Introduction to Binary Exploitation

Based on the slides, figures, code snippets and previous work of Martin Schwarzl

Why???

Many programs are written in memory unsafe languages like C.

- Operating system kernels (Linux)
- Browsers (Chromium)
- Runtime environments (JVM)

Why ME?

- Team captain of LosFuzzys (CTF team @ TU Graz)
- Researcher & teaching assistant @ IAIK TU Graz
- Almost 10 years of experience in reverse engineering and binary exploitation
- Academic publications in the field of binary exploitation and reverse engineering in submission

Why???

Real world example

- Full push to root
- We chained three different binary exploitations together
- We:
    - Got initial RCE
    - Escalated privileges to root
    - Escaped the sandbox

Binary Exploitation

The art of finding vulnerabilities in programs and leveraging them to gain control over the entire program.

Memory safety

"Memory safety is a concern in software development that aims to avoid software bugs that
cause security vulnerabilities dealing with random-access memory (RAM) access, such as
buffer overflows and dangling pointers."

Memory safety

- Can we prevent them?
- Yes Memory safe languages exist, but
  - Huge legacy codebases in C
  - C is often used in the lowest levels of software stacks (OS, drivers, etc.)
  - C is often used in performance-critical code

Typical memory safety violations

- Overflows or overreads on memory
- Invalid pointers
    - Null pointer dereferences
- Uninitialized memory access
- Invalid free
    - Use after free

Types of Memory Safety Violations

- Spatial memory safety violations
- Temporal memory safety violations

Spatial memory safety violations

Memory access is out of the object's bounds

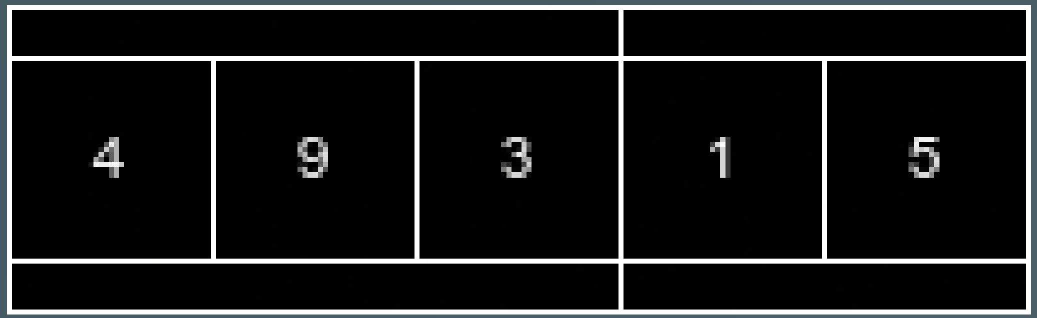
- Buffer overflows
- Out of bounds read/write
- Invalid pointer references
    - Null pointer dereferences

Buffers

- A buffer is a contiguous memory area
- Buffers are used to store contiguous data (arrays, structs, classes)
- Buffers have boundaries (start address and size)
- Buffer access is often done using simple pointer arithmetic
  - `buffer[i]` is equivalent to `*(buffer + i)`
  - buffer_start + i * sizeof(type)

Buffers

- Out-of-bounds access often accesses neighboring buffers



Buffer overflow

No bounds checks on adjacent memory areas

```
char buffer[10];
strcpy(buffer, "Hello, World!");
```

Out of bounds read/write

Native C arrays do not have bounds checks by default

```
int i = 15;
char buffer[10];
buffer[2] = 3; // CORRECT
buffer[i] = 4; // WRONG
```

Invalid pointer references

```
int *ptr = NULL;
*ptr = 10; // CRASH
```

Temporal memory safety violations

Memory access is performed after the object has been freed or before it has been initialized

- Use after free
- Double free
- Use of uninitialized memory

Use after free

- Referencing a resource after it was freed
- Often leads to crashes but not always
- Always leads to undefined behavior and unwanted side effects

```
int *ptr = malloc(sizeof(int));
free(ptr);
*ptr = 10; // Undefined behavior
```

Double free

- Theoretically easy to detect

```
int *ptr = malloc(sizeof(int));
free(ptr);
free(ptr); // Double free error on most libc implementations
```

- But not always...

```
int *ptr = malloc(sizeof(int));
int *pt2 = malloc(sizeof(int));
free(ptr);
free(ptr2);
free(ptr); // No error but double free
```

Use of uninitialized memory

- Who knows what's in there?

```
int x;
if (x == 10) {
    // ...
}
```

- Undefined behavior
- Always initialize your variables!

Stack

- Fundamental data structure in computer science
- Last-in, first-out (LIFO) policy
  - Push and pop operations
  - Most recent item is the first to be removed
- Stack is a region of memory
- Each thread has its dedicated stack

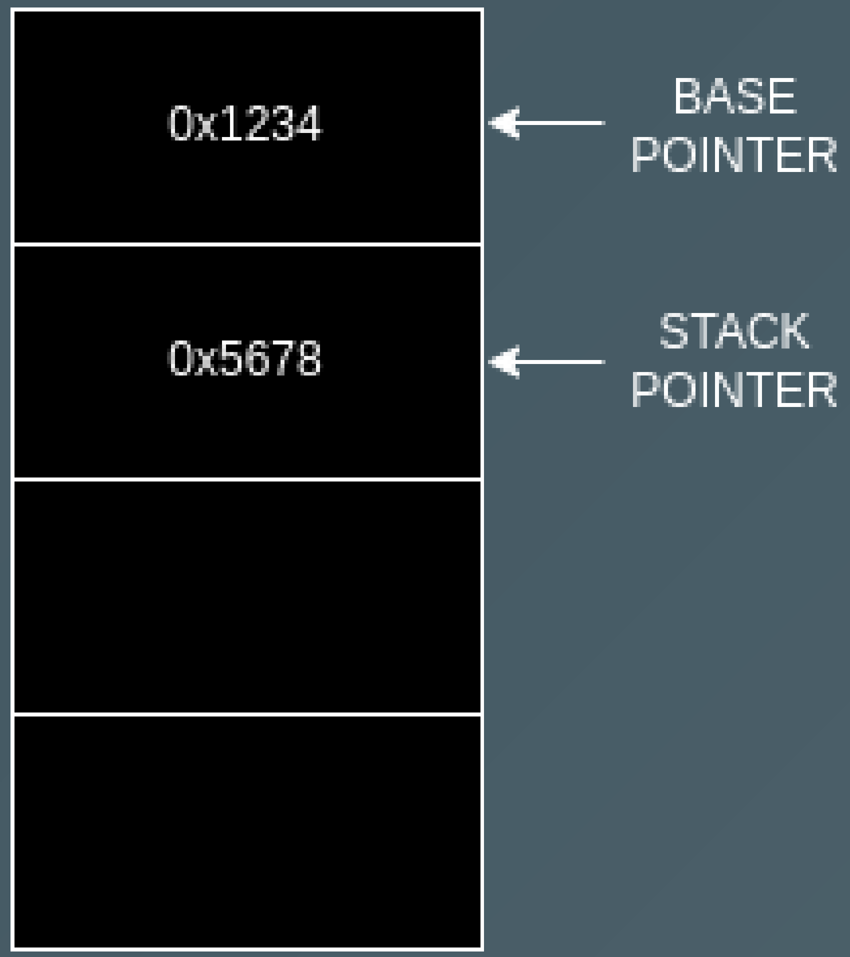
Stack pointer

- Special-purpose register
- Points to the top of the stack
- Growing downwards on most architectures

Stack operations: PUSH

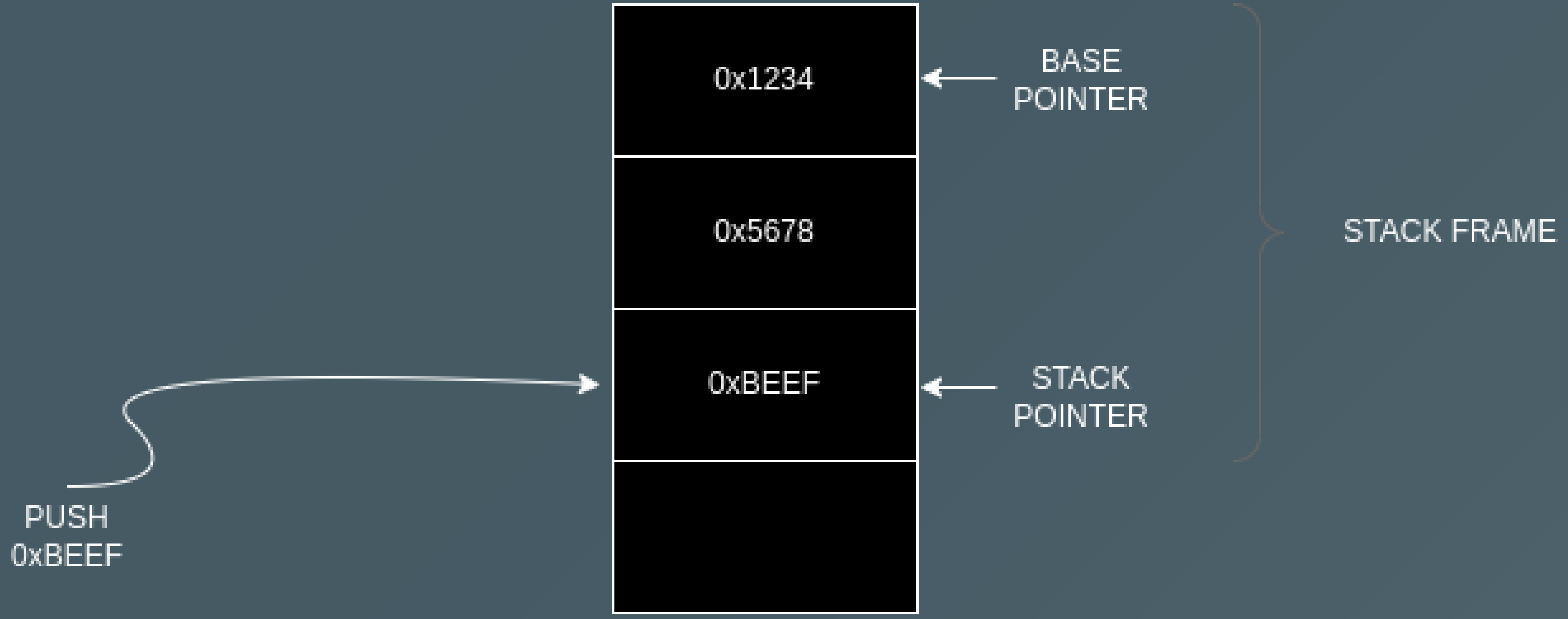
- Push: Add an item to the top of the stack
    - Decrease the stack pointer to allocate space for the new item
    - Copy the item to the new top of the stack

Stack push



PUSH
0xBEEF

Stack push

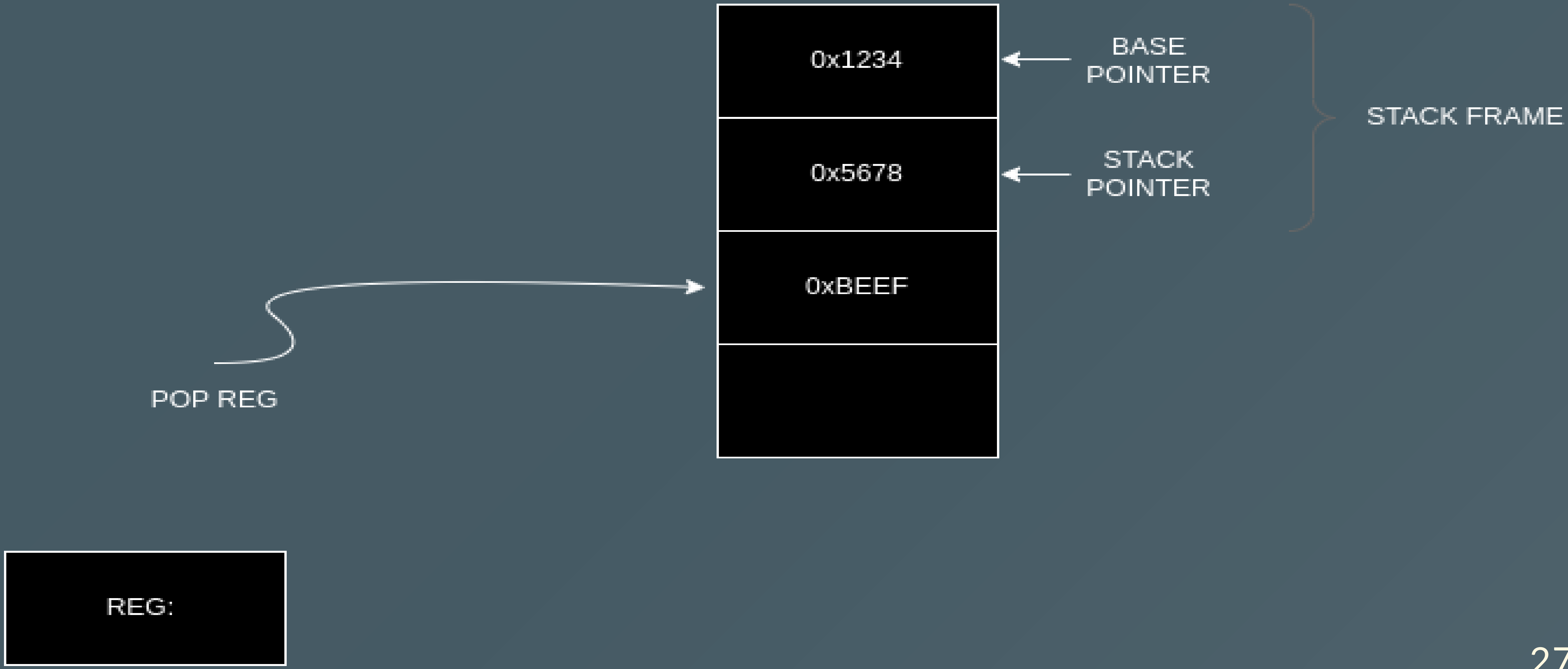


0x1234
0x5678
0xBEEF
BASE POINTER
STACK POINTER
STACK FRAME
PUSH 0xBEEF

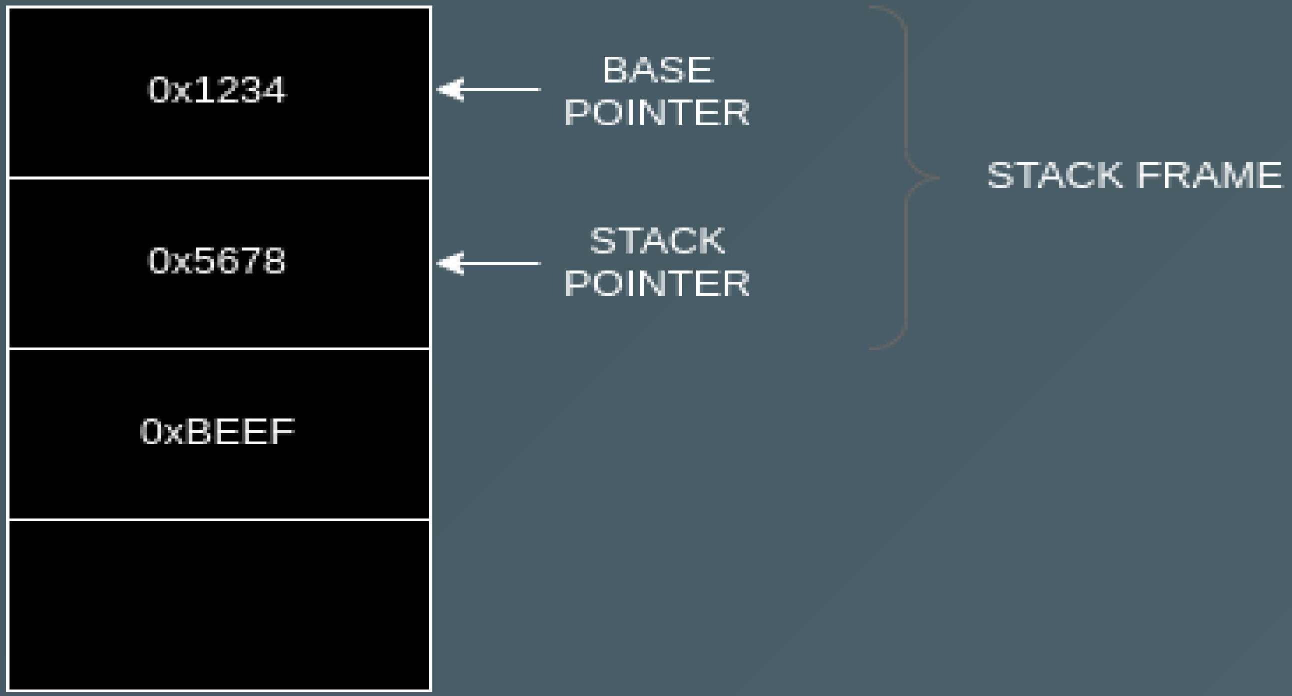
Stack operations: POP

- Pop: Remove the top item from the stack
    - Copy the item from the top of the stack to a register
    - Increase the stack pointer to deallocate the space
    - Memory is not erased or zeroed out

Stack pop


0x1234
BASE POINTER
STACK FRAME
0x5678
STACK POINTER
0xBEEF
POP REG
REG:

Stack pop


0x1234
0x5678
0xBEEF
BASE
POINTER
STACK
POINTER
STACK FRAME


REG = 0xBEEF

Callings conventions

- Specifies how functions are called and how parameters are passed
- Different architectures have different calling conventions
- Different conventions for different purposes
  - System calls
  - User-space functions
  - Library functions

x86-64 SYSTEM V ABI

- Most common calling convention on Linux
- Parameters are passed in registers
  - RDI, RSI, RDX, RCX, R8, R9
  - Additional parameters are passed on the stack
- Return value is passed in RAX

x86-32 calling convention

- Many different ones:
  - cdecl
  - stdcall
  - fastcall
  - thiscall

cdecl

- Common calling convention on x86-32 Unix systems
- Parameters are passed on the stack
    - Last parameter is pushed first (right to left)
- Return value is passed in EAX

stdcall

- Common calling convention on x86-32 Windows systems
- Parameters are passed on the stack
  - Last parameter is pushed first (right to left)
- Return value is passed in EAX

fastcall

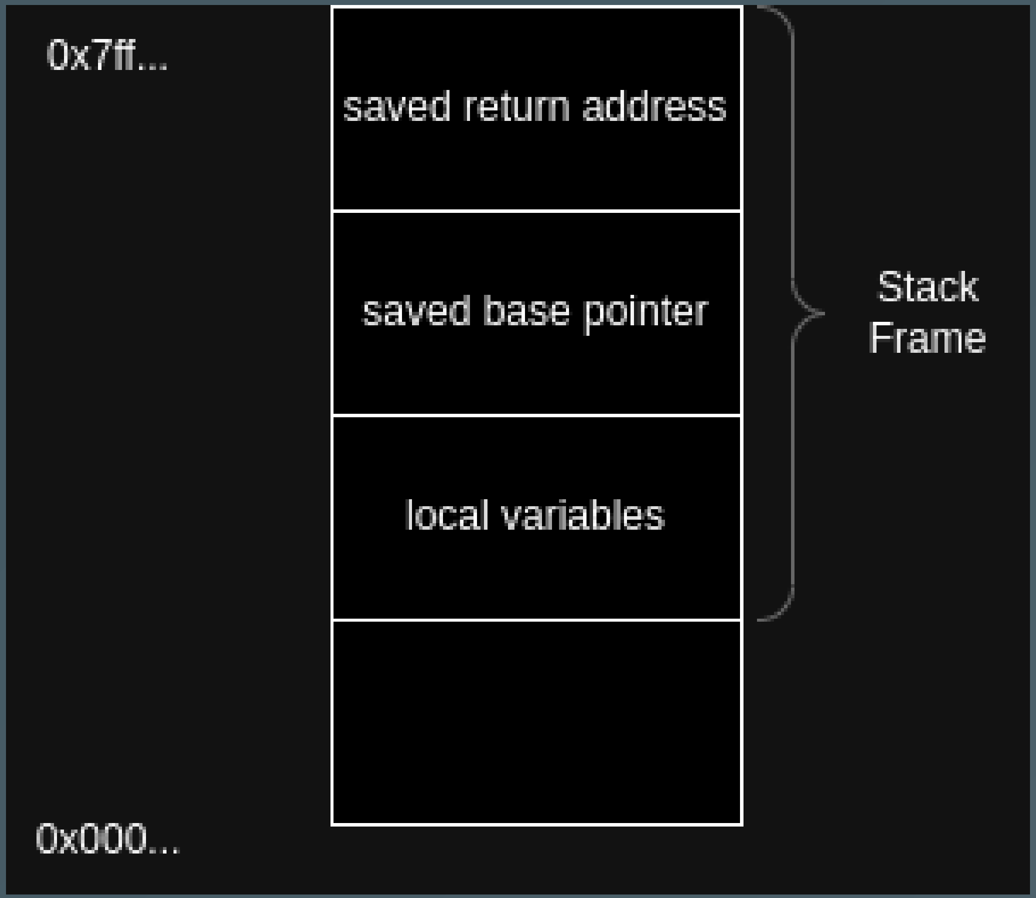
- Parameters are passed in registers
  - ECX, EDX, (and EAX)
  - Additional parameters are passed on the stack
- Return value is passed in EAX

thiscall

- Used in C++ for member functions
- Similar to stdcall
- The this pointer is passed in ECX

Stack frame

- A stack frame is a region of memory on the stack
- Contains:
  - Return address
  - Stack frame pointer
  - Local variables



Stack base pointer

- Special-purpose register
- Points to the base of the current stack frame
- Used to relatively access local variables and parameters
- The base pointer is saved and restored when calling functions

```
imul    ecx, dword ptr [ebp + 8] // Get a parameter on the stack
mov     dword ptr [ebp - 4], ecx // Write to a local variable
```

Calling functions

- When a function is called, a new stack frame is created
- The stack frame is "destroyed" when the function returns

Calling functions

Let's look at an example:

```c
// Function Definition
int foo(int a, int b, int c) {
    return a + b + c;
}
int main() {
    int a = 1, b = 2, c = 3;
    int result = foo(a, b, c); // Function Call
    printf("The sum is: %d\n", result);
    return 0;
}
```

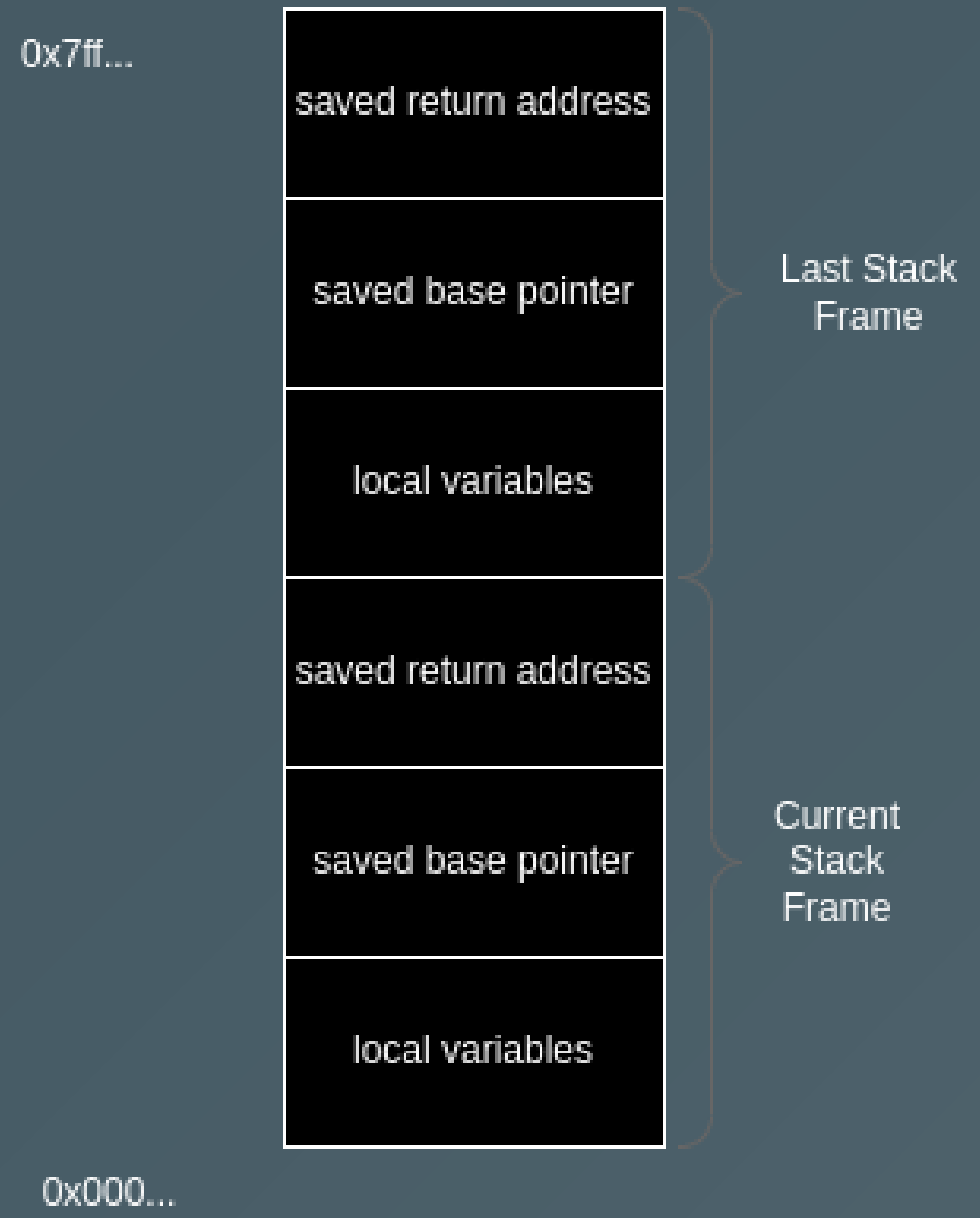
Calling functions

The call to `foo` will look like this (cdecl):

```
push c
push b
push a
call foo
```

Calling functions

`foo` will now have its own stack frame:



Calling functions

How does this work?

- The `call` instruction pushes the return address onto the stack
- The `call` instruction then jumps to the function
- The function then sets up its stack frame
  - Saves the base pointer
  - Allocates space for local variables (adjusts the stack pointer)
- The function then executes

Returning from functions

- Whenever a function returns, the stack frame is destroyed
  - The stack frame is destroyed by decreasing the stack pointer
  - The base pointer is restored
- The return value is placed in the appropriate register
- The `ret` instruction pops the return address from the stack and jumps to it

Returning from functions

Why do we use the stack?

- Registers are a limited resource
- The stack is a flexible data structure
- The stack is a convenient way to manage function calls
- Allows for recursion/nesting of function calls

Returning from functions

Why is this important?

Stack overflows

- Local variables are stored on the stack below the base pointer and the return address
- If we write enough data adjacently to a local variable, we can overwrite the return address
- We can then control the flow of the program

Stack overflows

Let's look at an example:

```c
void vulnerable_function() {
    char buffer[4];
    gets(buffer); // gets is unsafe and reads until a newline, no bounds checking
    return;
}
int main() {
    vulnerable_function();
    return 0;
}
```

Before calling gets, our stack frame looks like this:

```c
void vulnerable_function() {
    char buffer[4];
    gets(buffer); <-
}
int main() {
    vulnerable_function();
    return 0;
}
```

After inputting a string longer than 4 characters e.g. "AAAAAAAAAAAA":

```c
void vulnerable_function() {
    char buffer[4];
    gets(buffer);
    return; <-
}
int main() {
    vulnerable_function();
    return 0;
}
```

Stack overflows

What happens when we input a string longer than 4 characters?

- The buffer overflows
- The return address is overwritten
- Upon returning from `vulnerable_function`, the program will jump to the address we wrote into the buffer
- We can control the flow of the program

Stack overflows

- We can control the flow of the program
- What's next?
  - We can jump to shellcode
    - What if the buffer is not executable?

Stack overflows

- We can control the flow of the program
- What's next?
  - We can jump to shellcode
  - We can jump to a different part of the program
- => ROP

Return-oriented programming (ROP)

- ROP is a technique used to bypass DEP (Data Execution Prevention)
- DEP is a security feature that prevents the execution of code on the stack
    - Every executable page is marked as non-writable
- ROP uses existing code snippets in the process to execute arbitrary code

Return-oriented programming (ROP)

- ROP gadgets are short sequences of instructions
  - `pop rdi; ret`
- They end with a `ret` instruction
  - `ret` allows us to jump to the next gadget
  - Chaining gadgets together allows us to execute more complex operations
- Place rop chain on the stack and overwrite the return address

Return-oriented programming (ROP)

- Instructions can also be misaligned to forge new instructions
  - `0: 48 c7 c0 89 f8 c3 00 - mov rax,0xc3f889`
  - If we now jump to to the 4th byte, we get this:
  - `0: 89 f8 c3 - mov eax,edi; ret;`
- Gadgets can also be found in shared libraries
  - libc, etc.
- Given a large enough program or shared libraries, we can find enough gadgets to execute arbitrary code

Heap

- The heap is a region of memory used for dynamic memory allocation
  - Managed by the operating system
  - `malloc` is used to allocate memory on the heap
  - `free` is used to deallocate memory

Heap overflows

Let's look at an example:

```c
int main() {
    char *buffer = malloc(10);
    ...
    return 0;
}
```

`malloc` allocates 10 bytes of memory on the heap and returns a pointer to it.
What happens if we write more than 10 bytes to `buffer`?

Heap overflows

- The heap is a contiguous memory area
- Writing more than 10 bytes to `buffer` will overwrite adjacent memory areas
- What lies beyond `buffer`?
  - Metadata of the heap
  - Other heap allocations
    - Other variables
    - Function pointers (vtables)

Heap overflows

- Overwriting heap metadata can lead to arbitrary read/write
- Overwriting function pointers can lead to arbitrary code execution
- Overwriting other variables can alter the program's behavior
- => All of these can lead to arbitrary code execution

Heap overflows

Example: What happens if we input a long string?

```
int main() {
    char *buffer = malloc(10);
    char *other_buffer = malloc(10);
    strcpy(other_buffer, "test.txt");
    fgets(buffer, 100, stdin);
    puts(other_buffer);
    FILE *file = fopen(other_buffer, "r");
    ...
    return 0;
}
```

Heap overflows

- We overwrite some of the metadata of the heap
- If we now write even more data, we will eventually overwrite `other_buffer`
- We can control which file is opened

Use after free

- What happens if we free a pointer and then use it?
- The memory is not erased or zeroed out
- The memory is still there
- We can still read and write to it
- Those invalid pointers are called "dangling pointers"

Use after free

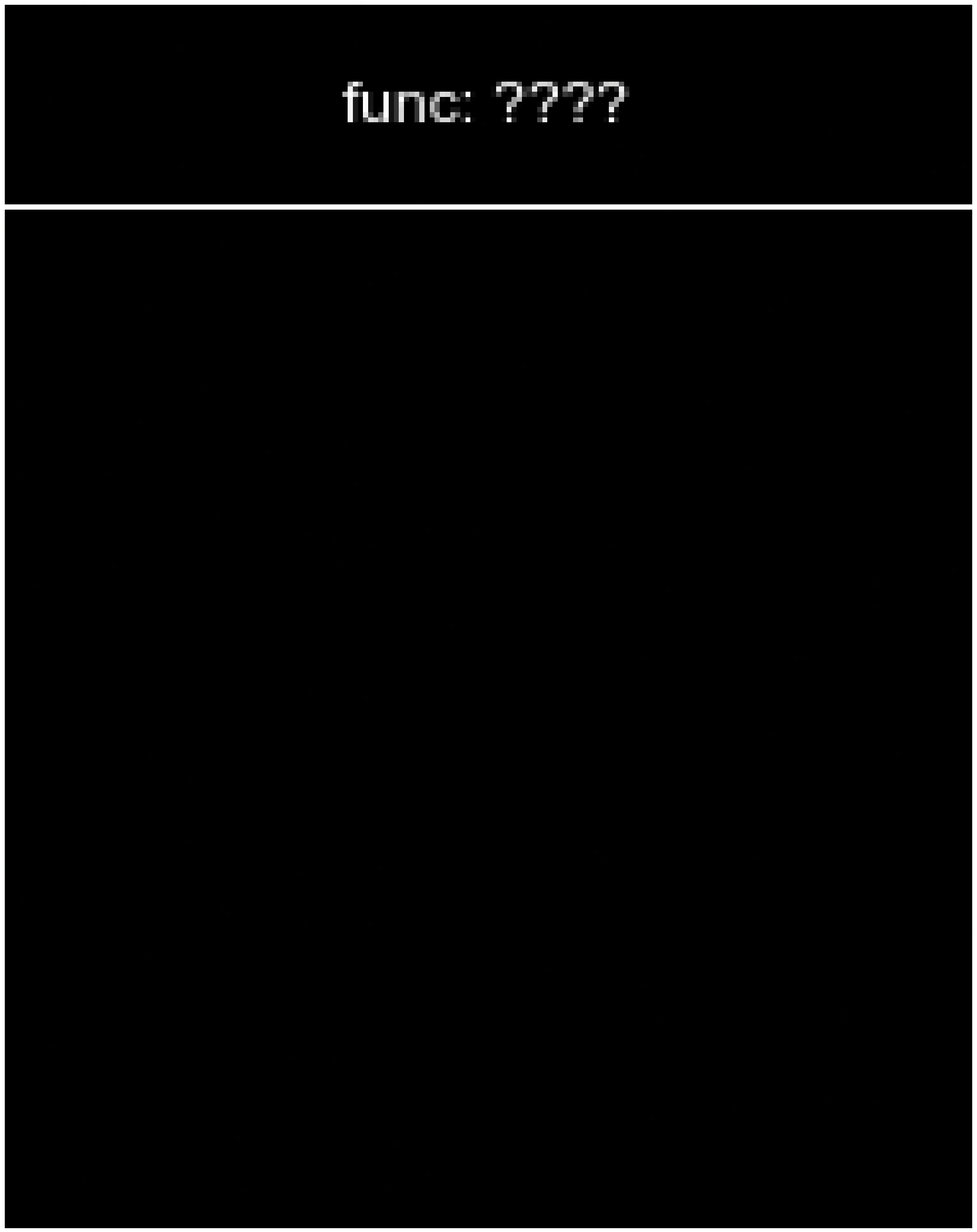
```
typedef struct {
    void (*func)(char*);
} func_ptr;

int main()
{
    func_ptr* func = malloc(sizeof(func_ptr));
    func->func = puts;
    func->func("Please enter your name");
    free(func);
    char* name = malloc(sizeof(size_t));
    fgets(name, sizeof(size_t), stdin);
    func->func(name);
    ...
```

Use after free

We get some memory via malloc:

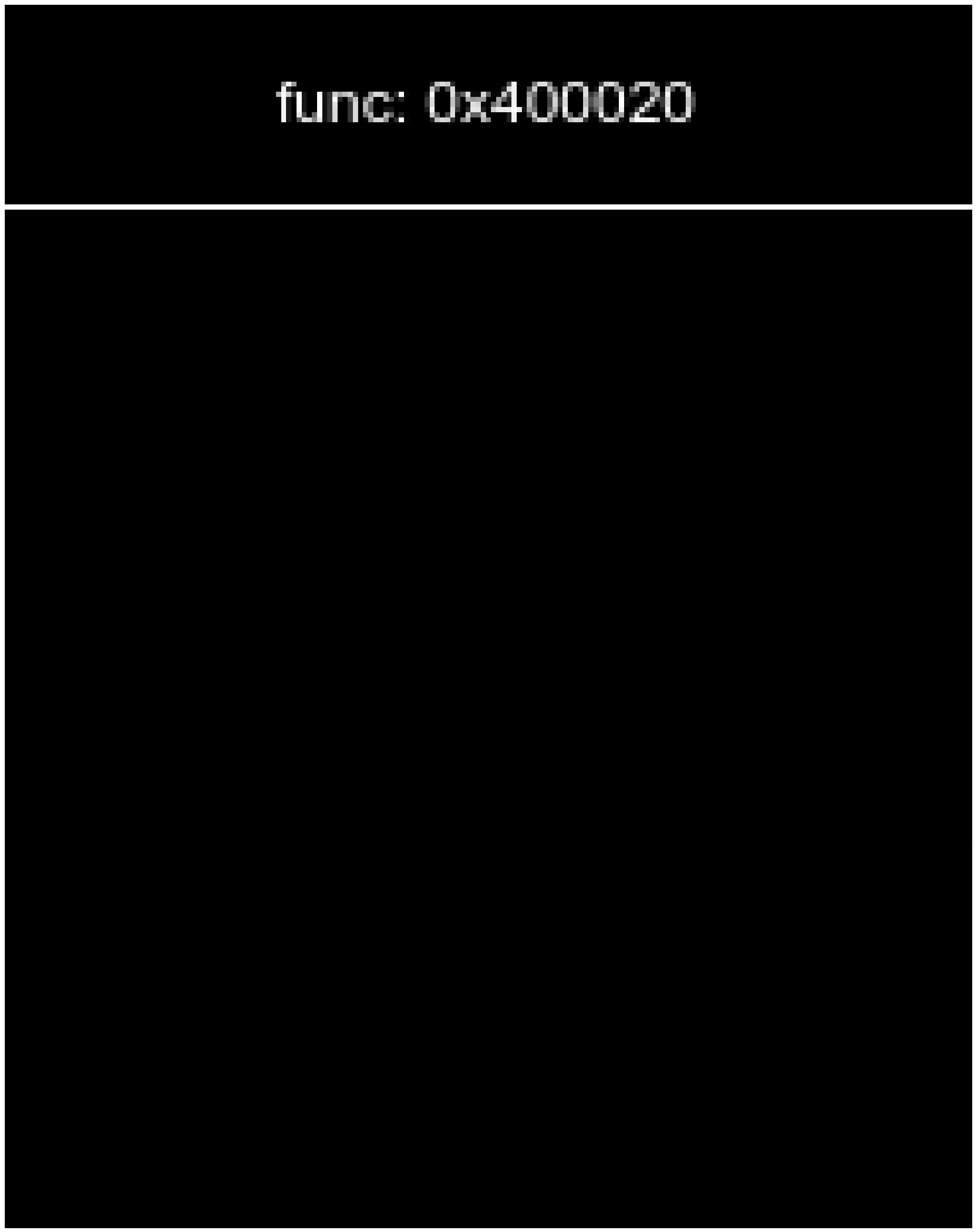
```
int main()
{
    func_ptr* func = malloc(sizeof(func_ptr)); <-
    func->func = puts;
    func->func("Please enter your name");
    free(func);
    char* name = malloc(sizeof(size_t));
    fgets(name, sizeof(size_t), stdin);
    func->func(name);
    ...
```



Use after free

We write to the memory the function pointer of puts:

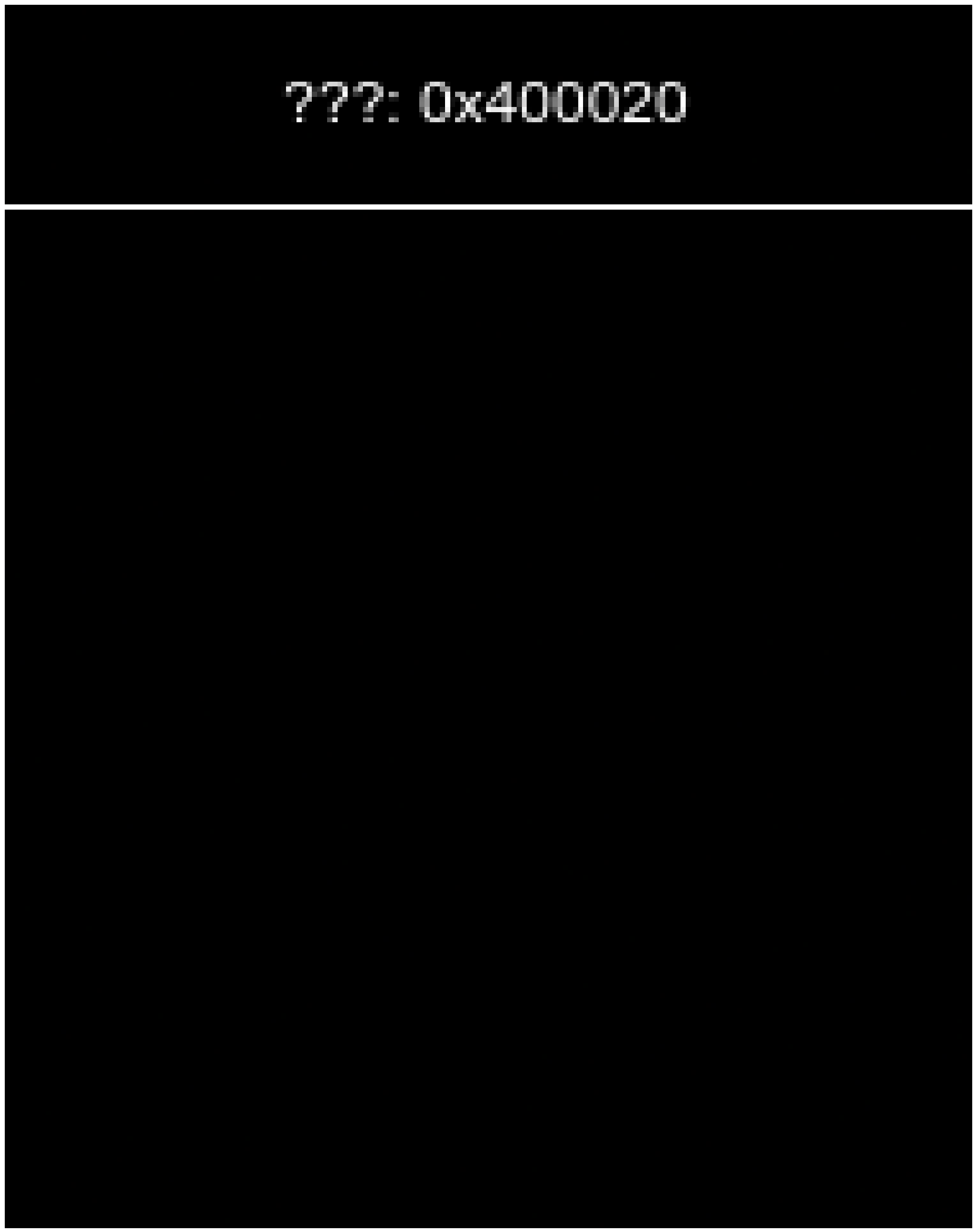
```
int main()
{
    func_ptr* func = malloc(sizeof(func_ptr));
    func->func = puts; <-
    func->func("Please enter your name");
    free(func);
    char* name = malloc(sizeof(size_t));
    fgets(name, sizeof(size_t), stdin);
    func->func(name);
    ...
```



Use after free

We free the memory:

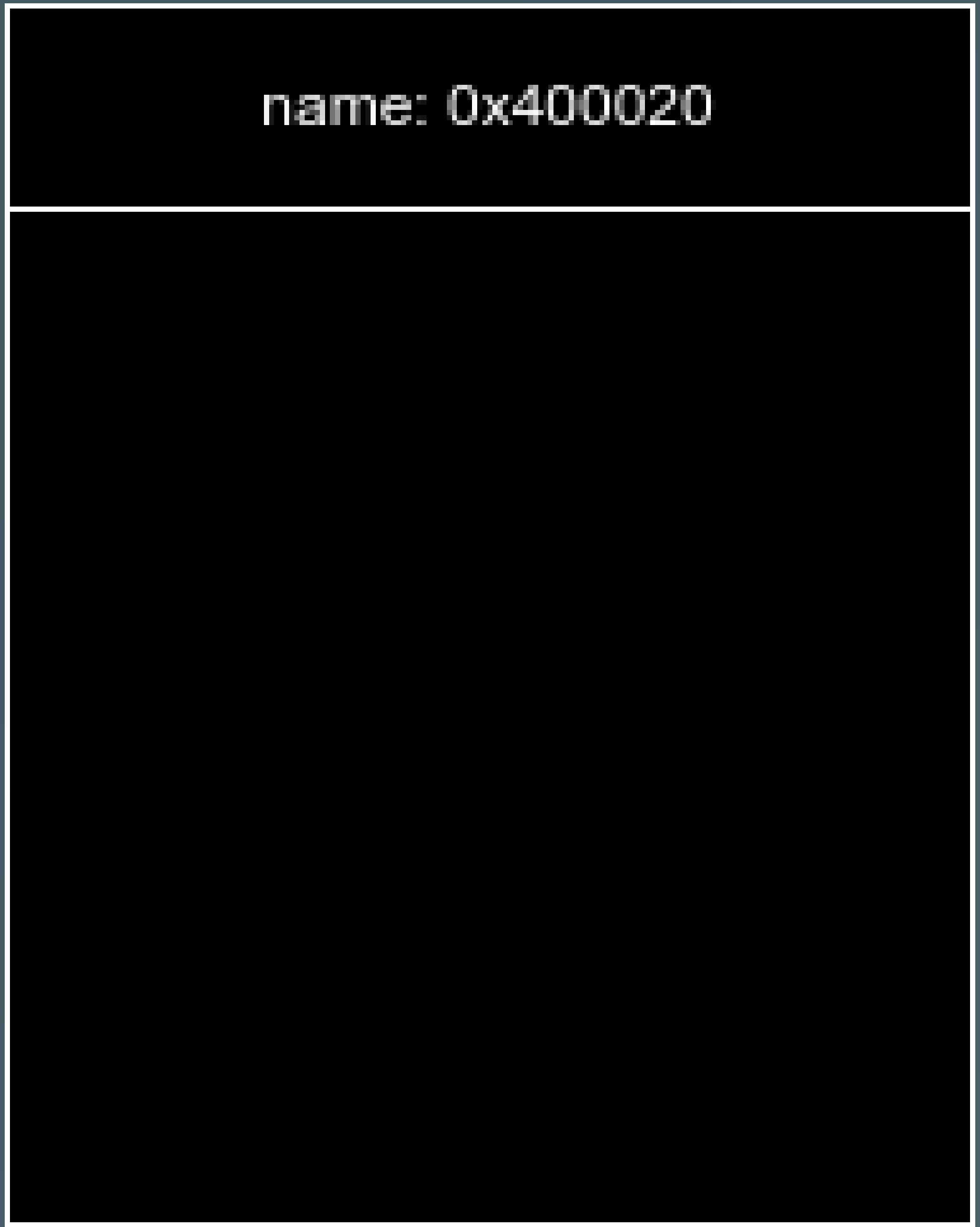
```
int main()
{
    func_ptr* func = malloc(sizeof(func_ptr));
    func->func = puts;
    func->func("Please enter your name");
    free(func); <-
    char* name = malloc(sizeof(size_t));
    fgets(name, sizeof(size_t), stdin);
    func->func(name);
    ...
```



Use after free

We allocate new memory for our name:
It is the same memory that was previously used for the function pointer

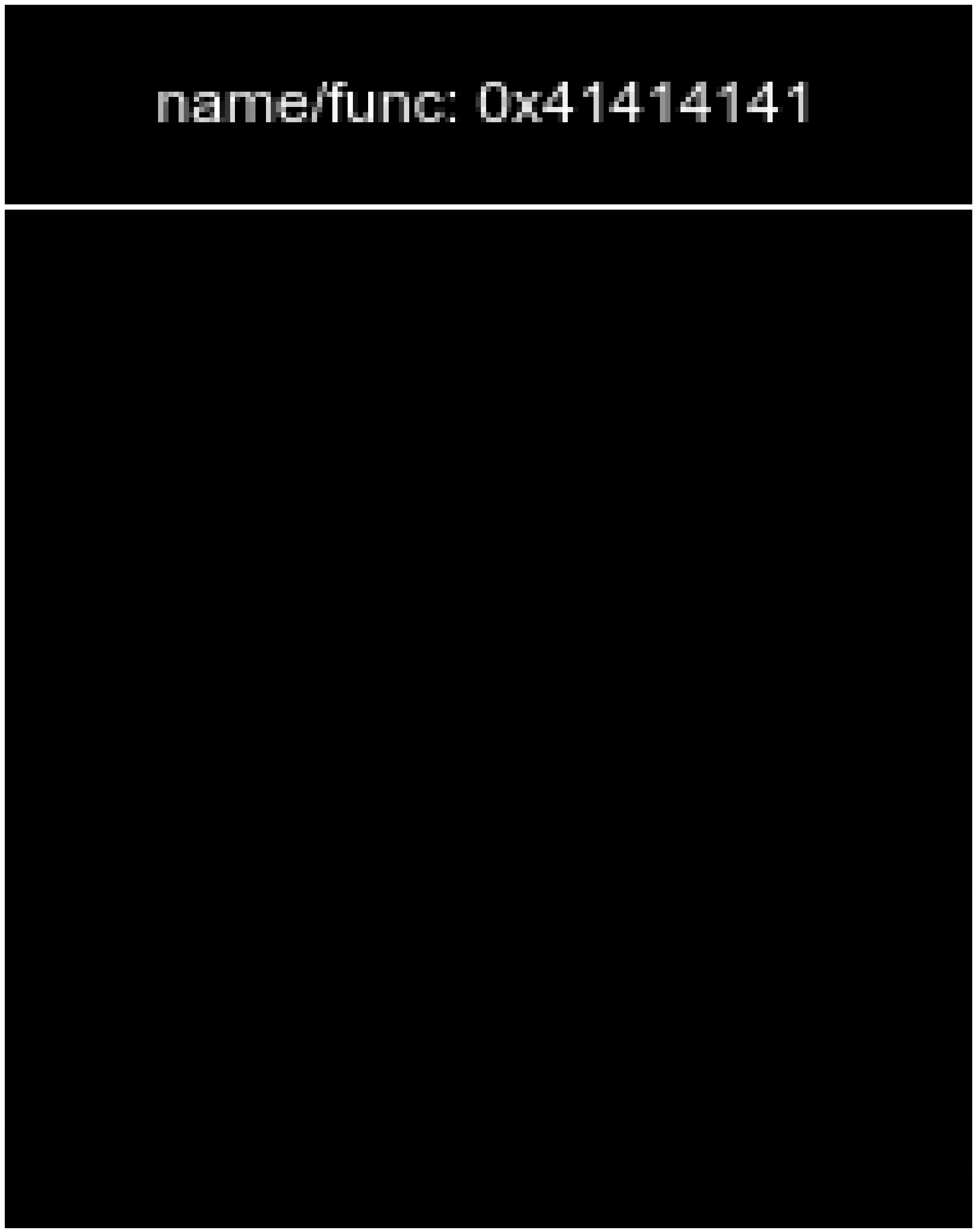
```
int main()
{
    func_ptr* func = malloc(sizeof(func_ptr));
    func->func = puts;
    func->func("Please enter your name");
    free(func);
    char* name = malloc(sizeof(size_t)); <-
    fgets(name, sizeof(size_t), stdin);
    func->func(name);
    ...
```



Use after free

We effectively write to the memory that was previously used for the function pointer:

```
int main()
{
    func_ptr* func = malloc(sizeof(func_ptr));
    func->func = puts;
    func->func("Please enter your name");
    free(func);
    char* name = malloc(sizeof(size_t));
    fgets(name, sizeof(size_t), stdin);
    func->func(name); <-
    ...
```



Use after free

- Since we never reset the dangling pointer, it still points to the memory we allocated
- malloc will return the same memory after free if the size constraints are met
- We can overwrite new pointers and at the same time overwrite the function pointer

Format string vulnerabilities

- Format strings are used to easily format output
  - `printf`, `sprintf`, ...
- The format string can contain format specifiers and converts parameters to strings
  - `%s`, `%d`, `%x`, `%p`, `%n`, `%n` etc.
- Examples:
  - `printf("Hello, %s", "World");`
  - `printf("The %s is: %d", "number", 10);`

Format string vulnerabilities

- Format string vulnerabilities occur when:
  - The user can control the format string
  - The format string mismatches with the number of arguments

Format string vulnerabilities

- What happens if the user can control the format string?
  - `printf(user_input);`?
  - => Truly arbitrary read/write

Format string vulnerabilities

- What happens if we use a format specifier but no argument?
  - `printf("The number is: %d");`
  - It still prints something?!?
  - => Leak data from registers or the stack

Common defenses

- Stack canaries
- Data execution prevention (DEP)
- Address space layout randomization (ASLR)

Stack canaries

- A random value is placed between the local variables and the return address
- The compiler generates code to check if the canary is still intact before returning from a function
- If the canary is not intact, the program will terminate

Stack canaries

- We can bypass stack canaries if:
    - We can leak the canary e.g. through a format string vulnerability
    - We can brute force the canary
        - May take a long time

Data execution prevention (DEP)

- All memory pages that are not explicitly marked as executable are non-executable
- Executable pages are marked as non-writable
- Prevents code execution on the stack and heap
- Prevents modifying executable code pages

Data execution prevention (DEP)

- We can bypass DEP if:
  - We can use ROP
  - We can use JIT (Just-In-Time) compilation
  - We can use return-to-libc etc.

Address space layout randomization (ASLR)

- Randomizes the base address of the stack, heap, and shared libraries
- Prevents attackers from knowing the exact memory layout
- Makes it harder to exploit memory corruption vulnerabilities

Address space layout randomization (ASLR)

- We can bypass ASLR if:
  - We can leak addresses
  - We can brute force addresses
    - May take a long time

Interested?

- CTFs (Capture The Flag)
- LosFuzzys @ TU Graz (CTF Team)
  - https://losfuzzys.net/
  - Come to our beginner trainings or play CTFs with us!

Interested in Binary Exploitation?

- TU Graz courses:
  - Course Number INP33404UF and INP33503UF | Information Security
    - https://iaik.tugraz.at/is
  - Course Number 705022 and 705023 | Secure Software Development
    - https://iaik.tugraz.at/ssd
  - ... many more on related topics!

Interested in Binary Exploitation?

Links and resources:

- https://github.com/shellphish/how2heap
- https://pwnable.kr - Binary exploitation challenges (0 to 100)
- https://pwnable.tw - Binary exploitation challenges (0 to 100)
- https://ropemporium.com/ - ROP challenges
- https://pwnlab.kr/ - More links to even MORE websites :)

Questions?