HARVARD

School of Engineering and Applied Sciences

Machine Programming 3: Procedures

CS61, Lecture 5

Prof. Stephen Chong

September 15, 2011

Announcements

- Assignment 2 (Binary bomb) due next week
  - If you haven't yet please create a VM to make sure the infrastructure works for you

Today

- Procedures
  - The stack
  - Stack frames
  - Leave
  - Register conventions
- x86_64

Procedure calls

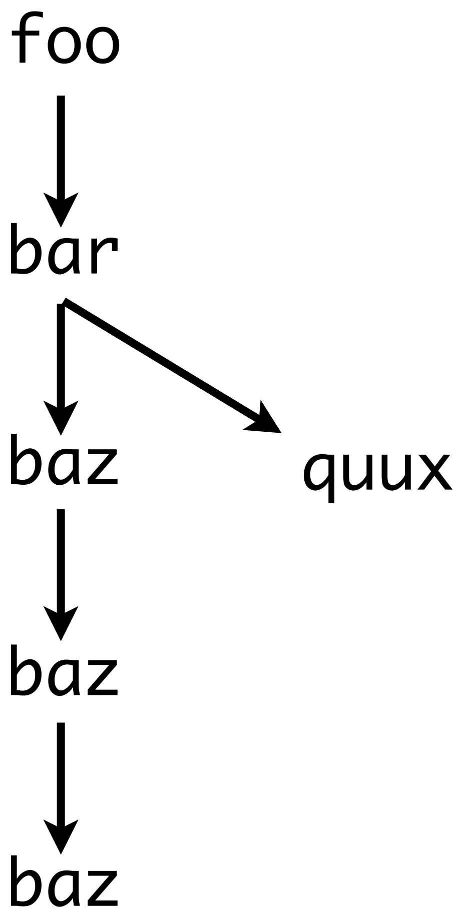
```
void foo(...) {
    ...
    bar();
    ...
}
```

```
void bar(...) {
   int x, y;
    x = baz();
    ...
    y = quux();
    ...
}
```

```
int baz(...) {
    int z;
    ...
    z = baz();
    ...
    return z;
}
```

```
int quux(...) {
    ...
    return 42;
}
```

Call chain

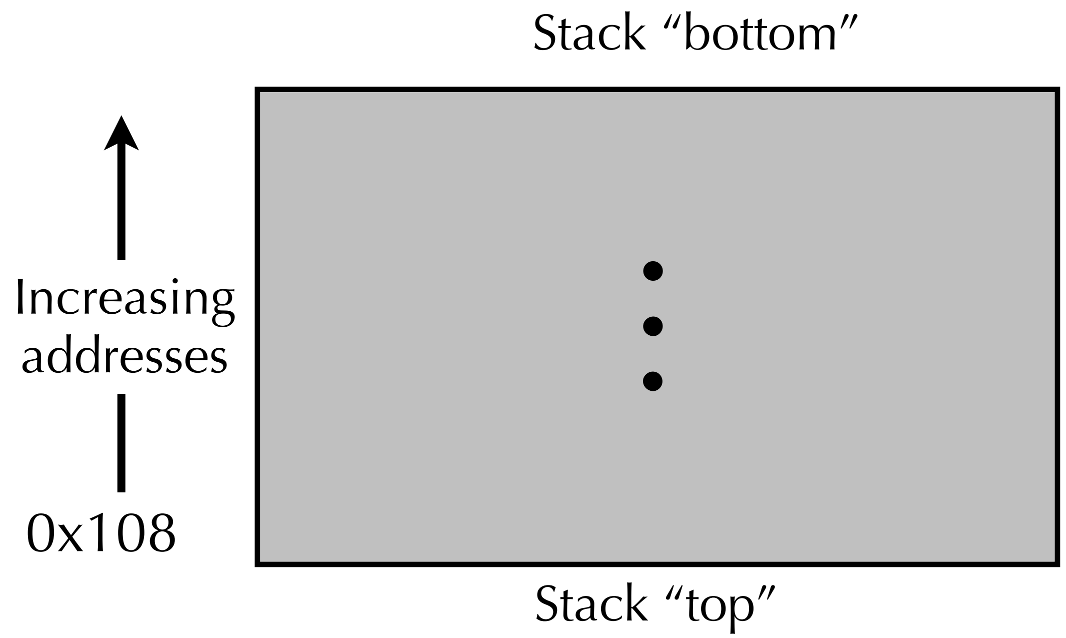


- How do we call procedures?
- Where do we store local variables (e.g., x,y,z)?
- How do we return values from procedures?
- How do we support recursion?

Stack

- Stack is used for handling function calls and local storage
  - Stores local variables, return address, saved registers, …
- Stack pointer `%esp` always holds address of top stack element
- Stack grows **downwards**!

`%eax`	`0x123`
`%edx`	`0`
`%esp`	`0x108`

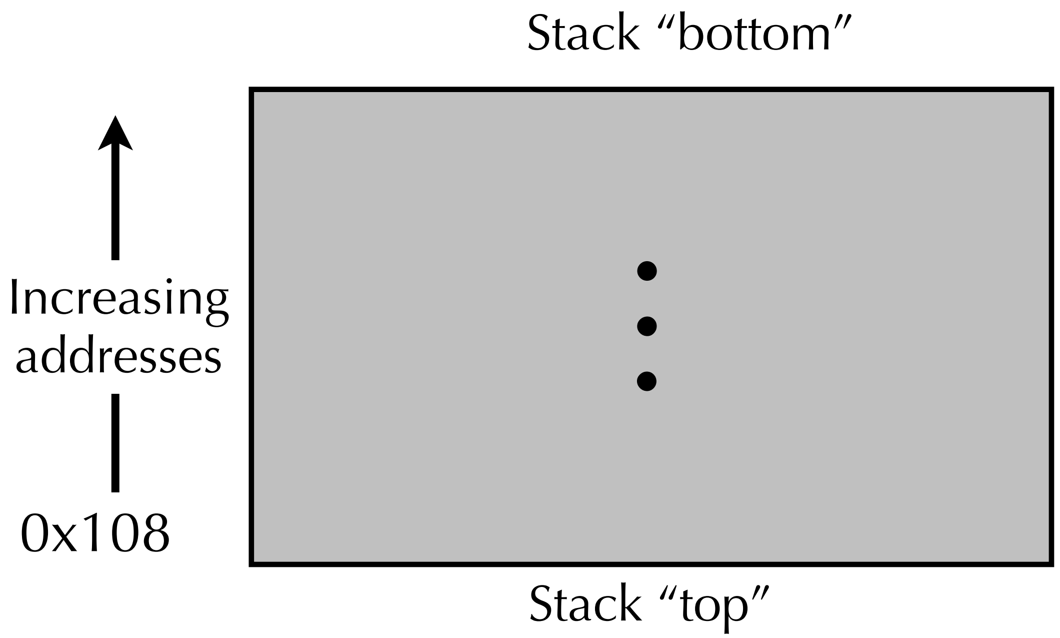


Pushing and popping

- Two data movement instructions for stack: `pushl` and `popl`
- `pushl` *src*
    - Push four bytes onto stack
    - Effect is

      $$R[\texttt{\%esp}] \leftarrow R[\texttt{\%esp}] - 4$$
      $$M[R[\texttt{\%esp}]] \leftarrow src$$
- E.g., `pushl %eax`

`%eax`	`0x123`
`%edx`	`0`
`%esp`	`0x108`



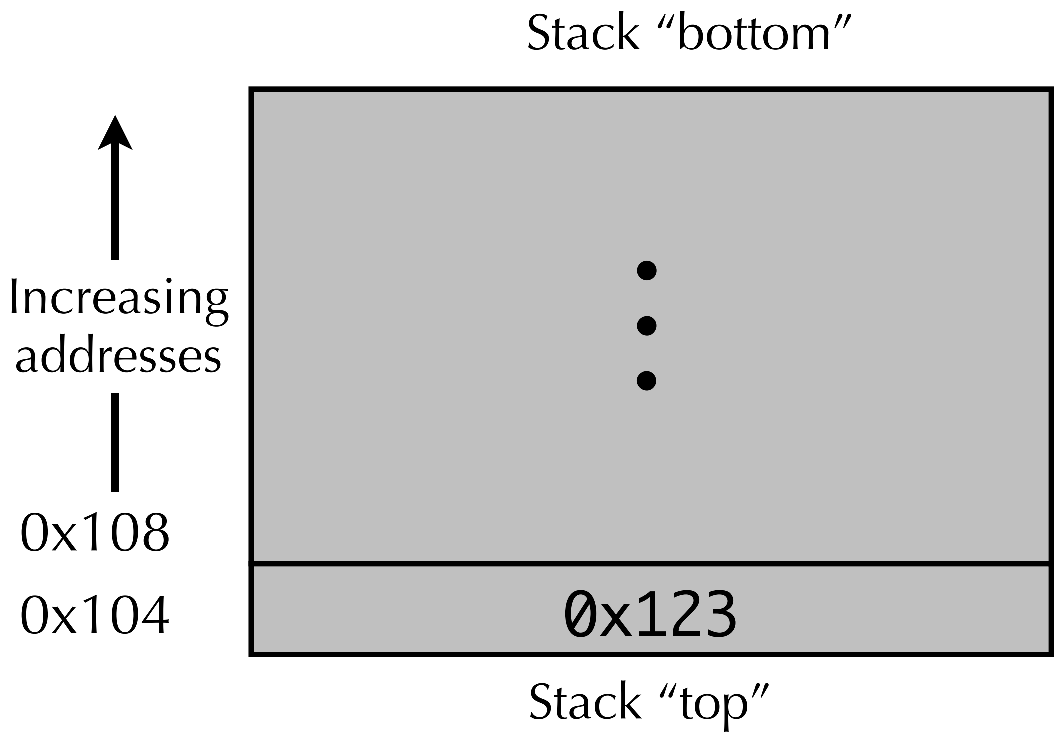
Pushing and popping

`%eax`	`0x123`
`%edx`	`0`
`%esp`	`0x104`

- Two data movement instructions for stack: `pushl` and `popl`
- `pushl` *src*
  - Push four bytes onto stack
  - Effect is

    $R[\texttt{\%esp}] \leftarrow R[\texttt{\%esp}] - 4$

    $M[R[\texttt{\%esp}]] \leftarrow src$
- E.g., `pushl %eax`



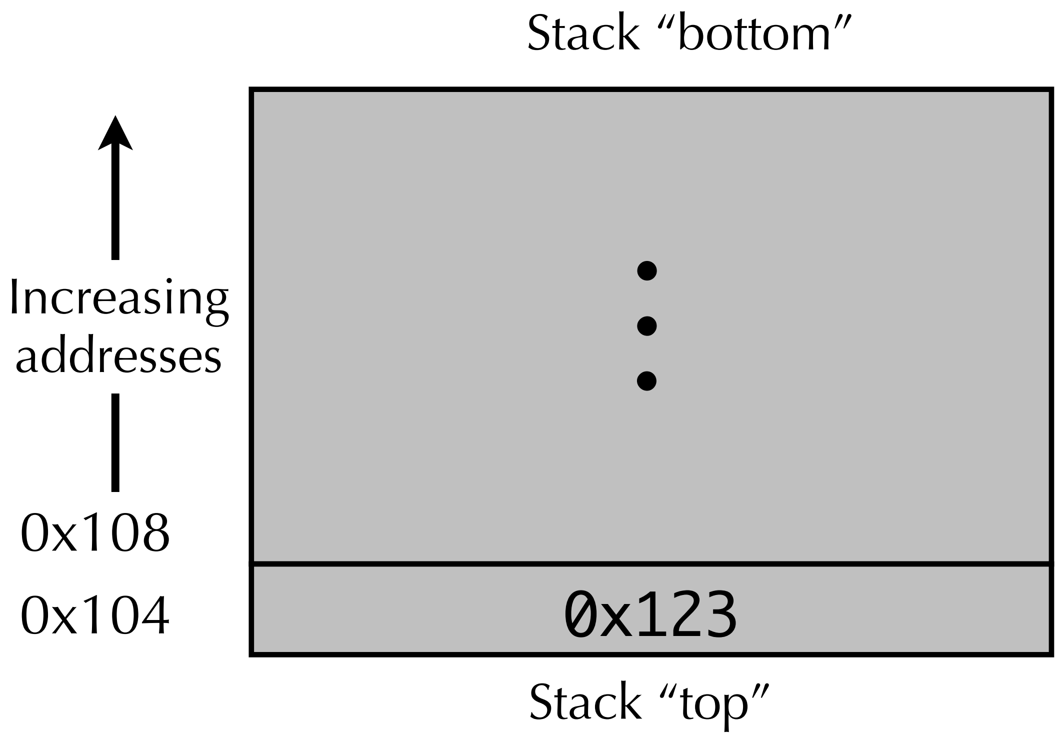
Pushing and popping

- `popl` *dest*
  - Pops four bytes from stack
  - Effect is

    dest ← M[R[`%esp`]]

    R[`%esp`] ← R[`%esp`] + 4
- E.g., `popl %edx`

`%eax`	`0x123`
`%edx`	`0`
`%esp`	`0x104`



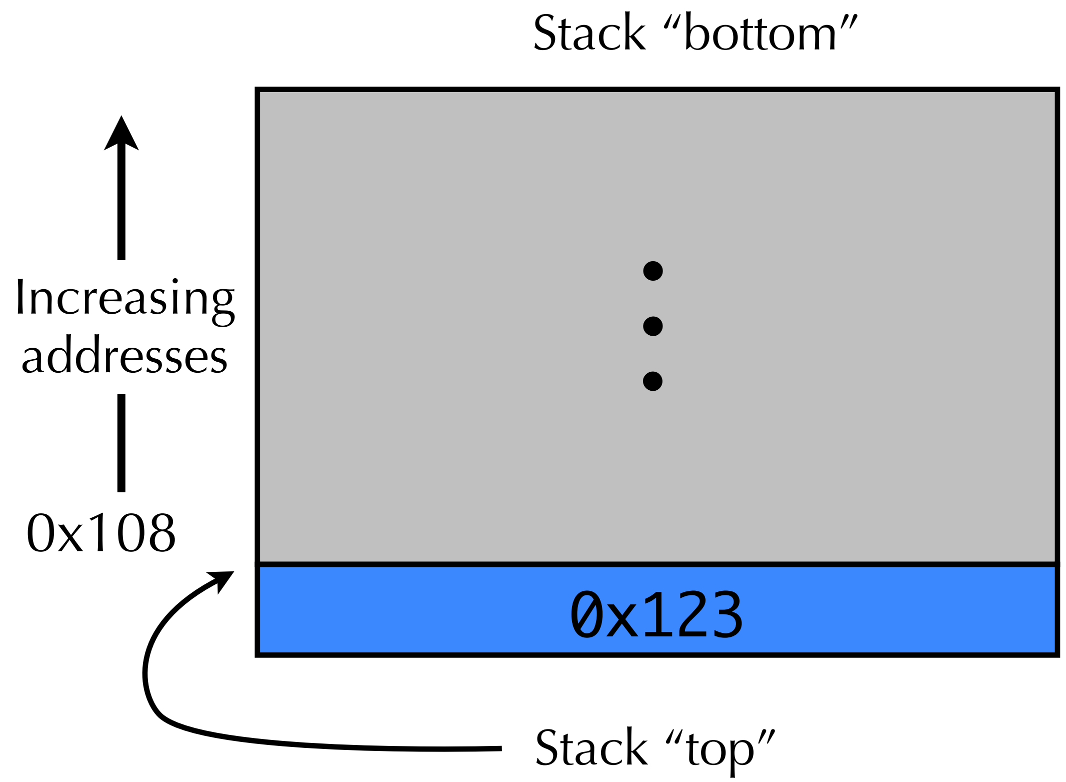
Pushing and popping

- `popl` *dest*
  - Pops four bytes from stack
  - Effect is

    $dest \leftarrow M[R[\texttt{\%esp}]]$

    $R[\texttt{\%esp}] \leftarrow R[\texttt{\%esp}] + 4$
- E.g., `popl %edx`

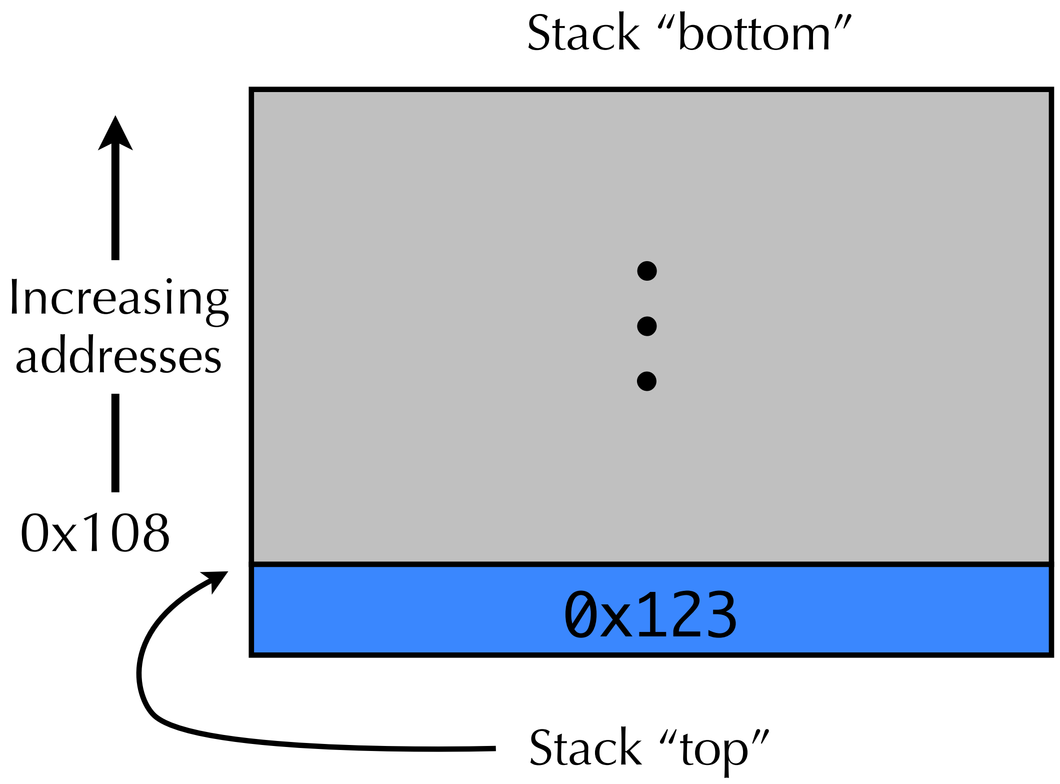
%eax	0x123
%edx	0x123
%esp	0x108



Examining the stack

- Can use `movl` to access and modify arbitrary values on the stack
  - No need to access just top element
  - Can “peek” at stack:
    - `movl 12(%esp), %eax`
  - Can “poke” stack:
    - `movl $0xdeadbeef, 12(%esp)`

%eax	0x123
%edx	0x123
%esp	0x108



Procedure control flow

- Stack is used to implement procedure call and return
- Procedure call
  - x86 instruction: `call` *address*
  - Pushes **return address** on stack, then jumps to *address*
  - What is the return address?
    - Address of instruction **after** the `call` instruction
    - E.g.,

```
804854e: e8 3d 06 00 00     call   8048b90 <main>
8048553: 50                 pushl  %eax
```

    - Return address is 0x8048553
- Procedure return
  - x86 instruction: `ret`
  - Pops return address from stack, and jumps to it

Procedure call example

```
804854e: e8 3d 06 00 00     call    8048b90 <main>
8048553: 50                 pushl   %eax
```

Before call

	⋮
0x114	
0x110	
0x10c	
0x108	0x123

%esp	0x108
%eip	0x804854e

After call

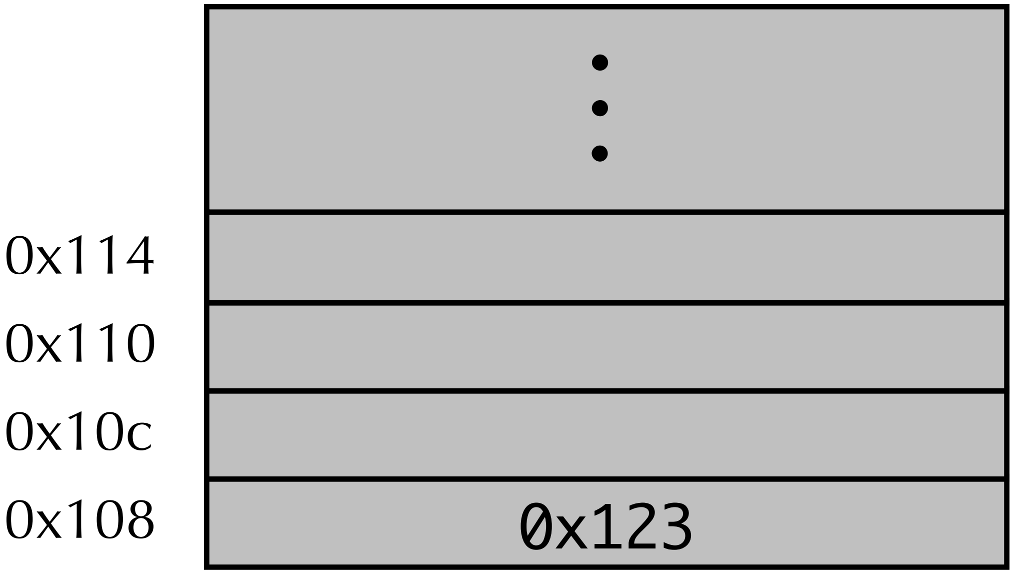
	⋮
0x114	
0x110	
0x10c	
0x108	0x123
0x104	0x8048553

%esp	0x104
%eip	0x8048b90

Procedure call example

```
804854e: e8 3d 06 00 00     call    8048b90 <main>
8048553: 50                 pushl   %eax
```

Before call



⋮

0x114

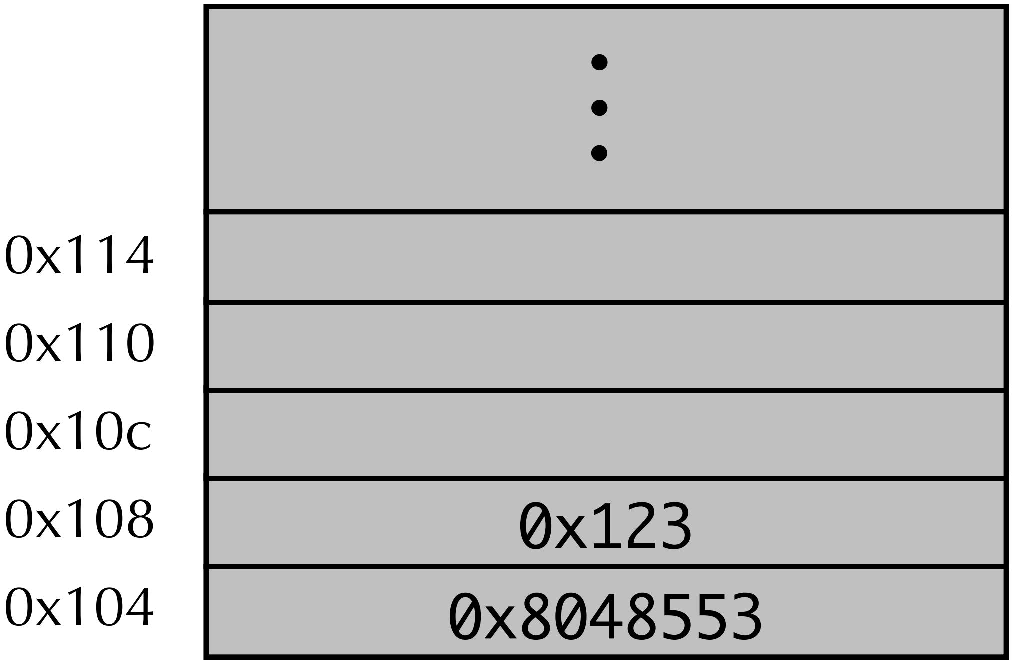
0x110

0x10c

0x108 0x123

%esp	0x108
%eip	0x804854e

After call



⋮

0x114

0x110

0x10c

0x108 0x123

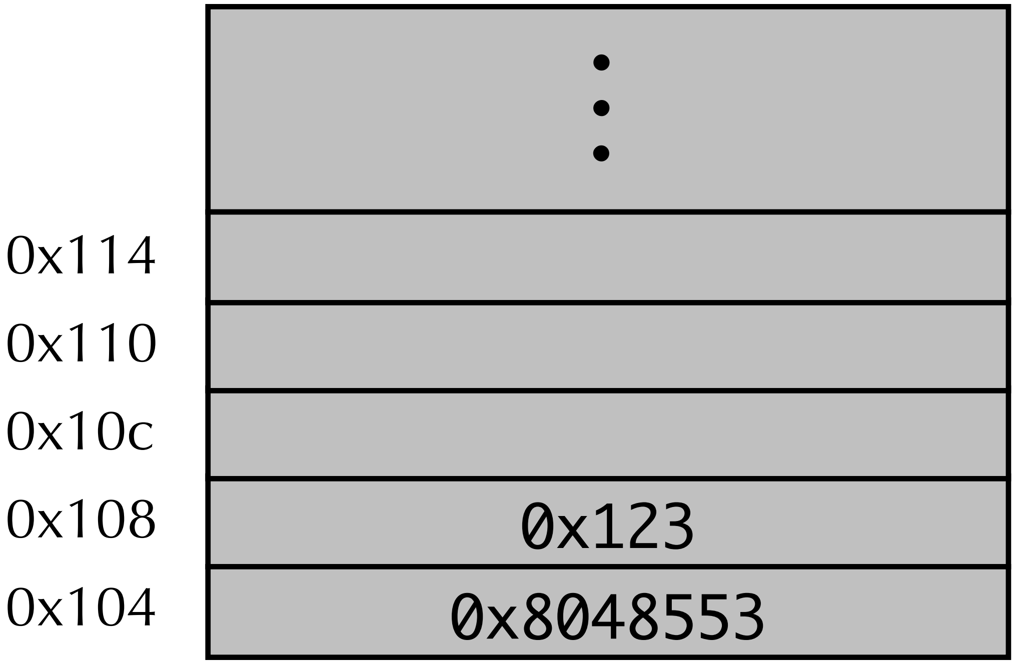
0x104 0x8048553

%esp	0x104
%eip	0x8048b90

Procedure return example

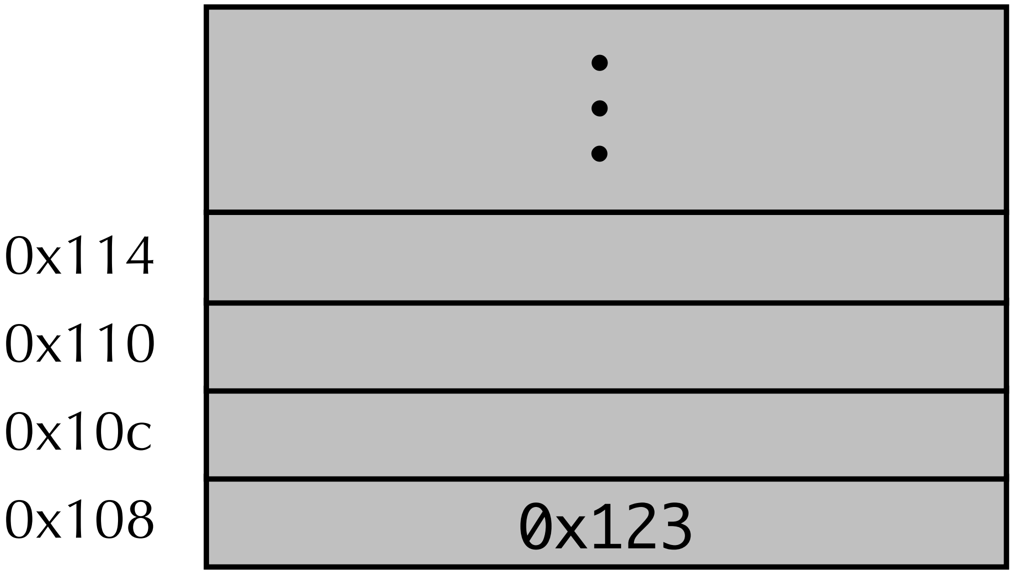
```
8048591: c3                  ret
```

Before return



%esp	0x104
%eip	0x8048b91

After return



%esp	0x108
%eip	0x8048553

Stack-based languages

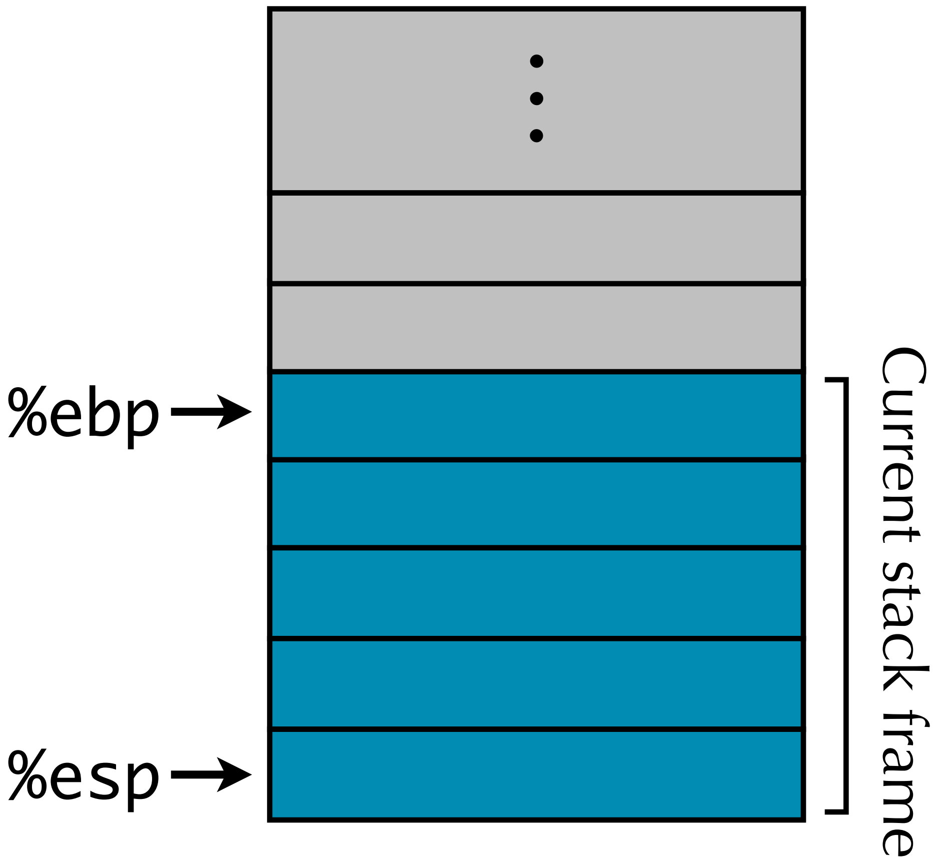
- Languages that support recursion
  - E.g., C, Pascal, Java
  - Must be able to support multiple instantiations of single procedure
    - Code must be **reenterant**

```
int rfact(int x) {
  int rval;
  if (x <= 1)
    return 1;
  rval = rfact(x-1);
  return rval * x;
}
```

- Each invocation of a procedure has its own local state
  - Arguments to the procedure (e.g., `x`)
  - Local variables within the procedure (e.g., `rval`)
  - Return address
- Where are these stored?

Stack frame

- Each procedure invocation has an associated **stack frame**
  - The “chunk” of the stack for that procedure invocation
  - Contains local variables, arguments to functions, and return address
  - Needed from when procedure called to when it returns
- Stack discipline
  - Stack frame released when procedure returns
  - Callee must return before caller does
- Current stack frame described by two registers
  - `%ebp`: frame pointer
    - Points to base (or “bottom”) of current stack frame
  - `%esp`: stack pointer
    - Points to stop of stack (i.e., top of current stack frame)



Stack frame example

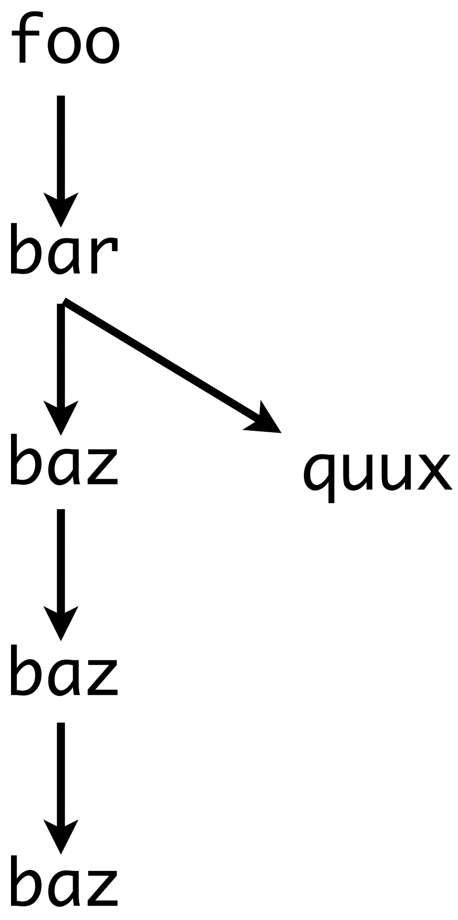
```
void foo(...) {
    ...
    bar();
    ...
}
```

```
void bar(...) {
   int x, y;
    x = baz();
    ...
    y = quux();
    ...
}
```

```
int baz(...) {
    int z;
    ...
    z = baz();
    ...
    return z;
}
```

```
int quux(...) {
    ...
    return 42;
}
```

Call chain

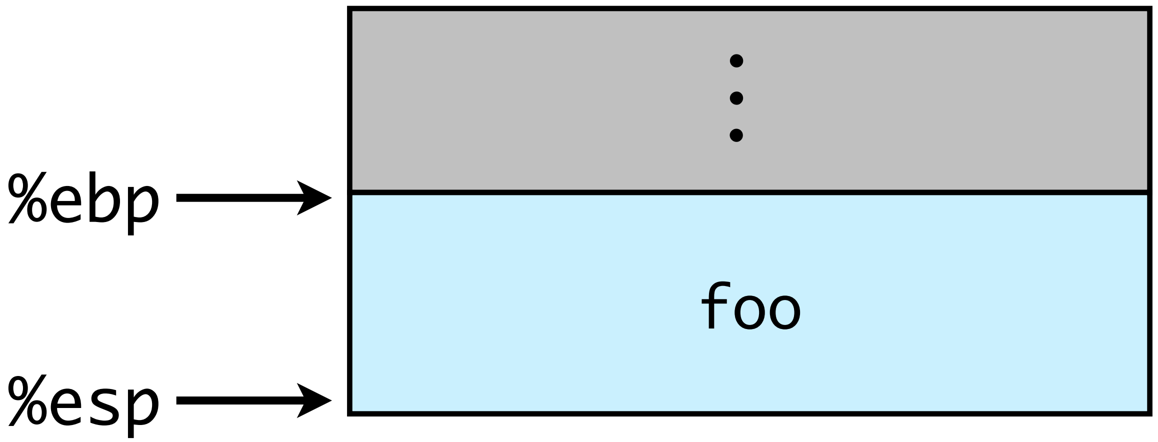


Stack frame example

```
void foo(...) {
   ...
   bar();
   ...
}
```

Call chain

foo



Stack frame example

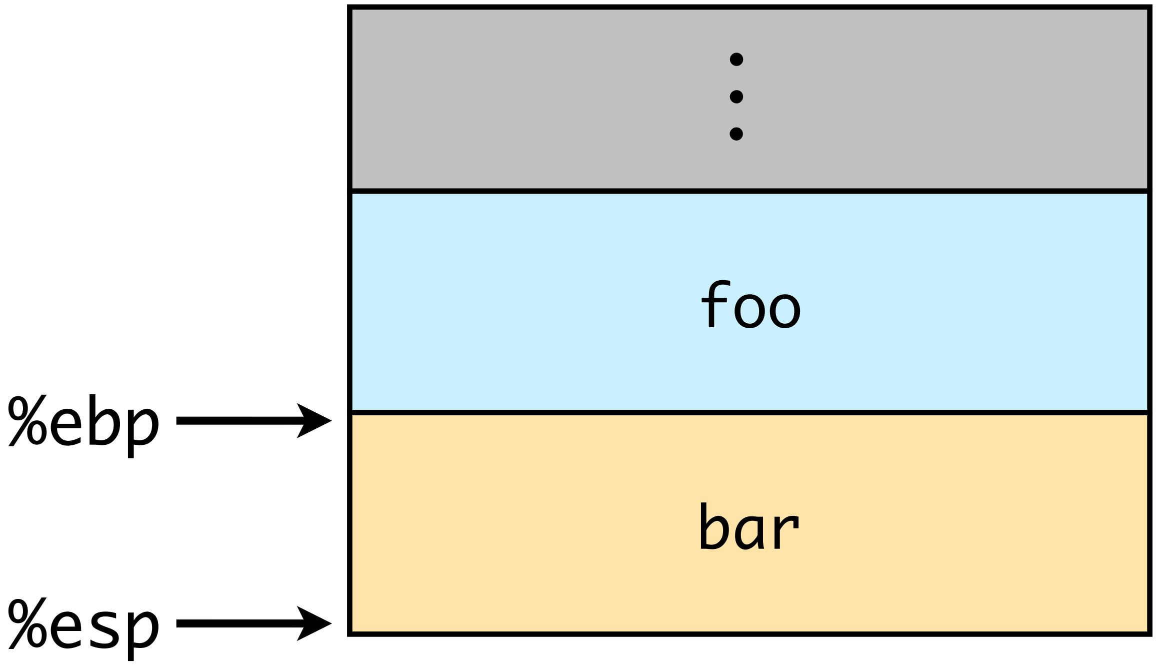
```
void foo(...) {

}
```

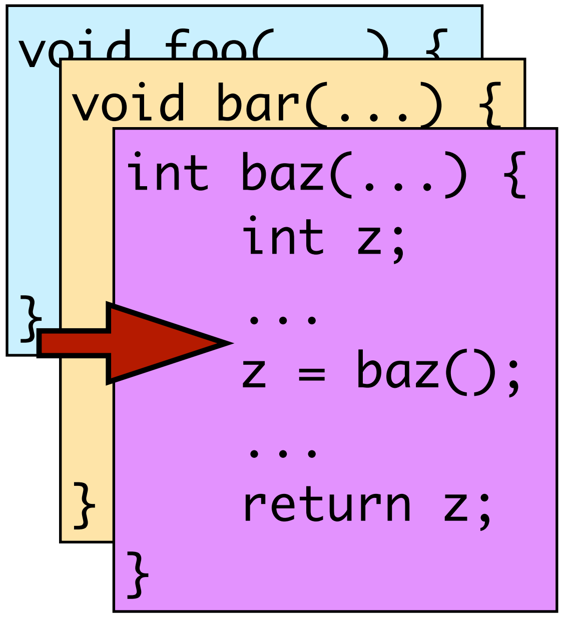
```
void bar(...) {
   int x, y;
   x = baz();
   ...
   y = quux();
   ...
}
```

Call chain

foo
↓
bar



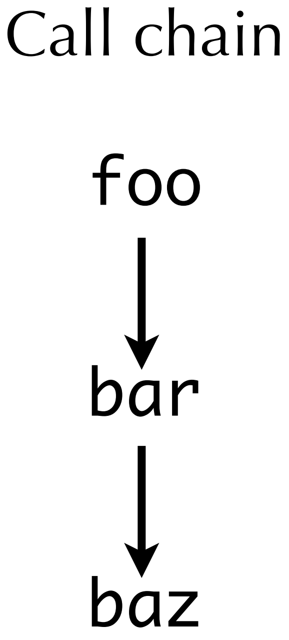
Stack frame example



```
void foo(...) {
}
```

```
void bar(...) {
}
```

```
int baz(...) {
    int z;
    ...
    z = baz();
    ...
    return z;
}
```

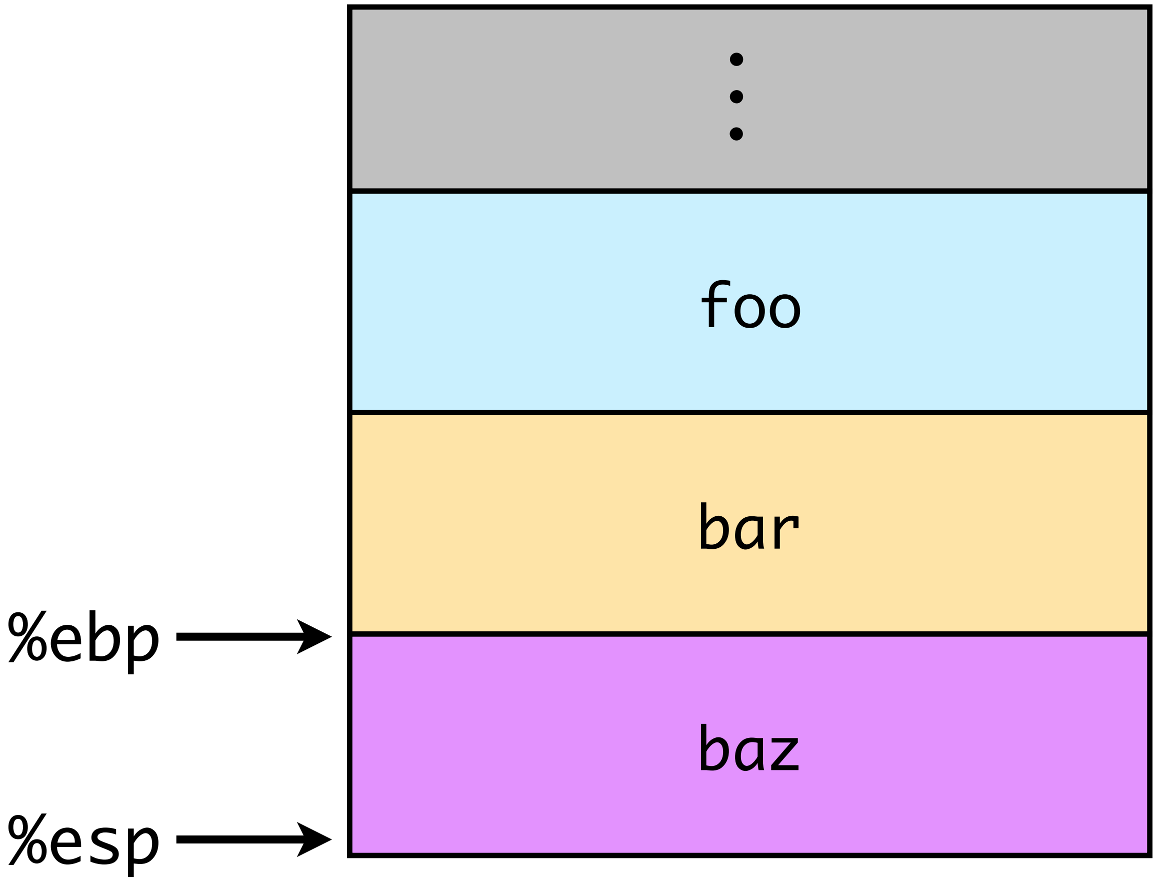


Call chain

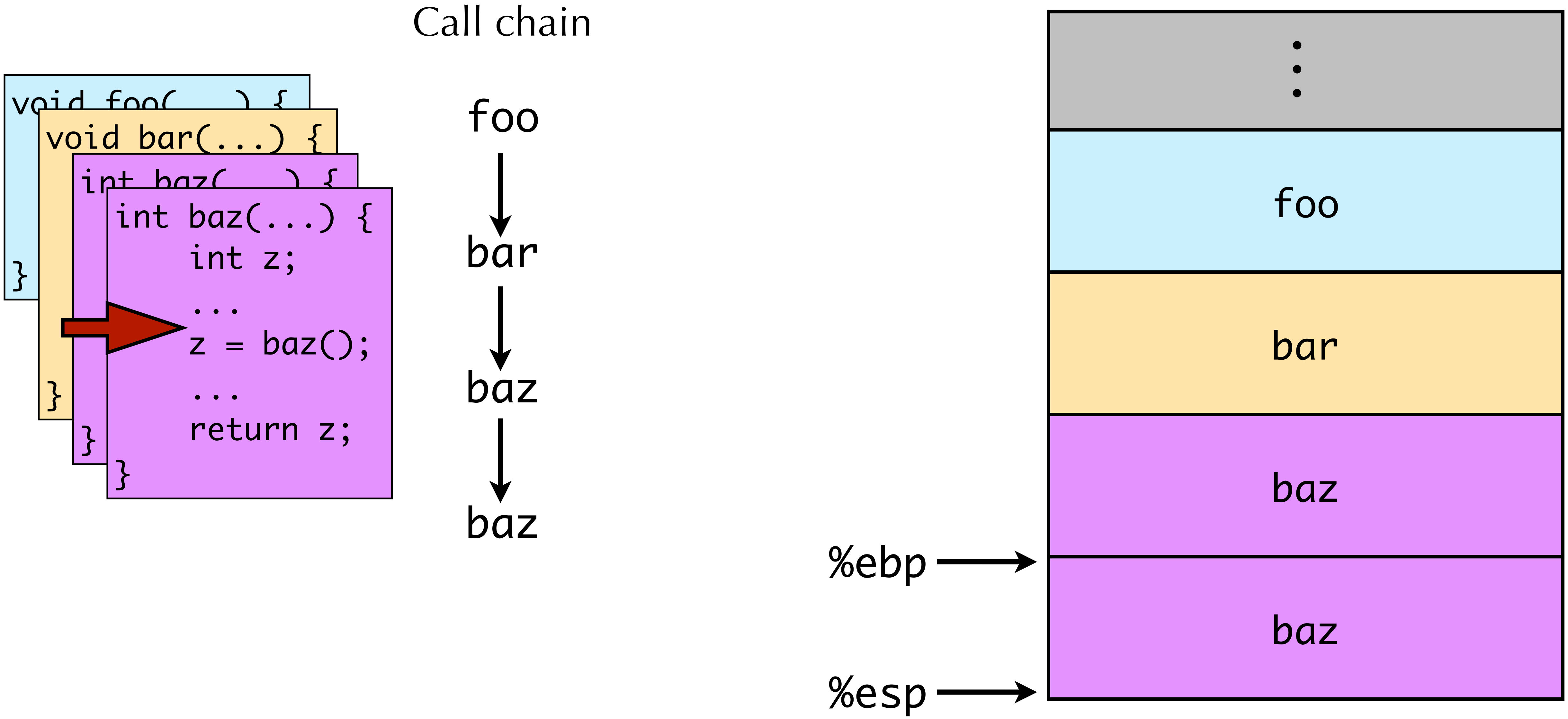
foo

bar

baz

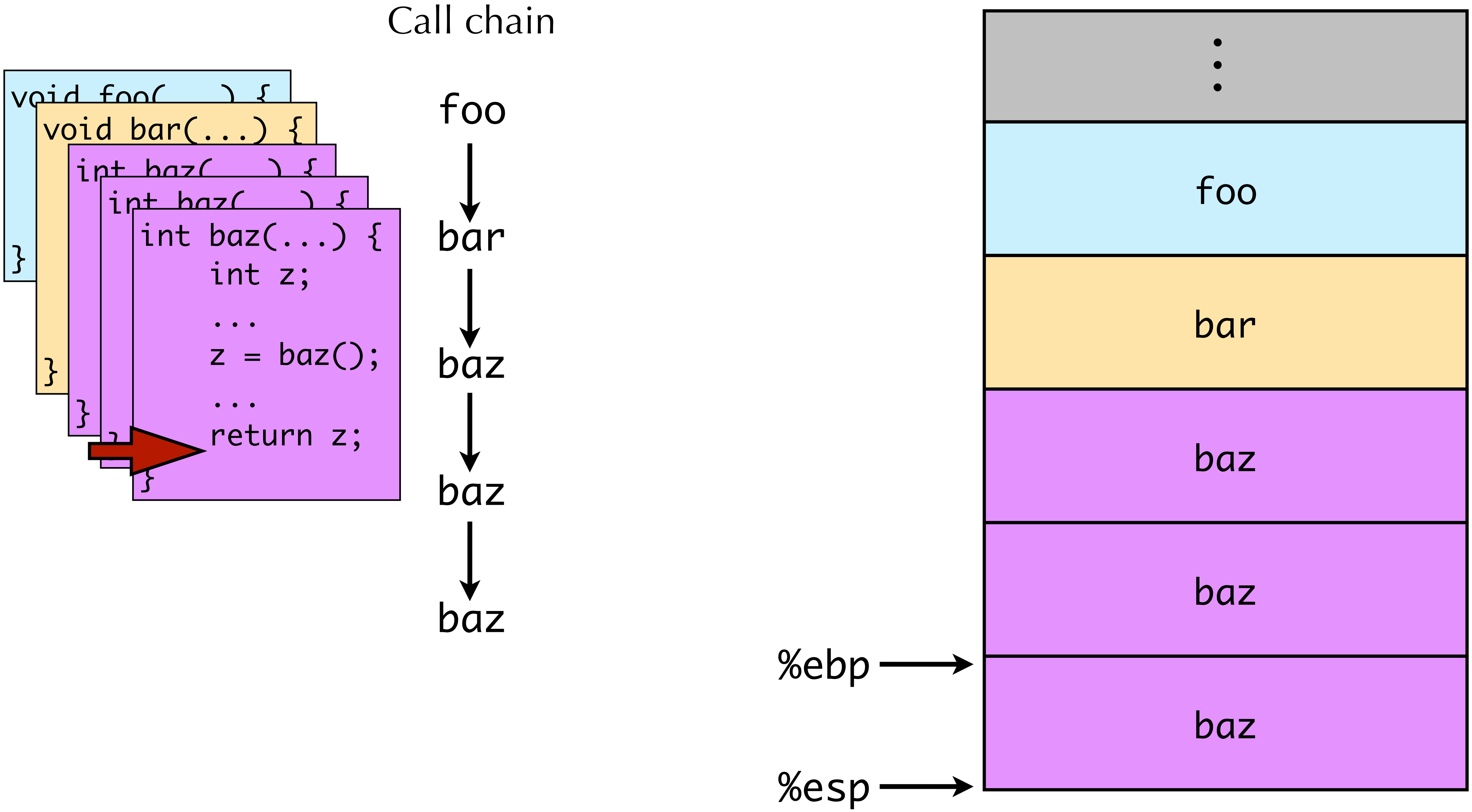


Stack frame example



```
int baz(...) {
     int z;
     ...
     z = baz();
     ...
     return z;
}
```

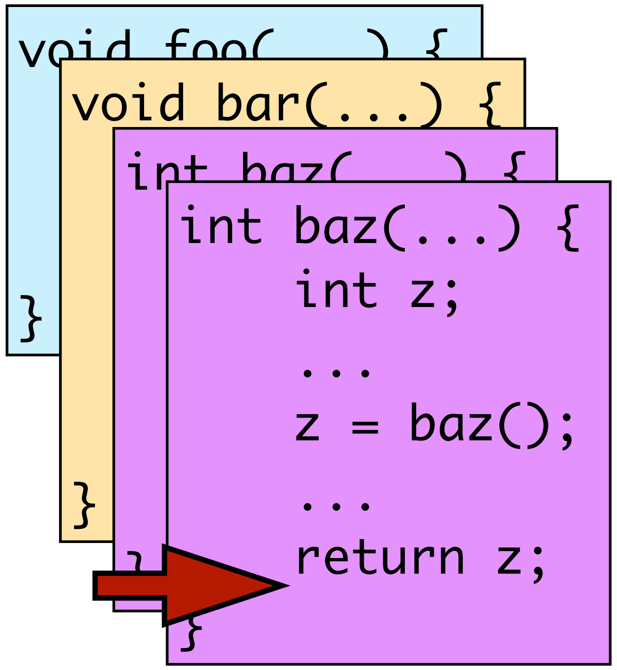
Stack frame example



Call chain

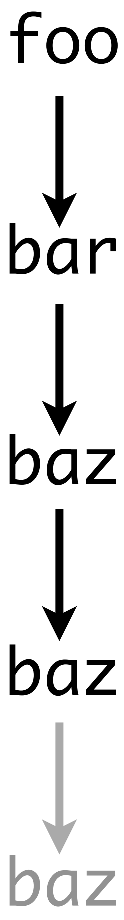
```
int baz(...) {
    int z;
    ...
    z = baz();
    ...
    return z;
}
```

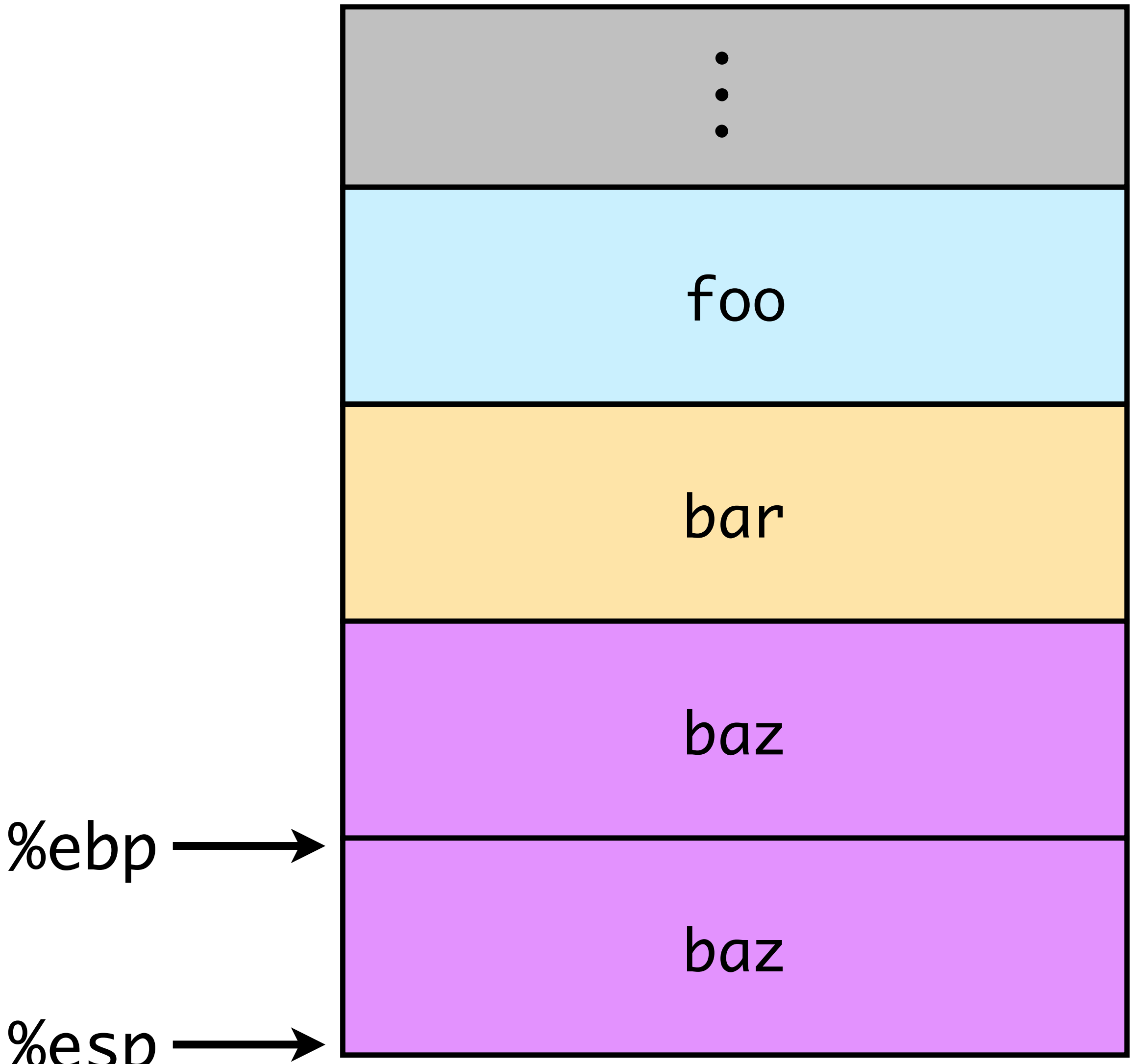
Stack frame example



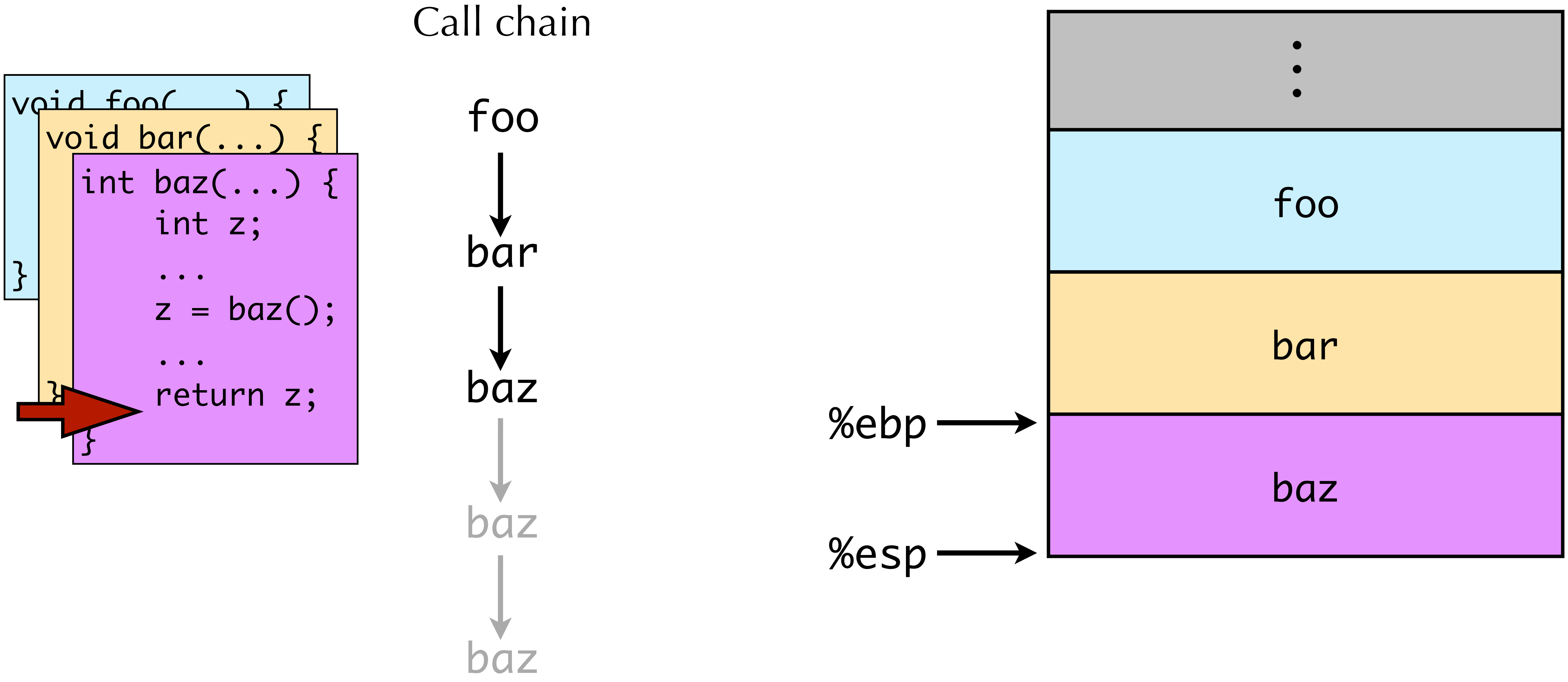
```
void foo(...) {
}
void bar(...) {
}
int baz(...) {
}
int baz(...) {
    int z;
    ...
    z = baz();
    ...
    return z;
}
```

Call chain





Stack frame example



```
void foo(...) {

}
```

```
void bar(...) {

}
```

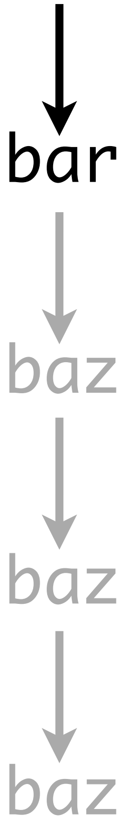
```
int baz(...) {
    int z;
    ...
    z = baz();
    ...
    return z;
}
```

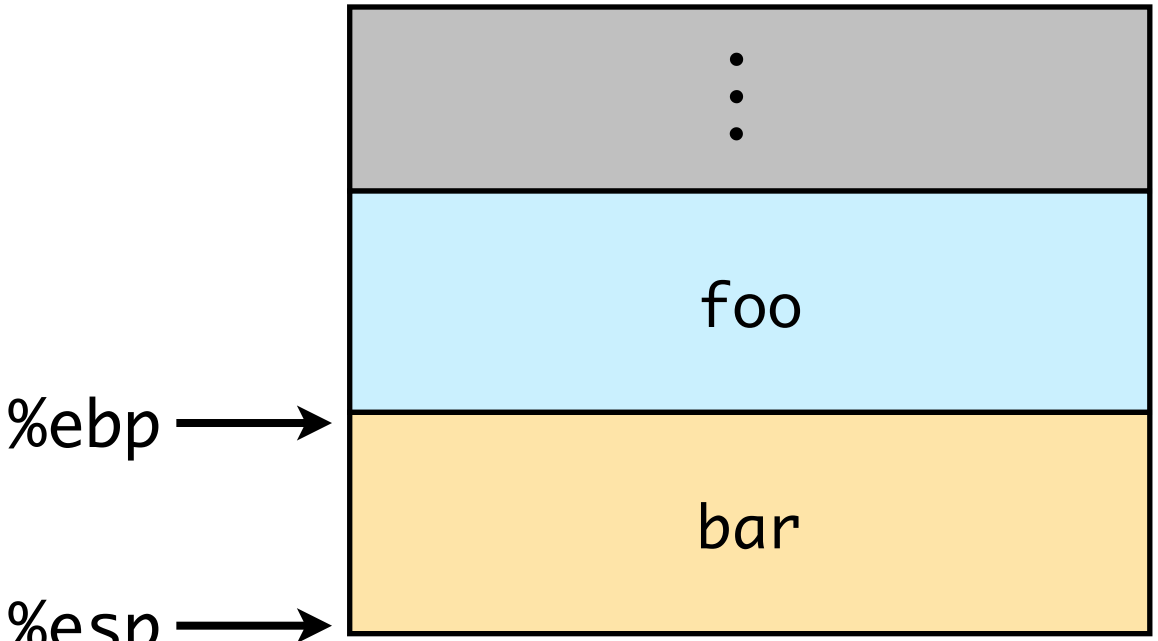
Stack frame example

```
void foo(...) {
}
```

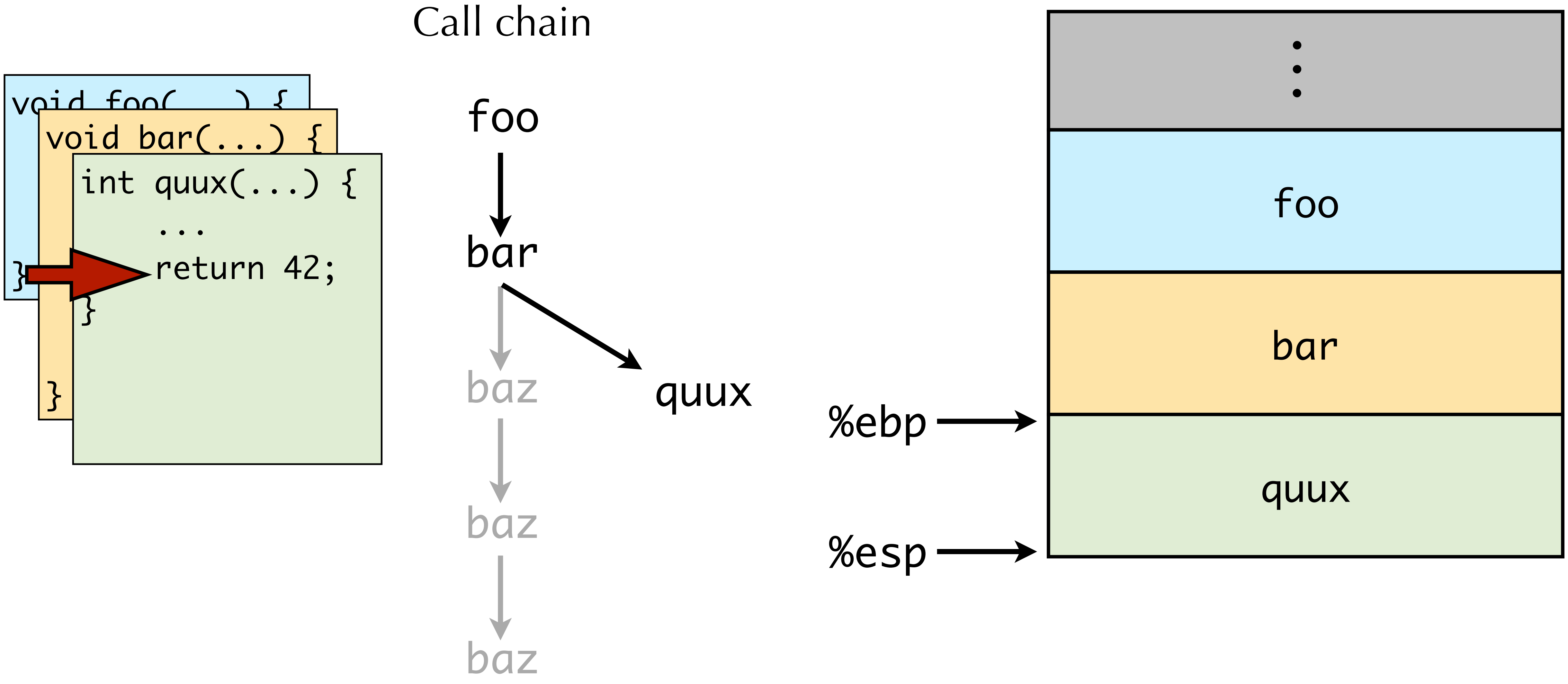
```
void bar(...) {
   int x, y;
    x = baz();
    ...
    y = quux();
    ...
}
```

Call chain





Stack frame example



```
void foo(...) {
}
```

```
void bar(...) {
}
```

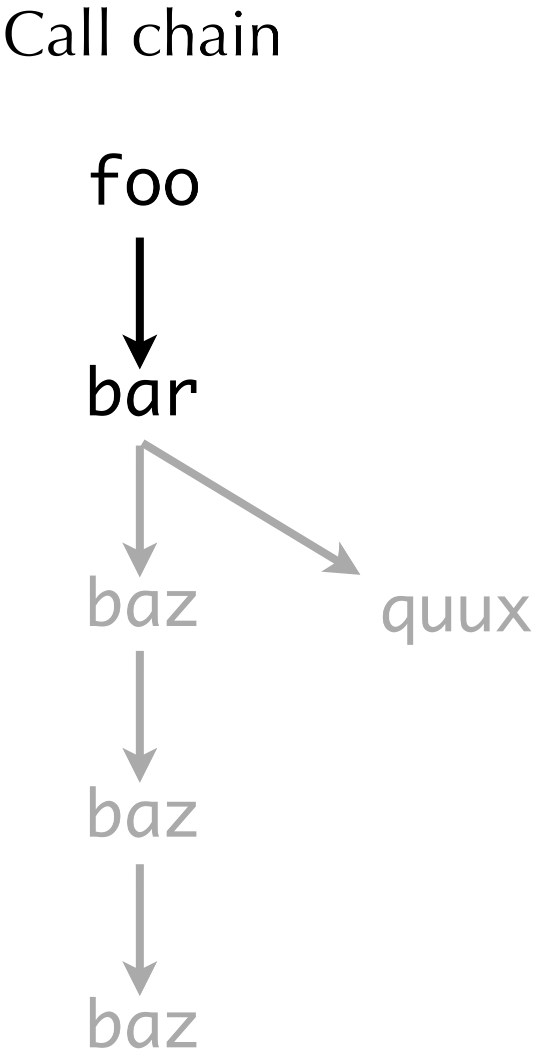
```
int quux(...) {
    ...
    return 42;
}
```

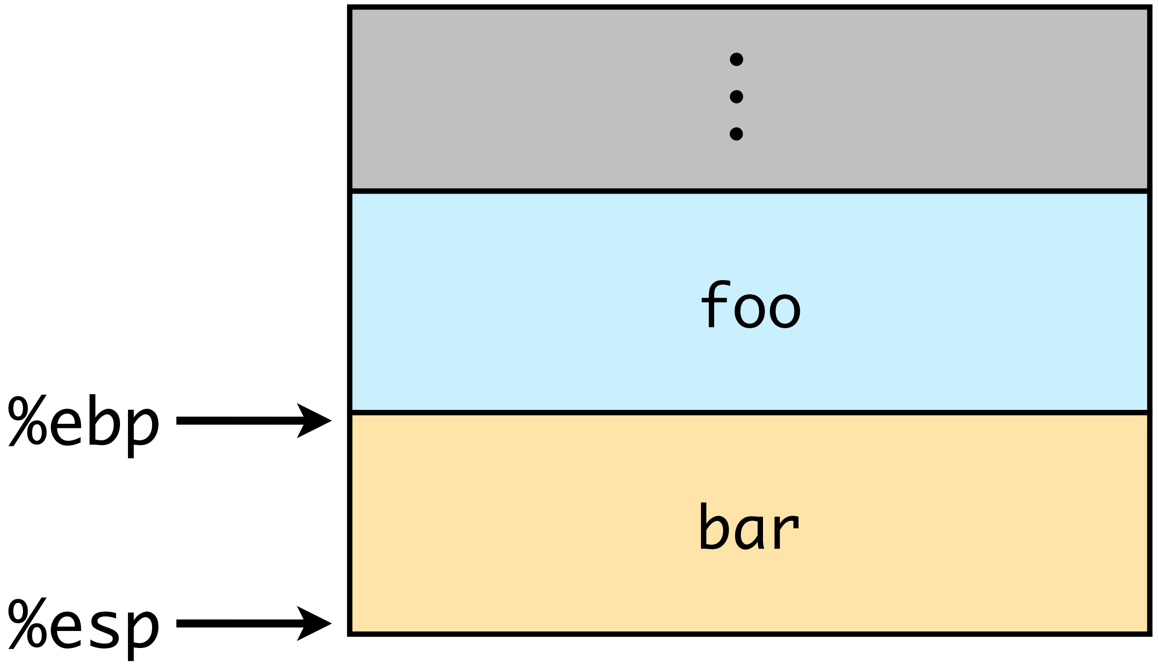
Stack frame example

```
void foo(...) {

}
```

```
void bar(...) {
   int x, y;
    x = baz();
    ...
    y = quux();
    ...
}
```

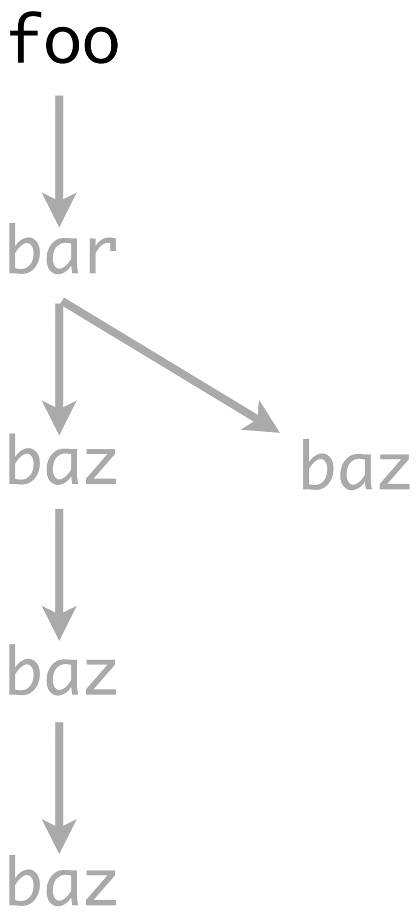


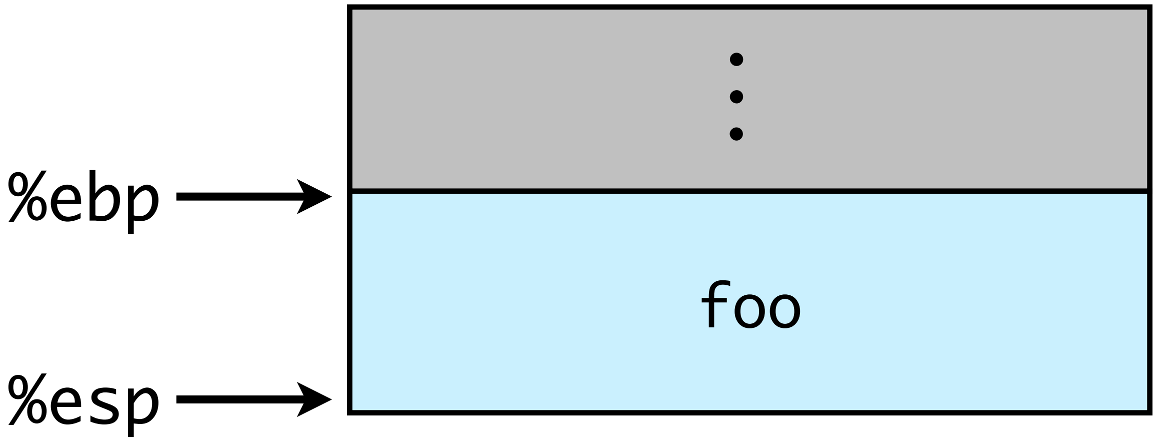


Stack frame example

```
void foo(...) {
     ...
     bar();
     ...
}
```

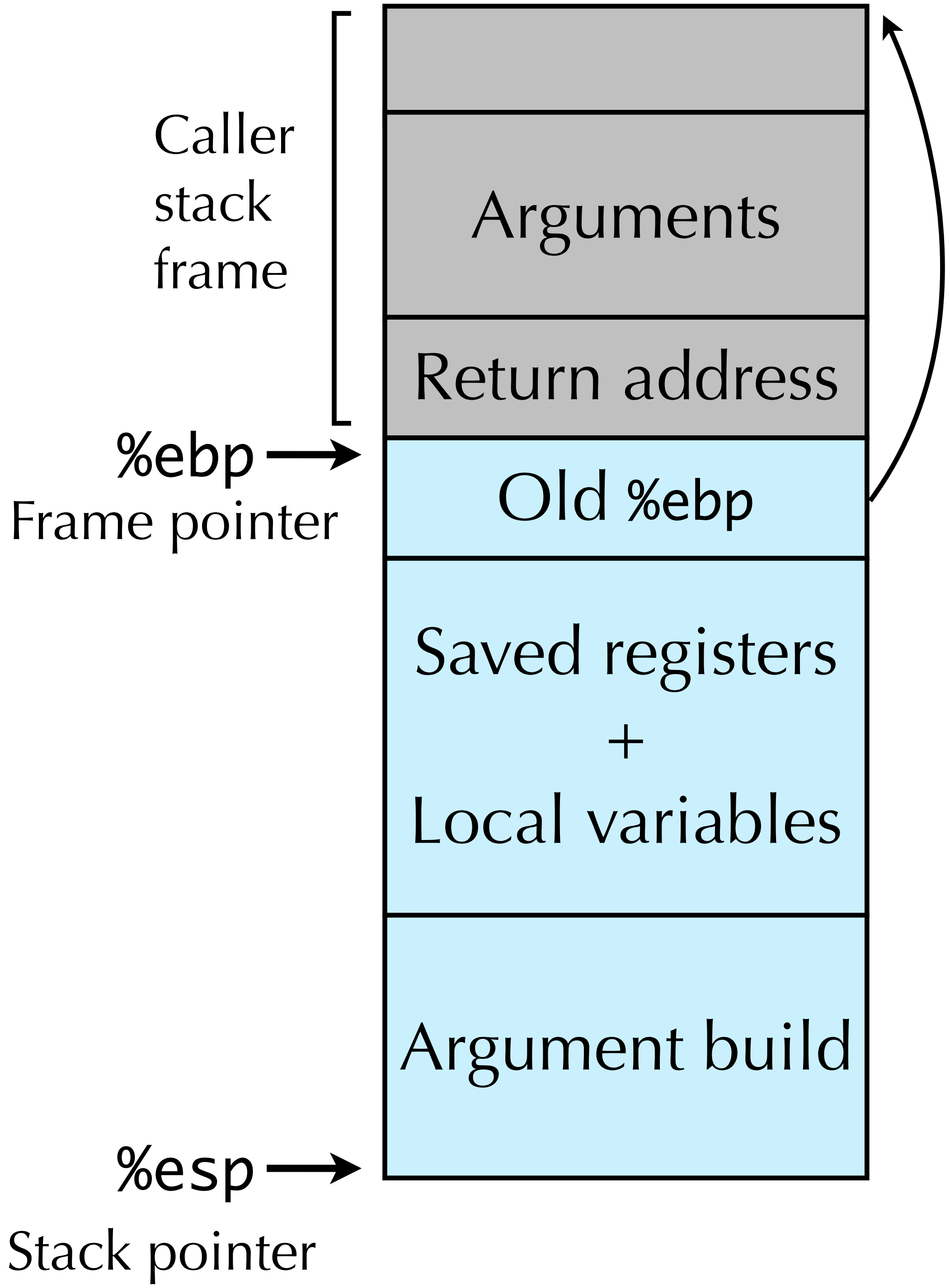
Call chain





x86/Linux stack frame

- The exact layout of a stack frame is a convention.
  - Depends on hardware, OS, and compiler used.
- x86/Linux stack frame contains:
  - Old value of `%ebp` (from previous frame)
  - Any saved registers (more later)
  - Local variables (if not kept in registers)
  - Arguments to function about to be called
- The **caller's** stack frame contains:
  - Return address – pushed by call instruction
  - Arguments for this function call



Swap revisited

```
/* Global vars */
int zip1 = 15213;
int zip2 = 91125;

void call_swap() {
  swap(&zip1, &zip2);
}
```

```
call_swap:
   ...
   pushl $zip2    # Push args
   pushl $zip1    #   on stack
   call swap      # Do the call
   ...
```

```
void swap(int *xp, int *yp) {
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

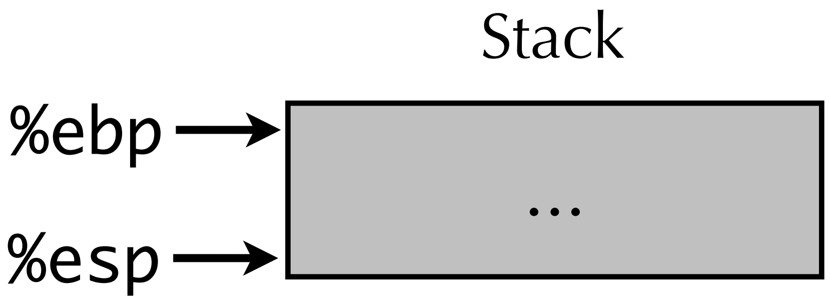
Swap revisited

```
/* Global vars */
int zip1 = 15213;
int zip2 = 91125;

void call_swap() {
  swap(&zip1, &zip2);
}
```

```
void swap(int *xp, int *yp) {
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
call_swap:
   ...
   pushl $zip2    # Push args
   pushl $zip1    #   on stack
   call swap      # Do the call
   ...
```



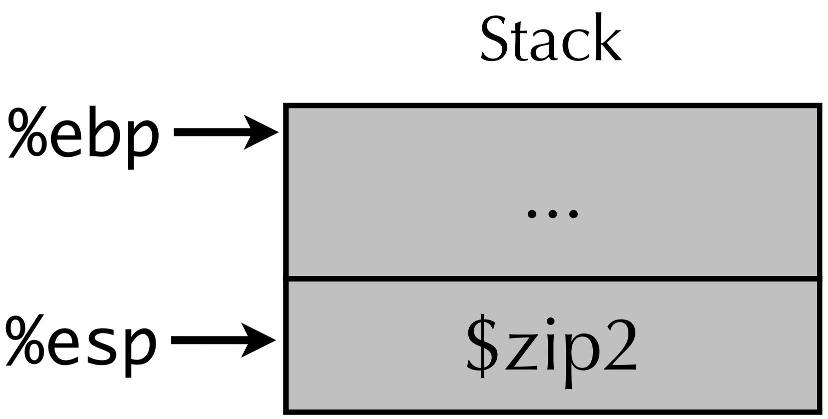
Swap revisited

```
/* Global vars */
int zip1 = 15213;
int zip2 = 91125;

void call_swap() {
  swap(&zip1, &zip2);
}
```

```
void swap(int *xp, int *yp) {
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
call_swap:
    ...
    pushl $zip2    # Push args
    pushl $zip1    #   on stack
    call swap      # Do the call
    ...
```



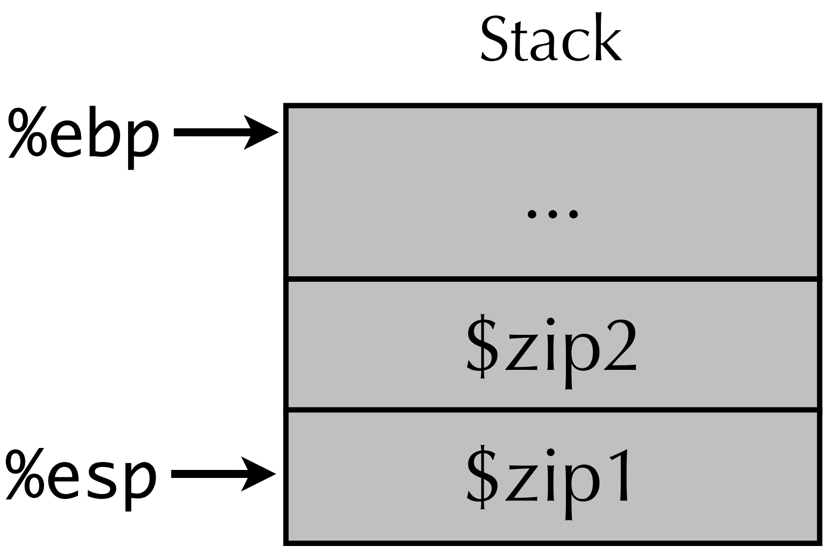
Swap revisited

```
/* Global vars */
int zip1 = 15213;
int zip2 = 91125;

void call_swap() {
  swap(&zip1, &zip2);
}
```

```
call_swap:
   ...
   pushl $zip2    # Push args
   pushl $zip1    #   on stack
   call swap      # Do the call
   ...
```

```
void swap(int *xp, int *yp) {
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```



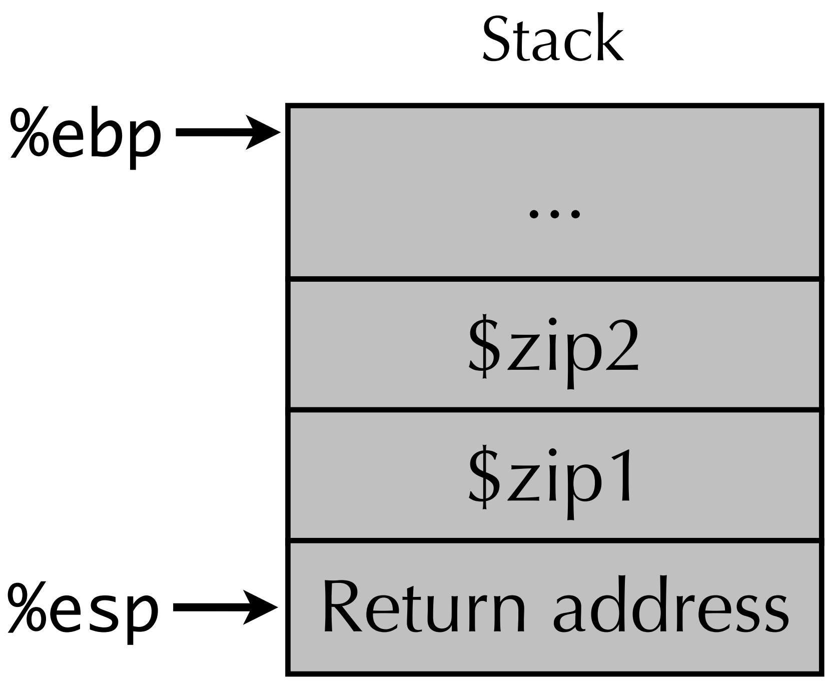
Swap revisited

```
/* Global vars */
int zip1 = 15213;
int zip2 = 91125;

void call_swap() {
  swap(&zip1, &zip2);
}
```

```
call_swap:
    ...
    pushl $zip2    # Push args
    pushl $zip1    #    on stack
    call swap      # Do the call
    ...
```

```
void swap(int *xp, int *yp) {
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```



Code for swap

```
void swap(int *xp, int *yp) {
  int t0 = *xp;
  int t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap:
  pushl %ebp
  movl %esp,%ebp
  pushl %ebx

  movl 12(%ebp),%ecx
  movl 8(%ebp),%edx
  movl (%ecx),%eax
  movl (%edx),%ebx
  movl %eax,(%edx)
  movl %ebx,(%ecx)

  movl -4(%ebp),%ebx
  movl %ebp,%esp
  popl %ebp
  ret
```

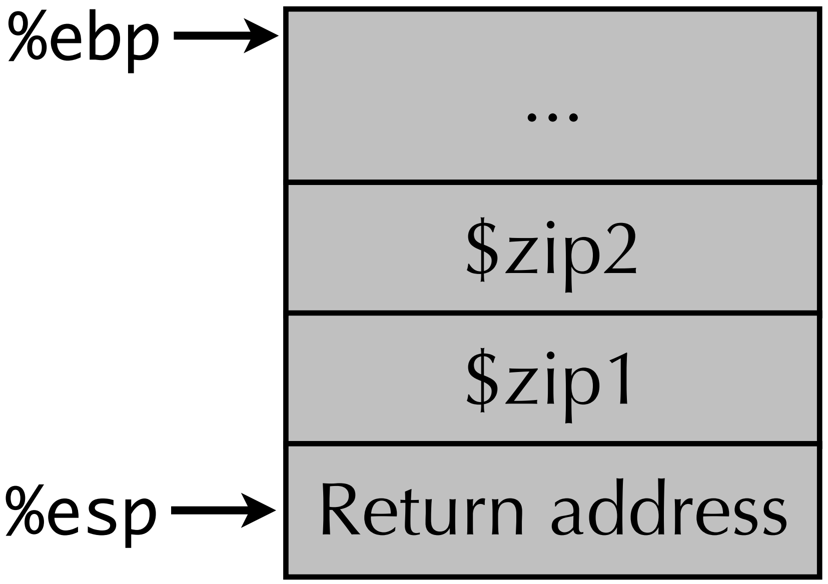
Set up

Body

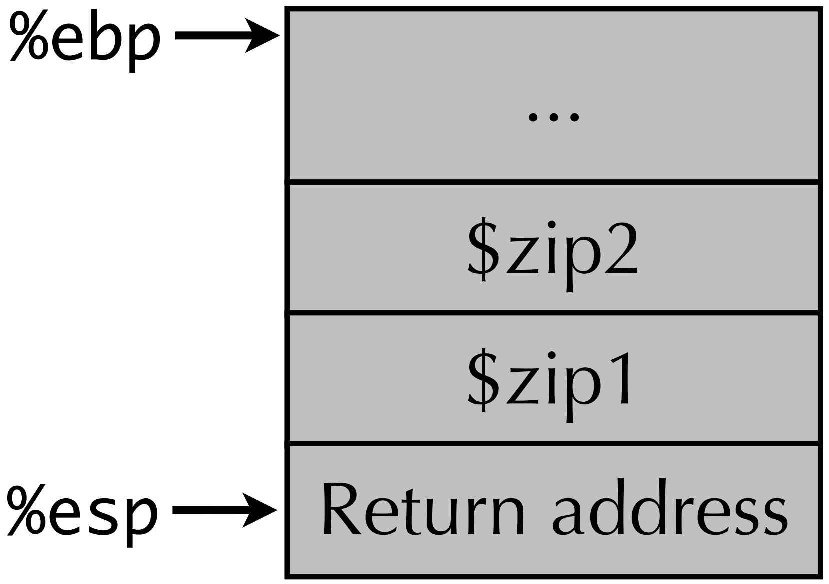
Finish

Swap setup

Stack entering swap



Resulting stack

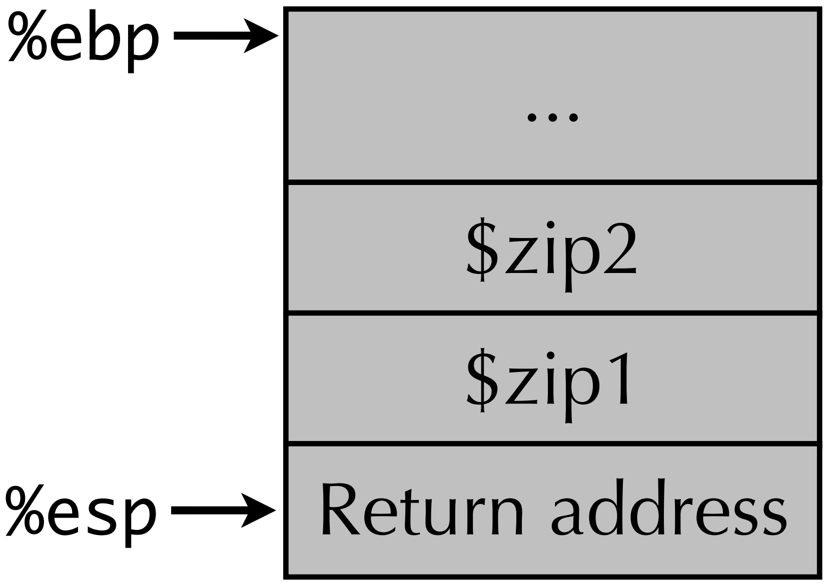


```
  pushl %ebp
  movl %esp,%ebp
  pushl %ebx
```

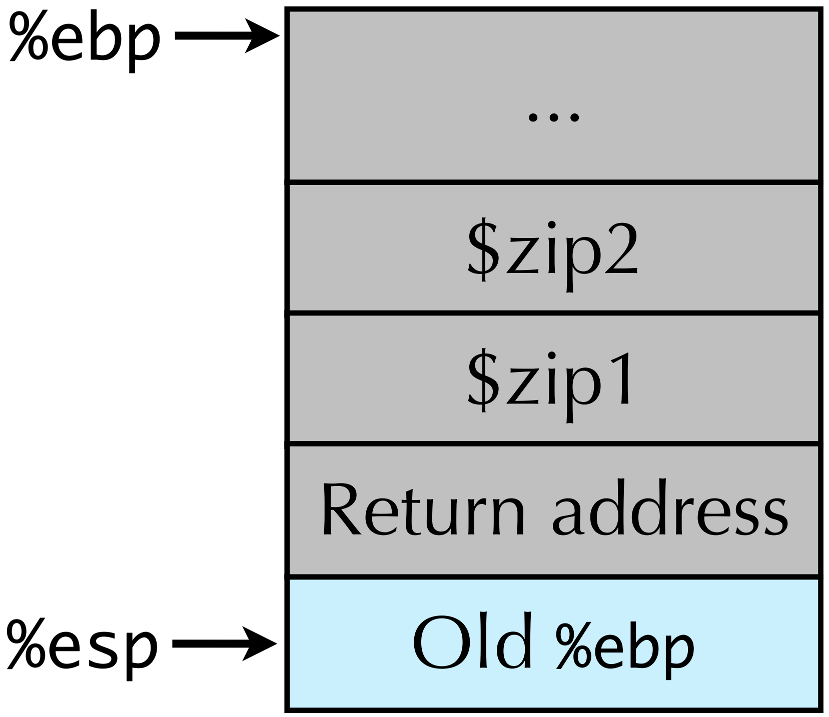
Set up

Swap setup

Stack entering swap



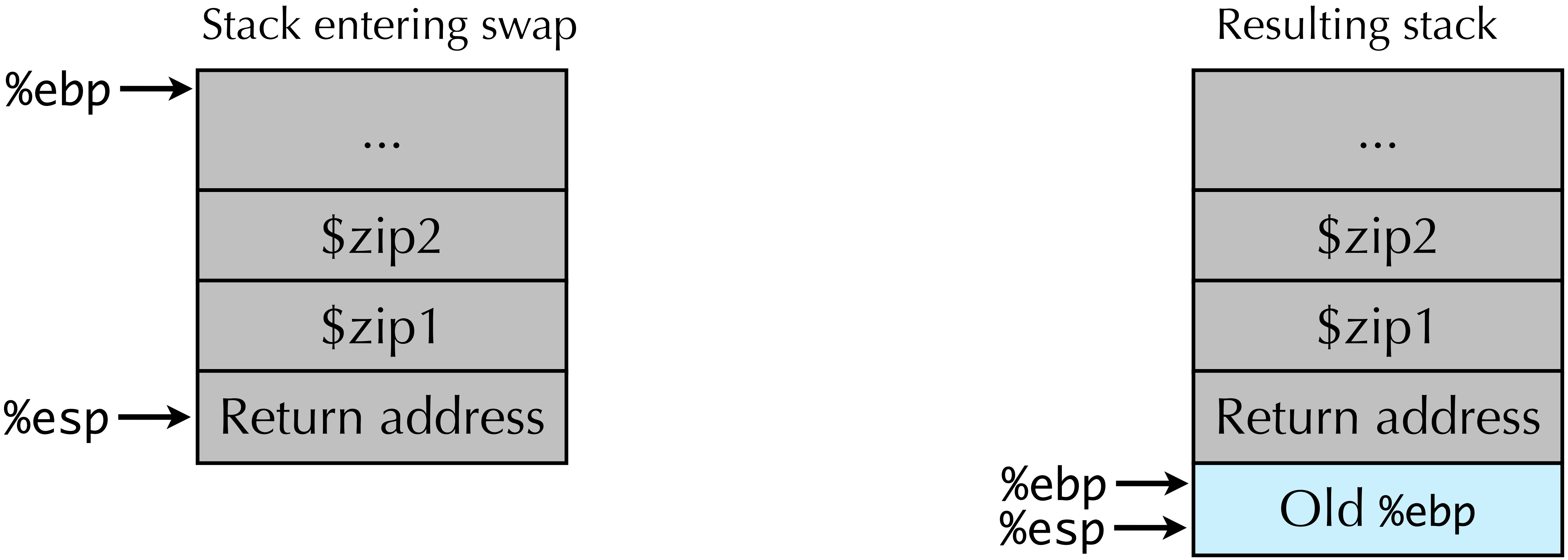
Resulting stack



```
    pushl %ebp
    movl %esp,%ebp
    pushl %ebx
```

Set up

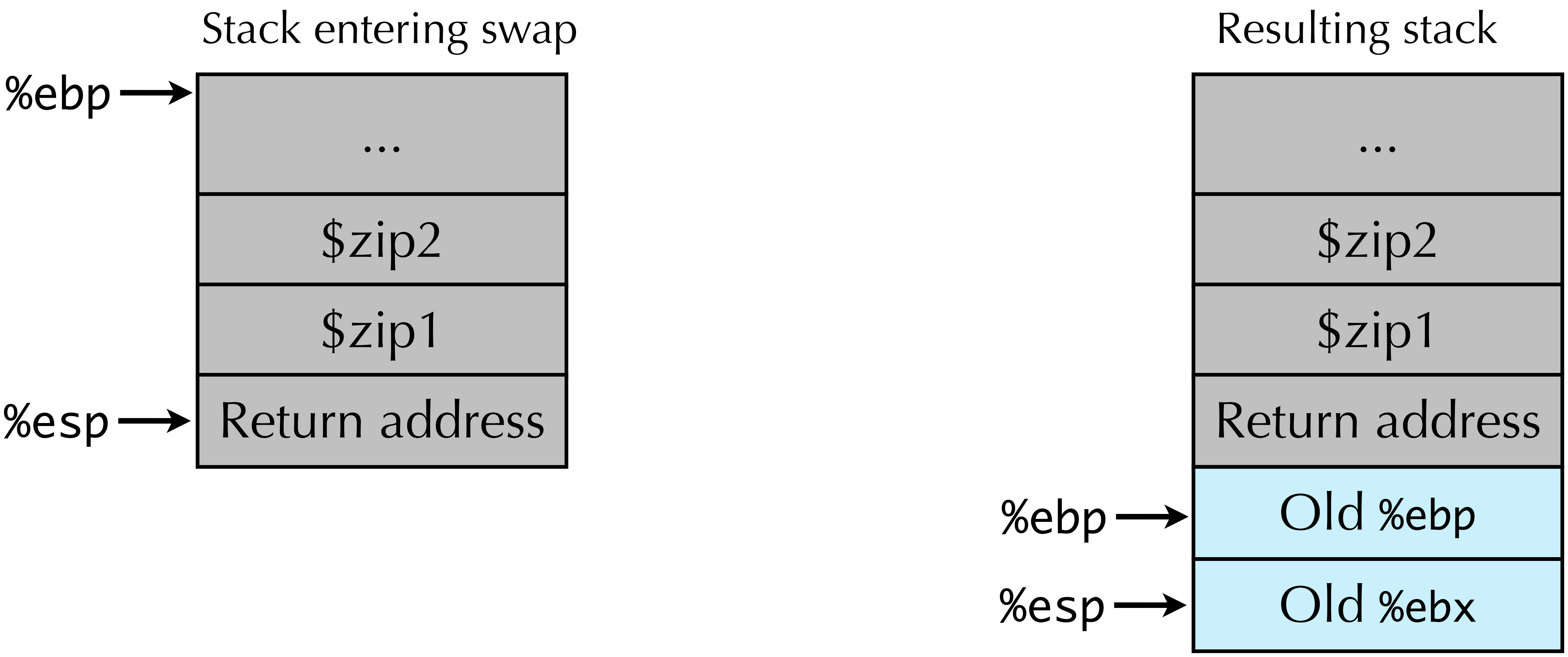
Swap setup



```
  pushl %ebp
  movl %esp,%ebp
  pushl %ebx
```

Set up

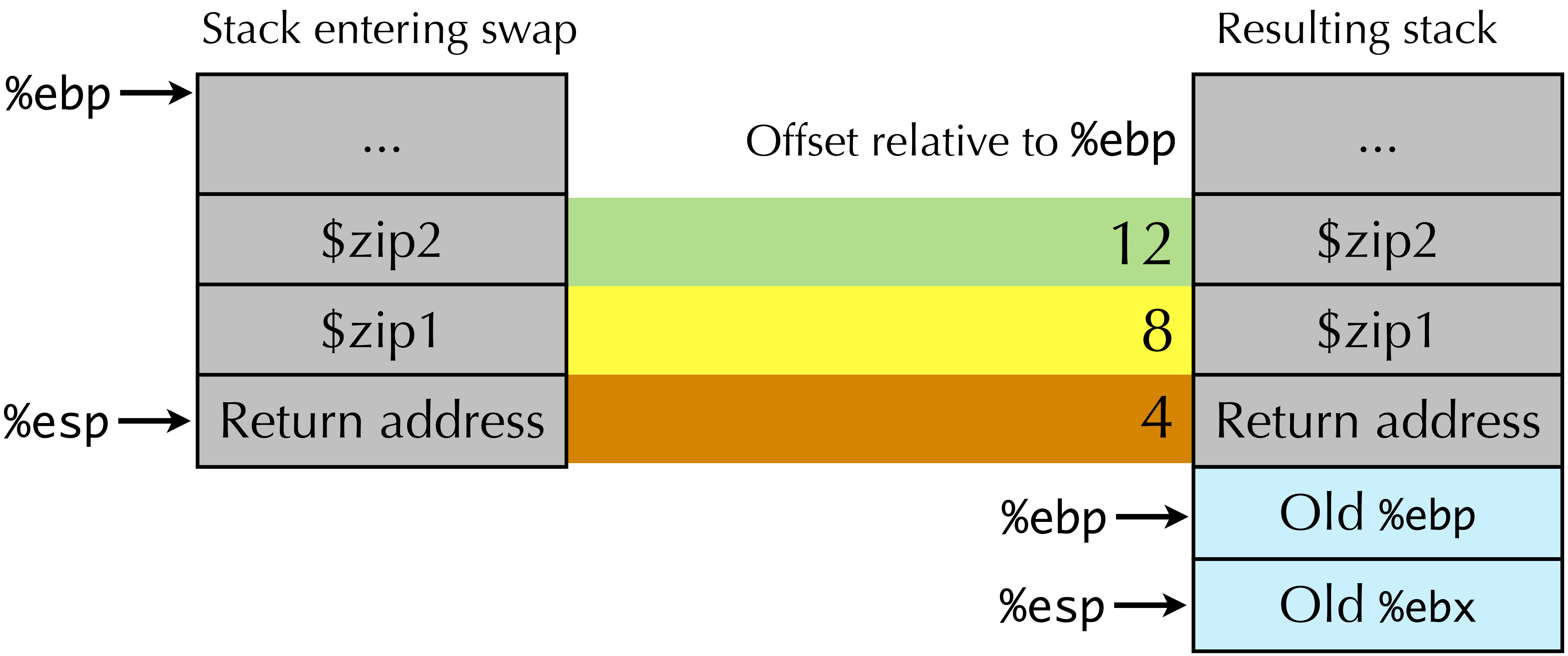
Swap setup



```
  pushl %ebp
  movl %esp,%ebp
  pushl %ebx
```

Set up

Swap body

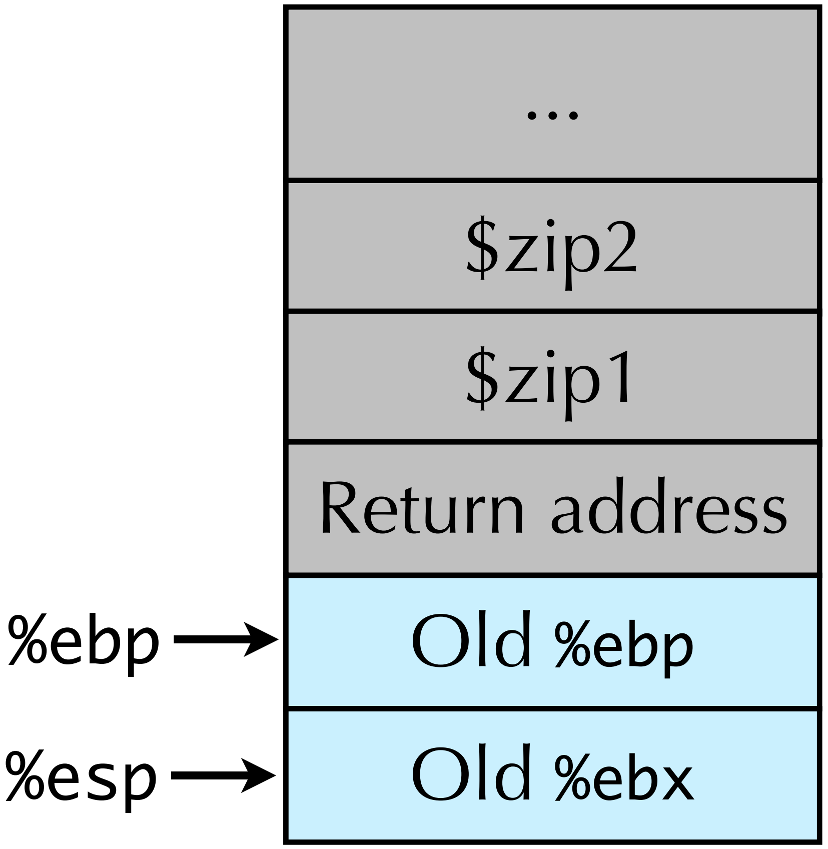


```
movl 12(%ebp),%ecx
movl 8(%ebp),%edx
movl (%ecx),%eax
movl (%edx),%ebx
movl %eax,(%edx)
movl %ebx,(%ecx)
```

Body

Swap finish

Stack at end swap body

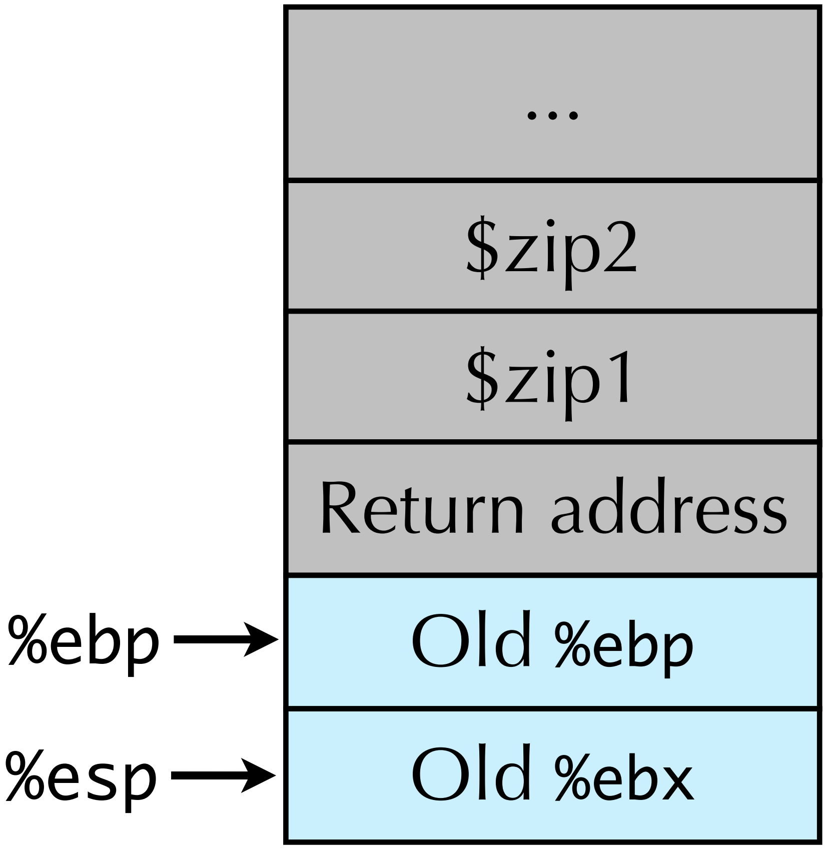


```
  movl -4(%ebp),%ebx
  movl %ebp,%esp
  popl %ebp
  ret
```

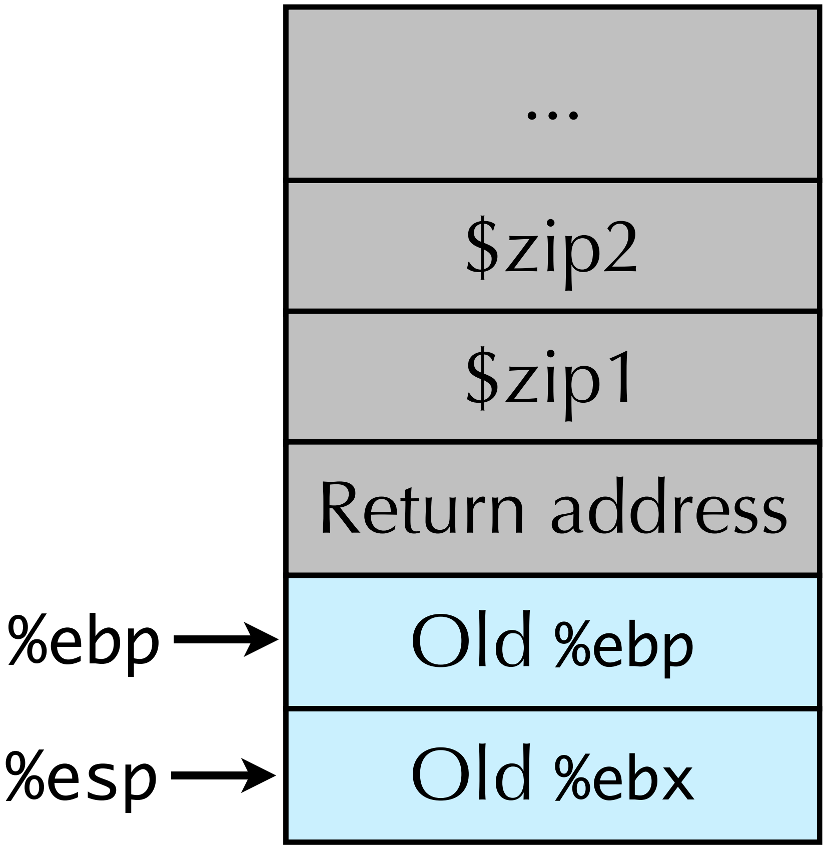
Finish

Swap finish

Stack at end swap body



Resulting stack

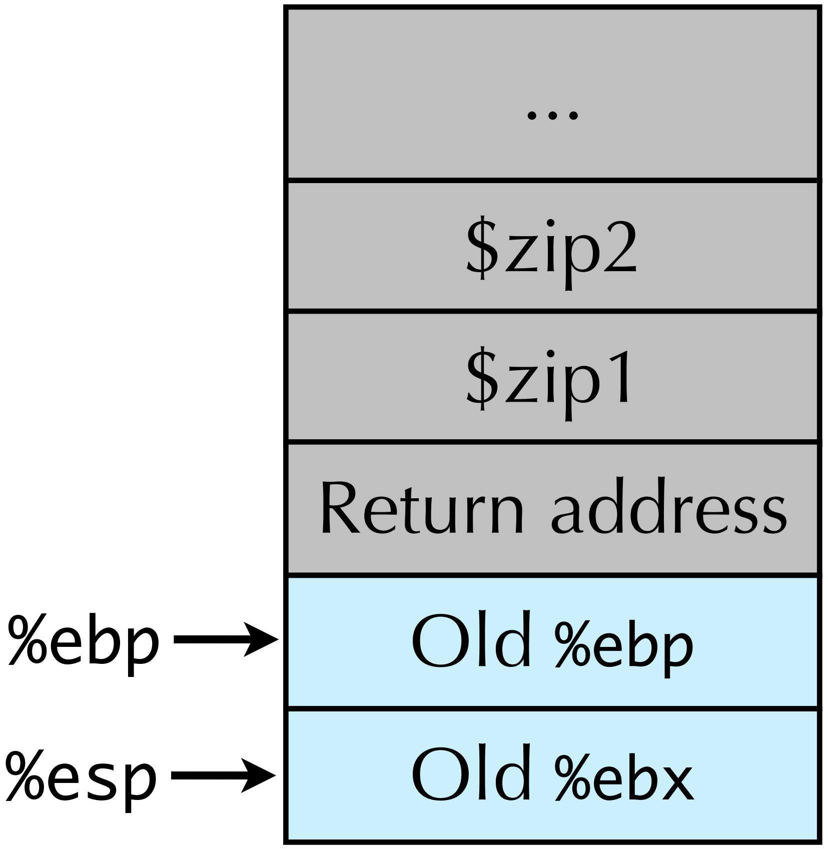


```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

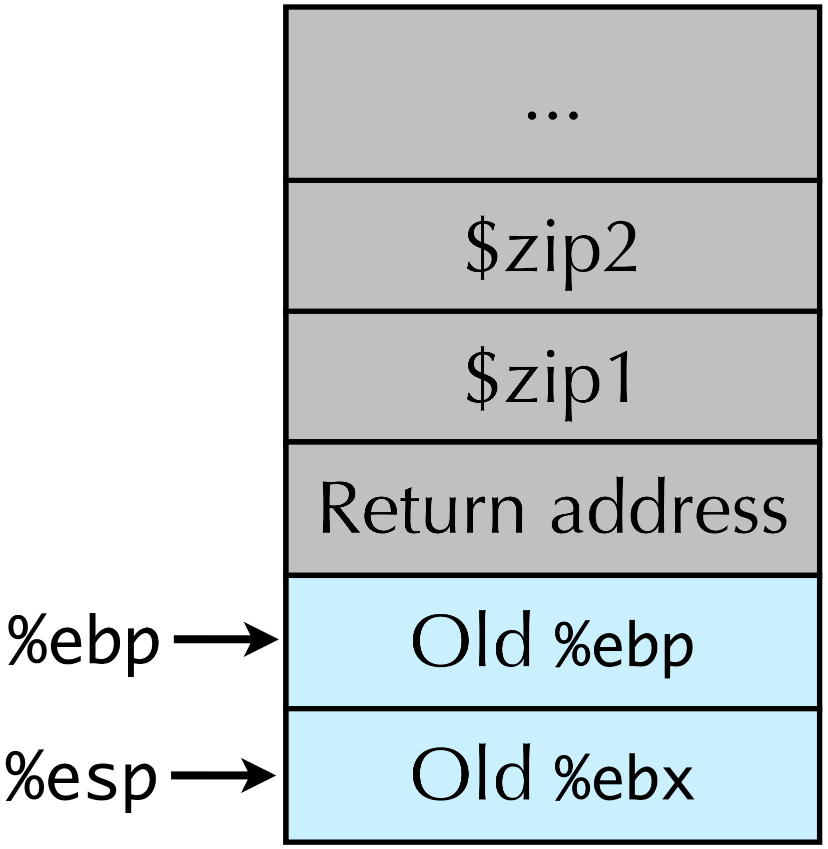
Finish

Swap finish

Stack at end swap body



Resulting stack

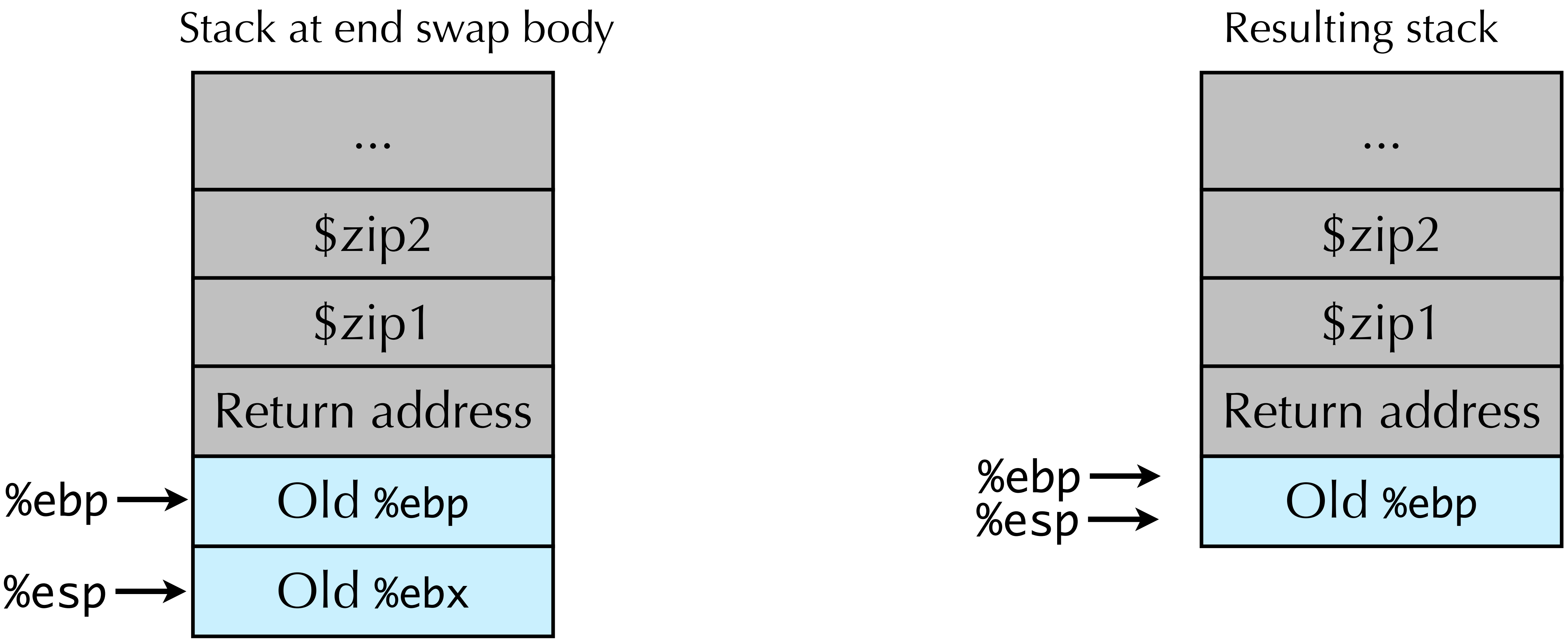


```
movl -4(%ebp),%ebx
movl %ebp,%esp
popl %ebp
ret
```

Finish

Restores old value of %ebx!

Swap finish

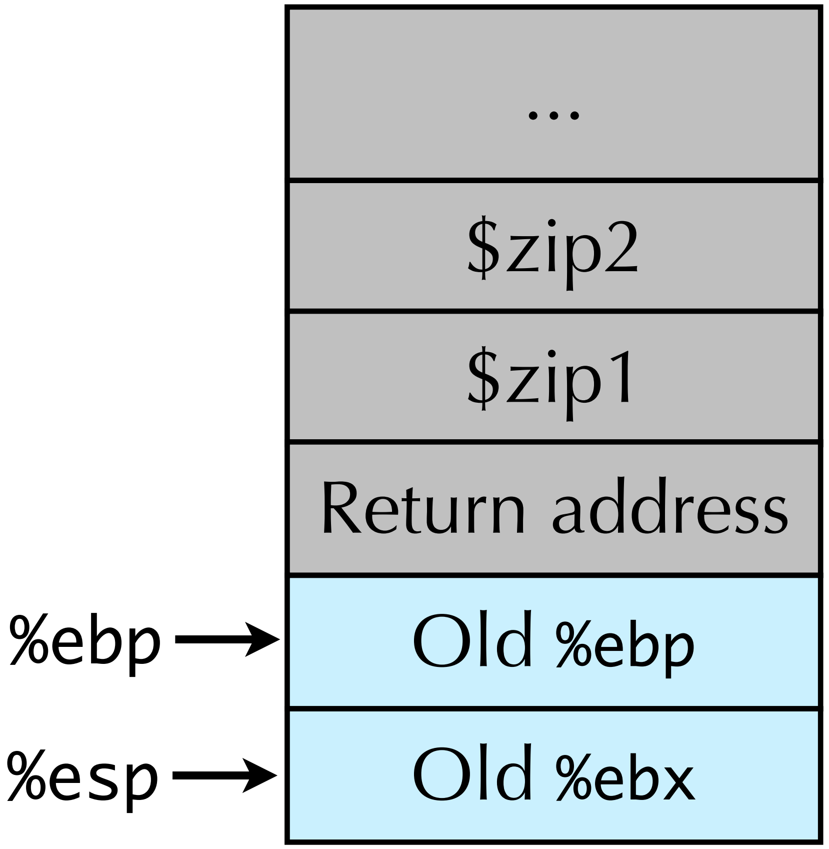


```
  movl -4(%ebp),%ebx
  movl %ebp,%esp
  popl %ebp
  ret
```

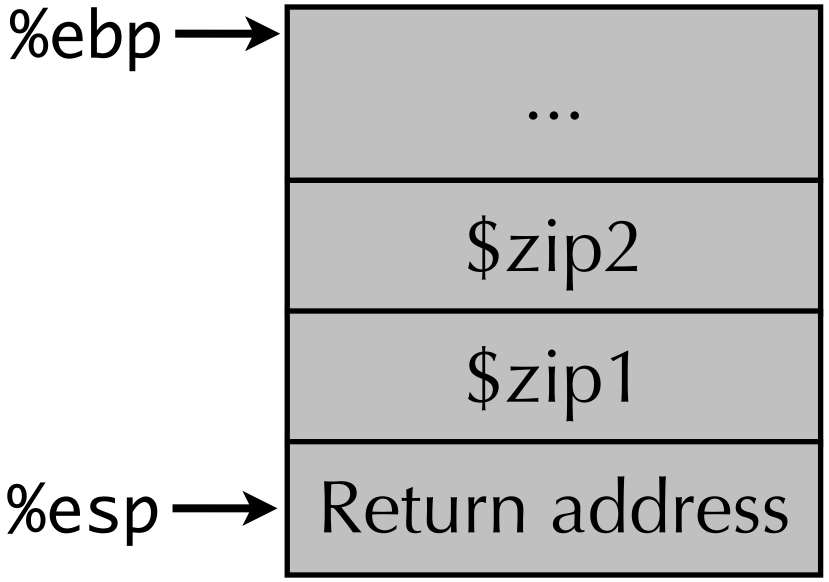
Finish

Swap finish

Stack at end swap body



Resulting stack

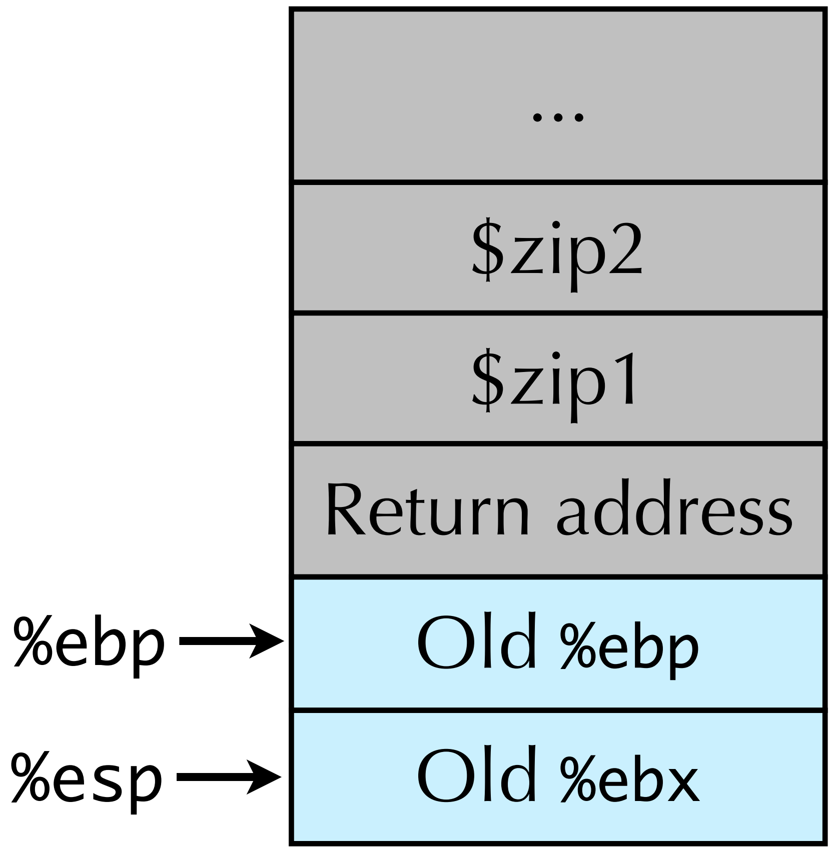


```
  movl -4(%ebp),%ebx
  movl %ebp,%esp
  popl %ebp
  ret
```

Finish

Swap finish

Stack at end swap body



...

$zip2

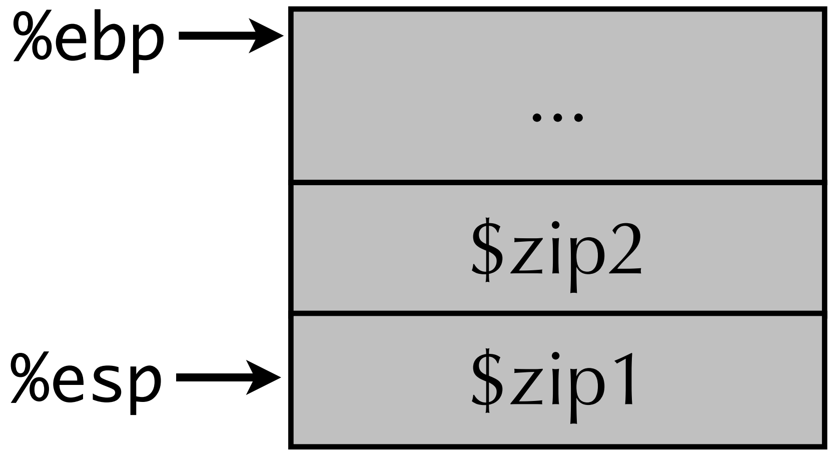
$zip1

Return address

%ebp → Old %ebp

%esp → Old %ebx

Resulting stack



%ebp → ...

$zip2

%esp → $zip1

```
  movl -4(%ebp),%ebx
  movl %ebp,%esp
  popl %ebp
  ret
```

Finish

`leave` instruction

- Actual disassembly of swap

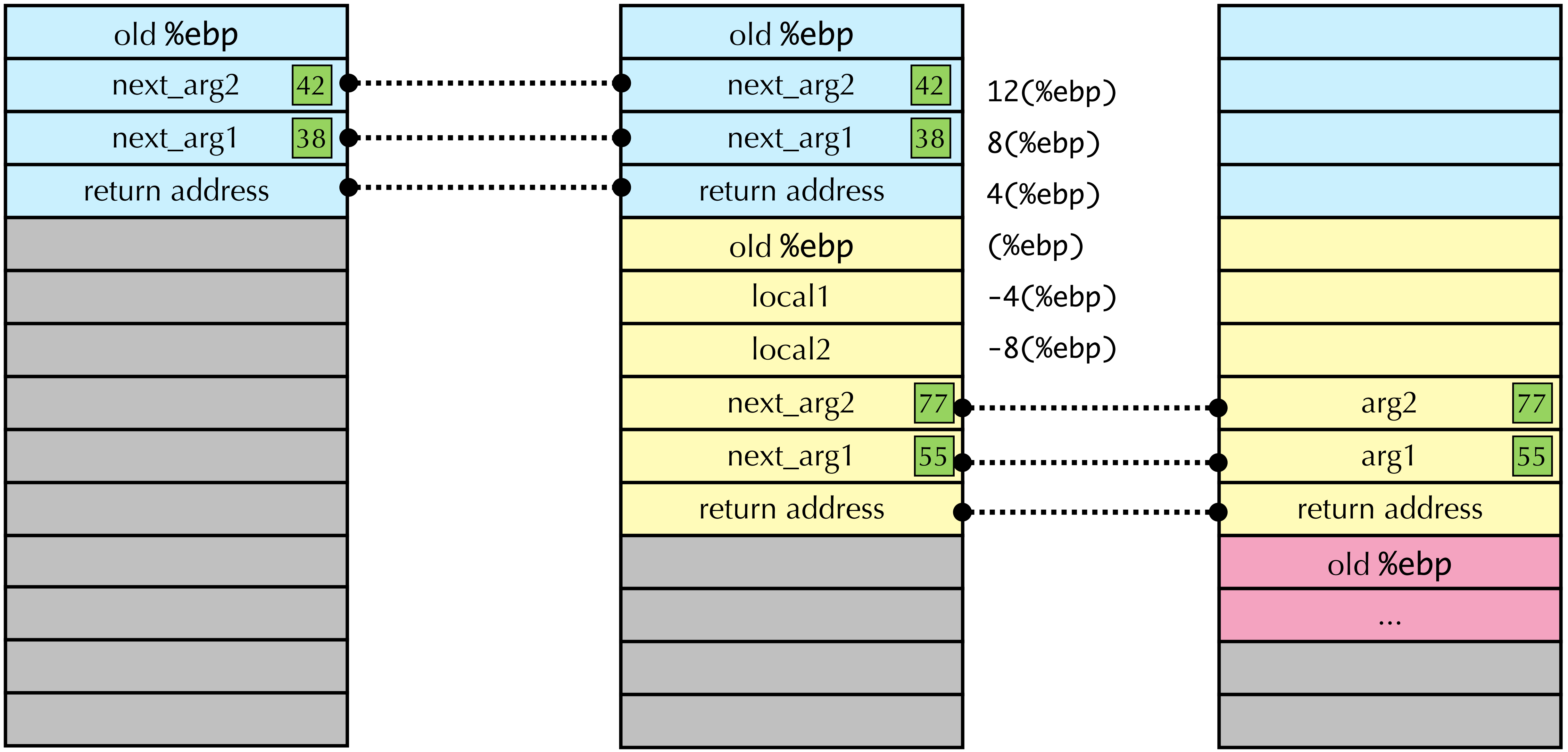
```
080483a4 <swap>:
 80483a4:    55          push   %ebp
 80483a5:    89 e5       mov    %esp,%ebp
 80483a7:    53          push   %ebx
 80483a8:    8b 55 08    mov    0x8(%ebp),%edx
 80483ab:    8b 4d 0c    mov    0xc(%ebp),%ecx
 80483ae:    8b 1a       mov    (%edx),%ebx
 80483b0:    8b 01       mov    (%ecx),%eax
 80483b2:    89 02       mov    %eax,(%edx)
 80483b4:    89 19       mov    %ebx,(%ecx)
 80483b6:    5b          pop    %ebx
 80483b7:    c9          leave
 80483b8:    c3          ret
```

```
  movl -4(%ebp),%ebx
  movl %ebp,%esp
  popl %ebp
  ret
```

- `leave` prepares the stack for returning
- `leave` is equivalent to

```
movl %ebp,%esp
popl %ebp
```

Stack frame cheat sheet



```
foo() {
  bar(38,42);
}
```

```
bar(int arg1, int arg2) {
  int local1, local2;
  ...
  baz(55,77);
}
```

```
baz(int arg1, int arg2) {
  ...
}
```

Return values

- By convention, the compiler leaves return value in `%eax`

```c
int absdiff(int x, int y)
{
    int result;
    if (x > y) {
        result = x-y;
    } else {
        result = y-x;
    }
    return result;
}
```

```
absdiff:
    pushl   %ebp
    movl    %esp, %ebp
    movl    8(%ebp), %edx
    movl    12(%ebp), %eax
    cmpl    %eax, %edx
    jle     .L7
    subl    %eax, %edx
    movl    %edx, %eax
.L8:
    leave
    ret
.L7:
    subl    %edx, %eax
    jmp     .L8
```

Return values

- By convention, the compiler leaves return value in %eax

```
int logical(int x, int y)
{
  int t1 = x^y;
  int t2 = t1 >> 17;
  int mask = (1<<13) - 7;
  int rval = t2 & mask;
  return rval;
}
```

```
logical:
     pushl %ebp
     movl %esp,%ebp

     movl 8(%ebp),%eax
     xorl 12(%ebp),%eax
     sarl $17,%eax
     andl $8185,%eax

     movl %ebp,%esp
     popl %ebp
     ret
```

- Works fine for 32-bit values
- For floating point values: other registers used
- For structs: return value is left on stack, caller must copy data elsewhere
    - Why must caller copy the data?

Register saving conventions

- When procedure `foo()` calls `bar()`
  `foo()` is the **caller**, `bar()` is the **callee**
- Suppose `bar()` needs to modify some registers when it run
  - But `foo()` is using some of the same registers for its own purposes

```
foo:
    ...
    movl $2138, %edx
    call bar
    addl %edx, %eax
    ...
    ret
```

```
bar:
    ...
    movl 8(%ebp), %edx
    addl $14850, %edx
    ...
    ret
```

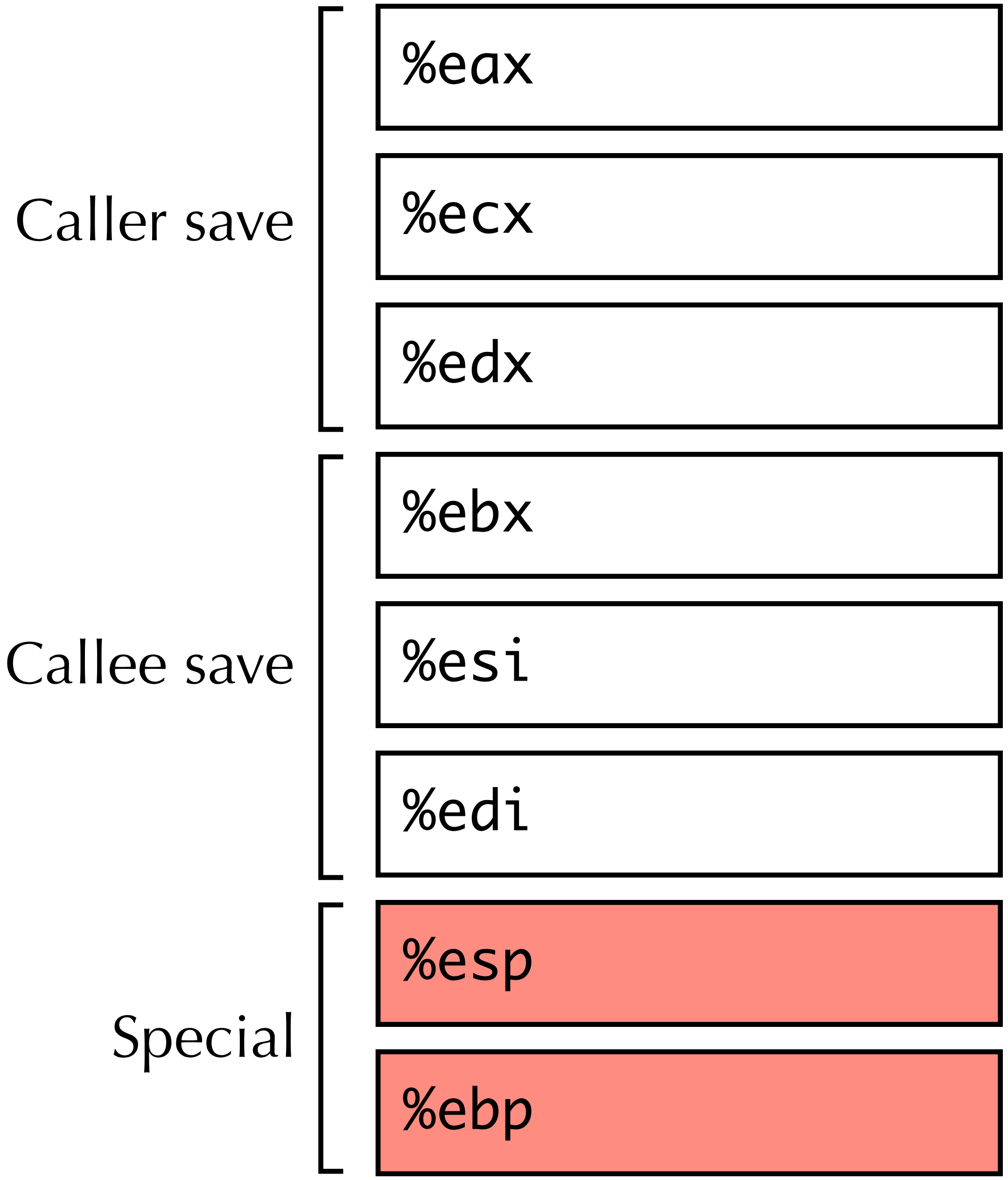
- Contents of `%edx` clobbered by `bar()`!

Register saving conventions

- Need to save some of the clobbered registers on the stack.
- Who saves the registers? The caller? The callee?
  - **Caller save:** caller saves registers in its stack frame before call
  - **Callee save:** callee saves registers it will clobber in its stack frame, and restores them before return
- What are advantages and disadvantages of each?
  - Caller save: caller must be conservative and save everything, since it doesn't know what callee will clobber.
  - Callee save: callee must be conservative and save everything, since it doesn't know what caller wants preserved.

x86/Linux register conventions

- x86/Linux uses a mixture of caller-save and callee-save!
- Three registers managed as caller-save
    - %eax, %ecx, %edx
- Three registers managed as callee-save
    - %ebx, %esi, %edi
- Frame and stack registers managed specially
    - %esp, %ebp



Procedures summary

- The stack makes function calls work!
    - Private storage for each invocation of a procedure call
    - Multiple function invocations don't clobber each other
    - Addressing of local variables and arguments is relative to stack frame `%ebp`
    - Recursion works too
    - Requires that procedures return in order of invocations (nesting is preserved)
- Procedures implemented using a combination of **hardware support** plus **software conventions**
    - Hardware support: `call`, `ret`, `leave`, `pushl`, `popl`
    - Software conventions: Register saving conventions, managing `%esp` and `%ebp`, managing layout of stack
        - Software conventions defined by the OS and the compiler.
        - No guarantee it will be the same on a different software platform.

Today

- Procedures
  - The stack
  - Stack frames
  - Leave
  - Register conventions
- x86_64

x86-64

- x86 (aka IA32) instruction set defined in about 1985
  - Has been dominant instruction format for many years
- x86-64 extends x86 to 64 bits
  - Originally developed by AMD (Advanced Micro Devices), Intel's competitor
    - Intel originally introduced Itanium (aka IA-64), a 64-bit ISA that was not backwards compatible. Not commercially successful.
  - Also referred to as AMD64, Intel64, and x64
- Currently in transition from 32 bits to 64 bits
  - Most new machines you buy will be 64 bits

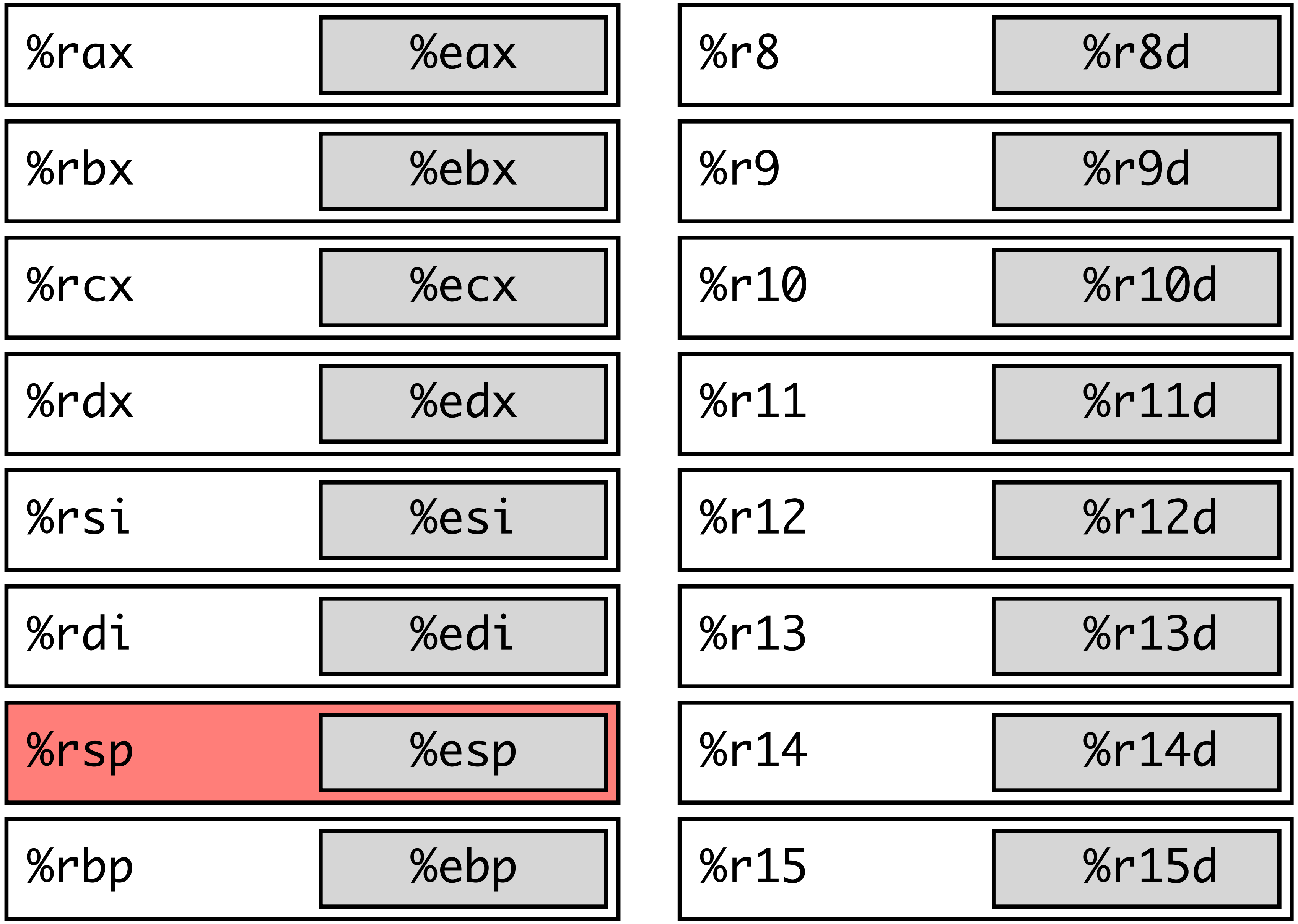
Differences between x86 and x86-64

- Data types

C declaration	Intel data type	Assembly code suffix	32-bit	64-bit
`char`	Byte	b	1	1
`short int`	Word	w	2	2
`int`	Double word	l	4	4
`long int`	Quad word	q	4	8
`long long int`	Quad word	q	8	8
`char *`	Quad word	q	4	8
`float`	Single precision	s	4	4
`double`	Double precision	d	8	8
`long double`	Extended precision	t	10/12	10/16

Differences between x86 and x86-64

- Registers
  - x86 has 8 registers
  - x86-64 has 16 registers
    - Each is 64 bits
    - Extend existing registers and add new ones
    - Make %ebp/%rbp general purpose



%rax	%eax	%r8	%r8d
%rbx	%ebx	%r9	%r9d
%rcx	%ecx	%r10	%r10d
%rdx	%edx	%r11	%r11d
%rsi	%esi	%r12	%r12d
%rdi	%edi	%r13	%r13d
%rsp	%esp	%r14	%r14d
%rbp	%ebp	%r15	%r15d

x86-64 instructions

- Long word `l` (4 Bytes) ↔ Quad word `q` (8 Bytes)
- New instructions:
  - `movl` → `movq`   `addl` → `addq`   `sall` → `salq` etc.
- 32-bit instructions generate 32-bit results
  - Set higher order bits of destination register to 0
  - E.g., `addl`
- `gcc` makes more efficient use of x86-64 instructions
  - E.g., more extensive use of conditional move operation
  - `gcc -m32` will produce 32-bit code

Procedure calls

- Up to six (integral) arguments can be passed in registers
  - Instead of on stack
  - `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, `%r9`
- Some procedures do not need a stack frame at all!
  - Few arguments,
    few local variables,
    no local arrays or structs,
    no need to take address of local variables,
    no need to pass arguments on stack to another function,
    ⇒ no need for stack frame
  - Can result in very low overhead for some function calls!

Stack frames

- No frame pointer!
  - x86_64 makes `%rbp/%ebp` general purpose
- Instead, procedures subtract a constant from stack pointer (`%rsp`) at beginning, add constant at procedure return
  - Accesses all stack elements via offsets from `%rsp`
  - No need for `%rbp`
- Stack frame size is constant during procedure call
  - Stack pointer does not fluctuate as in IA32
    - i.e., through pushes and pops

Next week

- Structures and arrays
- Buffer overruns

- Assignment 2 due Thursday