On the effectiveness of Full-ASLR on 64-bit Linux

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   - `randomize_va_space=3`
   - ASLR redesign
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What have we done?

We have deeply analyzed the effectiveness of the GNU/Linux ASLR and:

- Found a **weakness** on the current **GNU/Linux ASLR** implementation, named **offset2lib**.

- Built an attack which bypasses the NX, SSP and ASLR on a 64 bit system in < 1 sec.

- **Sent a small patch “ASLRv3”** (randomize_va_space = 3) to Linux developers, but **no response**.

- Some mitigation techniques against the offset2lib attack are presented.
ASLR Background

- ASLR does not remove vulnerabilities but make more difficult to exploit them.

- ASLR deters exploits which relays on knowing the memory map.

- ASLR is effective when all memory areas are randomise. Otherwise, the attacker can use these non-random areas.

- Full ASLR is achieved when:
  - Applications are compiled with PIE (-fpie -pie).
  - The kernel is configured with randomize_va_space = 2
    (stack, VDSO, shared memory, data segment)
Loading shared objects

The problem appears when the application is compiled with PIE because the GNU/Linux algorithm for loading shared objects works as follows:

- The **first** shared object is loaded at a **random position**.
- The next object is located right below (lower addresses) the last object.

![Diagram of shared object loading]

All libraries are located "side by side" at a **single random place**.
Offset2lib

$ cat /proc/<pid>/server_64_PIE

7fd1b414f000-7fd1b430a000 r-xp /lib/.../libc-2.19.so
7fd1b430a000-7fd1b450a000 ---p /lib/.../libc-2.19.so
7fd1b450a000-7fd1b450e000 r--p /lib/.../libc-2.19.so
7fd1b450e000-7fd1b4510000 rw-p /lib/.../libc-2.19.so
7fd1b4510000-7fd1b45150000 rw-p

7fd1b4515000-7fd1b4538000 r-xp /lib/.../ld-2.19.so
7fd1b4718000-7fd1b471b000 rw-p
7fd1b4734000-7fd1b4737000 rw-p
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7fd1b4739000-7fd1b473a000 rw-p

7fd1b473a000-7fd1b473c000 r-xp /root/server_64_PIE
7fd1b493b000-7fd1b493c000 r--p /root/server_64_PIE
7fd1b493c000-7fd1b493d000 rw-p /root/server_64_PIE
7fff981fa000-7fff9821b000 rw-p [stack]
7fff983fe000-7fff98400000 r-xp [vdso]
Offset2lib

$ cat /proc/<pid>/server_64_PIE

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**Offset2lib**

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We named this invariant distance **offset2lib** which:

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- It is a **constant distance** between two shared objects even in different executions of the application.

Any address of the app. → de-randomize all mmapped areas!!!
Why the Offset2lib is dangerous?

Offset2lib scope:

- **Realistic**: applications are more prone than libraries to errors.

- Makes some vulnerabilities **faster, easier and more reliable** to exploit them.

- It is not a self-exploitable vulnerability but an ASLR-design weakness exploitable.

- It opens new (and old) attack vectors.
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Hector Marco

Linux ASLR weakness: offset2lib

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**Next example:**
Offset2lib on a standard stack buffer overflow.
Building the attack

The steps to build the attack are:

1. Extracting static information
2. Brute force part of saved-IP
3. Calculate base app. address
4. Calculate library offsets
5. Obtain mmapped areas
1) Extracting static information

Our goal is to obtain an address belonging to the application.

We are going to obtain the `saved-IP` of vulnerable function caller.

**Offset2lib** with **saved-IP** ⇒ **all** mmapped areas.

```
0000000000001063 <attend_client>:
1063: 55  push %rbp
1064: 48 89 e5  mov %rsp,%rbp
1067: 48 81 ec 60 04 00 00  sub $0x460,%rsp
106e: 64 48 8b 04 25 28 00  mov %fs:0x28,%rax
1075: 00 00
...... ..... ......
12d7: 48 89 c7  mov %rax,%rdi
12da: e8 1c fc ff ff  callq efb <vuln_func>
12df: 48 8d 85 c0 fb ff ff  lea -0x440(%rbp),%rax
12e6: 48 89 c7  mov %rax,%rdi
...... ..... ......
```

STACK

```
...... ..... ..... 0x????????????????
......
......
......
......
......
......
```

BUFFER

```
......
......
......
......
......
......
......
......
```

RBP

```
......
......
......
......
```

Stack grows down
1) Extracting static information

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**Offset2lib with saved-IP ⇒ all mmapped areas.**
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**Offset2lib with saved-IP ⇒ all mmapped areas.**

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..... ..... .....  
```

---

 STACK  

---

BUFFER  

---

RBP  

---

Next IP  

---

STACK grows down  

---

Next IP  

---

Stack grows down  

---

0x??????????????????  

---

...  

---

...  

---

0x??????????????????  

---

...  

---

0x??????????????????  

---

...  

---


1) Extracting static information

Our goal is to obtain an address belonging to the application.

We are going to obtain the **saved-IP** of vulnerable function caller.

**Offset2lib** with **saved-IP** $\Rightarrow$ **all** mmapped areas.
1) Extracting static information

**Memory map**

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</table>

This value (**0x00007F**) can be obtained:

1. Running the application and showing the memory map.
2. Checking the source code if set any limit to stack.
1) Extracting static information

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</table>

STACK

```
7fd1b473a000-7fd1b473c000 r-xp /root/server_64_PIE
7fd1b493b000-7fd1b493c000 r--p /root/server_64_PIE
7fd1b493c000-7fd1b493d000 rw-p /root/server_64_PIE
```

Highest 24 bits

This value (0x00007F) can be obtained:

1. Running the application and showing the memory map.
2. Checking the source code if set any limit to stack.
1) Extracting static information

Since the executable has to be PAGE_SIZE aligned, the 12 lower bits will not change when the executable is randomly loaded.

ASM Code

```
0000000000001063 <attend_client>:
1063:  55  push %rbp
1064:  48 89 e5  mov %rsp,%rbp
1067:  48 81 ec 60 04 00 00  sub $0x460,%rsp
106e:  48 8b 04 25 28 00 00 mov %fs:0x28,%rax
1075:  00 00
1077:  48 89 45 f8  mov %rax,-0x8(%rbp)
107b:  31 c0  xor %eax,%eax
     ....  ....  ....
12d7:  48 89 c7  mov %rax,%rdi
12da:  e8 1c fc ff ff  callq efb <vuln_func>
12df:  48 8d 85 c0 fb ff ff  lea -0x440(%rbp),%rax
12e1:  48 89 c7  mov %rax,%rdi
     ....  ....  [From the ELF]  ....
```

STACK

```
...  ...
      BUFFER
      RBP
0x0007F???????????
      ...
...  ...
```
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12df: 48 8d 85 c0 fb ff ff lea -0x440(%rbp),%rax
12e1: 48 89 c7 mov %rax,%rdi
..... ..... [From the ELF] ..... 
```

STACK

```
..... ...
BUFFER
RBP
0x0007F?????2DF
..... ...
```

Lower 12 bits

Stack grows down
2) Brute forcing Saved-IP address

```c
void vuln_func(char *str, int lstr){
    char buff[48];
    int i = 0;
    ...
    for (i = 0; i < lstr; i++) {
        if (str[i] != '\n')
            buff[lbuff++] = str[i];
    ...
}
```

- The unknown 28 random bits: “byte-for-byte” attack.
- The first byte is “special”, we know the lowest 4 bits:
  - $0x?2_{16} \rightarrow ??10_2 \rightarrow 2^4 = 16$ attempts
  - \{0x02, 0x12, 0x22 ... 0xC2, 0xD2, 0xE2, 0xF2\}
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void vuln_func(char *str, int lstr) {
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  - $0x?_{16} \rightarrow ??_{10} \rightarrow 2^4 = 16$ attempts
  - \{0x02, 0x12, 0x22 ... 0xC2, 0xD2, 0xE2, 0xF2\}
- The remaining 3 bytes $\rightarrow$ standard “byte-for-byte” attack
  - $3 \times 2^8 = 768$ attempts.
- After execute the byte-for-byte we obtained $0x36C6FE$
2) Brute forcing Saved-IP address

```c
void vuln_func(char *str, int lstr)
{
    char buff[48];
    int i = 0;
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    }
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After execute the byte-for-byte we obtained $0x36C6FE$

We need to perform $\frac{2^4 + 3 \cdot 2^8}{2} = 392$ attempts on average.
3) Calculating base application address

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1063: 55 push %rbp
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1067: 48 81 ec 60 04 00 00 sub $0x460,%rsp
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12da: e8 1c fc ff ff callq efb <vuln_func>
12df: 48 8d 85 c0 fb ff ff lea -0x440(%rbp),%rax
12e6: 48 89 c7 mov %rax,%rdi
......

App_base = (savedIP & 0xFFF) - (CALLER_PAGE_OFFSET << 12)
3) Calculating base application address

```
0000000000001063 <attend_client>:
1063: 55  push %rbp
1064: 48 89 e5  mov %rsp,%rbp
1067: 48 81 ec 60 04 00 00  sub $0x460,%rsp
106e: 64 48 8b 04 25 28 00  mov %fs:0x28,%rax
1075: 00 00
1077: 48 89 45 f8  mov %rax,-0x8(%rbp)
107b: 31 c0 xor %eax,%eax
12d7: 48 89 c7  mov %rax,%rdi
12da: e8 1c fc ff ff  callq efb <vuln_func>
12df: 48 8d 85 c0 fb ff ff  lea -0x440(%rbp),%rax
12e6: 48 89 c7  mov %rax,%rdi

App_base = (savedIP & 0xFFF) - (CALLER_PAGE_OFFSET << 12)
```
3) Calculating base application address

```
0000000000001063 <attend_client>:
1063:  55    push %rbp
1064: 48 89 e5 mov %rsp,%rbp
1067: 48 81 ec 60 04 00 00 sub $0x460,%rsp
106e: 64 48 8b 04 25 28 00 mov %fs:0x28,%rax
1075: 00 00
1077: 48 89 45 f8 mov %rax,-0x8(%rbp)
107b: 31 c0 xor %eax,%eax
...... ..... ......
12d7: 48 89 c7 mov %rax,%rdi
12da: e8 1c fc ff ff callq efb <vuln_func>
```

```
App_base= (savedIP & 0xFFF) - (caller_page_offset << 12)
```

```
0x7F36C6FEB000=(0x7f36C6FEC2DF & 0xFFF)-(0x1000)
```
3) Calculating base application address

00000000000001063 <attend_client>:
1063: 55  push %rbp
1064: 48 89 e5  mov %rsp,%rbp
1067: 48 81 ec 60 04 00 00  sub $0x460,%rsp
106e: 64 48 8b 04 25 28 00  mov %fs:0x28,%rax
1075: 00 00
1077: 48 89 45 f8  mov %rax,-0x8(%rbp)
107b: 31 c0  xor %eax,%eax
......
12d7: 48 89 c7  mov %rax,%rdi
12da: e8 1c fc ff ff  callq efb <vuln_func>
12df: 48 8d 85 c0 fb ff ff  lea -0x440(%rbp),%rax
12e6: 48 89 c7  mov %rax,%rdi
......

\( \text{App. Base} = (\text{savedIP} \& 0xFFF) - (\text{CALLER_PAGE_OFFSET} \ll 12) \)

\( 0x7F36C6fEB000 = (0x7f36C6FEC2DF \& 0xFFF) - (0x1000) \)

App. Base = 0x7F36C6fEB000
4) Calculating library offsets

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Libc version</th>
<th>Offset2lib (bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CentOS 6.5</td>
<td>2.12</td>
<td>0x5b6000</td>
</tr>
<tr>
<td>Debian 7.1</td>
<td>2.13</td>
<td>0x5ac000</td>
</tr>
<tr>
<td>Ubuntu 12.04 LTS</td>
<td>2.15</td>
<td>0x5e4000</td>
</tr>
<tr>
<td>Ubuntu 12.10</td>
<td>2.15</td>
<td>0x5e4000</td>
</tr>
<tr>
<td>Ubuntu 13.10</td>
<td>2.17</td>
<td>0x5ed000</td>
</tr>
<tr>
<td>openSUSE 13.1</td>
<td>2.18</td>
<td>0x5d1000</td>
</tr>
<tr>
<td>Ubuntu 14.04.1 LTS</td>
<td>2.19</td>
<td>0x5eb000</td>
</tr>
</tbody>
</table>
5) Getting app. process mapping

Obtaining library base addresses:
- Application Base = 0x7FD1B473A000
- Offset2lib (libc) = 0x5eb000
- Offset2lib (ld) = 0x225000
5) Getting app. process mapping

Obtaining library base addresses:
- Application Base = 0x7FD1B473A000
- Offset2lib (libc) = 0x5eb000
- Offset2lib (ld) = 0x225000

\[
\text{Libc Base} = 0x7FD1B473A000 - 0x5eb000 = 0x7FD1B414F000
\]
5) Getting app. process mapping

Obtaining library base addresses:
- Application Base = 0x7FD1B473A000
- Offset2lib (libc) = 0x5eb000
- Offset2lib (ld) = 0x225000

Libc Base = 0x7FD1B473A000 - 0x5eb000 = 0x7FD1B414F000
Id Base = 0x7FD1B473A000 - 0x225000 = 0x7fd1b4515000
The vulnerable server

To show a more realistic PoC:

- Bypass NX, SSP, ASLR, FORTIFY or RELRO.
- We do not use GOT neither PLT.
- Valid for any application (Gadgets only from libraries)
- We use a fully updated Linux.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Comment</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>App. relocatable</td>
<td>Yes</td>
<td>-fpie -pie</td>
</tr>
<tr>
<td>Lib. relocatable</td>
<td>Yes</td>
<td>-Fpic</td>
</tr>
<tr>
<td>ASLR config.</td>
<td>Enabled</td>
<td>randomize_va_space = 2</td>
</tr>
<tr>
<td>SSP</td>
<td>Enabled</td>
<td>-fstack-protector-all</td>
</tr>
<tr>
<td>Arch.</td>
<td>64 bits</td>
<td>x86_64 GNU/Linux</td>
</tr>
<tr>
<td>NX</td>
<td>Enabled</td>
<td>PAE or x64</td>
</tr>
<tr>
<td>RELRO</td>
<td>Full</td>
<td>-wl,-z,-relro,-z,now</td>
</tr>
<tr>
<td>FORTIFY</td>
<td>Yes</td>
<td>-D_FORTIFY_SOURCE=2</td>
</tr>
<tr>
<td>Optimisation</td>
<td>Yes</td>
<td>-O2</td>
</tr>
</tbody>
</table>
Demo: Bypass NX, SSP and ASLR in < 1 sec.
How to prevent exploitation

There are many vectors to exploit this weakness: Imagination is the limit. Basically, an attacker needs:

1. The knowledge (information leak).
2. A way to use it.

There are many solutions to address this weakness:

- Avoid information leaks at once:
  - Don’t design weak applications/protocols.
  - Don’t write code with errors.
  - . . .

- Make the leaked information useless:
  - PaX patch
  - `randomize_va_space=3`
  - ASLRv4
  - RenewSSP: Improve stack-smashing-protector.
Solutions overview

The weakness

Solved with

PaX

ASLR patch: va_space = 3

The PoC

Solved with

RenewSSP

ASLR redesign: ASLRv4
What is wrong with the current ASLR design?

At a very abstract level the answer is:

**It does not honour MILS concepts**

- **MILS**: “Multiple Independent Levels of Security/Safety”.
- The whole system is as weak as the weakest part.
- Library vs. application code:
  - Library code is written by more experienced programmers.
  - Library code is intensively and extensively tested: many users used/abused it in many ways.
- Application code is more prone to programming bugs than libraries.
PaX Patch

- PaX defines three areas:
  - **delta_exec**: code, data, bss, brk.
  - **delta_mmap**: libraries, mapped files, thread stack, shared memory, ...
  - **delta_stack**: user stack.

- **PaX ASLR does not have this weakness.**
- PaX is very robust and complete.
- It is able to randomise even non-PIE applications.
- Unfortunately, some people think that it is a complex patch with, may be, too many features.
- It is not in the Linux mainstream.
On the effectiveness of Full-ASLR on 64-bit Linux

Hector Marco

ASLR

randomize_va_space=3

A very simple idea to workaround this weakness:

Place the executable and the libraries at different addresses
On the effectiveness of Full-ASLR on 64-bit Linux

Hector Marco

randomize_va_space=3

A very simple idea to workaround this weakness:

**Place the executable and the libraries at different addresses**

- If there is no relation between application executable and library addresses, then it is useless
- An executable memory leak cannot be used to build a library ROPs
- It has been implemented as a small Linux kernel patch

This is basically the same solution that the one used by PaX, but smaller.
With randomize_va_space=2

<table>
<thead>
<tr>
<th>Address</th>
<th>Permissions</th>
<th>Size</th>
<th>Offset</th>
<th>File</th>
</tr>
</thead>
<tbody>
<tr>
<td>7f621ffbb000</td>
<td>r-x</td>
<td>00000000</td>
<td>00:02</td>
<td>/lib/x86_64-linux-gnu/libc.so.6</td>
</tr>
<tr>
<td>7f6220176000</td>
<td>---p</td>
<td>001bb000</td>
<td>00:02</td>
<td>/lib/x86_64-linux-gnu/libc.so.6</td>
</tr>
<tr>
<td>7f6220376000</td>
<td>r--p</td>
<td>001bb000</td>
<td>00:02</td>
<td>/lib/x86_64-linux-gnu/libc.so.6</td>
</tr>
<tr>
<td>7f622037a000</td>
<td>rw-p</td>
<td>001bf000</td>
<td>00:02</td>
<td>/lib/x86_64-linux-gnu/libc.so.6</td>
</tr>
<tr>
<td>7f622037c000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>7f6220381000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>7f622059c000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>7f622059d000</td>
<td>r-x</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>7f622059e000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>7f62205a3000</td>
<td>rw-p</td>
<td>00022000</td>
<td>00:02</td>
<td>/lib64/ld-linux-x86-64.so.2</td>
</tr>
<tr>
<td>7f62205a4000</td>
<td>rw-p</td>
<td>00023000</td>
<td>00:02</td>
<td>/lib64/ld-linux-x86-64.so.2</td>
</tr>
<tr>
<td>7f62205a5000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>7f62205a6000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>/bin/hello_world_dynamic_pie</td>
</tr>
<tr>
<td>7f62207a6000</td>
<td>r--p</td>
<td>00000000</td>
<td>00:02</td>
<td>/bin/hello_world_dynamic_pie</td>
</tr>
<tr>
<td>7f62207a7000</td>
<td>r--p</td>
<td>00000000</td>
<td>00:02</td>
<td>/bin/hello_world_dynamic_pie</td>
</tr>
<tr>
<td>7ff47e15000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>0 [stack]</td>
</tr>
<tr>
<td>7ff47e63000</td>
<td>r--p</td>
<td>00000000</td>
<td>00:00</td>
<td>0 [vvar]</td>
</tr>
<tr>
<td>7ff47e65000</td>
<td>r-x</td>
<td>00000000</td>
<td>00:00</td>
<td>0 [vdso]</td>
</tr>
<tr>
<td>ffffffff60000000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>0 [vsyscall]</td>
</tr>
</tbody>
</table>
With randomize_va_space=3

```bash
# echo 3 > /proc/sys/kernel/randomize_va_space
# hello_world_dynamic_pie

<table>
<thead>
<tr>
<th>Address Range</th>
<th>Permissions</th>
<th>Size</th>
<th>File Path</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x54859ccd6000-0x54859ccd7000</td>
<td>r-xp</td>
<td>00000000</td>
<td>00:02</td>
<td>4896</td>
</tr>
<tr>
<td>0x54859ced6000-0x54859ced7000</td>
<td>r--p</td>
<td>00000000</td>
<td>00:02</td>
<td>4896</td>
</tr>
<tr>
<td>0x54859ced7000-0x54859ced8000</td>
<td>rw-p</td>
<td>00010000</td>
<td>00:02</td>
<td>4896</td>
</tr>
<tr>
<td>0x7f75be764000-0x7f75be91f000</td>
<td>r-xp</td>
<td>00000000</td>
<td>00:02</td>
<td>5192</td>
</tr>
<tr>
<td>0x7f75be91f000-0x7f75beb1f000</td>
<td>---p</td>
<td>001bb000</td>
<td>00:02</td>
<td>5192</td>
</tr>
<tr>
<td>0x7f75beb1f000-0x7f75beb23000</td>
<td>r--p</td>
<td>001bb000</td>
<td>00:02</td>
<td>5192</td>
</tr>
<tr>
<td>0x7f75beb23000-0x7f75beb25000</td>
<td>rw-p</td>
<td>001bf000</td>
<td>00:02</td>
<td>5192</td>
</tr>
<tr>
<td>0x7f75beb25000-0x7f75beb2a000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>0x7f75beb2a000-0x7f75beb4d000</td>
<td>r-xp</td>
<td>00000000</td>
<td>00:02</td>
<td>4917</td>
</tr>
<tr>
<td>0x7f75bed45000-0x7f75bed46000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>0x7f75bed46000-0x7f75bed47000</td>
<td>r-xp</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>0x7f75bed47000-0x7f75bed4c000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>0x7f75bed4c000-0x7f75bed4d000</td>
<td>r--p</td>
<td>00022000</td>
<td>00:02</td>
<td>4917</td>
</tr>
<tr>
<td>0x7f75bed4d000-0x7f75bed4e000</td>
<td>rw-p</td>
<td>00023000</td>
<td>00:02</td>
<td>4917</td>
</tr>
<tr>
<td>0x7f75bed4e000-0x7f75bed4f000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>0x7fffb3741000-0x7fffb3762000</td>
<td>rw-p</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>0x7fffb377b000-0x7fffb377d000</td>
<td>r--p</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>0x7fffb377d000-0x7fffb377f000</td>
<td>r-xp</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
<tr>
<td>ffffffffff600000-fffffffffffff601000</td>
<td>r-xp</td>
<td>00000000</td>
<td>00:00</td>
<td>0</td>
</tr>
</tbody>
</table>
ASLR redesign

- “Entropy” and “uncertainty” are a fuzzy concepts.
- ASLR goal is to hide the addresses of the program by making them random numbers.
- Is it possible to hide one address from an others?
- Can we place each library at a random place?
- Does it has a negative impact on the execution of the programs?
- The real question is:
  Why are all the mmapped areas located side by side?
The virtual space on 64bits is big.

Current x86_64 systems only implement 48 bits of virtual address space.

Linux allocates half of that space to the kernel.

The remaining $[0..2^{47} - 1]$ is still fairly huge space to play with.

Allocate each library at a different (random) position is possible.
ASLRv4 algorithm operation

mmap

Free/allocated
ASLRv4 algorithm operation
On the effectiveness of Full-ASLR on 64-bit Linux

Hector Marco

ASLR

ASLRv4 algorithm operation

mmap

Free/allocated

Valid/invalid

where?

0

\[2^{47}\]
ASLRv4 algorithm operation
On the effectiveness of Full-ASLR on 64-bit Linux

Hector Marco

ASLR

ASLRv4 algorithm operation

mmap

Free/allocated

Valid/invalid

Available range

OneShot

where?

mmap

Free/allocated

Valid/invalid

Available range

OneShot

Random

$2^{47}$
ASLRv4 algorithm operation

- mmap
- Free/allocated
- Valid/invalid
- Available range
- OneShot
- Find the target
Is it possible to exhaust the virtual memory space of the process (by using this random allocator) due to extreme fragmentation?

Note that the allocator operates at virtual memory addresses, and so the fragmentation cannot be solved using the paging system.

What is fragmentation?

Wikipedia: "External fragmentation arises when free memory is separated into small blocks and is interspersed by allocated memory."
ASLRv4 & fragmentation (I)

- Is it possible to exhaust the virtual memory space of the process (by using this random allocator) due to extreme fragmentation?
  
  Note that the allocator operates at virtual memory addresses, and so the fragmentation cannot be solved using the paging system.

- What is fragmentation?

  Wikipedia: "External fragmentation arises when free memory is separated into small blocks and is interspersed by allocated memory."
  
  Wilson: "The inability to reuse memory that is free"
The worst scenario (which will cause a fault) will occur when all the available free holes are one page smaller than the size requested (Robson).

What is the largest chunk of memory that is requested (let’s put aside the stack).

The largest library:

```
$ find /usr /lib /lib64 -name "*.so*" -ls | sort -r -n -k7 | head
... 66075200 oct 13 23:19 /usr/lib/firefox/libxul.so
... 54489264 nov 4 22:28 /usr/lib/libreoffice/program/libmergedlo.so
... 33135344 ago 15 09:33 /usr/lib/x86_64-linux-gnu/libwebkitgtk-1.0.so.0.22.10
... 26743968 mar 5 2014 /usr/lib/x86_64-linux-gnu/libLLVM-3.4.so.1
... 23512848 dic 27 2013 /usr/lib/x86_64-linux-gnu/libicudata.so.52.1
... 16718762 abr 12 2014 /usr/lib/x86_64-linux-gnu/liboctave.so.2.0.0
... 14785795 oct 22 10:08 /usr/lib/jvm/java-7-openjdk-amd64/jre/lib/amd64/server/libjvm.so
... 14632264 abr 12 2014 /usr/lib/x86_64-linux-gnu/liboctinterp.so.2.0.0
... 14150948 nov 4 22:28 /usr/lib/libreoffice/program/libswlo.so
```

The smallest chunk of memory is one page.
Number of requests needed to "fragment" the memory that badly:

\[ \frac{2^{47}}{52 \text{Mb}} \approx 1.312.342 \]

Minimum amount of memory that must be allocated:

\[ \frac{2^{47}}{52 \text{Mb}} \times 4 \text{kb} \approx 5.375.352.851 \text{b} \approx 5 \text{Gb} \]

You are close to exhaust the physical memory before you get a fragmentation fault, after making more than a million mmaps.
ASLRv4 & fragmentation (III)

- OK, I’m insane: I usually do millions of mmaps.
- What is the probability of facing the worst scenario?
- All the randomly blocks are placed exactly 52Mb apart.

\[ \sim (2^{47})^{1.312.342} \]

- According to OCTAVE:

  ```octave
  octave:32> (2^47)^1312342
  ans = Inf
  ```

- The end of the world is far more likely than running out of virtual space.
Brute forcing the SSP

In this PoC, before bypassing the ASLR, we had to bypass the SSP. A better implementation of the SSP would have blocked the attack.

- SSP is very effective\(^1\) to protect stack smashing.
- The canary (stack guard) is a fairly large random number on 32bits and a ginormous number on 64bits.
- Unfortunately, the byte-for-byte attack yields the SSP almost useless, as shown in the PoC.
- The problem is that all the children (on a forking server) inherit the same canary (the secret).

\(^1\)But not always, see CVE-2014-5439
What if every child process has a different canary value?

It will be **impossible** to make a **brute force attack**

- RenewSSP\(^2\) is an extension of the stack-protector technique which renews the reference-canary at key points during the execution of the application.
- One of such points is when a new process is created (forked).
- We showed (in a previous paper) that it is possible to renew the canary, set a new random value, on a child process and it can continue normally.

\(^2\)http://renewssp.com
On current systems with SSP (all existing ones):
⇒ brute force is possible because the attacker can discard the guessed values until the correct one is found.
⇒ It is a “sampling without replacement” statistical process.
⇒ Known also as: brute-force.

With RenewSSP:
⇒ a guessed value can not be discarded, because it may appear again.
⇒ It is a “sampling with replacement” statistical process.
⇒ Known also as: trial-and-test.

Regarding byte-for-byte: RenewSSP disables the possibility to split the attack into single bytes. Which renders the attack as a trial-and-test to the whole canary word.

With RenewSSP, the PoC showed on this presentation is prevented.
Conclusions

- Using offset2lib, we have shown the fastest way to bypass the ASLR on Linux 64 bits by exploiting a stack buffer overflow.

- Incrementing the ASLR entropy bits does not thwart our attack.

- We consider that PIE linked application prone to byte-for-byte attacks are not secure.

- We have proposed to Linux kernel developers the ASLRv3 which removes the weakness by randomising the distance between the libraries and the executable.

- A new design of the ASLR (ALSRv4), which increases the entropy, has been presented and discussed.

- As far as we know, the RenewSSP is the only technique which prevents the attack vector used in the PoC.
Questions ?

* Hector Marco-Gisbert http://hmarco.org
* Ismael Ripoll Ripoll http://personales.upv.es/iripoll
* Cyber-security research group at http://cybersecurity.upv.es

In collaboration with PacketStorm.