

CSE 410/518: Software Security

Instructor: Dr. Ziming Zhao

First off, Logistics!

Classes are recorded and released publicly on YouTube
But you have to attend the class in-person

Have a notebook in front of you
Bring your own laptop

<https://zzm7000.github.io/teaching/2023fallcse410518/index.html>

We have an online CTF platform for this class.

Feel free to interrupt me and ask questions.

Instructor and Teaching Assistant

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<http://cactilab.github.io>

Office hours: Monday 3:00 PM - 4:30 PM or by appointment

338B or <https://buffalo.zoom.us/j/95299258797?pwd=QlBhbjlIUlM5WmlETmFtOE5qT1Z5dz09>

YouTube Channel



CyberspACe securiTy and forensics lab (CactiLab)

@zimingzhao6619 296 subscribers 143 videos

CactiLab is in the Department of Computer Science and Engineering at Uni... >

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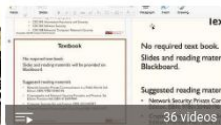
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About CactiLab

Research areas:

- Systems and software security (Arm Cortex-M, Cortex-A, RISC-V, FPGA, GPU, etc.)
- Security in/with ML/DL/LLM
- Autonomous driving security
- Formally verify the security properties of crypto protocols and system code
- Hacking/CTF platforms

We need students at all levels for funded research, volunteer work, independent study, undergraduate research experience, etc.

Students

Graduate (Master, PhD) - CSE 518 (3-credit)

Undergraduates (Sophomore, junior, senior) - CSE 410 (3-credit)

All are invited to slack ***cacti-workspace, #ubcse410518-fall2023***

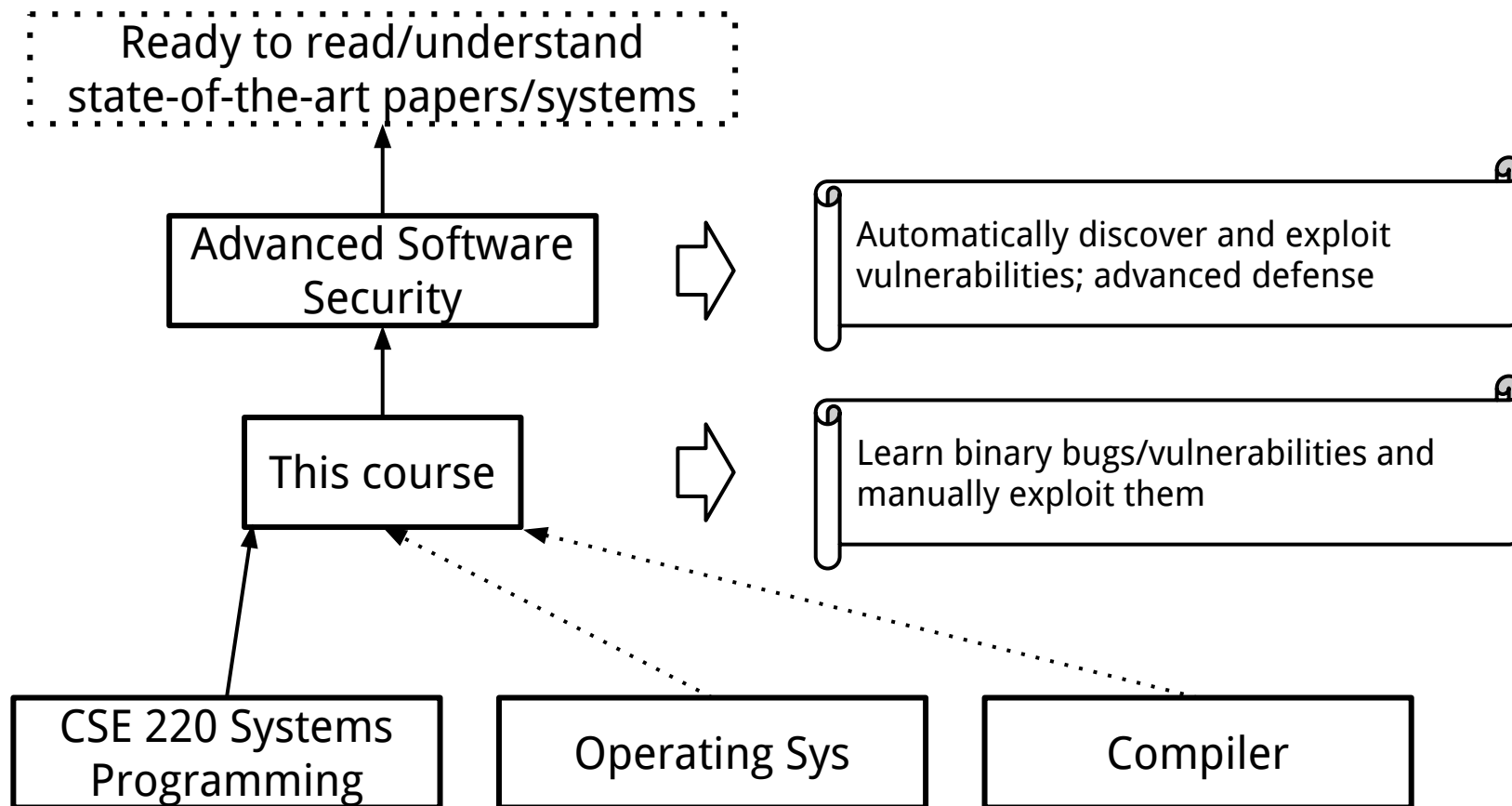
Course Goals

To provide you with good understanding of the **theories, principles, techniques** and **tools** used for binary software and system hacking and defense.

By software and system, I mean native software, binary, most likely developed in C/C++. The security of web software, Java, Python are out of the scope.

You will study, in-depth, binary reverse engineering, vulnerability classes, vulnerability analysis, exploit/shellcode development, defensive solutions, etc., to understand how to crack and protect **native** software. You will get your hands dirty.

If you want to be a systems/software security guy ...



This week's Agenda

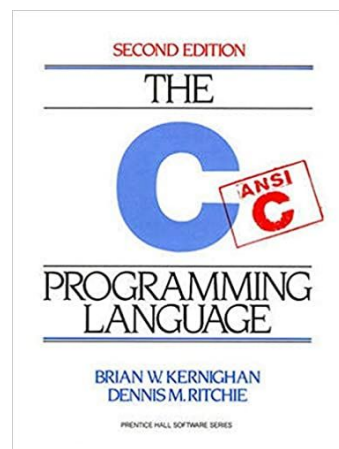
1. Class overview and logistics
2. Background knowledge
 - a. Compiler, linker, loader
 - b. x86 and x86-64 architectures and ISA
 - c. Linux file permissions
 - d. Set-UID programs
 - e. Memory map of a Linux process
 - f. System calls
 - g. Environment and Shell variables
 - h. Basic reverse engineering

Prerequisites

The real prerequisite:
The C Programming Language

Classes that will help you understand this class:
CSE 220 Systems Programming
CSE 421 Introduction to Operating Systems
CSE 521 Operating Systems

Other skills:
Reverse engineering (Using objdump, IDA Pro, Ghidra, etc.)
Debugging (GDB, pwngdb)
Google, reading, self-learning, getting hands dirty



Topics

Binary attack and defense using x86 and x86-64 as examples.
Discover **vulnerabilities**. Develop **exploits**. Memory corruption attacks.

1. Stack-based buffer overflow
2. Defenses against stack-based buffer overflow
3. Shellcode development
4. Format string vulnerabilities
5. Heap-based buffer overflow
6. Integer overflow
7. Return-oriented programming
8. ...

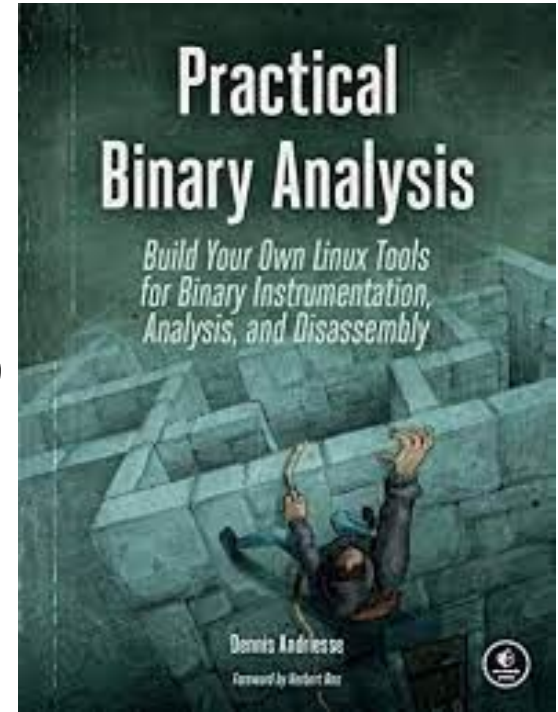
Related Books and Papers

SoK: Eternal War in Memory. IEEE S&P 2013

SoK: (State of) The Art of War: Offensive Techniques in Binary Analysis. IEEE S&P 2016

SoK: Shining Light on Shadow Stacks. IEEE S&P 2019

Practical Binary Analysis: Build Your Own Linux Tools for Binary Instrumentation, Analysis, and Disassembly



Related Books and Papers

SoK: Eternal War in Memory. IEEE S&P 2013

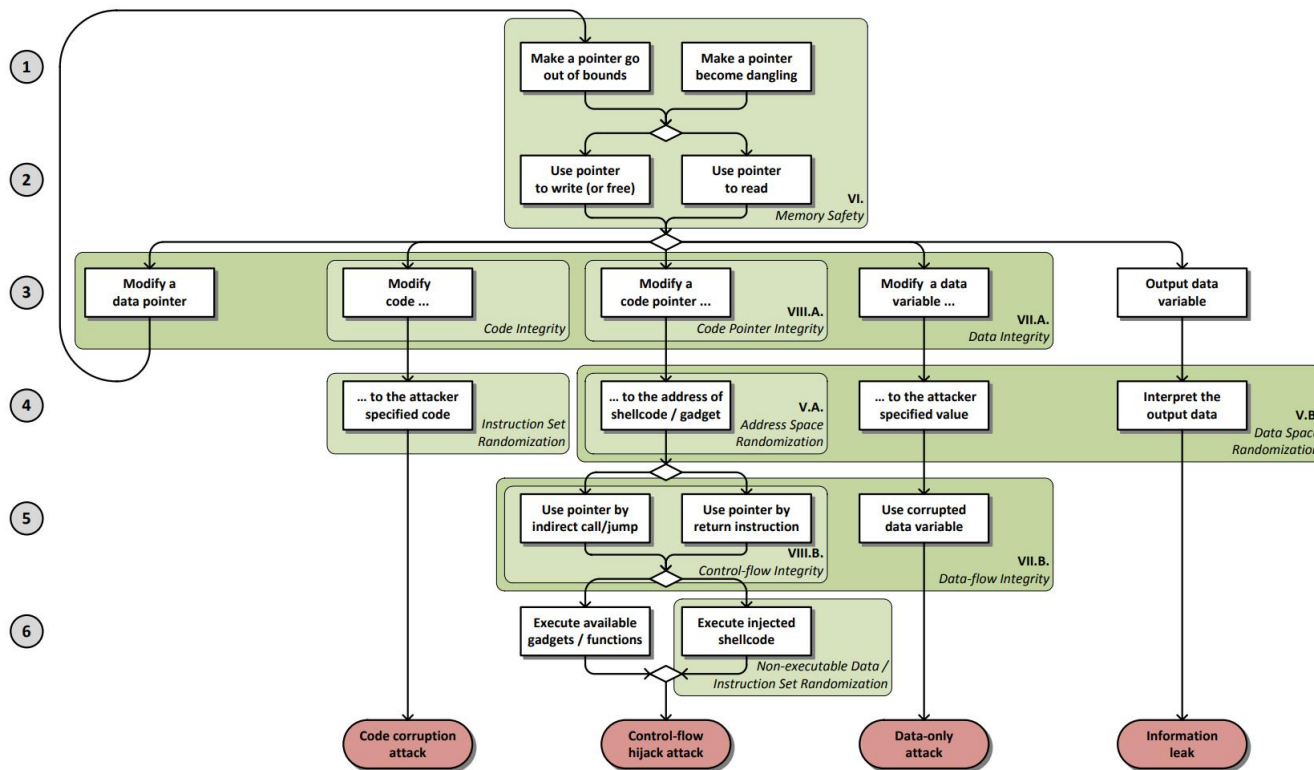


Figure 1. Attack model demonstrating four exploit types and policies mitigating the attacks in different stages

The Hacking Environment

CTFd Terminal Grades Users Scoreboard Challenges

Register Login

<http://cse410.cacti.academy/>

Only UB students can access this website. If you are off-campus, you need to VPN to connect to UB network to access

Register an account with your UB username and email address.

Welcome to CSE410/510 CTF Platform!

CSE410/510 CTF Platform for course practice problems on 0x86 architecture. The platform was created by [Ziming Zhao](#) and members of [CactiLab](#) at the [University at Buffalo](#).



New Environment Under Construction

CTFd Terminal Grades Users Scoreboard Challenges

Register Login

<http://pwniot.cacti.academy/>

Only UB students can access this website. If you are off-campus, you need to VPN to connect to UB network to access

Register an account with your UB username and email address.

Welcome to CSE410/510 CTF Platform!

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The Hacking Environment

Intel x86
x86-64, a.k.a amd64
Linux (Ubuntu)

Pwngdb
Pwntools
GDB peda
NSA Ghidra
Binary Ninja

Homework

Reading: book chapter, whitepaper, paper, blog, etc.

Hands-on: hacking, debugging, etc.

Submit before a class on UBLearns. We may discuss homework at the beginning of each class.

30% penalty if you submit within 10 mins after class starts. 0 points after 10 mins.

0 points for homework if plagiarising is found. No exceptions.

Disability Accommodations

If you need DA, please inform me in the first two weeks.

Hacking Assignment Rules

- For each hacking assignment, you will submit your exploit, a simple write-up, and screenshots to show it works
 - Simple write-up:
 - Briefly describe how you solve the challenge
 - Mention who you worked with if any in the write-up
- Discussion is encouraged. But, you cannot share your code, exploits, write-ups to your classmates or post them online.

Exams, a.k.a, Capture-the-Flag (CTF) Hacking

Midterm CTF: 3 hours

Final CTF: 3 hours

Grades

Area	No. Items	Points per Item	Points for Area
Homework	14	45	630
Exams (CTFs)	2		360
Midterm Exam (CTF)	1	160	
Final Exam (CTF)	1	200	
Attendance	14	1	14
Anonymous Course Evaluation Bonus	2	10	20
Total			1024

418 (Undergraduate)		518 (Graduate)	
Points	Grade	Points	Grade
874 -	A	924 -	A
850 - 874	A-	900 - 924	A-
820 - 850	B+	870 - 900	B+
780 - 820	B	830 - 870	B
750 - 780	B-	800 - 830	B-
720 - 750	C+	770 - 800	C+
650 - 720	C	700 - 770	C
550 - 650	D	600 - 700	D
0 - 550	F	0 - 600	F

Academic Integrity

Your first assignment is to read the CSE and UB academic integrity policies

Here are examples for your consideration

- you work on your laptop at a library with friends and step away from your computer without locking it
- you look at your neighbors' screen/papers during an exam, but don't copy their answers
- you take a piece of code from some website and give a link to the website at the end of the homework
- you work on a homework problem with friends, type the solution at home, but it's exactly the same as that of your friends

Academic Integrity

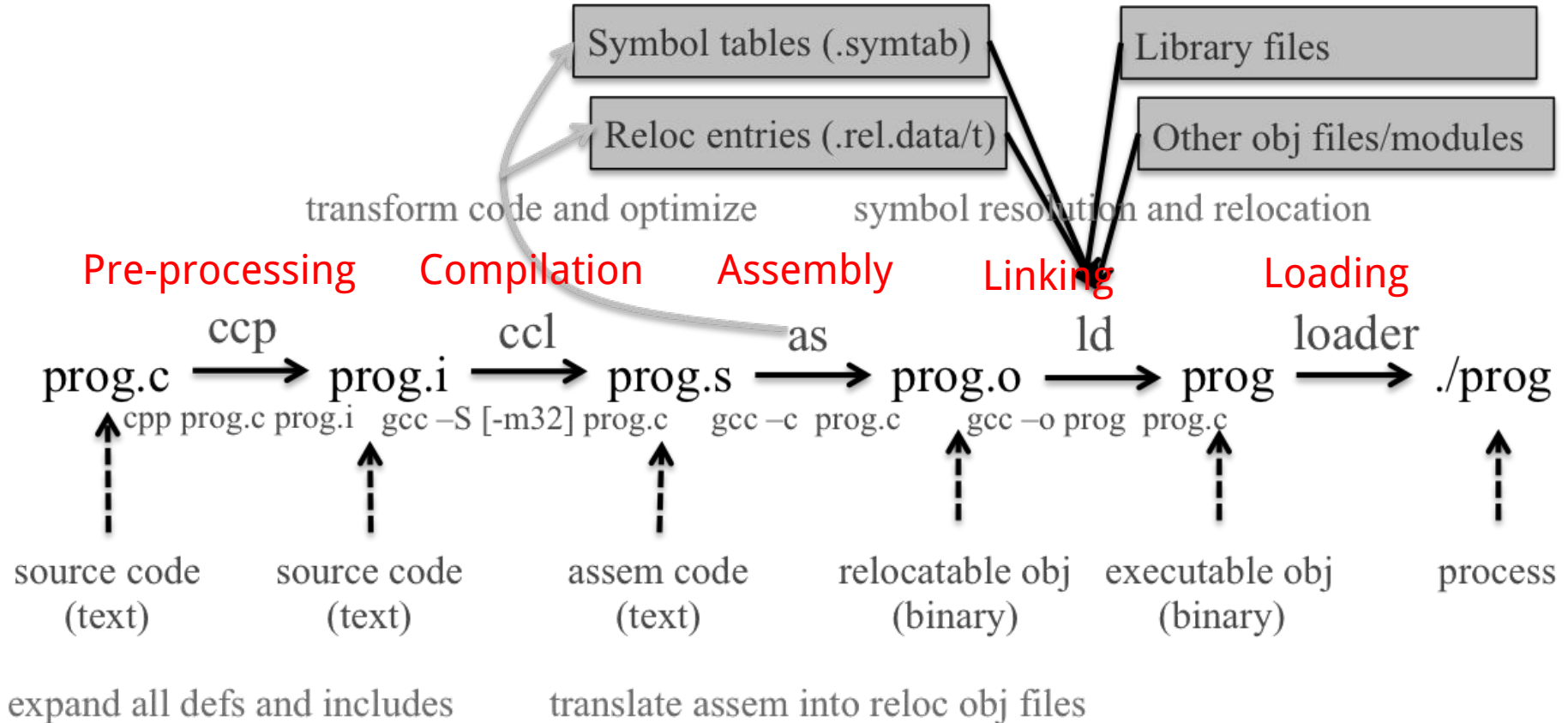
- Discussion is encourage. But, you cannot share your code, exploits to your classmates or post them online.
- The university, college, and department policies against academic dishonesty will be strictly enforced. To understand your responsibilities as a student read: UB Student Code of Conduct.
- Plagiarism or any form of cheating in homework, assignments, labs, or exams is subject to serious academic penalty.
- Any violation of the academic integrity policy will result in a 0 on the homework, lab or assignment, and even an **F** or **>F<** on the final grade. And, the violation will be reported to the Dean's office.

Ethical Hacking

- Do not attempt to violate the law.
- If you discover real-world vulnerabilities using the knowledge you learn from this class, report the vulnerabilities responsibly. Companies may reward you for that.

Background Knowledge: Compiler, linker, and loader

From a C program to a process



Loading and Executing a Binary Program on Linux

Validation (permissions, memory requirements etc.)

Operating system starts by setting up a new process for the program to run in, including a virtual address space.

The operating system maps an interpreter into the process's virtual memory.

Interpreter, e.g., `/lib/ld-linux.so` in Linux

The interpreter loads the binary into its virtual address space (the same space in which the interpreter is loaded).

It then parses the binary to find out (among other things) which dynamic libraries the binary uses.

The interpreter maps these into the virtual address space (using *mmap* or an equivalent function) and then performs any necessary last-minute relocations in the binary's code sections to fill in the correct addresses for references to the dynamic libraries.

Compiling a C program behind the scene (add_32 add_64)

add.c

```
#include "add.h"

#define BASE 50

int add(int a, int b)
{ return a + b +
  BASE;}
```

add.h

```
#ifndef ADD_H
#define ADD_H

int add(int, int);

#endif
```

main.c

```
/* This program has an integer overflow vulnerability. */
#include "add.h"
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#define USAGE "Add two integers with 50. Usage: add a b\n"

int main(int argc, char *argv[])
{
    int a = 0;
    int b = 0;

    if (argc != 3)
    {
        printf(USAGE);
        return 0;}

    a = atoi(argv[1]);
    b = atoi(argv[2]);
    printf("%d + %d + 50 = %d\n", a, b, add(a, b));
}
```

```
gcc -Wall -save-temps -P -m32 -O2 add.c main.c -o add_32
```

```
gcc -Wall -save-temps -P -O2 add.c main.c -o add_64
```

5 mins break

Background Knowledge:

x86 architecture

Data Types

There are 5 integer data types:

Byte – 8 bits.

Word – 16 bits.

Dword, Doubleword – 32 bits.

Quadword – 64 bits.

Double quadword – 128 bits.

Endianness

- Little Endian (Intel, ARM)

Least significant byte has lowest address

Dword address: 0x0

Value: 0x78563412

- Big Endian

Least significant byte has highest address

Dword address: 0x0

Value: 0x12345678

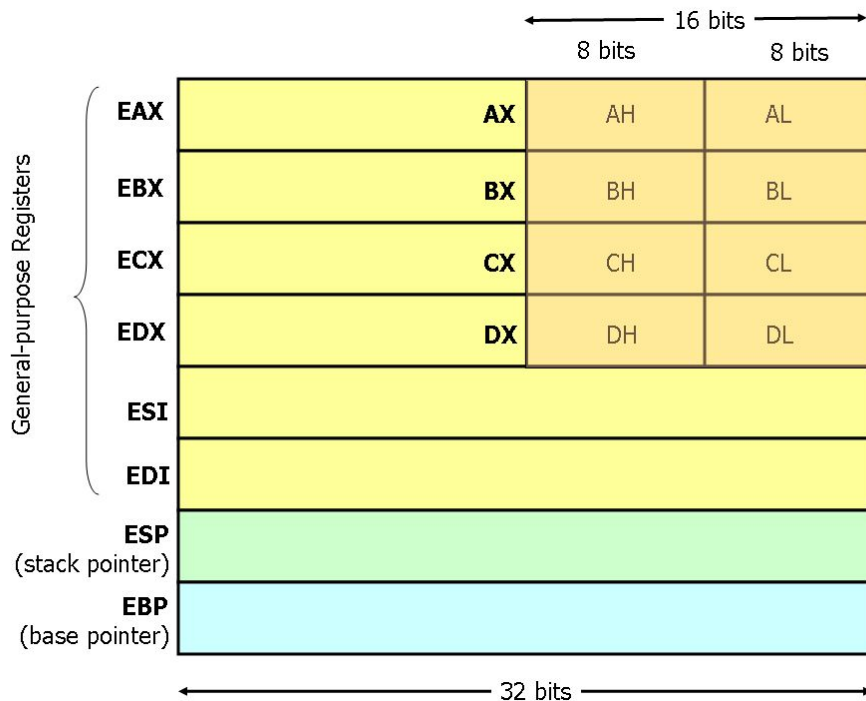
Address 0	0x12
Address 1	0x34
Address 2	0x56
Address 3	0x78

Base Registers

There are

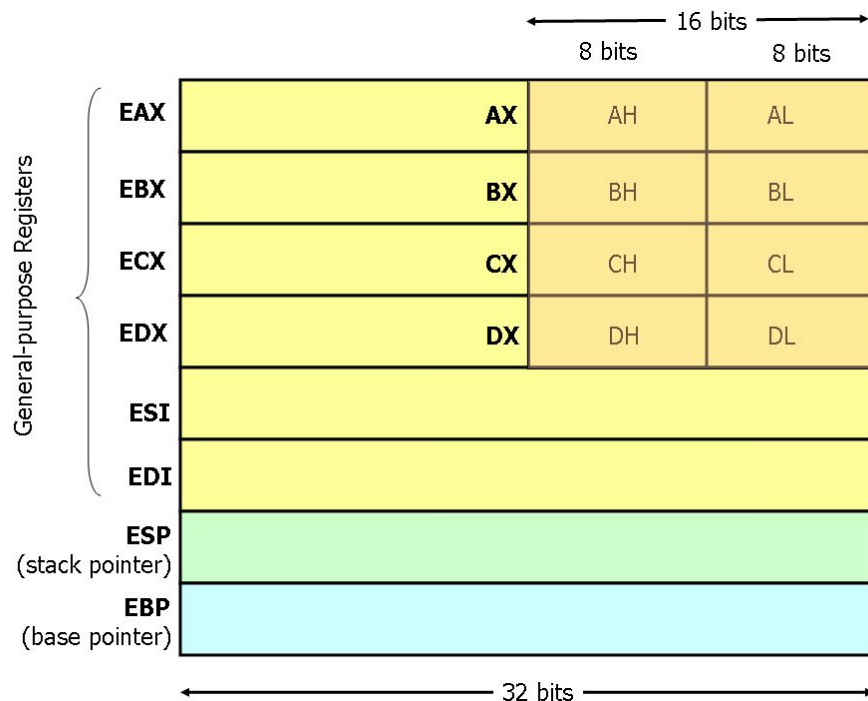
- Eight 32-bit “general-purpose” registers,
- One 32-bit EFLAGS register,
- One 32-bit instruction pointer register (eip), and
- Other special-purpose registers.

The General-Purpose Registers



- 8 general-purpose registers
- esp is the stack pointer
- ebp is the base pointer
- esi and edi are source and destination index registers for array and string operations

The General-Purpose Registers



- The registers `eax`, `ebx`, `ecx`, and `edx` may be accessed as 32-bit, 16-bit, or 8-bit registers.
- The other four registers can be accessed as 32-bit or 16-bit.

EFLAGS Register

The various bits of the 32-bit EFLAGS register are set (1) or reset/clear (0) according to the results of certain operations.

We will be interested in, at most, the bits

CF – carry flag

PF – parity flag

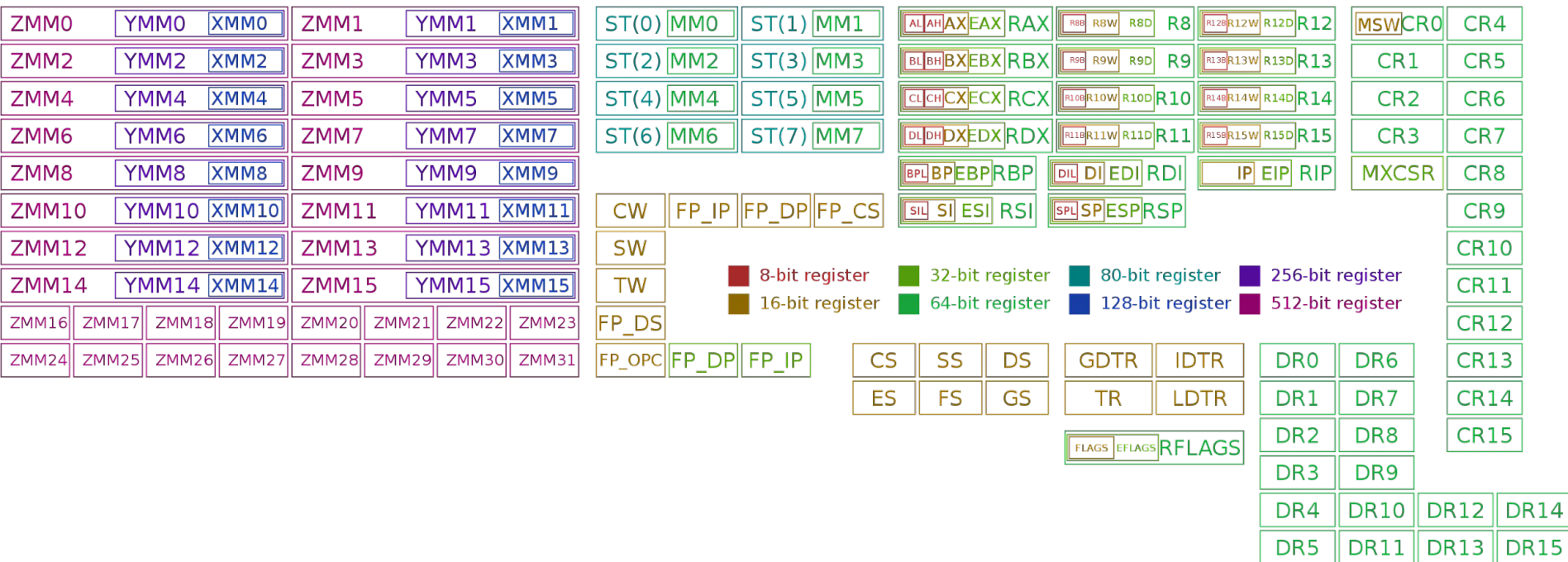
ZF – zero flag

SF – sign flag

Instruction Pointer (EIP)

Finally, there is the EIP register, which is the instruction pointer (program counter). Register EIP holds the address of the **next** instruction to be executed.

Registers on x86 and amd64



Instructions

Each instruction is of the form

label: mnemonic operand1, operand2, operand3

The label is optional.

The number of operands is 0, 1, 2, or 3, depending on the mnemonic .

Each operand is either

- An immediate value,
- A register, or
- A memory address.

Source and Destination Operands

Each operand is either a source operand or a destination operand.

A source operand, in general, may be

- An immediate value,
- A register, or
- A memory address.

A destination operand, in general, may be

- A register, or
- A memory address.

Instructions

hlt – 0 operands

halts the central processing unit (CPU) until the next external interrupt is fired

inc – 1 operand; inc <reg>, inc <mem>

add – 2 operands; add <reg>, <reg>

imul – 1, 2, or 3 operands; imul <reg32>, <reg32>, <con>

Intel Syntax Assembly and Disassembly

Machine instructions generally fall into three categories: data movement, arithmetic/logic, and control-flow.

<reg32> Any 32-bit register (eax, ebx, ecx, edx, esi, edi, esp, or ebp)

<reg16> Any 16-bit register (ax, bx, cx, or dx)

<reg8> Any 8-bit register (ah, bh, ch, dh, al, bl, cl, or dl)

<reg> Any register

<mem> A memory address (e.g., `[eax]` or `[eax + ebx*4]`); `[]` square brackets

<con32> Any 32-bit immediate

<con16> Any 16-bit immediate

<con8> Any 8-bit immediate

<con> Any 8-, 16-, or 32-bit immediate

Addressing Memory

Move from source (operand 2) to destination (operand 1)

mov [eax], ebx (read as MOVE FROM x to y) Load 4 bytes from the memory address in EBX into EAX.

mov eax, [esi - 4] Move 4 bytes at memory address ESI - 4 into EAX. */

mov [esi + eax * 1], cl Move the contents of CL into the byte at address ESI+EAX*1.

mov edx, [esi + ebx*4] Move the 4 bytes of data at address ESI+4*EBX into EDX.

Addressing Memory

The size directives BYTE PTR, WORD PTR, and DWORD PTR serve this purpose, indicating sizes of 1, 2, and 4 bytes respectively.

mov [ebx], 2 isn't this ambiguous? We can have a default.

mov BYTE PTR [ebx], 2 Move 2 into the single byte at the address stored in EBX.

mov WORD PTR [ebx], 2 Move the 16-bit integer representation of 2 into the 2 bytes starting at the address in EBX.

mov DWORD PTR [ebx], 2 Move the 32-bit integer representation of 2 into the 4 bytes starting at the address in EBX.

Data Movement Instructions

mov — Move

Syntax

mov <reg>, <reg>

mov <reg>, <mem>

mov <mem>, <reg>

mov <reg>, <con>

mov <mem>, <con>

Examples

mov eax, ebx — copy the value in EBX into EAX

mov byte ptr [var], 5 — store the value 5 into the byte at location var

Data Movement Instructions

push — Push on stack; decrements ESP by 4, then places the operand at the location ESP points to.

Syntax

push <reg32>

push <mem>

push <con32>

Examples

push eax — push eax on the stack

push [var] — push the 4 bytes at address var onto the stack

Data Movement Instructions

pop — Pop from stack

Syntax

pop <reg32>

pop <mem>

Examples

pop edi — pop the top element of the stack into EDI.

pop [ebx] — pop the top element of the stack into memory at the four bytes starting at location EBX.

LEA Instructions

lea — Load effective address; used for quick calculation

Syntax

`lea <reg32>, <mem>`

Examples

`Lea edi, [ebx+4*esi]` — the quantity $EBX+4*ESI$ is placed in EDI.

Arithmetic and Logic Instructions

add eax, 10 — EAX is set to $EAX + 10$

addb byte ptr [eax], 10 — add 10 to the single byte stored at memory address stored in EAX

sub al, ah — AL is set to $AL - AH$

sub eax, 216 — subtract 216 from the value stored in EAX

dec eax — subtract one from the contents of EAX

imul eax, [ebx] — multiply the contents of EAX by the 32-bit contents of the memory at location EBX. Store the result in EAX.

shr ebx, cl — Store in EBX the floor of result of dividing the value of EBX by 2^n where n is the value in CL.

Control Flow Instructions

jmp — Jump

Transfers program control flow to the instruction at the memory location indicated by the operand.

Syntax

`jmp <label> # direct jump`

`jmp <reg32> # indirect jump`

Example

`jmp begin` — Jump to the instruction labeled begin.

Control Flow Instructions

jcondition — Conditional jump

Syntax

je <label> (jump when equal)

jne <label> (jump when not equal)

jz <label> (jump when last result was zero)

jg <label> (jump when greater than)

jge <label> (jump when greater than or equal to)

jl <label> (jump when less than)

jle <label> (jump when less than or equal to)

Example

```
cmp ebx, eax
```

```
jle done
```

Control Flow Instructions

cmp — Compare

Syntax

```
cmp <reg>, <reg>
```

```
cmp <mem>, <reg>
```

```
cmp <reg>, <mem>
```

```
cmp <con>, <reg>
```

Example

```
cmp byte ptr [ebx], 10
```

```
jeq loop
```

If the byte stored at the memory location in EBX is equal to the integer constant 10, jump to the location labeled loop.

Control Flow Instructions

call — Subroutine call

The call instruction first **pushes the current code location onto the hardware supported stack** in memory, and then performs an **unconditional jump to the code** location indicated by the label operand. *Unlike the simple jump instructions, the call instruction saves the location to return to when the subroutine completes.*

Syntax

call <label>

call <reg32>

Call <mem>

Control Flow Instructions

ret — Subroutine return

The `ret` instruction implements a subroutine return mechanism. This instruction pops a code location off the hardware supported in-memory stack to the program counter.

Syntax

`ret`

The Run-time Stack

The run-time stack supports procedure calls and the passing of parameters between procedures.

The stack is located in memory.

The stack grows towards **low memory**.

When we push a value, esp is decremented.

When we pop a value, esp is incremented.

Stack Instructions

enter — Create a function frame

Equivalent to:

```
push ebp  
mov ebp, esp  
sub esp, Imm
```

Stack Instructions

leave — Releases the function frame set up by an earlier ENTER instruction.

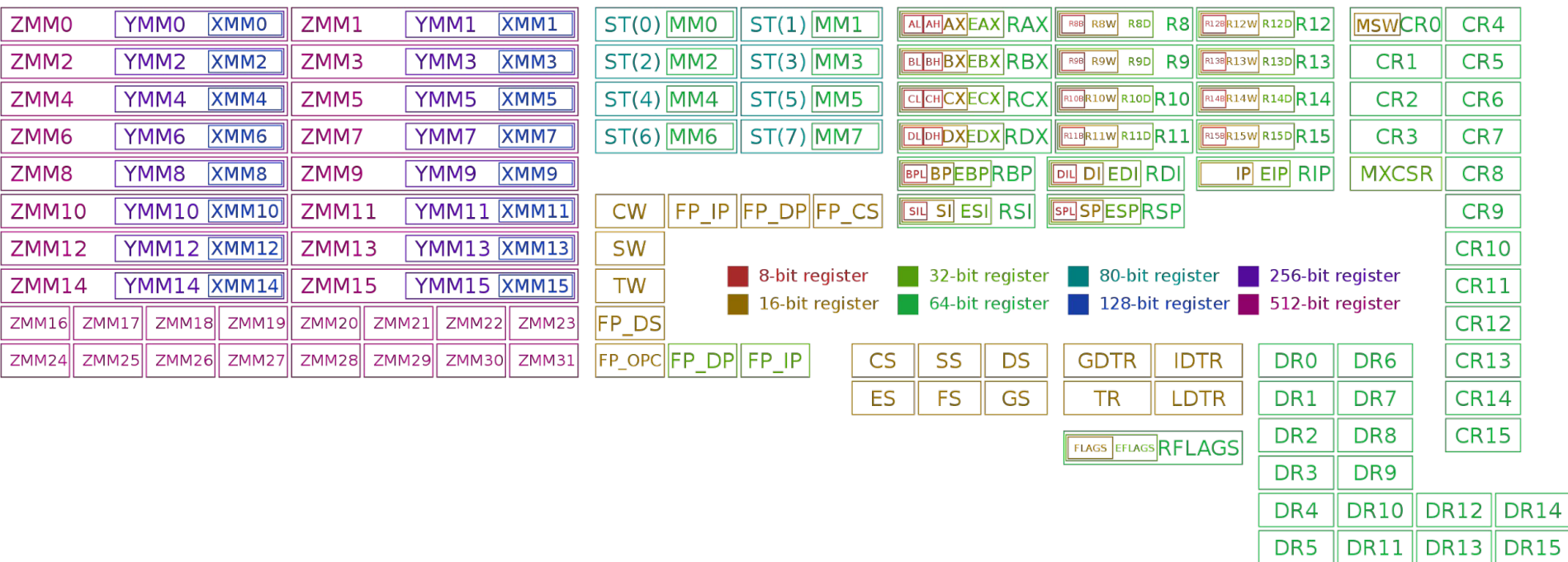
Equivalent to:

```
mov esp, ebp  
pop ebp
```

Background Knowledge:

amd64 architecture

Registers on x86 and x86-64



x86 vs. x86-64 (code/ladd)

main.c

```
/*  
This program has an integer overflow vulnerability.  
*/
```

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

```
long long ladd(long long *xp, long long y)  
{  
    long long t = *xp + y;  
    return t;  
}
```

```
gcc -Wall -m32 -O2 main.c -o ladd
```

```
gcc -Wall -O2 main.c -o ladd64
```

```
int main(int argc, char *argv[])
```

```
{  
    long long a = 0;  
    long long b = 0;
```

```
    if (argc != 3)  
    {  
        printf("Usage: ladd a b\n");  
        return 0;  
    }
```

```
    printf("The sizeof(long long) is %d\n", sizeof(long long));
```

```
    a = atoll(argv[1]);  
    b = atoll(argv[2]);
```

```
    printf("%lld + %lld = %lld\n", a, b, ladd(&a, b));  
}
```

x86 vs. x86-64 (code/ladd)

x86

```
000012c0 <ladd>:
 12c0:  f3 0f 1e fb      endbr32
 12c4:  8b 44 24 04      mov  eax,DWORD PTR [esp+0x4]
 12c8:  8b 50 04         mov  edx,DWORD PTR [eax+0x4]
 12cb:  8b 00           mov  eax,DWORD PTR [eax]
 12cd:  03 44 24 08      add  eax,DWORD PTR [esp+0x8]
 12d1:  13 54 24 0c      adc  edx,DWORD PTR [esp+0xc]
 12d5:  c3              ret
```

x86-64

```
00000000000001220 <ladd>:
 1220:  f3 0f 1e fa      endbr64
 1224:  48 8b 07         mov  rax,QWORD PTR [rdi]
 1227:  48 01 f0         add  rax,rsi
 122a:  c3              ret
```

```
objdump -M intel -d ladd_32
objdump -M intel -d ladd_64
```

Background Knowledge: Linux File Permissions

Permission Groups

Each file and directory has three user-based permission groups:

Owner – A user is the owner of the file. By default, the person who created a file becomes its owner. The Owner permissions apply only to the owner of the file or directory

Group – A group can contain multiple users. All users belonging to a group will have the same access permissions to the file. The Group permissions apply only to the group that has been assigned to the file or directory

Others – The others permissions apply to all other users on the system.

Permission Types

Each file or directory has three basic permission types defined for all the 3 user types:

Read – The Read permission refers to a user's capability to read the contents of the file.

Write – The Write permissions refer to a user's capability to write or modify a file or directory.

Execute – The Execute permission affects a user's capability to execute a file or view the contents of a directory.

File type: First field in the output is file type. If there is a - it means it is a plain file. If there is d it means it is a directory, c represents a character device, b represents a block device.

```
ziming@ziming-ThinkPad:~$ ls -l
total 530336
-rw-rw-r-- 1 ziming ziming 742772 Oct 29 2019 14-P2P.pdf
-rw-rw-r-- 1 ziming ziming 32956 Mar 21 23:21 19273679_G.webp
-rw-rw-r-- 1 ziming ziming 94868 Mar 21 23:20 200320_brigham.jpg
-rw-r--r-- 1 ziming ziming 700 Nov 18 2019 2.txt
-rw-r--r-- 1 ziming ziming 145408 Aug 20 2018 acpi_override
drwxr-xr-x 9 ziming ziming 4096 Mar 18 15:48 App
drwxrwxr-x 4 ziming ziming 4096 Apr 11 2019 Arduino
-rw-r--r-- 1 ziming ziming 163225 Jul 14 2019 autoproxy.pac
drwxr-xr-x 3 ziming ziming 4096 May 21 10:22 Desktop
drwxr-xr-x 3 ziming ziming 4096 Oct 11 2018 devel
drwxr-xr-x 3 ziming ziming 4096 Oct 26 2018 develqemu
drwxr-xr-x 4 ziming ziming 4096 May 19 14:31 Documents
drwxr-xr-x 4 ziming ziming 69632 May 24 10:11 Downloads
drwx----- 58 ziming ziming 4096 May 24 09:51 Dropbox
-rw-r--r-- 1 ziming ziming 144272 Aug 20 2018 dsdt.aml
-rw-r--r-- 1 ziming ziming 1075439 Aug 20 2018 dsdt.dsl
-rw-r--r-- 1 ziming ziming 1075439 Aug 20 2018 dsdt.dsl.ziming.manual
-rw-r--r-- 1 ziming ziming 1352883 Aug 20 2018 dsdt.hex
-rw-r--r-- 1 ziming ziming 0 Nov 6 2019 enclave.token
-rw-rw-r-- 1 ziming ziming 57747 Mar 21 23:20 ETj0lBjXkAMXVJs-630x390.jpg
-rw-r--r-- 1 ziming ziming 8980 Aug 16 2018 examples.desktop
```

Permissions for owner, group, and others

```
ziming@ziming-ThinkPad:~$ ls -l
total 530336
-rw-rw-r-- 1 ziming ziming 742772 Oct 29 2019 14-P2P.pdf
-rw-rw-r-- 1 ziming ziming 32956 Mar 21 23:21 19273679_G.webp
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drwxr-xr-x 9 ziming ziming 4096 Mar 18 15:48 App
drwxrwxr-x 4 ziming ziming 4096 Apr 11 2019 Arduino
-rw-r--r-- 1 ziming ziming 163225 Jul 14 2019 autoproxy.pac
drwxr-xr-x 3 ziming ziming 4096 May 21 10:22 Desktop
drwxr-xr-x 3 ziming ziming 4096 Oct 11 2018 devel
drwxr-xr-x 3 ziming ziming 4096 Oct 26 2018 develqemu
drwxr-xr-x 4 ziming ziming 4096 May 19 14:31 Documents
drwxr-xr-x 4 ziming ziming 69632 May 24 10:11 Downloads
drwx----- 58 ziming ziming 4096 May 24 09:51 Dropbox
-rw-r--r-- 1 ziming ziming 144272 Aug 20 2018 dsdt.aml
-rw-r--r-- 1 ziming ziming 1075439 Aug 20 2018 dsdt.dsl
-rw-r--r-- 1 ziming ziming 1075439 Aug 20 2018 dsdt.dsl.ziming.manual
-rw-r--r-- 1 ziming ziming 1352883 Aug 20 2018 dsdt.hex
-rw-r--r-- 1 ziming ziming 0 Nov 6 2019 enclave.token
-rw-rw-r-- 1 ziming ziming 57747 Mar 21 23:20 ETj0lBjXkAMXVJs-630x390.jpg
-rw-r--r-- 1 ziming ziming 8980 Aug 16 2018 examples.desktop
```


Link count

```
ziming@ziming-ThinkPad:~$ ls -l
total 530336
-rw-rw-r-- 1 ziming ziming 742772 Oct 29 2019 14-P2P.pdf
-rw-rw-r-- 1 ziming ziming 32956 Mar 21 23:21 19273679_G.webp
-rw-rw-r-- 1 ziming ziming 94868 Mar 21 23:20 200320_brigham.jpg
-rw-r--r-- 1 ziming ziming 700 Nov 18 2019 2.txt
-rw-r--r-- 1 ziming ziming 145408 Aug 20 2018 acpi_override
drwxr-xr-x 9 ziming ziming 4096 Mar 18 15:48 App
drwxrwxr-x 4 ziming ziming 4096 Apr 11 2019 Arduino
-rw-r--r-- 1 ziming ziming 163225 Jul 14 2019 autoproxy.pac
drwxr-xr-x 3 ziming ziming 4096 May 21 10:22 Desktop
drwxr-xr-x 3 ziming ziming 4096 Oct 11 2018 devel
drwxr-xr-x 3 ziming ziming 4096 Oct 26 2018 develqemu
drwxr-xr-x 4 ziming ziming 4096 May 19 14:31 Documents
drwxr-xr-x 4 ziming ziming 69632 May 24 10:11 Downloads
drwx----- 58 ziming ziming 4096 May 24 09:51 Dropbox
-rw-r--r-- 1 ziming ziming 144272 Aug 20 2018 dsdt.aml
-rw-r--r-- 1 ziming ziming 1075439 Aug 20 2018 dsdt.dsl
-rw-r--r-- 1 ziming ziming 1075439 Aug 20 2018 dsdt.dsl.ziming.manual
-rw-r--r-- 1 ziming ziming 1352883 Aug 20 2018 dsdt.hex
-rw-r--r-- 1 ziming ziming 0 Nov 6 2019 enclave.token
-rw-rw-r-- 1 ziming ziming 57747 Mar 21 23:20 ETj0lBjXkAMXVJs-630x390.jpg
-rw-r--r-- 1 ziming ziming 8980 Aug 16 2018 examples.desktop
```

Owner: This field provide info about the creator of the file.

```
ziming@ziming-ThinkPad:~$ ls -l
total 530336
-rw-rw-r-- 1 ziming ziming 742772 Oct 29 2019 14-P2P.pdf
-rw-rw-r-- 1 ziming ziming 32956 Mar 21 23:21 19273679_G.webp
-rw-rw-r-- 1 ziming ziming 94868 Mar 21 23:20 200320_brigham.jpg
-rw-r--r-- 1 ziming ziming 700 Nov 18 2019 2.txt
-rw-r--r-- 1 ziming ziming 145408 Aug 20 2018 acpi_override
drwxr-xr-x 9 ziming ziming 4096 Mar 18 15:48 App
drwxrwxr-x 4 ziming ziming 4096 Apr 11 2019 Arduino
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drwxr-xr-x 3 ziming ziming 4096 May 21 10:22 Desktop
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drwxr-xr-x 3 ziming ziming 4096 Oct 26 2018 develqemu
drwxr-xr-x 4 ziming ziming 4096 May 19 14:31 Documents
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-rw-r--r-- 1 ziming ziming 1352883 Aug 20 2018 dsdt.hex
-rw-r--r-- 1 ziming ziming 0 Nov 6 2019 enclave.token
-rw-rw-r-- 1 ziming ziming 57747 Mar 21 23:20 ETj0lBjXkAMXVJs-630x390.jpg
-rw-r--r-- 1 ziming ziming 8980 Aug 16 2018 examples.desktop
```

Group

```
ziming@ziming-ThinkPad:~$ ls -l
```

```
total 530336
```

```
-rw-rw-r-- 1 ziming ziming 742772 Oct 29 2019 14-P2P.pdf
-rw-rw-r-- 1 ziming ziming 32956 Mar 21 23:21 19273679_G.webp
-rw-rw-r-- 1 ziming ziming 94868 Mar 21 23:20 200320_brigham.jpg
-rw-r--r-- 1 ziming ziming 700 Nov 18 2019 2.txt
-rw-r--r-- 1 ziming ziming 145408 Aug 20 2018 acpi_override
drwxr-xr-x 9 ziming ziming 4096 Mar 18 15:48 App
drwxrwxr-x 4 ziming ziming 4096 Apr 11 2019 Arduino
-rw-r--r-- 1 ziming ziming 163225 Jul 14 2019 autoproxy.pac
drwxr-xr-x 3 ziming ziming 4096 May 21 10:22 Desktop
drwxr-xr-x 3 ziming ziming 4096 Oct 11 2018 devel
drwxr-xr-x 3 ziming ziming 4096 Oct 26 2018 develqemu
drwxr-xr-x 4 ziming ziming 4096 May 19 14:31 Documents
drwxr-xr-x 4 ziming ziming 69632 May 24 10:11 Downloads
drwx----- 58 ziming ziming 4096 May 24 09:51 Dropbox
-rw-r--r-- 1 ziming ziming 144272 Aug 20 2018 dsdt.aml
-rw-r--r-- 1 ziming ziming 1075439 Aug 20 2018 dsdt.dsl
-rw-r--r-- 1 ziming ziming 1075439 Aug 20 2018 dsdt.dsl.ziming.manual
-rw-r--r-- 1 ziming ziming 1352883 Aug 20 2018 dsdt.hex
-rw-r--r-- 1 ziming ziming 0 Nov 6 2019 enclave.token
-rw-rw-r-- 1 ziming ziming 57747 Mar 21 23:20 ETj0lBjXkAMXVJs-630x390.jpg
-rw-r--r-- 1 ziming ziming 8980 Aug 16 2018 examples.desktop
```


File size

```
ziming@ziming-ThinkPad:~$ ls -l
total 530336
-rw-rw-r-- 1 ziming ziming 742772 Oct 29 2019 14-P2P.pdf
-rw-rw-r-- 1 ziming ziming 32956 Mar 21 23:21 19273679_G.webp
-rw-rw-r-- 1 ziming ziming 94868 Mar 21 23:20 200320_brigham.jpg
-rw-r--r-- 1 ziming ziming 700 Nov 18 2019 2.txt
-rw-r--r-- 1 ziming ziming 145408 Aug 20 2018 acpi_override
drwxr-xr-x 9 ziming ziming 4096 Mar 18 15:48 App
drwxrwxr-x 4 ziming ziming 4096 Apr 11 2019 Arduino
-rw-r--r-- 1 ziming ziming 163225 Jul 14 2019 autoproxy.pac
drwxr-xr-x 3 ziming ziming 4096 May 21 10:22 Desktop
drwxr-xr-x 3 ziming ziming 4096 Oct 11 2018 devel
drwxr-xr-x 3 ziming ziming 4096 Oct 26 2018 develqemu
drwxr-xr-x 4 ziming ziming 4096 May 19 14:31 Documents
drwxr-xr-x 4 ziming ziming 69632 May 24 10:11 Downloads
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-rw-r--r-- 1 ziming ziming 144272 Aug 20 2018 dsdt.aml
-rw-r--r-- 1 ziming ziming 1075439 Aug 20 2018 dsdt.dsl
-rw-r--r-- 1 ziming ziming 1075439 Aug 20 2018 dsdt.dsl.ziming.manual
-rw-r--r-- 1 ziming ziming 1352883 Aug 20 2018 dsdt.hex
-rw-r--r-- 1 ziming ziming 0 Nov 6 2019 enclave.token
-rw-rw-r-- 1 ziming ziming 57747 Mar 21 23:20 ETj0lBjXkAMXVJs-630x390.jpg
-rw-r--r-- 1 ziming ziming 8980 Aug 16 2018 examples.desktop
```

Last modify time

```
ziming@ziming-ThinkPad:~$ ls -l
```

```
total 530336
```

-rw-rw-r--	1	ziming	ziming	742772	Oct 29	2019	14-P2P.pdf
-rw-rw-r--	1	ziming	ziming	32956	Mar 21	23:21	19273679_G.webp
-rw-rw-r--	1	ziming	ziming	94868	Mar 21	23:20	200320_brigham.jpg
-rw-r--r--	1	ziming	ziming	700	Nov 18	2019	2.txt
-rw-r--r--	1	ziming	ziming	145408	Aug 20	2018	acpi_override
drwxr-xr-x	9	ziming	ziming	4096	Mar 18	15:48	App
drwxrwxr-x	4	ziming	ziming	4096	Apr 11	2019	Arduino
-rw-r--r--	1	ziming	ziming	163225	Jul 14	2019	autoproxy.pac
drwxr-xr-x	3	ziming	ziming	4096	May 21	10:22	Desktop
drwxr-xr-x	3	ziming	ziming	4096	Oct 11	2018	devel
drwxr-xr-x	3	ziming	ziming	4096	Oct 26	2018	develqemu
drwxr-xr-x	4	ziming	ziming	4096	May 19	14:31	Documents
drwxr-xr-x	4	ziming	ziming	69632	May 24	10:11	Downloads
drwx-----	58	ziming	ziming	4096	May 24	09:51	Dropbox
-rw-r--r--	1	ziming	ziming	144272	Aug 20	2018	dsdt.aml
-rw-r--r--	1	ziming	ziming	1075439	Aug 20	2018	dsdt.dsl
-rw-r--r--	1	ziming	ziming	1075439	Aug 20	2018	dsdt.dsl.ziming.manual
-rw-r--r--	1	ziming	ziming	1352883	Aug 20	2018	dsdt.hex
-rw-r--r--	1	ziming	ziming	0	Nov 6	2019	enclave.token
-rw-rw-r--	1	ziming	ziming	57747	Mar 21	23:20	ETj0lBjXkAMXVJs-630x390.jpg
-rw-r--r--	1	ziming	ziming	8980	Aug 16	2018	examples.desktop

filename

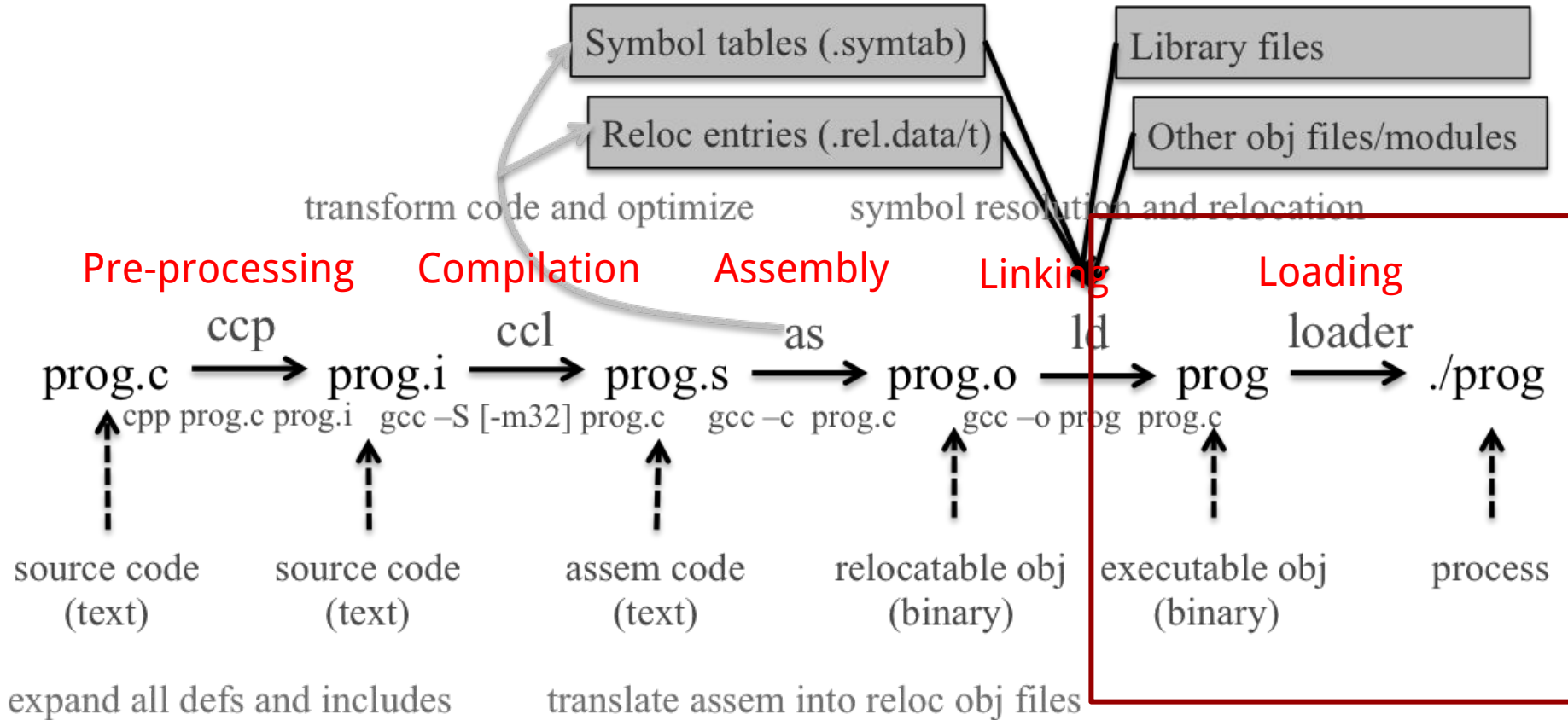
```
ziming@ziming-ThinkPad:~$ ls -l
```

```
total 530336
```

-rw-rw-r--	1	ziming	ziming	742772	Oct	29	2019	14-P2P.pdf
-rw-rw-r--	1	ziming	ziming	32956	Mar	21	23:21	19273679_G.webp
-rw-rw-r--	1	ziming	ziming	94868	Mar	21	23:20	200320_brigham.jpg
-rw-r--r--	1	ziming	ziming	700	Nov	18	2019	2.txt
-rw-r--r--	1	ziming	ziming	145408	Aug	20	2018	acpi_override
drwxr-xr-x	9	ziming	ziming	4096	Mar	18	15:48	App
drwxrwxr-x	4	ziming	ziming	4096	Apr	11	2019	Arduino
-rw-r--r--	1	ziming	ziming	163225	Jul	14	2019	autoproxy.pac
drwxr-xr-x	3	ziming	ziming	4096	May	21	10:22	Desktop
drwxr-xr-x	3	ziming	ziming	4096	Oct	11	2018	devel
drwxr-xr-x	3	ziming	ziming	4096	Oct	26	2018	develqemu
drwxr-xr-x	4	ziming	ziming	4096	May	19	14:31	Documents
drwxr-xr-x	4	ziming	ziming	69632	May	24	10:11	Downloads
drwx-----	58	ziming	ziming	4096	May	24	09:51	Dropbox
-rw-r--r--	1	ziming	ziming	144272	Aug	20	2018	dsdt.aml
-rw-r--r--	1	ziming	ziming	1075439	Aug	20	2018	dsdt.dsl
-rw-r--r--	1	ziming	ziming	1075439	Aug	20	2018	dsdt.dsl.ziming.manual
-rw-r--r--	1	ziming	ziming	1352883	Aug	20	2018	dsdt.hex
-rw-r--r--	1	ziming	ziming	0	Nov	6	2019	enclave.token
-rw-rw-r--	1	ziming	ziming	57747	Mar	21	23:20	ETj0lBjXkAMXVJs-630x390.jpg
-rw-r--r--	1	ziming	ziming	8980	Aug	16	2018	examples.desktop

Background Knowledge: Set-UID Programs

From a C program to a process



Real UID, Effective UID, and Saved UID

Each Linux/Unix **process** has 3 UIDs associated with it.

Real UID (RUID): This is the UID of the user/process that created THIS process. It can be changed only if the running process has EUID=0.

Effective UID (EUID): This UID is used to evaluate privileges of the process to perform a particular action. EUID can be changed either to RUID, or SUID if EUID!=0. If EUID=0, it can be changed to anything.

Saved UID (SUID): If the binary image file, that was launched has a Set-UID bit on, SUID will be the UID of the owner of the file. Otherwise, SUID will be the RUID.

Set-UID Program

The kernel makes the decision whether a process has the privilege by looking on the **EUID** of the process.

For non Set-UID programs, the effective uid and the real uid are the same. For Set-UID programs, **the effective uid is the owner of the program**, while the real uid is the user of the program.

What will happen is when a setuid binary executes, the process changes its Effective User ID (EUID) from the default RUID to the owner of this special binary executable file which in this case is - root.


```
ziming@ziming-ThinkPad:~$ ls -al /bin/
```

```
total 12676
drwxr-xr-x  2 root root    4096 May 26 00:14 .
drwxr-xr-x 26 root root    4096 May 18 09:57 ..
-rwxr-xr-x  1 root root 1113504 Jun  6 2019 bash
-rwxr-xr-x  1 root root  748968 Aug 29 2018 brltty
-rwxr-xr-x  3 root root   34888 Jul  4 2019 bunzip2
-rwxr-xr-x  1 root root 2062296 Mar  6 2019 busybox
-rwxr-xr-x  3 root root   34888 Jul  4 2019 bzipcat
lrwxrwxrwx  1 root root      6 Jul  4 2019 bzcmp -> bzdiff
-rwxr-xr-x  1 root root   2140 Jul  4 2019 bzdiff
lrwxrwxrwx  1 root root      6 Jul  4 2019 bzegrep ->
-rwxr-xr-x  1 root root   4877 Jul  4 2019 bzexe lrwxrwxrwx  1 root root      4 Aug 16 2018 sh -> dash
lrwxrwxrwx  1 root root      6 Jul  4 2019 bzfgrep -> lrwxrwxrwx  1 root root      4 Aug 16 2018 sh.distrib -> dash
-rwxr-xr-x  1 root root   3642 Jul  4 2019 bzgrep -> -rwxr-xr-x  1 root root   35000 Jan 18 2018 sleep
-rwxr-xr-x  3 root root   34888 Jul  4 2019 bzip2 -rwxr-xr-x  1 root root 139904 May 11 10:40 ss
-rwxr-xr-x  1 root root 14328 Jul  4 2019 bzip2recover lrwxrwxrwx  1 root root      7 Mar  6 2019 static-sh -> busybox
lrwxrwxrwx  1 root root      6 Jul  4 2019 bzless -> -rwxr-xr-x  1 root root   75992 Jan 18 2018 stty
-rwxr-xr-x  1 root root   1297 Jul  4 2019 bzmores -rwsr-xr-x  1 root root   44664 Mar 22 2019 su
-rwxr-xr-x  1 root root   35064 Jan 18 2018 cat -rwxr-xr-x  1 root root   35000 Jan 18 2018 sync
-rwxr-xr-x  1 root root 14328 Apr 21 2017 chacl -rwxr-xr-x  1 root root 182352 May  3 07:30 systemctl
lrwxrwxrwx  1 root root   63672 Jan 18 2018 chgrp lrwxrwxrwx  1 root root    20 May  3 07:30 systemd -> /lib/systemd/systemd
-rwxr-xr-x  1 root root   59608 Jan 18 2018 chmod -rwxr-xr-x  1 root root 10320 May  3 07:30 systemd-ask-password
-rwxr-xr-x  1 root root   67768 Jan 18 2018 chown -rwxr-xr-x  1 root root 14400 May  3 07:30 systemd-escape
-rwxr-xr-x  1 root root 10312 Jan 22 2018 chvt -rwxr-xr-x  1 root root 84328 May  3 07:30 systemd-hwdb
-rwxr-xr-x  1 root root 141528 Jan 18 2018 cp -rwxr-xr-x  1 root root 14416 May  3 07:30 systemd-inhibit
-rwxr-xr-x  1 root root 157224 Nov  5 2019 cpio -rwxr-xr-x  1 root root 18496 May  3 07:30 systemd-machine-id-setup
-rwxr-xr-x  1 root root 121432 Jan 25 2018 dash -rwxr-xr-x  1 root root 14408 May  3 07:30 systemd-notify
-rwxr-xr-x  1 root root 100568 Jan 18 2018 date -rwxr-xr-x  1 root root 43080 May  3 07:30 systemd-sysusers
-rwxr-xr-x  1 root root  76000 Jan 18 2018 dd -rwxr-xr-x  1 root root 71752 May  3 07:30 systemd-tmpfiles
-rwxr-xr-x  1 root root 84776 Jan 18 2018 df -rwxr-xr-x  1 root root 26696 May  3 07:30 systemd-tty-ask-password-agent
-rwxr-xr-x  1 root root 133792 Jan 18 2018 dir -rwxr-xr-x  1 root root 423312 Jan 21 2019 tar
-rwxr-xr-x  1 root root  72000 Mar  5 12:23 dmesg -rwxr-xr-x  1 root root 10104 Dec 30 2017 tempfile
-rwxr-xr-x  1 root root -rwxr-xr-x  1 root root 88280 Jan 18 2018 touch
-rwxr-xr-x  1 root root 30904 Jan 18 2018 true
-rwxr-xr-x  1 root root 584072 May  3 07:30 udevadm
-rwxr-xr-x  1 root root 14328 Aug 11 2016 ulockmgr_server
-rwsr-xr-x  1 root root 26696 Mar  5 12:23 umount
-rwxr-xr-x  1 root root 35032 Jan 18 2018 uname
```

-rwxr-xr-x	1	root	root	39103	Apr	23	2019	setupcon
lrwxrwxrwx	1	root	root	4	Aug	16	2018	sh -> dash
lrwxrwxrwx	1	root	root	4	Aug	16	2018	sh.distrib -> dash
-rwxr-xr-x	1	root	root	35000	Jan	18	2018	sleep
-rwxr-xr-x	1	root	root	139904	May	11	10:40	ss
lrwxrwxrwx	1	root	root	7	Mar	6	2019	static-sh -> busybox
-rwxr-xr-x	1	root	root	75992	Jan	18	2018	stty
-rwsr-xr-x	1	root	root	44664	Mar	22	2019	su
-rwxr-xr-x	1	root	root	35000	Jan	18	2018	sync
-rwxr-xr-x	1	root	root	182352	May	3	07:30	systemctl
lrwxrwxrwx	1	root	root	20	May	3	07:30	systemd -> /lib/systemd/systemd
-rwxr-xr-x	1	root	root	10320	May	3	07:30	systemd-ask-password
-rwxr-xr-x	1	root	root	14400	May	3	07:30	systemd-escape
-rwxr-xr-x	1	root	root	84328	May	3	07:30	systemd-hwdb
-rwxr-xr-x	1	root	root	14416	May	3	07:30	systemd-inhibit
-rwxr-xr-x	1	root	root	18496	May	3	07:30	systemd-machine-id-setup
-rwxr-xr-x	1	root	root	14408	May	3	07:30	systemd-notify
-rwxr-xr-x	1	root	root	43080	May	3	07:30	systemd-sysusers
-rwxr-xr-x	1	root	root	71752	May	3	07:30	systemd-tmpfiles
-rwxr-xr-x	1	root	root	26696	May	3	07:30	systemd-tty-ask-password-agent
-rwxr-xr-x	1	root	root	423312	Jan	21	2019	tar
-rwxr-xr-x	1	root	root	10104	Dec	30	2017	tempfile
-rwxr-xr-x	1	root	root	88280	Jan	18	2018	touch
-rwxr-xr-x	1	root	root	30904	Jan	18	2018	true
-rwxr-xr-x	1	root	root	584072	May	3	07:30	udevadm
-rwxr-xr-x	1	root	root	14328	Aug	11	2016	unlockmgr_server
-rwsr-xr-x	1	root	root	26696	Mar	5	12:23	umount
-rwxr-xr-x	1	root	root	35032	Jan	18	2018	uname

Example: rdsecret

main.c

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <pwd.h>

int main(int argc, char *argv[])
{
    FILE *fp = NULL;
    char buffer[100] = {0};

    // get ruid and euid
    uid_t uid = getuid();
    struct passwd *pw = getpwuid(uid);
    if (pw)
    {
        printf("UID: %d, USER: %s.\n", uid, pw->pw_name);
    }

    uid_t euid = geteuid();
    pw = getpwuid(euid);
```

```
    if (pw)
    {
        printf("EUID: %d, EUSER: %s.\n", euid, pw->pw_name);
    }

    print_flag();

    return(0);
}

void print_flag()
{
    FILE *fp;
    char buff[MAX_FLAG_SIZE];
    fp = fopen("flag", "r");
    fread(buff, MAX_FLAG_SIZE, 1, fp);
    printf("flag is : %s\n", buff);
    fclose(fp);
}
```


Background Knowledge: ELF Binary Files

ELF Files

The **Executable and Linkable Format (ELF)** is a common standard file format for *executable files, object code, shared libraries, and core dumps*. Filename extension *none, .axf, .bin, .elf, .o, .prx, .puff, .ko, .mod* and *.so*

Contains the program and its data. Describes how the program should be loaded (program/segment headers). Contains metadata describing program components (section headers).

Command *file*

```
ziming@ziming-XPS-13-9300:~$ file /bin/ls
/bin/ls: ELF 64-bit LSB shared object, x86-64, version 1 (SYSV), dynamically lin
ked, interpreter /lib64/ld-linux-x86-64.so.2, BuildID[sha1]=2f15ad836be3339dec0e
2e6a3c637e08e48aacbd, for GNU/Linux 3.2.0, stripped
ziming@ziming-XPS-13-9300:~$
```

file /bin/ls

```

zmling@zmling-XPS-13-9300:~$ readelf -a /bin/ls
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00
  Class:                   ELF64
  Data:                     2's complement, little endian
  Version:                  1 (current)
  OS/ABI:                   UNIX - System V
  ABI Version:              0
  Type:                     DYN (Shared object file)
  Machine:                  Advanced Micro Devices X86-64
  Version:                  0x1
  Entry point address:      0x67d0
  Start of program headers: 64 (bytes into file)
  Start of section headers: 140224 (bytes into file)
  Flags:                    0x0
  Size of this header:      64 (bytes)
  Size of program headers:  56 (bytes)
  Number of program headers: 13
  Size of section headers:  64 (bytes)
  Number of section headers: 30
  Section header string table index: 29

```

Section Headers:

[Nr]	Name	Type	Address	Offset
	Size	EntSize	Flags Link Info Align	
[0]	0000000000000000	NULL	0000000000000000	00000000
[1]	.interp 000000000000001c	PROGBITS	000000000000318 A 0 0 1	00000318
[2]	.note.gnu.propert 0000000000000020	NOTE	000000000000338 A 0 0 8	00000338
[3]	.note.gnu.build-i 0000000000000024	NOTE	000000000000358 A 0 0 4	00000358
[4]	.note.ABI-tag 0000000000000020	NOTE	00000000000037c A 0 0 4	0000037c
[5]	.gnu.hash 00000000000000e4	GNU_HASH	0000000000003a0 A 6 0 8	000003a0
[6]	.dynsym 00000000000000d8	DYNSYM	000000000000488 A 7 1 8	00000488
[7]	.dynstr 0000000000000064c	STRTAB	0000000000001190 A 0 0 1	00001190
[8]	.gnu.version 0000000000000116	VERSYM	00000000000017dc A 6 0 2	000017dc
[9]	.gnu.version_r 0000000000000070	VERNEED	00000000000018f8 A 7 1 8	000018f8
[10]	.rela.dyn 0000000000001350	RELA	0000000000001968 A 6 0 8	00001968
[11]	.rela.plt 00000000000009f0	RELA	0000000000002cb8 AI 6 25 8	00002cb8
[12]	.init 000000000000001b	PROGBITS	0000000000004000 AX 0 0 4	00004000
[13]	.plt 00000000000006b0	PROGBITS	0000000000004020 AX 0 0 16	00004020

INTERP: defines the library that should be used to load this ELF into memory.

LOAD: defines a part of the file that should be loaded into memory.

Sections:

.text: the executable code of your program.

.plt and **.got:** used to resolve and dispatch library calls.

.data: used for pre-initialized global writable data (such as global arrays with initial values)

.rodata: used for global read-only data (such as string constants)

.bss: used for uninitialized global writable data (such as global arrays without initial values)

Tools for ELF

gcc to make your ELF.

readelf to parse the ELF header.

objdump to parse the ELF header and disassemble the source code.

nm to view your ELF's symbols.

patchelf to change some ELF properties.

objcopy to swap out ELF sections.

strip to remove otherwise-helpful information (such as symbols).

kaitai struct (<https://ide.kaitai.io/>) to look through your ELF interactively.

Background Knowledge: Memory Map of a Linux Process

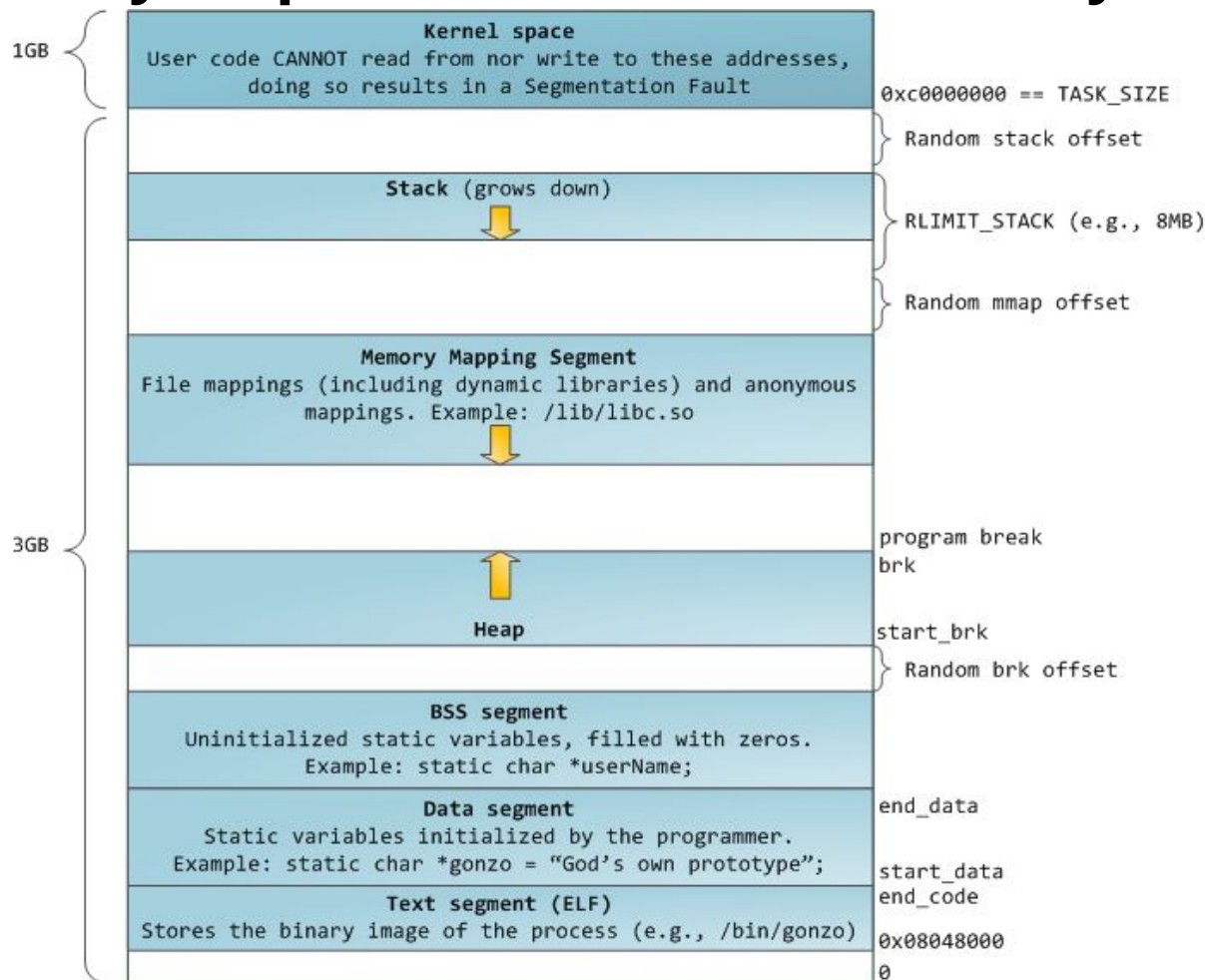
Memory Map of Linux Process (32 bit)

Each process in a multi-tasking OS runs in its own memory sandbox.

This sandbox is the **virtual address space**, which in 32-bit mode is **always a 4GB block of memory addresses**.

These virtual addresses are mapped to physical memory by **page tables**, which are maintained by the operating system kernel and consulted by the processor.

Memory Map of Linux Process (32 bit system)



<https://manybutfinite.com/pos-anatomy-of-a-program-in-memory/>

NULL Pointer in C/C++

```
int * pInt = NULL;
```

In possible definitions of NULL in C/C++:

```
#define NULL ((char *)0)
```

```
#define NULL 0
```

```
//since C++11
```

```
#define NULL nullptr
```

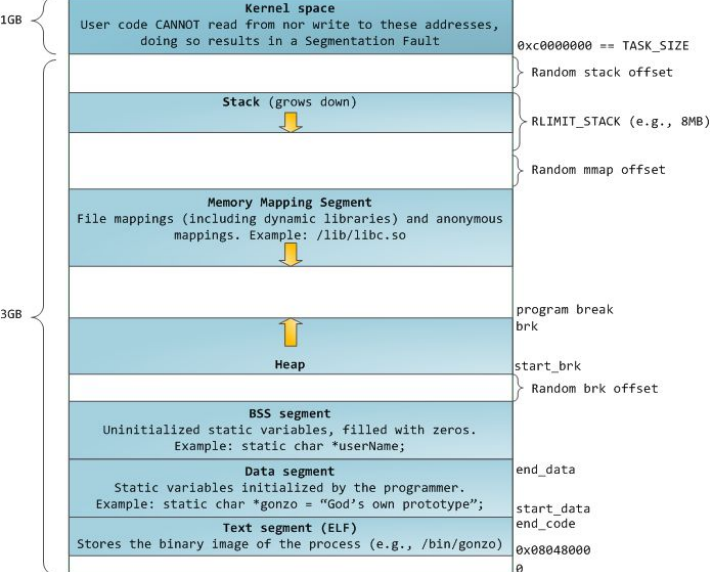
/proc/pid_of_process/maps

Example processmap.c

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

int main()
{
    getchar();
    return 0;
}
```

```
cat /proc/pid/maps
pmap -X pid
pmap -X `pidof pm`
```



```

ziming@ziming-ThinkPad:~/Dropbox/myTeaching/System Security - Attack and Defense for Binaries UB 2020/code/processmap$ pmap -X 21732
21732:  ./pm
Address Perm  Offset Device      Inode  Size  Rss  Pss  Referenced Anonymous LazyFree ShmemPmdMapped Shared_Hugetlb Private_Hugetlb Swap SwapPss Locked Mapping
56569000 r-xp 00000000 103:02 28575310 4 4 4 4 0 0 0 0 0 0 0 0 pm
5656a000 r--p 00000000 103:02 28575310 4 4 4 4 4 0 0 0 0 0 0 0 pm
5656b000 rw-p 00001000 103:02 28575310 4 4 4 4 4 0 0 0 0 0 0 0 pm
57cf2000 rw-p 00000000 00:00 0 136 4 4 4 4 0 0 0 0 0 0 0 [heap]
f7d73000 r-xp 00000000 103:02 2883591 1876 772 772 772 0 0 0 0 0 0 0 0 libc-2.27.so
f7f48000 ---p 001d5000 103:02 2883591 4 0 0 0 0 0 0 0 0 0 0 0 libc-2.27.so
f7f49000 r--p 001d5000 103:02 2883591 8 8 8 8 8 0 0 0 0 0 0 0 0 libc-2.27.so
f7f4b000 rw-p 001d7000 103:02 2883591 4 4 4 4 4 0 0 0 0 0 0 0 0 libc-2.27.so
f7f4c000 rw-p 00000000 00:00 0 12 8 8 8 8 0 0 0 0 0 0 0 0
f7f75000 rw-p 00000000 00:00 0 8 8 8 8 8 0 0 0 0 0 0 0 0
f7f77000 r--p 00000000 00:00 0 12 0 0 0 0 0 0 0 0 0 0 0 [vvar]
f7f7a000 r-xp 00000000 00:00 0 8 8 8 8 8 0 0 0 0 0 0 0 [vdso]
f7f7c000 r-xp 00000000 103:02 2883587 152 144 144 144 0 0 0 0 0 0 0 0 ld-2.27.so
f7fa2000 r--p 00025000 103:02 2883587 4 4 4 4 4 0 0 0 0 0 0 0 0 ld-2.27.so
f7fa3000 rw-p 00026000 103:02 2883587 4 4 4 4 4 0 0 0 0 0 0 0 0 ld-2.27.so
ffef3000 rw-p 00000000 00:00 0 132 12 12 12 12 12 0 0 0 0 0 0 0 [stack]
=====
2372 988 988 988 60 0 0 0 0 0 0 0 0 0 0 0 KB
  
```

Memory Map of Linux Process (64 bit system)

```
ziming@ziming-ThinkPad:~/Dropbox/myTeaching/System Security - Attack and Defense for Binaries UB 2020/code/processmap$ pmap -X 22891
```

22891:	./pm64																	
	Address	Perm	Offset	Device	Inode	Size	Rss	Pss	Referenced	Anonymous	LazyFree	ShmemPmdMapped	Shared_Hugetlb	Private_Hugetlb	Swap	SwapPss	Locked	Mapping
	55bf7ae37000	r-xp	00000000	103:02	28577490	4	4	4	4	0	0	0	0	0	0	0	0	pm64
	55bf7b037000	r--p	00000000	103:02	28577490	4	4	4	4	4	0	0	0	0	0	0	0	pm64
	55bf7b038000	rw-p	00001000	103:02	28577490	4	4	4	4	4	0	0	0	0	0	0	0	pm64
	55bf7cc0c000	rw-p	00000000	00:00	0	132	4	4	4	4	0	0	0	0	0	0	0	[heap]
	7fc7ebdb6000	r-xp	00000000	103:02	660090	1948	992	5	992	0	0	0	0	0	0	0	0	libc-2.27.so
	7fc7ebf9d000	---p	001e7000	103:02	660090	2048	0	0	0	0	0	0	0	0	0	0	0	libc-2.27.so
	7fc7ec19d000	r--p	001e7000	103:02	660090	16	16	16	16	16	0	0	0	0	0	0	0	libc-2.27.so
	7fc7ec1a1000	rw-p	001eb000	103:02	660090	8	8	8	8	8	0	0	0	0	0	0	0	libc-2.27.so
	7fc7ec1a3000	rw-p	00000000	00:00	0	16	12	12	12	12	0	0	0	0	0	0	0	
	7fc7ec1a7000	r-xp	00000000	103:02	660062	156	156	0	156	0	0	0	0	0	0	0	0	ld-2.27.so
	7fc7ec3a6000	rw-p	00000000	00:00	0	8	8	8	8	8	0	0	0	0	0	0	0	
	7fc7ec3ce000	r--p	00027000	103:02	660062	4	4	4	4	4	0	0	0	0	0	0	0	ld-2.27.so
	7fc7ec3cf000	rw-p	00028000	103:02	660062	4	4	4	4	4	0	0	0	0	0	0	0	ld-2.27.so
	7fc7ec3d0000	rw-p	00000000	00:00	0	4	4	4	4	4	0	0	0	0	0	0	0	
	7ffe05803000	rw-p	00000000	00:00	0	132	12	12	12	12	0	0	0	0	0	0	0	[stack]
	7ffe058b9000	r--p	00000000	00:00	0	12	0	0	0	0	0	0	0	0	0	0	0	[vvar]
	7ffe058bc000	r-xp	00000000	00:00	0	8	4	0	4	0	0	0	0	0	0	0	0	[vdso]
	fffffffff600000	r-xp	00000000	00:00	0	4	0	0	0	0	0	0	0	0	0	0	0	[vsyscall]
						4512	1236	89	1236	80	0	0	0	0	0	0	0	0 KB

Due

1. Academic integrity quiz is assigned. The academic integrity quiz must be answered correctly within the two weeks of classes to pass the course.
2. Homework-1 due before the class of Week-3