Machine Programming
Advanced Topics

CPSC 235 - Computer Organization

References

- Slides adapted from CMU

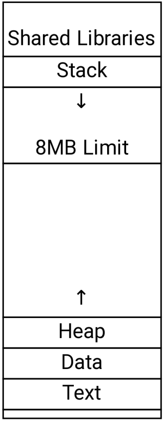
Outline

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

x86-64 Linux Memory Layout

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

x86-64 Linux Memory Layout



Memory Allocation Example

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

int global = 0;

int useless() { return 0; }

int main() {
    void *phuge1, *psmall2, *phuge3, *psmall4;
    int local = 0;
    phuge1 = malloc(1L << 28);  // 256 MB
    psmall2 = malloc(1L << 8);  // 256 B
    phuge3 = malloc(1L << 32);  // 4 GB
    psmall4 = malloc(1L << 8);  // 256 B
    // some print statements
}
```

x86-64 Example Addresses

Symbol	Example Address	Location
`local`	`0x00007ffe4d3be87c`	stack
`phuge1`	`0x00007f7262a1e010`	heap
`phuge3`	`0x00007f7162a1d010`	heap
`psmall4`	`0x000000008359d120`	heap
`psmall2`	`0x000000008359d010`	heap
`big_array`	`0x0000000080601060`	data
`huge_array`	`0x0000000000601060`	data
`main()`	`0x000000000040060c`	text
`useless()`	`0x0000000000400590`	text

- Note: there is a "gap" in the heap memory. More on this later.

Runaway Stack Example

```
int recurse(int x) {
    int a[1<<15];  // 128 KiB
    printf("x = %d.    a at %p\n", x, a);
    a[0] = (1<<14)-1;
    a[a[0]] = x-1;
    if (a[a[0]] == 0) {
        return -1;
    }
    return recurse(a[a[0]]) - 1;
}
```

- Functions store local data on stack in stack frame.
- Recursive functions cause deep nesting of stack frames.

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;
}
```

Memory Referencing Bug Example

- Example inputs/outputs
  - `fun(0)    ->    3.1400000000`
  - `fun(1)    ->    3.1400000000`
  - `fun(2)    ->    3.1399998665`
  - `fun(3)    ->    2.0000006104`
  - `fun(6)    ->    Stack smashing detected`
  - `fun(8)    ->    Segmentation fault`
- Results are system specific

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 is the number 1 technical cause of security vulnerabilities
  - What is the number 1 overall cause?
    - 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 Linux function `gets()`

```
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 specifier

Vulnerable Buffer Code

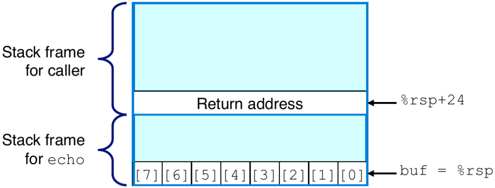
```
/* Echo Line */
void echo() {
    char buf[8]; // way too small
    gets(buf);
    puts(buf);
}

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

Buffer Overflow Disassembly

```
echo:
  subq  $24, %rsp   # allocate 24 bytes on stack
  movq  %rsp, %rdi  # compute buf as %rsp
  call  gets        # call gets
  movq  %rsp, %rdi  # compute buf as %rsp
  call  puts        # call puts
  addq  $24, %rsp   # deallocate stack space
  ret
```

Buffer Overflow Stack Example



Characters typed	Additional Corrupted State
0 - 7	None
9 - 23	Unused stack space
24 - 31	Return address
32+	Saved state in caller

Stack Smashing Attacks

- Overwrite the normal return address `A` with address of some other code `S`
- When `Q` executes `ret`, will jump to other code.

```
void P() {
    Q();
    ... // <- return address A
}
void Q() {
    char buf[64];
    gets(buf);
    ...
    return ...;
}
void S() {
    // something unexpected
}
```

Crafting Smashing String

- Target C code

```
void smash() {
    printf("I've been smashed!\n");
    exit(0);
}
```

- Target Disassembly

```
00000000004006c8 <smash>:
  4006c8:       48 83 ec 08
```

- Goal: craft a string that overwrites the return address with the address of the target function.

Performing Stack Smash

- Put hex string in file `smash-hex.txt`
- Use hexify program to convert hex digits to characters
  - Some of them are non-printing
- Provide as input to a vulnerable program.

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

```
void P() {
    Q();
    ...  // <- return address A
}

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

Preventing Buffer Overflow Attacks

- Avoid overflow vulnerabilities
- Employ system-level protections
- Have compiler use "stack canaries"

1. Avoid Overflow Vulnerabilities in Code

```
void echo() {
    char buf[4];
    fgets(buf, 4, stdin);
    puts(buf);
}
```

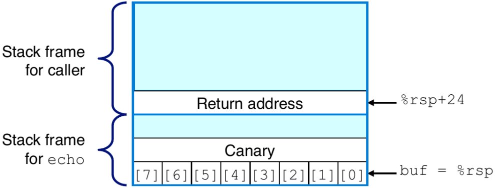
- For example, use library routines that limit string lengths
  - `fgets` instead of `gets`
  - `strncpy` instead of `strcpy`
  - Do not use `scanf` with `%s` conversion specifier
    - Use `fgets` to read the string
    - or use `%ns` where `n` is a suitable integer

System-Level Protections Can Help

- Randomize stack offsets
  - At start of program, allocate random amount of space on stack
  - Shift stack addresses for entire program
  - Makes it difficult for a hacker to predict the beginning of inserted code
- Non-executable code segments
  - In tradition x86 can mark region of memory as "read-only" or "writable"
    - Can execute anything readable
  - x86-64 added explicit "execute" permission
  - Stack marked as non-executable

Stack Canaries Can Help

- Idea
  - Place a special value ("canary") on stack just beyond buffer
  - Check for corruption before exiting function
- GCC Implementation
  - Flag `-fstack-protector`
- Example



Return-Oriented Programming Attacks

- Challenge (for hackers)
  - Stack randomization makes it hard to predict buffer location
  - Marking stack non-executable makes it hard to insert binary code
- Alternative Strategy
  - Use existing code
    - For example, library code fro 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

- C example code

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

- Disassembly

```
0000000000000000 <ab_plus_c>:
   0:   f3 0f 1e fa          endbr64
   4:   48 0f af fe          imul   %rsi,%rdi
   8:   48 8d 04 17          lea    (%rdi,%rdx,1),%rax
   c:   c3                   retq
```

  - rax $\leftarrow$ rdi + rdx
  - Gadget address = 0x8

- Use tail end of existing functions

Gadget Example #2

- C example code

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

- Disassembly

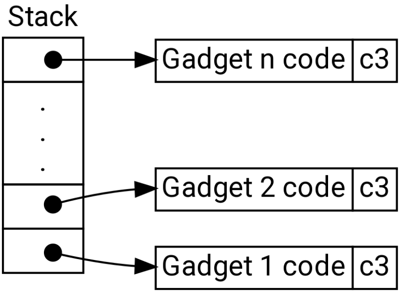
```
000000000000000d <setval>:
   d:   f3 0f 1e fa             endbr64
  11:   c7 07 d4 48 89 c7       movl   $0xc78948d4,(%rdi)
  17:   c3                      retq
```

  - Bytes `48 89 c7` encodes `movq %rax, %rdi%`
  - rdi ← rax
  - Gadget address = 0x15

- Repurpose byte codes

Return-Oriented Programming Execution

- Trigger with `ret` instruction
  - Will start executing Gadget 1
- Final `ret` in each gadget will start next one
  - `ret`: pop address from stack and jump to that address



Union Allocation

- Allocate according to largest element
- Can only use one field at a time
- Union example: 8 bytes total storage

```
union U1 {
    char c;   // 1 byte
    int i[2]; // 8 bytes
    double v; // 8 bytes
} *up;
```

- Struct example: 24 bytes total

```
struct S1 {
    char c;   // 1 byte + 3 bytes padding
    int i[2]; // 8 bytes + 4 bytes padding
    double v; // 8 bytes
} *up;
```

Using Union to Access Bit Patterns

```
typedef union {
    float f;
    unsigned u;
} bit_float_t;

float bit2float(unsigned u) {
    bit_float_t arg;
    arg.u = u;
    return arg.f;
}

unsigned float2bit(float f) {
    bit_float_t arg;
    arg.f = f;
    return arg.u;
}
```

Byte Ordering Revisited

- Idea
  - Short/long/quad words stored in memory as 2/4/8 consecutive bytes
  - Which byte is most (least) significant?
  - Can cause problems when exchanging binary data between machines
- Big Endian
  - Most significant byte has lowest address
  - Sparc, Internet
- Little Endian
  - Least significant byte has lowest address
  - x86, ARM
- Bi Endian
  - Can be configured either way
  - ARM

Summary of Compound Types in C

- Arrays
  - Contiguous allocation of memory
  - Aligned to satisfy every element's alignment requirement
  - Pointer to first element
  - No bounds checking
- Structures
  - Allocate bytes in order declared
  - Pad in middle and at end to satisfy alignment
- Unions
  - Overlay declarations
  - Way to circumvent type system

Summary

- Memory Layout
- Buffer Overflow
  - Vulnerability
  - Protection
  - Code Injection Attack
  - Return-Oriented Programming
- Unions