BIZ & IT —

How security flaws work: The buffer overflow

Starting with the 1988 Morris Worm, this flaw has bitten everyone from Linux to Windows.

PETER BRIGHT - 8/26/2015, 3:00 AM

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The buffer overflow has long been a feature of the computer security landscape. In fact the first self-propagating Internet worm—1988's Morris Worm—used a buffer overflow in the Unix `finger` daemon to spread from machine to machine. Twenty-seven years later, buffer overflows remain a source of problems. Windows infamously revamped its security focus after two buffer overflow-driven exploits in the early 2000s. And just this May, a buffer overflow found in a Linux driver left (potentially) millions of home and small office routers vulnerable to attack.

At its core, the buffer overflow is an astonishingly simple bug that results from a common practice. Computer programs frequently operate on chunks of data that are read from a file, from the network, or even from the keyboard. Programs allocate finite-sized blocks of memory—buffers—to store this data as they work on it. A buffer overflow happens when more data is written to or read from a buffer than the buffer can hold.

On the face of it, this sounds like a pretty foolish error. After all, the program knows how big the buffer is, so it should be simple to make sure that the program never tries to cram more into the buffer than it knows will fit. You'd be right to think that. Yet buffer overflows continue to happen, and the results are frequently a security catastrophe.

To understand why buffer overflows happen—and why their impact is so grave—we need to understand a little about how programs use memory and a little more about how programmers write their code. (Note that we'll look primarily at the stack buffer overflow. It's not the only kind of overflow issue, but it's the classic, best-known kind.)

Stack it up

Buffer overflows create problems only for native code—that is, programs which use the processor's instruction set directly rather than through some intermediate form such as in Java or Python. The overflows are tied to the way the processor and native code programs manipulate memory. Different operating systems have their own quirks, but every platform in common use today follows essentially the same pattern. To understand how these attacks work and some of the things people do to try to stop them, we first have to understand a little about how that memory is used.

The most important central concept is the memory address. Every individual byte of memory has a corresponding numeric address. When the processor loads and stores data from main memory (RAM), it uses the memory address of the location it wants to read and write from. System memory isn't just used for data; it's also used for the executable code that makes up our software. This means that every function of a running program also has an address.

In the early days of computing, processors and operating systems used physical memory addresses: each memory address corresponded directly to a particular piece of RAM. While some pieces of modern operating systems still have to use these physical memory addresses, all of today's operating systems use a scheme called virtual memory.

With virtual memory, the direct correspondence between a memory address and a physical location in RAM is broken. Instead, software and the processor operate using virtual memory addresses. The operating system and processor together maintain a mapping between virtual memory addresses and physical memory addresses.

This virtualization enables a range of important features. The first and foremost is *protected memory*. Every individual process gets its *own* set of addresses. For a 32-bit process, those addresses start at zero (for the first byte) and run up to 4,294,967,295 (or in hexadecimal, `0xffff'ffff`; 2^{32} - 1). For a 64-bit process, they run all the way up to 18,446,744,073,709,551,615 (`0xffff'ffff'ffff'ffff`, 2^{64} - 1). So, every process has its own address `0`, its own address `1`, its own address `2`, and so on and so forth.

(For the remainder of this article, I'm going to stick to talking about 32-bit systems, except where otherwise noted. 32- and 64-bit systems work in essentially the same ways, so everything translates well enough; it's just a little clearer to stick to one bitness.)

Because each process gets its own set of addresses, these scheme in a very straightforward way to prevent one process from damaging the memory of any other: all the addresses that a process can use reference memory belonging only to that process. It's also much easier for the processes to deal with; physical memory addresses, while they broadly work in the same way (they're just numbers that start at zero), tend to have wrinkles that make them annoying to use. For example, they're usually not contiguous; address `0x1ff8'0000` is used for the processor's System Management Mode memory; a small chunk of physical memory that's off limits to normal software. Memory from PCIe cards also generally occupies some of this address space. Virtual addresses have none of these inconveniences.

So what does a process have in its address space? Broadly speaking, there are four common things, of which three interest us. The uninteresting one is, in most operating systems, "the operating system kernel." For performance reasons, the address space is normally split into two halves, with the bottom half being used by the program and the top half being the kernel's address space. The kernel-half of the memory is inaccessible to the program's half, but the kernel itself can read the program's memory. This is one of the ways that data is passed to kernel functions.

The first things that we need to care about are the executables and libraries that constitute the program. The main executable and all its libraries are all loaded into the process' address space, and all of their constituent functions accordingly have memory addresses.

The second is the memory that the program uses for storing the data it's working on, generally called the heap. This might be used, for example, to store the document currently being edited, the webpage (and all its JavaScript objects, CSS, and so on) being viewed, or the map for the game being played.

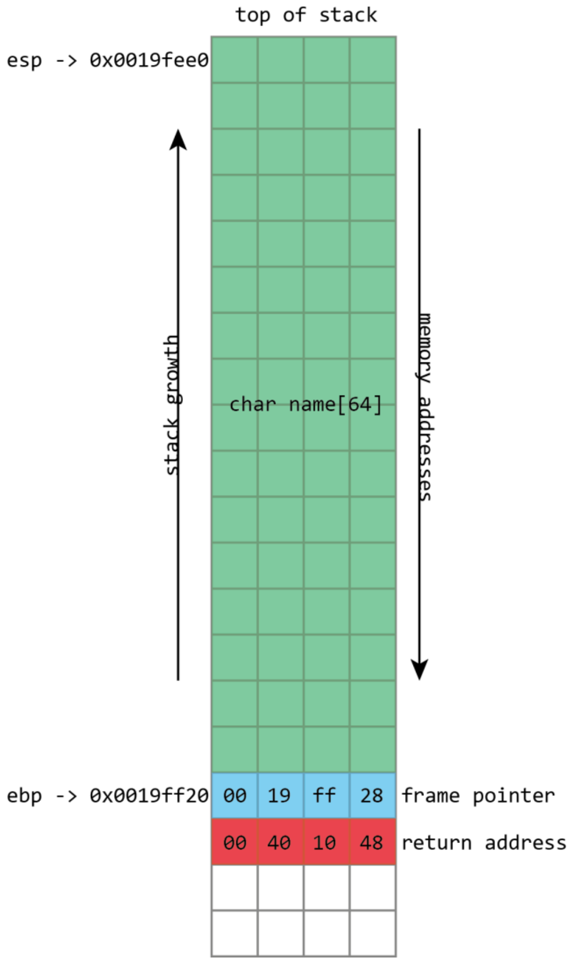
The third and most important is the call stack, generally just called the stack. This is the most complex aspect. Every thread in a process has its own stack. It's a chunk of memory that's used to keep track of both the function that a thread is currently running, as well as all the predecessor functions—the ones that were called to get to the current function. For example, if function `a` calls function `b`, and function `b` calls function `c`, then the stack will contain information about `a`, `b`, and `c`, in that order.

The call stack is a specialized version of the more general "stack" data structure. Stacks are variable-sized structures for storing objects. New objects can be added ("pushed") to one end of the stack (conventionally known as the "top" of the stack), and objects can be removed ("popped") from the stack. Only the top of the stack can be modified with a push or a pop, so the stack forces a kind of sequential ordering: the most recently pushed item is the one that gets popped first. The first item that gets pushed on the stack is the last one that gets popped.

The most important thing that the call stack does is to store *return addresses*. Most of the time, when a program calls a function, that function does whatever it is supposed to do (including calling other functions), and then returns to the function that called it. To go back to the calling function, there must be a record of what that calling function was: execution should resume from the instruction *after* the function call instruction. The address of this instruction is called the return address. The stack is used to maintain these return addresses: whenever a function is called, the return address is pushed onto the stack. Whenever a function returns, the return address is popped off the stack, and the processor begins executing the instruction at that address.

This stack functionality is so fundamentally important that most, if not all, processors include built-in support for these concepts. Consider x86 processors. Among the registers (small storage locations in the processor that can be directly accessed by processor instructions) that x86 defines, the two that are most important are `eip`, standing for "instruction pointer," and `esp`, standing for stack pointer.

`esp` always contains the address of the top of the stack. Each time something is pushed onto the stack, the value in `esp` is decreased. Each time something is popped from the stack, the value of `esp` is increased. This means that the stack grows "down;" as more things are pushed onto the stack, the address stored in `esp` gets lower and lower. In spite of this, the memory location referenced by `esp` is still called the "top" of the stack.



Enlarge / Here we see the basic layout of our stack with a 64 character buffer called `name`, then the frame pointer, and then the return address. `esp` has the address of the top of the stack, `ebp` has the address of the frame pointer.

`eip` gives the address of the currently executing instruction. The processor maintains `eip` itself. It reads the instruction stream from memory and increments `eip` accordingly so that it always has the instruction's address. x86 has an instruction for function calls, named `call`, and another one for returning from a function, named `ret`.

`call` takes one operand; the address of the function to call (though there are several different ways that this can be provided). When a `call` is executed, the stack pointer `esp` is decremented by 4 bytes (32-bits), and the address of the instruction following the `call`, the return address, is written to the memory location now referenced by `esp`—in other words, the return address is pushed onto the stack. `eip` is then set to the address specified as operand to `call`, and execution continues from that address.

`ret` does the opposite. The simple `ret` doesn't take any operands. The processor first reads the value from the memory address contained in `esp`, then increments `esp` by 4 bytes—it pops the return address from the stack. `eip` is set to this value, and execution continues from that address.

WATCH

1. How Buffer Overflows work: the stack

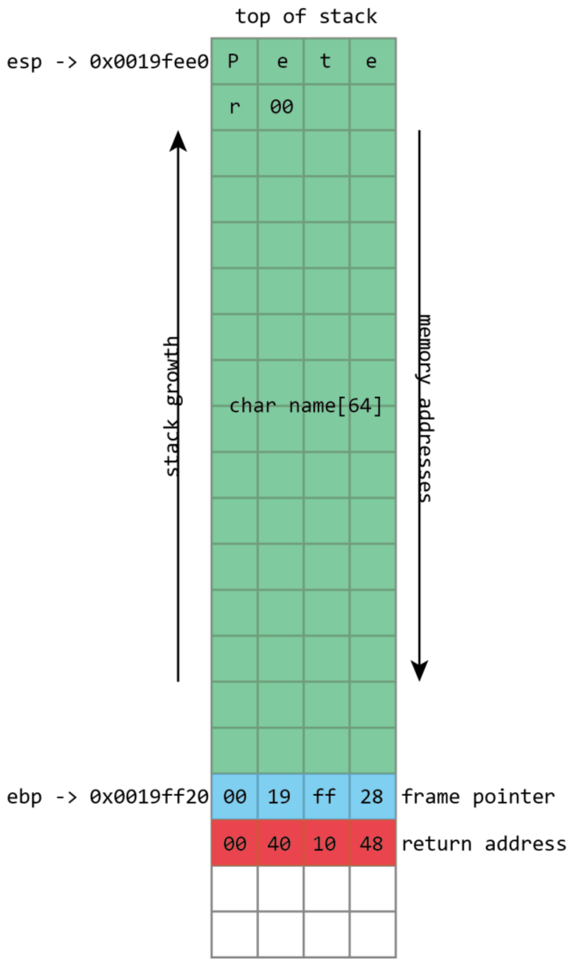
1. How Buffer Overflows Work: the stack

See `call` and `ret` in action.

If the call stack *only* contained a sequence of return addresses, there wouldn't be much scope for problems. The real problem comes with everything else that goes on the stack, too. The stack happens to be a quick and efficient place for storing data. Storing data on the heap is relatively complex; the program needs to keep track of how much space is available on the heap, how much space each piece of data is using, and various other bits of bookkeeping. But the stack is also simple; to make space for some data, just decrement the stack pointer. To tidy up when the data is no longer needed, increment the stack pointer.

This convenience makes the stack a logical place to store the variables that belong to a function. A function has a 256 byte buffer to read some user input? Easy, just subtract 256 from the stack pointer and you've created the buffer. At the end of the function, just add 256 back onto the stack pointer, and the buffer is discarded.

There are limitations to this. The stack isn't a good place to store very large objects; the total amount of memory available is usually fixed when a thread is created, and that's typically around 1MB in size. These large objects *must* be placed on the heap instead. The stack also isn't usable for objects that need to exist for longer than the span of a single function call. Because every stack allocation is undone when a function exits, any objects that exist on the stack can only live as long as a function is running. Objects on the heap, however, have no such restriction; they can hang around forever.



Enlarge / When we use the program correctly, the keyboard input is stored in the `name` buffer, followed by a null (zero) byte. The frame pointer and return address are unaltered.

This stack storage isn't just used for the named variables that programmers explicitly create in their programs; it can also be used for storing whatever other values the program may need to store. This is traditionally a particularly acute concern on x86. x86 processors don't have very many registers (there are only 8 integer registers in total, and some of those, like `eip` and `esp`, already have special purposes), and so functions can rarely keep all the values they need in registers. To free up space in a register while still ensuring that its current value can be retrieved later, the compiler will push the value of the register onto the stack. The value can then be popped later to put it back into a register. In compiler jargon, this process of saving registers so that they can be re-used is called *spilling*.

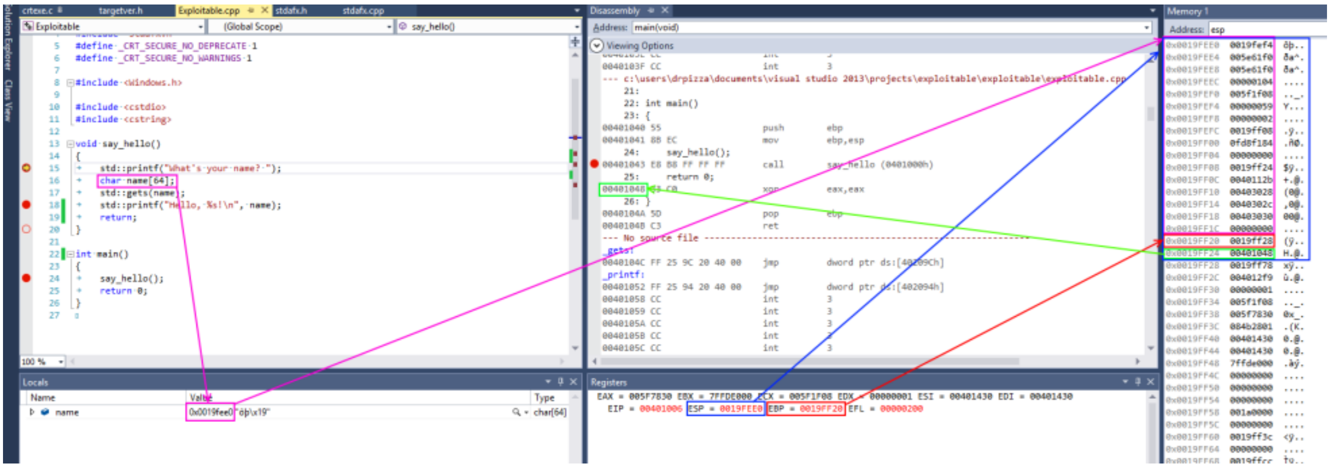
Finally, the stack is often used to pass arguments to functions. The calling function pushes each argument in turn onto the stack; the called function can then pop the arguments off. This isn't the only way of passing arguments—they can be passed in registers too, for example—but it's one of the most flexible.

the ... ively, it's useful to have a way of quickly referencing it.

The stack pointer *can* do this, but it's somewhat awkward: the stack pointer always points to the top of the stack, and so it moves around as things are pushed and popped. For example, a variable may start out with an address of at `esp + 4`. Two more values might be pushed onto the stack, meaning that the variable now has to be accessed at `esp + 12`. One of those values can then get popped off, so the variable is now at `esp + 8`.

This isn't an insurmountable difficulty, and compilers can easily handle the challenge. Still, it can make using the stack pointer to access anything other than "the top of the stack" awkward, especially for the hand-coded assembler.

To make things easier, it's common to maintain a second pointer, one that consistently stores the address of the *bottom* (start) of each stack frame—a value known as the *frame pointer*—and on x86, there's even a register that's generally used to store this value, `ebp`. Since this never changes within a given function, this provides a consistent way to access a function's variables: a value that's at `ebp - 4` will remain at `ebp - 4` for the whole of a function. This isn't just useful for humans; it also makes it easier for debuggers to figure out what's going on.



Enlarge / This screenshot from Visual Studio shows some of this in action for a simple x86 program. On x86 processors, the register named `esp` contains the address of the top stack, in this case `0x0019fee0`, highlighted in blue (on x86, the stack actually grows downwards, toward memory address `0`, but it's still called the top of the stack anyway). This function only has one stack variable, `name`, highlighted in pink. It's a fixed size 32-byte buffer. Because it's the only variable, its address is also `0x0019fee0`, the same as the top of the stack.

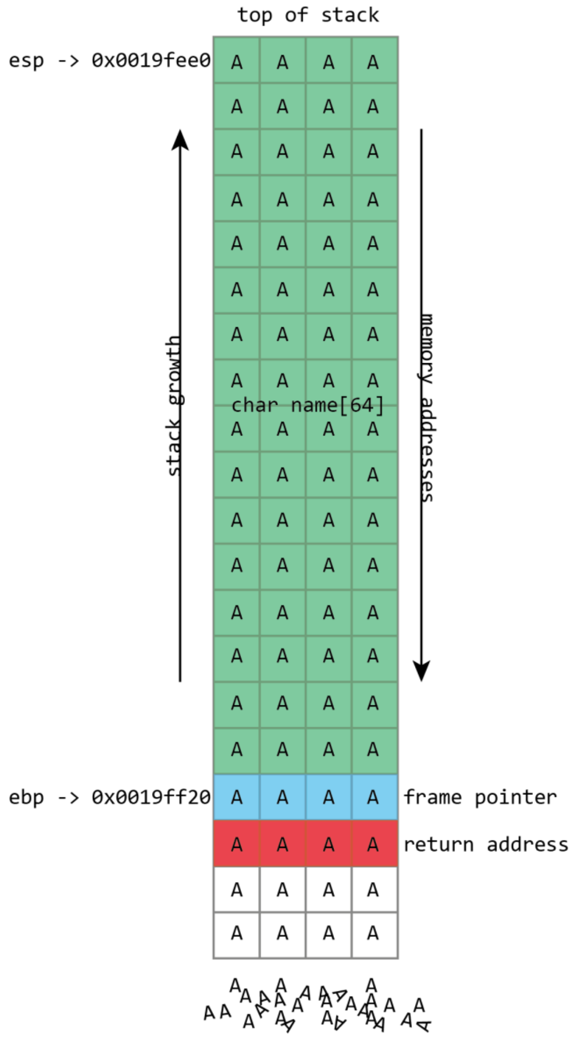
x86 also has a register called `ebp`, highlighted in red, that's (normally) dedicated to storing the location of the frame pointer. The frame pointer is placed immediately after the stack variables. Right after the frame pointer is the return address, highlighted in green. The return address references a code fragment with address `0x00401048`. This instruction comes immediately after a `call` instruction, making clear the way the return address is used to resume execution from where the calling function left off.

`name` in the above screenshot is the kind of buffer that's regularly overflowed. Its size is fixed at exactly 64 characters. In this case it's filled with a bunch of numbers, and it ends in a final null. As should be clear from the above picture, if more than 64 bytes are written into the `name` buffer, then other values on the stack will be damaged. If four extra bytes are written, the frame pointer will be destroyed. If *eight* extra bytes are written, both the frame pointer and the return address get overwritten.

Clearly this will lead to damaging the program's data, but the problem of buffer flows is more serious: they often lead to code execution. This happens because those overflowed buffers won't just overwrite data. They can also overwrite the other important thing kept on the stack—those return addresses. The return address controls which instructions the processor will execute when it's finished with the current function; it's meant to be some location within the calling function, but if it gets overwritten in a buffer overflow, it could point anywhere. If attackers can control the buffer overflow, they can control the return address; if they can control the return address, they can choose what code the processor executes next.

The process probably won't have some nice, convenient "compromise the machine" function for the attacker to run, but that doesn't really matter. The same buffer that was used to overwrite the return address can also be used to hold a short snippet of executable code, called shellcode, that will in turn download a malicious executable, or open up a network connection, or do whatever else the attacker fancies.

Traditionally, this was trivial to do because of a trait that may seem a little surprising: generally, each program would use the same memory addresses each time you ran it, even if you rebooted in between. This means that the location of the buffer on the stack would be the same each time, and so the value used to overwrite the return address could be the same each time. An attacker only had to figure out what the address was once, and the attack would work on *any* computer running the flawed code.



Enlarge /

Unfortunately gets() is a really stupid function. If we just hold down A on the keyboard it won't stop once it's filled the name buffer. It'll just keep on writing data to memory, overwriting the frame pointer, the return address, and anything and everything else it can.

JUMP TO END PAGE 1 OF 4

An attacker's toolkit

In an ideal world—for the attacker, that is—the overwritten return address can simply be the address of the buffer. When the program is reading input from a file or a network, this can often be the case for example.

Other times the attacker has to employ tricks. In functions that process human-readable text, the zero byte (or "null") is often treated specially; it indicates the end of a string, and the functions used for manipulating strings—copying them, comparing them, combining them—will stop whenever they hit the null character. This means that if the shellcode contains the null character, those routines are liable to break it.

WATCH

2. How Buffer Overflows work: overwriting the return address

See a buffer overflow in action. In this video, we put shellcode into the buffer and then overwrite the return address to execute it. Our shellcode runs the Windows calculator.

To handle this, attackers can use various techniques. Pieces of code can convert shellcode that contains null characters into equivalent sequences that avoid the problem byte. They can even handle quite strict restrictions; for example, an exploitable function may only accept input that can be typed on a standard keyboard.

The address of the stack itself often contains a null byte, which is similarly problematic: it means that the return address cannot be directly set to the address of the stack buffer. Sometimes this isn't a big issue, because some of the functions that are used to fill (and, potentially, overflow) buffers will write a null byte themselves. With some care, they can be used to put the null byte in just the right place to set the return address to that of the stack.

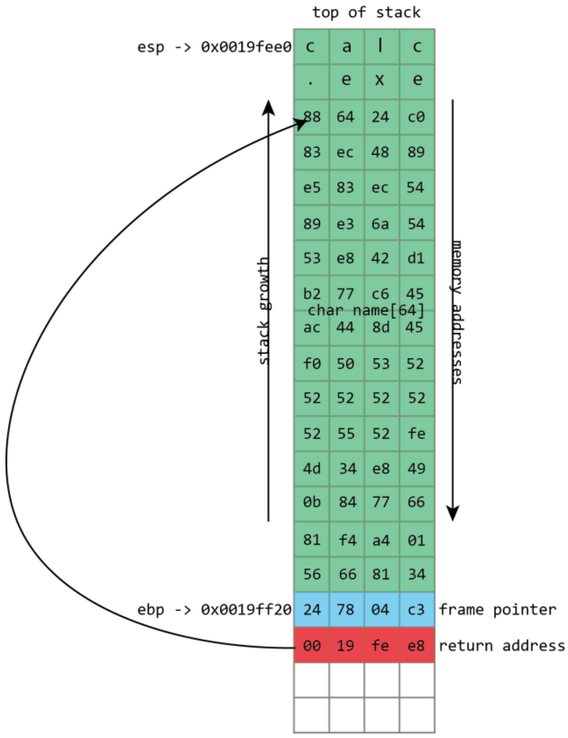
Even when that isn't possible, this situation can be handled with indirection. The program and all its libraries mean that memory is littered with executable code. Much of this executable code will have an address that's "safe," which is to say has no null bytes.

What the attacker has to do is find a usable address that contains an instruction such as x86's `call esp`, which treats the value of the stack pointer as the address of a function and begins executing it—a perfect match for a stack buffer that contains the shellcode. The attacker then uses the address of the `call esp` instruction to overwrite the return address; the processor will take an extra hop through this address but still end up running the shellcode. This technique of bouncing through another address is called "trampolining."

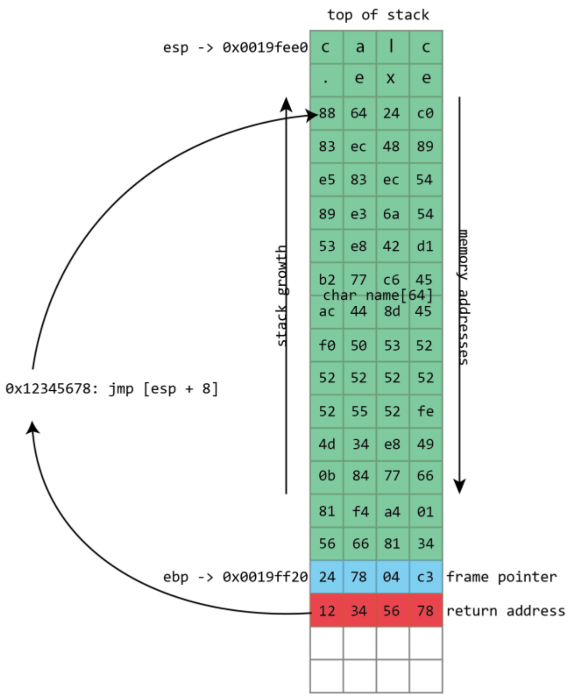
This works because, again, the program and all its libraries occupy the same memory addresses every time they run—even across reboots and even across different machines. One of the interesting things about this is that the library that provides the trampoline does not need to ever perform a `call esp` itself. It just needs to offer the two bytes (in this case `0xff` and `0xd4`) adjacent to each other. They could be part of some other instruction or even a literal number; x86 isn't very picky about this kind of thing. x86 instructions can be very long (up to 15 bytes!) and can be located at any address. If the processor starts reading an instruction from the middle—from the second byte of a four byte instruction, say—the result can often be interpreted as a completely different, but still valid, instruction. This can make it quite easy to find useful trampolines.

Sometimes, however, the attack can't set the return address to *exactly* where it needs to go. Although the memory layout is very similar, it might vary slightly from machine to machine or run to run. For example, the precise location of an exploitable buffer might vary back and forth by a few bytes depending on the system's name or IP address, or because a minor update to the software has made a very small change. To handle this, it's useful to be able to specify a return address that's *roughly* correct but doesn't have to be *exactly* correct.

This can be handled easily through a technique called the "NOP sled." Instead of writing the shellcode directly into the buffer, the attacker writes a large number of



Enlarge / **To exploit the overflow, instead of just writing As and smashing everything, the attacker fills the buffer with shellcode: a short piece of executable code that will perform some action of the attacker's choosing. The return address is then overwritten with an address referring to the buffer, directing the processor to execute the shellcode when it tries to return from a function call.**



Enlarge / **Sometimes it can be difficult to overwrite the return address with the address of the buffer. To handle this, we can overwrite the return address with the address of a piece of executable code found within the victim**

"NOP" instructions (meaning "no-op"; they're instructions that don't actually do anything), sometimes hundreds of them, before the real shellcode. To run the shellcode, the attacker only needs to set the return address to *somewhere* among these NOP instructions. As long as they land within the NOPs, the processor will quickly run through them until it reaches the real shellcode.

program (or its libraries). This fragment of code will transfer execution to the buffer for us.

Blame C

The core bug that enables these attacks, writing more to a buffer than the buffer has space for, sounds like something that should be simple to avoid. It's an exaggeration (but only a slight one) to lay the blame entirely on the C programming language and its more or less compatible offshoots, namely C++ and Objective-C. The C language is old, widely used, and essential to our operating systems and software. It's also appallingly designed, and while all these bugs are avoidable, C does its damnedest to trip up the unwary.

As an example of C's utter hostility to safe development, consider the function `gets()`. The `gets()` function takes one parameter—a buffer—and reads a line of data from standard input (which normally means "the keyboard"), then puts it into the buffer. The observant may have noticed that `gets()` doesn't include a parameter for the buffer's size, and as an amusing quirk of C's design, there's no way for `gets()` to figure out the buffer's size for itself. And that's because `gets()` just doesn't care: it will read from standard input until the person at the keyboard presses return, then try to cram everything into the buffer, even if the person typed far more than the buffer could ever contain.

This is a function that literally cannot be used safely. Since there's no way of constraining the amount of text typed at the keyboard, there's no way of preventing `gets()` from overflowing the buffer it is passed. The creators of the C standard did soon realize the problem; the 1999 revision to the C specification deprecated `gets()`, while the 2011 update removed it entirely. But its existence—and occasional usage—is a nice indication of the kind of traps that C will spring on its users.

The Morris worm, the first self-replicating malware that spread across the early Internet in a couple of days in 1988, exploited this function. The BSD 4.3 `fingerd` program listened for network connections on port 79, the `finger` port. `finger` is an ancient Unix program and corresponding network protocol used to see who's logged in to a remote system. It can be used in two ways; a remote system can be queried to see everyone currently logged in. Alternatively, it can be queried about a specific username, and it will tell you some information about that user.

Whenever a connection was made to the `finger` daemon, it would read from the network—using `gets()`–into a 512 byte buffer on the stack. In normal operation, `fingerd` would then spawn the `finger` program, passing it the username if there was one. The `finger` program was the one that did the real work of listing users or providing information about any specific user. `fingerd` was simply responsible for listening to the network and starting `finger` appropriately.

Given that the only "real" parameter is a possible username, 512 bytes is plainly a huge buffer. Nobody is likely to have a username anything like that long. But no part of the system actually enforced that constraint because of the use of the awful `gets()` function. Send more than 512 bytes over the network and `fingerd` would overflow its buffer. So this is exactly what Robert Morris did: his exploit sent 537 bytes to `fingerd` (536 bytes of data plus a new-line character, which made `gets()`

stop reading input), overflowing the buffer and overwriting the return address. The return address was set simply to the address of the buffer on the stack.

The Morris worm's executable payload was simple. It started with 400 NOP instructions, just in case the stack layout was slightly different, followed by a short piece of code. This code spawned the shell, `/bin/sh`. This is a common choice of attack payload; the `fingerd` program ran as root, so when it was attacked to run a shell, that shell also ran as root. `fingerd` was plumbed into the network, taking its "keyboard input" from the network and likewise sending its output back over the network. Both of these features are inherited by the shell executed by the exploit, meaning that the root shell was now usable remotely by the attacker.

While `gets()` is easy to avoid—in fact, even at the time of the Morris worm, a fixed version of `fingerd` that didn't use `gets()` was available—other parts of C are harder to ignore and no less prone to screw ups. C's handling of text strings is a common cause of problems. The behavior mentioned previously—stopping at null bytes—comes from C's string behavior. In C, a string is a sequence of characters, followed by a null byte to terminate the string. C has a range of functions for manipulating these strings. Perhaps the best pair are `strcpy()`, which copies a string from a source to a destination, and `strcat()`, which appends a source string to a destination. Neither of these functions has a parameter for the size of the destination buffer. Both will merrily read from their source forever until they reach a null character, filling up the destination and overflowing it without a care in the world.

Even when C's string handling functions *do* take a parameter for the buffer size, they can do so in a way that leads to errors and overflows. C offers a pair of siblings to `strcat()` and `strcpy()` called `strncat()` and `strncpy()`. The extra `n` in their names denotes that they take a size parameter, of sorts. But `n` is not, as many naive C programmers believe, the size of the buffer being written to; it is the number of characters from the source to copy. If the source runs out of characters (because a null byte is reached) then `strncpy()` and `strncat()` will make up the difference by copying more null bytes to the destination. At no point do the functions ever care about the actual size of the destination.

Unlike `gets(),` it is possible to use these functions safely; it's just difficult. C++ and Objective-C both include superior alternatives to C's functions, making string manipulation much simpler and safer, but they retain the old C capabilities for reasons of backwards compatibility.

Moreover, they retain C's fundamental weakness: buffers do not know their own size, and the language never validates the reads and writes performed on buffers, allowing them to overflow. This same behavior also led to the recent Heartbleed bug in OpenSSL. That wasn't an overflow; it was an over*read*; the C code in OpenSSL tried to read more from a buffer than the buffer contained, leaking sensitive information to the world.

JUMP TO END PAGE 2 OF 4

Fixing the leaks

Needless to say, it is not beyond the wit of mankind to develop languages in which reads from and writes to buffers are validated and so can never overflow. Compiled languages such as the Mozilla-backed Rust, safe runtime environments such as Java and .NET, and virtually every scripting language like Python, JavaScript, Lua, Python, and Perl are immune to this problem (although .NET does allow developers to explicitly turn off all the safeguards and open themselves up to this kind of bug once more should they so choose).

That the buffer overflow continues to be a feature of the security landscape is a testament to C's enduring appeal. This is in no small part due to the significant issue of legacy code. An awful lot of C code still exists, including the kernel of every major operating system and popular libraries such as OpenSSL. Even if developers want to use a safe language such as C#, they may need to depend on a third-party library written in C.

Performance arguments are another reason for C's continued use, though the wisdom of this approach was always a little unclear. It's true that compiled C and C++ tend to produce fast executables, and in some situations that matters a great deal. But many of us have processors that spend the vast majority of their time idling; if we could sacrifice, say, ten percent of the performance of our browsers in order to get a cast iron guarantee that buffer overflows—in addition to many other common flaws—were impossible, we might decide that would be a fair trade-off, if only someone were willing to create such a browser.

Nonetheless, C and its friends are here to stay; as such, so are buffer overflows.

Some effort is made to stop the overflow errors before they bite anyone. During development there are tools that can analyze source code and running programs to try to detect dangerous constructs or overflow errors before those bugs ever make their way into shipping software. New tools such as AddressSantizer and older ones such as Valgrind both offer this kind of capability.

However, these tools both require the active involvement of the developer, meaning not all programs use them. Systemic protections that strive to make buffer overflows less dangerous when they do occur can protect a much greater variety of software. In recognition of this, operating system and compiler developers have implemented a number of systems to make exploiting these overflows harder.

Some of these systems are intended to make specific attacker tasks harder. One set of Linux patches made sure that system libraries were all loaded at low addresses to ensure that they contained at least one null byte in their address; this makes it harder to use their addresses in any overflow that uses C string handling.

Other defenses are more general. Many compilers today have some kind of stack protection. A runtime-determined value known as a "canary" is written onto the end of the stack near where the return address is stored. At the end of every function, that value is checked for modification before the return instruction is issued. If the canary value has changed (because it has been overwritten in a buffer overflow) then the program will immediately crash rather than continue.

Perhaps the most important single protection is one variously known as W^X ("write exclusive-or execute"), DEP ("data execution prevention"), NX ("No Xecute"), XD ("eXecute Disable"), EVP ("Enhanced Virus Protection," a rather peculiar term sometimes used by AMD), XN ("eXecute Never"), and probably more. The principle here is simple. These systems strive to make memory either *writeable* (suitable for buffers) or *executable* (suitable for libraries and program code) but not *both*. Thus, even if an attacker can overflow a buffer and control the return address, the processor will ultimately refuse to execute the shellcode.

Whichever name you use, this is an important technique not least because it comes at essentially no cost. This approach leverages protective measures built into the processor itself as part of the hardware support for virtual memory.

As described before, with virtual memory every process gets its own set of private memory addresses. The operating system and processor together maintain a mapping from virtual addresses to *something else*; sometimes a virtual address corresponds to a physical memory address, sometimes it corresponds to a portion of a file on disk, and sometimes it corresponds to nothing at all because it has not been allocated. This mapping is granular, typically using 4,096 byte chunks called *pages*.

The data structures used to store the mapping don't just include the location (physical memory, disk, nowhere) of each page; they also contain (usually) three bits defining the page's protection: whether the page is readable, whether it is writeable, and whether it is executable. With this protection, areas of the process' memory that are used for data, such as the stack, can be marked as readable and writeable but not executable. Conversely, areas such as the program's executable code and libraries can be marked as readable and executable but not writeable.

One of the great things about NX is that it can be applied to existing programs retroactively just by updating the operating system to one that supports it. Occasionally programs do run into problems. Just-in-time compilers, used for things like Java and .NET, generate executable code in memory at runtime, and as such need memory that is both writeable and executable (though strictly, they don't need it to be both things simultaneously). In the days before NX, any memory that was readable was also executable, so these JIT compilers never had to do anything special to their read-writeable buffers. With NX, they need to make sure to change the memory protection from read-write to read-execute.

The need for something like NX was clear, especially for Microsoft. In the early 2000s, a pair of worms showed that the company had some serious code security problems: Code Red, which infected as many as 359,000 Windows 2000 systems running Microsoft's IIS Web server in July 2001, and SQL Slammer, which infected more than 75,000 systems running Microsoft's SQL Server database in January 2003. These were high-profile embarrassments.

Both of them exploited stack buffer overflows, and strikingly, though they came 13 and 15 years after the Morris worm, the method of exploitation was virtually identical. An exploit payload was placed into the buffer on the stack and the return address overwritten to execute it. (The only slight nuance was that both of these used the trampoline technique. Instead of setting the return address directly to the address of the stack, they set the return address to an instruction that in turn passes execution to the stack.)

Naturally, these worms were also advanced in other ways. Code Red's payload didn't just self-replicate; it also defaced webpages and attempted to perform denial of service attacks. SQL Slammer packed everything it needed to find new machines to exploit and spread through a network in just a few hundred bytes, and it left no footprint on machines it infected; reboot and it was gone. Both worms also worked on an Internet that was enormously larger than the one the Morris worm worked with, and hence they infected many more machines.

But the central issue, that of a straightforwardly exploitable stack buffer overflow, was an old one. These worms were both major news and made many people question the use of Windows in any kind of an Internet-facing, server capacity. Microsoft's response was to start taking security seriously. Windows XP Service Pack 2 was the first real product with this mindset. It utilized a number of software changes, including a software firewall, changes to Internet Explorer to prevent silent installation of toolbars, plugins—and NX support.

Hardware supporting NX has been mainstream since 2004, when Intel introduced the Prescott Pentium 4, and operating system support for NX has been widespread since Windows XP Service Pack 2. Windows 8 forced the issue even more by cutting off support for older processors that didn't have NX hardware.

Beyond NX

In spite of the spread of NX support, buffer overflows remain a security issue to this day. That's because a number of techniques were devised to bypass NX.

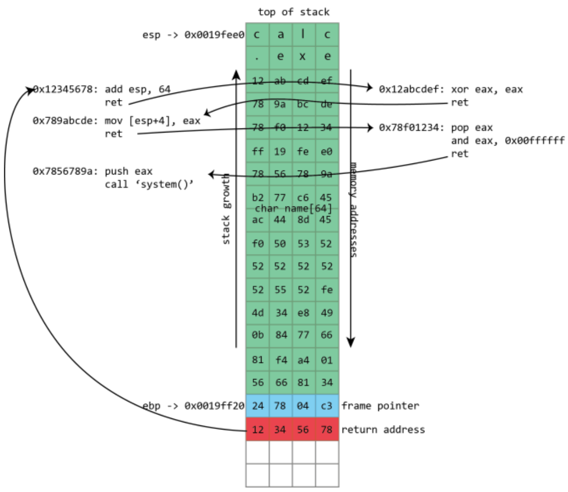
The first of these was similar to the trampolining trick already described to pass control to the shellcode in a stack buffer via an instruction found in another library or executable. Instead of looking for a fragment of executable code that will pass execution directly back to the stack, the attacker looks for a fragment that does something useful in its own right.

Perhaps the best candidate for this is the Unix `system()` function. `system()` takes one parameter: the address of a string representing a command line to be executed, and traditionally that parameter is passed on the stack. The attacker can create a command-line string and put it in the buffer to be overflowed, and because (traditionally) things didn't move around in memory, the address of that string would be known and could be put on the stack as part of the attack. The overwritten return address in this situation isn't set to the address of the buffer; it's set to the address of the `system()` function. When the function with the buffer overflow finishes, instead of returning to its caller, it runs the `system()` function to execute a command of the attacker's choosing.

This neatly bypasses NX. The `system()` function, being part of a system library, is already executable. The exploit doesn't have to execute code from the stack; it just has to *read* the command line from the stack. This technique is called "return-to-libc" and was invented in 1997 by Russian computer security expert Solar Designer. (libc is the name of the Unix library that implements many key functions, including `system()`, and is typically found loaded into every single Unix process, so it makes a good target for this kind of thing.)

While useful, this technique can be somewhat limited. Often functions don't take their arguments from the stack; they expect them to be passed in registers. Passing in command-line strings to execute is nice, but it often involves those annoying nulls, which can foul everything up. Moreover, it makes chaining multiple function calls very difficult. It can be done—provide multiple return addresses instead of one—but there's no provision for changing the order of arguments, using return values, or anything else.

Over the years, return-to-libc was generalized to alleviate these restrictions. In late 2001, a number of ways to extend return-to-libc to make multiple function calls was documented, along with solutions for the null byte problem. These techniques were nonetheless limited. A more complicated technique formally described in 2007 for the most part lifted all these restrictions: return-oriented-programming (ROP).



Enlarge /

Instead of filling the buffer with shellcode, we fill it with a sequence of return addresses and data. These return addresses pass control to existing fragments of executable code within the victim program and its libraries. Each fragment of code performs an operation and then returns, passing control to the next return address.

This used the same principle as from return-to-libc and trampolining but generalized further still. Where trampolining uses a single fragment of code to pass execution to shellcode in a buffer, ROP uses *lots* of fragments of code, called "gadgets" in the original ROP paper. Each gadget follows a particular pattern: it performs some operation (putting a value in a register, writing to memory, adding two registers, etc.) followed by a return instruction. The same property that makes x86 good for trampolining works here too; the system libraries loaded into a process contain *many hundreds* of sequences that can be interpreted as "perform an action, then return" and hence can be used in ROP-based attacks.

The gadgets are all chained together by a long sequence of return addresses (and any useful or necessary data) written to the stack as part of the buffer overflow. The return instructions leap from gadget to gadget with the processor rarely or never *calling* functions, only ever *returning* from them. Remarkably, it was discovered that, at least on x86, the number and variety of useful gadgets is such that an attacker can generally do *anything*; this weird subset of x86, used in a peculiar way, is often Turing complete (though the exact range of capabilities will depend on which libraries a given program has loaded and hence which gadgets are available).

As with return-to-libc, all the actual *executable code* is taken from system libraries, and so NX protection is useless. The greater flexibility of the approach means that exploits can do the things that are difficult even with chained return-to-libc, such as calling functions that take arguments in registers, using return values from one function as an argument for another, and much more besides.

The ROP payloads vary. Sometimes they're simple "create a shell"-style code. Another common option is to use ROP to call a system function to change the NX state of a page of memory, flipping it from being writable to being executable. Doing this, an attacker can use a conventional, non-ROP payload, using ROP only to make the non-ROP payload executable.

JUMP TO END PAGE 3 OF 4

Getting random

This weakness of NX has long been recognized, and a recurring theme runs throughout all these exploits: the attacker knows the memory addresses of the stack and system libraries ahead of time. Everything is contingent on this knowledge, so an obvious thing to try is removing that knowledge. This is what Address Space Layout Randomization (ASLR) does: it randomizes the position of the stack and the in-memory location of libraries and executables. Typically these will change either every time a program is run, every time a system is booted, or some combination of the two.

This greatly increases the difficulty of exploitation, because all of a sudden, the attacker doesn't know where the ROP instruction fragments will be in memory, or even where the overflowed stack buffer will be.

ASLR in many ways goes hand in hand with NX, because it shores up the big return-to-libc and return-oriented-programming gaps that NX leaves. Unfortunately, it's a bit more intrusive than NX. Except for JIT compilers and a few other unusual things, NX could be safely added to existing programs. ASLR is more problematic; programs and libraries need to ensure that they do not make any assumptions about the address they're loaded at.

On Windows, for example, this shouldn't be a huge issue for DLLs. DLLs on Windows have always supported being loaded at different addresses, but it could be an issue for EXEs. Before ASLR, EXEs would always be loaded at an address of `0x0040000` and could safely make assumptions on that basis. After ASLR, that's no longer the case. To make sure that there won't be any problems, Windows by default requires executables to indicate that they specifically support ASLR and opt in to enabling it. The security conscious can, however, force Windows to enable it for all executables and libraries even if programs don't indicate that they support it. This is almost always fine.

The situation is perhaps worse on x86 Linux, as the approach used for ASLR on that platform exacts a performance cost that may be as high as 26 percent. Moreover, this approach absolutely *requires* executables and libraries to be compiled with ASLR support. There's no way for an administrator to mandate the use of ASLR as there is in Windows. (x64 does not quite eliminate the performance cost of the Linux approach, but it does greatly alleviate it.)

When ASLR is enabled, it provides a great deal of protection against easy exploitation. ASLR still isn't perfect, however. For example, one restriction is the amount of randomness it can provide. This is especially acute on 32-bit systems. Although the memory space has more than 4 billion different addresses, not all of those addresses are available for loading libraries or placing the stack.

Instead, it's subject to various constraints. Some of these are broad goals. Generally, the operating system likes to keep libraries loaded fairly close together at one end of the process' address space, so that as much contiguous empty space is available to the application as possible. You wouldn't want to have one library loaded every 256MB throughout the memory space, because the biggest single allocation you'd be able to make would be a little less than 256MB, which limits the ability of applications to work on big datasets.

Executables and libraries generally have to be loaded so that they start on, at the very least, a page boundary. Normally, this means they must be loaded at an address that's a multiple of 4,096. Platforms can have similar conventions for the stack; Linux, for example, starts the stack on a multiple of 16 bytes. Systems under memory stress sometimes have to further reduce the randomness in order to fit everything in.

The impact of this varies, but it means that attackers can sometimes guess what an address will be and have a reasonable probability of guessing right. Even a fairly low chance—one in 256, say—can be enough in some situations. When attacking a Web server that will automatically restart crashed processes, it may not matter that 255 out of 256 attacks crash the server. It will simply be restarted, and the attacker can try again.

But on 64-bit systems, there's so much address space that this kind of guessing approach is untenable. The attacker could be stuck with a one in a million or one in a billion chance of getting it right, and that's a small enough chance as to not matter.

Guessing and crashing isn't much good for attacks on, say, browsers; no user is going to restart a browser 256 times in a row just so that an attacker can strike it lucky. As a result, exploiting this kind of flaw on a system with both NX and ASLR can't be done without help.

This help can come in many forms. One route in browsers is to use JavaScript or Flash—both of which contain JIT compilers that generate executable code—to fill large portions of memory with carefully constructed executable code. This produces a kind of large-scale NOP sled in a technique known as "heap spraying." Another approach is to find a secondary bug that inadvertently reveals memory addresses of libraries or of the stack, giving the attacker enough information to construct a custom set of ROP return addresses.

A third approach was again common in browsers: take advantage of libraries that don't use ASLR. Old versions of, for example, Adobe's PDF plugin or Microsoft's Office browser plugins didn't enable ASLR, and Windows by default doesn't force ASLR on non-ASLR code. If attackers could force such a library to load (by, for example, loading a PDF into a hidden browser frame) then they no longer needed to be too concerned about ASLR; they could just use that non-ASLR library for their ROP payload.

A never-ending war

The world of exploitation and mitigation techniques is one of cat and mouse. Powerful protective systems such as ASLR and NX raise the bar for taking advantage of flaws and together have put the days of the simple stack buffer overflow behind us, but smart attackers can still combine multiple flaws to defeat these protections.

The escalation continues. Microsoft's EMET ("Enhanced Mitigation Experience Toolkit") includes a range of semi-experimental protections that try to detect heap spraying or attempts to call certain critical functions in ROP-based exploits. But in the continuing digital arms war, even these have security techniques that have been defeated. This doesn't make them useless—the difficulty (and hence cost) of exploiting flaws goes up with each new mitigation technique—but it's a reminder of the need for constant vigilance.

Thanks to Melissa Elliott for her invaluable feedback.

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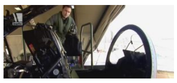

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