Hacking in C

Memory layout

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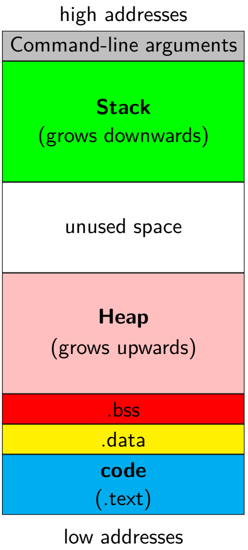
This lecture: look at the systematics of what is stored where

Memory segments

The OS allocates memory for data and code of each running process

- 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)



/proc/<pid>/maps, ps, and size

- Find information about memory allocation for process with PID `<pid>` in

  `/proc/<pid>/maps`

- For example:

```
008e6000-00b11000         rw-p 00000000 00:00 0   [heap]
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- Also information about dynamic libraries used by process
- List all processes with PID: `ps`
- Find information about memory segment sizes using `size`
- Use `size` on binary (`.o` file or executable)
- For more verbatim output can use `size -A`

Virtual memory

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- Use a *page table* to establish the mapping
- Essentially, use a different page table for each process
- If there is no entry for a virtual address in a processes' page table: exit with segmentation fault

Advantages of virtual memory

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- Can even assign more memory than is physically available
- Need to swap memory content to and from hard drive
- Can **separate address spaces** of different programs!
- OS can now ensure that one process cannot read/write another processes' memory

Bare-metal “memory management”

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- C is also used to program small embedded microcontrollers
- Sometimes run code *bare metal*, i.e., without OS
- No virtual memory, no segfaults
- Stack can happily grow into heap or data segment
- Typically rather little RAM, so this happens easily
- Nasty to debug behavior

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];
...
```

- The initialized variables `n` and `s` will be in .data
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- An OS can do this “on-demand”, i.e., when reading a variable for the first time
- Some platforms have a special non-initialized .bss subsection
- Example: AVR microcontrollers with a .noinit section

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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- Would get the same behavior if `x` was global
- ... but a global `x` could be modified also by other functions

The stack – a simple datastructure

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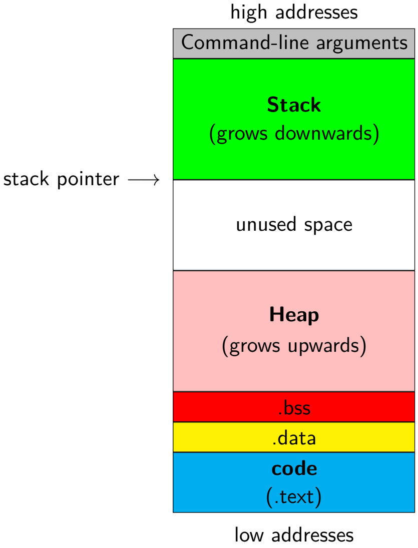
- Required for all these operations: pointer to the top
- Pointer can be
  - "hidden" (only modified by `PUSH` or `POP`)
  - "exposed" (allowing relative data access)
- On AVR: extra instructions to expose the stack pointer

Stack frames and the stack pointer

- Stack consists of *stack frames*
- Each function on the current *call stack* has its own frame
- Active frame is on top of the stack
- "Top of the stack": at low addresses
- Stack pointer points to end (low address) of active frame
- Stack pointer is typically in special register (`rsp` on AMD64)



Stack frames and the stack pointer

Example:

```
int func(int a, int b)
{
  ...
  return 10001;
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int main(void)
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  int x = func(42, 23)
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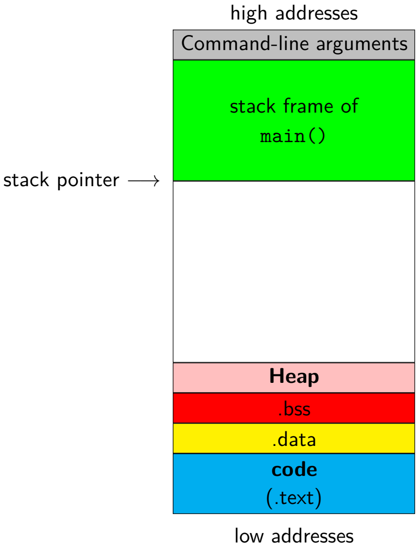

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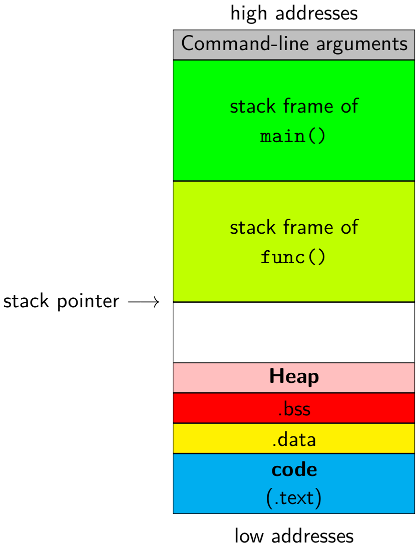
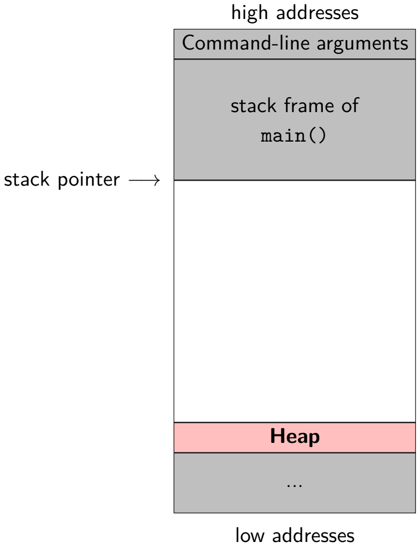


A zoom into the stack frame

- Stack before the function call



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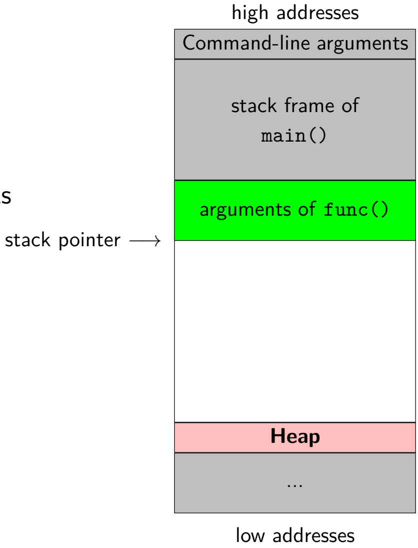

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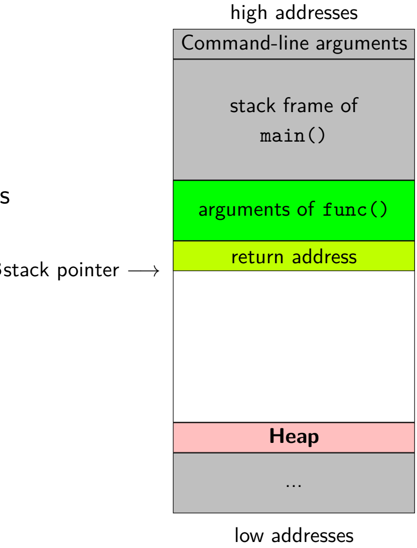

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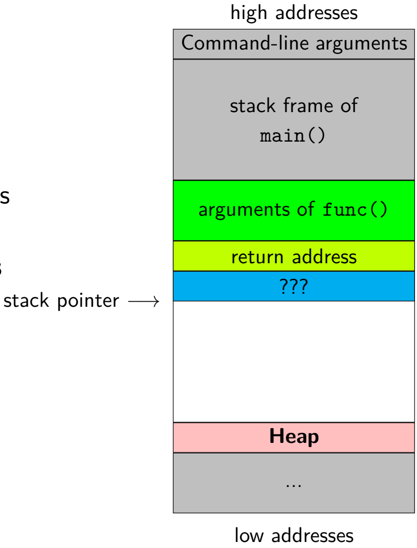

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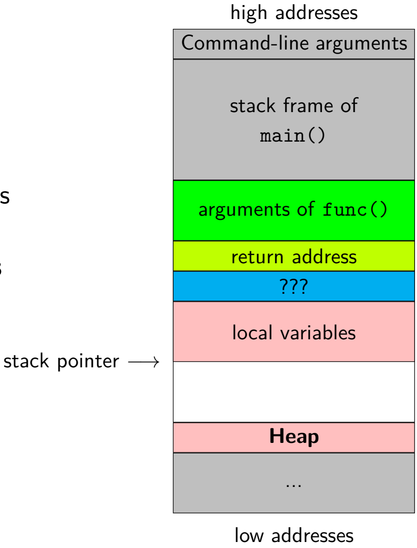
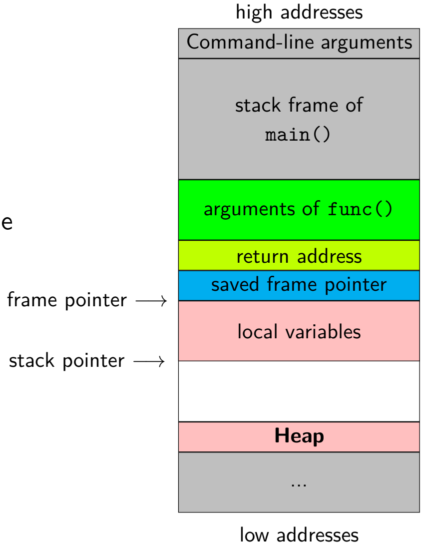


The frame pointer

- So what's with the ???. . . ?
- Traditionally also have an *frame pointer*
- Pointing to the end (high address) of the active stack frame
- On x86 in `ebp` register (AMD64: `rbp`)
- Function call also saves previous frame pointer on the stack
- On AMD64 commonly omitted:
  - Faster function calls
  - One additional register available



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- Otherwise limited by OS
- Under Linux, use `ulimit -s` to see stack size (in KB)
- Inside a C program, can use `getrlimit`
- Can also use `setrlimit` to request larger (or smaller) stack

Things that may go wrong on the stack

- Obviously, we may exhaust stack space
- Simple example: infinite recursion (`exhauststack.c`)
- This is known as **stack overflow**
- In safety critical environments need to avoid this!
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- Variables on the stack are not auto-initialized
- Reading uninitalized local variables allows to read local data from previous functions
- The stack mixes program and control data
- Writing beyond buffers may overwrite return addresses
- Main attack vector for "targeted undefined behavior"

. . . how bad is "wrong" exactly?

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

Hardware specifics

- Stack layout shown so far is typical
- Many details look different on different architectures:
  - Memory-segment layout may be different
  - (Some) function arguments may be passed through registers
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- Example: AMD64
  - Integer and pointer arguments are passed through `rdi`, `rsi`, `rdx`, `rcx`, `r8`, `r9`
  - Return value in `rax`
  - ... at least for Linux, Windows is subtly different

Limitations of the stack

```
int * table_of(int num, int len) {
  int table[len];
  for (int i=0; i <= len; i++) {
    table[i] = i * num;
  }
  return table; /* an int [] can be used as an int * */
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- Obvious other limitation: size!

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- Think about the heap as a large piece of scrap paper
- 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 (what else ;-))
- Space remains valid across function calls
- Every function that "knows" a pointer to the space can use it

`malloc`

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- Example of `malloc` usage:

```
int *x = malloc(10000 * sizeof(int));
```

- Request for space for $10\,000$ integers on the heap

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- Not true in all programming languages, e.g., not in C#

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- `table[i]` dereferences the pointer `table`
- Consequence: **undefined behavior!**

ALWAYS check for malloc failure!

- The following code is terribly unsafe:

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int *table = malloc(TABLESIZE * sizeof(int));
for(size_t i=0;i<TABLESIZE;i++)
  table[i] = 42;
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- Correct version:

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int *table = malloc(TABLESIZE * sizeof(int));
if(table == NULL) exit(-1);
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- Could alternatively use boolean behavior of `NULL`:

```
if(!table) exit(-1);
```

`free`

- You, the programmer, are in charge of *releasing* memory!
- When you don't need some allocated memory anymore, use

```
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- Here, `x` is a pointer to previously `malloc`'ed memory

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- The calls to `malloc` and `free` can be in different functions
- Not freeing `malloc`'ed memory is known as a *memory leak*

`realloc`

- Sometimes want to *expand* or *shrink* `malloc`'ed space
- Do this by using

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void *realloc(void *ptr, size_t new_size);
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- Content in the allocated area is preserved
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- Usage pattern:

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

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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- Not always that obvious, you may have *pointer aliases*
- 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!

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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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.

What's wrong with this code (part 1)?

```
int f()
{
  int *a = malloc(100 * sizeof(int));
  if(a == NULL) return -1;
  char *x = (char *)a;
  ...
  free(x);
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```

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- Fairly simple: double-free.

What's wrong with this code (part 2)?

```
int *f()
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  int a[100];
  for(i=0;i<100;i++)
    a[i] = i;
  return a;
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- Remember that an array can "decay" to a pointer to its first element

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int f()
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  int *a = malloc(100 * sizeof(int));
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  int *y = a;
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- 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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- Luckily there is tool assistance: `valgrind`

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- Run code is a sort of virtual machine, include memory checks
- Muuuuuuch slower than actually running the code, but:
  - Find memory leaks (`malloc` without `free`)
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- Generally good practice:
  - run your code in valgrind before submitting/publishing
  - make sure that valgrind reports no errors

`calloc`

- Remember that data on the stack is not initialized
- Global variables are initialized
- Memory space allocated with `malloc` is *not* initialized

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- Alternative: use calloc:

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void *calloc(size_t nitems, size_t size)
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- Request space for nitems elements of size size each
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- Alternative: use `calloc`:

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void *calloc(size_t nitems, size_t size)
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- Request space for `nitems` elements of size `size` each
- Memory space is initialized to zero
- 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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  - `int *p = calloc(nelems,sizeof(int));`?
- 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

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- One solution: maintain a table of all malloc'ed addresses and space
- Other solution: write information just before the pointer