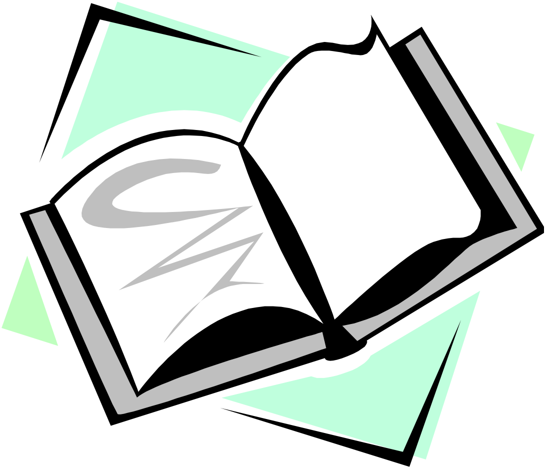
Information Security CS 526

Topic 8

Software Vulnerabilities

Readings for This Lecture

- Wikipedia
  - **Privilege escalation**
  - **Directory traversal**
  - **Time-of-check-to-time-of-use**
  - **Buffer overflow**
  - **Stack buffer overflow**
  - **Buffer overflow protection**
  - Format string attack
  - Integer overflow
- **Smashing The Stack For Fun And Profit by Aleph One**



Why Software Vulnerabilities Matter?

- When a process reads input from attacker, the process may be exploited if it contains vulnerabilities.
- When an attacker successfully exploits a vulnerability, he can
  - Crash programs: Compromises availability
  - Execute arbitrary code: Compromises integrity
  - Obtain sensitive information: Compromises confidentiality
- Software vulnerability enables the attacker to run with privileges of other users, violating desired access control policy

Attacks Exploiting Software Vulnerabilities

- Drive-by download (drive-by installation)
  - malicious web contents exploit vulnerabilities in browsers (or plugins) to download/install malware on victim system.
- Email attachments in PDF, Word, etc.
- Network-facing daemon programs (such as http, ftp, mail servers, etc.) as entry points.
- Privilege escalation
  - Attacker on a system exploits vulnerability in a root process and gains root privilege

Common Software Vulnerabilities

- Input validation
- Race conditions
  - Time-of-check-to-time-of-use (TOCTTOU)
- Buffer overflows
- Format string problems
- Integer overflows

Sources of Input that Need Validation

- What are sources of input for local applications?
  - Command line arguments
  - Environment variables
  - Configuration files, other files
  - Inter-Process Communication call arguments
  - Network packets

- What are sources of input for web applications?
  - Web form input
  - Scripting languages with string input

Command line as a Source of Input: A Simple example

```
void main(int argc, char ** argv) {
   char buf[1024];
   sprintf(buf,"cat %s",argv[1]);
 system ("buf");
}
```

What can go wrong?

- Can easily add things to the command by adding ;, using e.g., “a; ls”
- User can set command line arguments to almost anything, e.g., by using execve system call to start a program, the invoker has complete control over all command line arguments.

Environment variables

- Users can set the environment variables to anything
  - Using execve
  - Has some interesting consequences

- Examples:
  - PATH
  - LD_LIBRARY_PATH
  - IFS

Attack by Resetting PATH

- A setuid program has a system call: system(ls);
- The user sets his PATH to be . (current directory) and places a program ls in this directory
- The user can then execute arbitrary code as the setuid program

- Solution: Reset the PATH variable to be a standard form (i.e., “/bin:/usr/bin”)

Attack by Resetting IFS

- However, you must also reset the IFS variable
  - IFS is the characters that the system considers as white space
- If not, the user may add “s” to the IFS
  - system(ls) becomes system(l)
  - Place a function l in the directory
- Moral: things are intricately related and inputs can have unexpected consequences

Attack by Resetting LD_LIBRARY_PATH

- Assume you have a setuid program that loads dynamic libraries
- UNIX searches the environment variable LD_LIBRARY_PATH for libraries
- A user can set LD_LIBRARY_PATH to /tmp/attack and places his own copy of the libraries here
- Most modern C runtime libraries have fixed this by not using the LD_LIBRARY_PATH variable when the EUID is not the same as the RUID or the EGID is not the same as the RGID

A Web-Application Example: PHP passthru

- Idea
  - PHP passthru(*string*) executes command
  - Web-pages can construct *string* from user input and execute the commands to generate web content
  - Attackers can put “;” in input to run desired commands
- Example

```
echo 'Your usage log:<br />';
  $username = $_GET['username'];
  passthru(“cat /logs/usage/$username”);
```

- What if: “username=andrew;cat%20/etc/passwd”?

Directory Traversal Vulnerabilities in Web Applications

- A typical example of vulnerable application in php code is:

```
<?php
   $template = 'red.php';
   if ( isset( $_COOKIE['TEMPLATE'] ) )
   $template = $_COOKIE['TEMPLATE'];
   include ( "/home/users/phpguru/templates/" . $template );
?>
```

- Attacker sends

```
GET /vulnerable.php HTTP/1.0
Cookie: TEMPLATE=../../../../../../../../../etc/passwd
```

Checking input can be tricky: Unicode vulnerabilities

- Some web servers check string input
  - Disallow sequences such as ../ or \
  - But may not check unicode %c0%af for '/'
- IIS Example, used by Nimda worm

http://victim.com/scripts/../../winnt/system32/cmd.exe?<some command>

  - passes <some command> to cmd command
  - scripts directory of IIS has execute permissions
- Input checking would prevent that, but not this

http://victim.com/scripts/..%c0%af..%c0%afwinnt/system32/...

  - IIS first checks input, then expands unicode

Input Validation Summary

- Lessons:
  - Malicious inputs can become code, or change the logic to do things that are not intended
  - Inputs interact with each other, sometimes in subtle ways
- Use systematic approaches to deal with input validation
  - Avoid checking for bad things (blacklisting) if possible
    - The logic for blacklisting may not be exhaustive
    - Code where input is used may have different logic
  - Instead, check for things that are allowed (whitelisting)
  - Or, use systematic rewriting

Time-of-check-to-time-of-use

- **TOCTTOU**, pronounced "*TOCK too*“
- A class of software bug caused by changes in a system between the checking of a condition (such as authorization) and use of the results of the check.
  - When a process P requests to access resource X, the system checks whether P has right to access X; the usage of X happens later
  - When the usage occurs, perhaps P should not have access to X anymore.
  - The change may be because P changes or X changes.

An Example TOCTTOU

- In Unix, the following C code, when used in a setuid program, is a TOCTTOU bug:

Attacker tries to execute the following line in another process when this process reaches exactly this time:
Symlink("/etc/passwd", "file")

```
if (access("file", W_OK) != 0)
        { exit(1); }

fd = open("file", O_WRONLY);
write(fd, buffer, sizeof(buffer));
```

- Here, *access* is intended to check whether the real user who executed the setuid program would normally be allowed to write the file (i.e., *access* checks the real userid rather than effective userid).

TOCTTOU

- Exploiting a TOCTTOU vulnerabilities requires precise timing of the victim process.
  - Can run the attack multiple times, hoping to get lucky
- Most general attack may require “single-stepping” the victim, i.e., can schedule the attacker process after each operation in the victim
  - Techniques exist to “single-step” victim
- Preventing TOCTTOU attacks is difficult

What is Buffer Overflow?

- A **buffer overflow**, or **buffer overrun**, is an anomalous condition where a process attempts to store data beyond the boundaries of a fixed-length buffer.
- The result is that the extra data overwrites adjacent memory locations. The overwritten data may include other buffers, variables and program flow data, and may result in erratic program behavior, a memory access exception, program termination (a crash), incorrect results or — especially if deliberately caused by a malicious user — a possible breach of system security.
- Most common with C/C++ programs

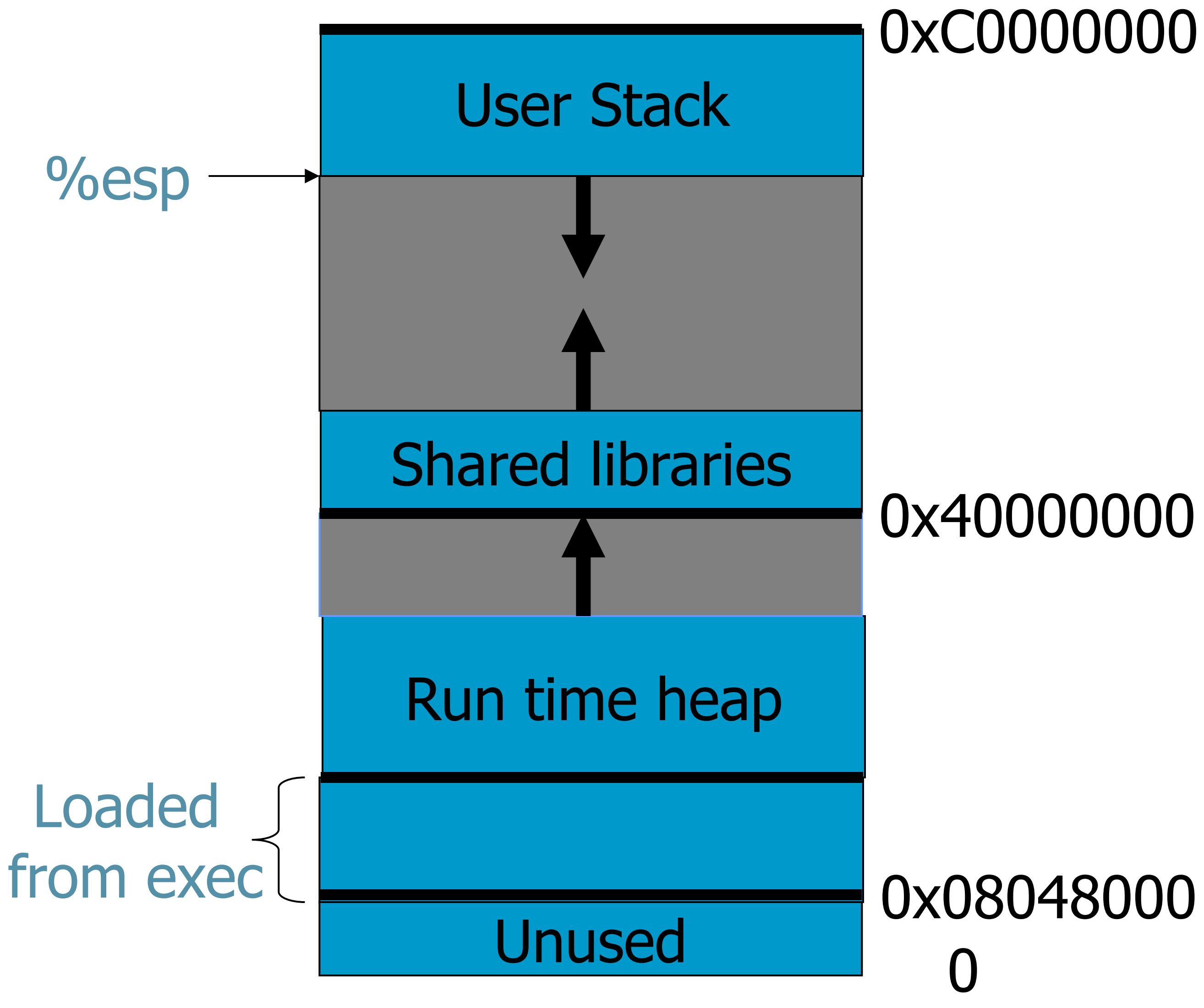
History

- Used in 1988's Morris Internet Worm
- Alphe One's "Smashing The Stack For Fun And Profit" in Phrack Issue 49 in 1996 popularizes stack buffer overflows
- Still extremely common today

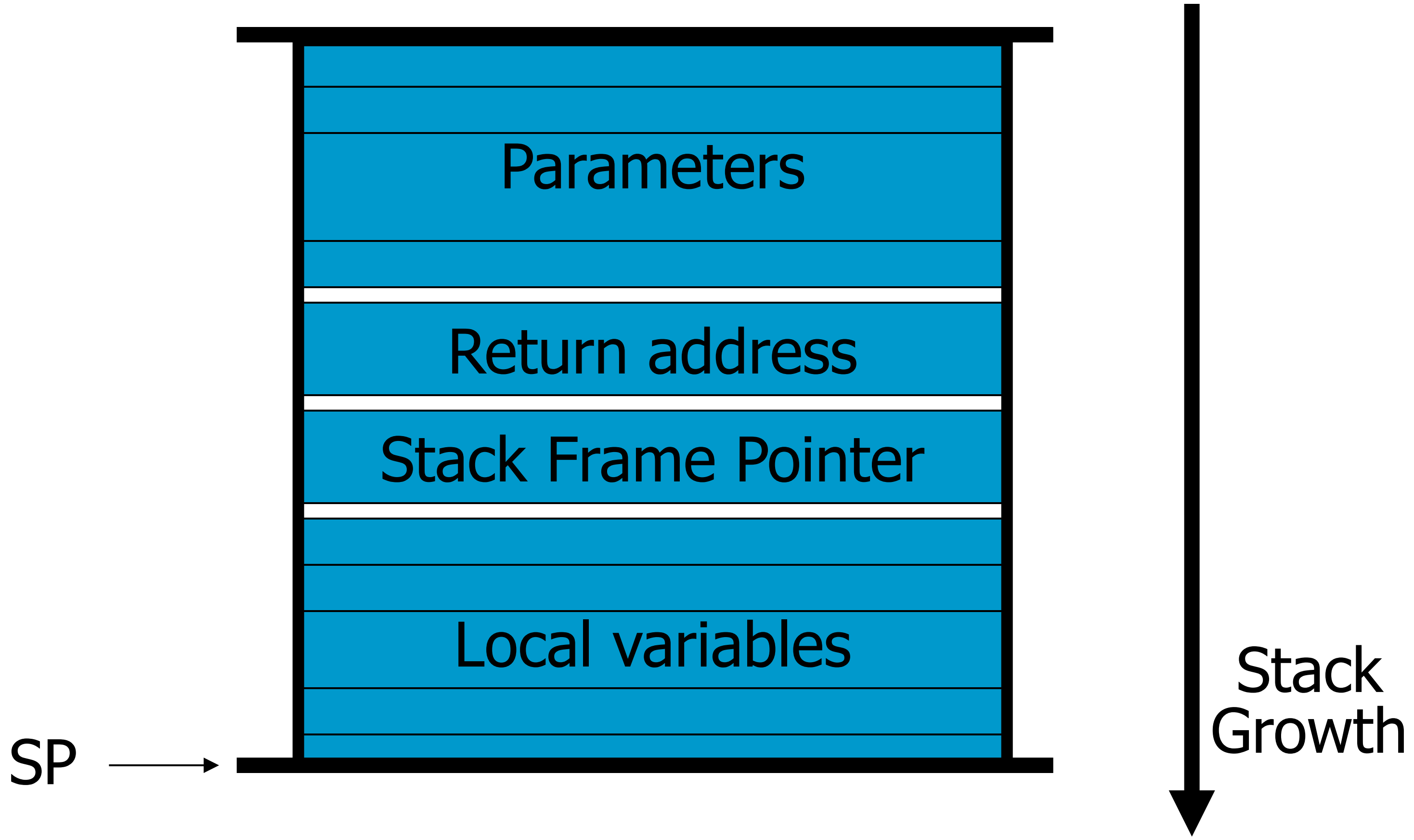
Types of Buffer Overflow Attacks

- Stack overflow
  - Shell code
  - Return-to-libc
    - Overflow sets ret-addr to address of libc function
  - Off-by-one
  - Overflow function pointers & longjmp buffers
- Heap overflow

Linux process memory layout



Stack Frame


Parameters
Return address
Stack Frame Pointer
Local variables
SP
Stack
Growth

What Happens in a Function Call?

```
void func(char *str) {
      char buf[128];
      strcpy(buf, str);
      ….
}
int main() {
   func("abc");
}
```

- Before main() calls func()
  - Push pointer to "abc" onto stack
  - Use "call func" assembly, which pushes current IP on stack
- Upon entering func()
  - Push stack frame pointer register (bp) on stack
  - Update sp to leave space for local variable.
- Upon leaving func()
  - Update sp to just below saved bp
  - Pop stack to bp, restore bp
  - Use "ret" assembly, which pop stack to IP

What are buffer overflows?

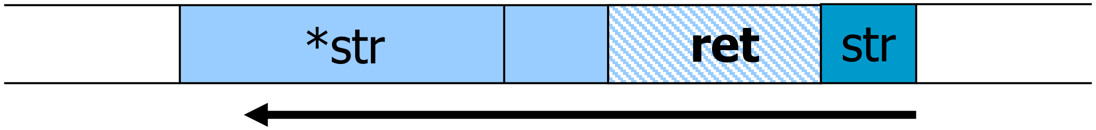
- Suppose a web server contains a function:

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

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

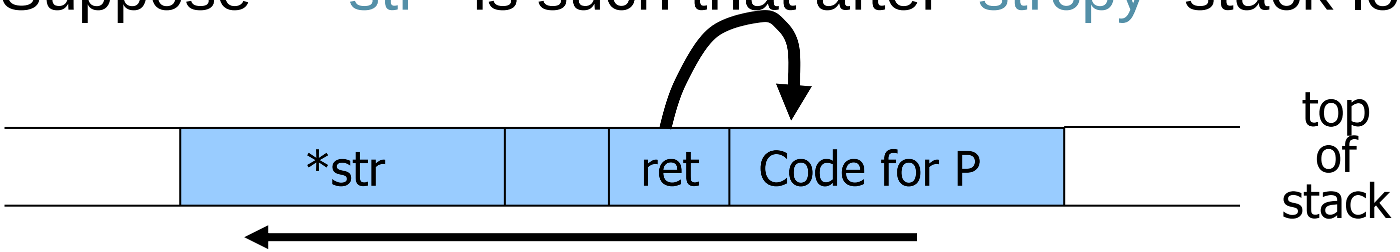
- When the function is invoked the stack looks like:

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



Basic stack exploit

- Main problem: no range checking in strcpy().
- 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 will be given a shell !!
- Note: attack code runs *in stack*.

Carrying out this attack requires

- Determine the location of injected code position on stack when func() is called.
  - So as to change stored return address on stack to point to it
  - Location of injected code is fixed relative to the location of the stack frame
- Program P should not contain the '\0' character.
  - Easy to achieve
- Overflow should not crash program before func() exits.

Some unsafe C lib functions

strcpy (char *dest, const char *src)

strcat (char *dest, const char *src)

gets (char *s)

scanf (const char *format, …)

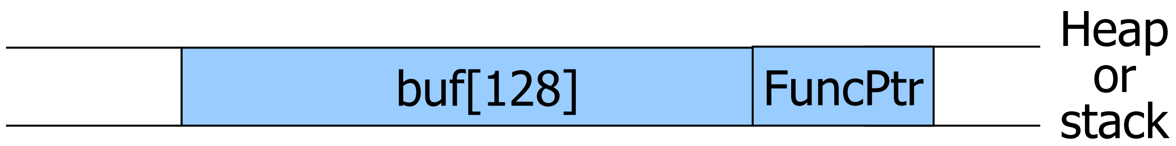
sprintf (conts char *format, …)

⋮

Other control hijacking opportunities

- In addition to overwrite return address on the stack, can also use overflow to overwrite the following:

- Function pointers: (used in attack on PHP 4.0.2)



  – Overflowing buf will override function pointer.

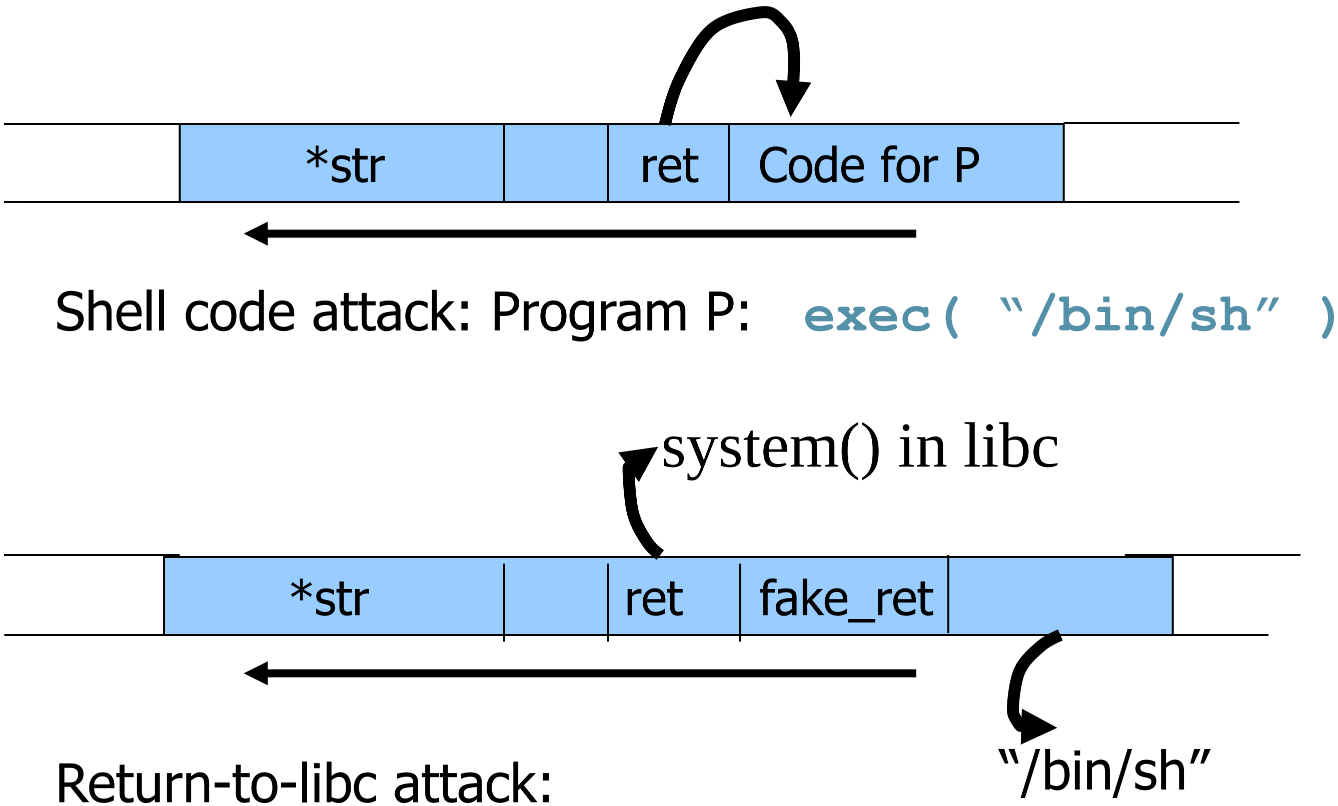
- Longjmp buffers: longjmp(pos) (used in attack on Perl 5.003)
  – Overflowing buf next to pos overrides value of pos.

return-to-libc attack

- “Bypassing non-executable-stack during exploitation using return-to-libs” by c0ntex
- Overflow ret address to point to injected shell code requires execution of injected code
  - Many defenses exist, e.g., data execution prevention
- Return-to-libc overwrites the return address to point to functions in libc (such as system())
  - Executing existing code
  - But set up the parameters so that the attacker gets a shell

return-to-libc attack

- Illustrating return-to-libc attack



Return-oriented programming

- Goal: executing arbitrary code without injecting any code.
- Observations:
  - Almost all instructions already exist in the process's address space, but need to piece them together to do what the attacker wants
- Attack:
  - Find instructions that are just before "return"
  - Set up the stack to include a sequence of addresses so that executing one instruction is followed by returning to the next one in the sequence.
- Effectiveness: has been shown that arbitrary program can be created this way

Off by one buffer overflow

- Sample code

```
func  f(char *input) {
  char buf[LEN];
  if (strlen(input) <= LEN) {
     strcpy(buf, input)
  }
}
```

What could go wrong here?

Heap Overflow

- Heap overflow is a general term that refers to overflow in data sections other than the stack
  - buffers that are dynamically allocated, e.g., by malloc
  - statically initialized variables (data section)
  - uninitialized buffers (bss section)

- Heap overflow may overwrite other date allocated on heap
- By exploiting the behavior of memory management routines, may overwrite an arbitrary memory location with a small amount of data.
  - E.g., SimpleHeap_free() does
    - hdr->next->next->prev := hdr->next->prev;

Finding buffer overflows

- Hackers find buffer overflows as follows:
  - Run web server on local machine.
  - **Fuzzing:** Issue requests with long tags.
    All long tags end with "$$$$$".
  - If web server crashes,
    search core dump for "$$$$$" to find
    overflow location.
- Some automated tools exist.
- Then use disassemblers and debuggers (e..g IDA-Pro) to construct exploit.
- How to defend against buffer overflow attacks?

Preventing Buffer Overflow Attacks

- Use type safe languages (Java, ML).
- Use safe library functions
- Use better software development process, e.g., manual code review
- Static source code analysis.
- Non-executable stack
- Run time checking: StackGuard, Libsafe, SafeC, (Purify), and so on.
- Address space layout randomization.

- Detection deviation of program behavior
- Access control to control aftermath of attacks… (covered later in course)

Static source code analysis

- Statically check source code to detect buffer overflows.
- Main idea: automate the code review process.
- Several tools exist:
  - Example: Coverity (Engler et al.): Test trust inconsistency.
- Find lots of bugs, but not all.

Bugs to Detect in Source Code Analysis

- Some examples

- Crash Causing Defects
- Null pointer dereference
- Use after free
- Double free
- Array indexing errors
- Mismatched array new/delete
- Potential stack overrun
- Potential heap overrun
- Return pointers to local variables
- Logically inconsistent code
- Uninitialized variables
- Invalid use of negative values
- Passing large parameters by value
- Underallocations of dynamic data
- Memory leaks
- File handle leaks
- Network resource leaks
- Unused values
- Unhandled return codes
- Use of invalid iterators

Data Execution Prevention

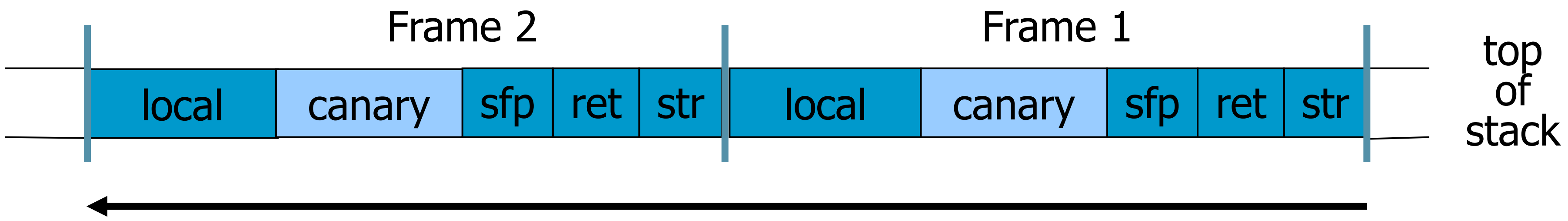
- Basic stack exploit can be prevented by marking stack segment as non-executable.
- More generally, prevent the execution of any memory page that can be dynamically changed
  - Supported in Windows since XP SP2. Code patches exist for Linux, Solaris.

Problems:

- Does not defend against `return-to-libc’ or “return-oriented programming”.
- Could potentially break JIT (just-in-time) compiling, or other legacy applications (e.g., LISP compiler)

Run time checking: StackGuard

- There are many run-time checking techniques …
- StackGuard tests for stack integrity.
  - Embed "canaries" in stack frames and verify their integrity prior to function return.



Canary Types

- <u>Random canary:</u>
  - Choose random string at program startup.
  - Insert canary string into every stack frame.
  - Verify canary before returning from function.
  - To corrupt random canary, attacker must learn current random string.
- <u>Terminator canary:</u>

  Canary = 0, newline, linefeed, EOF

  - String functions will not copy beyond terminator.
  - Hence, attacker cannot use string functions to corrupt stack.

Randomization: Motivations.

- Buffer overflow, return-to-libc, and return-oriented programing exploits need to know the (virtual) address to which pass control
  - Address of attack code in the buffer
  - Address of a standard kernel library routine
- Same address is used on many machines
  - Slammer infected 75,000 MS-SQL servers using same code on every machine
- Idea: introduce artificial diversity
  - Make stack addresses, addresses of library routines, etc. unpredictable and different from machine to machine

Address Space Layout Randomization

- Arranging the positions of key data areas randomly in a process' address space.
  - e.g., the base of the executable and position of libraries (libc), heap, and stack,
  - Effects: for return to libc, needs to know address of the key functions.
  - Attacks:
    - Repetitively guess randomized address
    - Spraying injected attack code
- Vista has this enabled, software packages available for Linux and other UNIX variants

Format string problem

```
int  func(char *user)  {
    fprintf( stdout, 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”

Correct form:

```
int  func(char *user)  {
    fprintf( stdout, “%s”, user);
}
```

Format string attacks (“%n”)

- printf(“%n”, &x) will change the value of the variable x
  - in other words, the parameter value on the stack is interpreted as a pointer to an integer value, and the place pointed by the pointer is overwritten

History

- Danger 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

Integer Overflow

- Integer overflow: an arithmetic operation attempts to create a numeric value that is larger than can be represented within the available storage space.
- Example:

Test 1:

```
short x = 30000;
short y = 30000;
printf("%d\n", x+y);
```

Test 2:

```
short x = 30000;
short y = 30000;
short z = x + y;
printf("%d\n", z);
```

Will two programs output the same?
Assuming short uses 16 bits.
What will they output?

Where Does Integer Overflow Matter?

- Allocating spaces using calculation.
- Calculating indexes into arrays
- Checking whether an overflow could occur

- Direct causes:
  - Truncation; Integer casting

C Data Types, Vary between Platforms

- short int 16bits [-32,768; 32,767]
- unsigned short int 16bits [0; 65,535]
- unsigned int 16bits [0; 4,294,967,295]
- Int 32bits
  [-2,147,483,648; 2,147,483,647]
- long int 32 bits
  [-2,147,483,648; 2,147,483,647]
- signed char 8bits [-128; 127]
- unsigned char 8 bits [0; 255]

When casting occurs in C?

- When assigning to a different data type
- Type promotion; for binary operators +, -, *, /, %, &, |, ^,
  - Integer types smaller than int are promoted when an operation is performed on them. If all values of the original type can be represented as an int, the value of the smaller type is converted to an int; otherwise, it is converted to an unsigned int.
  - There are other promotion rules when mixing signed with unsigned, and with integer types of different length
- For unary operators
  - ~ changes type, e.g., ~((unsigned short)0) is int
  - ++ and -- does not change type

Integer Overflow Vulnerabilities Example

- Example:

```
const long MAX_LEN = 20K;
Char   buf[MAX_LEN];
short len = strlen(input);
if (len < MAX_LEN)  strcpy(buf, input);
```

Can a buffer overflow attack occur?

If so, how long does input needs to be?

An Integer Overflow Vulnerabily Example (from Phrack)

```
int main(int argc, char *argv[]) {
    unsigned short s;  int i;   char buf[80];
    if (argc < 3){ return -1; }
    i = atoi(argv[1]);
    s = i;
    if(s >= 80)  {  printf(“Input too long!\n"); return -1; }
    printf("s = %d\n", s);
    memcpy(buf, argv[2], i);
    buf[i] = '\0'; printf("%s\n", buf); return 0;
}
```

Another Integer Overflow Vulnerability Example (from Phrack)

```
int copy_something(char *buf, int len){
  char kbuf[800];
  if(len > sizeof(kbuf)){      /* [1] */
    return -1;
  }
  return memcpy(kbuf, buf, len); /* [2] */
}
```

What could go wrong?

Yet Another Integer Overflow Vulnerability Example (from Phrack)

```
int table[800];
int insert_in_table(int val, int pos){
  if(pos > sizeof(table) / sizeof(int)) {
    return -1;
  }
  table[pos] = val; return 0;
}
```

What could go wrong?

Yet Another Example

```
// The function is supposed to return false when
// x+y overflows unsigned short.
// Does the function do it correctly?
bool  IsValidAddition(unsigned short x,
        unsigned short y) {
        if (x+y < x)
                return false;
        return true;
}
```

Coming Attractions …

- Malwares