Discussion 0: C, x86

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Contents

1 C

C is often the programming language of choice in operating systems. C grants programmers low-level access to memory which is very useful. You'll be reading and writing a lot of C code throughout this class.

Types

C is **statically typed** where types are known at compile time. However, C is also **weakly typed** meaning you can cast between any types. This gives the necessary flexibility for working with low-level memory, but it also opens up many avenues for errors if you're not careful.

The primitive types include `char`, `short`, `int`, `long`, `float`, and `double`. The size of data types may vary depending on the operating system, so it's best to check using the operator `sizeof`.

Arrays, denoted with `[]` (e.g. `int[]`), are contiguous regions of memory of fixed size. Each element is the size of the data type corresponding to that array. A **string** in C is just an array of characters with a last element as `null` to indicate the end of the string.

Users can define compound data types using `structs` which are contiguous pieces of memory comprised of multiple other data types.

Pointers are references that hold the address of an object in memory. Fundamentally, pointers are just unsigned integers of size equal to the number of bits supported by the operating system. Prefixing a pointer with `*` will return the value at the memory address that the pointer is holding. On the other hand, prefixing a variable with `&` will return the memory address of the variable.

Memory

A typical C program's memory is divided into five segments.

Segment	Purpose
Text	Machine code of the compiled program
Initialized Data	Initialized global and static memory
Uninitialized Data	Uninitialized global and static memory
Heap	Dynamically allocated memory
Stack	Local variables and argument passing

In general, memory can be thought of as a giant array with elements of one byte where a memory address indexes into this array.

Unlike stack memory, heap memory needs to be explicitly managed by the user. Memory can be allocated in the heap using `malloc`, `calloc`, or `realloc`. These all return a pointer to a chunk of memory in heap that is the size of the amount requested. When the memory is no longer being used, it needs to be explicitly released using `free`.

GNU Debugger (GDB)

GNU Debugger (**GDB**) is a powerful tool to debug your programs. While you may have skidded by CS 61C without using it, the complicated codebase for this class will require you to be proficient with GDB. Help will not be given to those who are not able to use GDB.

The general workflow of using GDB is as follows.

1. Compile the program using the `-g` flag.
2. Start GDB using `gdb <executable>`.
3. Set breakpoints using `break <linenum>`. You can also break at functions by using `break <func>`.
4. Run program with `run`. If the program takes in arguments, pass in those (i.e. `run arg1 arg2`).

5. Once you hit your breakpoint, examine using `print`. Other commands like `display`, `watch`, `set`, and many more will come in handy. You can also step line by line using `next`.

While you don't have to memorize all the GDB commands, you'll grow familiar with them the more you use them. When looking for certain functionality, check out the GDB User Manual[1].

1.1 Concept Check

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

   4 bytes

2. Consider strings initialized as

   string literal in read only section

   ```
   char* a = "162 is the best";
   char b[] = "162 is the best";
   ```

   Are `a` and `b` different? ↑ char array

   Yes, a is a char pointer, b is a char array

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

   nums and &nums[0] points to first element

   nums is the address of 152, & nums is the address of {152, 161, 162}

   &nums[0] will be {152, 161, 162

   &nums points to the entire array

[1] https://sourceware.org/gdb/current/onlinedocs/gdb/

1.2 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?

   12 bytes 16 bytes 9+1+7 (padding)

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

   2 bytes 24 bytes

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

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

   app is compiled with ABC defined so it will have different definition of helper_args_t from lib.c

   The program will now exhibit undefined behavior. What is the issue?

   multiple definition of helper_func

1.3 Debugging Segmentation Faults

Observe the following program from `singer.c` which aims to sort a string using quicksort. The program will use a string provided as the argument or defaults to `"IU is the best singer!"` if none is provided.

When the program is compiled and run, we get the output on the right. Use GDB to fix the issue.

To play with the following code yourself, you can fork the Discussion 0 Repl[2].

```
4  void swap(char* a, int i, int j) {
5    char t = a[i];
6    a[i] = a[j];
7    a[j] = t;
8  }
9
10 int partition(char* a, int l, int r){
11   int pivot = a[l];
12   int i = l, j = r+1;
13
14   while (1) {
15     do
16       ++i;
17     while (a[i] <= pivot && i <= r);
18
19     do
20       --j;
21     while (a[j] > pivot);
22
23     if (i >= j)
24       break;
25
26     swap(a, i, j);
27   }
28
29   swap(a, l, j);
30
31   return j;
32 }
33
34 void sort(char* a, int l, int r){
35   if (l < r){
36     int j = partition(a, l, r);
37     sort(a, l, j-1);
38     sort(a, j+1, r);
39   }
40 }
41
42 int main(int argc, char** argv){
43   char* a = NULL;
44
45   if (argc > 1)
```

```
> ./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] https://replit.com/@cs162-staff/intro

```
46      a = argv[1];
47    else
48      a = "IU is the best singer!";
49
50    printf("Unsorted: \"%s\"\n", a);
51    sort(a, 0, strlen(a) - 1);
52    printf("Sorted  : \"%s\"\n", a);
53  }
```

singer.c

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

compile with -g flags

2. When running the program without any arguments (i.e. using the default argument), what line does the segfault happen? Describe the memory operations happening in that line.

line 6 a[i] = a[j] in swap

This gets the jth element in a and assign it to the ith element in write to a[i]

3. Run the program with and without an argument and observe the memory address of `a` in the segfaulting

line. Why are the memory addresses so different?

The one without args is 0x555555556004

The one with args is 0x7fffffffe6e8

I think the first one args is in stack
the second one args is in bss

statically defined string resides in read only memory
string on the stack is writable

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

use malloc and strcpy to initialize string
or strdup

[a] https://man7.org/linux/man-pages/man3/strdup.3.html

2 x86

x86 is a family of instruction set architectures (ISA) developed by Intel. Unlike RISC-V from CS 61C, x86 is based on based on the complex instruction set computer (CISC) architecture. x86 being a family of ISAs means there are a variety of different dialects of this language. In this class, we will focus on the 32-bit ISA called **IA-32** or **i386** which is the common denominator for all 32-bit x86 processors and hence used in Pintos. While heavily related, this should not be confused with the 32-bit microprocessor i386, also known as Intel 80386). However, we will still occasionally mention the 64-bit ISA **x86-64** as you may come across during some non-Pintos assignments.

Registers

Registers are small storage spaces directly on the processor, allowing for fast memory access.

Recall from CS 61C that RISC-V had 31 **general purpose registers** (**GPR**) `x0 - x31` with appropriate ABI names (e.g. `x2` = `sp` for stack pointer). Due to architectural differences, x86 only has 8 GPRs.

Register	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)

Due to x86's 16-bit history, the GPRs started as 16-bits and were extended to 32-bits with the `e` prefix (e.g. `eax` for `ax`) and 64-bits with the `r` prefix (e.g. `rax` for `ax`). Each 16-bit GPR can be addressed by the 8-bit LSB (i.e. lower 8 bits) by replacing the last letter with `l` (e.g. `al` for `ax`). `ax`, `cx`, `dx`, and `bx` can also be addressed by the 8-bit MSB (i.e. higher 8 bits) by replacing the last letter with `h` (e.g. `ah` for `ax`).

Akin to the program counter register `pc` from RISC-V, x86 has an **instruction pointer register** `ip`. Like the GPRs, it is extended to 32-bits with the `e` prefix and 64-bits with `r` prefix. `ip` is a special register since it cannot be read and modified like a GPR (i.e. cannot use vanilla memory instructions).

There are other registers such as segment, EFLAGS, control, debug, test, floating point and many more. However, the GPRs and the instruction pointer register are the main ones you will work with in this class.

Syntax

Although IA-32 specifies the registers and instructions, there are two different syntaxes: Intel and AT&T. In this class, we will use the **AT&T syntax** because it is used by the GNU Assembler, the assembler for GCC and thus the standard for Pintos and most Unix-like operating systems like Linux. The two syntaxes have significant differences, so make sure to check which syntax is being used when referencing documentation.

Registers are preceded by a percent sign (e.g. `%eax` for `eax`). Immediates such as constants are preceded by a dollar sign (e.g. `$162` for the constant 162).

The general structure of a line of code is `inst src, dest`. For example, `$movl %ebx, %eax` will move the contents of `%ebx` into `%eax`.

Addressing memory uses the synax of `offset(base, index, scale)` where `base` and `index` are registers, and `offset` and `scale` are integers (`scale` can only take on values of 1, 2, 4, or 8). This accesses the data at memory address `base + index * scale + offset`. All parameters are optional, though most cases you will see will have `base` and `offset`. `scale` The following are some use cases of addressing memory with different instructions.

`mov 8(%ebx), %eax`	Move contents from the address ebx + 8 into eax
`mov %ecx, -4(%esi, %ebx, 8)`	Move contents in ecx into address esi + 8 * ebx - 4

One exception to the above syntax is when using the `lea` instruction which stands for "load effective address". `lea` operates directly on the memory addresses themselves and not the contents contained in the memory addresses. For instance, `lea 8(%ebx), %eax` would put the address ebx + 8 into eax, not the contents at that address.

Each instruction also has a suffix that signifies the operand size. `b` means byte (8 bits), `w` means word (16 bits), and `l` means long (32 bits). These are used when the the intended data size is ambiguous (e.g. `mov $0, (%esp)`).

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

The suffixes aren't always necessary when the intended data size can be inferred in some cases (e.g. using a 32-bit register as an operand means a 32-bit operation), but it is good practice to use them regardless.

A key difference of x86 from RISC-V is how much one instruction accomplishes due to its complicated instruction set. For instance, let's examine

Calling Convention

Calling convention is a procedure for how to call and return from functions. They specify stack management, passing in parameters, any registers that need to be saved, stack management, returning values, and more. There are two sets of rules: one for the caller of the function and one for the callee of the function.

Calling conventions are heavily tied into the language that's being compiled. In this class, we will use the calling convention defined by the i386 System V ABI as the default calling convention.

Caller

Before calling the function (i.e. prologue), the caller needs to

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 (i.e. store first parameter at the lowest address). Add necessary padding *before the parameters* to ensure a 16-byte alignment.

Then the caller calls the function by pushing the return address onto the stack and jumping to the function. Once the function call returns (i.e. epilogue), the caller needs to

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

Callee

Before executing any function logic (i.e. prologue), the callee needs to

1. Push EBP onto the stack and set ebp to be the new esp (i.e. stack pointer after pushing the ebp). This marks the start of a new stack frame.
2. Allocate stack space for any local variables (i.e. decrement esp).
3. Save callee-saved GPRs (ebx, edi, esi) onto the stack if used during the function call.

Then the callee performs the function logic. Before returning (i.e. epilogue), the callee needs too

1. Store the return value in eax.
2. Restore callee-saved GPRs (if any) from the prologue.

3. Deallocate local variables. While subtracting the correct amount will technically work, a less error prone way is to set esp to be the current ebp, effectively clearing the stack frame.
4. Restore caller's ebp from the stack.
5. Return from the function by popping the return address pushed by the caller in its prologue and jumping to it.

Instructions

There are a few commonly used instructions that will show up in nearly every assembly code due to the 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`

Keep in mind the effective column shows what the instruction is doing, but it may not exactly be what the processor does. In fact, `call` and `ret` access EIP directly using `mov` which is not allowed.

Optimizations

When compiling with some optimizations using GCC (e.g. `O3` flag), you may notice some violations of these calling conventions, most notably the saving of the base pointer. This is because the base pointer is not a necessity: the stack pointer is sufficient to address anything we need. Even when using RISC-V, the equivalent frame pointer was not saved during calling convention.

Another notable omission is the 16-byte stack alignment which GCC omits by default even without any optimizations. As a result, you will need to specify the `-fno-ipa-stack-alignment` flag when compiling to get the necessary 16-byte alignment.

2.1 Concept Check

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

   BP

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

   CISC combine instructions reduced instruction set

3. Write three different ways to clear the `eax` register (i.e. store a 0). leaves more Room for processor

```
and  %eax  %eax  0
mov  0     %eax
subl %eax, %eax
```

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

False, after the parameters have been pushed onto the stack

2.2 Reverse Engineering

A Pythagorean triplet $a < b < c$ satisfies the property $a^2 + b^2 = c^2$. `triplet.s` on the right returns the product of a Pythagorean triplet for which $a + b + c = 1000$. `triplet.s` has been assembled without optimizations based on a complete version of `triplet.c` given on the left. Unused labels and directives have been omitted in `triplet.s` for simplicity.

```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;
}
```

triplet.c

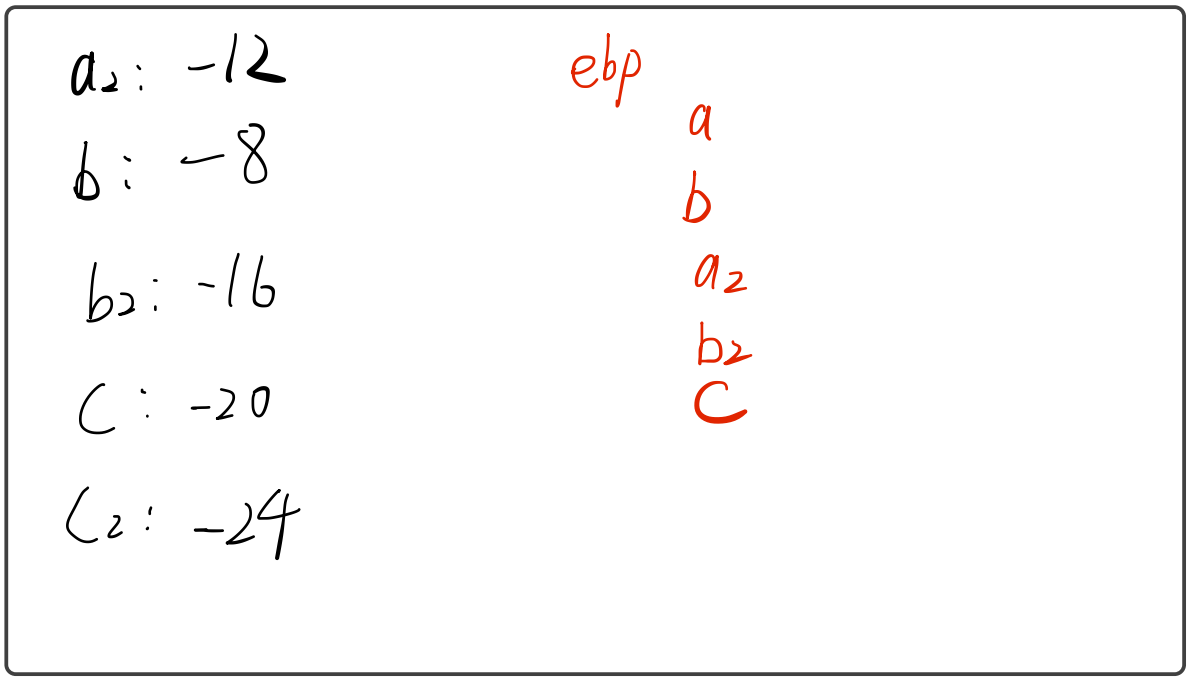
```
1  main:
2          pushl   %ebp
3          movl    %esp, %ebp
4          subl    $32, %esp
5          movl    $1, -4(%ebp)
6          jmp     .L2
7  .L7:
8          movl    -4(%ebp), %eax
9          imull   %eax, %eax
10         movl    %eax, -12(%ebp)
11         movl    -4(%ebp), %eax
12         movl    %eax, -8(%ebp)
13         jmp     .L3
14 .L6:
15         movl    -8(%ebp), %eax
16         imull   %eax, %eax
17         movl    %eax, -16(%ebp)   b2
18         movl    $1000, %eax
19         subl    -4(%ebp), %eax
20         subl    -8(%ebp), %eax
21         movl    %eax, -20(%ebp)
22         movl    -20(%ebp), %eax
23         imull   %eax, %eax
24         movl    %eax, -24(%ebp)
25         movl    -12(%ebp), %edx
26         movl    -16(%ebp), %eax
27         addl    %edx, %eax
28         cmpl    %eax, -24(%ebp)
29         jne     .L4
30         movl    -4(%ebp), %eax
31         imull   -8(%ebp), %eax
32         imull   -20(%ebp), %eax
33         jmp     .L5
34 .L4:
35         addl    $1, -8(%ebp)
36 .L3:
37         cmpl    $666, -8(%ebp)
38         jle     .L6
39         addl    $1, -4(%ebp)
```

```
40 .L2:
41          cmpl    $333, -4(%ebp)
42          jle     .L7
43          movl    $0, %eax
44 .L5:
45          leave
46          ret
```

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

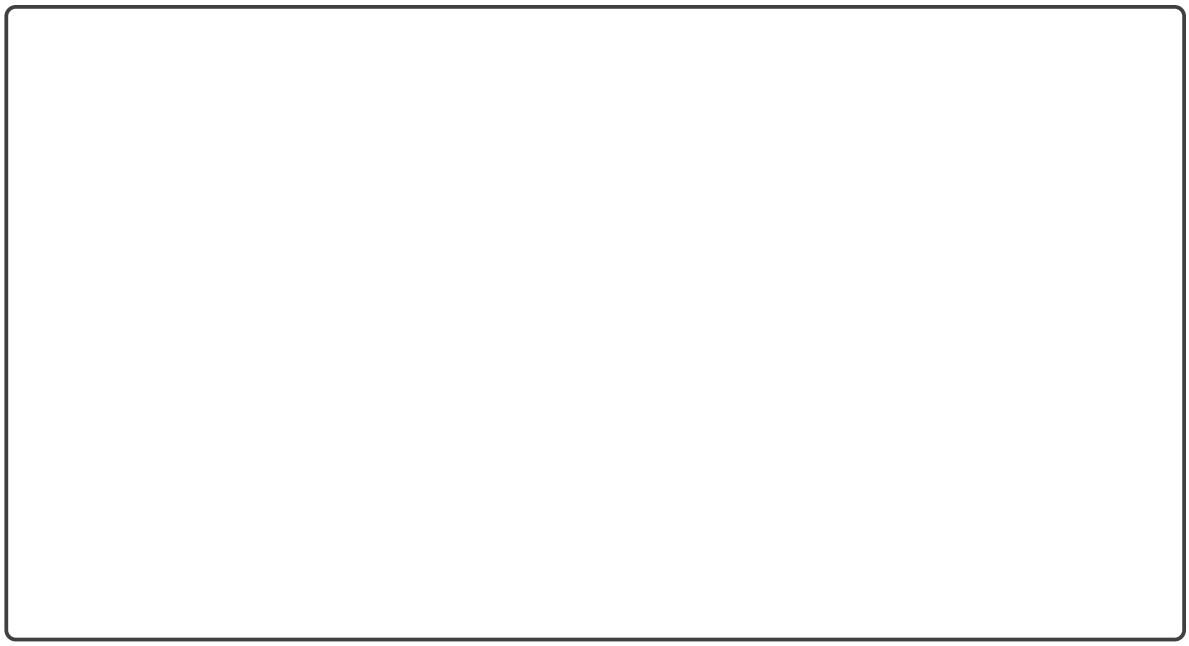
2. What is the end condition for the outer loop using `a`?

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



4. Fill in the missing code for `triplet.c`.

[a] https://gcc.gnu.org/pub/gcc/summit/2003/Optimal%20Stack%20Slot%20Assignment.pdf



2.3 Stack Frame

```c
int p = 0;

int bar(int x, int y, int z) {
  int w = x + y - z;
  return w + 1;
}

void foo(int a, int b) {
  p = a + b + bar(3, 4, 5);
}
```

foobar.c

```
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
```

[a] https://godbolt.org/z/a5cdaonYG

```
34          leave
35          ret
```

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

bar: 4.5.6 14.15
foo: 17.18.19.20 34.35

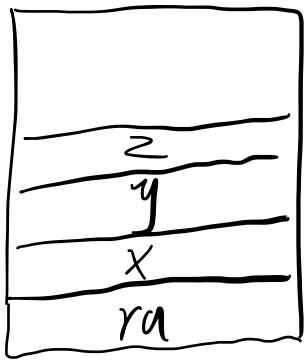
2. What does line 19 do in `call.s`? Why is it necessary?

push ebp in esp, initialize new stack Saves EBX (callee-saved register)

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

EDX is caller saved register

4. Draw the stack frame and contents of relevant registers after executing line 16 of `call.s`.



Stack Frame of foo's caller
padding
b
a
ra of foo's caller
EBP of foo's caller
EBX of foo's caller
5
4
3
ra of foo
EBP of foo
2

[a] https://gcc.gnu.org/onlinedocs/gcc-4.2.4/gcc/i386-and-x86_002d64-Options.html