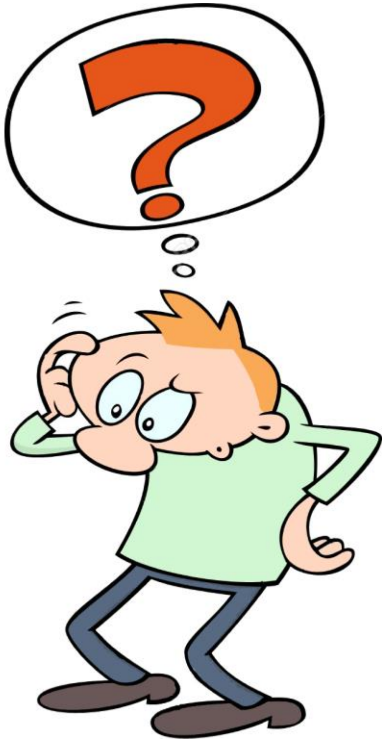
The HW/SW Interface

RISC-V
Procedures

`x0`	hard-wired zero	`t0-2 (x5-7)`	Caller
`ra (x1)`	Caller	`s0,1 (x8,9)`	Callee
`sp (x2)`	Callee	`a0-7 (x10-17)`	Caller
`gp (x3)`	-	`s2-s11 (x18-27)`	Callee
`tp (x4)`	-	`t3-6 (x28-31)`	Caller

Module Outline

- Problem Definition
- The Runtime Stack
- Solving Control Transfer
- Solving Parameter Passing
- Solving Local Storage Allocation
- The Calling Convention
- The Runtime Stack and Stack-Based Language
- Module Summary



Problem Definition

Calling Procedures/Functions/Methods

```
…
s = sumto(DATA, a1, a2);
…
```

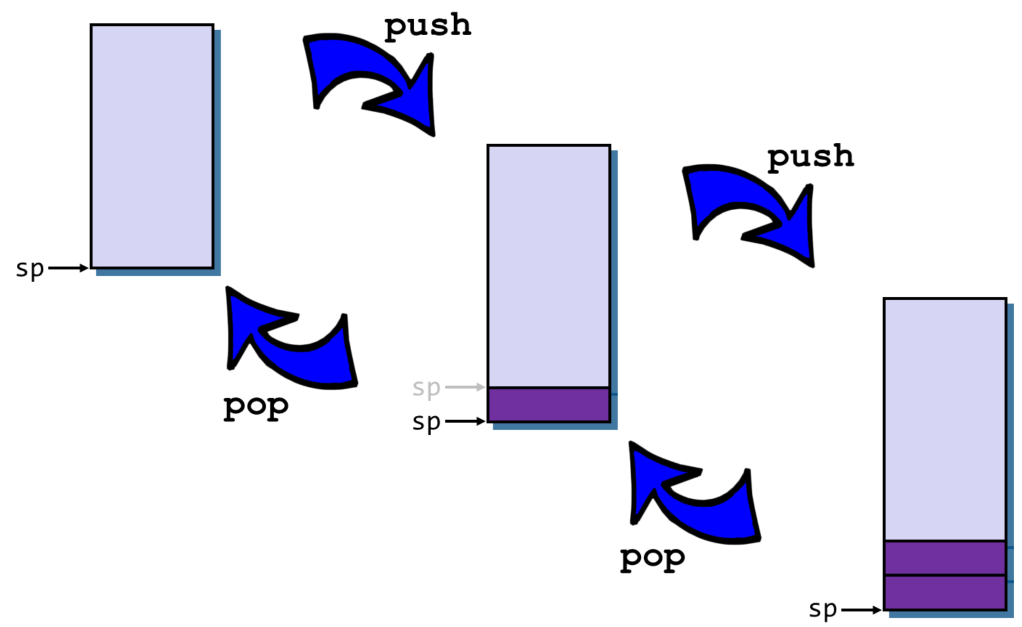
```
long sumto(long *a, int from, int to)
{
  long sum = 0;
  int i;

  for (i=from; i<to; i++) {
    sum += a[i];
  }

  return sum;
}
```

Calling Procedures/Functions/Methods

- Problems to solve
  1. **control transfer** : jump, come back
     pass control to `sumto` when the function is invoked,
     return to the calling code when `sumto` ends
  2. **parameter passing**
     pass arguments in caller to `sumto` such that `sumto` can access them. `sumto` needs to pass a return value back to the caller
  3. **storage for local variables** where?
     allow `sumto` to store and access local variables for the duration of its execution

```
…
s = sumto(DATA, a1, a2);
…
```

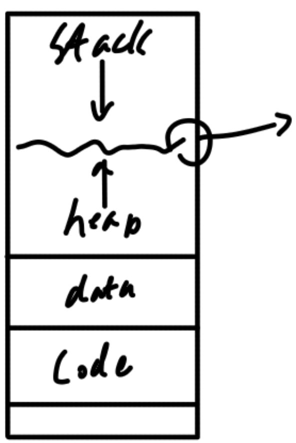
```
long sumto(long *a, int from, int to)
{
  long sum = 0;
  int i;

  for (i=from; i<to; i++) {
    sum += a[i];
  }

  return sum;
}
```



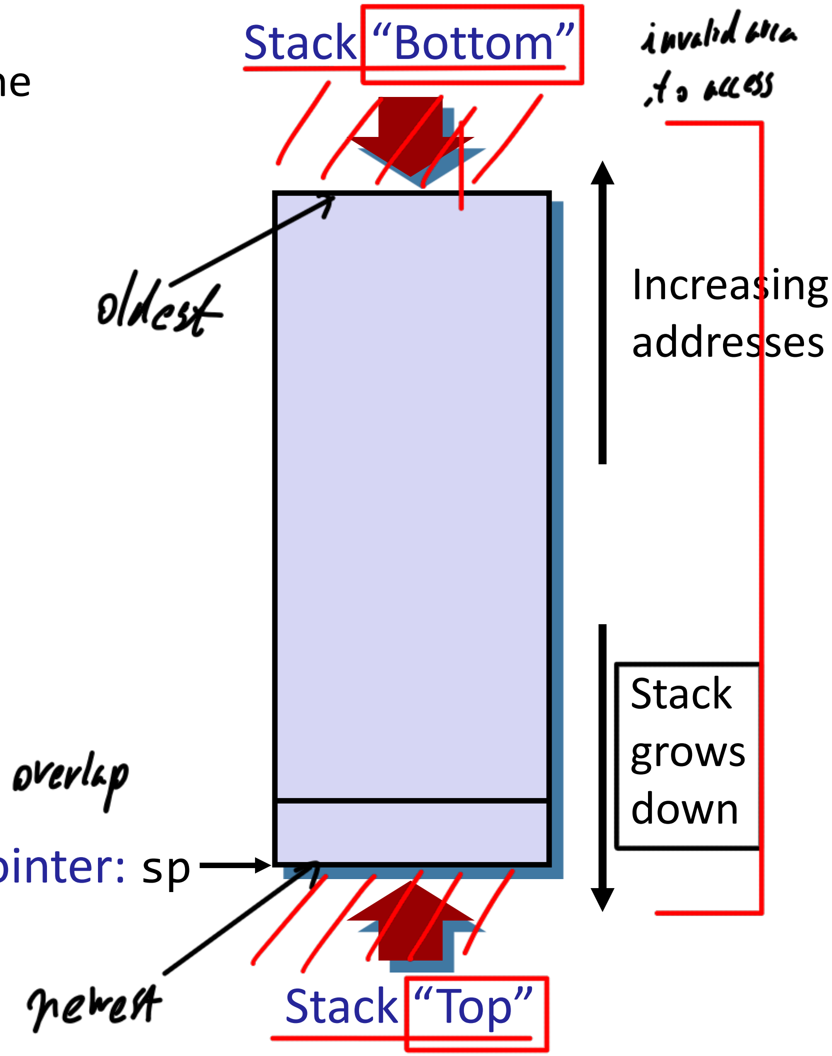
The Runtime Stack

The Runtime Stack :

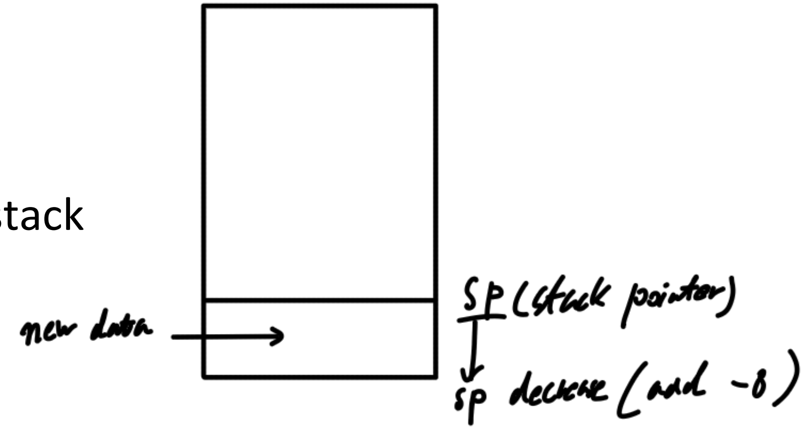
- Region of memory managed with stack discipline (last in, first out)
- Provides temporary storage for procedures
- Grows toward lower addresses (for historical reasons)
- Register sp (x2) points to top element on stack



opposite for prevent overlap

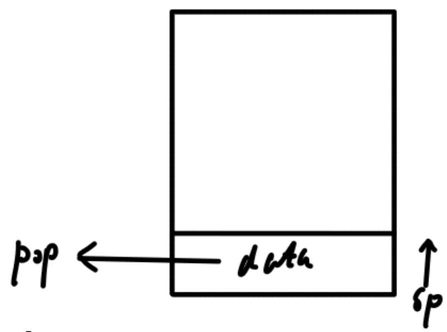


Pushing and Popping Data



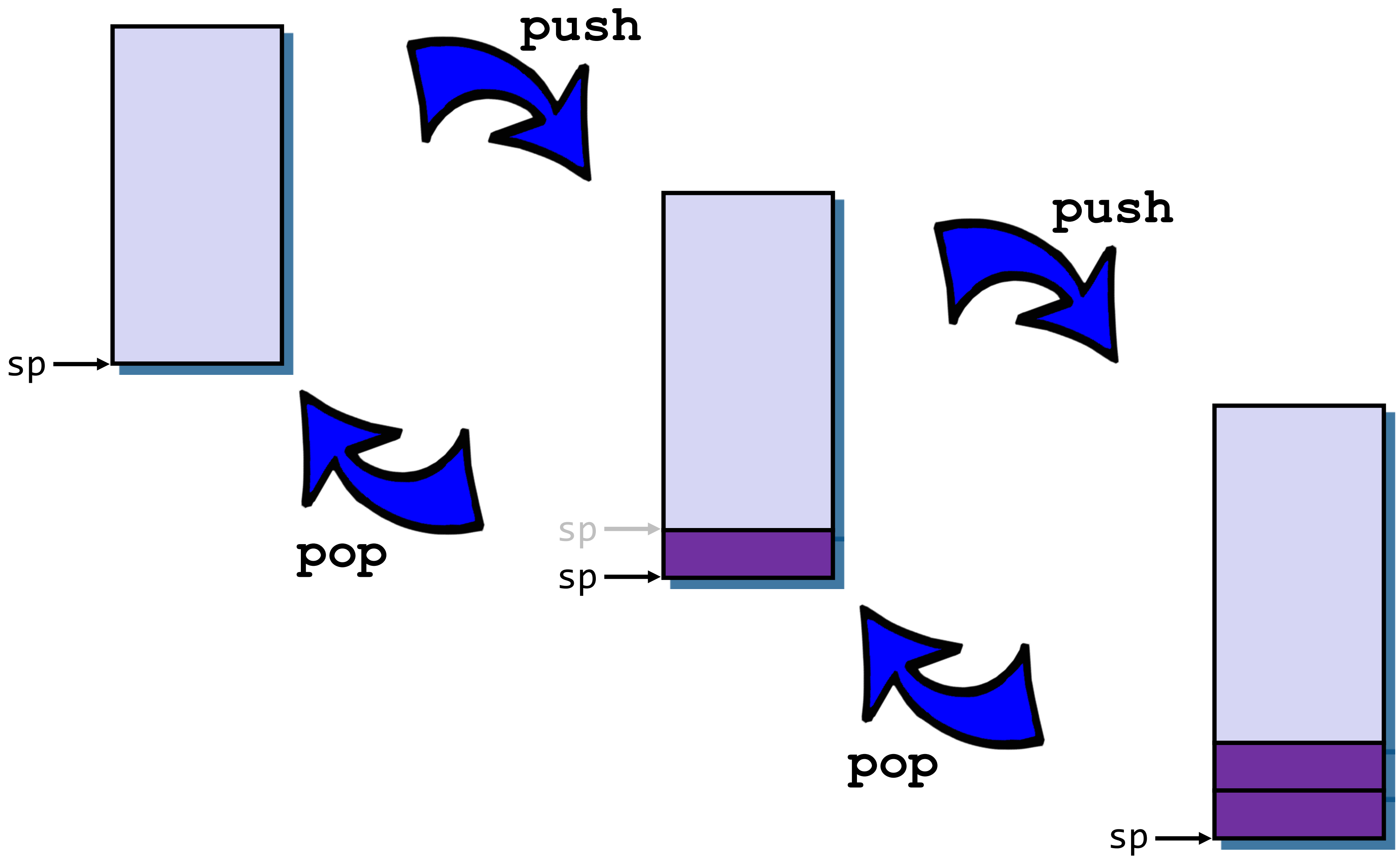
- **Push operation**
  - push a register on top of the stack
  - two part operation
    1. decrease stack pointer
    2. store element at sp

- **Pop operation**
  - pop the topmost element on the stack into a register
  - inverse of push
    1. load element at sp
    2. increment stack pointer



- **Single operation in most architectures**
  - two operations on RISC-V

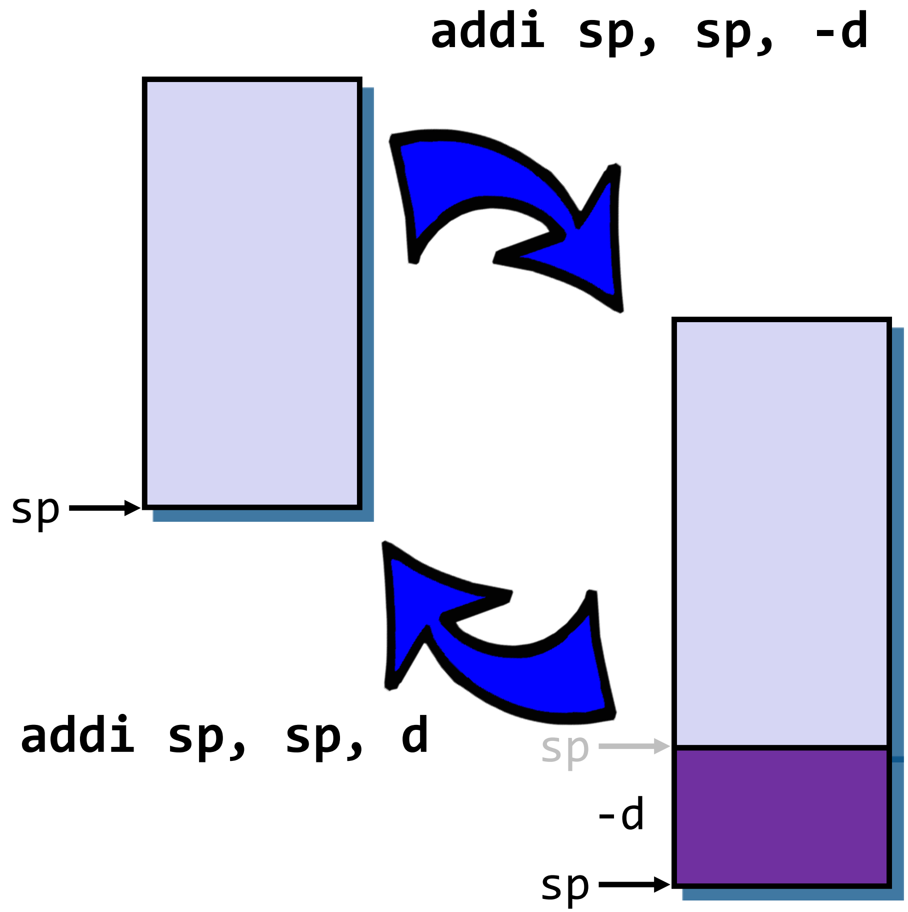
Pushing and Popping Data



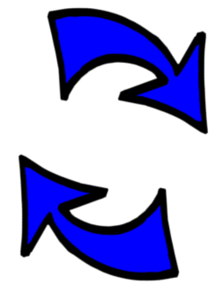
Allocate / Deallocate Memory on the Stack

- `addi sp, sp, -<amount>`
  - Decrement sp by amount
- `addi sp, sp, <amount>`
  - Increment sp by amount
- Coalesce multiple stack operations

```
addi  sp, sp, -24
sd    ra, 0(sp)
sd    fp, 8(sp)
sd    x9, 16(sp)
…
ld    x9, 16(sp)
ld    fp, 8(sp)
ld    ra, 0(sp)
addi  sp, sp, 24
```



`jal ra, <label>`



`jalr x0, 0(ra)`

Solving Control Transfer

Control Transfer: Naïve Approach

```
void foo(…)
{
  …
  s = sumto(DATA, a1, a2);
  …
}
```

```
long sumto(long *a,
       int from, int to)
{
  long i, sum = 0;

  for (i=from; i<to; i++) {
    sum += a[i];
  }

  return sum;
}
```

Setup function argument

```
00010188 <foo>:
 10188: addi   sp,sp,-32
 …
 1019c: ld     a2,0(sp)
 101a0: ld     a1,8(sp)
 101a4: addi   a0,gp,-104 # 11c68 <DATA>
 101a8: beq    x0, x0, <sumto>        # goto sumto
 101ac: ld     ra,24(sp)
 …
```

same as j

```
00010160 <sumto>:
 10160: mv     a4,a0
 …
 10178: add    a0,a0,a5
 1017c: addi   a1,a1,1
 10180: j      10168 <sumto+0x8>
 10184: beq    x0, x0, 0x101ac      # go back to foo
```

RA (Return Address)

Control Transfer: Why it doesn't work

```
void foo(…)
{
  …
  s = sumto(DATA, a1, a2);
  …
}
```

```
00010188 <foo>:
 …
 101a8: beq   x0, x0, <sumto>
 101ac: ld    ra,24(sp)
 …
```

```
void bar(…)
{
  …
  res = sumto(arr, 0, 5);
  …
}
```

```
00012248 <bar>:
 …
 12268: beq   x0, x0, <sumto>
 1226c: ld    ra,24(sp)
 …
```

```
long sumto(long *a,
       int from, int to)
{
  long i, sum = 0;

  for (i=from; i<to; i++) {
    sum += a[i];
  }

  return sum;
}
```

```
0000000000000044 <sumto>:
  44:      addi   sp,sp,-64
  ...
  a8:      mv     a0,a5
  ac:      ld     s0,56(sp)
  b0:      addi   sp,sp,64
  b4:      beq    x0, x0, 101ac or 1226c ??
```

must be Dynamic Value

Solving Procedure Control Flow

- **Store the return address whenever a procedure is called**
  - caller stores return address at known location
  - callee sets PC to return address
  - works nicely also for nested procedure calls

- **Architectural support**
  - **Invoking a procedure: `call <label>`**
    - store address of next instruction into known location
    - continue program at <procedure>
      `PC = <label>`

  - **Returning from a procedure: `ret`**
    - load return addres from known location into PC
      `PC = <return address>`

RISC-V Procedure Call Instructions

- **Procedure call: jump and link** → store and jump
  - Address of following instruction stored in register `ra (return address, x1)`
  - PC = <label>

jump to label

```
jal  ra, <label>
```

store next inst's address

return address

- **Procedure return: jump and link register**
  - Like `jal`, but jumps to 0 + address in `ra`
  - Use `x0` as `rd` (i.e., does not link)

target address

```
jalr x0, 0(ra)
```

① save address in x0

② jump to ra

- **Special uses**
  - jal x0, <label> used for unconditional branches
  - jalr used for computed jumps in switch statements

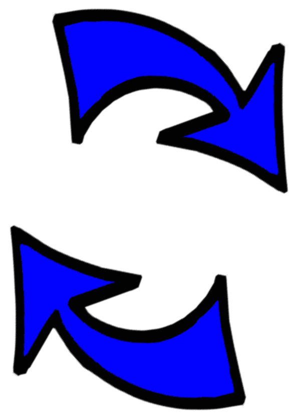
Solving Procedure Control Flow

```
void foo(…)
{
  …
  s = sumto(DATA, a1, a2);
  …
}
```

```
00010188 <foo>:
 …
 101a8: jal    ra,10160 <sumto>
 101ac: ld     ra,24(sp)
 …
```

`jal ra, <label>`

zero (x0)	
ra (x1)	101ac
x2	
x3	
x4	
…	
pc	10160



`jalr x0, 0(ra)`

zero (x0)	
ra (x1)	101ac
x2	
…	
pc	101ac

```
long sumto(long *a,…)
{
  long sum = 0;
  …
  return sum;
}
```

```
00010160 <sumto>:
 …
 10180: j      10168
 10184: jalr   x0, 0(ra)
```

Back to foo

RISC-V Jump and Link Instructions

- **Reality check**

```
$ riscv64-unknown-elf-gcc -march=rv64g -mabi=lp64d -Og -S sumto.c
$ riscv64-unknown-elf-gcc -march=rv64g -mabi=lp64d -Og -o sumto sumto.c
$ riscv64-unknown-elf-objdump -d sumto.o > sumto.dis
```

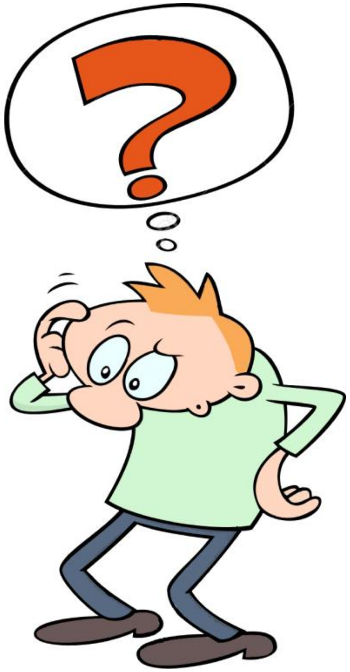
```
foo:
  addi   sp,sp,-32
  sd     ra,24(sp)
  addi   a1,sp,8
  mv     a0,sp
  call   getparm
  ld     a2,0(sp)
  ld     a1,8(sp)
  lui    a0,%hi(DATA)
  addi   a0,a0,%lo(DATA)
  call   sumto
  ld     ra,24(sp)
  addi   sp,sp,32
  jr     ra
```

sumto.s

```
00010184 <foo>:
 10184: addi   sp,sp,-32
 10188: sd     ra,24(sp)
 1018c: addi   a1,sp,8
 10190: mv     a0,sp
 10194  auipc  ra,0x0
 10198: jalr   ra # 10198 <foo+0x14>
 1019c: ld     a2,0(sp)
 101a0: ld     a1,8(sp)
 101a4: addi   a0,gp,-104 # 11c68 <DATA>
 101a8: jal    ra,10160 <sumto>
 101ac: ld     ra,24(sp)
 101b0: addi   sp,sp,32
 101b4: ret
```

save address

sumto.dis



RISC-V Jump and Link Instructions

- **Pseudoinstruction `call <label>` to implement calls**
  - translated by assembler/linker into actual instruction sequence
  - target address encoded as an **offset relative to program counter**
  - offset resolved when assembling/linking the executable
    - short call: target offset +- 1MiB (20 bit signed * 2)
      `jal   ra, <offset>`
    - far call: far or unknown targets
      ```
      auipc ra, <bits 32:12 of offset>
      jalr  ra, <bits 11:0 of offset>
      ```
      big address
    - show relocations with
      `$ objdump -dr`

return address
Callee saved

```
00010184 <foo>:
 10184: addi  sp,sp,-32
 10188: sd    ra,24(sp)
 1018c: addi  a1,sp,8
 10190: mv    a0,sp
 10194  auipc ra,0x0
 10198: jalr  ra # 10198 <foo+0x14>
 1019c: ld    a2,0(sp)
 101a0: ld    a1,8(sp)
 101a4: addi  a0,gp,-104 # 11c68 <DATA>
 101a8: jal   ra,10160 <sumto>
 101ac: ld    ra,24(sp)
 101b0: addi  sp,sp,32
 101b4: ret                  sumto.dis
```

- **Pseudoinstructions `jr <reg>`/`ret` to return from calls**
  - pseudoinstruction for
    `jalr x0, 0(ra)`

```
long foo(…)
{
  …
  s = sumto(DATA, a1, a2);
  …
}
```

```
long bar(…)
{
  …
  res = sumto(arr, 5, 22);
  …
}
```

```
long sumto(long *a, long from, long to)
{
  …
}
```

Solving Parameter Passing

Parameter Passing

- **Need a mapping between arguments and parameters**

```
long foo(…)
{
  …
  s = sumto(DATA, a1, a2);
  …
}
```

```
long bar(…)
{
  …
  res = sumto(arr, 5, 22);
  …
}
```

```
  *a = DATA
from = a1
  to = a2
```

```
  *a = arr
from = 5
  to = 22
```

```
long sumto(long *a, long from, long to)
{
  …
}
```

Solving Parameter Passing

- **Pass parameters in registers and on the runtime stack**
  - need a convention that defines which parameter maps to which register
  - RISC-V: pass first 8 parameters in registers a0-a7 (x10-x17), parameters >8 on stack

```
long foo(…)
{
  …
  s = sumto(DATA, a1, a2);
  …
}
```

```
long bar(…)
{
  …
  res = sumto(arr, 5, 22);
  …
}
```

```
mv     a2,a1
mv     a1,a0
lui    a0,%hi(DATA)
addi   a0,a0,%lo(DATA)
call   sumto
```

Set argument

```
li     a2,22
li     a1,5
mv     a0,t8
call   sumto
```

```
long sumto(long *a, long from, long to)
{
  // a0 = pointer to a
  // a1 = from
  // a2 = to
}
```

```
locals:
      addi  sp,sp,-208    # make room on stack
      mv    a0,sp         # a0 = sp
      addi  a1,sp,8       # a1 = sp+8
      sd    s0,192(sp)    # save s0
      sd    s1,184(sp)    # save s1
      sd    ra,200(sp)    # save ra
      …
      ld    ra,200(sp)    # restore ra
      ld    s0,192(sp)    # restore s0
      ld    s1,184(sp)    # restore s1
      addi  sp,sp,208     # restore sp
      jr    ra            # return
```

Solving Local Storage Allocation

Where do Local Variables Go?

```c
long locals(void)
{
  long a, b;
  long from, to, sum=0;
  long array[20];

  init_ab(&a, &b);

  from = a+b;
  to   = 3*a + 2*b;

  init_array(array);

  for (long i=from; i<to; i++) {
    sum += array[i];
  }

  return sum;
}
```

Where do Local Variables Go?

- Could try to allocate local variables to a (fixed) memory address

```
long locals(void)
{
  long a, b;
  long from, to, sum=0;
  long array[20];

  init_ab(&a, &b);

  from = a+b;
  to   = 3*a + 2*b;

  init_array(array);

  for (long i=from; i<to; i++) {
    sum += array[i];
  }

  return sum;
}
```

```
      …
      ld     a4,%lo(from.1508)(s0)
.L2:
      lui    a5,%hi(to.1509)
      ld     a5,%lo(to.1509)(a5)
      ble    a5,a4,.L5
      …
```

```
0x00010788: a
0x00010790: b
0x00010798: from
0x000107a0: to
…
```

Local Variable

Local Variable Mapping

- **Fails for recursive procedures**

```
int foo(int n)
{
  int a, b = 1;

  for (a=0; a<n; a++) {
    b = b + foo(n-1);
  }

  return b;
}
```

```
0x00010788: a
0x00010790: b
```

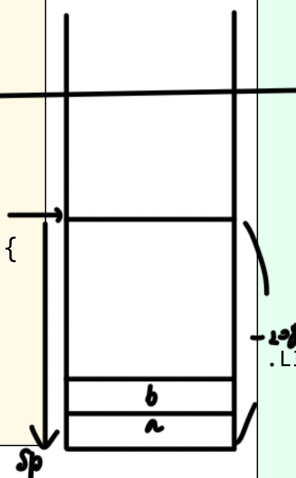
```
foo(2):
  b=1;
  a=0;
  a<n? yes: b=b + foo(1):
                  b=1;
                  a=0;
                  a<n? yes: b=b + foo(0)
                                  b=1;
                                  a=0;
                                  a<n? no
                                  return b (=1)
                          b=1 + 1 = 2
                  a++ (=1)
                  a<n? no
                  return b (=2)
            =1 + 2 = 3
  a++ (=2)
  a<n? NO!
```

Solving Local Variable Mapping

stack initialize

- **Allocate on runtime stack**

```
long locals(void)
{
  long a, b;
  long from, to, sum=0;
  long array[20];

  init_ab(&a, &b);

  from = a+b;
  to   = 3*a + 2*b;

  init_array(array);

  for (long i=from; i<to; i++) {
    sum += array[i];
  }

  return sum;
}
```




```
locals:
        addi   sp,sp,-208    # make room on stack
        mv     a0,sp         # a0 = sp             (= &a, a at mem[sp+0])
        addi   a1,sp,8       # a1 = sp+8           (= &b, b at mem[sp+8])
        sd     s0,192(sp)    # save s0
        sd     s1,184(sp)    # save s1
        sd     ra,200(sp)    # save ra
        call   init_ab       # init_ab(&a, &b)
        ld     a5,0(sp)      # a5 = a
        ld     s0,8(sp)      # s0 = b
        addi   a0,sp,16      # a0 = sp+16          (=&array)
        slli   s1,a5,1       # s1 = a<<1 = 2*a
        slli   a4,s0,1       # a4 = b<<1 = 2*b
        add    s1,s1,a5      # s1 = 2*a + a = 3*a
        add    s0,a5,s0      # s0 = a + b          (=from)
        add    s1,s1,a4      # s1 = 3*a + 2*b      (=to)
        call   init_array    # init_array(&array)
        bge    s0,s1,.L4     # to >= from ? goto .L4 (skip if nothing to do)
        addi   a3,sp,16      # a3 = sp+16          (=&array)
        slli   a5,s0,3       # a5 = from<<3 = from*8 (=offset into array[from])
        slli   a4,s1,3       # a4 = to<<3 = to*8   (=offset into array[to])
        add    a5,a3,a5      # a5 = &array[from]
        add    a4,a4,a3      # a4 = &array[to]
        li     a0,0          # a0 = 0              (=sum)
.L3:    ld     a3,0(a5)      # a3 = array[from]
        addi   a5,a5,8       # a5 = from+8         (=offset of next element)
        add    a0,a0,a3      # a0 = a0 + array[from]
        bne    a5,a4,.L3     # from != to? goto .L3
        ld     ra,200(sp)    # restore ra
        ld     s0,192(sp)    # restore s0
        ld     s1,184(sp)    # restore s1
        addi   sp,sp,208     # restore sp
        jr     ra            # return
.L4:    ld     ra,200(sp)    # restore ra
        ld     s0,192(sp)    # restore s0
        ld     s1,184(sp)    # restore s1
        li     a0,0          # return value = 0
        addi   sp,sp,208     # restore sp
        jr     ra            # return
```

on stack

register

- **Observations about locals**
  - some on stack (a,b, array)
  - some in registers (from, to, sum)
  - some eliminated (i)

`x0`	hard-wired zero
`ra (x1)`	Caller
`sp (x2)`	Callee
`gp (x3)`	-
`tp (x4)`	-

`t0-2 (x5-7)`	Caller
`s0,1 (x8,9)`	Callee
`a0-7 (x10-17)`	Caller
`s2-s11 (x18-27)`	Callee
`t3-6 (x28-31)`	Caller

The Calling Convention

The Calling Convention

```
void foo(…)
{
   …
   v = who(a, 1);
   …
}
```

```
int who(int, int)
{
   …
   return 5;
}
```

- The calling procedure is the **caller**, the called function is the **callee**
- **The Calling convention**: specification that defines
  - how parameters are passed
    - registers, stack
  - how return values are passed
    - register(s), stack
  - how registers are handled

Calling Convention on RISC-V

- **Arguments passed to functions via registers a0 – a7**
  - If more than 8 integral parameters, then pass rest on stack
  - a0 is used as the return register
- **All references to stack frame via stack pointer sp**

Argument

`x0` hard-wired zero	`t0-2 (x5-7)`
`ra (x1)`	`s0,1 (x8,9)`
`sp (x2)`	`a0-7 (x10-17)`
`gp (x3)`	`s2-s11 (x18-27)`
`tp (x4)`	`t3-6 (x28-31)`

Register Saving Conventions

- **What about the remaining registers?**

Caller

```
yoo(…) {
  who();
}
```

Callee

```
who(…) {
   …
}
```

- ***"Caller Save"***
  - registers that the callee can overwrite
    (caller assumes value is not preserved across procedure calls)
  - Caller saves temporary values in its frame before the call

    ↳ move to Callee save register

- ***"Callee Save"***
  - registers that the callee must preserve before overwriting with a new value
    (caller can reuse the value across procedure calls)
  - Callee saves temporary values in its frame before using

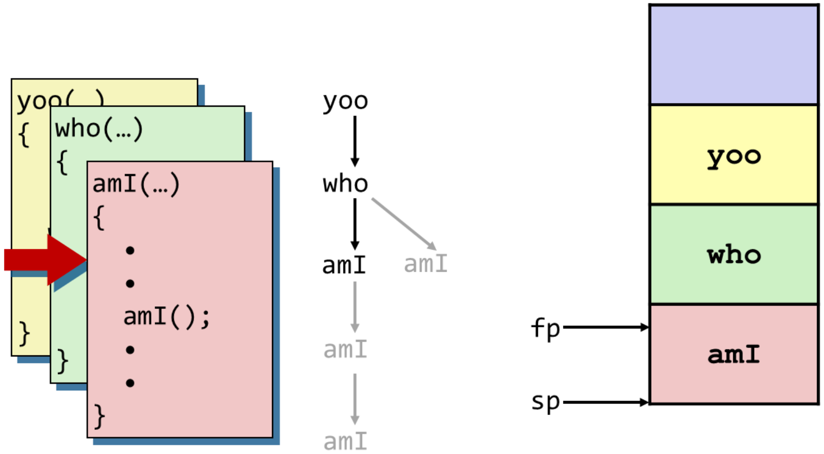
Calling Convention on RISC-V

- **Register saving convention**

`x0`	hard-wired zero
`ra (x1)`	Caller
`sp (x2)`	Callee
`gp (x3)`	-
`tp (x4)`	-

overlapable

`t0-2 (x5-7)`	Caller-only	Caller
`s0,1 (x8,9)`	Callee-only	Callee
`a0-7 (x10-17)`	argument/return	Caller
`s2-s11 (x18-27)`	Callee-only	Callee
`t3-6 (x28-31)`	Caller-only	Caller



The Runtime Stack and Stack-Based Language

Runtime Stack = Good Match for Stack-Based Languages

- Languages that support recursion
  - e.g., C, Pascal, Java
  - Code must be *"reentrant"*
    - Multiple simultaneous instantiations of single procedure
  - Need some place to store state of each instantiation
    - Arguments
    - Local variables
    - Return pointer

- Stack discipline
  - State for given procedure needed for limited time
    - From when called to when return
  - Callee returns before caller does

- Stack allocated in ***frames***
  - state for single procedure instantiation

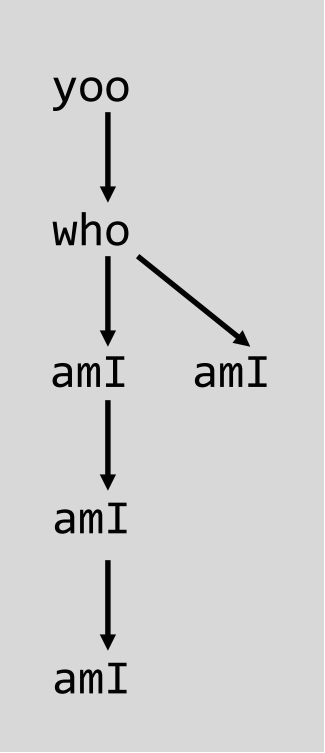
Call Chain Example

```
yoo(…)
{
  •
  •
  who();
  •
  •
}
```

```
who(…)
{
  • • •
  amI();
  • • •
  amI();
  • • •
}
```

```
amI(…)
{
  •
  •
  amI();
  •
  •
}
```

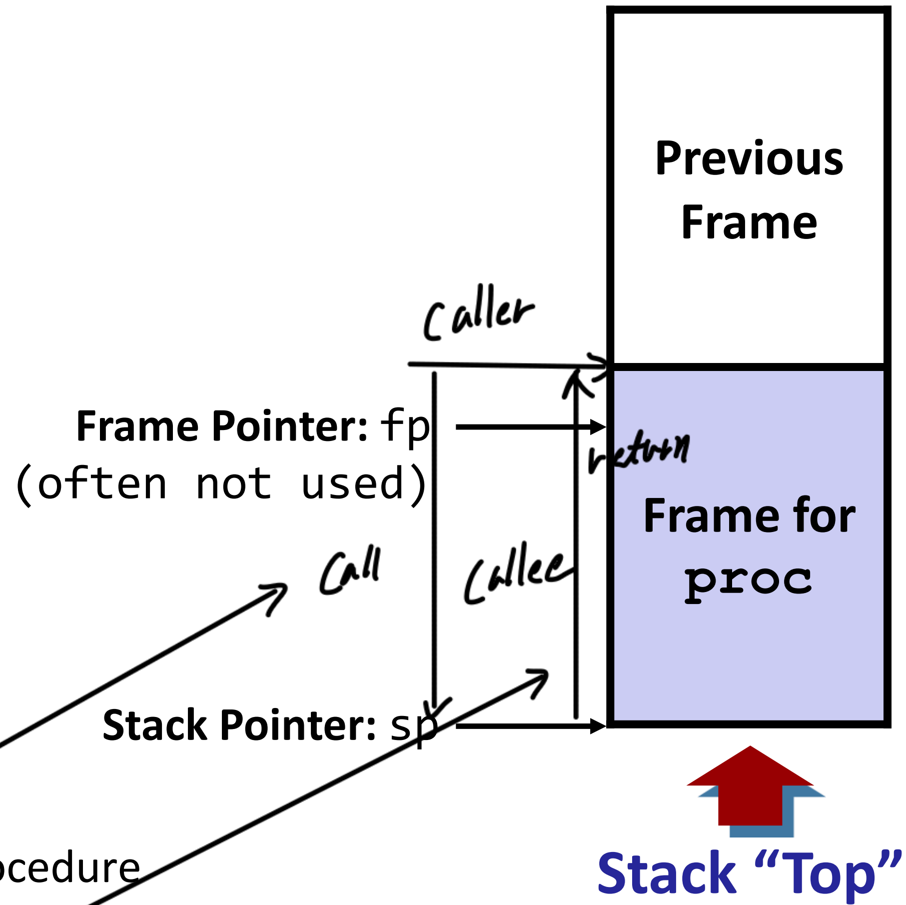
Example Call Chain



Procedure amI() is recursive

Stack Frames

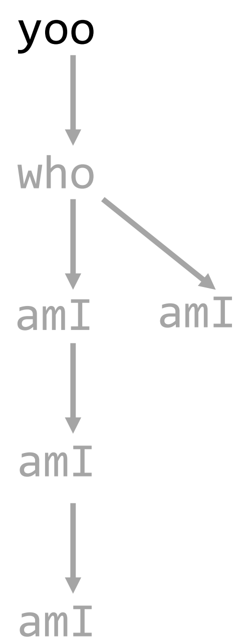
- Contents
  - Local variables
  - Return information
  - Temporary space

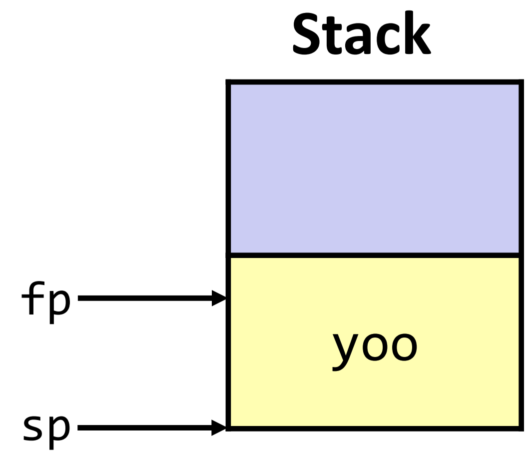


- Management
  - Space allocated when entering a procedure
    - "Set-up" code
  - Deallocated when returning to the caller
    - "Cleanup" code

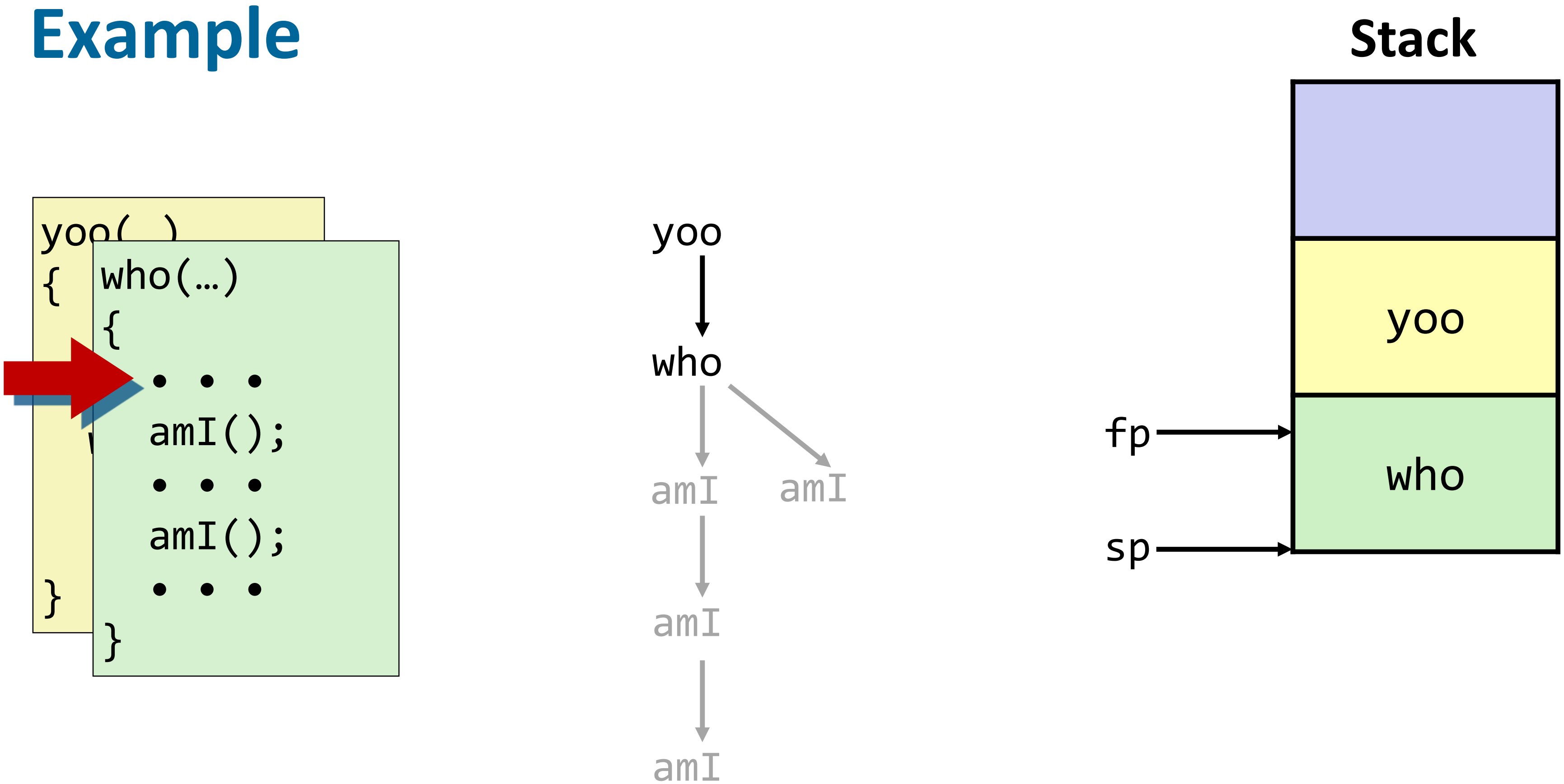
Example

```
yoo(…)
{
  •
  •
  who();
  •
  •
}
```

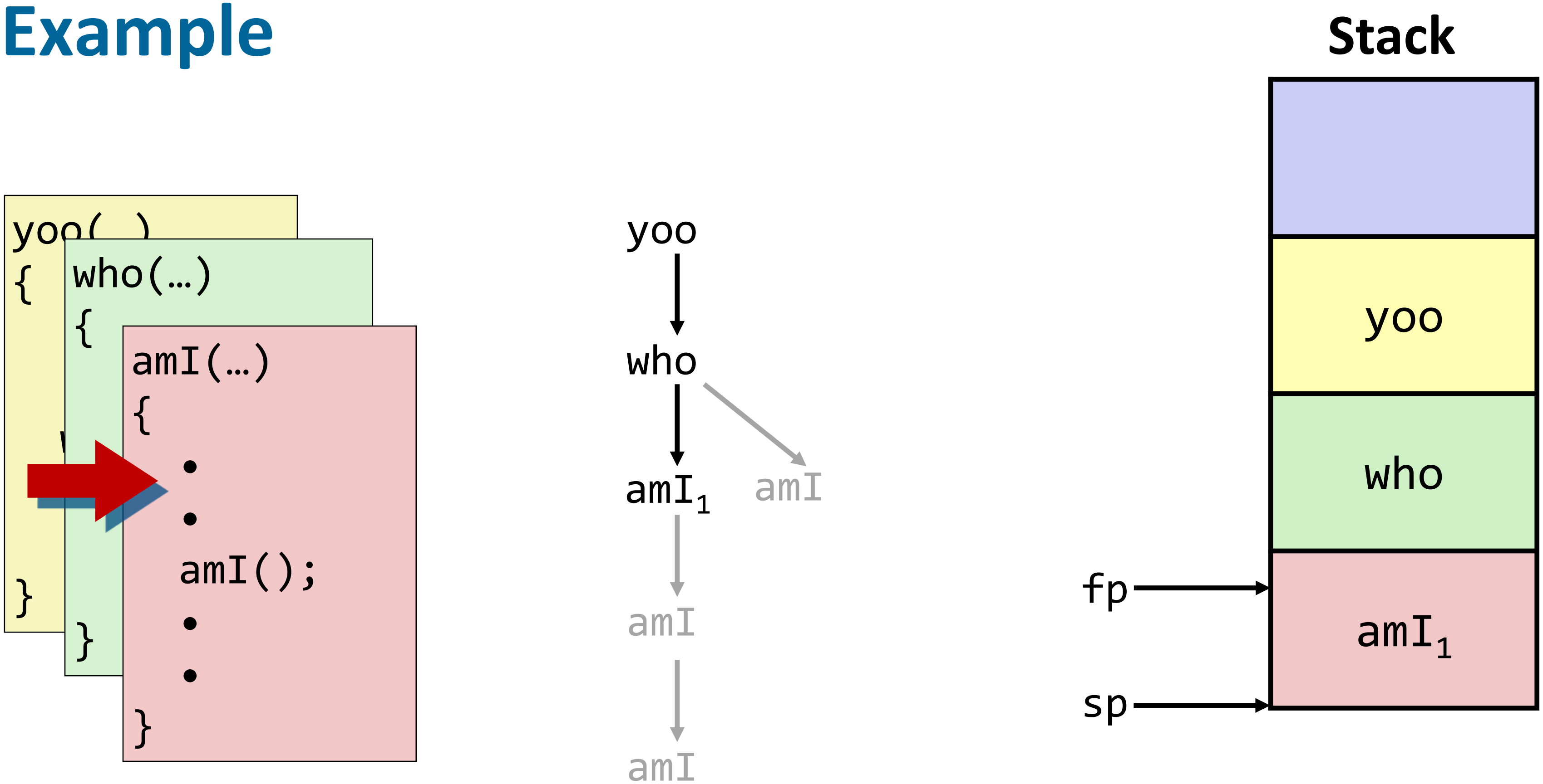




Example

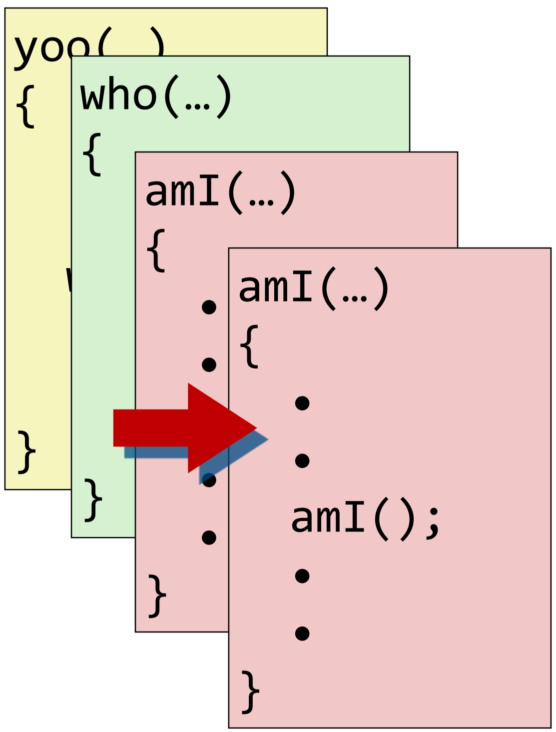


Example

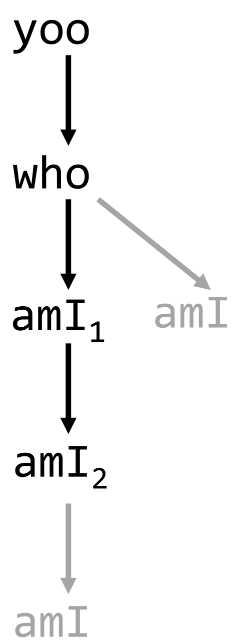


yoo(…)
{
who(…)
{
amI(…)
{
•
•
amI();
•
•
}
}
}
yoo
who
amI_1
amI
amI
amI
Stack
yoo
who
amI_1
fp
sp

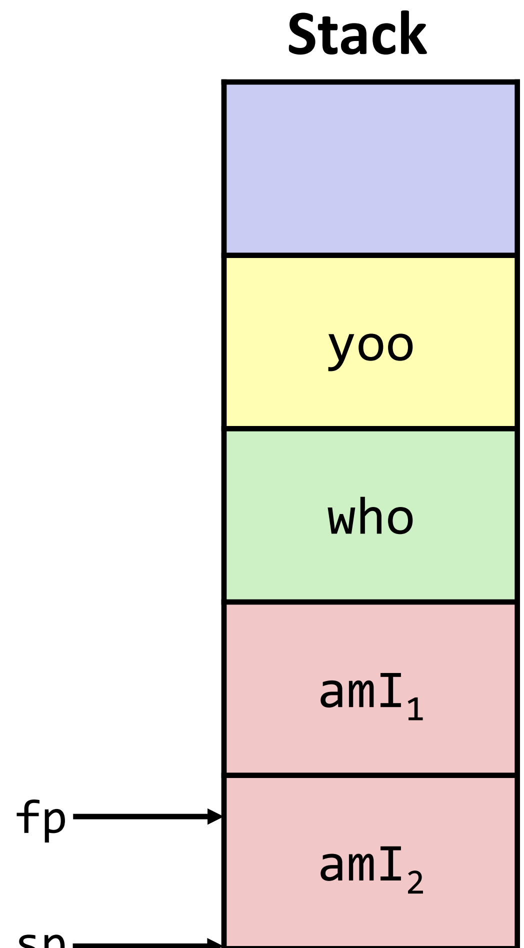
Example



yoo(…)
{
}
who(…)
{
}
amI(…)
{
}
amI(…)
{
amI();
}

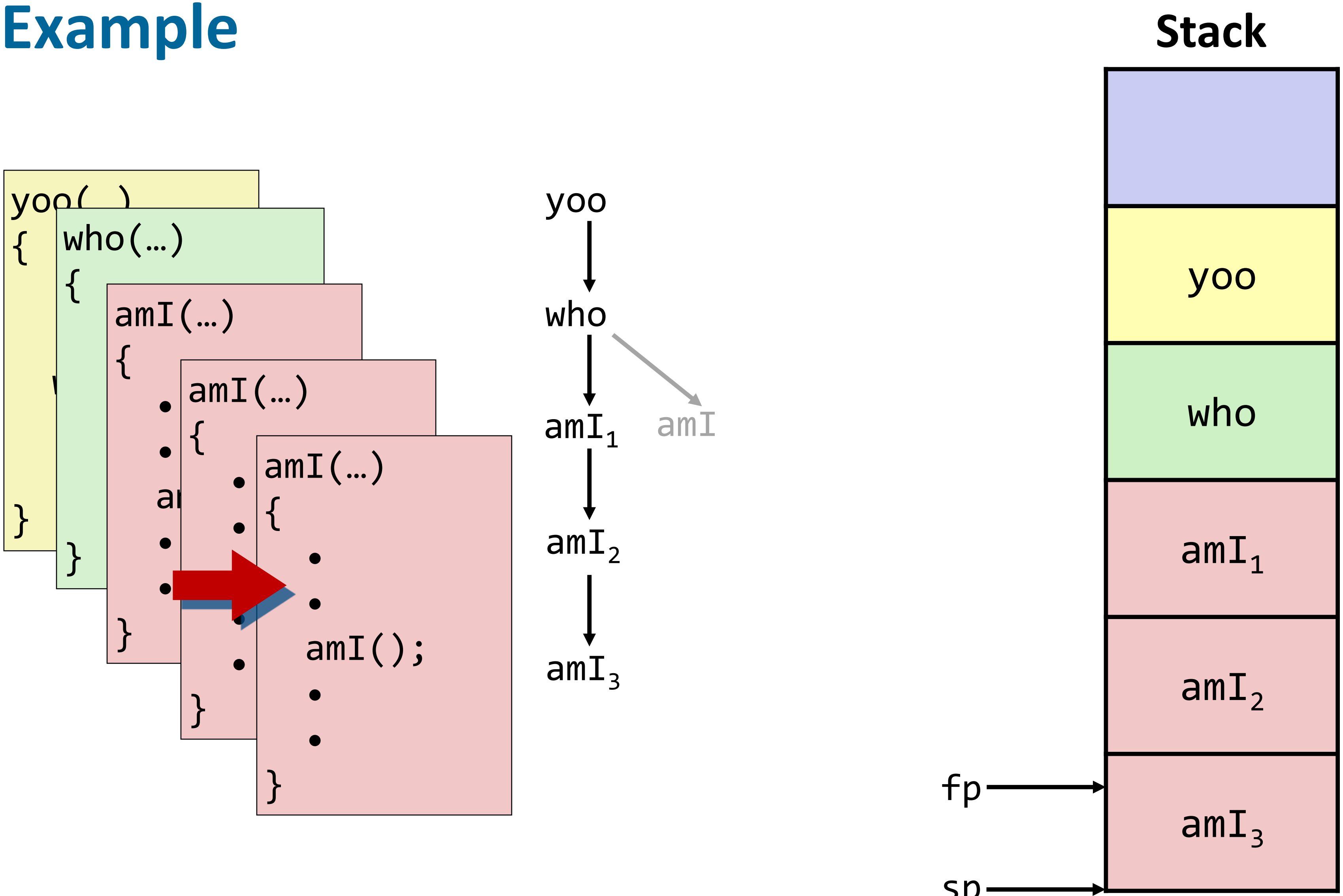


yoo
who
amI$_1$
amI
amI$_2$
amI



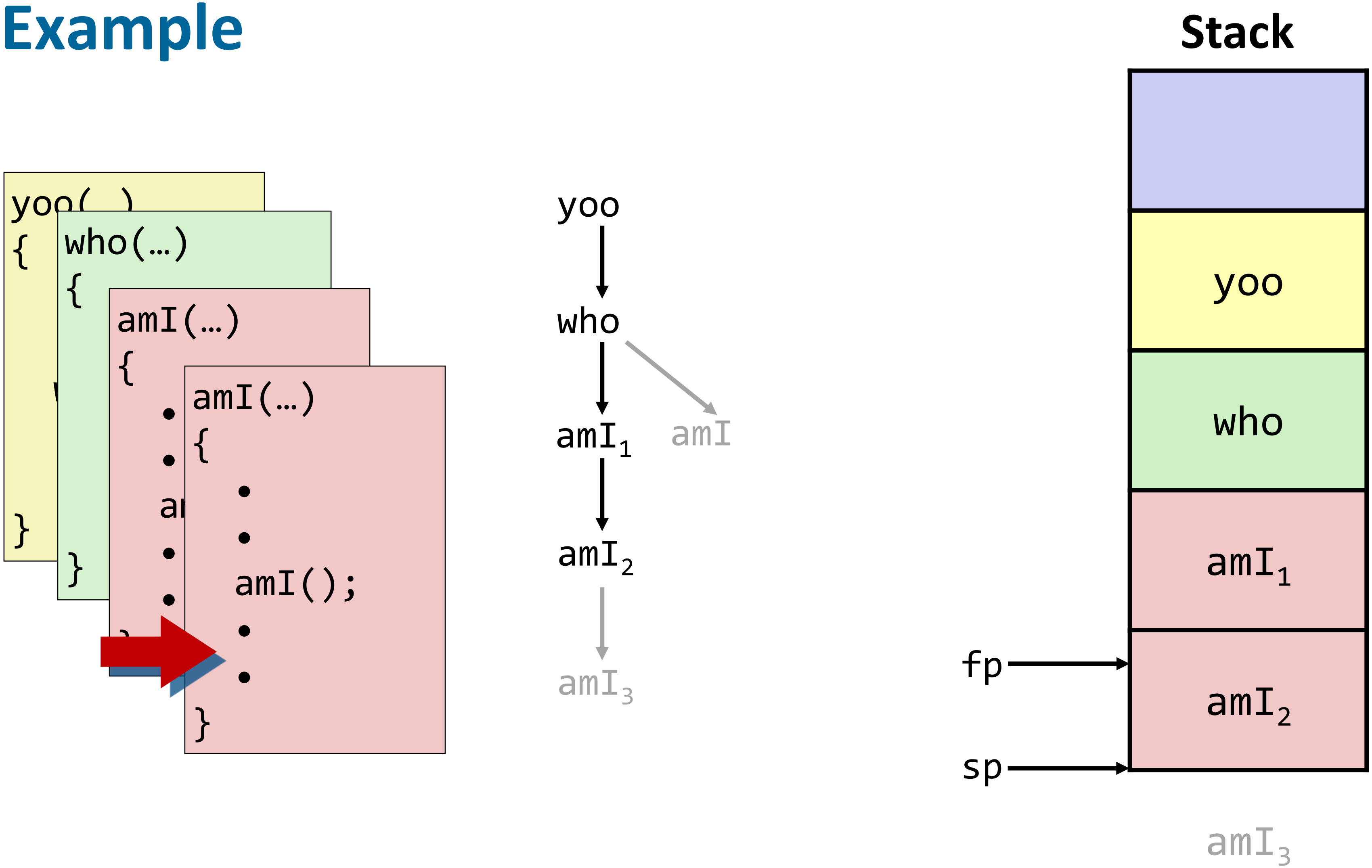
Stack
yoo
who
amI$_1$
amI$_2$
fp
sp

Example

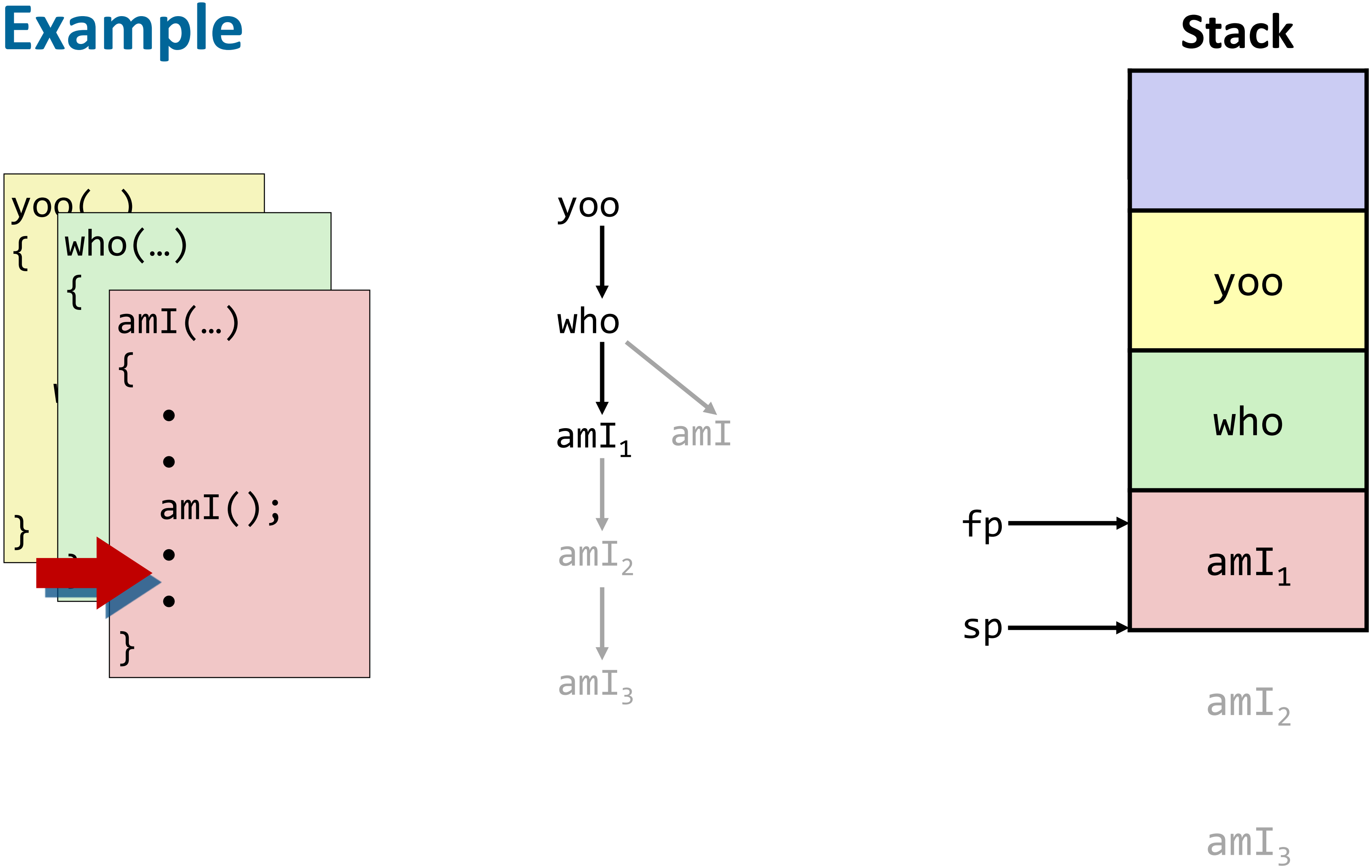


yoo(…)
{
}
who(…)
{
}
amI(…)
{
}
amI(…)
{
}
amI(…)
{
amI();
}
yoo
who
amI1
amI
amI2
amI3
Stack
yoo
who
amI1
amI2
amI3
fp
sp

Example


yoo(…)
{
}
who(…)
{
}
amI(…)
{
•
•
•
•
}
amI(…)
{
•
•
amI();
•
•
}
yoo
who
amI
amI1
amI2
amI3
Stack
yoo
who
amI1
amI2
fp
sp
amI3

Example

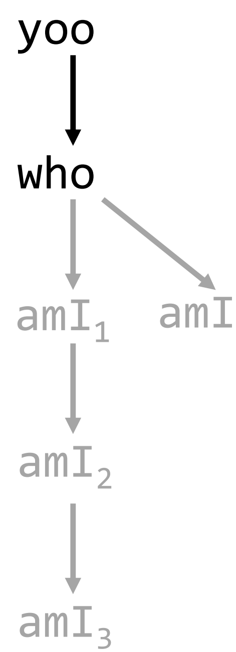


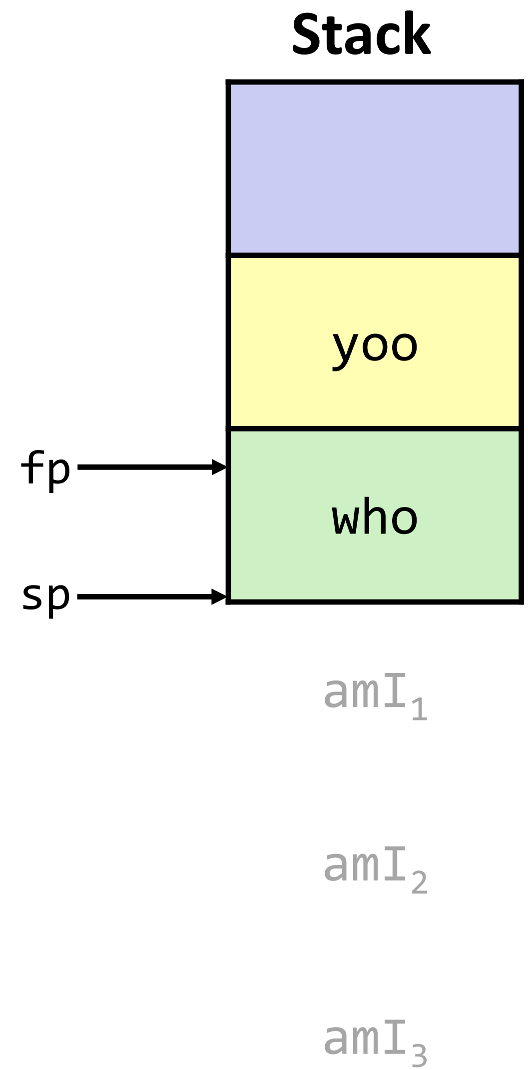
who(…)
{
amI(…)
{
•
•
amI();
•
•
}
yoo
who
amI1
amI
amI2
amI3
Stack
yoo
who
amI1
fp
sp
amI2
amI3

Example

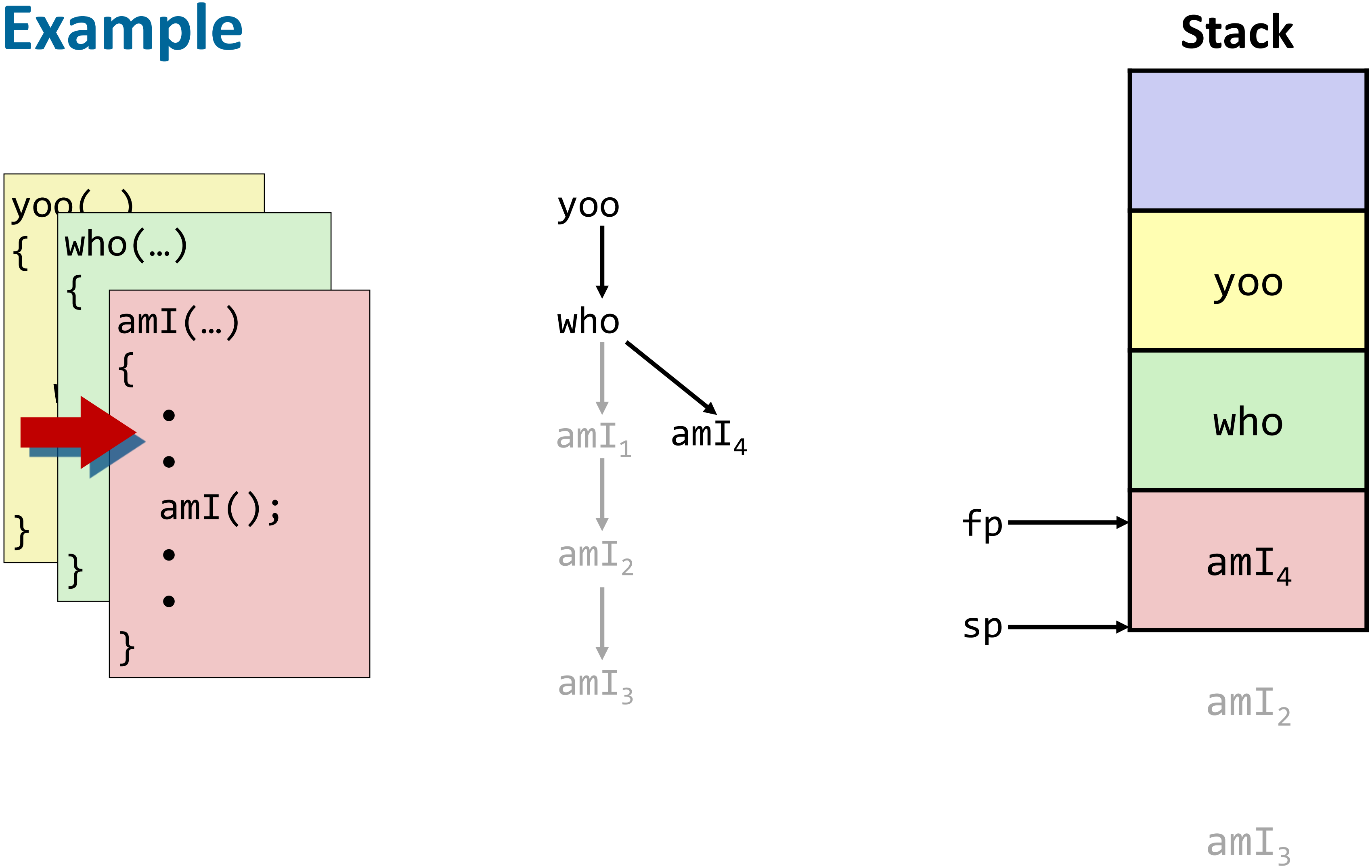
```
yoo(…)
{
  •
  •
}
```

```
who(…)
{
  • • •
  amI();
  • • •
  amI();
  • • •
}
```



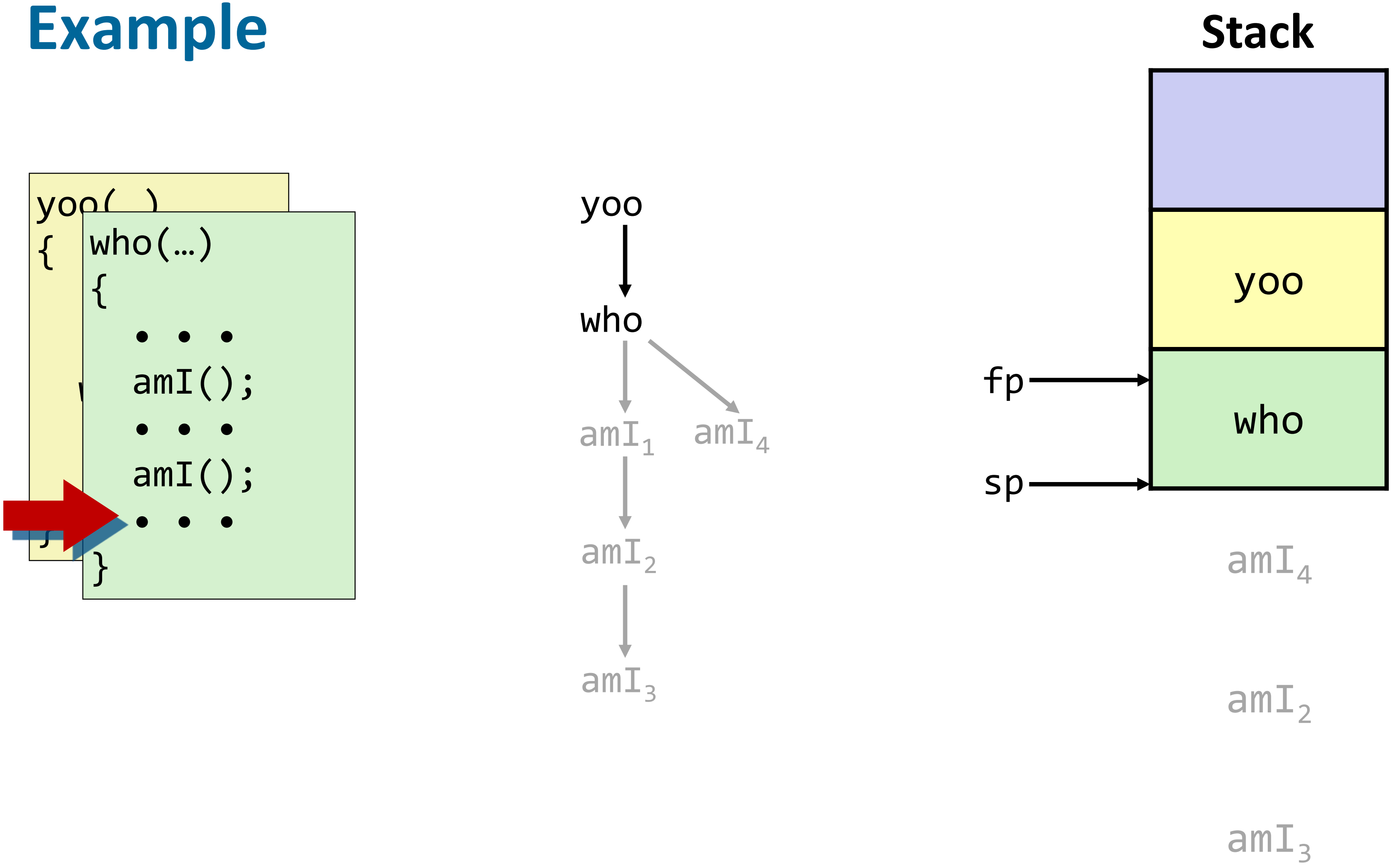


Example



yoo(…)
{
}
who(…)
{
}
amI(…)
{
•
•
amI();
•
•
}
yoo
who
amI$_1$
amI$_4$
amI$_2$
amI$_3$
Stack
yoo
who
amI$_4$
fp
sp
amI$_2$
amI$_3$

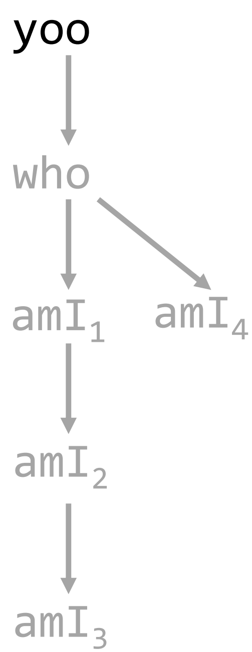
Example

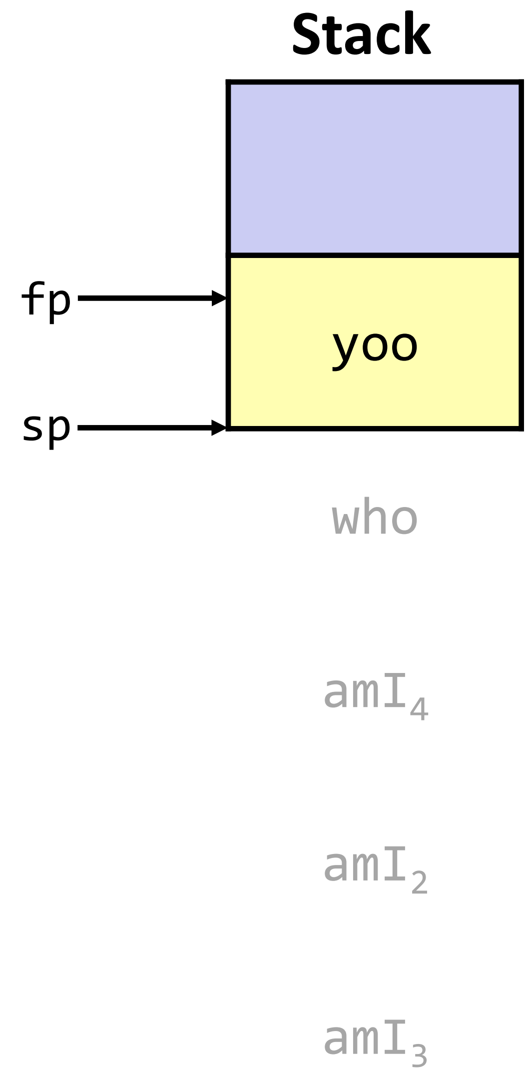


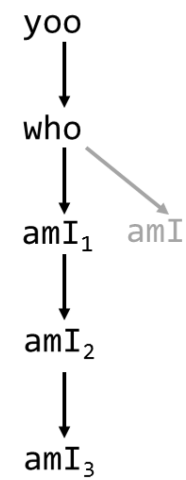
yoo(…)
{
who(…)
{
• • •
amI();
• • •
amI();
• • •
}
yoo
who
amI1
amI4
amI2
amI3
Stack
yoo
who
fp
sp
amI4
amI2
amI3

Example

```
yoo(…)
{
  •
  •
  who();
  •
  •
}
```





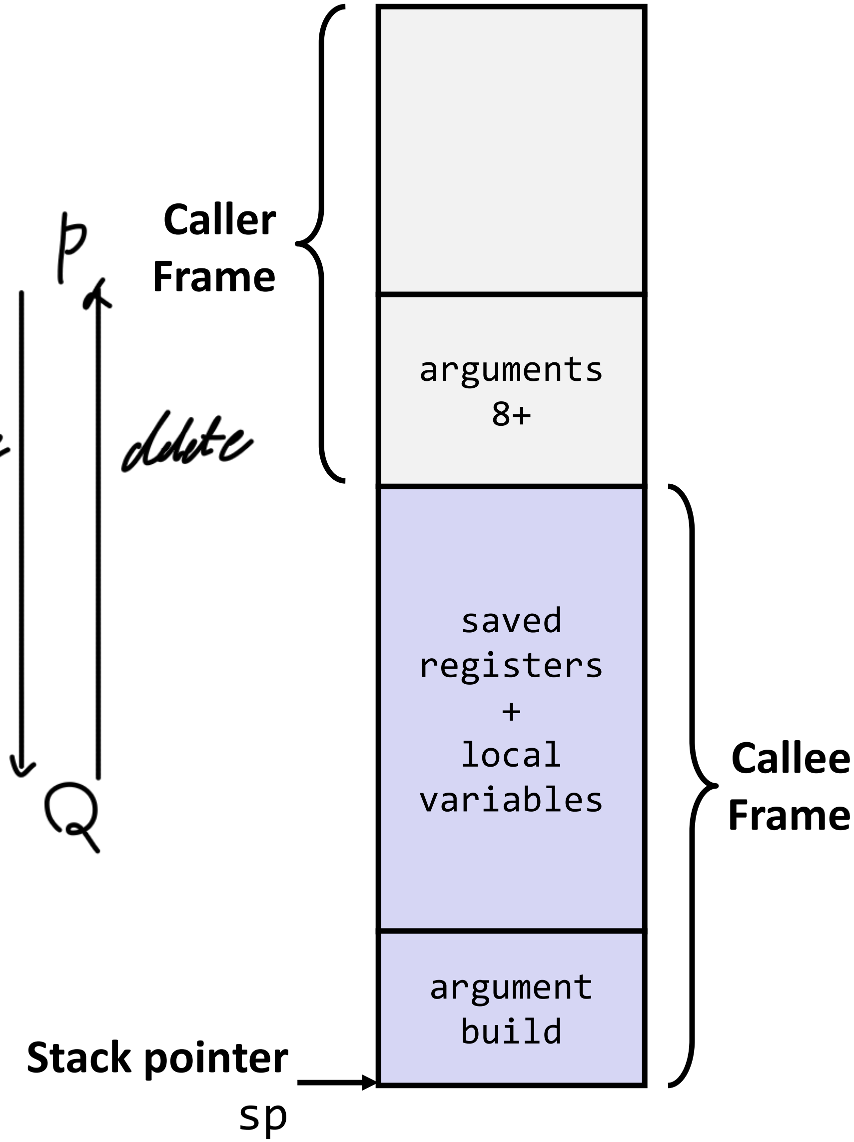


Module Summary

Module Summary

- **Procedures**
  - Stack is the right data structure for procedure call / return
    - If P calls Q, then Q returns before P
  - Recursion (& mutual recursion) handled by normal calling conventions
    - Can safely store values in local stack frame and in callee-saved registers
    - Put function arguments at top of stack
    - Result return in `a0-1`
  - Pointers are addresses of values
    - On stack or global

allocate



Module Summary

- **Calling convention**
  - "Contract" between the caller and the callee
  - How are parameters passed?
  - How are results returned?
  - Which registers must be preserved across function calls?
  - Which registers can be overwritten?
  - Note that, except for leaf procedures, all functions are both callee and caller!

`x0`	hard-wired zero	`t0-2 (x5-7)`	Caller
`ra (x1)`	Caller	`s0,1 (x8,9)`	Callee
`sp (x2)`	Callee	`a0-7 (x10-17)`	Caller
`gp (x3)`	-	`s2-s11 (x18-27)`	Callee
`tp (x4)`	-	`t3-6 (x28-31)`	Caller