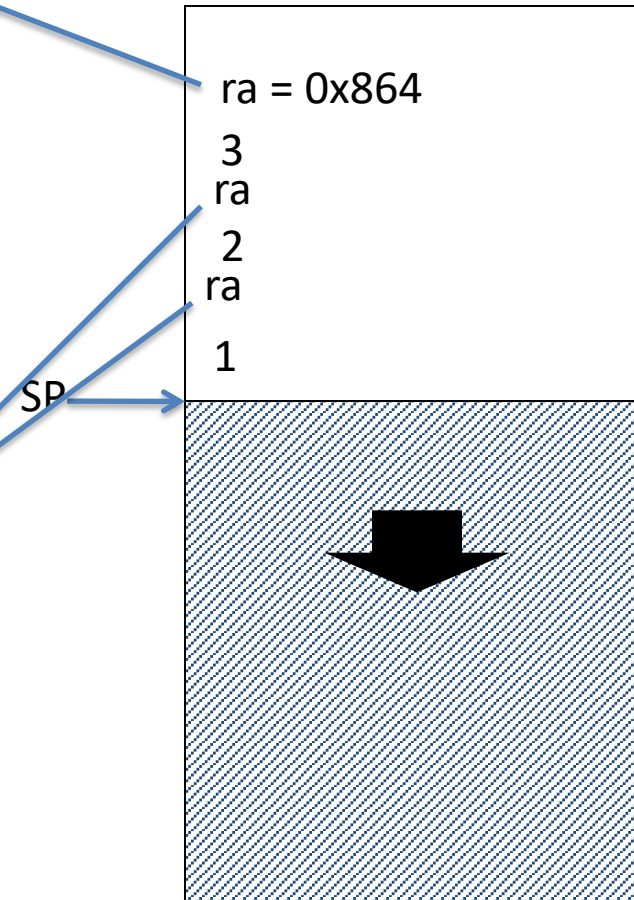
PC

ra = 0x864
3
ra
2
ra
1

SP

52

fact

$ra = L1 + 8
$a0 = 1
$v0 =
$t0 = 1
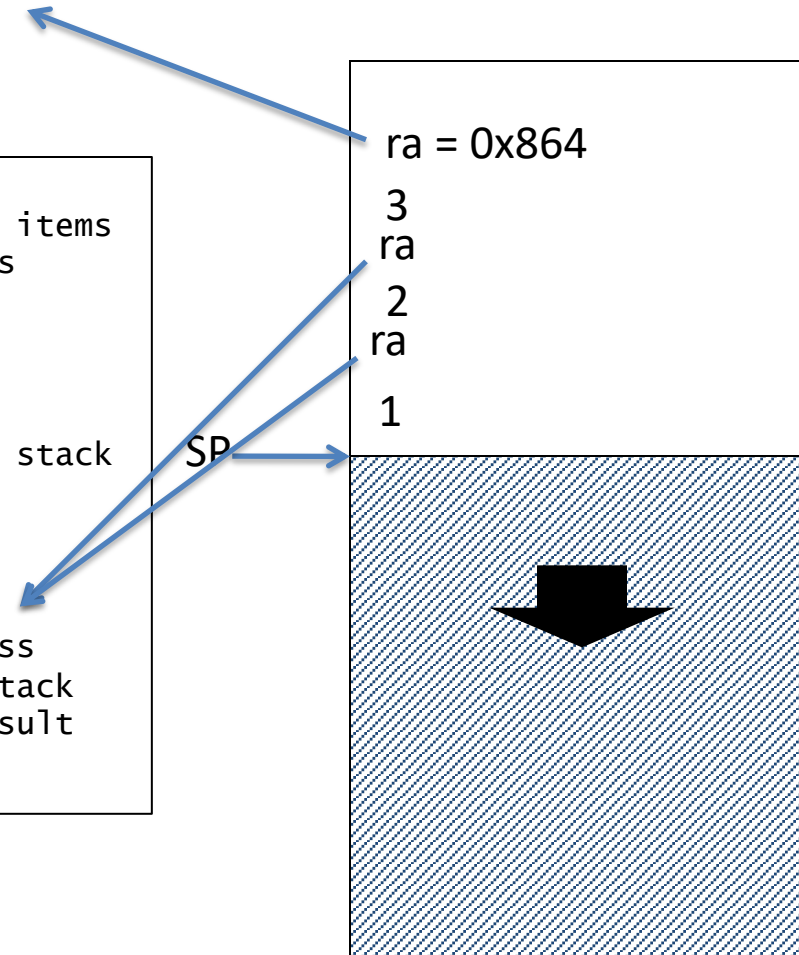
```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
        sw   $ra, 4($sp)       # save return address
        sw   $a0, 0($sp)       # save argument
        slti $t0, $a0, 2       # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1     # if so, result is 1
        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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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
```

PC

ra = 0x864
3
ra
2
ra
1

SP

fact

$ra = L1 + 8
$a0 = 1
$v0 = 1
$t0 = 1
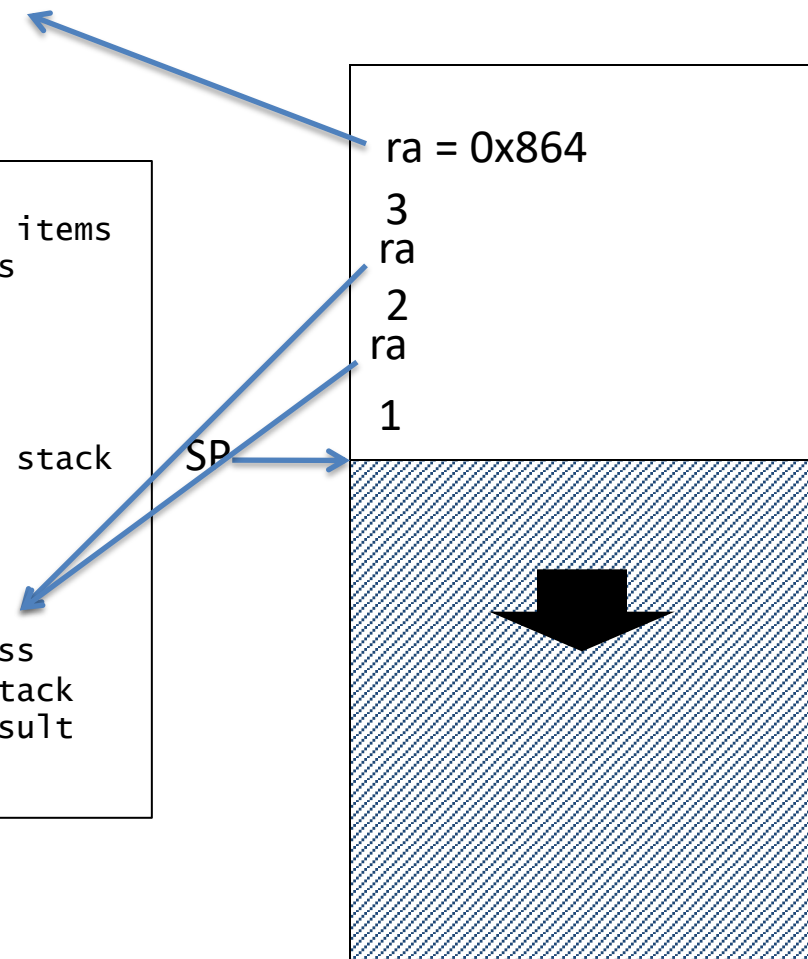
```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
        sw   $ra, 4($sp)       # save return address
        sw   $a0, 0($sp)       # save argument
        slti $t0, $a0, 2       # test for n < 2
        beq  $t0, $zero, L1
PC →    addi $v0, $zero, 1     # if so, result is 1
        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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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

3
ra

2
ra

1

SP

fact

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

```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
        sw   $ra, 4($sp)       # save return address
        sw   $a0, 0($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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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
3
ra
2
ra
1

SP

fact

$ra = L1 + 8
$a0 = 1
$v0 = 1
$t0 = 1
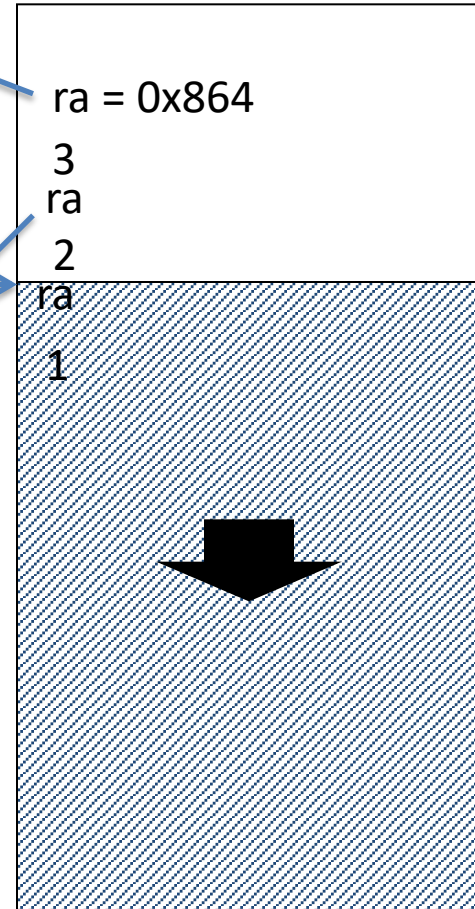
```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
        sw   $ra, 4($sp)       # save return address
        sw   $a0, 0($sp)       # save argument
        slti $t0, $a0, 2       # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1     # if so, result is 1
        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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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
3
ra
2
SP
ra
1

We will return to

$ra = L1 + 8
$a0 = 1
$v0 = 1
$t0 = 1
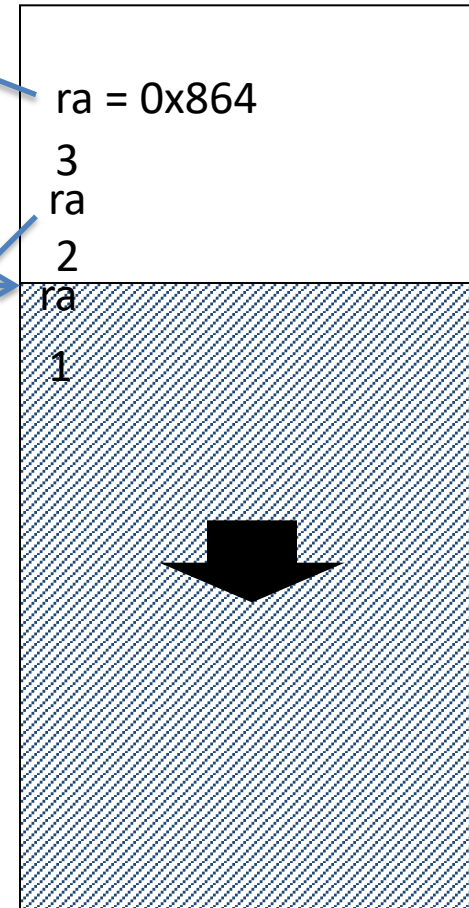
```
fact:
        addi $sp, $sp, -8       # adjust stack for 2 items
        sw   $ra, 4($sp)        # save return address
        sw   $a0, 0($sp)        # save argument
        slti $t0, $a0, 2        # test for n < 2
        beq  $t0, $zero, L1
        addi $v0, $zero, 1      # if so, result is 1
        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   $a0, 0($sp)        # restore original n
        lw   $ra, 4($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
```
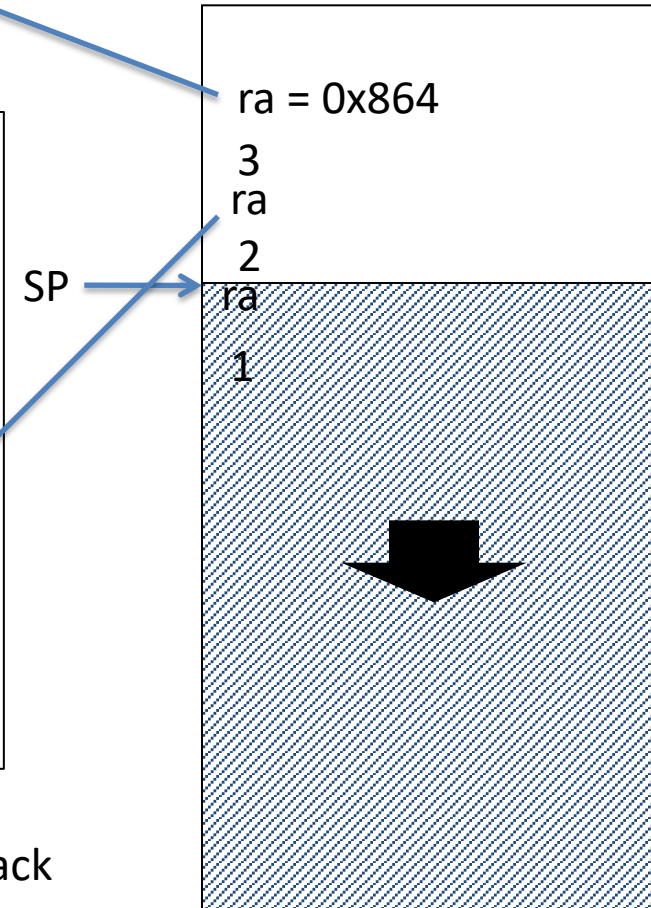
PC →

SP →

ra = 0x864

3
ra

2
ra

1

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

57

fact

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

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

PC

SP

ra = 0x864
3
ra
2
ra
1

58

fact

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

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

PC

ra = 0x864

3
ra

2
ra

1

SP

59

fact

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

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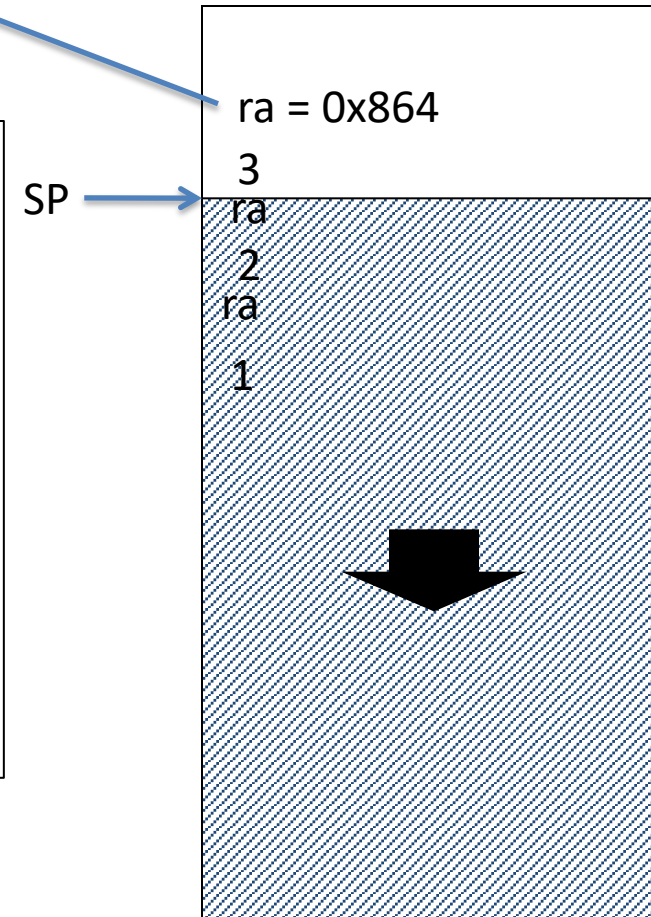
SP

ra = 0x864

3

ra

2

ra

1

fact

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

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

PC →

SP →

ra = 0x864
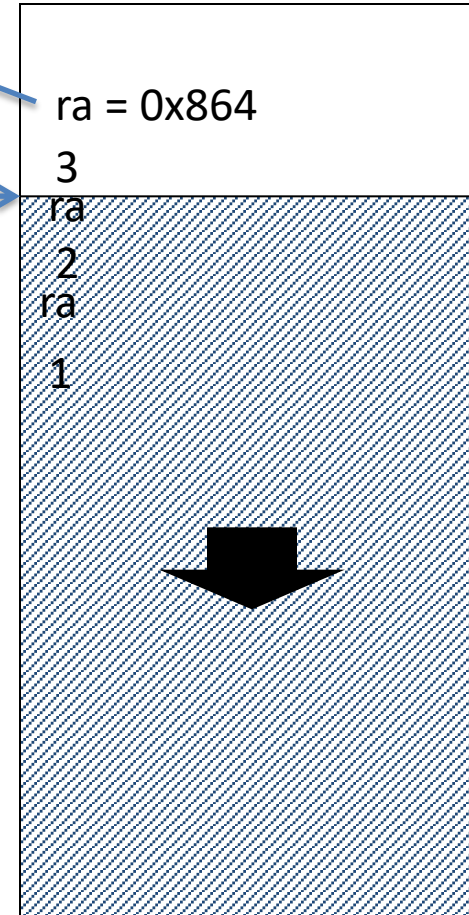
3
ra

2
ra

1

fact

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

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

PC

SP

ra = 0x864
3
ra
2
ra
1

fact

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

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

PC →

ra = 0x864

3
ra

2
ra

1

SP →

fact

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

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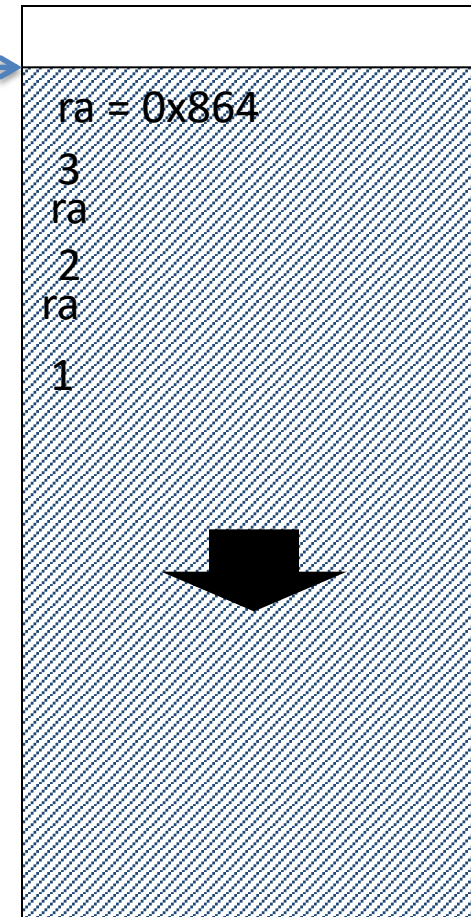
PC

SP

ra = 0x864
3
ra
2
ra
1

fact

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

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

PC →

SP →

ra = 0x864

3
ra

2
ra

1

fact

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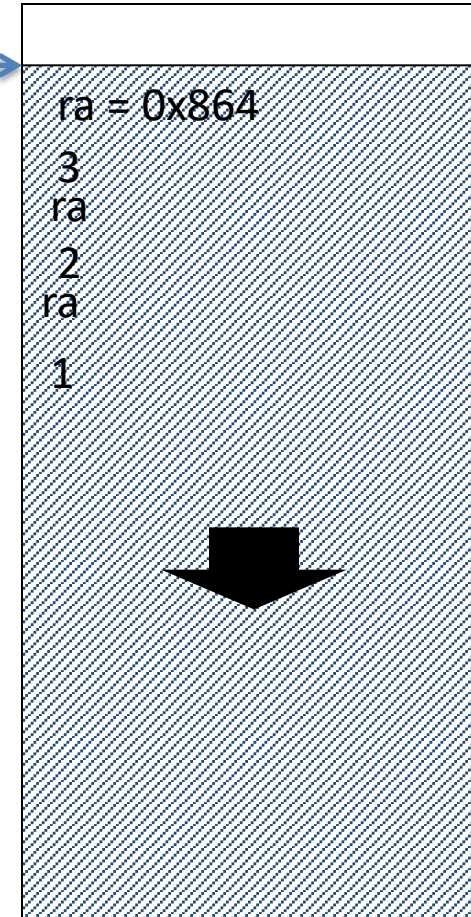$v0 = 6
$t0 = 1

```
fact:
        addi $sp, $sp, -8      # adjust stack for 2 items
        sw   $ra, 4($sp)       # save return address
        sw   $a0, 0($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   $a0, 0($sp)       # restore original n
        lw   $ra, 4($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
```
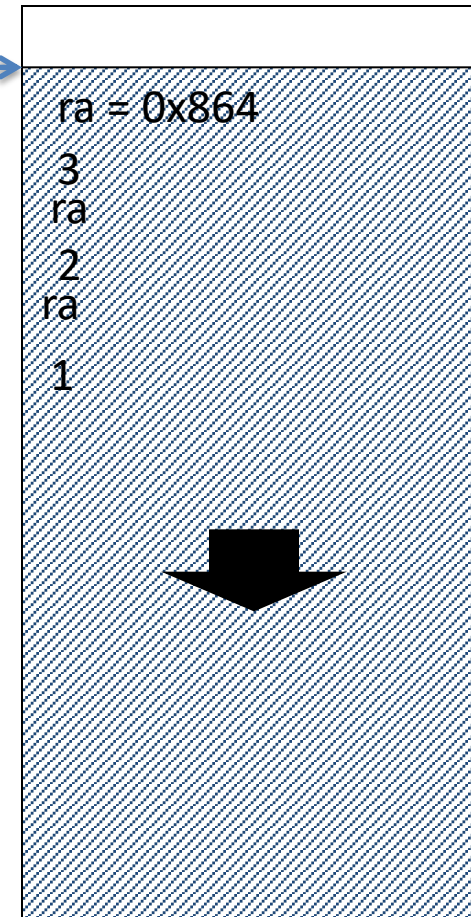
PC →

SP →

ra = 0x864

3
ra

2
ra

1

fact

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

SP →

ra = 0x864

3
ra

2
ra

1

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

Reading

- Next lecture: More Stack

- Problem set 4 due Friday

- Lab 3 due Sunday