CSCI 4907/6545 Software Security

Fall 2025

Instructor: Jie Zhou

Department of Computer Science

George Washington University

Slides materials are partially credited to Gang Tan of PSU.

Outline of Today's Lecture

- A C Program's Life Journey
- Memory
- Buffer overflows: common pitfalls and exploitation

SECOND EDITION

THE C PROGRAMMING LANGUAGE

ANSI C

BRIAN W. KERNIGHAN
DENNIS M. RITCHIE

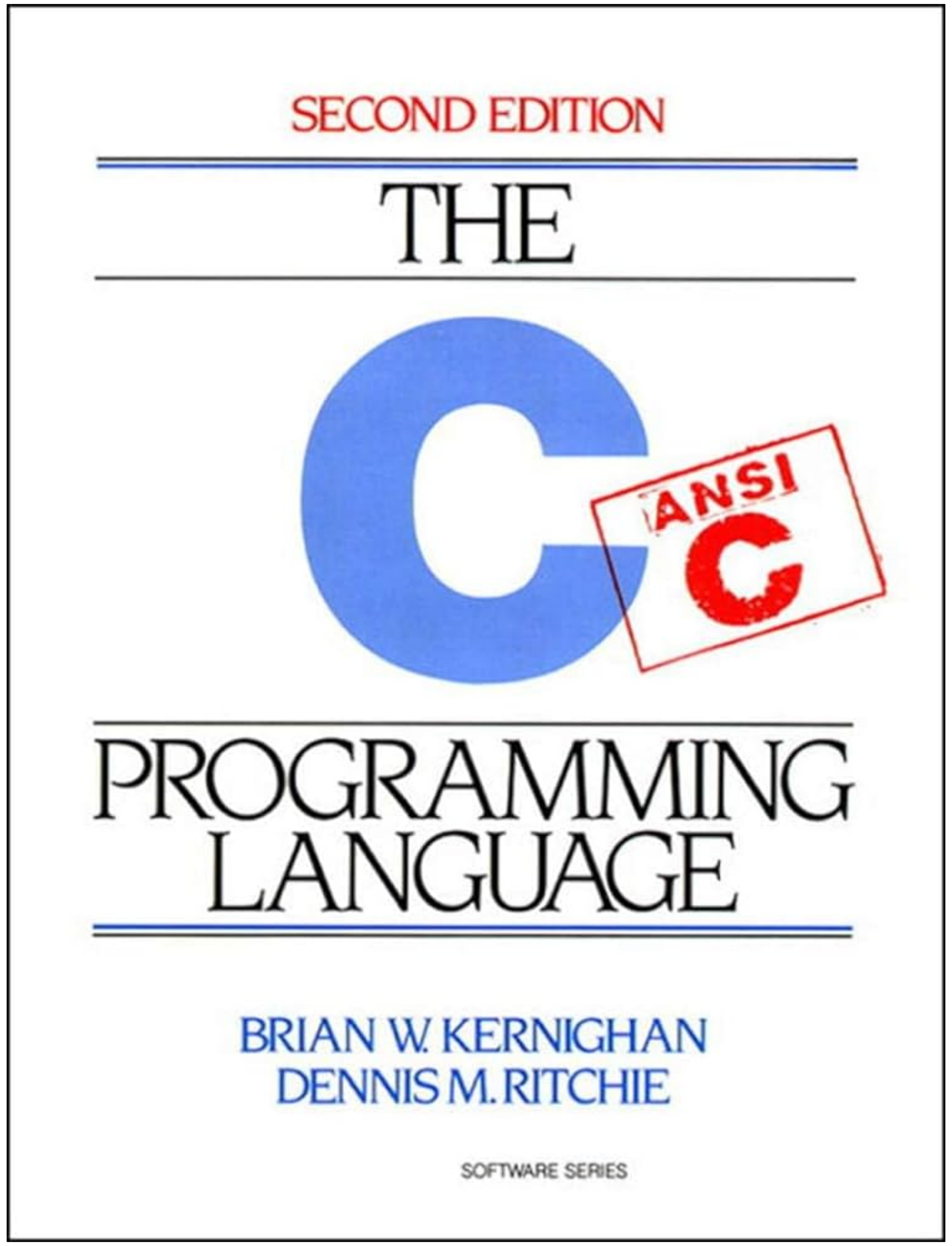
SOFTWARE SERIES

Programming in C is Simple

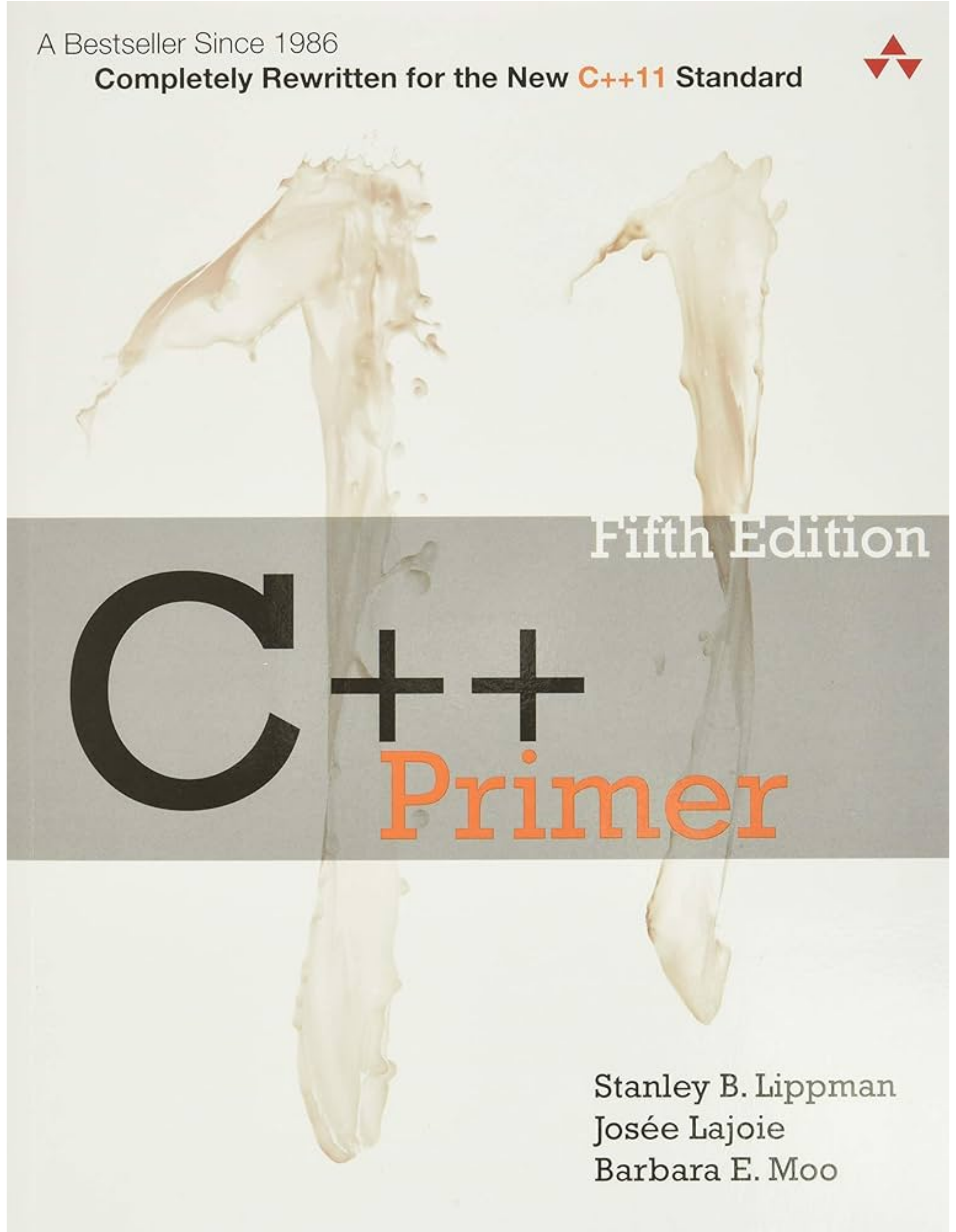
Simple and primitive language features

- Basic data types (char, integer, boolean, etc.)
- struct
- Pointers
- Basic control flow (conditional branches, loops, etc.)

Programming in C is Simple

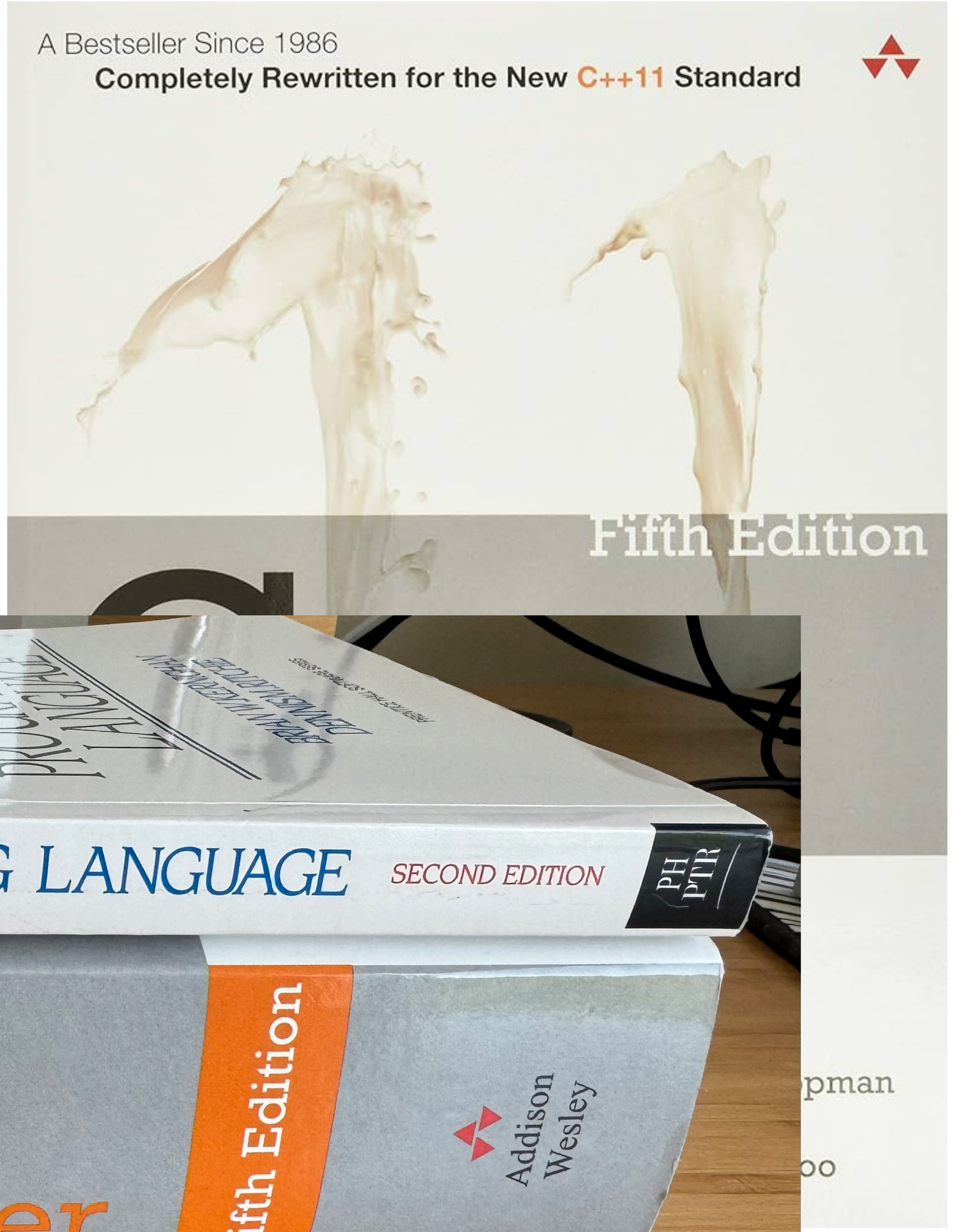


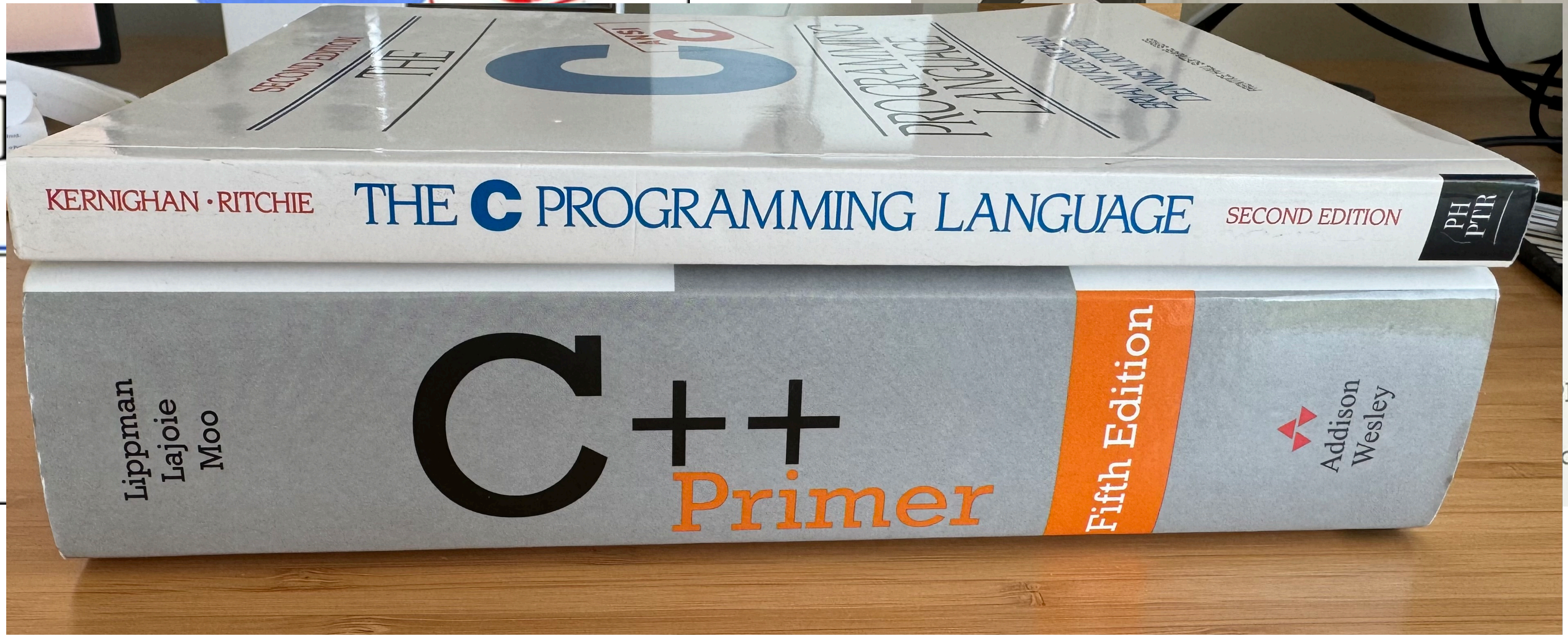
~200 pages



~1,000 pages

Programming in C is Simple





If so, why do we have so many bugs in C programs?

Programming *Correctly* in C is (*Extremely*) Hard

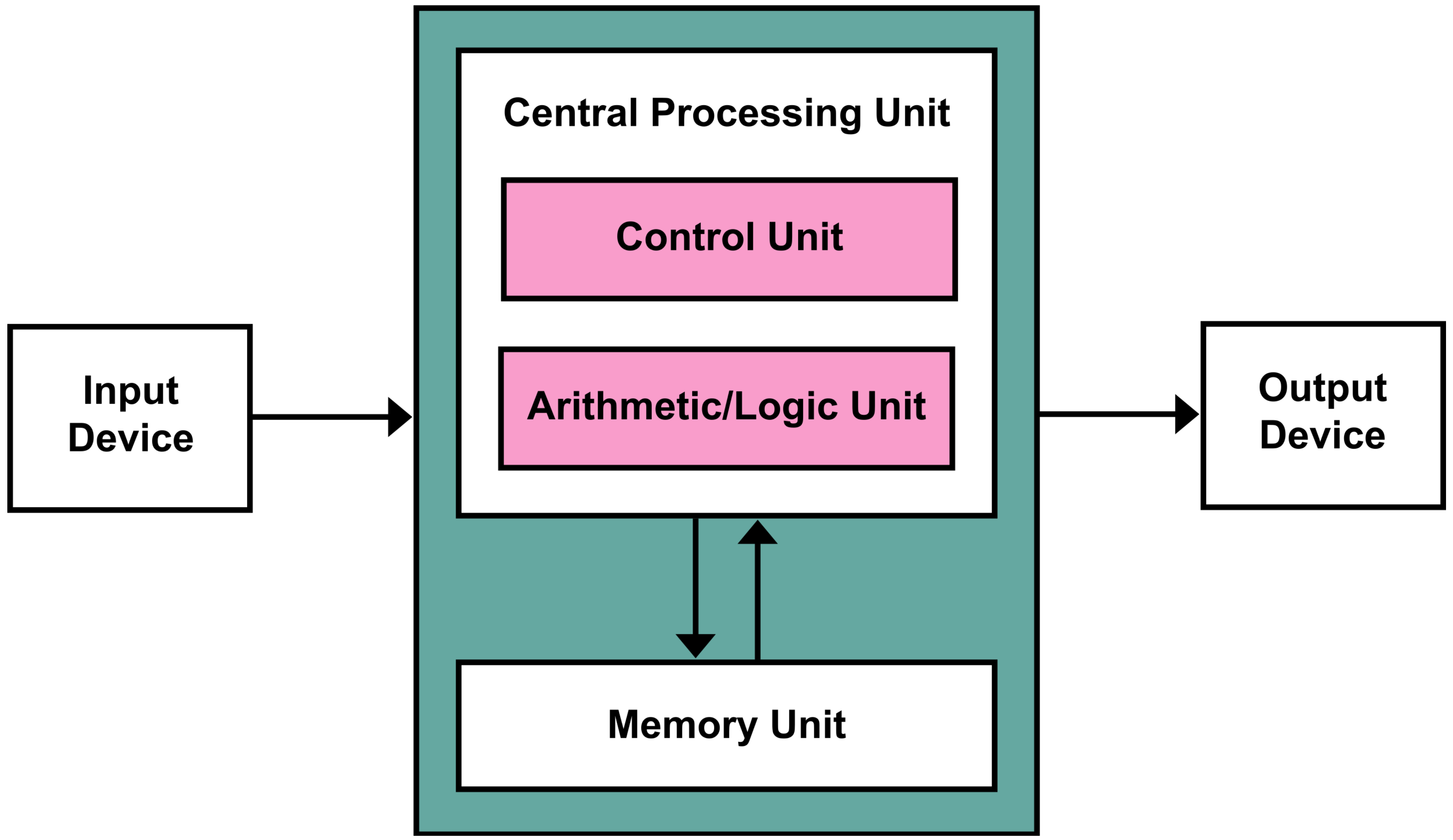
Simple and primitive language features

- Basic data types (char, integer, boolean, etc.)
- struct
- Pointers
- Basic control flow (conditional branches, loops, etc.)

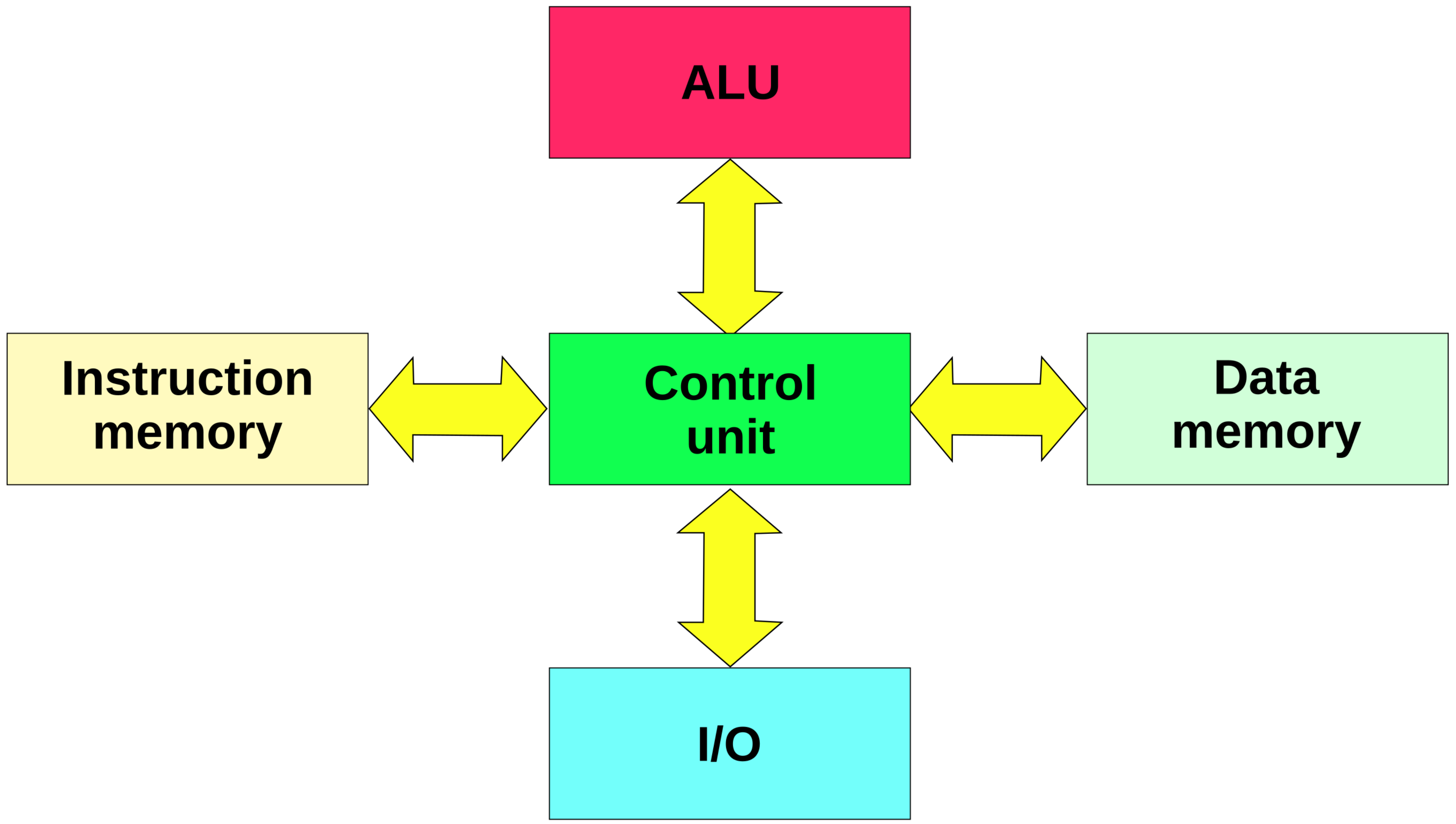
Pointer: Capability to manipulate memory.

- For C, pointer is usually implemented as a virtual address.
- But this is not the only way to implement pointers.

Architecture of Modern Computers

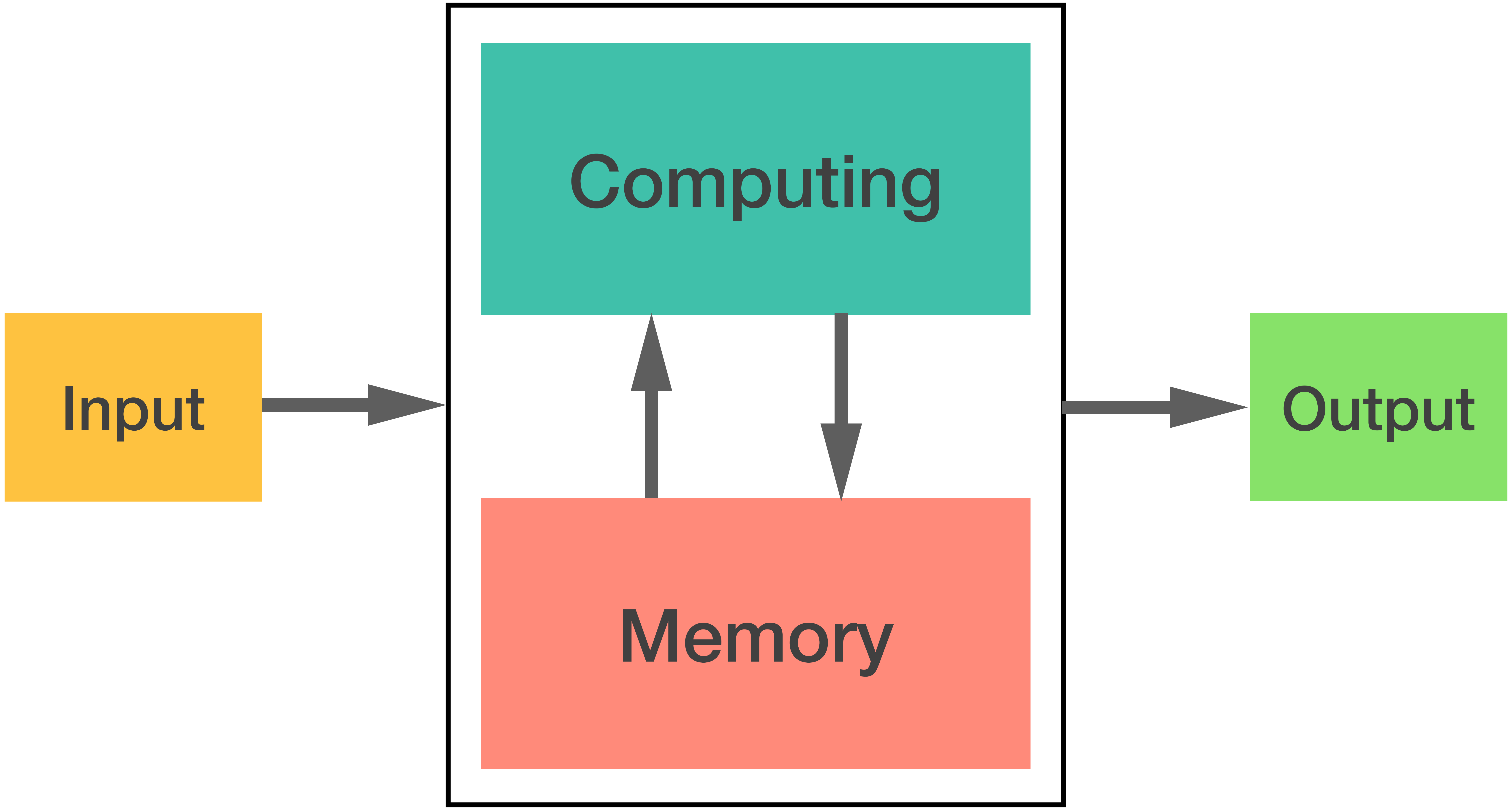


von Neumann Architecture



Harvard Architecture

Architecture of Modern Computers



Programming *Correctly* in C is (Extremely) Hard

Simple and primitive language features

- Basic data types (char, integer, boolean, etc.)
- struct
- Pointers
- Basic control flow (conditional branches, loops, etc.)

Pointer: Capability to manipulate memory.

- For C, pointer is usually implemented as a virtual address.
- But this is not the only way to implement pointers.

C pointers can do almost arbitrary memory manipulation!

- The correctness is at the discretion of programmers.

Hello World Program

```c
#include <stdio.h>

int main(int argc, char *argv[]) {
    printf("Hello, world!\n”);

    return 0;
}
```

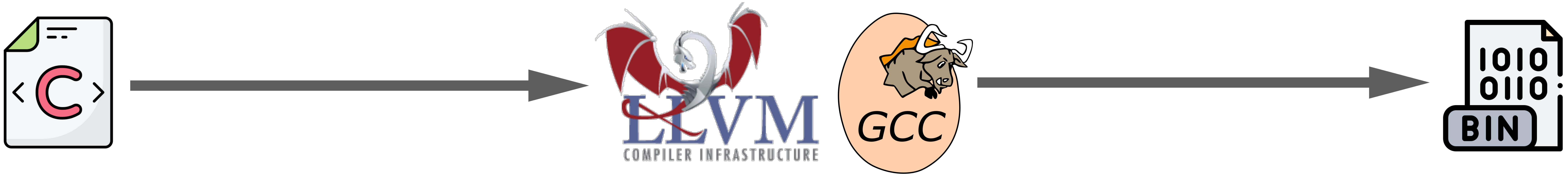
hello.c

- Size of this `.c` file: 98 bytes
- Source line of code: 7

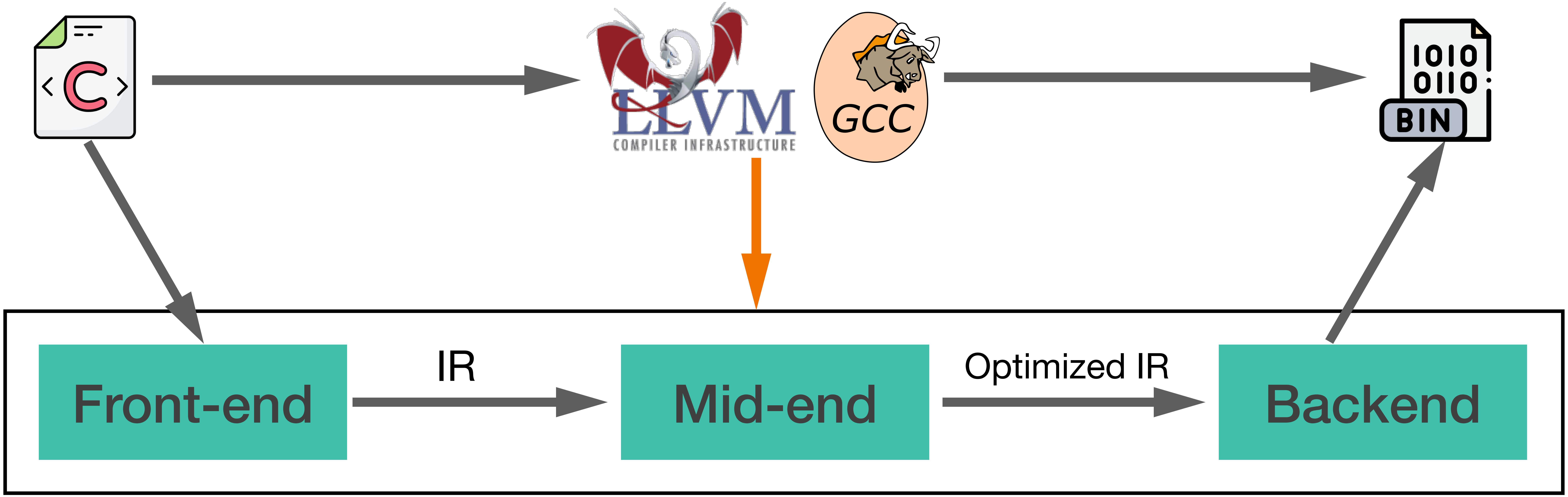
```
$ gcc hello.c -o hello
$ ./hello
```

- Size of the hello binary: 17 KB
- Instructions executed: 657,679

Life of a C Program: Compilation



Life of a C Program: Compilation



- Lexical analysis
- Parsing
- Semantic analysis
- Intermediate Representation (IR) code generation

- IR Optimizations

- Native CodeGen
- Linking

Life of a C Program: Execution

Loading → **Execution** → **Termination**

Loading

- Initializing memory layout
- (Optional) Dynamic linking, e.g. `libc`
- Environment initialization, e.g., stack setup
- Setting program counter (PC) to `_start()`

Execution

- `_start()` calls `main()`
- `main() runs the program`

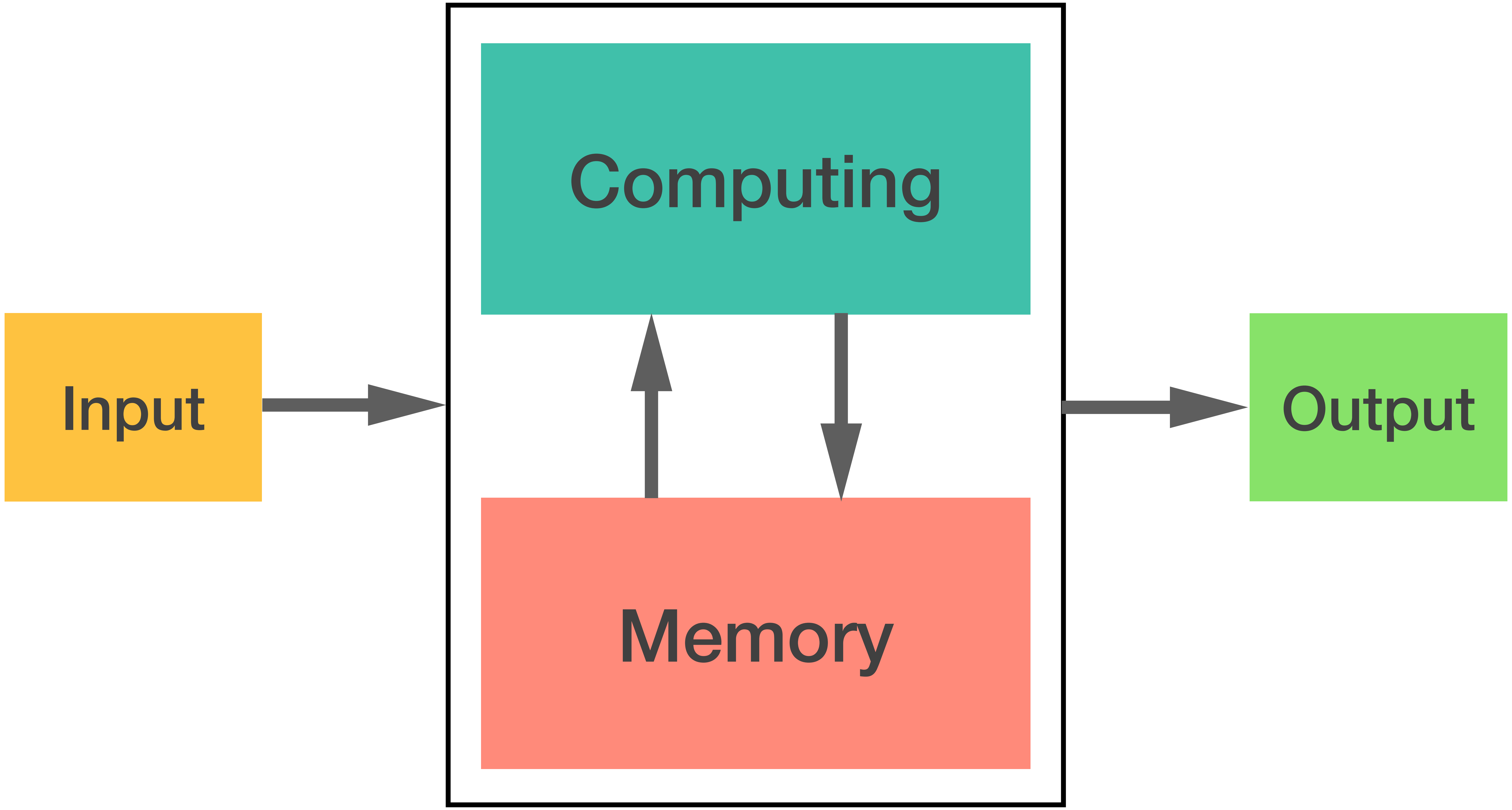
Termination

- `main()` returns,
- `_start()` calls `exit()`
- cleanup and shutdown

CIA Security Triad

- **Confidentiality**: An attacker cannot recover protected data.
- **Integrity**: An attacker cannot modify protected data.
- **Availability**: An attacker cannot stop/hinder computation.

Architecture of Modern Computers



Definition: Threat Model

The abilities and resources of the attacker

- Threat models enable structured reasoning about the attack surface.

- Awareness of entry points (and associated threats) to break into the target.
- Look at systems from an attacker's perspective:
  - Decompose application: **identify structure**
  - Determine and rank threats
  - Determine countermeasures and mitigations

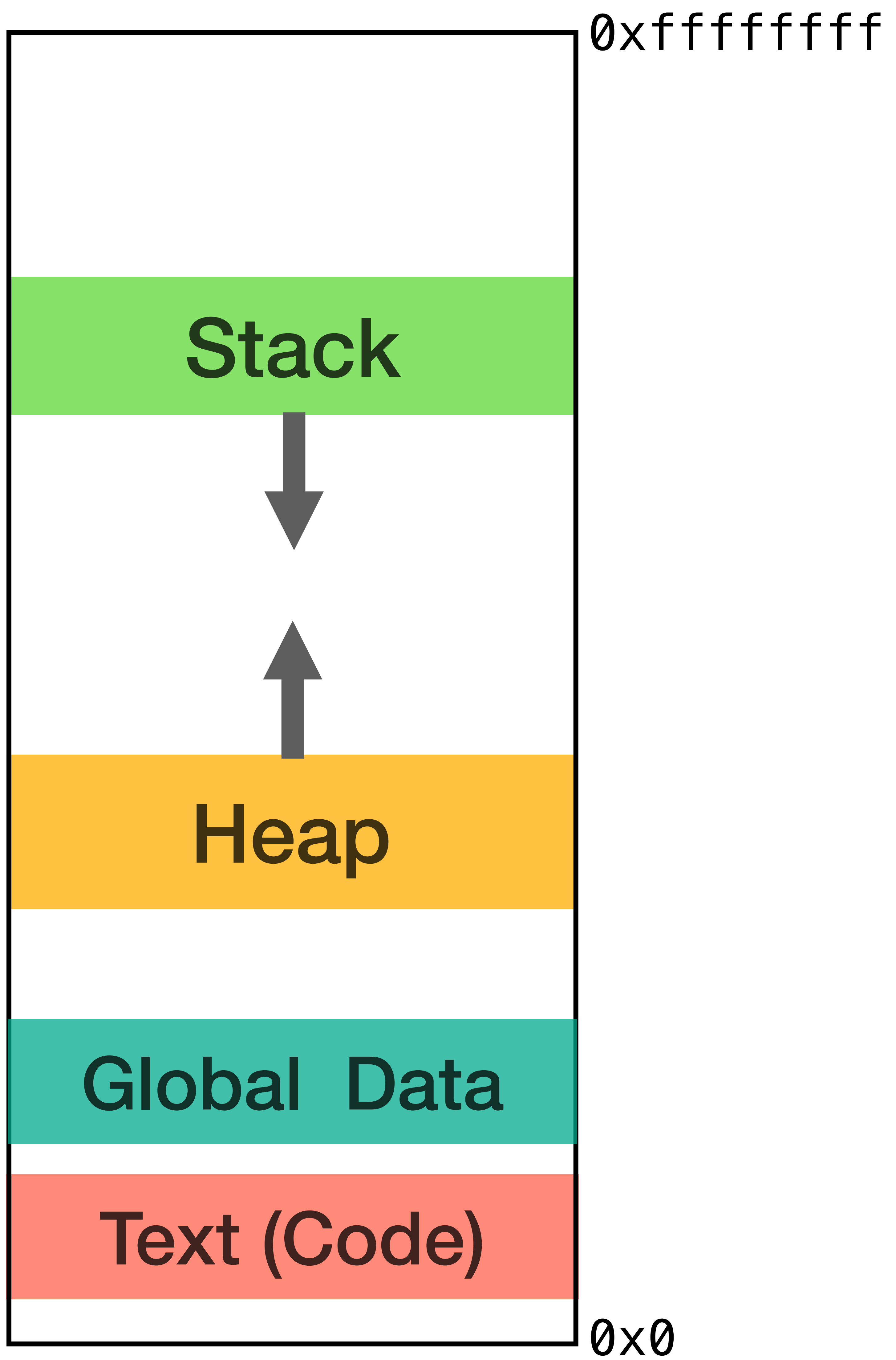
Further reading:

https://owasp.org/www-community/Threat_Modeling

Address Space of a C Program on x86-32

What do programs need in memory?

- Code
- Data
  - Globals
  - Stack for local variables
  - Heap for dynamic memory

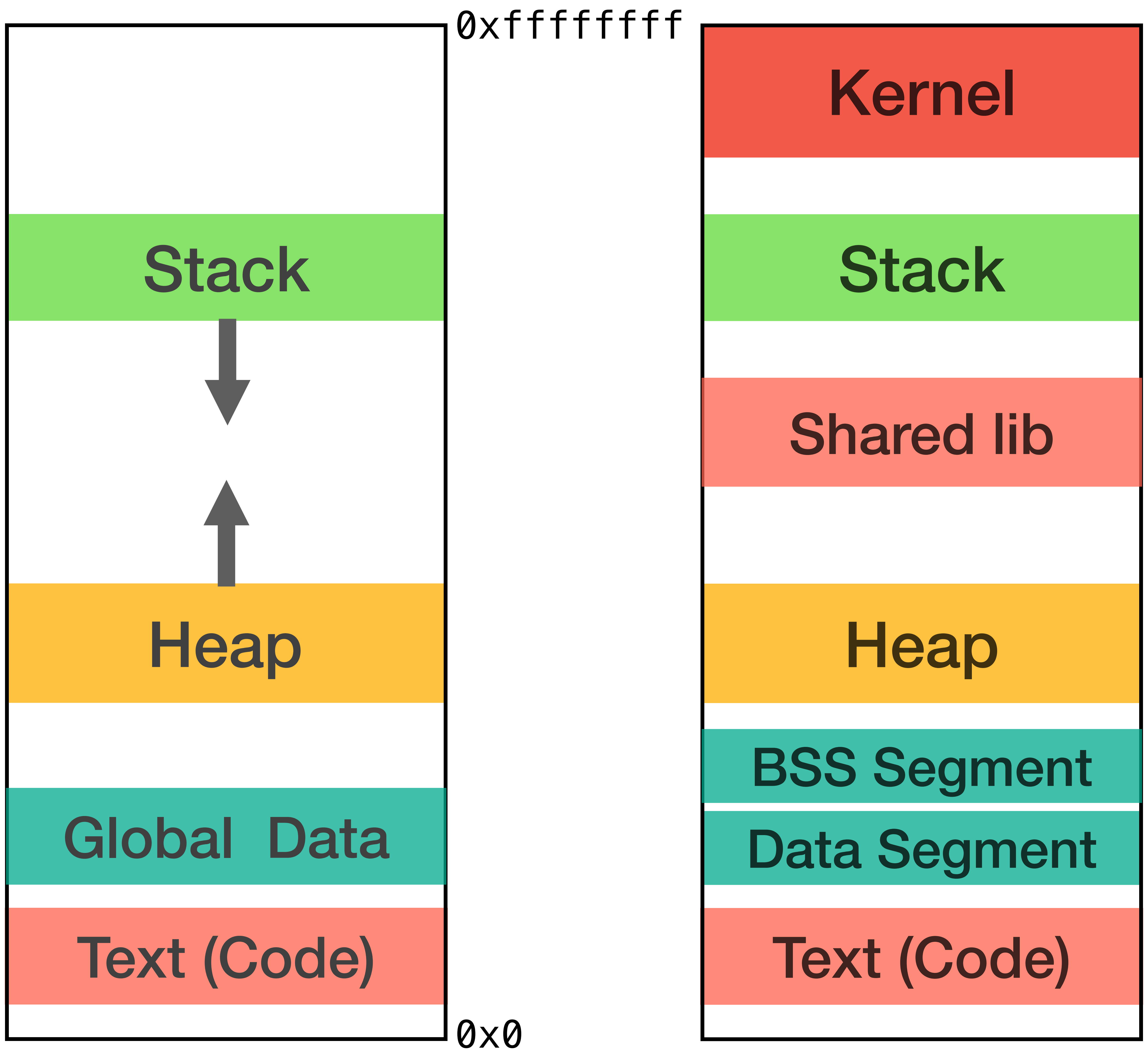


Address Space of a C Program on x86-32

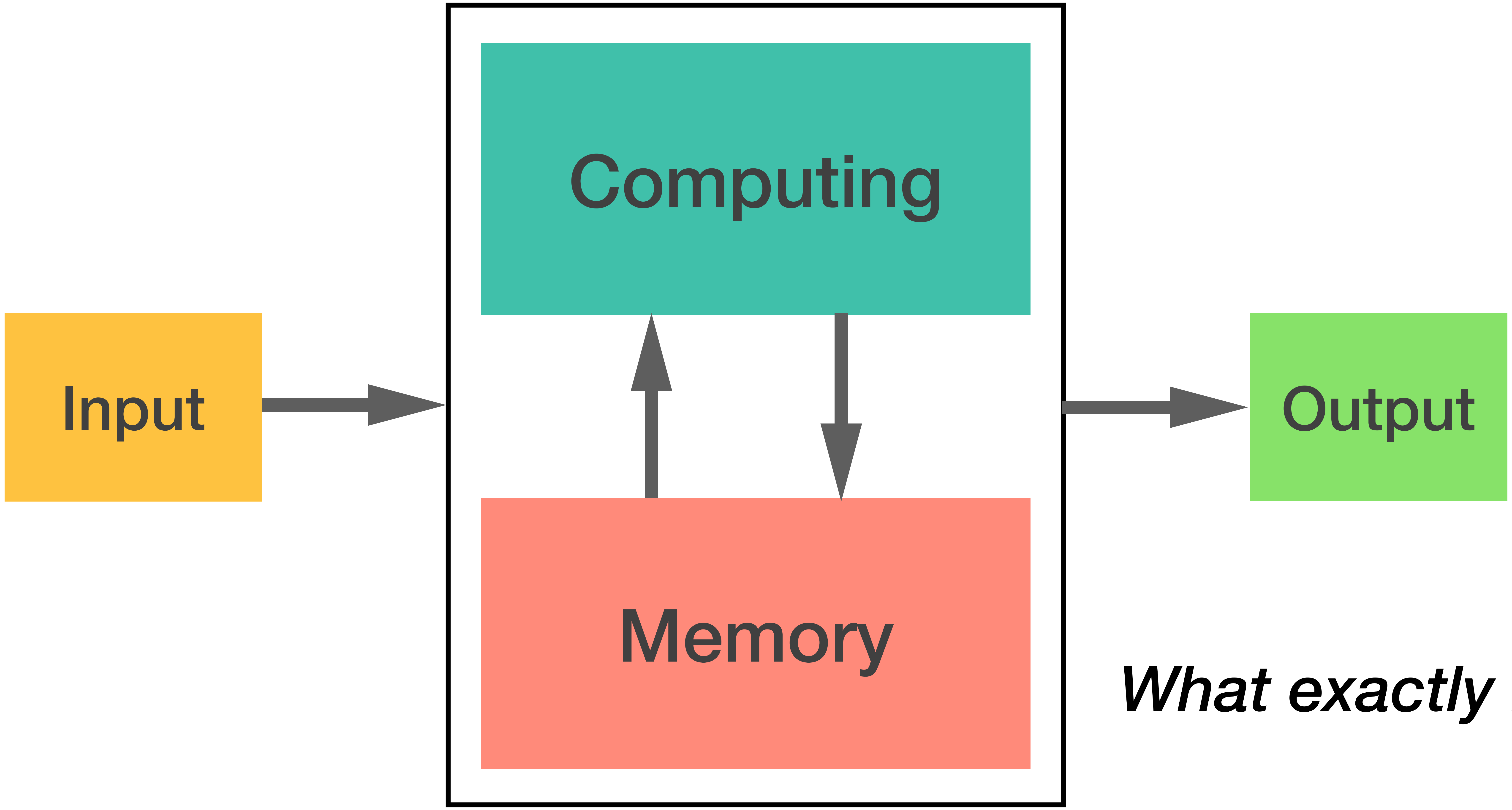
What do programs need in memory?

- Code
- Data Segment
  - Initialized global variables
- BSS Segment
  - Uninitialized global data
- Heap
- Shared libraries
- Stack
- Kernel

Check "`/proc/pid/maps`" to see how memory mapping looks in a real system.



Architecture of Modern Computers



What exactly is memory?

Usable Memory From a C Programmer's Perspective:

Virtual Address Space (+ Registers)

AMD64/x86-64 ISA

- General-purpose registers
  - rax–rdx, rsi, rdi, r8–r15
  - rbp, rsp
- Program counter
  - rip
- Segment registers
  - cs, ss, ds, ss, es, fs, gs
- Control registers
  - cr0, cr2, cr3, cr4

What can go wrong in memory?

It is Too Easy to Write Bugs

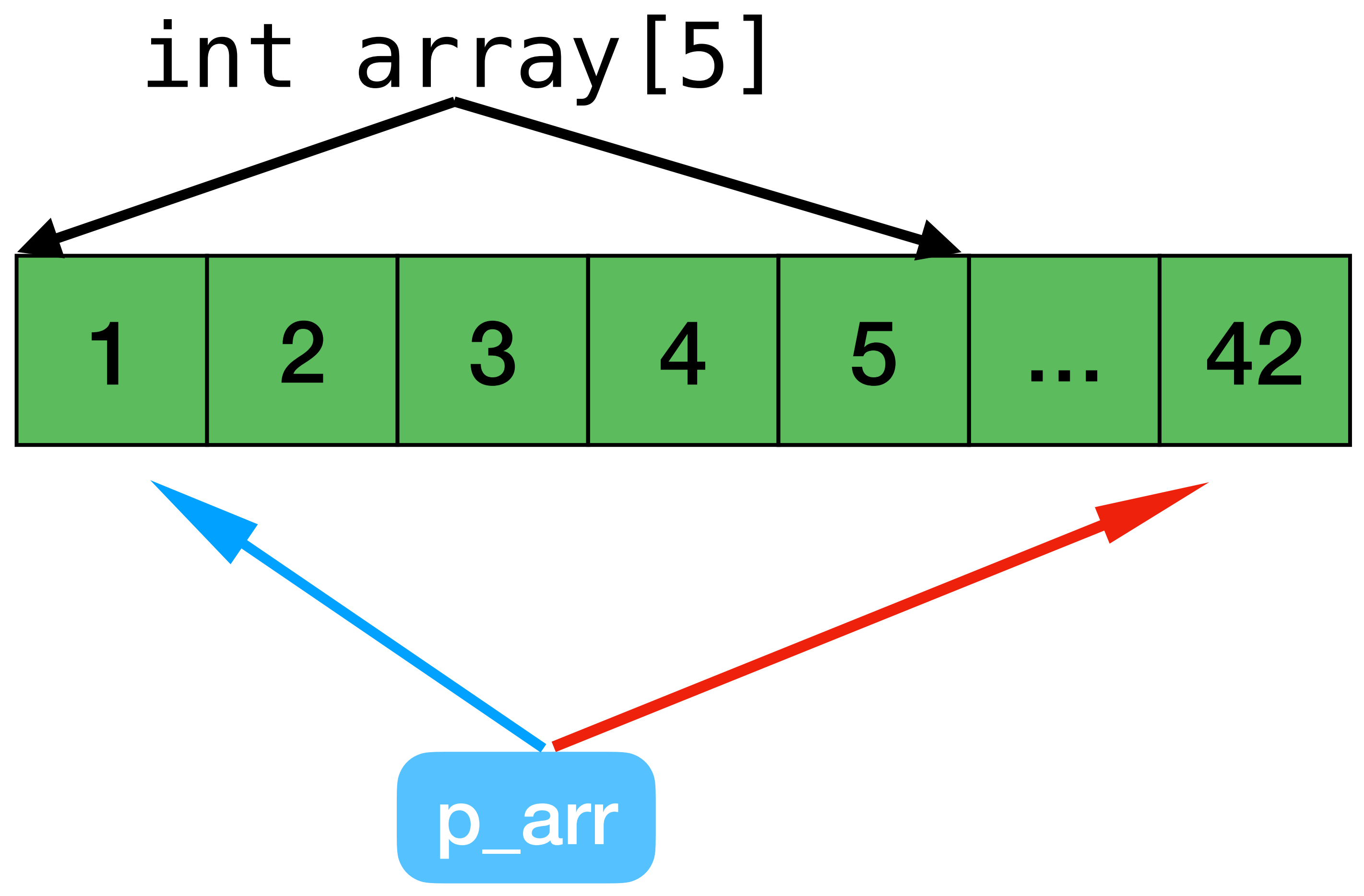
```c
#include <stdio.h>

int main(int argc, char *argv[]) {
    char user_name[32];
    scanf("%s", user_name);
    printf("Hello, %s!\n", user_name);
}
```

What if user's name is longer than 32 characters?

What if the user deliberately/maliciously input something than 32 characters?

Buffer Overflows

Reading/writing a buffer out of its bounds.



- It is C/C++ programmers' job to ensure such errors do not happen.
- In contract, most modern languages (e.g., Java, Rust, …) prevent buffer overflows by performing automatic bounds checking.
- The first Internet worm, Morris Worm, and many subsequent ones (CodeRed, Blaster, ...) exploited buffer overflows.
- Buffer overflows are still among the most commonly exploited vulnerabilities.

Buffer Overflows

cwe.mitre.org/top25/archive/2024/2024_kev_list.html

Common Weakness Enumeration

A community-developed list of SW & HW weaknesses that can become vulnerabilities

Top 25

Home > CWE Top 25 > 2024 CWE Top 10 KEV Weaknesses

Home | About ▼ | Learn ▼ | Access Content ▼ | Community ▼ | Search ▼

2024 CWE Top 10 KEV Weaknesses

Top 25 Home | Share via: X | View in table format | KEV Key Insights | KEV Methodology

1. Out-of-bounds Write
   CWE-787 | CVEs in KEV: 18 | Rank Last Year: 3 (up 2) ▲
2. Access of Resource Using Incompatible Type ('Type Confusion')
   CWE-843 | CVEs in KEV: 6 | Rank Last Year: 8 (up 6) ▲
3. Improper Neutralization of Special Elements used in an OS Command ('OS Command Injection')
   CWE-78 | CVEs in KEV: 6 | Rank Last Year: 5 (up 2) ▲
4. Improper Control of Generation of Code ('Code Injection')
   CWE-94 | CVEs in KEV: 7 | Rank Last Year: 33 (up 29) ▲
5. Deserialization of Untrusted Data
   CWE-502 | CVEs in KEV: 5 | Rank Last Year: 6 (up 1) ▲
6. Improper Limitation of a Pathname to a Restricted Directory ('Path Traversal')
   CWE-22 | CVEs in KEV: 5 | Rank Last Year: 9 (up 3) ▲
7. Missing Authentication for Critical Function
   CWE-306 | CVEs in KEV: 6 | Rank Last Year: 10 (up 3) ▲
8. Improper Neutralization of Special Elements used in an SQL Command ('SQL Injection')
   CWE-89 | CVEs in KEV: 4 | Rank Last Year: 11 (up 3) ▲
9. Use After Free
   CWE-416 | CVEs in KEV: 5 | Rank Last Year: 1 (down 8) ▼
10. Improper Neutralization of Special Elements used in a Command ('Command Injection')
    CWE-77 | CVEs in KEV: 4 | Rank Last Year: 15 (up 5) ▲

One Common Source of Pitfalls:
C String Manipulation

Using Strings in C

- C provides many string functions in its libraries (`libc`)
- For example, we use the `strcpy` function to copy one string to another:

```
#include <string.h>

char string1[] = "Hello, world!";
char string2[20];
strcpy(string2, string1);
```

Using Strings in C

- Another lets us compare strings:

```
char string3[] = "this is";
char string4[] = "a test";
if(strcmp(string3, string4) == 0) {
    printf("strings are equal\n");
} else {
    printf("strings are different\n”);
}
```

- This code fragment will print "strings are different". Notice that `strcmp` does not return a boolean result.

Note: Use the “man page” to check how to use `libc` functions, e.g., “`man strcmp`”

Other Common String Functions

- `strlen`: Get the length of a string
- `strcat`/`strncat`: String concatenation
- `gets`/`fgets`: Receive inputs to a string
- `strdup`: Duplicate a string
- `strstr`: Locate a substring
- …

Common String Manipulation Errors

- Buffer overflows
- Null-termination errors
- Off-by-one errors
- …

gets: Unbounded String Copies

```
char *gets(char *s);
```

- Get a string from standard input to the destination buffer
- Does not restrict the size of the input
- Can overflow the destination fixed-size buffer

```
#include <stdio.h>

int main(int argc, char *argv[]) {
    char user_name[32];
    scanf("%s", user_name);
    printf("Hello, %s!\n", user_name);
}
```

gets: Unbounded String Copies

```
char *gets(char *s);
```

- Get a string from standard input to the destination buffer
- Does not restrict the size of the input
- Can overflow the destination fixed-size buffer

```
#include <stdio.h>

int main(int argc, char *argv[]) {
    char user_name[32];
    gets(user_name);
    printf("Hello, %s!\n", user_name);
}
```

strcpy and strcat

```
char *strcpy(char *dest, const char *src);
char *strcat(char *dest, const char *src);
```

- Copy/Concatenate a string to another
- Do not consider the size of the destination buffer
- Can overflow the destination fixed-size buffer

```
int main(int argc, char *argv[]) {
    char name[2048];
    strcpy(name, argv[1]);
    strcat(name, " = ");
    strcat(name, argv[2]);
    ...
```

Better String Library Functions

- Functions that restrict the number of bytes are recommended.
- Never use `gets(char *s)`
  - Use `fgets(char *s, int size, FILE *stream)` instead

From gets to fgets

```
char *fgets(char *s, int size, FILE *stream);
```

“fgets reads in at most one less than size characters from stream and stores them into the buffer pointed to by s. Reading stops after an EOF or a newline. If a newline is read, it is stored into the buffer. A terminating null byte ('\0') is stored after the last character in the buffer.”

```
#include <stdio.h>

int main(int argc, char *argv[]) {
    char user_name[32]; 33
    fgets(user_name, 32, stdin);
    printf("Hello, %s!\n", user_name);
}
```

Better String Library Functions

- Functions that restrict the number of bytes are recommended.
- Never use `gets(char *s)`
  - Use `fgets(char *s, int size, FILE *stream)` instead
- `gets()` has been deprecated since 2007.

Better String Library Functions

- Instead of `strcpy()`, use `strncpy()`
- Instead of `strcat()`, use `strncat()`
- Instead of `sprintf()`, use `snprintf()`

But Still Need Care

```
char *strncpy(char *dest, const char *src, size_t n);
```

- Copy *at most* n char from src to dest. Stop at nth `char` or `'\0'`.
- What happens if the size of src is n or greater:
  - Only the first n char will get copied
  - dest may not be null-terminated!

C Strings Are Assumed/Expected to Be Null-terminated.

Null-termination Errors

```c
int main(int argc, char* argv[]) {
     char a[16], b[16];
     strncpy(a, "0123456789abcdef", sizeof(a));
     printf("%s",a);
     strcpy(b, a);
}
```

What will be printed out?

```
jie@gwsyssec: /tmp
$ clang copy.c -o copy
jie@gwsyssec: /tmp
$ ./copy
0123456789abcdef??
            ??jie@gwsyssec: /tmp
```

- a[] not properly terminated
  - Undefined behaviors, e.g., segmentation fault if `printf` is executed.

Null-termination Errors

```c
int main(int argc, char* argv[]) {
    char a[16], b[16];
    strncpy(a, "0123456789abcdef", sizeof(a));
    printf("%s",a);
    strcpy(b, a);
}
```

What will be printed out?

```
$ clang copy.c -o copy
jie@gwsyssec: /tmp
$ ./copy
0123456789abcdef??
                  ??jie@gwsyssec: /tmp
$ ./copy
0123456789abcdef(??jie@gwsyssec: /tmp
$ ./copy
0123456789abcdef?86?jie@gwsyssec: /tmp
```

- a [ ] not properly terminated.
  - Undefined behaviors, e.g., segmentation fault if printf is executed.

How to fix it?

`strcpy` to `strncpy`

- Do not replace `strcpy(dest, src)` by

```
strncpy(dest, src, sizeof(dest))
```

  but by

```
strncpy(dest, src, sizeof(dest) -1);
dest[sizeof(dest) - 1] = '\0';
```

  if dest should be null-terminated.

- You never have this headache in memory-safe languages (e.g., Rust).
- Further, `strncpy` has big performance penalty vs. `strcpy`.
  - It NIL-fills the remainder of the destination

But Still Need Care

```
char *strncpy(char *dest, const char *src, size_t n);
```

- Copy *at most* n char from src to dest. Stop at nth char or ‘\0’.
- What happens if the size of src is n or greater:
  - Only the first n char will get copied
  - dest may not be null-terminated!
- What happens if `dest`’s buffer is smaller than n?
  - We may have a buffer overflow bug!

Signed vs. Unsigned Numbers

```
char buf[N];
int len;
...
if (len > N) {
    error("Invliad length");
    return;
}
read(fd, buf, len);
```

What if `len` is negative?

```
ssize_t read(int fd, void *buf, size_t count);
```

len will be cast to unsigned and negative length overflows, e.g., -1 -> 2^32 - 1 = 4294967295

Checking for Negative Lengths

```
char buf[N];
int len;
...
if (len < 0 || len > N) {
    error("Invliad length");
    return;
}
read(fd, buf, len);
```

Any other problems?

However, it still has a problem if the `buf` is going to be treated as a C string.

A Good Version

```
char buf[N];
int len;
...
if (len < 0 || len > N) {
    error("Invliad length");
    return;
}
read(fd, buf, len);
buf[len] = ‘\0’; // null terminate buf
```

Is it really a good version?

A Good Version

```
char buf[N];
int len;
...
if (len < 0 || len > N - 1) {
    error("Invliad length");
    return;
}
read(fd, buf, len);
buf[len] = ‘\0’; // null terminate buf
```

Exploiting Buffer Overflows

How Can Buffer Overflow *Bugs* Lead to *Vulnerabilities*?

- All the examples look like simple programming bugs.
- How can they possibly enable attackers to do bad things?

Bugs vs. Vulnerabilities

Wikipedia: *"A software bug is a bug in computer software."*

Wikipedia: *"In engineering, a bug is a design **defect** in an engineered system that causes an undesired result."*

Wikipedia: *"Vulnerabilities are **flaws** in a computer system that weaken the overall security of the system."*

Vulnerabilities -> Exploitable Bugs

https://en.wikipedia.org/wiki/Vulnerability_(computer_security)

How Can Buffer Overflow *Bugs* Lead to *Vulnerabilities*?

- All the examples look like simple programming bugs.
- How can they possibly enable attackers to do bad things?
  - Stack smashing to exploit buffer overflows
  - Illustrate the technique using AMD64 (x86-64) architecture

Definition: Threat Model

The abilities and resources of the attacker

- Threat models enable structured reasoning about the attack surface.

- Awareness of **entry points** (and associated threats) to break into the target.
- Look at systems from an attacker's perspective:
  - Decompose application: **identify structure**
  - Determine and rank threats
  - Determine countermeasures and mitigations

Further reading:

https://owasp.org/www-community/Threat_Modeling

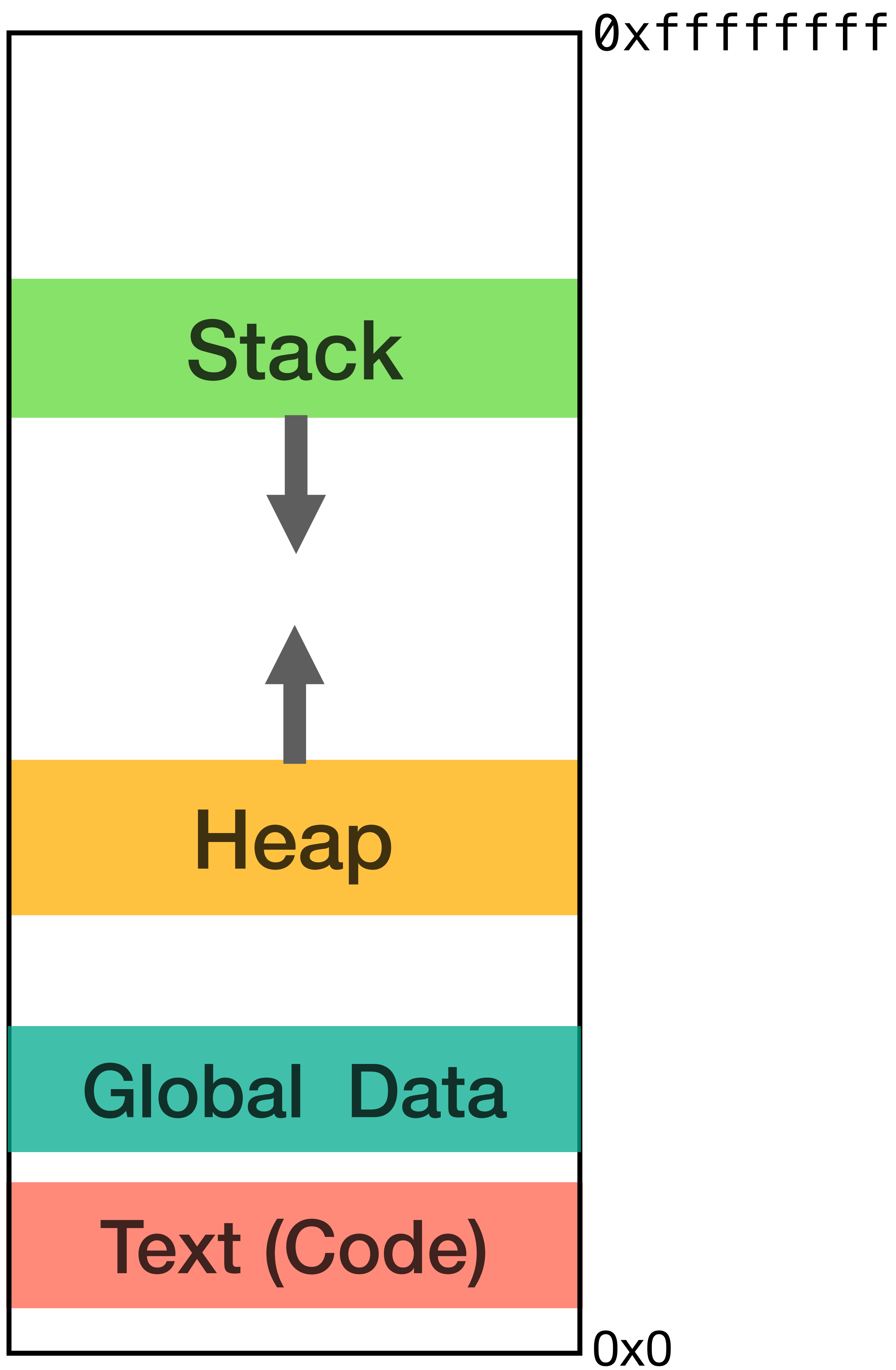
How Can Buffer Overflow *Bugs* Lead to *Vulnerabilities*?

- All the examples look like simple programming bugs.
- How can they possibly enable attackers to do bad things?
  - Stack smashing to exploit buffer overflows
  - Illustrate the technique using ADM64 (x86-64) architecture
- We start with some background
  - Program stack management
  - AMD64/x86-64

Address Space of a C Program on x86-32

What do programs need in memory?

- Code
- Data
  - Globals
  - Stack for local variables
  - Heap for dynamic memory

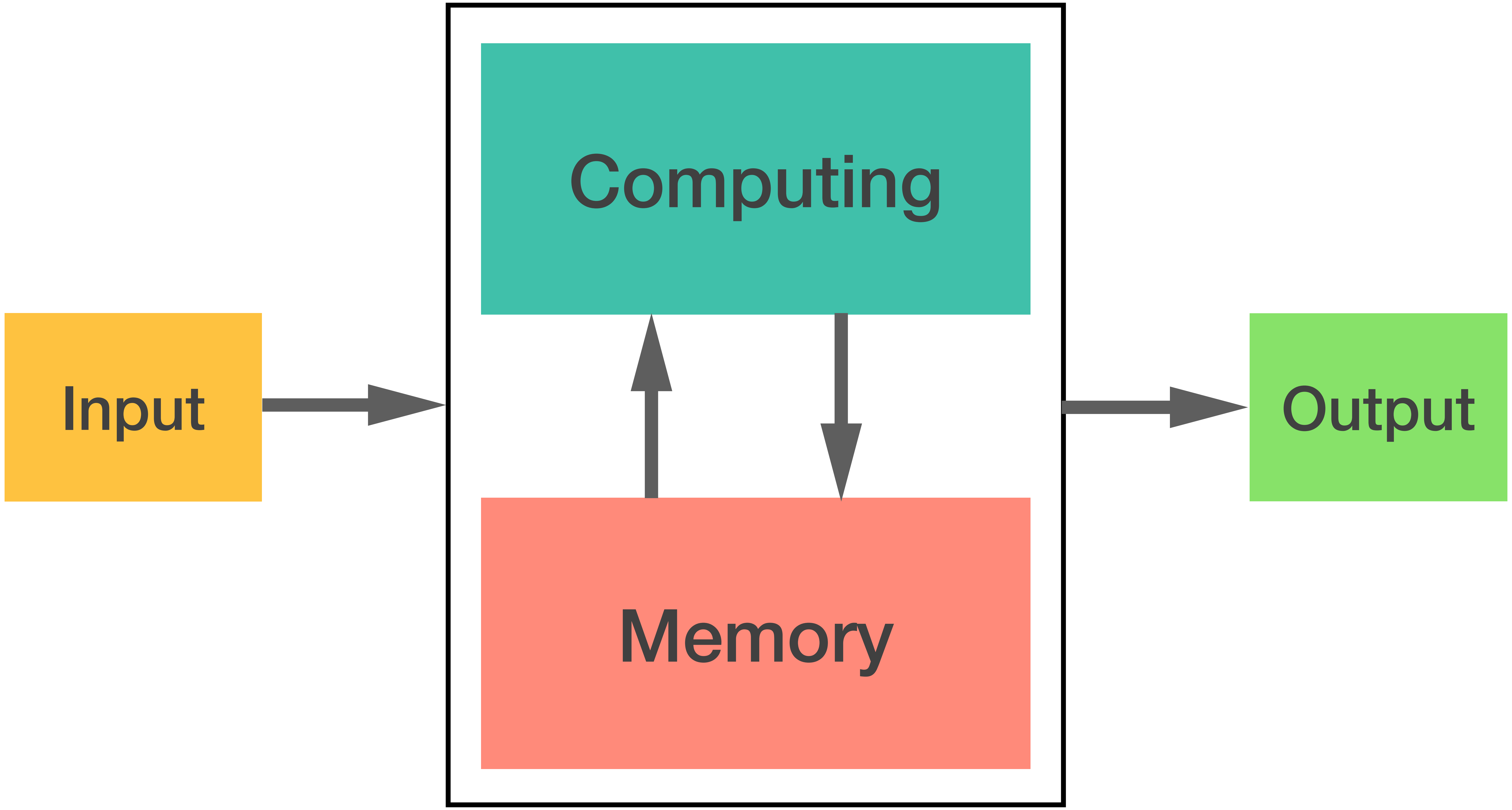


Program Stack

- For implementing function calls and returns

Why do we need functions?

Architecture of Modern Computers

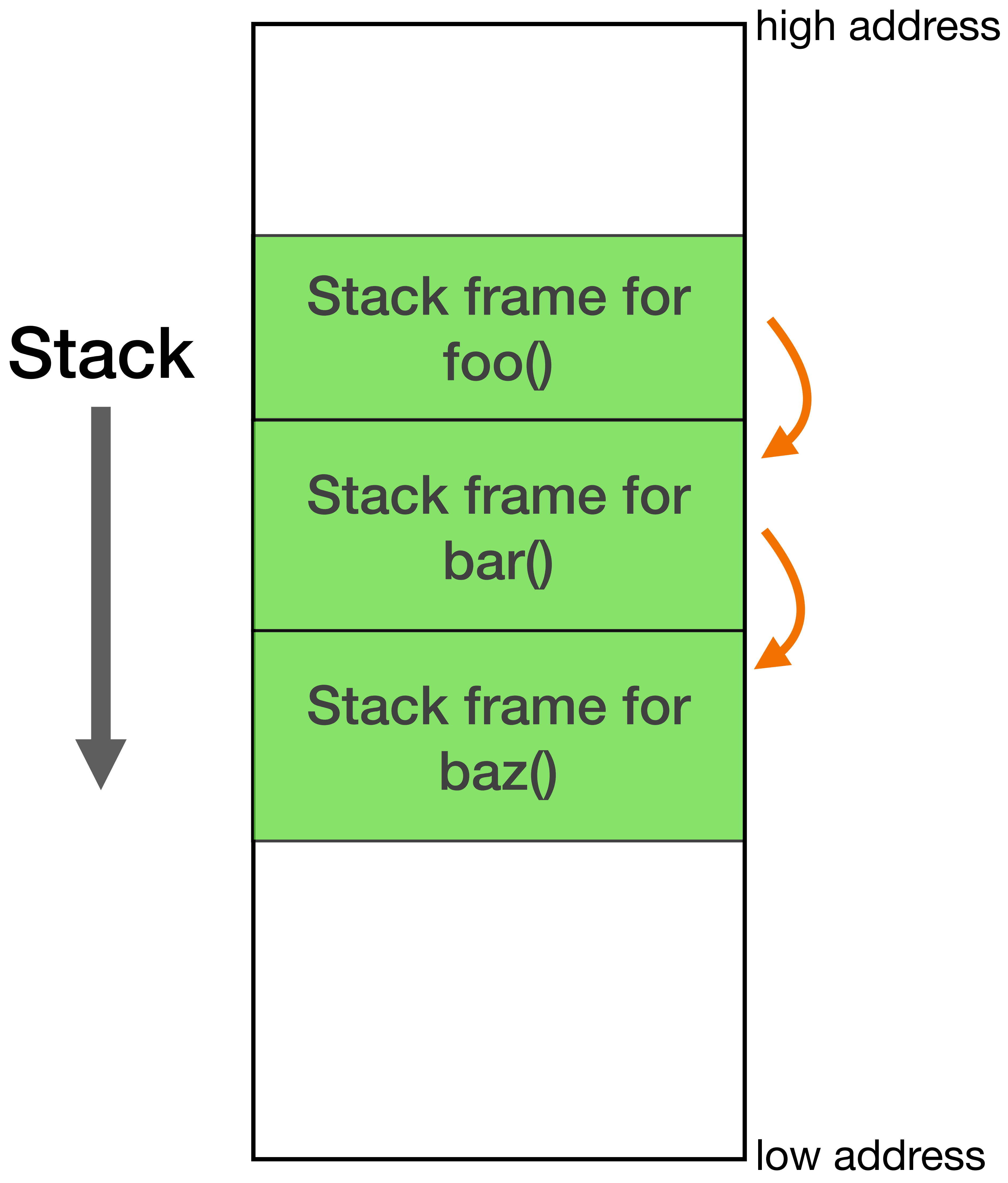


Program Stack

- For implementing function calls and returns
- A stack frame is created for the called function (i.e., the callee)
  - Whenever the caller function calls the callee
- The frame keeps track of program execution state by storing
  - Local variables
  - Some arguments to the callee
    - Depending on the calling convention
  - Return address of the calling function (caller)
  - ……

Program Stack

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

... bar(...) {
    baz(...);
    ...
}

... baz(...) {
    ...
}
```



Stack Frames

- Stack grows from high memory address to low memory address.
- The stack pointer points to the top of the stack.
  - RSP in Intel x86-64
- The frame pointer points to the end of the current frame.
  - also called the base pointer
  - RBP in Intel x86-64
- The stack is modified during
  - function calls, by the caller
  - function initialization, by the callee
  - function execution, by the callee
  - returning from a function, by the callee

Calling Convention

How functions/subroutines pass arguments and return values at the macro-architecture level.

```c
void foo() {
    ...
    bar(a, b, c, d, e, f, g, h);
    ...
}

long bar(long a, long b, long c, long d,
         long e, long f, long g, long h) {
   long xx = a * b * c * d * e * f * g * h;
   long yy = a + b + c + d + e + f + g + h;
   long zz = utilfunc(xx, yy, xx % yy);
   return zz + 20;
}
```

- Where to put all the arguments?
- Where to put the return value?

Usable Memory From a C Programmer's Perspective:

Virtual Address Space (+ Registers)

Background: AMD64/x86-64

- Pointers and long integer are 64-bit long.
  - Integer arithmetic operations support 8, 16, 32, and 64 bits
- 16 general-purpose registers; each 64-bit long

AMD64/x86-64 ISA

- General-purpose registers
  - rax–rdx, rsi, rdi, r8–r15
  - rbp, rsp
- Program counter
  - rip
- Segment registers
  - cs, ss, ds, ss, es, fs, gs
- Control registers
  - cr0, cr2, cr3, cr4

Background: AMD64/x86-64

- Pointers and long integer are 64-bit long
  - Integer arithmetic operations support 8, 16, 32, and 64 bits
- 16 general-purpose registers; each 64-bit long
- Calling conventions pass arguments first in registers, then via stack.
  - System V AMD 64 ABI: Pass the first 6 arguments in registers
    - UNIX-like operating systems (e.g. Linux) use this calling convention.
    - Microsoft has its own calling convention.
  - As a result, some procedures do not need to access the stack at all.

System V AMD64 Calling Convention

How functions/subroutines pass arguments and return values at the macro-architecture level.

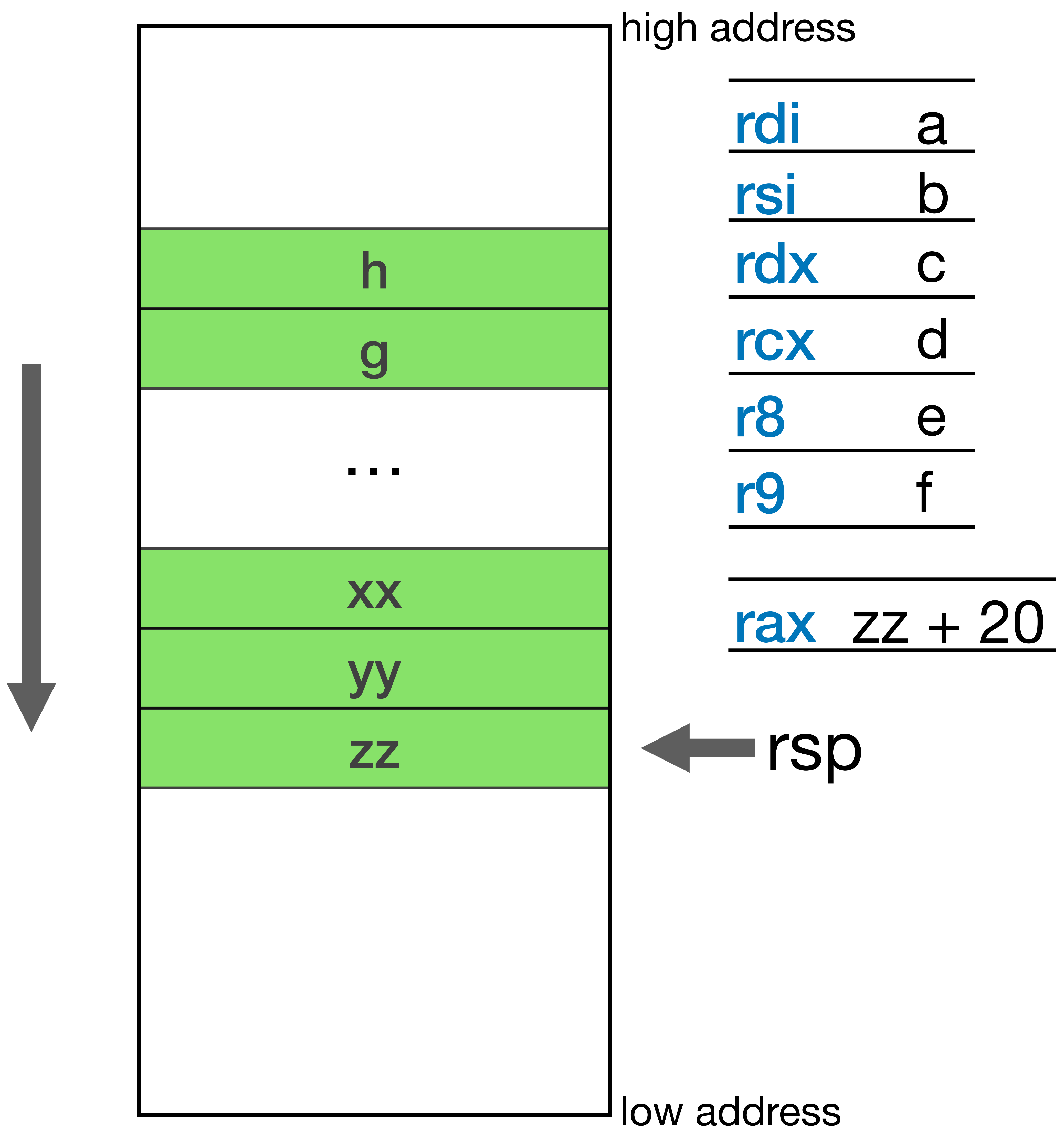
```
void foo() {
    ...
    bar(a, b, c, d, e, f, g, h);
    ...
}

long bar(long a, long b, long c, long d,
         long e, long f, long g, long h) {
   long xx = a * b * c * d * e * f * g * h;
   long yy = a + b + c + d + e + f + g + h;
   long zz = utilfunc(xx, yy, xx % yy);
   return zz + 20;
}
```

- Where to put all the arguments?
- Where to put the return value?

- Arguments are passed
  - in registers: rdi, rsi, rdx, rcx, r8, r9
  - then via stack
- Return value is passed via
  - in registers: rax, rdx
  - then via stack

System V AMD64 Calling Convention

```c
void foo() {
    ...
    bar(a, b, c, d, e, f, g, h);
    ...
}

long bar(long a, long b, long c, long d,
         long e, long f, long g, long h) {
   long xx = a * b * c * d * e * f * g * h;
   long yy = a + b + c + d + e + f + g + h;
   long zz = utilfunc(xx, yy, xx % yy);
   return zz + 20;
}
```

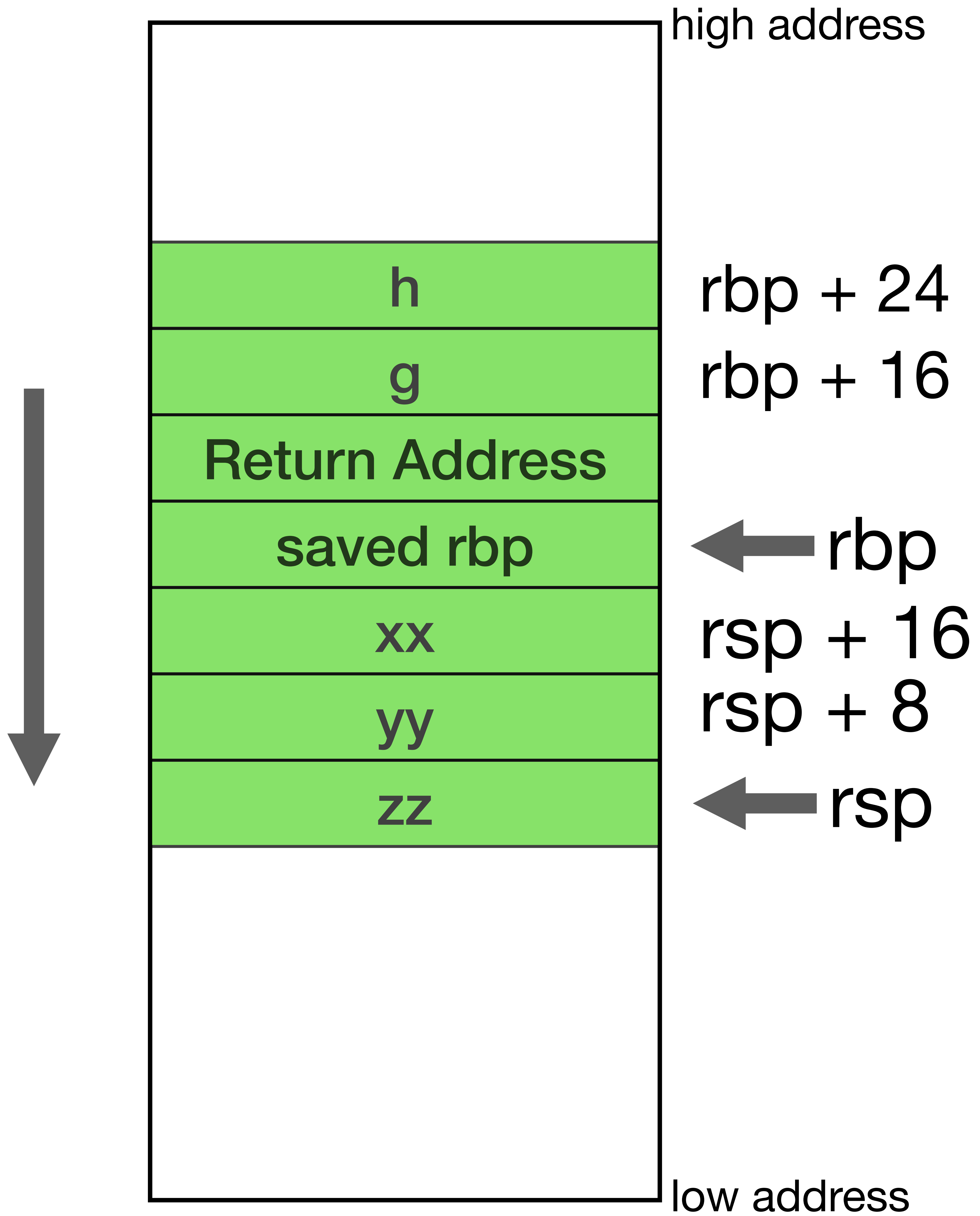


What is missing in the frame?

- There is only one rbp & rsp.
- Where to return to the caller?

System V AMD64 Calling Convention

```
void foo() {
    ...
    bar(a, b, c, d, e, f, g, h);
    ...
}

long bar(long a, long b, long c, long d,
         long e, long f, long g, long h) {
   long xx = a * b * c * d * e * f * g * h;
   long yy = a + b + c + d + e + f + g + h;
   long zz = utilfunc(xx, yy, xx % yy);
   return zz + 20;
}
```



What is missing in the frame?

- There is only one rbp & rsp.
- Where to return to the caller?

How are function frames set up?

Function Frame Setup

1. Callsite
2. Function Initialization
3. Function Return

Example Illustrating Stack Buffer Overflows

```c
void foo(int a, int b) {
      char buffer[12];
      gets(buffer);
      return;
}

int main() {
      int x;
      x = 0;
      foo(1,2);
      x = 1;
      printf("%d\n",x);
      return 0;
}
```

```
(gdb) disassemble main
Dump of assembler code for function main:
   0x0000000000001170 <+0>:     push   %rbp
   0x0000000000001171 <+1>:     mov    %rsp,%rbp
   0x0000000000001174 <+4>:     sub    $0x10,%rsp
   0x0000000000001178 <+8>:     movl   $0x0,-0x4(%rbp)
   0x000000000000117f <+15>:    movl   $0x0,-0x8(%rbp)
   0x0000000000001186 <+22>:    mov    $0x1,%edi
   0x000000000000118b <+27>:    mov    $0x2,%esi
   0x0000000000001190 <+32>:    call   0x1150 <foo>
   0x0000000000001195 <+37>:    movl   $0x1,-0x8(%rbp)
   0x000000000000119c <+44>:    mov    -0x8(%rbp),%esi
   0x000000000000119f <+47>:    lea    0xe5e(%rip),%rdi
   0x00000000000011a6 <+54>:    mov    $0x0,%al
   0x00000000000011a8 <+56>:    call   0x1030 <printf@plt>
   0x00000000000011ad <+61>:    xor    %eax,%eax
   0x00000000000011af <+63>:    add    $0x10,%rsp
   0x00000000000011b3 <+67>:    pop    %rbp
   0x00000000000011b4 <+68>:    ret
```

Compiled by clang-14 on Linux/AMD64

Function Calls

```
foo(1,2);
```

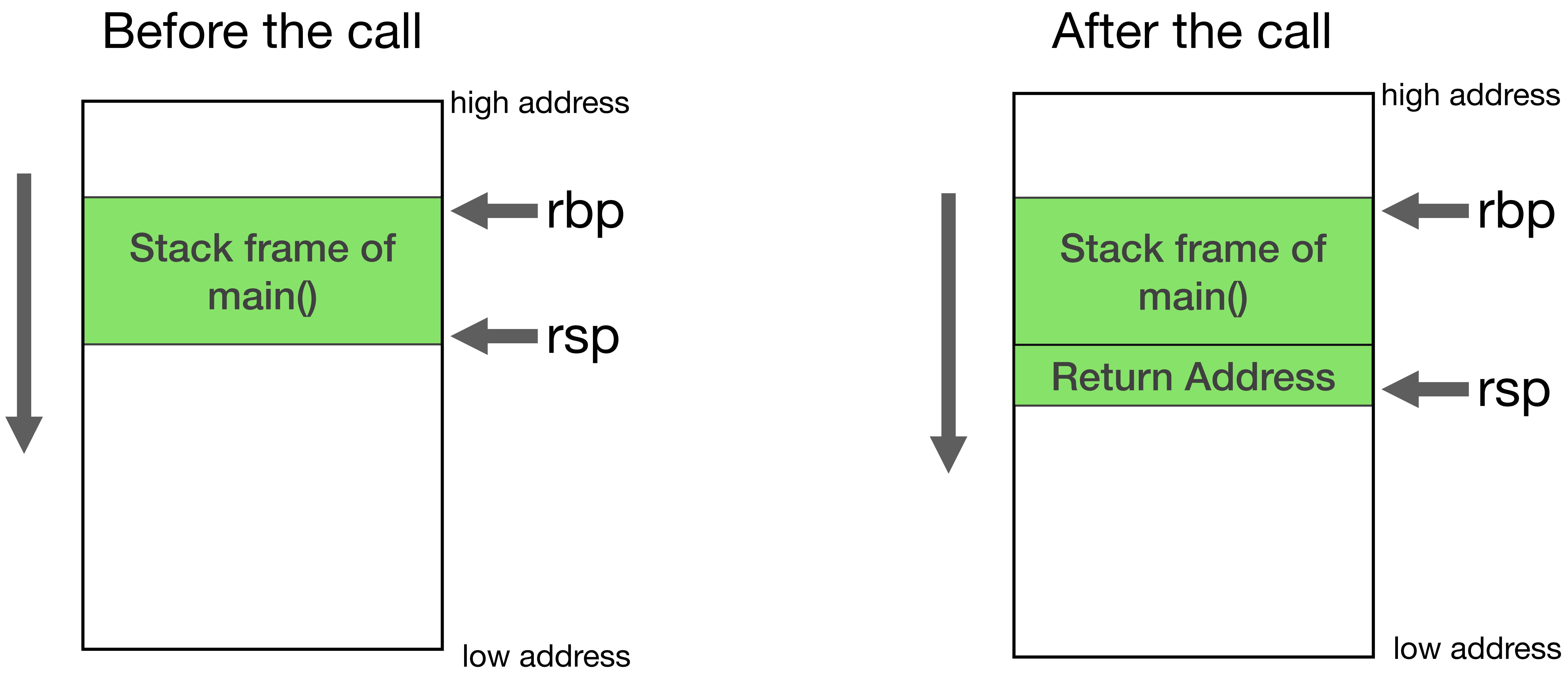
```
0x0000000000001186 <+22>:    mov    $0x1,%edi
0x000000000000118b <+27>:    mov    $0x2,%esi
0x0000000000001190 <+32>:    call   0x1150 <foo>
```

- Arguments are passed
  - in registers: rdi, rsi, rdx, rcx, r8, r9, then via stack

- Pass the 1st argument to edi (the lower half of rdi)
- Pass the 2nd argument to esi (the lower half of rsi)
- Push the return address onto the stack, and jump to the callee function

Function Calls: Stack

```
0x0000000000001186 <+22>:    mov    $0x1,%edi
0x000000000000118b <+27>:    mov    $0x2,%esi
0x0000000000001190 <+32>:    call   0x1150 <foo>
```



Function Initialization

```c
void foo(int a, int b) {
      char buffer[12];
      gets(buffer);
      return;
}
```

```
Dump of assembler code for function foo:
   0x0000000000001150 <+0>:     push   %rbp
   0x0000000000001151 <+1>:     mov    %rsp,%rbp
   0x0000000000001154 <+4>:     sub    $0x20,%rsp
   0x0000000000001158 <+8>:     mov    %edi,-0x4(%rbp)
   0x000000000000115b <+11>:    mov    %esi,-0x8(%rbp)
   0x000000000000115e <+14>:    lea    -0x14(%rbp),%rdi
   0x0000000000001162 <+18>:    mov    $0x0,%al
   0x0000000000001164 <+20>:    call   0x1040 <gets@plt>
   0x0000000000001169 <+25>:    add    $0x20,%rsp
   0x000000000000116d <+29>:    pop    %rbp
   0x000000000000116e <+30>:    ret
```

Function Initialization

```
void foo(int a, int b) {
      char buffer[12];
      gets(buffer);
      return;
}
```

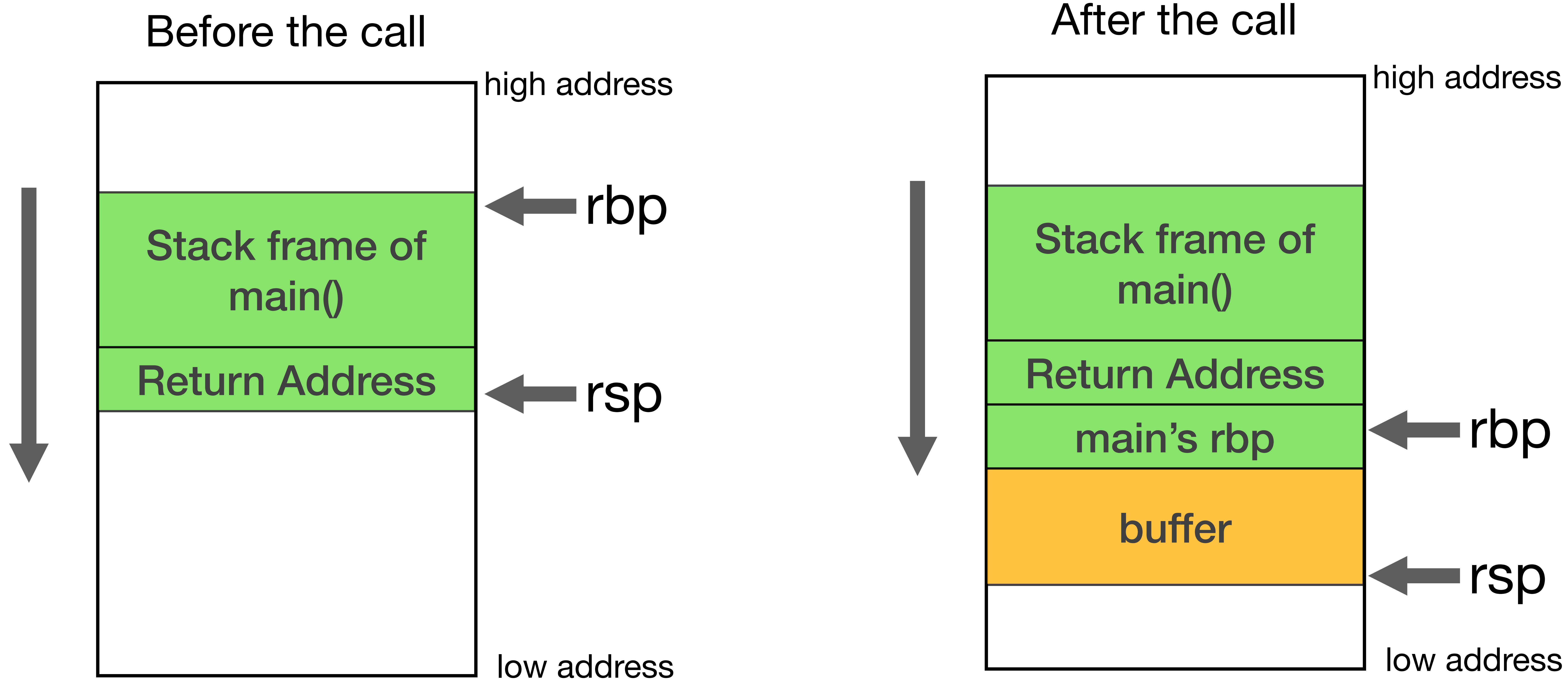
```
0x0000000000001150 <+0>:     push   %rbp
0x0000000000001151 <+1>:     mov    %rsp,%rbp
0x0000000000001154 <+4>:     sub    $0x20,%rsp
```

- Save the old frame pointer
- Set the new frame pointer
- Allocate space for local variables

Function Initialization: Stack

```
void foo(int a, int b) {
      char buffer[12];
      gets(buffer);
      return;
}
```

```
0x0000000000001150 <+0>:     push   %rbp
0x0000000000001151 <+1>:     mov    %rsp,%rbp
0x0000000000001154 <+4>:     sub    $0x20,%rsp
```



Anything unexpected?

Function Return

```
void foo(int a, int b) {
      char buffer[12];
      gets(buffer);
      return;
}
```

```
0x0000000000001169 <+25>:    add    $0x20,%rsp
0x000000000000116d <+29>:    pop    %rbp
0x000000000000116e <+30>:    ret
```

```
push   %rbp
mov    %rsp,%rbp
sub    $0x20,%rsp
```

Function Initialization

- Deallocate the space for local data
- Restore the old frame pointer
- Get the return address and jump to it

Function Return: Using the `leave` Instruction

```
void foo(int a, int b) {
      char buffer[12];
      gets(buffer);
      return;
}
```

```
push    %rbp
mov     %rsp,%rbp
sub     $0x20,%rsp
```

Function Initialization

```
0x00000000000011d0 <+71>:    leave
0x00000000000011d1 <+72>:    ret
```

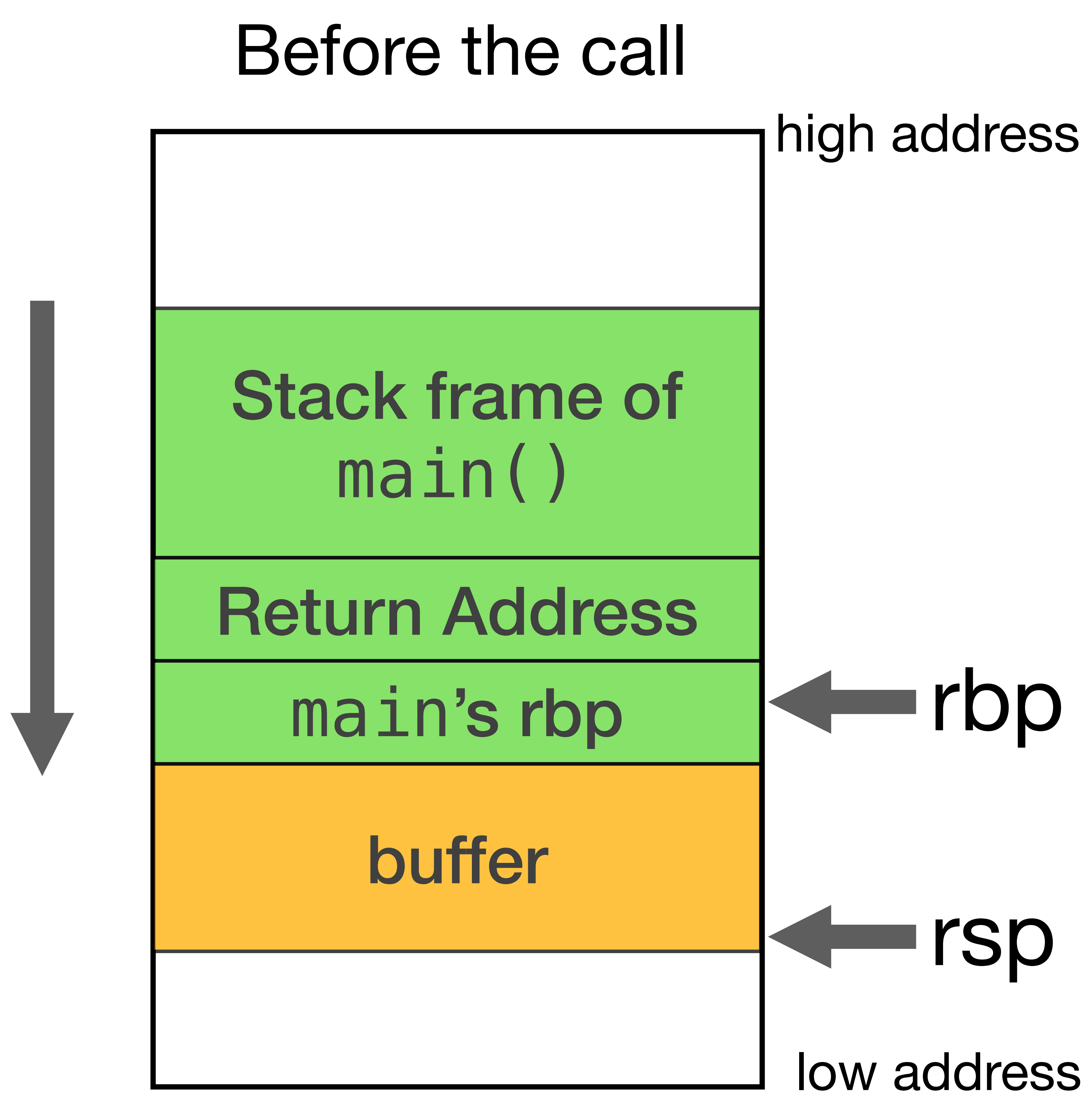
- `leave`: Shorthand for two instructions
  - `mov %rbp, %rsp`
  - `pop %rbp`

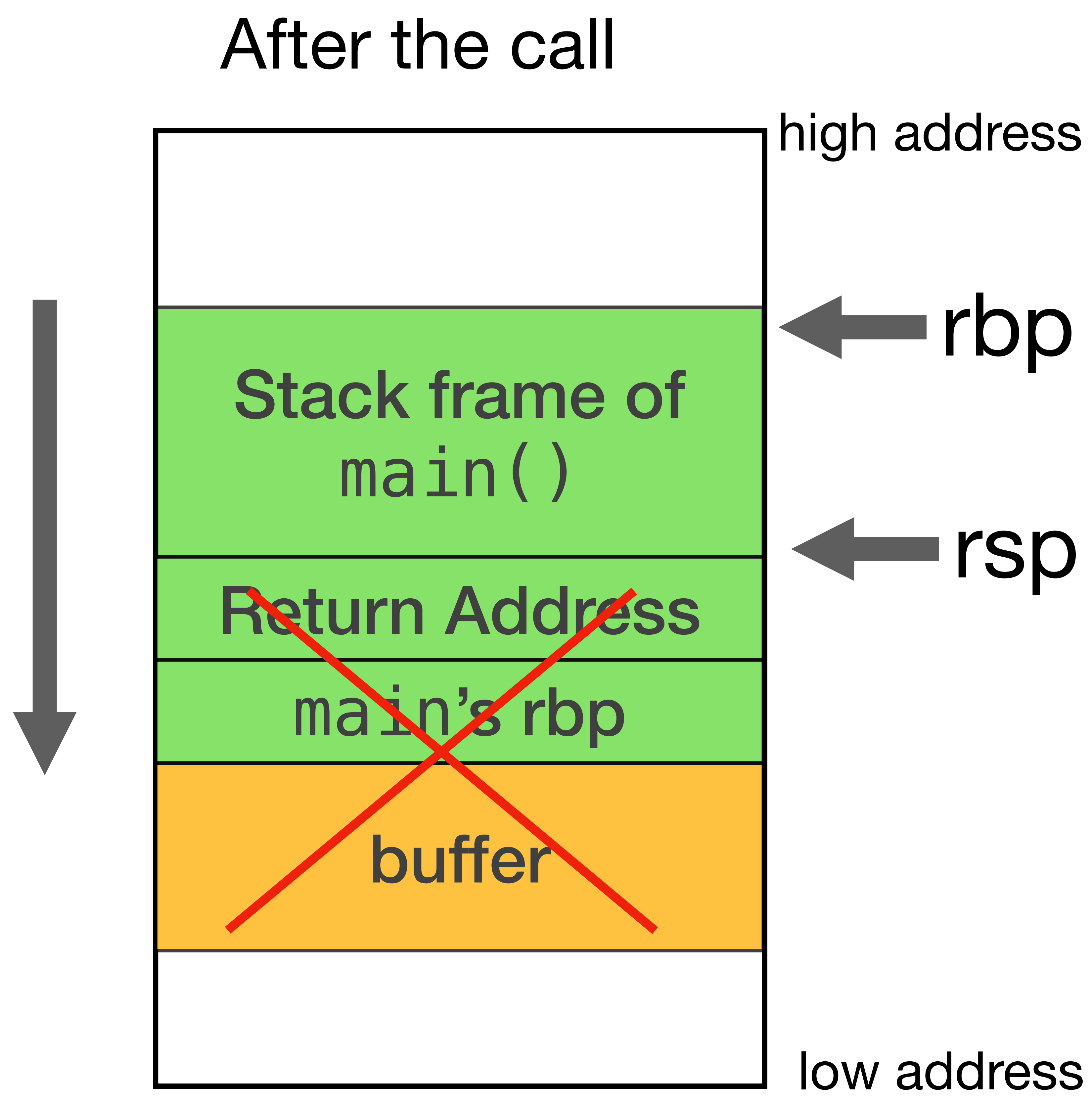
- Deallocate the space for local data
- Restore the old frame pointer
- Get the return address and jump to it

Function Return: Stack

```c
void foo(int a, int b) {
      char buffer[12];
      gets(buffer);
      return;
}
```

```
0x0000000000001169 <+25>:    add    $0x20,%rsp
0x000000000000116d <+29>:    pop    %rbp
0x000000000000116e <+30>:    ret
```





What could attackers do?

Definition: Threat Model

The abilities and resources of the attacker

- Threat models enable structured reasoning about the attack surface.

- Awareness of entry points (and associated threats) to break into the target.
- Look at systems from an attacker's perspective:
  - Decompose application: **identify structure**
  - Determine and rank threats
  - Determine countermeasures and mitigations

Further reading:

https://owasp.org/www-community/Threat_Modeling

Definition: Threat Model

The abilities and resources of the attacker

- Threat models enable structured reasoning about the attack surface.

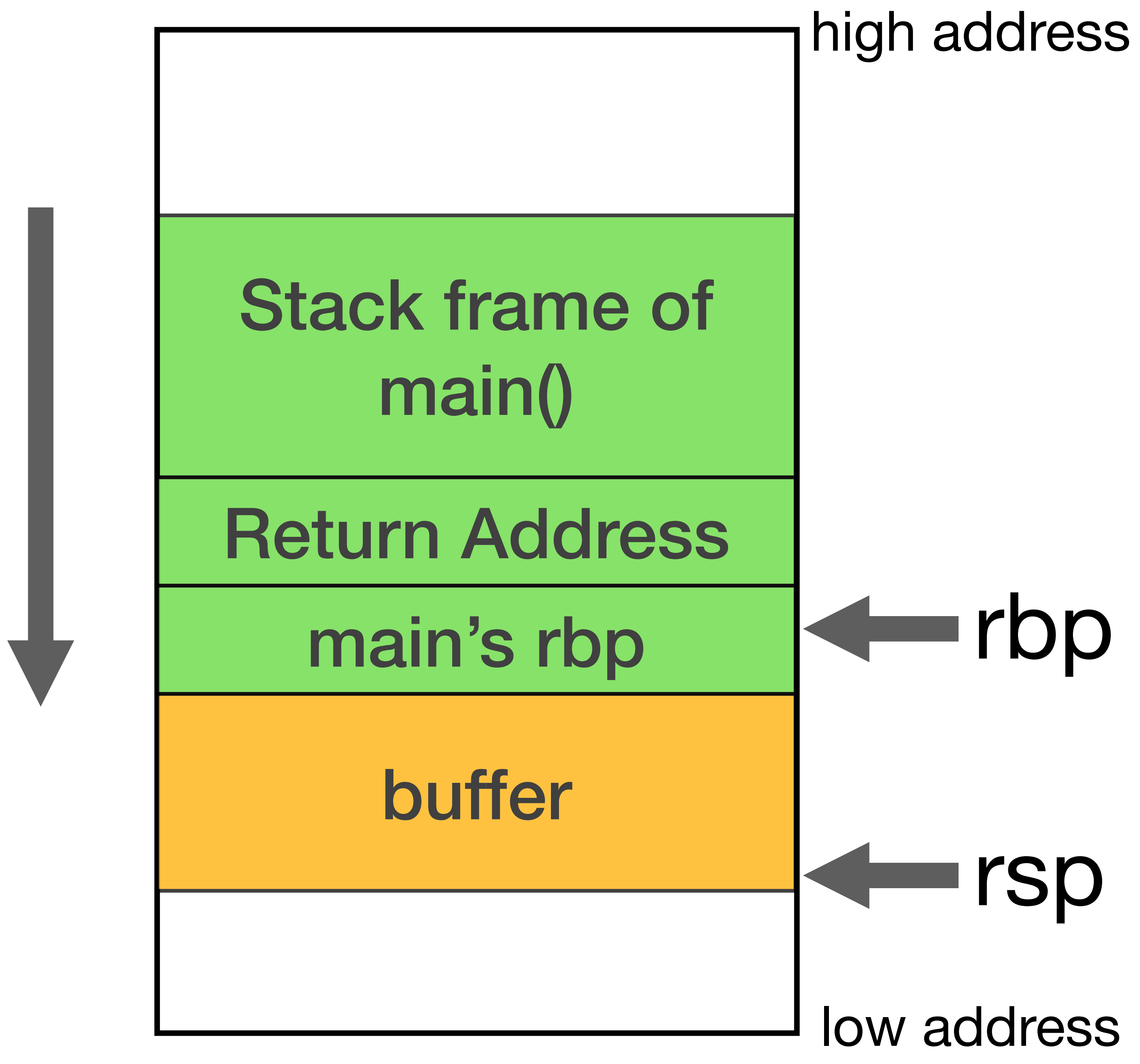
- Awareness of **entry points** (and associated threats) to break into the target.
- Look at systems from an attacker’s perspective:
  - Decompose application: **identify structure**
  - Determine and rank threats
  - Determine countermeasures and mitigations

Further reading:

https://owasp.org/www-community/Threat_Modeling

Exploiting Buffer Overflows

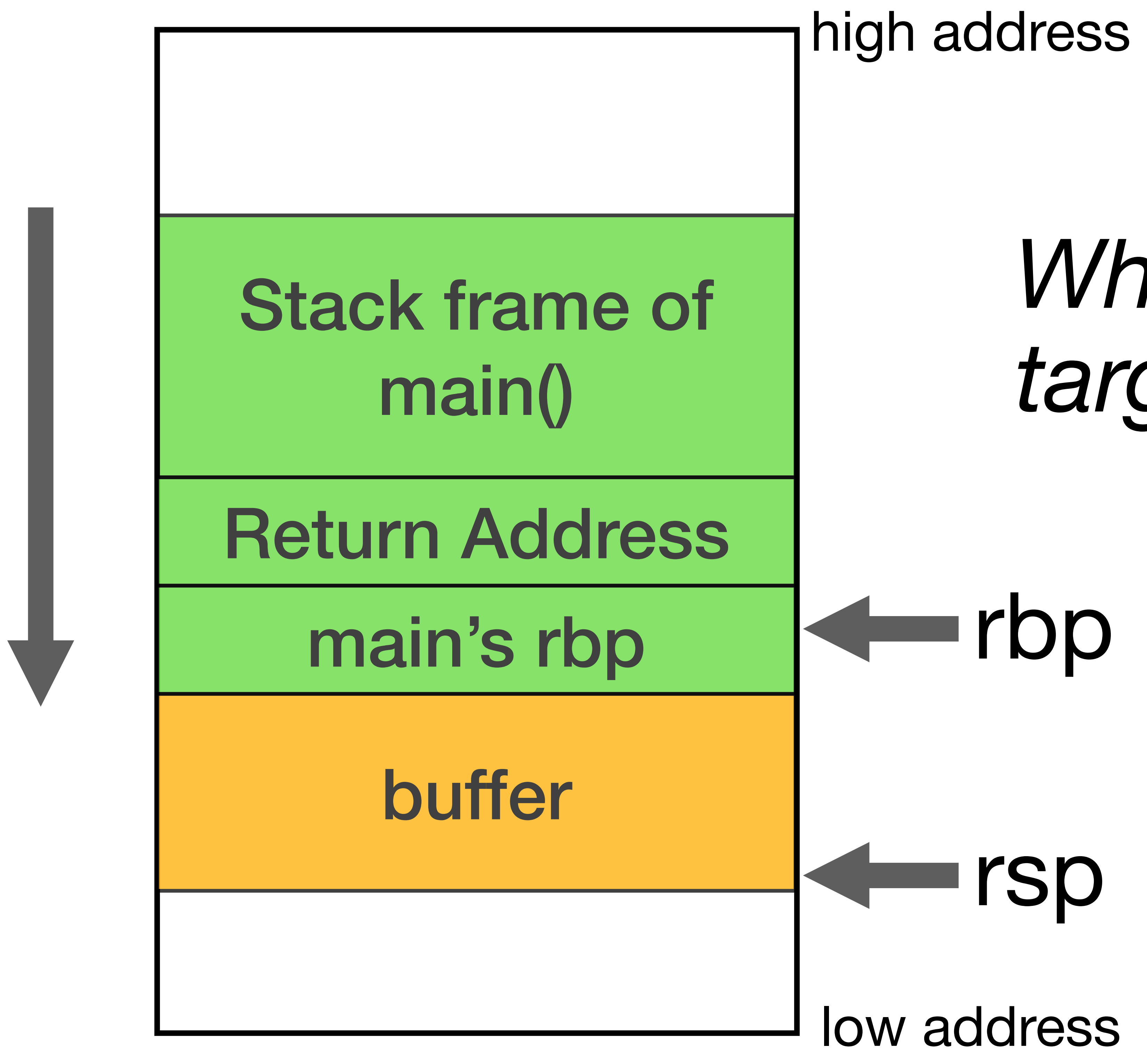
```c
void foo(int a, int b) {
     char buffer[12];
     gets(buffer);
     return;
}

int main() {
     int x;
     x = 0;
     foo(1,2);
     x = 1;
     printf("%d\n",x);
     return 0;
}
```



Attackers can control the input of buffer to overwrite the stack!

Exploiting Buffer Overflows

```
void foo(int a, int b) {
      char buffer[12];
      gets(buffer);
      return;
}

int main() {
      int x;
      x = 0;
      foo(1,2);
      x = 1;
      printf("%d\n",x);
      return 0;
}
```



What are the interesting targets to attackers?

Attackers can control the input of buffer to overwrite the stack!

Smashing the Stack

- Occurs when a buffer overflow overwrites data in the program stack.
- Successful exploits can overwrite the return address on the stack.
  - Could lead to arbitrary code execution on the target machine

Smashing the Stack

```
void foo(int a, int b) {
      char buffer[12];
      gets(buffer);
      return;
}

int main() {
      int x;
      x = 0;
      foo(1,2);
      x = 1;
      printf(“%d\n",x);
      return 0;
}
```

What happens if we input a large string?

./demo ffffffffffffffffffffff…fffff

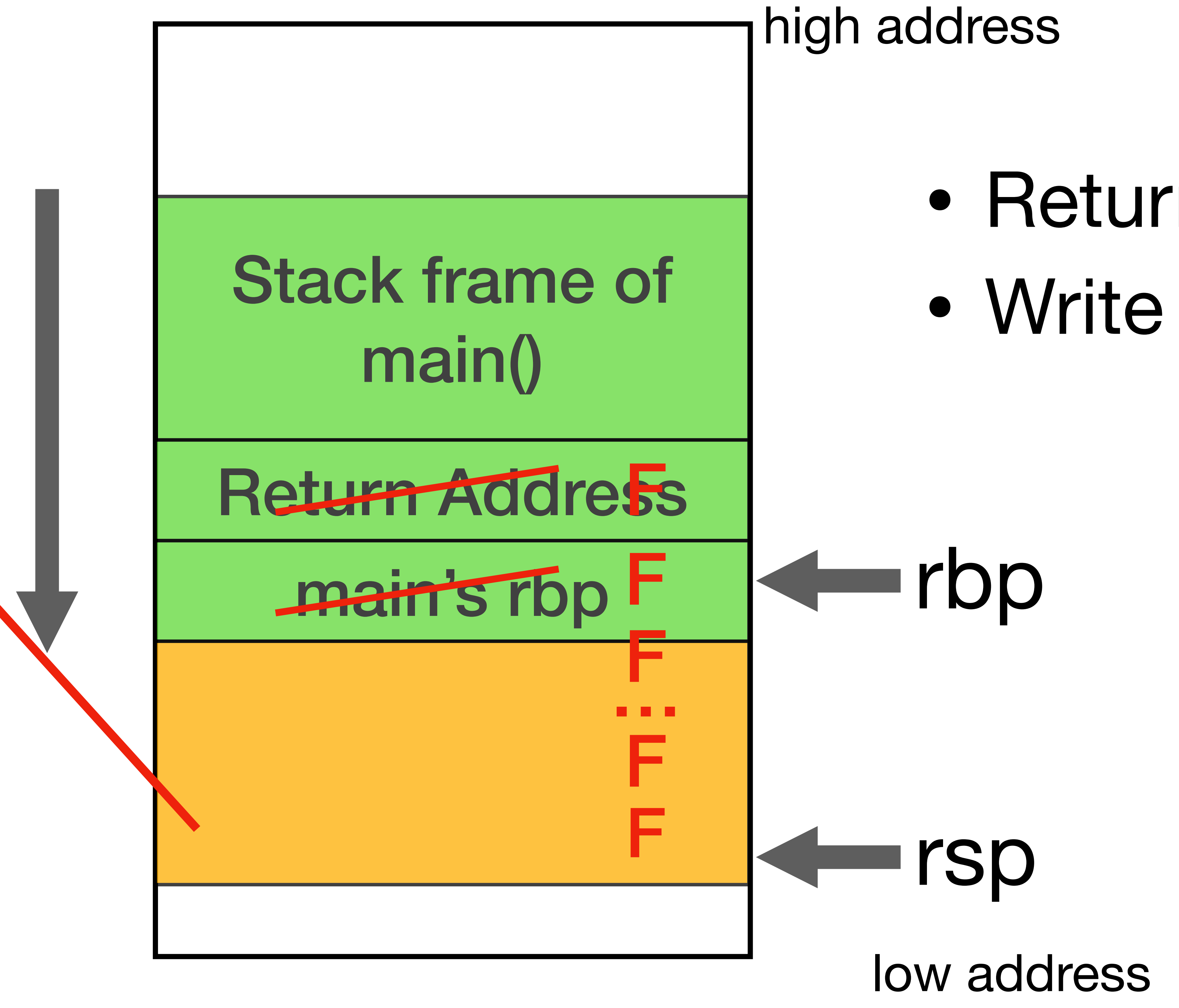
Segmentation fault

Smashing the Stack: What Happened?

```
void foo(int a, int b) {
      char buffer[12];
      gets(buffer);
      return;
}
```

What happens if we input a large string?

./example ffffffffffffffffffffff…fffff

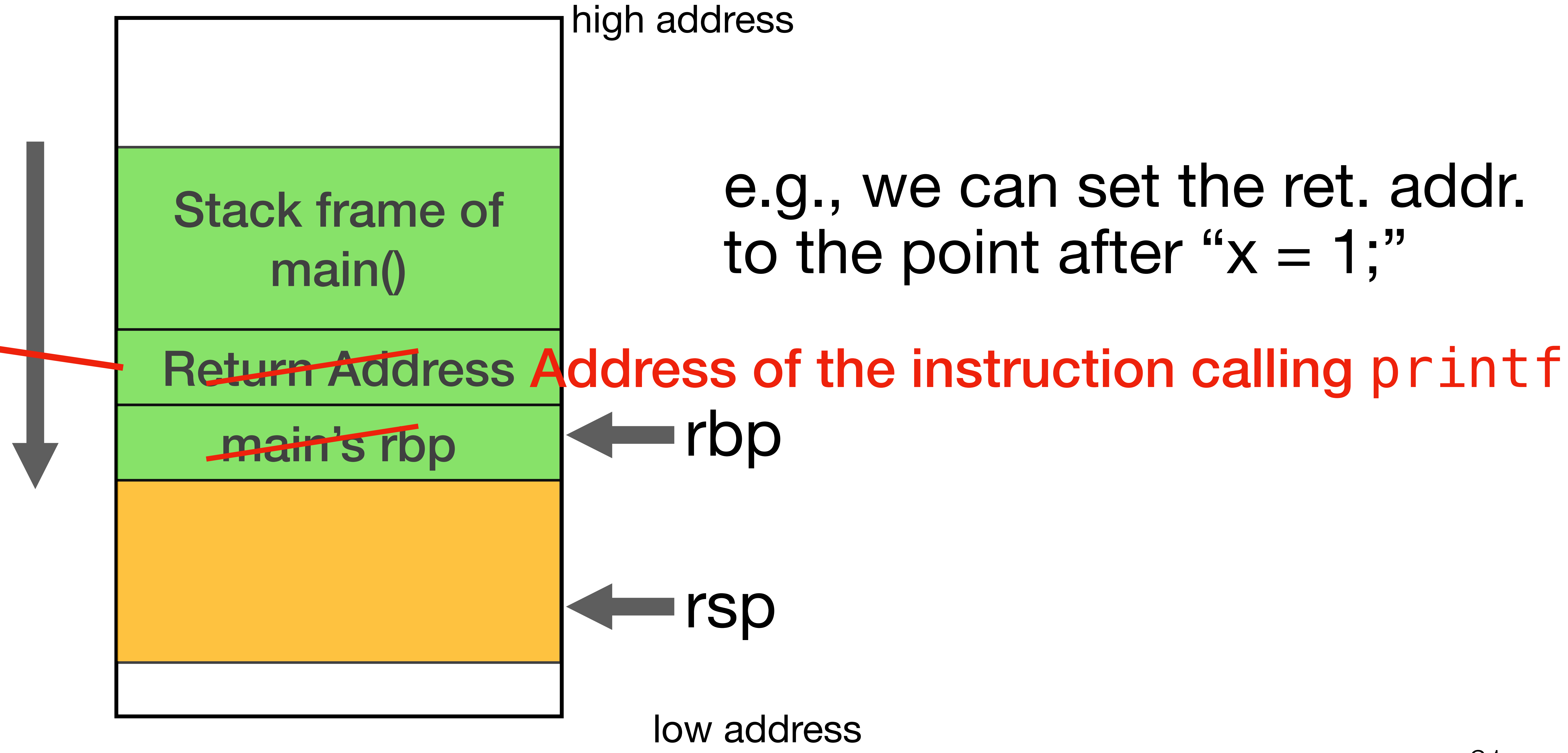


- Return to an invalid address
- Write to an unwritable address

Smashing the Stack: Figure out a Nasty Input

```c
void foo(int a, int b) {
      char buffer[12];
      gets(buffer);
      return;
}

int main() {
      int x;
      x = 0;
      foo(1,2);
      x = 1;
      printf("%d\n",x);
      return 0;
}
```

./demo ? What to input?



e.g., we can set the ret. addr. to the point after “x = 1;”

Definition: Software Security

Allow *intended* use of software and prevent *unintended* use that may cause harm

Goal: Prevent information “mishaps”, but don’t stop good things from happening

- Good things include functionality or legal information access.
- Tradeoff between functionality and security is the key.

E-Voting

Good things: convenience of voting; fast tallying; voting for the disabled; …

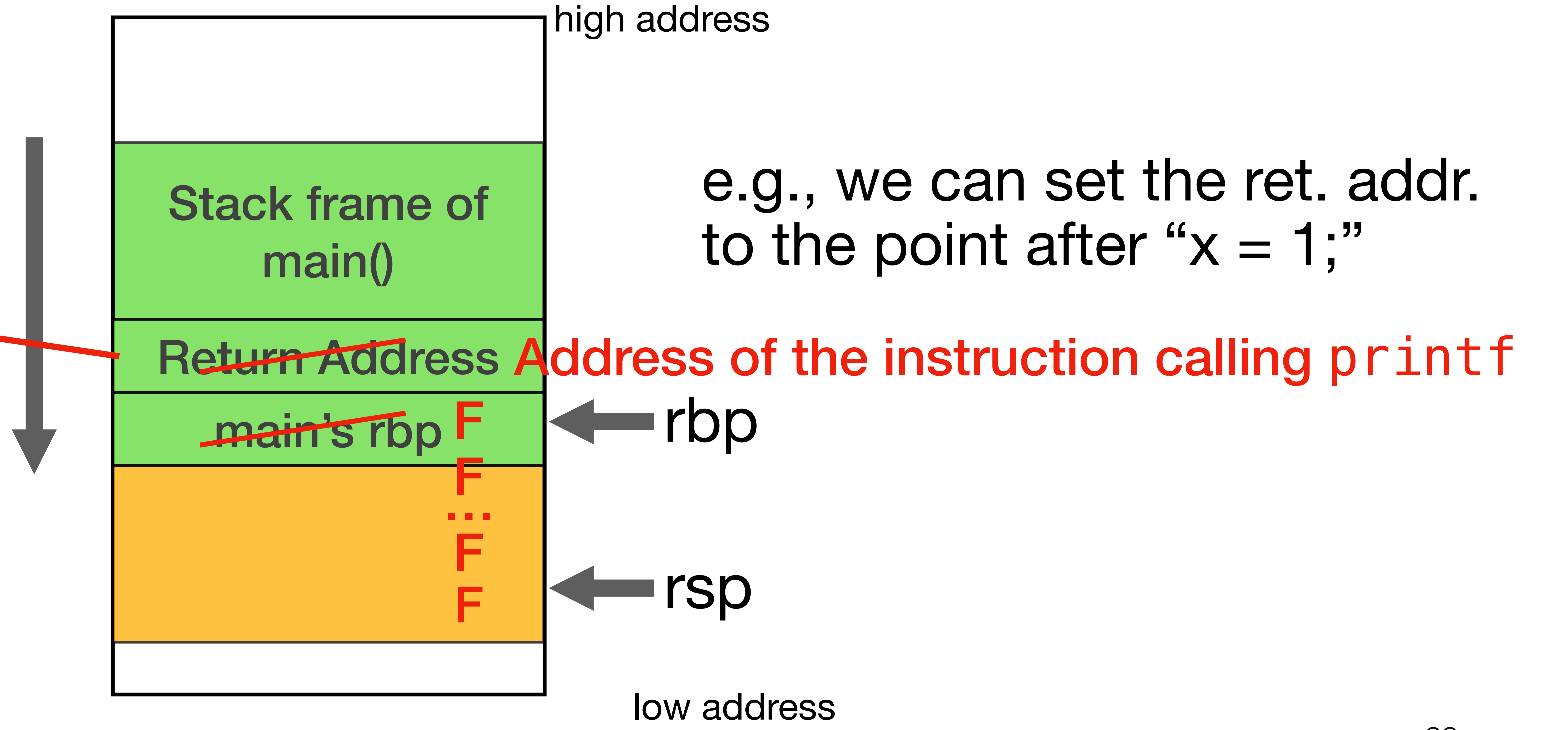
The convenience comes with risks

- Buggy voting software/hardware
- Changed e-voting software by insiders
- …

Smashing the Stack: Figure out a Nasty Input

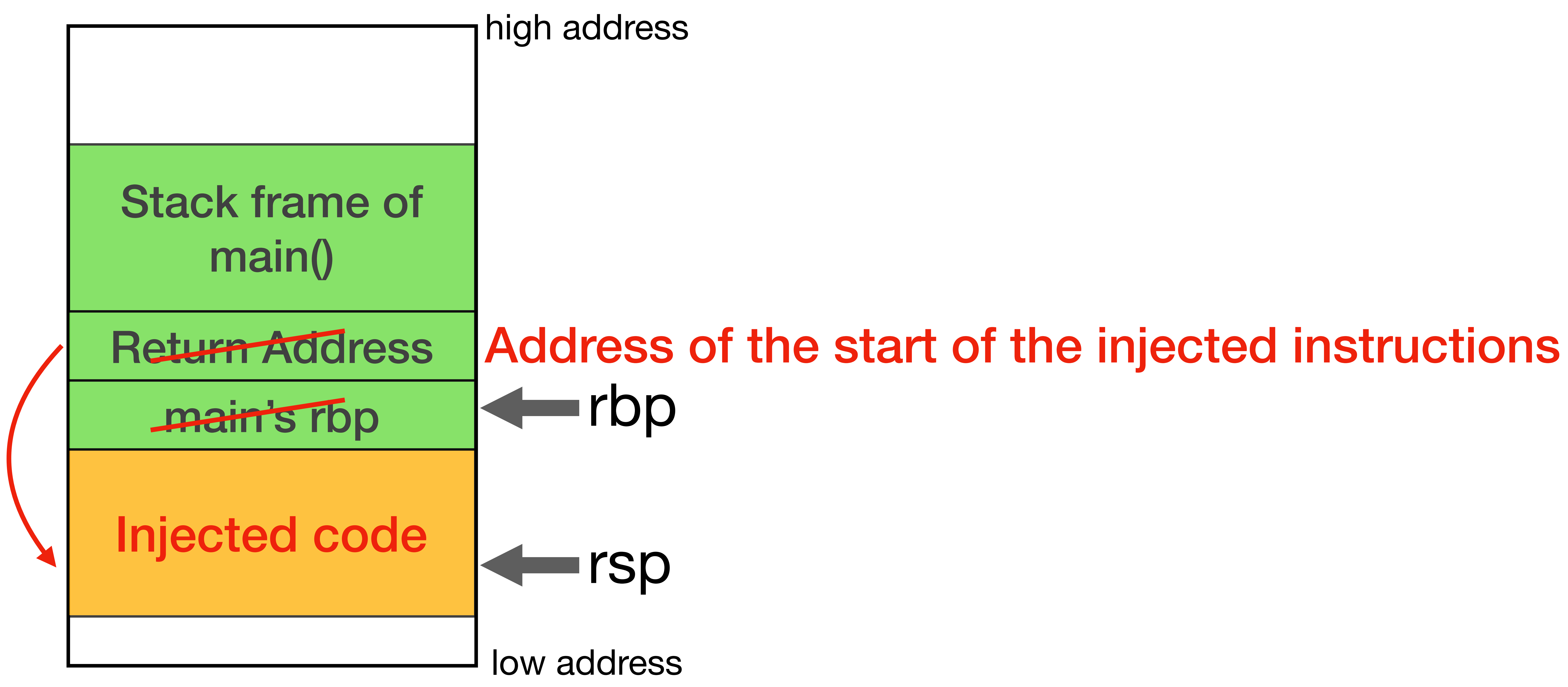
```
void foo(int a, int b) {
      char buffer[12];
      gets(buffer);
      return;
}

int main() {
      int x;
      x = 0;
      foo(1,2);
      x = 1;
      printf("%d\n",x);
      return 0;
}
```

./demo ? What to input?



e.g., we can set the ret. addr. to the point after “x = 1;”

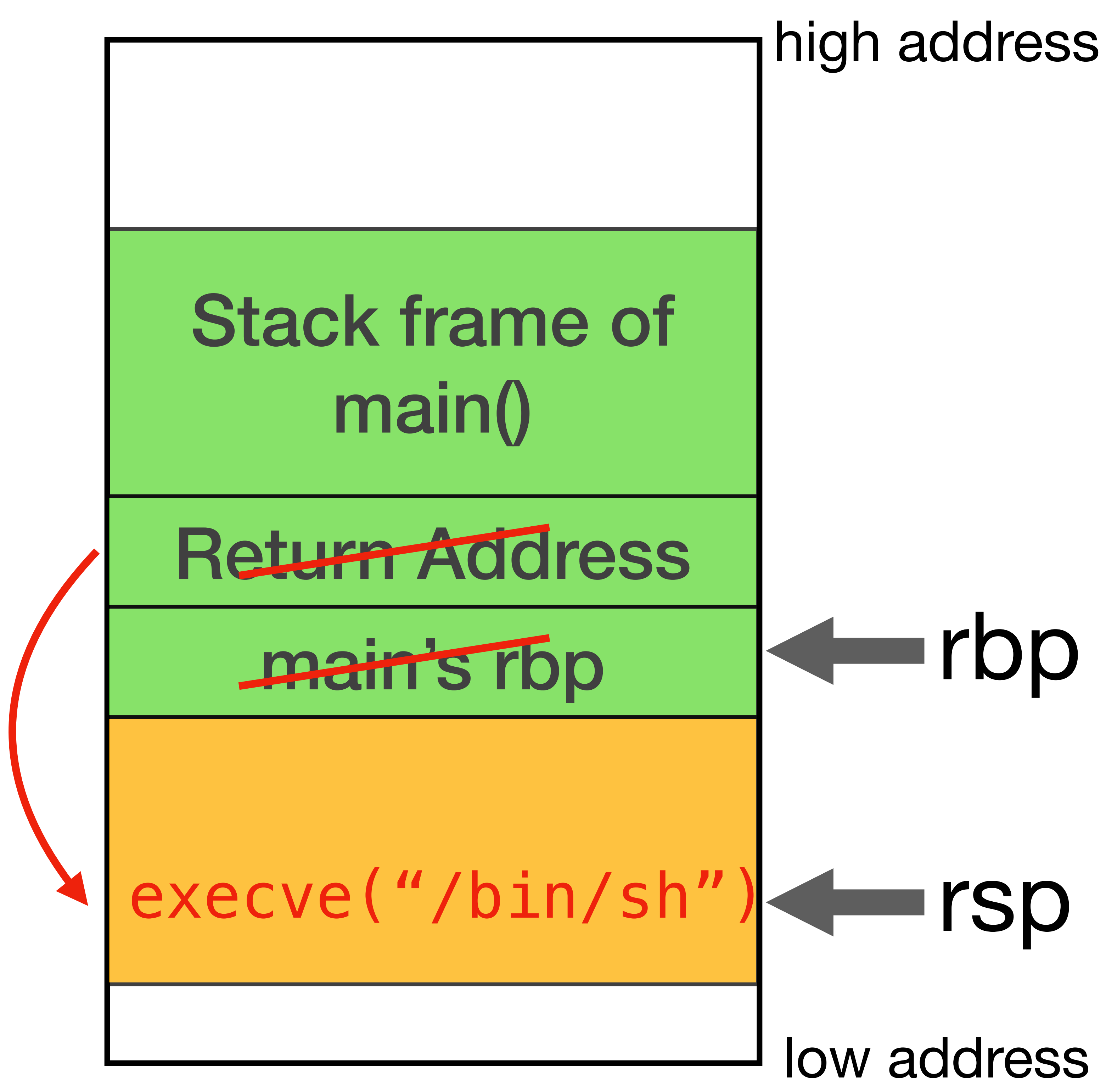
Smashing the Stack: Code Injection



Code Injection

- Attacker creates a malicious input—a specially crafted input that contains a pointer to malicious code included in the input.
- When the function returns, control is transferred to the malicious code.
  - Injected code runs with the permission of the vulnerable program when the function returns.
  - Programs running with root or other elevated privileges are normally targeted.

Smashing the Stack: Injecting Shell Code



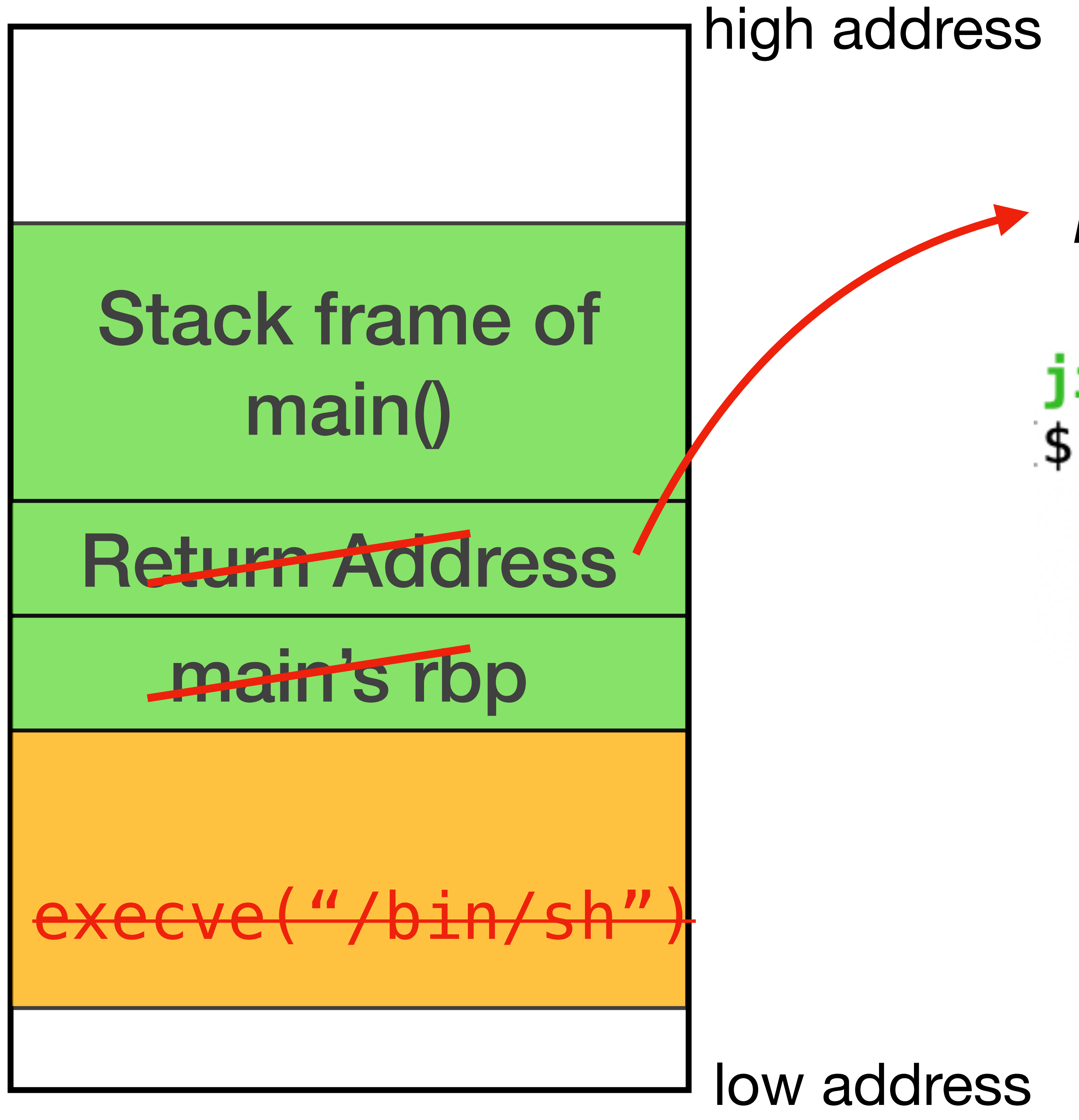
- This brings up a shell.
- Attackers can execute *any* command in the shell.
- The shell has the same privilege as the process.

- Good news:
  - C/C++ stack is not executable by default.

- Bad news:
  - Code injection works in other cases, e.g. JIT, certain embedded systems, etc.

How to circumvent this non-executable-stack restriction?

Exploiting Existing and Executable Code



How about "returning" to some existing code?

```
jie@gwsyssec: ~/courses/csci6545/lectures
$ ldd demo
        linux-vdso.so.1 (0x00007ffffadfd000)
        libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f48a2c00000)
        /lib64/ld-linux-x86-64.so.2 (0x00007f48a2efc000)
```

```
(gdb) info proc mappings
process 74581
Mapped address spaces:

          Start Addr           End Addr       Size     Offset  Perms  objfile
      0x555555554000     0x555555555000     0x1000        0x0  r--p   /home/jie/courses/csci6545/lectures/demo
      0x555555555000     0x555555556000     0x1000     0x1000  r-xp   /home/jie/courses/csci6545/lectures/demo
      0x555555556000     0x555555557000     0x1000     0x2000  r--p   /home/jie/courses/csci6545/lectures/demo
      0x555555557000     0x555555558000     0x1000     0x2000  r--p   /home/jie/courses/csci6545/lectures/demo
      0x555555558000     0x555555559000     0x1000     0x3000  rw-p   /home/jie/courses/csci6545/lectures/demo
      0x7ffff7c00000     0x7ffff7c28000    0x28000        0x0  r--p   /usr/lib/x86_64-linux-gnu/libc.so.6
      0x7ffff7c28000     0x7ffff7dbd000   0x195000    0x28000  r-xp   /usr/lib/x86_64-linux-gnu/libc.so.6
      0x7ffff7dbd000     0x7ffff7e15000    0x58000   0x1bd000  r--p   /usr/lib/x86_64-linux-gnu/libc.so.6
      0x7ffff7e15000     0x7ffff7e16000     0x1000   0x215000  ---p   /usr/lib/x86_64-linux-gnu/libc.so.6
      0x7ffff7e16000     0x7ffff7e1a000     0x4000   0x215000  r--p   /usr/lib/x86_64-linux-gnu/libc.so.6
      0x7ffff7e1a000     0x7ffff7e1c000     0x2000   0x219000  rw-p   /usr/lib/x86_64-linux-gnu/libc.so.6
      0x7ffff7e1c000     0x7ffff7e29000     0xd000        0x0  rw-p
      0x7ffff7fa6000     0x7ffff7fa9000     0x3000        0x0  rw-p
      0x7ffff7fbb000     0x7ffff7fbd000     0x2000        0x0  rw-p
      0x7ffff7fbd000     0x7ffff7fc1000     0x4000        0x0  r--p   [vvar]
      0x7ffff7fc1000     0x7ffff7fc3000     0x2000        0x0  r-xp   [vdso]
      0x7ffff7fc3000     0x7ffff7fc5000     0x2000        0x0  r--p   /usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2
      0x7ffff7fc5000     0x7ffff7fef000    0x2a000     0x2000  r-xp   /usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2
      0x7ffff7fef000     0x7ffff7ffa000     0xb000    0x2c000  r--p   /usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2
      0x7ffff7ffb000     0x7ffff7ffd000     0x2000    0x37000  r--p   /usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2
      0x7ffff7ffd000     0x7ffff7fff000     0x2000    0x39000  rw-p   /usr/lib/x86_64-linux-gnu/ld-linux-x86-64.so.2
      0x7ffffffde000     0x7ffffffff000    0x21000        0x0  rw-p   [stack]
  0xffffffffff600000 0xffffffffff601000     0x1000        0x0  --xp   [vsyscall]
```

Exploiting Existing and Executable Code

- `system()` libc function

NAME top

system - execute a shell command

LIBRARY top

Standard C library (*libc*, *-lc*)

SYNOPSIS top

```
#include <stdlib.h>

int system(const char *command);
```

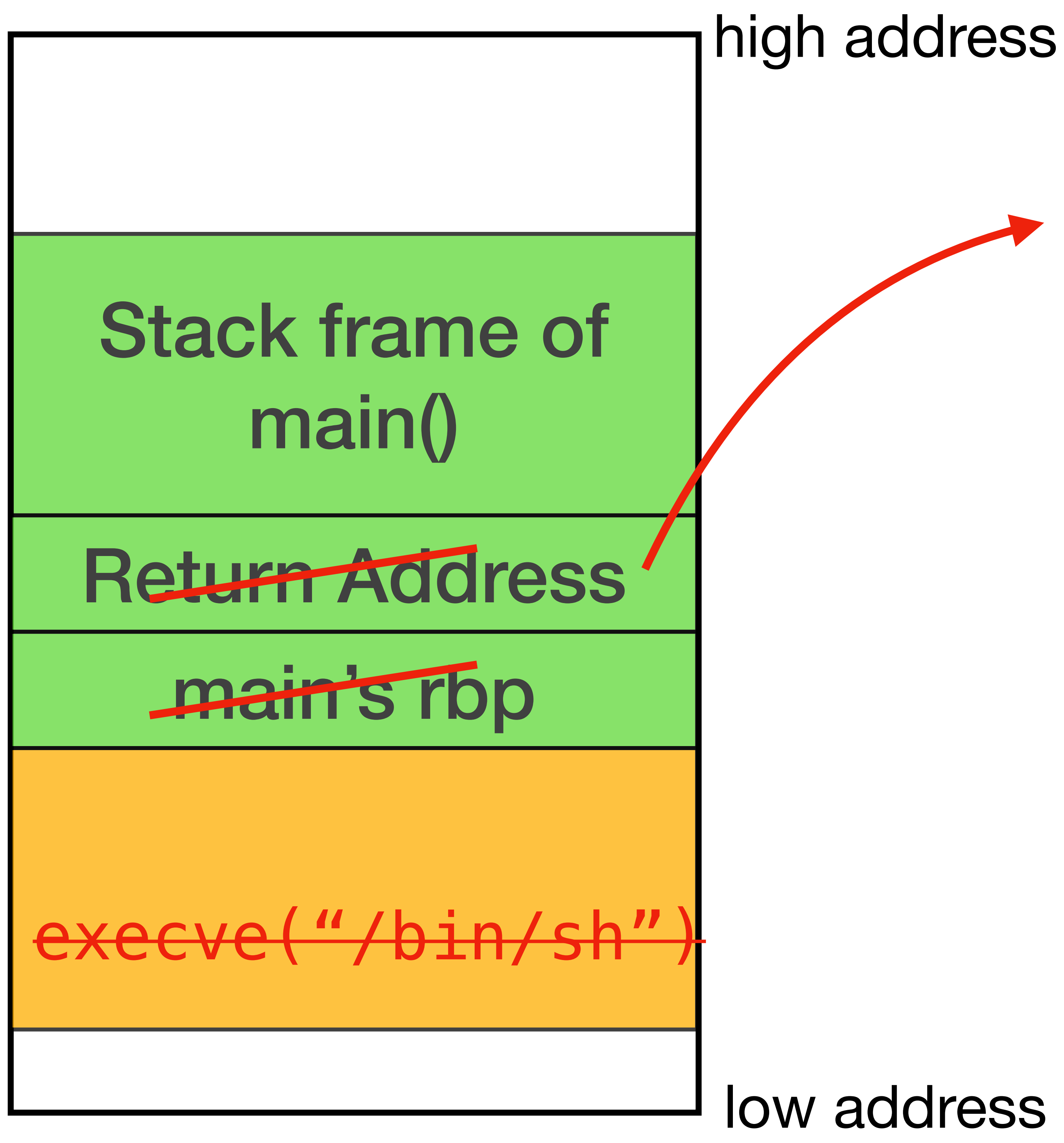
DESCRIPTION top

The **system**() library function behaves as if it used fork(2) to create a child process that executed the shell command specified in *command* using execl(3) as follows:

```
execl("/bin/sh", "sh", "-c", command, (char *) NULL);
```

system() returns after the command has been completed.

Exploiting Existing and Executable Code



"return" to `system()`

```
(gdb) disassemble system
Dump of assembler code for function system:
   0x00007ffff7c50d70 <+0>:     endbr64
   0x00007ffff7c50d74 <+4>:     test   %rdi,%rdi
   0x00007ffff7c50d77 <+7>:     je     0x7ffff7c50d80 <system+16>
   0x00007ffff7c50d79 <+9>:     jmp    0x7ffff7c50900
   0x00007ffff7c50d7e <+14>:    xchg   %ax,%ax
   0x00007ffff7c50d80 <+16>:    sub    $0x8,%rsp
   0x00007ffff7c50d84 <+20>:    lea    0x1878f5(%rip),%rdi
   0x00007ffff7c50d8b <+27>:    call   0x7ffff7c50900
   0x00007ffff7c50d90 <+32>:    test   %eax,%eax
   0x00007ffff7c50d92 <+34>:    sete   %al
   0x00007ffff7c50d95 <+37>:    add    $0x8,%rsp
   0x00007ffff7c50d99 <+41>:    movzbl %al,%eax
   0x00007ffff7c50d9c <+44>:    ret
```

Return-to-libc(ret2libc) Attack: Exploiting `system()`

- `system()` libc function

NAME top

system – execute a shell command

LIBRARY top

Standard C library (*libc*, *-lc*)

SYNOPSIS top

```
#include <stdlib.h>

int system(const char *command);
```

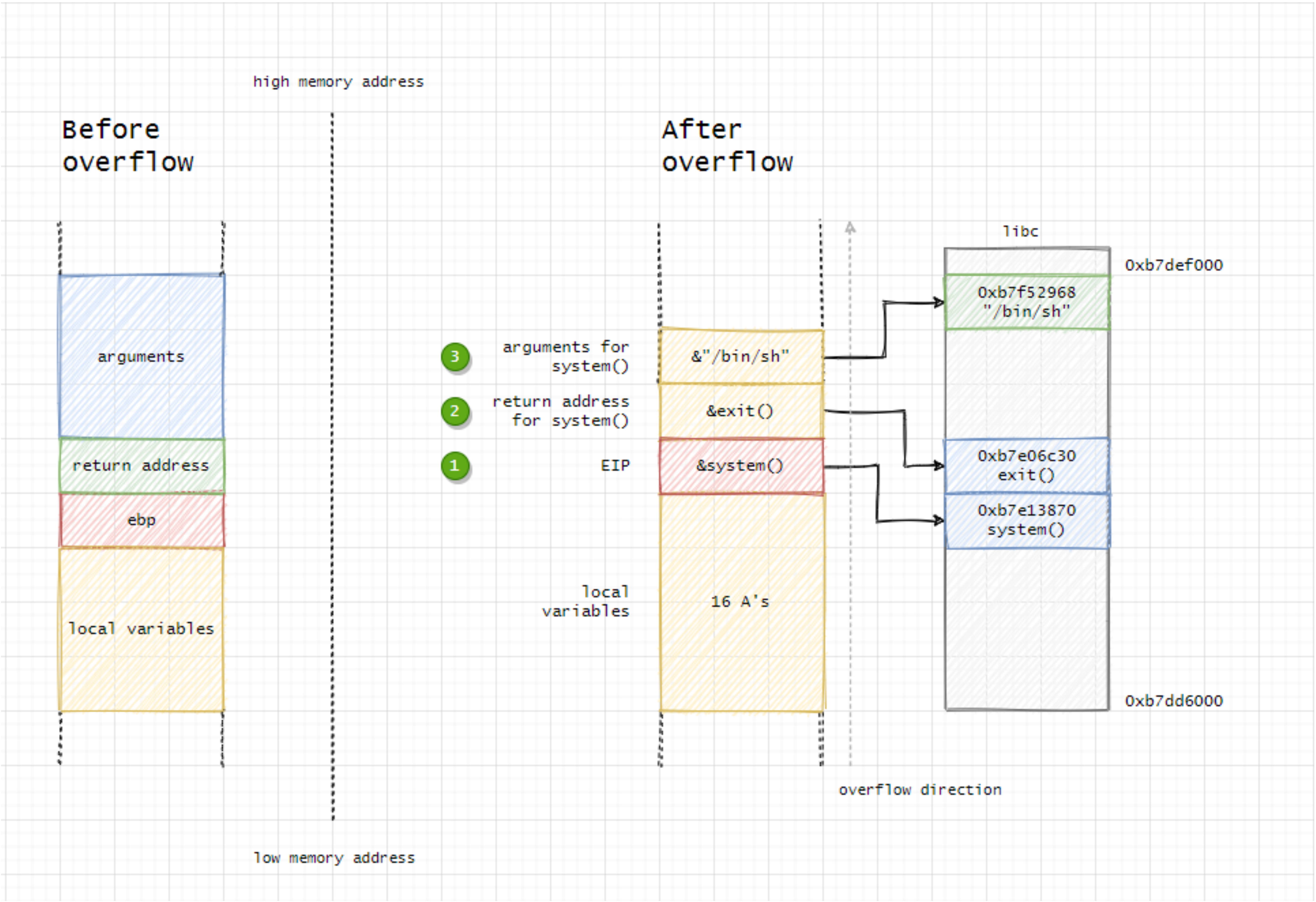
DESCRIPTION top

The **system**() library function behaves as if it used fork(2) to create a child process that executed the shell command specified in *command* using execl(3) as follows:

```
execl("/bin/sh", "sh", "-c", command, (char *) NULL);
```

system() returns after the command has been completed.

Exploiting ret2libc on x86-32

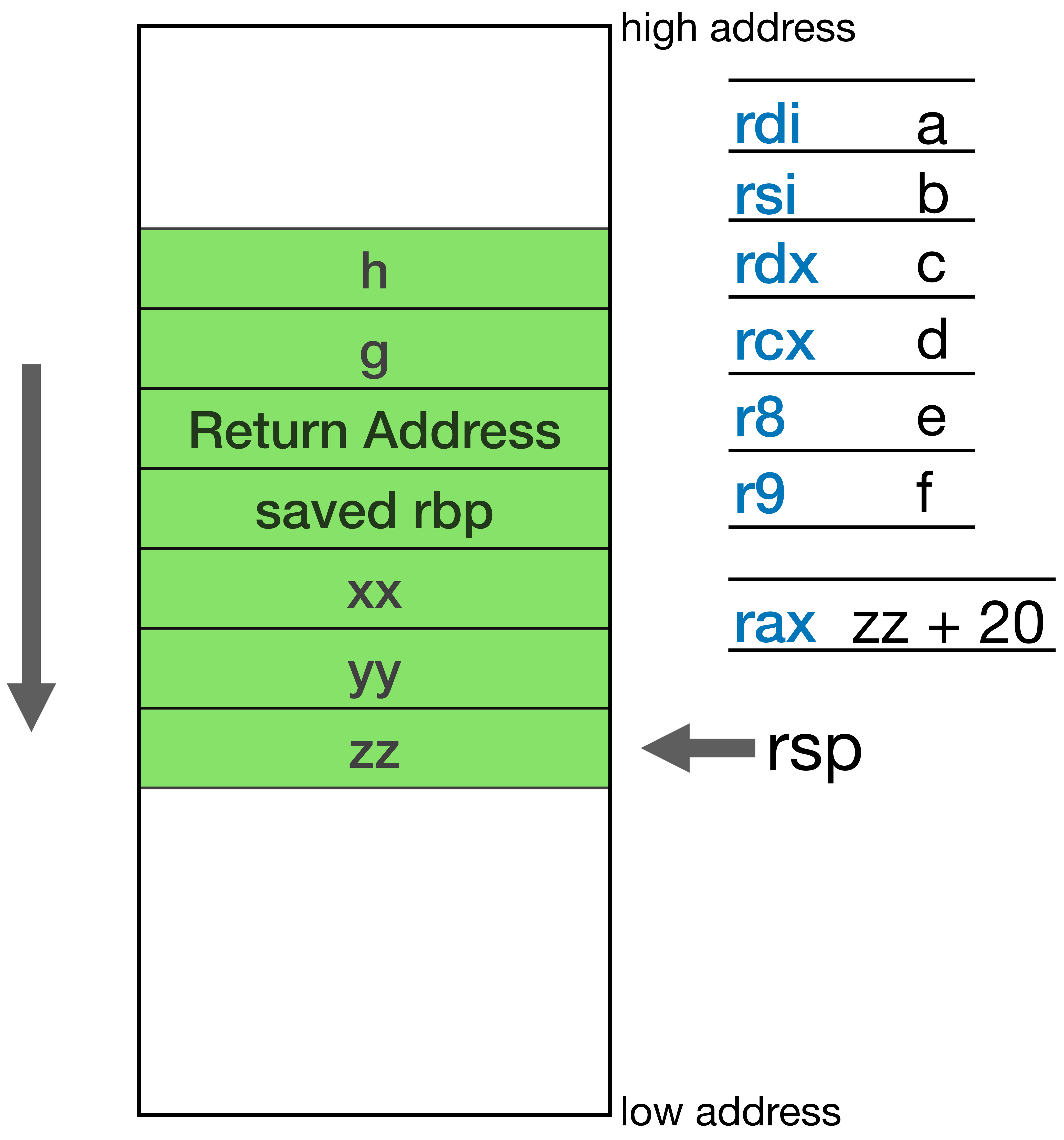


Stack memory layout of a 32-bit vulnerable program

https://www.ired.team/offensive-security/code-injection-process-injection/binary-exploitation/return-to-libc-ret2libc

System V ADM64 Calling Convention

```
void foo() {
    ...
    bar(a, b, c, d, e, f, g, h);
    ...
}

long bar(long a, long b, long c, long d,
         long e, long f, long g, long h) {
   long xx = a * b * c * d * e * f * g * h;
   long yy = a + b + c + d + e + f + g + h;
   long zz = utilfunc(xx, yy, xx % yy);
   return zz + 20;
}
```



How to put malicious data in target registers?

Come to the Next Lecture!

GDB (GNU Debugger)

Debugger: A program that debuggs (examines) other programs.

- See what status a running/crashed program is in.
  - Inspect virtual addresses and registers

GDB basics:

https://medium.com/@amit.kulkarni/gdb-basics-bf3407593285

GDB (GNU Debugger)

- Examine code (source and assembly)
- Control execution
  - Break point (where to stop)
  - Next line/instruction/next function/break point
- Examine memory/register
  - Variable's value
  - Value in register
  - Value in a virtual address
- Powerful commands/techniques
  - `info`
  - `define hook-stop`
  - `help + command name`

Other Tools for Studying Binaries

- `objdump`
- `strings`
- `readelf`
- `nm`
- `hexdump`
- `ldd`