CSE 127: Computer Security

WI24

Lecture 4 - Buffer Overflow Attacks and Defenses

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Announcements

Assignment 1 Due Tonight
Assignment 2 Released

Reminder:
Lecture - Canvas
Discussion - Canvas
OH info - google calendar (link on Canvas)
Slides - Canvas, Community Notes, Website
Assignments - Website, Canvas,
Gradescope (Submission)

Practice Question

As a new intern at ABC Inc, Alice erroneously performed the below into a memory for an array with 3 elements. What kind of vulnerability is this?

```
Int main () {
Char s[3];
Strcpy (s, “welcome to my program”);
}
```

a. SQL Injection
b. Buffer Overflow
c. Cross Site Scripting
d. None of the above

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a. SQL Injection

b. Buffer Overflow

c. Cross Site Scripting

d. None of the above

What's wrong with this program?

```
void vulnerable(int len, char *data) {
    char buf[64];
    if (len > 64)
        return;
    memcpy(buf, data, len);
}
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    memcpy(buf, data, len);
}
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NAME memcpy - copy memory area

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

SYNOPSIS

```
#include <string.h>

void *memcpy(void *dest, const void *src, size_t
n);
```

DESCRIPTION The **memcpy**() function copies *n* bytes from memory area *src* to memory area *dest*. The memory areas must not overlap. Use memmove(3) if the memory areas do overlap.

RETURN VALUE The **memcpy**() function returns a pointer to *dest*.

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    memcpy(buf, data, len);
}
```

Why? -

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RETURN VALUE The **memcpy**() function returns a pointer to *dest*.

What's wrong with this program?

```
void vulnerable(int len = 0xffffffff, char *data) {
    char buf[64];
    if (len = -1> 64)
        return;
   memcpy(buf, data, len = 0xffffffff);
}
```

Let’s fix it

```
void safe(size_t len, char *data) {
    char buf[64];
    if (len > 64)
        return;
    memcpy(buf, data, len);
}
```

Is this program safe?

```
void f(size_t len, char *data) {
    char *buf = malloc(len+2);
    if (buf == NULL)
        return;
    memcpy(buf, data, len);
    buf[len] = '\n';
    buf[len+1] = '\0';
}
```

Is this program safe?

```
void f(size_t len = 0xffffffff, char *data) {
    char *buf = malloc(len+2 = 0x00000001);
    if (buf == NULL)
        return;
    memcpy(buf, data, len = 0xffffffff);
    buf[len] = '\n';
    buf[len+1] = '\0';
}
```

No!

Three flavors of integer overflows

- Truncation bugs
  - e.g. assigning an int64_t into int32_t
- Arithmetic overflow bugs
  - e.g. adding huge unsigned numbers
- Sign bugs
  - e.g. treating signed number as unsigned

Still relevant classes of bugs

Issue 952406: Security: Possible OOB related to chrome_sqlite3_malloc
Reported by mlfbr...@stanford.edu on Fri, Apr 12, 2019, 1:59 PM PDT

Code

VULNERABILITY DETAILS
Possible OOB with chrome_sqlite3_malloc

REPRODUCTION CASE
There's a pattern of using sqlite malloc functions that call chrome_sqlite3_malloc in combination with traditional memory operations (e.g., memcpy). There may be invariants that make this ok, or a principle here that I am not aware of. Thanks for your time.

chrome_sqlite3_malloc takes an int size argument, while memcpy takes a size_t size argument. On x86-64 this means that chrome_sqlite_3_malloc's size argument is width 32, while memcpy's is width 64. This can lead to potentially concerning wrapping behavior for extreme allocation sizes (depending on the compiler, optimizations, etc).

For example:

Function fts3UpdateDocTotals
(https://cs.chromium.org/chromium/src/third_party/sqlite/patched/ext/fts3/fts3_write.c?type=cs&q=fts3UpdateDocTotals&g=0&l=3399)

(1) a = sqlite3_malloc((sizeof(u32)+10)*nStat);
(https://cs.chromium.org/chromium/src/third_party/sqlite/patched/ext/fts3/fts3_write.c?type=cs&q=fts3UpdateDocTotals&g=0&l=3416)
...
(2) memset(a, 0, sizeof(u32)*(nStat));
(https://cs.chromium.org/chromium/src/third_party/sqlite/patched/ext/fts3/fts3_write.c?type=cs&q=fts3UpdateDocTotals&g=0&l=3434)

Depending on optimization level etc, this may turn into:

(1)
size = mul i32 nstat 14
chrome_sqlite3_malloc(size)

(2)
tmp = sign extend nstat to i64
size = shl tmp 2
memset(size)

If nstat is a very large i32, the multiplication in step (1) *may* wrap. Nothing in (2) will wrap because of the sign extend, leading to an OOB.

Mitigating buffer overflows

Lecture objectives:

- Understand how to mitigate buffer overflow attacks
- Understand the tradeoffs of different mitigations
- Understand how mitigations can be bypassed.

Can we just avoid writing C code that has buffer overflow bugs?

Yes! Avoid unsafe functions!

strcpy, strcat, gets, etc.

(strncpy, strncat, fgets)

This is a good idea in general…

Yes! Avoid unsafe functions!

- strcpy, strcat, gets, etc.
- This is a good idea in general…
- But…
  - Requires manual code rewrite
  - Non-library functions may be vulnerable
    - e.g. user creates their own strcpy
  - No guarantee you found everything
  - Alternatives are also error-prone!

Yes! Avoid unsafe functions!

Even printf is tricky

If buf is under control of attacker, is

printf(buf) safe?

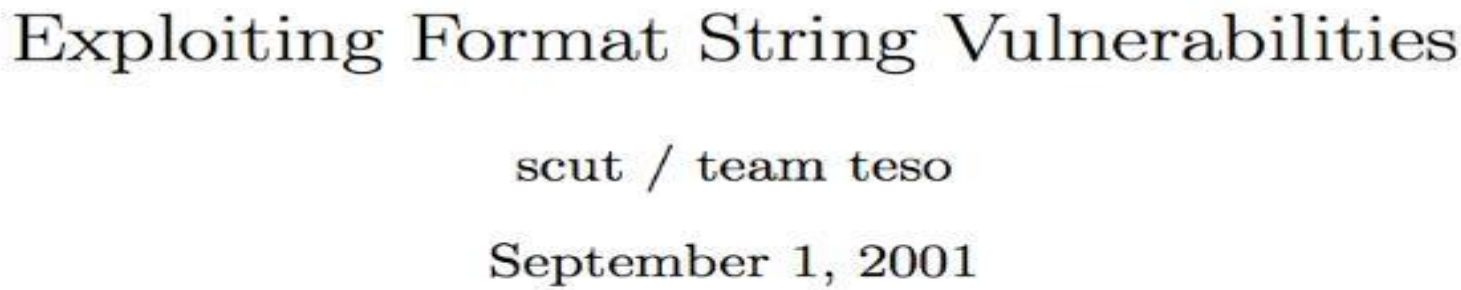
Yes! Avoid unsafe functions!

Even printf is tricky

If buf is under control of attacker, is printf(“%s\n”, buf) safe?

printf can be used to read and write memory

==⇒ control flow hijacking!



Exploiting Format String Vulnerabilities

scut / team teso

September 1, 2001

https://cs155.stanford.edu/papers/formatstring-1.2.pdf

If we can’t avoid writing buggy C code, Can we prevent or mitigate exploitation?

Buffer overflow mitigations

- Avoid unsafe functions

→ Stack canaries

- Separate control stack
- Memory writable or executable, not both (W^X)
- Address space layout randomization

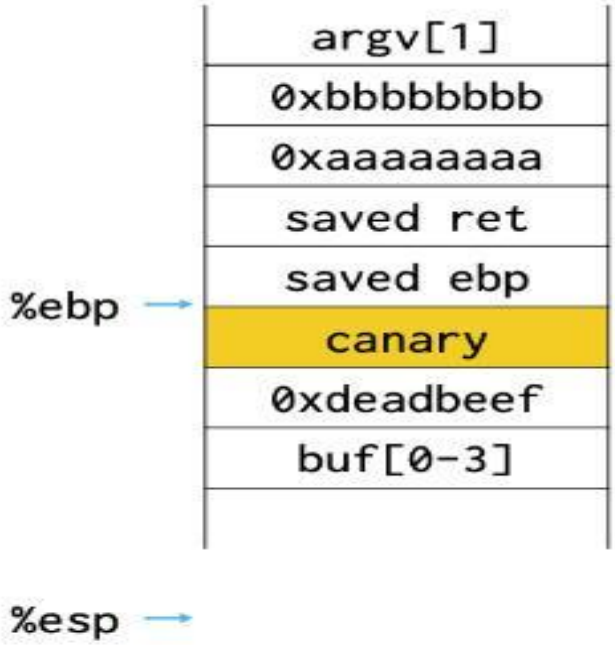
Canary in a Coal Mine

Stack canaries

- Prevent control flow hijacking by detecting overflows
- **Idea:**
  - Place canary between local variables and saved frame pointer and return address
  - Check canary before jumping to return address
- **Approach:**
  - Modify function prologues and epilogues

High-level example

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
void foo() {
    printf("hello all!!\n");
    exit(0);
}
void func(int a, int b, char *str) {
    int c = 0xdeadbeef;
    char buf[4];
    strcpy(buf,str);
}
int main(int argc, char**argv) {
    func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
    return 0;
}
```



Compiled without canaries

```
1   #include <stdio.h>
2   #include <stdlib.h>
3   #include <string.h>
4
5   void foo() {
6     printf("hello all!!\n");
7     exit(0);
8   }
9
10  void func(int a, int b, char *str) {
11    int c = 0xdeadbeef;
12    char buf[4];
13    strcpy(buf,str);
14  }
15
16  int main(int argc, char**argv) {
17    func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
18    return 0;
19  }
```

```
func(int, int, char*):
        pushl   %ebp
        movl    %esp, %ebp
        subl    $24, %esp
        movl    $-559038737, -12(%ebp)
        subl    $8, %esp
        pushl   16(%ebp)
        leal    -16(%ebp), %eax
        pushl   %eax
        call    strcpy
        addl    $16, %esp
        nop
        leave
        ret
```

Compiled with -fstack-protector-strong

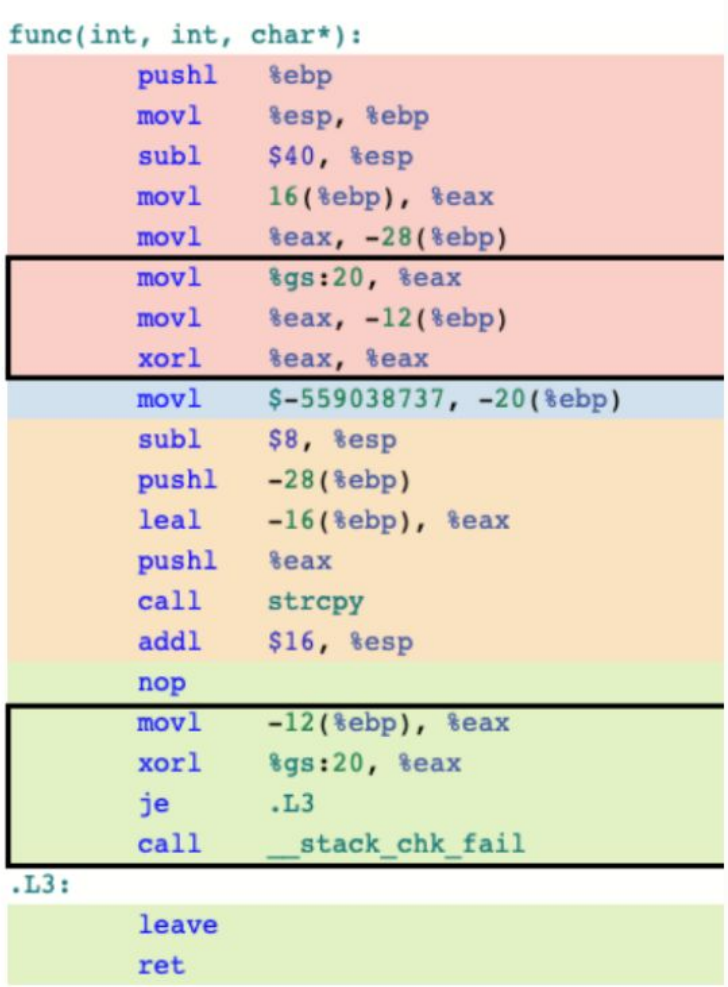
```
1   #include <stdio.h>
2   #include <stdlib.h>
3   #include <string.h>
4
5   void foo() {
6     printf("hello all!!\n");
7     exit(0);
8   }
9
10  void func(int a, int b, char *str) {
11    int c = 0xdeadbeef;
12    char buf[4];
13    strcpy(buf,str);
14  }
15
16  int main(int argc, char**argv) {
17    func(0xaaaaaaaa,0xbbbbbbbb,argv[1]);
18    return 0;
19  }
```

```
func(int, int, char*):
        pushl   %ebp
        movl    %esp, %ebp
        subl    $40, %esp
        movl    16(%ebp), %eax
        movl    %eax, -28(%ebp)
        movl    %gs:20, %eax
        movl    %eax, -12(%ebp)
        xorl    %eax, %eax
        movl    $-559038737, -20(%ebp)
        subl    $8, %esp
        pushl   -28(%ebp)
        leal    -16(%ebp), %eax
        pushl   %eax
        call    strcpy
        addl    $16, %esp
        nop
        movl    -12(%ebp), %eax
        xorl    %gs:20, %eax
        je      .L3
        call    __stack_chk_fail
.L3:
        leave
        ret
```

Compiled with -fstack-protector-strong

write canary from %gs:20 to stack -12(%ebp)

compare canary in %gs:20 to value on stack -12(%ebp)



Tradeoffs of stack canaries

- **Easy to deploy:** Can implement mitigation as compiler pass (i.e. don't need to change your code)
- **Performance:** Every protected function is more expensive

No stack protection

```
func(int, int, char*):
        pushl   %ebp
        movl    %esp, %ebp
        subl    $24, %esp
        movl    $-559038737, -12(%ebp)
        subl    $8, %esp
        pushl   16(%ebp)
        leal    -16(%ebp), %eax
        pushl   %eax
        call    strcpy
        addl    $16, %esp
        nop
        leave
        ret
```

-fstack-protector-strong

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.L3:
        leave
        ret
```

Can we defeat stack canaries?

- **Assumption:** Impossible to subvert control flow without corrupting the canary.

- Think outside the box

Can we defeat stack canaries?

- **Assumption:** Impossible to subvert control flow without corrupting the canary.
- Think outside the box
  - Overwrite function pointer elsewhere on the stack/heap
  - Pointer subterfuge
  - memcpy buffer overflow with fixed canary
  - Learn the canary

Review of Pointers

int x = 5;
Int y=0;

int *ip; (* is used to declare a pointer)

ip = &x; (& operator is to specify the address-of x, X is not a pointer)

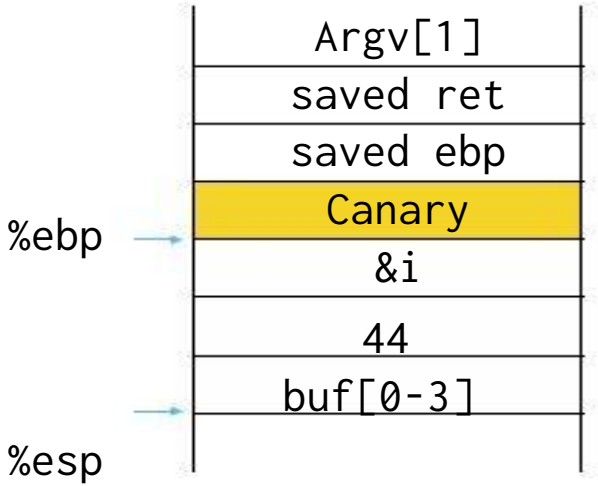
- At this point we have now told ip what address to point to

y=*ip (dereference)

- At this point we have set the variable y to the value at ip

i=42
*ptr = &i (address of i)

```
#include <string.h>
void foo() {
  printf("hello all!!\n");
  exit(0);
}
int i = 42;
void func(char *str) {
  int *ptr = &i;
  int val = 44;
  char buf[4];
  strcpy(buf,str);
} *ptr = val;
int main(int argc, char**argv) {
  func(argv[1]);
} return 0;
```



Pointer subterfuge

```
#include <stdio.h>
#include <string.h>
void foo() {
  printf("hello all!!\n");
  exit(0);
}

void func(char *str) {
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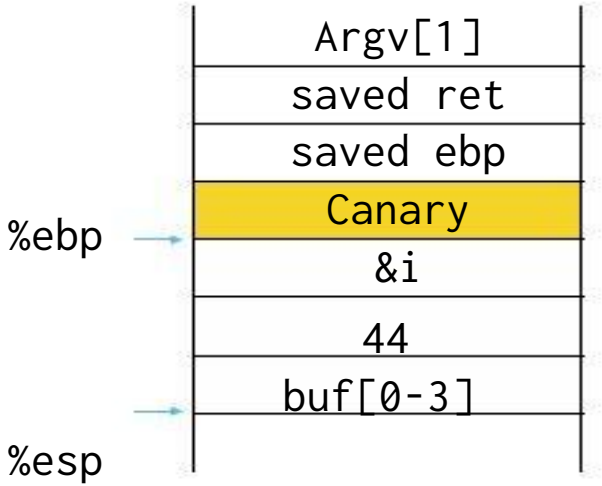

Pointer subterfuge

```
#include <stdio.h>
#include <string.h>
void foo() {
0x08049b95:   printf("hello all!!\n");
  exit(0);
}
int i = 42;
void func(char *str) {
  int *ptr = &i;
  int val = 44;
  char buf[4];
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  *ptr = val;
  }
int main(int argc, char**argv) {
  func(argv[1]);
  return 0;
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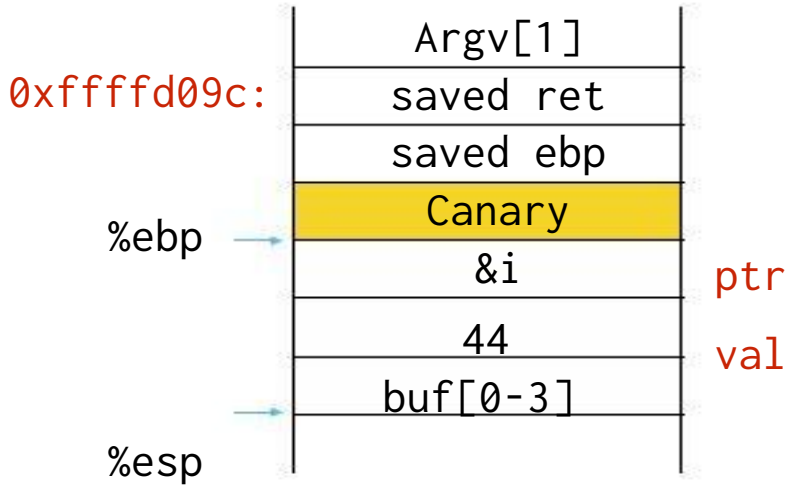

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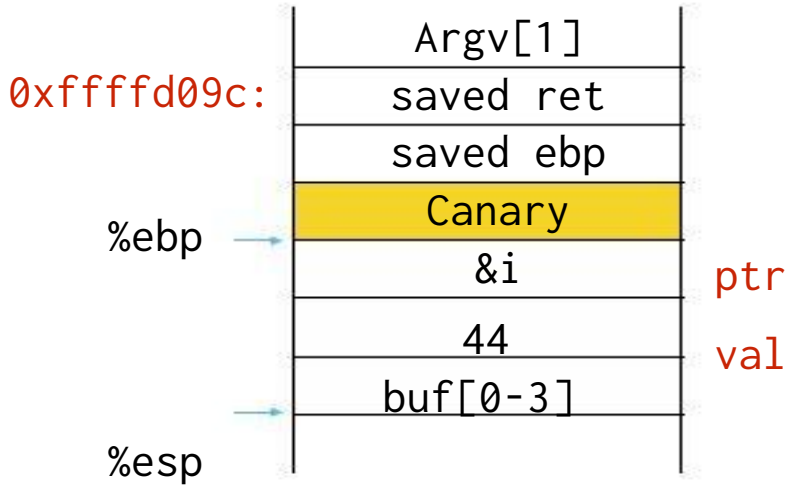

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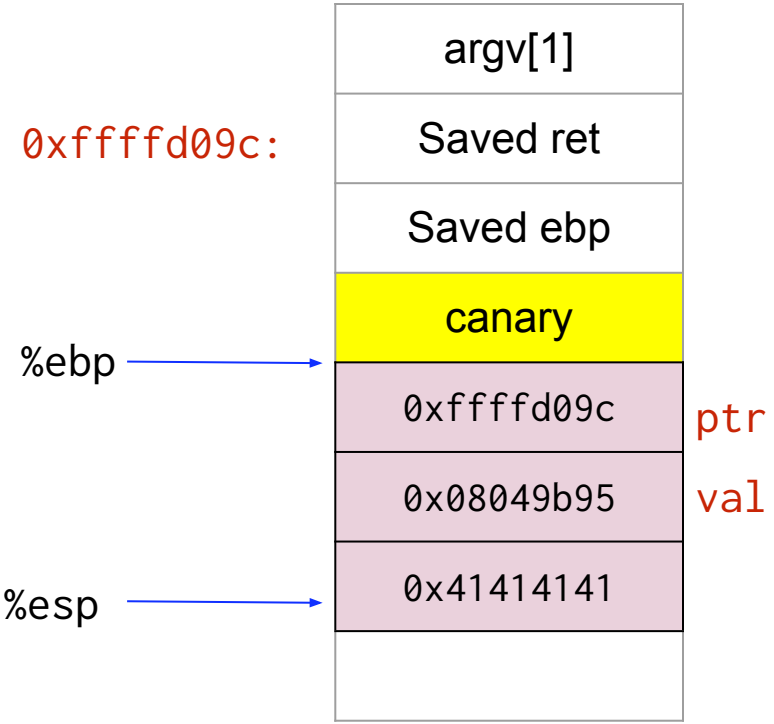

As input, we are going to give str some As and the address of the ret and foo function.

```
#include <stdio.h>
#include <string.h>
void foo() {
  printf("hello all!!\n");
  exit(0);
}
int i = 42;

void func(char *str) {
  int *ptr = &i;
  int val = 44;
  char buf[4];
  strcpy(buf,str);
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  }
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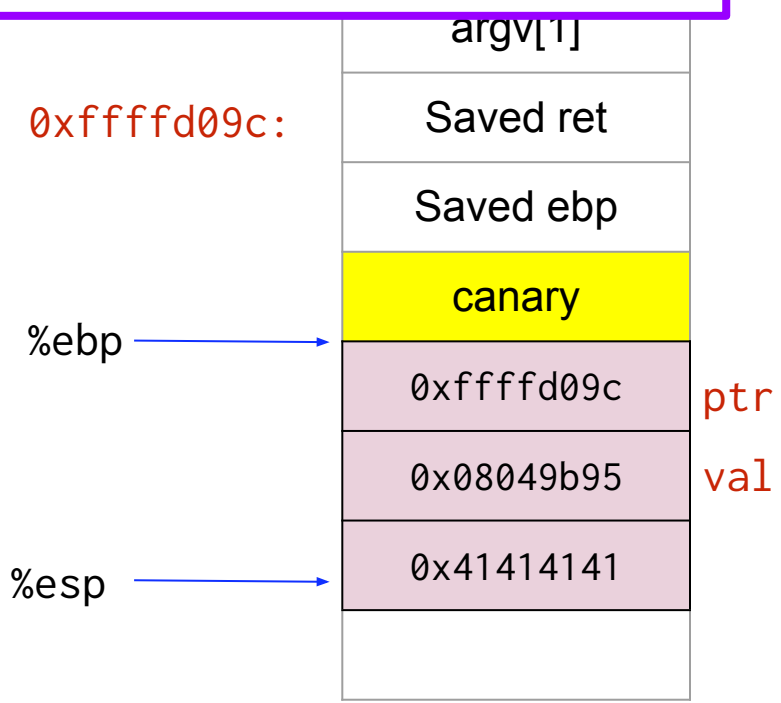
  return 0;
```

0x08049b95:



At this point, the saved ret is still an address from main's stack frame. This is because once func is run, it is supposed to return to main.

```
0x08049b95:
                #include <stdio.h>
                #include <string.h>
                void foo() {
                  printf("hello all!!\n");
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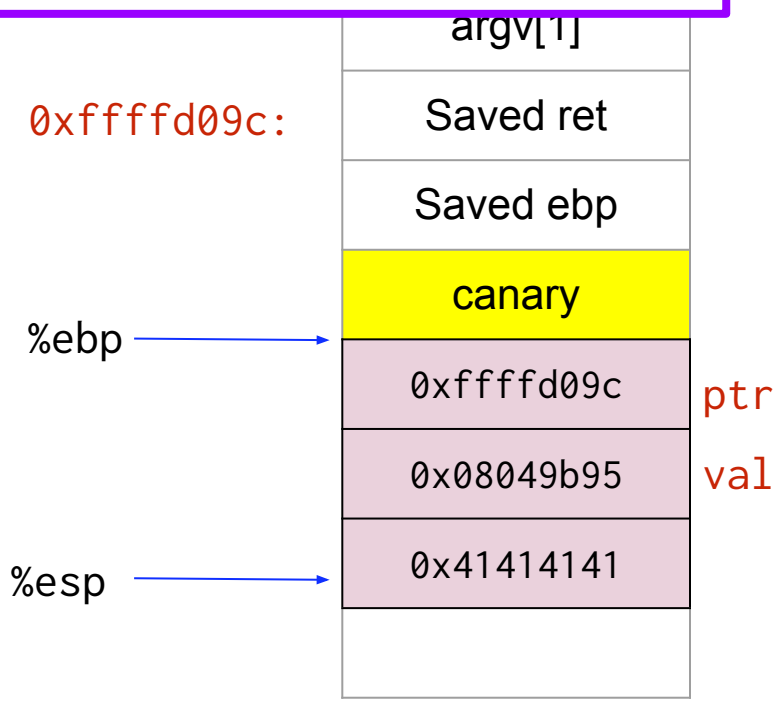

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  *ptr = val;
  }
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  func(argv[1]);
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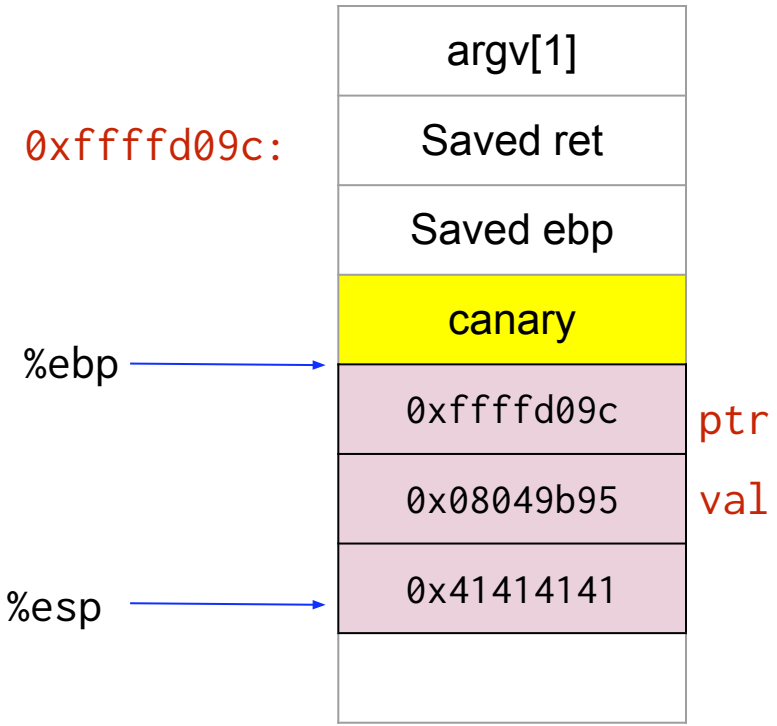
```



Pointer subterfuge

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                #include <stdio.h>
                #include <string.h>
                void foo() {
0x08049b95:       printf("hello all!!\n");
                  exit(0);
                }
                int main(int argc, char**argv) {
                  func(argv[1]);
                  return 0;
```
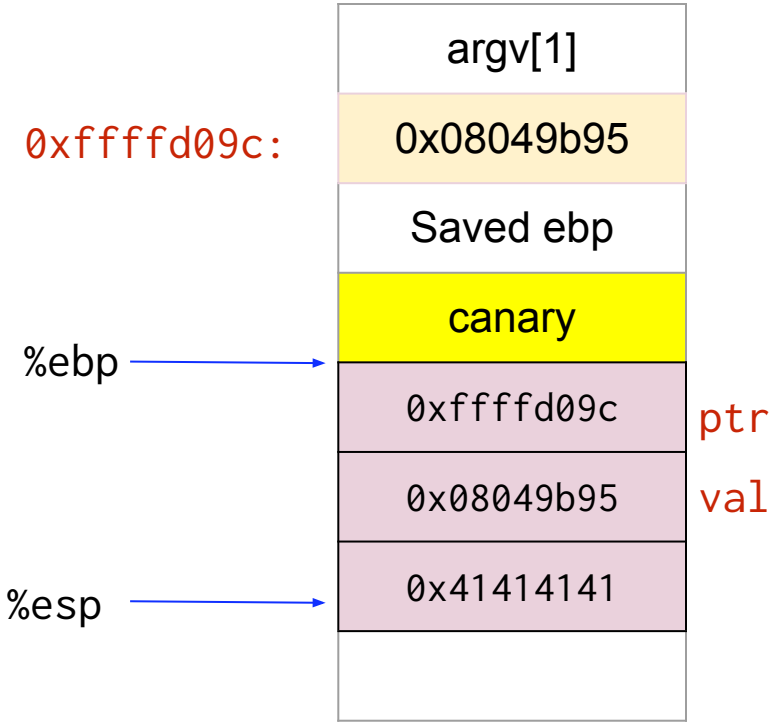

Ptr is a pointer. *ptr=val (we set the value of ptr to the address of foo).

This means that the value stored at the address ptr is referencing is now the same at val

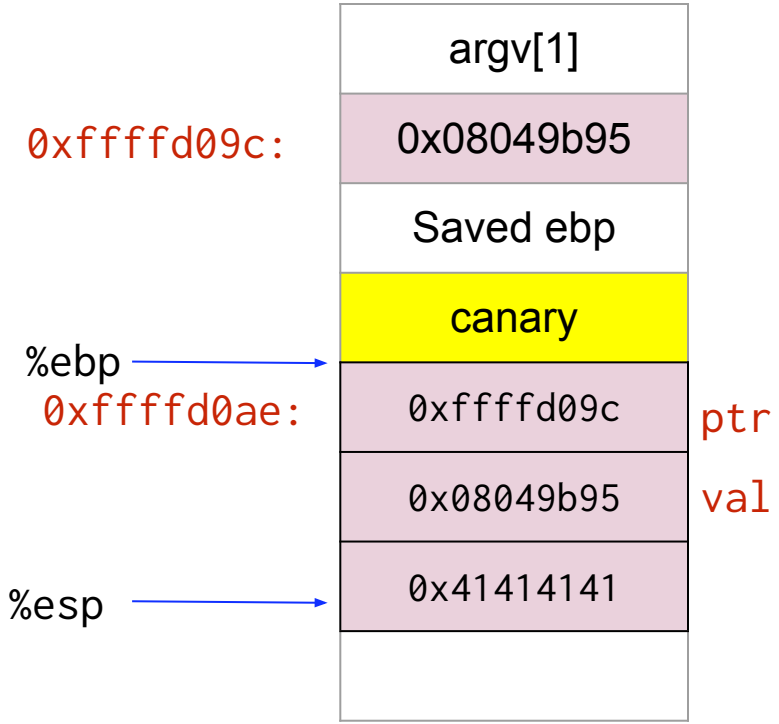


Pointer subterfuge

```
0x08049b95:
#include <stdio.h>
#include <string.h>
void foo() {
  printf("hello all!!\n");
  exit(0);
}
int i = 42;
```

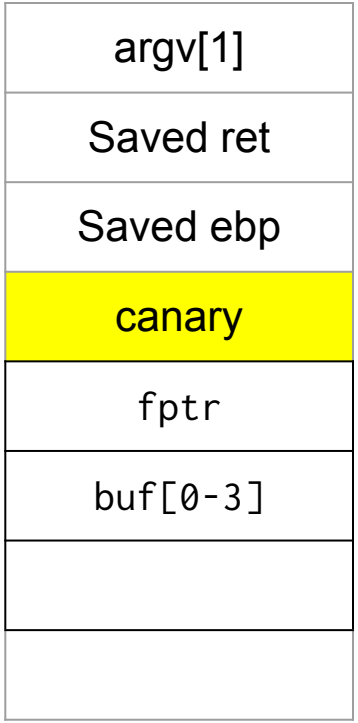
Also, the canary hasn't changed

```
  int val = 44;
  char buf[4];
  strcpy(buf,str);
  *ptr = val;
  }
int main(int argc, char**argv) {
  func(argv[1]);
  return 0;
```



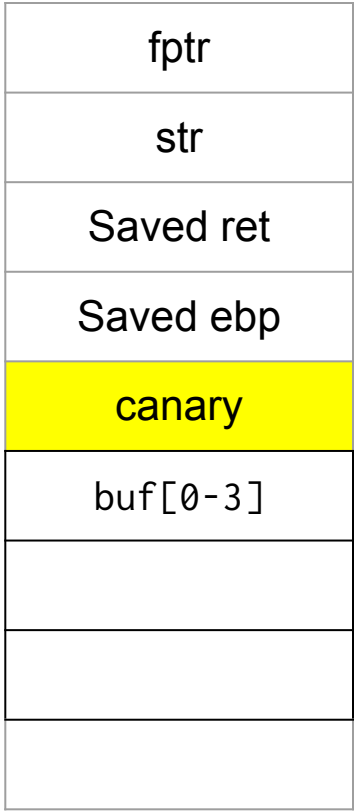
Overwrite function pointer on stack

```
void func(char *str) {
    void (*fptr)() = &bar;
    char buf[4];
    strcpy(buf,str);
    fptr()
}
```



Or overwrite a function pointer argument

```
void func(char *str, void (*fptr)()) {
    char buf[4];
    strcpy(buf,str);
    fptr()
}
```



What can we do about this?

- **Problem:** Overflowing locals and arguments can allow attacker to hijack control flow

  Solution:

  - Move buffers closer to canaries vs. lexical order
  - Copy args to top of stack

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  - Move buffers closer to canaries vs. lexical order
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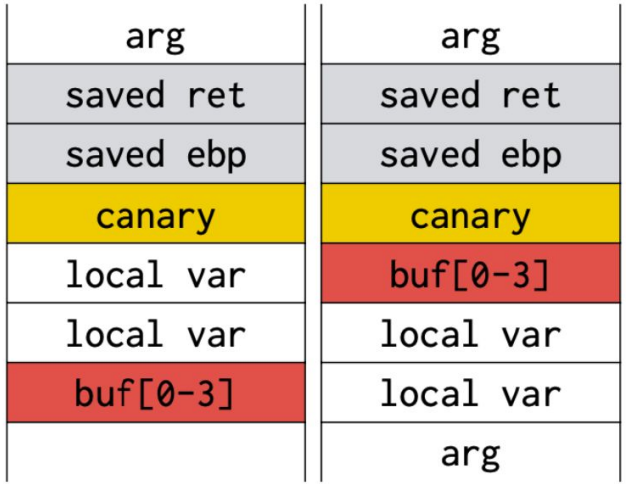


Your compiler does this already

-fstack-protector

- Functions with char bufs ≥ ssp-buffer-size (default=8)
- Functions with variable-sized alloca()s

Your compiler does this already

-fstack-protector

- Functions with char bufs ≥ ssp-buffer-size (default=8)
- Functions with variable-sized alloca()s

-fstack-protector-strong

- Functions with local arrays of any size/type
- Functions that have references to local stack variables

Your compiler does this already

-fstack-protector

- Functions with char bufs ≥ ssp-buffer-size (default=8)
- Functions with variable-sized alloca()s

-fstack-protector-strong

- Functions with local arrays of any size/type
- Functions that have references to local stack variables

-fstack-protector-all:

- All functions!

Zooming in on our compiled code

```
func(int, int, char*):
        pushl   %ebp
        movl    %esp, %ebp
        subl    $40, %esp
        movl    8(%ebp), %eax
        movl    %eax, -28(%ebp)
        movl    12(%ebp), %eax
        movl    %eax, -32(%ebp)
        movl    16(%ebp), %eax
        movl    %eax, -36(%ebp)
        movl    %gs:20, %eax
        movl    %eax, -12(%ebp)
        xorl    %eax, %eax
        movl    $-559038737, -20(%ebp)
        subl    $8, %esp
        pushl   -36(%ebp)
        leal    -16(%ebp), %eax
        pushl   %eax
        call    strcpy
        addl    $16, %esp
        nop
        movl    -12(%ebp), %eax
        xorl    %gs:20, %eax
        je      .L4
        call    __stack_chk_fail
.L4:
        leave
        ret
```

copy arg1

copy arg2

copy arg3

write canary

Can we defeat stack canaries?

- **Assumption:** Impossible to subvert control flow without corrupting the canary.

  Think outside the box

-
  - Overwrite function pointer elsewhere on the stack/heap
  - Pointer subterfuge

  → memcpy buffer overflow with fixed canary

  - Learn the canary

How do we pick canaries?

- Pick a clever value!
  - E.g. 0x000d0aff (0, CR, NL, -1) to terminate string operations like strcpy and gets
  - Even if attacker knows value, can't overwrite past canary!

Not all overflows are due to strings

Many other functions handle buffers

- E.g. memcpy, memmove, read
- These are also error-prone!

```
void func(char *str) {
    char buf[1024];
}   memcpy(buf,str, strlen(str));
```

How do we pick canaries?

- Pick a random value!
  - When?

Can we defeat stack canaries?

- **Assumption:** Impossible to subvert control flow without corrupting the canary.

  Think outside the box

-
  - Overwrite function pointer elsewhere on the stack/heap
  - Pointer subterfuge
  - memcpy buffer overflow with fixed canary

  → Learn the canary

Learn the canary

- Approach 1: chained vulnerabilities
  - Exploit one vulnerability to read the value of the canary
  - Exploit a second to perform stack buffer overflow

- Modern exploits chain multiple vulnerabilities
  - Recent Chinese government iPhone exploit: 14 vulns!

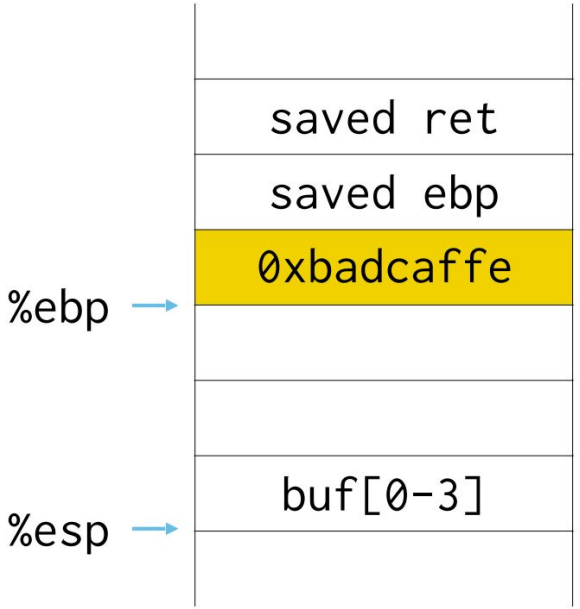
Learn the canary

- Approach 2: brute force servers (e.g. Apache2)
  - Main server process:
    - Establish a listening socket.
    - Fork several workers: if any die, fork a new one!
  - Worker process:
    - Accept connection on listening socket and process request

Perfect for brute forcing

- Forked process has same memory layout and contents as parent, including canary values!

- The fork on crash lets us try different canary values



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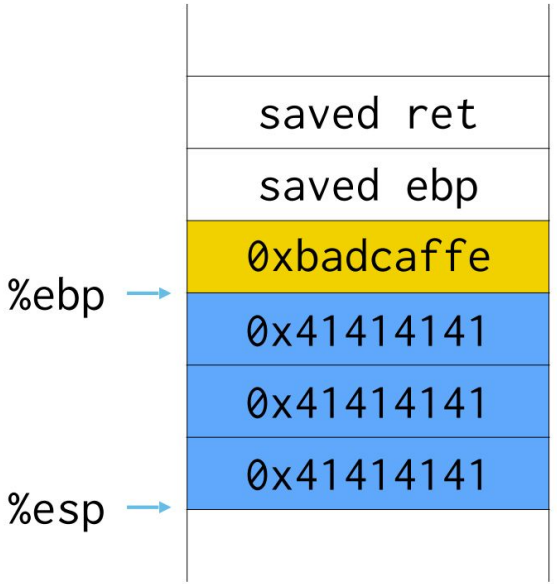

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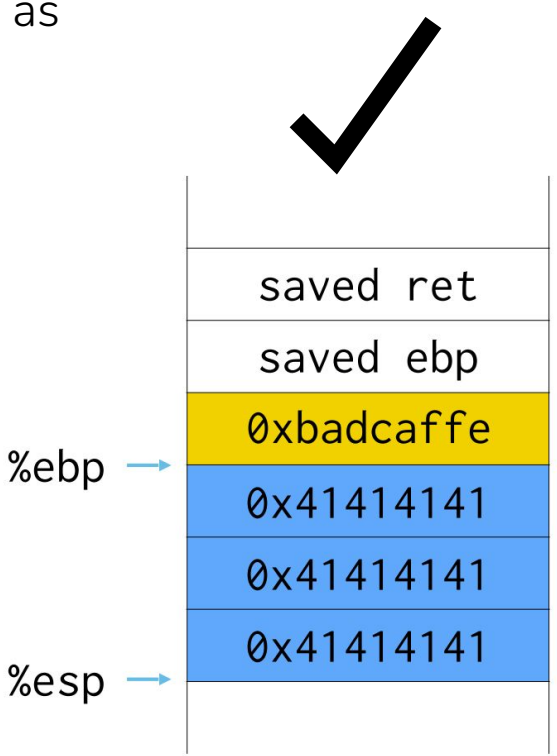

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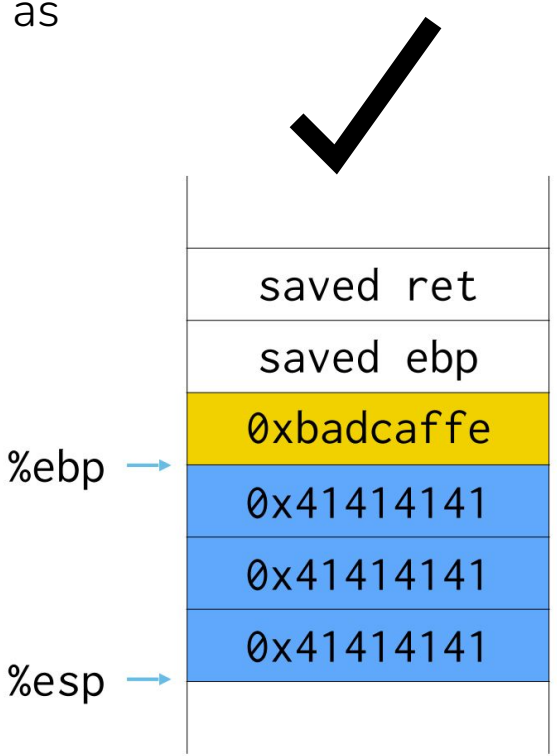

Figured out size of buffer!

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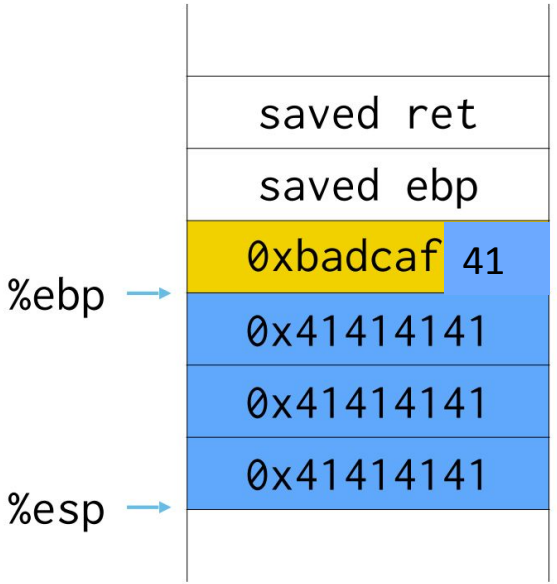

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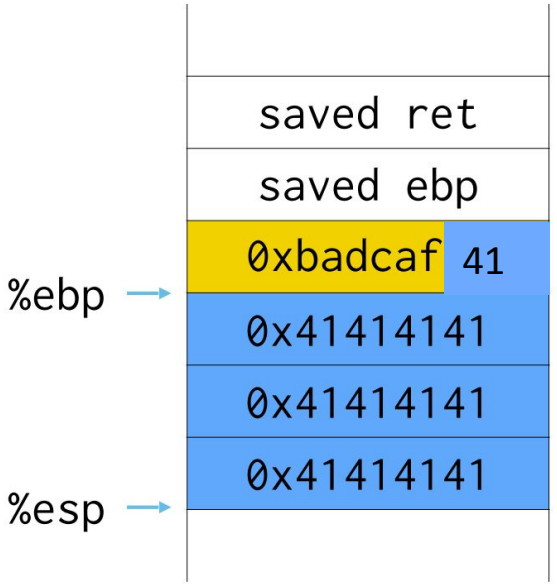

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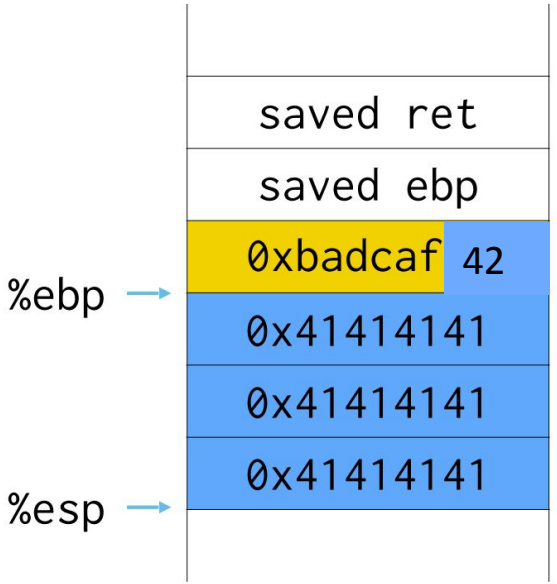

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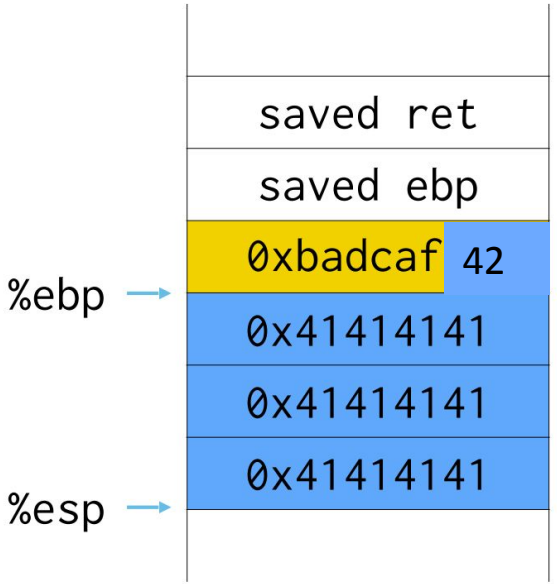

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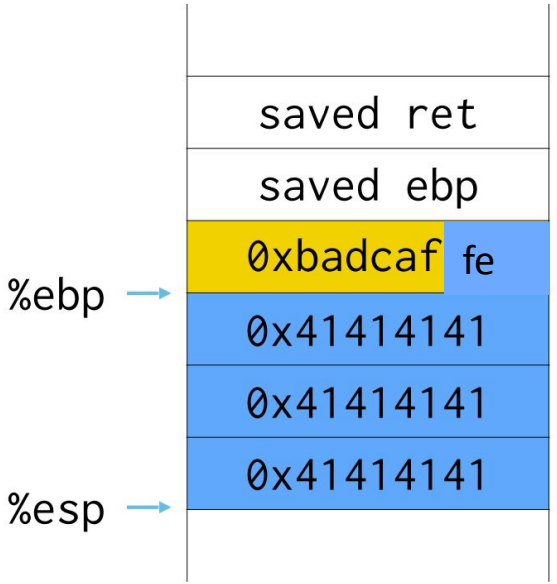

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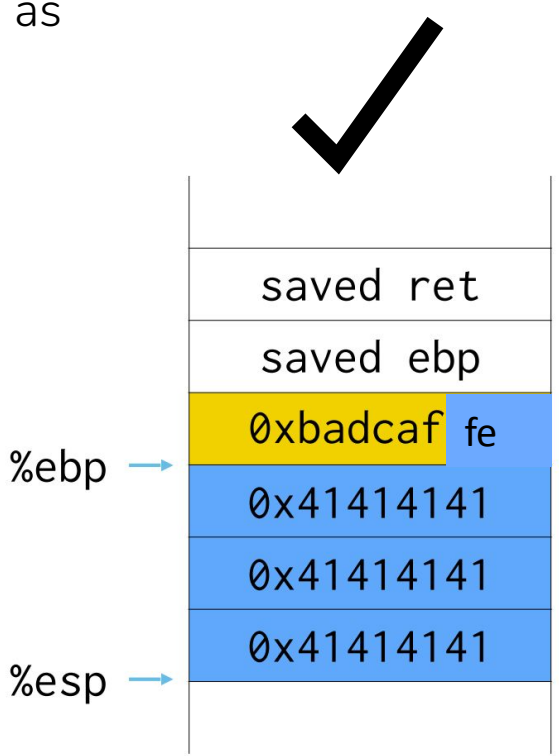

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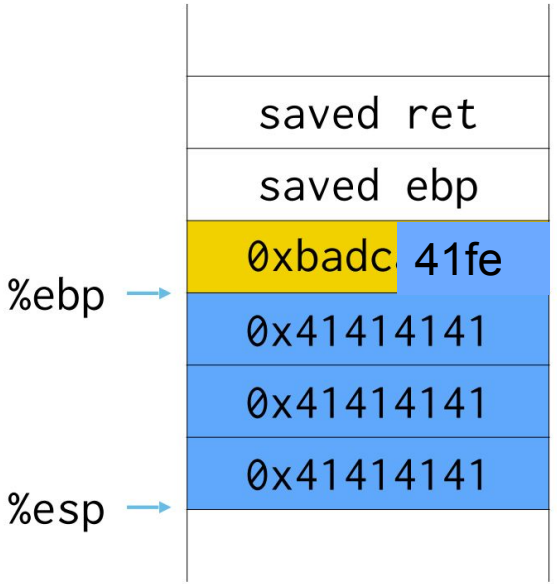

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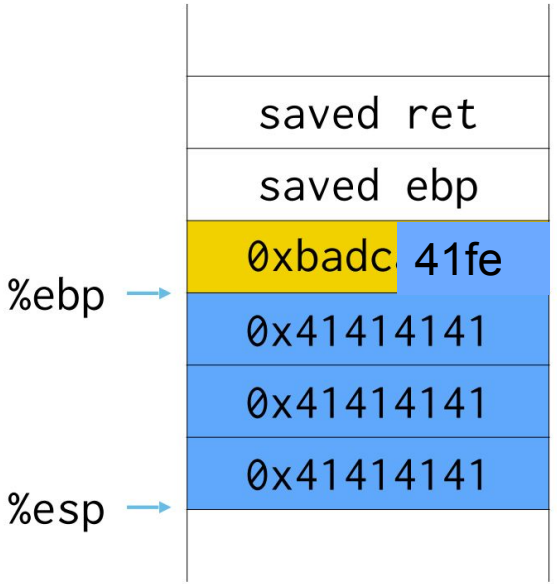

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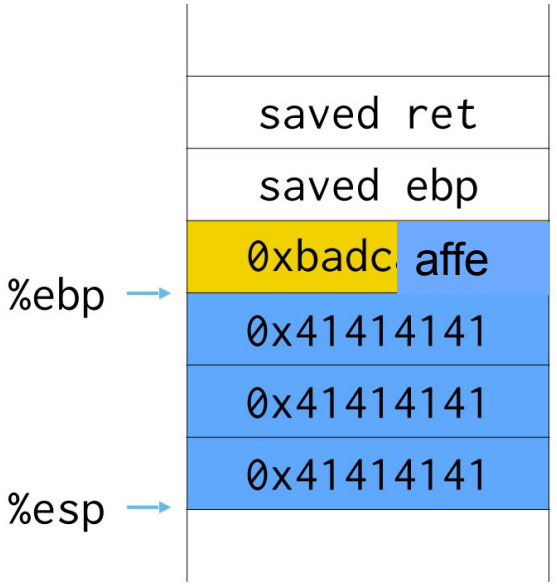

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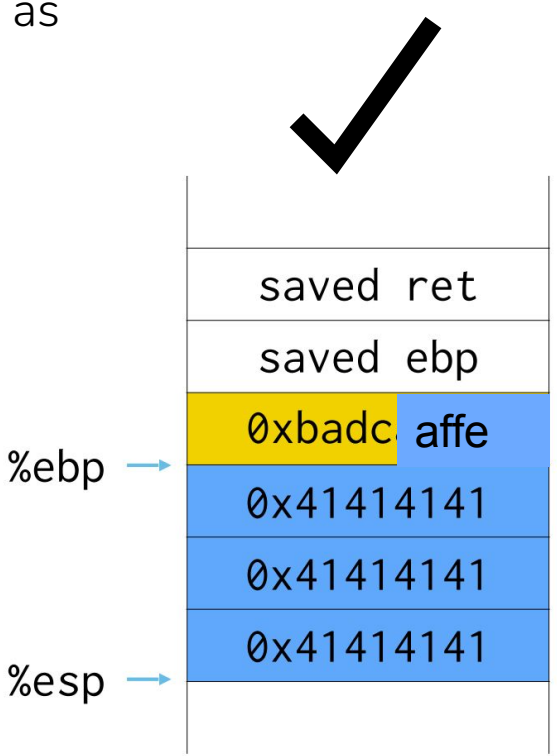

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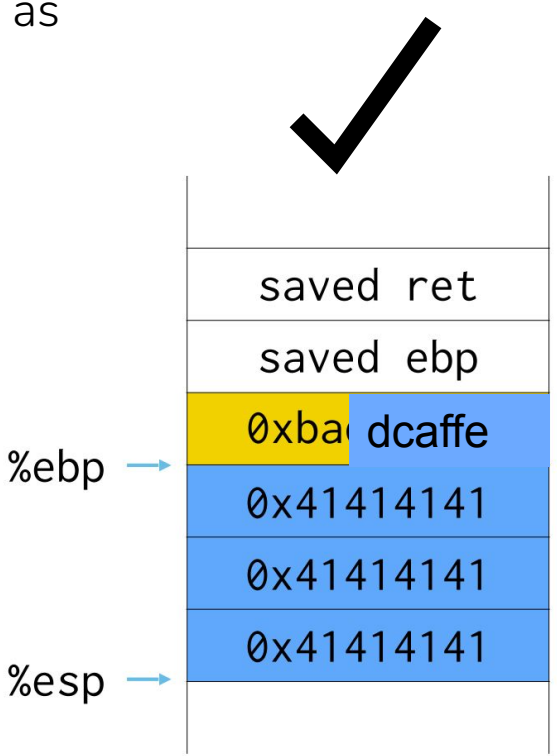

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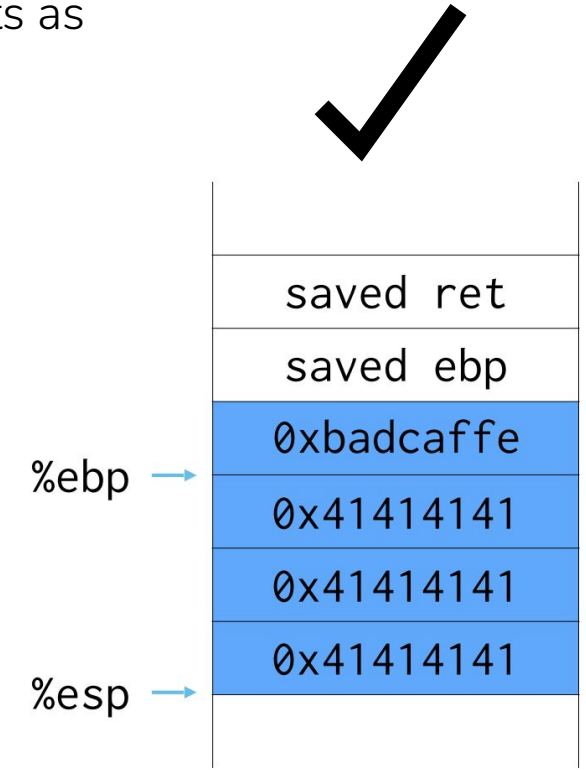


Buffer overflow mitigations

- Avoid unsafe functions
- Stack canaries

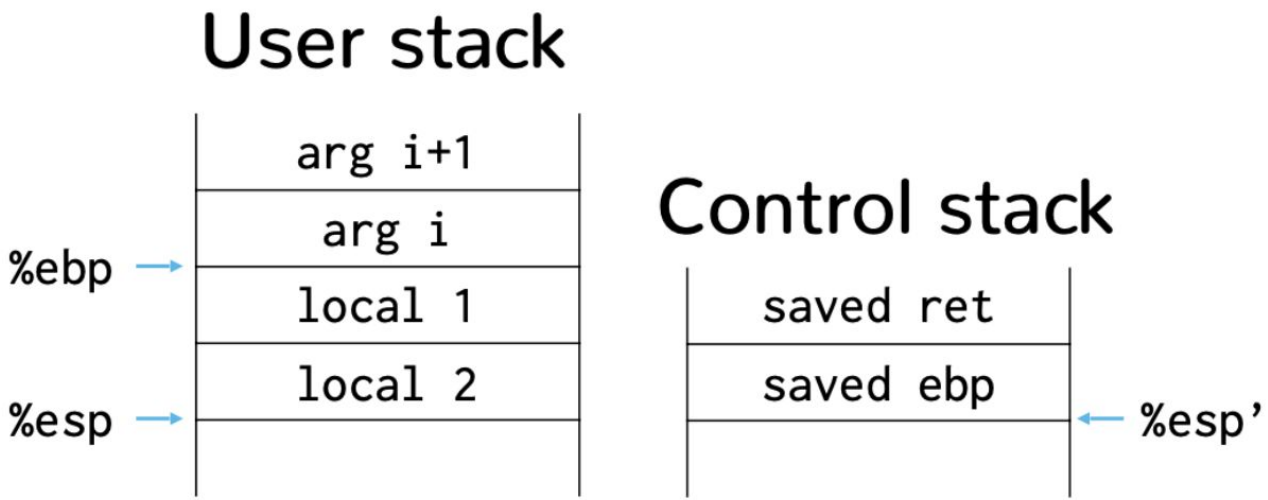
→ Separate control stack

- Memory writable or executable, not both (W^X)
- Address space layout randomization

Separate control stack

Problem: Control data is stored next to data

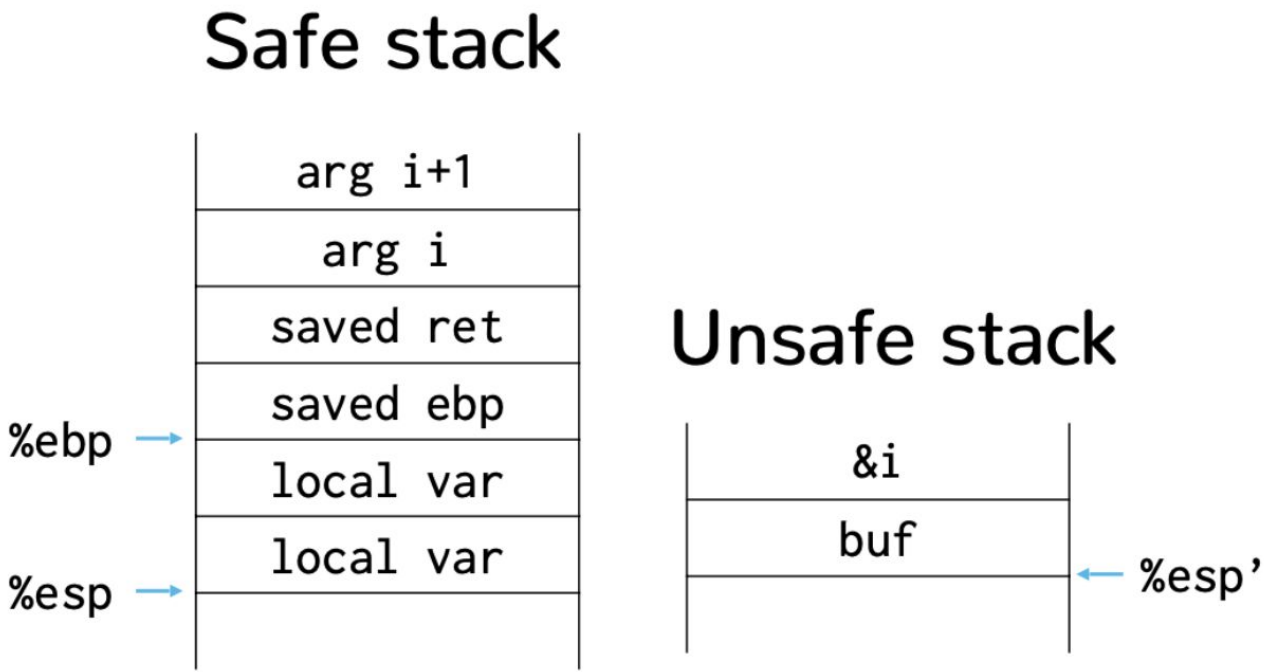
Solution: Bridge the implementation and abstraction gap: separate the control stack



Safe stack

Problem: Unsafe data structures stored next to control

Solution: Move unsafe data structures to separate stack



How do we implement a separate stack?

- There is no actual separate stack
  - We only have linear memory and load/store instructions
- Put the safe/separate stack in a random place in the address space
  - Location of control/safe stack is secret

How do we defeat this?

Find a function pointer and overwrite it to point to shellcode!

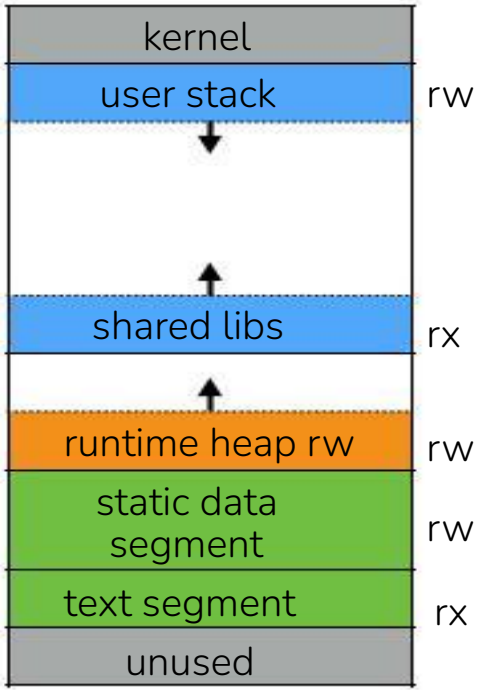
Buffer overflow mitigations

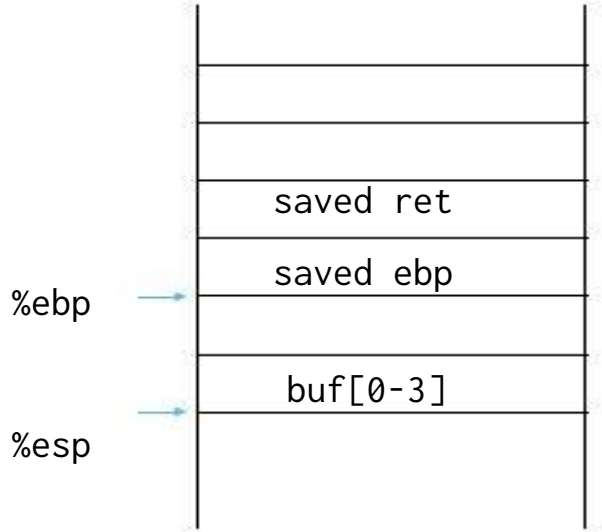
- Avoid unsafe functions
- Stack canaries
- Separate control stack
- → Memory writable or executable, not both (W^X)
- Address space layout randomization

W^X: write XOR execute

- **Goal:** Prevent execution of shell code from the stack
- **Insight:** Use memory page permission bits
  - Use MMU to ensure memory cannot be both writeable and executable at the same time
- Many names for same idea:
  - XN: eXecute Never
  - W^X: Write XOR eXecute
  - DEP: Data Execution Prevention

Recall our memory layout





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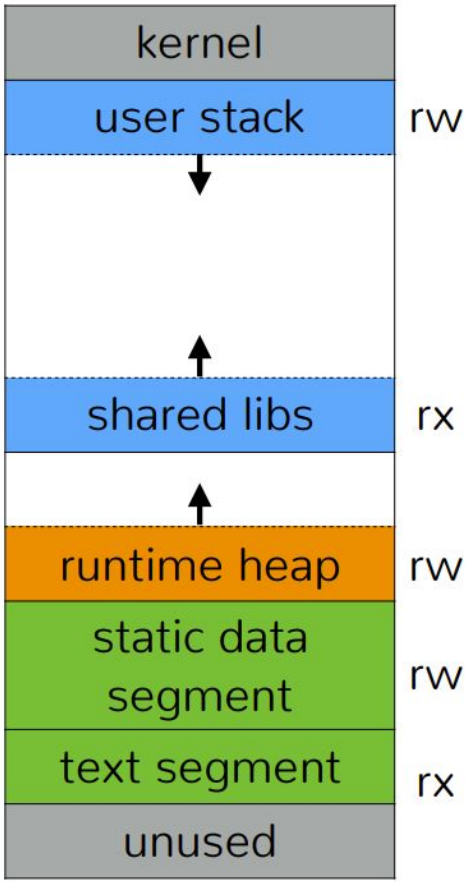

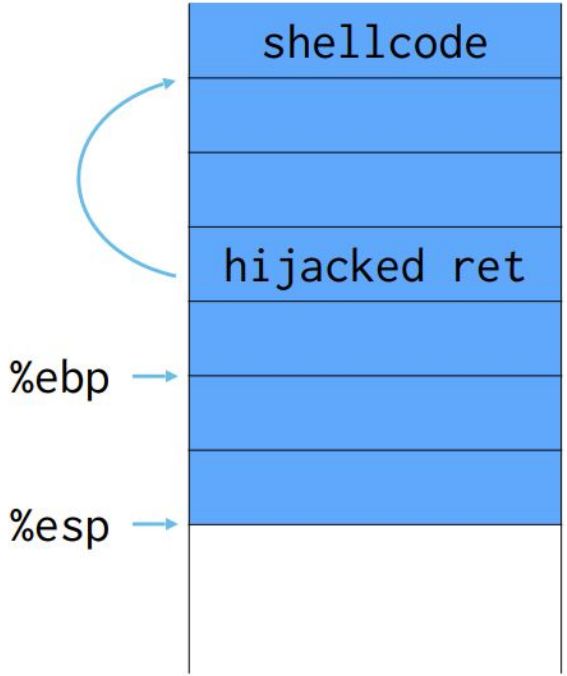

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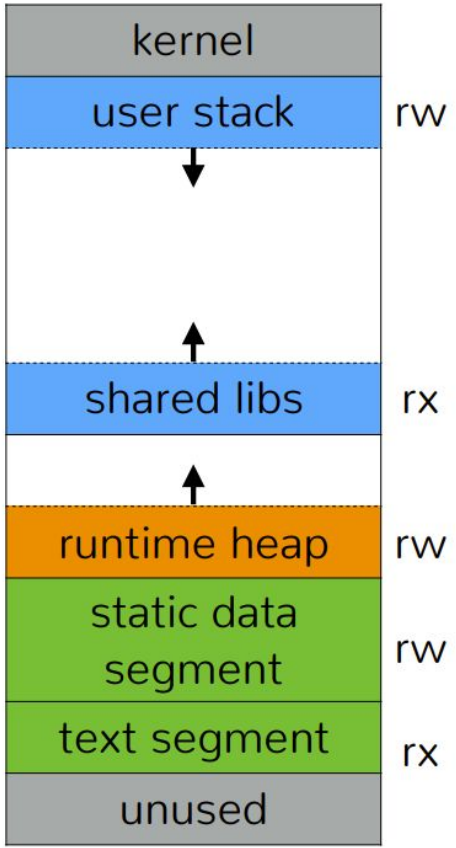
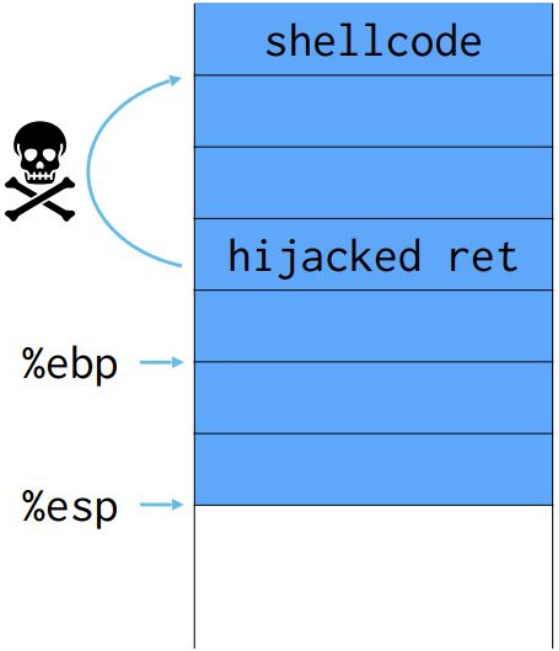


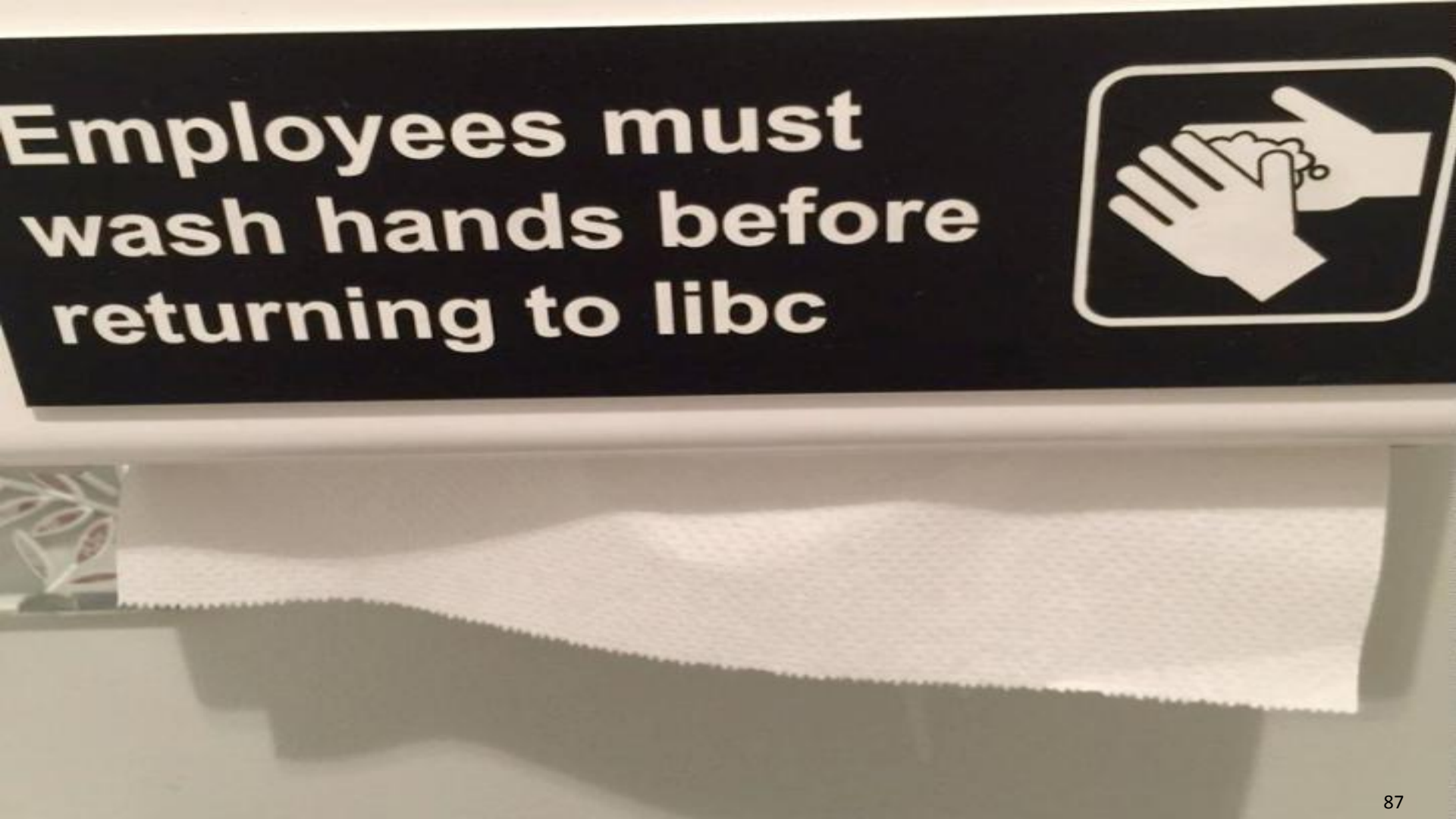


W^X tradeoffs

- **Easy to deploy:** No code changes or recompilation
- **Fast:** Enforced in hardware
  - Downside: What do you do on embedded devices?
- Some pages need to be both writeable and executable
  - Why?

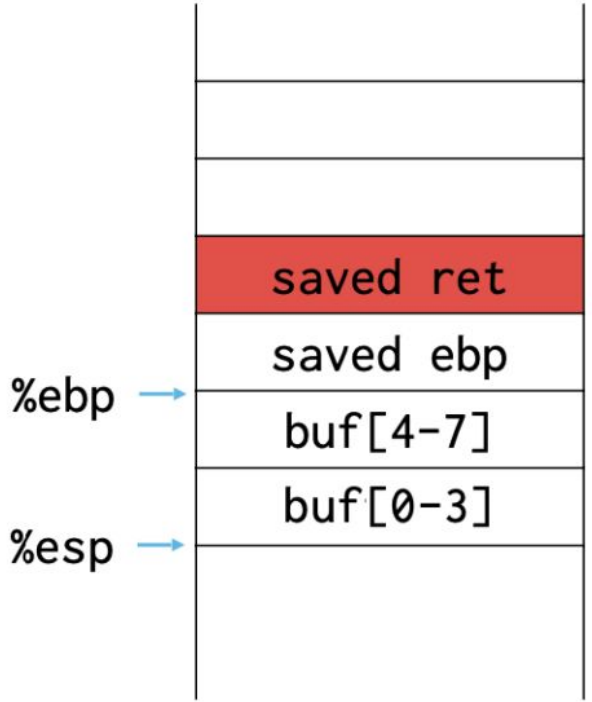
How can we defeat W^X?

- Can still write to return address stored on the stack
  - Jump to existing code
- Search executable for code that does what you want
  - E.g. if program calls `system("/bin/sh")` you're done
  - libc is a good source of code (return-into-libc attacks)

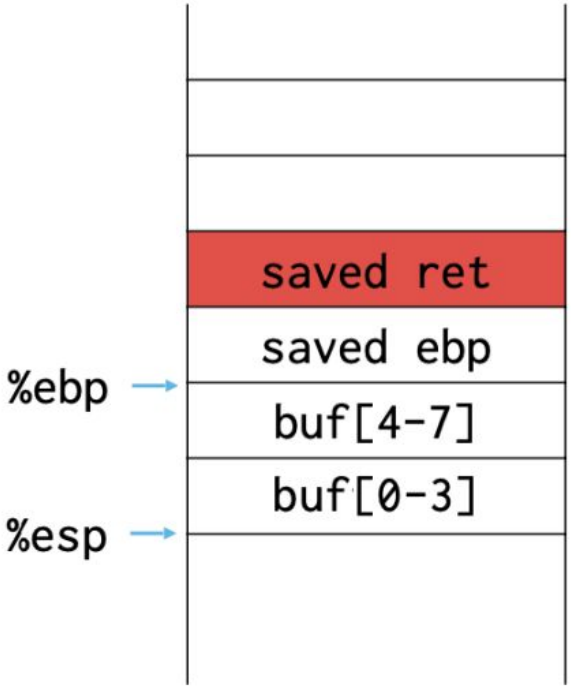

Employees must
wash hands before
returning to libc

Redirecting control flow to system()

- We redirected control flow earlier to foo()
- Calling system() is the same, but need to have argument string “/bin/sh” on stack.

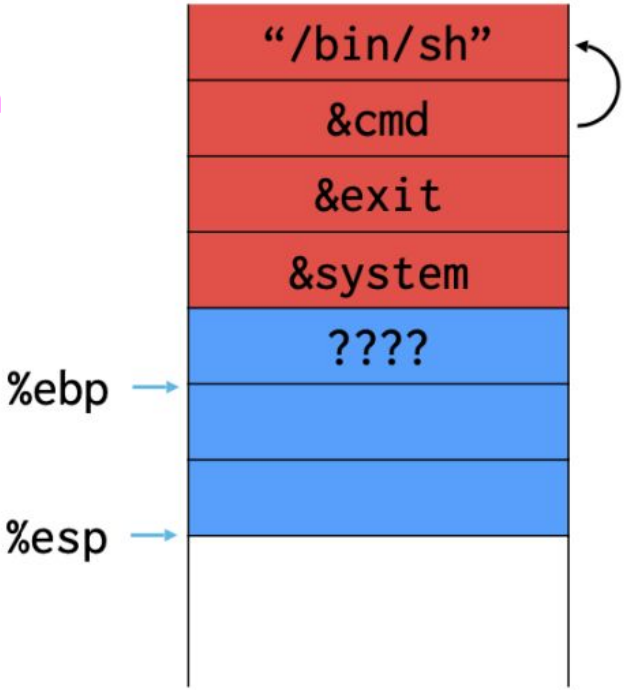


Redirecting control flow to system()



Remember: &system is the address of system()

→

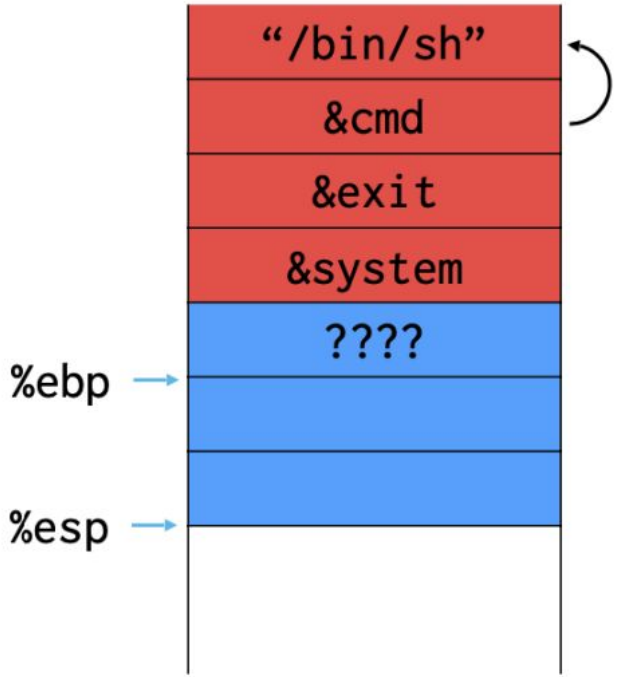


Redirecting control flow to system()

leave → movl %ebp, %esp
pop %ebp

→ popl %eip

ret

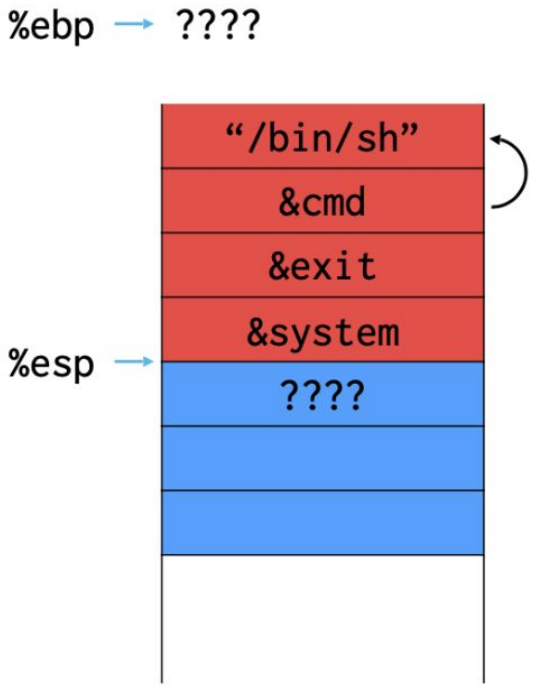


Redirecting control flow to system()

After leave

leave → movl %ebp, %esp
pop %ebp

ret → popl %eip

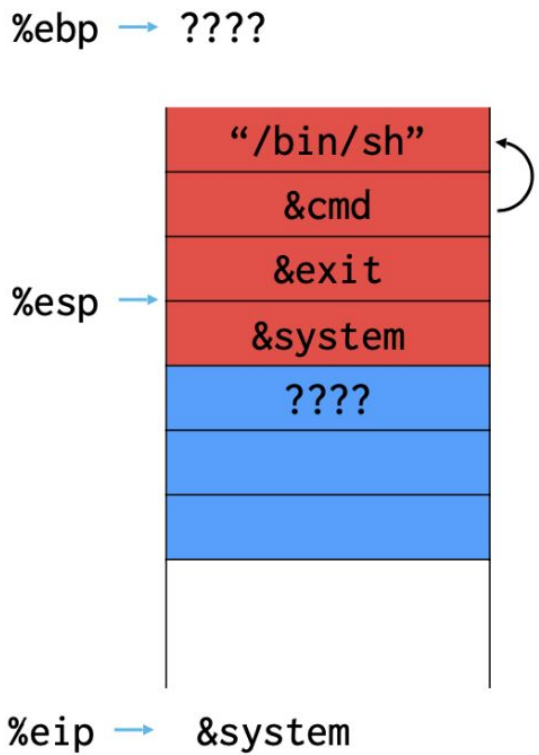


Redirecting control flow to system()

After ret

leave → movl %ebp, %esp
pop %ebp

ret → popl %eip



To system this looks like a normal call

But I want to execute shellcode, not just call system()!

Can we inject code?

- Just-in-time compilers produce data that becomes executable code

- JIT spraying:
  1. Spray heap with shellcode (and NOP slides)
  2. Overflow code pointer to spray area

What does JIT shellcode look like?

```
1  var g1 = 0;
2  ...
3  var g7 = 0;
4
5  for (var i=0; i<100000; ++i) {
6          g1 = 50011;       \\ pop ebx; ret;
7          g2 = 50009;       \\ pop ecx; ret;
8          g3 = 12828721;    \\ xor eax, eax; ret;
9          g4 = 12811696;    \\ mov 0x7d, al; ret;
10         g5 = 12833329;    \\ xor edx, edx; ret;
11         g6 = 12781490;    \\ mov 0x7,  dl; ret;
12         g7 = 12812493;    \\ int 0x80; ret;
13 }
```

The Devil is in the Constants: Bypassing Defenses in Browser JIT Engines

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Michalis Polychronakis, Stony Brook University, mikepo@cs.stonybrook.edu
Georgios Portokalidis, Stevens Institute of Tech., gportoka@stevens.edu
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Buffer overflow mitigations

- Avoid unsafe functions
- Stack canaries
- Separate control stack
- Memory writable or executable, not both (W^X)

↪ Address space layout randomization (ASLR)

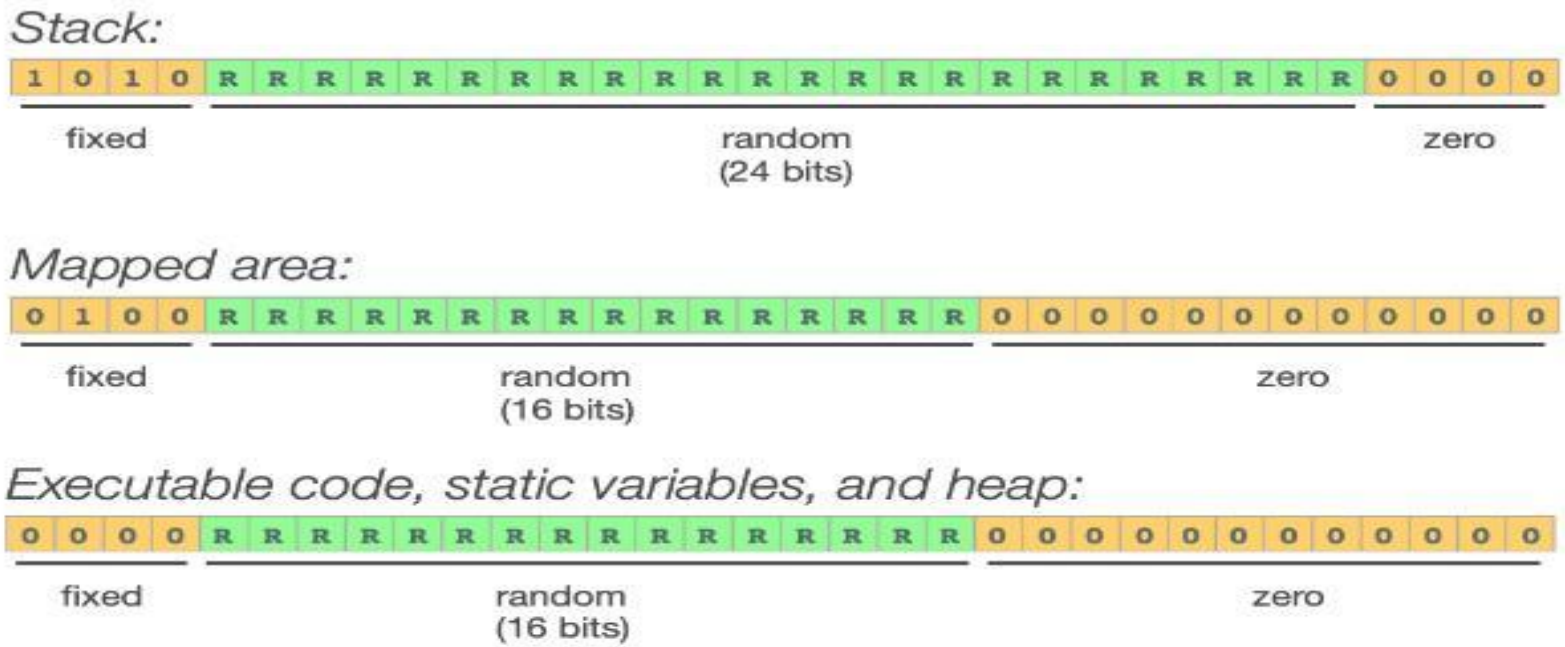
Address Space Layout Randomization (ASLR)

- Traditional exploits need precise addresses
  - stack-based overflows: shellcode
  - return-into-libc: library addresses

- **Insight:** Make it harder for attacker to guess location of shellcode/libc by randomizing the address of different memory regions

How much do we randomize?

32-bit PaX ASLR (x86)



ASLR Tradeoffs

- **Intrusive:** Need compiler, linker, loader support
  - Process layout must be randomized
  - Programs must be compiled to not have absolute jumps
- **Incurs overhead:** Increases code size and performance overhead
- Also mitigates heap-based overflow attacks

When do we randomize?

Many options.

- At boot?
- At compile/link time?
- At run/load time?
- On fork?

What’s the tradeoff?

How can we defeat ASLR?

- `-fno-pie` binaries have fixed code and data addresses
  - Enough to carry out control flow hijacking attacks
- Each region has random offset, but layout is fixed
  - Single address in a region leaks every address in region
- Brute force for 32-bit binaries and/or pre-fork binaries
- Heap spray for 64-bit binaries

Buffer overflow mitigations

- Avoid unsafe functions
- Stack canaries
- Separate control stack
- Memory writable or executable, not both (W^X)
- Address space layout randomization (ASLR)

None are perfect, but in practice they raise the bar dramatically.