ECE 382N-Sec (FA25):

L10: Memory Safety

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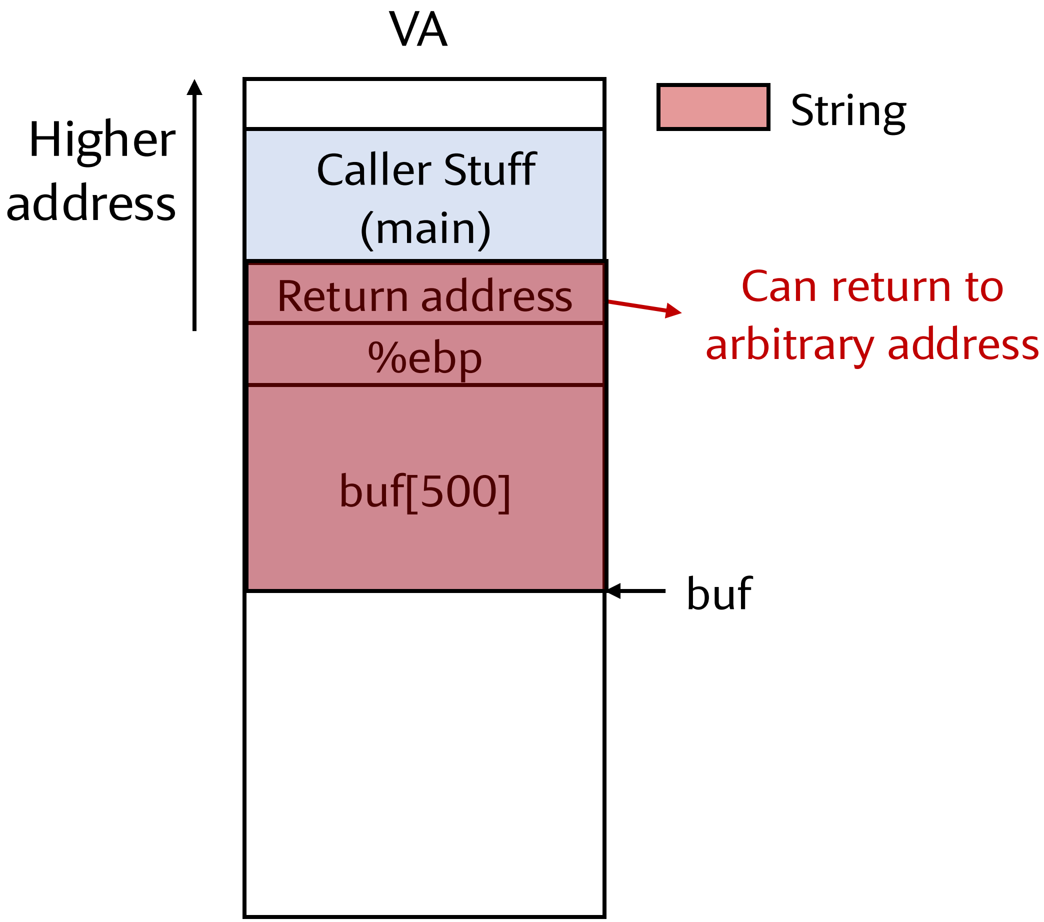
Buffer Overflow Attacks

https://www.youtube.com/watch?v=1S0aBV-Waeo




```
int main(int argc, char **argv) {
  char buf[500];

  strcpy(buf, argv[1]);
  return 0;
}
```

No bounds check

argv[1] is under the attacker's control:
Set argv[1] to "a long long string …"

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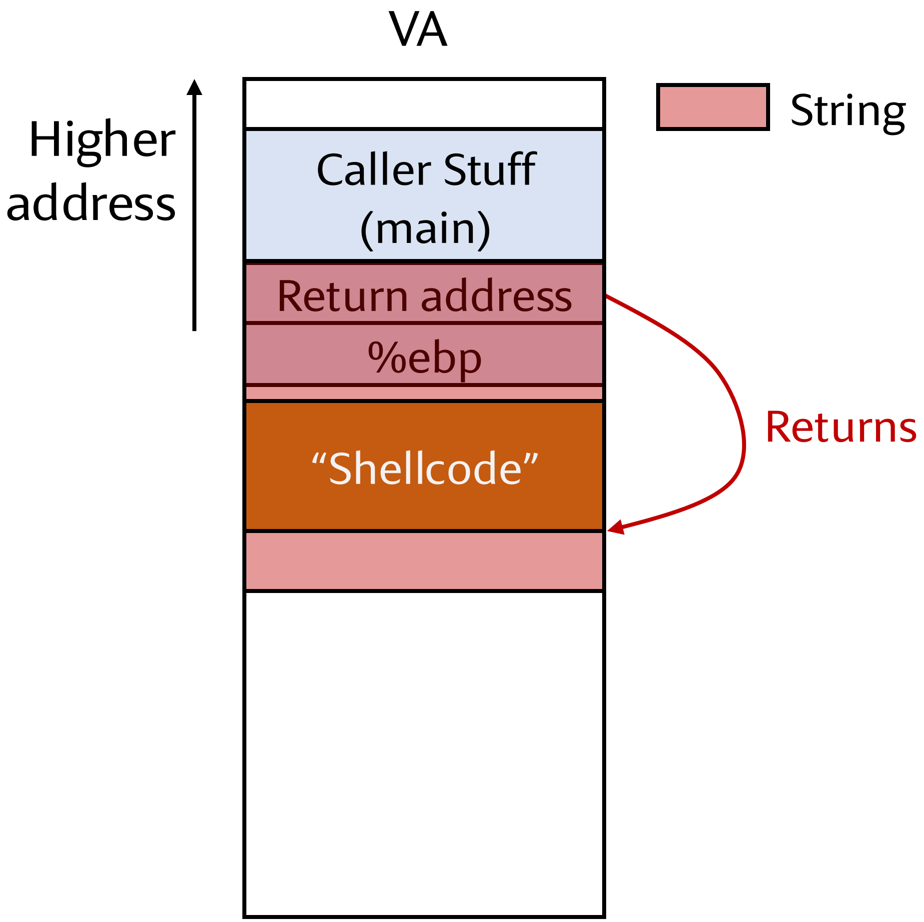


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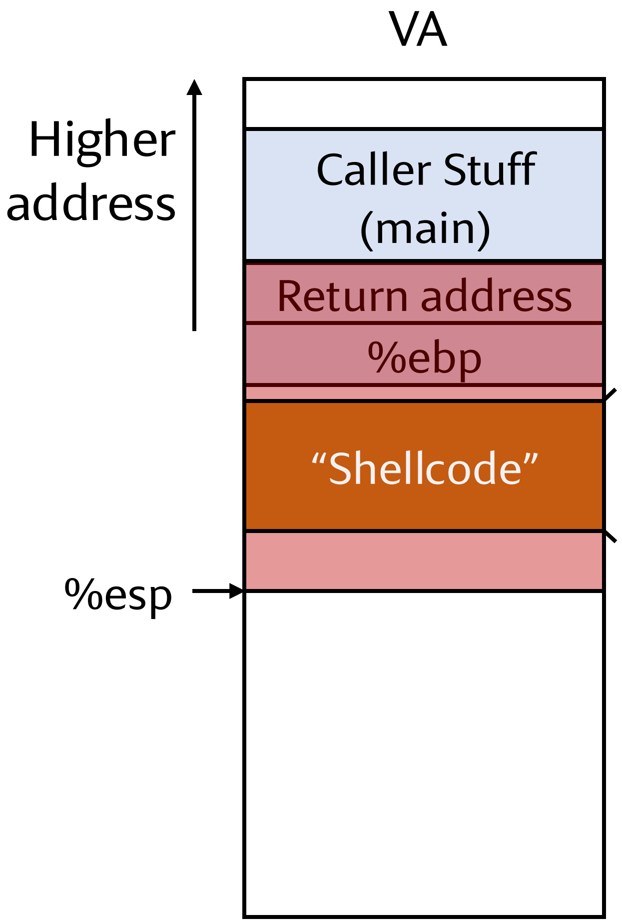
The Shell Code

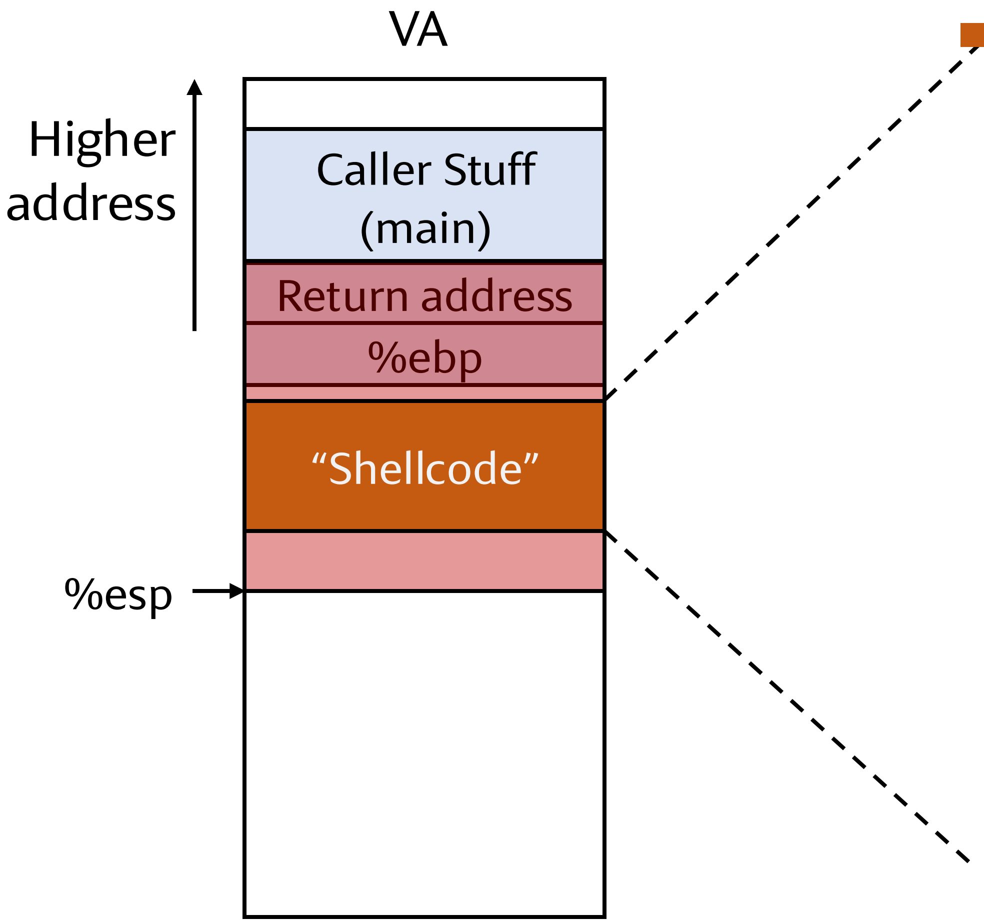



```
xor     eax,eax
sub     esp,0x1
mov     BYTE PTR [esp],al
push    0x68737a2f
push    0x6e69622f
push    0x7273752f
mov     esi,esp
push    eax
push    esi
mov     al,0xb
mov     ebx,esi
mov     ecx,esp
xor     edx,edx
int     0x80
mov     al,0x1
xor     ebx,ebx
int     0x80
```

```
Calling syscall 0xb (32-bit Linux):
execve(
  const char *pathname, // ebx
  char *const argv[],   // ecx
  char *const envp[]    // edx
)
```

```
Goal: execve(“/usr/bin/zsh”,
{“/usr/bin/zsh”, NULL}, NULL);
```

The Shell Code




```
xor     eax,eax                  // %eax = 0;
sub     esp,0x1
mov     BYTE PTR [esp],al
push    0x68737a2f
push    0x6e69622f
push    0x7273752f
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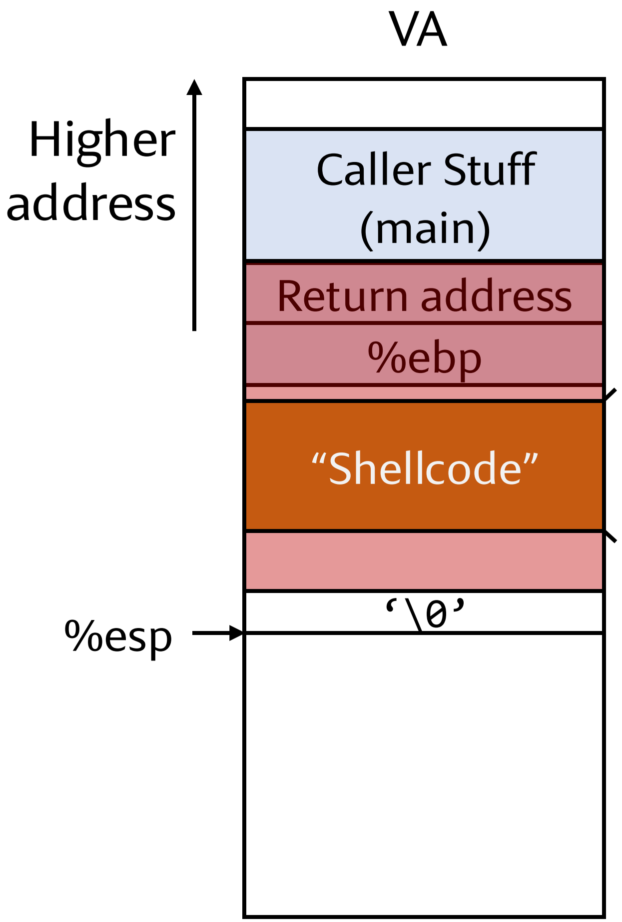


```
xor    eax,eax              // %eax = 0;
sub    esp,0x1
mov    BYTE PTR [esp],al    // Add the trailing ‘\0’
push   0x68737a2f
push   0x6e69622f
push   0x7273752f
mov    esi,esp
push   eax
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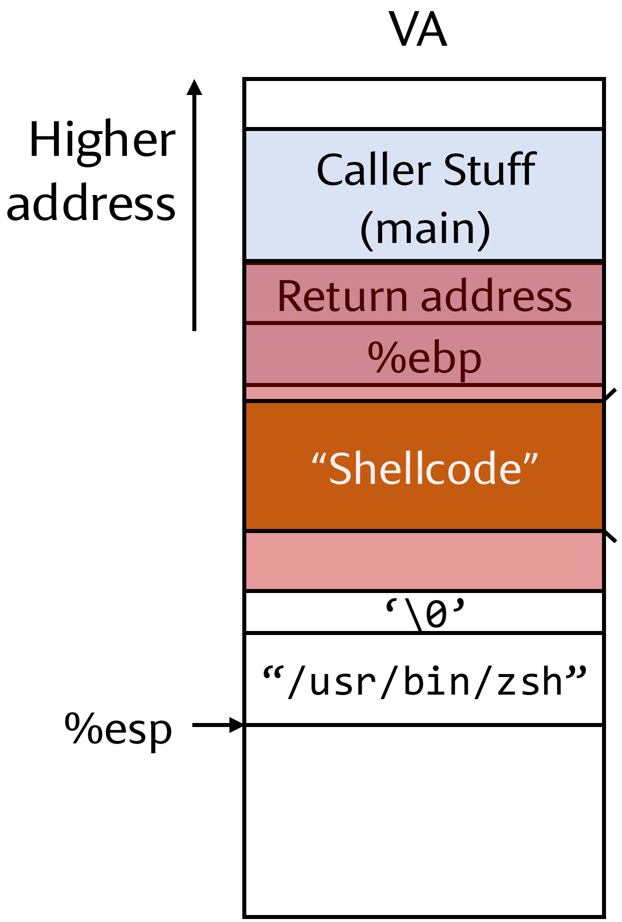


```
xor     eax,eax              // %eax = 0;
sub     esp,0x1
mov     BYTE PTR [esp],al    // Add the trailing ‘\0’
push    0x68737a2f           // “/zsh”
push    0x6e69622f           // “/bin”
push    0x7273752f           // “/usr”
mov     esi,esp
push    eax
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mov     al,0xb
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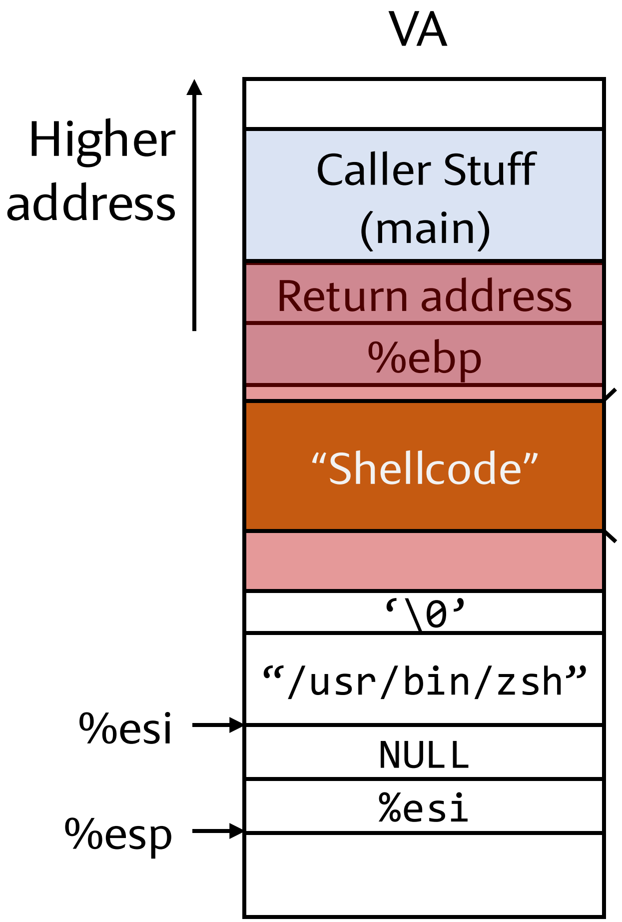
The Shell Code




```
xor     eax,eax                // %eax = 0;
sub     esp,0x1
mov     BYTE PTR [esp],al      // Add the trailing '\0'
push    0x68737a2f             // "/zsh"
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mov     esi,esp
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mov     ecx,esp
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int     0x80
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int     0x80
```

Calling syscall 0xb:

```
execve(
  const char *pathname, // ebx
  char *const argv[],   // ecx
  char *const envp[]    // edx
)

execve(
  "/usr/bin/zsh",             // ebx
  {"/usr/bin/zsh", NULL},     // ecx
  NULL                        // edx
)
```

The setuid Bit and the sudoedit Vulnerability (CVE-2021-3156)

setuid: Allows users to run a program with the privileges of the program's owner

```
neilz@meyer-lemon:~$ cat /etc/shadow
cat: /etc/shadow: Permission denied
neilz@meyer-lemon:~$ ls -l /etc/shadow
-rw-r----- 1 root shadow 1632 Oct  9 11:13 /etc/shadow
neilz@meyer-lemon:~$ ls -l $(which cat)
-rwxr-xr-x 1 root root 39384 Jun 22 11:21 /usr/bin/cat
neilz@meyer-lemon:~$ ls -l $(which passwd)
-rwsr-xr-x 1 root root 64152 May 30  2024 /usr/bin/passwd
```

The setuid Bit and the sudoedit Vulnerability (CVE-2021-3156)

setuid: Allows users to run a program with the privileges of the program's owner

CVE-2021-3156 Detail

Description

Buffer overflow!

Sudo before 1.9.5p2 contains an off-by-one error that can result in a heap-based buffer overflow, which allows privilege escalation to root via "sudoedit -s" and a command-line argument that ends with a single backslash character.

Metrics

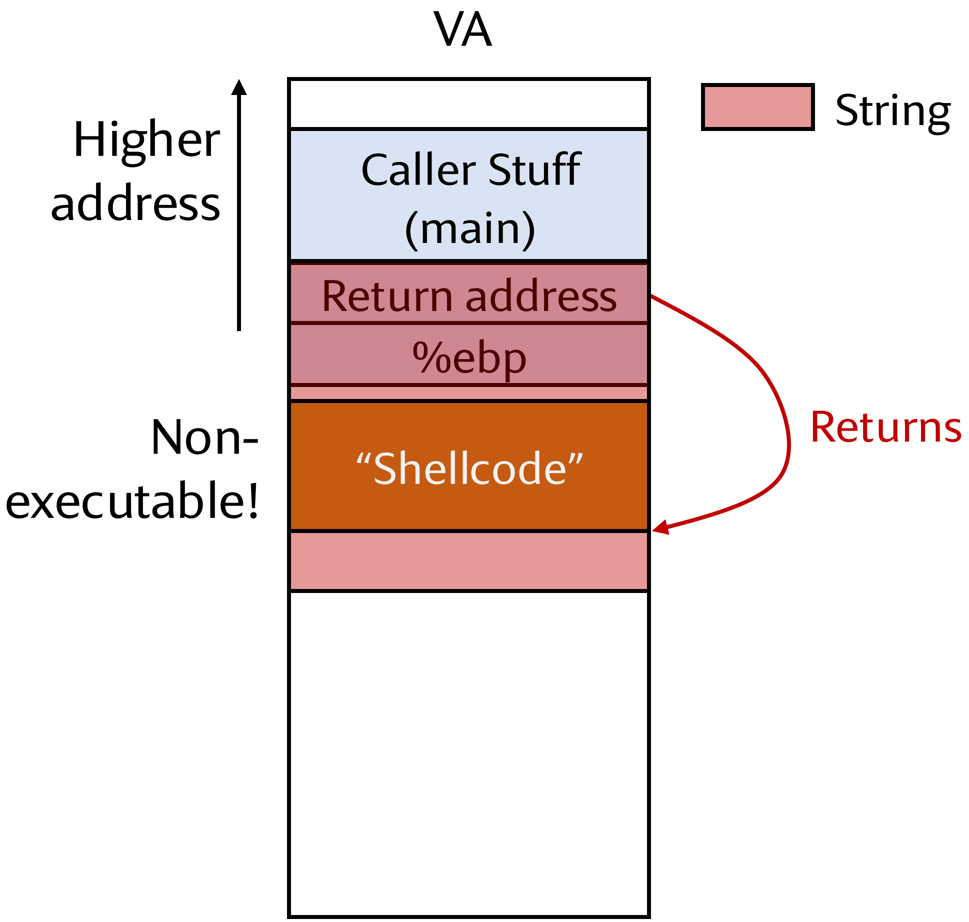
CVSS Version 4.0 | CVSS Version 3.x | CVSS Version 2.0

NVD enrichment efforts reference publicly available information to associate vector strings. CVSS information contributed by other sources is also displayed.

CVSS 3.x Severity and Vector Strings:

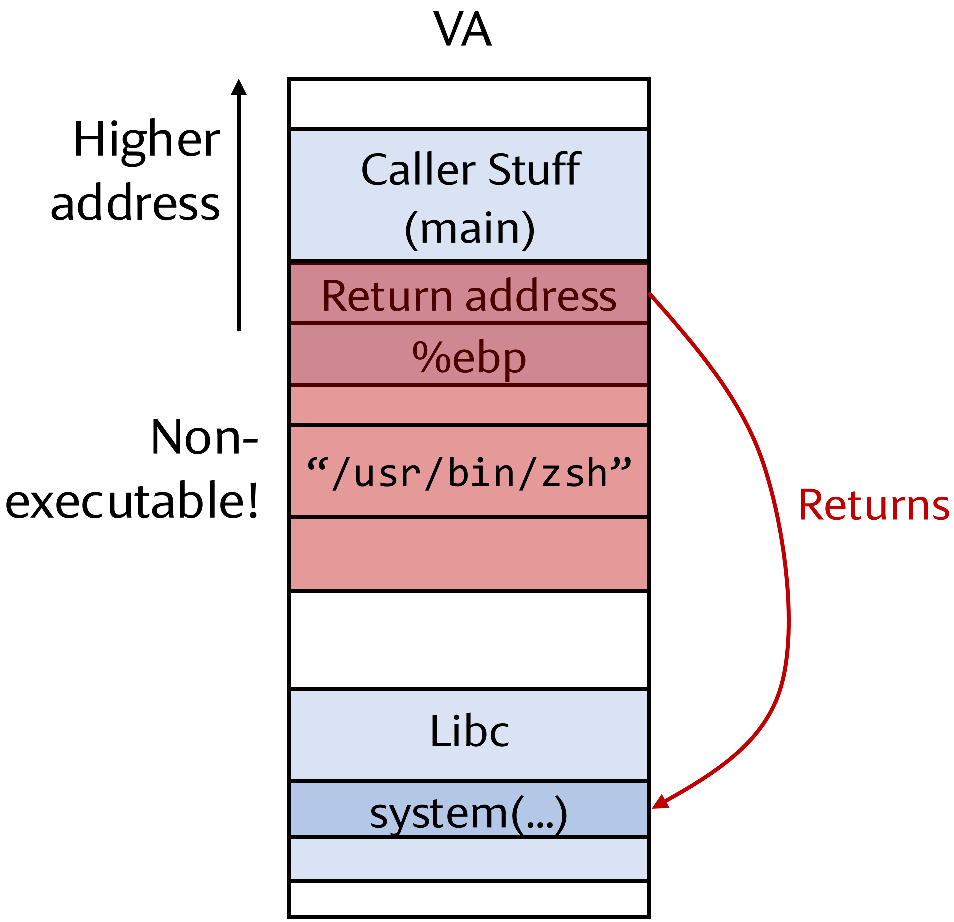
NIST: NVD	**Base Score:** 7.8 HIGH	**Vector:** CVSS:3.1/AV:L/AC:L/PR:L/UI:N/S:U/C:H/I:H/A:H
ADP: CISA-ADP	**Base Score:** 7.8 HIGH	**Vector:** CVSS:3.1/AV:L/AC:L/PR:L/UI:N/S:U/C:H/I:H/A:H

Mitigation 1: Data Execution Prevention (DEP)



Policy: a page is either writable or executable, but not both! (i.e., W⊕X)

Code-Reuse Attack: Return-to-Library



Libc "system" function: executes a shell command

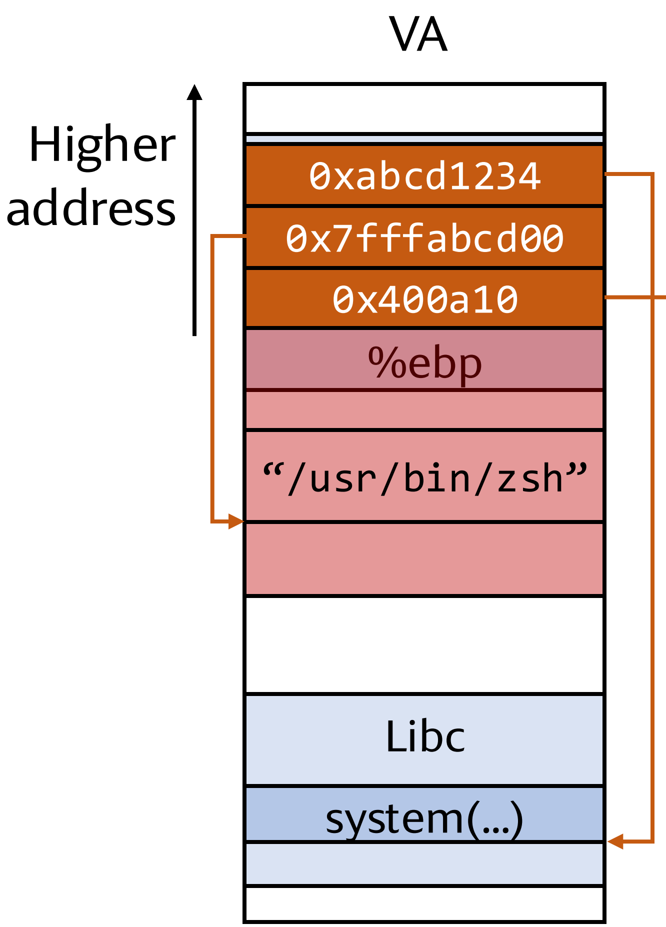
`int system(const char *command);`

Goal:

`system("/usr/bin/zsh");`

Problem: The first argument of the "system" function is passed through register %rdi, which is not under attacker's control

Code-Reuse Attack: Return-Oriented Programming (ROP)



Somewhere in the binary:

```
...
0x400a10: pop rdi;
0x400a11: ret;
```

“\x5f\xc3”

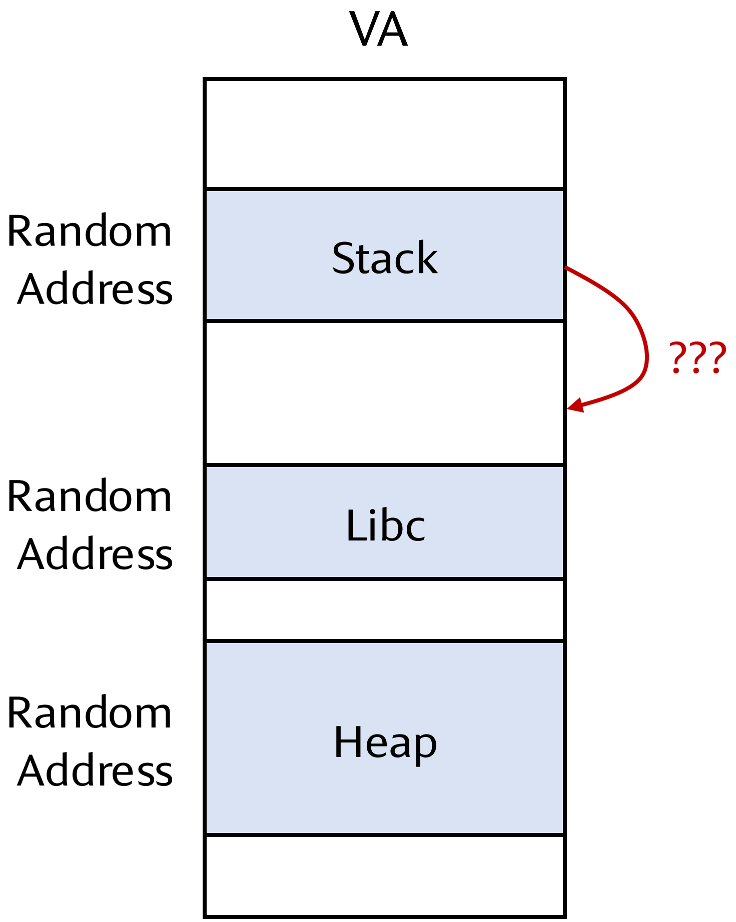
Exploiting variable-length, unaligned instruction.

Example:

```
0x400bf0: mov QWORD PTR [rdi-0x3d],rbx
```

“\x48\x89\x5f\xc3”

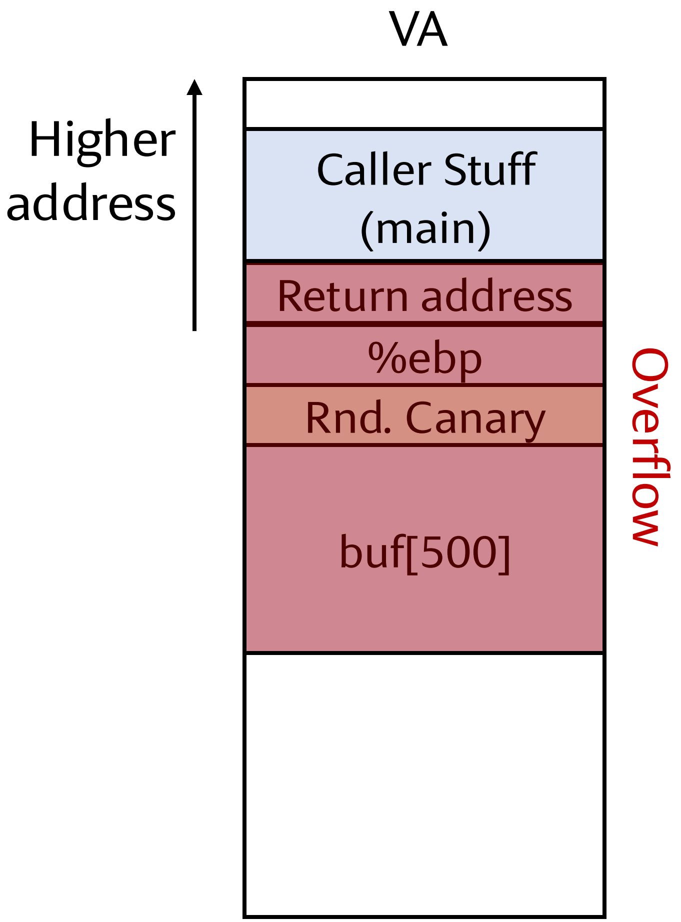
Mitigation 2: Address Space Layout Randomization



Approach: allocate the stack, heap, and libraries at a random address before each execution

Mitigation 3: Control-Flow Integrity (CFI)

Protecting returns: Stack canary

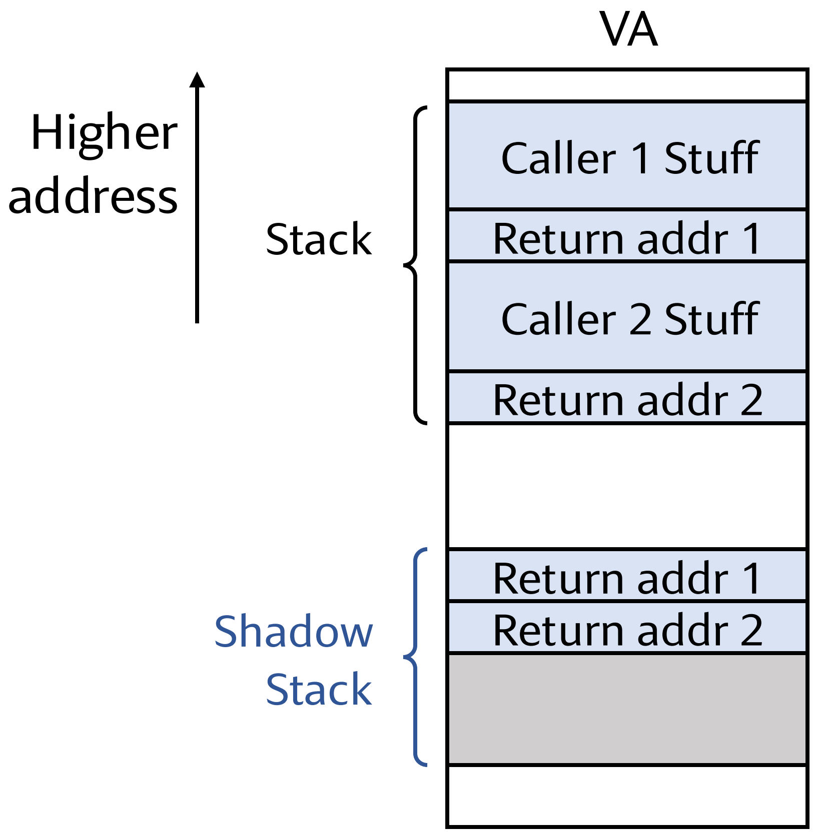


Approach: put a random (64-bit) canary value between the return address & %ebp and the current stack frame
⇒ Check if the canary is modified before returning

The canary is a global random constant for every process or thread

Mitigation 3: Control-Flow Integrity (CFI)

Hardware support: Intel Control-flow Enforcement Technology (CET)



- When executing a “call” instruction, the CPU saves a copy of the return address in a shadow stack
- The shadow stack is NOT writable by normal stores
- When the callee returns, the CPU pops the saved address from the shadow stack and compares it against the address popped from the stack
    - Mismatch ⇒ CPU raises a fault

What about indirect jumps/calls?

Mitigation 3: Control-Flow Integrity (CFI)

Hardware support: Intel Control-flow Enforcement Technology (CET)

Indirect Branch Tracking:

- New instruction “endbr”
  - 32-bit: endbr32
  - 64-bit: endbr64

- Indirect jumps and calls must land on an “endbr” instruction

Allowed

Blocked

```
-------- Function starts ---------
0x00001189      endbr64
0x0000118d      push rbp
0x0000118e      mov rbp, rsp
0x00001191      mov dword [var_4h], edi
0x00001194      mov eax, dword [var_4h]
0x00001197      add eax, 1
0x0000119a      pop rbp
0x0000119b      ret
```

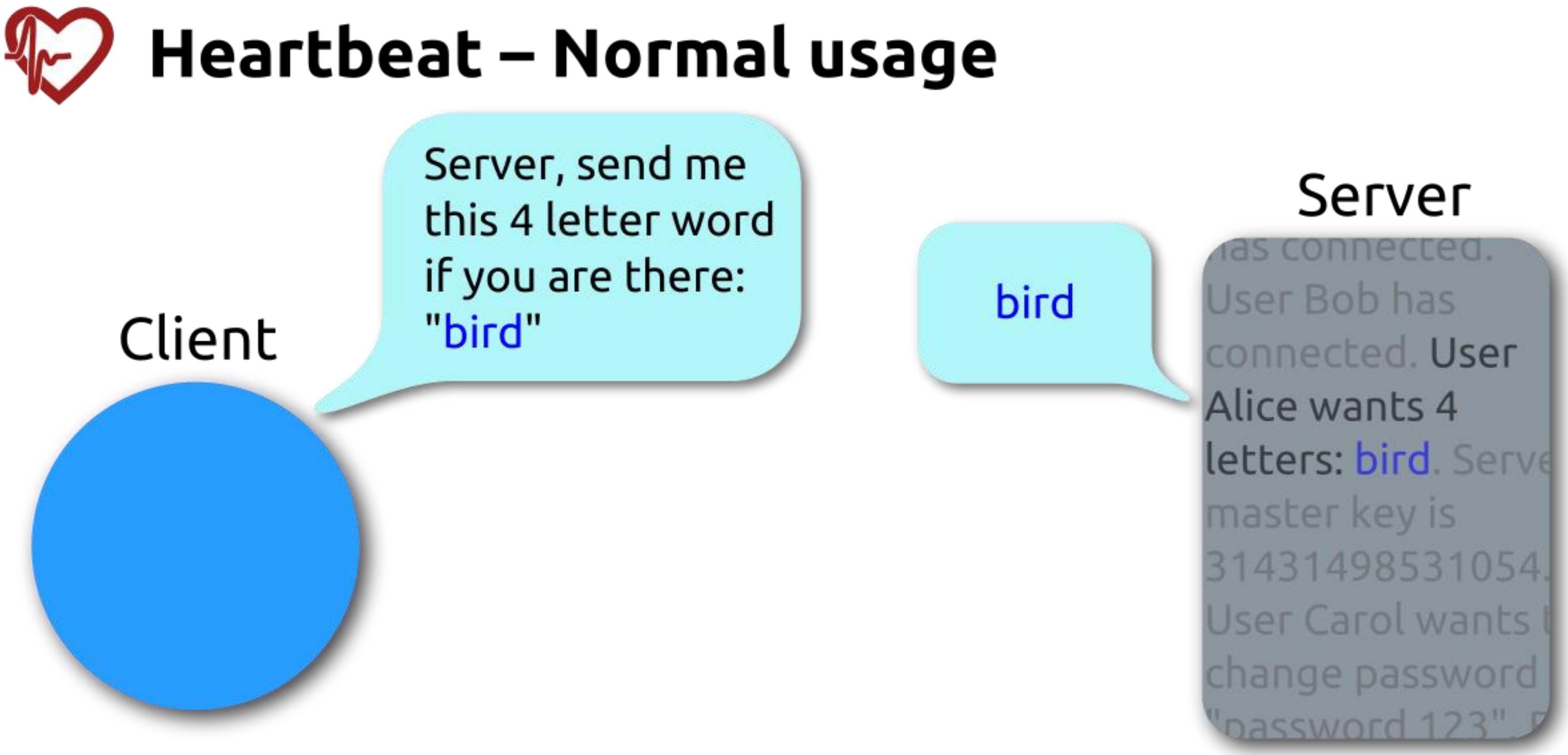
Spatial Memory Safety

De-referencing an out-of-bound pointer:

- Out-of-bound writes → Buffer overflow
    - Compromise program integrity

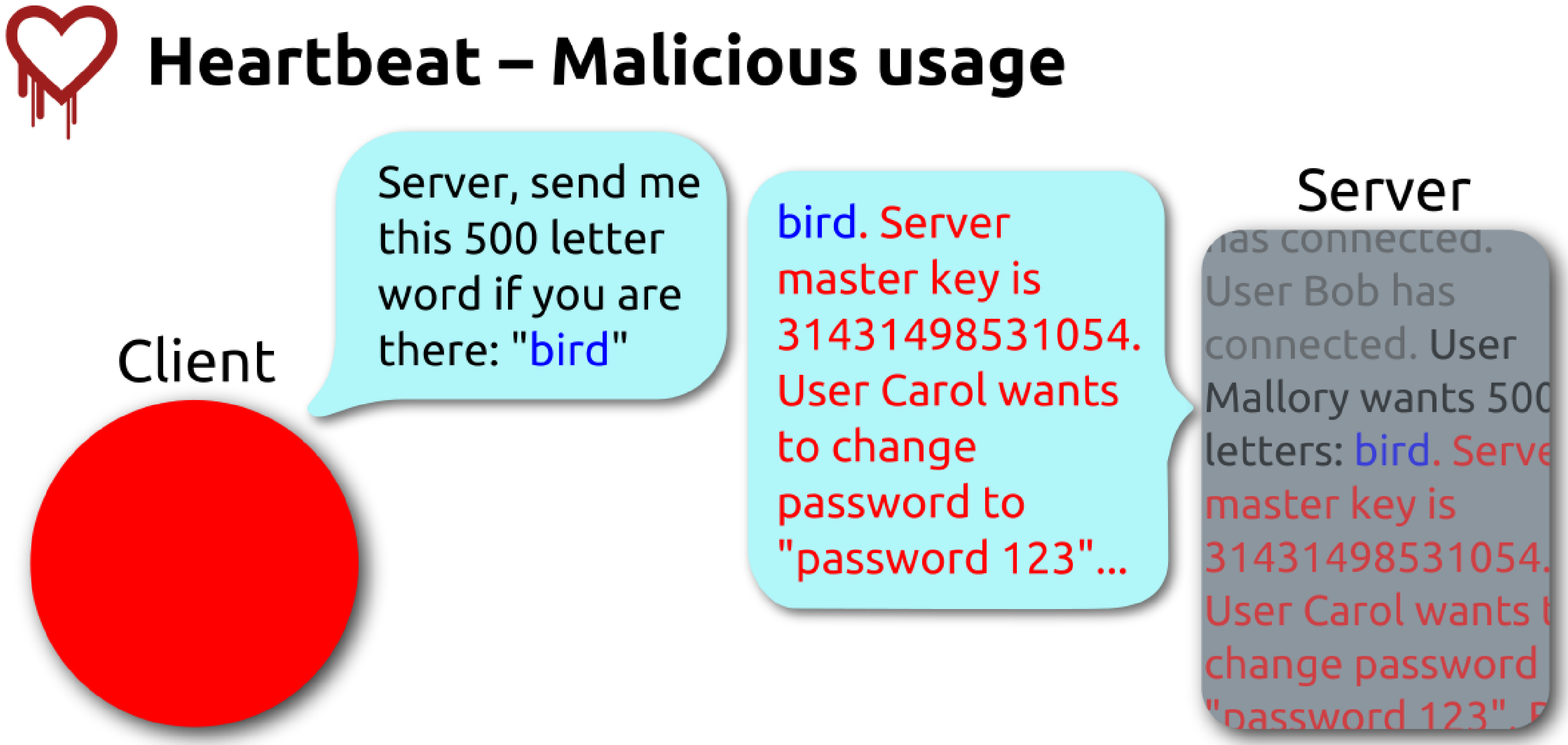
- Out-of-bound reads → Buffer over-read
    - Information leakage. Can lead to integrity attack
        - E.g., leaking the stack canary
    - Another high-profile example: Heartbleed

Heartbleed (CVE-2014-0160)



*https://en.wikipedia.org/wiki/Heartbleed#/media/File:Simplified_Heartbleed_explanation.svg

Heartbleed (CVE-2014-0160)



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Temporal Memory Safety - Use-after-Free

De-referencing a dangling pointer that points to a deleted object

```c
typedef struct {
    int id;
    char[60] secret;
} Obj; // 64B

char *buf = malloc(64);
// ...
free(buf);

Obj *obj = malloc(sizeof(Obj));

printf(“%s\n”, &buf[4]);
```

```c
typedef void (*myfunc)();
typedef struct {
    int id;
    myfunc *func;
} Obj; // 16B

char *buf = malloc(16);
// ...
free(buf);

Obj *obj = malloc(sizeof(Obj));

buf[…] = …;
obj->func(); // compromised!
```

Temporal Memory Safety – Double-Free

The only thing worse than double-free is double-dipping!

```
char *a = malloc(10); // 0x5683fe74e6b0
char *b = malloc(10); // 0x5683fe74e6d0
char *c = malloc(10); // 0x5683fe74e6f0

free(a);
free(b);
free(a);

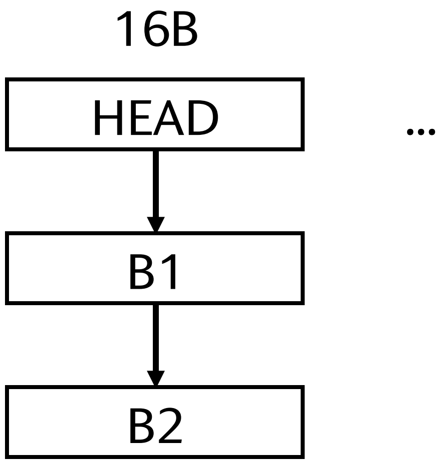
char *d = malloc(10); // 0x5683fe74e6b0
char *e = malloc(10); // 0x5683fe74e6d0
char *f = malloc(10); // 0x5683fe74e6b0
```

But why? Is malloc really that lazy?

*Requires tcache disabled on modern glic

Fastbins

A small software cache for holding recently freed small memory chunks



free(B2)

Fastbins

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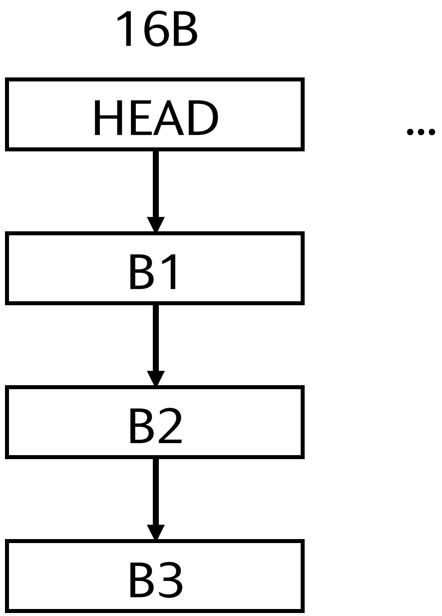

free(B3)

Fastbins

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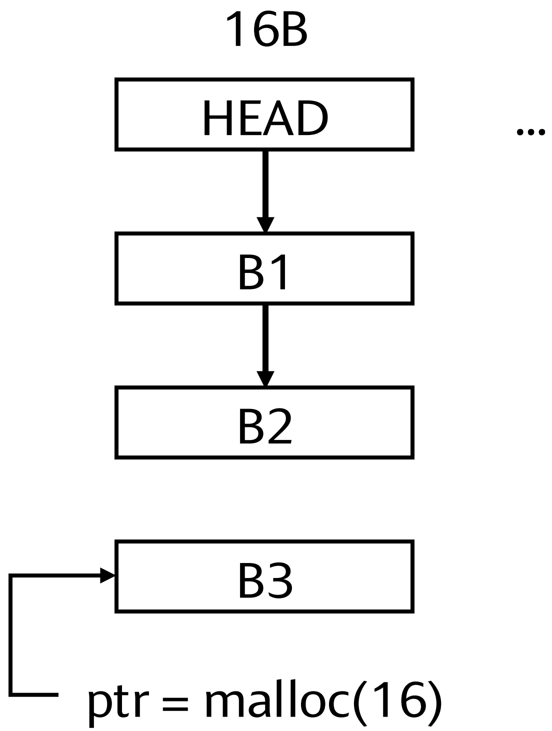

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free(a);
free(b);
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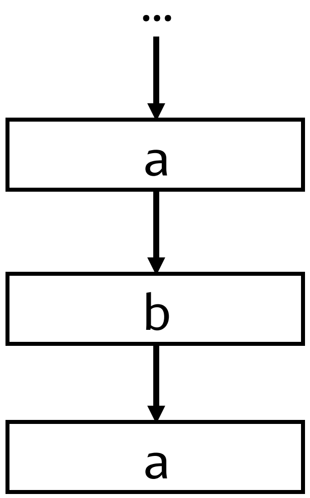
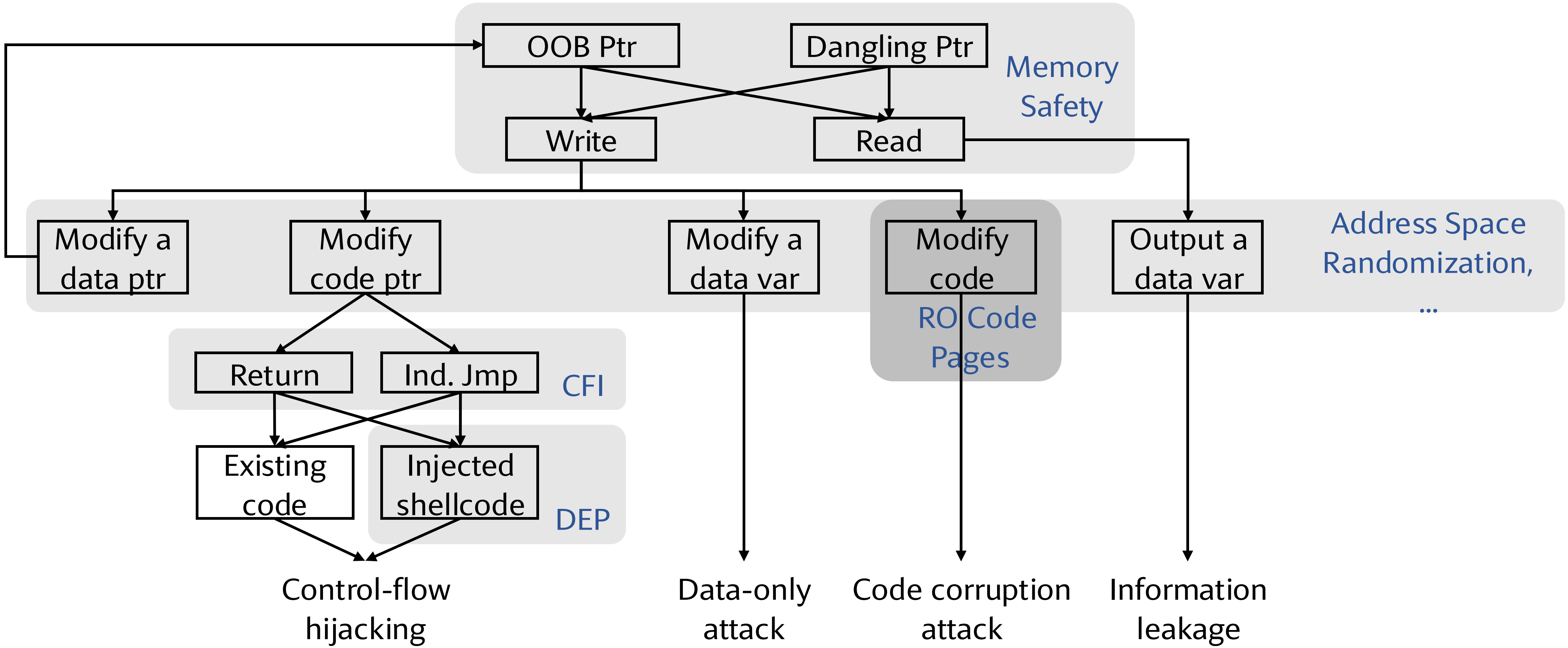
```



*Requires tcache disabled on modern glic

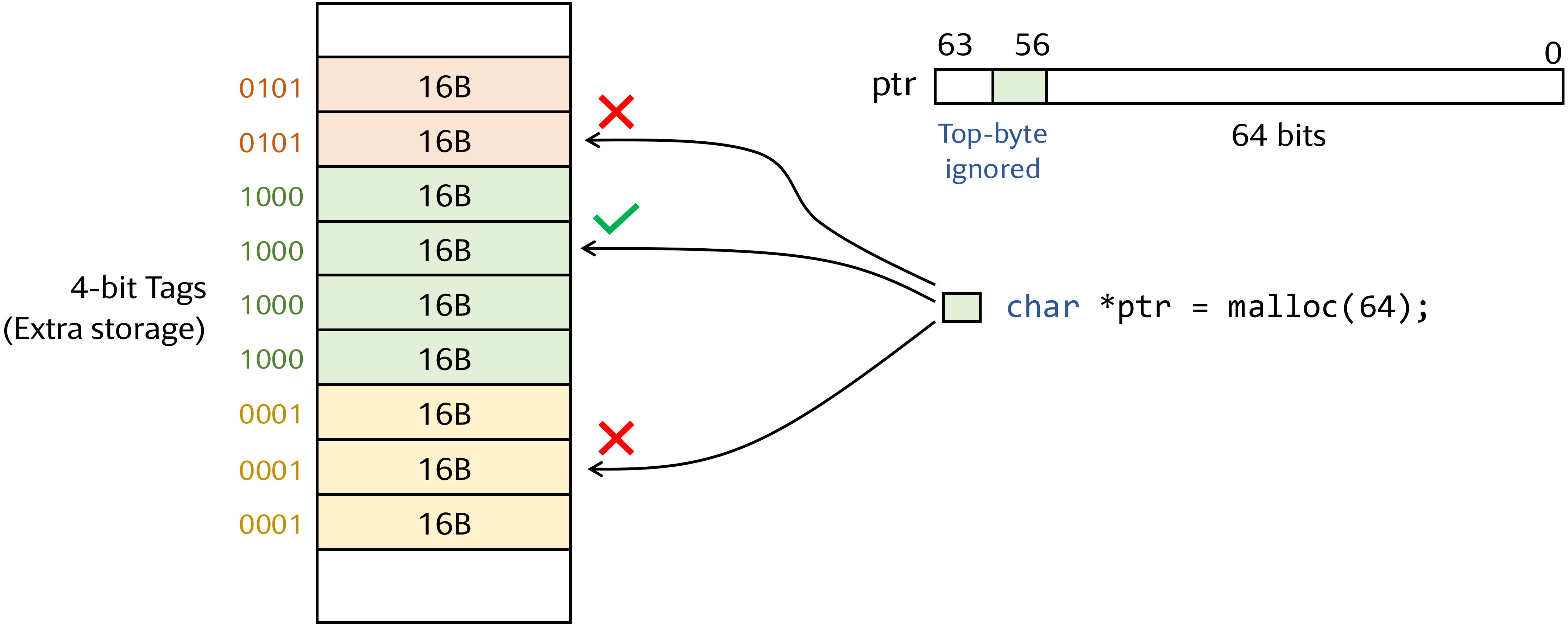
Adapted from “SoK: Eternal War in Memory”[1] (Simplified[2])



[1]Szekeres et al., “SoK: Eternal War in Memory,” SP ’13
[2]Only a subset of defenses are listed. Some adaptations are made.

Memory Safety Technique – Memory Tag Extension (MTE)

Both memory blocks and pointers are tagged



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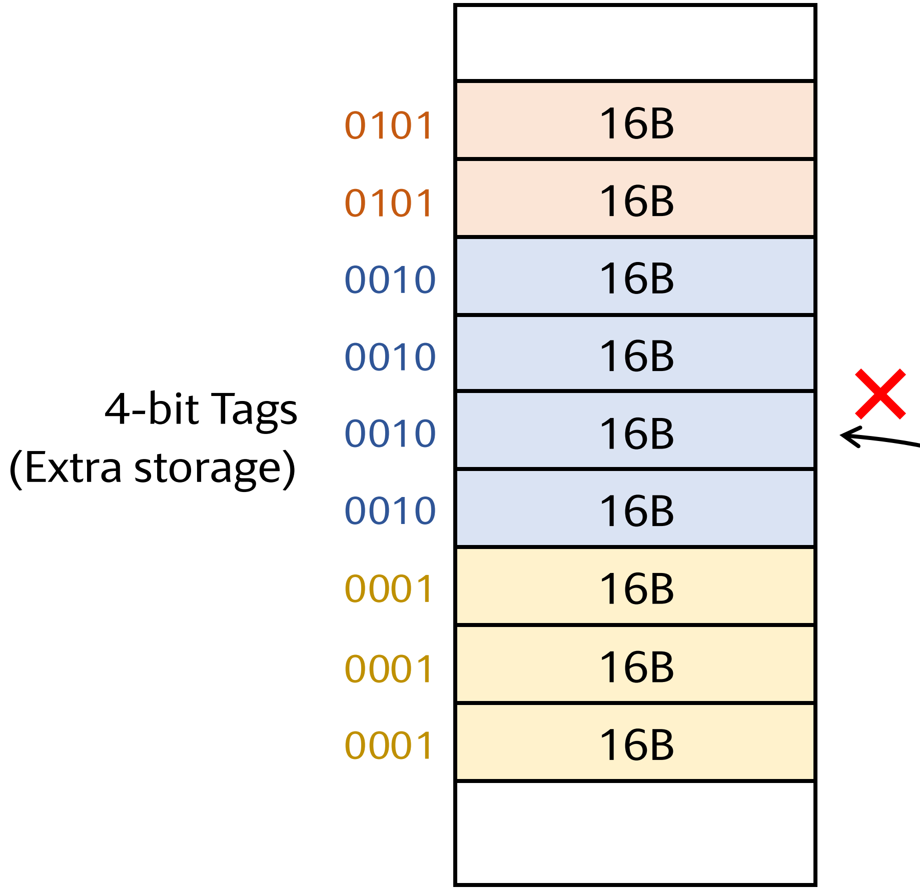

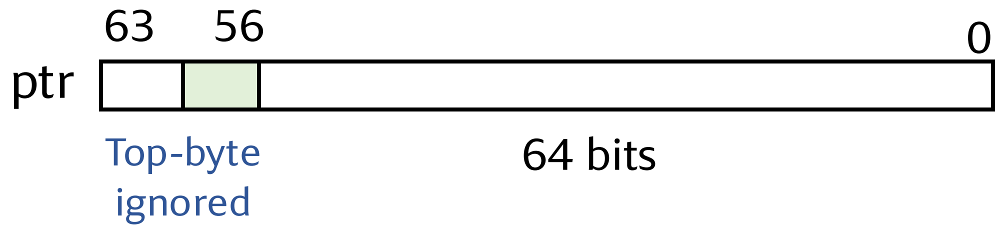


```
char *ptr = malloc(64);
...
free(ptr); // re-color
...
*ptr;
```