CSE467: Computer Security

10. Canary & DEP & ROP

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The slide is based on Prof. Sang Kil Cha's lecture slide

Quiz #1

- Score will be released soon!

HW2 Announcement

The due date has been extended!

- Due: Oct. 24, 11:59PM => **Oct. 26, 11:59PM**
  - (There was a VPN issue during Chuseok, so you may have had trouble accessing it ☹)

HW2 Announcement

- Software security
  - Hacking practice: Capture the Flag (CTF)

- CTF server: http://10.20.12.187:4000/
  - This server can only be accessed from the UNIST internal network.
  - Please use a *VPN* to access from outside! Just log in to https://vpn.unist.ac.kr and turn on VPN.

- Each flag is in the following format: `flag{some_string}`
  - e.g., `flag{C0N9R@7u1aT1on!}`

Setting up a vagrant on M1/M2 MacBooks

- The solution we strongly recommend is to dockerize the environment

1. Install docker
2. `$ mkdir YOUR_PATH; cd YOUR_PATH`
3. Download our `Dockerfile` (https://websec-lab.github.io/courses/2023f-cse467/hw/Dockerfile) to `YOUR_PATH`
4. `$ docker build --tag cse467 .`
5. `$ docker run -it -v <ABSOLUTE_PATH_HOST_DIR>:/data --name cse467_container cse467 /bin/bash`

Setting up a vagrant on M1/M2 MacBooks

- **If you want to stop your container:** press `ctrl+d`

- **If you want to resume your container:**
  1. `$ docker start cse467_container`
  2. `$ docker attach cse467_container`

Recap: Format String Vulnerability

```
// ...
recv(sock, buf, sizeof(buf), 0);
printf(buf);
```

- buf = “Hello”   // No problem
- buf = "%d.%d.%d\n”   // Leak memory

Recap: Format String Vulnerability

- Format string vulnerability allows us to ***read arbitrary memory*** contents on the stack

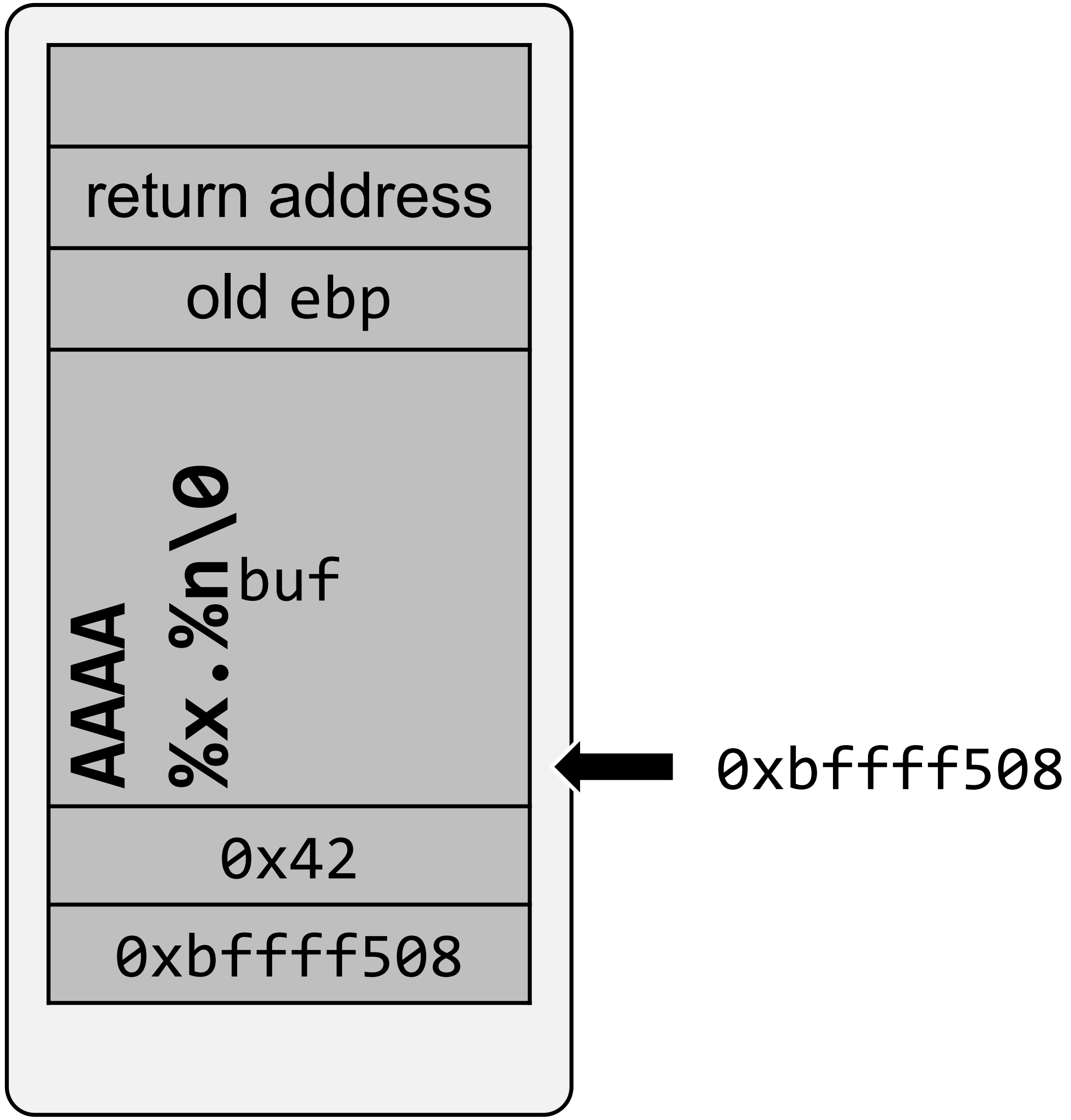
What about ***arbitrary memory write***?

Recap: Format String Vulnerability

Format	Meaning
%d	Decimal output
%x	Hexadecimal output
%u	Unsigned decimal output
%s	String output
%n	# of bytes written so far

Nothing printed for %n

Recap: Format String Vulnerability



Virtual memory

```
// ...
recv(sock, buf, sizeof(buf), 0);
printf(buf);
```

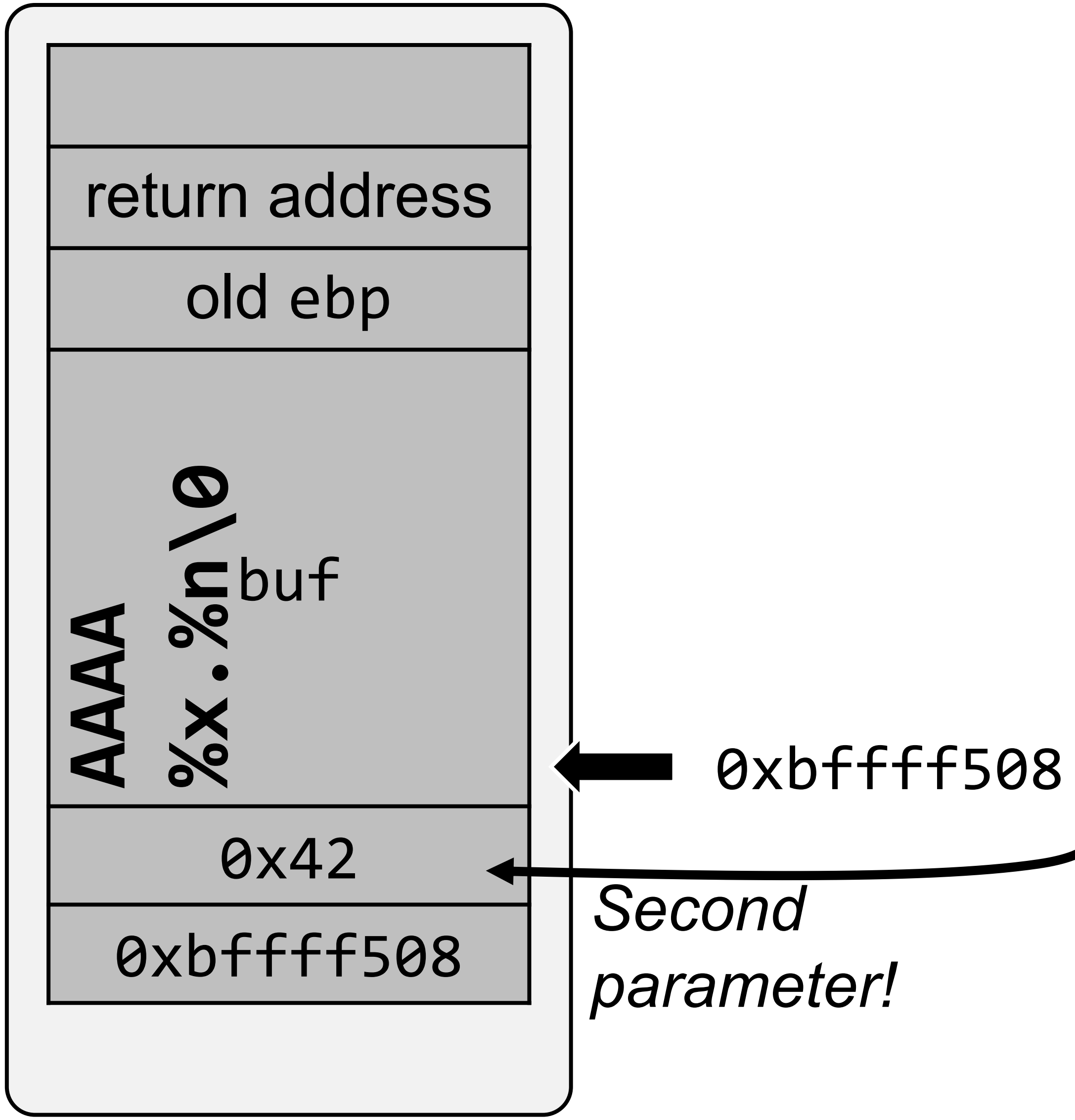
buf = “AAAA%x.%n”

Printed value:
AAAA

Recap: Format String Vulnerability


```
// ...
recv(sock, buf, sizeof(buf), 0);
printf(buf);
```

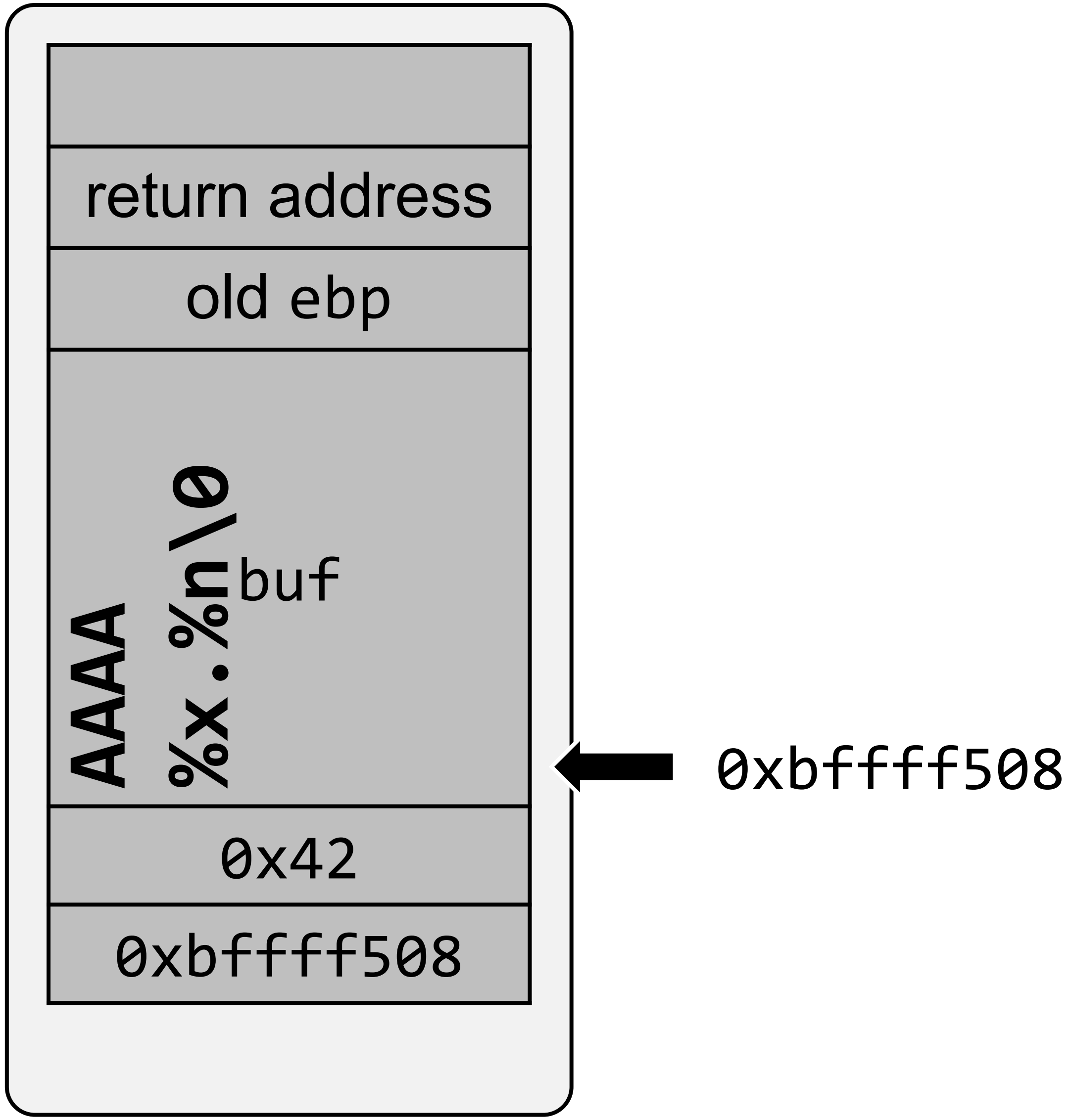
buf = “AAAA%x.%n”



Virtual memory

Printed value:
AAAA42

Recap: Format String Vulnerability



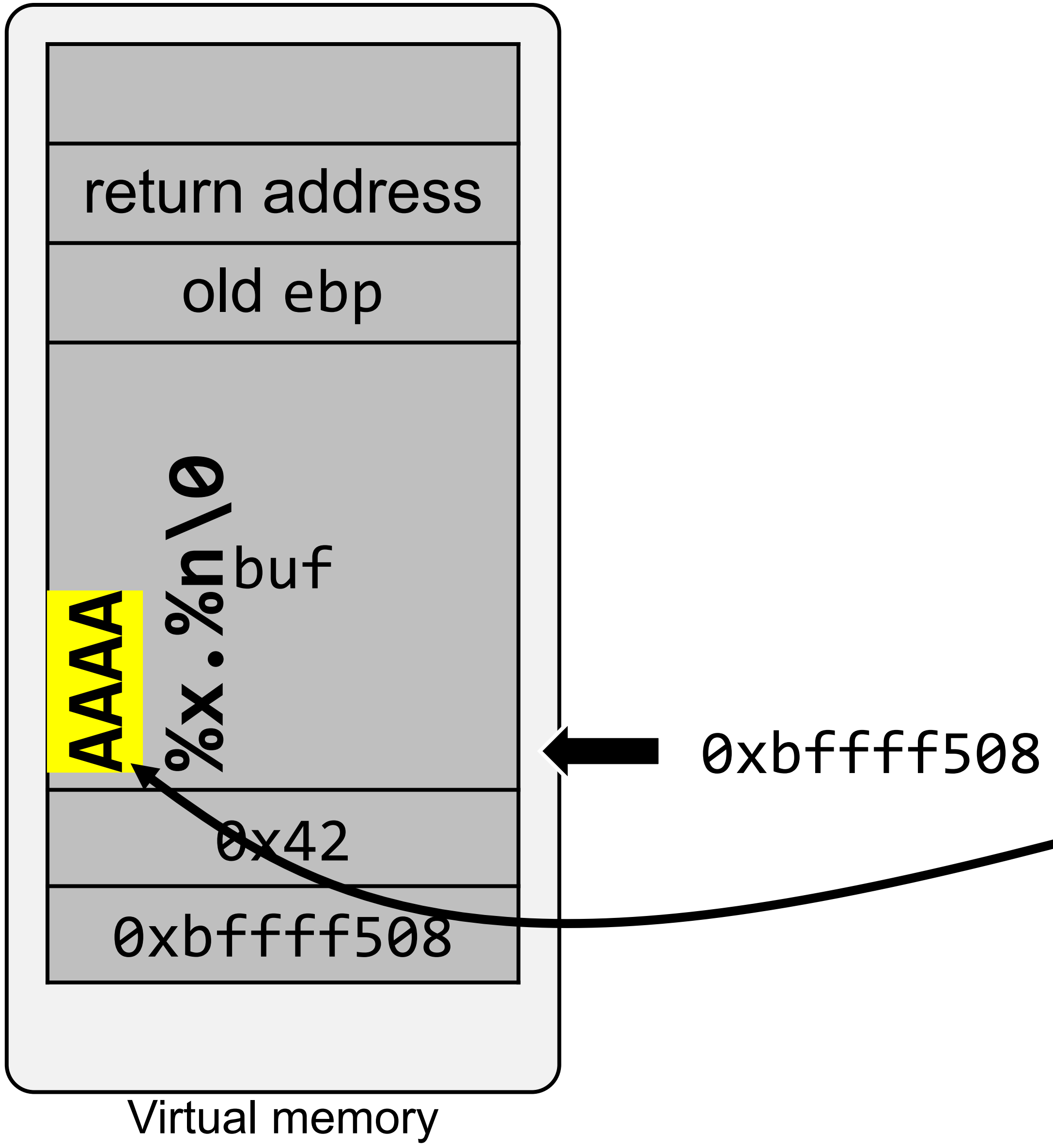
Virtual memory

```
// ...
recv(sock, buf, sizeof(buf), 0);
printf(buf);
```

buf = “AAAA%x.%n”

Printed value:
AAAA42.

Recap: Format String Vulnerability




```
// ...
recv(sock, buf, sizeof(buf), 0);
printf(buf);
```

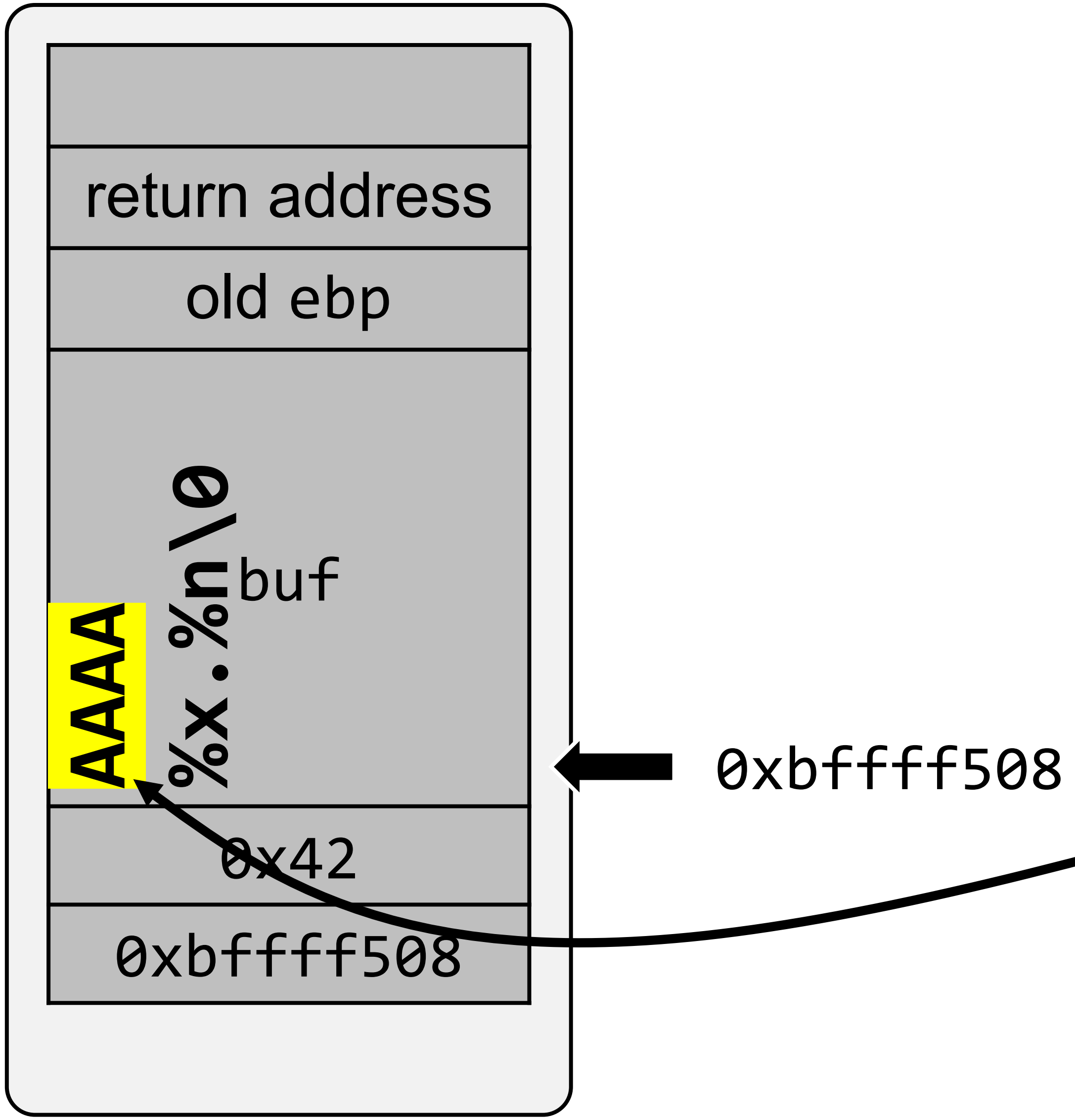
buf = “AAAA%x.%n”

Third parameter!

Printed value:
AAAA42.

Write ? to the address 0x41414141

Recap: Format String Vulnerability



Virtual memory

```
// ...
recv(sock, buf, sizeof(buf), 0);
printf(buf);
```

buf = “AAAA%x.%n”

Third parameter!

Printed value:

$\underbrace{\text{AAAA42.}}_{7}$

Write 7 to the address 0x41414141

Recap: Optimization with Dollar Sign ($)

- Enables direct access to the *n*-th parameter
- Syntax: `%<n>$<format specifier>`
- Example

```
printf(“%d, %d, %d, %2$d\n”, 1, 2, 3);
// prints 1, 2, 3, 2
```

Recap: Optimization with Dollar Sign ($)


```
$ echo “AAAABBBBAAAADBBB%8722d%hn%58850d%hn” | ./fmt
```

```
$ echo “BBBBDBBB%8730d%1$hn%58850d%2$hn” | ./fmt
```

Recap: Integer Overflow

- Happens because the size of registers is fixed

Logically,

`0xffffffff + 1 = 0x100000000`

But, in reality, on x86,

`0xffffffff + 1 = 0`

Recap: Why Integer Overflows Matter?

- Usually, an integer overflow itself does not lead to control flow hijack exploits
- However, integer overflows can cause an ***unexpected buffer overflows***

Recap: Example

```
int catvars(char *buf1, char *buf2, unsigned len1, unsigned len2)
{
    char mybuf[256];
    if((len1 + len2) > 256) {
       return -1;
    }
    memcpy(mybuf, buf1, len1);
    memcpy(mybuf + len1, buf2, len2);

    do_some_stuff(mybuf);

    return 0;
}
```

Recap: Exam

What if `len1=0x104` and `len2=0xfffffffc`?

```
int catvars(char *buf1, char *buf2, unsigned len1, unsigned len2)
{
    char mybuf[256];
    if((len1 + len2) > 256)
       return -1;
    }
    memcpy(mybuf, buf1, len1);
    memcpy(mybuf + len1, buf2, len2);

    do_some_stuff(mybuf);

    return 0;
}
```

Len1=0x104 (=260)
→ Overflow already!

Prevention vs. Mitigation

- Preventing buffer overflows
  - Buffer overflows will never happen

- Mitigating buffer overflows
  - Buffer overflows <u>will happen</u>, but will be ***hard to exploit them***

How to Prevent Buffer Overflows?

Do NOT use C/C++!

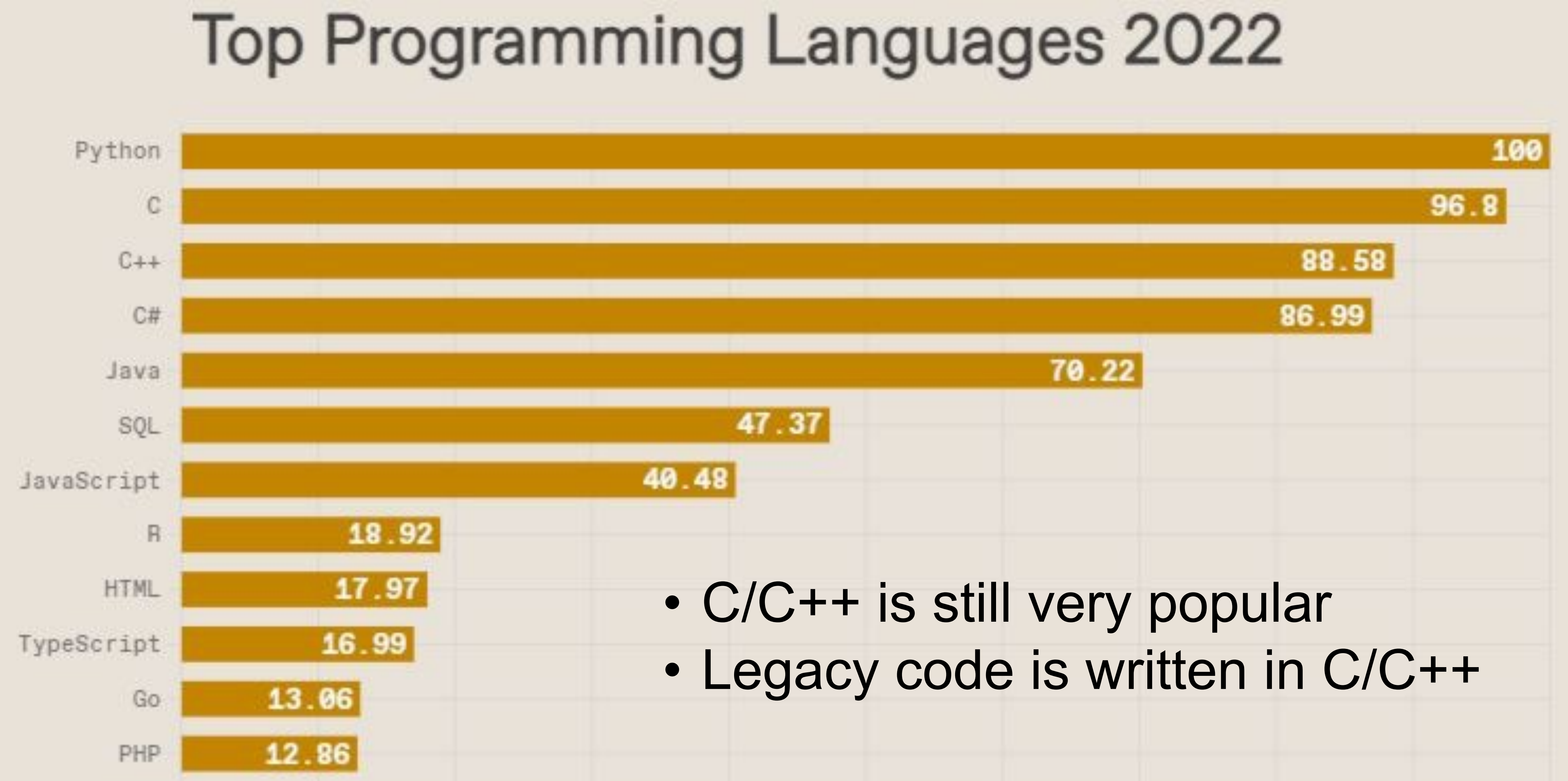
C is the root of evil!

Easy to Prevent Buffer Overflows!

Have you ever seen buffer overflows in other safe languages such as F#, OCaml, Haskell, Python, etc.?

```
>>> x = array(‘l’, [1,2,3])
>>> x[4]
Traceback (most recent call last):
  File "<stdin>", line 1, in <module>
IndexError: array index out of range
```

Unfortunately though ...



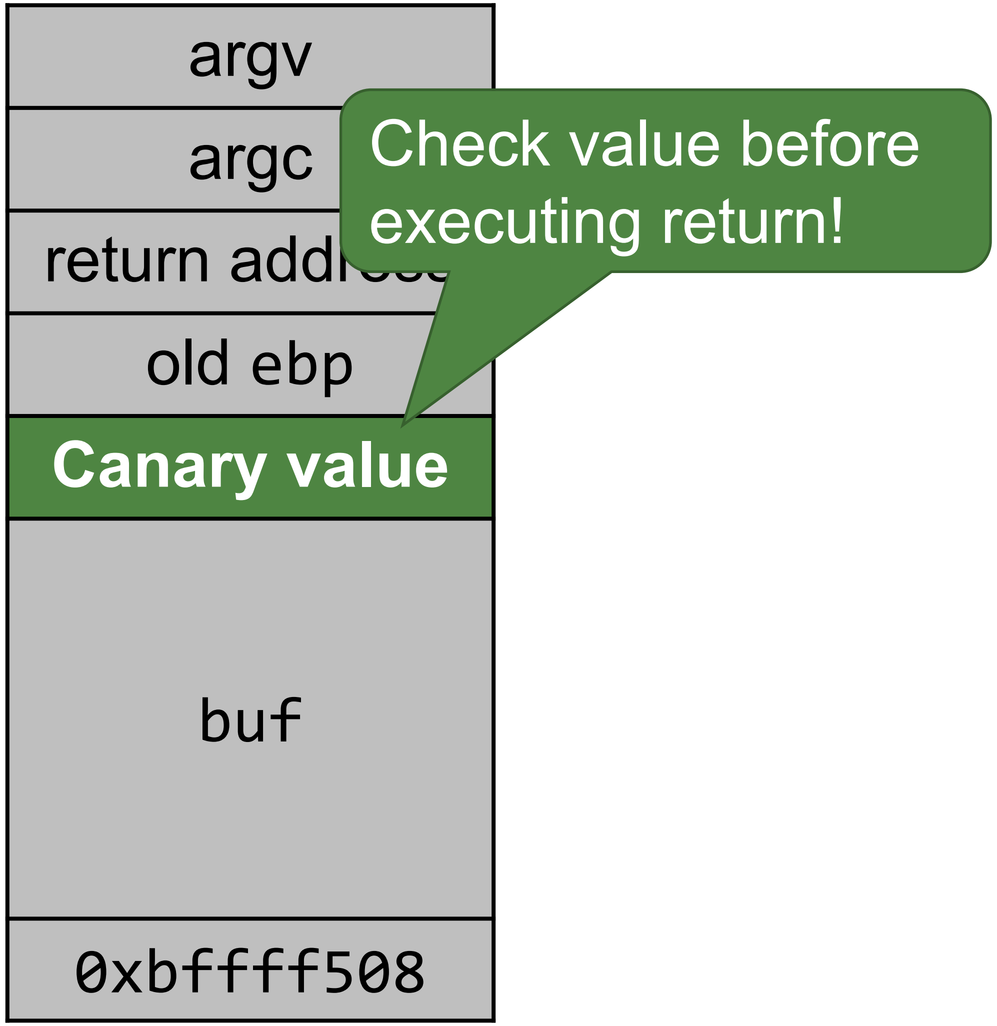
- C/C++ is still very popular
- Legacy code is written in C/C++

Okay ...

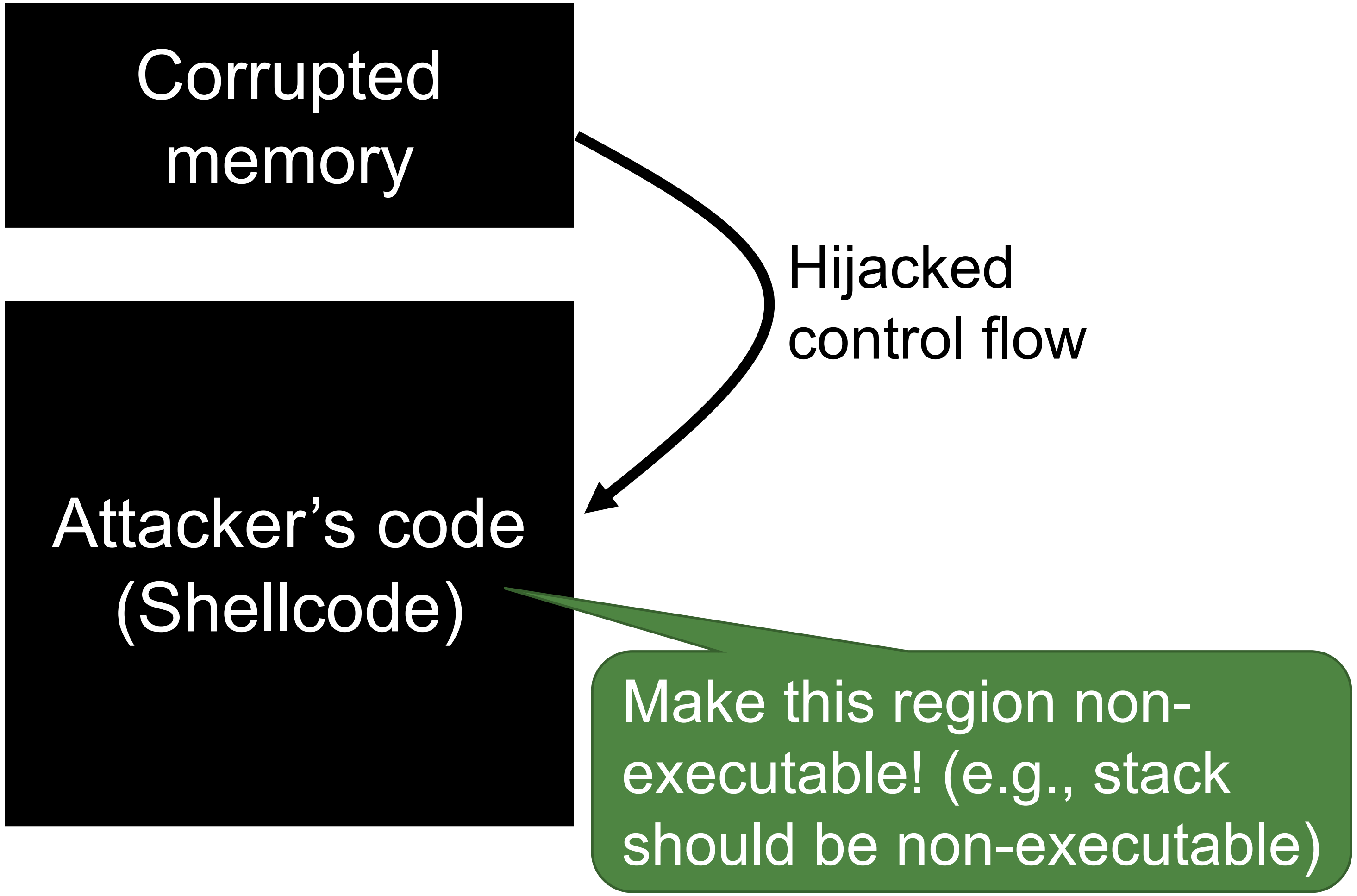
Let’s mitigate it then ☹

Preview: Mitigating Memory Corruption Bugs

Mitigation #1: Canary



Mitigation #2: NX (No eXcute)



Buffer Overflow Mitigation #1: Canary

is a bird

Image from https://naturalworldpets.co.uk/blogs/pet-advice/guide-to-caring-for-canaries

Canary in a Cole Mine

- The bird would act as an early warning for harmful gas

Image from https://www.forbes.com/sites/kionasmith/2019/12/31/the-canary-in-the-coal-mine-isnt-ancient-history

Mitigating Buffer Overflows with Canary

- Early warnings of buffer overflows

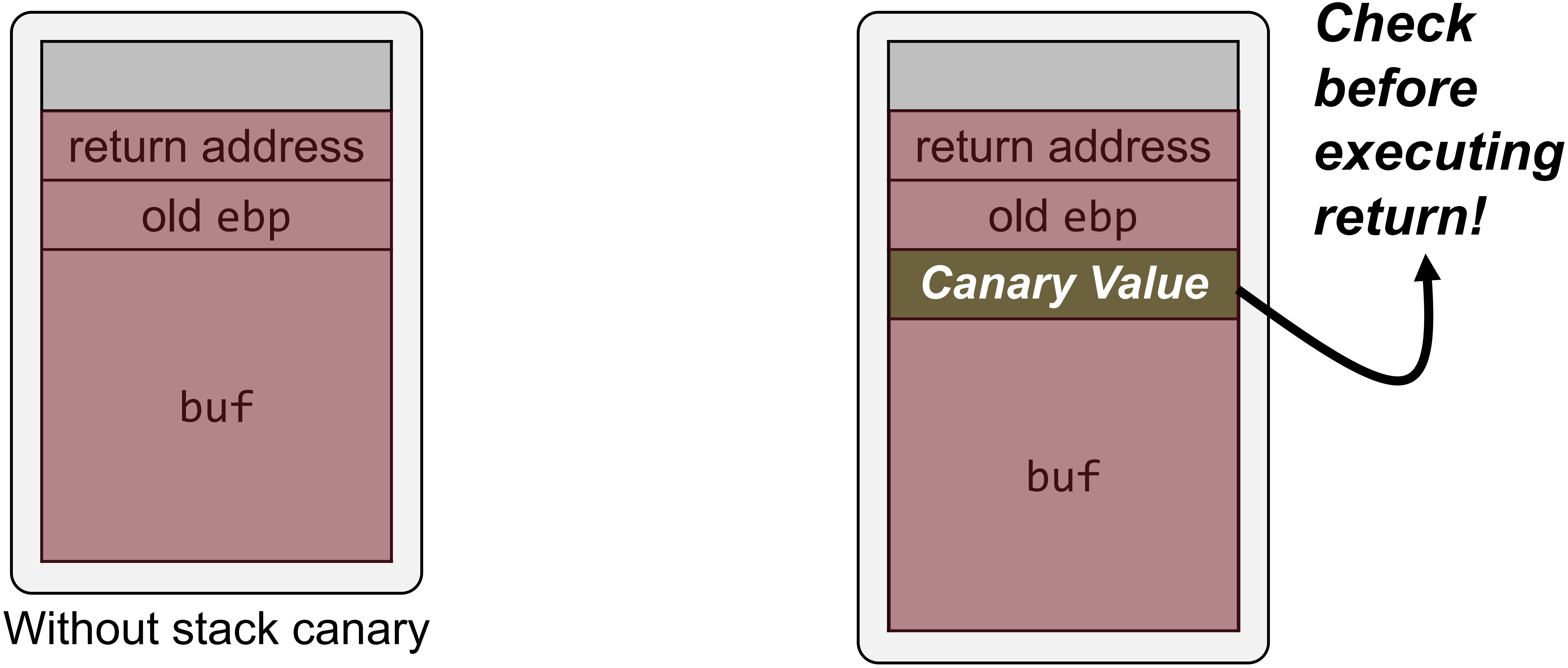
- First introduced in 1998

StackGuard: Automatic Adaptive Detection and Prevention of Buffer-Overflow Attacks, ***USENIX Security 1998***

- Not necessarily used for stack, but can also be used for heap

Stack Canary (a.k.a. Stack Cookie)

- Key idea: insert a <u>checking value</u> before the return address



Without stack canary

With stack canary

Stack Canary (a.k.a. Stack Cookie)

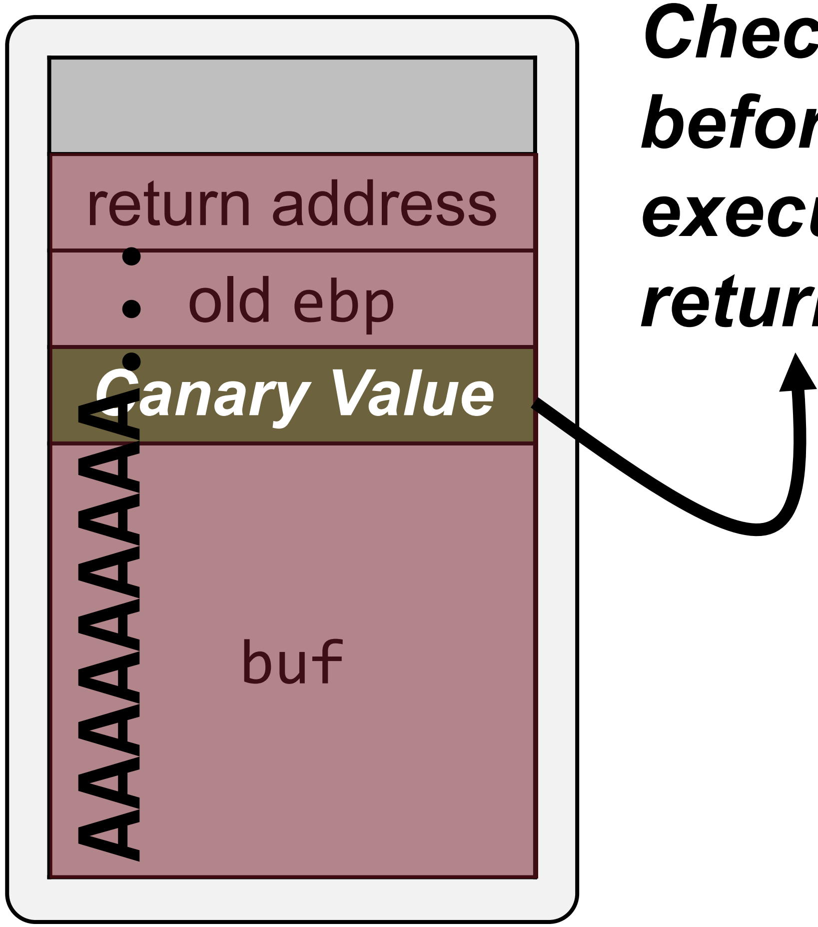
- Key idea: insert a checking value before the return address

Before executing return, check…

(Inserted canary value) (Current canary value)

Canary Value ≠ **0x41414141**

Overflow is occurred!
Stop the program

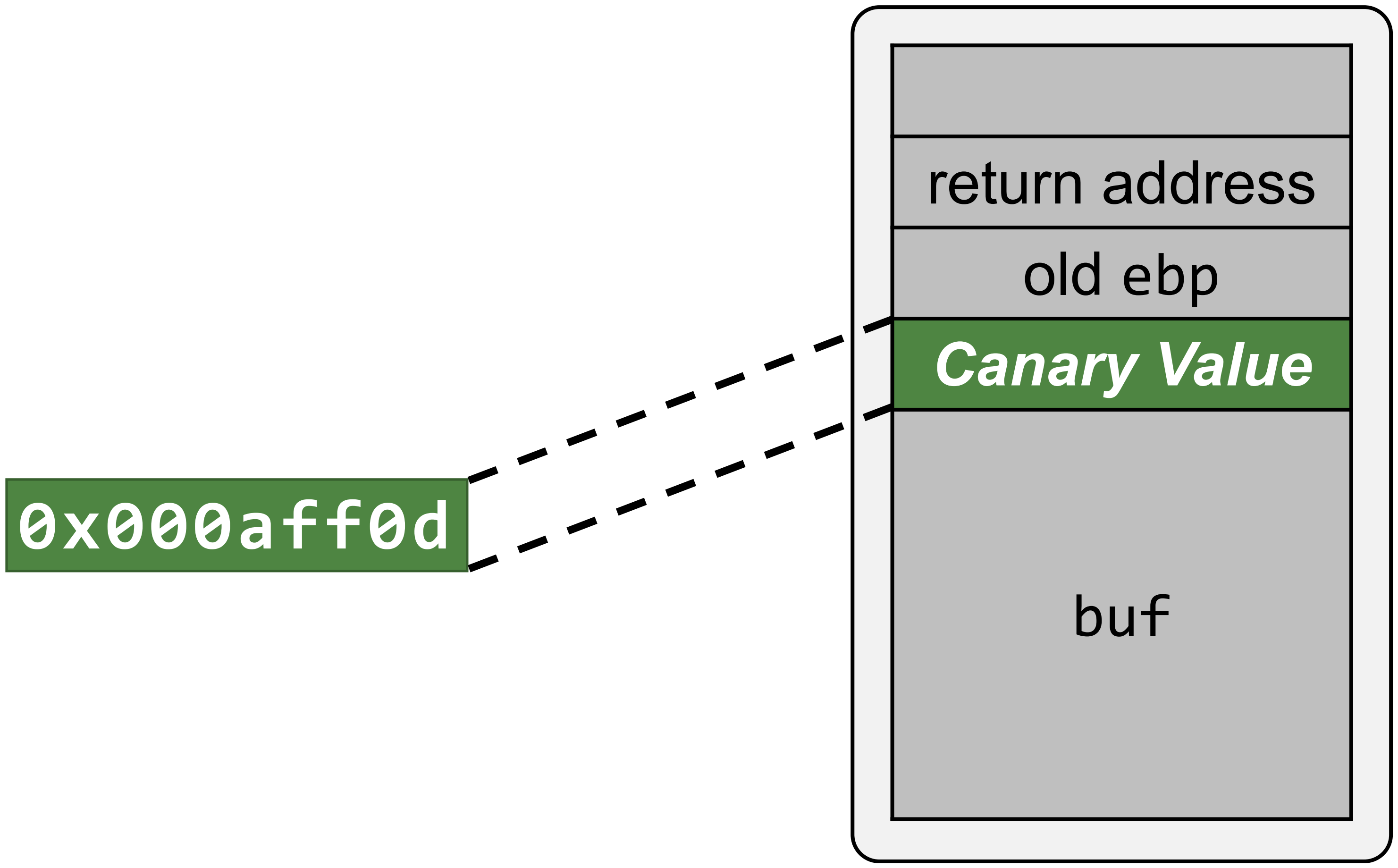


Check before executing return!

With stack canary

StackGuard (1998)

- Uses a constant canary value `0x000aff0d`

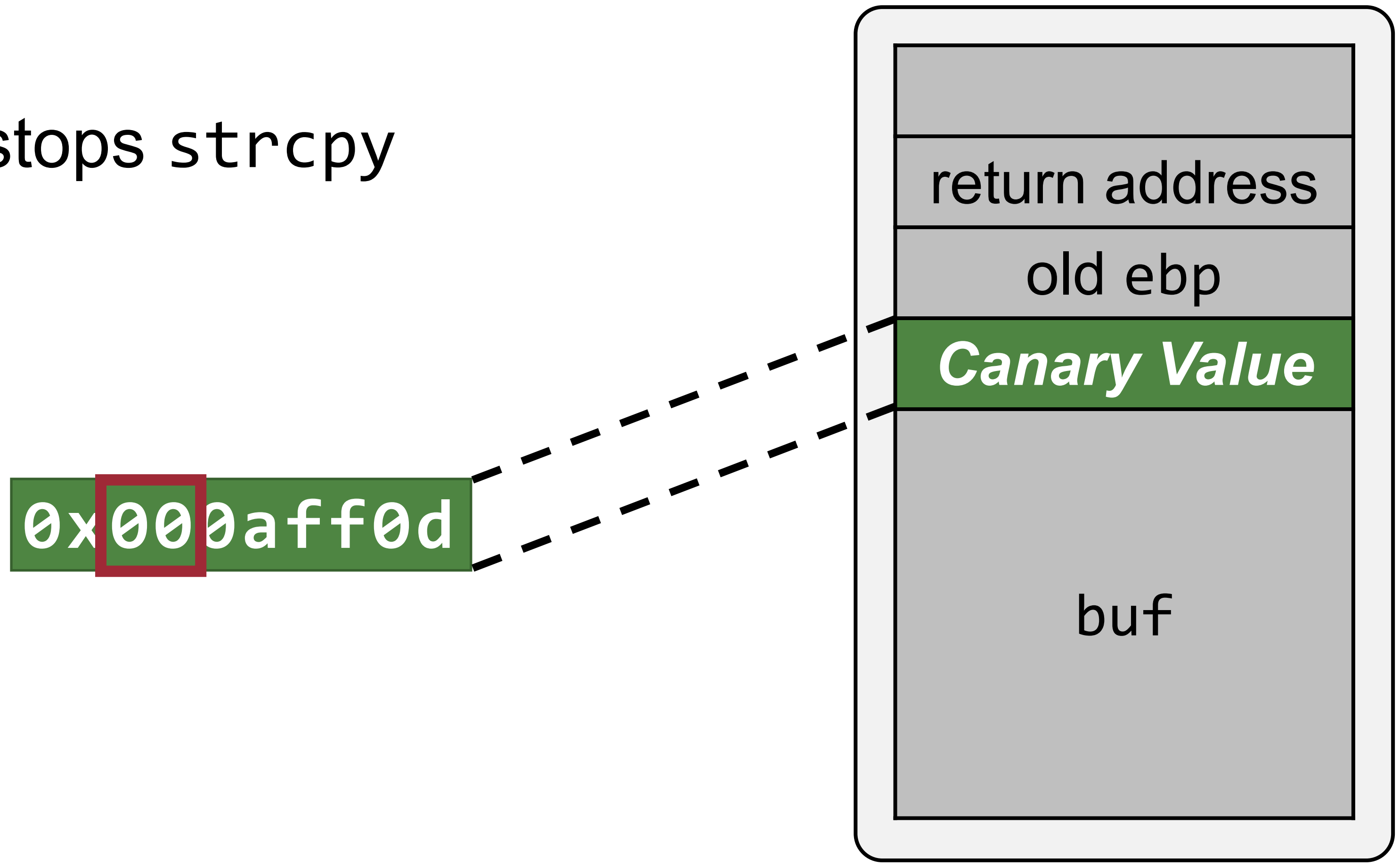


With stack canary

StackGuard (1998)

- Uses a constant canary value `0x000aff0d`

✓ `0x00` stops `strcpy`

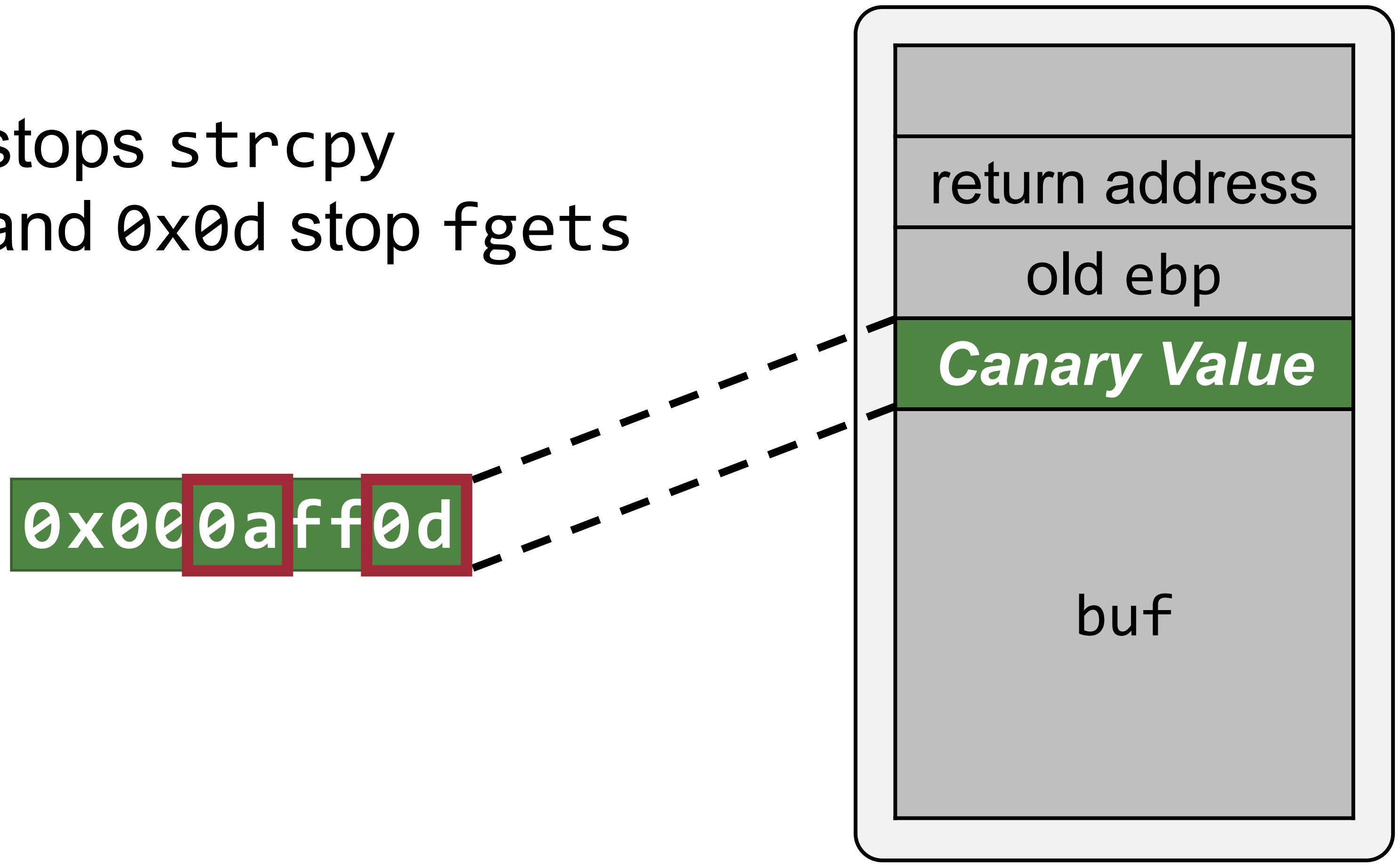


With stack canary

StackGuard (1998)

- Uses a constant canary value `0x000aff0d`

✓ `0x00` stops `strcpy`
✓ `0x0a` and `0x0d` stop `fgets`

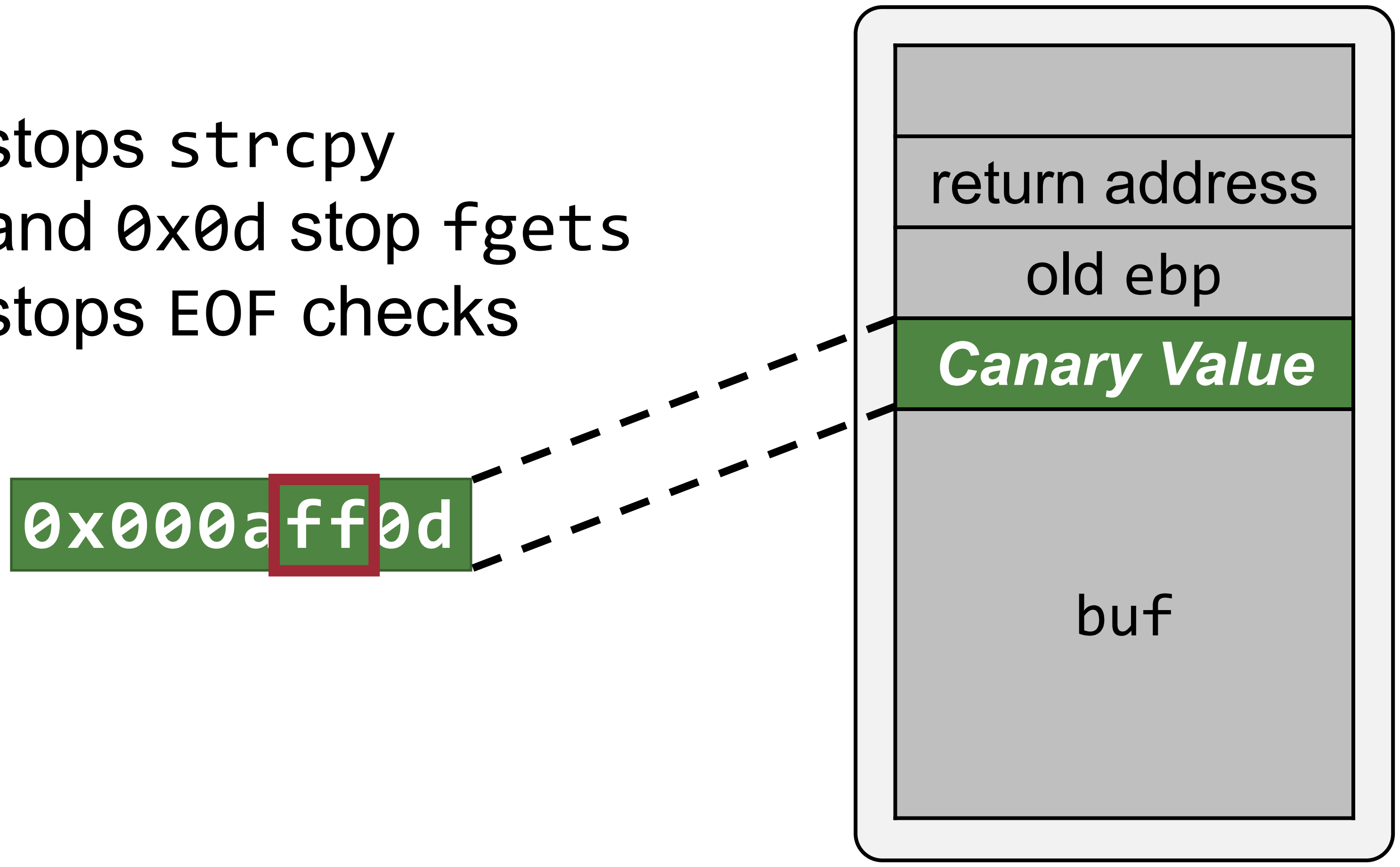


With stack canary

StackGuard (1998)

- Uses a constant canary value `0x000aff0d`

✓ `0x00` stops `strcpy`
✓ `0x0a` and `0x0d` stop `fgets`
✓ `0xff` stops EOF checks



With stack canary

Problem of Using a Constant Canary Value

`memcpy?`

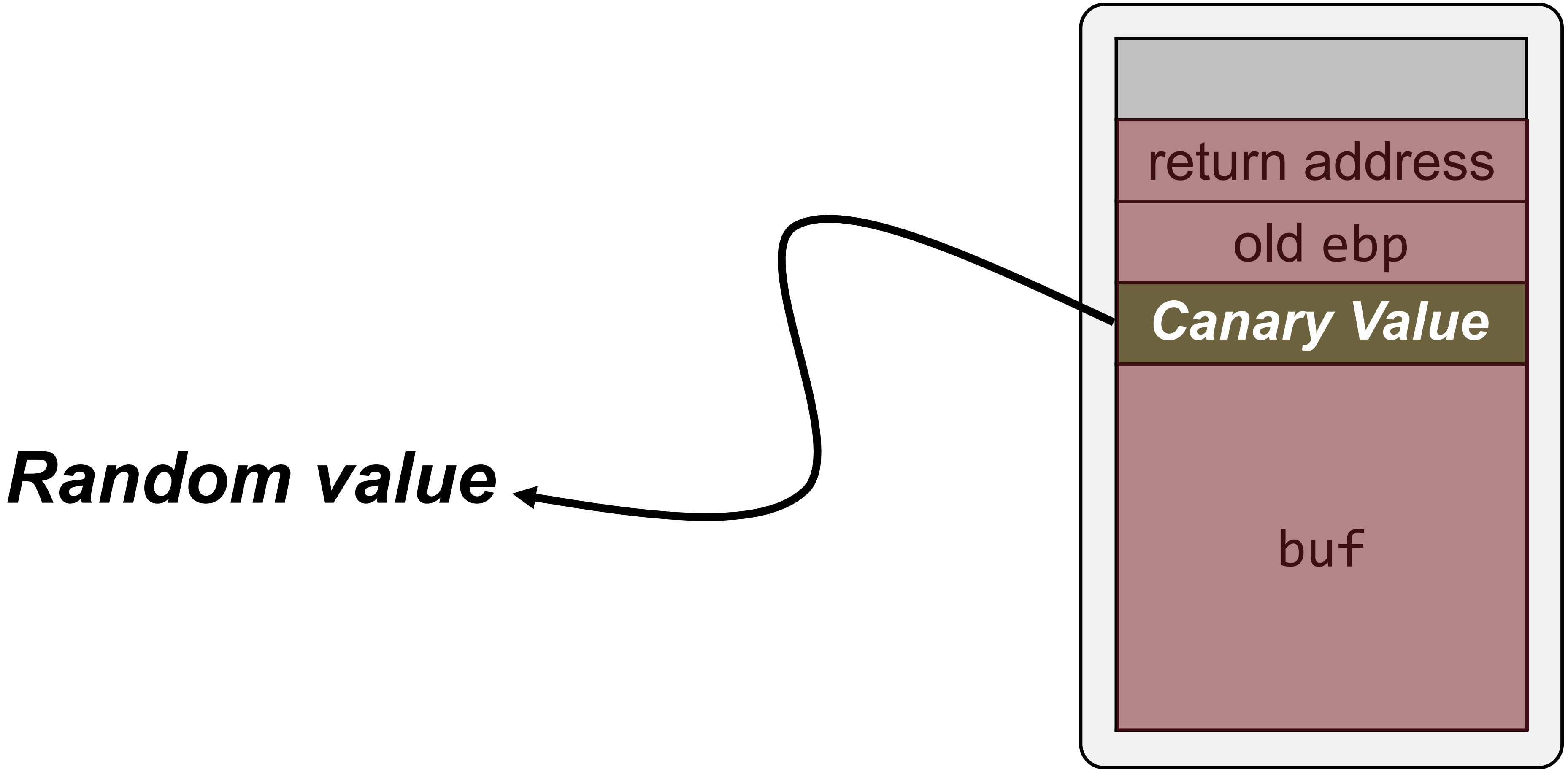
Problem of Using a Constant Canary Value


```
memcpy(void dest, void src, size_t n)
```

The `memcpy()` function copies **n bytes** from memory area `src` to memory area `dest`

Random Canaries

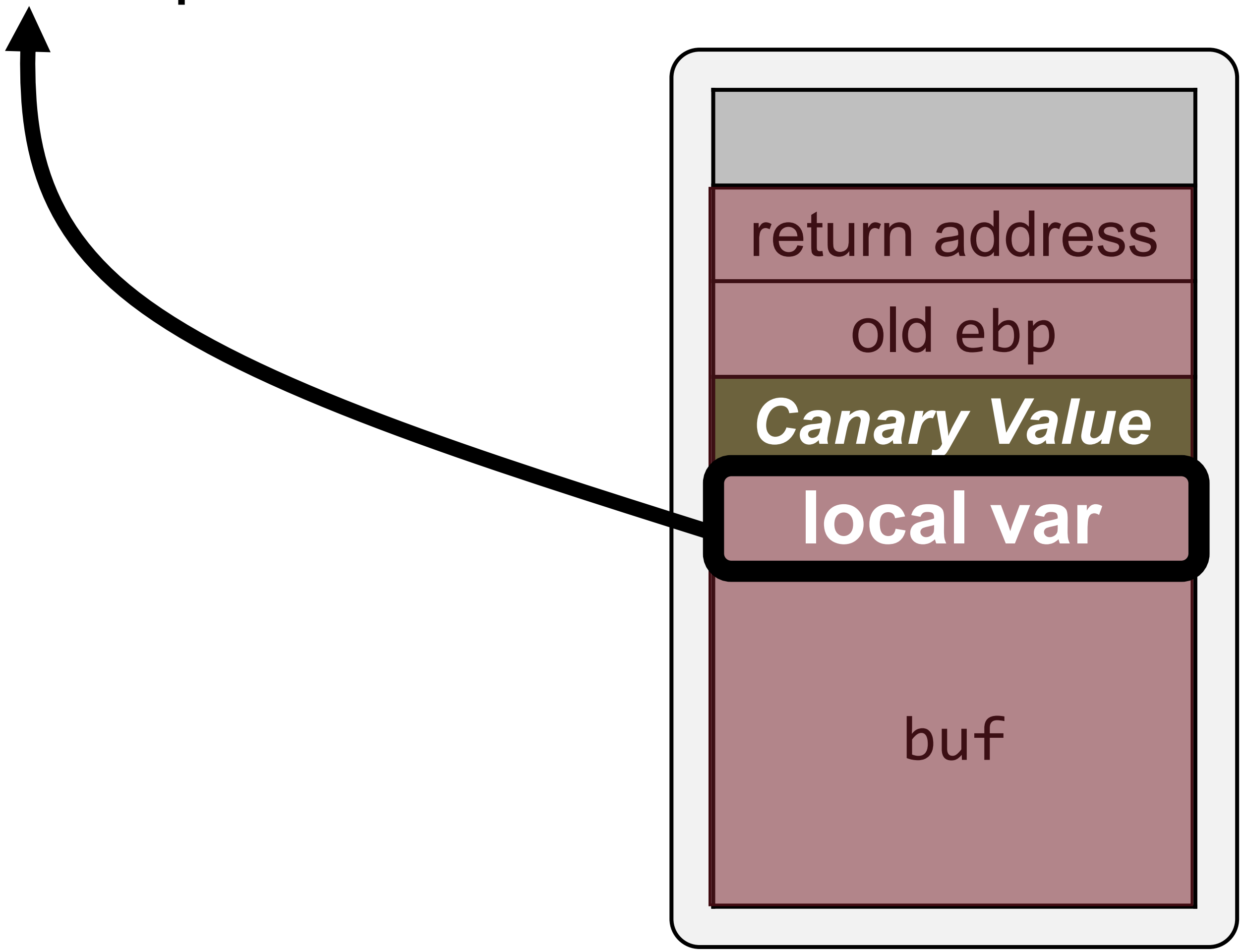
- Pick a random value at process initialization, put it on the stack



With stack canary

Problem Still Exists

- Local variables are not protected!



With stack canary

Solution: Reordering Local Variables

- Always put local buffers <u>after local pointers</u>
- This idea is implemented by GCC 4.1 in 2005

GCC Stack Canary Implementation

```
80483fb: push  ebp
80483fc: mov   ebp, esp
80483fe: sub   esp, 0x100
8048404: push  DWORD PTR [ ebp+0x8 ]
8048407: lea   eax, [ ebp-0x100 ]
804840d: push  eax
804840e: call  80482d0 <strcpy@plt>
8048413: add   esp, 0x8
8048416: leave
8048417: ret
```

Without stack canary

`gcc -fno-stack-protector`

```
804844b: push ebp
804844c: mov  ebp, esp
804844e: sub  esp,0 x108
8048454: mov  eax,DWORD PTR [ ebp+0x8 ]
8048457: mov  DWORD PTR [ ebp-0x108 ], eax
804845d: mov  eax, gs:0x14
8048463: mov  DWORD PTR [ ebp-0x4 ], eax
8048466: xor  eax, eax
8048468: push DWORD PTR [ ebp-0x108 ]
804846e: lea  eax, [ ebp-0x104 ]
8048474: push eax
8048475: call 8048320
804847a: add  esp, 0x8
804847d: mov  eax, DWORD PTR [ ebp-0x4 ]
8048480: xor  eax, DWORD PTR gs:0x14
8048487: je   804848e
8048489: call 8048310 <__stack_chk_fail@plt>
804848e: leave
804848f: ret
```

With **stack canary**

`gcc -fstack-protector`

GCC Stack Canary Implementation

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804848e: leave
804848f: ret
```

With **stack canary**

`gcc -fstack-protector`

GCC Stack Canary Implementation

Random canary value at gs:0x14

```
esp
x108
eax,DWORD PTR [ ebp+0x8 ]
8048457: mov    DWORD PTR [ ebp-0x108 ], eax
804845d: mov    eax, gs:0x14
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8048487: je     804848e
8048489: call 8048310 <__stack_chk_fail@plt>
804848e: leave
804848f: ret
```

With **stack canary**

`gcc -fstack-protector`

Who Initializes [gs:0x14]?

Runtime Dynamic Linker (RTLD) does it every time it launches **a process**

```
// Below is roughly what RTLD does at process creation time

uintptr_t ret;
int fd = open("/dev/urandom", O_RDONLY);
if (fd >= 0) {
    ssize_t len = read(fd, &ret, sizeof(ret));
    if (len == (ssize_t) sizeof(ret)) {
        // inlined assembly for moving ret to [gs:0x14]
    }
}
```

GCC Stack Canary Implementation

Random canary value at gs:0x14

Move canary value onto the stack

Why?

```
                esp
                x108
        eax,DWORD PTR [ ebp+0x8 ]
8048457: mov    DWORD PTR [ ebp-0x108 ], eax
804845d: mov   eax, gs:0x14
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With **stack canary**

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8048468: push DWORD PTR [ ebp-0x108 ]
              ebp-0x104 ]
804847a: add       0x8
804847d: mov  eax, DWORD PTR [ ebp-0x4 ]
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8048487: je   804848e
8048489: call 8048310 <__stack_chk_fail@plt>
804848e: leave
804848f: ret
```

Get current canary value from stack

Compare to the original canary value

Jump to the `leave` instruction if equal

With **stack canary**

`gcc -fstack-protector`

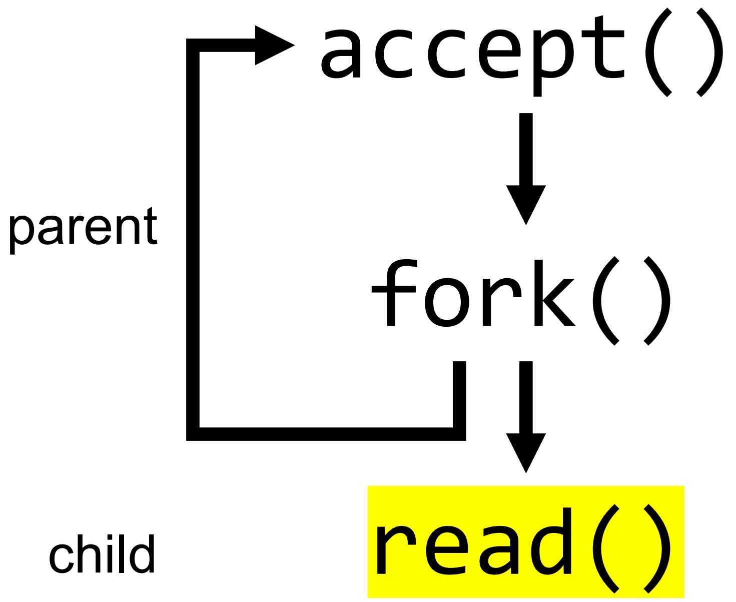
GCC Canary Implementation

- Uses a random canary value for every process creation
- Puts buffers after any local pointers on the stack

Attacking Canary Protection

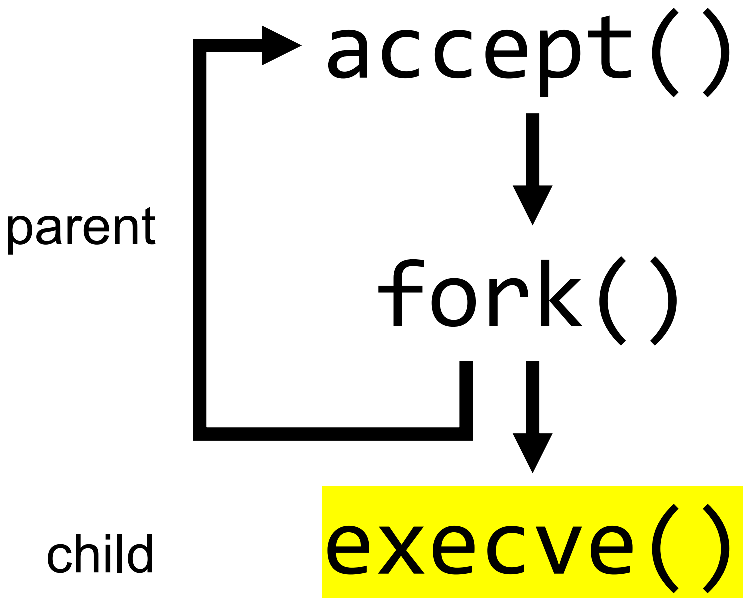
Reused Canary Value

- Uses a random canary value for ***every process creation***



Server Type #1

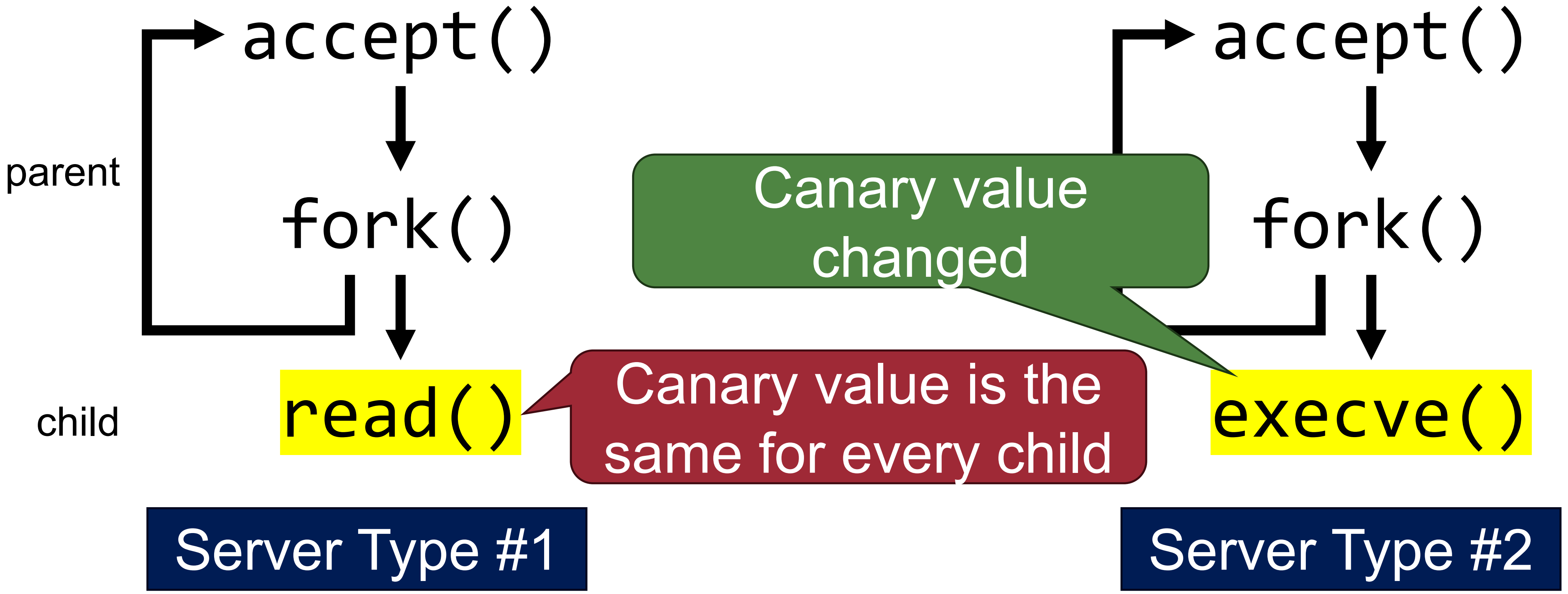
e.g., OpenSSH does this



Server Type #2

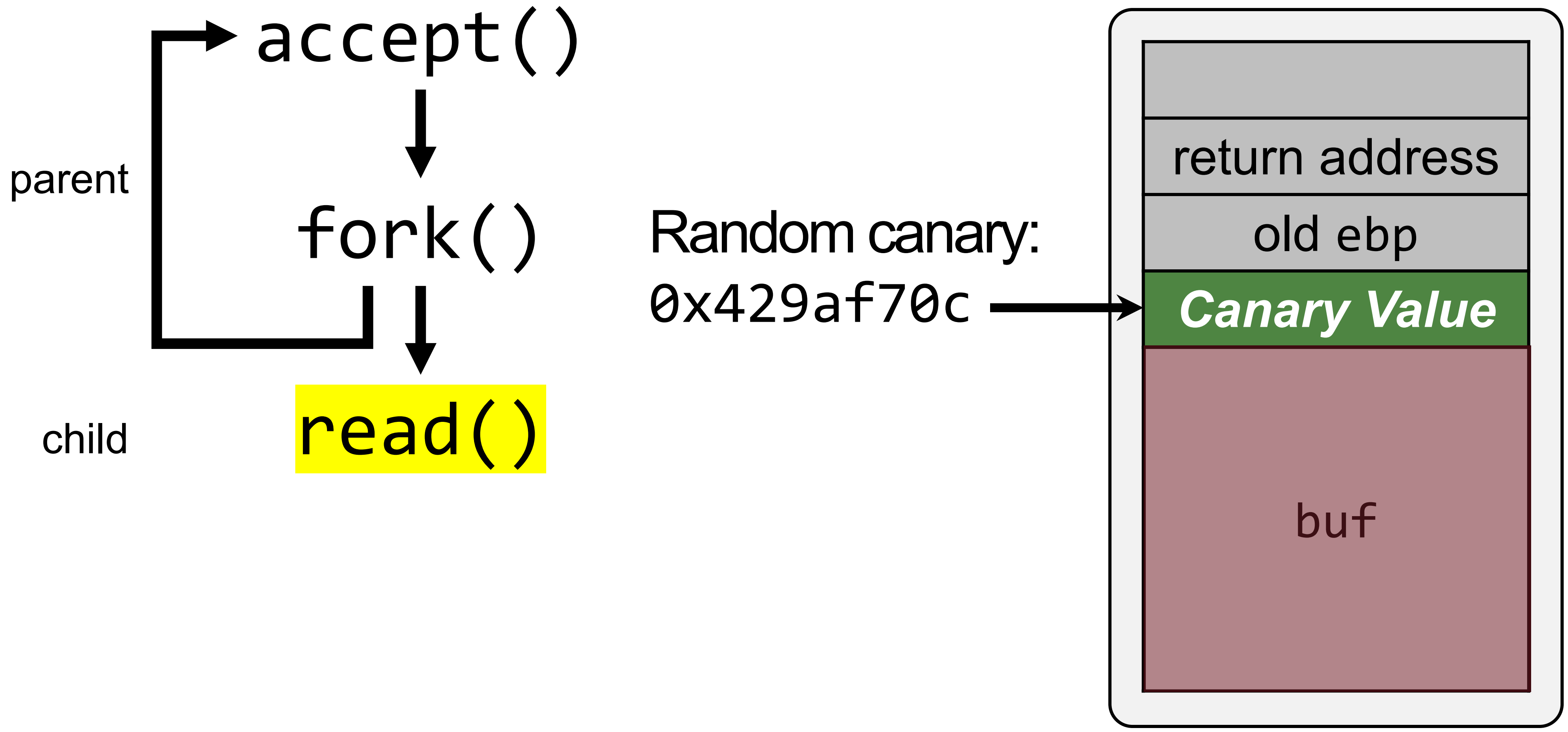
Reused Canary Value

- Uses a random canary value for ***every process creation***



e.g., OpenSSH does this

Attack #1: Byte-by-Byte Brute Forcing

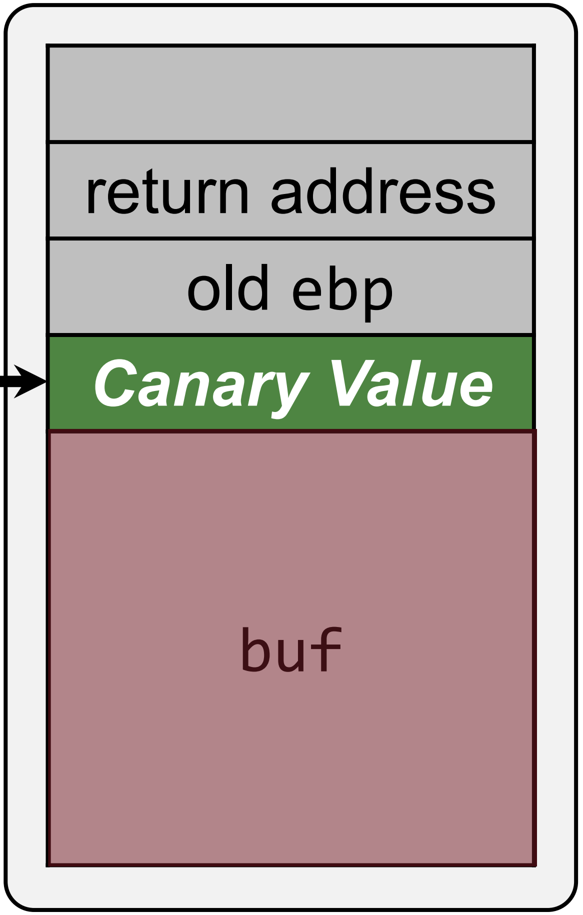


With stack canary

Attack #1: Byte-by-Byte Brute Forcing

Try to overwrite only 1 byte with a character from `\x00` to `\xff` until the program does not crash

Random canary:
`0x429af70c`



With stack canary

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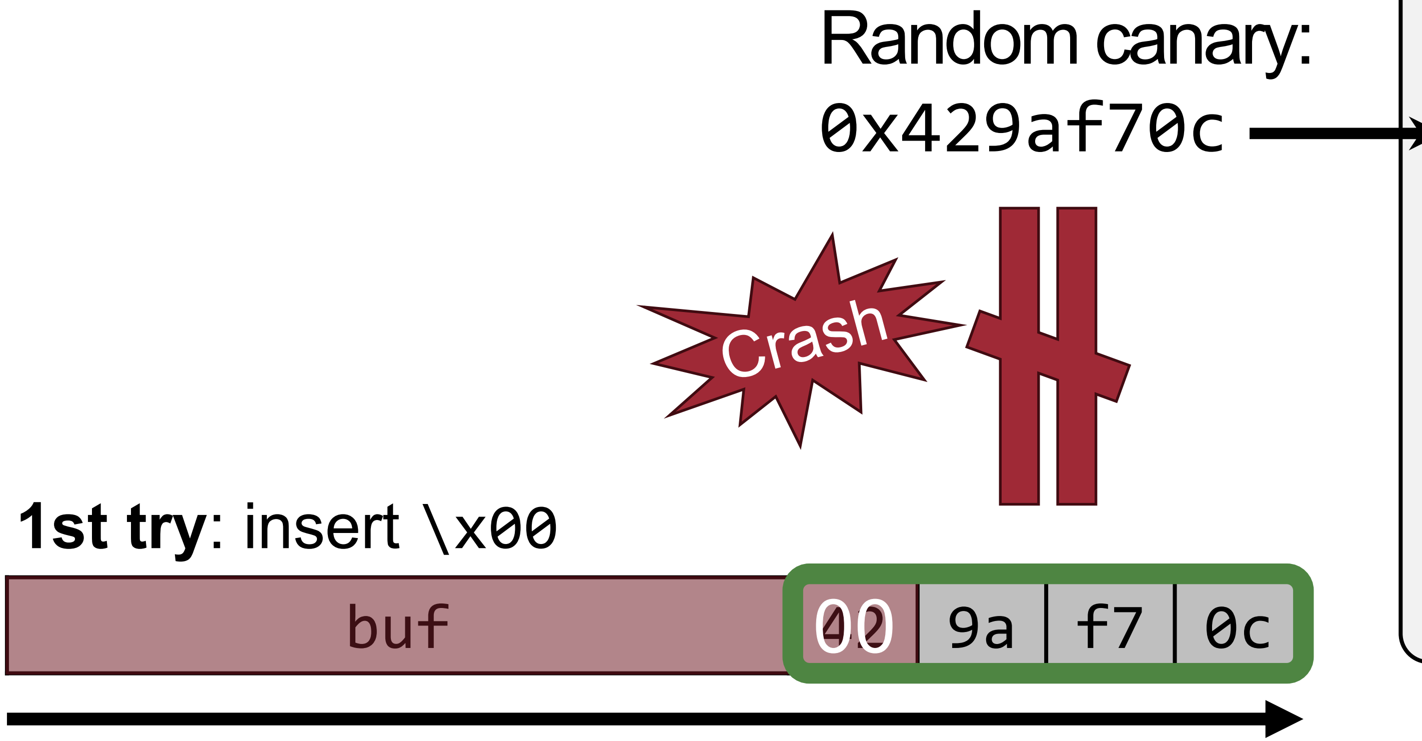

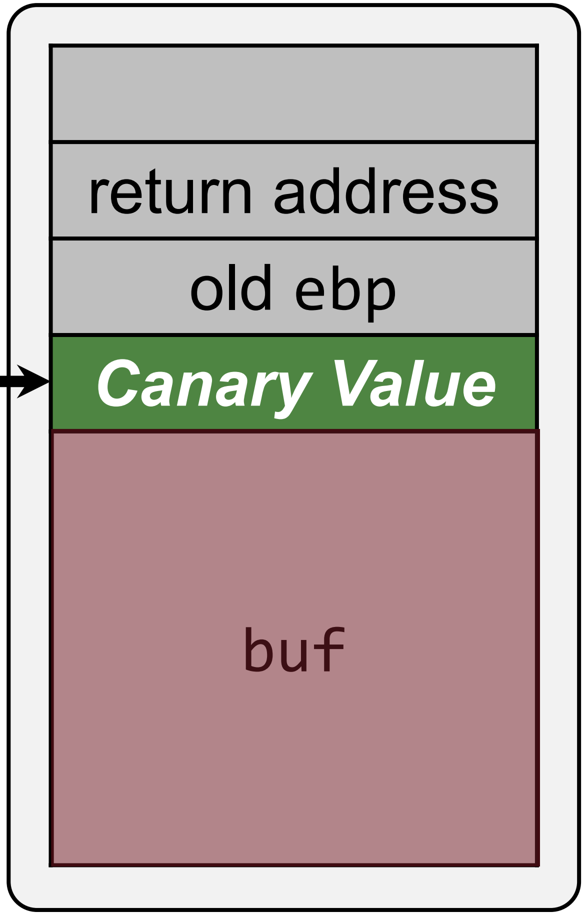

With stack canary

Attack #1: Byte-by-Byte Brute Forcing

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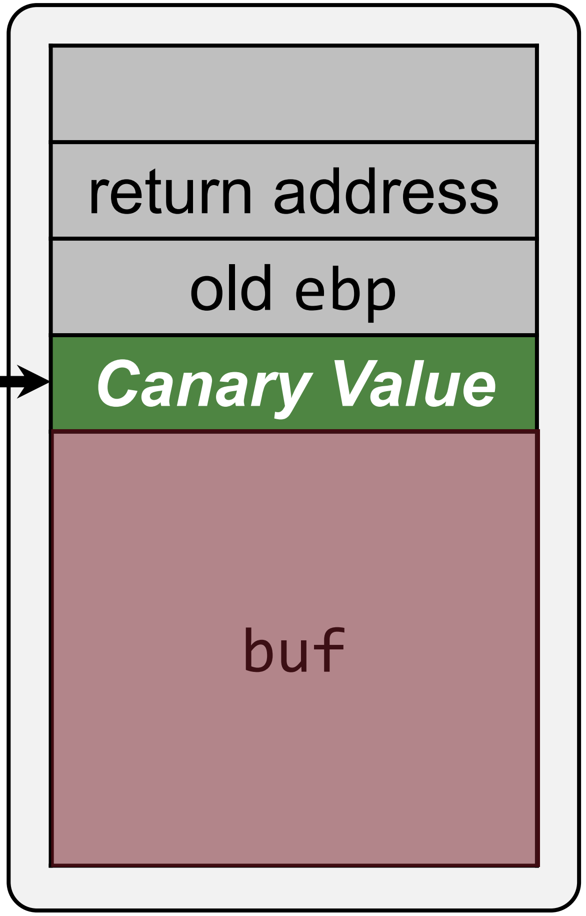
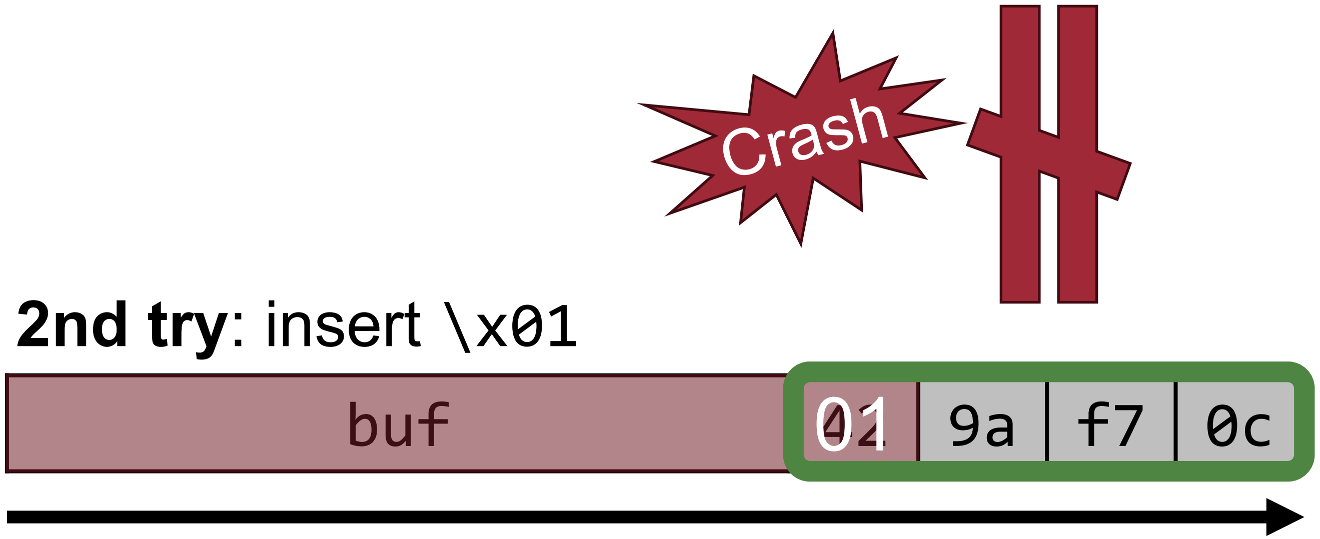


With stack canary

2nd try: insert `\x01`



Attack #1: Byte-by-Byte Brute Forcing

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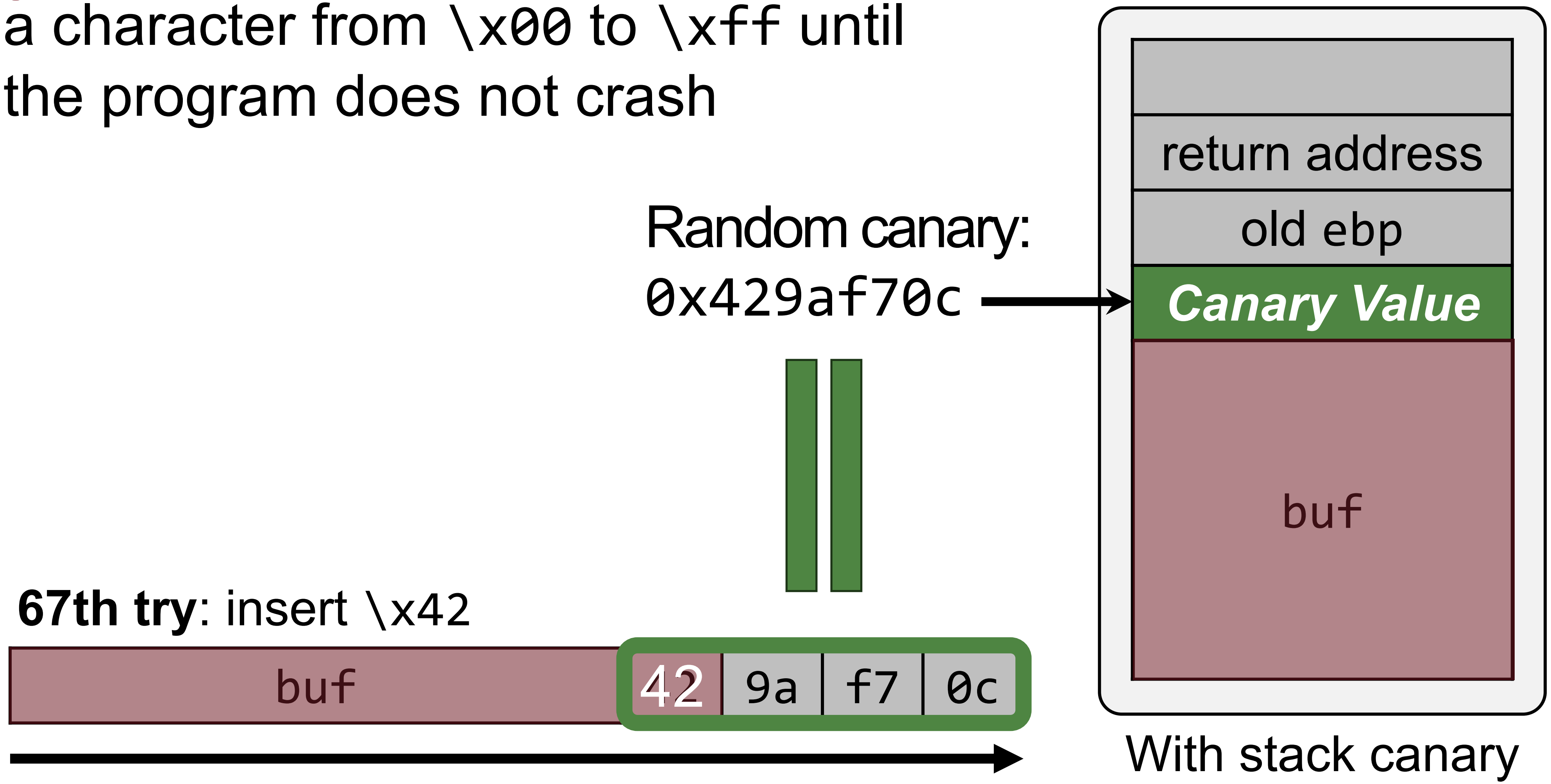


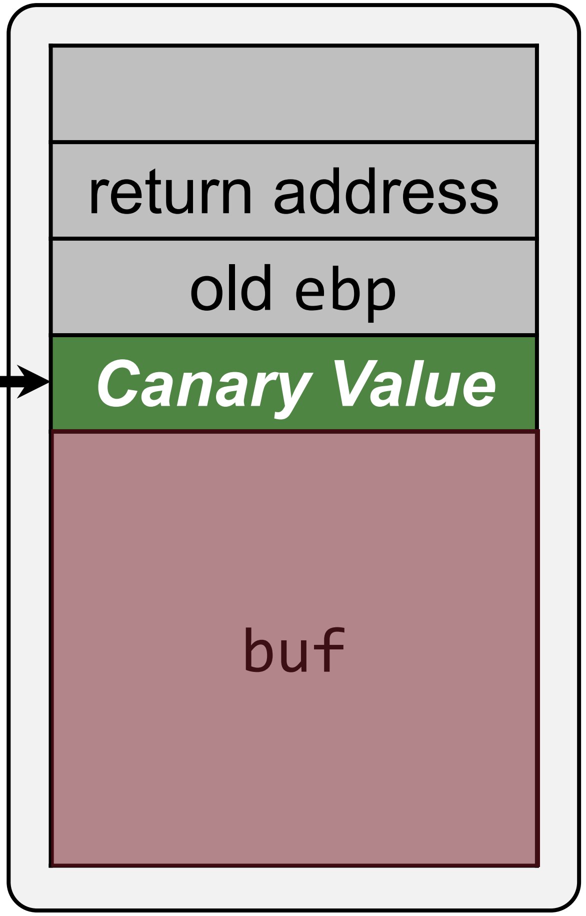
Attack #1: Byte-by-Byte Brute Forcing

Try to overwrite only 1 byte with a character from `\x00` to `\xff` until the program does not crash

Random canary:
`0x429af70c`

Do the same for all 4 bytes!
⇒ Worst case?

67th try: insert `\x42`



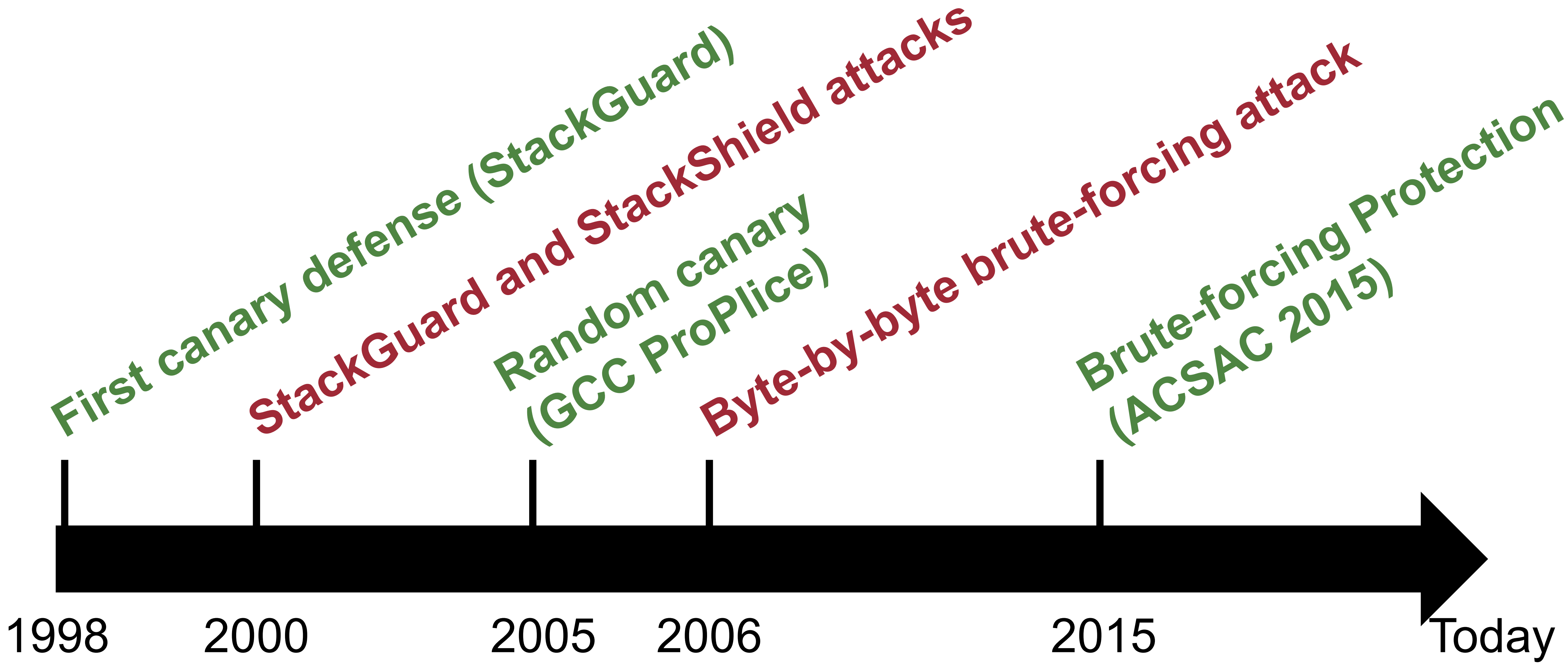
With stack canary

Protecting Canary Brute-Forcing Attack

(Optional Reading)

DynaGuard: Armoring Canary-based Protections against Brute-force Attacks, ***ACSAC 2015***

Canary Attack and Defense Timeline

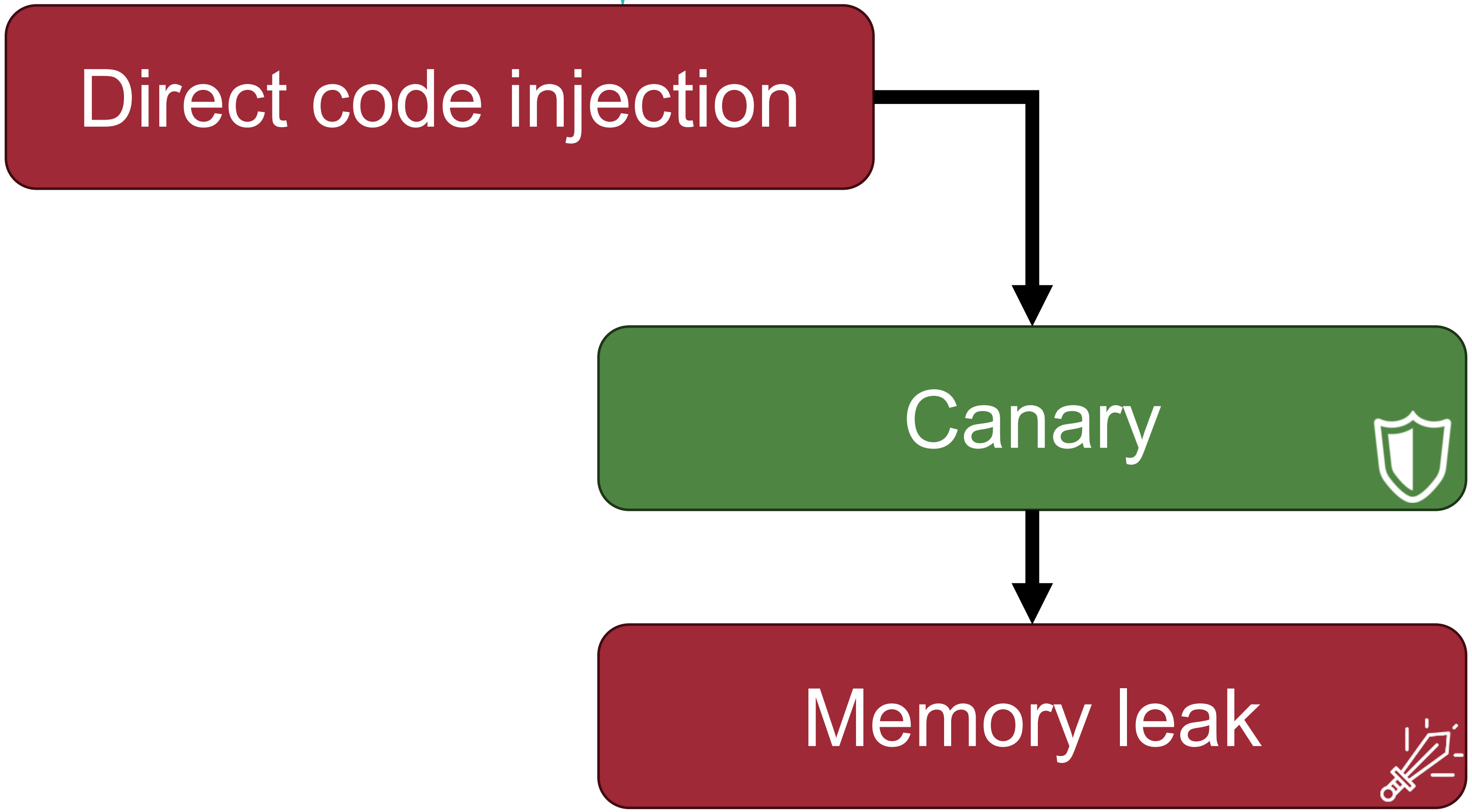


Attack #2: Leaking Canary Value

- If there is another vulnerability that allows us to ***leak*** stack contents, then we can easily bypass the canary check

- Canary is inherently vulnerable to *format string attacks*

Control Hijack Attack / Defense So Far



Buffer Overflow Mitigation #2: NX

NX (No eXecute)

a.k.a Data Execution Prevention* (***DEP***)

Stack stores data, but not code. Therefore, OS makes the stack memory area ***non-executable***

* DEP ***prevents*** data execution, but it does not prevent buffer overflows

NX (No eXecute)

AMD Athlon™ Processor Competitive Comparison

FEATURES	AMD ATHLON™ CPU	PENTIUM® 4
Architecture Introduction	2006	2000
Infrastructure	Socket AM2	Socket LGA775
Process Technology	90 nanometer, SOI 65 nanometer, SOI	90 nanometer
64-bit Instruction Set Support	Yes, AMD64 technology	Depends, EM64T on some Pentium® 4 series
Enhanced Virus Protection for Windows® XP SP2*	Yes	Depends

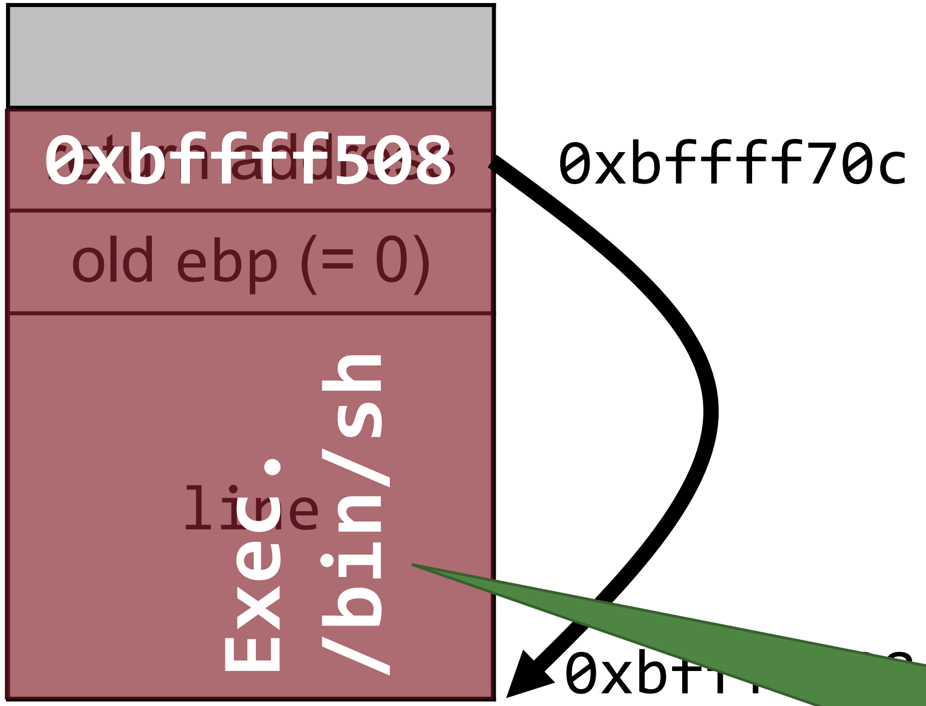
W ⊕ X (Write XOR eXecute) Policy

On Linux, it is called W ⊕ X

- Every page should be either writable or executable, but NOT both

- Even though we can put a shellcode to a writable buffer, we cannot execute it if this policy is enabled

Mitigating Control Flow Hijack with DEP



Make this region ***non-executable***!
(e.g., stack should be non-executable)

DEP on Stack using execstack

- Tool to set, clear, or query NX stack flag of binaries

```
$ /usr/sbin/execstack -c <filename> ; clear NX flag
$ /usr/sbin/execstack -s <filename> ; set NX flag
$ /usr/sbin/execstack -q <filename> ; query NX flag
```

When NX is set, return-to-stack exploit will fail
(i.e., the program will crash)

But,

DEP does not prevent buffer overflows. It prevents return-to-stack exploits, though

Any other ways to exploit buffer overflows?

Code-Reuse Attacks

Bypassing DEP

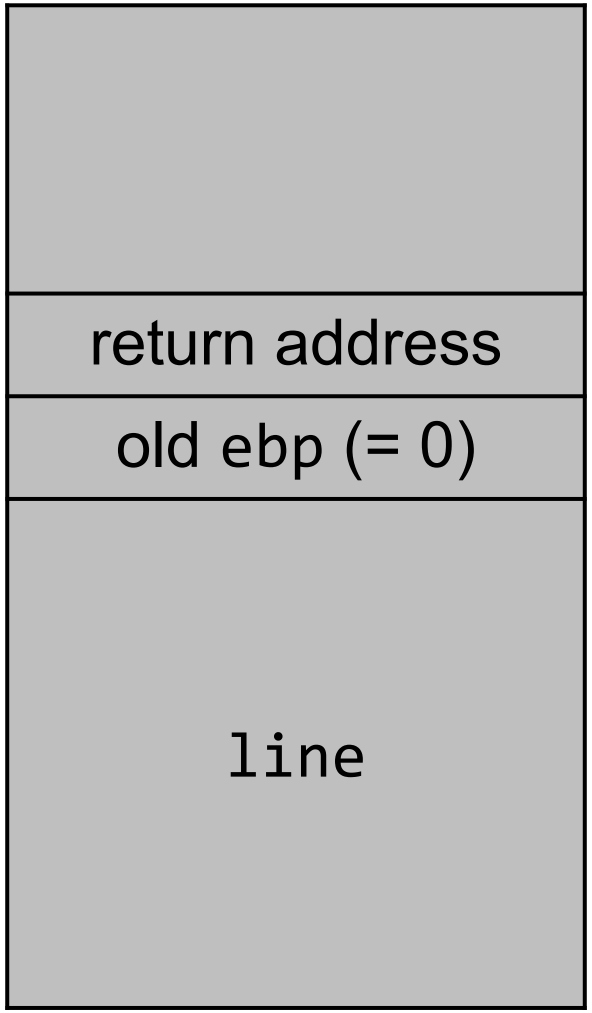
- Return-to-stack exploit is disabled
- But, we can still jump to an arbitrary address of ***existing code*** **(=** ***Code Reuse Attack*****)**

Code Reuse Attack #1: Return-to-Libc

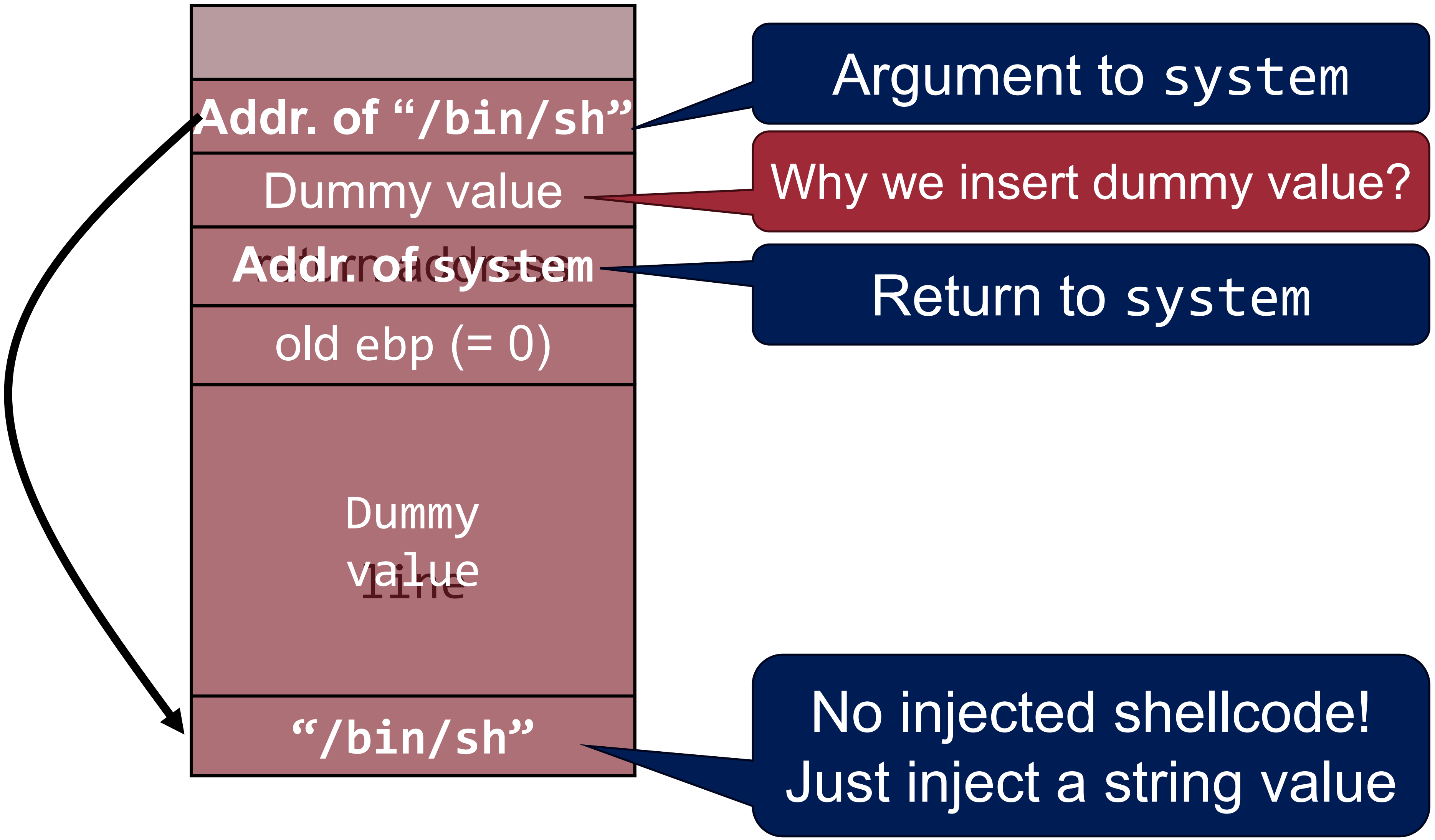
- LIBC (LIBrary C) is a standard library that most programs commonly use
  - For example, `printf` is in LIBC

- Many useful functions in LIBC to execute
  - `exec` family: `execl`, `execlp`, `execle`, …
  - `system`
  - `mprotect`
  - `mmap`

Code Reuse Attack #1: Return-to-Libc



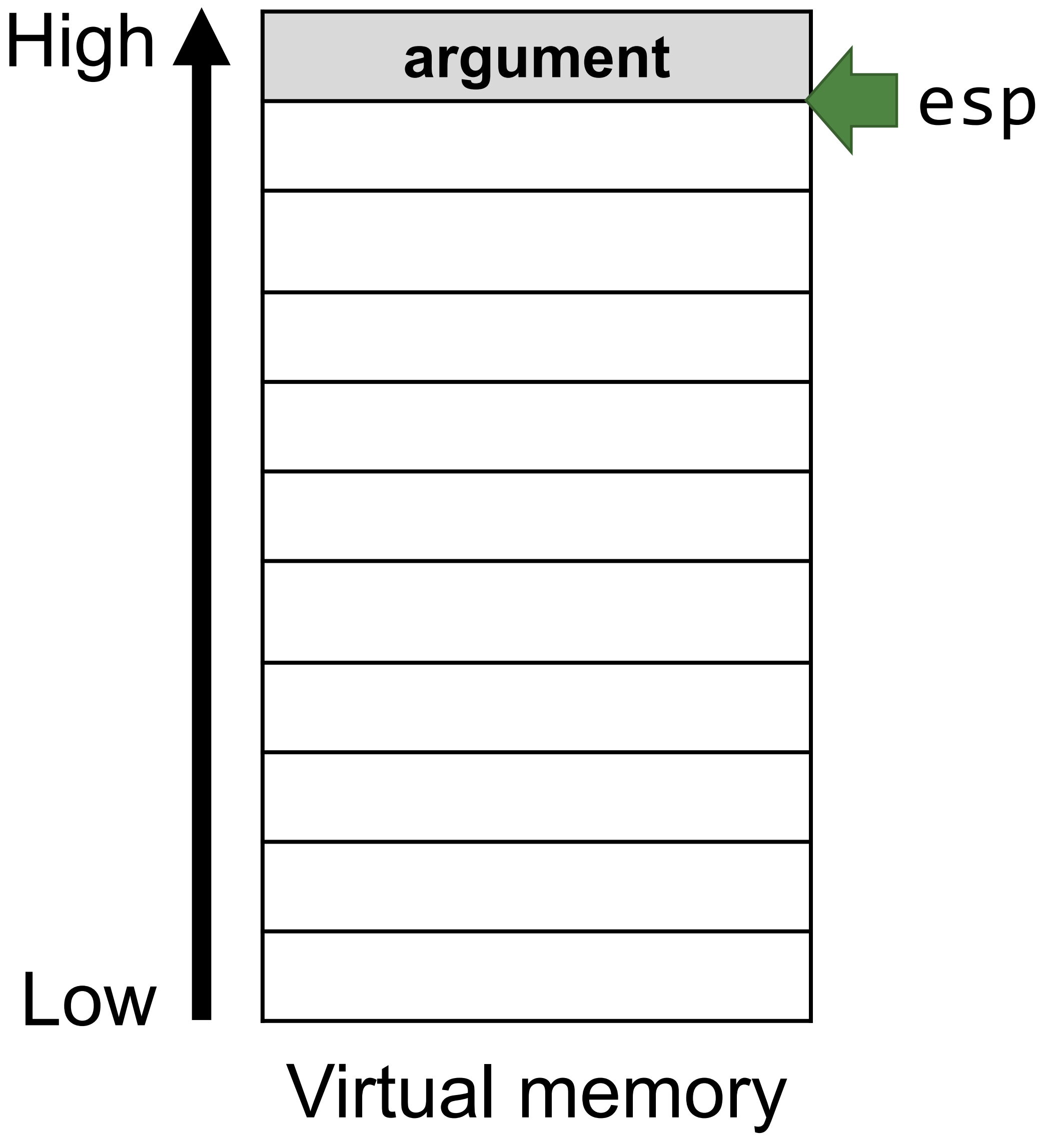
Code Reuse Attack #1: Return-to-Libc



Recap: Function Call (call)

```
    …
    call system
nextret:
    nop
    nop
    ...
system (in libc):
    nop
    nop
```

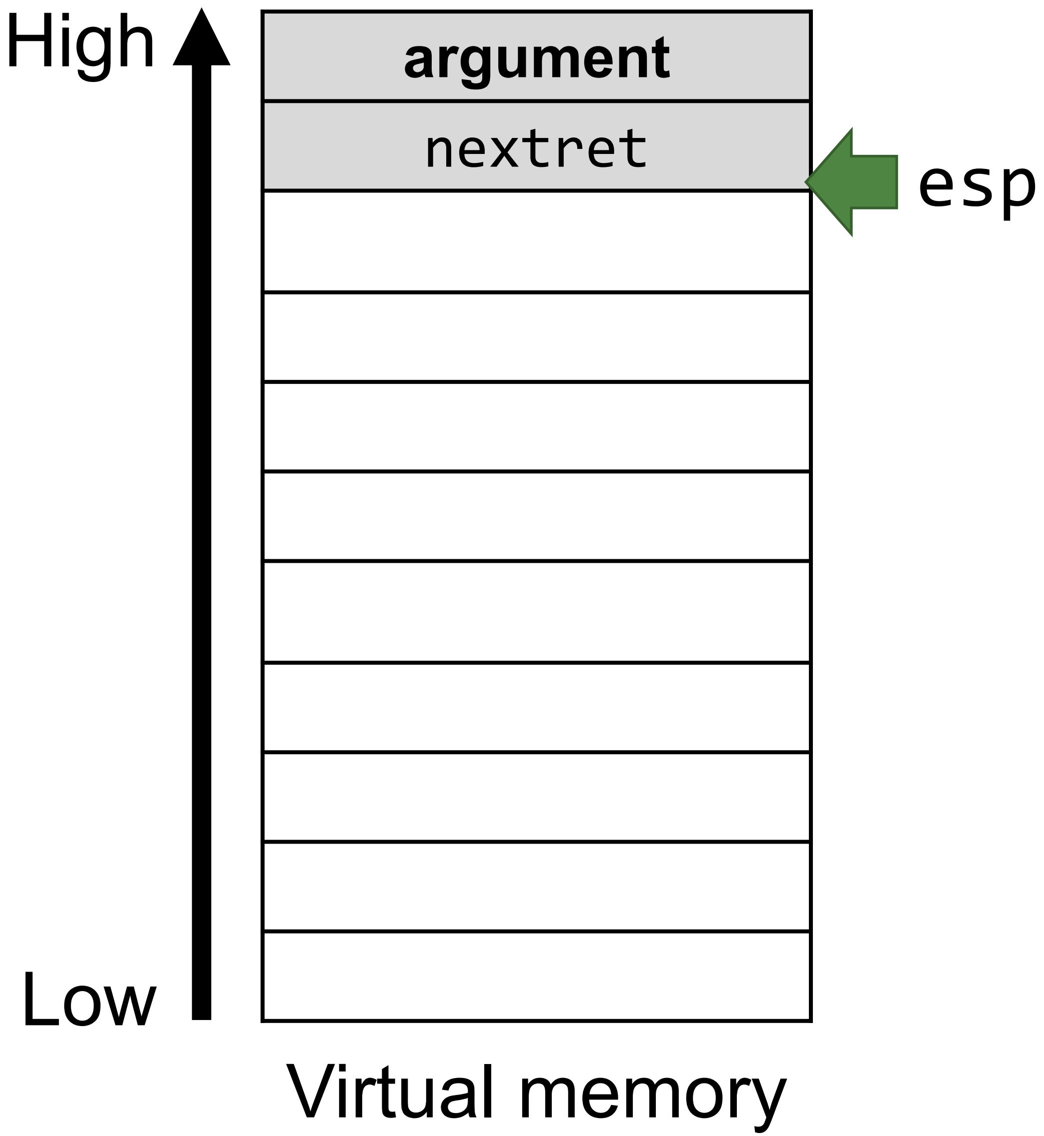
```
push nextret
jmp system
```



Recap: Function Call (call)

```
    …
    call system
nextret:
    nop
    nop
    ...
system (in libc):
    nop
    nop
```

```
push nextret
jmp system
```

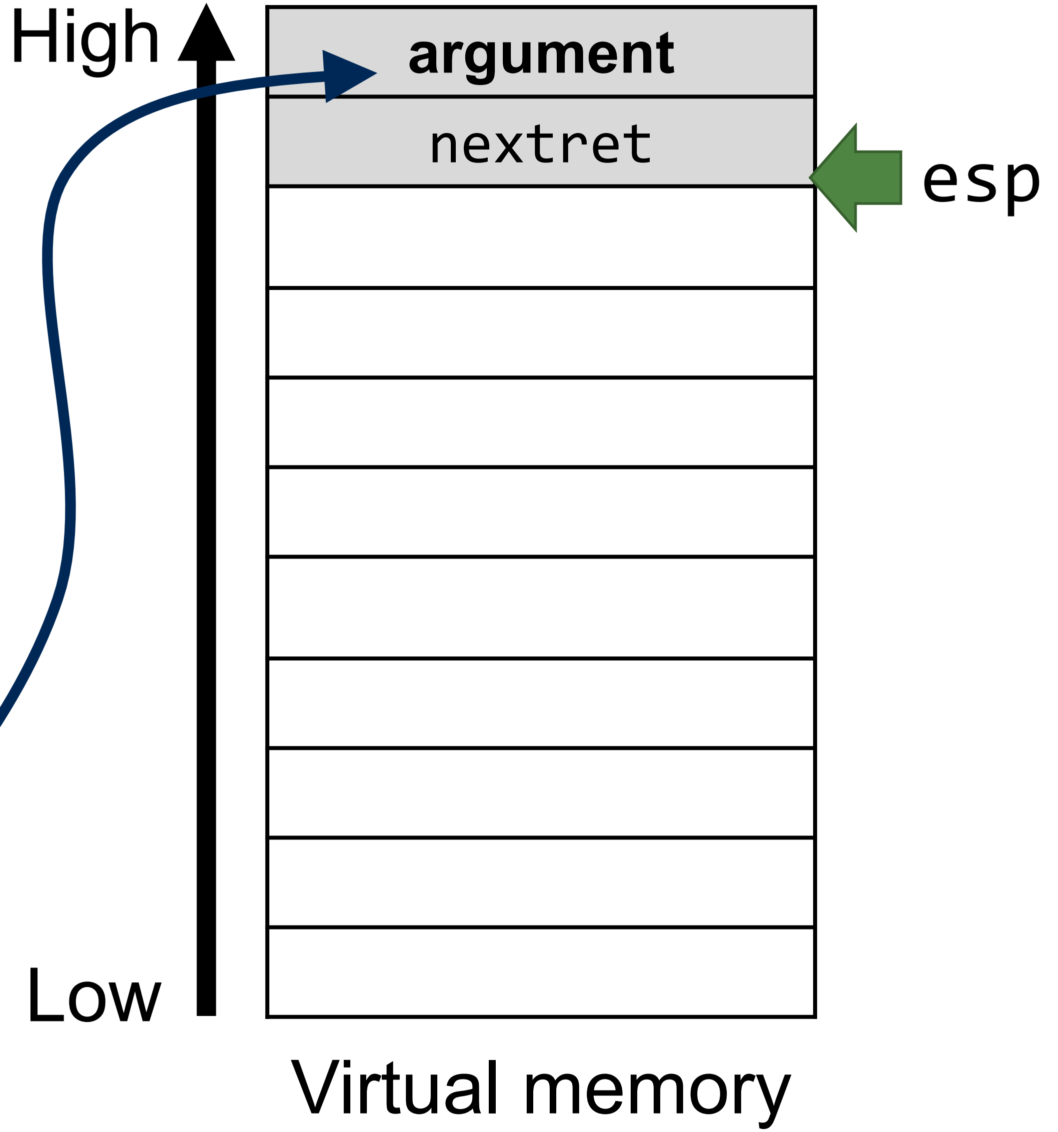


Recap: Function Call (call)

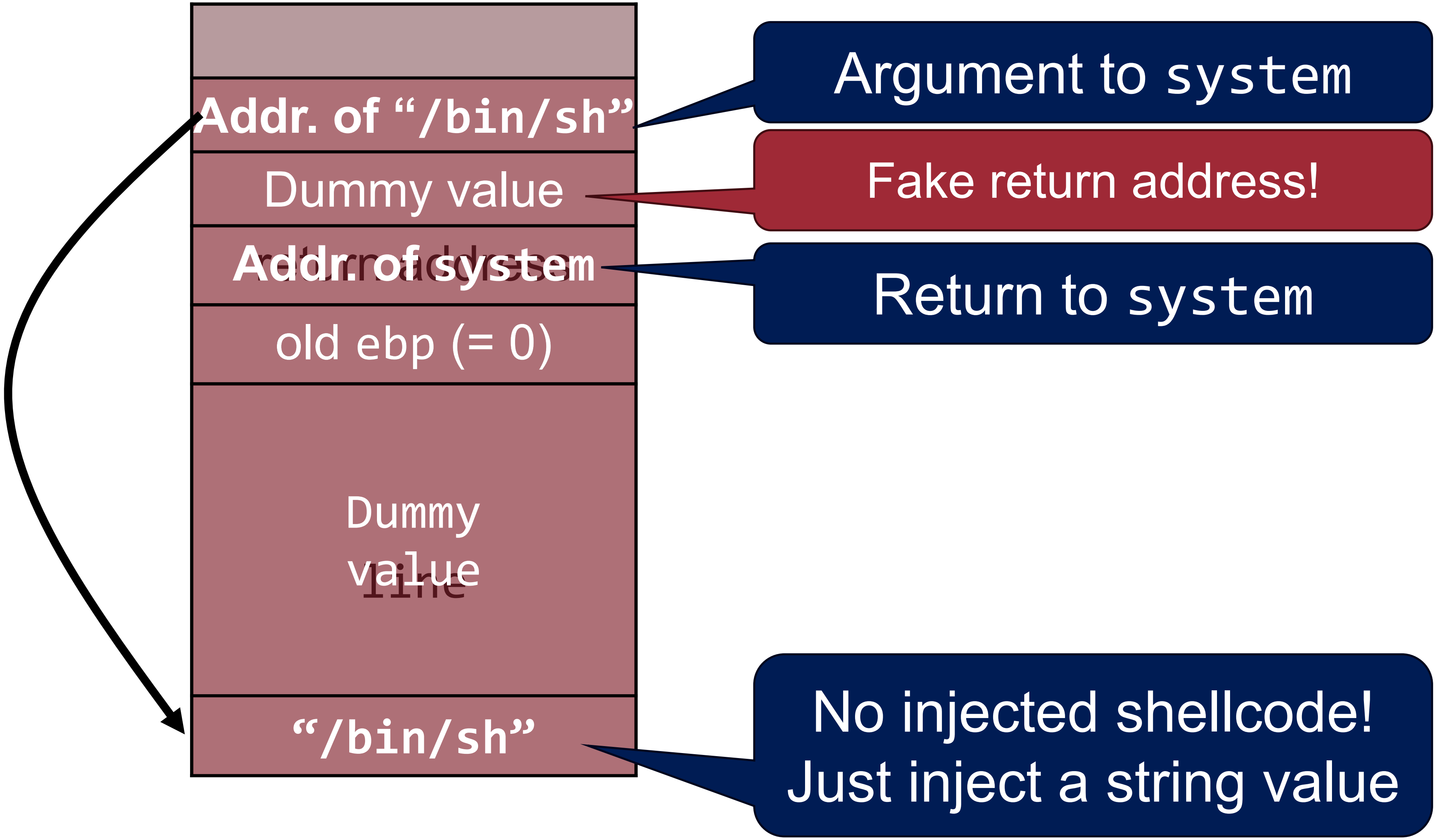

```
    …
    call system
nextret:
    nop
    nop
    ...
system (in libc):
    nop
    nop
```

```
push nextret
jmp system
```

Recognize `esp+0x4` as first parameter



Code Reuse Attack #1: Return-to-Libc



Return-oriented Programming (ROP)

Code Reuse Attack #2: ROP

Generalized Code Reuse Attack

Formally introduced by Hovav in CCS 2007

"The Geometry of Innocent Flesh on the Bone: Return-to-libc without Function Calls (on the x86)"

Motivation of ROP

Return-to-Libc requires LIBC function calls, but can **we spawn a shell without the use of LIBC functions**?

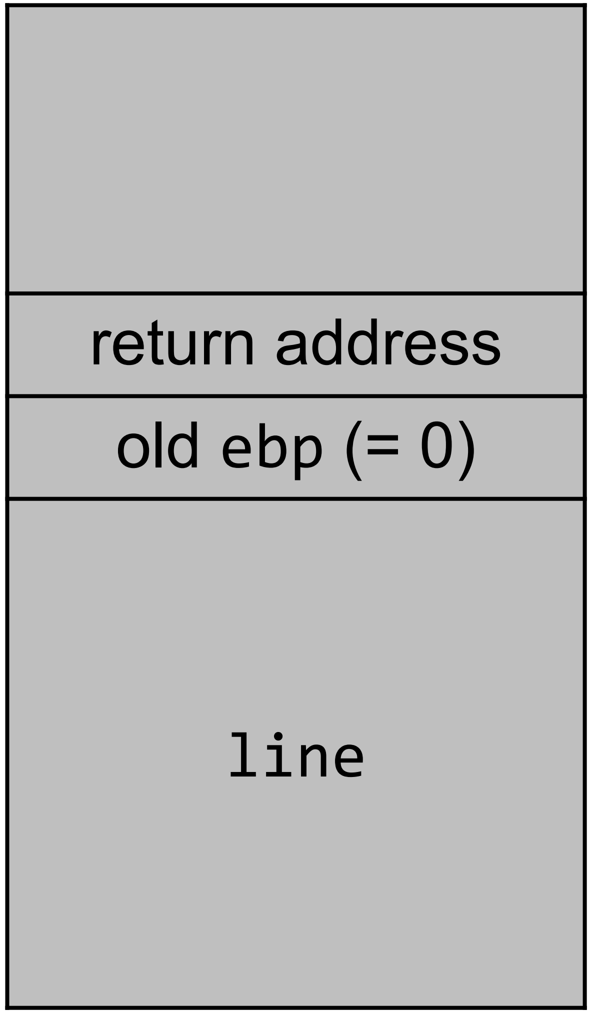
- Different versions of LIBC
- LIBC may not be used at all
- Some functions in LIBC can be excluded

Return (ret) Chaining

Attacker's goal:

execute following instructions

```
add eax, ebx
mov ecx, eax
inc ecx
mov edx, 42
```



Return (ret) Chaining

Attacker's goal:

execute following instructions

```
add eax, ebx
mov ecx, eax
inc ecx
mov edx, 42
```

42
Address of C
Address of B
Address of A
old ebp (= 0)
Dummy value

Return (ret) Chaining

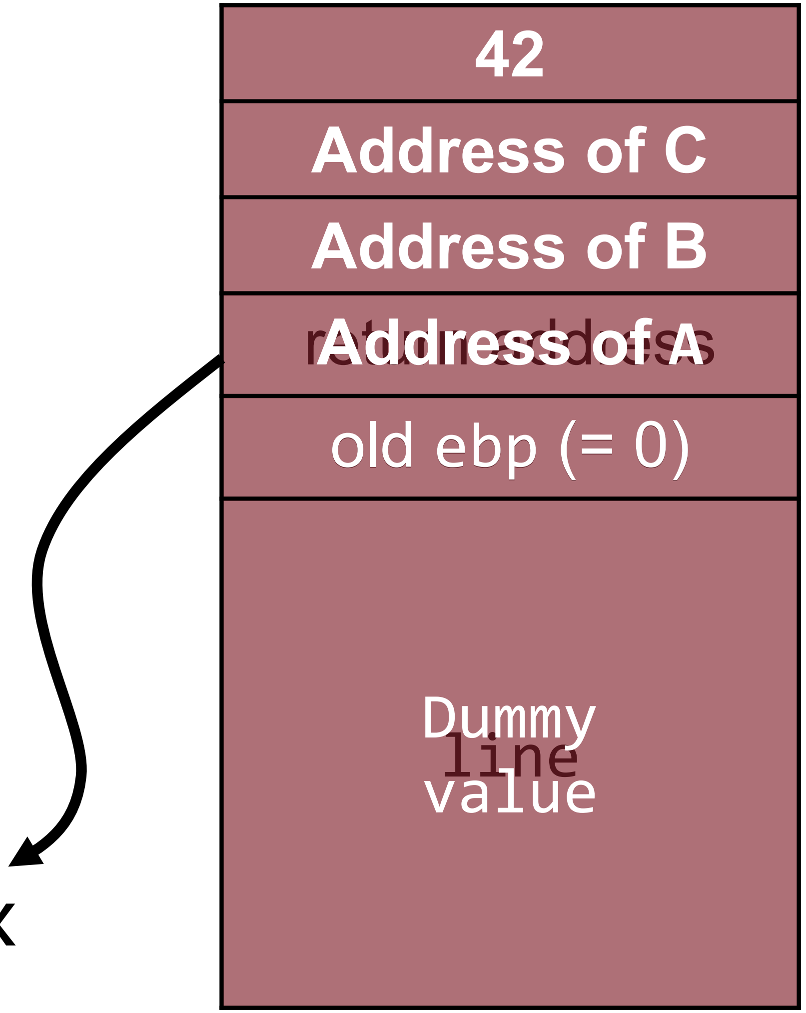
Attacker's goal:
execute following instructions

```
add eax, ebx
mov ecx, eax
inc ecx
mov edx, 42
```

Somewhere in the binary code

A

```
add eax, ebx
ret
```



Return (ret) Chaining

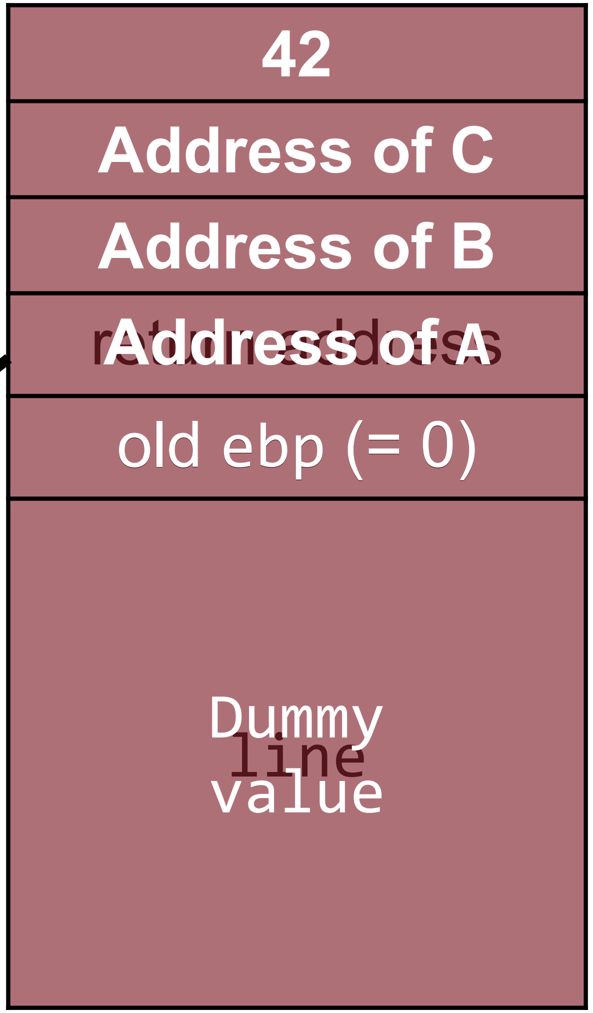
Attacker's goal:
execute following instructions

```
add eax, ebx
mov ecx, eax
inc ecx
mov edx, 42
```

ROP Gadget:
Instruction sequence that ends with `ret`

A

```
add eax, ebx
ret
```



Return (ret) Chaining

Attacker's goal:
execute following instructions

```
add eax, ebx
mov ecx, eax
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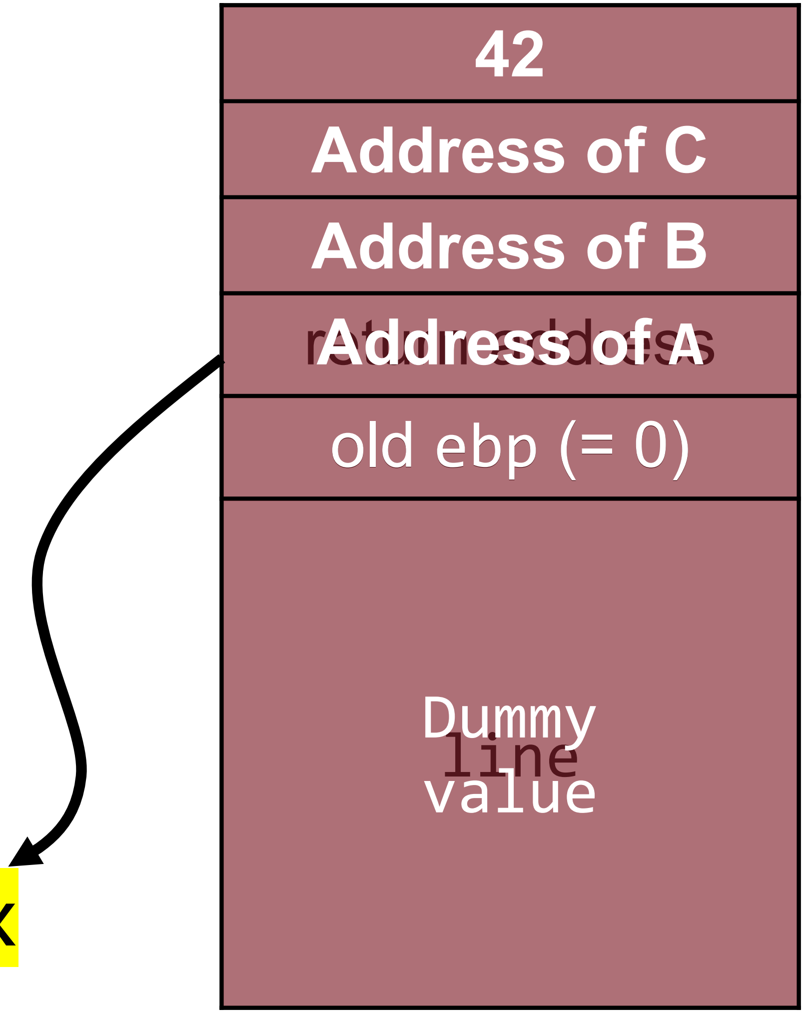
mov edx, 42
```



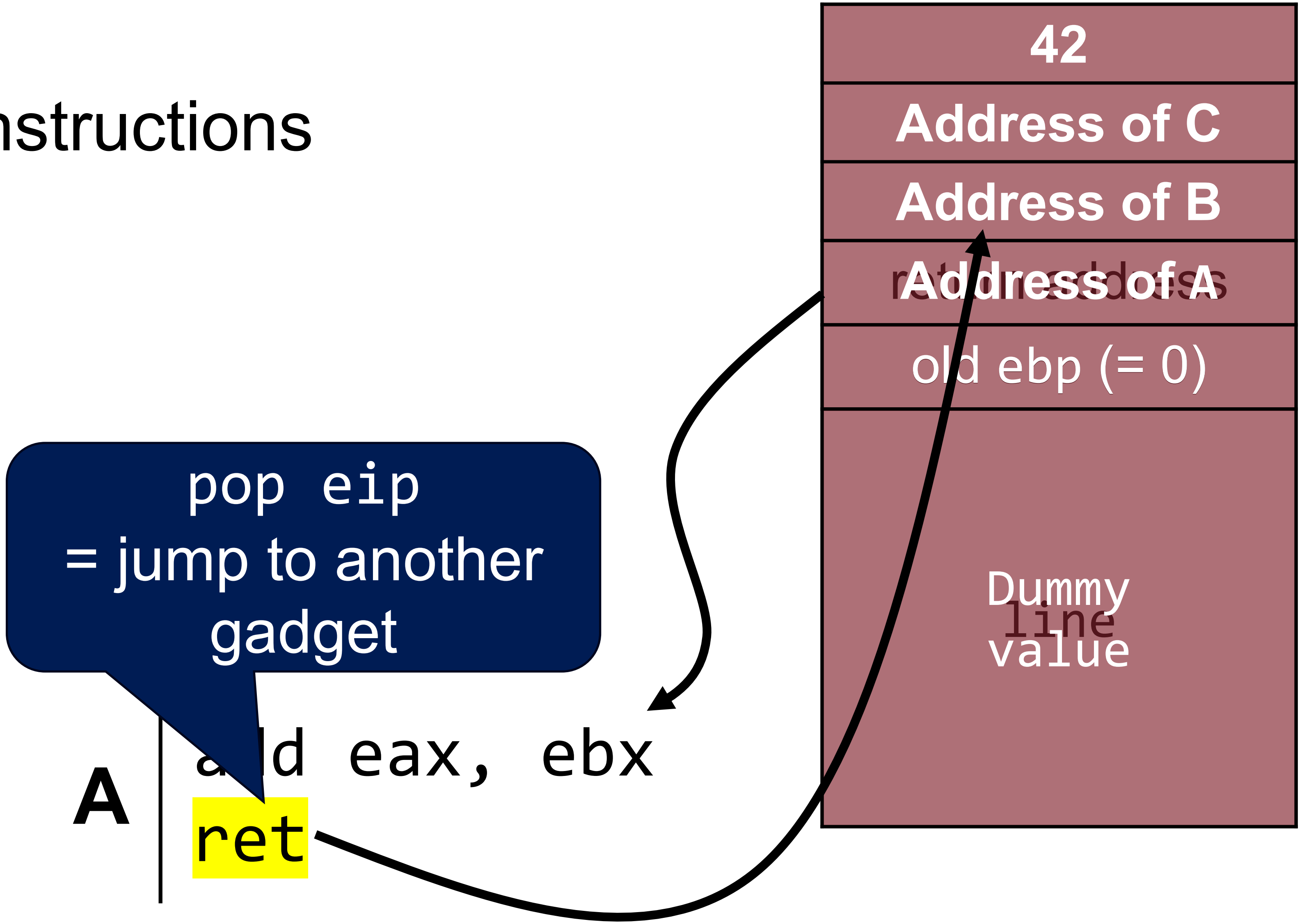
A

```
add eax, ebx
ret
```

Return (ret) Chaining

Attacker's goal:
execute following instructions

```
add eax, ebx
mov ecx, eax
inc ecx
mov edx, 42
```



Return (ret) Chaining

Attacker's goal:
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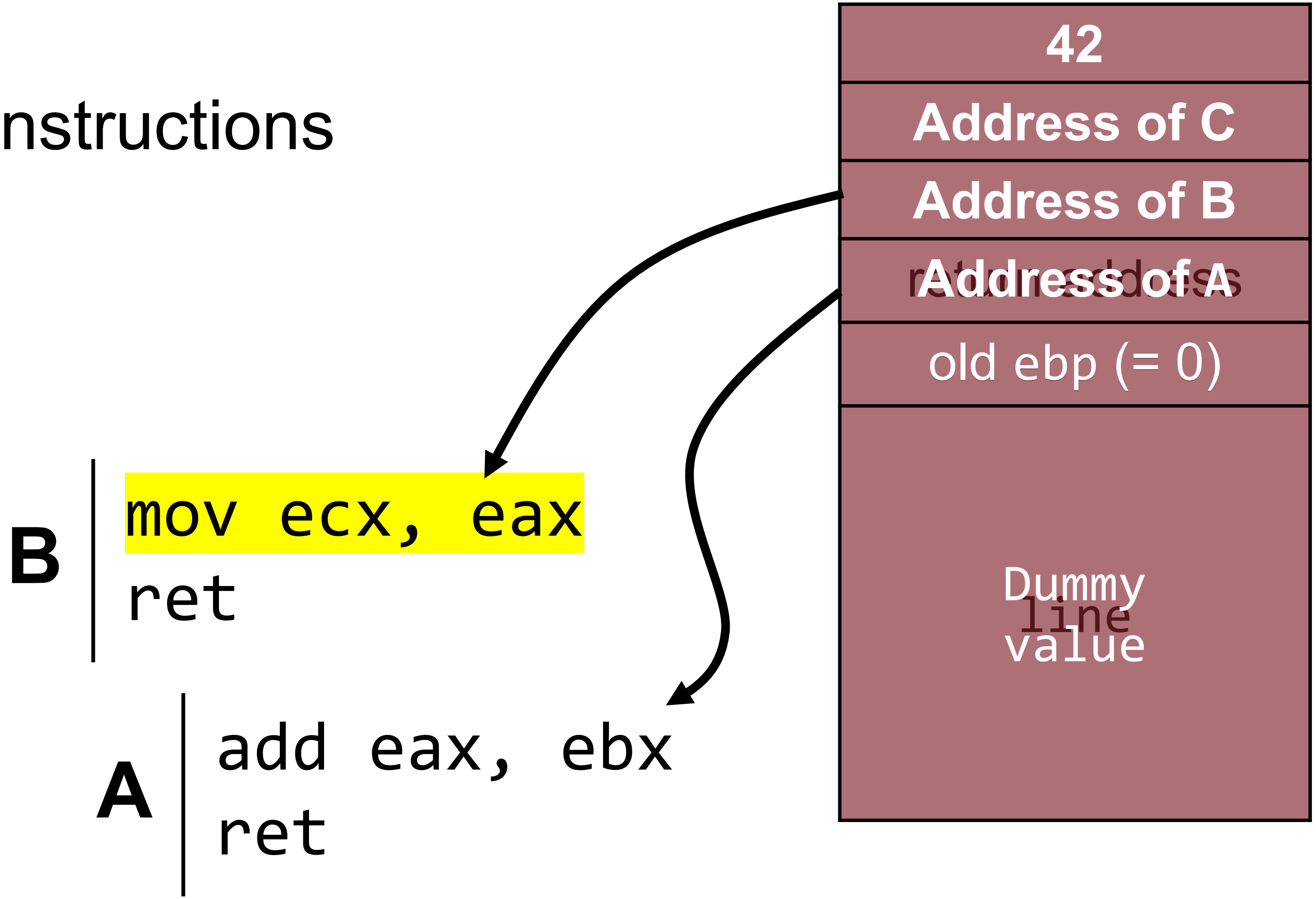


Return (ret) Chaining

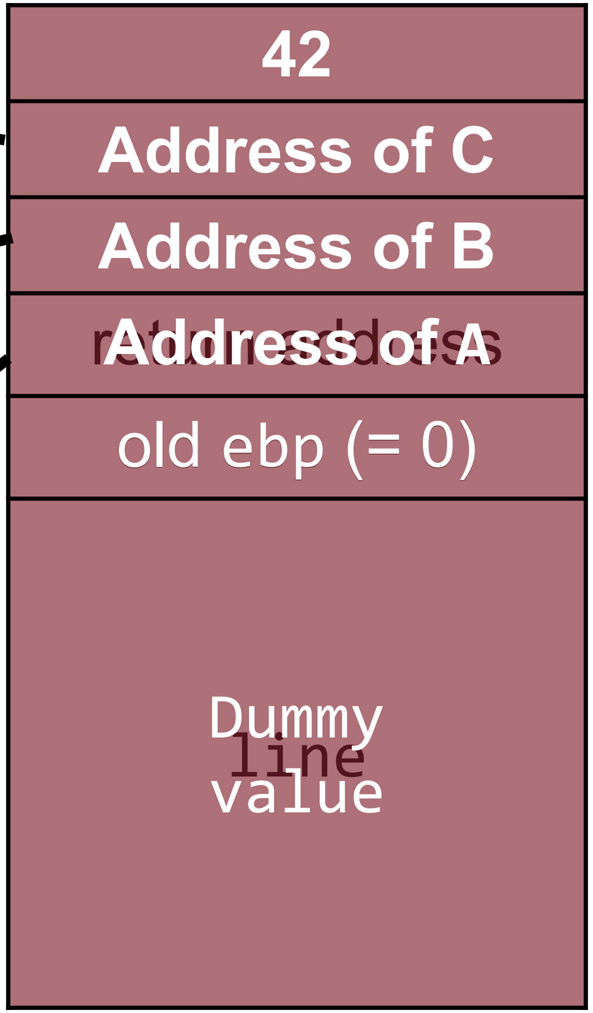
Attacker's goal:
execute following instructions

```
add eax, ebx
mov ecx, eax
inc ecx
mov edx, 42
```

C
```
inc ecx
pop edx
ret
```

B
```
mov ecx, eax
ret
```

A
```
add eax, ebx
ret
```



Return (ret) Chaining

Attacker's goal:

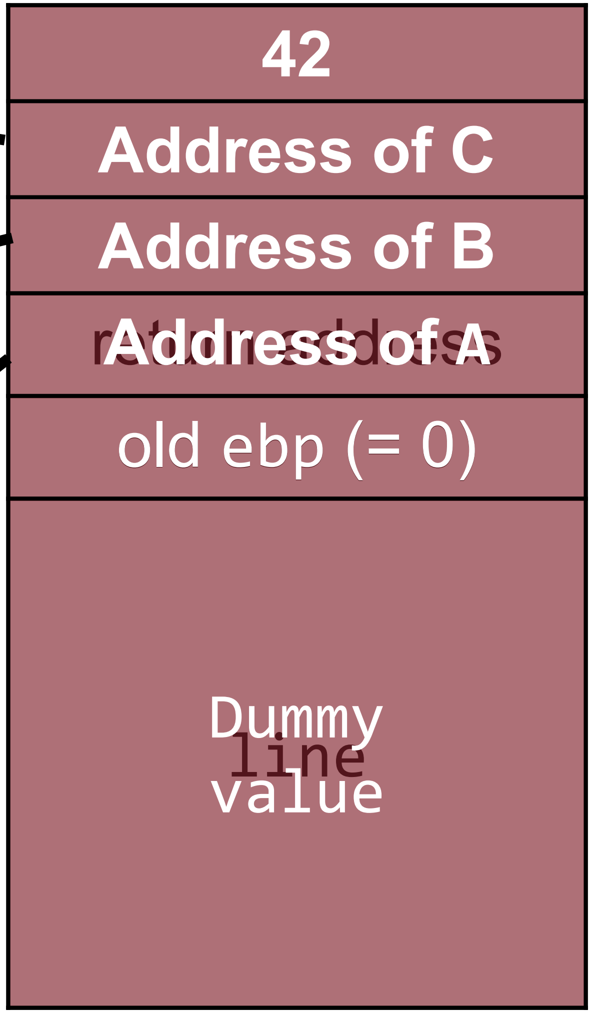
execute following instructions

```
add eax, ebx
mov ecx, eax
inc ecx
mov edx, 42
```

C
```
inc ecx
pop edx
ret
```

B
```
mov ecx, eax
ret
```

A
```
add eax, ebx
ret
```



Return (ret) Chaining

Attacker's goal:
execute following instructions

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add eax, ebx
mov ecx, eax
inc ecx
mov edx, 42
```
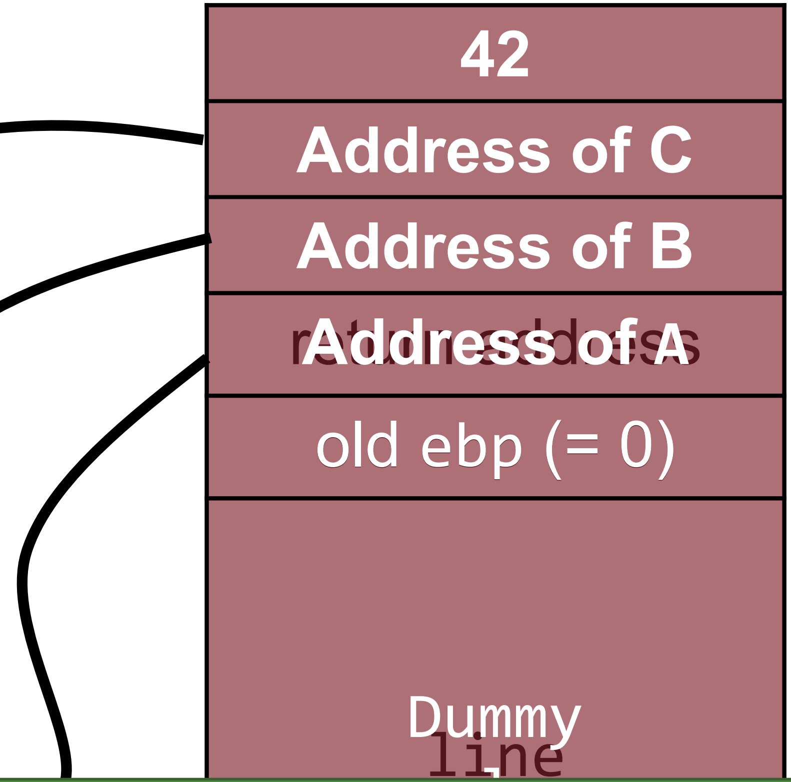

C

```
inc ecx
pop edx
ret
```

B

```
mov ecx, eax
ret
```



Return chaining with ROP gadgets
allows **arbitrary computation!**

ROP Practice

Goal: Modify `ptr` to be `0x42424242` with ROP

```
mov [ptr], 0x42424242
```

Gadget **A**

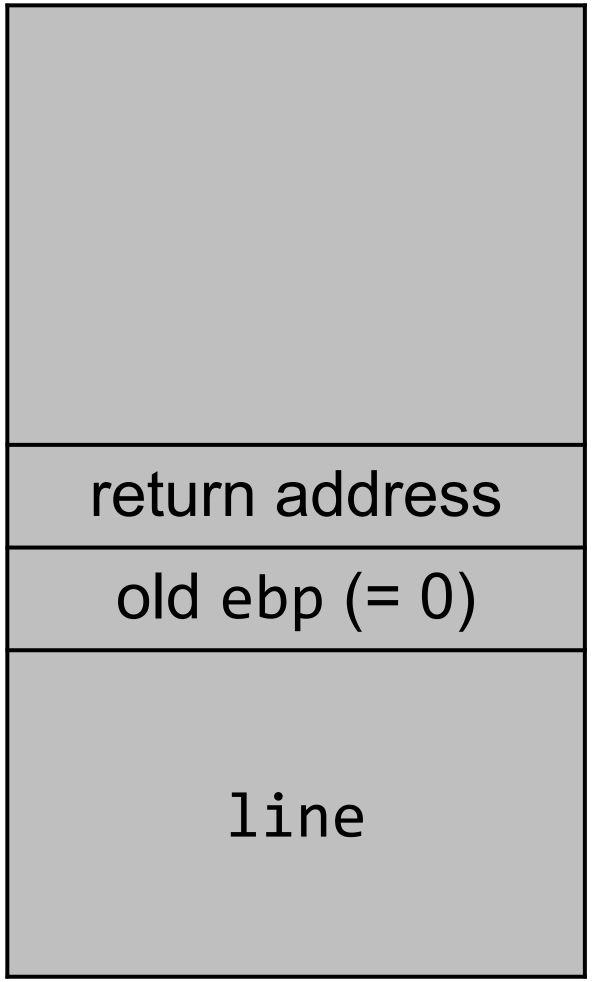
```
pop eax
ret
```

Gadget **B**

```
pop ebx
ret
```

Gadget **C**

```
mov [eax], ebx
ret
```



ROP Workflow

1. Disassemble binary

2. Identify useful instruction sequences (i.e., gadgets)
   - E.g., an instruction sequence that ends with `ret` is useful
   - E.g., an instruction sequence that ends with `jmp reg` can be useful (`pop eax; jmp eax`)

3. Assemble gadgets to perform some computation
   - E.g., spawning a shell

Challenge: Gathering as **many gadgets** as possible

Many Gadgets in Regular Binaries?

x86 instructions have their lengths ranging from 1 byte to 18 bytes, i.e., it uses ***variable-length encoding***

x86 instructions have variable lengths

```
08048aac <main>:
 8048aac:       8d 4c 24 04             lea    ecx,[esp+0x4]
 8048ab0:       83 e4 f0                and    esp,0xfffffff0
 8048ab3:       ff 71 fc                push   DWORD PTR [ecx-0x4]
 8048ab6:       55                      push   ebp
 8048ab7:       89 e5                   mov    ebp,esp
 8048ab9:       51                      push   ecx
 8048aba:       83 ec 14                sub    esp,0x14
 8048abd:       c7 45 f0 88 ad 0a 08    mov    DWORD PTR [ebp-0x10],0x80aad88
 8048ac4:       c7 45 f4 00 00 00 00    mov    DWORD PTR [ebp-0xc],0x0
 8048acb:       83 ec 04                sub    esp,0x4
 8048ace:       6a 00                   push   0x0
 8048ad0:       8d 45 f0                lea    eax,[ebp-0x10]
 8048ad3:       50                      push   eax
 8048ad4:       68 88 ad 0a 08          push   0x80aad88
 8048ad9:       e8 02 39 01 00          call   805c3e0 <__execve>
 ...
```

Many Gadgets in Regular Binaries?

x86 instructions have their lengths ranging from 1 byte to 18 bytes, i.e., it uses ***variable-length encoding***

Therefore, there can be both **intended** and **unintended gadgets** in x86 binaries

Disassembling x86

```
eip
↓
e8 05 ff ff ff            call 8048330
81 c3 59 12 00 00         add ebx,0x1259
```

What if we disassemble the code from the second byte (05)?

Unintended ret Insturction


```
   eip
    ↓
e8 05 ff ff ff              add eax, 0x81ffffff
81 c3 59 12 00 00           ret
```

Unintended ret Insturction

```
   eip
    ↓
e8 05 ff ff ff              add eax, 0x81ffffff
81 c3 59 12 00 00           ret
```

Unintended ret Insturction


```
   eip
    ↓
e8 05 ff ff ff              add eax, 0x81ffffff
81 c3 59 12 00 00           ret
```

Many Gadgets in Regular Binaries?

Also, program size may matter!

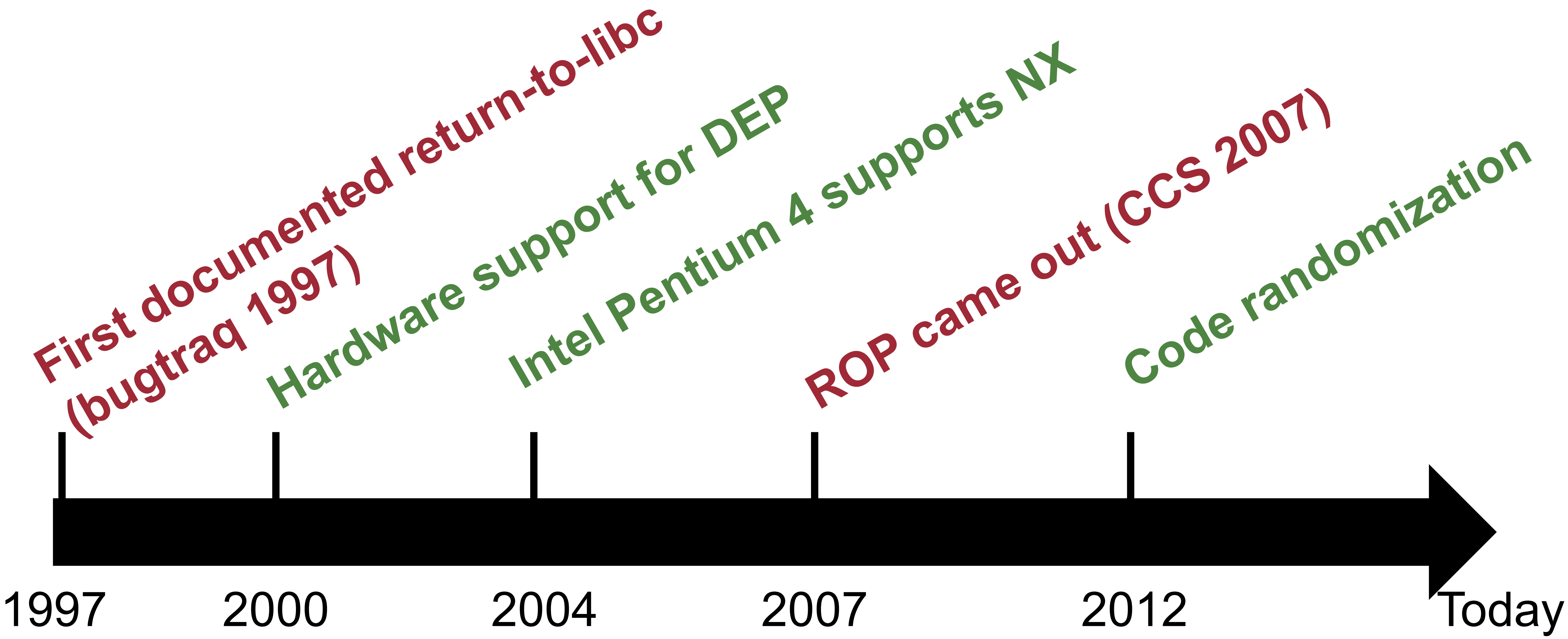
Larger code ⇒ More chance to get useful gadgets

Question

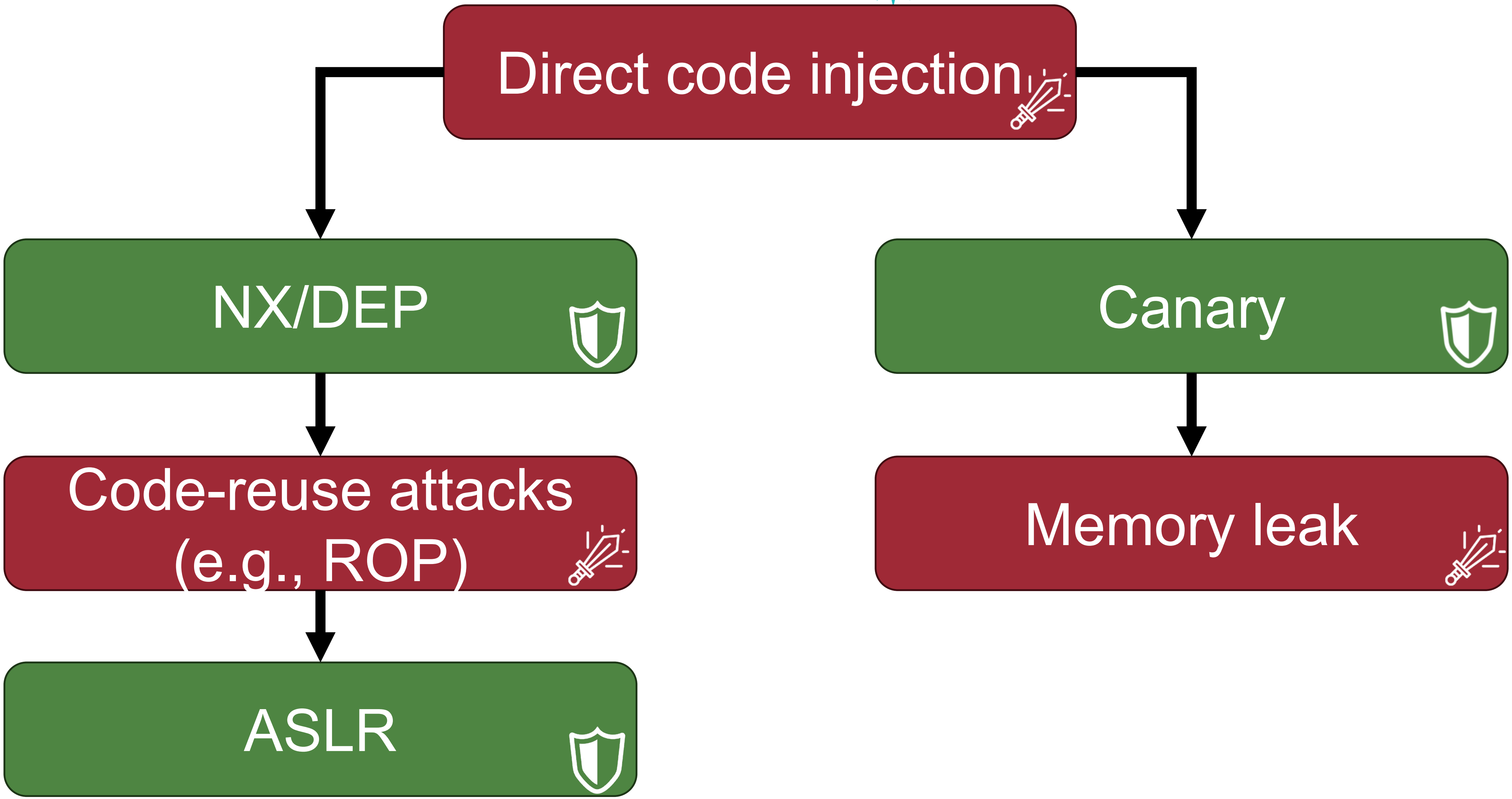
How can we mitigate code reuse attacks (ROP)?

Address randomization (ASLR)!
(next lecture)

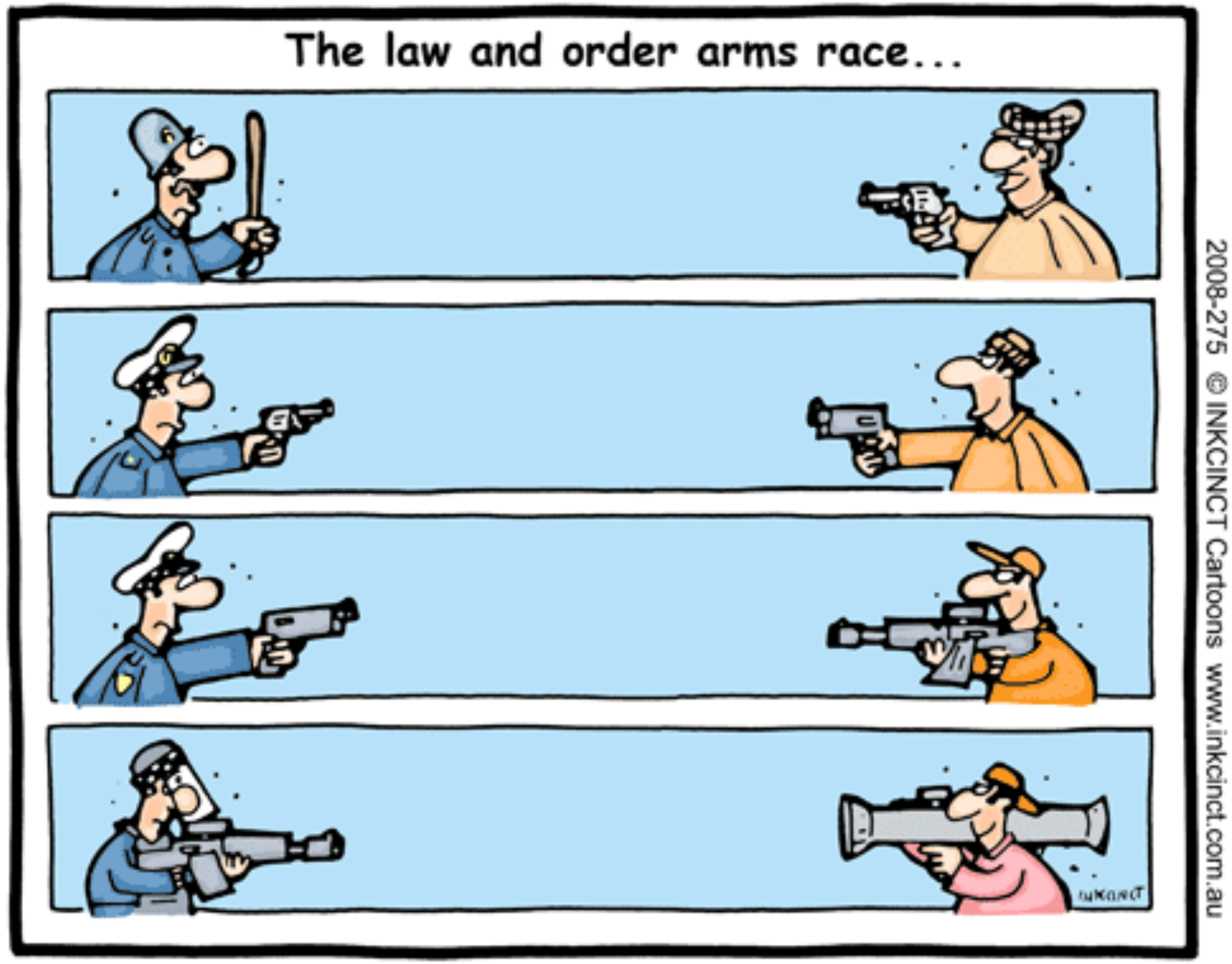
DEP and Code Reuse Attacks



Control Hijack Attack / Defense So Far



Arms Race in Security



Summary

- Two mitigation techniques against control flow hijacks
  - Stack canary
  - NX (or DEP)

- Code reuse attacks allow an attacker to bypass DEP
- Many mitigation techniques are proposed for code reuse attacks, which will be covered next.

Question?