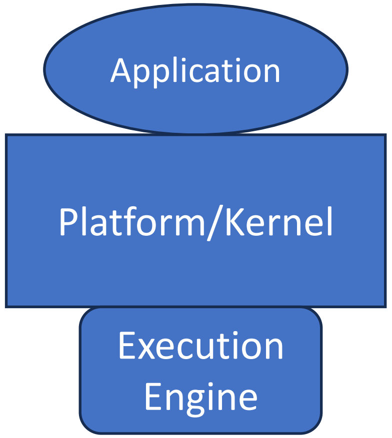
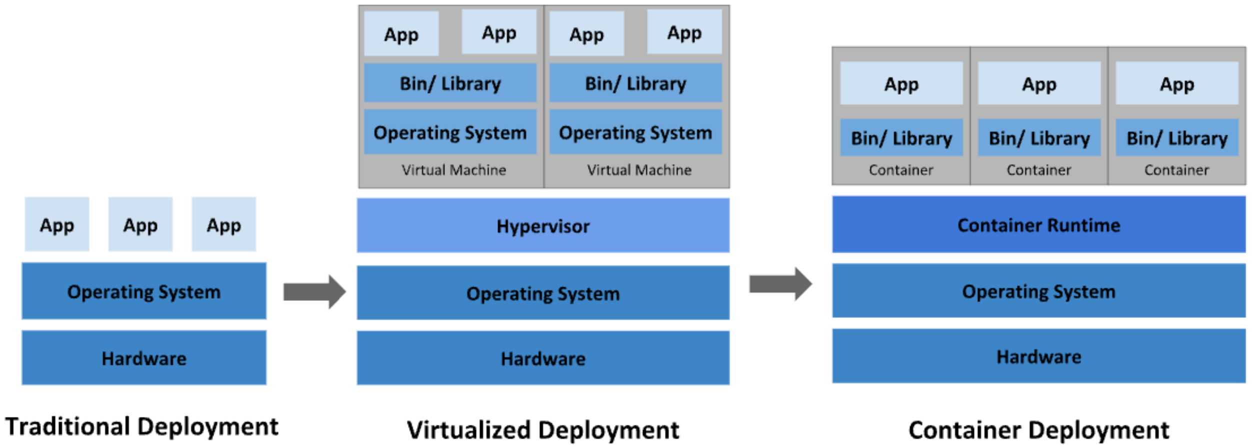
CS5231: Systems Security

Module 1: Memory Safety Vulnerabilities
(Part 1) Basis

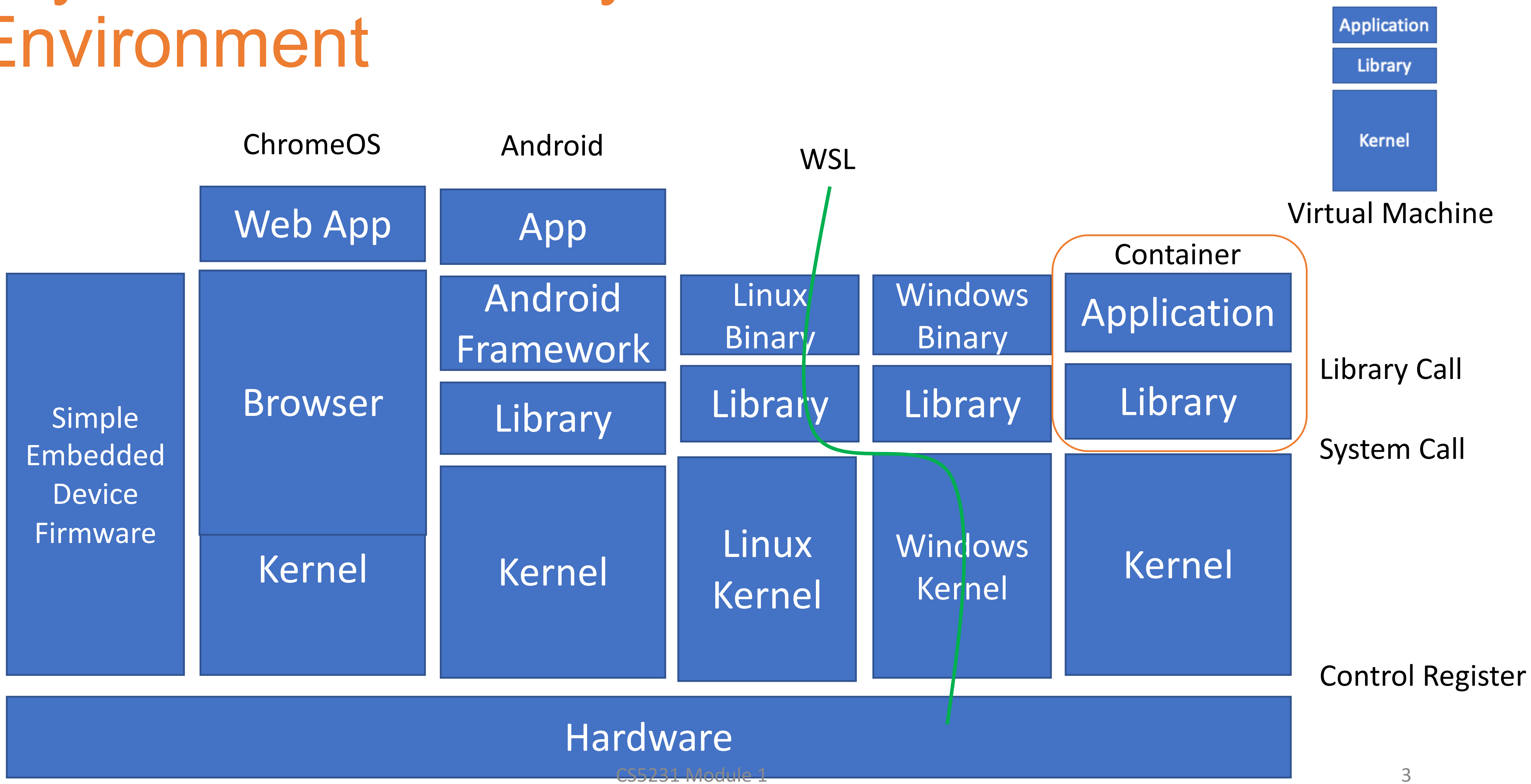
What is a System?

- A ***platform*** supporting program ***execution***.
  - Embedded system
  - DOS, Windows/Linux/MacOS
  - Mobile OS (Android, iOS, Blackberry)
  - Browser
  - Virtual Machine
  - Container
  - Cloud
  - …

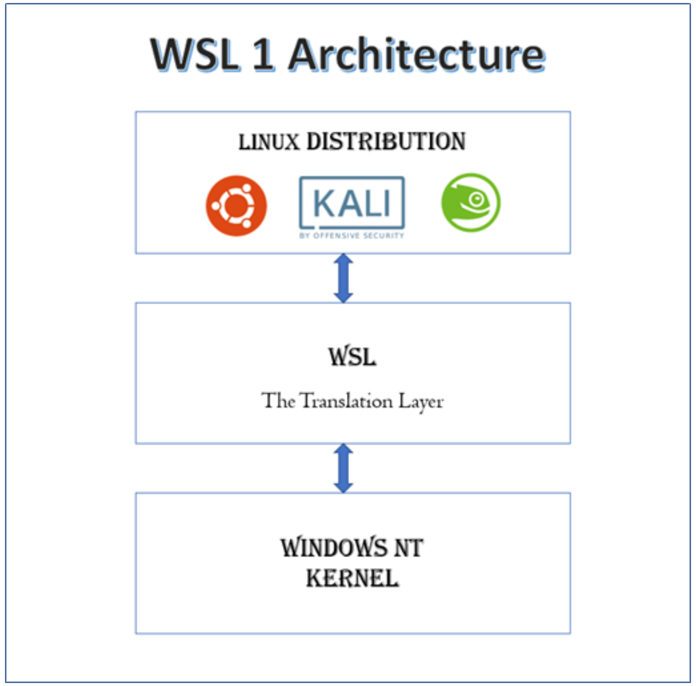


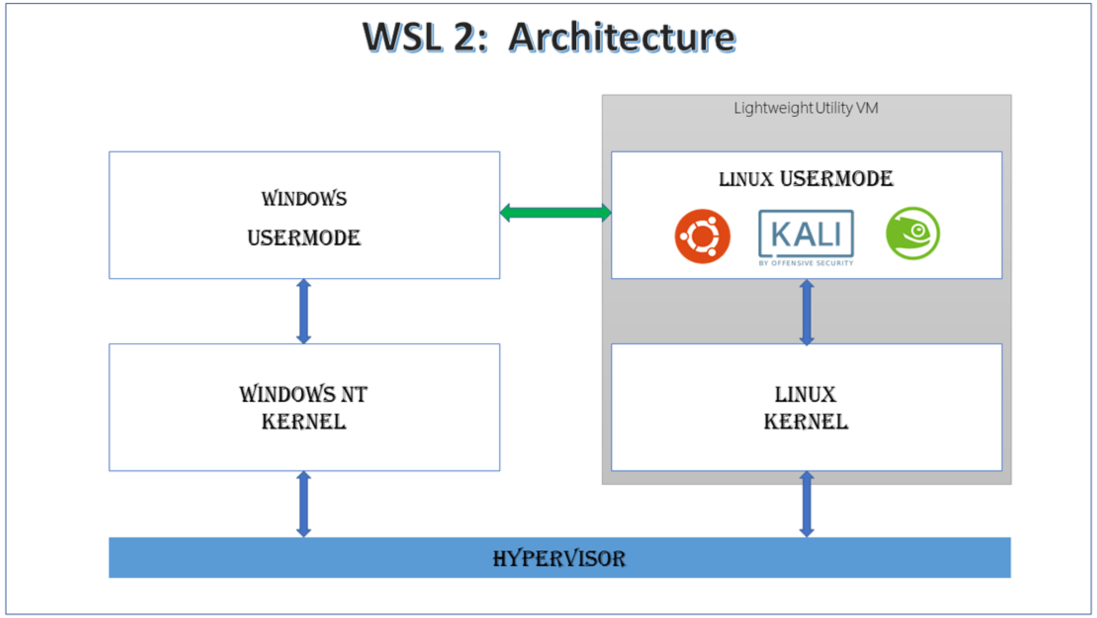


Layers and Flexibility of Execution Environment



Windows Subsystem for Linux (WSL)





Discussion

- How to run a Linux GUI program on WSL?
  - Kernel
  - System call
  - Library
  - X Window server

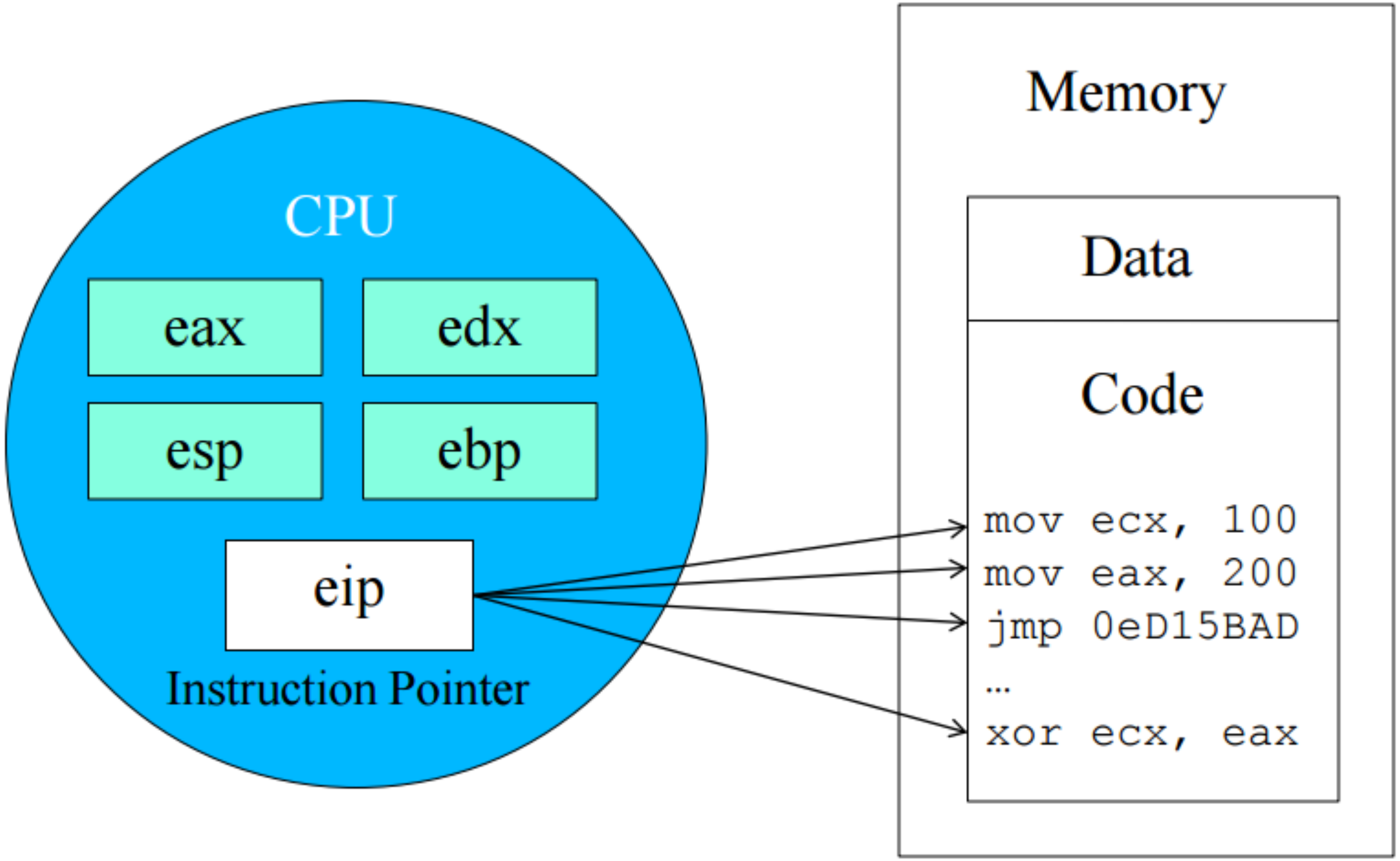
Semester Plan

- Module 1: Memory error and defense
- Module 2: System auditing and provenance
- Module 3: Kernel security

- Midterm: Week 8 (October 11)
- Quiz: take-home online quiz

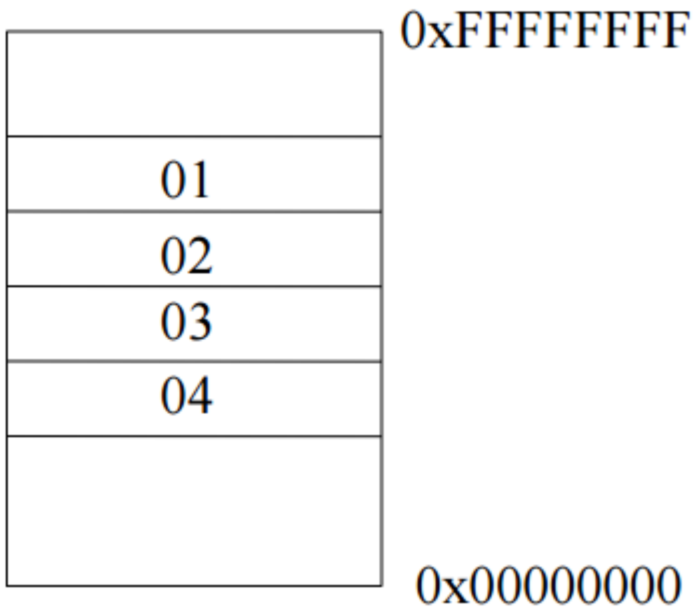
Execution on CPU

Basics: The x86 Machine Model



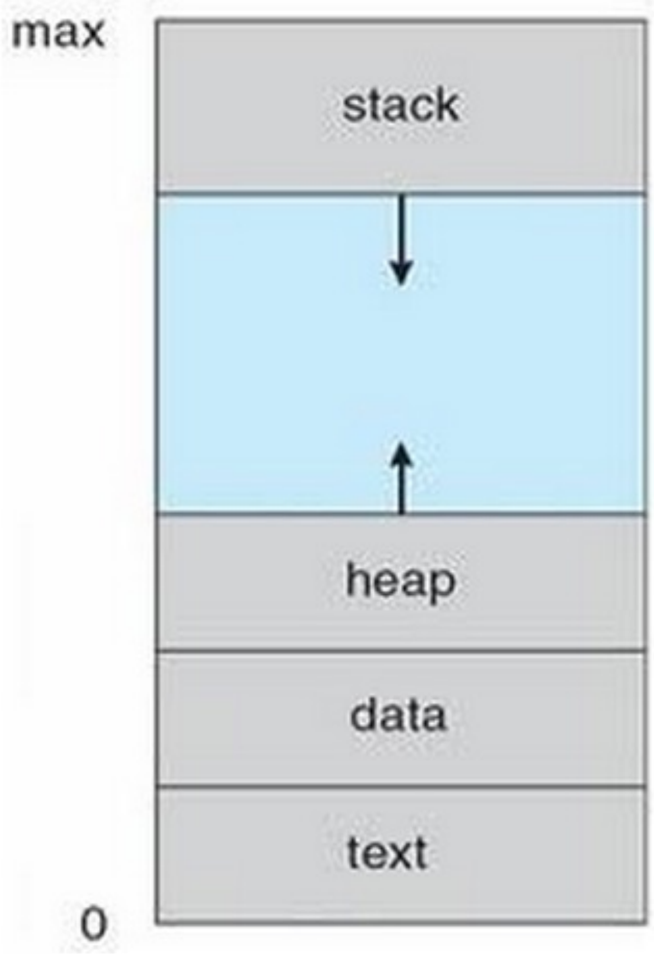
Basics: The x86 Machine Model

- Both code and data are represented as numbers
- Code
  - `lea ecx, [esp+4]` represented as `0x8d 0x4c 0x24 0x04`
- Data
  - On Intel CPUs, least significant bytes is put at lower addresses
  - It is called little endian
  - For example, `0x01020304`



Basics: The x86 Machine Model

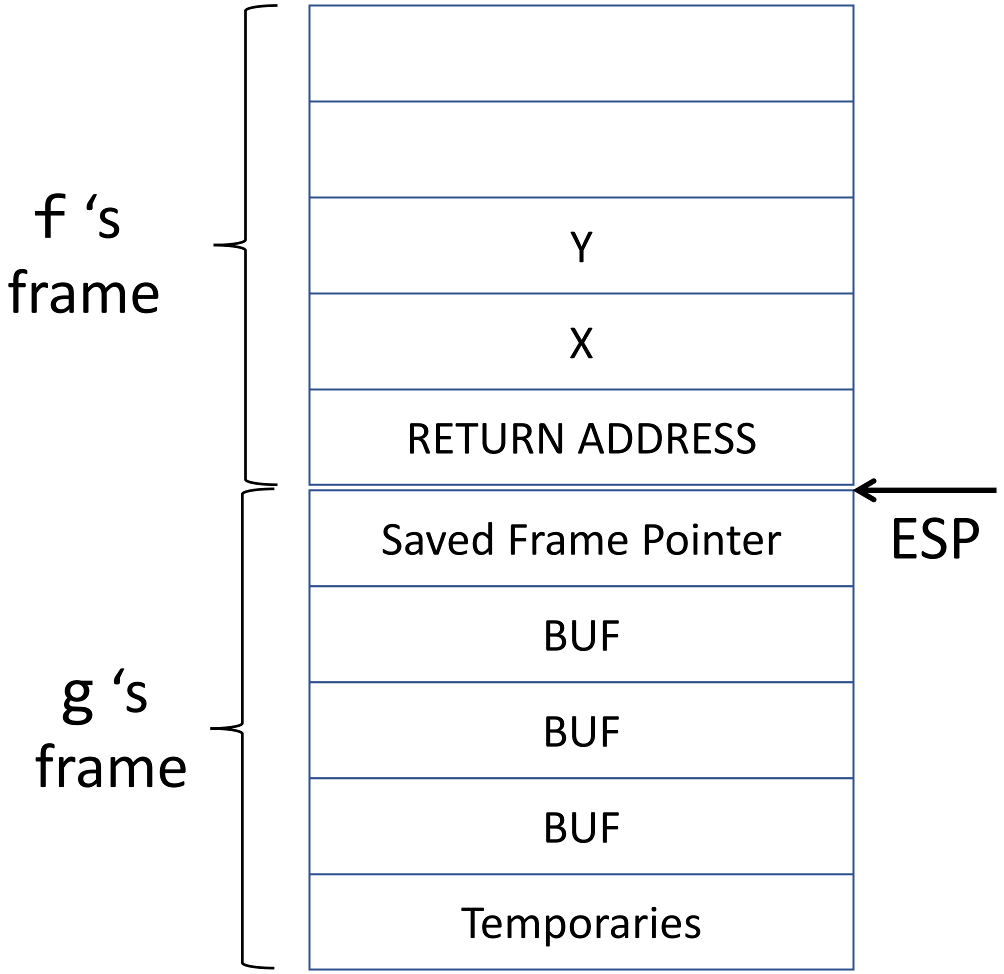
- Registers, Instructions, Stack, EIP
- Addressing modes, offset addresses
  - `mov 0x12[ebp], ecx`
- Stack grows down, other memory accesses move up.



Stack Frames

```
int f() {
…
  g (x, y);
}

int g(int x, int y) {
  char buf[50];
  scanf("%s", buf);
}
```

```
.g

push ebp

…
call scanf
…
pop ebp
ret
```



What address will it return to?

See It Using gdb

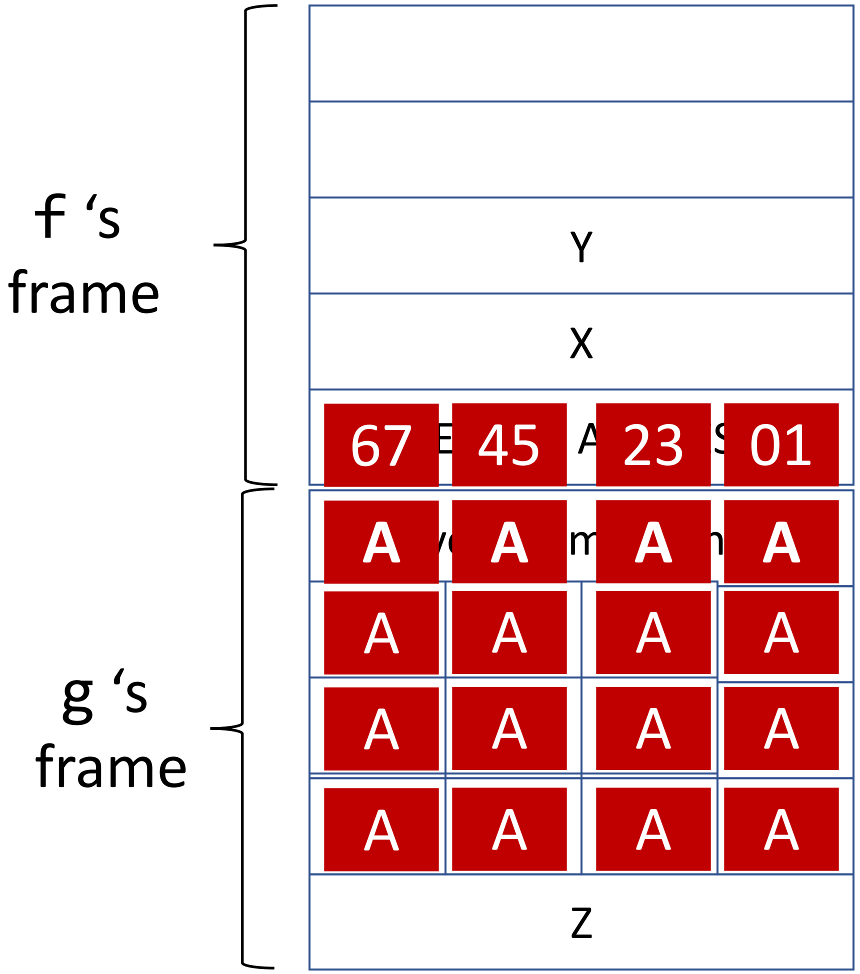
- Compile program and run gdb
  - `gcc –o sample -g sample.c`
  - `gdb sample`
- gdb commands
  - Set break point: `break <functionname>`
  - Check register values: `info registers`
  - Check variables: `print <variablename>`
  - Inspect memory: `x/b <variable_or_address>`

Spatial Memory Errors: Buffer Overflows

Buffer Overflows

```
int f() {
…
  g (x, y);
}

int g(int x, int y) {
  char buf[50];
  scanf("%s", buf);
}
```

```
.g

push ebp

…
call scanf
…
pop ebp
ret
```



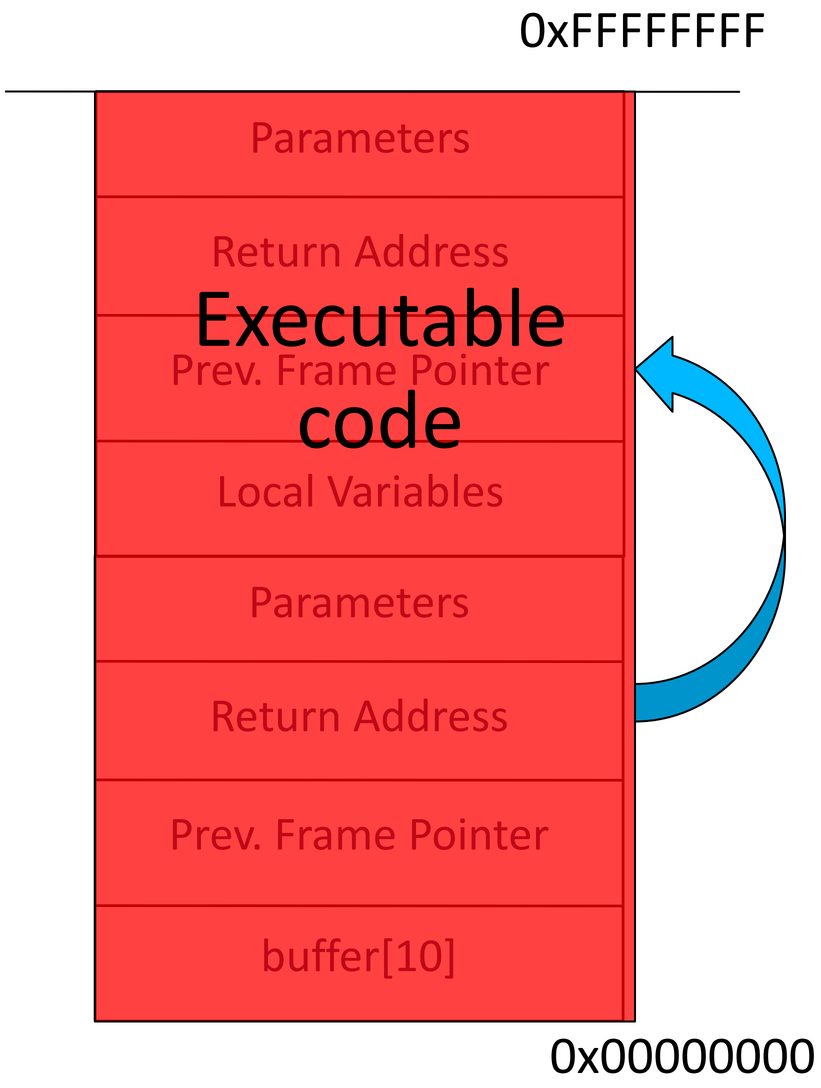
What address will it return to?

Buffer Overflow

```
void
  sample_function(void)
  {
        char buffer[10];
        gets(buffer);
        return;
  }

main()
  {

        sample_function();
        printf("Loc 1\n");

        sample_function();
        printf("Loc 2\n");
  }
```

Malicious Code Injection

- Remember executable code also represented as bytes
- Attackers can include code in the input
  - Called shell code
- They can arrange the return address to point to the injected code

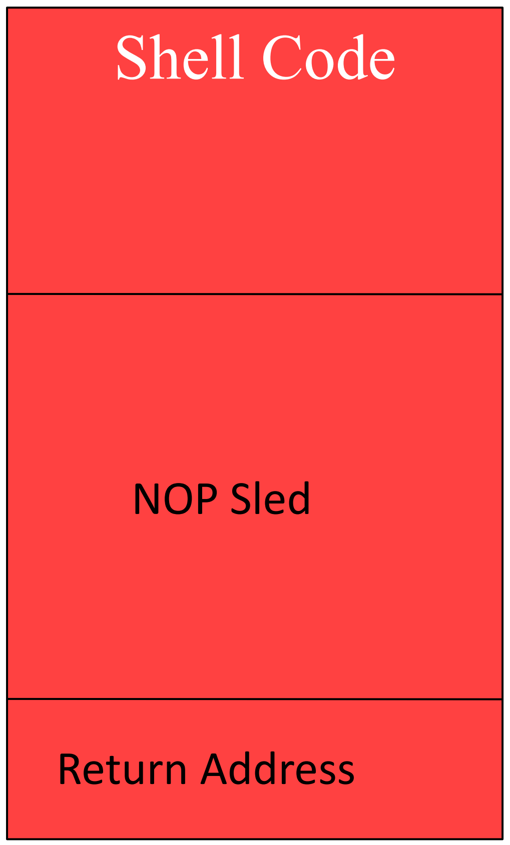


Can They Know the Exact Address of Injected Code?

- Attackers can analyze the vulnerable program using a debugger to find out the address of target stack frame.
- Directly jump into system libraries
  - E.g., system() will execute a command
  - Where is its arguments?
- Sometimes, attacks only know the possible range of the code they injected

NOP Sled

- Instruction NOP, No Operation.
  - Tell CPU to do nothing and fetch the next instruction
- Including a large block of NOP instructions in the injected code as *landing area*
- Execution will reach shell code as long as return address pointing to somewhere in the NOP sled



Shell Code Example

```
int main(int argc,
  char*argv[])
  {
                char *sh;
                char *args[2];

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

- Shell Code

```
90 90 eb 1a 5e 31 c0 88 46 07
  8d 1e 89 5e 08 89 46 0c b0
  0b 89 f3 8d 4e 08 8d 56 0c
  cd 80 e8 e1 ff ff ff 2f 62
  69 6e 2f 73 68 20 20 20 20
  20 20
```

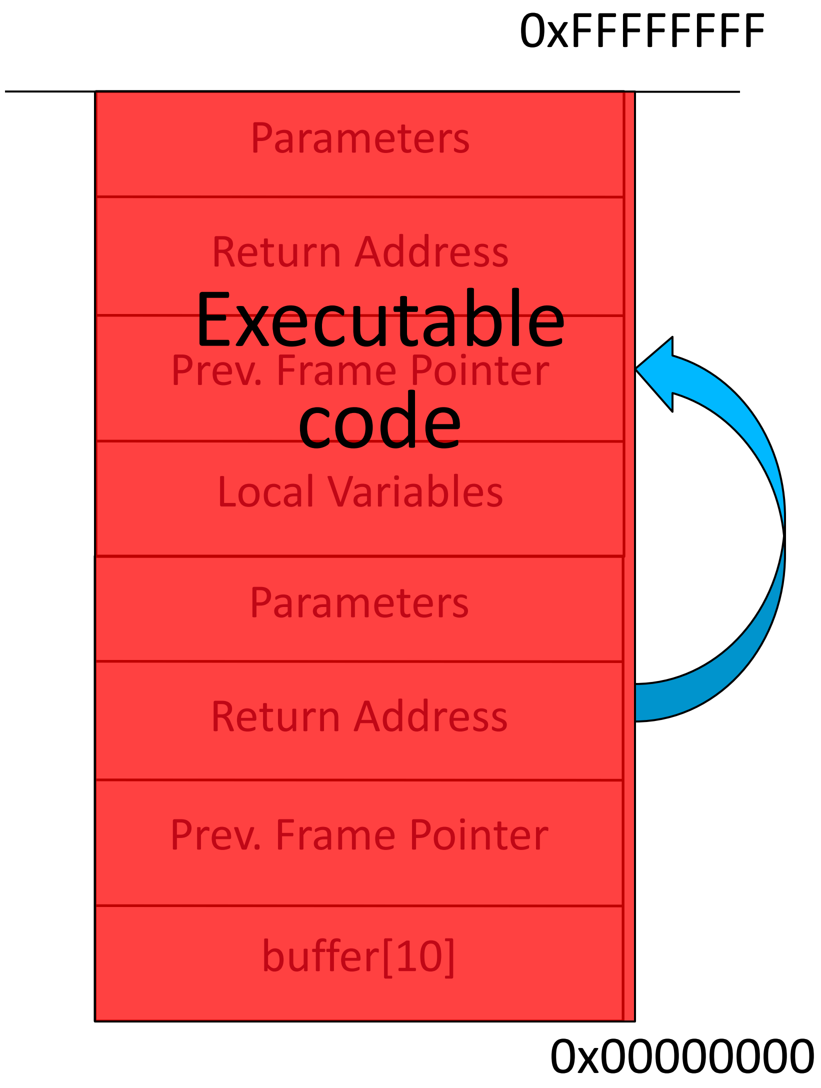
Targets of Buffer Overflow Attack

- Memories that control program execution
  - Return address
  - Function pointer
  - Virtual function table
- Important variables in program
  - Variable storing user id
  - Current balance of bank application
  - …

Buffer Overflow Defense

Requirements of BO

- Existence of vulnerability
- Overwriting important data
- Known location of injected code
- Executable code in input



Essential Steps of Buffer Overflow

- Three essential steps
  - Attack Code Injection
    - How did you inject the attack code?
  - Control Flow Hijacking
    - How did you guess the address of attack code?
  - Attack Code Execution
    - How did you write the shellcode?

Buffer Overflow Defense (1)

- Existence of vulnerability
- Overwriting important data
- Known location of injected code
- Executable code in input

Safe Language and Coding

- Choose a safe programming language
  - Strong notion of variable types, such as Java
- Safe coding techniques
  - Pay attention to loops
  - Explicitly specify size of destination buffer
- Use safe libraries

Some Unsafe C Lib Functions

- `strcpy(char *dest,  const char *src)`
- `strcat(char *dest, const char *src)`
- `gets(char *s)`
- `sprintf(conts char *format, … )`

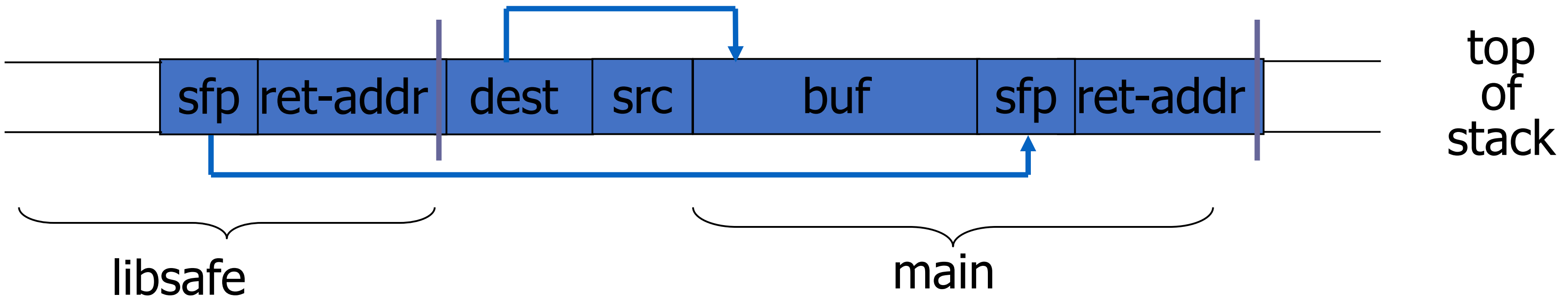
- Safe versions:
- `strncpy, strncat, fgets, snprintf`

Code Checking Tools

- Tools checking for vulnerabilities using static source code analysis
  - ITS4 (It is the Software, Stupid --- Security Scanner)
  - RATS (Rough Auditing Tool for Security)
  - Flawfinder

Security Extension -- Libsafe

- Idea: Making unsafe functions safe!
  - Intercepts calls to strcpy (dest, src)
    - Validates sufficient space in current stack frame:
      |frame-pointer – dest| > strlen(src)
    - If so, does strcpy.
      Otherwise, terminates application.



Buffer Overflow Defense (2)

- Existence of vulnerability
- Overwriting important data
- Known location of injected code
- Executable code in input

MemGuard

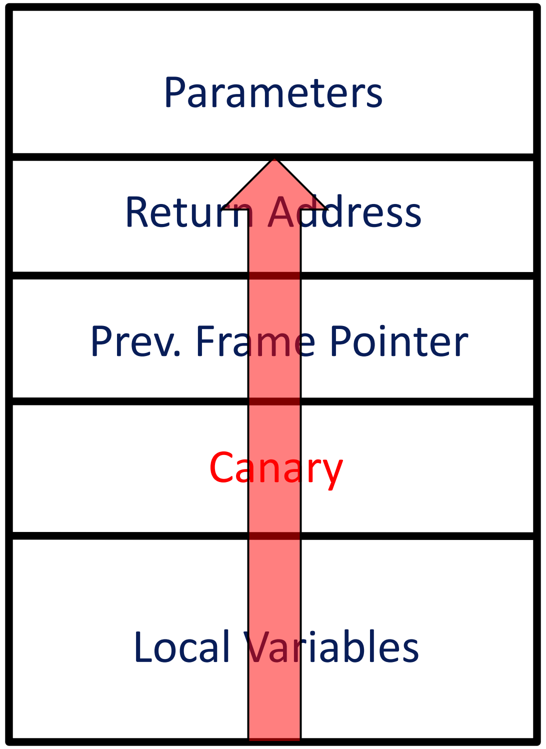
- Main idea: prevent return address from changing via mark it as read-only.
  - Extend VM model to protect user pages (such as return address in stack).
  - Ex: GCC's function_prologue and function_epilogue
- Flaw:
  - *Performance penalties*
    - Loading VM hardware is a privileged operation, and so the application process must trap to kernel mode to protect a word.

StackGuard

- Main idea: the technique used to smash the stack currently always involve sequential memory writing.
  - If the return address in stack was destroyed, the content before the return address must be destroyed, too.
  - Keep a “canary word” before return address and check this word before function returns
- Simple Demo
  - http://nsfsecurity.pr.erau.edu/bom/StackGuard.html

StackGuard

- Put a value below saved frame pointer upon entering the function, called canary
- Check canary value before function exit
- Changed canary value indicates an overflow
- Turned on by default in current gcc, try it out!



Flaw in static canary

- What if the attacker can easily guess the canary value?

- Workaround?
    - randomize canary-word

Buffer Overflow Defense (3)

- Existence of vulnerability
- Overwriting important data
- Known location of injected code
- Executable code in input

Why Randomization?

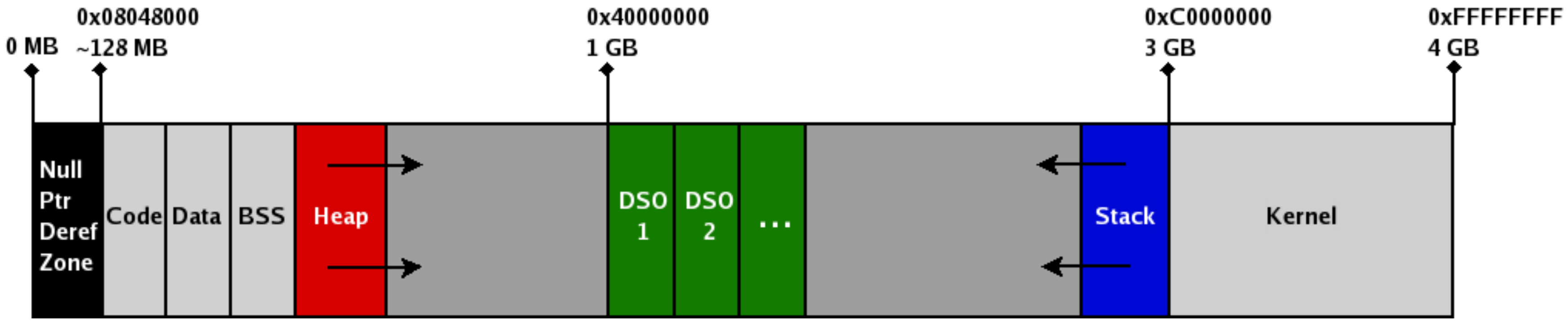
- Buffer overflow and return-into-libc exploits need to know the (virtual) address to which pass control
  - Address of attack code in the buffer
  - Address of a standard kernel library routine
- Same address is used on many machines
  - Slammer infected 75,000 MS-SQL servers using same code on every machine
- Idea: introduce artificial diversity
  - Make stack addresses, addresses of library routines, etc. unpredictable and different from machine to machine

Address Space Layout Randomization (ASLR)

- ASLR renders exploits *which depend on predetermined memory addresses* useless by randomizing the layout of the virtual memory address space.
  - Base addresses of stack, heap, and code segment
- Randomization can be done at compile- or link-time, or by rewriting existing binaries
- Several implementations available
  - E.g., PaX ASLR

An Example: Linux VM System

- Each process has its own 32-bit address space
- Regions are page aligned
- Code & data regions fixed
- Multiple instances, same memory layout
- Traditional locations of heap, user stack, mmap
  - Randomization moves these three regions



ASLR in Linux

```
liangzk@precision:~
File  Edit  View  Terminal  Tabs  Help
[liangzk@precision ~]$ sleep 100 &
[1] 28834
[liangzk@precision ~]$ cat /proc/28834/maps
004fa000-00514000 r-xp 00000000 fd:00 9568320    /lib/ld-2.5.so
00514000-00515000 r-xp 00019000 fd:00 9568320    /lib/ld-2.5.so
00515000-00516000 rwxp 0001a000 fd:00 9568320    /lib/ld-2.5.so
00518000-00656000 r-xp 00000000 fd:00 9569531    /lib/libc-2.5.so
00656000-00658000 r-xp 0013e000 fd:00 9569531    /lib/libc-2.5.so
00658000-00659000 rwxp 00140000 fd:00 9569531    /lib/libc-2.5.so
00659000-0065c000 rwxp 00659000 00:00 0
00f1e000-00f1f000 r-xp 00f1e000 00:00 0          [vdso]
08048000-0804c000 r-xp 00000000 fd:00 13598780   /bin/sleep
0804c000-0804e000 rw-p 00003000 fd:00 13598780   /bin/sleep
09f3a000-09f5b000 rw-p 09f3a000 00:00 0          [heap]
b7c16000-b7c17000 r--p 00949000 fd:00 1599402    /usr/lib/locale/locale-archive
b7c17000-b7cee000 r--p 00191000 fd:00 1599402    /usr/lib/locale/locale-archive
b7cee000-b7eee000 r--p 00000000 fd:00 1599402    /usr/lib/locale/locale-archive
b7eee000-b7ef0000 rw-p b7eee000 00:00 0
bfe1a000-bfe2f000 rw-p bffea000 00:00 0          [stack]
[liangzk@precision ~]$
```

```
liangzk@precision:~
File  Edit  View  Terminal  Tabs  Help
[liangzk@precision ~]$ sleep 100 &
[1] 29196
[liangzk@precision ~]$ cat /proc/29196/maps
00110000-0024e000 r-xp 00000000 fd:00 9569531    /lib/libc-2.5.so
0024e000-00250000 r-xp 0013e000 fd:00 9569531    /lib/libc-2.5.so
00250000-00251000 rwxp 00140000 fd:00 9569531    /lib/libc-2.5.so
00251000-00254000 rwxp 00251000 00:00 0
004fa000-00514000 r-xp 00000000 fd:00 9568320    /lib/ld-2.5.so
00514000-00515000 r-xp 00019000 fd:00 9568320    /lib/ld-2.5.so
00515000-00516000 rwxp 0001a000 fd:00 9568320    /lib/ld-2.5.so
0052b000-0052c000 r-xp 0052b000 00:00 0          [vdso]
08048000-0804c000 r-xp 00000000 fd:00 13598780   /bin/sleep
0804c000-0804e000 rw-p 00003000 fd:00 13598780   /bin/sleep
09c48000-09c69000 rw-p 09c48000 00:00 0          [heap]
b7c97000-b7c98000 r--p 00949000 fd:00 1599402    /usr/lib/locale/locale-archive
b7c98000-b7d6f000 r--p 00191000 fd:00 1599402    /usr/lib/locale/locale-archive
b7d6f000-b7f6f000 r--p 00000000 fd:00 1599402    /usr/lib/locale/locale-archive
b7f6f000-b7f71000 rw-p b7f6f000 00:00 0
bfc47000-bfc5c000 rw-p bffea000 00:00 0          [stack]
[liangzk@precision ~]$
```

Buffer Overflow Defense (4)

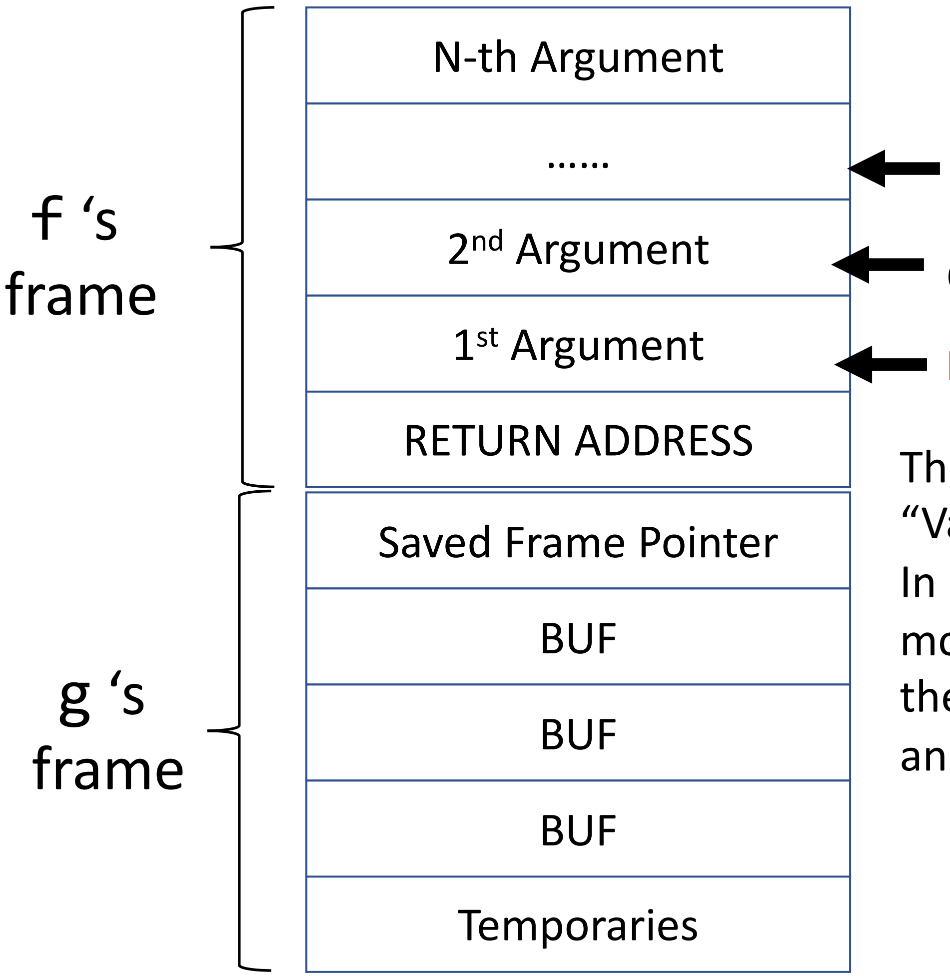
- Existence of vulnerability
- Overwriting important data
- Known location of injected code
- Executable code in input

Non-Executable Stack

- Using CPU's memory management unit to mark stack as non-executable
- Vulnerable program crashes if it jump to the stack for execution
- But there are legitimate reasons to put code on stack
  - Self-modifying code, e.g., Skype
  - Linux signal handlers

Spatial Memory Errors:
Format String Bugs

Variable Argument Functions (Example – Printf / Scanf)



On 32-bit (X86)

Integer

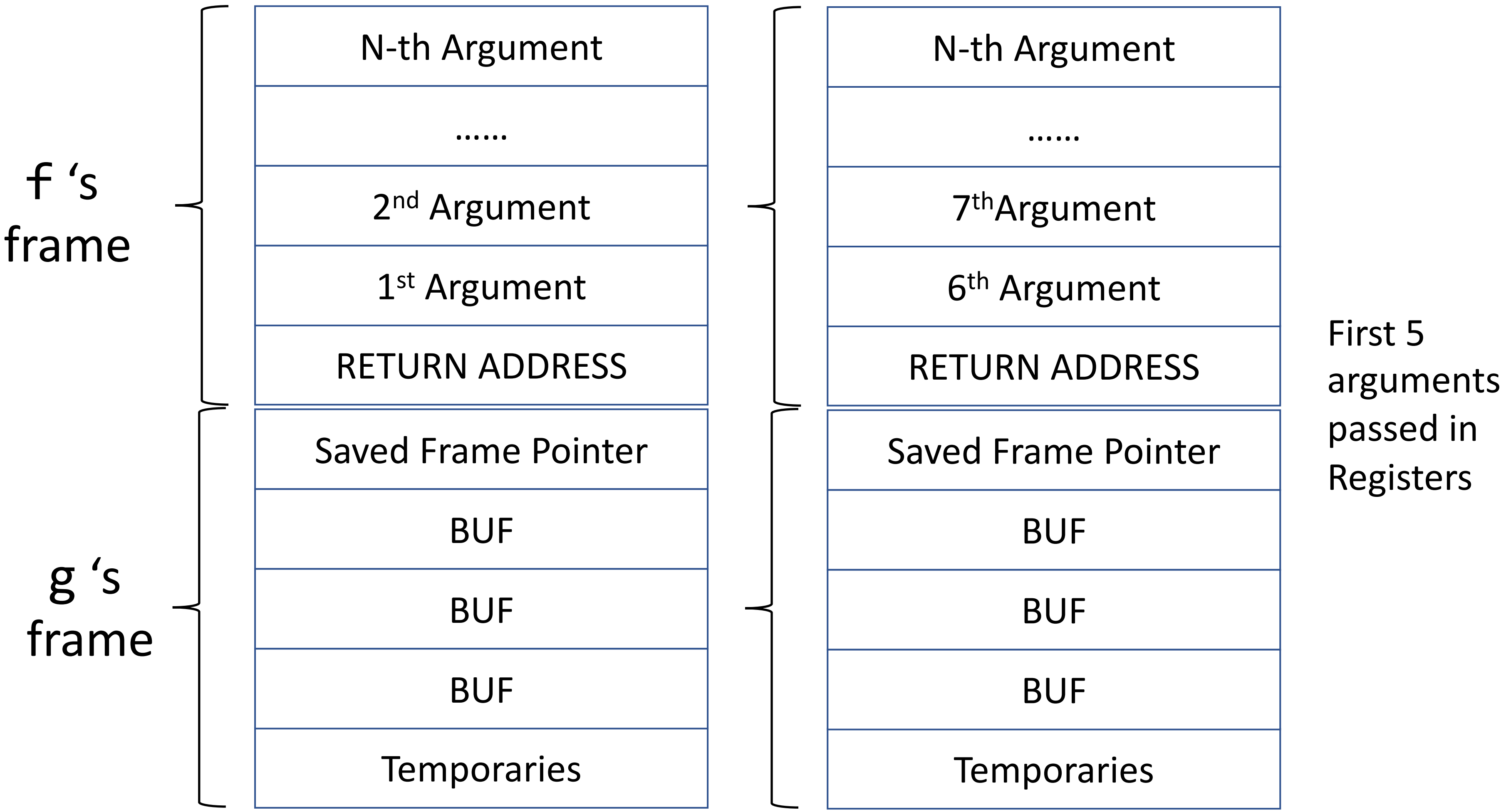
Character String Pointer

Format String: Example "%s%d"

The format string is "interpreted" by the "Variable-argument" function (callee).
In this example, there are expected to be 2 more arguments after the format string: the first one is a character string pointer, and the next one is integer

[Format String Vulns.]

Architectural Differences (x86 vs x64)



On 32-bit (X86)

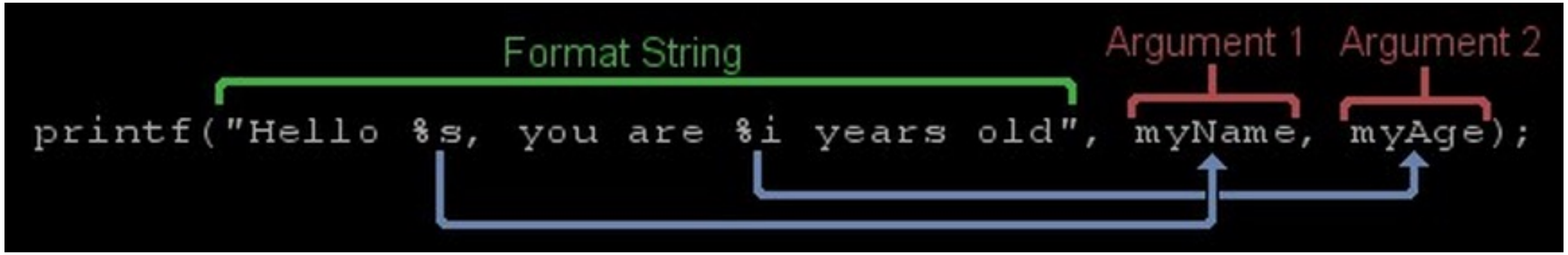
On 64-bit (X64)

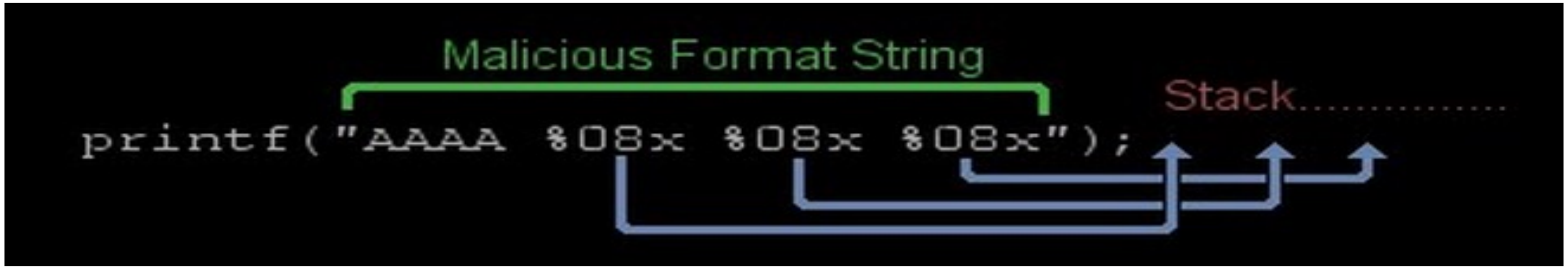
Format String Vulnerabilities

```
#include <stdio.h>

int main()
{
    srand(time(NULL));

    char localStr[100];
    int magicNumber = rand() % 100;
    int userCode = 0xBBBBBBBB;

    printf("Username? ");
    fgets(localStr, sizeof(localStr), stdin);

    printf("Hello ");
    printf(localStr);
    printf("What is the access code? ");

     scanf(“%d”, &userCode);
    if (userCode == magicNumber)
        printf("You win!\n");
…}
```


[Format String Vulns.](#)

Format String Vulnerabilities





Format String Vulnerabilities

```
#include <stdio.h>

int main()
{
    srand(time(NULL));

    char localStr[100];
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    int userCode = 0xBBBBBBBB;

    printf("Username? ");
    fgets(localStr, sizeof(localStr), stdin);

    printf("Hello ");
    printf(localStr);
```

AAAA %08x %08x %08x %08x %08x %08x %08x %08x %08x %08x %08x %08x %08x %08x %08x %08x %08x

```
    scanf(“%d”, &userCode);
    if (userCode == magicNumber)
        printf("You win!\n");
… }
```

The “main” stack frame

Saved Frame Pointer
userCode
magicNumber
localStr [100]
Temporaries

Format String Specifiers

Format String: Example “%s%d”

Format Specifiers

%d - print as number
%p - print as pointer
%c - print as character
%s - read from the address provided and print bytes until the NULL byte is reached
%n - write number of bytes already printed in the address provided
<n>$ - accesses the nth positional argument with respect to printf (ex: %5$p)

Temporal Memory Errors: Use-after-free & Double Free

Lifetime & Scope of Variables

- **Scope**:
  - Region of code where a variable can be accessed
  - E.g. Global, Function-local, Heap (dynamic)
- **Lifetime**:
  - Portion of program execution during which storage is guaranteed
  - E.g. Auto vs. static

Are Programming Language Abstractions

- Not instruction set / hardware abstractions

```
1. int z=0;
2. int g(int x, int y) {
3.      char* buf;
4.      buf = malloc (50);
5.      scanf(“%s”, buf);
6.      free (buf);
7. …
8. }
```

Variable	Scope	Lifetime
z	Global, Line 1-8	Throughout the program
x	Local, Line 3-7	Execution of g
y	Local, Line 3-7	Execution of g
buf	Local, Line 3-7	Execution of g
“%s”	Constant Literal, Line 5	Execution of Line 5 (undefined?)
*buf	Heap, Line 4-7	Line 5-6

Question

```c
int foo() {
int *p;
        {
        int x = 5;
        p = &x;
        }
return *p;
}
```

What will this program return?

Answer:
Undefined behavior as per C11 standard

Why?
- The lifetime of x is within the inner {}
- The compiler can choose to remove the storage for “x”
- The pointer p is in scope at the last line
- The pointed-to object, however, is accessed out of scope!

Temporal Memory Errors
Example: Use-after-free

Temporal Mem Error: When program accesses mem. beyond its valid lifetime!

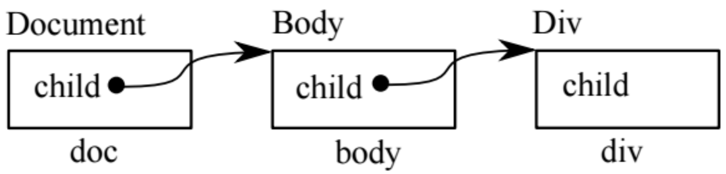
```
class Div: Element;
class Body: Element;
class Document {
  Element* child;
};

// (a) memory allocations
Document *doc = new Document();
Body *body = new Body();
Div *div = new Div();

// (b) using memory: propagating pointers
doc->child = body;
body->child = div;

// (c) memory free: doc->child is now dangled
delete body;

```



Dangling Pointers [NDSS'15]

Summary & Key Takeaways

- Memory Errors / Vulnerabilities
  - Spatial & Temporal
- Worst case: Can give attackers capability to read / write any value anywhere in memory
- Hardware does <u>not</u> give memory safety