CS-3002: Information Security

Lecture # 13: Control Hijacking Attacks and Defenses

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This Lecture

- Basic Control Hijacking Attacks
- More Control Hijacking Attacks
- Format String Bugs
- Platform Defenses
- Run-Time Defenses
- Advance Hijacking Attacks

Basic Control Hijacking Attacks

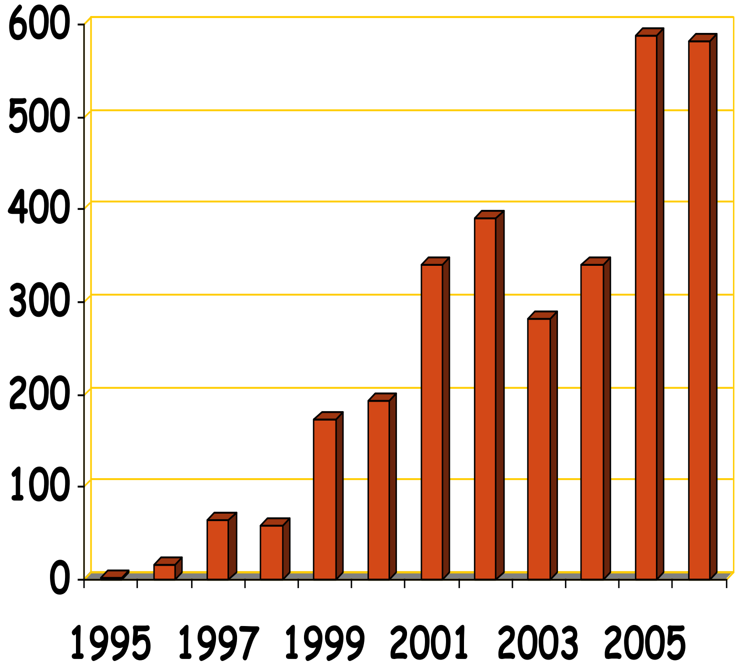
Control hijacking attacks

- <u>Attacker's goal</u>:
  - Take over target machine (e.g. web server, email 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 (moris worm)



≈20% of all vuln.

2005-2007: ≈ 10%

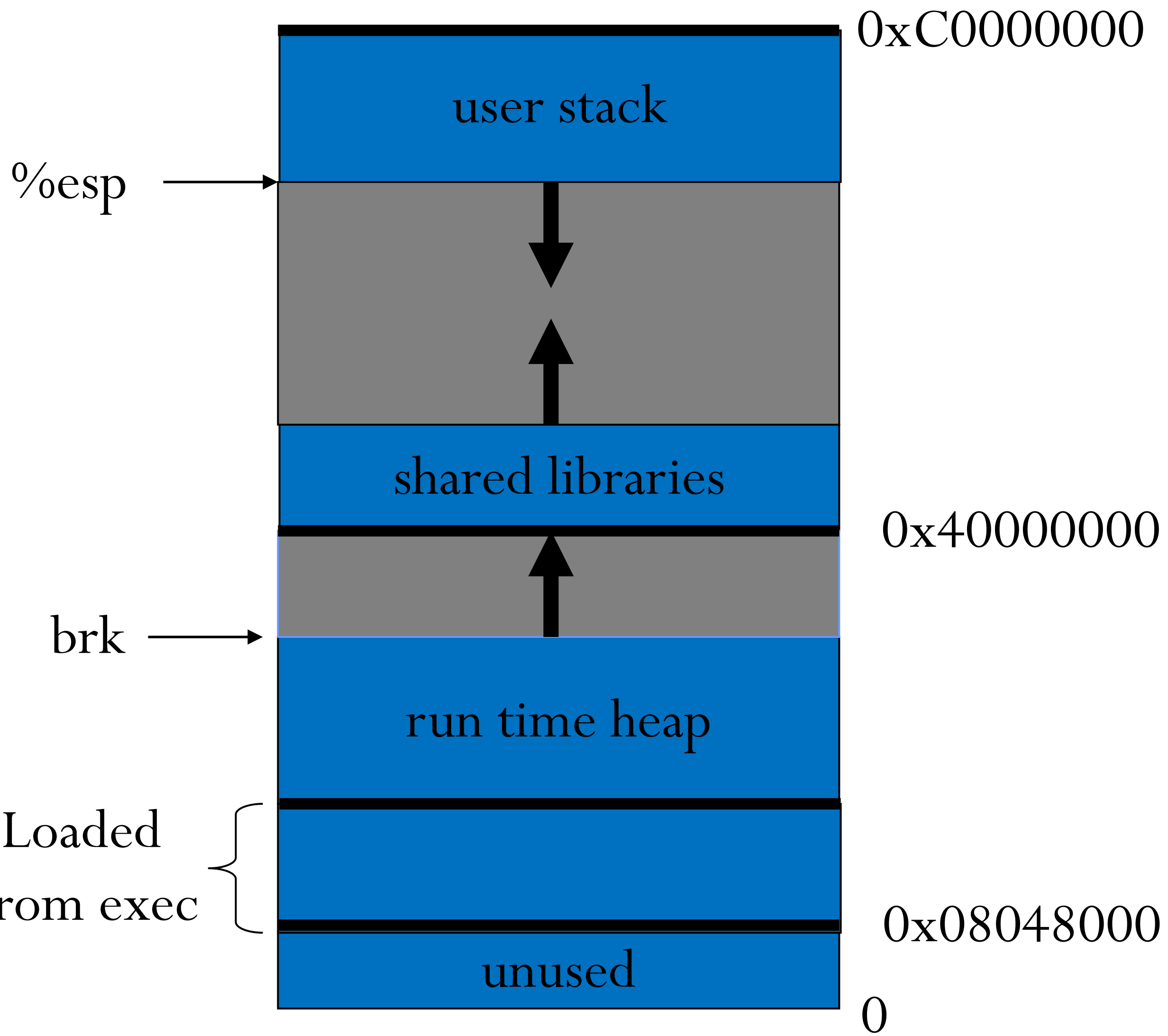
Source: NVD/CVE

What is needed

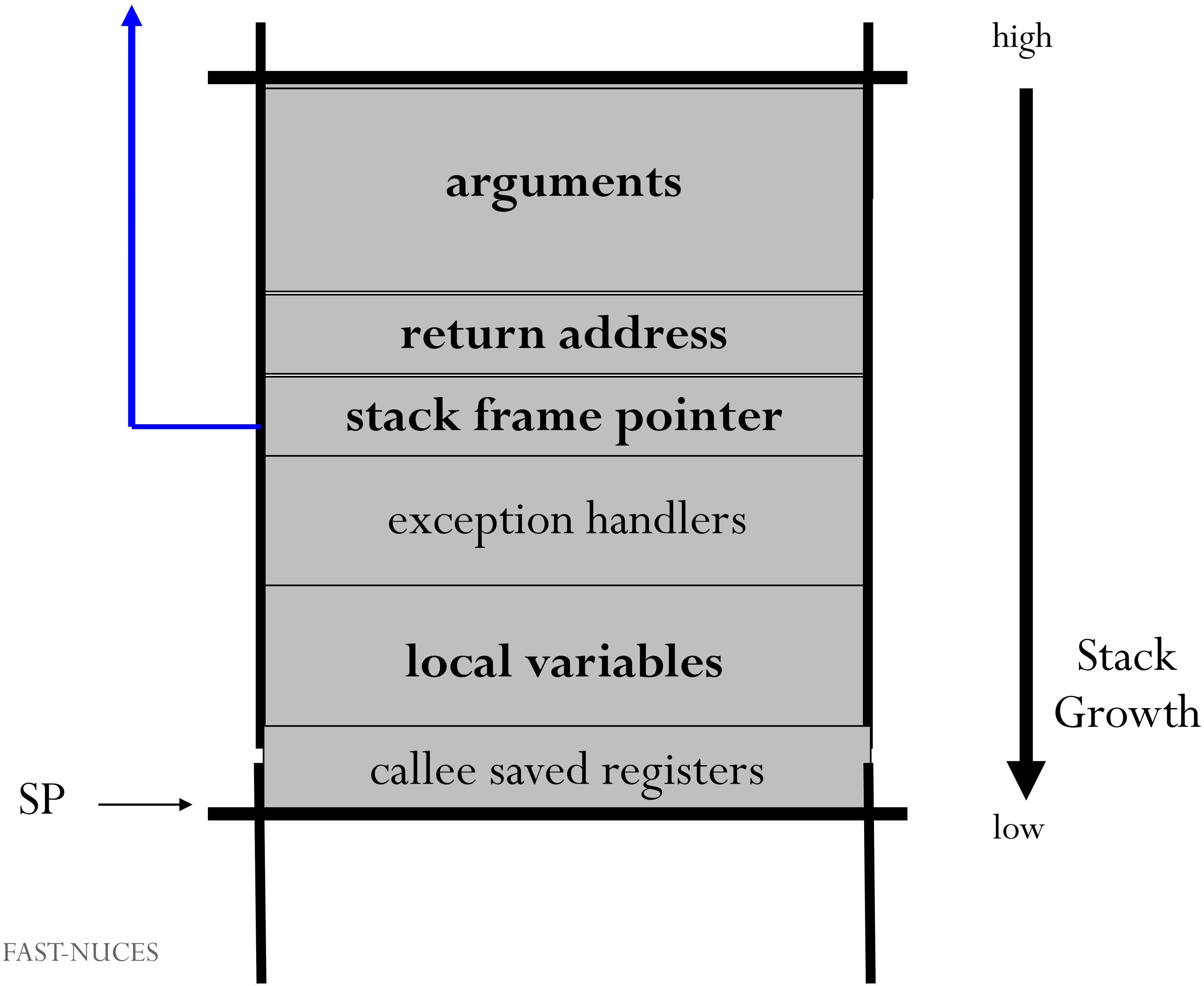
- Understanding C functions, the stack, and the heap.
- Know how system calls are made
- The exec() system call

- 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



Stack Frame (created every time a new function is invoked)

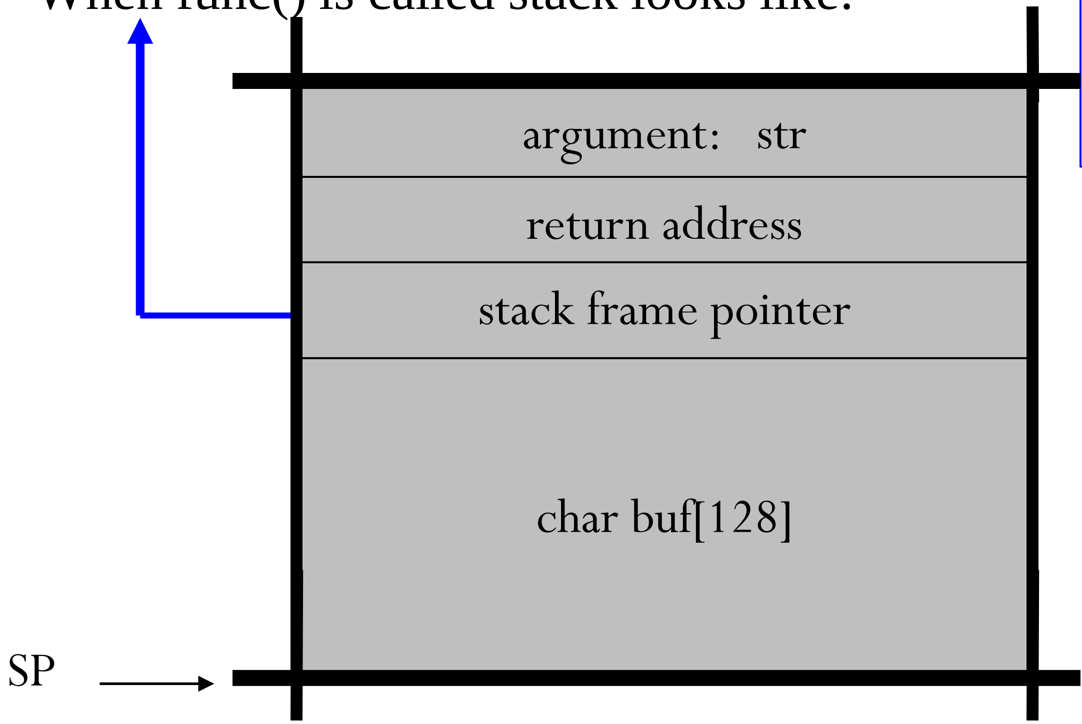


What are buffer overflows?

Suppose a web server contains a function:

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

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

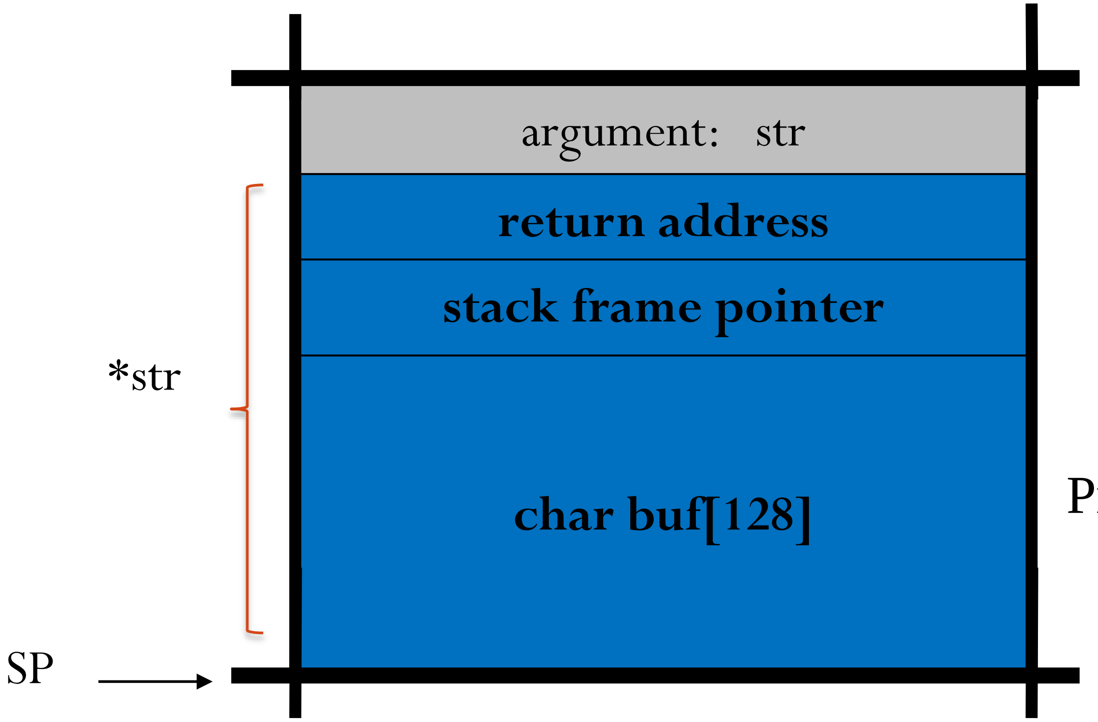
When func() is called stack looks like:



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:

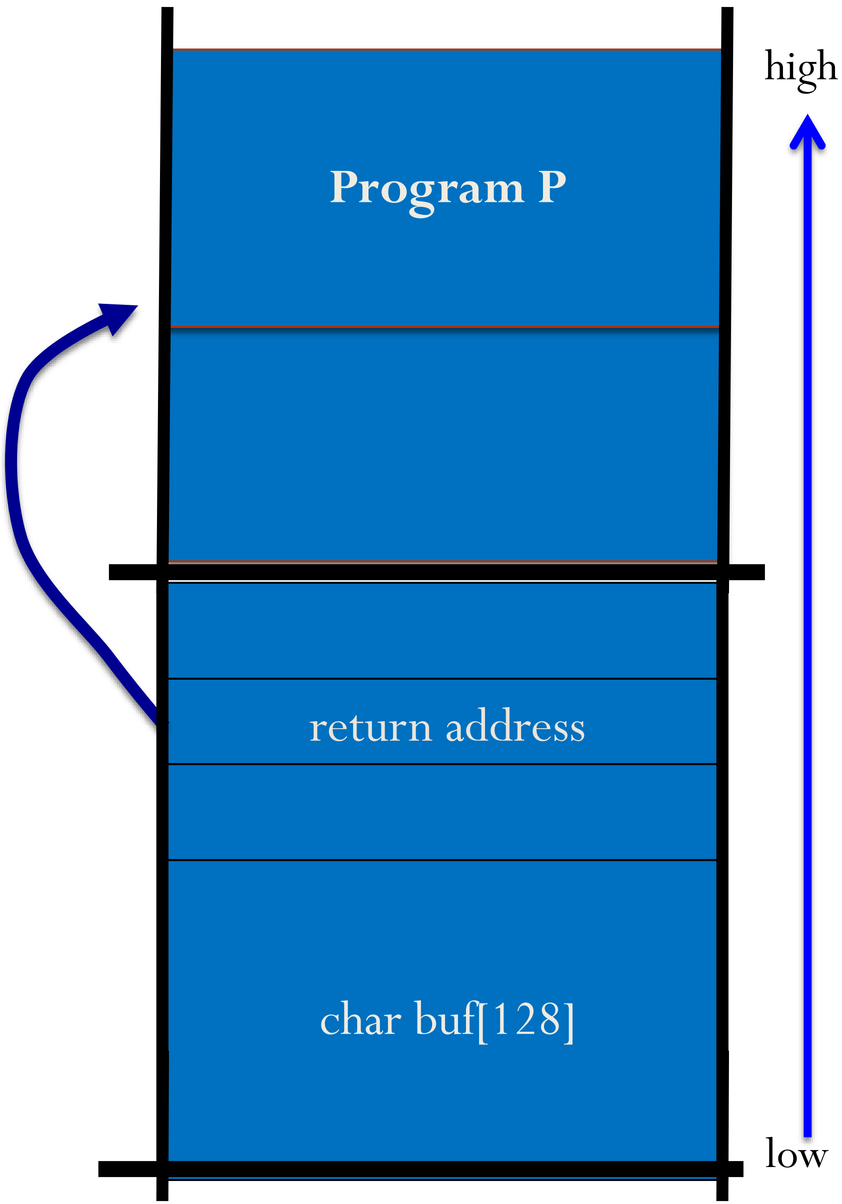
no length checking in strcpy()

Basic stack exploit

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

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

(exact shell code by Aleph One)



When func() exits, the user gets shell !

Note: attack code P runs *in stack*.

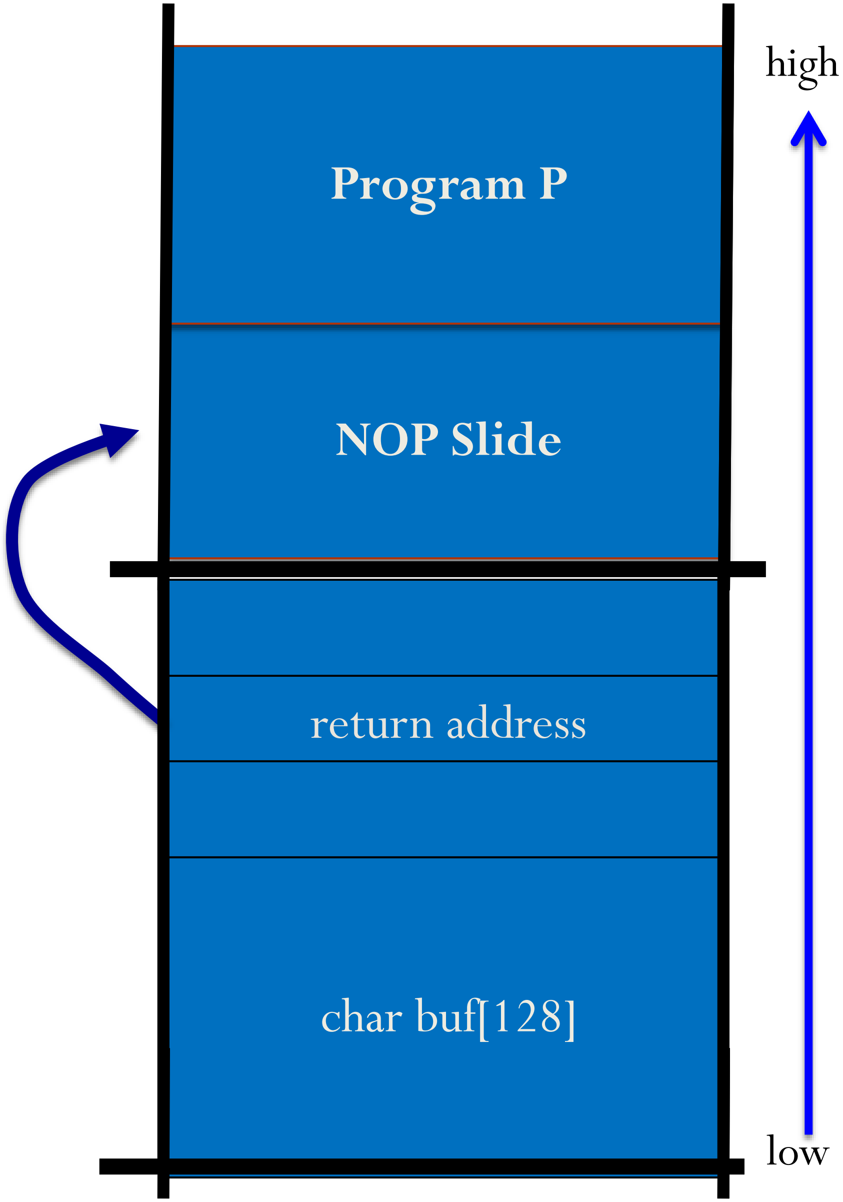
The NOP slide

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() exists.

- Sample remote stack smashing overflows:
  - (2007) Overflow in Windows animated cursors (ANI). LoadAniIcon()
  - (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.

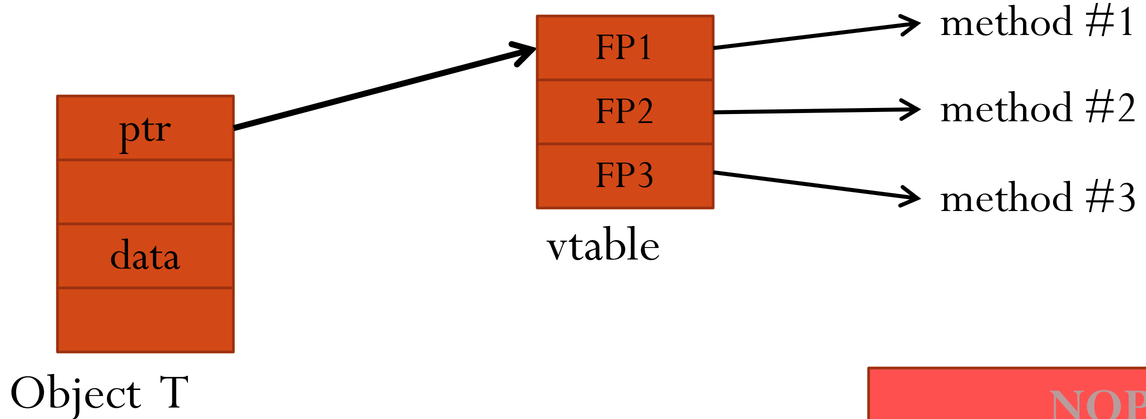
- Function pointers: (e.g. PHP 4.0.2, MS MediaPlayer Bitmaps)

  - Overflowing buf will override function pointer.

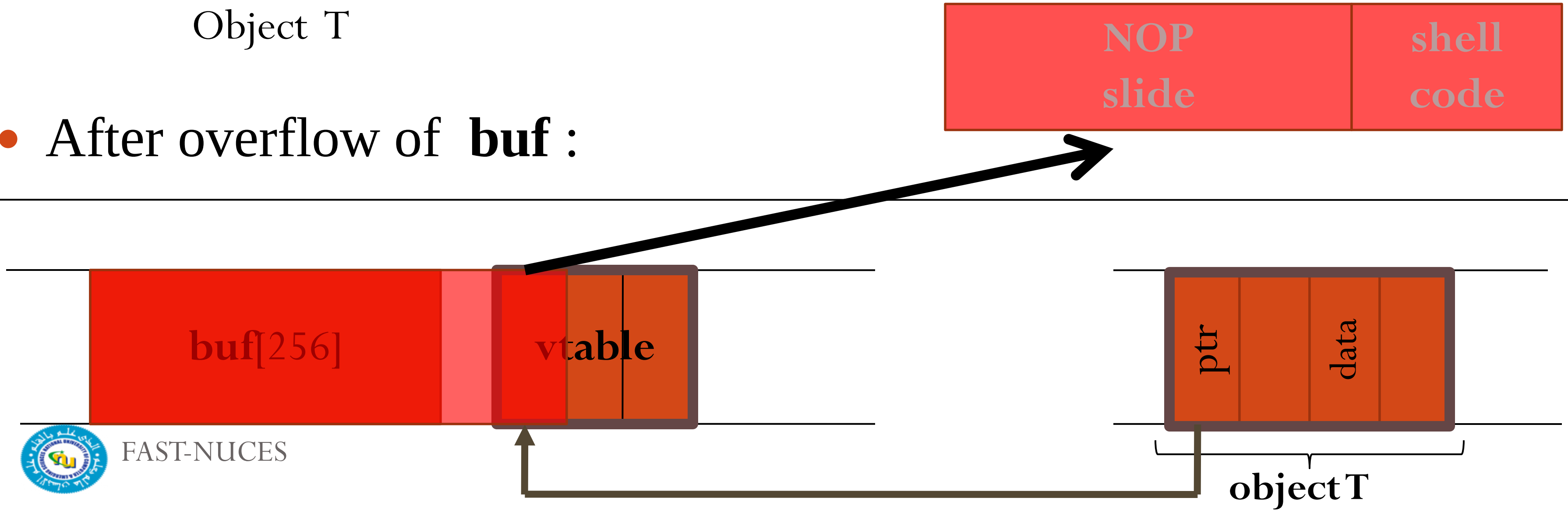
- Longjmp buffers: longjmp(pos) (e.g. Perl 5.003)
  - Overflowing buf next to pos overrides value of pos.

Corrupting method pointers

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



- After overflow of **buf** :



Finding buffer overflows

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

More Control Hijacking Attacks

More Hijacking Opportunities

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

Integer Overflows (Phrack issue 60)

Problem: what happens when int exceeds max value?

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

$$c = 0x80 + 0x80 = 128 + 128 \quad \Rightarrow \quad c = 0$$

$$s = 0xff80 + 0x80 \quad \Rightarrow \quad s = 0$$

$$m = 0xffffff80 + 0x80 \quad \Rightarrow \quad m = 0$$

Can this be exploited?

An example

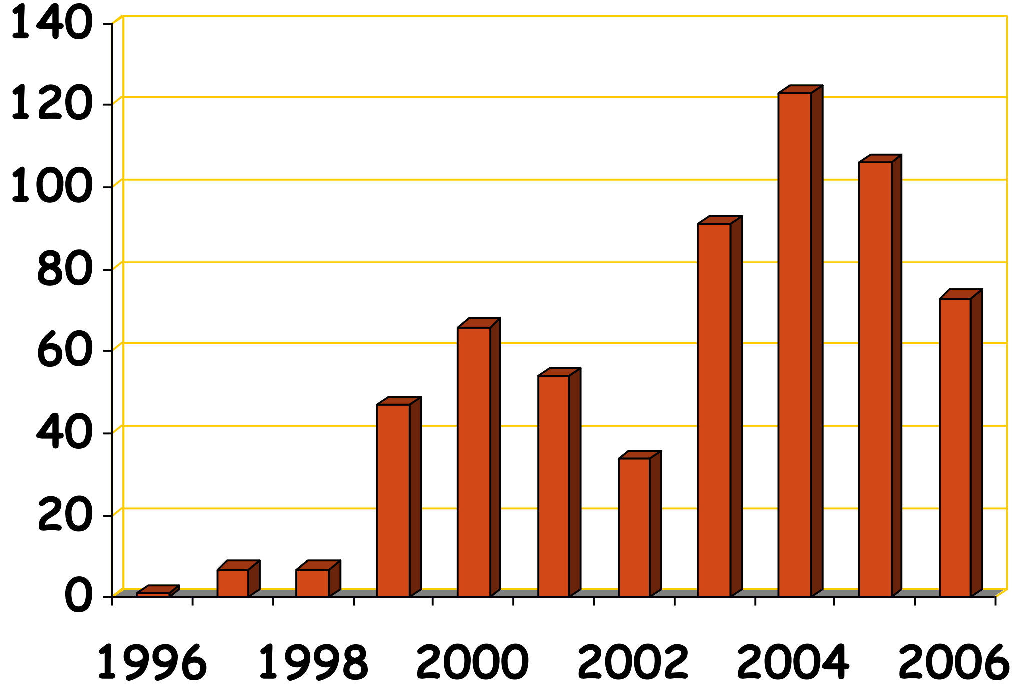
```
void  func( char *buf1, *buf2,    unsigned int len1, len2) {
      char temp[256];
      if  (len1 + len2 > 256)  {return -1}            // length check
      memcpy(temp, buf1, len1);                       // cat buffers
      memcpy(temp+len1, buf2, len2);
      do-something(temp);            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

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

$\Rightarrow$ len1+len2 = 0

Second memcpy() will overflow heap !!

Integer overflow exploit stats



Source: NVD/CVE

Format String Bug

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?
- Full exploit using user = “%n” (directive to allow writing in memory)
- Correct form (always be explicit about your format string): `fprintf( stdout, “%s”, user);`

History

- First exploit discovered in June 2000.
- Examples:
  - wu-ftpd 2.* : remote root
  - Linux rpc.statd: remote root
  - IRIX telnetd: remote root
  - BSD chpass: local root

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”)

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

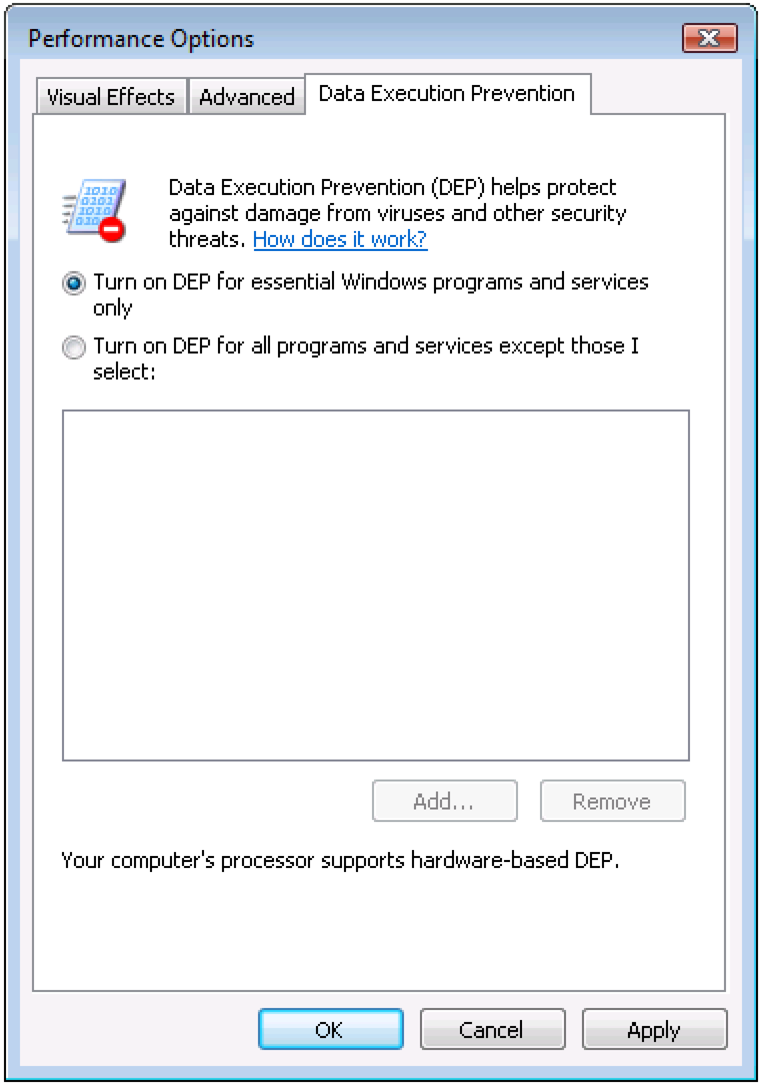
3. Add runtime code to detect overflows exploits
   - Halt process when overflow exploit detected
   - StackGuard, LibSafe, …

Marking memory as non-execute (W^X)

Prevent attack code execution by marking stack and heap as **non-executable**

- 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: Data execution protection)
    - Boot.ini : **/noexecute=OptIn** or **AlwaysOn**
    - Visual Studio: **/NXCompat[:NO]**
- Limitations:
  - Some apps need executable heap (e.g. JITs).
  - Does not defend against \`**return-to-libc**' exploits

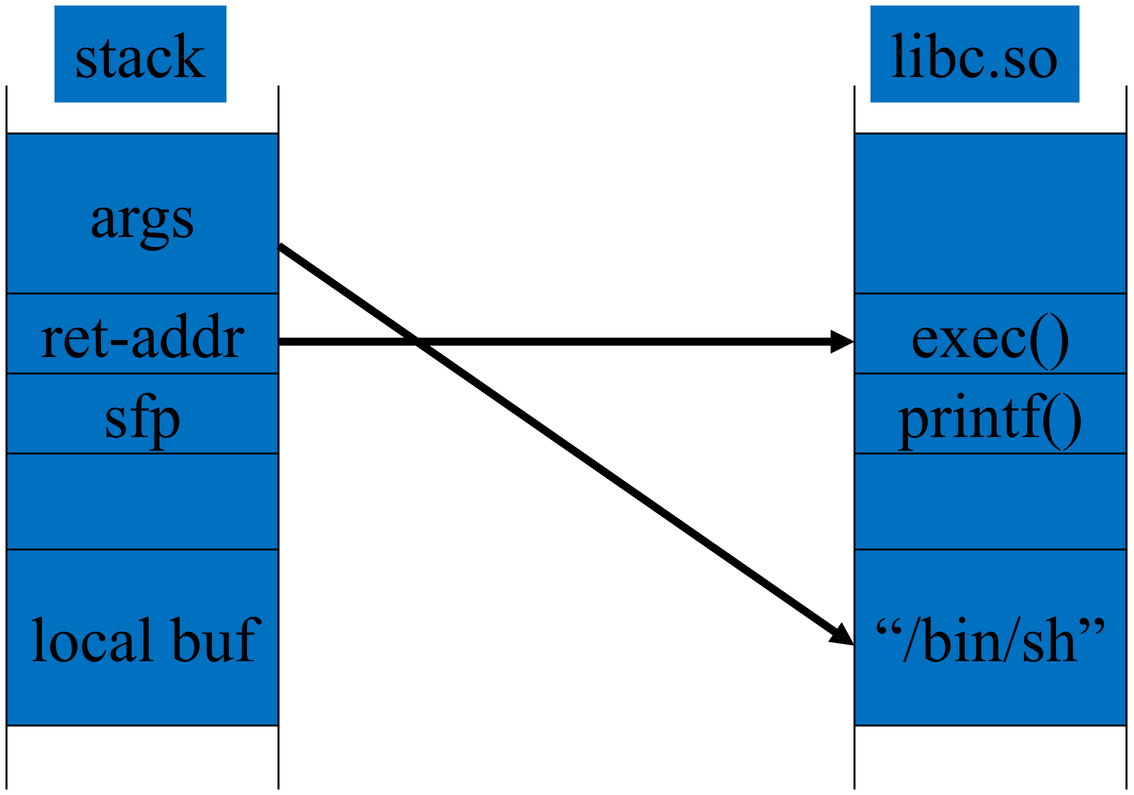
Examples: DEP controls in Windows



DEP terminating a program

Attack: return to libc

- Control hijacking without executing code



Response: randomization

- **<u>ASLR</u>**: (Address Space Layout Randomization)
  - Map shared libraries to rand location in process memory

    $\Rightarrow$ Attacker cannot jump directly to exec function
  - <u>Deployment</u>: (/DynamicBase)
    - **Windows** Vista: 8 bits of randomness for DLLs
      - aligned to 64K page in a 16MB region $\Rightarrow$ 256 choices
    - **Linux** (via PaX): 16 bits of randomness for libraries
  - More effective on 64-bit architectures
- <u>Other randomization methods</u>:
  - Sys-call randomization: randomize sys-call id's
  - Instruction Set Randomization (ISR)

ASLR Example

Booting twice loads libraries into different locations:

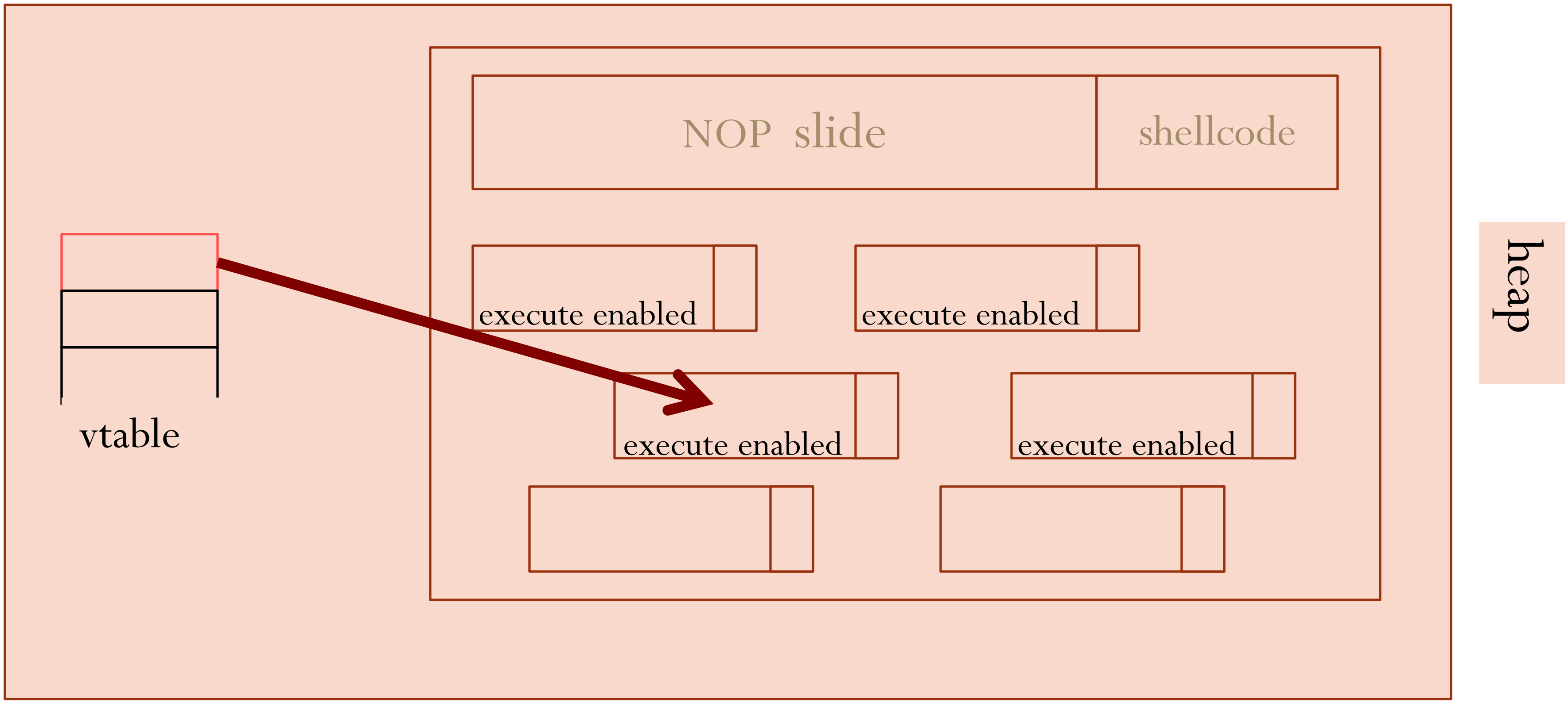
ntlanman.dll	0x6D7F0000	Microsoft® Lan Manager
ntmarta.dll	0x75370000	Windows NT MARTA provider
ntshrui.dll	0x6F2C0000	Shell extensions for sharing
ole32.dll	0x76160000	Microsoft OLE for Windows

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

Some attacks remain: JiT spraying

Idea:

1. Force Javascript JiT to fill heap with executable shellcode
2. then point SFP anywhere in spray area

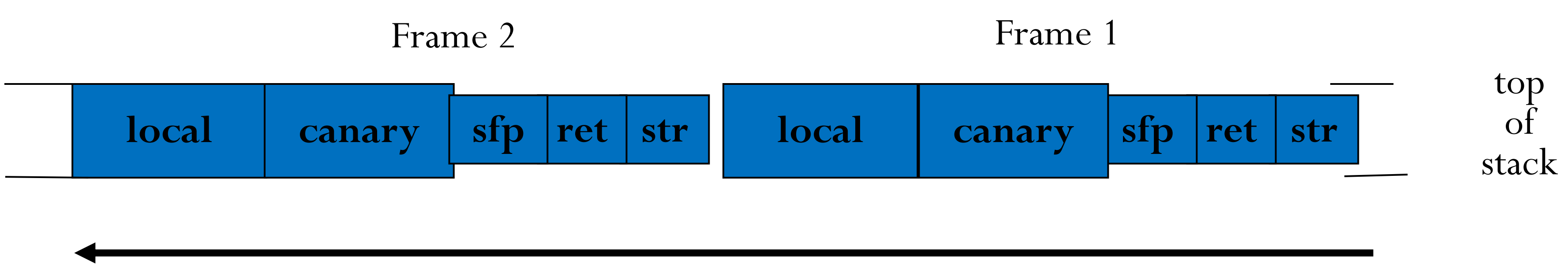


Run-Time Defenses

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 (4-8 bytes) 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.

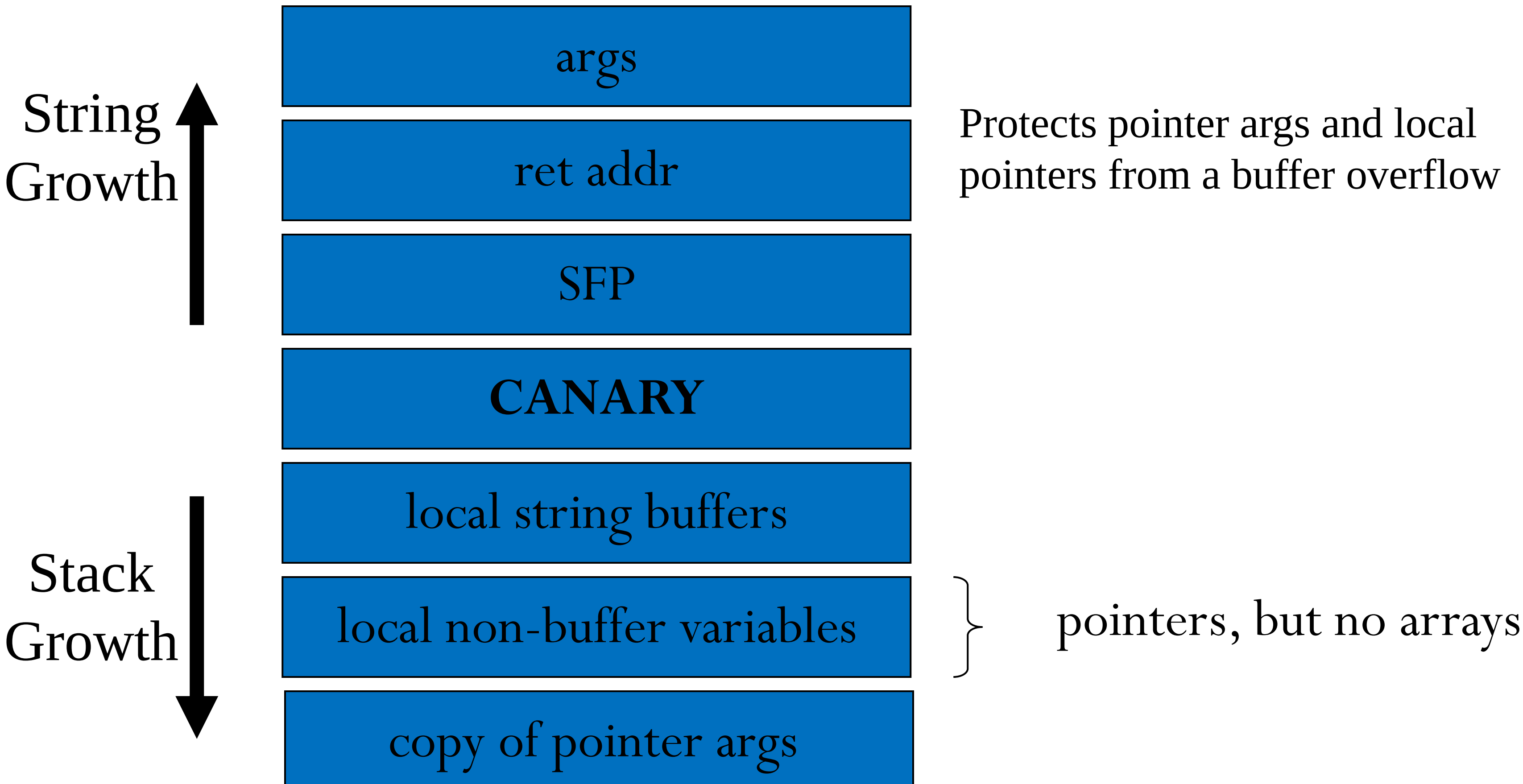
- Terminator canary: Canary = {0, newline, linefeed, EOF}
  - String functions will not copy beyond terminator.
  - Attacker cannot use string functions to corrupt stack.
  - Not used as often

StackGuard (Cont.)

- StackGuard implemented as a GCC (compiler) patch.
  - Program must be recompiled.
- Minimal performance effects: 8% for Apache.
- Note: Canaries don't provide full proof 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.



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

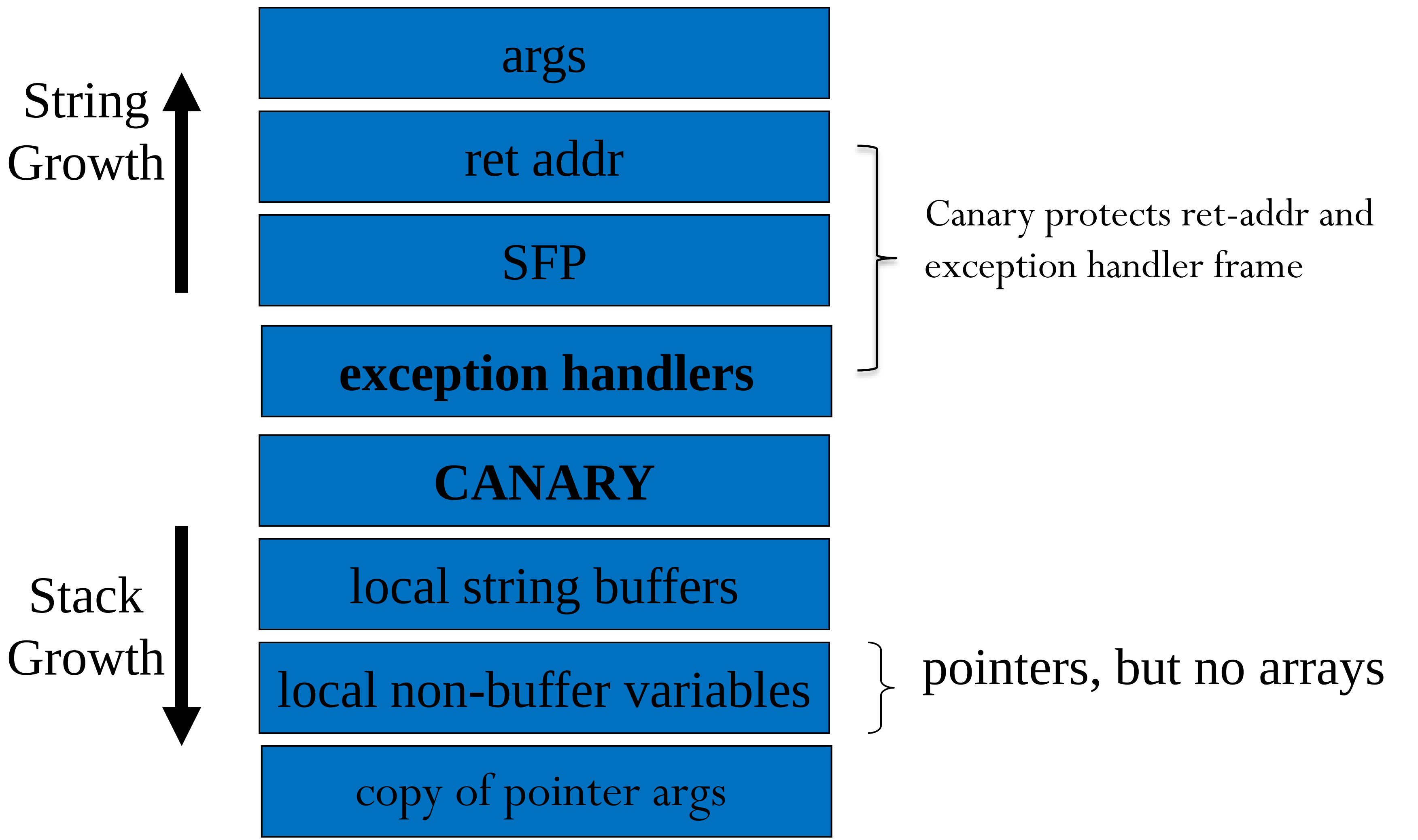
Function epilog:

```
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



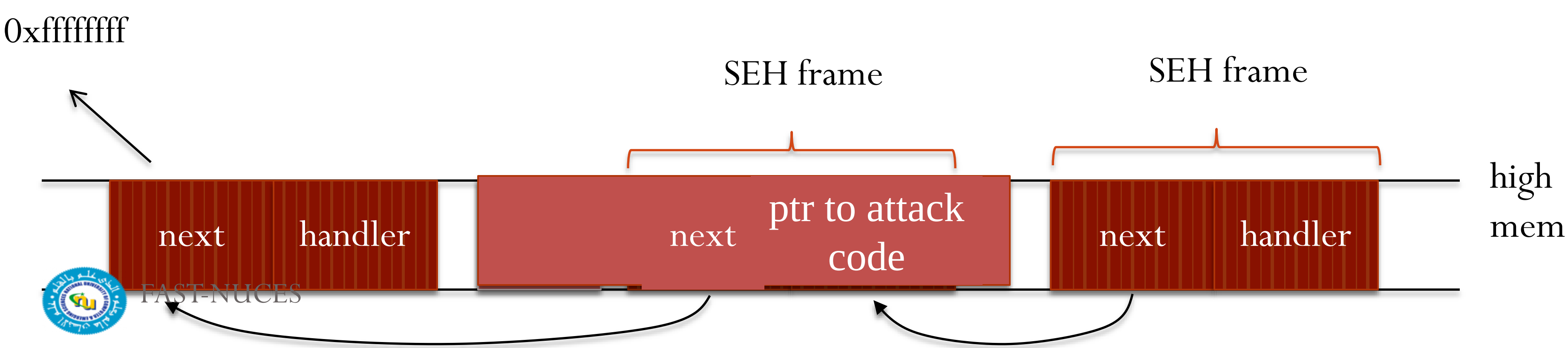
Evading /GS with exception handlers

- 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

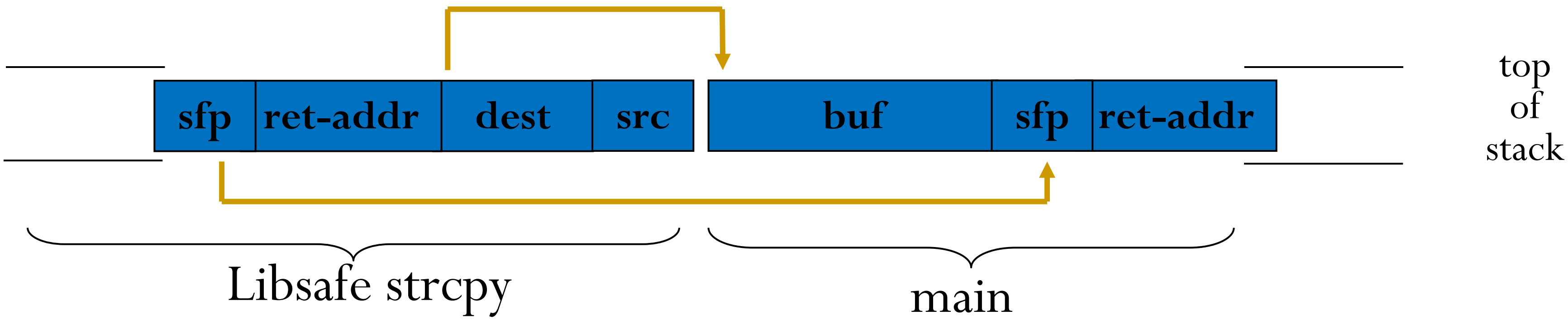
- Canaries are an important defense tool, but do not prevent all control hijacking attacks:
  - Heap-based attacks still possible
  - Integer overflow attacks still possible
  - /GS by itself does not prevent Exception Handling attacks

    (also need SAFESEH and SEHOP)

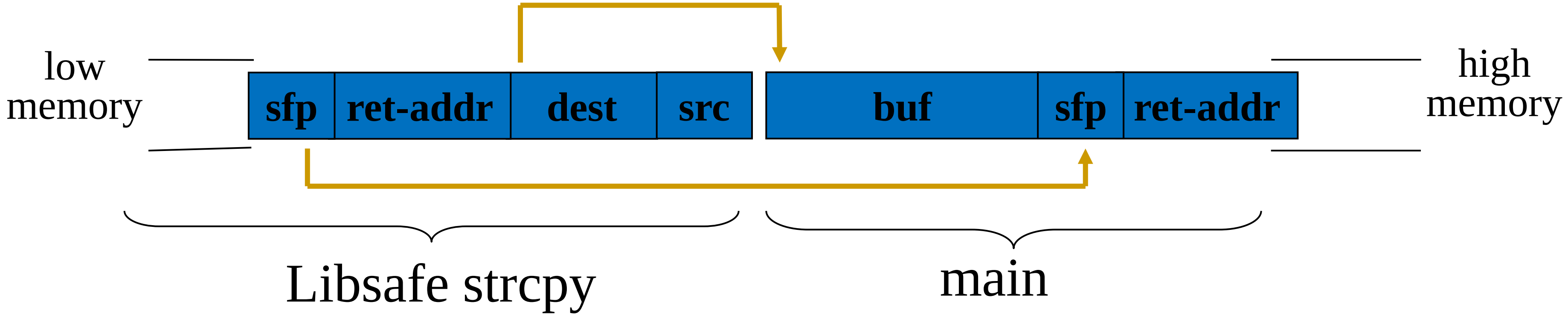
What if can’t recompile: Libsafe

- 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.

More methods …

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

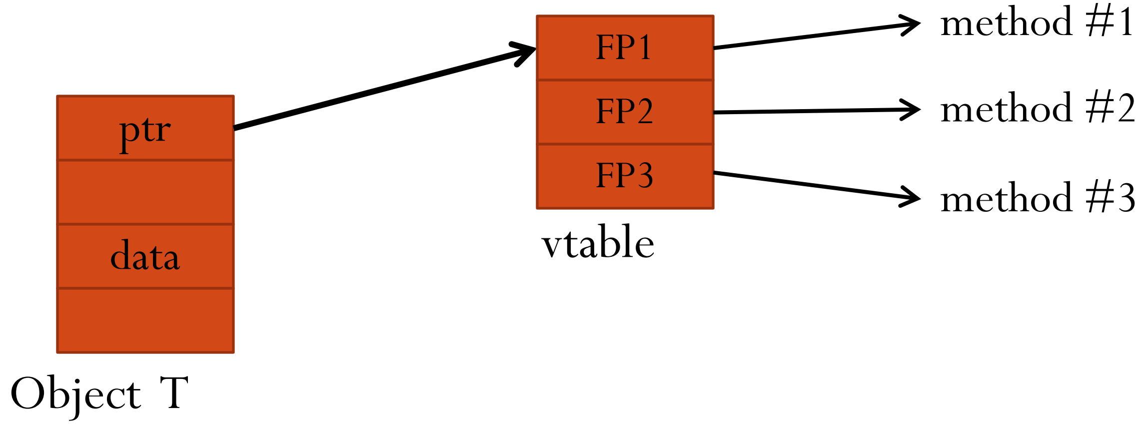
Advanced Hijacking Attacks

Heap Spray Attacks

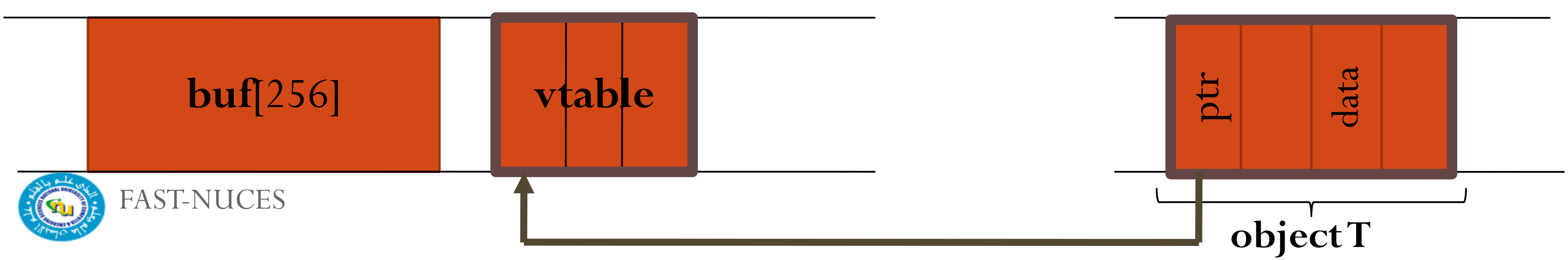
A reliable method for exploiting heap overflows

Heap-based control hijacking

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

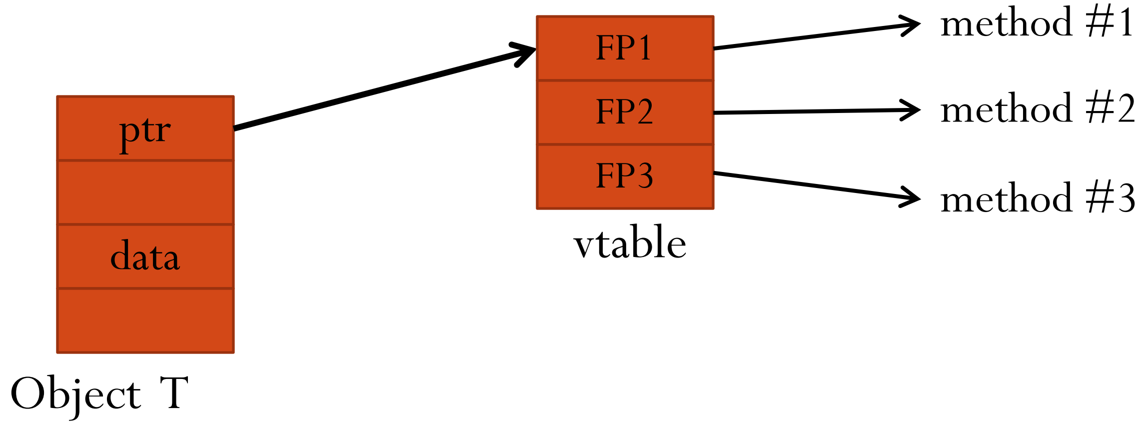


- Suppose vtable is on the heap next to a string object:

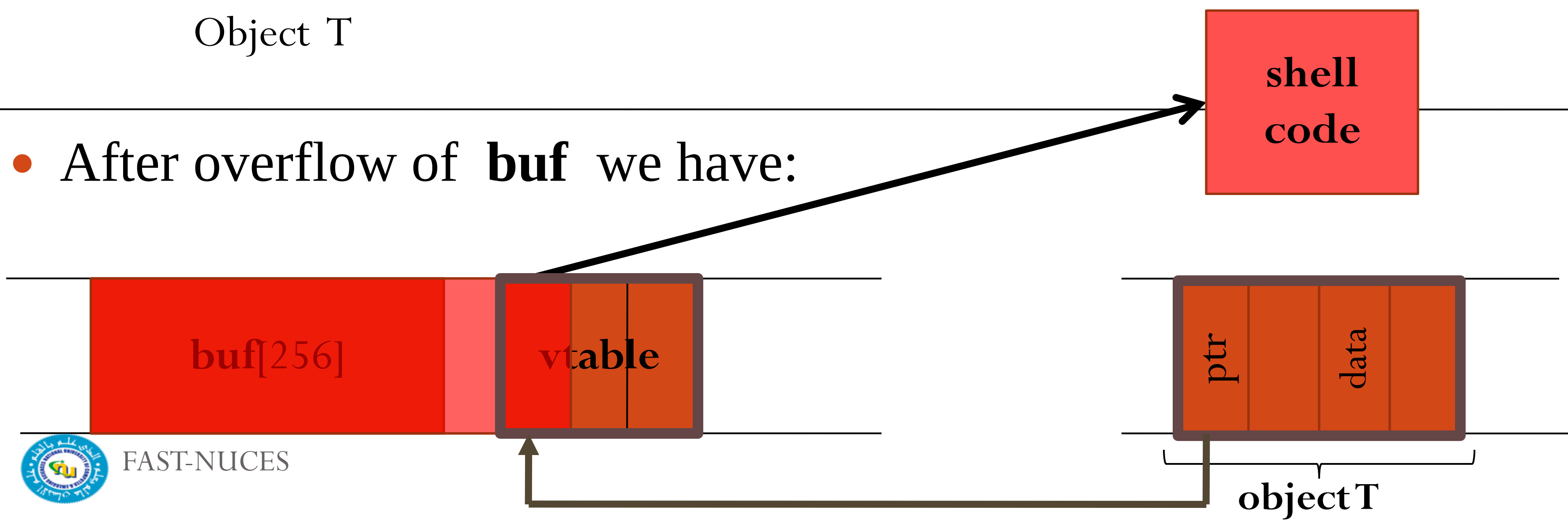


Heap-based control hijacking

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



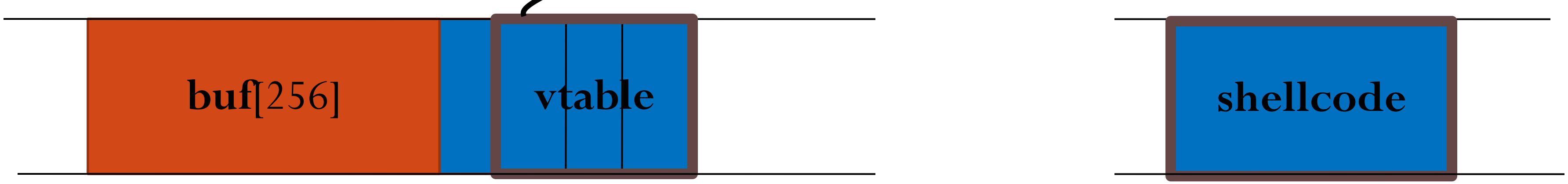
- After overflow of **buf** we have:



A reliable exploit?

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

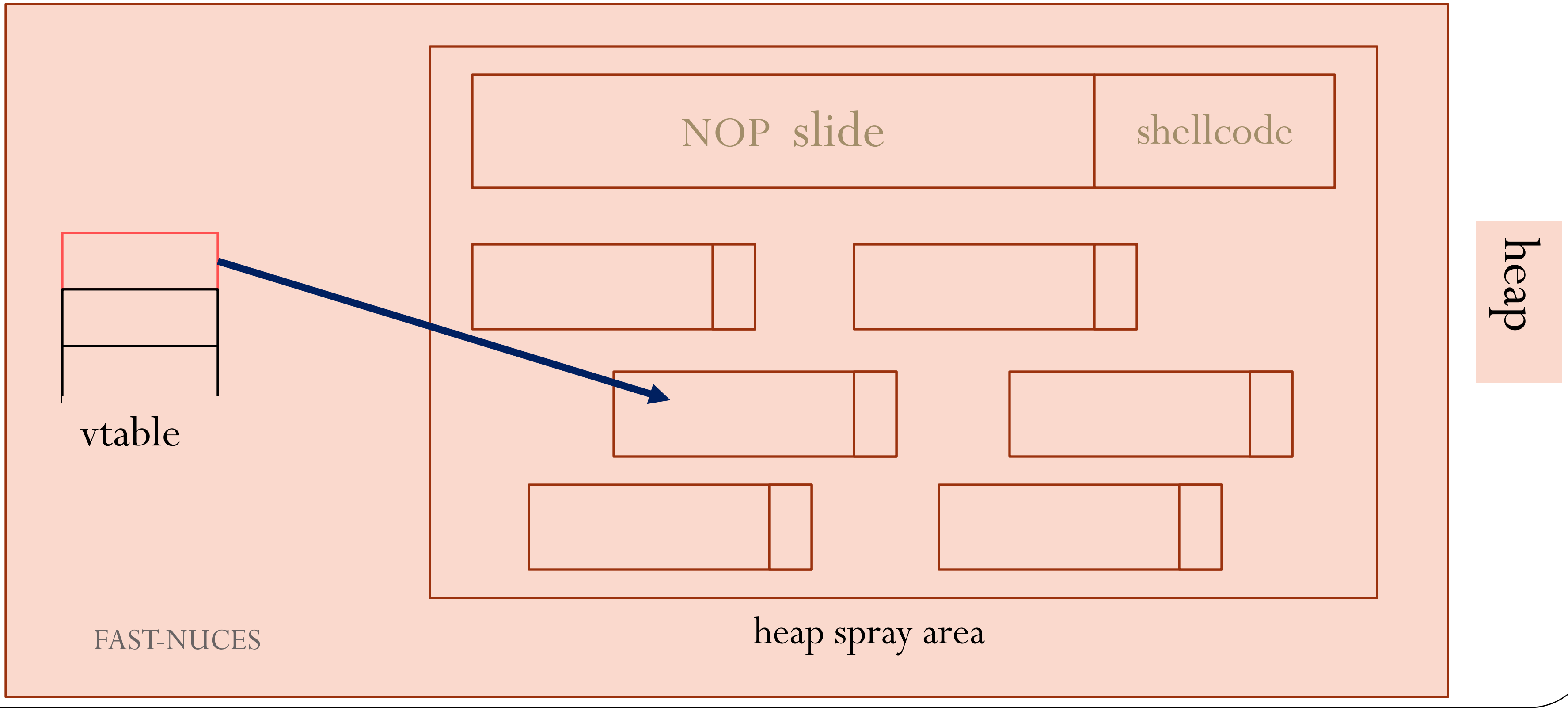
Problem: attacker does not know where browser places **shellcode** on the heap ???



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



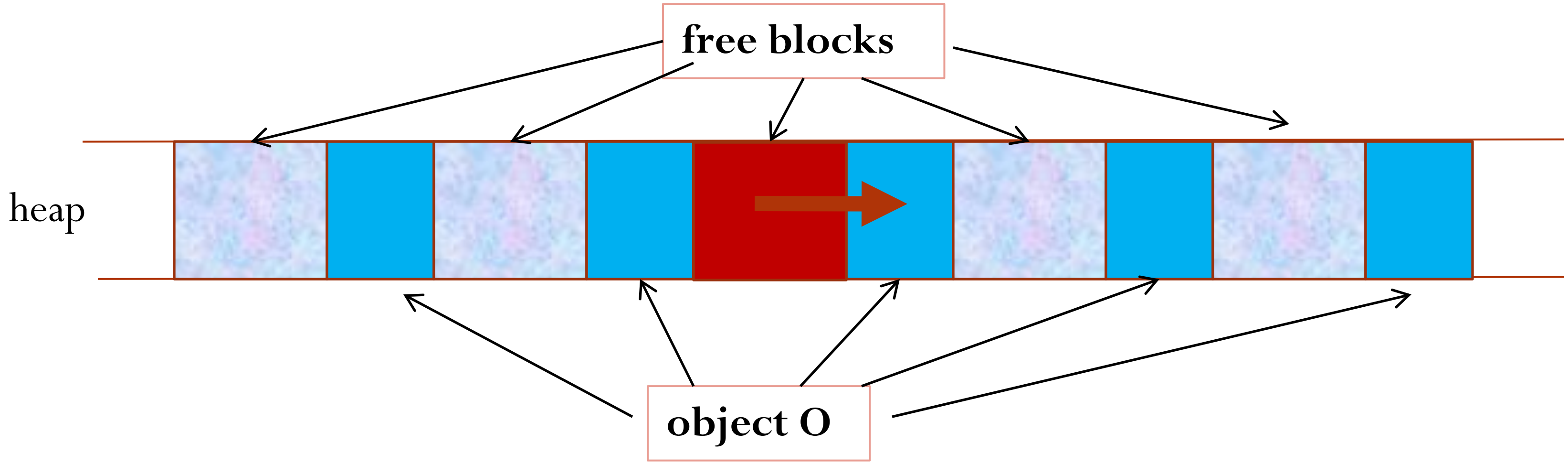
Javascript heap spraying

```
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

[RLZ'08]

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

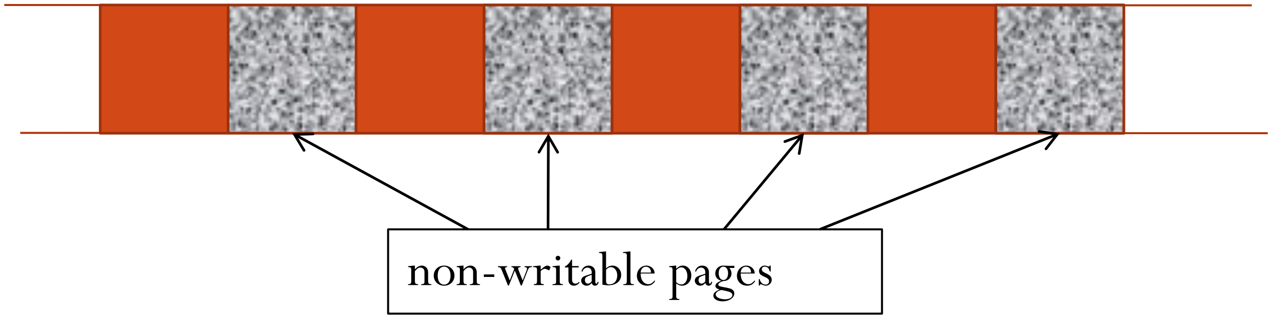
- Improvements: Heap Feng Shui [S'07]
  - Reliable heap exploits **on IE** without spraying
  - Gives attacker full control of IE heap from Javascript

(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

Acknowledgements

Material in this lecture are taken from the slides prepared by:

- Prof. Dan Boneh (Standford)