CITS3007 Secure Coding
C language, intro to buffer overflows

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Outline

- ▶ C language topics – which bits of C should you know?
- ▶ Systems programming refresher – privilege levels and system calls
- ▶ Vulnerabilities – buffer overflows
  - ▶ the Morris Internet worm

C language refresher

Importance

Although created over 50 years ago, the C language has a privileged place in the software industry.

- ▶ Most modern operating systems (e.g. Linux, Windows and macOS) are written in C
  - ▶ their *interfaces* are defined in C
- ▶ Many programming languages have their primary implementation in C (e.g. Python, JavaScript, Lua, Bash)
- ▶ C often serves as a "lingua franca" when extending languages or developing programs written in multiple languages
  - ▶ For instance, the Python language can be extended by writing new built-in modules in C.

Features

C was created as an efficient systems programming language, and was first used to re-write portions of the Unix operating system so as to make them more portable.

It aims to give the programmer a **high level of control** over the organization of data and the operations performed on that data.

Features

C inherited some features from the language PL/I, but unfortunately in some cases opted for less security than PL/I.

For instance, buffer overflows (which we look at shortly) were rare in PL/I, as it required that programmers always specify a maximum length for strings:[1] C does not implement this feature.

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[1] Karger & Schell (2002)

Features

C leaves many details about the behaviour of programs (for instance, what range of numbers an `int` can hold) to the compiler, and the details can vary from platform to platform.

The intention is to allow the compiler to use the **most efficient types** and **most efficient processor instructions** for the platform it is targeting.

Language standards

We will largely discuss the C11 standard,[2] which is still in widespread use.

That said, as long as your code compiles and runs correctly using the standard CITS3007 development environment, you are welcome to use the C17 version of the language if you wish.[3]

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[2]ISO/IEC 9899:2011. See ISO/IEC 9899:201x at https://www.open-std.org for a draft version.

[3]gcc can be instructed to use C17 by passing -std=c17 to the compiler.

Language references and texts

If you're not already familiar with C:

▶ The **CITS2002 Systems Programming** website has good recommendations on (both free and non-free) C textbooks: https://teaching.csse.uwa.edu.au/units/CITS2002/c-books.php

Language references and texts

If you are already familiar with C:

- ▶ The **ISO/IEC C11 standard** is a bit wordy, and the vocabulary takes a bit of getting used to – but it's not *that* difficult to follow, and it's the final word on what a legal C11 program should do.
- ▶ **https://cppreference.com** actually has very good coverage of C header files and functions.
  Just make sure you're reading the right one.
- ▶ from a corresponding C++ page, follow the "C language" links down the bottom of page
- ▶ C language topics should have a URL that looks like
  https://en.cppreference.com/w/c/SOMETHING

Major surprises

Some of the following features of C often surprise people coming from other languages:

▶ (Almost) everything is an integer (or derived from an integer type)

▶ There is no such type as "string"

▶ Assignment ("=") will only sometimes do what you think it should do

▶ If you misuse memory (e.g. going outside the bounds of an array), you get no warnings or exceptions about this – the compiler assumes you know what you're doing

    ▶ Instead of exceptions, the behaviour of your program becomes **undefined** – it literally has no meaning, is not a valid C program, and the compiler is allowed to generate whatever compiled code it likes.

Integers in C

C has a large number of integral data types.[4] The most common are:

> **standard integer types**
>
> ▶ standard signed integer types: `signed char`, `short int`, `int`, `long int`, and `long long int`
> ▶ standard unsigned integer types: `_Bool` (also available as `bool`), `unsigned char`, `unsigned short int`, `unsigned int`, `unsigned long int`, and `unsigned long long int`
> ▶ the `char` type.

What range of integers these can hold, and which of these types are equivalent to each other, is implementation dependent.

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[4]In fact, nearly every type you see in this unit (besides function types) is either an integer type, or derived from (array or `struct` or pointer to) integer types.

Integers in C

standard integer types

- ▶ standard signed integer types: `signed char`, `short int`, `int`, `long int`, and `long long int`
- ▶ standard unsigned integer types: `_Bool` (also available as `bool`), `unsigned char`, `unsigned short int`, `unsigned int`, `unsigned long int`, and `unsigned long long int`
- ▶ the `char` type.

The C11 standard states that the `char` type is equivalent to *either* `signed char` or `unsigned char`, but which one is the case is implementation-defined.

It says the size of a `char` is one byte, and has at least 8 bits, but *doesn't* otherwise constrain how many bits exist in a byte (this, too, is implementation-defined).[5]

---

[5] The `CHAR_BIT` macro in `<limits.h>` will tell you the number of bits per byte. On Unix-like OSs, the macro `NBBY`, defined in `<sys/param.h>`, will give the same result.

Floating point types

C also has three "real floating types", but we will be less concerned with them.

real floating types

▶ `float`
▶ `double`
▶ `long double`

(It also has three corresponding types for complex numbers, which we won't use at all.)

Functions in C

All executable statements in C must be written inside a procedure – C calls its procedures "functions".

C functions may return a result, in which case the signature of the function will indicate the return type. For instance:

```
int square(int x);
```

The function declared above takes one argument (an int), and returns an int value.

Functions in C

```
void print_int_to_terminal(int x);
```

Alternatively, a function may be declared as having return type void, in which case it *doesn't* return any value as a result.

Both void and non-void functions may have *side effects*: they may for instance modify the values of global variables, perform output to the terminal, or alter the state of files or attached devices.

Function declarations and definitions

A function **declaration** "tells" code following it about a function:

```
int square(int x);
```

A function **definition** provides the "body" of the function:

```
int square(int x) {
  return x * x;
}
```

Scope in C

C has two basic types of scope:

▶ **global scope** (or "file scope"): for variables declared outside all functions. These are visible from the declaration, to the end of the file.

▶ **block scope**: for variables declared within a function or statement block. These are visible from the declaration, to the end of the function or statement block.

For global variables (and for functions, which are always global – C doesn't have nested functions): adding the keyword `static` before them ensures that the variable or function is *only* visible from within that file.

Limiting scope is C's primary method of implementing information hiding.

Scope in C

global, usable
in any file

from
another file

global, this
file only

```c
int OUR_NUM = 42;
int OTHER_NUM ;
static int OUR_PRIVATE_NUM ;
int multiply (int m, int n) {
    int i, res = 0;        <----------------    local variable
                                                declarations
    for (i = 0; i < n; i++) {
        int tmp = res + m;     <--------    local to block
        res = tmp;
    }
    return res;
}
```

Arrays in C

C provides support for 1-dimensional and multi-dimensional arrays.

1-dimensional array

```
#define ARRAY_SIZE 10
int some_array[ARRAY_SIZE];
```

2-dimensional array

```
#define ARRAY_HEIGHT 5
#define ARRAY_WIDTH  10
int two_d_array[ARRAY_HEIGHT][ARRAY_WIDTH];
```

Strings in C

C does not provide a separate datatype for strings – rather, strings are considered to be arrays of chars, with the NUL character (which has ASCII code 0) acting as a terminator.

String
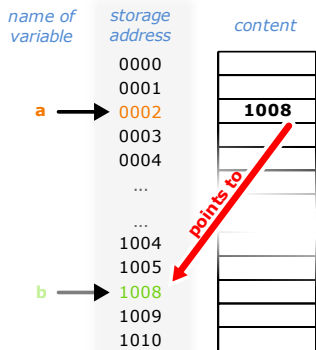
```c
// this declaration:
char my_str[] = "cat";
// is equivalent to:
char my_str[4] = { 'c', 'a', 't', '\0'};
```

Pointers in C

Pointer types in C hold a reference to an entity of some *other* type. For instance a "pointer to `int`" (written `int *`) holds a reference to an `int`.

It's usually convenient to think of this "reference" as the address of a location in memory, but the C11 standard does not require that to be the case.

A pointer and the variable it references[1]

[1]Image courtesy of Wikipedia, https://commons.wikimedia.org/wiki/File:Pointers.svg

Pointers in C

C allows the use of **pointer arithmetic**. In addition to performing (say) addition on two integer values, we can perform it on one pointer value and one integer value.

```
int * p1 = NULL;
int * p2 = p1 + 4;
```

Adding 4 to a pointer doesn't move it along by 4 memory locations; it moves it along by 4 × the size of whatever is being pointed to (an int, in the example above).

We can also subtract one pointer from another, and perform equality and inequality comparisons on two pointers (==, <, >, <=, and >=).

Pointers in C

Many languages disallow pointer arithmetic, since its use can easily result in invalid pointers (pointers that do not reference a properly initialized object of the correct type).

C allows it; it is up to the programmer to ensure they comply with the standard's rules as to when a pointer is valid.

If the programmer fails to comply with those rules, the result usually is that the behaviour of the program is *undefined*.

(In other words: the program has no well-defined "meaning", according to the C11 standard; and the standard places no constraints on what behaviour it may have.)

Pointers in C
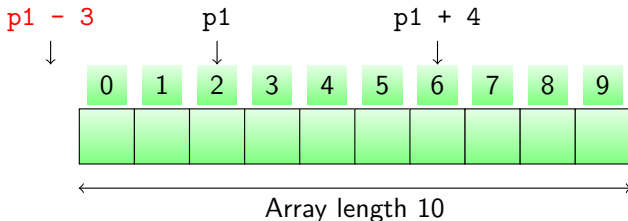
For instance: if arithmetic is performed on a pointer which references some element of an array, and the resulting pointer would go outside the bounds of the array,[6] then the behaviour of the program is undefined.

---

[6]To be precise: the pointer must point either to an element of the array, or the position one past the last element.

Pointers in C

A pointer to a variable can be obtained using the '&' ("address-of") operator, and pointers can be dereferenced using '*' (the dereference operator).

variable   pointer

```
int  some_num = 42;
int * num_addr  = &some_num;
*num_addr = 99;   <----------------------------   dereferencing
printf("the number is: %d\n", some_num);                a pointer
// prints "the number is 99"
```

Lifetime

Variables have a **storage duration** that determines their "lifetime".

▶ Memory for **global** variables is allocated when the program starts running, and persists until the program exits

▶ However, the majority of variables in a program are **local** variables, and have what is called "automatic storage duration"

    ▶ This basically means they "disappear" when the function they are declared in exits, and the memory allocated to them is reclaimed

    ▶ If you've somehow managed to hang onto a reference to this memory, the behaviour of your program is *undefined*

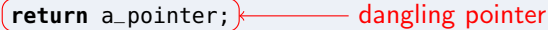## Automatic lifetime and dangling pointers

Consider this function:

```
int * myfunc() {
  int a_local_var = 36;
  int * a_pointer = &a_local_var;
  return a_pointer;
}
```

There's nothing wrong with returning a pointer – lots of functions do it (like the standard function getenv – char* getenv (const char* name) – which gives you the value of an environment variable).

But a caller of myfunc will receive a pointer to memory which has been reclaimed – a "dangling pointer" – and such a pointer results in undefined behaviour.

dangling pointers

myfile.c

```c
int * myfunc() {
  int a_local_var = 36;
  int * a_pointer = &a_local_var;
  return a_pointer;         ←——————— dangling pointer
}
```

Compilers will generally not warn you about this – the above code compiles with `gcc -pedantic -Wall -Wextra` with no warnings.

Code static analyzers exist which *will* warn you – more about them, later.

e.g. `clang-tidy myfile.c` will give the output

```
1 warning generated.
myfile.c:4:3: warning: Address of stack memory associated with local
variable 'a_local_var' returned to caller [clang-analyzer-core.StackAddrEscapeBase]
  return a_pointer;
  ^
```

Dynamically allocated memory

- ▶ Data which we want to persist beyond the execution time of a function needs either to be global, or to be allocated in a region of memory called the **heap**.
- ▶ Memory allocated on the heap is said to be "dynamically allocated"
- ▶ The primary C functions used to manage dynamic memory are
  - ▶ `malloc`, for allocating memory, and
  - ▶ `free`, for releasing it.

```
void *malloc(size_t size);
void free(void *ptr);
```

Dynamically allocated memory

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

int* make_arr(int n) {
  int* arr = malloc(n * sizeof(int));
  return arr;
}
int main() {
  int n;
  printf("How big an array to allocate? ");
  scanf("%d",&n); // insecure, prefer scanf_s
  int* arr = make_arr(n);
  for(i = 0; i < n; i++)
    arr[i] = n;
  free(arr);
}
```

(See cppreference.com for details of `scanf_s`.)

Dynamically allocated memory

▶ Once a pointer has been `free`d, using that pointer's value at all
– even without dereferencing it – is undefined behaviour.

```
int *p = malloc(sizeof(int));
free(p);
if (p == NULL) {
  // ...
```

▶ So is calling `free` on a pointer more than once.

▶ Attempting to read from `malloc`ed memory before it has been
initialized results in an "indeterminate value" – not undefined,
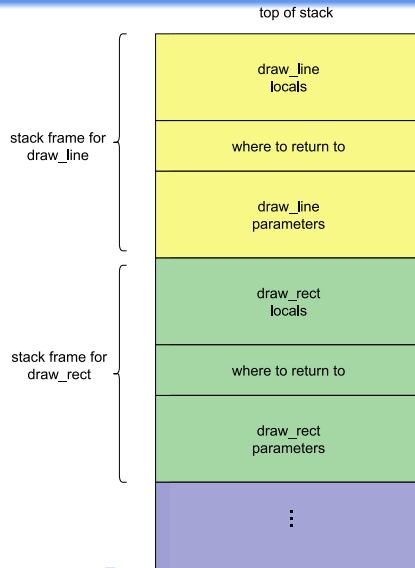but almost certainly not what you want

Memory: call stack

On most architectures, calls to C functions work something like this:

- ▶ Every time a C function starts executing, space is allocated for its parameters and local variables on the call stack
    - ▶ for each function that is entered, a stack frame gets pushed *on*to the call stack
    - ▶ the stack frame consists of enough memory to store the function parameters, local variables and a record of where to return to
    - ▶ when the function is exited, a stack frame gets taken *off* the call stack
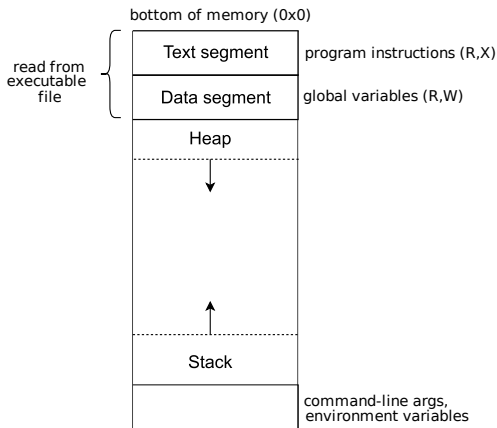
C language refresher
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Operating system services
ооооо

Vulnerabilities: buffer overflows
ооооооооооооооо

Memory: call stack


```
void draw_line(point* p1, point* p2){
 // ...
}
void draw_rect(point* topLeft, point* botRight){
 point p1 = {.x=topLeft→x, .y=topLeft→y };
 point p2 = {.x=botRight→x,.y=topLeft→y };
 draw_line(&p1, &p2);
 // ...
}
```

top of stack

draw_line
locals

where to return to

draw_line
parameters

stack frame for
draw_line

draw_rect
locals

where to return to

draw_rect
parameters

stack frame for
draw_rect

⋮

Memory: process memory layout

The layout of a process's data in virtual memory looks something like this.

bottom of memory (0x0)

read from executable file

Text segment	program instructions (R,X)
Data segment	global variables (R,W)
Heap	
Stack	
	command-line args, environment variables

On Linux, `cat /proc/some_pid/maps` shows the virtual address space of a process. (Try `cat /proc/self/maps` to get the address space of the `cat` process itself.)

The **text** segment is typically made *shareable*, so that multiple processes can be run from one executable file and share a single copy (safe, since it's read-only).

Typedefs

C allows types to be given "aliases", using the typedef keyword.

The original type comes *first*, then the alias.

```
typedef int colour;
```

Structs

C provides structs to create composite data types ("product types") in which a related set of variables can be grouped together in one contiguous block of memory.

```
struct address {
  char * street_number;
  char * street_name;
  char * suburb;
  int postcode;
};
void my_func() {
  // we can initialize ...
  struct address some_addr = { // like this:
      "13a", "Cooper St", "Nedlands", 6009
  };
  struct address other_addr = { // or like this (since C99)
      .postcode = 6009, .suburb = "Nedlands",
      .street_number = "13a", .street_name = "Cooper St"
  };
}
```

Struct members

```
typedef struct {
  char * street_number;
  char * street_name;
  char * suburb;
  int postcode;
} address;
```

struct members can be accessed using the "." (member access) operator.

If, rather than a struct, you have a *pointer* to a struct, use the "->"
(member access through pointer) operator.

```
void my_func(struct address a, struct address *pa) {
  printf("postcode of a: %d\n",  a.postcode);
  printf("postcode of pa: %d\n", pa->postcode);
}
```

enums

C allows user-defined data types which assign meaningful names to integral constants:

```
enum shape_operation {
  draw = −1,
  move,
  delete = 4,
  hide
};
```

Enumerated types are *integer types*, and so can be used anywhere an integer could be. As a result, they offer no real *type safety*: nothing distinguishes an `enum shape_operation` from (say) a `signed int`.[7]

---

[7]Each enumerated type is compatible with some *integral* type which can hold all the values, but it's implementation-defined what type that is.

Unions

A C `union` may hold *multiple* different types, of different sizes – but only one type at a time.

For instance, suppose we receive a "blob" of data from over the network which represents a message. The first 8 bits (1 byte) are a code that tell us what the rest of the "blob" means:

- ▶ `0` indicates it's a double
- ▶ `1` indicates it's an int

Unions

We could use the following to represent these messages:

```c
union double_or_int {
  double d;
  int i;
};

struct message {
  char message_type;
  union double_or_int;
};
```

Unions

```
union double_or_int {
  double d;
  int i;
};

struct message {
  char message_type;
  union double_or_int;
};
```

We can then correctly decode a message with code like this:

```
void decode_message(struct message * m) {
  if (m.message_type == 0) {
    double d = m->d;
    printf("It's a double: %f\n", d;
  } else if (m.message_type == 1) {
    int i = m->i;
    printf("It's an int: %d\n", i;
  }
}
```

Unions – a problem

```
void decode_message(struct message * m) {
  if (m.message_type == 0) {
    double d = m→d;
    printf("It's a double: %f\n", d;
  } else if (m.message_type == 1) {
    int i = m→i;
    printf("It's an int: %d\n", i;
  }
}
```

We've *assumed* here that a char is 8 bits in size. And on every reasonable platform available today, it is (but see here).

If we want to make sure, we can use C11's **static assert** feature to verify the size.

```
#include <assert.h>
#include <limits.h>
// This will be checked at compile time.
static_assert(CHAR_BIT == 8, "only works if a char is 8 bits");
```

Function pointers

Pointers to *functions* can be passed around and used in C.

The syntax for function pointers is not especially pleasant.

```
// pointer to a void function taking an int
void (*func_ptr)(int);

void use_ptr(void (*p)(int)) {
  p(42); // call pointed-to function
}

void print_num(int n) {
  printf("the number is %d\n", n);
}

int main() {
  func_ptr = print_num;
  use_ptr(func_ptr);
}
```

Operating system services

Privilege levels

Access to devices, particular data, or some CPU instructions may be *protected* by hardware – only sufficiently privileged code (e.g. kernel code) may access them.

(Why? Suppose all user applications could directly access the disk hardware at any time. The filesystem would be in danger of becoming corrupted. The OS manages orderly access to the hardware.)

For instance, Intel's processors provide 4 privilege levels, conceptualized as rings, where inner rings are the most "trusted", and outer rings the least.

Ring 3
Ring 2
Ring 1
Ring 0

Kernel

Operating system services (e.g. drivers)
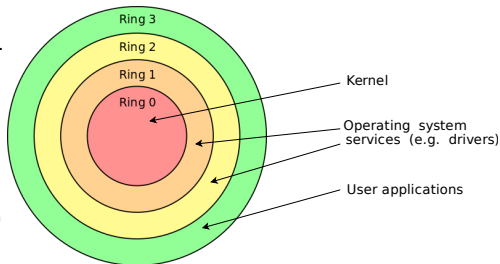
User applications

Privilege levels

A user application is normally executed at a low level of privilege, and is prohibited from accessing or modifying the memory of other programs, or resources belonging to inner rings; attempting to do so triggers a particular type of *fault* (which can be thought of as a sort of "exception"), e.g. a general protection fault.

System calls

System calls constitute the "API" of an operating system kernel – they are the programmatic way to request a service from the kernel.

They allow code running in one of the outer levels (user programs) to obtain a service from one of the inner levels.

An example system call:
the open system call on Unix-like systems opens a file for reading or writing.

```
int open(const char *pathname, int flags, mode_t mode);
```

System calls

From a programmer's point of view, system calls "look" like functions; however, rather than having a normal function body, they typically are implemented as assembly code routines, which do the following:

- ▶ store all the information the kernel needs to provide the requested service in a fixed location
- ▶ execute a "software interrupt", which causes the kernel to jump to an "interrupt handler", which examines the information provided
- ▶ the kernel executes some fragment of kernel code that provides the requested service
- ▶ control is then returned to the program that requested the service.

(For more details, refer to e.g. https://www.cs.montana.edu/courses/spring2005/518/Hypertextbook/jim/index.html or any operating systems textbook.)

Vulnerabilities: buffer overflows

Historical case: Morris worm

- ▶ Robert Tappan Morris, a graduate student at Cornell, created the "worm" in 1988 to see if it could be done
- ▶ It was a program intended to propagate slowly from host to host and measure the size of the Internet
- ▶ But due to coding errors on Morris's part, the worm created new copies as fast as it could, and infected machines became overloaded

Historical case: Morris worm

▶ Robert Tappan Morris, a graduate student at Cornell, created the "worm" in 1988 to see if it could be done

▶ It was a program intended to propagate slowly from host to host and measure the size of the Internet

▶ But due to coding errors on Morris's part, the worm created new copies as fast as it could, and infected machines became overloaded

▶ Morris was convicted under the Computer Fraud and Abuse Act, and sentenced to 3 years probation and 400 hours community service

Morris worm

The Morris worm used multiple vulnerabilities to copy itself from host to host.

One was a **buffer overflow** vulnerability in a network service. This sort of vulnerability is still one of the most common (and most dangerous) types of vulnerability today.

2023 CWE Top 25 Most Dangerous Software Weaknesses

1 Out-of-bounds Write
CWE-787 | CVEs in KEV: 70 | Rank Last Year: 1

Improper Neutralization of Input During Web Page Generati...

Source: https://cwe.mitre.org/top25/

Morris worm – buffer overflow

▶ On Unix systems, service programs are called "daemons", and typically they will run in the background, waiting for client programs to connect.

▶ The Morris worm attacked a service called `fingerd` – today a service like LDAP (the Lightweight Directory Access Protocol) would be equivalent

    ▶ (UWA uses a version of LDAP.)

▶ The service reported information about a user on a host – full name, office location, phone extension, etc

▶ `fingerd` typically allowed anyone to connect, and it used a function called `gets` to read the incoming request.

Morris worm – gets

If you invoke the command `man gets`, you will see the following

```
NAME
       gets — get a string from standard input (DEPRECATED)

SYNOPSIS
       #include <stdio.h>

       char *gets(char *s);

DESCRIPTION
       Never use this function.
```

Morris worm – gets

```
BUGS
        Never use gets().  Because it is impossible to tell
        without knowing the data in advance how many characters
        gets() will read, and because gets()  will  continue
        to store characters past the end of the buffer, it is
        extremely dangerous to use. It has been used to break
        computer security.  Use fgets() instead.

        For more information, see CWE—242 (aka "Use of Inherently
        Dangerous Function") at
        http://cwe.mitre.org/data/definitions/242.html
```

And if you try to compile code containing gets, gcc will tell you

warning: the 'gets' function is dangerous and should not be used.

Morris worm – gets

Rusty Russell (an Australian Linux kernel contributor) proposed a rating scheme for APIs ranging from +10 ("It's impossible to get wrong") to -10 ("It's impossible to get right.").

  10. It's impossible to get wrong.
   9. The compiler/linker won't let you get it wrong.
   8. The compiler will warn if you get it wrong.
   7. The obvious use is (probably) the correct one.

. . .

  -7. The obvious use is wrong.
  -8. The compiler will warn if you get it right.
  -9. The compiler/linker won't let you get it right.
 -10. It's impossible to get right.

The `gets` function falls firmly into the "-10" level.

So what's the issue?

gets

The signature for `gets` is:

```
char *gets(char *s);
```

It reads a line of input from the standard input stream. The idea is that you pass it the address of a **buffer** (array) into which it should copy the line it read.

Here's an example of use:

```
#define BUFSIZE 512
// ...
char buf[BUFSIZE];
printf("Please enter your name and press <Enter>\n");
gets(buf);
```

gets

```
#define BUFSIZE 512
// ...
char buf[BUFSIZE];
printf("Please enter your name and press <Enter>\n");
gets(buf);
```

The problem is that there is *no* way of telling gets how big the
buffer buf is. If there are more than 512 characters on the line being
read, gets doesn't stop – it just keeps copying characters into
memory, past the end of buf.

As we saw when we discussed pointers, this is *undefined behaviour* –
at this point, there are no guarantees about what the program will
do.

buffer overflows

```
#define BUFSIZE 512
// ...
char buf[BUFSIZE];
printf("Please enter your name and press <Enter>\n");
gets(buf);
```

So what will be sitting in memory after buf?

buf here is a local variable, sitting in the current stack frame. After it come other local variables, so those will get overwritten; and then the *return address*, the location in memory to go to once the current function has finished; and then the parameters passed to the current function.

buffer overflows

```
#define BUFSIZE 512
// ...
char buf[BUFSIZE];
printf("Please enter your name and press <Enter>\n");
gets(buf);
```

If you're sending a message to the `fingerd` process, and you know the structure of its stack frame, you can deliberately overwrite the return address so that execution jumps to code of your choosing (known as "smashing the stack").

In fact, the data you send could include instructions for executing some arbitrary program (e.g. the shell), and you could force the program to jump to the instructions you just wrote.

buffer overflows

At least, that's how the stack could be exploited at the time the Morris worm was written.

On modern machines, there are several protections in place against this sort of attack:

► stack canaries
► address-space layout randomisation (ASLR)
► write XOR execute permissions
► source fortification

More on these in future lectures!

References

▶ Karger, P. A., and R. R. Schell. "Thirty Years Later: Lessons from the Multics Security Evaluation." 18th Annual Computer Security Applications Conference, 2002. Proceedings., IEEE Comput. Soc, 2002, pp. 119–26, https://doi.org/10.1109/CSAC.2002.1176285.