COMP26020 Programming Languages and Paradigms Part 1: C Programming

Memory Safety

```
└─$ ./basic-test-suite
basic-test-suite.c:344:allocate:PASS
basic-test-suite.c:347:init_rand:PASS
basic-test-suite.c:348:init_zeros:PASS
basic-test-suite.c:349:init_identity:PASS
basic-test-suite.c:352:equal:PASS
basic-test-suite.c:355:sum:PASS
basic-test-suite.c:356:scalar_product:PASS
basic-test-suite.c:357:transposition:PASS
basic-test-suite.c:358:product:PASS
basic-test-suite.c:363:dump_file:PASS
basic-test-suite.c:366:load_from_file:PASS
basic-test-suite.c:369:dump_and_load_from_file:PASS
basic-test-suite.c:372:equal_file:PASS
basic-test-suite.c:375:sum_file:PASS
basic-test-suite.c:376:scalar_product_file:PASS
[1]    15440 segmentation fault  ./basic-test-suite
┌─pierre@pop ~/Desktop/comp26020/lab/lab1/code ‹master●›
└─$ 
```

Memory Unsafety in C Programs

- C, and other languages e.g. C++ **are inherently memory unsafe**
- There is absolutely no check at runtime if memory accessed is initialised, allocated, or mapped
- In most cases the compiler won't warn you either

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  - etc.

Memory Unsafety in C Programs

- Memory errors are **hard to detect, hard to debug**
    - No warning/error at compile-time
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⚠️ These bugs have huge security implications! ⚠️

Exploiting these bugs an attacker can:

- Leak sensitive data (e.g. passwords, crypto keys)
- Tamper with sensitive data
- Escalate privileges
- Take over the entire program

Microsoft: 70 percent of all security bugs are memory safety issues

Percentage of memory safety issues has been hovering at 70 percent for the past 12 years.

By Catalin Cimpanu for Zero Day | February 11, 2019 | Topic: Security

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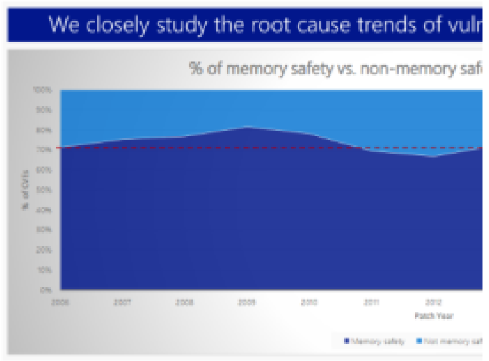
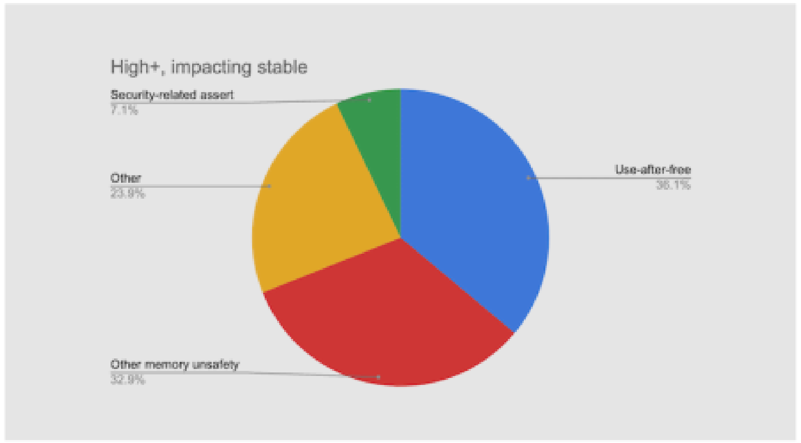


Image: Matt Miller

Chrome: 70% of all security bugs are memory safety issues

Google software engineers are looking into ways of eliminating memory management-related bugs from Chrome.

By Catalin Cimpanu for Zero Day | May 23, 2020 | Topic: Security



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ZDNet Security
Your weekly update on security around the globe, featuring research, threats, and more.

Sources: https://zd.net/3q8axgo, https://zd.net/3wfFHU7

Example 1: Infoleak

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Assume the following scenario:

- A security-sensitive program is distributed in binary-only form
- It contains sensitive data: a password
- An attacker has access to the binary only and aims to figure out the password

Example 1: Infoleak

Original code:

```c
char *welcome_message = "Hi there! How is it going?\n"; // 27 char
char *password = "secret";
char entered_password[128];

int main(int argc, char **argv) {
    for(int i=0; i<27; i++)  // Print welcome message character by character
        printf("%c", welcome_message[i]);

    printf("Please input the password:\n");
    scanf("%s", entered_password);

    if(!strcmp(entered_password, password)) { printf("Passowrd ok!\n"); /* ... */ }
    else { printf("Wrong password! aborting\n"); }

    return 0;
}
```

23-memory-safety/infoleak-orig.c

Example 1: Infoleak

Updated code (`welcome_message` shortened):

```c
char *welcome_message = "Hi there!\n"; // shortened welcome message, only 11 chars now
char *password = "secret";
char entered_password[128];

int main(int argc, char **argv) {
    for(int i=0; i<27; i++)
        printf("%c", welcome_message[i]);

    printf("Please input the password:\n");
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23-memory-safety/infoleak-updated.c

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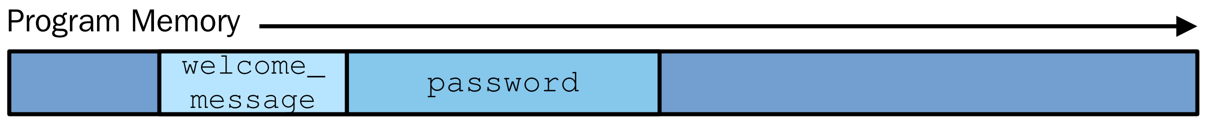
23-memory-safety/infoleak-updated.c



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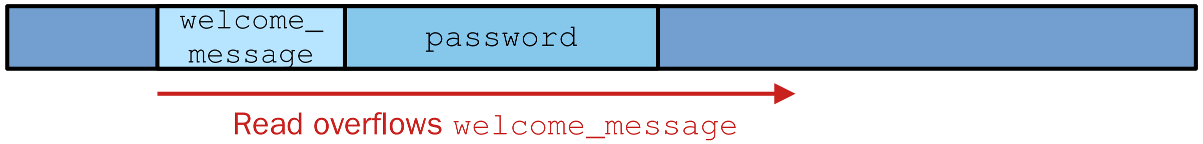

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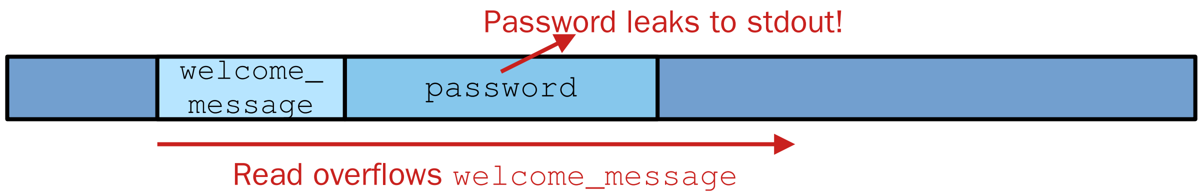

Example 2: Sensitive Data Tampering

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Assume the following scenario:

- Same type of program performing a password check
- This time we assume that the attacker has access to the source code (e.g. open source program)
- For that reason the password is stored encrypted
- Attacker aims to bypass the password check

Example 2: Sensitive Data Tampering

```c
char user_input[32] = "0000000000";
char password_hash[32] = "tfdsfu"; // "secret" encrypted with caesar cypher with shift 1

int main(int argc, char **argv) {

    if(argc != 2) { printf("Usage: %s <password>\n", argv[0]); return 0; }

    strcpy(user_input, argv[1]);
    caesar_encrypt(user_input);

    if(!strncmp(password_hash, user_input, strlen(password_hash))) {
        printf("login success!\n");
        /* do important stuff  ... */
    } else { printf("wrong password!\n");  }

    return 0;
}
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23-memory-safety/tampering.c

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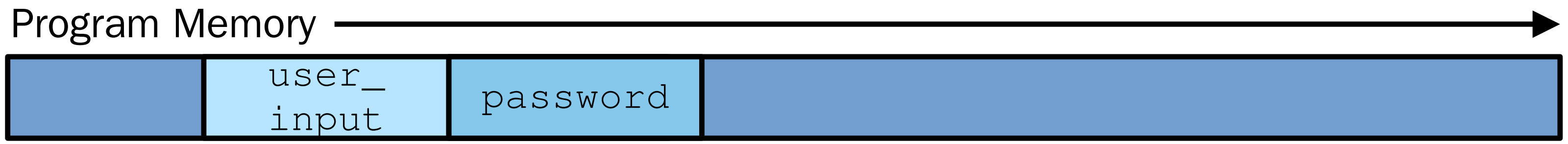

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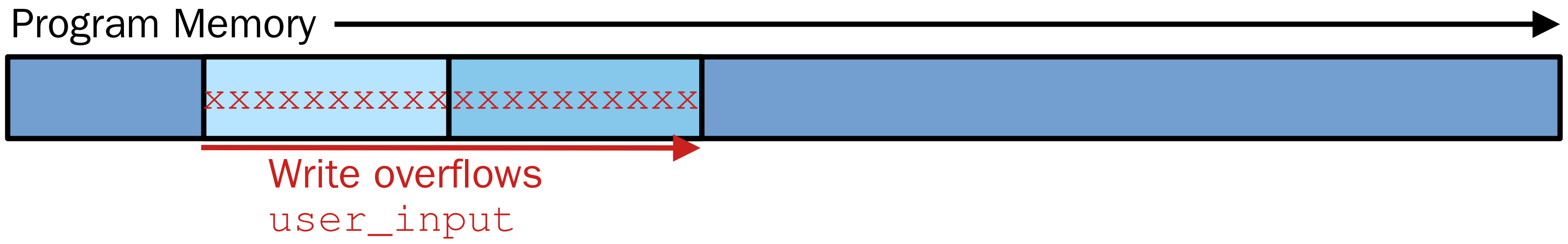

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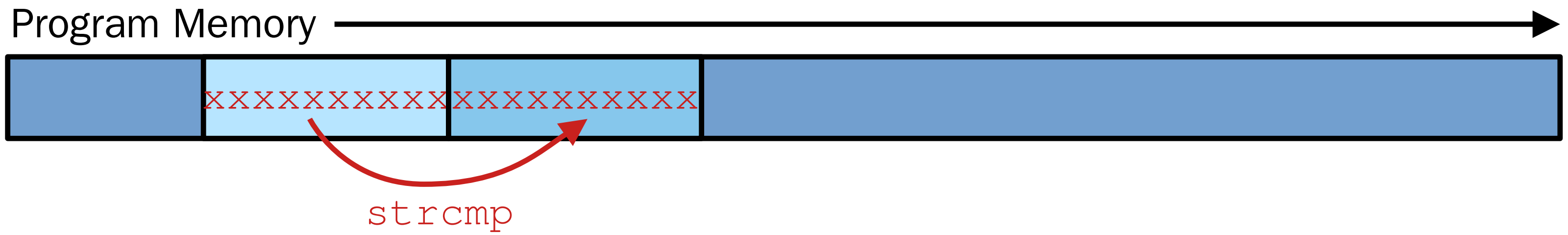
23-memory-safety/tampering.c



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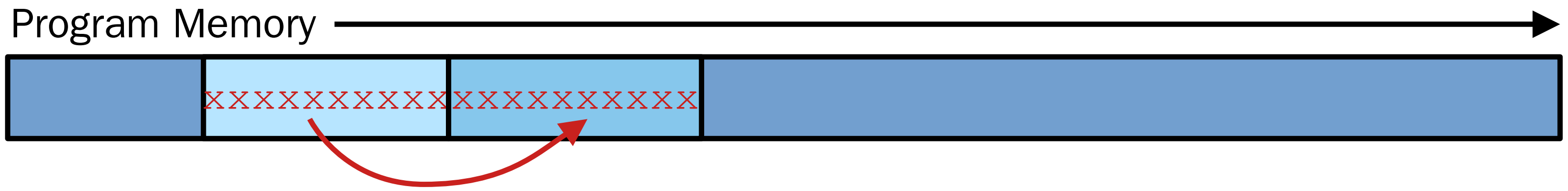
23-memory-safety/tampering.c



`strcmp` → strings are equal, password accepted!

Example 3: Stack Smashing

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- Classic control flow hijacking attack:
  - Attacker has external (e.g. command line) access to the program
  - Attacker exploits a bug to make the program execute code it's not supposed to
- Originally proposed in 1996 here: http://www.phrack.org/archives/issues/49/14.txt
- First let's see how the CPU manage function calls/returns

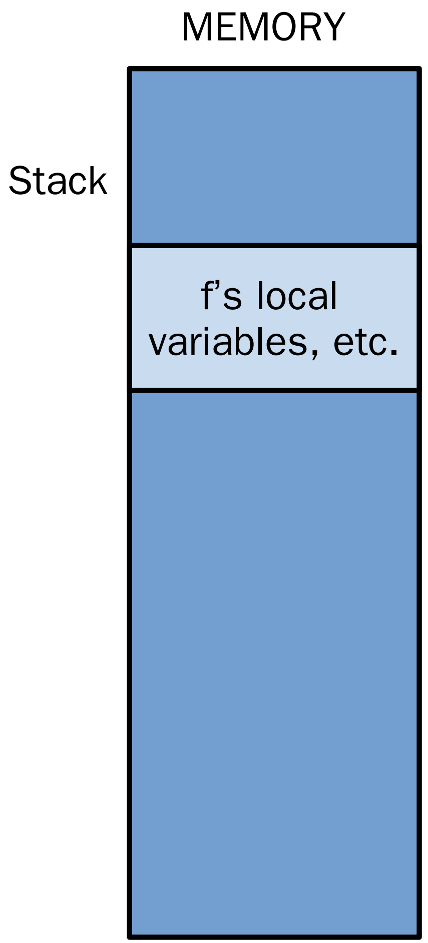
Example 3: Stack Smashing

C CODE

```
int f(double param)
{
    /* ... */
    g(x);
    /* ... */
}

void g(int param) {
    /* ... */
    return;
}
```

Example 3: Stack Smashing



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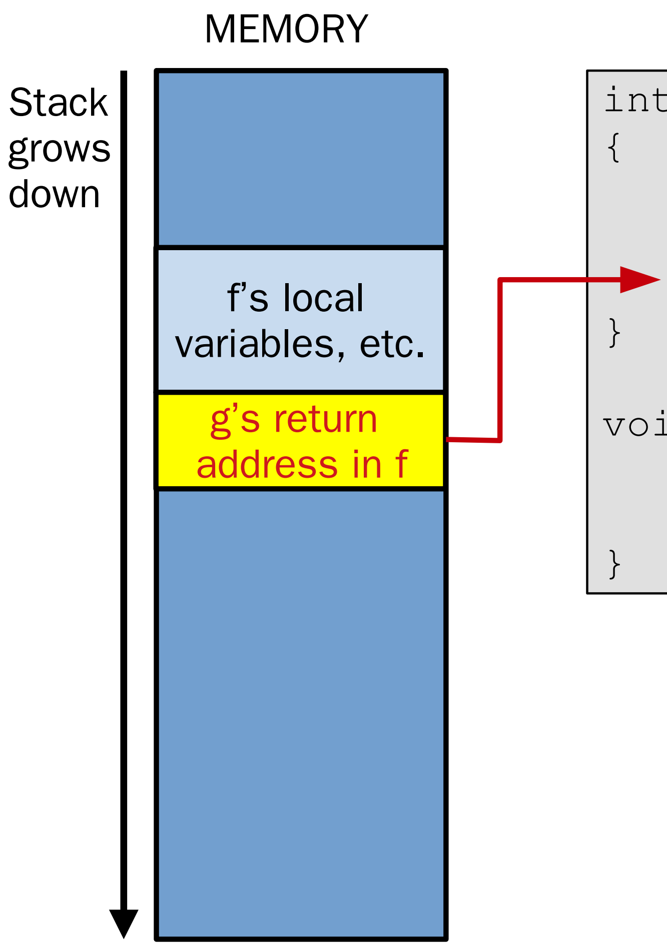

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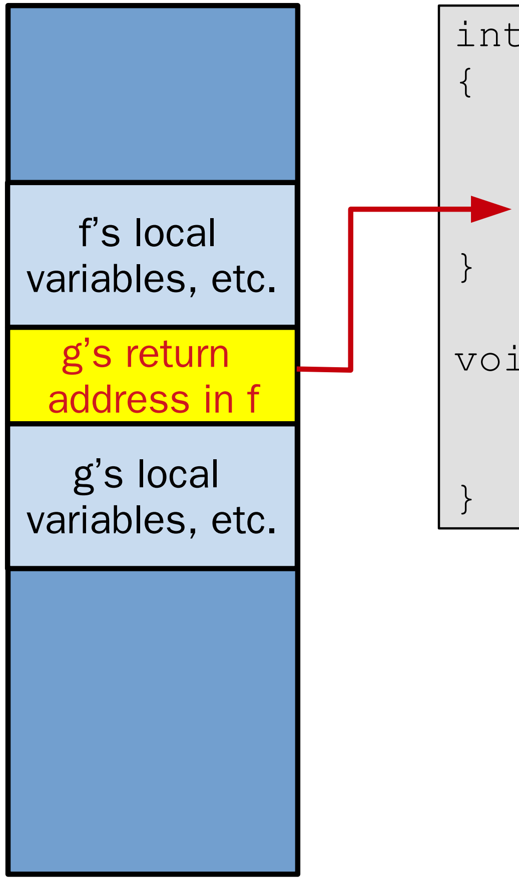
MACHINE INSTRUCTIONS

```
callq    <g's address>
```

Push return address on the stack and jump to g()

Example 3: Stack Smashing

MEMORY



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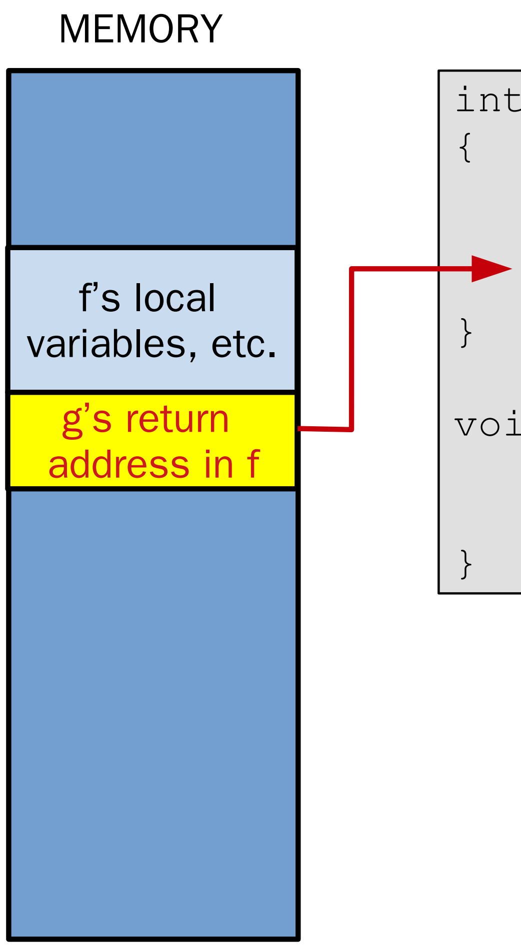

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```

MACHINE INSTRUCTIONS

```
callq    <g's address>
```

```
ret
```

CPU pops return address from the stack and jumps there

Example 3: Stack Smashing

```c
char *password = "upqtfdsfu"; // properly encrypted password

void security_critical_function() { printf("launching nukes!!\n"); }

void preprocess_input(char *string) {
    char local_buffer[16];
    strcpy(local_buffer, string);
    /* work on local buffer ... */
    return;
}

int main(int argc, char **argv) {
    if (argc != 2) { printf("usage: %s <password>\n", argv[0]); return -1; }

   preprocess_input(argv[1]);
   caesar_encrypt(argv[1]);

    if(!strncmp(password, argv[1], strlen(password)))
        security_critical_function();
    else printf("Unauthorised user!\n");

    return 0;
}
```

23-memory-safety/stack-smashing.c

Example 3: Stack Smashing

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int main(int argc, char **argv) {
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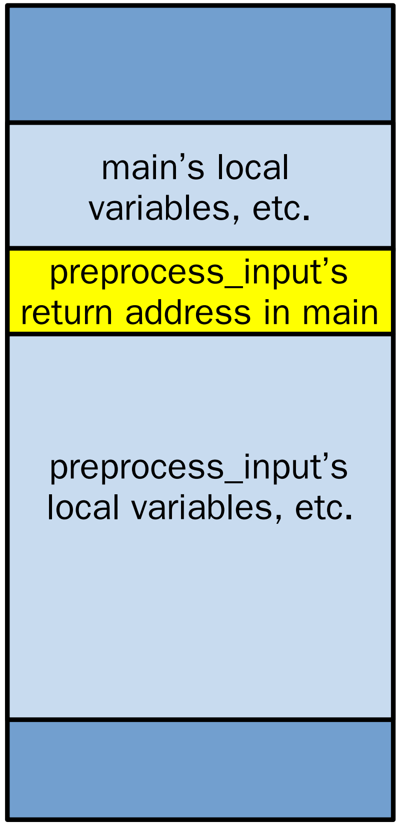
23-memory-safety/stack-smashing.c


main's local variables, etc.
preprocess_input's return address in main
preprocess_input's local variables, etc.

Stack layout in memory when preprocess_input runs

Example 3: Stack Smashing

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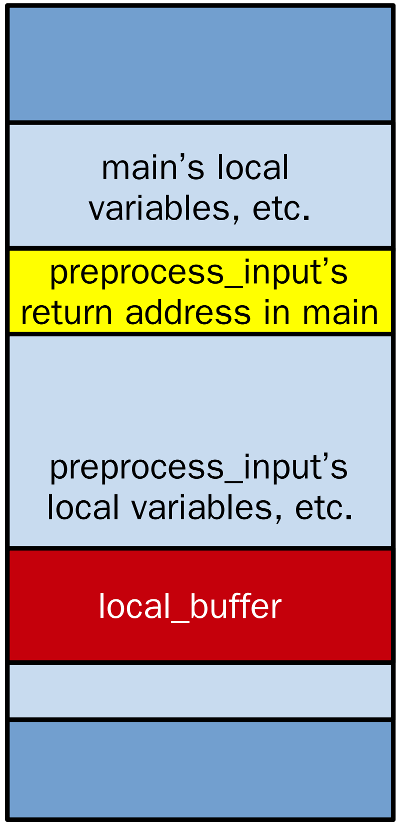
23-memory-safety/stack-smashing.c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preprocess_input's local variables, etc.
local_buffer

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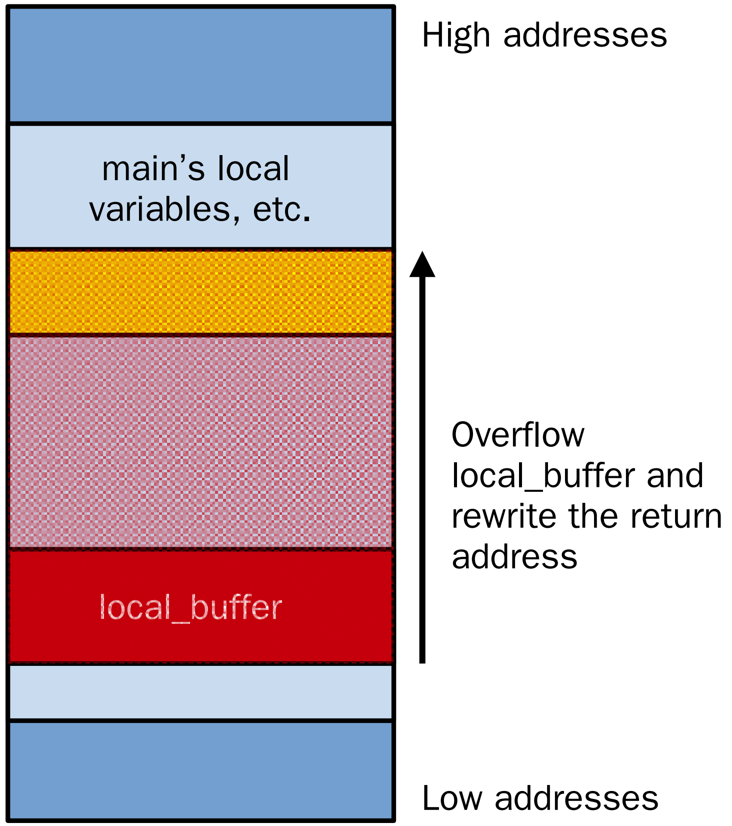
High addresses
main's local variables, etc.
Overflow local_buffer and rewrite the return address
local_buffer
Low addresses

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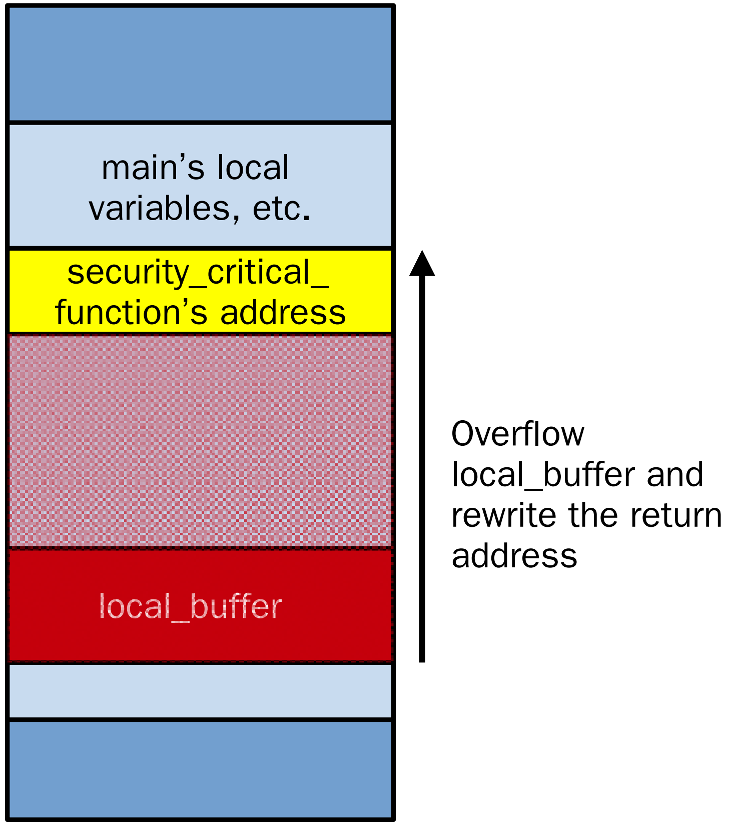
```

23-memory-safety/stack-smashing.c


main's local variables, etc.
security_critical_ function's address
local_buffer
Overflow local_buffer and rewrite the return address

Example 3: Stack Smashing

```c
char *password = "upqtfdsfu";

void security_critical_function() {
    printf("launching nukes!!\n");
}

void preprocess_input(char *string) {
    char local_buffer[16];
    strcpy(local_buffer, string);
    /* work on local buffer ... */
}

int main(int argc, char **argv) {
    if (argc != 2) { /* ... */ }

    preprocess_input(argv[1]);
    caesar_encrypt(argv[1]);

    if(!strncmp(password, argv[1],
            strlen(password)))
        security_critical_function();
    else printf("Unauthorised user!\n");
    return 0;
}
```

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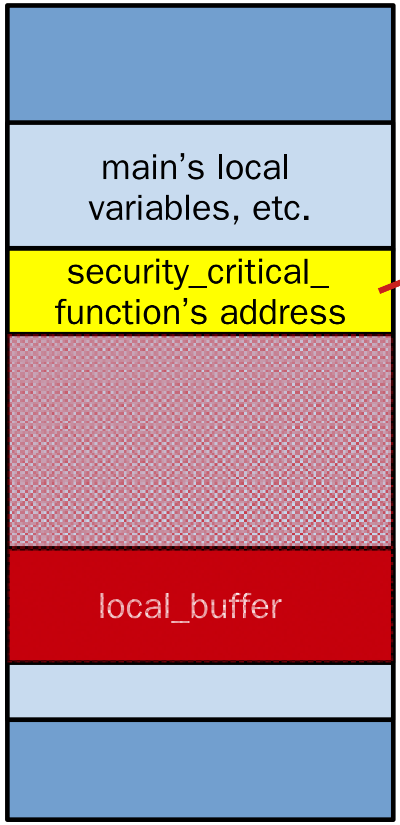
main's local variables, etc.
security_critical_function's address
local_buffer

ret → CPU jumps to security_critical_function(), bypassing the password check!

Example 4: Use-After-Free

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```c
typedef struct {
    double member1; double member2;
    void (*member3)(int);
} my_struct;

void print_hello(int x) {
    printf("Hello, parameter: %d\n", x);
}

void security_critical_function() {
    printf("Launching nukes!\n");
    /* ... */
}

//
```

```c
int main(int argc, char **argv) {
    /* allocate and init ms */
    my_struct *ms = malloc(sizeof(my_struct));
    ms->member1 = 42.0; ms->member2 = 42.0;
    ms->member3 = &print_hello;
    /* call the function pointer */
    ms->member3(12);

    free(ms);
    char *buffer = malloc(12);
    strcpy(buffer, argv[1]);

    ms->member3(12);
    /* check a password, runs sec_crit_fn */
}
```

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Example 4: Use-After-Free

```c
typedef struct {
    double member1; double member2;
    void (*member3)(int);
} my_struct;

void print_hello(int x) {
    printf("Hello, parameter: %d\n", x);
}

void security_critical_function() {
    printf("Launching nukes!\n");
    /* ... */
}

//
```

```c
int main(int argc, char **argv) {
    /* allocate and init ms */
    my_struct *ms = malloc(sizeof(my_struct));
    ms->member1 = 42.0; ms->member2 = 42.0;
    ms->member3 = &print_hello;
    /* call the function pointer */
    ms->member3(12);

    free(ms);
    char *buffer = malloc(12);
    strcpy(buffer, argv[1]);

    ms->member3(12);
    exit(0);
}
```

23-memory-safety/stack-smashing.c

- `member2` is a **function pointer**
  - Can be dynamically set and called at runtime

Example 4: Use-After-Free

```c
typedef struct {
    double member1; double member2;
    void (*member3)(int);
} my_struct;

void print_hello(int x) {
    printf("Hello, parameter: %d\n", x);
}

void security_critical_function() {
    printf("Launching nukes!\n");
    /* ... */
}

//
```

```c
int main(int argc, char **argv) {
    /* allocate and init ms */
    my_struct *ms = malloc(sizeof(my_struct));
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    ms->member3 = &print_hello;
    /* call the function pointer */
    ms->member3(12);

    free(ms);
    char *buffer = malloc(12);
    strcpy(buffer, argv[1]);

    ms->member3(12);
    /* check a password, runs sec_crit_fn */
}
```

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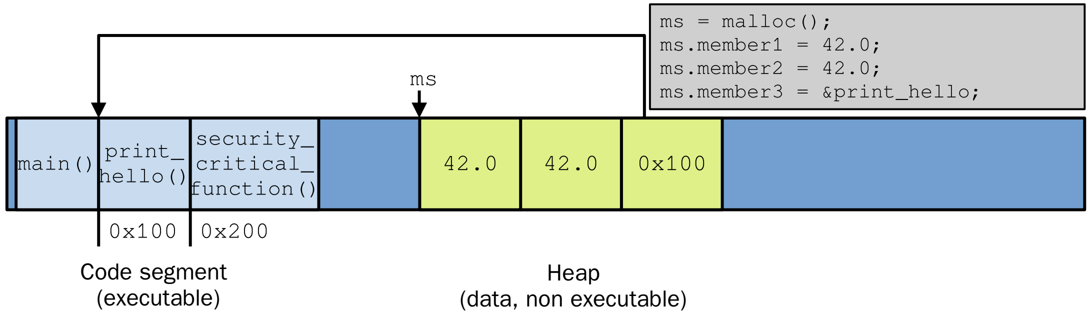
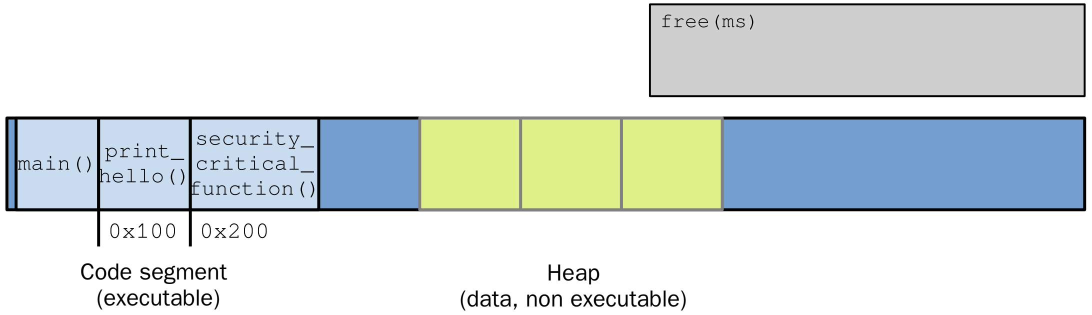

```
ms = malloc();
ms.member1 = 42.0;
ms.member2 = 42.0;
ms.member3 = &print_hello;
```
ms
main()
print_hello()
security_critical_function()
42.0
42.0
0x100
0x100
0x200
Code segment (executable)
Heap (data, non executable)

Example 4: Use-After-Free

```c
typedef struct {
    double member1; double member2;
    void (*member3)(int);
} my_struct;

void print_hello(int x) {
    printf("Hello, parameter: %d\n", x);
}

void security_critical_function() {
    printf("Launching nukes!\n");
    /* ... */
}

//
```

```c
int main(int argc, char **argv) {
    /* allocate and init ms */
    my_struct *ms = malloc(sizeof(my_struct));
    ms->member1 = 42.0; ms->member2 = 42.0;
    ms->member3 = &print_hello;
    /* call the function pointer */
    ms->member3(12);

    free(ms);
    char *buffer = malloc(12);
    strcpy(buffer, argv[1]);

    ms->member3(12);
    /* check a password, runs sec_crit_fn */
}
```

23-memory-safety/stack-smashing.c


free(ms)
main()
print_hello()
security_critical_function()
0x100
0x200
Code segment (executable)
Heap (data, non executable)

Example 4: Use-After-Free

```c
typedef struct {
    double member1; double member2;
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} my_struct;

void print_hello(int x) {
    printf("Hello, parameter: %d\n", x);
}

void security_critical_function() {
    printf("Launching nukes!\n");
    /* ... */
}

//
```

```c
int main(int argc, char **argv) {
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    char *buffer = malloc(12);
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}
```

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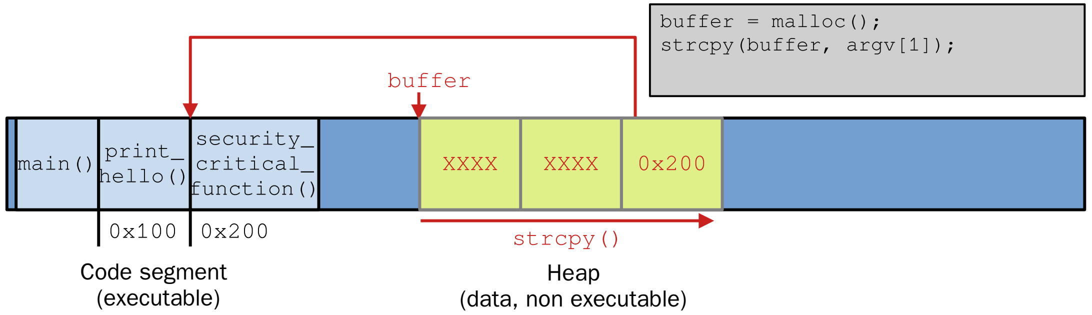
```c
buffer = malloc();
strcpy(buffer, argv[1]);
```

Example 4: Use-After-Free

```c
typedef struct {
    double member1; double member2;
    void (*member3)(int);
} my_struct;

void print_hello(int x) {
    printf("Hello, parameter: %d\n", x);
}

void security_critical_function() {
    printf("Launching nukes!\n");
    /* ... */
}

//
```

```c
int main(int argc, char **argv) {
    /* allocate and init ms */
    my_struct *ms = malloc(sizeof(my_struct));
    ms->member1 = 42.0; ms->member2 = 42.0;
    ms->member3 = &print_hello;
    /* call the function pointer */
    ms->member3(12);

    free(ms);
    char *buffer = malloc(12);
    strcpy(buffer, argv[1]);

    ms->member3(12);
    /* check a password, runs sec_crit_fn */
}
```

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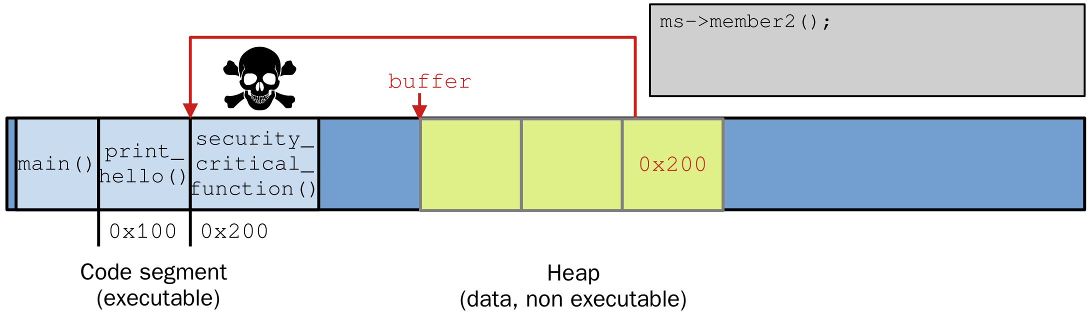

Summary

- C is **not memory safe**
- Memory issues benign at a first glance can have **huge security consequences**
- How to avoid these?

Feedback form: https://bit.ly/3iybv0Y