CS162

Discussion 0

C, x86

01/20/23

Staff

Announcements

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
		Homework 0 Release				
	Project 0 Release		Homework 0 Due	Homework 1 Release	Early Drop Deadline	Group Formation Form Due
		Project 0 Due	Project 1 Release			

Important Policies

Contact staff through Ed.

- Use cs162@eecs.berkeley.edu to reach head TA and professors if Ed is insufficient.
- Only use individual emails for private matters.

3 midterms (check website for date and time).

- Exam conflict forms will be released ~3 weeks prior to exams.

Slip day policy:

- We provide 4 HW slip days and 5 Project slip days which are meant for emergencies
  - Extension form available for DSP and those with extenuating circumstances
  - Form is also accessible from the course website

Discussions 0 and 1 are **optional**.

- Feel free to attend different TAs’ sections to find a teaching style that suits you best.
- Attendance for discussion 2 and onward are **mandatory**. Preference forms will be available soon.

Follow office hours policies of filling out a **detailed ticket** and being present in the OH room (Soda 347) when your ticket is taken.

- Almost all OH will be **in person**. There are a couple of online OHs meant specifically for those who absolutely cannot make it in person.
- Take advantage of empty office hours by **starting assignments early**.

Post your questions on Ed in the appropriate threads.

- No private debugging posts allowed.

C

Types

C is **statically typed** (i.e. types are known at compile time).

C is **weakly typed** (i.e. can cast between any types).

Primitive types are `char`, `short`, `int`, `long`, `float`.

Arrays are contiguous pieces of memory of a homogenous type

- Denoted with `[]` (e.g. `int []` for an array of integers).
- **String** is an array of `chars` with last element being `null`

Build compound types using `structs`

- Also contiguous in memory

Pointers are references that hold the address of an object in memory.

- Essentially just unsigned integers.
- Prefix a pointer with * to return the value at the memory address that the pointer is holding.
- Prefix a variable with & to return the memory address of the variable.

Little Endian	+3	+2	+1	+0	
0x7FFFFFFC	00	00	00	08	int a = 8
0x7FFFFFF8	FF	FF	FF	FF	int b = -1
0x7FFFFFF4	7F	FF	FF	FC	int *p = &a
0x7FFFFFF0	27	CE	00	'O'	27, CE are garbage
0x7FFFFFEC	'T'	'N'	'I'	'P'	char s[] = "PINTO"

0x7FFFFFE8	00	00	00	02	struct point {
					  int x;
					  int y;
					};
					
					struct point pt = {16, 2}

0x7FFFFFE4	00	00	00	10	

Memory

Typical C program is divided into five segments.

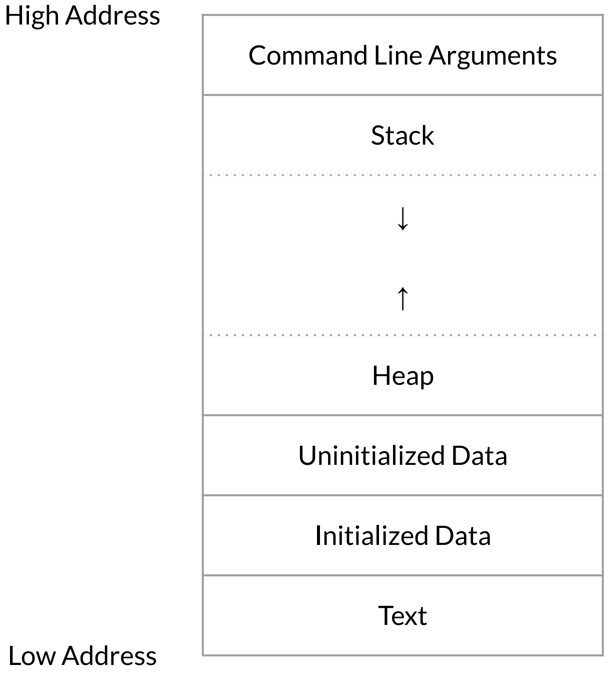
- **Text** contains machine code of the compiled program.
- **(Un)initialized data** contains (un)initialized global/static memory.
- **Heap** contains dynamically allocated memory.
- **Stack** contains local variables and arguments.
- Initialized strings and global constants may be stored in read-only segments (.rodata).

Think of memory as a giant array with elements of one byte.

- Memory addresses = indices of array.

Heap memory needs to be explicitly managed by the user.

- Allocate memory using `malloc`, `calloc`, `realloc` which return a pointer to a chunk of memory.
- Release memory using `free`.



High Address

Command Line Arguments

Stack

↓

↑

Heap

Uninitialized Data

Initialized Data

Text

Low Address

GNU Debugger (GDB)

Need to learn how to use it for 162 even if you skidded by 61C without it.

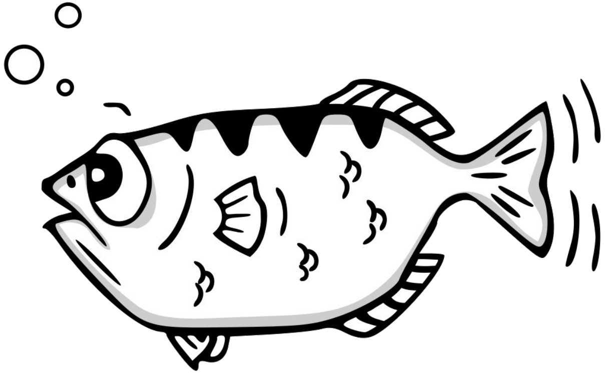
- Staff will not help during OH unless you are able to use GDB.

General workflow of using GDB.

1. Compile program using `-g` flag.
2. Start GDB using `gdb <executable name>`.
3. Set breakpoints using `break <line number>`. Can also break at functions using `break <function name>`.
4. Run program with run. If the program takes in arguments, pass in those after `run` (i.e. `run arg1 arg2 …`).
5. Once breakpoint is hit, examine variables using `print`. Other commands like `display`, `watch`, and `set` are also useful.

Use GDB frequently to become familiar with the commands.

Check out GDB manual for more details.



Concept Check

1. Consider a valid double pointer `char** dbl_char` in a 32-bit system. What is returned by `sizeof(*dbl_char)`?

2. Consider strings `char* a = "162 is the best"` and `char b[] = "162 is the best"`. Are a and b different?

3. Suppose you have an integer array `int nums[3] = {152, 161, 162}`. What are the differences between `nums`, `&nums`, and `&nums[0]`?

Concept Check

1. **Consider a valid double pointer `char** dbl_char` in a 32-bit system. What is returned by `sizeof(*dbl_char)`?**

   Dereferencing a double pointer gives a single pointer. 32-bit systems have 32-bit = 4 byte memory addresses.

2. Consider strings `char* a = "162 is the best"` and `char b[] = "162 is the best"`. Are a and b different?

3. Suppose you have an integer array `int nums[3] = {152, 161, 162}`. What are the differences between `nums`, `&nums`, and `&nums[0]`?

Concept Check

1. Consider a valid double pointer `char** dbl_char` in a 32-bit system. What is returned by `sizeof(*dbl_char)`?

   Dereferencing a double pointer gives a single pointer. 32-bit systems have 32-bit = 4 byte memory addresses.

2. **Consider strings `char* a = "162 is the best"` and `char b[] = "162 is the best"`. Are `a` and `b` different?**

   Yes. `a` points to a string literal in the read-only segment (.rodata) while `b` resides on the stack.

3. Suppose you have an integer array `int nums[3] = {152, 161, 162}`. What are the differences between `nums`, `&nums`, and `&nums[0]`?

Concept Check

1. Consider a valid double pointer `char** dbl_char` in a 32-bit system. What is returned by `sizeof(*dbl_char)`?

   Dereferencing a double pointer gives a single pointer. 32-bit systems have 32-bit = 4 byte memory addresses.

2. Consider strings `char* a = "162 is the best"` and `char b[] = "162 is the best"`. Are a and b different?

   Yes. a points to a string literal in the read-only segment (.rodata) while b resides on the stack.

3. **Suppose you have an integer array `int nums[3] = {152, 161, 162}`. What are the differences between `nums`, `&nums`, and `&nums[0]`?**

   The three all return the same memory address, but `nums` and `&nums[0]` points to the first element of `nums` while `&nums` points to the entire list.

   Incrementing each pointer by 1 will result in increase of `sizeof(int)` for nums and `&nums[0]` but an increase of `3 * sizeof(int)` for `&nums`.

Headers

```c
#include <stdio.h>
#include "lib.h"

int main(int argc, char** argv) {
  helper_args_t helper_args;
  helper_args.string = argv[0];
  helper_args.target = '/';
  char* result = helper_func(&helper_args);
  printf("%s\n", result);
  return 0;
}
```

App.c

```c
typedef struct helper_args {
#ifdef ABC
 char* aux;
#endif
 char* string;
 char target;
} helper_args_t;
char* helper_func(helper_args_t* args);
```

lib.h

```c
#include "lib.h"

char* helper_func(helper_args_t* args) {
  int i;
  for (i = 0; args->string[i] != '\0'; i++)
    if (args->string[i] == args->target)
      return &args->string[i + 1];
  return args->string;
}
```

lib.c

You build the program on a 64-bit machine as follows.

```
> gcc -c app.c -o app.o
> gcc -c lib.c -o lib.o
> gcc app.o lib.o -o app
```

1. What is the size of a `helper_args_t` struct?

2. Suppose you add a `#define ABC` at the top of `lib.h`. What is the size of a `helper_args_t` struct?

Headers

```c
#include <stdio.h>
#include "lib.h"

int main(int argc, char** argv) {
  helper_args_t helper_args;
  helper_args.string = argv[0];
  helper_args.target = '/';
  char* result = helper_func(&helper_args);
  printf("%s\n", result);
  return 0;
}
```

App.c

```c
typedef struct helper_args {
#ifdef ABC
 char* aux;
#endif
 char* string;
 char target;
} helper_args_t;
char* helper_func(helper_args_t* args);
```

lib.h

```c
#include "lib.h"

char* helper_func(helper_args_t* args) {
  int i;
  for (i = 0; args->string[i] != '\0'; i++)
    if (args->string[i] == args->target)
      return &args->string[i + 1];
  return args->string;
}
```

lib.c

1. What is the size of a `helper_args_t` struct?

16 bytes. Only `char* string` and `char target` meaning 9 bytes but GCC pads structs.

2. Suppose you add a `#define ABC` at the top of `lib.h`. What is the size of a `helper_args_t` struct?

Headers

```c
#include <stdio.h>
#include "lib.h"

int main(int argc, char** argv) {
  helper_args_t helper_args;
  helper_args.string = argv[0];
  helper_args.target = '/';
  char* result = helper_func(&helper_args);
  printf("%s\n", result);
  return 0;
}
```

App.c

```c
typedef struct helper_args {
#ifdef ABC
 char* aux;
#endif
 char* string;
 char target;
} helper_args_t;
char* helper_func(helper_args_t* args);
```

lib.h

```c
#include "lib.h"

char* helper_func(helper_args_t* args) {
  int i;
  for (i = 0; args->string[i] != '\0'; i++)
    if (args->string[i] == args->target)
      return &args->string[i + 1];
  return args->string;
}
```

lib.c

1. What is the size of a `helper_args_t` struct?

16 bytes. Only `char* string` and `char target` meaning 9 bytes but GCC pads structs.

2. Suppose you add a **`#define ABC`** at the top of **`lib.h`**. What is the size of a **`helper_args_t`** struct?

24 bytes. Additional 8 bytes from **`char* aux`** since ABC is defined.

Headers

```c
#include <stdio.h>
#include "lib.h"

int main(int argc, char** argv) {
  helper_args_t helper_args;
  helper_args.string = argv[0];
  helper_args.target = '/';
  char* result = helper_func(&helper_args);
  printf("%s\n", result);
  return 0;
}
```

App.c

```c
typedef struct helper_args {
#ifdef ABC
 char* aux;
#endif
 char* string;
 char target;
} helper_args_t;
char* helper_func(helper_args_t* args);
```

lib.h

```c
#include "lib.h"

char* helper_func(helper_args_t* args) {
  int i;
  for (i = 0; args->string[i] != '\0'; i++)
    if (args->string[i] == args->target)
      return &args->string[i + 1];
  return args->string;
}
```

lib.c

3. Suppose you build the program in a different way with the original files (i.e. none of the changes from previous questions apply).

```
> gcc -DABC -c app.c -o app.o
> gcc -c lib.c -o lib.o
> gcc app.o lib.o -o app
```

The program will now exhibit undefined behavior. Why?

Headers

```c
#include <stdio.h>
#include "lib.h"

int main(int argc, char** argv) {
  helper_args_t helper_args;
  helper_args.string = argv[0];
  helper_args.target = '/';
  char* result = helper_func(&helper_args);
  printf("%s\n", result);
  return 0;
}
```

App.c

```c
typedef struct helper_args {
#ifdef ABC
 char* aux;
#endif
 char* string;
 char target;
} helper_args_t;
char* helper_func(helper_args_t* args);
```

lib.h

```c
#include "lib.h"

char* helper_func(helper_args_t* args) {
  int i;
  for (i = 0; args->string[i] != '\0'; i++)
    if (args->string[i] == args->target)
      return &args->string[i + 1];
  return args->string;
}
```

lib.c

3. Suppose you build the program in a different way with the original files (i.e. none of the changes from previous questions apply).

```
> gcc -DABC -c app.c -o app.o
> gcc -c lib.c -o lib.o
> gcc app.o lib.o -o app
```

The program will now exhibit undefined behavior. Why?

`app.c` is compiled with ABC defined but `lib.c` is not

- `main` stored `argv[0]` at address of `helper_args` + 8
- `helper_func` access address of `args` when accessing `args->string`
- First 8 bytes of `args` which `helper_func` is accessing is garbage

Debugging Segmentation Faults

```c
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```c
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = "IU is the best singer!";

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted  : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted  : "    !Tabeeeeeghiinnorssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

1. We want to debug the program using GDB. How should we compile the program?

Debugging Segmentation Faults

```c
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```c
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = "IU is the best singer!";

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted  : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted  : "    !Tabeeeeeghiinnorssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

1. We want to debug the program using GDB. How should we compile the program?

```
gcc -g singer.c -o singer
```

Need a -g flag for debugging.

Debugging Segmentation Faults

```c
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```c
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = "IU is the best singer!";

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted  : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted  : "    !Tabeeeeeghiinnorssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

2. When running the program without any arguments, what line does the segfault happen? Describe the memory operations happening in that line.

Debugging Segmentation Faults

```c
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```c
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = "IU is the best singer!";

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted   : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted   : "    !Tabeeeeghiinnorsssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

2. When running the program without any arguments, what line does the segfault happen? Describe the memory operations happening in that line.

Find segfaulting line by letting the program run until it encounters the fault.

```
> gcc -g singer.c -o singer
> gdb singer
(gdb) run
Starting program: /home/runner/intro/singer
Unsorted: "IU is the best char!"

Program received signal SIGSEGV, Segmentation
fault.
0x00005646308006c8 in swap (a=0x564630800904
"IU is the best singer!", i=1, j=21)
   at singer.c:6
6      a[i] = a[j];
```

Ignore “warning: Error disabling address space randomization: Operation not permitted” if using Replit.

Debugging Segmentation Faults

```
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = "IU is the best singer!";

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted  : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted  : "    !Tabeeeeeghiinnorssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

2. When running the program without any arguments, what line does the segfault happen? Describe the memory operations happening in that line.

Use `backtrace` for more comprehensive breakdown.

```
(gdb) backtrace
#0  0x00005646308006c8 in swap
(a=0x564630800904 "IU is the best singer!",
i=1, j=21)
   at singer.c:6
#1  0x0000564630800773 in partition
(a=0x564630800904 "IU is the best singer!",
l=0, r=21)
   at singer.c:26
#2  0x00005646308007bd in sort
(a=0x564630800904 "IU is the best singer!",
l=0, r=21)
   at singer.c:36
#3  0x0000564630800861 in main (argc=1,
argv=0x7ffd04ac7098) at singer.c:51
```

Debugging Segmentation Faults

```c
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```c
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = "IU is the best singer!";

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted  : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted  : "    !Tabeeeeeghiinnorssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

2. When running the program without any arguments, what line does the segfault happen? Describe the memory operations happening in that line.

Two memory operations

1. Read from `a[j]`.
2. Write to `a[i]`.

Debugging Segmentation Faults

```c
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```c
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = "IU is the best singer!";

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted  : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted  : "    !Tabeeeeeghiinnorsssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

3. Run the program with and without an argument and observe the memory addresses of a in the segfaulting line. Why are the memory addresses so different?

Debugging Segmentation Faults

```c
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```c
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = "IU is the best singer!";

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted  : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted  : "    !Tabeeeeeghiinnorssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

3. Run the program with and without an argument and observe the memory addresses of a in the segfaulting line. Why are the memory addresses so different?

Break at line 6 using GDB.

```
> gdb singer
(gdb) break 6
Breakpoint 1 at 0x6ab: file singer.c, line 6.
(gdb) run
Starting program: /home/runner/intro/singer
Unsorted: "IU is the best singer!"

Breakpoint 1, swap (
   a=0x5624e4600904 "IU is the best singer!",
i=1, j=21)
   at singer.c:6
6     a[i] = a[j];
(gdb) print a
$1 = 0x5624e4600904 "IU is the best singer!"
```

Debugging Segmentation Faults

```c
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```c
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = "IU is the best singer!";

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted  : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted  : "    !Tabeeeeeghiinnorssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

3. Run the program with and without an argument and observe the memory addresses of a in the segfaulting line. Why are the memory addresses so different?

Break at line 6 using GDB.

```
(gdb) run "Taeyeon is the best singer!"
The program being debugged has been started
already.
Start it from the beginning? (y or n) y
Starting program: /home/runner/intro/asuna
"Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"

Breakpoint 1, swap (
   a=0x7ffcce01bfe5 "Taeyeon is the best
singer!", i=1, j=26)
   at asuna.c:6
(gdb) print a
$2 = 0x7ffcce01bfe5 "Taeyeon is the best
singer!"
```

Debugging Segmentation Faults

```
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = "IU is the best singer!";

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted  : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted  : "    !Tabeeeeeghiinnorsssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

3. Run the program with and without an argument and observe the memory addresses of a in the segfaulting line. Why are the memory addresses so different?

No argument: 0x5624e4600904

- Statically defined strings stored in read-only segment (.rodata).

With argument: 0x7ffcce01bfe5

- Arguments are passed in through the stack.

Debugging Segmentation Faults

```c
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```c
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = "IU is the best singer!";

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted  : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted  : "    !Tabeeeeeghiinnorssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

4. How should the code be changed to fix the segfault?

Debugging Segmentation Faults

```c
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```c
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = "IU is the best singer!";

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted  : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted  : "    !Tabeeeeeghiinnorssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

4. How should the code be changed to fix the segfault?

Write to a[i] is the problem since it’s in read-only data → need to put a in writable memory.

Allocate memory on the heap and put the default string on there.

- Accomplish with `malloc` followed by `strcpy`.
- Equivalently, use `strdup`.

Replace line 48.

Debugging Segmentation Faults

```c
void swap(char* a, int i, int j) {
  char t = a[i];
  a[i] = a[j];
  a[j] = t;
}

int partition(char* a, int l, int r){
  int pivot = a[l];
  int i = l, j = r+1;

  while (1) {
    do
      ++i;
    while (a[i] <= pivot && i <= r);

    do
      --j;
    while (a[j] > pivot);

    if (i >= j)
      break;

    swap(a, i, j);
  }

  swap(a, l, j);

  return j;
}
```

```c
void sort(char* a, int l, int r){
  if (l < r){
    int j = partition(a, l, r);
    sort(a, l, j-1);
    sort(a, j+1, r);
  }
}

int main(int argc, char** argv){
  char* a = NULL;

  if (argc > 1)
    a = argv[1];
  else
    a = strdup("IU is the best singer!");

  printf("Unsorted: \"%s\"\n", a);
  sort(a, 0, strlen(a) - 1);
  printf("Sorted  : \"%s\"\n", a);
}
```

```
> ./singer "Taeyeon is the best singer!"
Unsorted: "Taeyeon is the best singer!"
Sorted  : "    !Tabeeeeeghiinnorssstty"
> ./singer
Unsorted: "IU is the best singer!"
Segmentation fault (core dumped)
```

4. How should the code be changed to fix the segfault?

Write to a[i] is the problem since it's in read-only data → need to put a in writable memory.

Allocate memory on the heap and put the default string on there.

- Accomplish with `malloc` followed by `strcpy`.
- Equivalently, use `strdup`.

Replace line 48.

x86

Registers

Registers are small storage spaces directly on the processor.

- Allows for fast memory access.

General purpose registers (GPR) store both data and addresses.

- x86 has 8, RISC-V has 32 (x0-x31).
- Started as 16-bits, extend to 32-bit using e prefix (e.g. EAX for AX).
- Access 8-bit LSB by replacing last letter with l (e.g. AL for AX).
- Access 8-bit MSB by replacing last letter with h (e.g. AH for AX) only for AX, BX, CX, DX.

Instruction pointer register holds address of next instruction to execute.

- Called ip which can be extended with e prefix like a GPR.
- Can't be read/modified like a GPR using regular memory instructions.

	Name	Purpose
AX	Accumulator	I/O port access, arithmetic, interrupt calls
BX	Base	Base pointer for memory access
CX	Counter	Loop counting, bit shifts
DX	Data	I/O port access, arithmetic, interrupt calls
SP	Stack Pointer	Top address of stack
BP	Base Pointer	Base address of stack
SI	Source Index	Source for stream operations (e.g. string)
DI	Destination Index	Destination for stream operations (e.g. string)

Syntax

Use **AT&T Syntax** not Intel which is used by GCC.

Prefix registers with **%** (e.g. `%eax`), constants with **$** (e.g. `$4`).

General structure is **`inst src, dest`**.

Address memory with **`offset(base, index, scale)`**.

- `base`, `index` = registers, `offset` = any integer, `scale`= 1, 2, 4, or 8.
- Accesses data at address `base + index * scale + offset`.
- All parameters optional but will see base and offset usually.
- Using `lea` instruction will operate on the address itself not contents.

Suffix instructions to signify operand size.

- Not always necessary but should use them regardless.

`mov 8(%ebx), %eax`	Move contents from address EBX + 8 into EAX
`mov %ecx, -4(%esi, %ebx, 8)`	Move contents in ECX into address ESI + 8 * EBX - 4
`lea 8(%ebx), %eax`	Puts EBX + 8 into EAX

`movb $0, (%esp)`	Zero out a single byte from ESP
`movw $0, (%esp)`	Zero out two bytes from ESP
`movl $0, (%esp)`	Zero out four bytes from ESP

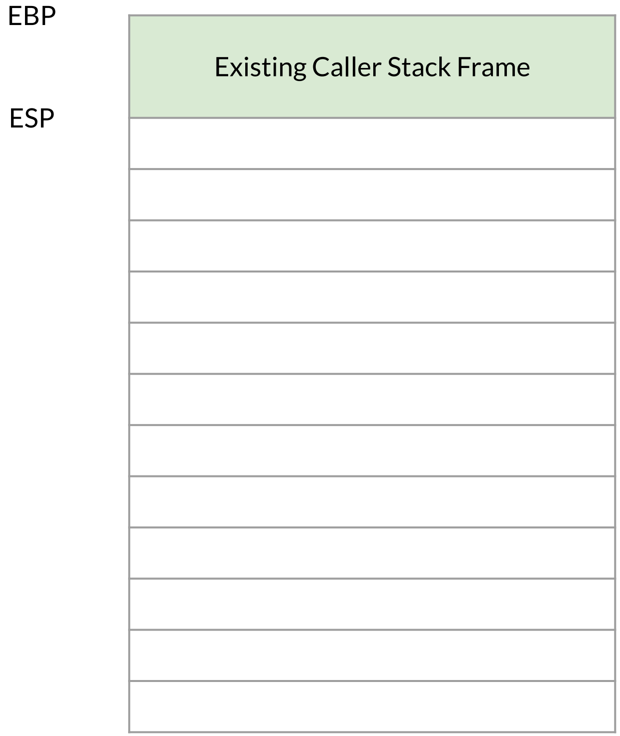
Calling Convention

Calling convention is a procedure for how to call and return from functions.

- Specifies stack management, argument passing, register saving, etc.
- One set of rule *each* for the **caller** and **callee**

Many different calling conventions, will use the one defined in **i386 System V ABI** in this class.

Calling Convention



EBP

Existing Caller Stack Frame

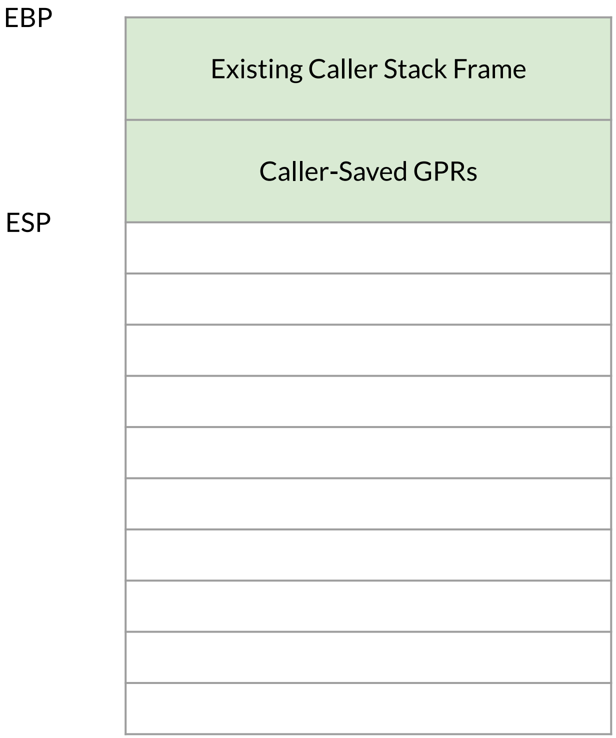
ESP

Calling Convention

Caller

Before calling the function (i.e. **prologue**),

1. **Save caller-saved GPRs (EAX, ECX, EDX) onto the stack *if needed after the function call*.**

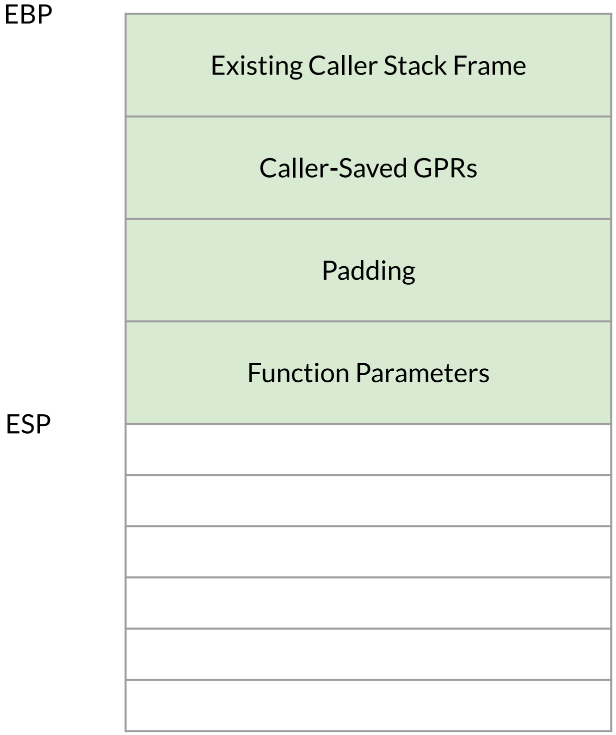


Calling Convention

Caller

Before calling the function (i.e. **prologue**),

1. Save caller-saved GPRs (EAX, ECX, EDX) onto the stack *if needed after the function call.*
2. **Push parameters onto the stack in reverse order. Add necessary padding *before the parameters* to ensure a 16-byte alignment.**



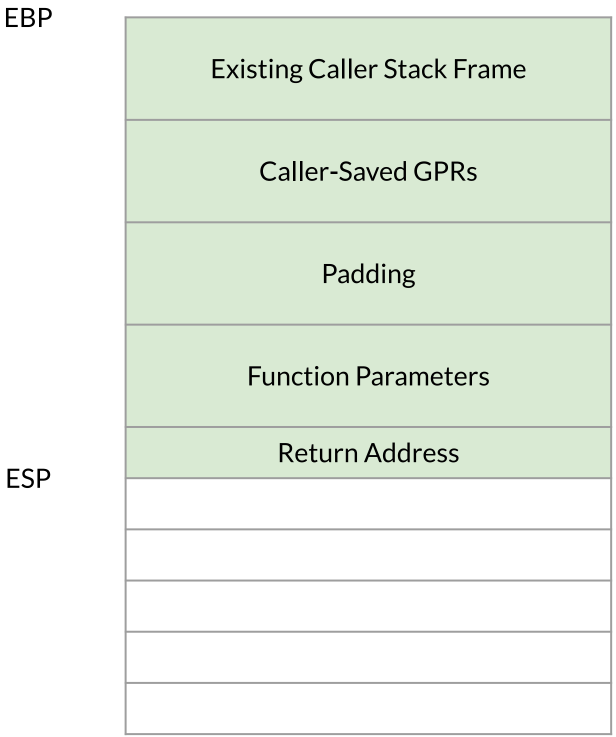
Calling Convention

Caller

Before calling the function (i.e. **prologue**),

1. Save caller-saved GPRs (EAX, ECX, EDX) onto the stack *if needed after the function call*.
2. Push parameters onto the stack in reverse order. Add necessary padding *before the parameters* to ensure a 16-byte alignment.

Call function by pushing the return address onto the stack and jumping to the function.

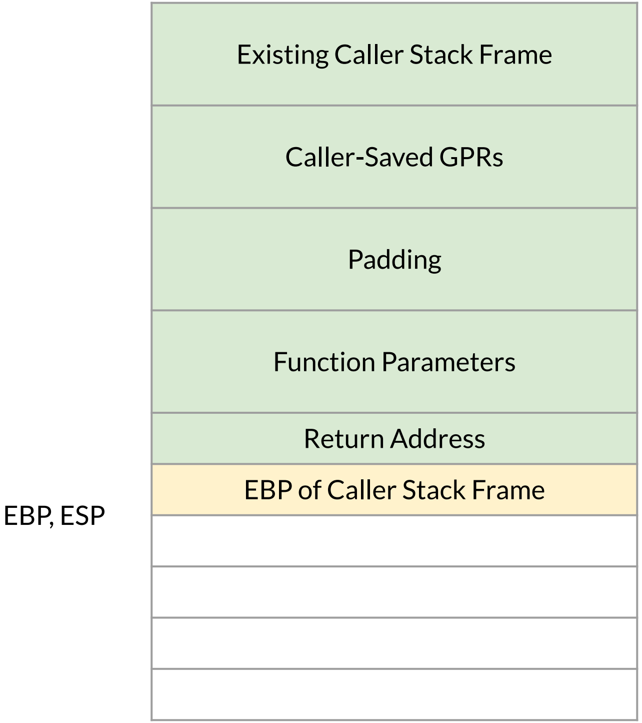


Calling Convention

Callee

Before executing any function logic (i.e. prologue),

1. **Push EBP onto the stack and set EBP to be the new ESP.**

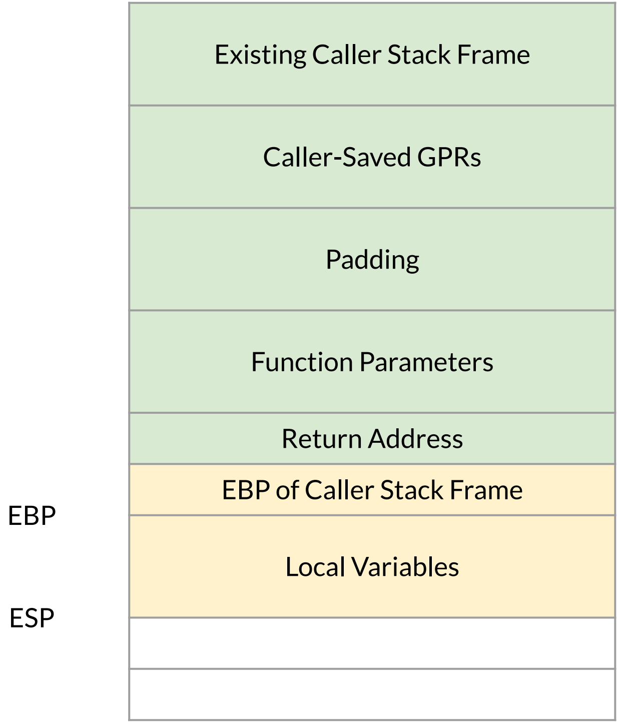


Calling Convention

Callee

Before executing any function logic (i.e. prologue),

1. Push EBP onto the stack and set EBP to be the new ESP.
2. **Allocate stack space for local variables.**

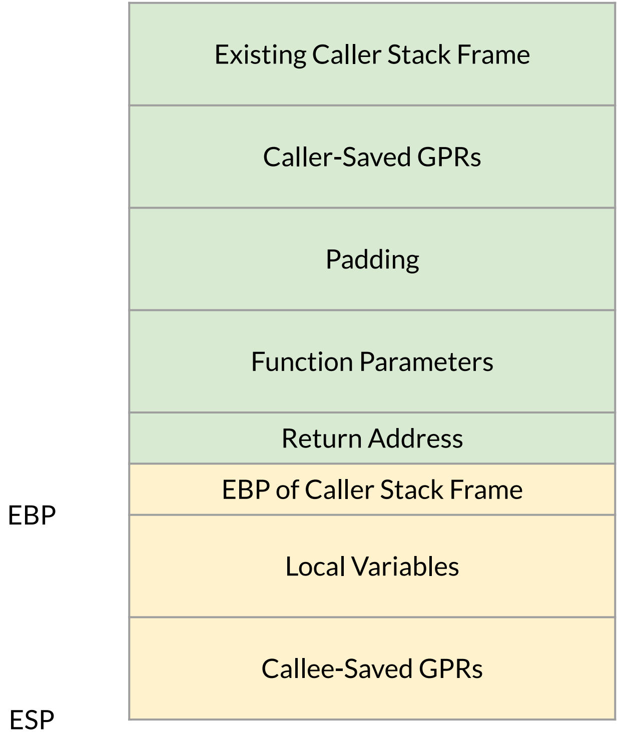


Calling Convention

Callee

Before executing any function logic (i.e. prologue),

1. Push EBP onto the stack and set EBP to be the new ESP.
2. Allocate stack space for local variables.
3. **Save callee-saved GPRs (EBX, EDI, ESI) onto the stack *if used during the function logic.***



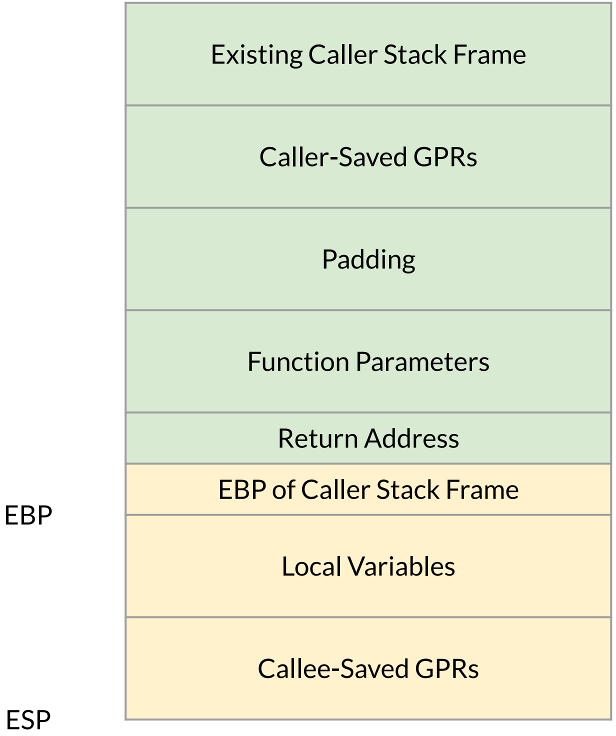
Calling Convention

Callee

Before executing any function logic (i.e. prologue),

1. Push EBP onto the stack and set EBP to be the new ESP.
2. Allocate stack space for local variables.
3. Save callee-saved GPRs (EBX, EDI, ESI) onto the stack *if used during the function logic*.

Perform function logic.



Existing Caller Stack Frame

Caller-Saved GPRs

Padding

Function Parameters

Return Address

EBP of Caller Stack Frame

Local Variables

Callee-Saved GPRs

Calling Convention

Callee

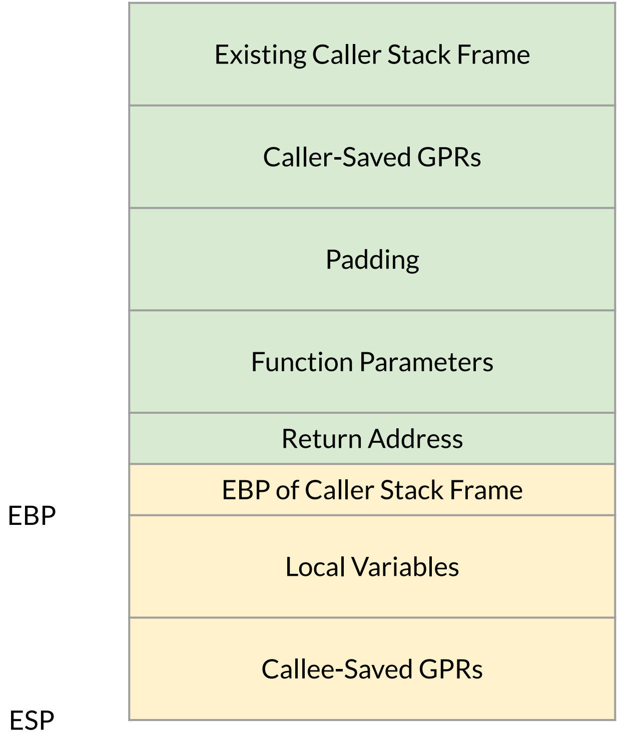
Before executing any function logic (i.e. prologue),

1. Push EBP onto the stack and set EBP to be the new ESP.
2. Allocate stack space for local variables.
3. Save callee-saved GPRs (EBX, EDI, ESI) onto the stack *if used during the function logic*.

Perform function logic.

Before returning (i.e. **epilogue**),

1. **Store return value in EAX.**



Calling Convention

Callee

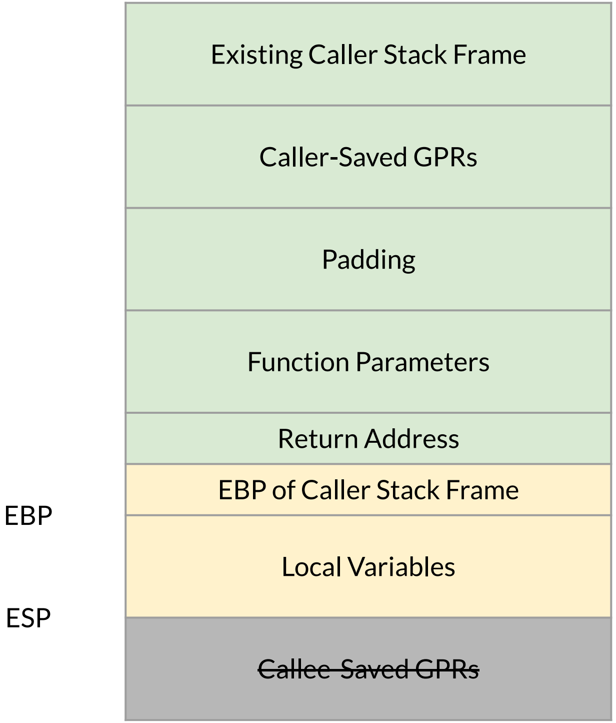
Before executing any function logic (i.e. prologue),

1. Push EBP onto the stack and set EBP to be the new ESP.
2. Allocate stack space for local variables.
3. Save callee-saved GPRs (EBX, EDI, ESI) onto the stack *if used during the function logic*.

Perform function logic.

Before returning (i.e. **epilogue**),

1. Store return value in EAX.
2. **Restore callee-saved GPRs if any from the prologue.**



Calling Convention

Callee

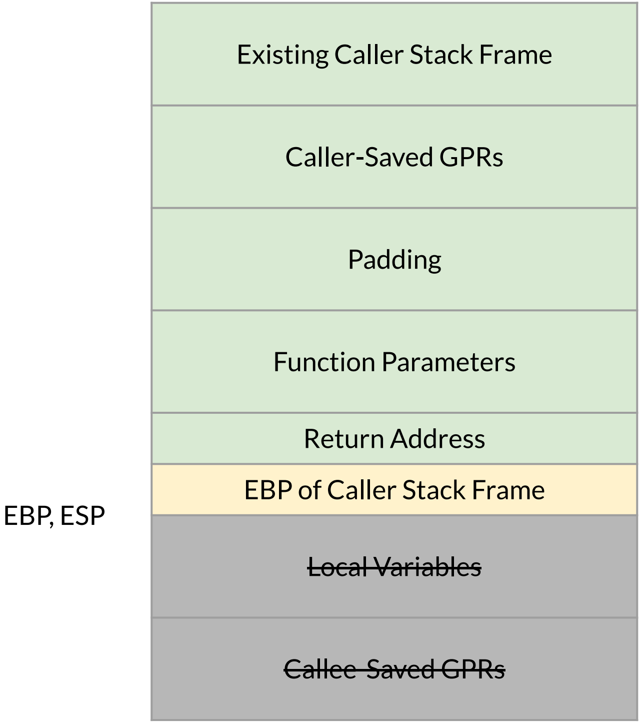
Before executing any function logic (i.e. prologue),

1. Push EBP onto the stack and set EBP to be the new ESP.
2. Allocate stack space for local variables.
3. Save callee-saved GPRs (EBX, EDI, ESI) onto the stack *if used during the function logic.*

Perform function logic.

Before returning (i.e. **epilogue**),

1. Store return value in EAX.
2. Restore callee-saved GPRs if any from the prologue.
3. Deallocate local variables.



Calling Convention

Callee

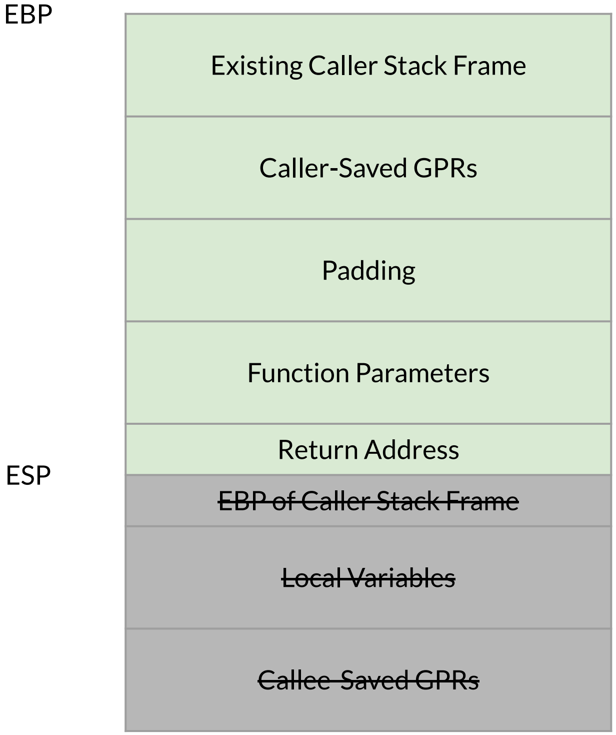
Before executing any function logic (i.e. prologue),

1. Push EBP onto the stack and set EBP to be the new ESP.
2. Allocate stack space for local variables.
3. Save callee-saved GPRs (EBX, EDI, ESI) onto the stack *if used during the function logic.*

Perform function logic.

Before returning (i.e. **epilogue**),

1. Store return value in EAX.
2. Restore callee-saved GPRs if any from the prologue.
3. Deallocate local variables.
4. **Restore caller's EBP from stack.**



Calling Convention

Callee

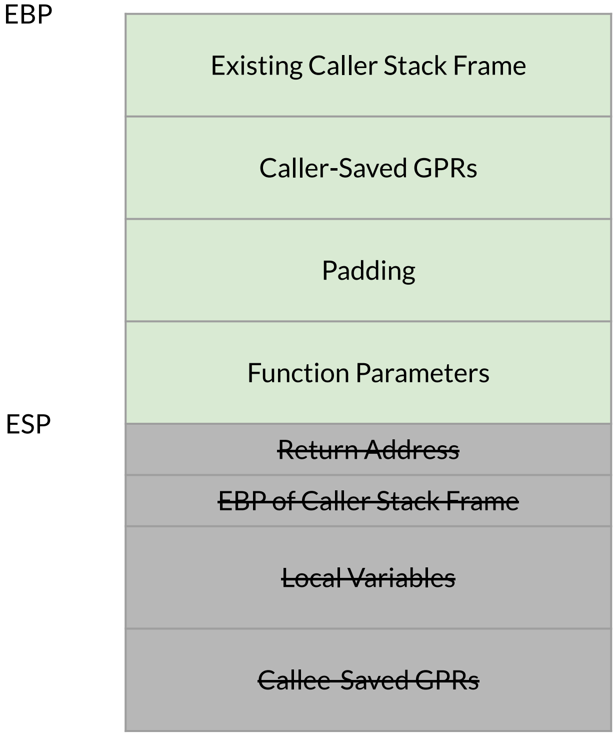
Before executing any function logic (i.e. prologue),

1. Push EBP onto the stack and set EBP to be the new ESP.
2. Allocate stack space for local variables.
3. Save callee-saved GPRs (EBX, EDI, ESI) onto the stack *if used during the function logic*.

Perform function logic.

Before returning (i.e. **epilogue**),

1. Store return value in EAX.
2. Restore callee-saved GPRs if any from the prologue.
3. Deallocate local variables.
4. Restore caller's EBP from stack.
5. **Return from function call by popping the return address pushed by the caller in its prologue and jumping to it.**



EBP

Existing Caller Stack Frame

Caller-Saved GPRs

Padding

Function Parameters

ESP

~~Return Address~~

~~EBP of Caller Stack Frame~~

~~Local Variables~~

~~Callee-Saved GPRs~~

Calling Convention

Caller

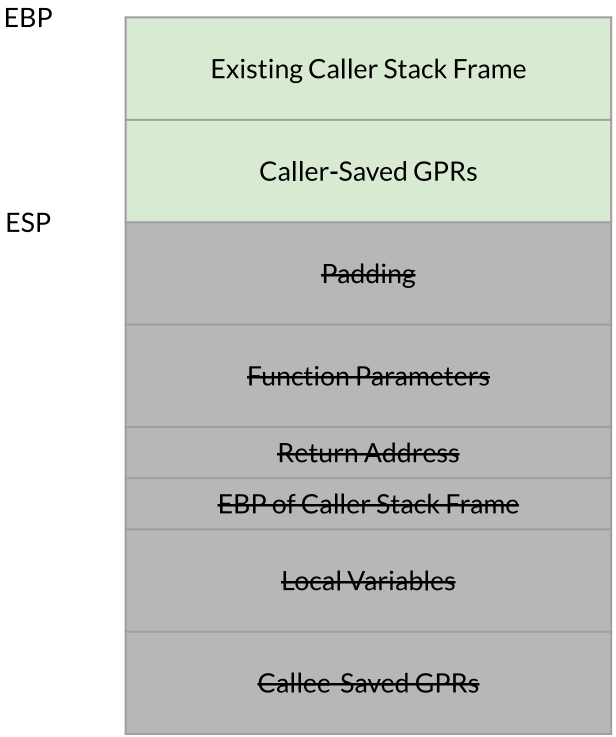
Before calling the function (i.e. **prologue**),

1. Save caller-saved GPRs (EAX, ECX, EDX) onto the stack *if needed after the function call*.
2. Push parameters onto the stack in reverse order. Add necessary padding *before the parameters* to ensure a 16-byte alignment.

Call function by pushing the return address onto the stack and jumping to the function.

Once function call returns (i.e. **epilogue**),

1. **Remove parameters from the stack.**



Calling Convention

Caller

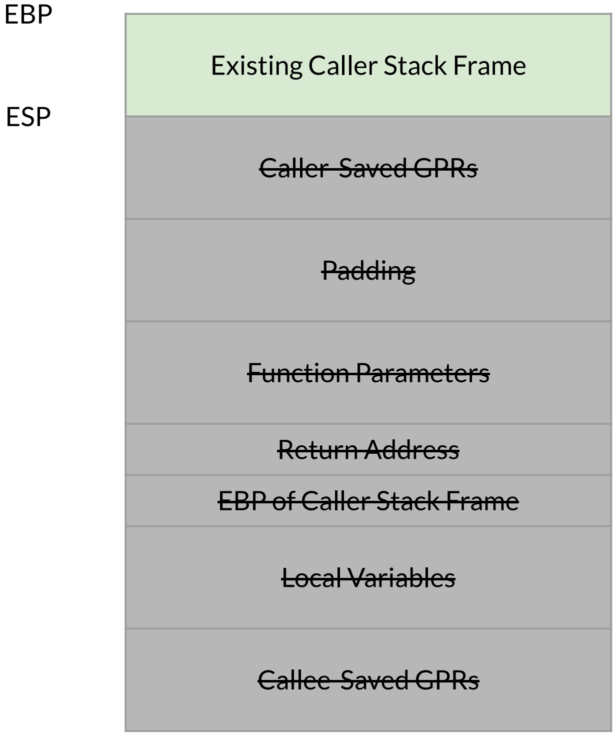
Before calling the function (i.e. **prologue**),

1. Save caller-saved GPRs (EAX, ECX, EDX) onto the stack *if needed after the function call*.
2. Push parameters onto the stack in reverse order. Add necessary padding *before the parameters* to ensure a 16-byte alignment.

Call function by pushing the return address onto the stack and jumping to the function.

Once function call returns (i.e. **epilogue**),

1. Remove parameters from the stack.
2. Restore caller-saved GPRs if any from the prologue.



Calling Convention

Caller

Before calling the function (i.e. **prologue**),

1. Save caller-saved GPRs (EAX, ECX, EDX) onto the stack *if needed after the function call*.
2. Push parameters onto the stack in reverse order. Add necessary padding *before the parameters* to ensure a 16-byte alignment.

Call function by pushing the return address onto the stack and jumping to the function.

Once function call returns (i.e. **epilogue**),

1. Remove parameters from the stack.
2. Restore caller-saved GPRs if any from the prologue.

Callee

Before executing any function logic (i.e. prologue),

1. Push EBP onto the stack and set EBP to be the new ESP.
2. Allocate stack space for local variables.
3. Save callee-saved GPRs (EBX, EDI, ESI) onto the stack *if used during the function logic*.

Perform function logic.

Before returning (i.e. **epilogue**),

1. Store return value in EAX.
2. Restore callee-saved GPRs if any from the prologue.
3. Deallocate local variables.
4. Restore caller's EBP from stack.
5. Return from function call by popping the return address pushed by the caller in its prologue and jumping to it.

Calling Convention

Instruction	Purpose	Effective

`pushl src`	Push `src` onto stack	`subl $4, %esp`
		`movl src, (%esp)`

`popl dest`	Pop from stack into `dest`	`movl (%esp), dest`
		`addl $4, %esp`

`call addr`	Push return address onto stack and jump to `addr`	`pushl %eip`
		`jump addr`

`leave`	Restore EBP and ESP to previous stack frame	`movl %ebp, %esp`
		`popl %ebp`

`ret`	Pop return address from stack and jump to it	`popl %eip`

Concept Check

1. Between SP and BP, which has a higher memory address?

2. Based on the differences of RISC and CISC, why might x86 have fewer GPRs compared to RISC-V?

3. Write three different ways to clear the \code{eax} register (i.e. store a 0).

4. True or False: Right before the caller jumps to the desired function, the stack must be 16-byte aligned.

Concept Check

1. **Between SP and BP, which has a higher memory address?**

   BP. Stack grows downwards → top of the stack (SP) moves towards lower addresses

2. Based on the differences of RISC and CISC, why might x86 have fewer GPRs compared to RISC-V?

3. Write three different ways to clear the EAX register (i.e. store a 0).

4. True or False: Right before the caller jumps to the desired function, the stack must be 16-byte aligned.

Concept Check

1. Between SP and BP, which has a higher memory address?

   BP. Stack grows downwards → top of the stack (SP) moves towards lower addresses

2. **Based on the differences of RISC and CISC, why might x86 have fewer GPRs compared to RISC-V?**

   Reduced instruction set → less hardware space needed for transistors → more room for GPRs

3. Write three different ways to clear the EAX register (i.e. store a 0).

4. True or False: Right before the caller jumps to the desired function, the stack must be 16-byte aligned.

Concept Check

1. Between SP and BP, which has a higher memory address?

   BP. Stack grows downwards → top of the stack (SP) moves towards lower addresses

2. Based on the differences of RISC and CISC, why might x86 have fewer GPRs compared to RISC-V?

   Reduced instruction set → less hardware space needed for transistors → more room for GPRs

3. **Write three different ways to clear the EAX register (i.e. store a 0).**

   ```
   movl $0, %eax            subl %eax, %eax          xorl %eax, %eax
   ```

4. True or False: Right before the caller jumps to the desired function, the stack must be 16-byte aligned.

Concept Check

1. Between SP and BP, which has a higher memory address?

   BP. Stack grows downwards → top of the stack (SP) moves towards lower addresses

2. Based on the differences of RISC and CISC, why might x86 have fewer GPRs compared to RISC-V?

   Reduced instruction set → less hardware space needed for transistors → more room for GPRs

3. Write three different ways to clear the EAX register (i.e. store a 0).

   ```
   movl $0, %eax          subl %eax, %eax          xorl %eax, %eax
   ```

4. **True or False: Right before the caller jumps to the desired function, the stack must be 16-byte aligned.**

   False. Stack needs to be 16-byte aligned *after parameters have been pushed* onto the stack. Return address is pushed right before jumping.

Reverse Engineering

```c
int main(void) {
  for (int a = 1; _____________) {
    int a2 = _____;
    for (int b = ________________) {
      int b2 = _____;
      int c = ____________;
      int c2 = _____;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

1. What is the memory address of a relative to the base pointer?

```asm
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
.L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
 .L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
.L4:
        addl    $1, -8(%ebp)
.L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
.L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
.L5:
        leave
        ret
```

Reverse Engineering

```c
int main(void) {
  for (int a = 1; _____________) {
    int a2 = _____;
    for (int b = ________________) {
      int b2 = _____;
      int c = ____________;
      int c2 = _____;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
 .L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
 .L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
 .L4:
        addl    $1, -8(%ebp)
 .L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
 .L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
 .L5:
        leave
        ret
```

1. What is the memory address of a relative to the base pointer?

   4 bytes below the base pointer (i.e. EBP - 4).

Reverse Engineering

```
int main(void) {
  for (int a = 1; _____________) {
    int a2 = _____;
    for (int b = ________________) {
      int b2 = _____;
      int c = ____________;
      int c2 = _____;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
.L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
 .L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
.L4:
        addl    $1, -8(%ebp)
.L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
.L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
.L5:
        leave
        ret
```

2. What is the end condition for the outer loop using a?

Reverse Engineering

```c
int main(void) {
  for (int a = 1; _____________) {
    int a2 = _____;
    for (int b = ________________) {
      int b2 = _____;
      int c = ____________;
      int c2 = _____;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

2. What is the end condition for the outer loop using a?

   a must be greater than 333.

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
.L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
 .L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
.L4:
        addl    $1, -8(%ebp)
.L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
.L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
.L5:
        leave
        ret
```

Reverse Engineering

```c
int main(void) {
  for (int a = 1; _____________) {
    int a2 = _____;
    for (int b = ________________) {
      int b2 = _____;
      int c = ____________;
      int c2 = _____;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
.L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
.L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
.L4:
        addl    $1, -8(%ebp)
.L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
.L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
.L5:
        leave
        ret
```

3. What are the memory addresses the local variables (a2, b, b2, c, c2) relative to the base pointer?

Reverse Engineering

```c
int main(void) {
  for (int a = 1; _____________) {
    int a2 = _____;
    for (int b = ________________) {
      int b2 = _____;
      int c = ____________;
      int c2 = _____;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
.L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
.L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
.L4:
        addl    $1, -8(%ebp)
.L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
.L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
.L5:
        leave
        ret
```

3. What are the memory addresses the local variables (a2, b, b2, c, c2) relative to the base pointer?

   a2 = EBP - 12

   b = EBP - 8

   b2 = EBP - 16

   c = EBP - 20

   c2 = EBP - 24

Reverse Engineering

```c
int main(void) {
  for (int a = 1; _____________) {
    int a2 = _____;
    for (int b = ________________) {
      int b2 = _____;
      int c = ____________;
      int c2 = _____;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

4. Fill in the missing code.

```
main:
       pushl   %ebp
       movl    %esp, %ebp
       subl    $32, %esp
       movl    $1, -4(%ebp)
       jmp     .L2
.L7:
       movl    -4(%ebp), %eax
       imull   %eax, %eax
       movl    %eax, -12(%ebp)
       movl    -4(%ebp), %eax
       movl    %eax, -8(%ebp)
       jmp     .L3
 .L6:
       movl    -8(%ebp), %eax
       imull   %eax, %eax
       movl    %eax, -16(%ebp)
       movl    $1000, %eax
       subl    -4(%ebp), %eax
       subl    -8(%ebp), %eax
       movl    %eax, -20(%ebp)
       movl    -20(%ebp), %eax
       imull   %eax, %eax
       movl    %eax, -24(%ebp)
       movl    -12(%ebp), %edx
       movl    -16(%ebp), %eax
       addl    %edx, %eax
       cmpl    %eax, -24(%ebp)
       jne     .L4
       movl    -4(%ebp), %eax
       imull   -8(%ebp), %eax
       imull   -20(%ebp), %eax
       jmp     .L5
.L4:
       addl    $1, -8(%ebp)
.L3:
       cmpl    $666, -8(%ebp)
       jle     .L6
       addl    $1, -4(%ebp)
.L2:
       cmpl    $333, -4(%ebp)
       jle     .L7
       movl    $0, %eax
.L5:
       leave
       ret
```

Reverse Engineering

```
int main(void) {
  for (int a = 1; a <= 333; a++) {
    int a2 = _____;
    for (int b = ________________) {
      int b2 = _____;
      int c = ____________;
      int c2 = _____;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

4. Fill in the missing code.

```
main:
       pushl   %ebp
       movl    %esp, %ebp
       subl    $32, %esp
       movl    $1, -4(%ebp)
       jmp     .L2
.L7:
       movl    -4(%ebp), %eax
       imull   %eax, %eax
       movl    %eax, -12(%ebp)
       movl    -4(%ebp), %eax
       movl    %eax, -8(%ebp)
       jmp     .L3
.L6:
       movl    -8(%ebp), %eax
       imull   %eax, %eax
       movl    %eax, -16(%ebp)
       movl    $1000, %eax
       subl    -4(%ebp), %eax
       subl    -8(%ebp), %eax
       movl    %eax, -20(%ebp)
       movl    -20(%ebp), %eax
       imull   %eax, %eax
       movl    %eax, -24(%ebp)
       movl    -12(%ebp), %edx
       movl    -16(%ebp), %eax
       addl    %edx, %eax
       cmpl    %eax, -24(%ebp)
       jne     .L4
       movl    -4(%ebp), %eax
       imull   -8(%ebp), %eax
       imull   -20(%ebp), %eax
       jmp     .L5
.L4:
       addl    $1, -8(%ebp)
.L3:
       cmpl    $666, -8(%ebp)
       jle     .L6
       addl    $1, -4(%ebp)
.L2:
       cmpl    $333, -4(%ebp)
       jle     .L7
       movl    $0, %eax
.L5:
       leave
       ret
```

Reverse Engineering

```c
int main(void) {
  for (int a = 1; a <= 333; a++) {
    int a2 = a * a;
    for (int b = ________________) {
      int b2 = _____;
      int c = ____________;
      int c2 = _____;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

4. Fill in the missing code.

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
.L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
 .L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
.L4:
        addl    $1, -8(%ebp)
.L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
.L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
.L5:
        leave
        ret
```

Reverse Engineering

```
int main(void) {
  for (int a = 1; a <= 333; a++) {
    int a2 = a * a;
    for (int b = a; b <= 666; b++) {
      int b2 = _____;
      int c = ____________;
      int c2 = _____;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

4. Fill in the missing code.

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
.L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
.L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
.L4:
        addl    $1, -8(%ebp)
.L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
.L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
.L5:
        leave
        ret
```

Reverse Engineering

```c
int main(void) {
  for (int a = 1; a <= 333; a++) {
    int a2 = a * a;
    for (int b = a; b <= 666; b++) {
      int b2 = b * b;
      int c = ____________;
      int c2 = _____;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

4. Fill in the missing code.

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
.L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
.L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
.L4:
        addl    $1, -8(%ebp)
.L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
.L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
.L5:
        leave
        ret
```

Reverse Engineering

```c
int main(void) {
  for (int a = 1; a <= 333; a++) {
    int a2 = a * a;
    for (int b = a; b <= 666; b++) {
      int b2 = b * b;
      int c = 1000 - a - b;
      int c2 = _____;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

4. Fill in the missing code.

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
.L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
 .L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
.L4:
        addl    $1, -8(%ebp)
.L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
.L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
.L5:
        leave
        ret
```

Reverse Engineering

```c
int main(void) {
  for (int a = 1; a <= 333; a++) {
    int a2 = a * a;
    for (int b = a; b <= 666; b++) {
      int b2 = b * b;
      int c = 1000 - a - b;
      int c2 = c * c;
      if (_____________) {
        return _________;
      }
    }
  }
  return 0;
}
```

4. Fill in the missing code.

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
.L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
.L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
.L4:
        addl    $1, -8(%ebp)
.L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
.L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
.L5:
        leave
        ret
```

Reverse Engineering

```c
int main(void) {
  for (int a = 1; a <= 333; a++) {
    int a2 = a * a;
    for (int b = a; b <= 666; b++) {
      int b2 = b * b;
      int c = 1000 - a - b;
      int c2 = c * c;
      if (a2 + b2 == c2) {
        return _________;
      }
    }
  }
  return 0;
}
```

4. Fill in the missing code.

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
.L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
.L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
.L4:
        addl    $1, -8(%ebp)
.L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
.L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
.L5:
        leave
        ret
```

Reverse Engineering

```c
int main(void) {
  for (int a = 1; a <= 333; a++) {
    int a2 = a * a;
    for (int b = a; b <= 666; b++) {
      int b2 = b * b;
      int c = 1000 - a - b;
      int c2 = c * c;
      if (a2 + b2 == c2) {
        return a * b * c;
      }
    }
  }
  return 0;
}
```

4. Fill in the missing code.

```
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $32, %esp
        movl    $1, -4(%ebp)
        jmp     .L2
.L7:
        movl    -4(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -12(%ebp)
        movl    -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        jmp     .L3
 .L6:
        movl    -8(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -16(%ebp)
        movl    $1000, %eax
        subl    -4(%ebp), %eax
        subl    -8(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    -20(%ebp), %eax
        imull   %eax, %eax
        movl    %eax, -24(%ebp)
        movl    -12(%ebp), %edx
        movl    -16(%ebp), %eax
        addl    %edx, %eax
        cmpl    %eax, -24(%ebp)
        jne     .L4
        movl    -4(%ebp), %eax
        imull   -8(%ebp), %eax
        imull   -20(%ebp), %eax
        jmp     .L5
.L4:
        addl    $1, -8(%ebp)
.L3:
        cmpl    $666, -8(%ebp)
        jle     .L6
        addl    $1, -4(%ebp)
.L2:
        cmpl    $333, -4(%ebp)
        jle     .L7
        movl    $0, %eax
.L5:
        leave
        ret
```

Stack Frame

```
                 call.s
1  p:
2          .zero    4
3  bar:
4          pushl    %ebp
5          movl     %esp, %ebp
6          subl     $16, %esp
7          movl     8(%ebp), %edx
8          movl     12(%ebp), %eax
9          addl     %edx, %eax
10         subl     16(%ebp), %eax
11         movl     %eax, -4(%ebp)
12         movl     -4(%ebp), %eax
13         addl     $1, %eax
14         leave
15         ret
16 foo:
17         pushl    %ebp
18         movl     %esp, %ebp
19         pushl    %ebx
20         subl     $4, %esp
21         movl     8(%ebp), %edx
22         movl     12(%ebp), %eax
23         leal     (%edx,%eax), %ebx
24         subl     $4, %esp
25         pushl    $5
26         pushl    $4
27         pushl    $3
28         call     bar
29         addl     $16, %esp
30         addl     %ebx, %eax
31         movl     %eax, p
32         nop
33         movl     -4(%ebp), %ebx
34         leave
35         ret
```

1. Which lines of code correspond to a caller/callee prologue?

Stack Frame

```
                    call.s
1  p:
2          .zero    4
3  bar:
4          pushl    %ebp
5          movl     %esp, %ebp
6          subl     $16, %esp
7          movl     8(%ebp), %edx
8          movl     12(%ebp), %eax
9          addl     %edx, %eax
10         subl     16(%ebp), %eax
11         movl     %eax, -4(%ebp)
12         movl     -4(%ebp), %eax
13         addl     $1, %eax
14         leave
15         ret
16 foo:
17         pushl    %ebp
18         movl     %esp, %ebp
19         pushl    %ebx
20         subl     $4, %esp
21         movl     8(%ebp), %edx
22         movl     12(%ebp), %eax
23         leal     (%edx,%eax), %ebx
24         subl     $4, %esp
25         pushl    $5
26         pushl    $4
27         pushl    $3
28         call     bar
29         addl     $16, %esp
30         addl     %ebx, %eax
31         movl     %eax, p
32         nop
33         movl     -4(%ebp), %ebx
34         leave
35         ret
```

1. Which lines of code correspond to a caller/callee prologue?

foo/bar as caller/callee

24-27 = caller prologue

29 = caller epilogue

4-6 = callee prologue

13-15 = callee epilogue

foo as callee

17-20 = callee prologue

33-35 = callee epilogue

Stack Frame

```
                call.s
1  p:
2          .zero    4
3  bar:
4          pushl    %ebp
5          movl     %esp, %ebp
6          subl     $16, %esp
7          movl     8(%ebp), %edx
8          movl     12(%ebp), %eax
9          addl     %edx, %eax
10         subl     16(%ebp), %eax
11         movl     %eax, -4(%ebp)
12         movl     -4(%ebp), %eax
13         addl     $1, %eax
14         leave
15         ret
16 foo:
17         pushl    %ebp
18         movl     %esp, %ebp
19         pushl    %ebx
20         subl     $4, %esp
21         movl     8(%ebp), %edx
22         movl     12(%ebp), %eax
23         leal     (%edx,%eax), %ebx
24         subl     $4, %esp
25         pushl    $5
26         pushl    $4
27         pushl    $3
28         call     bar
29         addl     $16, %esp
30         addl     %ebx, %eax
31         movl     %eax, p
32         nop
33         movl     -4(%ebp), %ebx
34         leave
35         ret
```

2. What does line 19 do in `call.s`? Why is it necessary?

Stack Frame

```
                call.s
1  p:
2           .zero   4
3  bar:
4           pushl   %ebp
5           movl    %esp, %ebp
6           subl    $16, %esp
7           movl    8(%ebp), %edx
8           movl    12(%ebp), %eax
9           addl    %edx, %eax
10          subl    16(%ebp), %eax
11          movl    %eax, -4(%ebp)
12          movl    -4(%ebp), %eax
13          addl    $1, %eax
14          leave
15          ret
16 foo:
17          pushl   %ebp
18          movl    %esp, %ebp
19          pushl   %ebx
20          subl    $4, %esp
21          movl    8(%ebp), %edx
22          movl    12(%ebp), %eax
23          leal    (%edx,%eax), %ebx
24          subl    $4, %esp
25          pushl   $5
26          pushl   $4
27          pushl   $3
28          call    bar
29          addl    $16, %esp
30          addl    %ebx, %eax
31          movl    %eax, p
32          nop
33          movl    -4(%ebp), %ebx
34          leave
35          ret
```

2. What does line 19 do in `call.s`? Why is it necessary?

   Saves EBX register since it’s callee-saved and `foo` uses it. Doesn’t matter that `bar` never uses EBX.

Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

3. Why is EDX not saved by `foo` before calling `bar` despite the register being overwritten in `bar`?

Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

3. Why is EDX not saved by `foo` before calling `bar` despite the register being overwritten in `bar`?

   EDX does not need to persist after the function call.

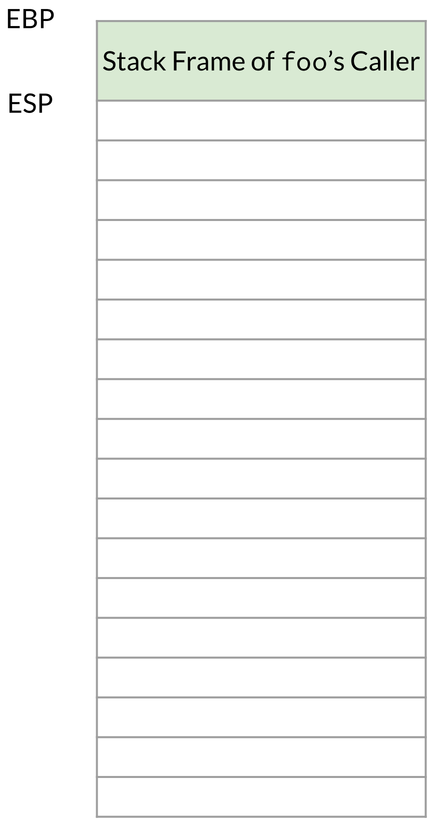
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	
EBX	
EDX	



EBP

ESP

Stack Frame of foo’s Caller

Stack Frame

```
                    call.s
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	
EBX	
EDX	

EBP	Stack Frame of foo's Caller
	Padding
	b
	a
	Return Addr of foo's Caller
ESP	

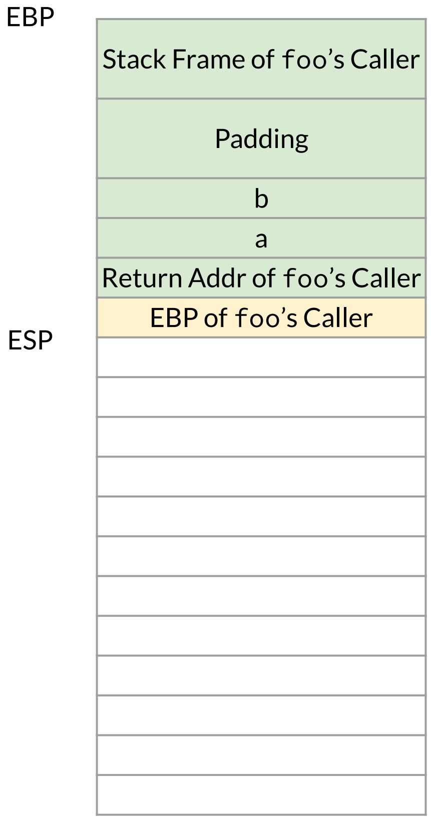
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	
EBX	
EDX	



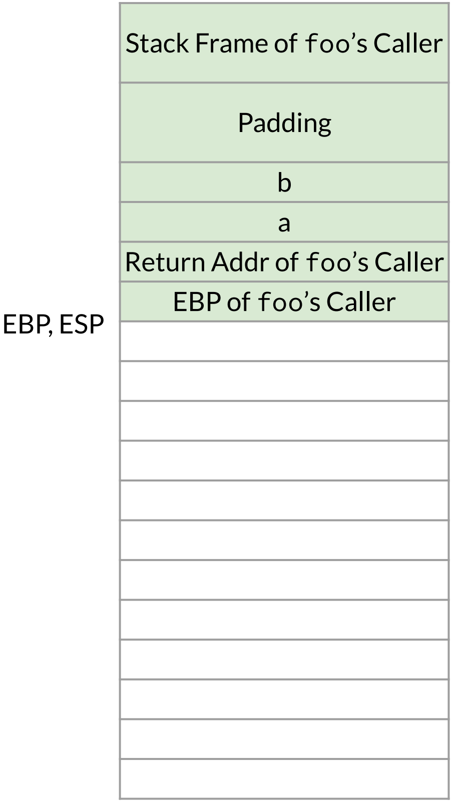
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	
EBX	
EDX	



Stack Frame of foo's Caller

Padding

b

a

Return Addr of foo's Caller

EBP, ESP

EBP of foo's Caller

Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	
EBX	
EDX	

	Stack Frame of foo's Caller
	Padding
	b
	a
	Return Addr of foo's Caller
EBP	EBP of foo's Caller
ESP	EBX of foo's Caller

Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	
EBX	
EDX	

	Stack Frame of foo's Caller
	Padding
	b
	a
	Return Addr of foo's Caller
EBP	EBP of foo's Caller
	EBX of foo's Caller
ESP	

Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	
EBX	
EDX	a

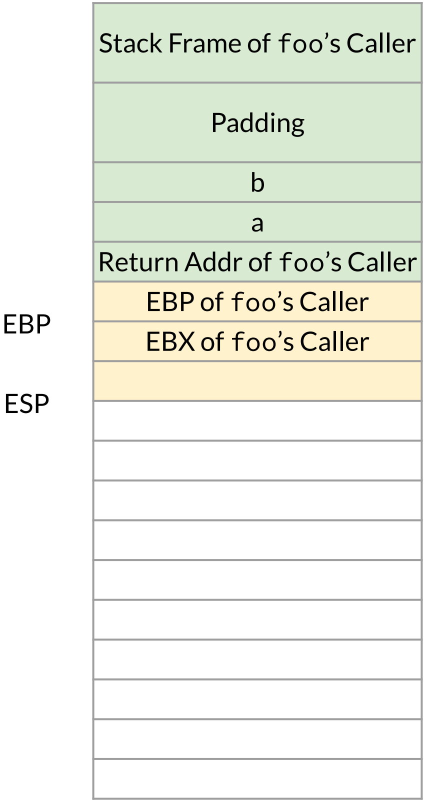
	Stack Frame of foo's Caller
	Padding
	b
	a
	Return Addr of foo's Caller
EBP	EBP of foo's Caller
	EBX of foo's Caller
ESP	

Stack Frame

```
                call.s
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	b
EBX	
EDX	a



	Stack Frame of foo’s Caller
	Padding
	b
	a
	Return Addr of foo’s Caller
EBP	EBP of foo’s Caller
	EBX of foo’s Caller
ESP	

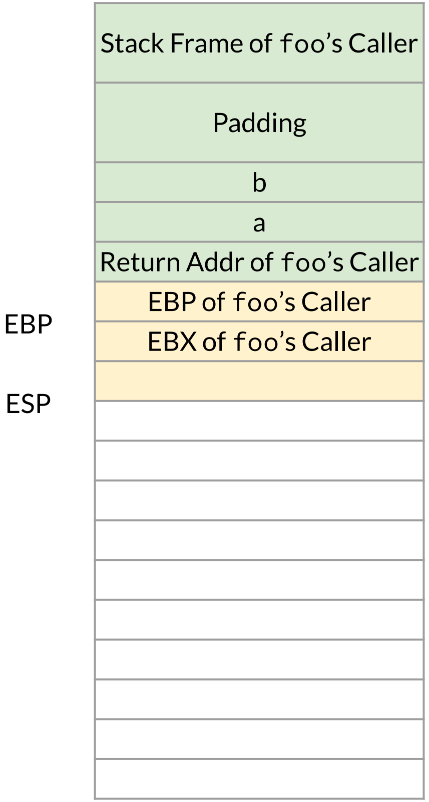
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	b
EBX	a + b
EDX	a



Stack Frame of foo’s Caller

Padding

b

a

Return Addr of foo’s Caller

EBP

EBP of foo’s Caller

EBX of foo’s Caller

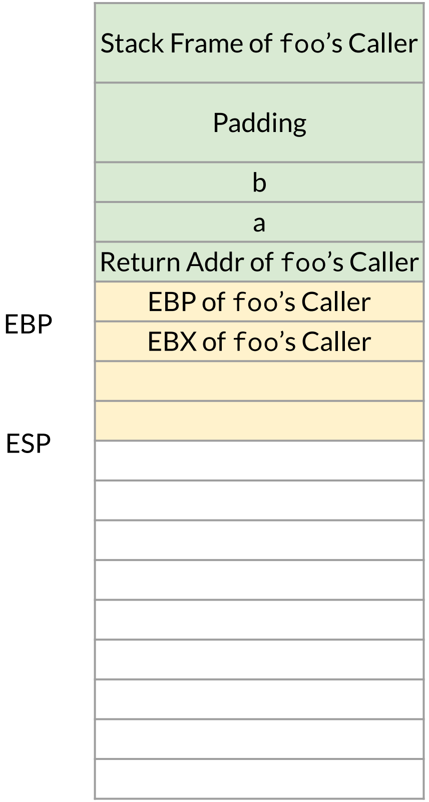
ESP

Stack Frame

```
                  call.s
p:
        .zero     4
bar:
        pushl     %ebp
        movl      %esp, %ebp
        subl      $16, %esp
        movl      8(%ebp), %edx
        movl      12(%ebp), %eax
        addl      %edx, %eax
        subl      16(%ebp), %eax
        movl      %eax, -4(%ebp)
        movl      -4(%ebp), %eax
        addl      $1, %eax
        leave
        ret
foo:
        pushl     %ebp
        movl      %esp, %ebp
        pushl     %ebx
        subl      $4, %esp
        movl      8(%ebp), %edx
        movl      12(%ebp), %eax
        leal      (%edx,%eax), %ebx
        subl      $4, %esp
        pushl     $5
        pushl     $4
        pushl     $3
        call      bar
        addl      $16, %esp
        addl      %ebx, %eax
        movl      %eax, p
        nop
        movl      -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	b
EBX	a + b
EDX	a



Stack Frame of foo’s Caller

Padding

b

a

Return Addr of foo’s Caller

EBP of foo’s Caller

EBX of foo’s Caller

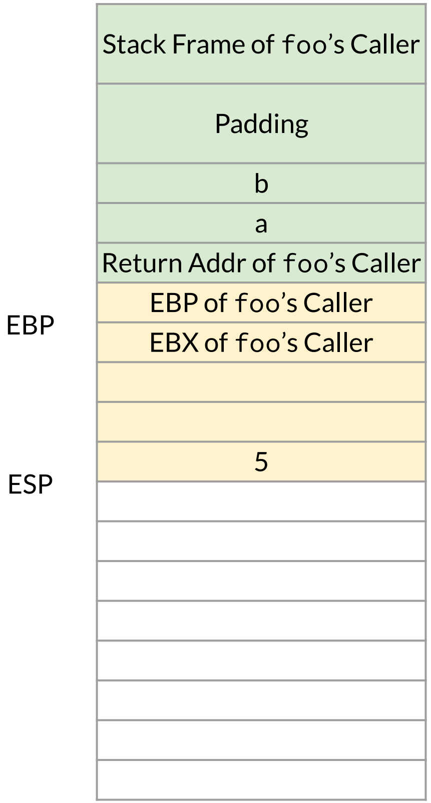
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	b
EBX	a + b
EDX	a



Stack Frame of foo's Caller

Padding

b

a

Return Addr of foo's Caller

EBP — EBP of foo's Caller

EBX of foo's Caller

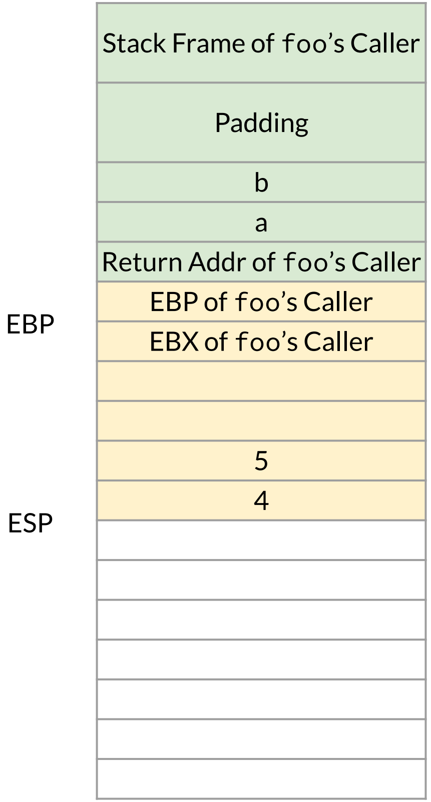
ESP — 5

Stack Frame

```
                call.s
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	b
EBX	a + b
EDX	a



Stack Frame of foo’s Caller

Padding

b

a

Return Addr of foo’s Caller

EBP — EBP of foo’s Caller

EBX of foo’s Caller

5

ESP — 4

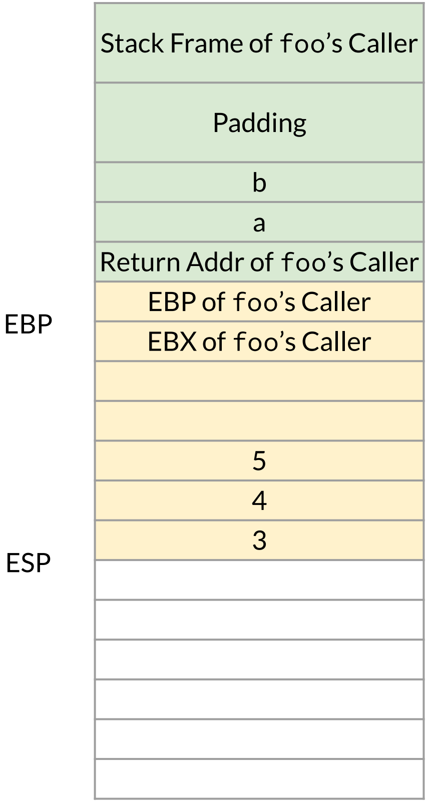
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	b
EBX	a + b
EDX	a



Stack Frame of foo’s Caller

Padding

b

a

Return Addr of foo’s Caller

EBP — EBP of foo’s Caller

EBX of foo’s Caller

5

4

ESP — 3

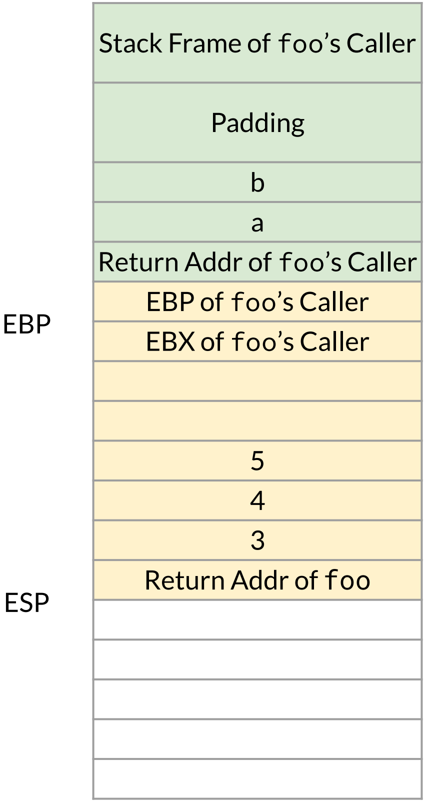
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	b
EBX	a + b
EDX	a



	Stack Frame of foo's Caller
	Padding
	b
	a
	Return Addr of foo's Caller
EBP	EBP of foo's Caller
	EBX of foo's Caller
	5
	4
	3
ESP	Return Addr of foo

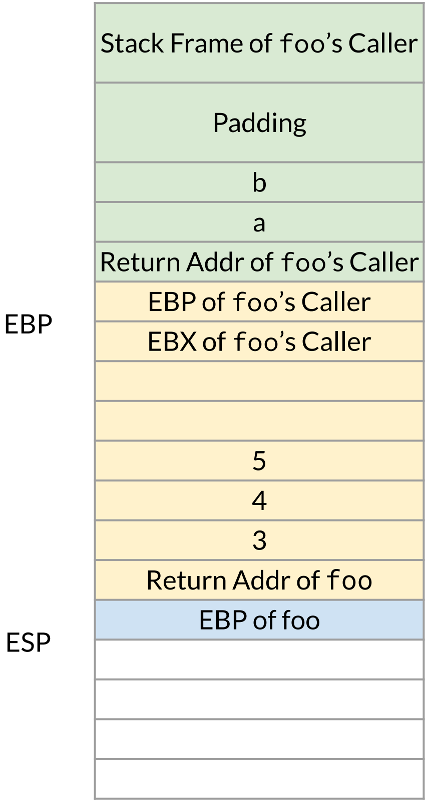
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	b
EBX	a + b
EDX	a



Stack Frame of foo's Caller

Padding

b

a

Return Addr of foo's Caller

EBP — EBP of foo's Caller

EBX of foo's Caller

5

4

3

Return Addr of foo

ESP — EBP of foo

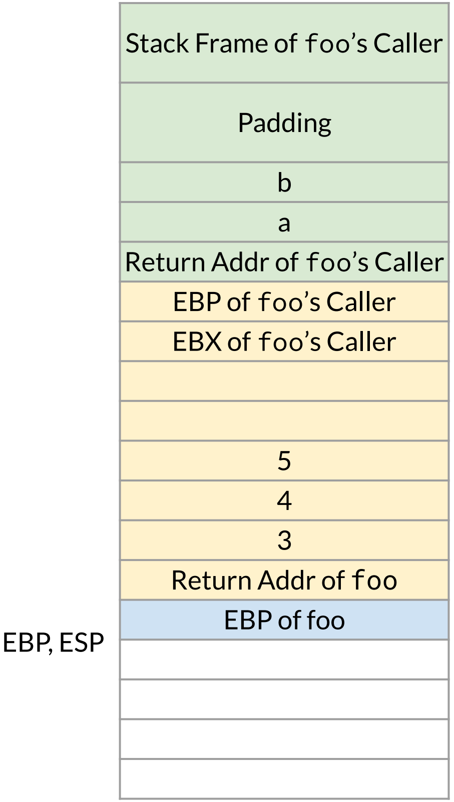
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	b
EBX	a + b
EDX	a



Stack Frame of foo's Caller

Padding

b

a

Return Addr of foo's Caller

EBP of foo's Caller

EBX of foo's Caller

5

4

3

Return Addr of foo

EBP, ESP

EBP of foo

Stack Frame

```
                call.s
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	b
EBX	a + b
EDX	a

	Stack Frame of foo's Caller
	Padding
	b
	a
	Return Addr of foo's Caller
	EBP of foo's Caller
	EBX of foo's Caller
	5
	4
	3
	Return Addr of foo
EBP	EBP of foo
ESP	

Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	b
EBX	a + b
EDX	3

	Stack Frame of foo's Caller
	Padding
	b
	a
	Return Addr of foo's Caller
	EBP of foo's Caller
	EBX of foo's Caller
	5
	4
	3
	Return Addr of foo
EBP	EBP of foo
ESP	

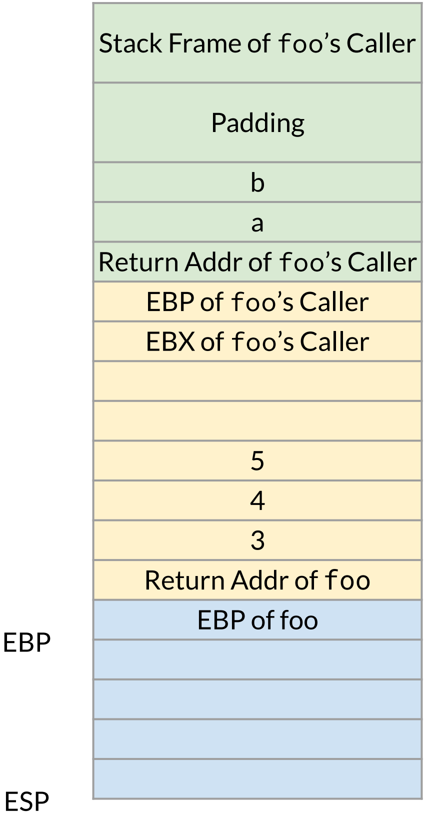
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	4
EBX	a + b
EDX	3



Stack Frame of foo's Caller

Padding

b

a

Return Addr of foo's Caller

EBP of foo's Caller

EBX of foo's Caller

5

4

3

Return Addr of foo

EBP of foo

EBP

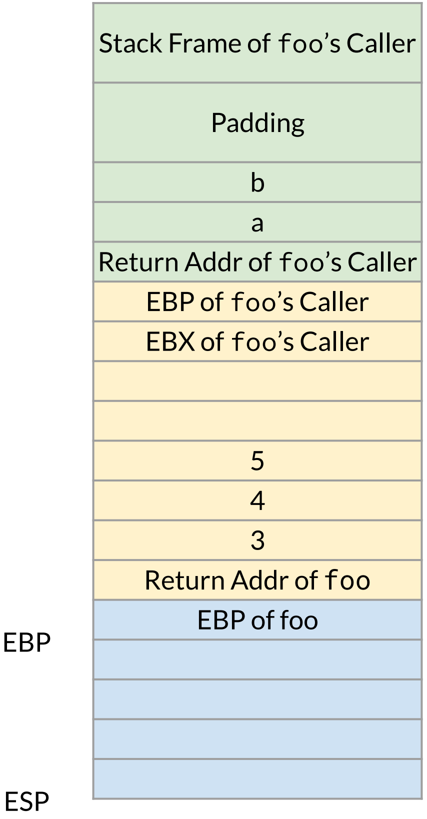
ESP

Stack Frame

```
                call.s
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	7
EBX	a + b
EDX	3



Stack Frame of foo's Caller

Padding

b

a

Return Addr of foo's Caller

EBP of foo's Caller

EBX of foo's Caller

5

4

3

Return Addr of foo

EBP of foo

Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	2
EBX	a + b
EDX	3

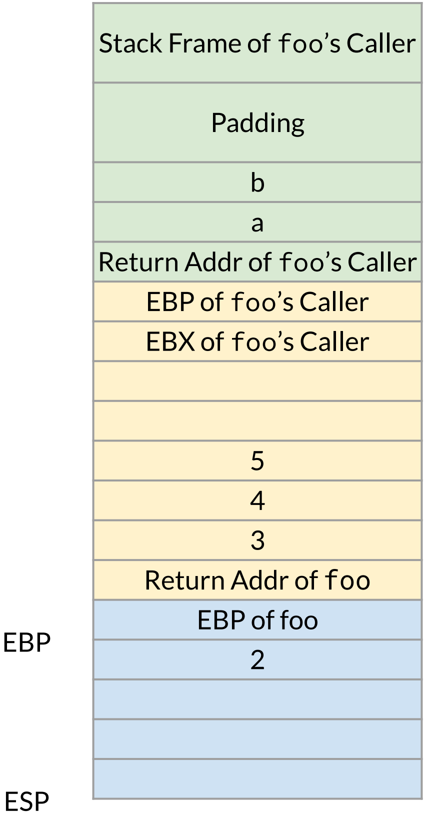
	Stack Frame of foo's Caller
	Padding
	b
	a
	Return Addr of foo's Caller
	EBP of foo's Caller
	EBX of foo's Caller
	5
	4
	3
	Return Addr of foo
EBP	EBP of foo
ESP	

Stack Frame

```
                call.s
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	2
EBX	a + b
EDX	3



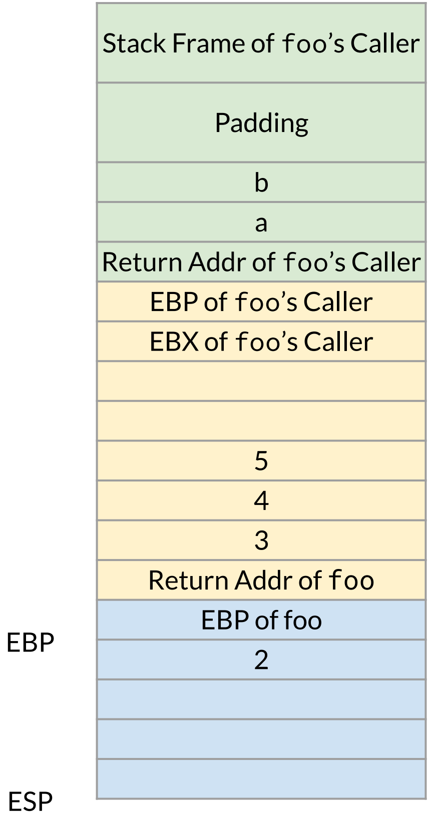
	Stack Frame of foo's Caller
	Padding
	b
	a
	Return Addr of foo's Caller
	EBP of foo's Caller
	EBX of foo's Caller
	5
	4
	3
	Return Addr of foo
EBP	EBP of foo
	2
ESP	

Stack Frame

```
                call.s
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	2
EBX	a + b
EDX	3



Stack Frame of foo's Caller

Padding

b

a

Return Addr of foo's Caller

EBP of foo's Caller

EBX of foo's Caller

5

4

3

Return Addr of foo

EBP of foo

2

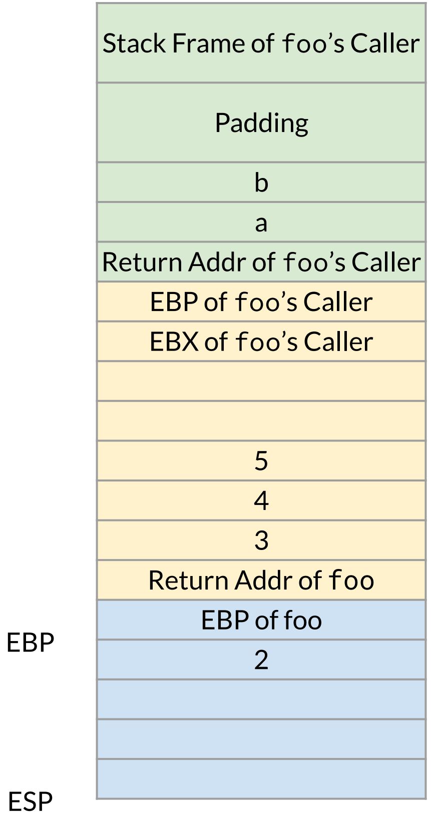
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	3
EBX	a + b
EDX	3



Stack Frame of foo's Caller

Padding

b

a

Return Addr of foo's Caller

EBP of foo's Caller

EBX of foo's Caller

5

4

3

Return Addr of foo

EBP of foo

2

EBP

ESP

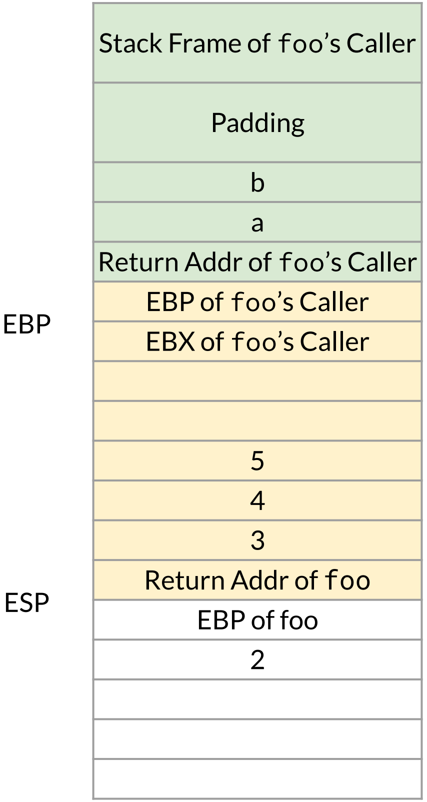
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	3
EBX	a + b
EDX	3



	Stack Frame of `foo`’s Caller
	Padding
	b
	a
	Return Addr of `foo`’s Caller
	EBP of `foo`’s Caller
EBP	EBX of `foo`’s Caller
	5
	4
	3
	Return Addr of `foo`
ESP	EBP of foo
	2

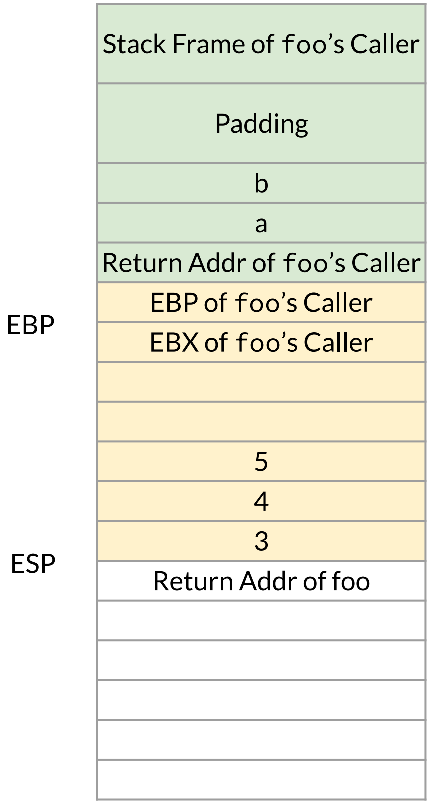
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	3
EBX	a + b
EDX	3



Stack Frame of foo's Caller

Padding

b

a

Return Addr of foo's Caller

EBP

EBP of foo's Caller

EBX of foo's Caller

5

4

3

ESP

Return Addr of foo

Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	3
EBX	a + b
EDX	3

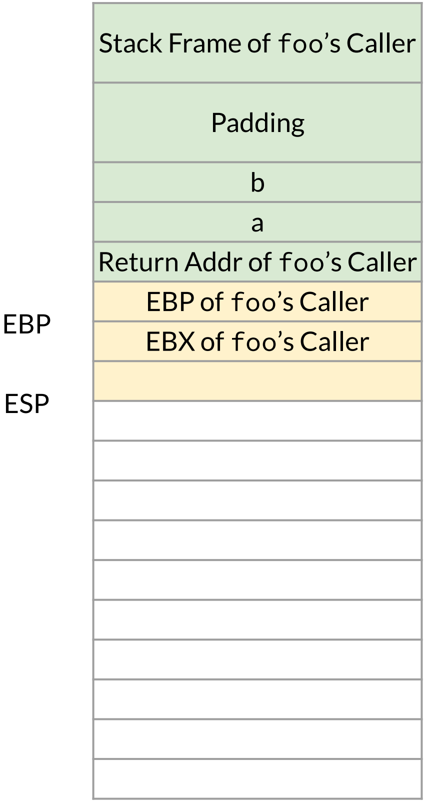
	Stack Frame of foo's Caller
	Padding
	b
	a
	Return Addr of foo's Caller
EBP	EBP of foo's Caller
	EBX of foo's Caller
ESP	
	5
	4
	3

Stack Frame

```
                 call.s
p:
       .zero    4
bar:
       pushl    %ebp
       movl     %esp, %ebp
       subl     $16, %esp
       movl     8(%ebp), %edx
       movl     12(%ebp), %eax
       addl     %edx, %eax
       subl     16(%ebp), %eax
       movl     %eax, -4(%ebp)
       movl     -4(%ebp), %eax
       addl     $1, %eax
       leave
       ret
foo:
       pushl    %ebp
       movl     %esp, %ebp
       pushl    %ebx
       subl     $4, %esp
       movl     8(%ebp), %edx
       movl     12(%ebp), %eax
       leal     (%edx,%eax), %ebx
       subl     $4, %esp
       pushl    $5
       pushl    $4
       pushl    $3
       call     bar
       addl     $16, %esp
       addl     %ebx, %eax
       movl     %eax, p
       nop
       movl     -4(%ebp), %ebx
       leave
       ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	3 + a + b
EBX	a + b
EDX	3



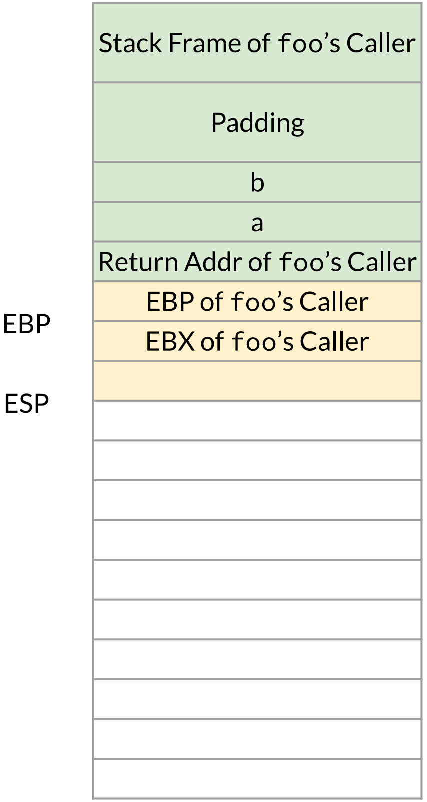
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	3 + a + b
EBX	EBX of foo's Caller
EDX	3



Stack Frame of foo's Caller

Padding

b

a

Return Addr of foo's Caller

EBP — EBP of foo's Caller

EBX of foo's Caller

ESP

Stack Frame

```
                  call.s
p:
        .zero     4
bar:
        pushl     %ebp
        movl      %esp, %ebp
        subl      $16, %esp
        movl      8(%ebp), %edx
        movl      12(%ebp), %eax
        addl      %edx, %eax
        subl      16(%ebp), %eax
        movl      %eax, -4(%ebp)
        movl      -4(%ebp), %eax
        addl      $1, %eax
        leave
        ret
foo:
        pushl     %ebp
        movl      %esp, %ebp
        pushl     %ebx
        subl      $4, %esp
        movl      8(%ebp), %edx
        movl      12(%ebp), %eax
        leal      (%edx,%eax), %ebx
        subl      $4, %esp
        pushl     $5
        pushl     $4
        pushl     $3
        call      bar
        addl      $16, %esp
        addl      %ebx, %eax
        movl      %eax, p
        nop
        movl      -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	3 + a + b
EBX	EBX of foo's Caller
EDX	3

EBP	Stack Frame of foo's Caller
	Padding
	b
	a
ESP	Return Addr of foo's Caller
	EBP of foo's Caller
	EBX of foo's Caller

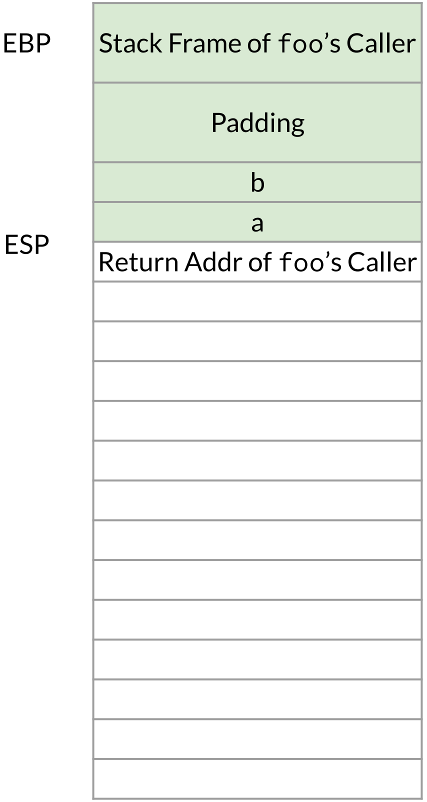
Stack Frame

call.s

```
p:
        .zero   4
bar:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        addl    %edx, %eax
        subl    16(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    -4(%ebp), %eax
        addl    $1, %eax
        leave
        ret
foo:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   %ebx
        subl    $4, %esp
        movl    8(%ebp), %edx
        movl    12(%ebp), %eax
        leal    (%edx,%eax), %ebx
        subl    $4, %esp
        pushl   $5
        pushl   $4
        pushl   $3
        call    bar
        addl    $16, %esp
        addl    %ebx, %eax
        movl    %eax, p
        nop
        movl    -4(%ebp), %ebx
        leave
        ret
```

4. Draw the stack frame with ESP and EBP and contents of EAX, EBX, EDX registers.

EAX	3 + a + b
EBX	EBX of foo's Caller
EDX	3



EBP

Stack Frame of foo's Caller

Padding

b

a

ESP

Return Addr of foo's Caller