Control Flow, Call Graphs and Subroutine Construction

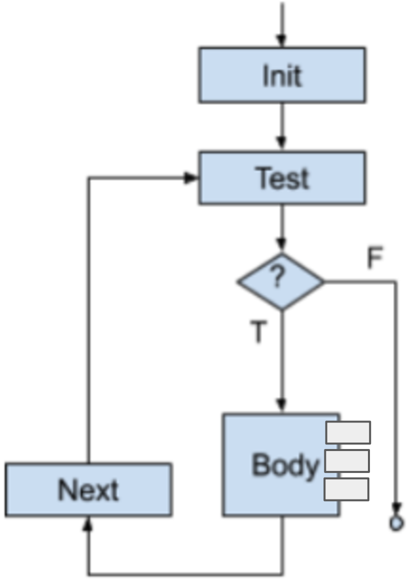
Control Flow Graph

- A graphic representation of the representation between basic blocks
- A basic block:
    - a list of instructions with
    - a single entry point (starting point)
    - a single exit point (last instruction)
- Such representations model the behavior of our code
- Recall the while loop, and other control structures

- What about subroutines calls

  (subroutine: general term for …

  methods, functions, procedures, etc.)

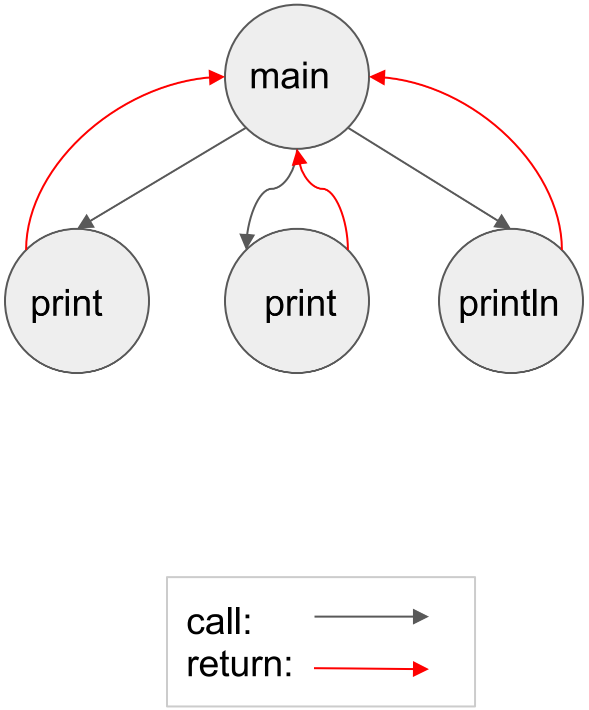


While Loop

Call Graph

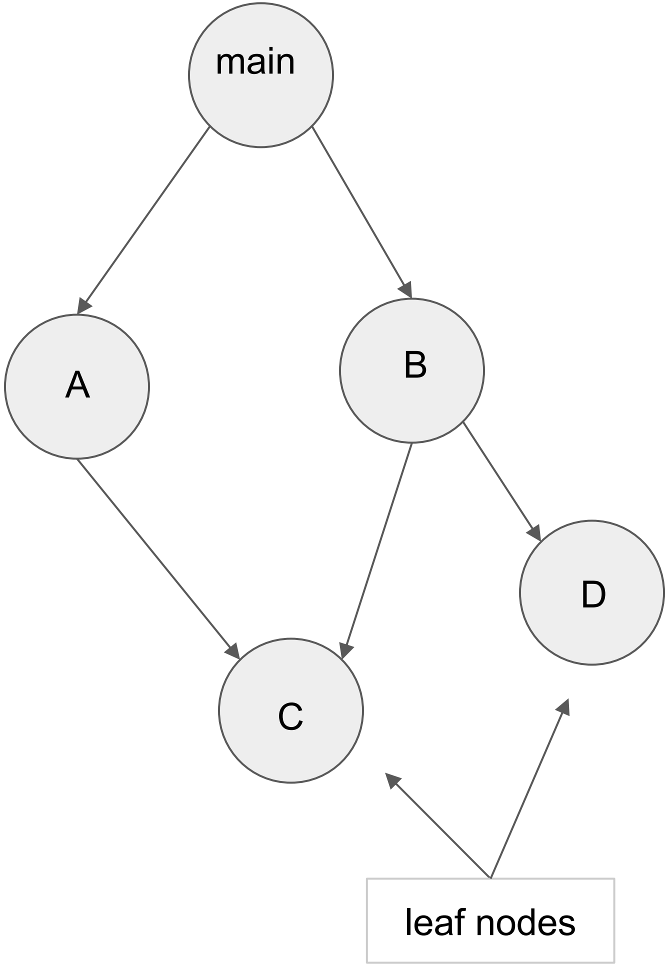
- a control flow graph depicting the relationships between subroutines
- Call Graph for the "Hello World" program

```
class HelloWorld
{
   public static void main(String args[])
   {
      System.out.print("Hello ");
      System.out.print("World");
      System.out.println("");
   }
}
```



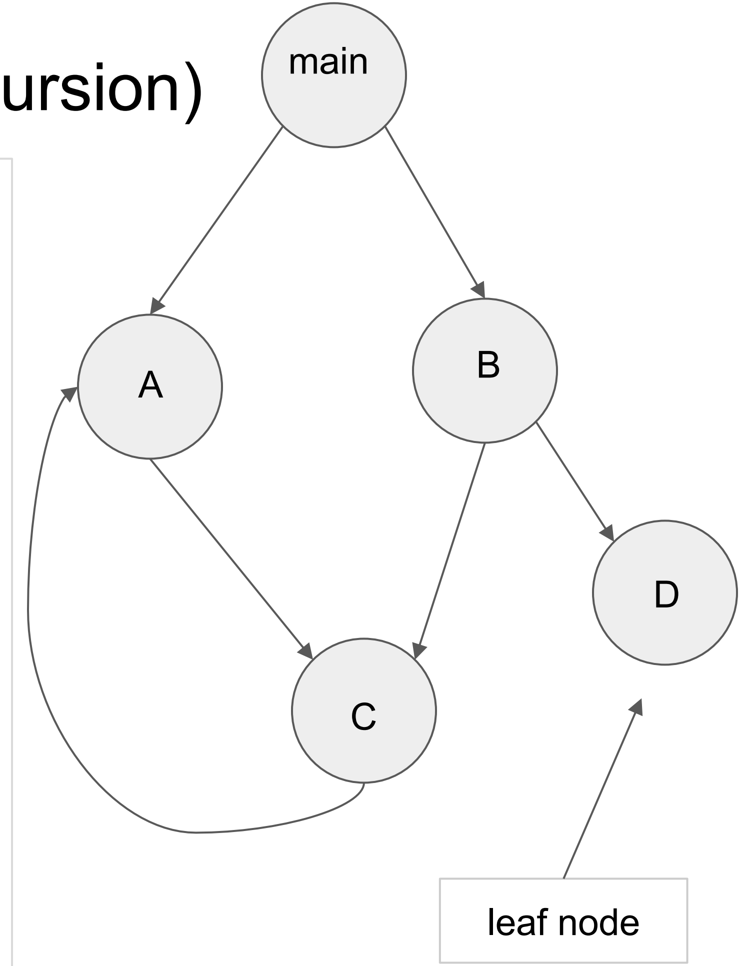
Call Graph II

```
public static void A(void) {
    int x = 5;
    C();
}
public static void B(void) {
    C();
    D();
}
public static void C(void) {
    ;
}
public static void D(void) {
    ;
}

public static void main(String args[])
   {
      A();
      B();
   }
}
```



Call Graph with a Loop (Recursion)

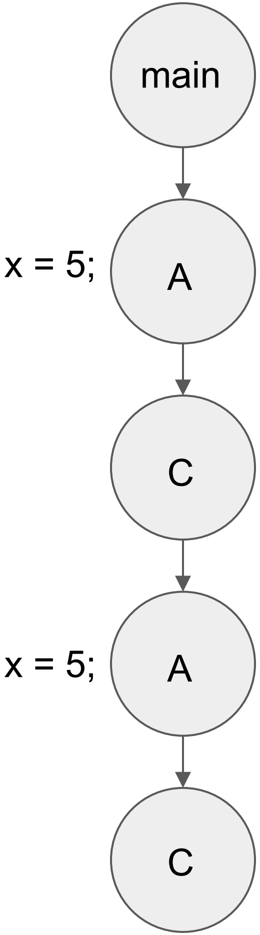
```
public static void A(void) {
    int x = 5;
    C();
}
public static void B(void) {
    C();
    D();
}
public static void C(void) {
    A();
}
public static void D(void) {
    ;
}

public static void main(String args[])
   {
      A();
      B();
   }
}
```



leaf node

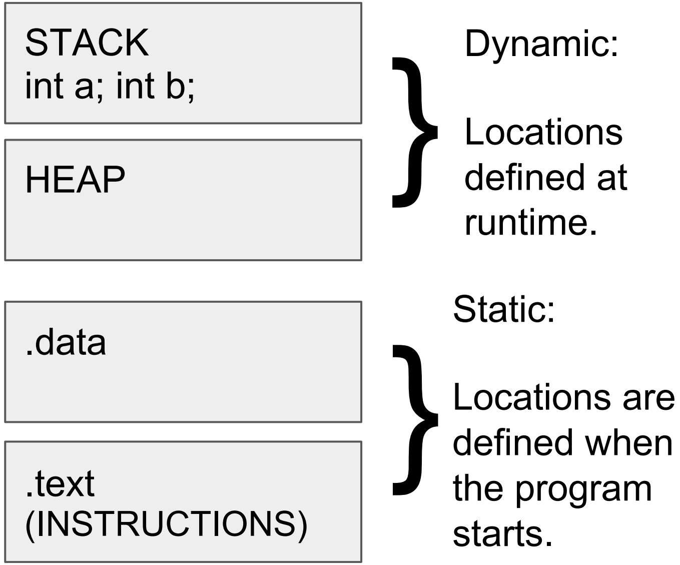
Dynamic Call Graph (Runtime)

```
public static void A(void) {
    ~~static~~ int x = 5;
    C();
}
public static void B(void) {
    C();
    D();
}
public static void C(void) {
    A();
}
public static void D(void) {
    ;
}

public static void main(String args[])
   {
      A();
      B();
   }
}
```



Memory Organization (Java program)

```
class Main {

 public static int x = 5;
 int y = 7;

 public int addNumbers(int a, int b) {
    int sum = a + b;
    return sum;
  }

  public static void main(String[] args) {
       int num1 = 25;
       int num2 = 15;

   // create an object of Main
    Main obj = new Main();
    int result = obj.addNumbers(num1, num2);
    System.out.println("Sum is: " + result);
  }
}
```



STACK
int a; int b;

HEAP

Dynamic:

Locations defined at runtime.

.data

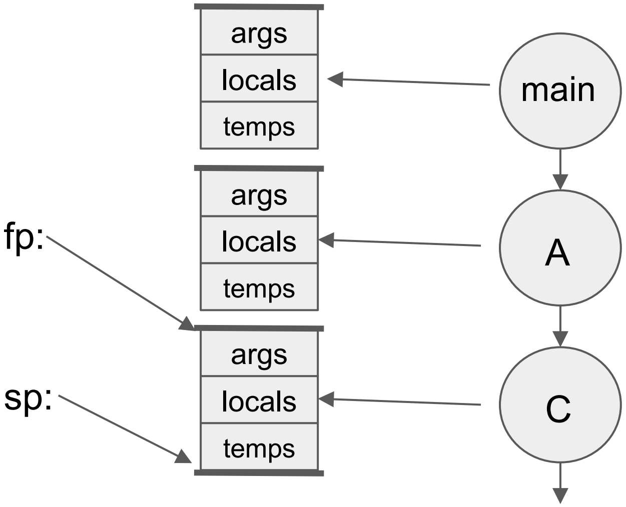
.text
(INSTRUCTIONS)

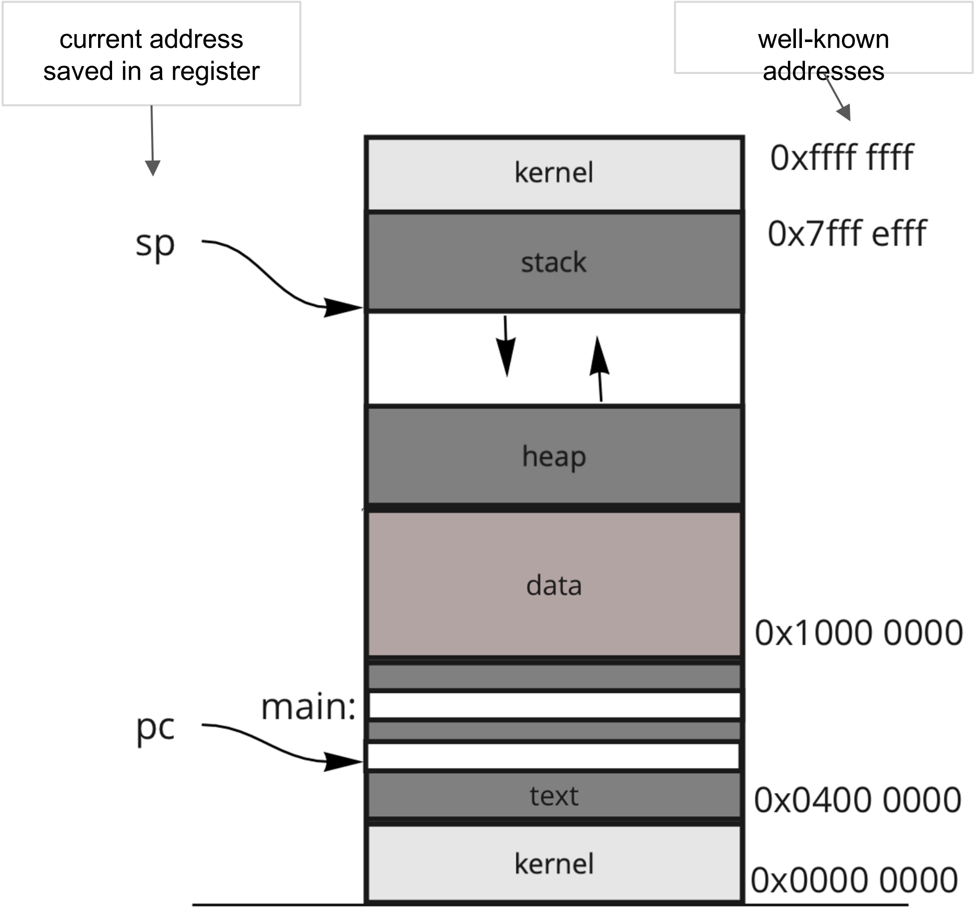
Static:

Locations are defined when the program starts.

Frames

- Frame: a collection of variables:
  - Classes variables → "heap"
  - Methods variables → "stack"
  - Static variables → ".data"

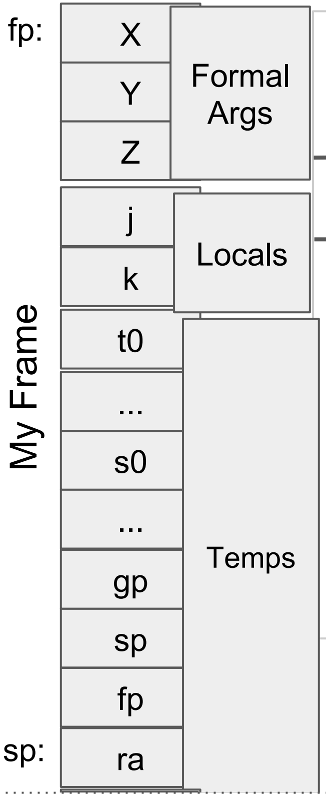




Layout of the Frame

```
int my(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

- When do we store values onto the frame?
  - in theory?
  - in practice?



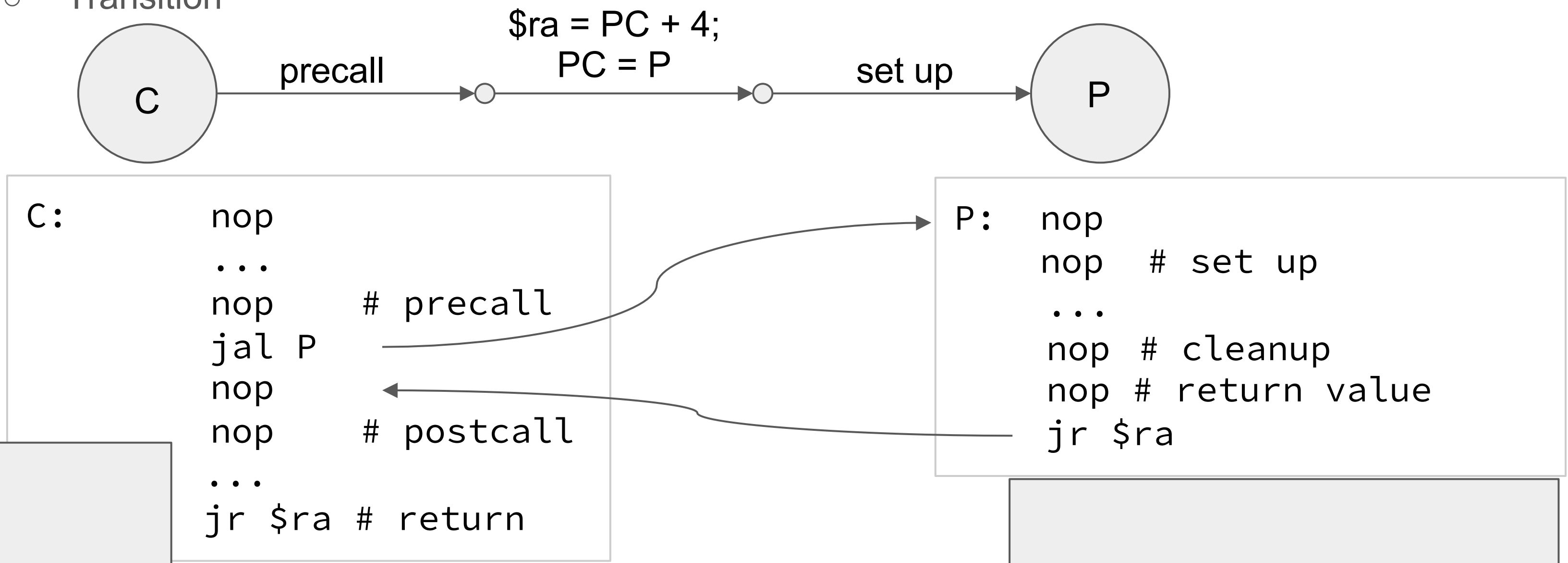
```
X  ⇔    0($fp)
Y  ⇔   -4($fp)
Z  ⇔   -8($fp)
j  ⇔  -12($fp)
k  ⇔  -16($fp)
t0 ⇔  -20($fp)
-
t9 ⇔  -56($fp)
s0 ⇔  -60($fp)
s7 ⇔  -88($fp)
gp ⇔  -92($fp)
sp ⇔  -96($fp)
fp ⇔  -100($fp)
ra ⇔  -104($fp)
```

Referencing variables

Subroutine Transition: Calling a Subroutine

1. The Client (C) needs to:
   - Place actual args into the Frame
   - Precall (preparation for the call)
   - Transition

2. The Producer (P) needs to:
   - Setup
   - Do it's Thing



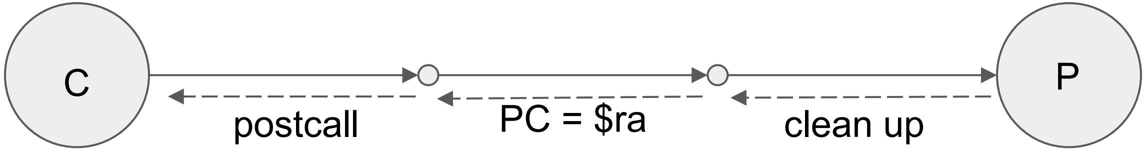
```
C:       nop
         ...
         nop    # precall
         jal P
         nop
         nop    # postcall
         ...
         jr $ra # return
```

```
P:   nop
     nop   # set up
      ...
      nop  # cleanup
      nop # return value
      jr $ra
```

Subroutine Transition: Return from a Subroutine

2. The Client (C) needs to:
   - ○ Postcall
   - ○ Continue doing it's thing

1. The Producer (P) needs to:
   - ○ Clean up
   - ○ Position the return value
   - ○ Transition back



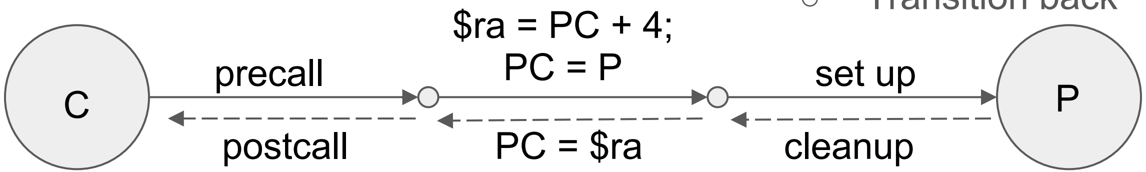
```
C:        nop
          ...
          nop    # precall
          jal P
          nop
          nop    # postcall
          ...
          jr $ra # return
```

```
P:   nop
     nop   # set up
      ...
      nop  # cleanup
      nop # return value
      jr $ra
```

MIPS: Subroutine Process

2. The Client (C) needs to:
   - Postcall ← Restore saved registers
   - Do it's Thing

1. The Producer (P) needs to:
   - Cleanup ← Restore S registers
   - Position the return value
   - Transition back



```
C:        nop
          ...
          nop    # precall
          jal P
          nop
          nop    # postcall
          ...
          jr $ra # return
```

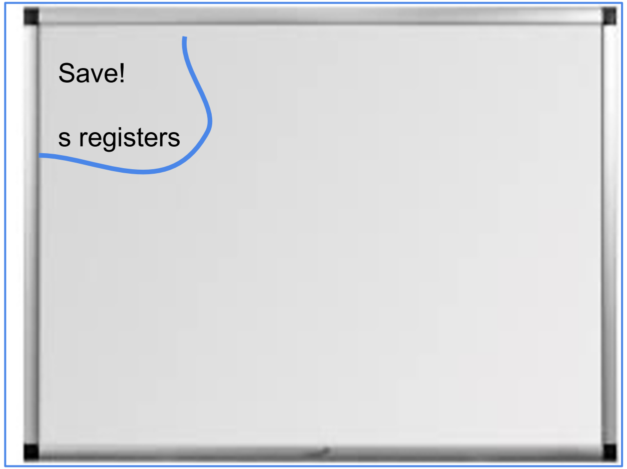
```
P:  nop
    nop  # set up
     ...
     nop # cleanup
     nop # return value
     jr $ra
```

Subroutines

- Causes:
  - a change in control-flow: `jal sub, jr $ra`
  - a change in ownership of registers

- A Subroutine Calling Convention Exists
  - pushing arguments onto the stack
    - MIPS Conventions ($a0, $a1, $a2, $a3) → {$v0, $v1}
  - preserving registers (e.g., temps) onto the stack

- Special cases (short circuit the MIPS Calling Convention)
  - Main subroutine: the first subroutine in the dynamic call graph
    - No need to save the "s" registers upon entry
    - Give preference to "s" register utilization
  - Leaf Subroutines: the last subroutine in the dynamic call graph
    - Give preference to "t" register utilization

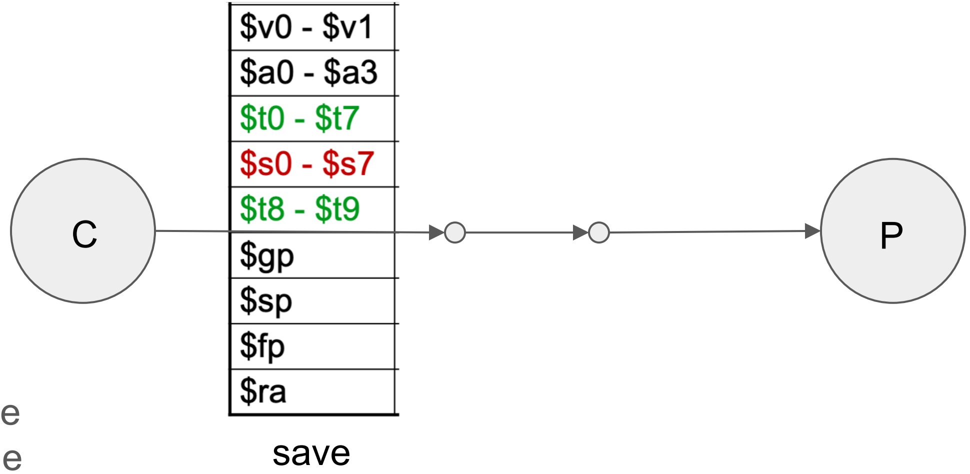


Save!

s registers

Shared Resource: Registers

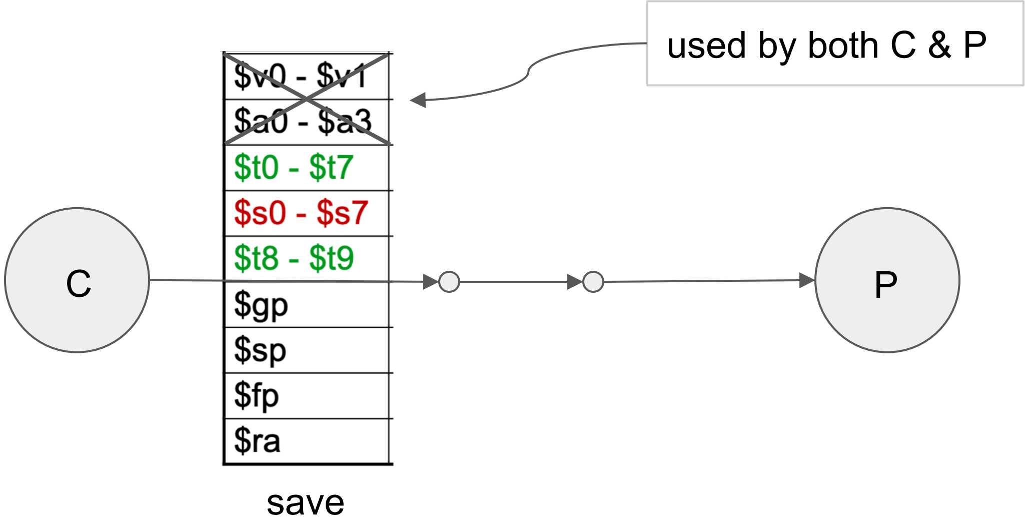
- You need to perform setup and cleanup routines for any shared resource!
- Precall:
  - Save what you need,
  - ~~Clear what you want private,~~
  - Leave alone what is passed along!
- Brute Force Approach:
  - ignore: $zero, $at, $k1, $k2
  - save all other registers
  - especially:
    - $gp: might as well!
    - $sp: this is the end of my frame
    - $fp: this is the start of my frame
    - $ra: this is my "return to" location



Shared Resource: Registers

- You need to perform setup and cleanup routines for any shared resource!

- Semi-Optimal
  - ignore: $zero, $at, $k1, $k2
  - save only registers in local use
  - but always save:
    - $gp: might as well!
    - $sp: this is the end of my frame
    - $fp: this is the start of my frame
    - $ra: this is my "return to" location



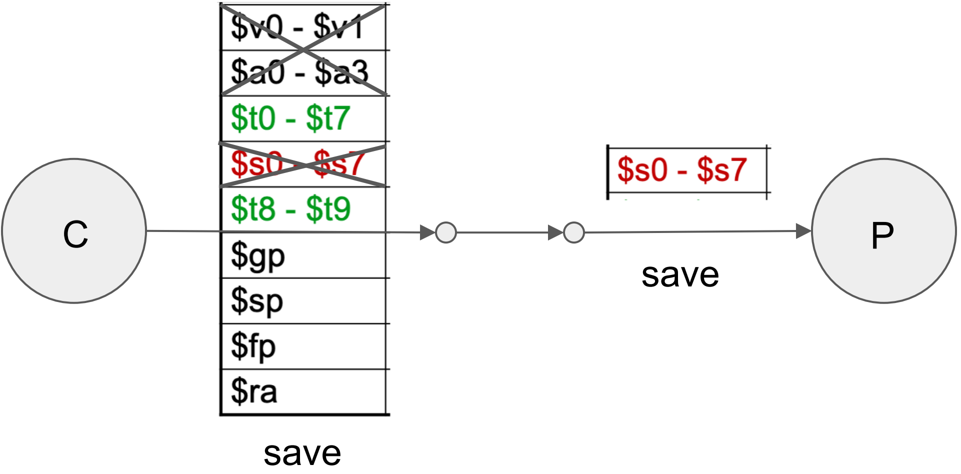
used by both C & P

save
~~$v0 - $v1~~
~~$a0 - $a3~~
$t0 - $t7
$s0 - $s7
$t8 - $t9
$gp
$sp
$fp
$ra

Shared Resource: Registers

- You need to perform setup and cleanup routines for any shared resource!

- MIPS Conventions
  - Client (C): saves:
    - all T registers
    - $gp: might as well!
    - $sp: this is the end of my frame
    - $fp: this is the start of my frame
    - $ra: this is my "return to" location
  - Provider (P): saves:
    - all S registers

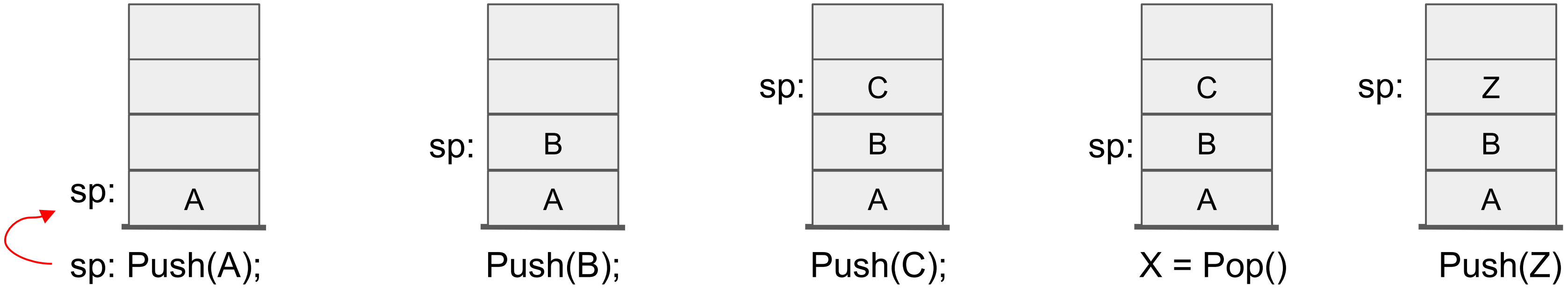


Stack Operations

```
Push(a) ⇔
    sp = sp + 1
    sp[0] = a
```

```
x = Pop() ⇔
    x = sp[0]
    sp = sp - 1
```

- Stack is an abstract data structure
- The stack is an array of words
- Operations:
  - Push: Push(A), Push(B), Push(C)
  - Pop: X = Pop();
  - Push: Push(Z);



But the MIPS Way

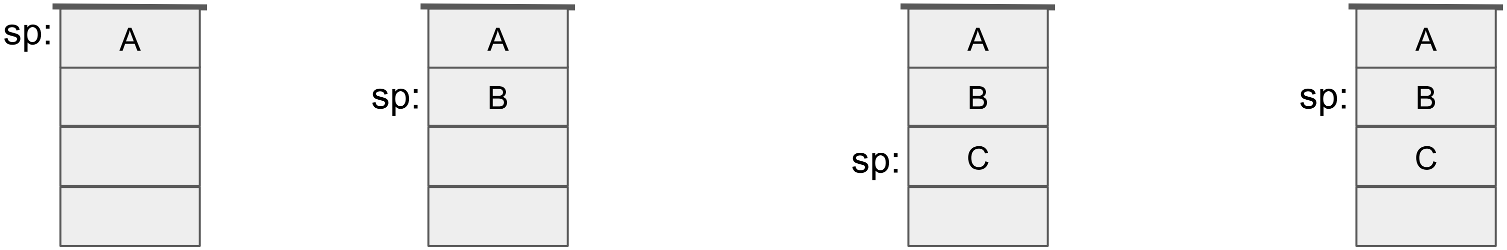
- Stack is an abstract data structure
- The stack is an array of words
- Operations:
  - Push: Push(A), Push(B), Push(C)
  - Pop: X = Pop();
- sp: points to the current top of stack

```
Push(a) ⇔
    sp = sp - 1
    sp[0] = a
```

```
x = Pop() ⇔
        x = sp[0]
        sp = sp + 1
```

```
Push(a) ⇔
    subi $sp, $sp, 4
    sw $a0, 0($sp)
```

```
x = Pop() ⇔
        lw $v0, 0($sp)
        addi $sp, $sp, 4
```



Push(A);   Push(B);   Push(C);   X = Pop()

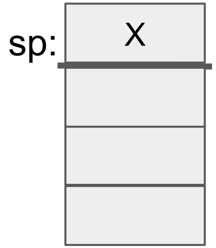
Multiple Pushes / Pops

```
Push(a) ⇔
    sp = sp - 1
    sp[0] = a
```

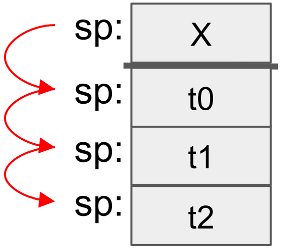
```
x = Pop() ⇔
        x = sp[0]
        sp = sp + 1
```

```
Push(a) ⇔
    subi $sp, $sp, 4
    sw $a0, 0($sp)
```

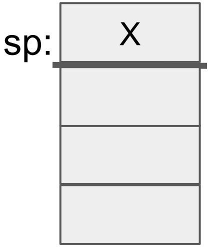
```
x = Pop() ⇔
        lw $v0, 0($sp)
        addi $sp, $sp, 4
```

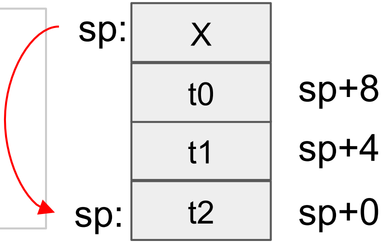


```
Push(t0);
Push(t1);
Push(t2);
```



```
subi $sp, $sp, 12
sw $t0, 8($sp)
sw $t1, 4($sp)
sw $t2, 0($sp)
```





```
t0 = Pop();
t1 = Pop();
t2 = Pop();
```

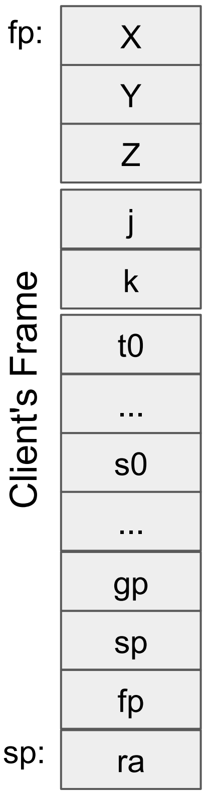
```
lw $t0, 8($sp)
lw $t1, 4($sp)
lw $t2, 0($sp)
addi $sp, $sp, 12
```

Frames in Detail

s

ls

ps


fp:

X

Y

Z

j

k

t0

...

s0

...

gp

sp

fp

ra

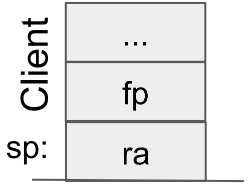
sp:

Client's Frame

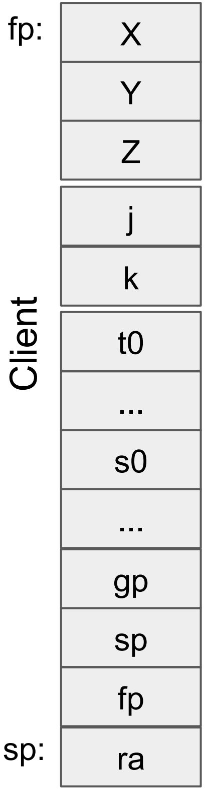
- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($sp), $v0
  - jr $ra   # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0

```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

```
X  ⇔   0($fp)
Y  ⇔  -4($fp)
Z  ⇔  -8($fp)
j  ⇔ -12($fp)
k  ⇔ -16($fp)
t0 ⇔ -20($fp)
-
t9 ⇔ -56($fp)
s0 ⇔ -60($fp)
s7 ⇔ -88($fp)
gp ⇔ -92($fp)
sp ⇔ -96($fp)
fp ⇔ -100($fp)
ra ⇔ -104($fp)
```



Calling "sub"



- ➡ Precall steps before "sub"
    - ○ push args
    - ○ save registers
    - ○ jal sub # jump and link
- Steps to set up
    - build the frame
        - fp = sp + arg_size
        - sp = fp - frame_size
    - save S registers
- Steps to clean up
    - restore S registers
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```
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}
```
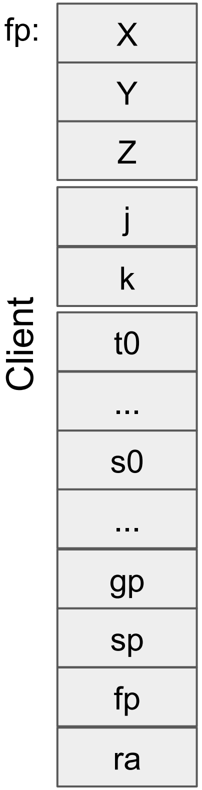

X	⇔	0($fp)
Y	⇔	-4($fp)
Z	⇔	-8($fp)
j	⇔	-12($fp)
k	⇔	-16($fp)
t0	⇔	-20($fp)
...		
t9	⇔	-56($fp)
s0	⇔	-60($fp)
s7	⇔	-88($fp)
gp	⇔	-92($fp)
sp	⇔	-96($fp)
fp	⇔	-100($fp)
ra	⇔	-104($fp)

Calling "sub"



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  - save registers
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- Steps to set up
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    - fp = sp + arg_size
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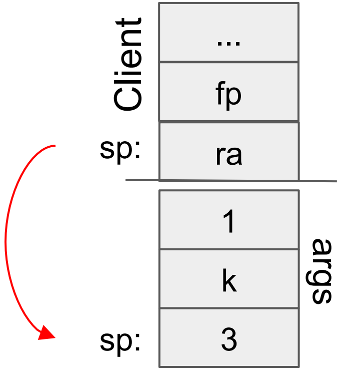
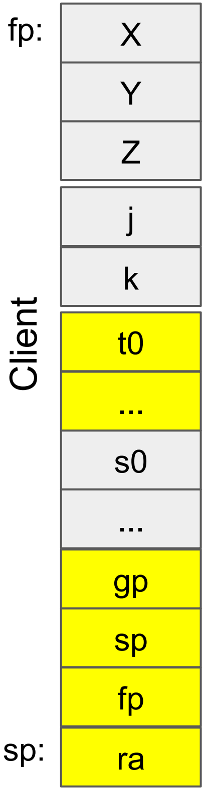


```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

```
X  ⇔   0($fp)
Y  ⇔  -4($fp)
Z  ⇔  -8($fp)
j  ⇔ -12($fp)
k  ⇔ -16($fp)
t0 ⇔ -20($fp)
...
t9 ⇔ -56($fp)
s0 ⇔ -60($fp)
s7 ⇔ -88($fp)
gp ⇔ -92($fp)
sp ⇔ -96($fp)
fp ⇔ -100($fp)
ra ⇔ -104($fp)
```

Calling "sub"


fp:
X
Y
Z
j
k
Client
t0
...
s0
...
gp
sp
fp
sp:
ra

- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
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  - position the return value: ($sp), $v0
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  - restore registers
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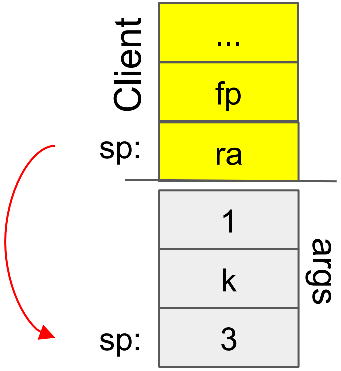
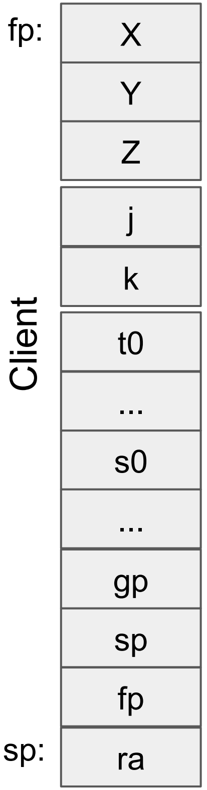

Client
...
fp
sp:
ra
1
k
sp:
3
args

```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

X	⇔	0($fp)
Y	⇔	-4($fp)
Z	⇔	-8($fp)
j	⇔	-12($fp)
k	⇔	-16($fp)
t0	⇔	-20($fp)
...		
t9	⇔	-56($fp)
s0	⇔	-60($fp)
s7	⇔	-88($fp)
gp	⇔	-92($fp)
sp	⇔	-96($fp)
fp	⇔	-100($fp)
ra	⇔	-104($fp)

Transition to "sub"



- Precall steps before "sub"
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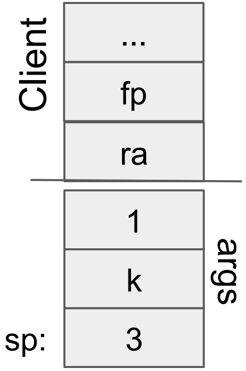
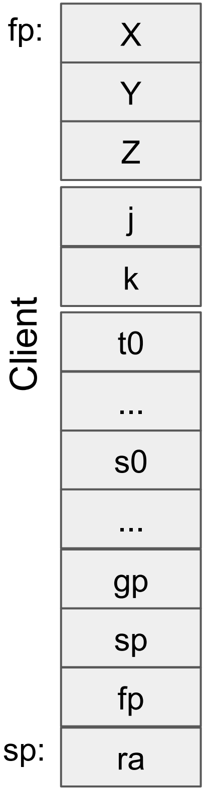
  - move return value?
    - -4($sp), ($fp), or $v0



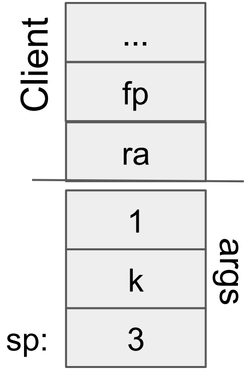
```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

X	⇔	0($fp)
Y	⇔	-4($fp)
Z	⇔	-8($fp)
j	⇔	-12($fp)
k	⇔	-16($fp)
t0	⇔	-20($fp)
...		
t9	⇔	-56($fp)
s0	⇔	-60($fp)
s7	⇔	-88($fp)
gp	⇔	-92($fp)
sp	⇔	-96($fp)
fp	⇔	-100($fp)
ra	⇔	-104($fp)

Producer: The set up



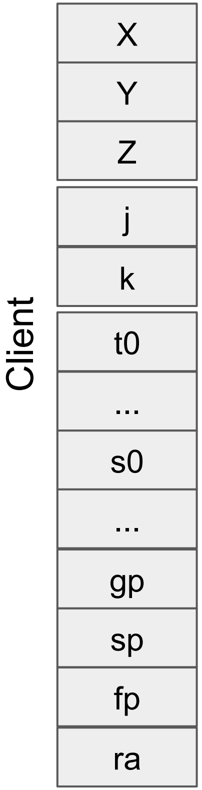
- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- ➡ Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($sp), $v0
  - jr $ra   # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0



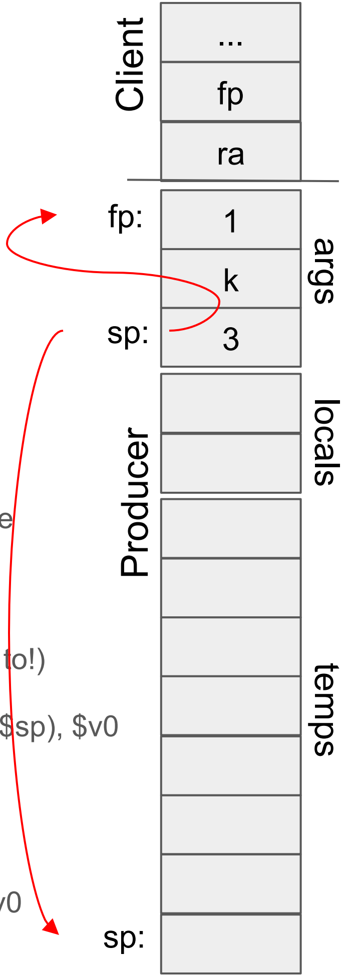
```
int sub(int X, int Y, int Z) {
 ➡ int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

```
X  ⇔   0($fp)
Y  ⇔  -4($fp)
Z  ⇔  -8($fp)
j  ⇔ -12($fp)
k  ⇔ -16($fp)
t0 ⇔ -20($fp)
...
t9 ⇔ -56($fp)
s0 ⇔ -60($fp)
s7 ⇔ -88($fp)
gp ⇔ -92($fp)
sp ⇔ -96($fp)
fp ⇔ -100($fp)
ra ⇔ -104($fp)
```

Producer: The set up



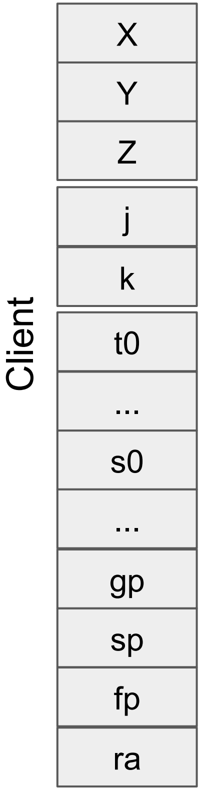
- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($sp), $v0
  - jr $ra # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0



```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

X	⇔	0($fp)
Y	⇔	-4($fp)
Z	⇔	-8($fp)
j	⇔	-12($fp)
k	⇔	-16($fp)
t0	⇔	-20($fp)
...		
t9	⇔	-56($fp)
s0	⇔	-60($fp)
s7	⇔	-88($fp)
gp	⇔	-92($fp)
sp	⇔	-96($fp)
fp	⇔	-100($fp)
ra	⇔	-104($fp)

Producer: The set up


Client

X

Y

Z

j

k

t0

...

s0

...

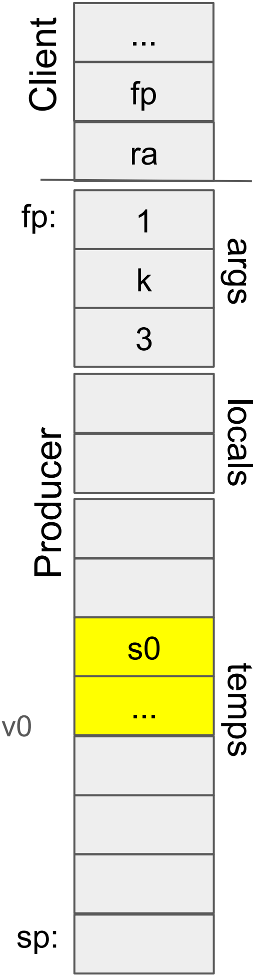
gp

sp

fp

ra

- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($sp), $v0
  - jr $ra # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0


Client

...

fp

ra

fp:

1

k

3

args

Producer

locals

s0

...

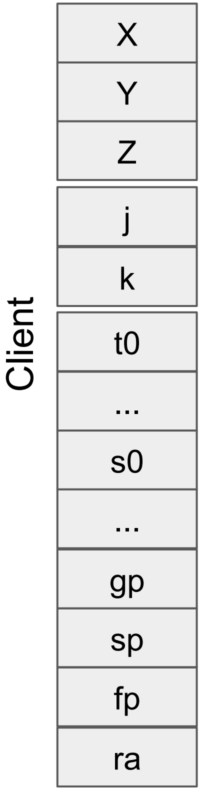
temps

sp:

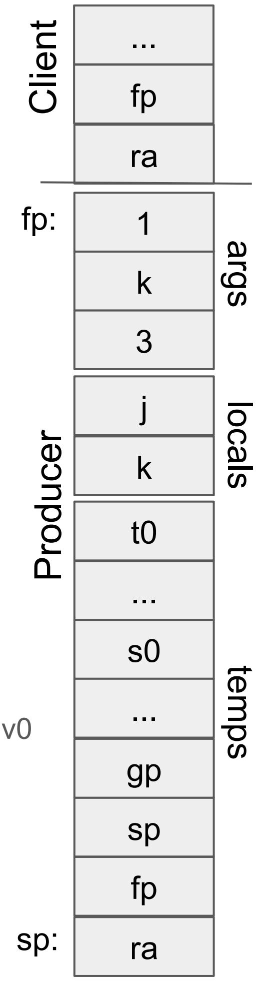
```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

X	⇔	0($fp)
Y	⇔	-4($fp)
Z	⇔	-8($fp)
j	⇔	-12($fp)
k	⇔	-16($fp)
t0	⇔	-20($fp)
...		
t9	⇔	-56($fp)
s0	⇔	-60($fp)
s7	⇔	-88($fp)
gp	⇔	-92($fp)
sp	⇔	-96($fp)
fp	⇔	-100($fp)
ra	⇔	-104($fp)

Executing "sub"



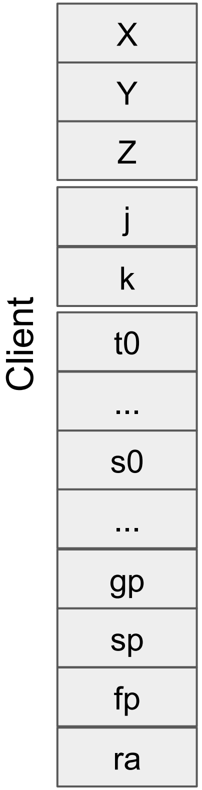
- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($sp), $v0
  - jr $ra   # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0



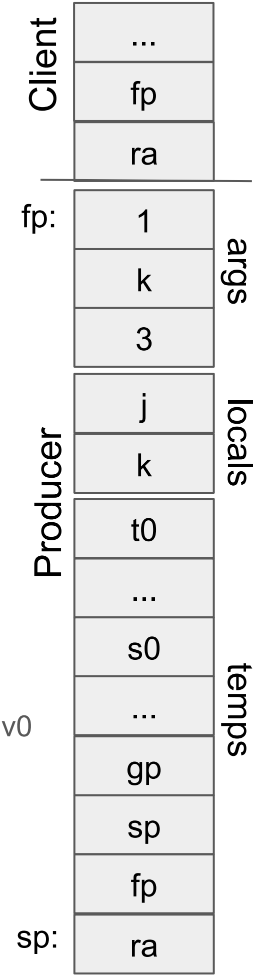
```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

```
X  ⇔    0($fp)
Y  ⇔   -4($fp)
Z  ⇔   -8($fp)
j  ⇔  -12($fp)
k  ⇔  -16($fp)
t0 ⇔  -20($fp)
...
t9 ⇔  -56($fp)
s0 ⇔  -60($fp)
s7 ⇔  -88($fp)
gp ⇔  -92($fp)
sp ⇔  -96($fp)
fp ⇔ -100($fp)
ra ⇔ -104($fp)
```

Returning from "sub"



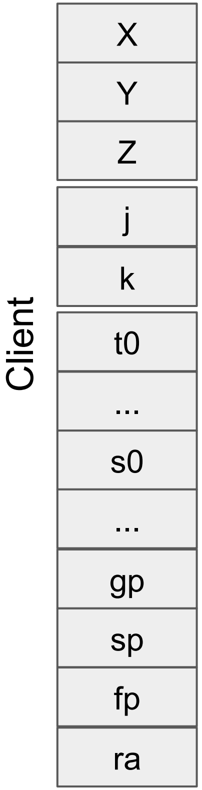
- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($sp), $v0
  - jr $ra   # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0



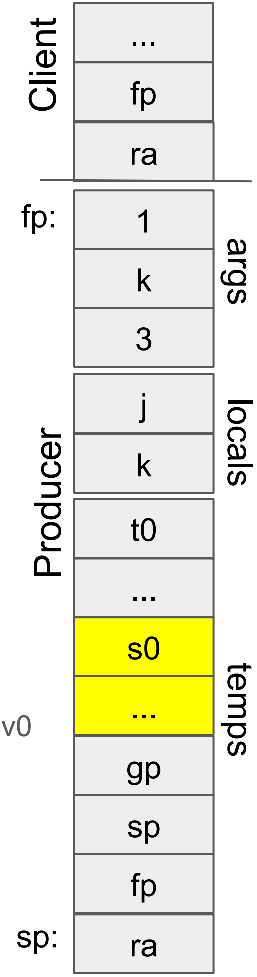
```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

```
X  ⇔   0($fp)
Y  ⇔  -4($fp)
Z  ⇔  -8($fp)
j  ⇔ -12($fp)
k  ⇔ -16($fp)
t0 ⇔ -20($fp)
...
t9 ⇔ -56($fp)
s0 ⇔ -60($fp)
s7 ⇔ -88($fp)
gp ⇔ -92($fp)
sp ⇔ -96($fp)
fp ⇔ -100($fp)
ra ⇔ -104($fp)
```

Returning from "sub"



- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($sp), $v0
  - jr $ra   # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0

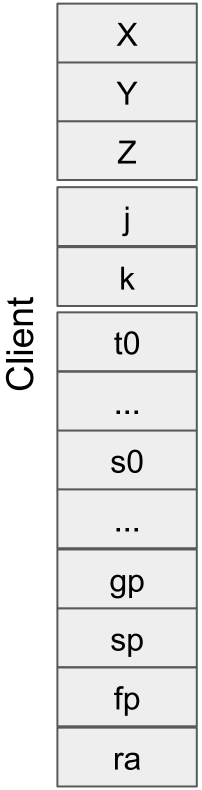


```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

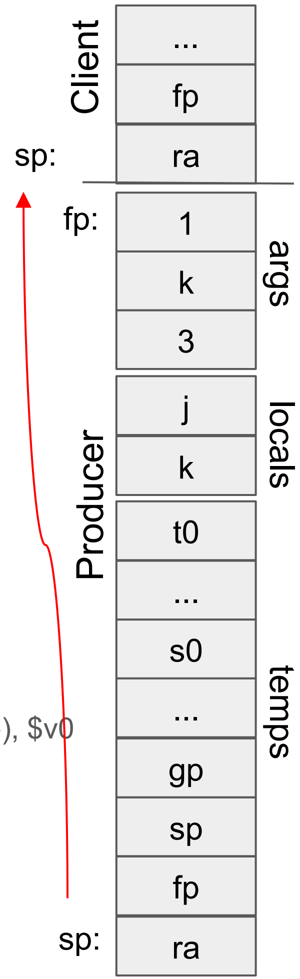
```
X  ⇔   0($fp)
Y  ⇔  -4($fp)
Z  ⇔  -8($fp)
j  ⇔ -12($fp)
k  ⇔ -16($fp)
t0 ⇔ -20($fp)
...
t9 ⇔ -56($fp)
s0 ⇔ -60($fp)
s7 ⇔ -88($fp)
gp ⇔ -92($fp)
sp ⇔ -96($fp)
fp ⇔ -100($fp)
ra ⇔ -104($fp)
```

```
lw $s0, -60($fp)
lw $s1, -64($fp)
lw $s2, -68($fp)
…
lw $s7, -88($fp)
```

Returning from "sub"



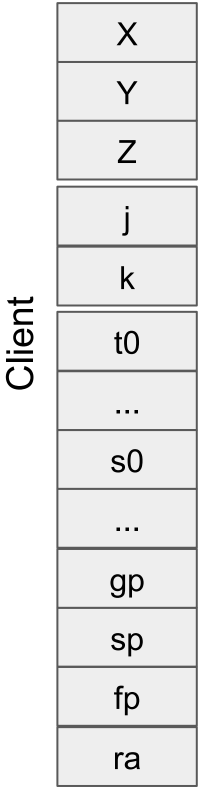
- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - ➡ delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($sp), $v0
  - jr $ra   # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0



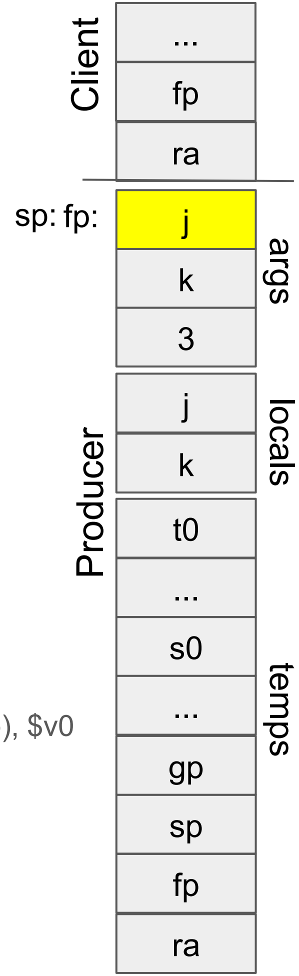
```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
  ➡ return j;
}
```

```
X  ⇔   0($fp)
Y  ⇔  -4($fp)
Z  ⇔  -8($fp)
j  ⇔ -12($fp)
k  ⇔ -16($fp)
t0 ⇔ -20($fp)
...
t9 ⇔ -56($fp)
s0 ⇔ -60($fp)
s7 ⇔ -88($fp)
gp ⇔ -92($fp)
sp ⇔ -96($fp)
fp ⇔ -100($fp)
ra ⇔ -104($fp)
```

Returning from "sub"



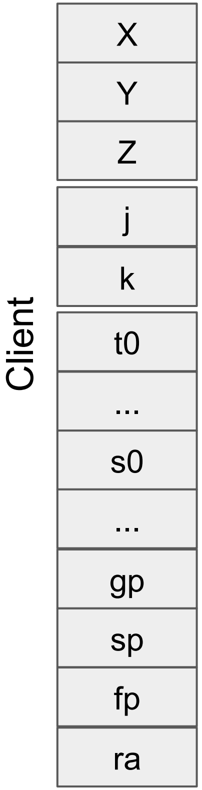
- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - ➡ position the return value: ($sp), $v0
  - jr $ra   # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0



```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
➡   return j;
}
```

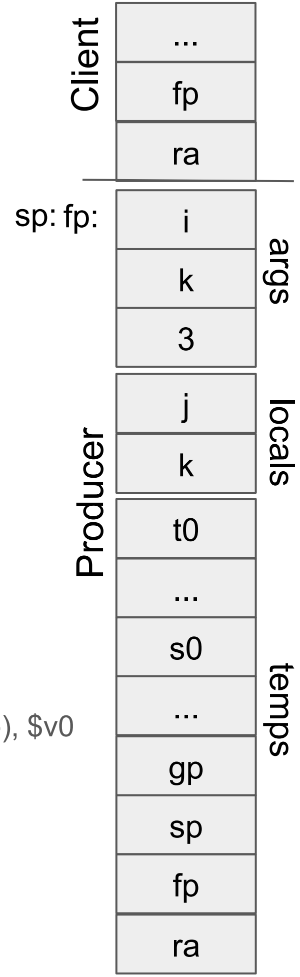
```
X  ⇔    0($fp)
Y  ⇔   -4($fp)
Z  ⇔   -8($fp)
j  ⇔  -12($fp)
k  ⇔  -16($fp)
t0 ⇔  -20($fp)
...
t9 ⇔  -56($fp)
s0 ⇔  -60($fp)
s7 ⇔  -88($fp)
gp ⇔  -92($fp)
sp ⇔  -96($fp)
fp ⇔ -100($fp)
ra ⇔ -104($fp)
```

Transition back


Client

X
Y
Z
j
k
t0
...
s0
...
gp
sp
fp
ra

- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($sp), $v0
  - ➡ jr $ra # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0


Client

...
fp
ra

sp: fp:

Producer

args
i
k
3

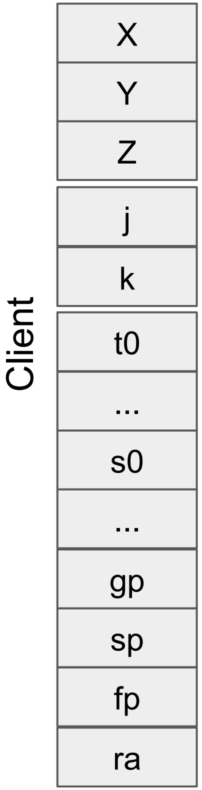
locals
j
k

temps
t0
...
s0
...
gp
sp
fp
ra

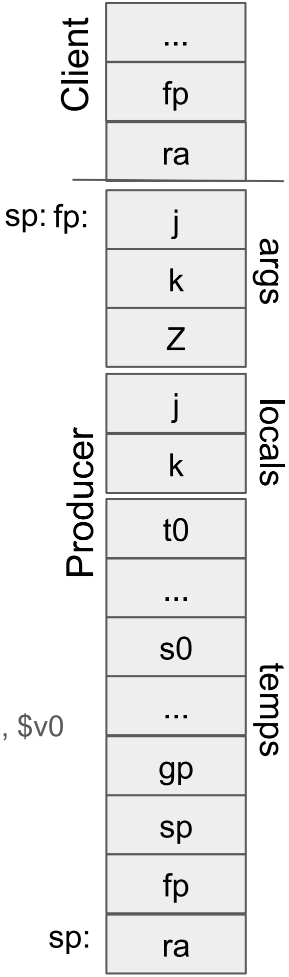
```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
  ➡ return j;
}
```

```
X  ⇔   0($fp)
Y  ⇔  -4($fp)
Z  ⇔  -8($fp)
j  ⇔ -12($fp)
k  ⇔ -16($fp)
t0 ⇔ -20($fp)
...
t9 ⇔ -56($fp)
s0 ⇔ -60($fp)
s7 ⇔ -88($fp)
gp ⇔ -92($fp)
sp ⇔ -96($fp)
fp ⇔ -100($fp)
ra ⇔ -104($fp)
```

Client: The Postcall



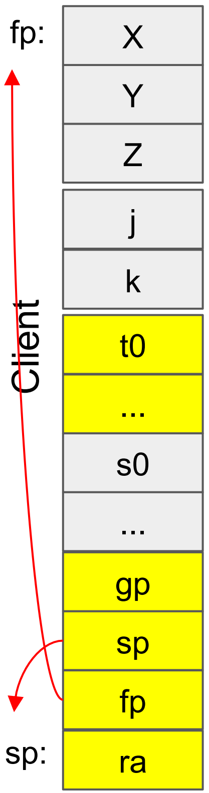
- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($sp), $v0
  - jr $ra   # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0



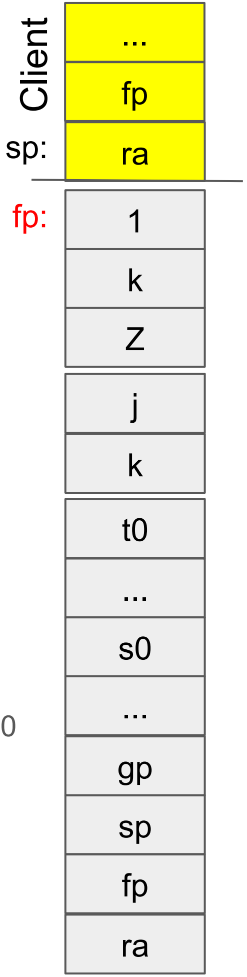
```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

```
X  ⇔   0($fp)
Y  ⇔  -4($fp)
Z  ⇔  -8($fp)
j  ⇔ -12($fp)
k  ⇔ -16($fp)
t0 ⇔ -20($fp)
...
t9 ⇔ -56($fp)
s0 ⇔ -60($fp)
s7 ⇔ -88($fp)
gp ⇔ -92($fp)
sp ⇔ -96($fp)
fp ⇔ -100($fp)
ra ⇔ -104($fp)
```

Client: The set up



- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($fp), $v0
  - jr $ra   # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0

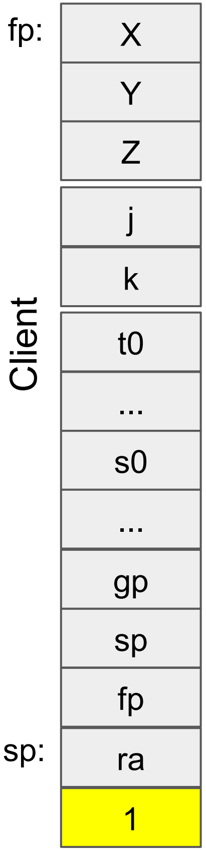


```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

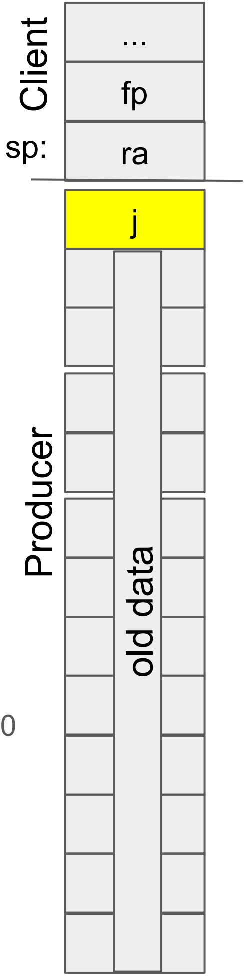
```
X  ⇔    0($fp)
Y  ⇔   -4($fp)
Z  ⇔   -8($fp)
j  ⇔  -12($fp)
k  ⇔  -16($fp)
t0 ⇔  -20($fp)
...
t9 ⇔  -56($fp)
s0 ⇔  -60($fp)
s7 ⇔  -88($fp)
gp ⇔  -92($fp)
sp ⇔  -96($fp)
fp ⇔ -100($fp)
ra ⇔ -104($fp)
```

```
lw $sp, 4($fp)
lw $fp, 4($sp)
-------------
lw $t0, -20($fp)
lw $t1, -24($fp)
…
lw $ra, -104($fp)
```

Client: The Postcall



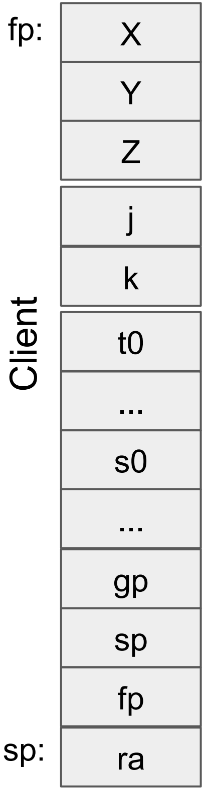
- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($fp), $v0
  - jr $ra # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0



```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
    ;
    return j;
}
```

X	⇔	0($fp)
Y	⇔	-4($fp)
Z	⇔	-8($fp)
j	⇔	-12($fp)
k	⇔	-16($fp)
t0	⇔	-20($fp)
...		
t9	⇔	-56($fp)
s0	⇔	-60($fp)
s7	⇔	-88($fp)
gp	⇔	-92($fp)
sp	⇔	-96($fp)
fp	⇔	-100($fp)
ra	⇔	-104($fp)

The Next Instruction:



- Precall steps before "sub"
  - push args
  - save registers
  - jal sub # jump and link
- Steps to set up
  - build the frame
    - fp = sp + arg_size
    - sp = fp - frame_size
  - save S registers
- Steps to clean up
  - restore S registers
  - delete the frame (no need to!)
    - but sp = fp + 1
  - position the return value: ($fp), $v0
  - jr $ra   # jump register
- Postcall steps after "sub"
  - restore registers
  - move return value?
    - -4($sp), ($fp), or $v0

```
int sub(int X, int Y, int Z) {
    int j;
    int k = Y + Z

    j = sub(1, k, 3);
➡   ;
    return j;
}
```

```
X  ⇔   0($fp)
Y  ⇔  -4($fp)
Z  ⇔  -8($fp)
j  ⇔ -12($fp)
k  ⇔ -16($fp)
t0 ⇔ -20($fp)
...
t9 ⇔ -56($fp)
s0 ⇔ -60($fp)
s7 ⇔ -88($fp)
gp ⇔ -92($fp)
sp ⇔ -96($fp)
fp ⇔ -100($fp)
ra ⇔ -104($fp)
```

Client -- Producer Convention Caveats:

- Main Memory is slow:
  - first 4 arguments should not be passed via the stack but via: $a0, $a1, $a2, $a3
  - the 2 return values should not be passed via the stack but via: $v0, $v1

- Although there are 32 general purpose registers:
  - Can't use: $zero, $at, $k1, $k2
  - If you use: $gp, $sp, $fp, $ra
    - you must take steps to save--restore these registers at call boundaries
  - if you use: $a0, $a1, $a2, $a3, $v0, $v1
    - you must take steps to save--restore these registers at call boundaries

- A compiler MUST follow this convention,
  - but the assembly level programmer can "optimize" their code!