Buffer Overflows

CSE 351 Spring 2024

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Playlist: CSE 351 24Sp Lecture Tunes!

Relevant Course Information

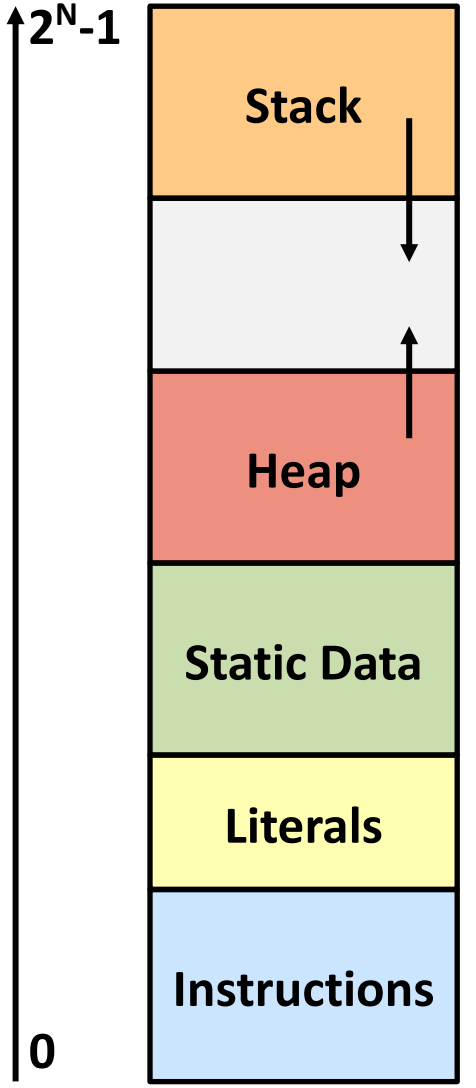
- Lab 2 due tonight & Lab 3 releasing today, due May 8th
  - You will have everything you need for it by the end of this lecture!
- HW13/14 due May 1st, HW15 due May 3rd
- Mid-Quarter Assessment results & write-up coming soon!
- Canvas Mid-Quarter Survey releasing on May 1st
  - Part of EPA grade
  - Particularly focusing on TA feedback
  - Due May 6th

Buffer Overflows

- Address space layout review
- Input buffers on the stack
- Overflowing buffers and injecting code
- Defenses against buffer overflows

Review: General Memory Layout

- Stack
  - Local variables (procedure context)
- Heap
  - Dynamically allocated as needed
  - `new`, `malloc()`, `calloc()`, …
- Statically-allocated Data
  - Read/write: global variables (Static Data)
  - Read-only: string literals (Literals)
- Code/Instructions
  - Executable machine instructions
  - Read-only



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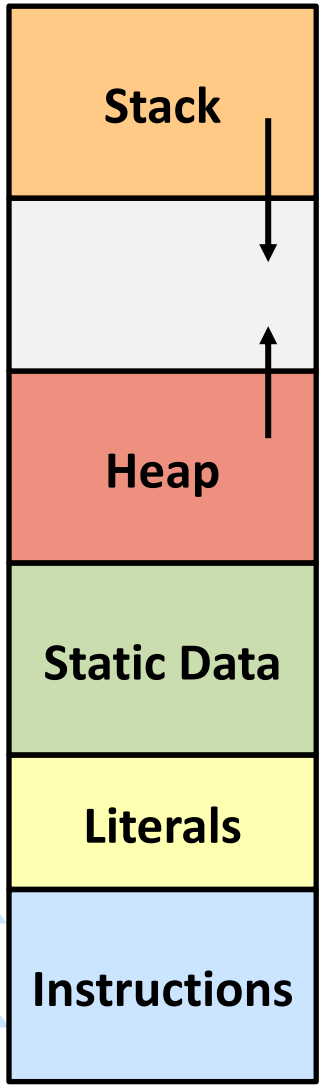
Memory Allocation Example

```
char big_array[1L<<24];  /* 16 MB */

int global = 0;

int useless() { return 0; }

int main() {
  void *p1, *p2;
  int local = 0;
  p1 = malloc(1L << 28);  /* 256 MB */
  p2 = malloc(1L << 8);   /* 256 B */
  /* Some print statements ... */
}
```



not drawn to scale!

Where does everything go?

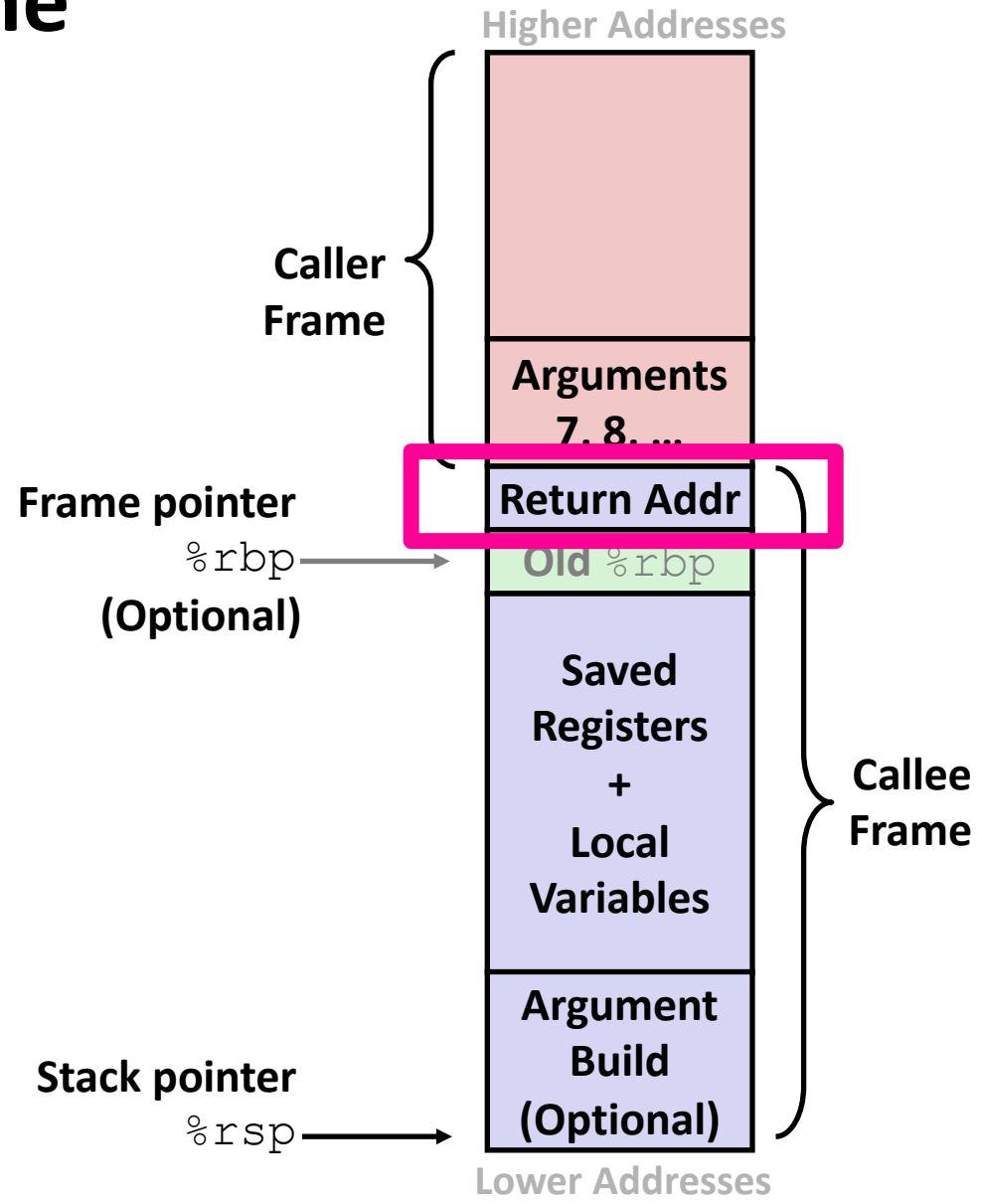
What Is a Buffer?

- A **buffer** is an array used to temporarily store data
- You've probably seen "video buffering…"
  - The video is being written into a buffer before being played

- Buffers can also be used to store user input… 🤔

Reminder: x86-64/Linux Stack Frame

- Caller's Stack Frame
  - Arguments (if > 6 args) for this call
- Current/Callee Stack Frame
  - Return address, pushed by `call` instruction
  - Old frame pointer (optional)
  - Caller-saved registers pushed before setting up arguments for a function call
  - Callee-saved registers pushed before using long-term registers
  - Local variables, if can't be kept in registers
  - "Argument build" area—Need to call a function with >6 arguments? Put them here!



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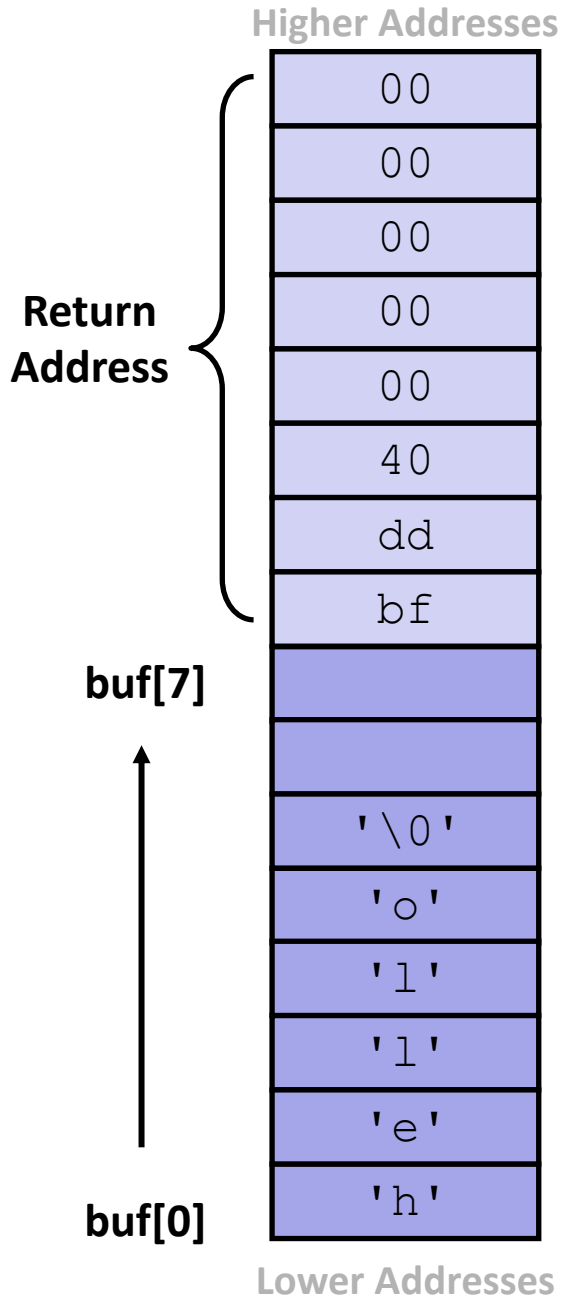
Buffer Overflow in a Nutshell

- Stack grows *down* towards lower addresses
- Buffer grows *up* towards higher addresses
- If we write past the end of the array, we overwrite data on the stack!



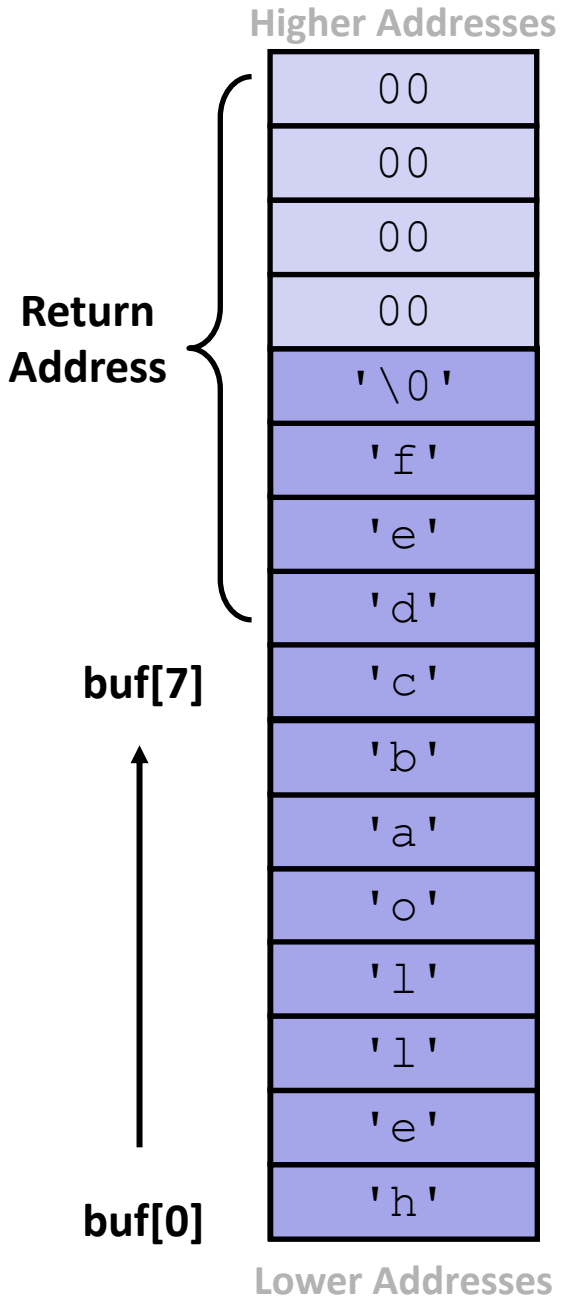

```
Enter input: hello
```

No overflow ☺

Buffer Overflow in a Nutshell

- Stack grows *down* towards lower addresses
- Buffer grows *up* towards higher addresses
- If we write past the end of the array, we overwrite data on the stack!

```
Enter input: helloabcdef
```



Buffer Overflow in a Nutshell

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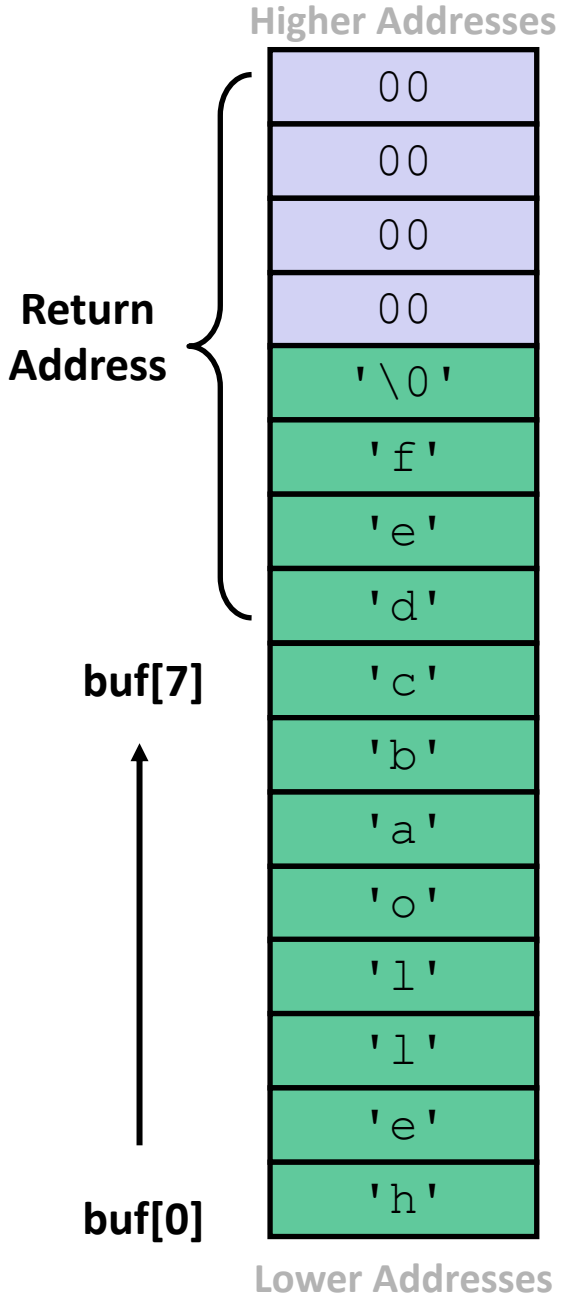



```
Enter input: helloabcdef
```

Buffer overflow! ☹

Buffer Overflow in a Nutshell

- Buffer overflows on the stack can overwrite "interesting" data
  - Attackers just choose the right inputs

- Simplest form: sometimes called "stack smashing"
  - Unchecked length on string input into bounded array causes overwriting of stack data
  - Specifically, try to change the return address of the current procedure!

- Why is this a big deal?
  - It was the #1 **technical** cause of security vulnerabilities!
    - e.g. Heartbleed, cloudbleed, etc.
    - #1 overall cause is social engineering/user ignorance 😬

So let's see how systems let us do this…

String Library Code

- Actual source code implementation of Unix function `gets()`:

```
/* Get string from stdin
one character at a time */
char* gets(char* dest) {
    int c = getchar(); // read 1 byte
    char* p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

pointer to start of an array

same as:

```
*p = c;
p++;
```

What could go wrong in this code?

String Library Code

- Actual source code implementation of Unix function `gets()`:

```
/* Get string from stdin
one character at a time */
char* gets(char* dest) {
    int c = getchar(); // read 1 byte
    char* p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getchar();
    }
    *p = '\0';
    return dest;
}
```

Similar problems with other Unix functions:

- `strcpy`: Copies string of arbitrary length to a dst
- `scanf`, `fscanf`, `sscanf`, when given `%s` specifier

🚨 No way to specify **limit** on number of characters to read! 🚨
The `man` page for `gets(3)` now says "BUGS: Never use `gets()`."

An Example: Vulnerable Buffer Code

```
void call_echo() {
    echo();
}
```

```
/* Echo Line */
void echo() {
    char buf[8];  /* Way too small! */
    gets(buf);    /* Read input into buf */
    puts(buf);    /* Print output from buf */
}
```

```
unix> ./buf-nsp
Enter string: 123456789012345
123456789012345
```

```
unix> ./buf-nsp
Enter string: 1234567890123456
Segmentation fault (core dumped)
```

Buffer Overflow Disassembly (`buf-nsp`)

call_echo:

```
0000000000401177 <call_echo>:
  401177:  48 83 ec 08           sub    $0x8,%rsp
  40117b:  b8 00 00 00 00        mov    $0x0,%eax
  401180:  e8 c1 ff ff ff        callq  401146 <echo>
  401185:  48 83 c4 08           add    $0x8,%rsp
  401189:  c3                    retq
```

return address to place on stack

echo:

```
 0000000000401146 <echo>:
  401146:  48 83 ec 18           sub    $0x18,%rsp
    ...                           ... calls printf ...
  401159:  48 8d 7c 24 08        lea    0x8(%rsp),%rdi
  40115e:  b8 00 00 00 00        mov    $0x0,%eax
  401163:  e8 e8 fe ff ff        callq  401050 <gets@plt>
  401168:  48 8d 7c 24 08        lea    0x8(%rsp),%rdi
  40116d:  e8 be fe ff ff        callq  401030 <puts@plt>
  401172:  48 83 c4 18           add    $0x18,%rsp
  401176:  c3                    retq
```

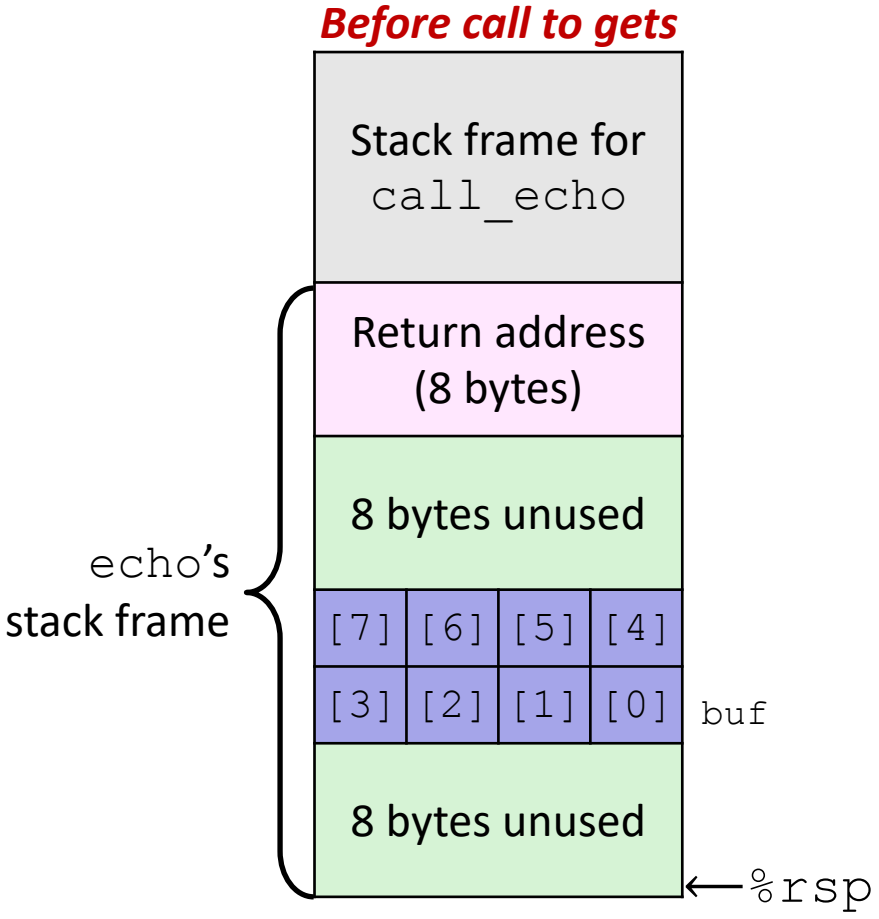
Allocate 24 bytes in stack (compiler's choice)

Calculate address location to be passed to `gets`

Calculate address location to be passed to `puts`

Clean up stack & return

Buffer Overflow Stack

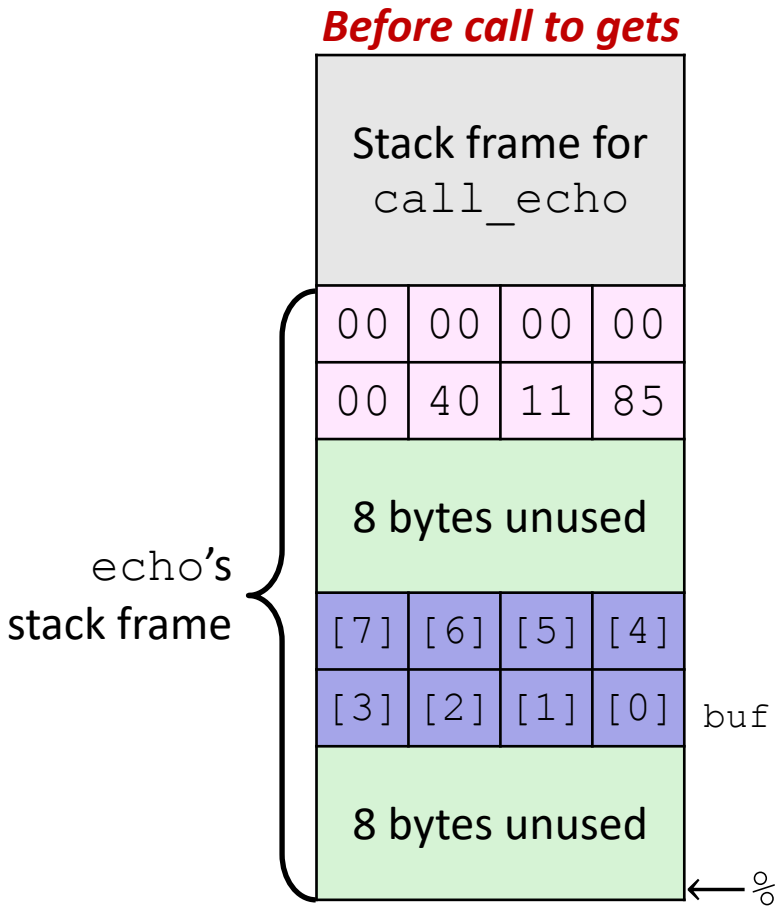



```
/* Echo Line */
void echo()
{
    char buf[8];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
  subq   $24, %rsp
    ...
  leaq   8(%rsp), %rdi
  mov    $0x0,%eax
  call   gets
    ...
```

Note: addresses increasing right-to-left, bottom-to-top

Buffer Overflow Setup



call_echo:

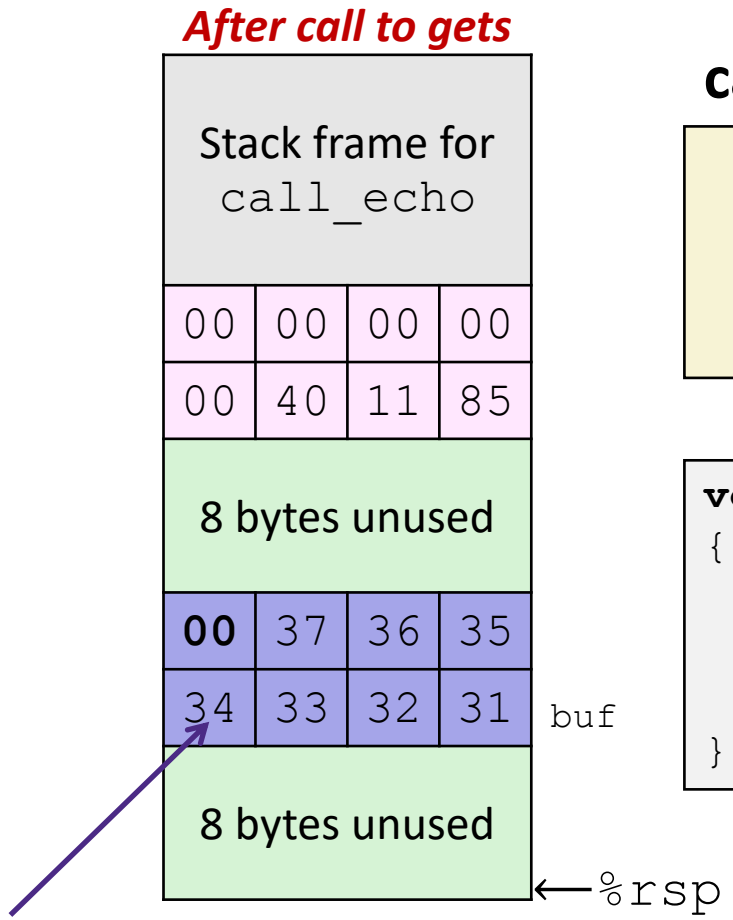
```
   . . .
   401180:  callq  401146 <echo>
   401185:  add    $0x8,%rsp
   . . .
```

```
void echo()
{
    char buf[8];
    gets(buf);
    . . .
}
```

```
echo:
   subq   $24, %rsp
    ...
   leaq   8(%rsp), %rdi
   mov    $0x0,%eax
   call   gets
    ...
```

Note: addresses increasing right-to-left, bottom-to-top

Buffer Overflow Example #1: 1234567



Note: Digit "*N*" is just 0x3*N* in ASCII!

call_echo:

```
   . . .
   401180:  callq  401146 <echo>
   401185:  add    $0x8,%rsp
   . . .
```

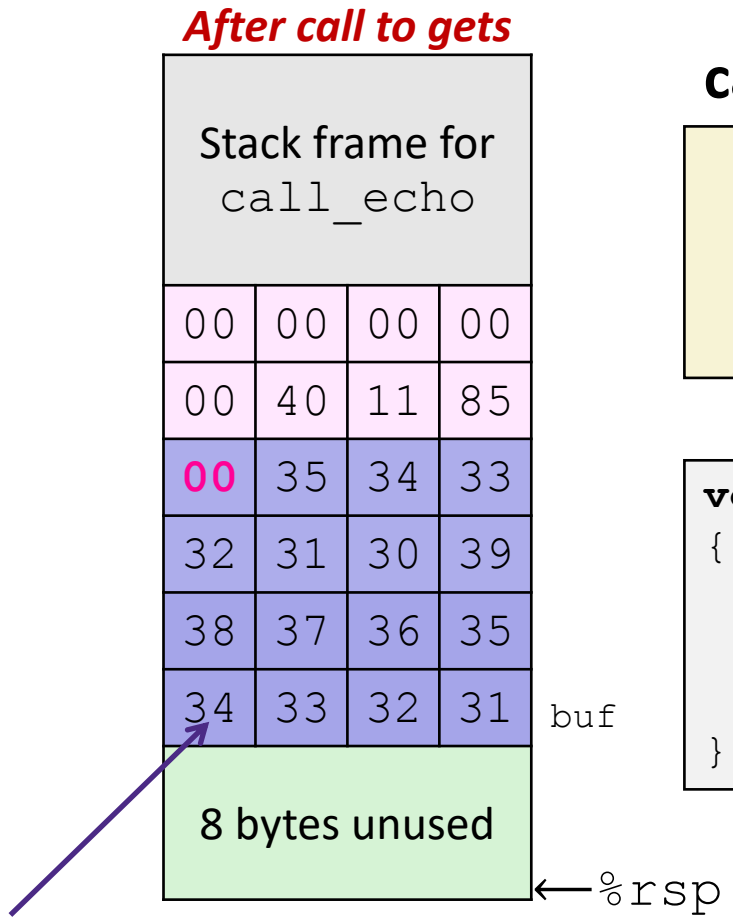
```
void echo()
{
    char buf[8];
    gets(buf);
    . . .
}
```

```
echo:
   subq   $24, %rsp
    ...
   leaq   8(%rsp), %rdi
   mov    $0x0,%eax
   call   gets
    ...
```

```
unix> ./buf-nsp
Enter string: 1234567
1234567
```

All good! No overflow. Phew!

Buffer Overflow Example #2: 123456789012345



Note: Digit "*N*" is just 0x3*N* in ASCII!

call_echo:

```
   . . .
   401180:  callq  401146 <echo>
   401185:  add    $0x8,%rsp
   . . .
```

```
void echo()
{
    char buf[8];
    gets(buf);
    . . .
}
```

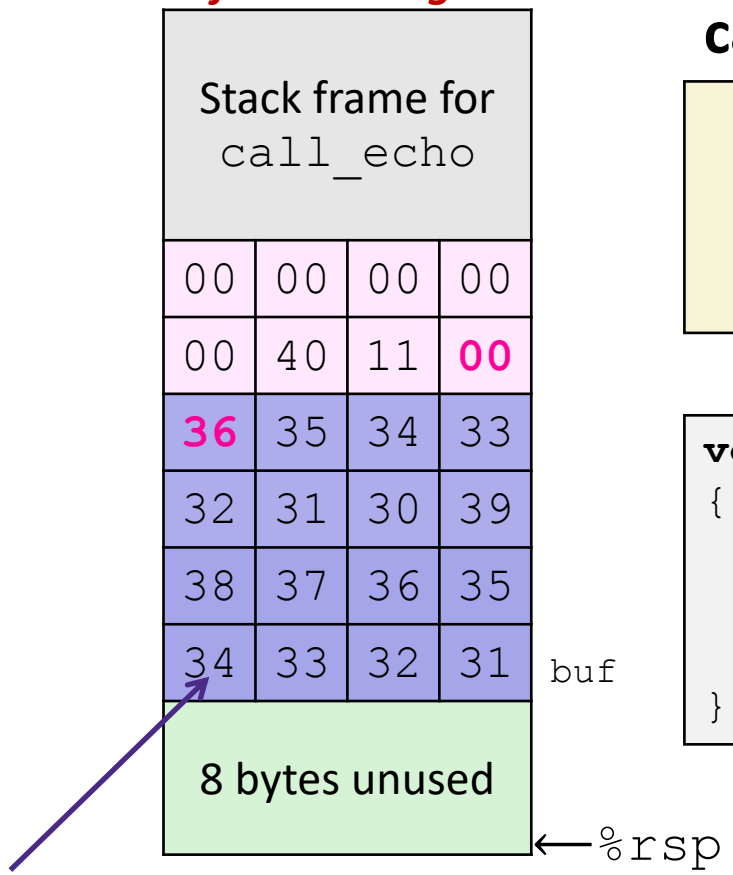
```
echo:
   subq   $24, %rsp
    ...
   leaq   8(%rsp), %rdi
   mov    $0x0,%eax
   call   gets
    ...
```

```
unix> ./buf-nsp
Enter string: 123456789012345
123456789012345
```

Overflowed buffer, but did not corrupt state.

Buffer Overflow Example #3: 1234567890123456

After call to gets



Note: Digit "*N*" is just 0x3*N* in ASCII!

call_echo:

```
   . . .
   401180:  callq  401146 <echo>
   401185:  add    $0x8,%rsp
   . . .
```

```
void echo()
{
    char buf[8];
    gets(buf);
    . . .
}
```

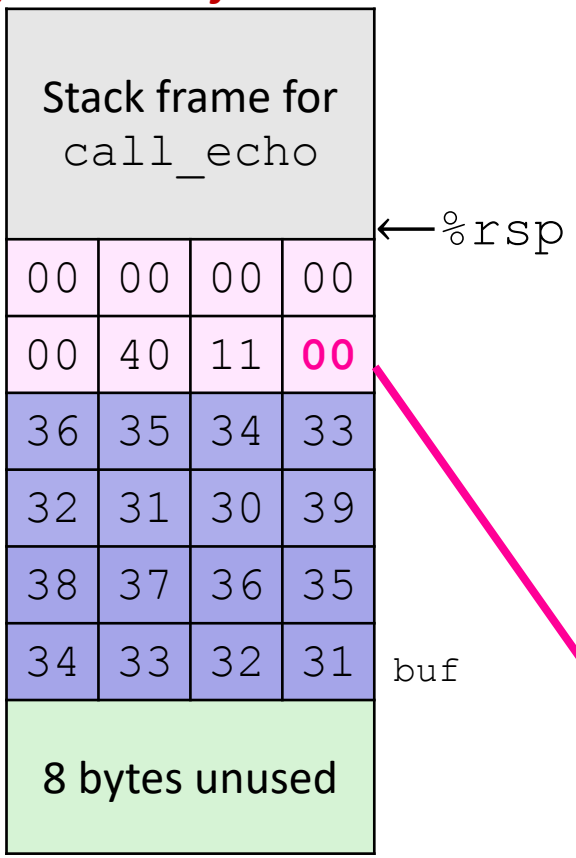
```
echo:
   subq   $24, %rsp
    ...
   leaq   8(%rsp), %rdi
   mov    $0x0,%eax
   call   gets
    ...
```

```
unix> ./buf-nsp
Enter string: 12345678901234566
Segmentation fault (core dumped)
```

Overflowed buffer and corrupted return pointer!

Buffer Overflow Example #3 Explained

After return from echo




```
0000000000004010d0 <register_tm_clones>:
  4010d0:  lea    0x2f61(%rip),%rdi
  4010d7:  lea    0x2f5a(%rip),%rsi
  4010de:  sub    %rdi,%rsi
  4010e1:  mov    %rsi,%rax
  4010e4:  shr    $0x3f,%rsi
  4010e8:  sar    $0x3,%rax
  4010ec:  add    %rax,%rsi
  4010ef:  sar    %rsi
  4010f2:  je     401108
  4010f4:  mov    0x2efd(%rip),%rax
  4010fb:  test   %rax,%rax
  4010fe:  je     401108
  401100:  jmpq   *%rax
  401102:  nopw   0x0(%rax,%rax,1)
  401108:  retq
```

"Returns" to a valid instruction, but **bad indirect jump**
so program signals `SIGSEGV, Segmentation fault`

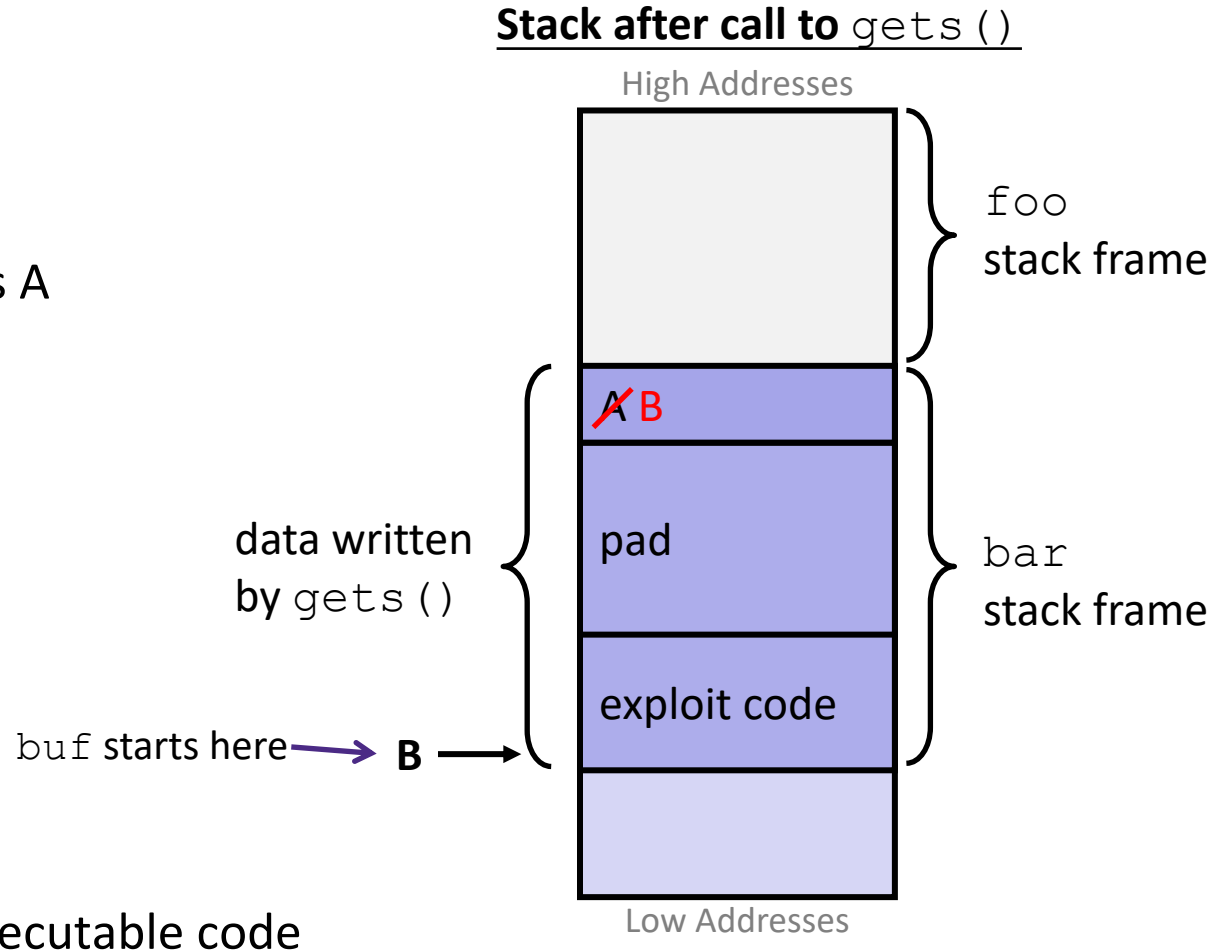
Attack Time

Malicious Use of Buffer Overflow: Code Injection Attacks

```
void foo(){
  bar();
A:...
}
```

return address A

```
int bar() {
  char buf[64];
  gets(buf);
  ...
  return ...;
}
```



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