UNIVERSITÄT DES SAARLANDES

Max Planck Institute for Software Systems

Practical Aspects of Security

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Control Hijacking Attacks

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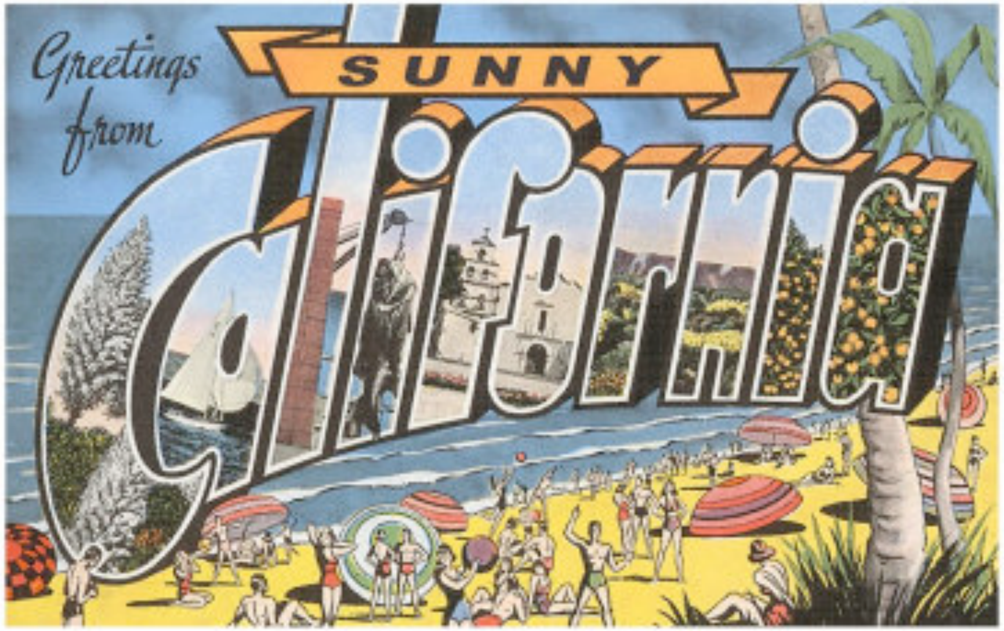
Substituting Prof. Backes



Control hijacking attacks

- Attacker's goal:
  - Take over target machine (e.g. web server)
    - Execute arbitrary code on target by hijacking application control flow

This lecture: **attacks!**

- **Buffer overflows**
  - Stack-based attacks (stack smashing)
  - Heap-based attacks
  - Return-to-libc and return-oriented programming
- Integer overflow attacks
- Format string vulnerabilities

- Project 1: writing exploits

Assumptions are vulnerabilities

- How to successfully attack a system:
  1) Discover what assumptions were made
  2) Craft an exploit outside those assumptions
  3) Profit

- Two assumptions often exploited:
  - Target buffer is large enough for source data
    - Buffer overflows deliberately break this assumption
  - Computer integers behave like math integers
    - Integer overflows violate this assumption

Assumptions about control flow

- We write our code in languages that offer several layers of abstraction over machine code; even C
  - High-level statements: "=" (assign), ";" (seq), **if**, **while**, **for**, etc.
  - Procedures / functions
- Naturally, our execution model assumes:
  - Basic statements (e.g. assign) are atomic
  - Only one of the branches of an if statement can be taken
  - Functions start at the beginning
  - They (typically) execute from beginning to end
  - And, when done, they return to their call site
  - Only the code in the program can be executed
  - The set of executable instructions is limited to those output during compilation of the program

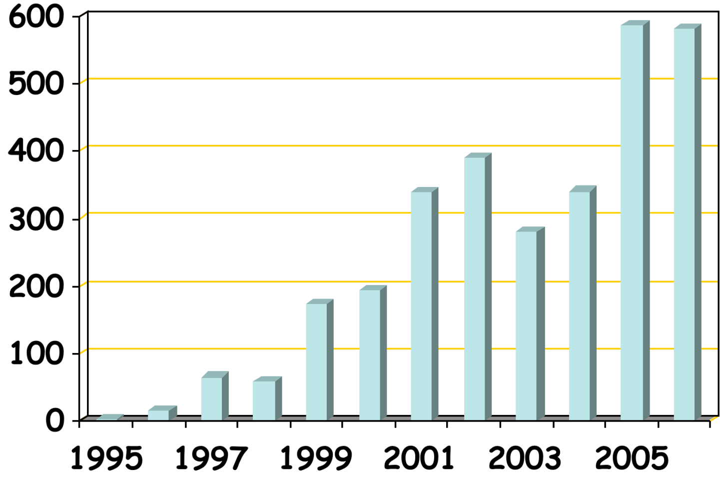
Assumptions about control flow

- We write our code in languages that offer several layers of abstraction over machine code; even C
  - High-level statements: "=" (assign), ";" (seq), **if**, **while**, **for**, etc.
  - Procedures / functions
- **But, actually, at the level of machine code**
  - Each basic statement compiled down to many instructions
  - There is no restriction on the target of a jump
  - Can start executing in the middle of functions
  - A fragment of a function may be executed
  - Returns can go to any program instruction
  - Dead code (e.g. unused library functions) can be executed
  - On the x86, can start executing not only in the middle of functions, but in the middle of instructions!

BUFFER OVERFLOWS

Buffer overflows

- Extremely common bug
- First major exploit: 1988 Internet Worm (targeted fingerd)



≈20% of all vuln.

2005-2007: ≈ 10%

Source: NVD/CVE

Many unsafe C lib functions

strcpy (char *dest, const char *src)

strcat (char *dest, const char *src)

gets (char *s)

scanf (const char *format, …)

sprintf (char * str, const char * format, ...)

…

- “Safe” versions sometimes misleading
  - strncpy() leaves buffer unterminated if strlen(src) ≥ length arg.
  - strncpy(), strncat()   encourage off by 1 bugs
    (dest buffer needs to have at least strlen(src) + 1 bytes allocated)

Eliminating unsafe functions doesn't fix everything

- It could break things even more though (legacy code)
- Vulnerable code often written using explicit loops and pointer arithmetic

Not only this is vulnerable:

```
int is_file_foobar( char* one, char* two ) {
  // must have strlen(one) + strlen(two) < MAX_LEN
  char tmp[MAX_LEN];
  strcpy( tmp, one );
  strcat( tmp, two );
  return strcmp( tmp, "file://foobar" );
}
```

But also this:

```
int is_file_foobar_using_loops( char* one, char* two ) {
  // must have strlen(one) + strlen(two) < MAX_LEN
  char tmp[MAX_LEN];
  char* b = tmp;
  for( ; *one != '\0'; ++one, ++b ) *b = *one;
  for( ; *two != '\0'; ++two, ++b ) *b = *two;
  *b = '\0';
  return strcmp( tmp, "file://foobar" );
}
```

Finding buffer overflows: fuzzing

- To find overflow:
  - Run target app on local machine
  - Issue requests with long strings that end with "$$$$$"
  - If app crashes,
    search core dump for "$$$$$" to find overflow location

- Many automated tools exist: called fuzzers

- Then use disassemblers and debuggers to construct exploit
  - The GNU Project Debugger (GDB) – free software
  - IDA-Pro – commercial

Buffer overflows

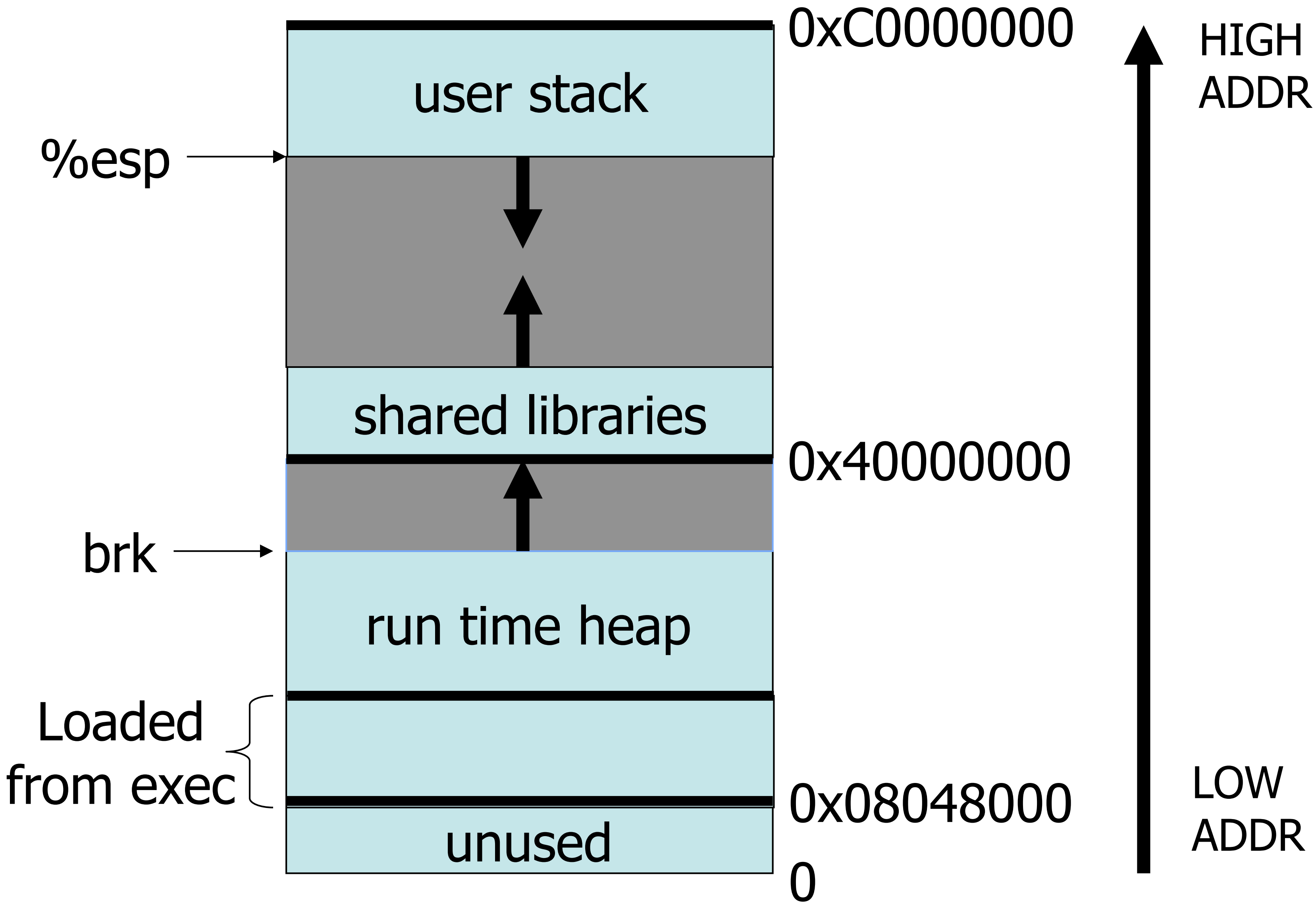
STACK-BASED ATTACKS

What is needed for building exploits

- Understanding C functions and the stack
- Some familiarity with machine code
- Know how systems calls are made (e.g. exec)
  - For project you will use “off-the-shelf” payload: **“shellcode”**

- Attacker needs to know which CPU and OS are running on the target machine:
  - Our examples are for x86 running Linux (same as vm for project)
  - Details vary slightly between different CPUs and OSs:
    - **Little endian (x86)** vs. big endian (Motorola)
    - Stack growth direction: **down** (x86 and most others)
    - Stack frame structure (OS and compiler dependent)

Linux process memory layout



x86 __cdecl function-call convention

Caller:

foo(1,2,3);

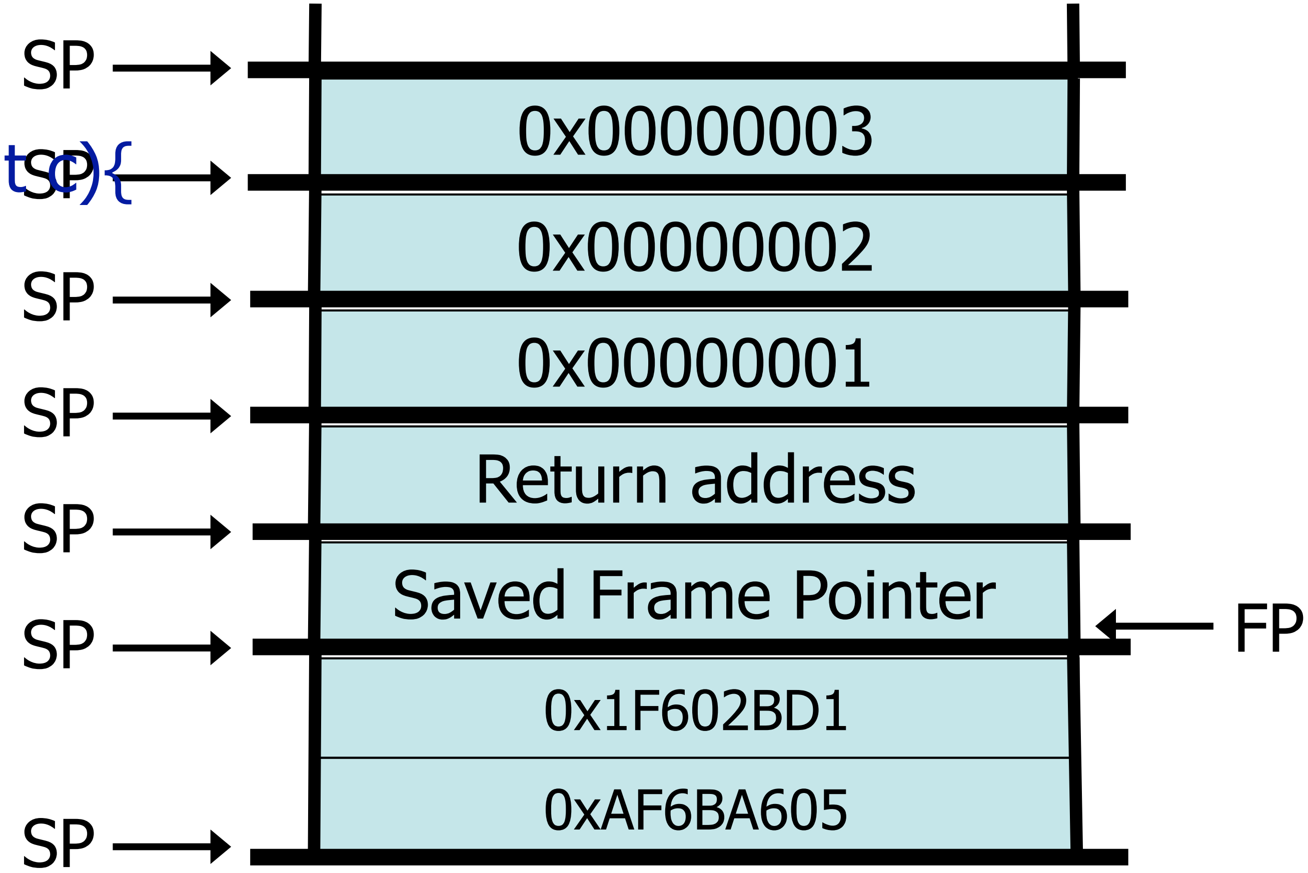
Callee:

void foo(int a,int b,int c){
  char buffer[5];
}

asm:

```
pushl $3 ← IP
pushl $2 ← IP
pushl $1 ← IP
call foo ← IP
next instr
```

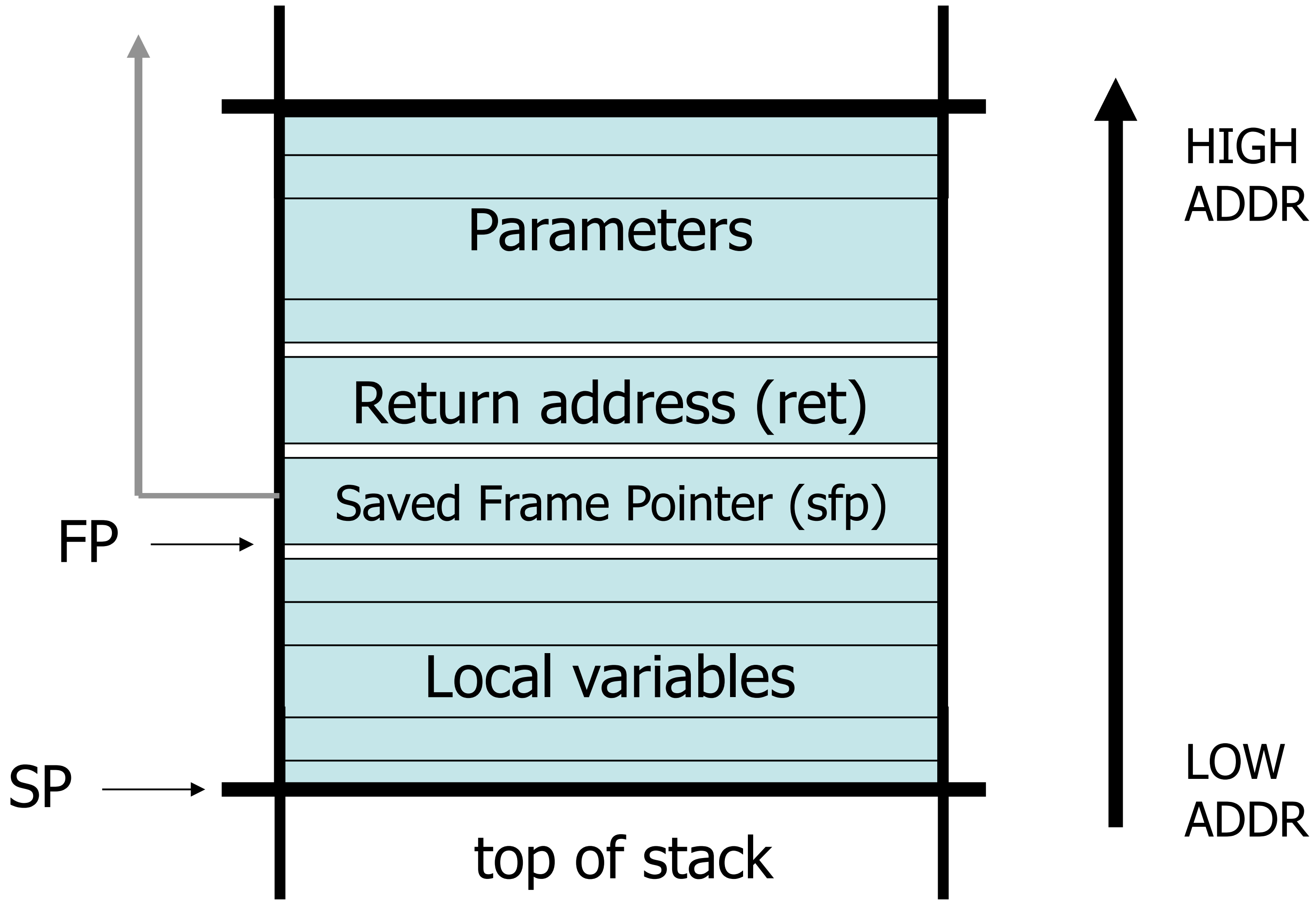
```
pushl %ebp ← IP
movl %esp,%ebp ← IP
subl $8,%esp ← IP
```



x86 __cdecl function-call convention

- Push parameters onto the stack, from right to left
- **`call`** the function (pushes %eip+j to stack; return address)
- Save and update the FP (`push` %ebp + `mov` %esp,%ebp)
- Allocate local variables (`sub` $n,%esp)
- *Perform the function's purpose*
- Release local storage (`add` $n,%esp)
- Restore the old FP (**`leave`** = `mov` %esp,%ebp + `pop` %ebp)
- **`ret`** from function (pops return address and jumps to it)
- Clean up parameters (`add` $m,%esp)

Stack Frame


Parameters
Return address (ret)
Saved Frame Pointer (sfp)
Local variables
top of stack
FP
SP
HIGH ADDR
LOW ADDR

Smashing the stack

- Example of vulnerable function:

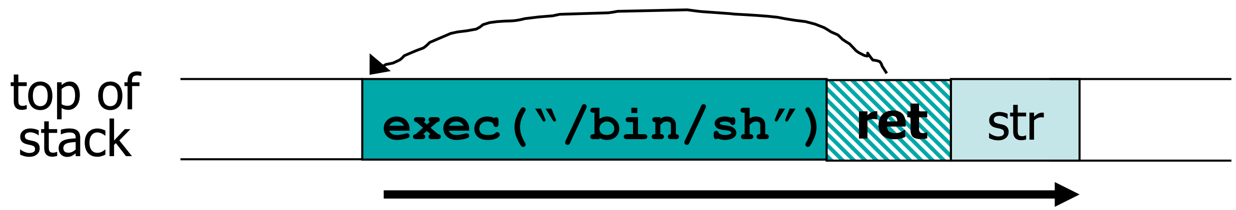
```
void foo(char *str) {
    char buf[128];

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

- When the function foo is invoked the stack looks like:

- What if `*str` is 136 bytes long? After `strcpy`:

Return address clobbering

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



(exact shellcode given by Aleph One)

- When foo returns, the user will be given a shell!
  - If web server calls foo() with given URL attacker can get shell by entering long URL in a browser!
- Attack executes data from the stack
  - x86 allows data on the stack to be executed as code

Exploiting buffer overflows

- Some complications:
  - Need to determine/guess position of ret
  - Shellcode should not contain the '\0' character
  - Overflow should not crash program before foo() exists
- Remotely exploitable overflows by return address clobbering:
  - (2005) Overflow in MIME type field in MS Outlook
  - (2005) Overflow in Symantec Virus Detection

```
Set test = CreateObject("Symantec.SymVAFileQuery.1")
test.GetPrivateProfileString "file", [long string]
```

Stack-based attacks: many variants

- Return address clobbering
- Overwriting function pointers (e.g. PHP 4.0.2, MediaPlayer BMP)

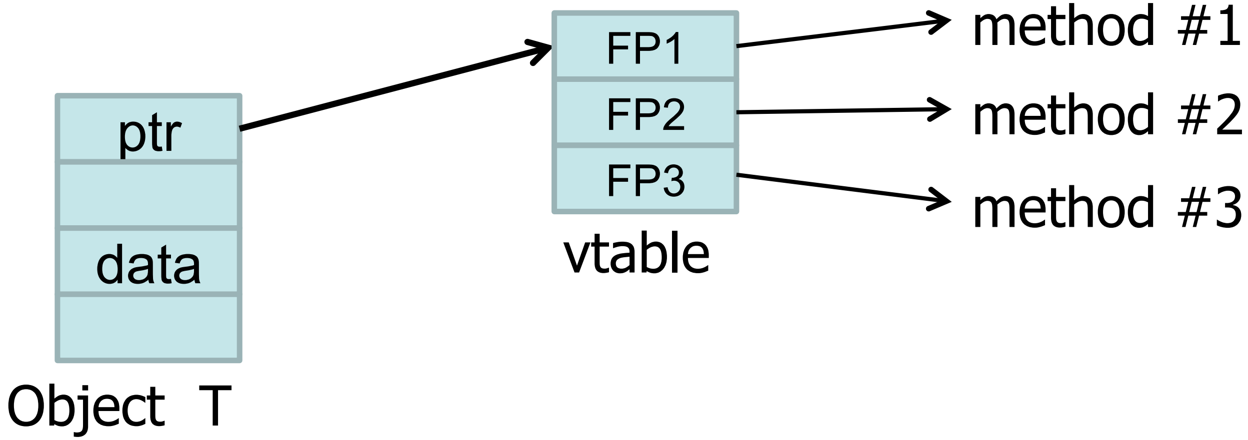
- Overwriting exception-handler pointers (C++)
  - Need to cause an exception afterwards
- Overwriting longjmp buffers (e.g. Perl 5.003)
  - Mechanism for error handling in C
- Overwriting saved frame pointer (SFP)
  - Off-by-one error is enough: one byte buffer overflow!
  - First return (leave) sets SP to overwritten SFP
  - Second return (ret) jumps to fake top of stack

Buffer overflows

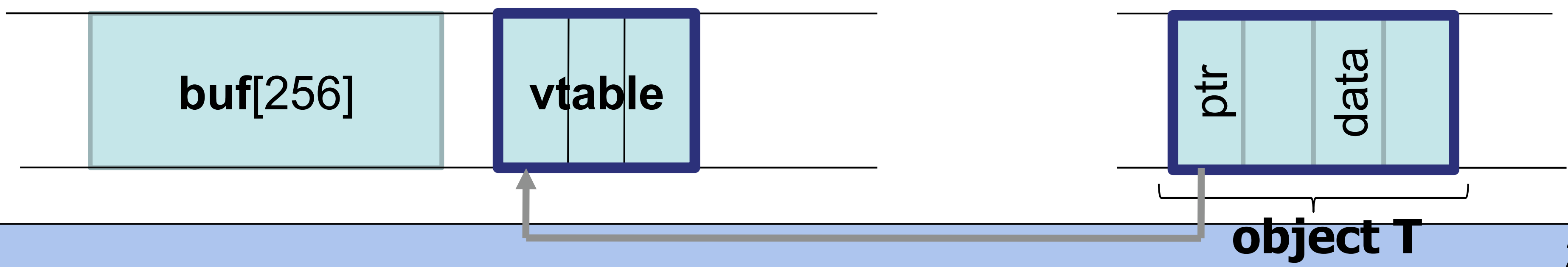
HEAP-BASED ATTACKS

Heap-based attacks

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

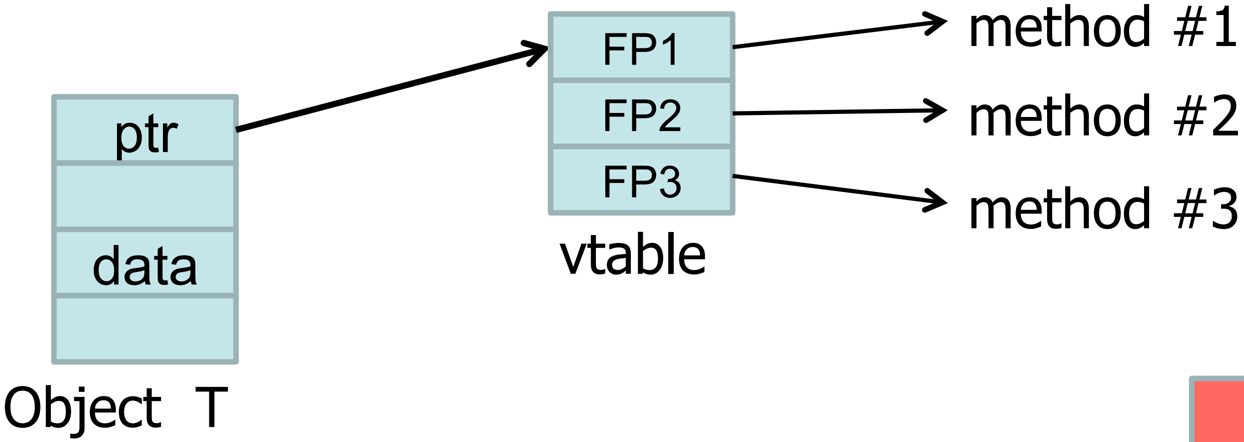


- Suppose vtable is on the heap next to a string object:

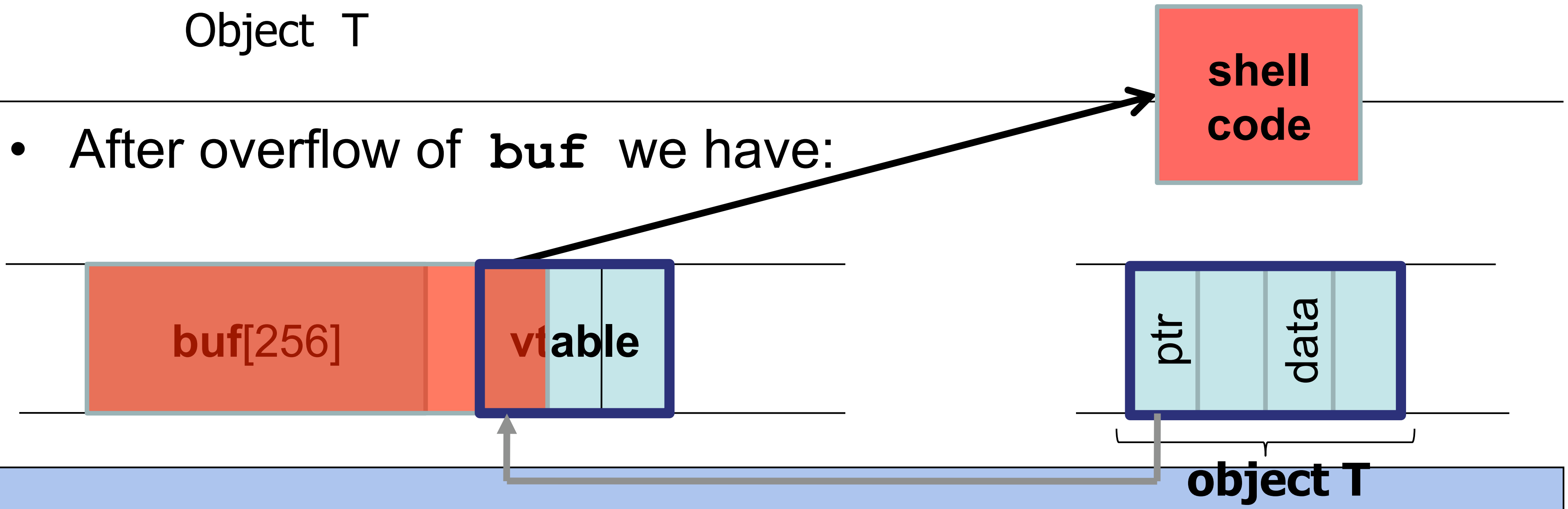


Heap-based attacks

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



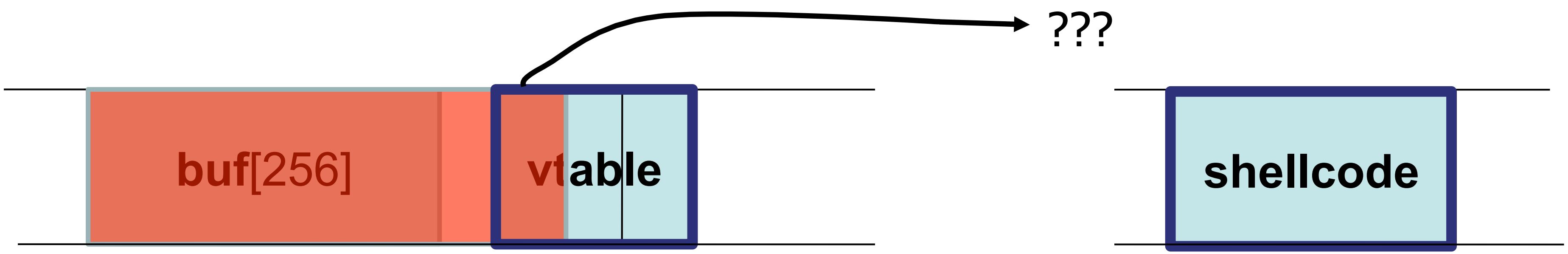
- After overflow of **`buf`** we have:



A reliable exploit?

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

cause-overflow( overflow-string ); // overflow internal buf[ ]
</SCRIPT>
```

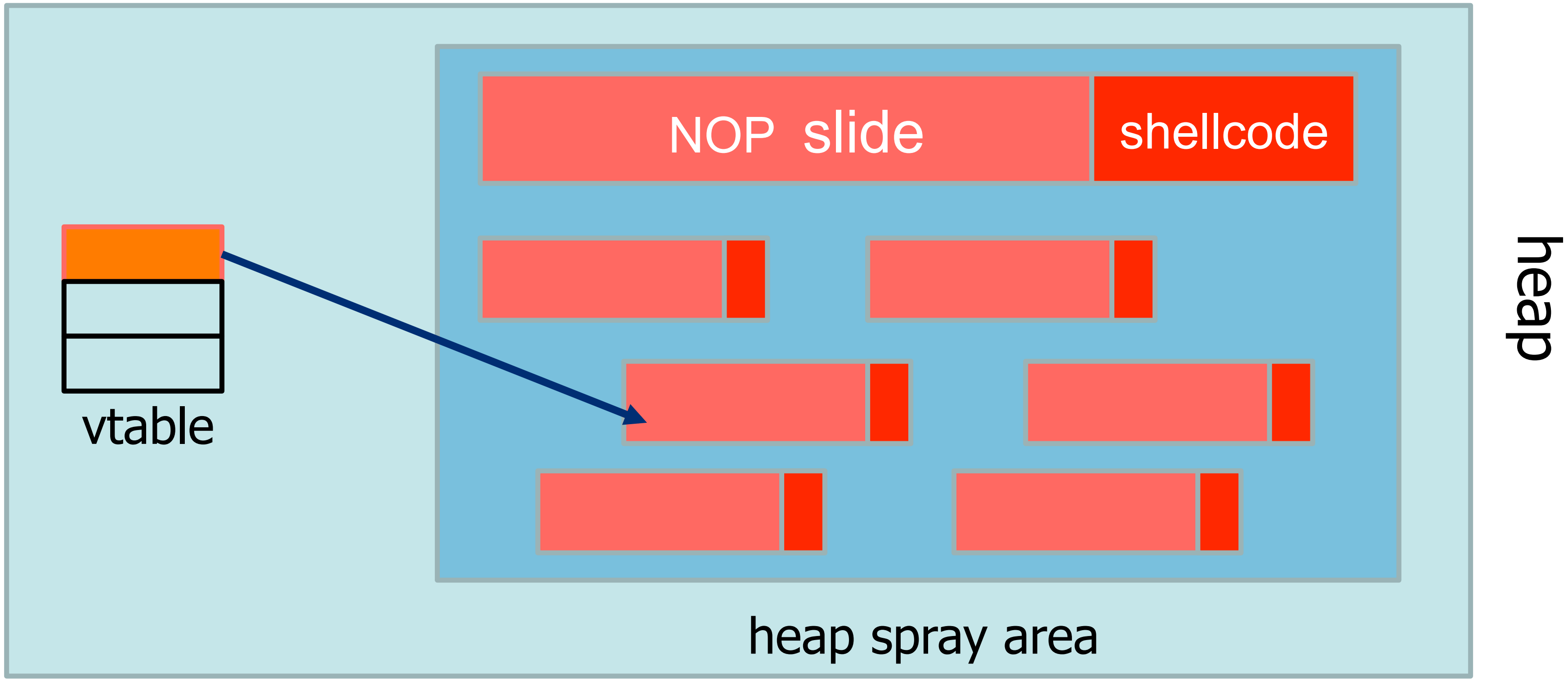
Problem: attacker does not know where browser places **shellcode** on the heap



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



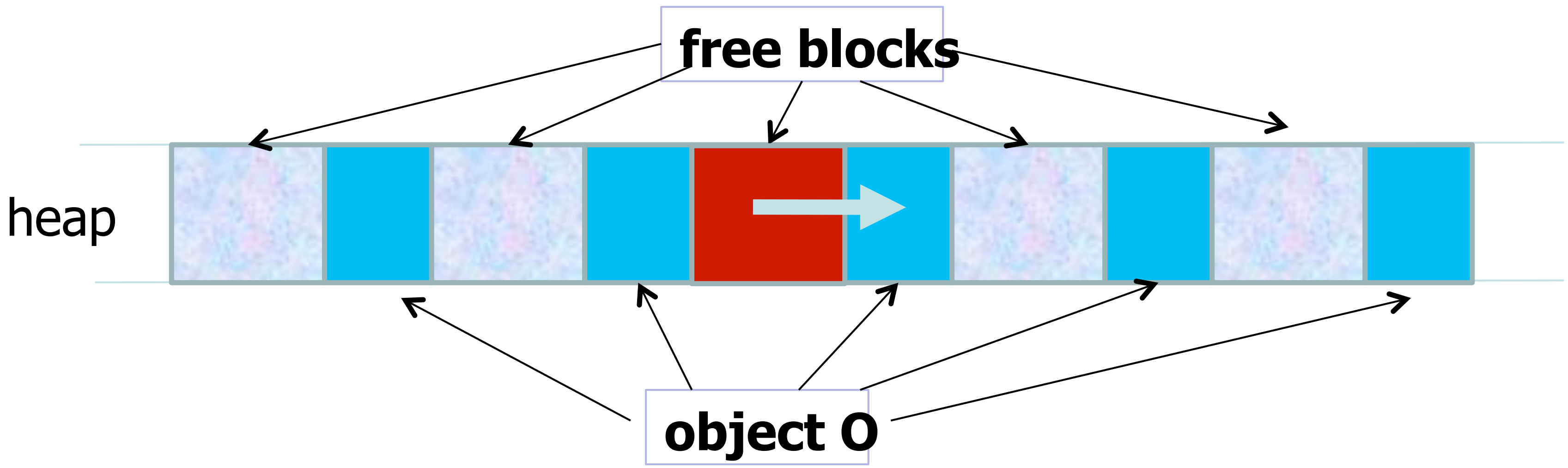
Javascript heap spraying

```
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 vulnerable buffer in Javascript and cause overflow
  - Successfully used against a Safari PCRE overflow [DHM'08]

Many heap spray exploits

[RLZ'08]

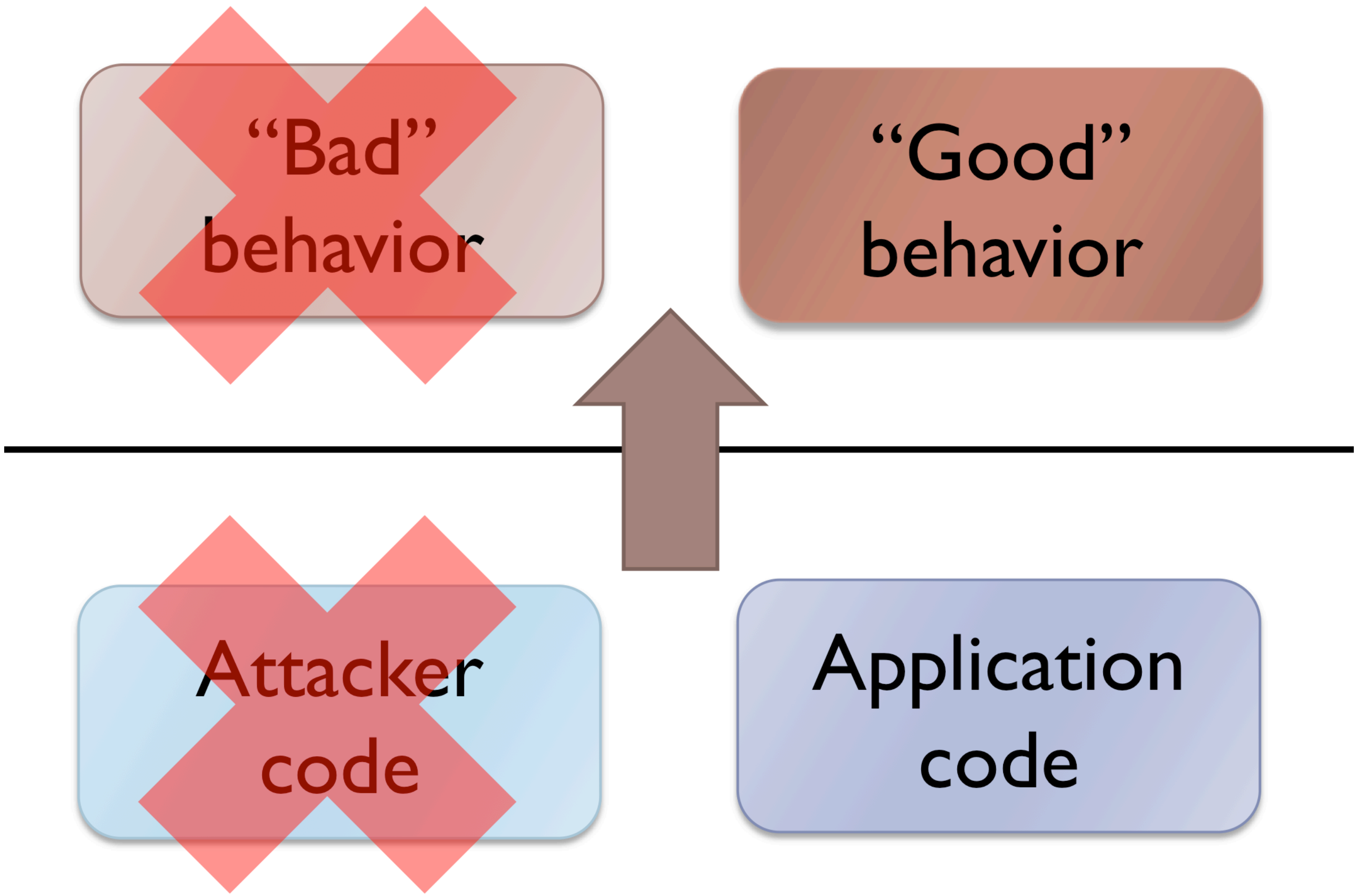
Date	Browser	Description
11/2004	IE	IFRAME Tag BO
04/2005	IE	DHTML Objects Corruption
01/2005	IE	.ANI Remote Stack BO
07/2005	IE	javaprxy.dll COM Object
03/2006	IE	createTextRang RE
09/2006	IE	VML Remote BO
03/2007	IE	ADODB Double Free
09/2006	IE	WebViewFolderIcon setSlice
09/2005	FF	0xAD Remote Heap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

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

Buffer overflows

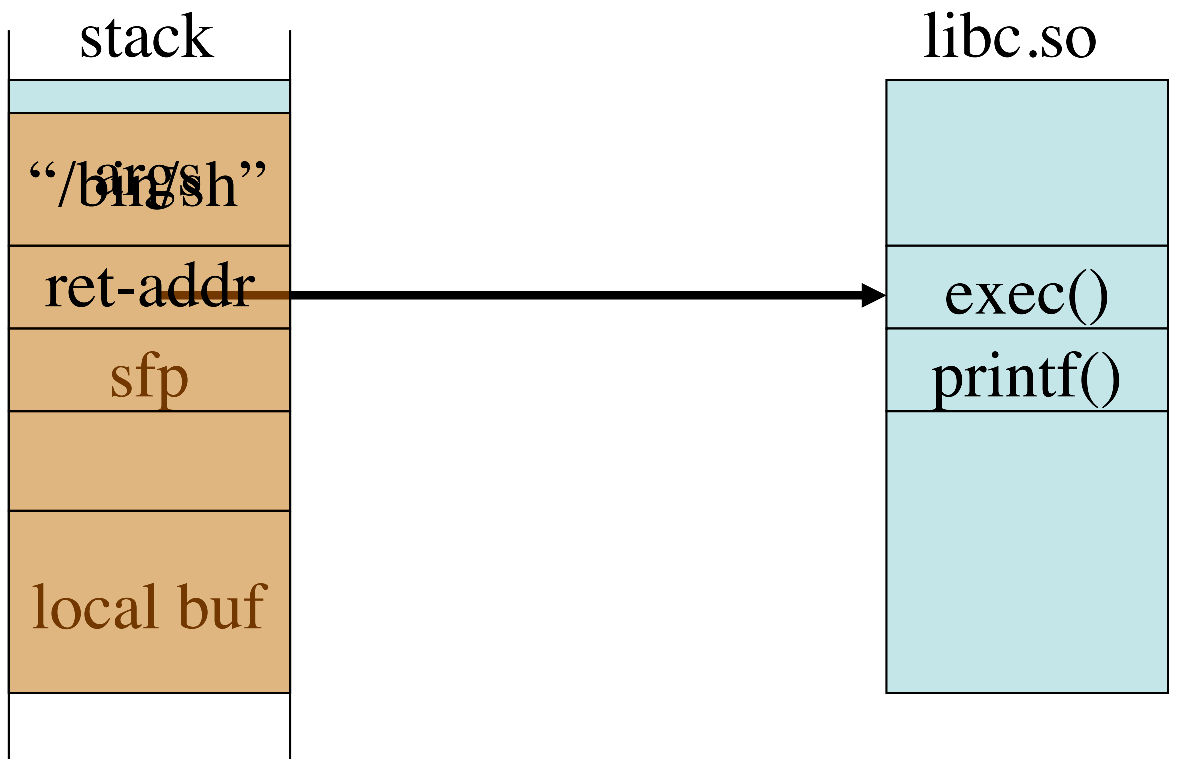
Return-to-libc Attacks and Return-Oriented Programming

One more false assumption



Return-to-libc

- Control hijacking without code injection
  - Call library function (e.g. system) or dead code

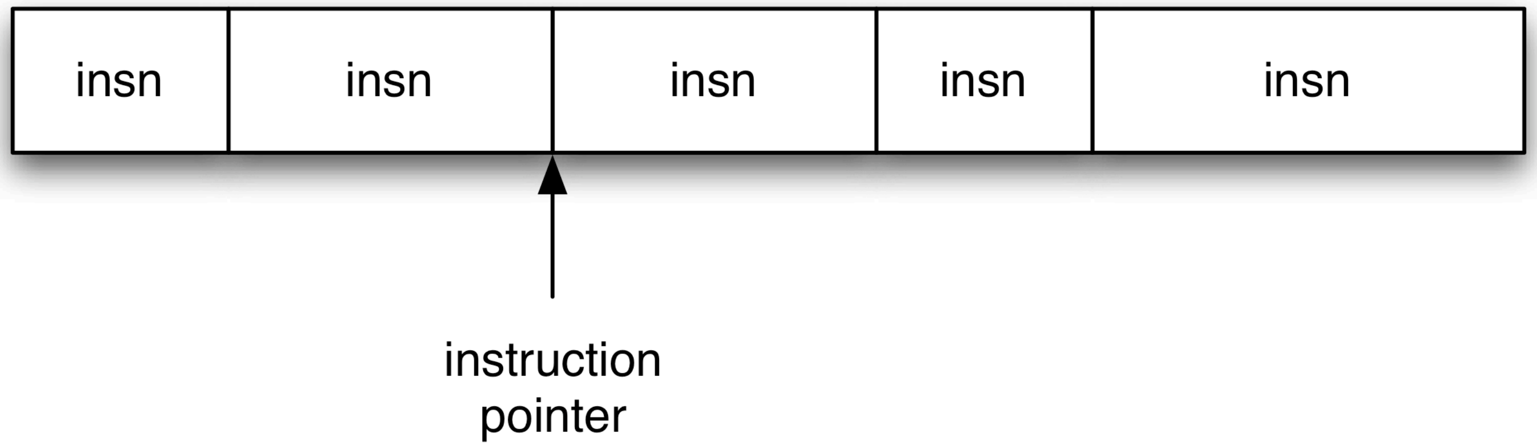


- Remove security-sensitive functions from *shared* libraries?
  - this might break legitimate uses

Return-Oriented Programming

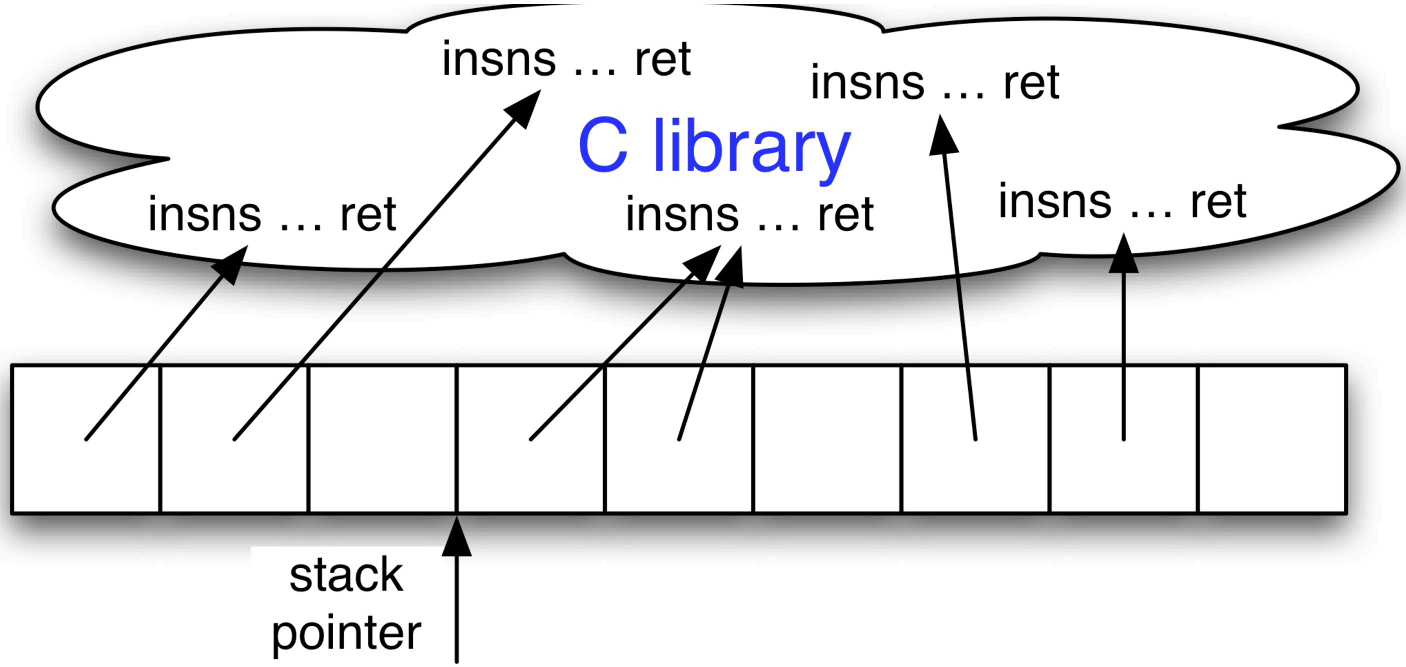
- When calling library/dead functions not helpful
  - e.g. if system is removed from libc.so
- Execute “opportunistic” code
  - Code in the middle of a function
  - Code obtained by jumping in the middle of instructions
    - x86 instructions are variable length
- Arbitrary(!) behavior without code injection
  - *if arbitrary jumping around within existing, executable code is permitted then an attacker can cause any desired, bad behavior, without code injection*
  - libc.so provides sufficiently large code base for this
- Reference: [Shacham et. al. ’07 & ‘09]

Ordinary programming (machine level)



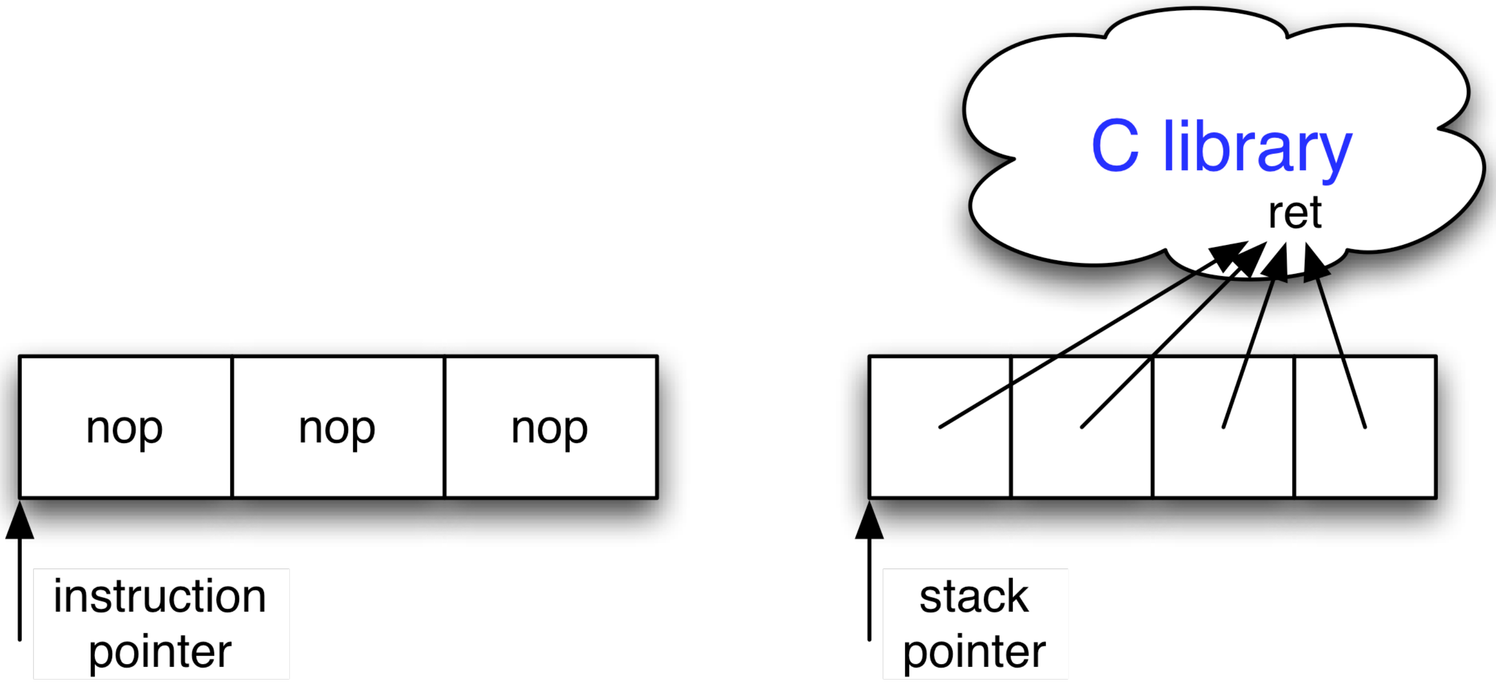
- IP determines which instruction to fetch and execute
- IP incremented automatically after executing instr.
- Control flow (jumps) by changing IP

Return-oriented programming (machine level)

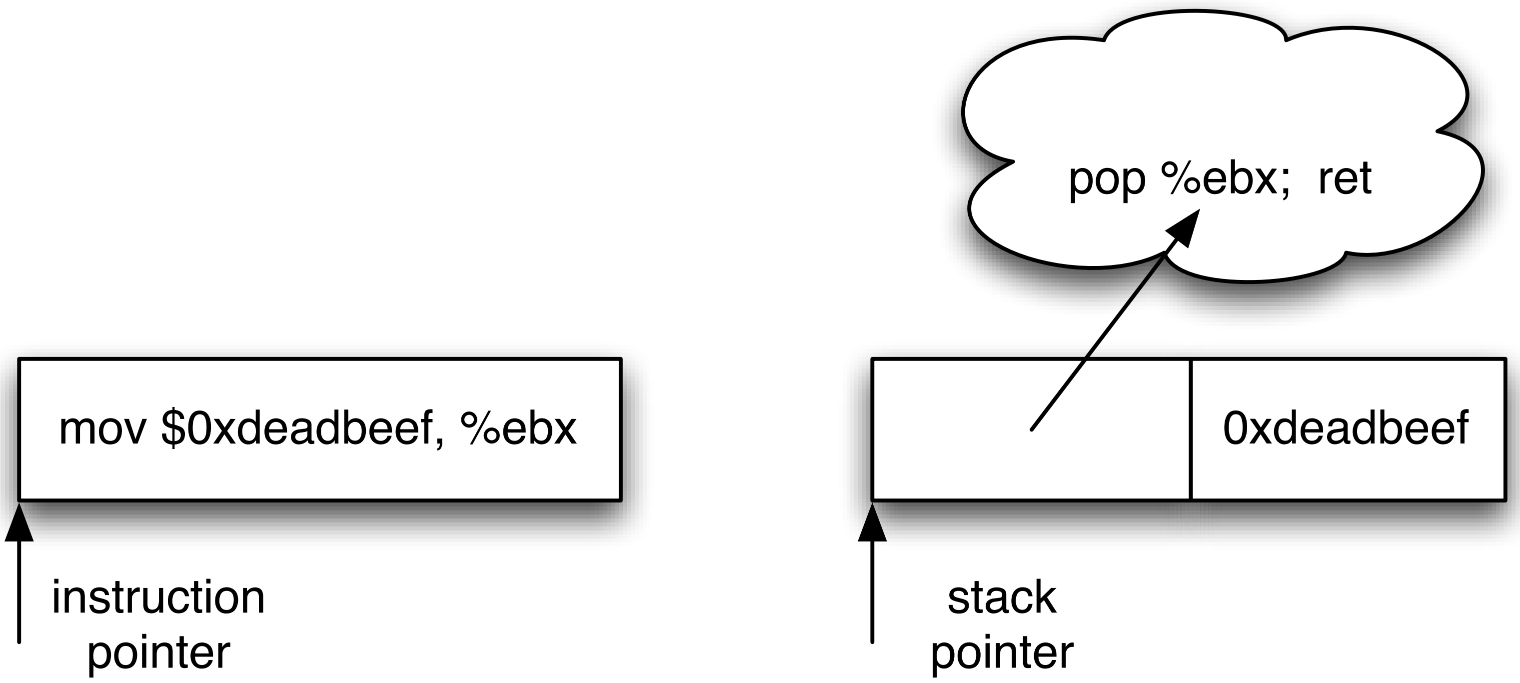


- SP determines which insns. to execute next
- SP incremented by the `ret` at the end of insns.
- Control flow (jumps) by changing SP (sub $n,%esp)

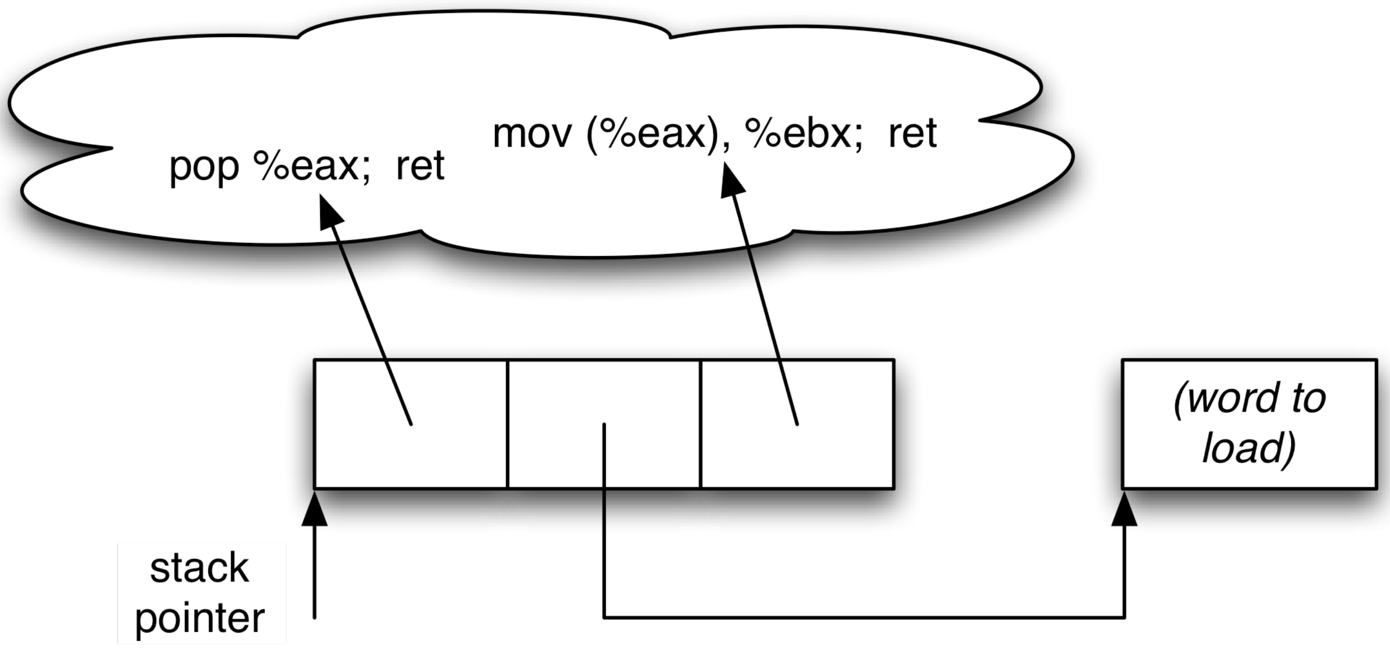
NOP


C library
ret
nop
nop
nop
instruction pointer
stack pointer

Load immediate constant



Gadgets: multiple instruction sequences



- Example: load from memory into register
  - Load address of source word into %eax
  - Load memory at (%eax) into %ebx

Are there enough useful instruction sequences?

- In Linux libc, one in 178 bytes is a `ret` (0xc3)
  - One in 475 bytes is an opportunistic, or unintended, `ret`

Intended instruction	Bytes	Unintended instruction
movl $0x00000001, -44(%ebp)	c7	
	45	
	d4	
	01	
	00	
	00	
	00	add %dh, %bh
test $0x00000007, %edi	f7	
	c7	movl $0x0F000000, (%edi)
	07	
	00	
	00	
	00	
setnzb -61(%ebp)	0f	
	95	xchg %ebp, %eax
	45	inc%ebp
	c3	ret

Return-oriented compiler

- Generates shellcode given high-level exploit program

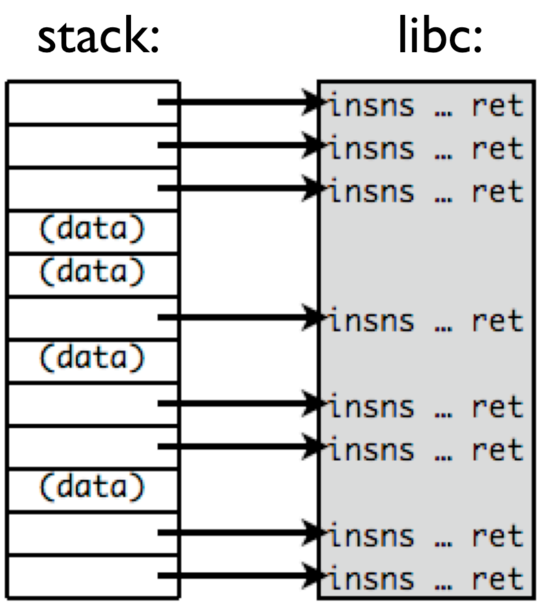
```
var arg0     = "/bin/sh";
var arg0Ptr = &arg0;
var arg1Ptr = 0;
trap(59, &arg0, &(arg0Ptr), NULL);
```

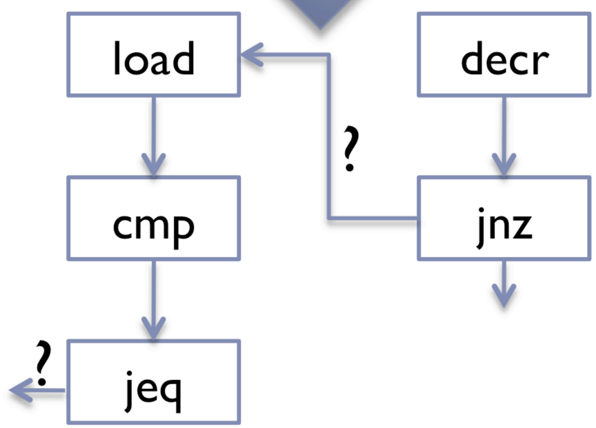
- Turing complete language
  - Sorting an array uses 152 gadgets, 381 instr. seq. (24 KB)
- No code injection!
- Not only on x86/CISC!
  - Also works on RISC (SPARC)

Return-oriented programming: workflow

```
connect back to attacker
while socket not eof
    read line
    fork, exec named progs
```

```
…
again:              …
mov i(s), ch        decr i
cmp ch,'|'          jnz again
jeq pipe            …
…
```





INTEGER OVERFLOWS

Integer overflows

- Writing too large value into int causes it to “wrap around”
  - Assigning int to short
  - Arithmetic: int = int + int or int = int * int
- Example

```
int table[800];

int insert_in_table(int val, int pos){
  if(pos > sizeof(table) / sizeof(int))
    return -1;
  table[pos] = val;
  // *(table + (pos * sizeof(int))) = val
  return 0;
}
```

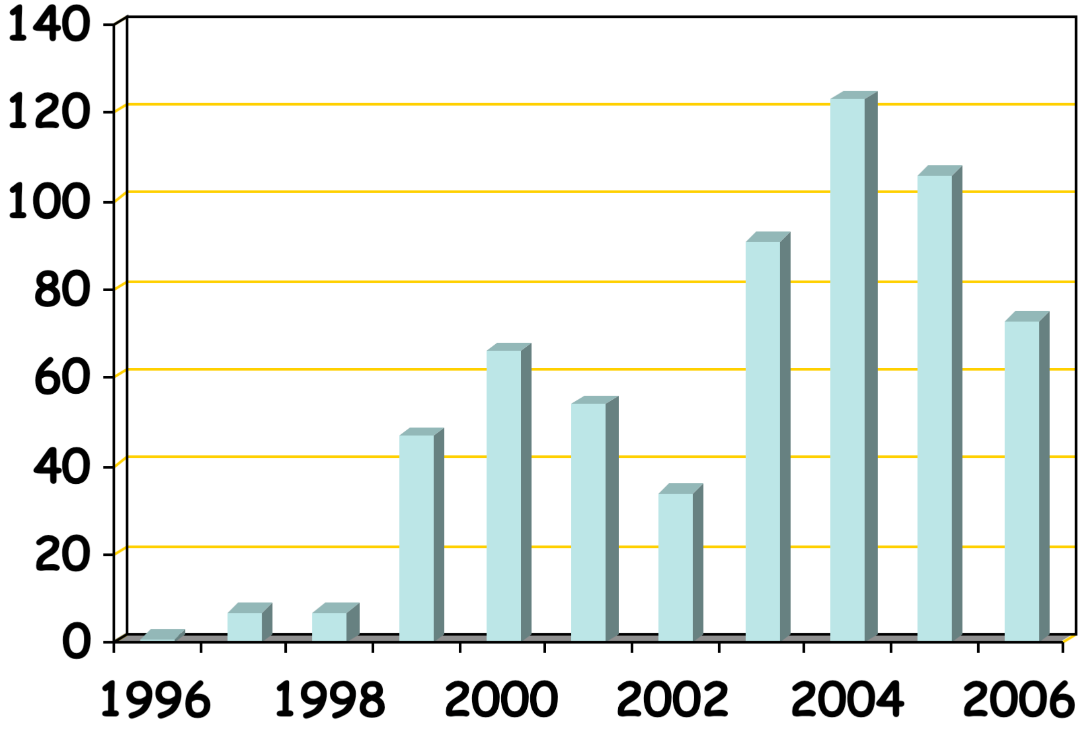
Not always easy to exploit

- Example (OpenSSH 3.3)

```
nresp = packet_get_int();
if (nresp > 0) {
 response = xmalloc(nresp*sizeof(char*));
 for (i = 0; i < nresp; i++)
  response[i] = packet_get_string(NULL);
}
```

  - If `nresp=1073741824` allocates a 0-bype buffer and overflows

Integer overflow stats



Source: NVD/CVE

FORMAT STRING VULNERABILITIES

Format string vulnerabilities

```
int func(char *user)  {
   printf(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 if user = "%n"

- Correct form:

```
int func(char *user)  {
   printf("%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
  - …
- Any function using a format string is vulnerable!
  - Printing: printf, fprintf, sprintf, …
  - Logging: syslog, err, warn

Exploiting

- 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”)
- Read this for details:
  - Exploiting Format String Vulnerabilities, scut/team teso

Overflow using format string

```
char errmsg[512],  outbuf[512];

sprintf (errmsg, “Illegal command: %400s”, user);
      ...
sprintf( outbuf, errmsg );
```

- What if user = “%500d <nops> <shellcode>”
  - Bypass “%400s” limitation.
  - Will overflow outbuf, and get a shell

References

- Smashing The Stack For Fun And Profit, Aleph One
- Heap Feng Shui in JavaScript, Alexander Sotirov
- Return-Oriented Programming, Shacham et. al. 2009
- Basic Integer Overflows, blexim
- Exploiting Format String Vulnerabilities, scut/team teso

Project 1:

WRITING EXPLOITS

Project 1: writing exploits

- 7 vulnerable programs you need to exploit
  - should be increasingly difficult
  - buffer and integer overflows + format string vulnerabilities
- One practice target (target0)
  - Return address clobbering: should help you get started
  - will be exploited in the next tutorial
- Exploit skeletons provided + Aleph One’s shellcode
  - no need to write much code
  - will probably spend most time thinking, reading and debugging
- VMware virtual machine running Linux (Debian)
  - your exploits need to work in the vm

Project 1: writing exploits

- Teams of up to 2 people
  - if 2 people then should submit only one common set of exploits
- You get points only for successful exploits
  - need only 5 points for maximum grade, the rest are bonus
- The early bird catches the worm
  - additional bonus points for being the first to exploit a target
  - check status page first, if target still “available” send by email
- Hint #1: start early
- Hint #2: gdb is your friend
- Hint #3: use tutorials, office hours, bulletin board

Project 1: useful references

- Smashing The Stack For Fun And Profit, Aleph One
- Buffer overflows demystified, Murat
- The Frame Pointer Overwrite, klog
- Basic Integer Overflows, blexim
- Exploiting Format String Vulnerabilities, scut/team teso
- How to hijack the Global Offset Table with pointers for root shells, c0ntex
- Intel Architecture Guide for Software

HAVE FUN!