Machine Program: Procedure

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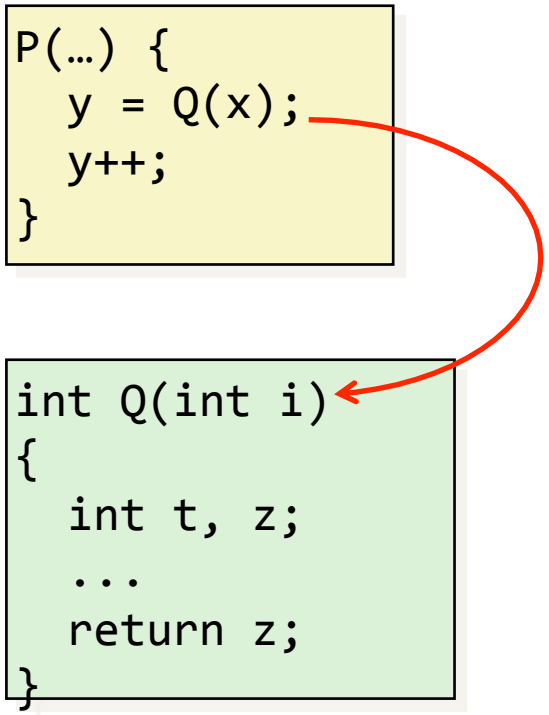
Slides based on Tiger Wang

What we've learnt about how hardware runs a program?

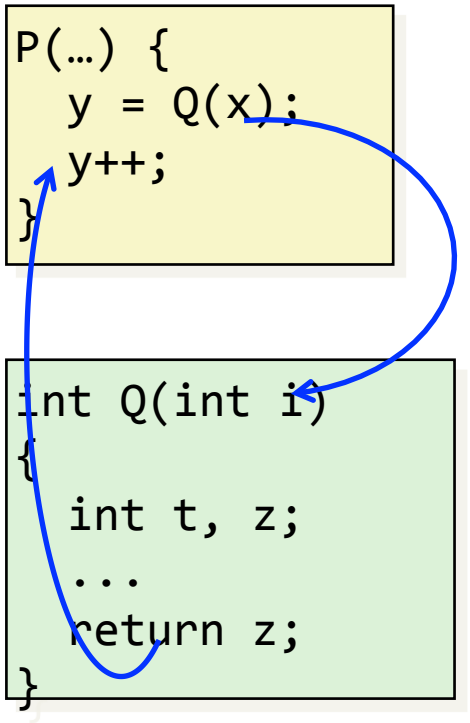
- Where are data and instructions stored?
  - memory: heap, stack, data, text
  - some local variables may reside in registers only
- Modes of execution:
  - Sequential:
    - PC (%rip) is changed to point to the next instruction
  - Control flow: jmp, conditional jmp
    - PC (%rip) is changed to point to the jump target address
  - **Today→ procedure call**

Requirements of procedure calls?



1. Passing control

Requirements of procedure calls?



1. Passing control
2. Passing Arguments & return value

Requirements of procedure calls?

```
P(…) {
  y = Q(x);
  y++;
}
```

```
int Q(int i)
{
  int t, z;
  ...
  return z;
}
```

1. Passing control
2. Passing Arguments & return value
3. Allocate / deallocate local variables

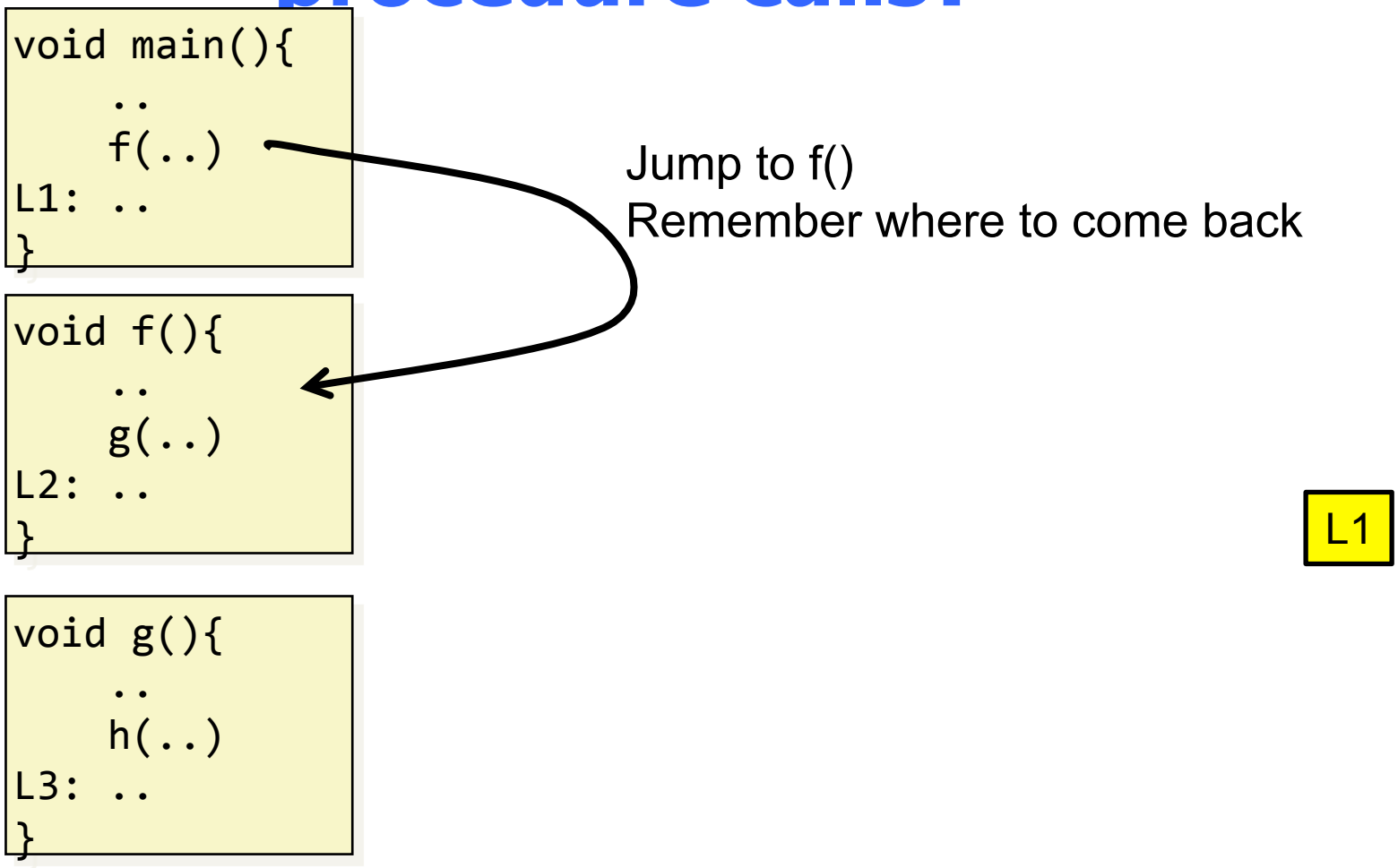
How to transfer control for procedure calls?

```
void main(){
    ..
    f(..)
L1: ..
}
```

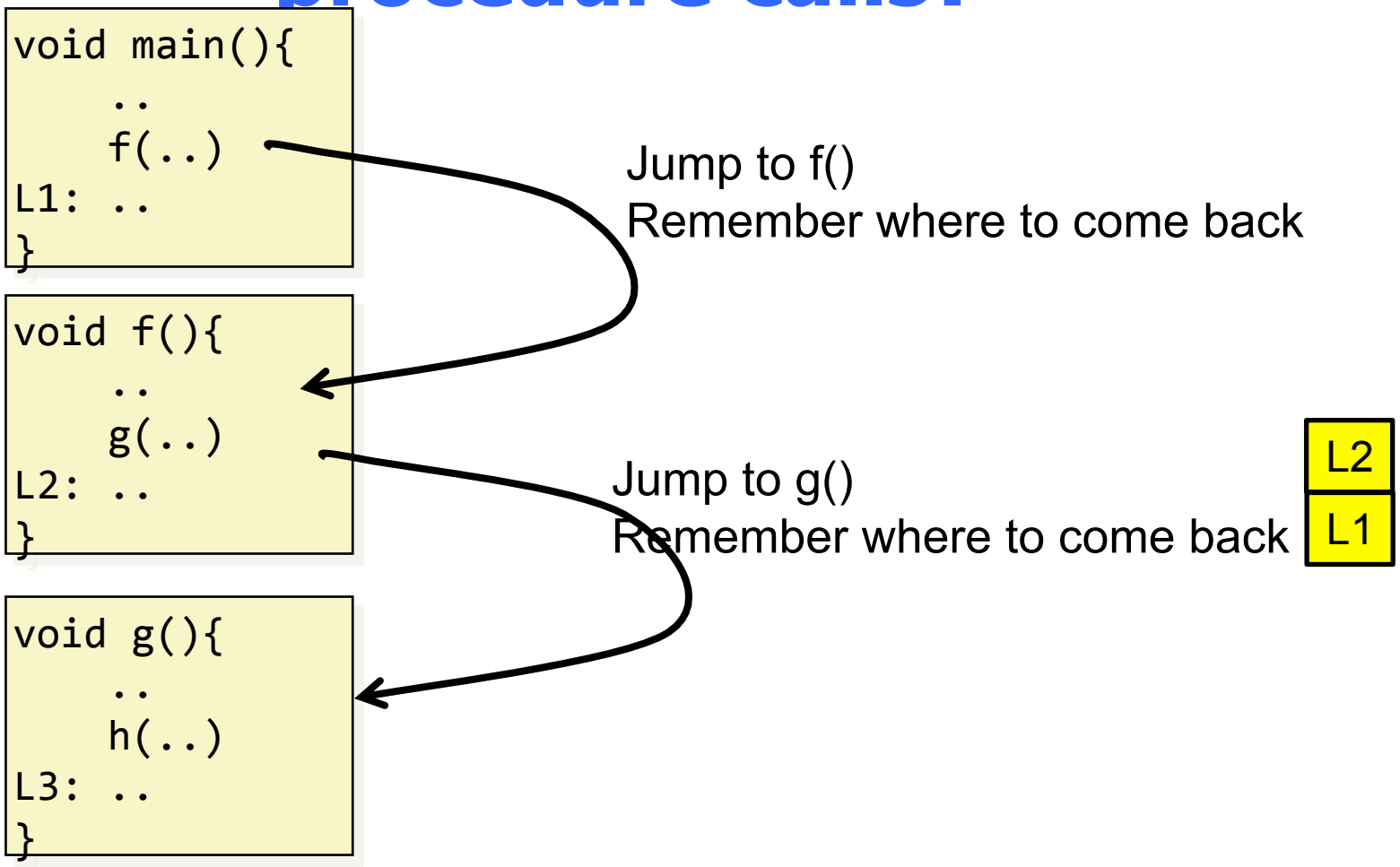
```
void f(){
    ..
    g(..)
L2: ..
}
```

```
void g(){
    ..
    h(..)
L3: ..
}
```

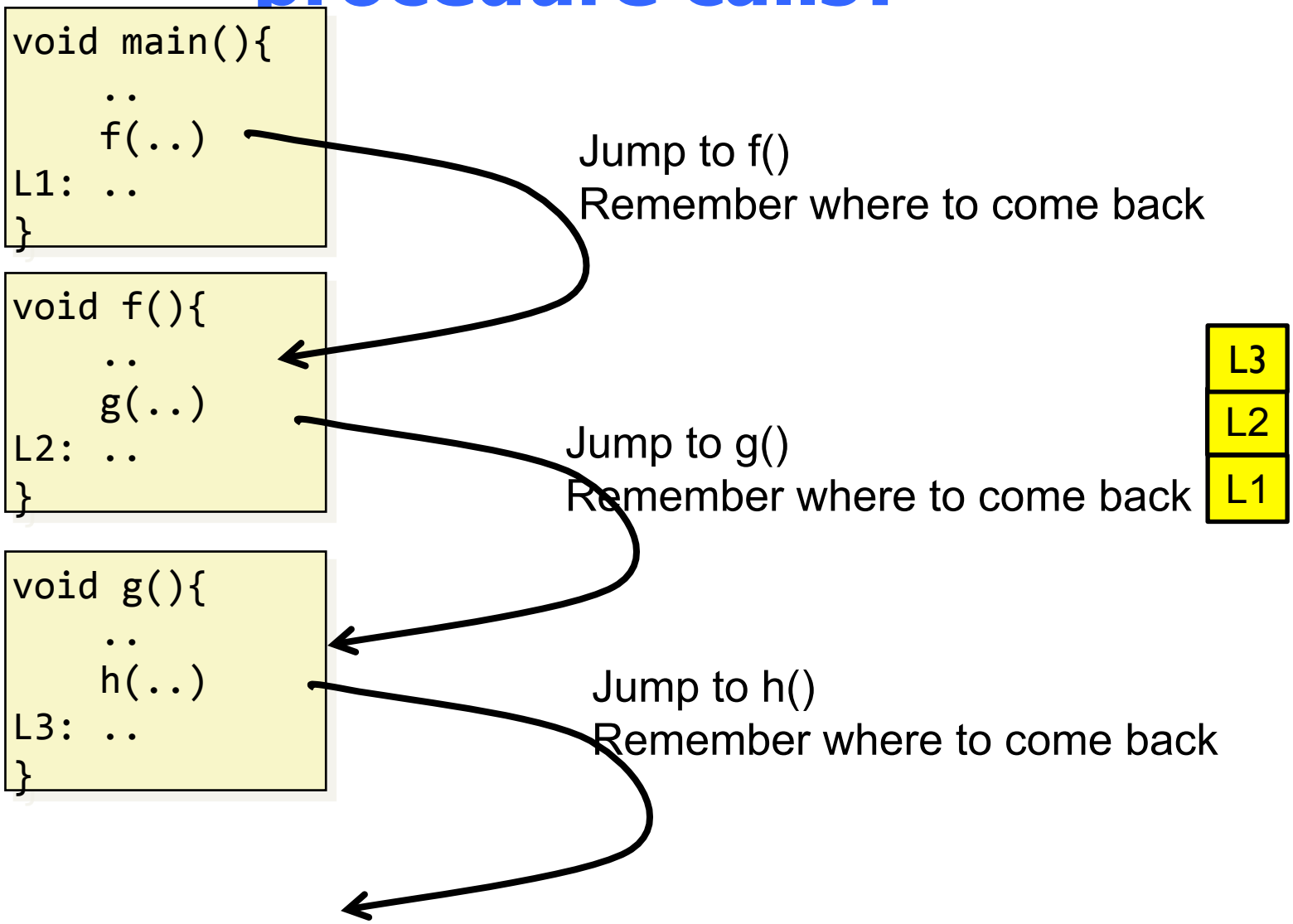
How to transfer control for procedure calls?



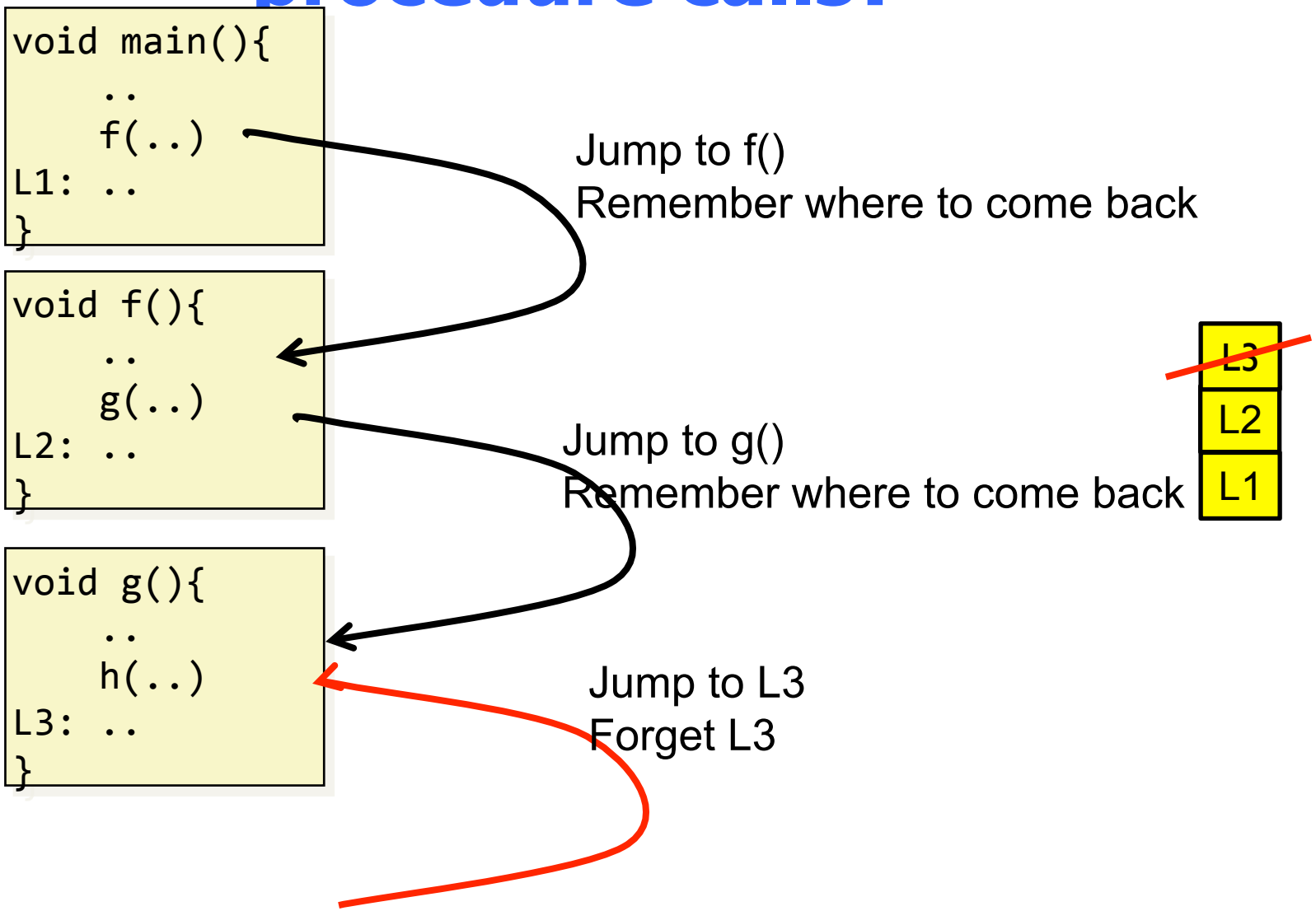
How to transfer control for procedure calls?



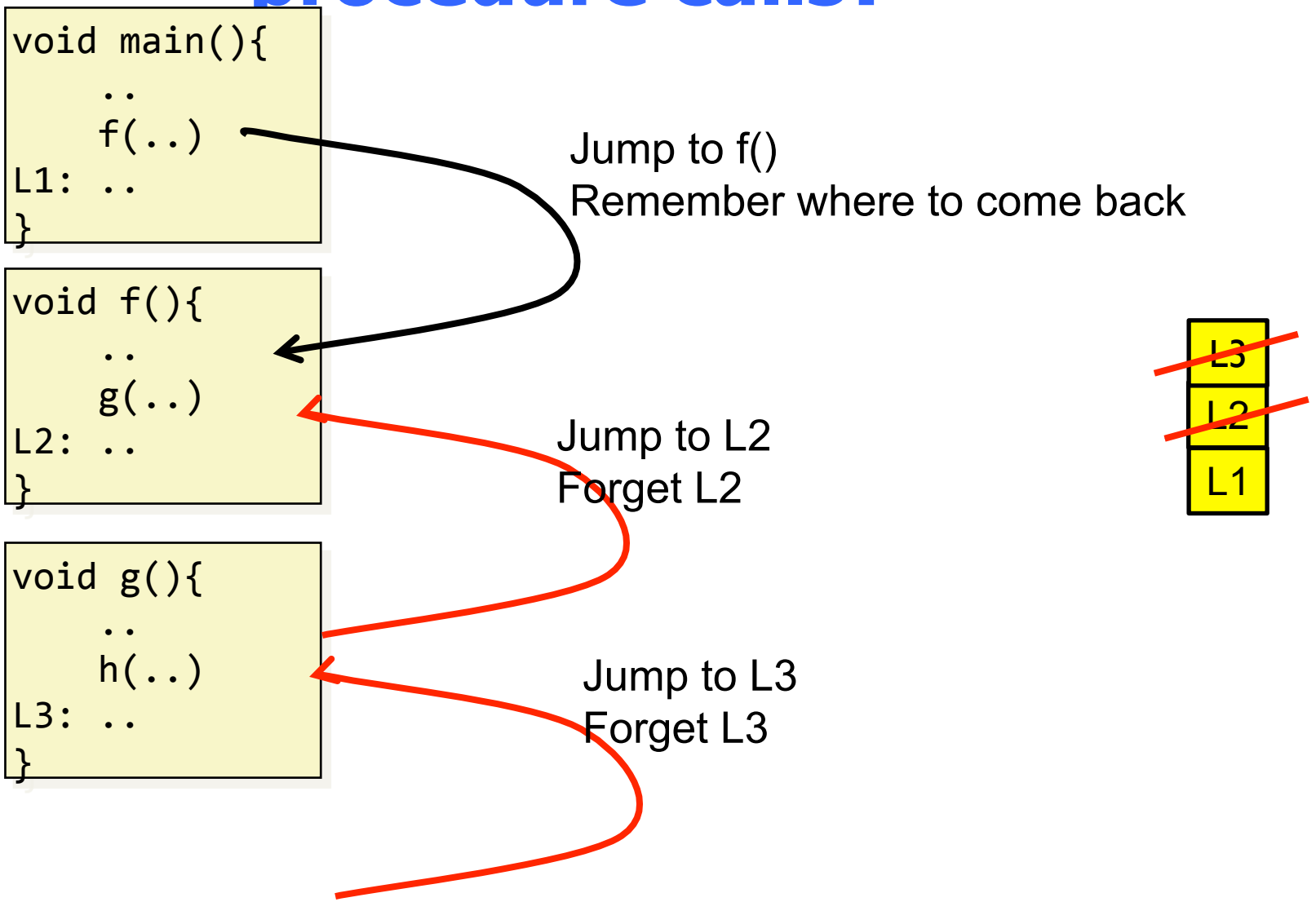
How to transfer control for procedure calls?



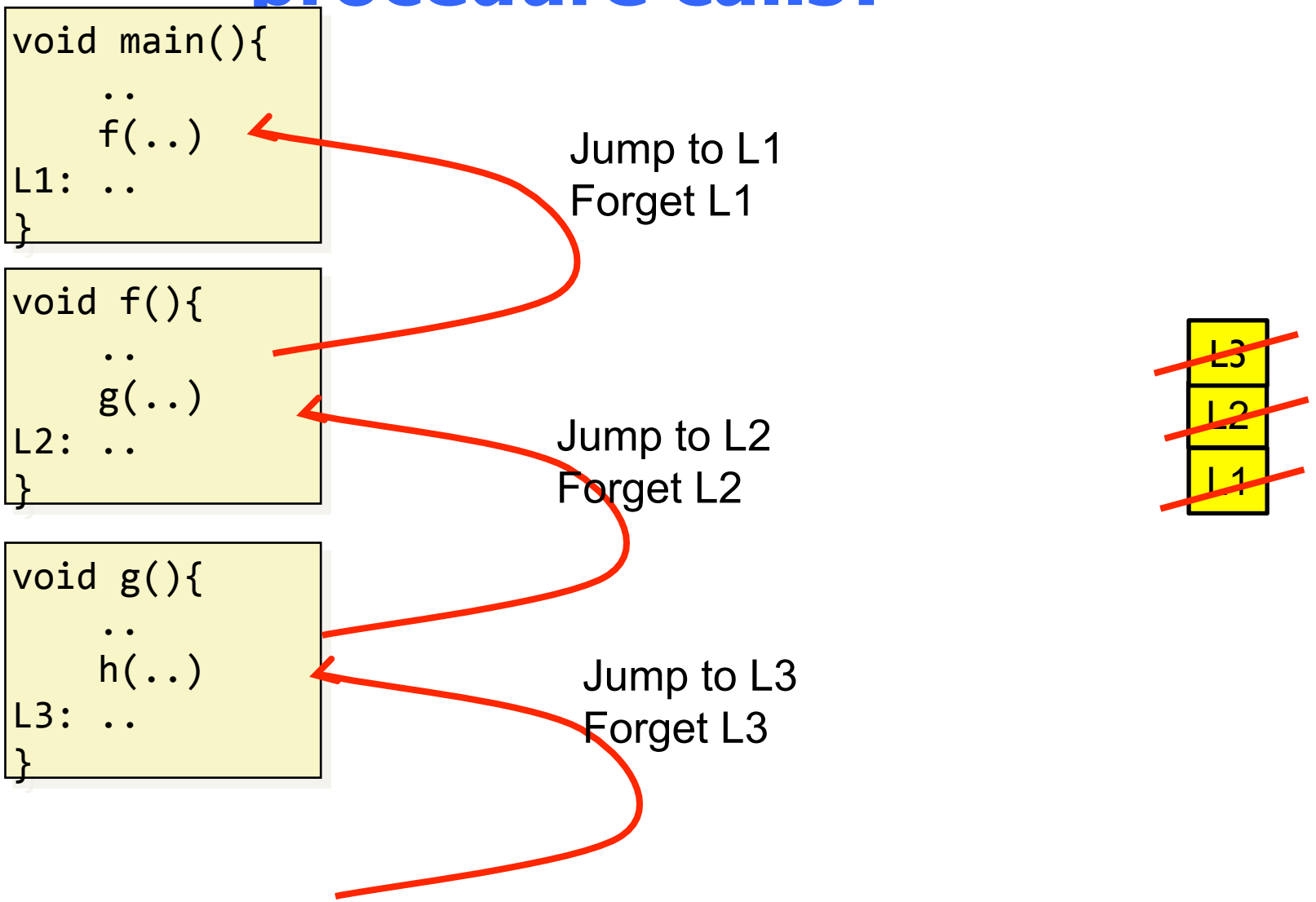
How to transfer control for procedure calls?



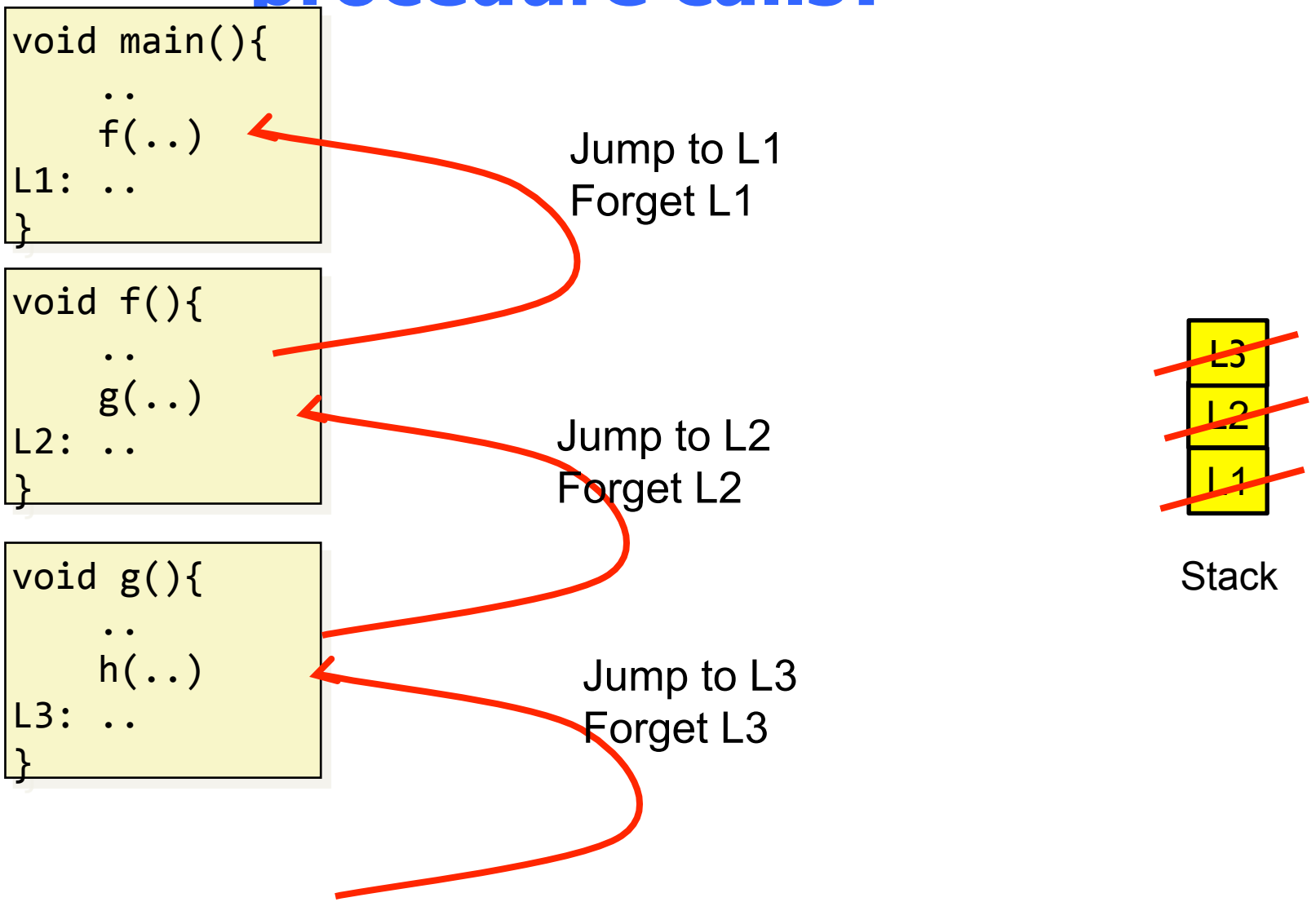
How to transfer control for procedure calls?

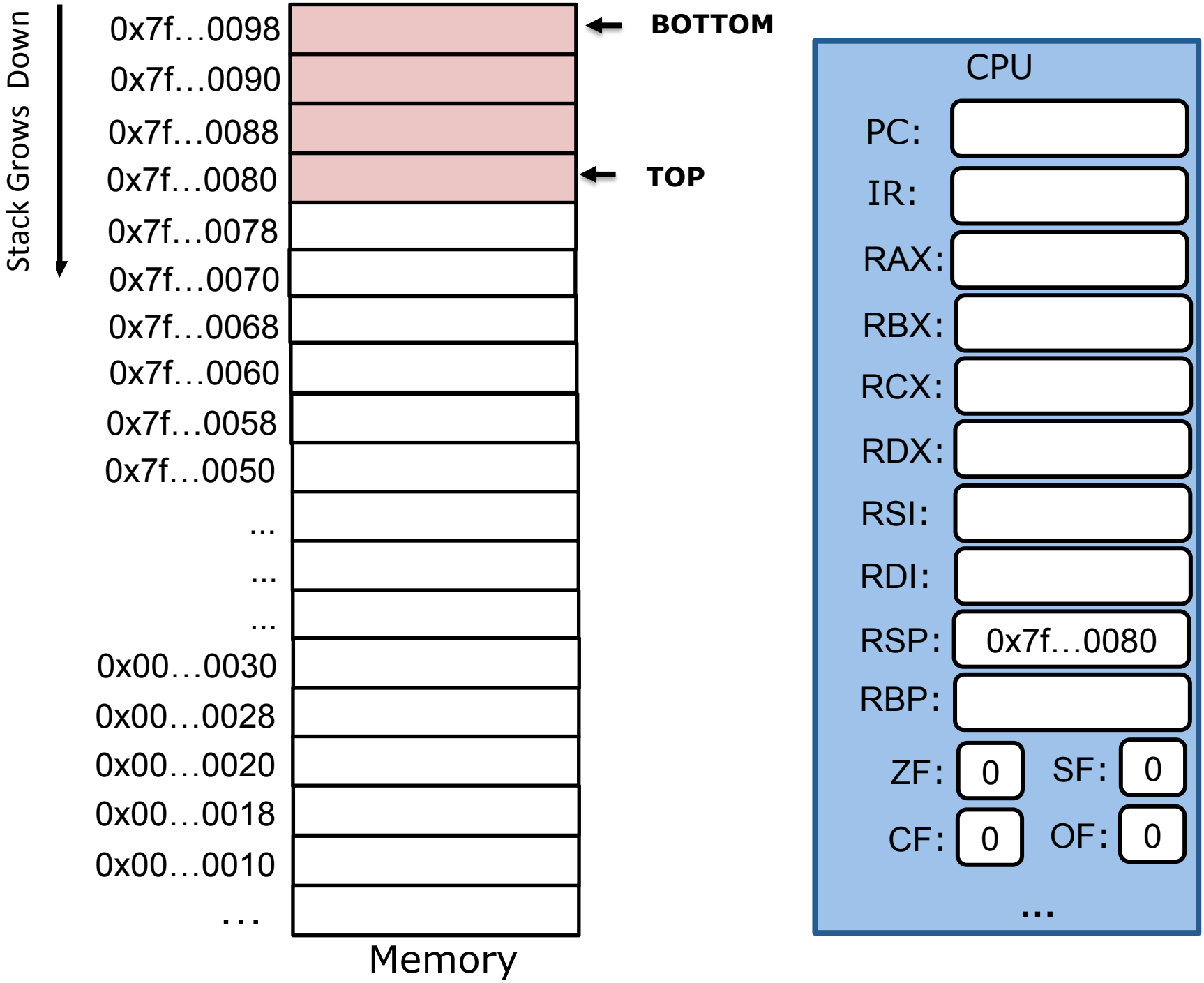


How to transfer control for procedure calls?



How to transfer control for procedure calls?

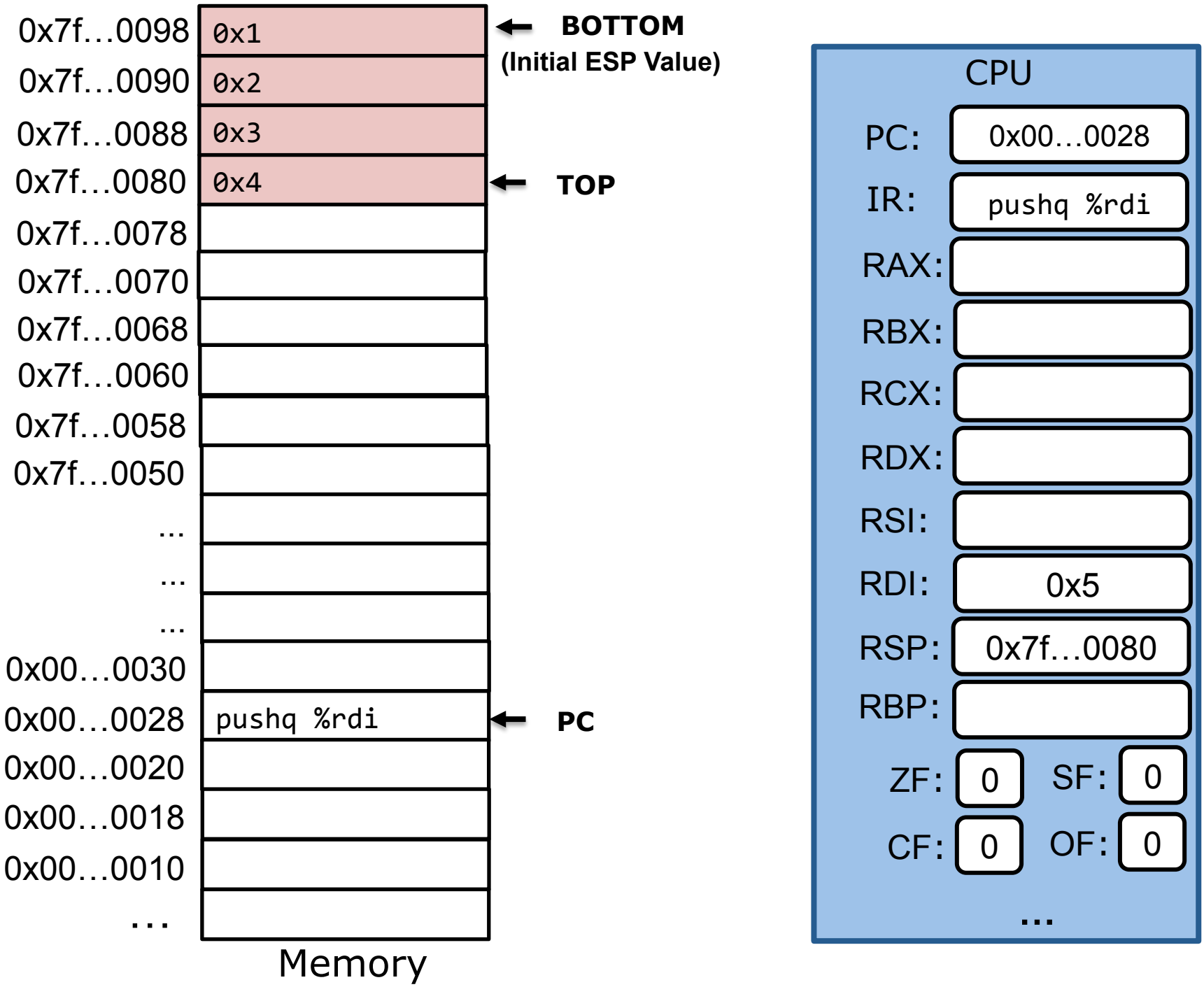


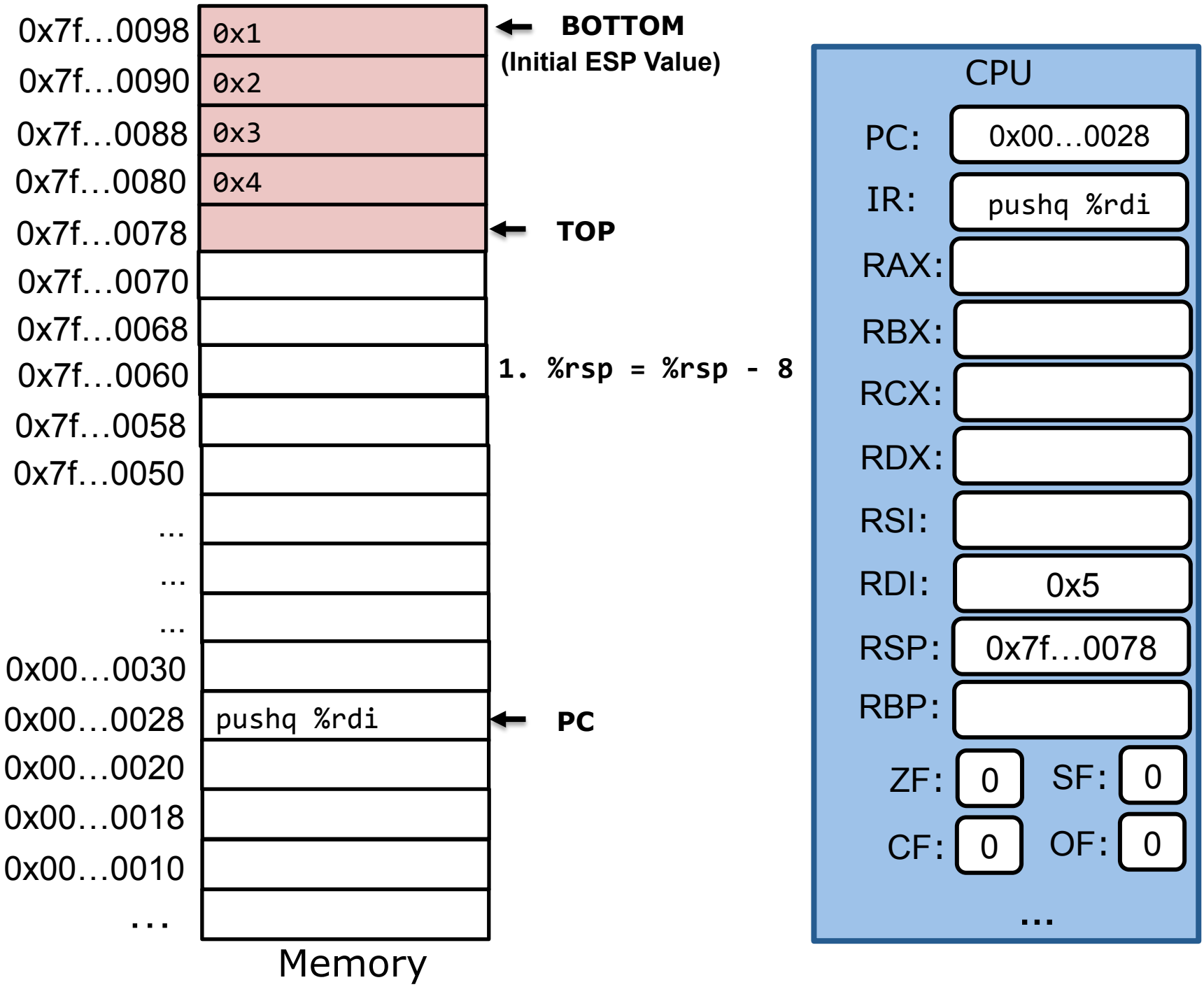

Stack Grows Down
0x7f…0098
0x7f…0090
0x7f…0088
0x7f…0080
0x7f…0078
0x7f…0070
0x7f…0068
0x7f…0060
0x7f…0058
0x7f…0050
...
...
...
0x00…0030
0x00…0028
0x00…0020
0x00…0018
0x00…0010
...
BOTTOM
TOP
Memory
CPU
PC:
IR:
RAX:
RBX:
RCX:
RDX:
RSI:
RDI:
RSP:
0x7f…0080
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
...

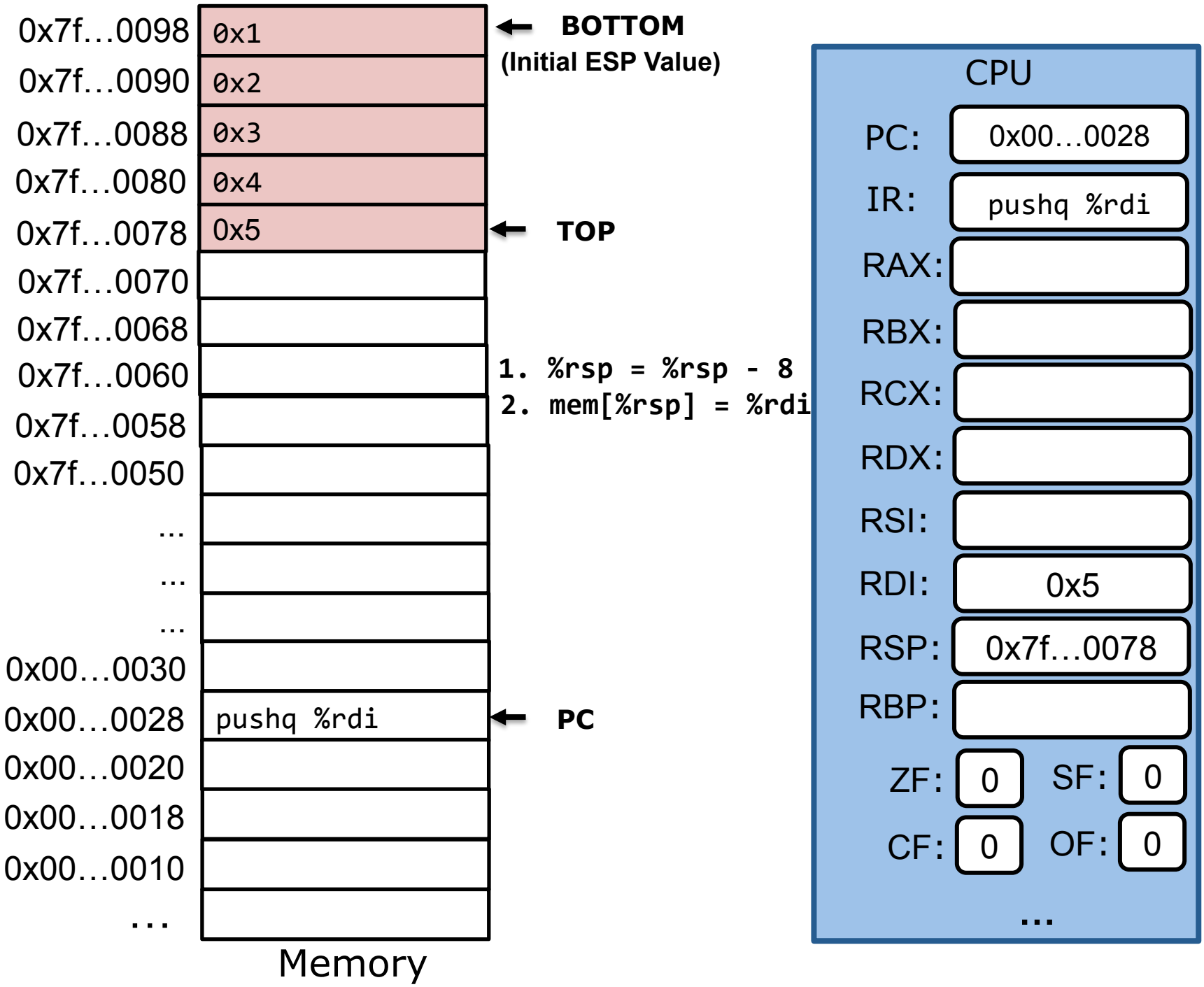
Stack – push Instruction

`pushq` `src`

- Decrement %rsp by 8
- Write operand at address given by `%rsp`


0x7f…0098
0x1
BOTTOM
(Initial ESP Value)
0x7f…0090
0x2
0x7f…0088
0x3
0x7f…0080
0x4
TOP
0x7f…0078
0x7f…0070
0x7f…0068
0x7f…0060
0x7f…0058
0x7f…0050
…
…
…
0x00…0030
0x00…0028
pushq %rdi
PC
0x00…0020
0x00…0018
0x00…0010
…
Memory
CPU
PC:
0x00…0028
IR:
pushq %rdi
RAX:
RBX:
RCX:
RDX:
RSI:
RDI:
0x5
RSP:
0x7f…0080
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
…

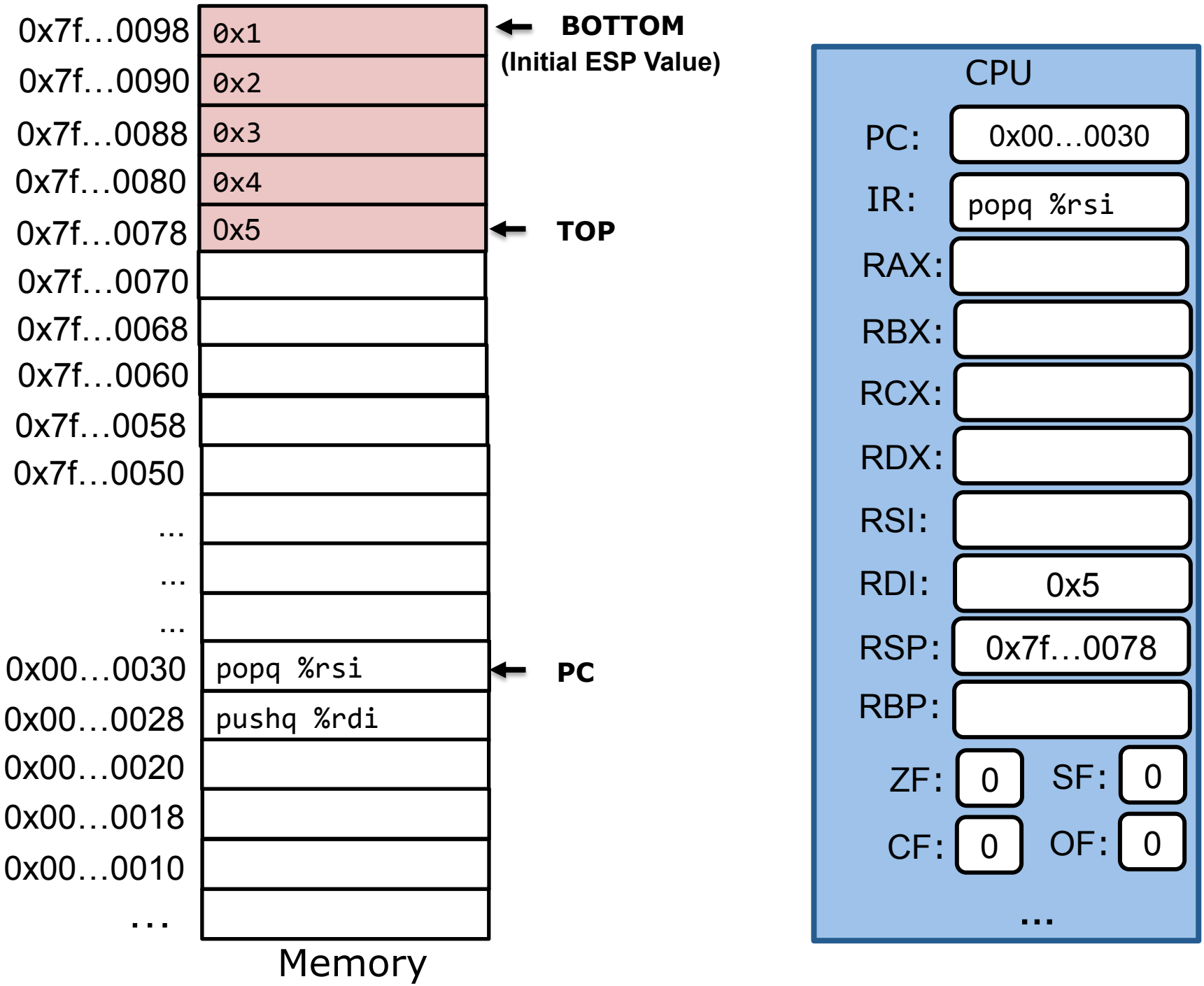

0x7f…0098
0x1
BOTTOM
(Initial ESP Value)
0x7f…0090
0x2
0x7f…0088
0x3
0x7f…0080
0x4
0x7f…0078
TOP
0x7f…0070
0x7f…0068
0x7f…0060
1. %rsp = %rsp - 8
0x7f…0058
0x7f…0050
…
…
…
0x00…0030
0x00…0028
pushq %rdi
PC
0x00…0020
0x00…0018
0x00…0010
…
Memory
CPU
PC:
0x00…0028
IR:
pushq %rdi
RAX:
RBX:
RCX:
RDX:
RSI:
RDI:
0x5
RSP:
0x7f…0078
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
…

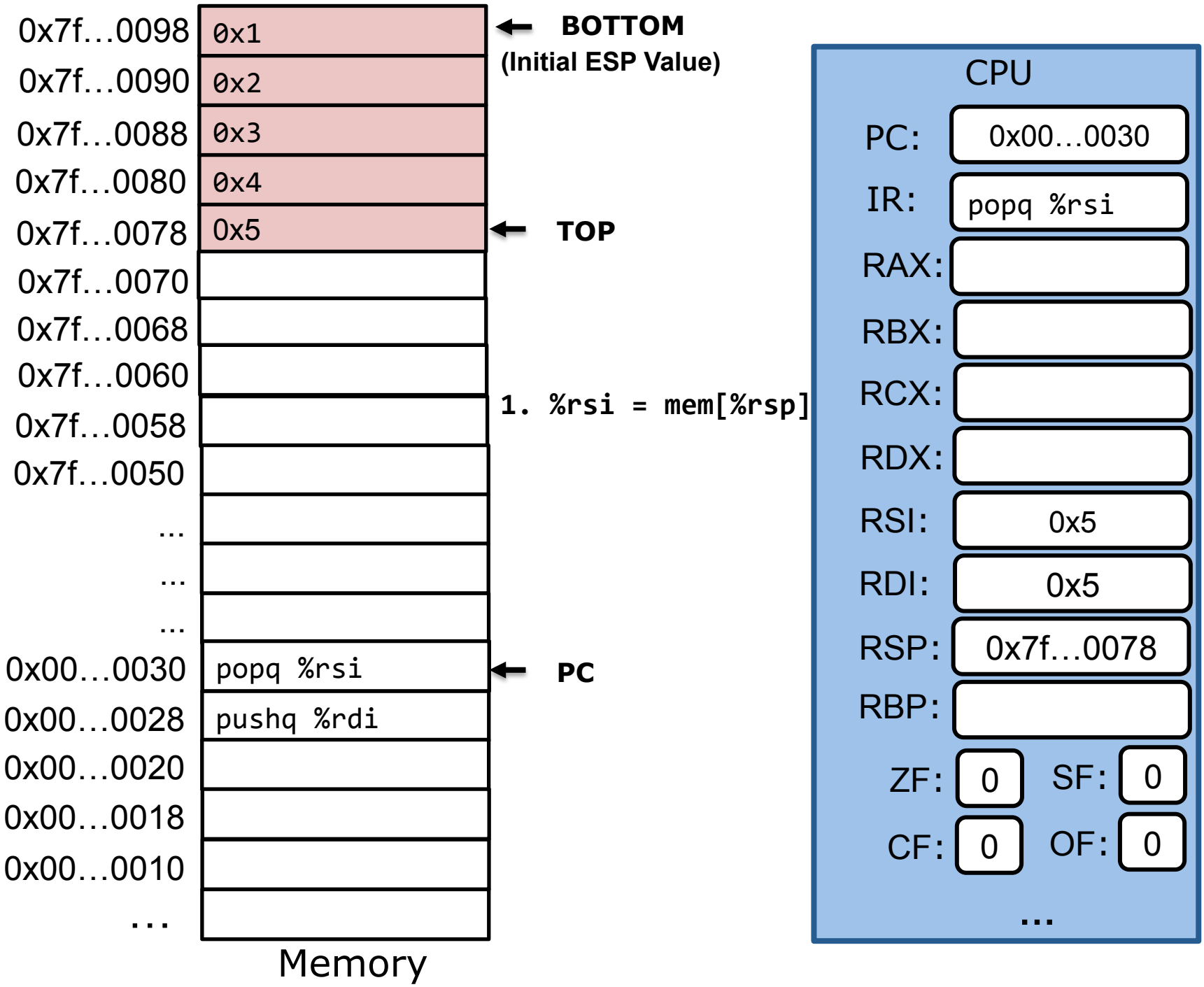

0x7f…0098
0x1
BOTTOM
(Initial ESP Value)
0x7f…0090
0x2
0x7f…0088
0x3
0x7f…0080
0x4
0x7f…0078
0x5
TOP
0x7f…0070
0x7f…0068
0x7f…0060
1. %rsp = %rsp - 8
2. mem[%rsp] = %rdi
0x7f…0058
0x7f…0050
…
…
…
0x00…0030
0x00…0028
pushq %rdi
PC
0x00…0020
0x00…0018
0x00…0010
…
Memory
CPU
PC:
0x00…0028
IR:
pushq %rdi
RAX:
RBX:
RCX:
RDX:
RSI:
RDI:
0x5
RSP:
0x7f…0078
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
…

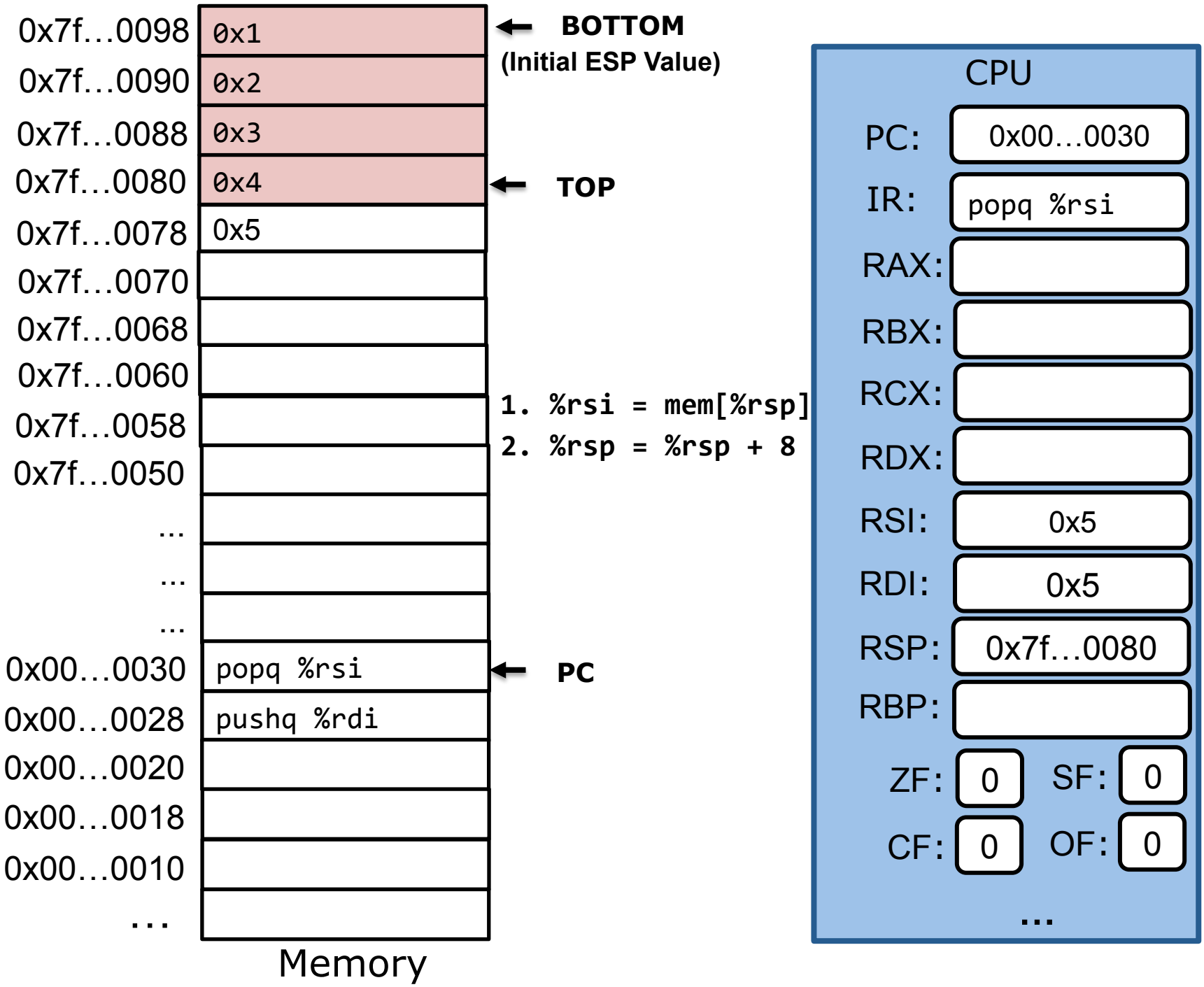
Stack – pop Instruction

`popq` `dest`

- Store the value at address `%rsp` to dest
- Increment %rsp by 8


0x7f…0098
0x1
BOTTOM
(Initial ESP Value)
0x7f…0090
0x2
0x7f…0088
0x3
0x7f…0080
0x4
0x7f…0078
0x5
TOP
0x7f…0070
0x7f…0068
0x7f…0060
0x7f…0058
0x7f…0050
…
…
…
0x00…0030
popq %rsi
PC
0x00…0028
pushq %rdi
0x00…0020
0x00…0018
0x00…0010
…
Memory
CPU
PC:
0x00…0030
IR:
popq %rsi
RAX:
RBX:
RCX:
RDX:
RSI:
RDI:
0x5
RSP:
0x7f…0078
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
…


0x7f…0098
0x7f…0090
0x7f…0088
0x7f…0080
0x7f…0078
0x7f…0070
0x7f…0068
0x7f…0060
0x7f…0058
0x7f…0050
…
…
…
0x00…0030
0x00…0028
0x00…0020
0x00…0018
0x00…0010
…
0x1
0x2
0x3
0x4
0x5
popq %rsi
pushq %rdi
BOTTOM
(Initial ESP Value)
TOP
1. %rsi = mem[%rsp]
PC
Memory
CPU
PC:
0x00…0030
IR:
popq %rsi
RAX:
RBX:
RCX:
RDX:
RSI:
0x5
RDI:
0x5
RSP:
0x7f…0078
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
…


0x7f…0098
0x1
BOTTOM
(Initial ESP Value)
0x7f…0090
0x2
0x7f…0088
0x3
0x7f…0080
0x4
TOP
0x7f…0078
0x5
0x7f…0070
0x7f…0068
0x7f…0060
1. %rsi = mem[%rsp]
2. %rsp = %rsp + 8
0x7f…0058
0x7f…0050
…
…
…
0x00…0030
popq %rsi
PC
0x00…0028
pushq %rdi
0x00…0020
0x00…0018
0x00…0010
…
Memory
CPU
PC:
0x00…0030
IR:
popq %rsi
RAX:
RBX:
RCX:
RDX:
RSI:
0x5
RDI:
0x5
RSP:
0x7f…0080
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
…

Call instruction: control transfer from caller to callee

`call` `label`

- Push return address on stack
  - return address = current pc + 8
- Jump to the address of the label

```
int add(int a, int b) {
  int c = a + b;
  return c;
}
```

```
int main() {
    int c = add(0, 2);
    printf("%d\b", c);
    return 0;
}
```

Call instruction: control transfer from caller to callee

`call` label

- Push return address on stack
  - return address = current pc + 8
- Jump to the address of the label

```
gcc -Og -S main.c
```

```
add:
    leal (%rdi,%rsi), %eax
    ret
```

```
main:
    movl    $2, %esi
    movl    $0, %edi
    call    add
    movl    %eax, %edx
     ...
```

return address points to this instruction

Call instruction: control transfer from caller to callee

`call label`

```
gcc main.c
objdump -d a.out
```

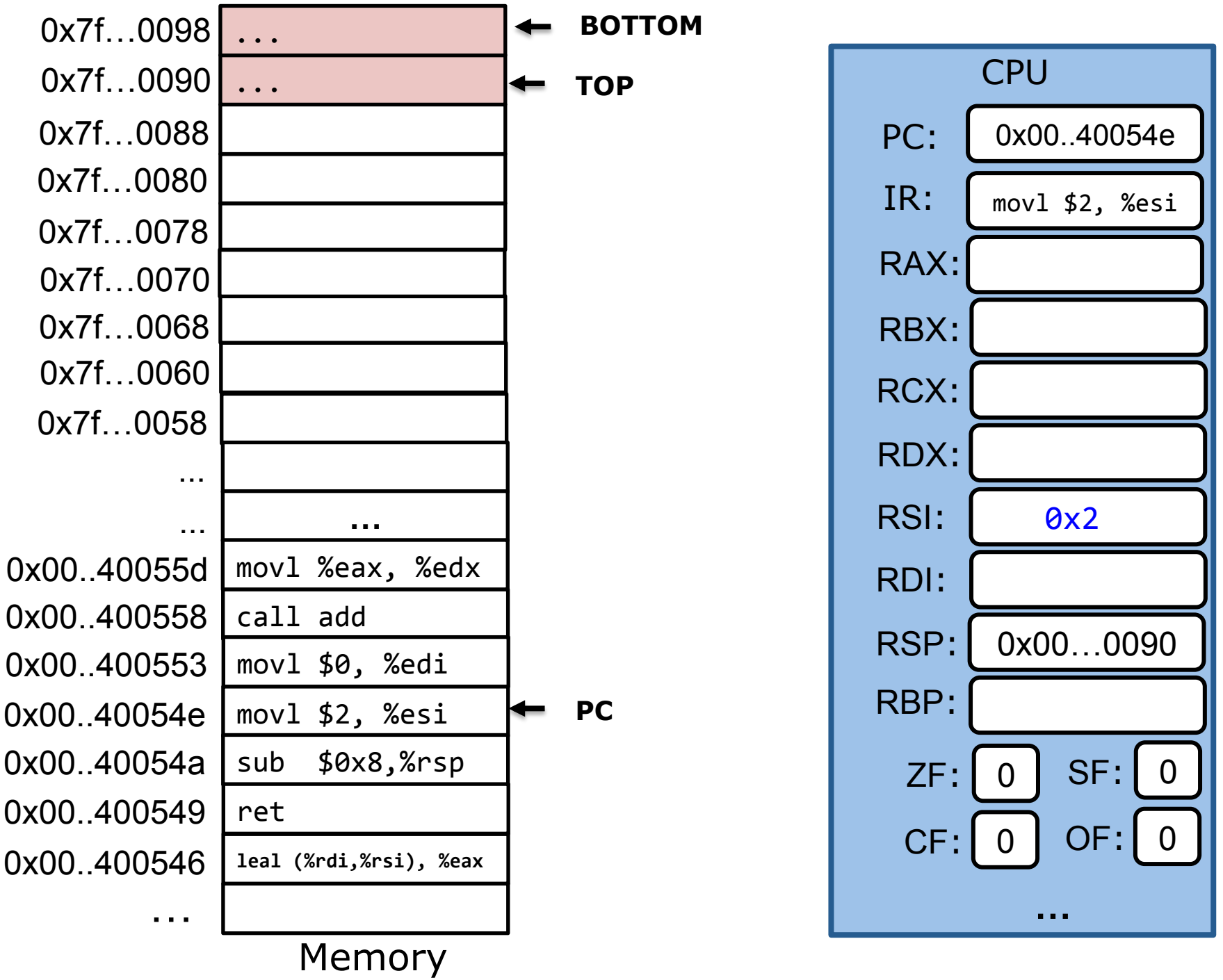
```
0000000000400546 <add>:
        400546:    8d 04 37          lea    (%rdi,%rsi,1),%eax
        400549:    c3                retq

000000000040054a <main>:
        40054a:    48 83 ec 08       sub    $0x8,%rsp
        40054e:    be 02 00 00 00    mov    $0x2,%esi
        400553:    bf  00 00 00 00   mov    $0x0,%edi
        400558:    e8 e9 ff ff ff    callq  400546 <add>
        40055d:    89 c2             mov    %eax,%edx
```

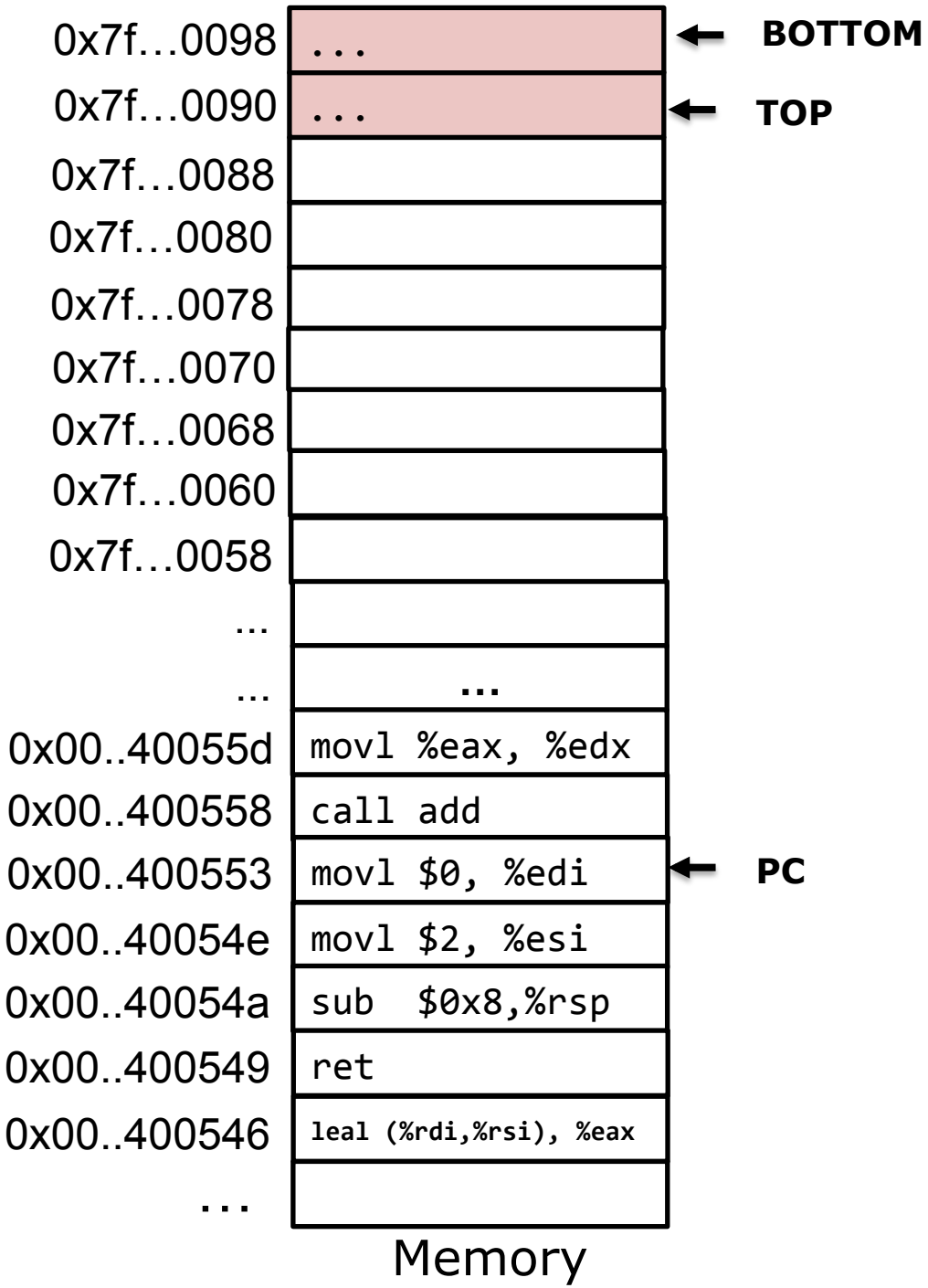
Ret instruction: control transfer from callee back to caller

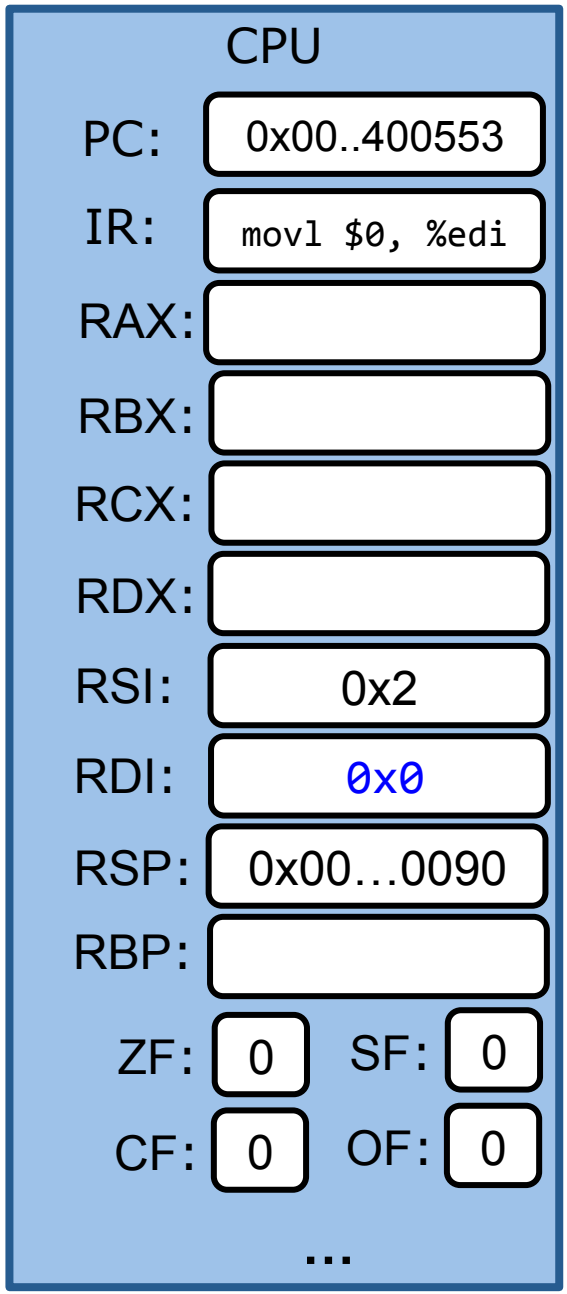
`ret`

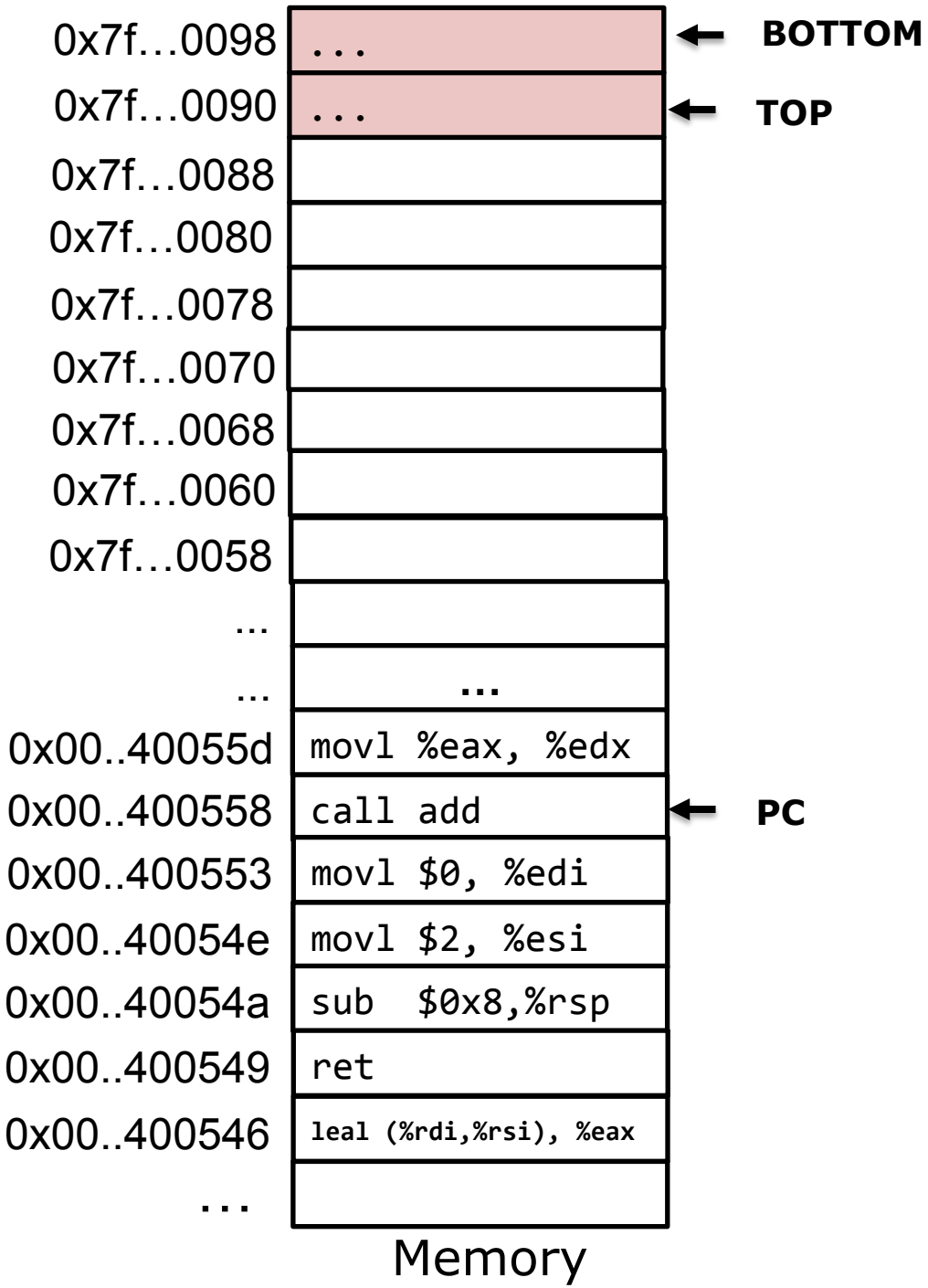
- Pop 8 bytes from the stack to PC
  - pc = mem[%rsp], %rsp = %rsp +8

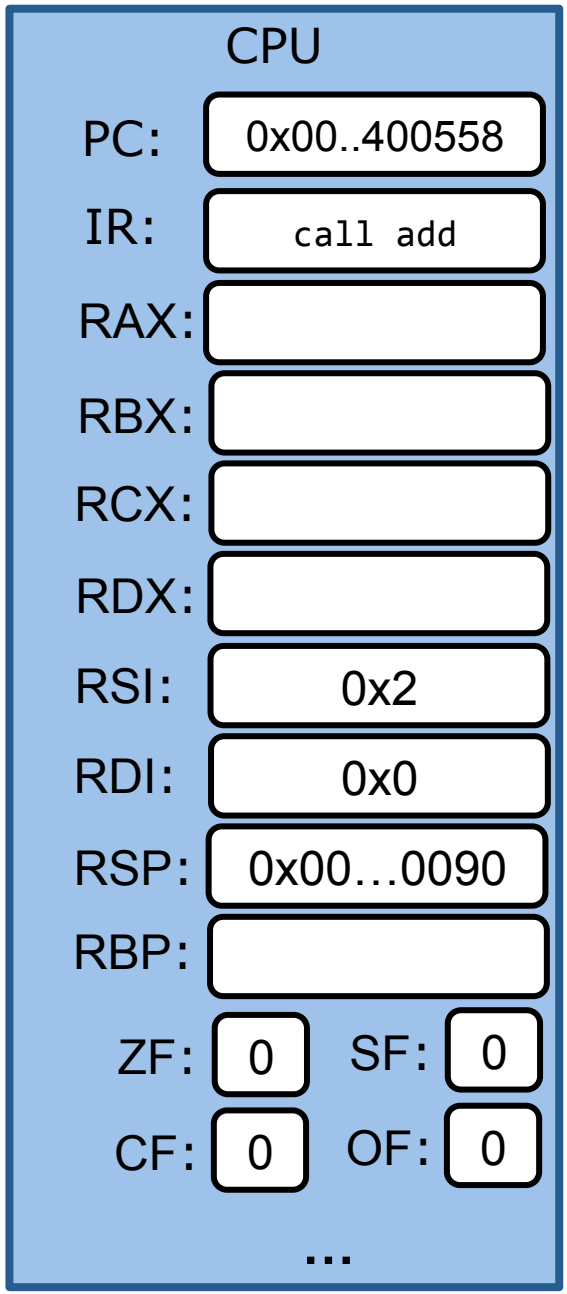
```
0000000000400546 <add>:
        400546:   8d 04 37          lea   (%rdi,%rsi,1),%eax
        400549:   c3                retq

000000000040054a <main>:
        40054a:   48 83 ec 08       sub   $0x8,%rsp
        40054e:   be 02 00 00 00    mov   $0x2,%esi
        400553:   bf  00 00 00 00   mov   $0x0,%edi
        400558:   e8 e9 ff ff ff    callq 400546 <add>
        40055d:   89 c2             mov   %eax,%edx
```

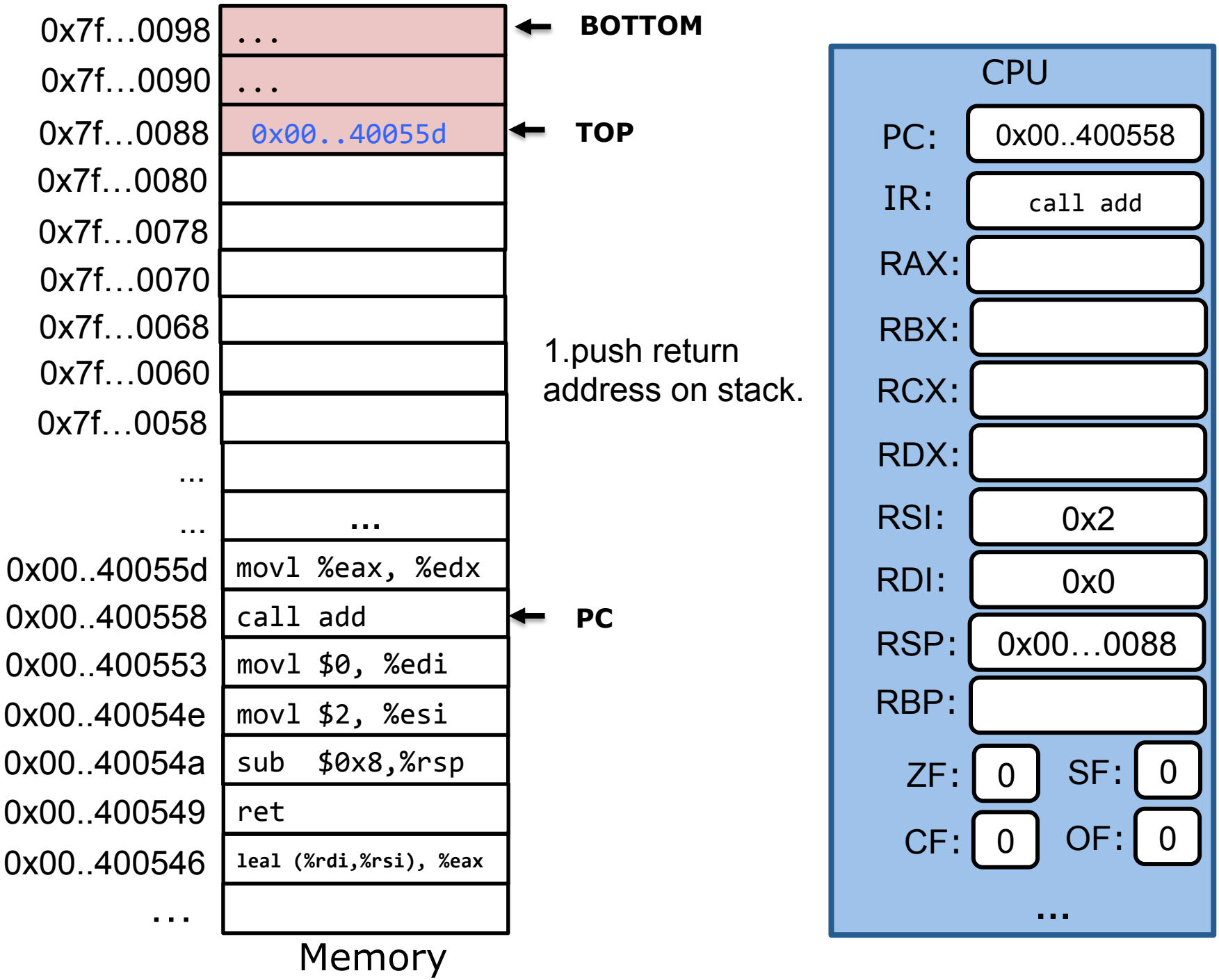

0x7f…0098
...
BOTTOM
0x7f…0090
...
TOP
0x7f…0088
0x7f…0080
0x7f…0078
0x7f…0070
0x7f…0068
0x7f…0060
0x7f…0058
…
…
…
0x00..40055d
movl %eax, %edx
0x00..400558
call add
0x00..400553
movl $0, %edi
0x00..40054e
movl $2, %esi
PC
0x00..40054a
sub $0x8,%rsp
0x00..400549
ret
0x00..400546
leal (%rdi,%rsi), %eax
…
Memory
CPU
PC:
0x00..40054e
IR:
movl $2, %esi
RAX:
RBX:
RCX:
RDX:
RSI:
0x2
RDI:
RSP:
0x00…0090
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
…

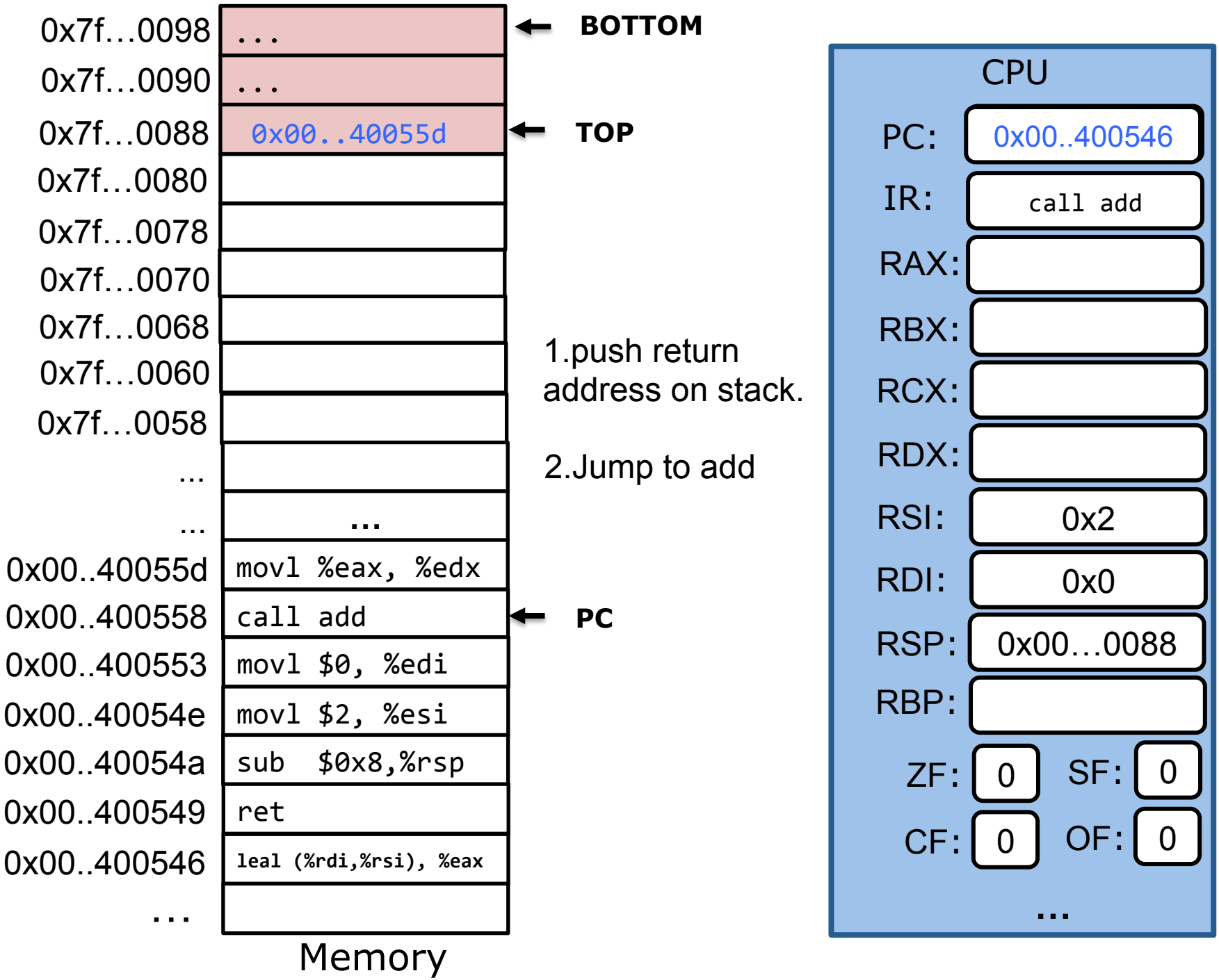

0x7f…0098
...
BOTTOM
0x7f…0090
...
TOP
0x7f…0088
0x7f…0080
0x7f…0078
0x7f…0070
0x7f…0068
0x7f…0060
0x7f…0058
…
…
...
0x00..40055d
movl %eax, %edx
0x00..400558
call add
0x00..400553
movl $0, %edi
PC
0x00..40054e
movl $2, %esi
0x00..40054a
sub $0x8,%rsp
0x00..400549
ret
0x00..400546
leal (%rdi,%rsi), %eax
…
Memory

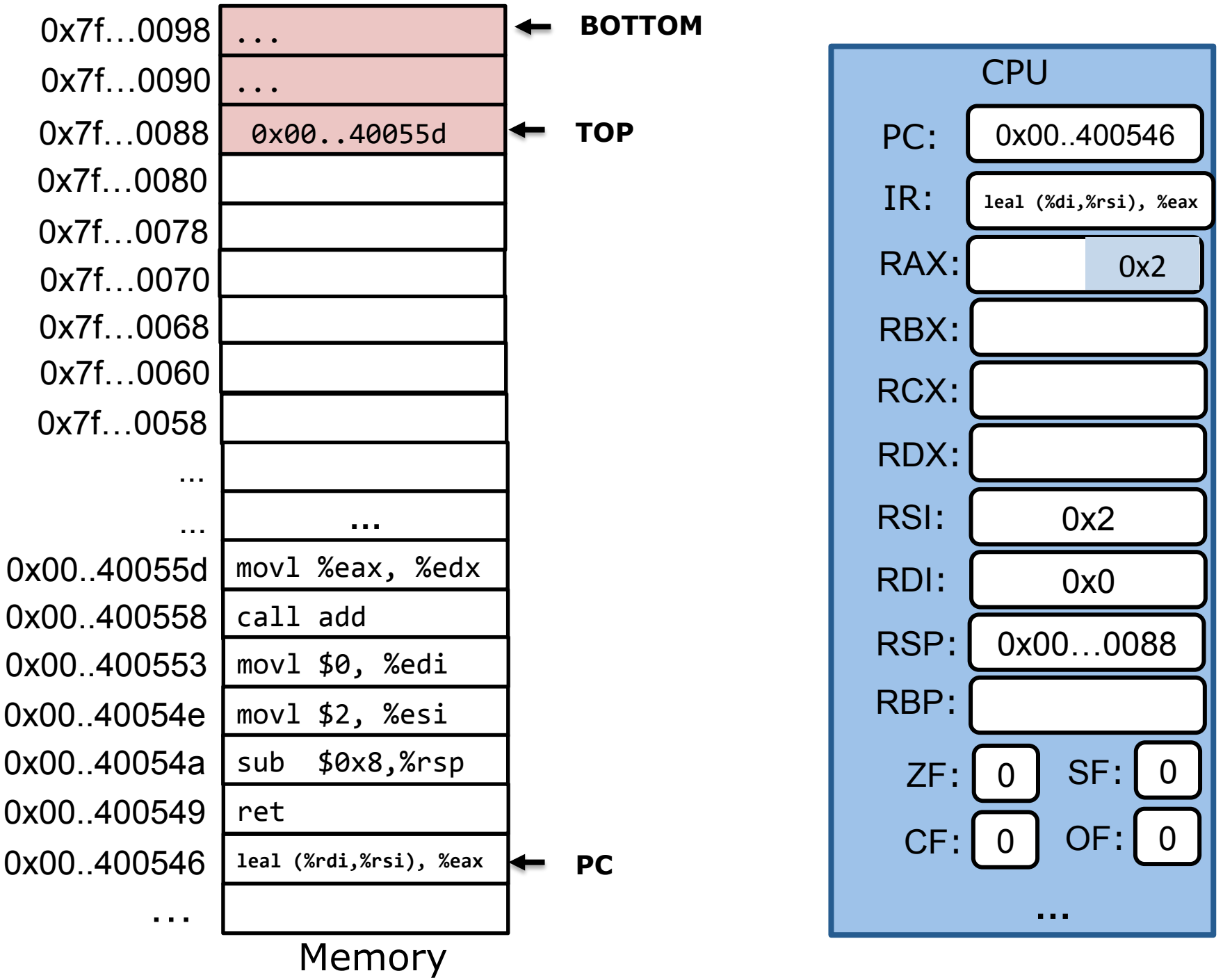

CPU
PC:
0x00..400553
IR:
movl $0, %edi
RAX:
RBX:
RCX:
RDX:
RSI:
0x2
RDI:
0x0
RSP:
0x00…0090
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
…

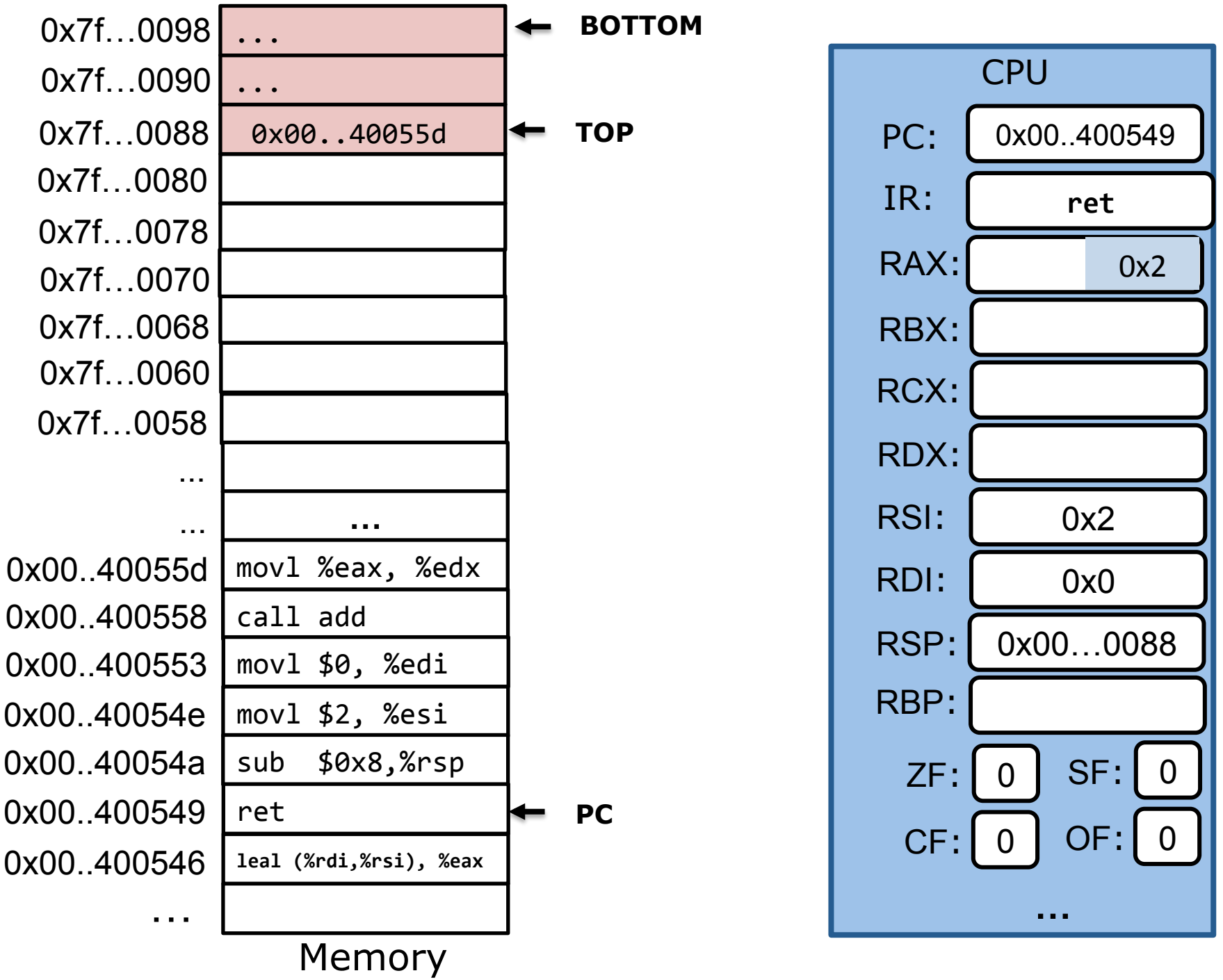

0x7f…0098
...
BOTTOM
0x7f…0090
...
TOP
0x7f…0088
0x7f…0080
0x7f…0078
0x7f…0070
0x7f…0068
0x7f…0060
0x7f…0058
...
...
...
0x00..40055d
movl %eax, %edx
0x00..400558
call add
PC
0x00..400553
movl $0, %edi
0x00..40054e
movl $2, %esi
0x00..40054a
sub $0x8,%rsp
0x00..400549
ret
0x00..400546
leal (%rdi,%rsi), %eax
...
Memory


CPU
PC:
0x00..400558
IR:
call add
RAX:
RBX:
RCX:
RDX:
RSI:
0x2
RDI:
0x0
RSP:
0x00…0090
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
...


0x7f…0098
...
BOTTOM
0x7f…0090
...
0x7f…0088
0x00..40055d
TOP
0x7f…0080
0x7f…0078
0x7f…0070
0x7f…0068
0x7f…0060
0x7f…0058
...
...
0x00..40055d
movl %eax, %edx
0x00..400558
call add
PC
0x00..400553
movl $0, %edi
0x00..40054e
movl $2, %esi
0x00..40054a
sub $0x8,%rsp
0x00..400549
ret
0x00..400546
leal (%rdi,%rsi), %eax
...
Memory
1.push return address on stack.
CPU
PC:
0x00..400558
IR:
call add
RAX:
RBX:
RCX:
RDX:
RSI:
0x2
RDI:
0x0
RSP:
0x00…0088
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
...


0x7f…0098
...
BOTTOM
0x7f…0090
...
0x7f…0088
0x00..40055d
TOP
0x7f…0080
0x7f…0078
0x7f…0070
0x7f…0068
0x7f…0060
0x7f…0058
...
...
0x00..40055d
movl %eax, %edx
0x00..400558
call add
PC
0x00..400553
movl $0, %edi
0x00..40054e
movl $2, %esi
0x00..40054a
sub $0x8,%rsp
0x00..400549
ret
0x00..400546
leal (%rdi,%rsi), %eax
...
Memory
1.push return address on stack.
2.Jump to add
CPU
PC:
0x00..400546
IR:
call add
RAX:
RBX:
RCX:
RDX:
RSI:
0x2
RDI:
0x0
RSP:
0x00…0088
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
...


0x7f…0098
...
BOTTOM
0x7f…0090
...
0x7f…0088
0x00..40055d
TOP
0x7f…0080
0x7f…0078
0x7f…0070
0x7f…0068
0x7f…0060
0x7f…0058
...
...
0x00..40055d
movl %eax, %edx
0x00..400558
call add
0x00..400553
movl $0, %edi
0x00..40054e
movl $2, %esi
0x00..40054a
sub $0x8,%rsp
0x00..400549
ret
0x00..400546
leal (%rdi,%rsi), %eax
PC
...
Memory
CPU
PC:
0x00..400546
IR:
leal (%di,%rsi), %eax
RAX:
0x2
RBX:
RCX:
RDX:
RSI:
0x2
RDI:
0x0
RSP:
0x00…0088
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
...


0x7f…0098
...
BOTTOM
0x7f…0090
...
0x7f…0088
0x00..40055d
TOP
0x7f…0080
0x7f…0078
0x7f…0070
0x7f…0068
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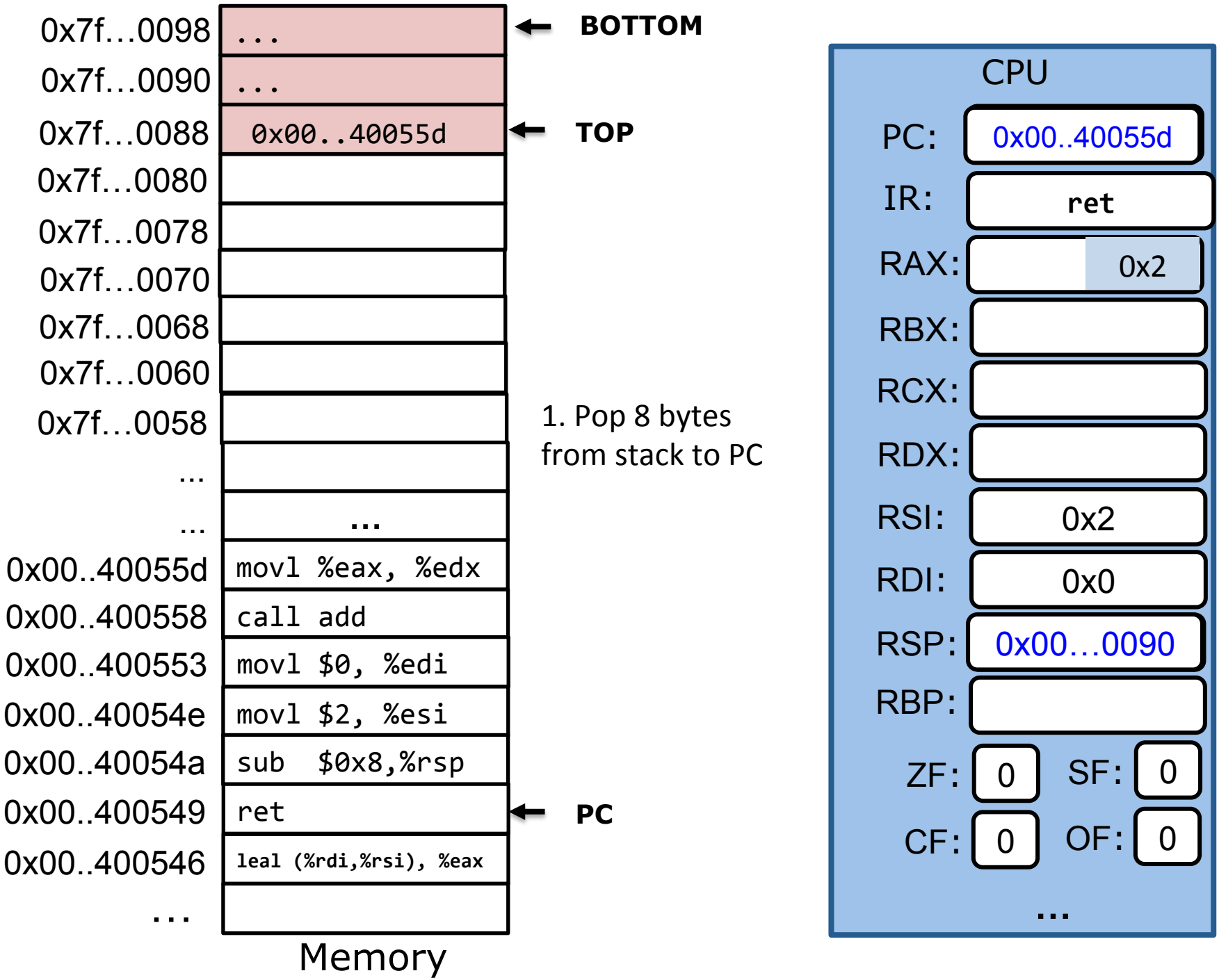
RDI:
0x0
RSP:
0x00…0088
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
...


0x7f…0098
...
BOTTOM
0x7f…0090
...
0x7f…0088
0x00..40055d
TOP
0x7f…0080
0x7f…0078
0x7f…0070
0x7f…0068
0x7f…0060
0x7f…0058
1. Pop 8 bytes from stack to PC
...
...
...
0x00..40055d
movl %eax, %edx
0x00..400558
call add
0x00..400553
movl $0, %edi
0x00..40054e
movl $2, %esi
0x00..40054a
sub $0x8,%rsp
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leal (%rdi,%rsi), %eax
...
Memory
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RDX:
RSI:
0x2
RDI:
0x0
RSP:
0x00…0090
RBP:
ZF:
0
SF:
0
CF:
0
OF:
0
...

Where to store function arguments and return values?

- Hardware does not dictate where arguments and return value are stored
  - It's up to the software (compilers).
- Where to put arguments and return value?
  - Arguments and return value are allocated when function is called, de-allocated when function returns.
  - Must do such allocation/de-allocation very fast

Where to store function arguments and return values?

- Two possible designs:
  - Store on stack
  - Use registers

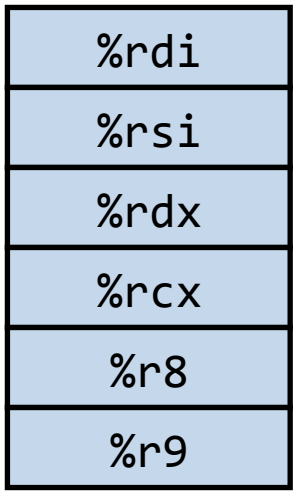
Registers are much faster than memory but there are only a few of them

- The chosen design → the calling convention
  - All code on a computer system must obey the same convention
  - Otherwise, libraries won't work

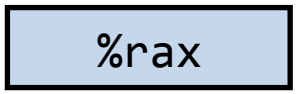
C/UNIX's calling convention

Registers

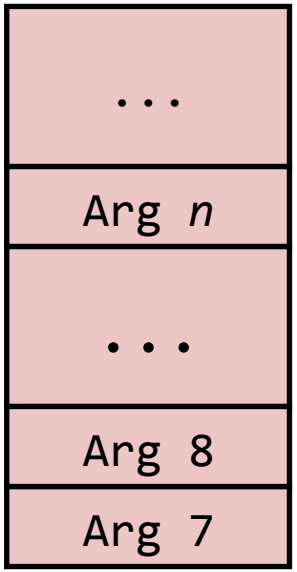
First 6 arguments



Return value



Stack



Only allocate stack space when needed

Calling convention: args, return vals

Registers

- First 6 Arguments: %rdi, %rsi, %rdx, %rcx, %r8, %r9
- Return value: %rax

```
int add(int a, int b, int c, int d, int e, int f, int g, int h) {
  int r = a + b + c + d + e + f + g + h;
  return r;
}

int main() {
    int c = add(1, 2, 3, 4, 5, 6, 7, 8);
    printf("%d\b", c);
    return 0;
}
```

Calling convention: args, return vals

```
int add(int a, int b, int c, int d, int e, int f, int g, int h) {
  int r = a + b + c + d + e + f + g + h;
  return r;
}
int main() {
    int c = add(1, 2, 3, 4, 5, 6, 7, 8);
    printf("%d\b", c);
    return 0;
}
```

```
main:
    pushq   $8
    pushq   $7
    movl    $6, %r9d
    movl    $5, %r8d
    movl    $4, %ecx
    movl    $3, %edx
    movl    $2, %esi
    movl    $1, %edi
    call    add
```

```
add:
    addl    %esi, %edi
    addl    %edi, %edx
    addl    %edx, %ecx
    addl    %r8d, %ecx
    addl    %r9d, %ecx
    movl    %ecx, %eax
    addl    8(%rsp), %eax
    addl    16(%rsp), %eax
    ret
```

8(%rsp) stores g

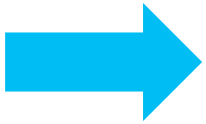
16(%rsp) stores h

what does (%rsp) store?

How to allocate/deallocate local vars?

- For primitive data types, use registers whenever possible
- Allocate local array/struct variables on the stack

```
int main() {
      int a[10];
      clear_array(a, 10);
      return 0;
}
```



```
main:
      subq    $48, %rsp
      movl    $10, %esi
      movq    %rsp, %rdi
      call    clear_array
      movl    $0, %eax
      addq    $48, %rsp
      ret
```

array allocation

array de-allocation

Calling convention: Caller vs. callee-save registers

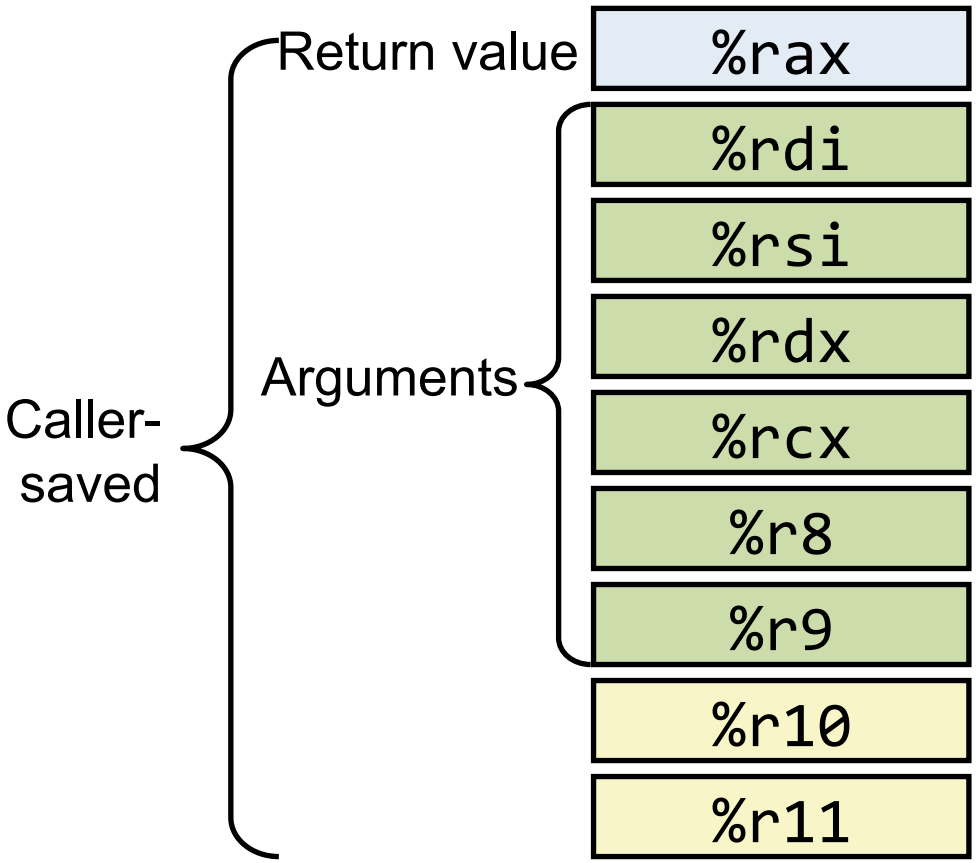
- What can the caller assume about the content of a register across function calls?

```
int foo() {
   int a;     // suppose a is stored in %r12
   a = .... // compute result of a

   int r = bar();

   int result = r + a; // does %r12 still store the value of a?
   return result;
}
```

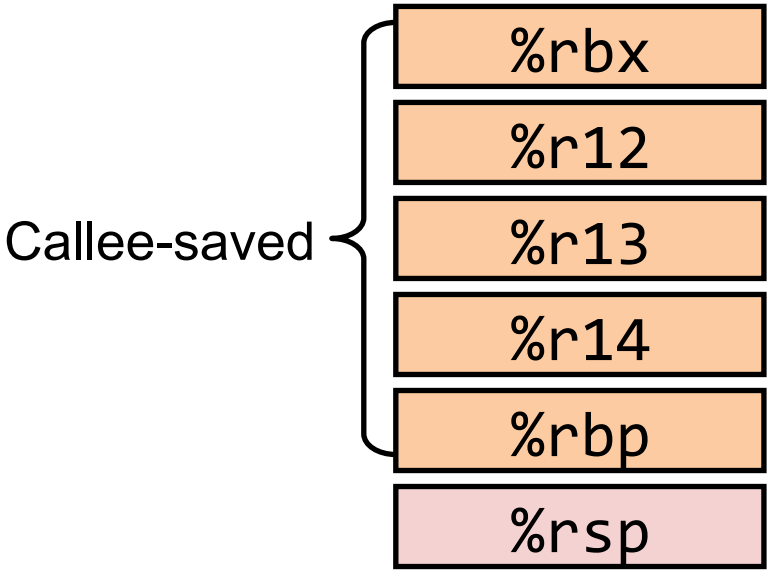
Calling convention: register saving

- Caller saved
  - If caller is going to need X's value after the call, it saves X on stack before the call and restores X after the call
- Callee saved
  - If callee is going to use Y, it saves Y on stack before using and restores Y before returning to caller

Calling convention: Register saving



Callee can directly use these registers



Caller can assume these registers are unchanged.

Example

```
int add2(int a, int b)
{
  return a + b;
}
```

```
add2:
    leal    (%rdi,%rsi), %eax
    ret
```

```
int add3(int a, int b, int c)
{
  int r = add2(a, b);
  r = r + c;
  return r;
}
```

```
add3:
    pushq   %rbx
    movl    %edx, %ebx
    movl    $0, %eax
    call    add2
    addl    %ebx, %eax
    popq    %rbx
    ret
```

Registers

- *First 6 Arguments: %rdi, %rsi, %rdx, %rcx, %r8, %r9*
- *Return value: %rax*

Example

```
int add2(int a, int b)
{
  return a + b;
}
```

```
int add3(int a, int b, int c)
{
  int r = add2(a, b);
  r = r + c;
  return r;
}
```

```
add2:
    leal    (%rdi,%rsi), %eax
    ret
```

```
add3:
    pushq   %rbx
    movl    %edx, %ebx
    movl    $0, %eax
    call    add2
    addl    %ebx, %eax
    popq    %rbx
    ret
```

save %rbx (callee-save) before overwriting it

%rdx (contains c) is caller save, i.e. may be changed by add2

c is copied to %ebx, which is callee save

restore %rbx before ret

Registers

First 6 Arguments: %rdi, %rsi, %rdx, %rcx, %r8, %9

Return value: %rax