Hacking in C

Exploring Stack and Heap

Thom Wiggers

Last week

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- Pointers

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- The horrible ways strings ruin your day
- Some bit of slide-karaoke about memory that wasn't prepared

This week

The stack
  Local variables
  The stack

The heap

Special memory segments

Wrapping up memory

Reading the stack

Extra content
  Memory quizzes
  Finding memory bugs

Table of Contents

Local variables

Imagine the following program

```
#include "headers.h"

int main(int argc, char* argv[]){
    int a = 3;
    int b = 4;
    int c = some_function();
    return 0;
}

int some_function() {
    char arr[100] = {0};
    return 3;
}
```

How could we manage variables efficiently?

Properties of local variables

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- Only exist during the function call

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- Clearly not an option

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There's such a manager for heap variables, but those are usually somewhat long-lived! We can do better for the local variables.

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- At the bottom of the ladder is `int main()`

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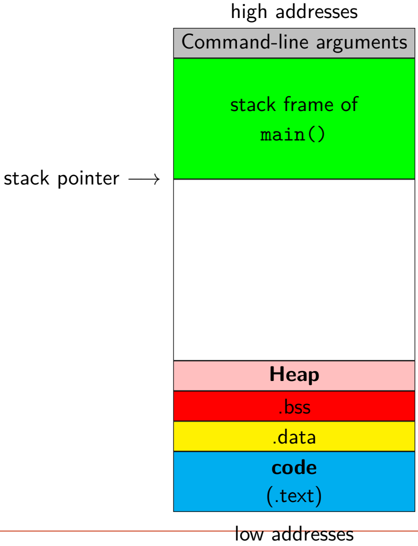
- Push your local variables on top of the stack
- When you call a function, also push those variables on top of the stack
- When that function returns, just pop off those variables from the stack and they're gone
- Only thing to keep track of: where is the top of the stack

Stack frames and the stack pointer

Example:

```
int func(int a, int b)
{
  ...
  return 10001;
}

int main(void)
{
  ...
  int x = func(42, 23)
  ...
}
```



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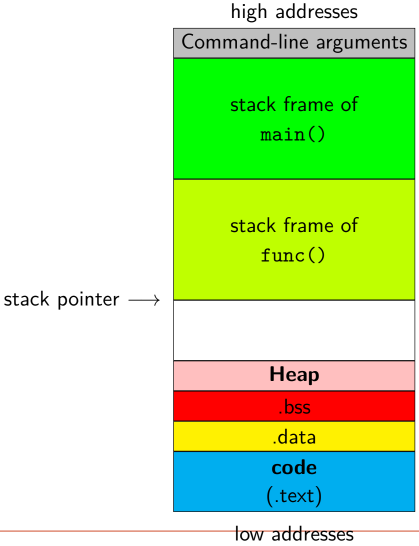

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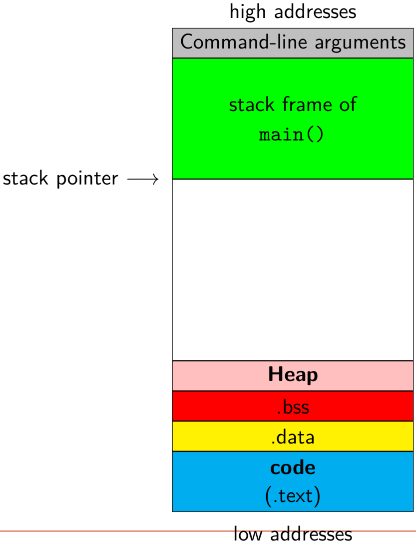
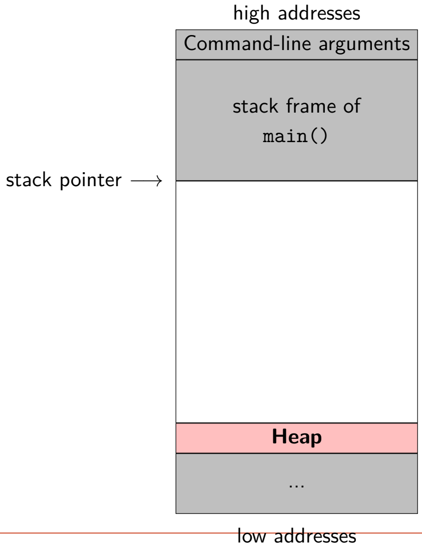


A zoom into the stack frame

- Stack before the function call



high addresses

Command-line arguments

stack frame of `main()`

stack pointer ⟶

Heap

...

low addresses

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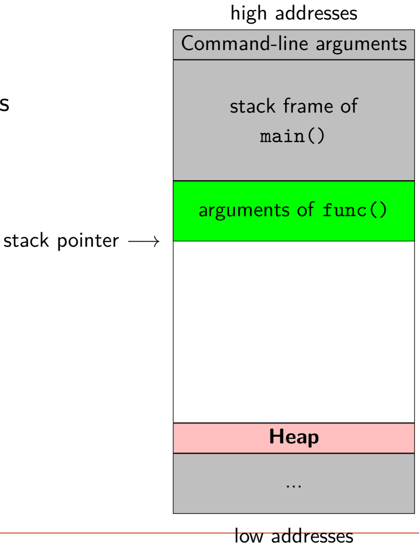

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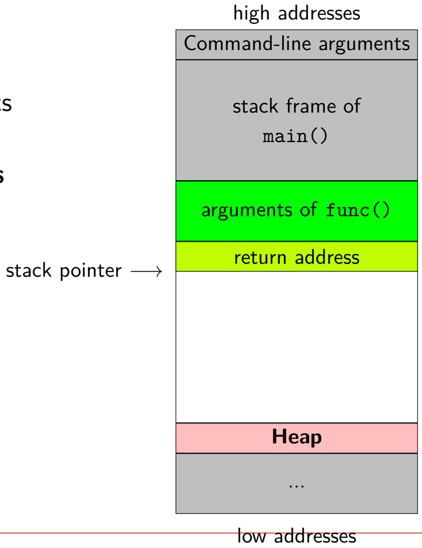

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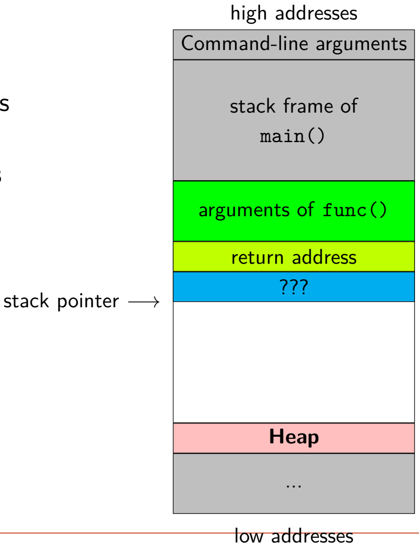

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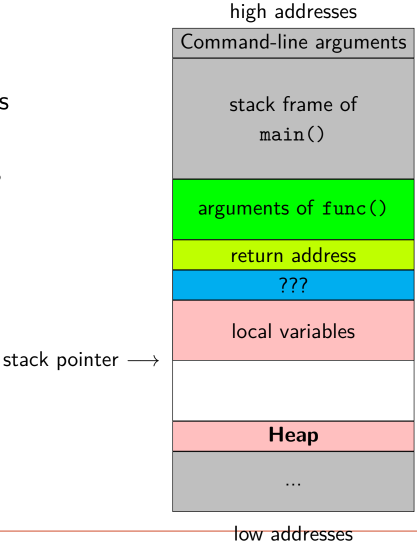

The frame pointer

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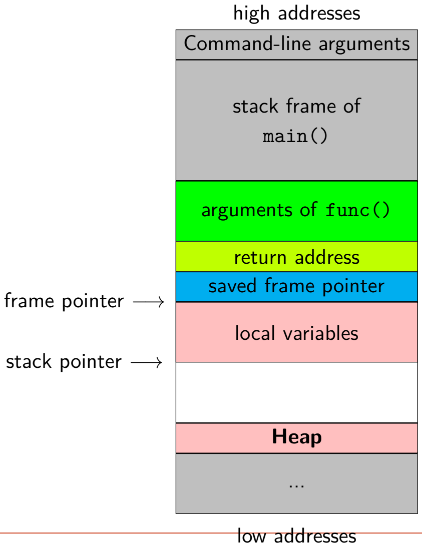

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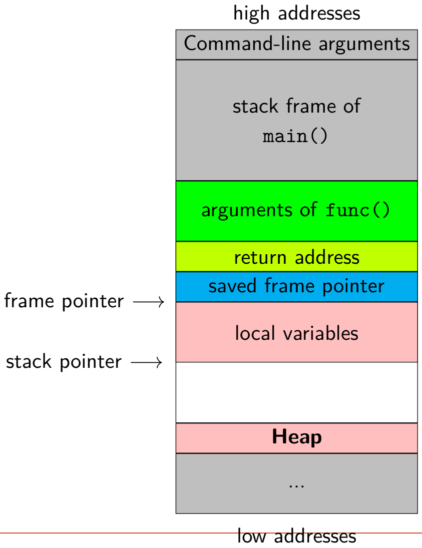

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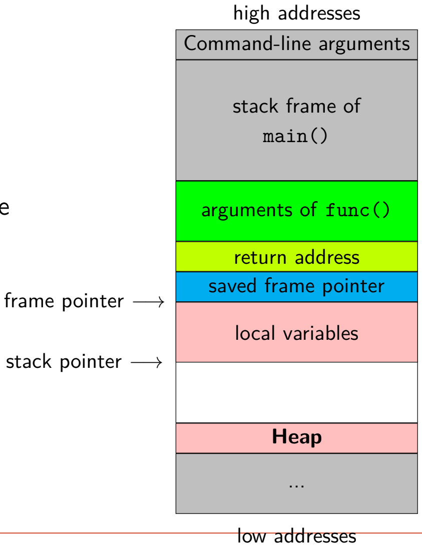

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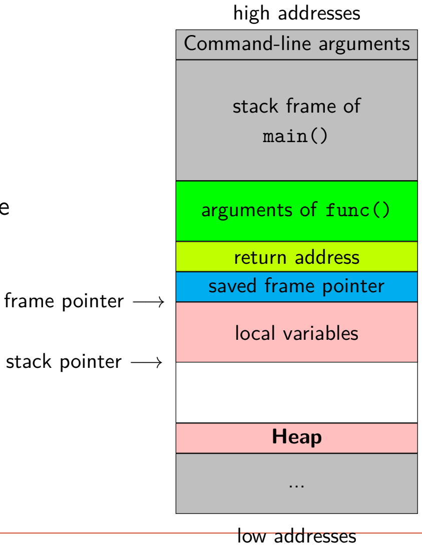

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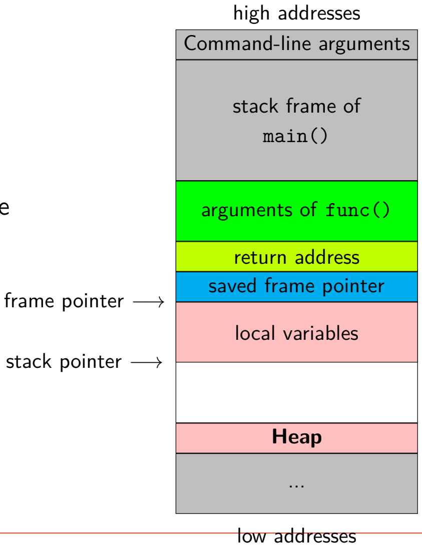

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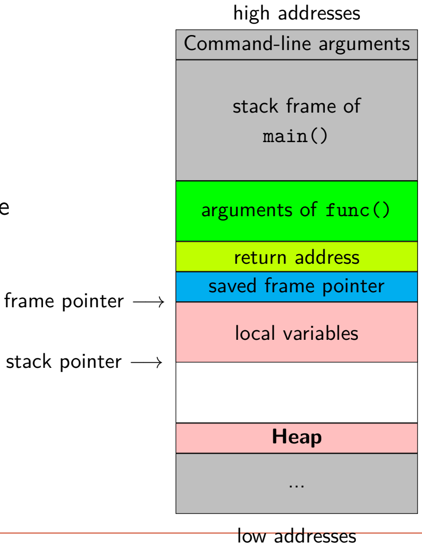

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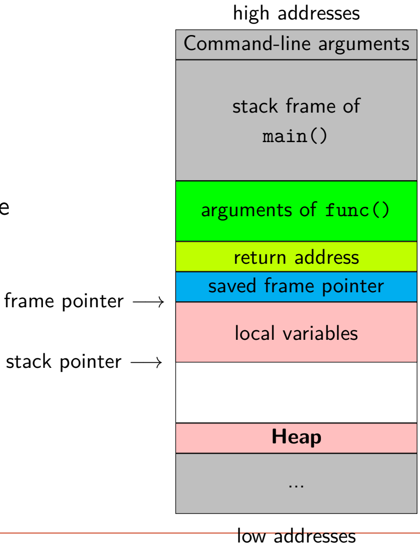

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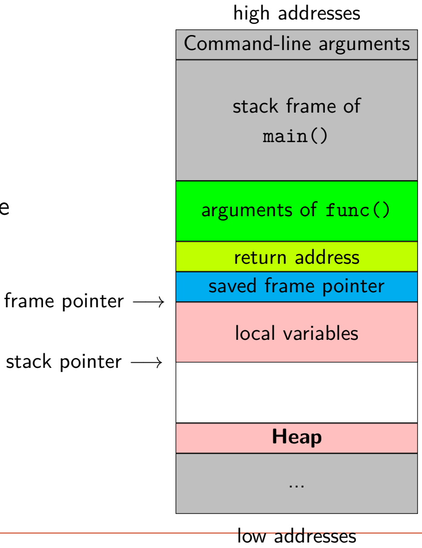

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‡ Returned via register on x64, ARM, ARMv8 and probably other platforms

Stack overflow

- You're probably aware of `https://stackoverflow.com`
- Named for running out of stack space: a *stack overflow*
- Limits set by:
  - Hardware
  - Operating system
- Get (set) limit on Linux via
  - `ulimit -s` (`ulimit -s kb`) on the shell (sets for the current shell)
  - `getrlimit()` (`setrlimit()`) in C

Common stack bugs

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- Writing beyond buffers may overwrite frame pointers or return addresses
  - Segmentation fault, if you overwrote with garbage
  - A hacked system, if you overwrote with the address of your attack code. . .

. . . how bad is “wrong” exactly?

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Toyota's killer firmware: Bad design and its consequences

Michael Dunn -October 28, 2013

EDN MOMENT
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“On Thursday October 24, 2013, an Oklahoma court ruled against Toyota in a case of unintended acceleration that lead to the death of one the occupants. Central to the trial was the Engine Control Module’s (ECM) firmware.”

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"A litany of other faults were found in the code, including buffer overflow, unsafe casting, and race conditions between tasks."

Limitations of the stack

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int* table_of(int num, int len) {
  int table[len];
  for (int i=0; i <= len; i++) {
    table[i] = i * num;
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- Obvious other limitation: size!

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- We can request (large) continuous space on the piece of paper
- Note that “continuous” is easily ensured by virtual memory
- This space is accessible through a pointer
- Space remains valid across function calls
- Every function that “knows” a pointer to the space can use it

`malloc`

- Function to request space: `void *malloc(size_t nbytes)`
- Need to `#include <stdlib.h>` to use `malloc`
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- A `void *` implicitly casts to and from any other pointer type
- Remember that this is *not* the case in C++!
- Example of `malloc` usage:
  ```
  int *x = malloc(10000 * sizeof(int));
  ```
- Request for space for 10 000 integers on the heap

NULL

- The value `NULL` is guaranteed to not point to a valid address
- The following code produces **undefined behavior**:

```
int *x = NULL;
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- The following code produces **undefined behavior**:

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int *x = NULL;
int i = *x;
```

- Important to note: `NULL` is not the same as `0`
- In boolean expressions, `NULL` evaluates to false
- These two lines have the same semantics:

```
if(x == NULL) { printf("NULL\n"); }
if(!x) { printf("NULL\n"); }
```

ALWAYS check for malloc failure!

- The following code is terribly unsafe:

```
int *table = malloc(TABLESIZE * sizeof(int));
for(size_t i=0;i<TABLESIZE;i++){
  table[i] = 42;
}
```

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- Correct version:

  ```
  int *table = malloc(TABLESIZE * sizeof(int));
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  ```

- Could alternatively use boolean behavior of `NULL`:

  ```
  if(!table) exit(255);
  ```

`free`

- You, the programmer, are in charge of *releasing* memory!
- When you don't need some allocated memory anymore, use `free(x);`
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- Can be super annoying to debug

`realloc`

- Sometimes want to *expand* or *shrink* `malloc`'ed space
- Do this by using
  `void *realloc(void *ptr, size_t new_size);`
- Content in the allocated area is preserved
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- If return value is `NULL`, previously allocated memory is not freed!
- Usage pattern:

```
xnew = realloc(x, NEWSIZE);
if(xnew == NULL) {
  free(x);
  exit(-1); // or continue with old size of x
} else {
  x = xnew;
}
```

`calloc`

- Remember that data on the stack is not initialized
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- Example usage:

  ```
  int *p = calloc(1000, sizeof(int));
  if(p == NULL) { exit(-1); }
  ```
- Request space for 1000 integers, all initialized to zero

`malloc` vs. `calloc`

- Aside from initialization, any difference between
    - `int *p = malloc(nelems*sizeof(int));` and
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- Multiplication `nelems*sizeof(int)` can overflow!
- Result: successful allocation, but of *much less* memory!
- Another difference:
  - `malloc` doesn't guarantee you that you can *use* the memory you requested
  - Linux optimistically grants you the memory
  - Later *access* to this memory may still fail
  - `calloc` gives you memory that is actually "backed" by the OS
  - But if you don't actually use it, it'll slow you down

Heap management

- Remember `free`?:

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- Other solution: write information just before the pointer

Dangling pointers, double-free, ...

- **Never** use a pointer after it has been freed, e.g.,

```
int *x = malloc(SIZEX * sizeof(int));
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free(x);
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printf("Let's see what the value of x is now: %p\n", x);
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- This is **undefined behaviour**

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- Pointer alias: multiple pointers to the same location
- Never "lose" the last pointer to a location
- This inevitable creates a memory leak: you *cannot* `free` anymore!

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Memory segments

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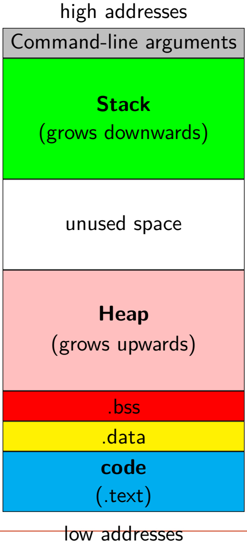
- stack: for local variables (including command-line arguments)



Memory segments

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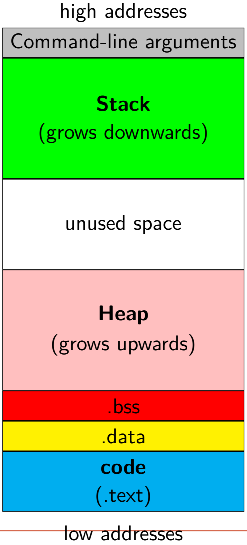
- heap: For *dynamic* memory



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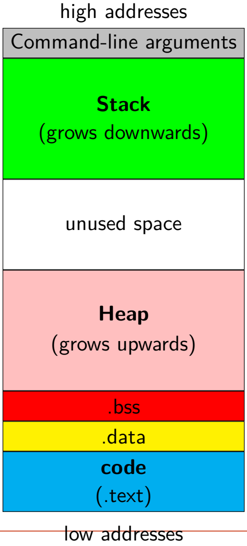
high addresses

Command-line arguments

Stack
(grows downwards)

unused space

Heap
(grows upwards)

.bss

.data

code
(.text)

low addresses

Memory segments

We now covered the stack and the heap, the most important segments, but there are more

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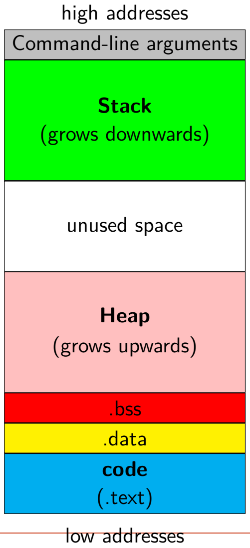
- data segment:
    - global and static uninitialized variables (`.bss`)



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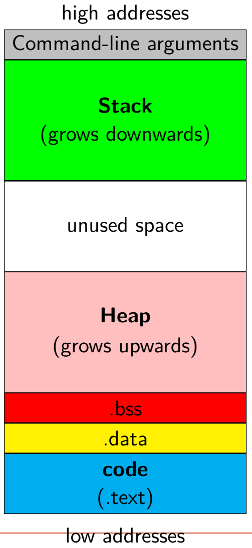

Memory segments

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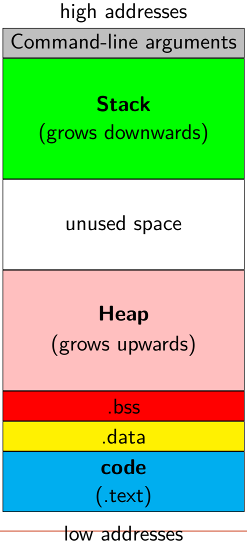
- stack: for local variables (including command-line arguments)
- heap: For *dynamic* memory
- data segment:
  - global and static uninitialized variables (`.bss`)
  - global and static initialized variables (`.data`)
- code segment: code (and possibly constants)



Global variables

- Global variables are declared outside of all functions
- Example:

```
#include <stdio.h>
long n = 12345678;
char *s = "hello world!\n";
int a[256];
...
```

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- Example: AVR microcontrollers with a `.noinit` section
  - Typically your processes on such a device don't have secrets from each other because you wrote all of them.

Static variables

- A static variable is local, but keeps its value across calls
- Example:

```
void f()
{
  static int x = 0;
  printf("%d\n", x++);
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```

- If `x` was not declared static, this function would always print `0`

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- Different for static `x`; output increases by one for every call
- Would get the same behavior if `x` was global
- ... but a global `x` could be modified also by other functions

Table of Contents

Stack vs. heap vs. data segment

Data segment

- Data in the data segment exists throughout the whole execution of the program
  - global variables accessible to every function
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- Stack space automatically removed when returning from a function
- Certain risk of overflowing the stack

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- Space on the stack *allocated automatically*
- Stack space automatically removed when returning from a function
- Certain risk of overflowing the stack

Heap

- Space on the heap needs to be *requested manually* (`malloc`)
- Request may be denied (`NULL` return) and this must be handled
- Space on the heap needs to be *freed manually* (`free`)
- Risk of memory leaks, double frees, etc.

Table of Contents

Remember `printf`?

> `int printf(const char *format, ...);`
>
> *[printf] writes the output under the control of a* ***format string*** *that specifies how subsequent arguments are converted for output.* *src: man 3 printf*

Having fun with `printf`

What does the following program do?

```
// program.c
int main(int argc, char* argv[]) {

    printf(argv[1]);
}
```

```
~$ gcc -Wall -Wextra -Wpedantic -o program program.c
(gcc8 complains **only** about unused variable argc)
~$ ./program hi
hi
```

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What does the following program do *wrongly*?

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// program.c
int main(int argc, char* argv[]) {
    // should have been printf("%s", argv[1]);
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How do we make this program misbehave?

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What happens if we run `./program %x`?

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```

What happens if we run `./program %x`?
It will print the second argument of `printf`, even if it's not there!

Remember `printf`?

```
int printf(const char *format, ...);
```

*[printf] writes the output under the control of a **format string** that specifies how subsequent arguments are converted for output.* src: `man 3 printf`

Format string attacks

- Reading data known since 1989
- First attack that broke something in 1999
- Remember, C is from 1972!
- Allows to read data from the stack and heap.
- Easy to spot: if there is no `"` after `printf(`, it's suspicious
- If we want compiler warnings from `gcc`, we need to use `-Wformat=2`, because of course why switch this on by default.
- The clang compiler *does* report these by default.

Side-step: calling a function on `x86_64`

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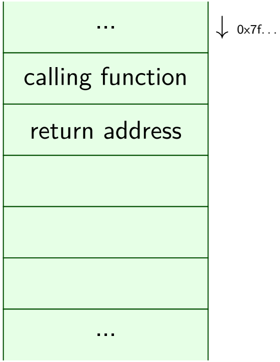

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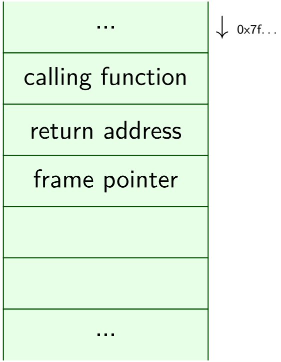

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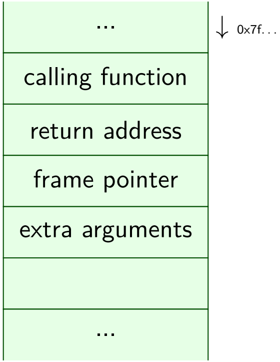

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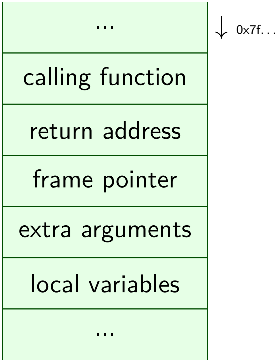

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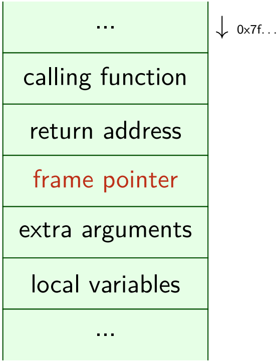
4. Put the remaining arguments (g, h) on the stack.
5. Jump to the address of `func`



Side-step: calling a function on `x86_64`

If we want to call a function `func(a, b, c, d, e, f, g, h)`, your computer does the following:

1. Put return address on the stack
2. Store the frame pointer
3. Put the first six arguments (a...f) in registers
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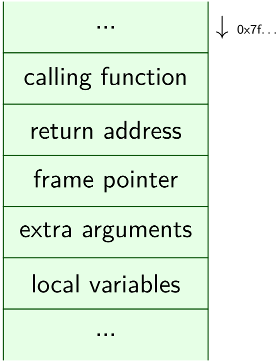
Why do we put arguments into registers?



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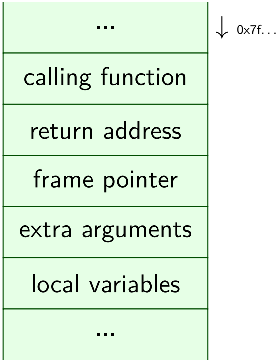

Putting the first few arguments in registers saves a lot of time waiting for memory.

So what do we see?

- So if we run `./printf %p`, we will print the value of the second register that would contain an argument.
- If we print `./printf '%7$p'`, we will print the first 8 bytes on the stack.

`printf` is a powerful debugger

```
#include <stdio.h>
void do_print(char* string)
  { printf(string); }

int main(int argc, char** argv) {
  long bla = 0xDEADC0DECAFEF00D;
  do_print(argv[1]);
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./printf "$(perl -e ’print "%p "x14’)"
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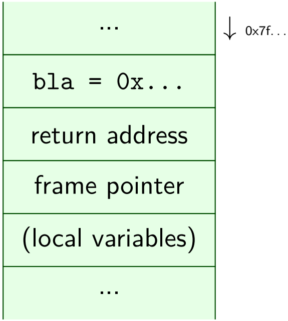

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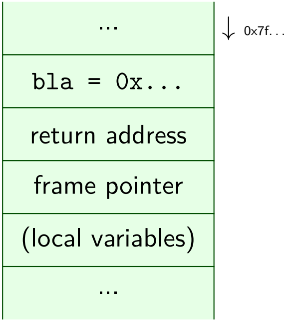

…

bla = 0x...

return address

frame pointer

(local variables)

…

```
./printf "$(perl -e ’print "%p "x14’)"
  0x7fffffffe4e8 0x7fffffffe500 0x7ffff7f82578 0x7ffff7f83be0
  0x7ffff7f83be0 (nil) 0x7fffffffe810 0x7fffffffe400 0x555555555199
  0x7fffffffe4e8 0x255555050 0x7fffffffe4e0 0xdeadc0decafef00d
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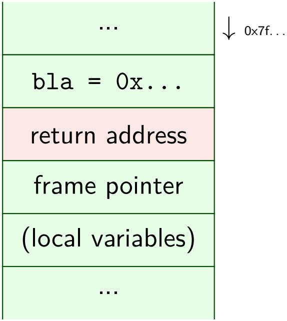

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Table of Contents

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  if(a == NULL) return -1;
  char *x = (char *)a;
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  free(x);
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- Fairly simple: double-free.

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- No check whether `malloc` returned `NULL`
- The function is *so* wrong, that this isn’t even really a problem
- The `free` is used on a *stack* address
- The value of `y` is lost after `return`
- Cannot `free` the allocated memory anymore

`valgrind`

- Memory bugs are hard to find manually
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- Generally good practice:
  - run your code in valgrind before submitting/publishing
  - make sure that valgrind reports no errors

Sanitizers

- Another way to do these sorts of checks is using `libasan`
- Compile your code with `-fsanitize=address`
- Will slow down your code because it's doing checks all the time
- Will terminate when it finds bad behaviour
- Other sanitizers available
  - `-fsanitize=undefined`
  - `-fsanitize=memory`
  - `-fsanitize=thread`
  - `-fsanitize=leak`
- Not all of them can be used together, some are not useful by themselves.