

# Lecture 11: Code and data interactions, buffer overflows

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February 16, 2026

601.229 Computer Systems Fundamentals



# Buffer overflows

# A dangerous function

```
#include <stdio.h>

char *gets(char *s);
```

gets reads a single line of input from `stdin` and stores it in the character array pointed to by `s`

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gets reads a single line of input from `stdin` and stores it in the character array pointed to by `s`

Why is this dangerous?

# A dangerous function

```
#include <stdio.h>

char *gets(char *s);
```

gets reads a single line of input from `stdin` and stores it in the character array pointed to by `s`

Why is this dangerous?

There is no way to ensure that the character array is large enough to store the input

# Clicker quiz!

Clicker quiz omitted from public slides

# Memory safety

- ▶ C is a *memory-unsafe* language
  - ▶ No bounds checking of array accesses
  - ▶ No restrictions on pointers:

```
uint64_t x = 0xDEADBEEF;  
char *s = (char *) x;  
strcpy(s, "Hello, world!");
```

- ▶ Invalid memory references are an all-too-common source of bugs in C programs
- ▶ What are the consequences of an invalid memory reference?

- ▶ If you're *lucky*, an invalid memory reference will crash the program with a *segmentation violation*, a.k.a. segfault
- ▶ Recall (from Lecture 6) using the `pmap` program to view a running program's memory map:

```
29208:    ./art
0000562d71c36000      4K r-x-- art
0000562d71e36000      4K r---- art
0000562d71e37000      4K rw--- art
0000562d735fc000    132K rw---  [ anon ]
...etc...
```

- ▶ Memory references outside a valid region of virtual memory, or which violate access permissions (e.g., store to read-only region), result in a processor exception that is handled by the OS kernel
- ▶ Usual result is that OS sends a *signal* that terminates the running program



# Memory corruption

- ▶ A much worse consequence of an invalid memory store: data is corrupted
  - ▶ A variable or array element is overwritten
  - ▶ A saved register value or temporary value is overwritten
  - ▶ A return address is overwritten (this is particularly bad, as we'll see shortly)
- ▶ In general, once a program makes an invalid memory reference, it cannot be trusted to behave correctly
  - ▶ This is why valgrind is such an important tool

# A dangerous program

Based on example in textbook (code in buf.zip on course website):

```
#include <stdio.h>

void echo(void) {
    char buf[4];
    gets(buf);
    puts(buf);
}

int main(void) {
    printf("Enter a line of text:\n");
    echo();
    return 0;
}
```

# A dangerous program

Based on example in textbook (code in buf.zip on course website):

```
#include <stdio.h>

void echo(void) {
    char buf[4];    <-- small buffer, safe only if string length 3 or less
    gets(buf);
    puts(buf);
}

int main(void) {
    printf("Enter a line of text:\n");
    echo();
    return 0;
}
```

# Compiling and running

```
$ gcc -Og -no-pie -Wall -Wextra -fno-stack-protector -o danger danger.c
...warning about implicit declaration of gets omitted...
...warning from linker about gets being dangerous omitted...
$ ./danger
Enter a line of text:
Hi there!
Hi there!
$ echo $?
0
```

# Compiling and running

```
$ gcc -Og -no-pie -Wall -Wextra -fno-stack-protector -o danger danger.c
...warning about implicit declaration of gets omitted...
...warning from linker about gets being dangerous omitted...
$ ./danger
Enter a line of text:
Hi there!
Hi there!
$ echo $?
0
```

Wait...why did the program behave correctly?

# Inspect the generated code

gcc's -S option translates C code (.c file) into assembly language (.s file)

```
$ gcc -Og -no-pie -fno-stack-protector -S danger.c
...warning about implicit declaration of gets omitted...
$ head -8 danger.s
        .file          "danger.c"
        .text
        .globl         echo
        .type          echo, @function

echo:
.LFB23:
        .cfi_startproc
        pushq          %rbx
```

# The echo function (assembly code)

Cleaned-up version of the echo function:

echo:

```
    pushq    %rbx
    subq     $16, %rsp
    leaq     12(%rsp), %rbx
    movq     %rbx, %rdi
    movl     $0, %eax
    call     gets@PLT
    movq     %rbx, %rdi
    call     puts@PLT
    addq     $16, %rsp
    popq     %rbx
    ret
```

# The echo function (assembly code)

Cleaned-up version of the echo function:

echo:

```
    pushq    %rbx                <-- save %rbx (callee-saved register)
    subq     $16, %rsp
    leaq     12(%rsp), %rbx
    movq     %rbx, %rdi
    movl     $0, %eax
    call     gets@PLT
    movq     %rbx, %rdi
    call     puts@PLT
    addq     $16, %rsp
    popq     %rbx
    ret
```



# The echo function (assembly code)

Cleaned-up version of the echo function:

echo:

```
    pushq    %rbx
    subq     $16, %rsp      <-- reserve 16 bytes of space in stack frame
    leaq     12(%rsp), %rbx
    movq     %rbx, %rdi
    movl     $0, %eax
    call     gets@PLT
    movq     %rbx, %rdi
    call     puts@PLT
    addq     $16, %rsp
    popq     %rbx
    ret
```

# The echo function (assembly code)

Cleaned-up version of the echo function:

echo:

```
    pushq    %rbx
    subq     $16, %rsp
    leaq     12(%rsp), %rbx  <-- put base address of buf in %rbx
    movq     %rbx, %rdi
    movl     $0, %eax
    call     gets@PLT
    movq     %rbx, %rdi
    call     puts@PLT
    addq     $16, %rsp
    popq     %rbx
    ret
```

# The echo function (assembly code)

Cleaned-up version of the echo function:

echo:

```
    pushq    %rbx
    subq     $16, %rsp
    leaq     12(%rsp), %rbx
    movq     %rbx, %rdi    <-- pass base address of buf to gets
    movl     $0, %eax
    call     gets@PLT
    movq     %rbx, %rdi
    call     puts@PLT
    addq     $16, %rsp
    popq     %rbx
    ret
```

# The echo function (assembly code)

Cleaned-up version of the echo function:

echo:

```
    pushq    %rbx
    subq     $16, %rsp
    leaq     12(%rsp), %rbx
    movq     %rbx, %rdi
    movl     $0, %eax      <-- no vector args to gets
    call     gets@PLT
    movq     %rbx, %rdi
    call     puts@PLT
    addq     $16, %rsp
    popq     %rbx
    ret
```

# The echo function (assembly code)

Cleaned-up version of the echo function:

echo:

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    subq     $16, %rsp
    leaq     12(%rsp), %rbx
    movq     %rbx, %rdi
    movl     $0, %eax
    call     gets@PLT      <-- call gets
    movq     %rbx, %rdi
    call     puts@PLT
    addq     $16, %rsp
    popq     %rbx
    ret
```

# The echo function (assembly code)

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    movq     %rbx, %rdi
    call     puts@PLT
    addq     $16, %rsp
    popq     %rbx
    ret
```

<-- pass base address of buf to puts

# The echo function (assembly code)

Cleaned-up version of the echo function:

echo:

```
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    subq     $16, %rsp
    leaq     12(%rsp), %rbx
    movq     %rbx, %rdi
    movl     $0, %eax
    call     gets@PLT
    movq     %rbx, %rdi
    call     puts@PLT      <-- call puts
    addq     $16, %rsp
    popq     %rbx
    ret
```

# The echo function (assembly code)

Cleaned-up version of the echo function:

echo:

```
    pushq    %rbx
    subq     $16, %rsp
    leaq     12(%rsp), %rbx
    movq     %rbx, %rdi
    movl     $0, %eax
    call     gets@PLT
    movq     %rbx, %rdi
    call     puts@PLT
    addq     $16, %rsp      <-- de-allocate space in stack frame
    popq     %rbx
    ret
```



# The echo function (assembly code)

Cleaned-up version of the echo function:

echo:

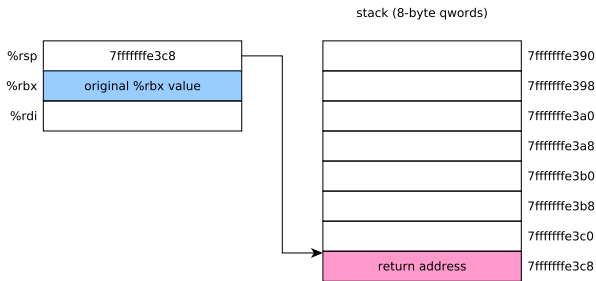
```
    pushq    %rbx
    subq     $16, %rsp
    leaq     12(%rsp), %rbx
    movq     %rbx, %rdi
    movl     $0, %eax
    call     gets@PLT
    movq     %rbx, %rdi
    call     puts@PLT
    addq     $16, %rsp
    popq     %rbx          <-- restore %rbx
    ret
```

# Tracing the danger program

On entry to echo function:

echo:

```
    pushq    %rbx
    subq     $16, %rsp
    leaq     12(%rsp), %rbx
    movq     %rbx, %rdi
    movl     $0, %eax
    call     gets@PLT
    movq     %rbx, %rdi
    call     puts@PLT
    addq     $16, %rsp
    popq     %rbx
    ret
```

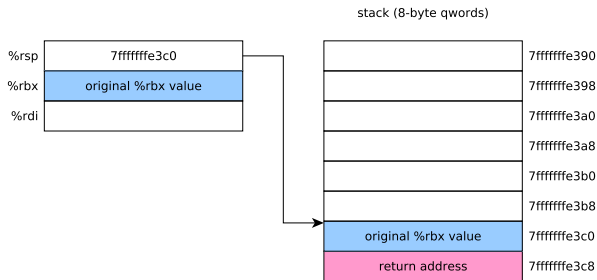


# Tracing the danger program

After pushing %rbx:

echo:

```
pushq    %rbx
subq     $16, %rsp
leaq     12(%rsp), %rbx
movq     %rbx, %rdi
movl     $0, %eax
call     gets@PLT
movq     %rbx, %rdi
call     puts@PLT
addq     $16, %rsp
popq     %rbx
ret
```

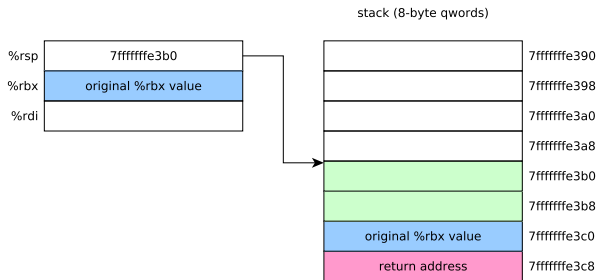


# Tracing the danger program

After reserving 16 bytes in stack frame:

echo:

```
pushq    %rbx
subq     $16, %rsp
leaq     12(%rsp), %rbx
movq     %rbx, %rdi
movl     $0, %eax
call     gets@PLT
movq     %rbx, %rdi
call     puts@PLT
addq     $16, %rsp
popq     %rbx
ret
```

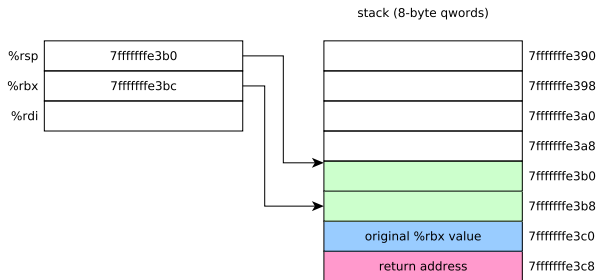


# Tracing the danger program

After loading base address of buf into %rbx:

echo:

```
pushq    %rbx
subq     $16, %rsp
leaq     12(%rsp), %rbx
movq     %rbx, %rdi
movl     $0, %eax
call     gets@PLT
movq     %rbx, %rdi
call     puts@PLT
addq     $16, %rsp
popq     %rbx
ret
```

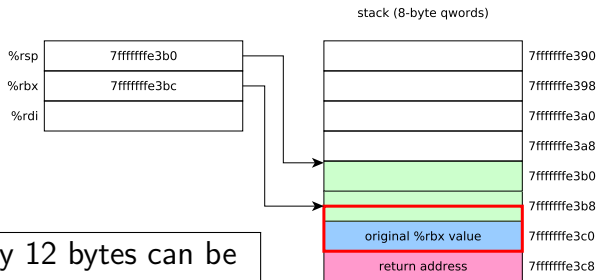


# Tracing the danger program

After loading base address of buf into %rbx:

echo:

```
pushq    %rbx
subq     $16, %rsp
leaq     12(%rsp), %rbx
movq     %rbx, %rdi
movl     $0, %eax
call     gets@PLT
movq     %rbx, %rdi
call     puts@PLT
addq     $16, %rsp
popq     %rbx
ret
```

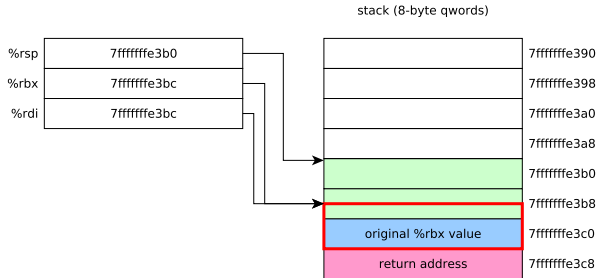


# Tracing the danger program

Pass base address of buf to gets:

echo:

```
pushq    %rbx
subq     $16, %rsp
leaq     12(%rsp), %rbx
movq     %rbx, %rdi
movl     $0, %eax
call     gets@PLT
movq     %rbx, %rdi
call     puts@PLT
addq     $16, %rsp
popq     %rbx
ret
```

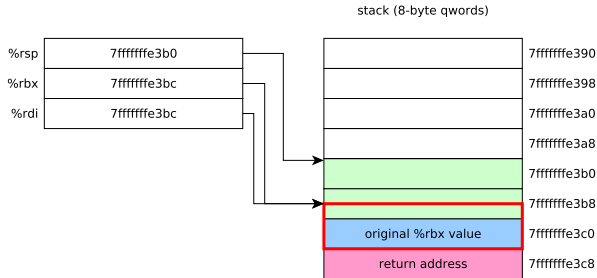


# Tracing the danger program

Just before call to gets:

echo:

```
    pushq    %rbx
    subq     $16, %rsp
    leaq     12(%rsp), %rbx
    movq     %rbx, %rdi
    movl     $0, %eax
    call     gets@PLT
    movq     %rbx, %rdi
    call     puts@PLT
    addq     $16, %rsp
    popq     %rbx
    ret
```





# Explanation of behavior

- ▶ The danger program appeared to work when the input was `Hi there!` because the string only requires 10 bytes to store, and 12 bytes were available
- ▶ The saved `%rbx` value is partially overwritten, but `main` (the caller) wasn't using that register
  - ▶ Hard to know whether `main`'s caller was using it

# Explanation of behavior

- ▶ The danger program appeared to work when the input was `Hi there!` because the string only requires 10 bytes to store, and 12 bytes were available
- ▶ The saved `%rbx` value is partially overwritten, but `main` (the caller) wasn't using that register
- ▶ Hard to know whether `main`'s caller was using it

We got lucky

# Overwriting the return address

- ▶ When the return address is overwritten, control won't return to the correct instruction when the function returns
- ▶ What could happen?

# The code could crash

```
$ ./danger  
Enter a line of text:  
Hello, world!  
Hello, world!  
Segmentation fault (core dumped)
```

# The code could crash

```
$ ./danger
Enter a line of text:
Hello, world!
Hello, world!
Segmentation fault (core dumped)
```

- ▶ The string `Hello, world!` requires 14 bytes to represent, so the first two bytes of the return address are overwritten
- ▶ Control returns to a zeroed region of memory
- ▶ The bytes `00 00` encode the instruction `add %al, (%rax)`
- ▶ `%rax` contains the return value of `puts`, which is 14
- ▶ No memory is mapped at address 14, so a segmentation fault occurs

# Vulnerability to untrusted data

- ▶ Let's assume that the input sent to the program is *untrusted*
  - ▶ I.e., we should assume that it was generated by a malicious user who wants to take control of our computer and do nefarious things
  - ▶ For many kinds of programs — especially network applications — most or all input data is untrusted
- ▶ Because of the buffer overflow, the input sent to the program can change the echo function's return address to an arbitrary value
- ▶ This means the malicious user has (some) control over which code executes when the function returns
  - ▶ **This is extremely bad!**
- ▶ If a malicious actor (“attacker”) knows that a buffer overflow bug exists, what does it allow them to do?

# Executing arbitrary code from the stack

- ▶ In the previous (32-bit) x86 architecture, any region of memory marked as readable is also *executable*
- ▶ The attacker can send code that will be written onto the stack
  - ▶ The malicious data must overwrite the return address with the location of the exploit code (on the compromised stack)
  - ▶ This requires knowing (or guessing) the stack pointer's value (so that control “returns” to the code on the stack)

# Nop sleds

- ▶ To make arbitrary code execution more feasible, attacker can construct a “nop sled”: a long series of `nop` (do nothing) instructions leading to exploit code
- ▶ As long as forged return address hits the nop sled, the exploit code will execute
- ▶ This allows the exploit to work (with some probability) even if the exact stack pointer value isn't known (the guess just has to be “close enough”)



# Exploiting existing code

- ▶ Another way of exploiting a buffer overflow is to overwrite the return address with the address of an instruction in the running program
- ▶ If the target instruction is chosen carefully, it may be able to cause the execution of an arbitrary function with arbitrary arguments
- ▶ For example, if the return address is overwritten with a code address leading to the execution of the `system` function, an arbitrary program could be executed
- ▶ The exploit must somehow manage to forge argument(s): `pop` instructions are useful for this

# The costs of buffer overflow vulnerabilities

- ▶ Security compromises of computer systems cost the U.S. economy many *billions* of dollars annually
- ▶ Buffer overflows are an important category of security vulnerability
  - ▶ But there are many other types of vulnerabilities!

# Mitigations for buffer overflows

# Mitigations for buffer overflows

- ▶ What can we do about buffer overflows?
  - ▶ Write code that doesn't have bugs
  - ▶ Use memory-safe programming languages
  - ▶ Make stack non-executable
  - ▶ Address space randomization
  - ▶ Detect stack smashing

# Write code that doesn't have bugs

- ▶ There are lots of things we can do to improve code quality:
  - ▶ Thorough testing
  - ▶ Code reviews
  - ▶ Static analysis
- ▶ These are all good ideas, and they will help
  - ▶ None of these techniques will catch all bugs

# Use memory-safe programming languages

- ▶ There are programming languages which guarantee memory safety: Java, Rust (except for “unsafe” code), etc.
  - ▶ Memory references are checked at compile time and/or runtime to ensure that only valid memory locations are accessed by the program
- ▶ These languages can (in principle) eliminate the possibility of buffer overflows
  - ▶ Other kinds of security vulnerabilities are still possible
- ▶ Choose the right language for the job

# Make stack non-executable

- ▶ x86-64 systems allow regions of memory to be marked as non-executable
  - ▶ Attempt to execute code from non-executable regions results in a processor exception which can be handled by the OS kernel
- ▶ This can eliminate the possibility of a buffer overflow resulting in arbitrary code execution from the stack
- ▶ Recall example memory map from Lecture 6 (stack is not executable):  
00007fff84484000      132K rw---      stack
- ▶ This does not eliminate the possibility of security vulnerabilities, but it makes them harder to implement

# Address space randomization

- ▶ For exploits which depend on knowing the current (approximate) stack pointer value, the OS kernel can randomly choose where to place the stack in memory
- ▶ Code and data in *position-independent* executables can be loaded into memory at arbitrary addresses
  - ▶ Exploits depending on a return address jumping to a specific instruction become less likely to succeed
- ▶ Address space randomization techniques make exploits more difficult, but don't make them impossible



# Detect stack smashing

- ▶ Compiler can generate code to detect improper modification of stack memory:
  - ▶ On procedure entry, store a “stack canary” value near the return address
  - ▶ Prior to return, check the canary value
  - ▶ If canary was modified, terminate program
- ▶ Canary value generated randomly, cannot easily be guessed
- ▶ Return address (in theory) can't be overwritten without also overwriting canary value
- ▶ Small runtime overhead incurred on instrumented function calls
- ▶ Enabled by default in recent Linux/gcc



Not actually a canary