Machine-Level Programming V: Advanced Topics

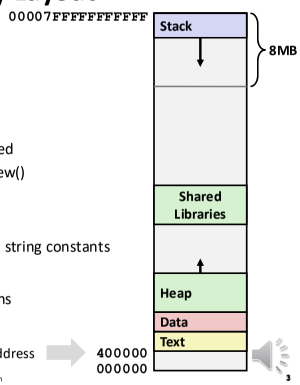
Today

- **Memory Layout**
- **Buffer Overflow**
  - Vulnerability
  - Protection
- **Unions**

x86-64 Linux Memory Layout

not drawn to scale

- **Stack**
  - Runtime stack (8MB limit)
  - E. g., local variables
- **Heap**
  - Dynamically allocated as needed
  - When call malloc(), calloc(), new()
- **Data**
  - Statically allocated data
  - E.g., global vars, `static` vars, string constants
- **Text / Shared Libraries**
  - Executable machine instructions
  - Read-only



Memory Allocation Example

not drawn to scale

```
char big_array[1L<<24];  /* 16 MB */
char huge_array[1L<<31]; /*  2 GB */

int global = 0;

int useless() { return 0; }

int main ()
{
    void *p1, *p2, *p3, *p4;
    int local = 0;
    p1 = malloc(1L << 28); /* 256 MB */
    p2 = malloc(1L << 8);  /* 256  B */
    p3 = malloc(1L << 32); /*   4 GB */
    p4 = malloc(1L << 8);  /* 256  B */
 /* Some print statements ... */
}
```

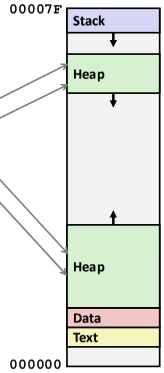
Where does everything go?

x86-64 Example Addresses

not drawn to scale

address range ~2^{47}

local	0x00007ffe4d3be87c
p1	0x00007f7262a1e010
p3	0x00007f7162a1d010
p4	0x000000008359d120
p2	0x000000008359d010
big_array	0x0000000080601060
huge_array	0x0000000000601060
main()	0x000000000040060c
useless()	0x0000000000400590



Today

- Memory Layout
- **Buffer Overflow**
  - Vulnerability
  - Protection
- Unions

Recall: Memory Referencing Bug Example

```
typedef struct {
  int a[2];
  double d;
} struct_t;

double fun(int i) {
  volatile struct_t s;
  s.d = 3.14;
  s.a[i] = 1073741824; /* Possibly out of bounds */
  return s.d;
}
```

```
fun(0)  →   3.14
fun(1)  →   3.14
fun(2)  →   3.1399998664856
fun(3)  →   2.00000061035156
fun(4)  →   3.14
fun(6)  →   Segmentation fault
```


Memory Referencing Bug Example

```
typedef struct {
  int a[2];
  double d;
} struct_t;
```

```
fun(0)  →   3.14
fun(1)  →   3.14
fun(2)  →   3.1399998664856
fun(3)  →   2.00000061035156
fun(4)  →   3.14
fun(6)  →   Segmentation fault
```

Explanation:

	Critical State	6
	?	5
	?	4
struct_t	d7 ... d4	3
struct_t	d3 ... d0	2
struct_t	a[1]	1
struct_t	a[0]	0

Location accessed by `fun(i)`

Such problems are a BIG deal

- **Generally called a "buffer overflow"**
  - when exceeding the memory size allocated for an array
- **Why a big deal?**
  - It's the #1 technical cause of security vulnerabilities
    - #1 overall cause is social engineering / user ignorance
- **Most common form**
  - Unchecked lengths on string inputs
  - Particularly for bounded character arrays on the stack
    - sometimes referred to as stack smashing

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);
}
```

← btw, how big is big enough?

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

```
unix>./bufdemo-nsp
Type a string:01234567890123456789012
01234567890123456789012
```

```
unix>./bufdemo-nsp
Type a string:012345678901234567890123
Segmentation Fault
```


Buffer Overflow Disassembly

echo:

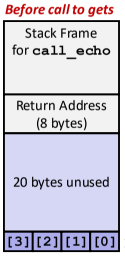
```
00000000004006cf <echo>:
 4006cf:  48 83 ec 18           sub    $0x18,%rsp
 4006d3:  48 89 e7              mov    %rsp,%rdi
 4006d6:  e8 a5 ff ff ff        callq  400680 <gets>
 4006db:  48 89 e7              mov    %rsp,%rdi
 4006de:  e8 3d fe ff ff        callq  400520 <puts@plt>
 4006e3:  48 83 c4 18           add    $0x18,%rsp
 4006e7:  c3                    retq
```

call_echo:

```
 4006e8:   48 83 ec 08            sub    $0x8,%rsp
  4006ec:  b8 00 00 00 00         mov    $0x0,%eax
  4006f1:  e8 d9 ff ff ff         callq  4006cf <echo>
  4006f6:  48 83 c4 08            add    $0x8,%rsp
  4006fa:  c3                     retq
```

Buffer Overflow Stack

Before call to gets

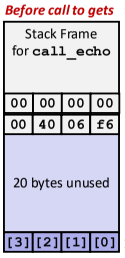



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
   subq   $24, %rsp
   movq   %rsp, %rdi
   call   gets
   . . .
```


Buffer Overflow Stack Example

Before call to gets




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

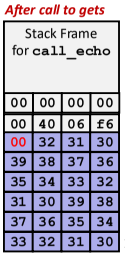
```
echo:
   subq   $24, %rsp
   movq   %rsp, %rdi
   call   gets
   . . .
```

call_echo:

```
   . . .
   4006f1:  callq  4006cf <echo>
   4006f6:  add    $0x8,%rsp
   . . .
```


Buffer Overflow Stack Example #1

After call to gets




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

```
echo:
   subq   $24, %rsp
   movq   %rsp, %rdi
   call   gets
   . . .
```

call_echo:

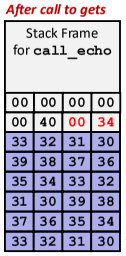
```
   . . .
   4006f1:  callq  4006cf <echo>
   4006f6:  add    $0x8,%rsp
   . . .
```

```
unix>./bufdemo-nsp
Type a string:0123456789012345678901234
0123456789012345678901234
```

Overflowed buffer, but did not corrupt state

Buffer Overflow Stack Example #2

After call to gets




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

```
echo:
   subq   $24, %rsp
   movq   %rsp, %rdi
   call   gets
   . . .
```

call_echo:

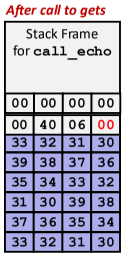
```
   . . .
   4006f1:  callq  4006cf <echo>
   4006f6:  add    $0x8,%rsp
   . . .
```

```
unix>./bufdemo-nsp
Type a string:01234567890123456789012345
Segmentation Fault
```

Overflowed buffer and corrupted return pointer

Buffer Overflow Stack Example #3

After call to gets




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

```
echo:
   subq   $24, %rsp
   movq   %rsp, %rdi
   call   gets
   . . .
```

call_echo:

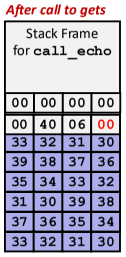
```
   . . .
   4006f1:  callq  4006cf <echo>
   4006f6:  add    $0x8,%rsp
   . . .
```

```
unix>./bufdemo-nsp
Type a string:012345678901234567890123
012345678901234567890123
```

Overflowed buffer, corrupted return pointer, but program seems to work!

Buffer Overflow Stack Example #3 Explained

After call to gets

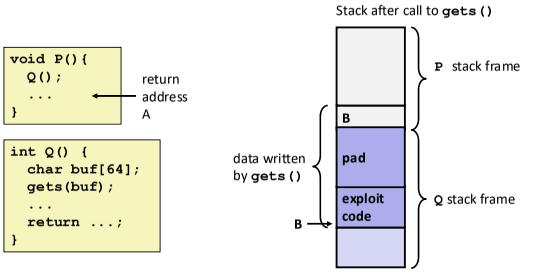


register_tm_clones:

```
   . . .
   400600:  mov    %rsp,%rbp
   400603:  mov    %rax,%rdx
   400606:  shr    $0x3f,%rdx
   40060a:  add    %rdx,%rax
   40060d:  sar    %rax
   400610:  jne    400614
   400612:  pop    %rbp
   400613:  retq
```

"Returns" to unrelated code
Lots of things happen, without modifying critical state
Eventually executes `retq` back to `main`

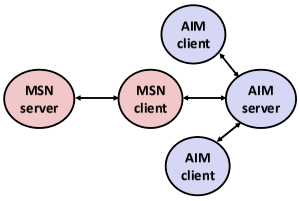
Code Injection Attacks



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

Example 2: IM War

- July, 1999
  - Microsoft launches MSN Messenger (instant messaging system).
  - Messenger clients can access popular AOL Instant Messaging Service (AIM) servers



Exploits Based on Buffer Overflows

- *Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines*
- Distressingly common in real progams
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult
- Examples across the decades
  - Original "Internet worm" (1988)
  - "IM wars" (1999)
  - Twilight hack on Wii (2000s)
  - ... and many, many more
- You will learn some of the tricks in attacklab
  - Hopefully to convince you to never leave such holes in your programs!!

IM War (cont.)

- August 1999
  - Mysteriously, Messenger clients can no longer access AIM servers
  - Microsoft and AOL begin the IM war:
    - AOL changes server to disallow Messenger clients
    - Microsoft makes changes to clients to defeat AOL changes
    - At least 13 such skirmishes
  - What was really happening?
    - AOL had discovered a buffer overflow bug in their own AIM clients
    - They exploited it to detect and block Microsoft: the exploit code returned a 4-byte signature (the bytes at some location in the AIM client) to server
    - When Microsoft changed code to match signature, AOL changed signature location

Example: the original Internet worm (1988)

- Exploited a few vulnerabilities to spread
  - Early versions of the finger server (fingerd) used `gets()` to read the argument sent by the client:
    - `finger droh@cs.cmu.edu`
  - Worm attacked fingerd server by sending phony argument:
    - `finger "exploit-code padding new-return-address"`
    - exploit code: executed a root shell on the victim machine with a direct TCP connection to the attacker.
- Once on a machine, scanned for other machines to attack
  - invaded ~6000 computers in hours (10% of the Internet ☺)
    - see June 1989 article in *Comm. of the ACM*
  - the young author of the worm was prosecuted...
  - and CERT was formed... still homed at CMU

OK, what to do about buffer overflow attacks

- Avoid overflow vulnerabilities
- Employ system-level protections
- Have compiler use "stack canaries"
- Lets talk about each...

1. Avoid Overflow Vulnerabilities in Code (!)

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

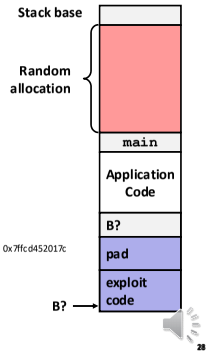
- For example, use library routines that limit string lengths
  - `fgets` instead of `gets`
  - `strncpy` instead of `strcpy`
  - Don't use `scanf` with `%s` conversion specification
    - Use `fgets` to read the string
    - Or use `%ns` where `n` is a suitable integer

2. System-Level Protections can help

- Randomized stack offsets
  - At start of program, allocate random amount of space on stack
  - Shifts stack addresses for entire program
  - Makes it difficult for hacker to predict beginning of inserted code
  - E.g.: 5 executions of memory allocation code

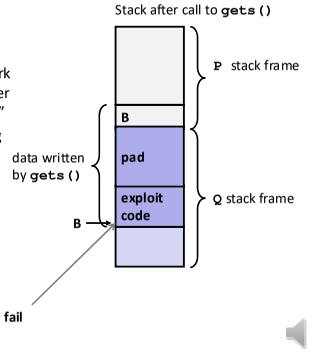
```
local  0x7ffe4d3be87c  0x7fff75a4f9fc  0x7ffeadb7c80c  0x7ffeaea2fdac  0x7ffcd452017c
```

  - Stack repositioned each time program executes



2. System-Level Protections can help

- Nonexecutable code segments
  - In traditional x86, can mark region of memory as either "read-only" or "writeable"
    - Can execute anything readable
  - X86-64 added explicit "execute" permission
  - Stack marked as non-executable



3. Stack Canaries can help

- Idea
  - Place special value ("canary") on stack just beyond buffer
  - Check for corruption before exiting function
- GCC Implementation
  - `-fstack-protector`
  - Now the default (disabled earlier)

```
unix>./bufdemo-sp
Type a string:0123456
0123456
```

```
unix>./bufdemo-sp
Type a string:01234567
*** stack smashing detected ***
```

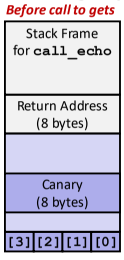
Protected Buffer Disassembly

echo:

```
40072f:  sub    $0x18,%rsp
400733:  mov    %fs:0x28,%rax
40073c:  mov    %rax,0x8(%rsp)
400741:  xor    %eax,%eax
400743:  mov    %rsp,%rdi
400746:  callq  4006e0 <gets>
40074b:  mov    %rsp,%rdi
40074e:  callq  400570 <puts@plt>
400753:  mov    0x8(%rsp),%rax
400758:  xor    %fs:0x28,%rax
400761:  je     400768 <echo+0x39>
400763:  callq  400580 <__stack_chk_fail@plt>
400768:  add    $0x18,%rsp
40076c:  retq
```

Setting Up Canary

Before call to gets

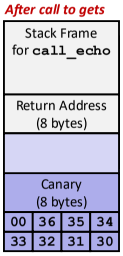



```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    gets(buf);
    puts(buf);
}
```

```
echo:
    . . .
    movq    %fs:40, %rax   # Get canary
    movq    %rax, 8(%rsp)  # Place on stack
    xorl    %eax, %eax     # Erase canary
    . . .
```

Checking Canary

After call to gets




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

Input: *0123456*

```
echo:
    . . .
    movq    8(%rsp), %rax     # Retrieve from
stack
    xorq    %fs:40, %rax      # Compare to canary
    je      .L6               # If same, OK
    call    __stack_chk_fail  # FAIL
.L6:        . . .
```


Return-Oriented Programming Attacks

- **Challenge (for hackers)**
  - Stack randomization makes it hard to predict buffer location
  - Marking stack nonexecutable makes it hard to insert binary code
- **Alternative Strategy**
  - Use existing code
    - E.g., library code from stdlib
  - String together fragments to achieve overall desired outcome
  - *Does not overcome stack canaries*
- **Construct program from *gadgets***
  - Sequence of instructions ending in `ret`
    - Encoded by single byte `0xc3`
  - Code positions fixed from run to run
  - Code is executable

Gadget Example #1

```
long ab_plus_c
  (long a, long b, long c)
{
   return a*b + c;
}
```

```
00000000004004d0 <ab_plus_c>:
  4004d0:  48 0f af fe   imul %rsi,%rdi
  4004d4:  48 8d 04 17   lea (%rdi,%rdx,1),%rax
  4004d8:  c3            retq
```

rax ← rdi + rdx

Gadget address = 0x4004d4

- **Use tail end of existing functions**

Gadget Example #2

```
void setval(unsigned *p) {
    *p = 3347663060u;
}
```

Encodes `movq %rax, %rdi`

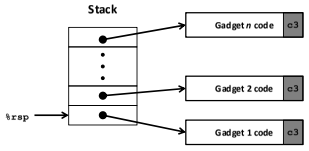
```
<setval>:
  4004d9:  c7 07 d4 48 89 c7   movl  $0xc78948d4,(%rdi)
  4004df:  c3                  retq
```

rdi ← rax

Gadget address = 0x4004dc

- **Repurpose byte codes**

ROP Execution



- **Trigger with `ret` instruction**
  - Will start executing Gadget 1
- **Final `ret` in each gadget will start next one**

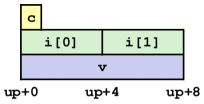
Today

- Memory Layout
- Buffer Overflow
  - Vulnerability
  - Protection
- **Unions**

Union Allocation

- Allocate according to largest element
- Can only use one field at a time

```
union U1 {
  char c;
  int i[2];
  double v;
} *up;
```




```
struct S1 {
  char c;
  int i[2];
  double v;
} *sp;
```