Stack-Based Buffer Overflow Attack

Austin Wolfe
CIT-485-001
April 10, 2021

Introduction

Listed in the “2020 CWE Top 25 Most Dangerous Software Weaknesses”, on cwe.mitre.org, is the “Out-of-bounds Write [3]”. Listed under this category is the stack-based buffer overflow; a stack-based buffer overflow condition happening where a buffer allocated on the stack is being overwritten, which is one of the meanings of “Out-of-bounds write” [5]. The buffer overflow vulnerability is a classic memory attack showing up throughout the history of computer security:

> The Morris worm in 1998 took advantage of a buffer overflow problem in the finger application, aiding the worm’s attack on remote systems [6]. The Code Red Worm in 2001 took advantage of unknown buffer overflow in a tool called ISAPI used by Microsoft’s Internet Information Services (ISS) version 4 and 5, which was the access point used for the worm which infected more than 250,000 systems in nine hours [7]. SQL Slammer in 2003 exploited a buffer overflow problem in the MS-SQL monitor service leading to a drop in CPU utilization on infected systems, hindering performance[8]. In 2015, seven bugs in the Android operating system (version 2.2) called Stagefright acted as “backdoors for remote code execution and privilege escalation [11]”.

The classic stack-based buffer overflow is the topic of this paper, with the point being to understand a classic attack that still can happen today, especially with older or outdated devices, and to understand these concepts to have the knowledge needed to learn more advanced topics on buffer overflow in the future.

A buffer is “a contiguous block of computer memory that holds multiple instances of the same data type [2]”, and since C and C++ are the languages most common to buffer overflow vulnerabilities, the example code in this paper will mostly be in C, the buffer conditions most commonly in the form of buffer arrays. To overflow a buffer means to write more to the buffer than what it it’s intended initialized size; the buffer overflows, overwriting past the bounds of the buffer and into contiguous areas of memory. The exploit of a buffer overflow condition can lead to memory corruption which can cause software to crash or allow the attacker to inject and execute some code that they choose. We will look at programs allocated in stack memory, witnessing what can potentially happen to programs compiled containing a buffer overflow condition.

This paper examines the memory structure that allows for buffers overflows, particularly in the stack memory region, and we examine scenarios and C functions that lead to these vulnerabilities in programs. We also examine how to exploit the buffer overflow vulnerability to execute code, creating shellcode designed to return a root owned shell to the attacker by adding these instructions into memory during the buffer overflow. We also look at coding, operating system, and compiler countermeasures that are implemented to deal with these buffer overflow vulnerabilities, along with ways to get around these countermeasures.

Memory Layout

The way buffer overflow attacks work can only be fully understood by first examining how a processes data is organized in memory. C programs are divided into five segments: Text segment, data segment, BSS segment, heap, and stack.

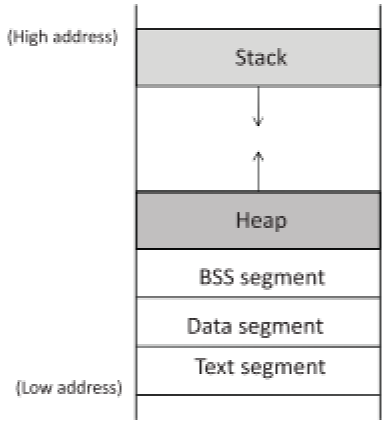


Figure 1: Program Memory Layout

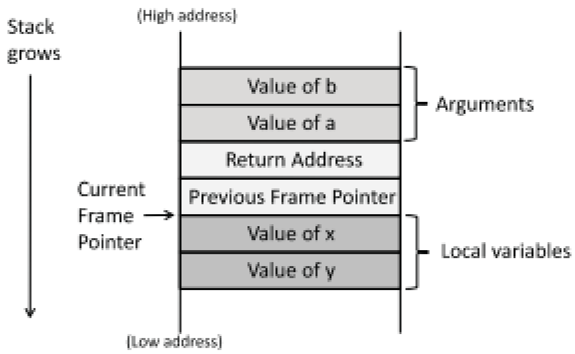
Source: [1]

Descriptions of the segments in Figure 1 are as follows: The text Segment is usually read only and contains the binary executable code of the program. The data segment stores static/global variables initialized by the programmer. The BSS segment stores uninitialized static and global variables with zeros being stored for the uninitialized variables by the operating system. The heap is used as a space for allocating dynamic memory, and the stack is used for storing the local variables inside functions and the data that pertains to that function, like return addresses and arguments. The stack segment will be a major focus of this paper.

The Stack

The stack is used to determine what instructions a program should run and when, allowing the programming instructions and data a static location to be stored. Functions are pushed onto the stack in stack frames when called, and popped off of the stack on returns. A stack frames holds the function parameters, local variables, and data telling how to return to the previous stack frame [2]. In the Figure 1 example, it should be noted that the stack is shown growing down towards lower addresses (this is the way the stack grows on computers with intel processors). This means that the growing part of the stack is at lower memory addresses. Since the stack is growing down, the bottom part exists at lower memory addresses; this bottom part being a fixed address that is dynamically adjusted by the kernel at run-time [2]. The stack grows or shrinks when the CPU uses instructions to “push” and “pop” data onto and off the stack in last in first out (LIFO) que.

To demonstrate the layout of a function’s stack frame, the Figure 2 is provided, followed by the code snippet to which is corresponds.




```
void func(int a, int b)
{
   int x, y;

   x = a + b;
   y = a - b;
}
```

Figure 2: Function’s stack frame layout

Source: [1]

When the **func()** function is called, the memory space for the stack frame is allocated onto the stack with regions for the arguments, return address (containing the address of the location in which to return after the function finishes), previous frame pointer, and the local variables. These memory segments are pushed onto the stack frame in this order.

The previous frame pointer section on the stack holds the previous frame address (the one before the current function call), and this value comes from being stored in the frame pointer register, which points to a fixed point (address) on the stack frame. The reason it points to a fixed place on the stack is because compilers cannot predict the runtime status of the stack, and since memory addresses need to be known to access the data inside and pertaining to functions, the frame pointer register points to a fixed location and is used along with an offset to calculate arguments and local variable addresses of functions [1]. In x86 (32 bit) architecture, the frame pointer register, is called ebp. The **ebp** register always points to the stack frame of the current function, but it allocates the previous stack frame into the previous frame pointer segment on stack when jumping to another function, so when returning from that function, the previous stack frame (which belongs to the function that was returned to) is not lost. There is also the **%esp** register (stack pointer) which points to the top of the stack.

Stack Buffer-Overflow Attack

The point of a buffer overflow attack is to write past the memory allocated on the stack reserved for a buffer, overwriting higher memory addresses, in hopes to rewrite these stack segments with our own code. So, in Figure 2, where you see return address, the goal is to change that address to one that points to the address of the attackers malicious code. There are some C standard library functions that allow for the copying of too much memory into a buffer intended for a smaller byte size.

Susceptible C Functions

C functions like **strcpy**, **sprintf**, **strcat**, and **gets** copy data from one location to another [1]. How they know to stop copying data is determine by using certain characters (NULL character '\0' in **strcpy()**). Since the length of the data is controlled by some character and not a specified maximum byte size (buffer length), the programmer can change this data to allow more data to be copied, allowing for overflow on the stack. In the buffer overflow examples in this paper, **strcpy()** will be used to copy data into a buffer array.

```
char *strcpy(char * destination, const char * source);
```

When a buffer overflow condition is found the attacker to add their own code onto the stack, and overwriting the return address with a new address that points to this code. In the following example the prebuilt VM discussed in [1] is used (Ubuntu, Version 16.04.2, 32-bit). The compiler is GCC version 5.4.0.

The following program called **stack.c** [1] is a Set-UID root program that contains a buffer overflow vulnerability. The goal of exploiting the Set-UID root program's buffer overflow vulnerability is so malicious code can be injected and run with root privileges. The code to be injected into this program will run a root shell (called shellcode). The program is compiled with gcc to the executable binary called **stack**, turning off current buffer overflow countermeasures on this VM for the program (will discuss in more detail in countermeasures section) and then the ownership of the compiled program is changed and made into a root owned Set-UID program.

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

int foo(char *str)
{
    char buffer[100];

    /* The following statement has a buffer overflow problem */
    strcpy(buffer, str);

    return 1;
}
```

```
int main(int argc, char **argv)
{
    char str[400];
    FILE *badfile;

    badfile = fopen("badfile", "r");

    /* the first arg in fread is a pointer to a buffer to store what
       is being read in from the file */
    fread(str, sizeof(char), 300, badfile);
    foo(str);

    printf("Returned Properly\n");
    return 1;
}
```

This program reads 300 bytes from the binary file **badfile** with the **fread()** function and stores it at the **str** pointer. This pointer address (**str**) is then supplied to the **foo()** function, and then the array starting at this pointer address is copied into **foo**'s local buffer called **array** using the **strcpy()** function. If the number of bytes read to this array is of size 100 or less, then the program runs normal, but copying in the 300 bytes causes buffer overflow.

Putting malicious code onto the stack

Since the source code **stack.c** is known and we know it is a root owned Set-UID program, it is easier to exploit. In order to write some shellcode, it is better (within this experiment) to determine where in memory the function **foo()** is allocated (the function containing the buffer overflow condition), instead of guessing, so the shellcode can be written to correspond to the correct memory addresses.

Compiling stack.c with the debugger flag turned on allows us to use gdb to set a break point at the **foo()** function with the **b** command and then using the **run** command to run and then stop the program inside the function **foo()** [1, p. 76]. Once there, the **p** command can be used to obtain the base pointer (**ebp**) address, the address of the buffer array called **buffer**. We can see in the stack diagram of the program **stack,** in Figure 3, where the data of the **foo()** function is allocated.

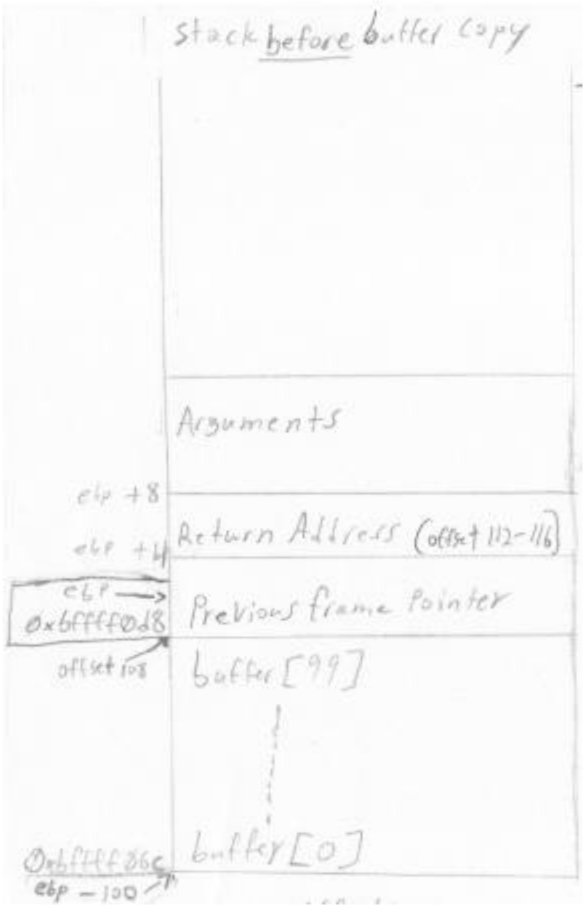


Figure 3: Stack before buffer copy

Source: Adapted from [1]

Since the previous frame pointer segment and the return address segment is 4 bytes each and the address of ebp is known, it is now easy to find the offsets for the return address and the arguments segment, which is first address that can be jumped to in order to reach where the malicious code will be stored. The distance between the beginning of the buffer and the return address is also important for knowing at what point in the shellcode to store the new return address (the address pointing to the malicious code). This is easy to know, since all that needs to be done is to subtract the buffer address from the ebp address and then add 4 to get the distance (distance = 0xbffff0d8-0xbffff06c + 4 = 112). With these addresses now know, the shell code can be constructed. The Idea behind the shellcode is to overwrite the stack at particular areas when badfile is read into the buffer to run the malicious code. The problem of getting to the malicious code can be made easier with NOP instructions that advance the program counter to the next location. All the return address needs to do is hit one of the NOP instruction and the malicious code will eventually execute, thus creating multiple entry points for the injected malicious code. Figure 5 compares the stack after the buffer copy with and without NOP instructions.

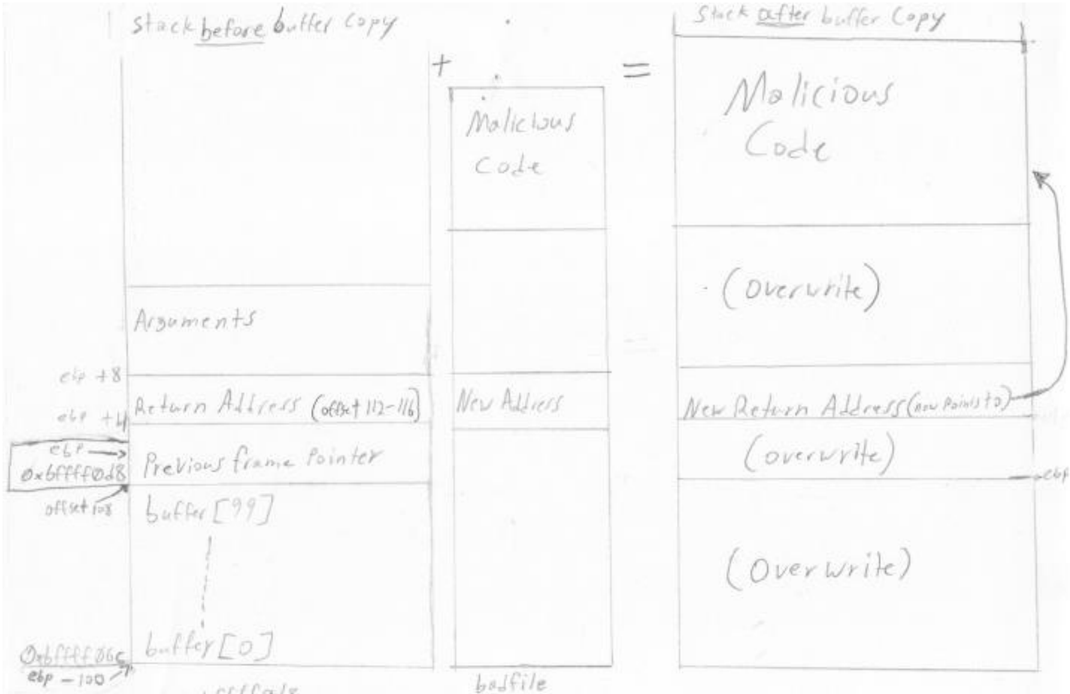


Figure 4: Before and after buffer copy

Source: adapted from [1]

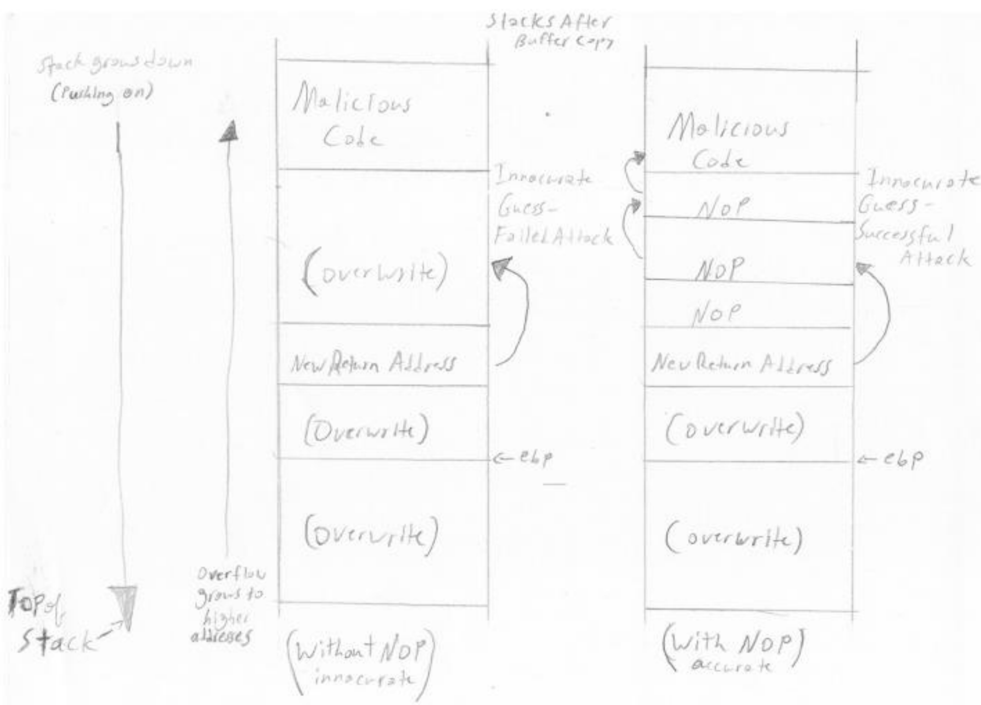


Figure 5: Stack with and without NOP instructions

Source: Adapted from [1].

Countermeasures

Tools and techniques have been created to counteract stack-based buffer overflow attacks. These can be categorized into these groups: static-analysis, compiler modifications, operating system modifications, and hardware modifications [10]. These categories are often combined to help prevent buffer overflow attacks, due to countermeasure for these countermeasures that were created over time.

Checking Source Code for Vulnerabilities

One way to prevent buffer overflow attacks is to make sure there are no buffer overflow conditions in the source code. One way of doing this is to use programming languages check for buffer overflow, like Python and Java, which have automatic boundary checking [1][10]. But because C is used when low level data manipulation is needed, a good way for uncovering software flaws mentioned in [10], is to do source code review.

In [13], a secure code review is said to be meant for identifying “specific security related flaws within the code that a malicious user could leverage to compromise confidentiality, integrity, and availability of the application”, and mentioned as an example of this type of security flaw is a buffer input that has not been checked, leading to buffer overflow, that could, “allow a malicious user to execute arbitrary code with escalated privileges”. In [13] it is also mentioned that though secure source code reviews may not find all flaws, but “it should arm developers with information to help make the application’s source code more sound and secure”, and that it is no “silver bullet”, but a “strong part of an overall risk mitigation program to protect an application”.

An example of something simple to look for during a source code review of C code are unsafe memory copy functions: Functions like **strcpy**, **strcat**, **sprintf**, and **gets** don’t require programmers to specify the maximum length of the data that they are working with [1]. Instead, the safer versions of these functions should be used, which are **strncpy**, **strncat**, **snprintf**, and **fgets**. Safer functions don’t make it impossible for buffer overflow, but only making them less likely: “If a developer specifies a length that is larger than the actual size of the buffer, there will still be a buffer overflow vulnerability” [1,p. 86].

Libsafe

Libsafe helps with the previously mentioned unsafe functions. It is a dynamically loaded library that gets preloaded along with processes that it needs to protect [14]. During the preloading, the libsafe library is “injected between the program code and the dynamically loadable standard C library functions”, and because of this is able to “intercept and bounds-check” arguments in those unsafe functions before letting them execute. Libsafe can be bypassed because “It gives a limited amount of protection against attacks[13, p. 110]”, monitoring only the unsafe functions, but not detecting buffer overflow, “if a string is copied byte by byte”.

Address Layout Randomization (ASLR)

For attackers to exploit a buffer overflow on the stack, they need to know the locations of the stack in memory so they can guess where to tell a program to jump to run their injected malicious code. ASLR is used at the operating system's loader program [1]. For older devices not using ALSR, the stack was placed at a fixed address, making it easier for attackers to guess the addresses they needed to know for getting the program to return to their injected code. But, the stack doesn't have to be at a fixed address: When source code is compiled into binary code, the addresses for all the data on the stack are not hard-coded into the binary[1]. These addresses are actually represented based on the offset to the frame pointer (%ebp) or the stack pointer (%esp), not the start of the stack, so the stack can start at any place in memory as long as the %ebp and %esp registers hold the correct values. ASLR takes advantage of this by randomizing the position of not only the stack, but the heap and libraries used by a program, which makes it harder for attackers to know the address of their malicious code in memory [12].

There have been techniques developed to counter ASLR: using non-ASLR modules, partial %eip overwrite, and brute force [12]. Using non-ASLR modules can cause the countermeasure to not work properly in the case where processes that use ASLR load in non-ASLR modules, allowing an attacker to run shellcode with the **jmp %esp** command. In a partial %eip overwrite, part or the eip register can be overwritten, or "use trustworthy information disclosure in the stack" [12, p.109], to find what the real %eip is, using it to calculate a precise location (this technique also relies on non-ASLR modules).

The brute force technique is made possible by measuring the available randomness in address space; one way to measure this is entropy [1, p. 90]. A memory region's base address can take 2^n possibilities for locations, all equally probable. On 32-bit Linux devices using static ASLR, stacks have 19 bits of entropy, meaning the base address of the stack can have 2^19 = 524,288 possible locations. This number is low enough to be exhausted quickly using brute force. This can be done by writing a script to repeatedly run the buffer overflow attack until the memory address is correct, causing the attackers malicious code to run.

Stackshield and StackGuard

Compilers control the layout of the stack since they are how the source code gets turned into binary, so they have the ability to insert countermeasures into the binary that can check for or eliminate some steps needed to carry out a buffer overflow attack [1]. Two of these countermeasures are called Stackshield and StackGuard, and they both check if the return address has been changed before a function returns.

Stackshield copies the return address into a shadow stack, which can't be overflown [1]. The compiler puts instructions into the binary that copies the return address into this safer place so (with other compiler inserted instructions) a comparison can be made of the return address saved in the safe place with the one on the stack, before the function returns, to see if there is a difference, indicating buffer overflow. Stackshield does not protect %ebp, and since %ebp is copied to %esp after a function return, can be used to exploit programs [12].

Another compiler technique that checks if the function return address has been changed is StackGuard. StackGuard places a special value, called a guard, or "canary"[12], onto the stack between the return and address and local variables (where a buffer would be located). This is used to detect when a return address is overwritten [1].

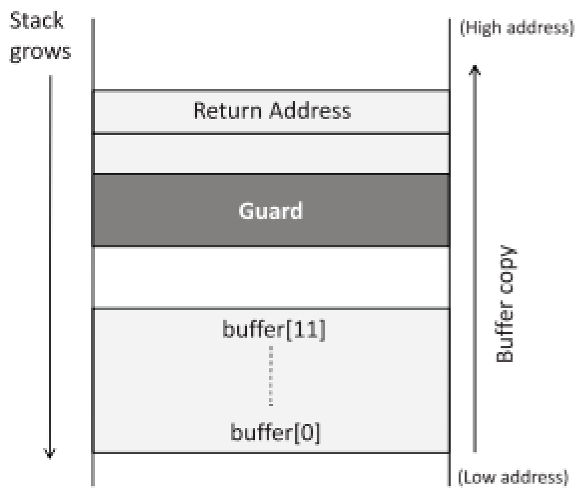


Figure 6: "The idea of StackGuard"

Source: [1, p.24].

The guard is a non-predictable value, and before a function returns, the value is checked to see if it has been changed. If the guard has been changed, then that is a signal that the return address might be overwritten, but it doesn't necessarily mean that the return addresses value has been modified.

Since the compiler is adding the code to a function, it is important for that code to be written so it can be added to and protect any function. The following is an example of how a compiler may add this code, which is a guard, to a function. Since the following is just example code implemented by a human and not by a compiler, we don't know for sure how close the variable defined first in the code will be to the return address; this is because the order in which variables are allocated to the stack is decided by the compiler [1].

```
void foo (char *str)
{

   char buffer[12];
   strcpy (buffer, str);

   return;
}
```

Figure 7:Function Before Adding the Guard

Source: [1].

Figure 7 shows the function before the guard code is added and Figure 8 shows the same function with the guard code added.

```
// This global variable will be initialized with a random
// number in the main function.
int secret;

void foo (char *str)
{
   int guard;
   guard = secret;

   char buffer[12];
   strcpy (buffer, str);

   if (guard == secret)
      return;
   else
      exit(1);
}
```

Figure 8:Function After Adding the Guard

Source: [1].

The **guard** variable is initialized with a secret, which is a random number. So that the random number is generated inside a main function (not shown here), so that the secret number is different each time the program runs. Now, when there is overflow, and as long as an attacker does not know the guard's secret value, we know that if there was any kind of modification to the return address, then the guard will also have to be changed [12]. The only way to mod the return address without the guard giving it away is to overwrite the guard with the same value; this is why the secret number must not be guessable. The secret value should never be hard-coded into the code or placed on the stack where it can be overwritten. The secret can be stored in the heap and BSS memory segments. In Figure 8, the uninitialized global variable, **secret**, gets put in the BSS segment.

Non-executable Stack

CPUs part of the Modern hardware architecture use something called the NX bit, which stands for No-execute, which is used to separate code from data [1]. Operating systems can use this to mark areas in memory as non-executable, which means code in an area like stack memory will not execute. When a stack is made non-executable, performing a stack-based buffer overflow attack to run malicious injected code, like the examples used in this paper will no longer work. There is a countermeasure to a non-executable stack, called a **return-to-libc** attack, but is not discussed here. More information on this topic can be found in [1], in chapter 5.

Conclusion

Stack-based buffer overflows occur when a function allocated onto the stack, containing a buffer with unchecked boundaries, is overwritten. Overwriting contiguous memory spaces on the stack can cause a program to crash or allow an attacker to change a function’s return address to redirect the flow of the program to execute the attackers injected malicious code. This type of attack can allow an attacker access to a shell with escalated privileges on a victim’s computer. We have seen countermeasures to the stack-based buffer overflow attacks and some ways around those countermeasure, like the brute-force technique to get around 32-bit memory address randomization.

The stack-based buffer overflow attack was one of the most successful software attacks for a long time, particularly because it is easy to make coding mistakes [1]. The creation and implementation of counter measures onto computers throughout time has helped combat these attacks, though even now, there are still exploits for memory corruption leading to code execution. The modern CPU has a built-in countermeasure that set the stack to be non-executable by default, which prevents injected malicious code from running, but even this countermeasure can be defeated with a **return-to-libc** attack [1]. But, not all machines in the world are up to date, and safe coding practices still need to be a priority, especially when using C and C++. This category of attack is listed even now on cwe.mitre.org as one of the most dangerous software attacks, even with all the countermeasures that have been developed.

References

[1] Du, Wenliang. “Buffer Overflow Attack.” *Computer & Internet Security: A Hands-on Approach*, 2nd ed., Wenliang Du, 2019, pp. 63–98, http://www.bu.edu/honoringeve/files/2009/09/paranoid-reading-and-reparative-reading.pdf. PDF file.

[2] Aleph One. (n.d.). College of Engineering and Computer Science. http://cecs.wright.edu/people/faculty/tkprasad/courses/cs781/alephOne.html.

[3] *Common Weakness Enumeration*. CWE. (n.d.). https://cwe.mitre.org/data/definitions/1350.html.

[5] *Common Weakness Enumeration*. CWE. (n.d.). https://cwe.mitre.org/data/definitions/121.html.

[6] Orman, H. (n.d.). *The Morris Worm: A Fifteen-Year Perspective*. www.cs.umd.edu. https://www.cs.umd.edu/class/fall2019/cmsc818O/papers/morris-worm.pdf.

[7] Berghel, Hal. “The Code Red Worm.” *Doi-Org.Northernkentuckyuniversity.Idm.Oclc.Org*, Association for Computing Machinery, Dec. 2001, doi-org.northernkentuckyuniversity.idm.oclc.org/10.1145/501317.501328.

[8] “The MS-SQL Slammer Worm.” *ScienceDirect*, 1 Mar. 2003, linkinghub.elsevier.com/retrieve/pii/S1353485803003106.

[10] Kuperman, Benjamin A., et al. “Detection and Prevention of Stack Buffer Overflow Attacks.” *Communications of the ACM*, vol. 48, no. 11, Nov. 2005, pp. 51–56. *EBSCOhost*, search.ebscohost.com/login.aspx?direct=true&db=edb&AN=18740803&site=eds-live.

[11] Akcay, Fatma Kevser. “Android’s Performance Anxiety: An In-Depth Analysis of the Stagefright Bugs.” *Dash.Harvard.Edu*, 26 Mar. 2019, dash.harvard.edu/handle/1/38811442.

[12] SOLANKI, J., SHAH, A., & MANIK LAL DAS. (2014). Secure Patrol: Patrolling Against Buffer Overflow Exploits. *Information Security Journal (Print)*, *23*(1–3), 107–117.

[13] “Secure Code Review.” *The MITRE Corporation*, 10 Apr. 2015, www.mitre.org/publications/systems-engineering-guide/enterprise-engineering/systems-engineering-for-mission-assurance/secure-code-review.

[14] Baratloo, Arash, et al. “Transparent Run-Time Defense Against Stack Smashing Attacks.” *Web.Eecs.Umich.Edu*, web.eecs.umich.edu/~aprakash/security/handouts/baratloo00transparent.pdf.