Secure by default
Anti-exploit techniques and hardenings in SUSE products

Johannes Segitz
SUSE Security Team

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Who am I?

Johannes Segitz, security engineer (Nuremberg, Germany)

- Code review
- Product pentesting

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First time in Nashville, great city (but I'll have to go on a diet after this week)

Outline

Buffer overflows and protections:

- Stack canaries
- Fortify source
- Address space layout randomization
- No-execute memory (NX, W^X)
- Stack clash protection
- RELRO

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Used by SUSE products, there are other protection mechanisms out there

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This is short overview of what we're doing.

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A problem in languages in which you manage your own memory (primary example is C)

Really simple example:

```c
#include <string.h>

int main(int argc, char **argv) {
  char buffer[20];

  strcpy(buffer, argv[1]);

  return EXIT_SUCCESS;
}
```

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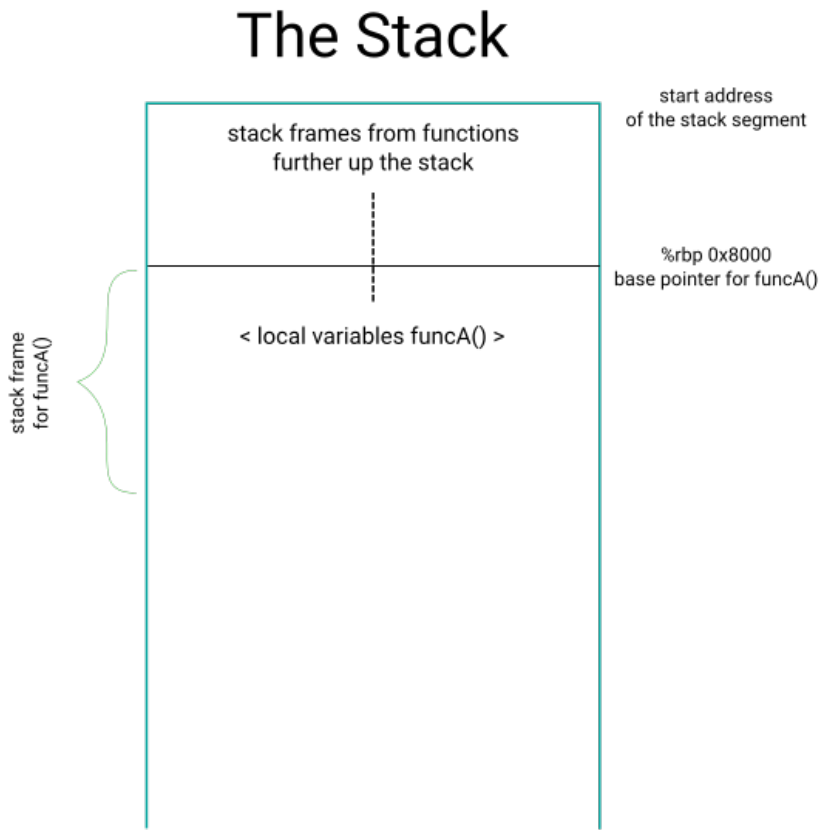
Sometimes the check is there but faulty or can be circumvented (think integer overflows)

Why is this a problem?

Because in data of the application and control information about execution is mixed




```c
/*
 * some simple, fuzzy code for explaining
 * the stack frame setup
 *
 * hex addresses are just rounded samples
 * for better readability
 */

void funcB(uint32_t num)
{
    uint64_t local_var;
    register uint32_t index;

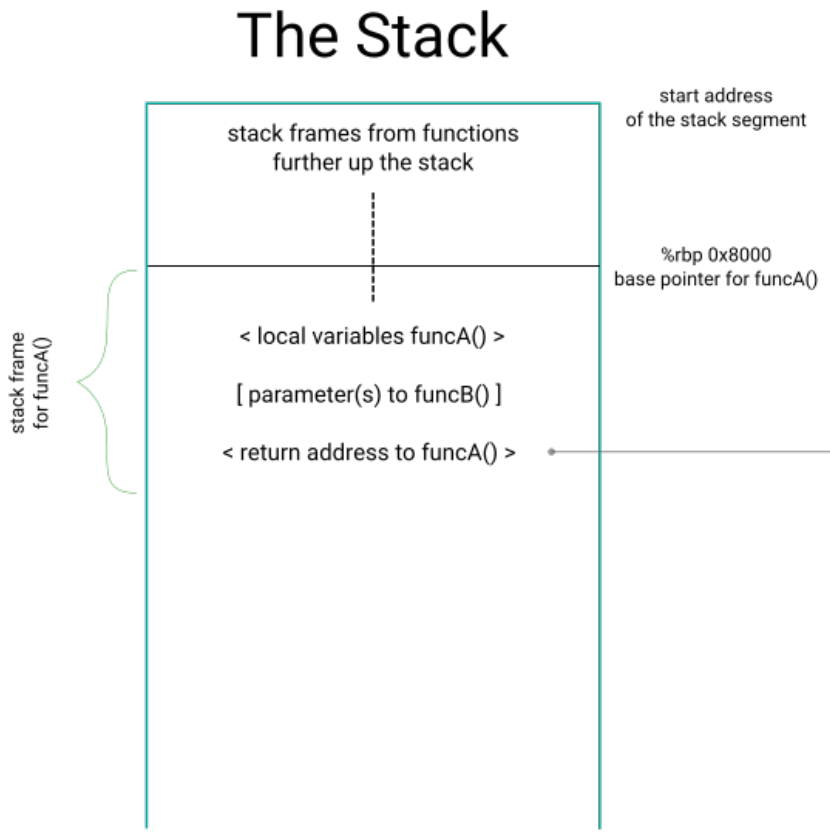
    /* some more code */
}

void funcA()
{
    /* some local vars */
    funcB(some_num);

    /* some more code */
}
```

Why is this a problem?

Part of the control information (saved instruction pointer RIP/EIP) is the address where execution will continue after the current function

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If a buffer overflow happens this control information can be overwritten

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If this is done carefully arbitrary code can be executed

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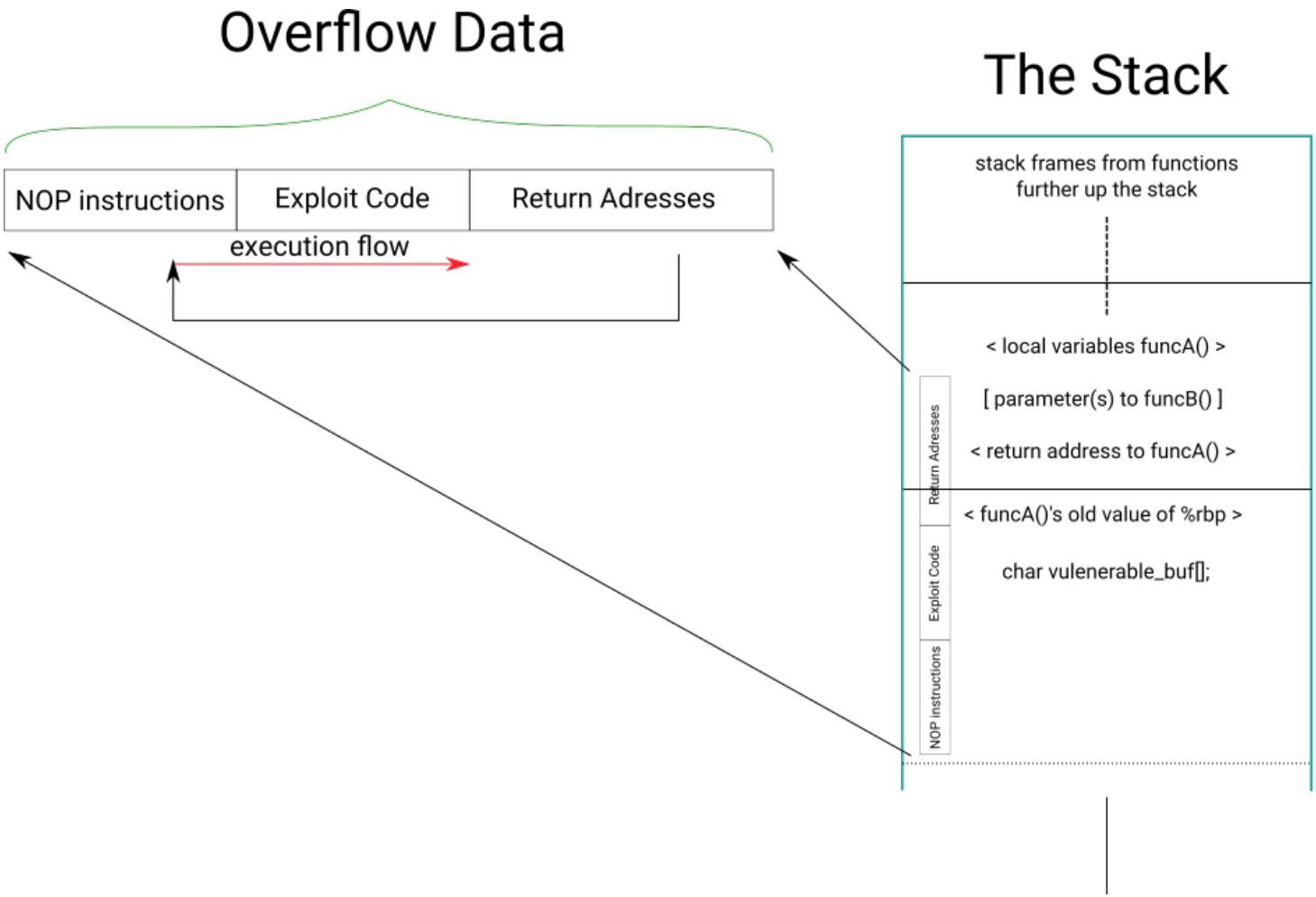

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- Function pointers
- Exceptions handlers
- Other application specific data (`is_admin` flag ...)

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- Function pointers
- Exceptions handlers
- Other application specific data (`is_admin` flag ...)

So what can be done against these problems?

Just use Java for everything. Done! We're safe ;)

Simple 32 bit exploitation

```
#include <unistd.h>

void vulnerable( void ) {
  char buffer[256];

  read(0, buffer, 512);

  return;
}

int main(int argc, char **argv) {
  vulnerable();

  return EXIT_SUCCESS;
}
```

Demo time

Mitigations: Stack canaries

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- Terminator canaries: NULL, CR, LF, and -1

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- `-fstack-protector-all`: extra code for each and every function
- `-fstack-protector-explicit`: extra code every function annotated with `stack_protect`

Mitigations: Stack canaries

Short reminder of the example code:

```
#include <string.h>

int main(int argc, char **argv)
{
  char buffer[20];

  strcpy(buffer, argv[1]);

  return EXIT_SUCCESS;
}
```

Mitigations: Stack canaries

Original code:

```
00000000000006b0 <main>:
 6b0:   55                      push   rbp
 6b1:   48 89 e5                mov    rbp,rsp
 6b4:   48 83 ec 30             sub    rsp,0x30
 6b8:   89 7d dc                mov    DWORD PTR [rbp-0x24],edi
 6bb:   48 89 75 d0             mov    QWORD PTR [rbp-0x30],rsi
 6bf:   48 8b 45 d0             mov    rax,QWORD PTR [rbp-0x30]
 6c3:   48 83 c0 08             add    rax,0x8
 6c7:   48 8b 10                mov    rdx,QWORD PTR [rax]
 6ca:   48 8d 45 e0             lea    rax,[rbp-0x20]
 6ce:   48 89 d6                mov    rsi,rdx
 6d1:   48 89 c7                mov    rdi,rax
 6d4:   e8 87 fe ff ff          call   560 <strcpy@plt>
 6d9:   b8 00 00 00 00          mov    eax,0x0
 6de:   c9                      leave
 6df:   c3                      ret
```

Mitigations: Stack canaries

Protected code:

```
0000000000000720 <main>:
 720:   55                          push   rbp
 721:   48 89 e5                    mov    rbp,rsp
 724:   48 83 ec 30                 sub    rsp,0x30
 728:   89 7d dc                    mov    DWORD PTR [rbp-0x24],edi
 72b:   48 89 75 d0                 mov    QWORD PTR [rbp-0x30],rsi
 72f:   64 48 8b 04 25 28 00        mov    rax,QWORD PTR fs:0x28
 736:   00 00
 738:   48 89 45 f8                 mov    QWORD PTR [rbp-0x8],rax
 73c:   31 c0                       xor    eax,eax
 73e:   48 8b 45 d0                 mov    rax,QWORD PTR [rbp-0x30]
 742:   48 83 c0 08                 add    rax,0x8
 746:   48 8b 10                    mov    rdx,QWORD PTR [rax]
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 74d:   48 89 d6                    mov    rsi,rdx
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 753:   e8 68 fe ff ff              call   5c0 <strcpy@plt>
 758:   b8 00 00 00 00              mov    eax,0x0
 75d:   48 8b 4d f8                 mov    rcx,QWORD PTR [rbp-0x8]
 761:   64 48 33 0c 25 28 00        xor    rcx,QWORD PTR fs:0x28
 768:   00 00
 76a:   74 05                       je     771 <main+0x51>
 76c:   e8 5f fe ff ff              call   5d0 <__stack_chk_fail@plt>
 771:   c9                          leave
 772:   c3                          ret
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- Can be used to cause DoS

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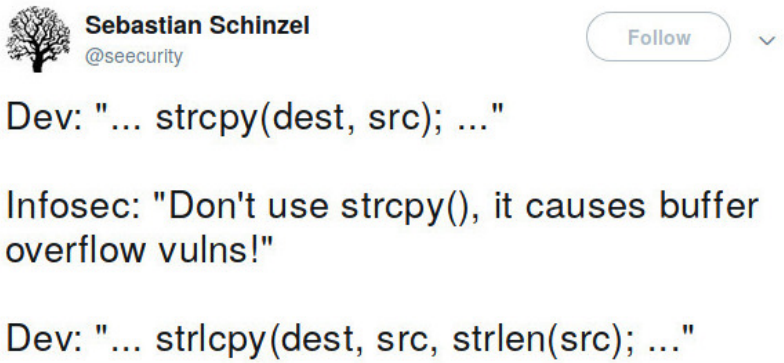

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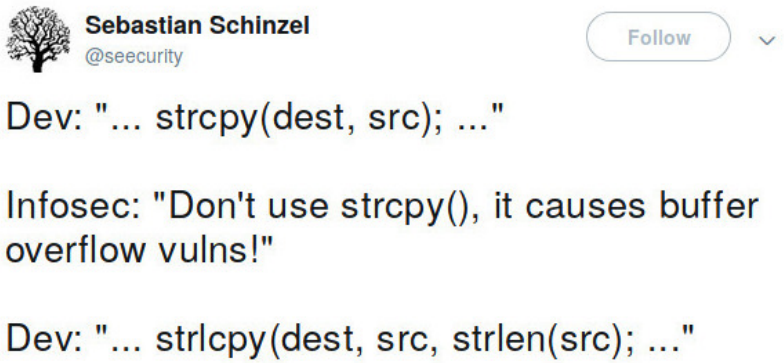

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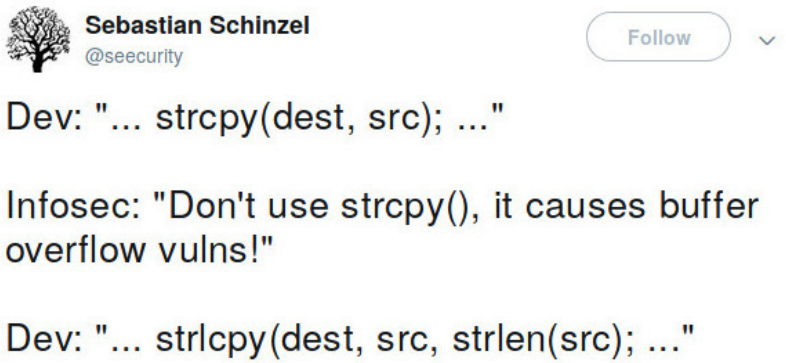

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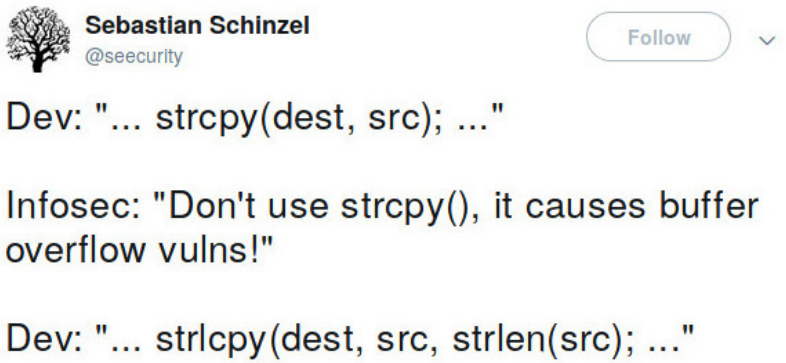

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Enabled since SUSE Linux Enterprise Server 10

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```c
void fun(char *s) {
  char buf[0x100];
  strcpy(buf, s);
  /* Don't allow gcc to optimise away the buf */
  asm volatile("" :: "m" (buf));
}

int main(int argc, char **argv)
{
  fun( argv[1] );

  return EXIT_SUCCESS;
}
```

Example based on Matthias' work

Mitigations: Fortify source

```
000000000000006b0 <fun>:
 6b0:   55                      push   rbp
 6b1:   48 89 e5                mov    rbp,rsp
 6b4:   48 81 ec 10 01 00 00    sub    rsp,0x110
 6bb:   48 89 bd f8 fe ff ff    mov    QWORD PTR [rbp-0x108],rdi
 6c2:   48 8b 95 f8 fe ff ff    mov    rdx,QWORD PTR [rbp-0x108]
 6c9:   48 8d 85 00 ff ff ff    lea    rax,[rbp-0x100]
 6d0:   48 89 d6                mov    rsi,rdx
 6d3:   48 89 c7                mov    rdi,rax
 6d6:   e8 85 fe ff ff          call   560 <strcpy@plt>
 6db:   90                      nop
 6dc:   c9                      leave
 6dd:   c3                      ret
```

Mitigations: Fortify source

`gcc -o fortify -O2 -D_FORTIFY_SOURCE=2 fortify.c`

```
0000000000000700 <fun>:
 700:   48 81 ec 08 01 00 00    sub    rsp,0x108
 707:   48 89 fe                mov    rsi,rdi
 70a:   ba 00 01 00 00          mov    edx,0x100
 70f:   48 89 e7                mov    rdi,rsp
 712:   e8 69 fe ff ff          call   580 <__strcpy_chk@plt>
 717:   48 81 c4 08 01 00 00    add    rsp,0x108
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But it comes with almost no cost, so enable it

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Memory segments (stack, heap and code) are loaded at random locations

Atttackers don't know return addresses into exploit code or C library code reliably any more

Mitigations: ASLR

```
bash -c 'cat /proc/$$/maps'
56392d605000-56392d60d000 r-xp 00000000 fe:01 12058638  /bin/cat
<snip>
56392dd05000-56392dd26000 rw-p 00000000 00:00 0         [heap]
7fb2bd101000-7fb2bd296000 r-xp 00000000 fe:01 4983399
     /lib/x86_64-linux-gnu/libc-2.24.so
<snip>
7fb2bd6b2000-7fb2bd6b3000 r--p 00000000 fe:01 1836878
     /usr/lib/locale/en_AG/LC_MESSAGES/SYS_LC_MESSAGES
<snip>
7fffd5c36000-7fffd5c57000 rw-p 00000000 00:00 0         [stack]
7fffd5ce9000-7fffd5ceb000 r--p 00000000 00:00 0         [vvar]
7fffd5ceb000-7fffd5ced000 r-xp 00000000 00:00 0         [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0 [vsyscall]
```

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<snip>
7fb2bd6b2000-7fb2bd6b3000 r--p 00000000 fe:01 1836878
     /usr/lib/locale/en_AG/LC_MESSAGES/SYS_LC_MESSAGES
<snip>
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```

```
for i in `seq 1 5`; do bash -c 'cat /proc/$$/maps | grep stack'; done
7ffcb8e0f000-7ffcb8e30000 rw-p 00000000 00:00 0 [stack]
7fff64dc9000-7fff64dea000 rw-p 00000000 00:00 0 [stack]
7ffc3b408000-7ffc3b429000 rw-p 00000000 00:00 0 [stack]
7ffcee799000-7ffcee7ba000 rw-p 00000000 00:00 0 [stack]
7ffd4b904000-7ffd4b925000 rw-p 00000000 00:00 0 [stack]
```

Mitigations: ASLR

`cat /proc/sys/kernel/randomize_va_space` shows you the current settings for your system.

- **0**: No randomization
- **1**: Randomize positions of the stack, VDSO page, and shared memory regions
- **2**: Randomize positions of the stack, VDSO page, shared memory regions, and the data segment

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To get the full benefit you need to compile your binaries with `-fPIE`

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- Brute forcing still an issue if restart is not handled properly.
- Can be circumvented by chaining an information leak into the exploit
- Some exotic software might rely on fixed addresses (think inline assembly)
- Sometimes you have usable memory locations in registers

Mitigations: No-execute memory

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The most interesting memory regions for this feature to use are the stack and heap memory regions

A stack overflow could still take place, but it is not be possible to *directly* return to a stack address for execution

Mitigations: No-execute memory

Modern processors support memory to be mapped as non-executable

Another term for this feature is NX or W^X

The most interesting memory regions for this feature to use are the stack and heap memory regions

A stack overflow could still take place, but it is not be possible to *directly* return to a stack address for execution

```
bash -c 'cat /proc/$$/maps | grep stack'
7ffcb8e0f000-7ffcb8e30000 rw-p 00000000 00:00 0 [stack]
```

Mitigations: NX

Limitations

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- Use existing code in the exploited program

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Mitigations: NX

Limitations

- Use existing code in the exploited program
- Return to libc: Use existing functions
- ROP (Return Oriented Programming): Structure the data on the stack so that instruction sequences ending in `ret` can be used

Mitigations: Stack clash protection

Heap and stack live both in the address space of the process and they grow dynamically

```
bash -c 'cat /proc/$$/maps | egrep "(heap|stack)"'
55dc4ffbe000-55dc4ffdf000 rw-p 00000000 00:00 0                          [heap]
7ffce8c2b000-7ffce8c4c000 rw-p 00000000 00:00 0                          [stack]
```

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So what happens if those two meet?

Guard page is inserted between stack and heap, causes an segmentation fault if they clash

Mitigations: Stack clash protection

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After that you can write to the stack to modify data on the heap or the other way around

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To prevent this compile code with: `-fstack-clash-protection`

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Ensures access to every page when doing large allocations

Mitigations: Stack clash protection

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

void
fancyprint( char *str1, char *str2 )
{
  char *name = (char *) alloca (strlen (str1) + strlen (str2) + 1);
  stpcpy (stpcpy (name, str1), str2);
  printf("%s\n", name );
}

int
main( int argc, char *argv[]) {
  if ( argc < 3 ) {
    return EXIT_FAILURE;
  }

  fancyprint( argv[1], argv[2] );
  return EXIT_SUCCESS;
}
```

Mitigations: Stack clash protection

```
<+39>:    call   0x400500 <strlen@plt>
<+44>:    add    rax,rbx
<+47>:    add    rax,0x1
<+51>:    lea    rdx,[rax+0xf]
<+55>:    mov    eax,0x10
<+60>:    sub    rax,0x1
<+64>:    add    rax,rdx
<+67>:    mov    ecx,0x10
<+72>:    mov    edx,0x0
<+77>:    div    rcx
<+80>:    imul   rax,rax,0x10
<+84>:    sub    rsp,rax
<+87>:    mov    rax,rsp
<+90>:    add    rax,0xf
<+94>:    shr    rax,0x4
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400616:       48 83 c0 01             add    rax,0x1
40061a:       48 8d 50 0f             lea    rdx,[rax+0xf]
40061e:       b8 10 00 00 00          mov    eax,0x10
400623:       48 83 e8 01             sub    rax,0x1
400627:       48 01 d0                add    rax,rdx
40062a:       b9 10 00 00 00          mov    ecx,0x10
40062f:       ba 00 00 00 00          mov    edx,0x0
400634:       48 f7 f1                div    rcx
400637:       48 6b c0 10             imul   rax,rax,0x10
40063b:       48 89 e2                mov    rdx,rsp
40063e:       48 85 c0                test   rax,rax
400641:       74 28                   je     40066b <fancyprint+0x84>
400643:       48 3d 00 10 00 00       cmp    rax,0x1000
400649:       72 16                   jb     400661 <fancyprint+0x7a>
40064b:       48 2d 00 10 00 00       sub    rax,0x1000
400651:       48 81 ec 00 10 00 00    sub    rsp,0x1000
400658:       48 89 e2                mov    rdx,rsp
40065b:       48 83 0a 00             or     QWORD PTR [rdx],0x0
40065f:       eb e2                   jmp    400643 <fancyprint+0x5c>
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High value mitigation with almost no downsides. See CVE-2018-16864 ("System down")

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Enabled since SUSE Linux Enterprise Server 15, all SLE 12 updates receive the protection automatically

RELRO

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If binaries are

- are compiled with `-fPIE`, `-fPIC`
- use dynamic libraries

relocations are necessary

RELRO

Example code:

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

int
main( int argc, char *argv[] ) {
  printf("Hello world\n");

  printf("Nice to see you again\n");
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RELRO

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First `printf` will need to go through relocation process, second `printf` can jump directly.

Demo time

RELRO

The entries in these tables can be overwritten to execute different code

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Partial RELRO (protects against overflows in global variables) since SUSE Linux Enterprise Server 10

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Partial RELRO (protects against overflows in global variables) since SUSE Linux Enterprise Server 10

Full RELRO is in testing in Factory

Drawbacks of full RELRO:

- Startup time is increased in large programs (thousands of symbols)

Outlook

Exploitation got harder, but this is an ongoing struggle

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- Shadow stacks
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ROP is used in a lot of modern exploits:

- Shadow stacks
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These mitigations are currently rather costly, hard to convince users to take the hit

So keep your systems updated

Thank you for your attention!

Questions?

Slides at https://users.suse.com/~jsegitz/talks/2019.04-susecon.pdf
Or just scan: