CSE 597: Security of Emerging Technologies
Module: Vulnerabilities

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Language of Choice for Systems Programming: C/C++

- Systems software
  - OS; hypervisor; web servers; firmware; network controllers; device drivers; compilers; …
- Benefits of C/C++: programming model close to the machine model; flexible; efficient
- BUT **error-prone**
  - C/C++ not memory safe; huge security risk
  - Debugging memory errors is a headache
    - Perhaps on par with debugging multithreaded programs

Buffer Overflows

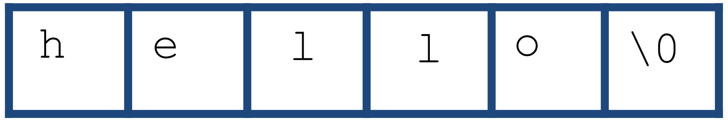
- Refer to reading/writing a buffer out of its bounds
  - Programmers' job in C/C++ to not do this
  - In contrast, many modern languages (Java, Python, …) prevent buffer overflows by performing automatic bounds-checking

- The first Internet worm, and many subsequent ones (CodeRed, Blaster, …) exploited buffer overflows

- Buffer overflows still cause many security alerts nowadays
  - E.g., check out CERT, cve.mitre.org, or bugtraq

C-style Strings

- C-style strings consist of a contiguous sequence of characters, terminated by and including the first null character.
  - String length is the number of bytes preceding the null character.
  - The number of bytes required to store a string is the number of characters plus one (times the size of each character).



`h`	`e`	`l`	`l`	`o`	`\0`

Using Strings in C

- C provides many string functions in its libraries (libc)
- For example, we use the strcpy function to copy one string to another:

```
#include <string.h>
char string1[] = "Hello, world!";
char string2[20];
strcpy(string2, string1);
```

Using Strings in C

- Another lets us compare strings

```
char string3[] = "this is"; char
string4[] = "a test";
if(strcmp(string3, string4) == 0)
 printf("strings are equal\n");
else printf("strings are different\n")
```

- This code fragment will print "strings are different". Notice that strcmp does **not** return a boolean result.

Other Common String Functions

- strlen: getting the length of a string
- strcpy/strncpy: string copying
- strcat/strncat: string concatenation
- gets, fgets: receive input to a string
- …

Common String Manipulation Errors

- Programming with C-style strings, in C or C++, is error prone
- Common errors include
  - buffer overflows
  - null-termination errors
  - off-by-one errors
  - …

gets: Unbounded String Copies

- Occur when data is copied from an unbounded source to a fixed-length character array

```
void main(void) {
 char Password[8];
 puts("Enter a 8-character password:");
 gets(Password);
 printf("Password=%s\n",Password);
}
```

strcpy and strcat

- The standard string library functions do not know the size of the destination buffer

```
int main(int argc, char *argv[]) {
    char name[2048];
    strcpy(name, argv[1]);
    strcat(name, " = ");
    strcat(name, argv[2]);
    ...
}
```

Better String Library Functions

- Functions that restrict the number of bytes are often recommended
- Never use gets(buf)
  - Use **fgets(buf, size, stdin)**instead

From gets to fgets

- char *fgets(char *BUF, int N, FILE *FP);
  - *"Reads at most N-1 characters from FP until a newline is found. The characters including to the newline are stored in BUF. The buffer is terminated with a 0."*

```
void main(void) {
    char Password[~~8~~]; 9
    puts("Enter a 8-character password:");
    fgets(Password, ~~8~~, stdin);
    …                           9
}
```

Better String Library Functions

- Instead of strcpy(), use strncpy()
- Instead of strcat(), use strncat()
- Instead of sprintf(), use snprintf()

But Still Need Care

- char *strncpy(char *s1, const char *s2, size_t n);
  - *“Copy not more than n characters (including the null character) from the array pointed to by s2 to the array pointed to by s1; If the string pointed to by s2 is shorter than n characters, null characters are appended to the destination array until a total of n characters have been written.”*
  - What happens if the size of s2 is n or greater
    - It gets truncated
    - **And s1 may not be null-terminated!**

Null-Termination Errors

```
int main(int argc, char* argv[]) {
  char a[16], b[16];
  strncpy(a, "0123456789abcdef", sizeof(a));
  printf(“%s\n”,a);
  strcpy(b, a);
}
```

a[] not properly terminated. Possible segmentation fault if printf(“%s\n”,a);

How to fix it?

strcpy to strncpy

- Don’t replace
    - strcpy(dest, src)
  - by
    - strncpy(dest, src, sizeof(dest)) but by
    - strncpy(dest, src, sizeof(dest)-1)
    - dst[sizeof(dest)-1] = `\0`;
  - if dest should be null-terminated!

- You never have this headache in memory-safe languages
- Further, strncpy has big performance penalty vs. strcpy
  - It NIL-fills the remainder of the destination

Signed vs Unsigned Numbers

```
char buf[N];
int i, len;

read(fd, &len, sizeof(len));
if (len > N)
  {error (“invalid length"); return; }
read(fd, buf, len);
```

We forget to check for negative lengths

`len` cast to unsigned and negative length overflows

*slide by Eric Poll

Checking for Negative Lengths

```
char buf[N];
int i, len;

read(fd, &len, sizeof(len));
if (len > N || len < 0)
    {erro  (“invalid length"); return; }
    r
read(fd, buf, len);
```

It still has a problem
if the buf is going to be treated as a C string.

*slide by Eric Poll

A Good Version

```
char buf[N];
int i, len;

read(fd, &len, sizeof(len));
if (len > N-1 || len < 0)
    {erro  (“invalid length"); return;  }
    r
read(fd, buf, len);
buf[len] = '\0'; // null terminate buf
```

*slide by Eric Poll

Integer Overflows

- An **integer overflow** occurs when an integer is increased beyond its maximum value or decreased beyond its minimum value

- Standard integer types (signed)
  - signed char, short int, int, long int, long long int

- Signed overflow vs unsigned overflow
  - An unsigned overflow occurs when the underlying representation can no longer represent an integer value.
  - A signed overflow occurs when a value is carried over to the sign bit

Overflow Examples

```
unsigned int ui;
signed int si;
ui = UINT_MAX; // 4,294,967,295;
ui++;
printf(“ui = %u\n", ui);
```

ui = 0

```
si = INT_MAX; // 2,147,483,647
si++;
printf(“si = %d\n", si);
```

si = -2,147,483,648

Overflow Examples, cont’d

```
ui = 0;
ui--;
printf(“ui = %u\n", ui);
```

ui = 4,294,967,295

```
si = INT_MIN; // -2,147,483,648;
si--;
printf(“si = %d\n", si);
```

si = 2,147,483,647

Integer Overflow Example

```
int main(int argc, char *const *argv) {
  unsigned short int total;
  total = strlen(argv[1]) + strlen(argv[2])
  + 1;
  char *buff = (char *) malloc(total);
  strcpy(buff, argv[1]);
  strcat(buff, argv[2]);
}
```

What if the total variable is overflowed because of the addition operation?

Buffer Overflow

- Stack overflow: overflow a memory region on the stack (e.g., overwrite a return address)
- Heap overflow: overflow a memory region dynamically allocated on the heap

```
int authenticated = 0;
char *packet = (char *)malloc(1000);

while (!authenticated) {
  PacketRead(packet);
  if (Authenticate(packet))
    authenticated = 1;
}
if (authenticated)
 ProcessPacket(packet);
```

What happens if PacketRead overflows the packet buffer and overwrite important data in memory?

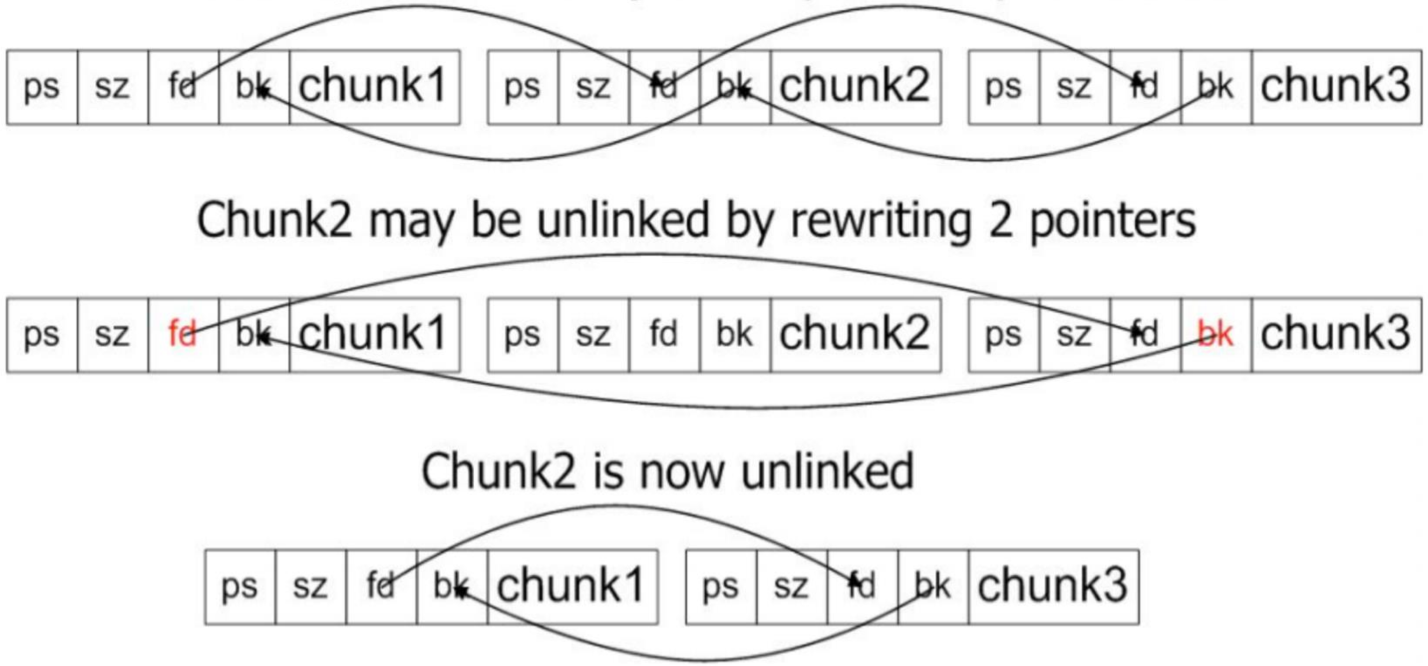
Overflow Heap Meta-Data

- Heap allocators (AKA memory managers)
  - What regions have been allocated and their sizes
  - What regions are available for allocation
- Heap allocators maintain metadata such as chunk size, previous, and next pointers
  - Metadata adjusted during heap-management functions
    - malloc() and free()
  - Heap metadata often adjacent to heap user data

Example Heap Allocator

- Maintain a doubly-linked list of allocated and free chunks
- malloc() and free() modify this list

An Example of Removing a Chunk



Chunk2 may be unlinked by rewriting 2 pointers

Chunk2 is now unlinked

- free() removes a chunk from allocated list
  - chunk2->bk->fd = chunk2->fd
  - chunk2->fd->bk = chunk2->bk

Attacking the Example Heap Allocator

- By overflowing chunk2, attacker controls bk and fd of chunk2
- Suppose the attacker wants to write value to memory address addr
  - Attacker sets chunk2->fd to be value
  - Attacker sets chunk2->bk to be addr-offset, where offset is the offset of the fd field in the structure

Attacking the Example Heap Allocator

- free() changed in the following way
  - chunk2->bk->fd = chunk2->fd becomes
    (addr-offset)->fd = value, the same as (*addr)=value
  - chunk2->fd->bk= chunk2->bk becomes
    value->bk = addr-offset
- The first memory write achieves the attacker's goal
  - Arbitrary memory writes

Use After Free

- Error: Program frees memory on the heap, but then references that memory as if it were still valid
  - Adversary can control data written using the freed pointer
- AKA use of dangling pointers

Use After Free

```
int main(int argc, char **argv) {
  char *buf1, *buf2, *buf3;

  buf1 = (char *) malloc(BUFSIZE1);

  free(buf1);


  buf2 = (char *) malloc(BUFSIZE2);
  buf3 = (char *) malloc(BUFSIZE2);
  strncpy(buf1, argv[1], BUFSIZE1-1);
  …

}
```

What happens here?

Use After Free

- When the first buffer is freed, that memory is available for reuse right away
- Then, the following buffers are possibly allocated within that memory region

```
buf2 = (char *) malloc(BUFSIZE2); buf3 =
(char *) malloc(BUFSIZE2);
```

- Finally, the write using the freed pointer may overwrite buf2 and buf3 (and their metadata)

```
strncpy(buf1, argv[1], BUFSIZE1-1);
```

Use After Free

- Most effective attacks exploit data of another type

```
struct A {
   void (*fnptr)(char *arg);
   char *buf;
};

struct B {
   int B1; int
   B2;
   char info[32];
};
```

Use After Free

- Free A, and allocate B does what?

```
x = (struct A *)malloc(sizeof(struct A));
free(x);
y = (struct B *)malloc(sizeof(struct B));
```

Use After Free

- How can you exploit it?

```
x = (struct A *)malloc(sizeof(struct A));
free(x);
y = (struct B *)malloc(sizeof(struct B));

y->B1 = 0xDEADBEEF;
x->fnptr(x->buf);
```

- Assume that
  - The attacker controls what to write to y->B1
  - There is a later use-after-free that performs a call using "x->fnptr"
- Become a popular vulnerability to exploit – over 60% of CVEs in 2018

Exercise: Find the Use-After-Free Error and Provide a fix

```
#include <stdlib.h>

struct node {
 struct node *next;
};

void func(struct node *head) { struct
 node *p;
 for (p = head; p != NULL; p = p->next) {
  free(p);
 }
}
```

Prevent Use After Free

- Difficult to detect because these often occur in complex runtime states
  - Allocate in one function
  - Free in another function
  - Use in a third function
- It is not fun to check source code for all possible pointers
  - Are all uses accessing valid (not freed) references?
  - In all possible runtime states

Prevent Use After Free

- What can you do that is not too complex?
  - You can set all freed pointers to NULL
    - Getting a null-pointer dereference if using it
    - Nowadays, OS has built-in defense for null-pointer deference
  - Then, no one can use them after they are freed
  - Complexity: need to set all aliased pointers to NULL

Related Problem: Double Free

```
main(int argc, char **argv)
{
     …
     buf1 = (char *) malloc(BUFSIZE1);
     free(buf1);
     buf2 = (char *) malloc(BUFSIZE2);
     strncpy(buf2, argv[1], BUFSIZE2-1);
     free(buf1);
     free(buf2);
}
```

`What happens here?`

Double Free

- Free buf1, then allocate buf2
  - buf2 may occupy the same memory space of buf1
- buf2 gets user-supplied data

```
strncpy(buf2, argv[1], BUFSIZE2-1);
```

- Free buf1 again
  - Which may use some buf2 data as metadata
  - And may mess up buf2's metadata
- Then free buf2, which uses really messed up metadata

What’s Wrong?

```
#include <stdlib.h>

int f(size_t n) {
  int error_condition = 0;

  int *x = (int *)malloc(n * sizeof(int));
  if (x == NULL)
    return -1;

  /* Use x and set error_condition on error. */
  …

  if (error_condition == 1) {
    /* Handle error */
    free(x);
  }

  free(x);
  return error_condition;
}
```

What's Wrong? Fix?

```
#include <stdlib.h>

/* p is a pointer to dynamically allocated memory. */
void func(void *p, size_t size) {
  p2 = realloc(p, size);
  if (p2 == NULL) {
    free(p);
    return;
  }
}
```

When size == 0, realloc(p,0) same As free(p)

Double Free

- So, "double free" can achieve the same effect as some heap overflow vulnerabilities
  - So, can be addressed in the same way
  - But, you can also save yourself some headache by setting freed pointers to NULL
  - Some new heap allocators nowadays have built-in defense against double free