NEU CY 5770 Software Vulnerabilities and Security

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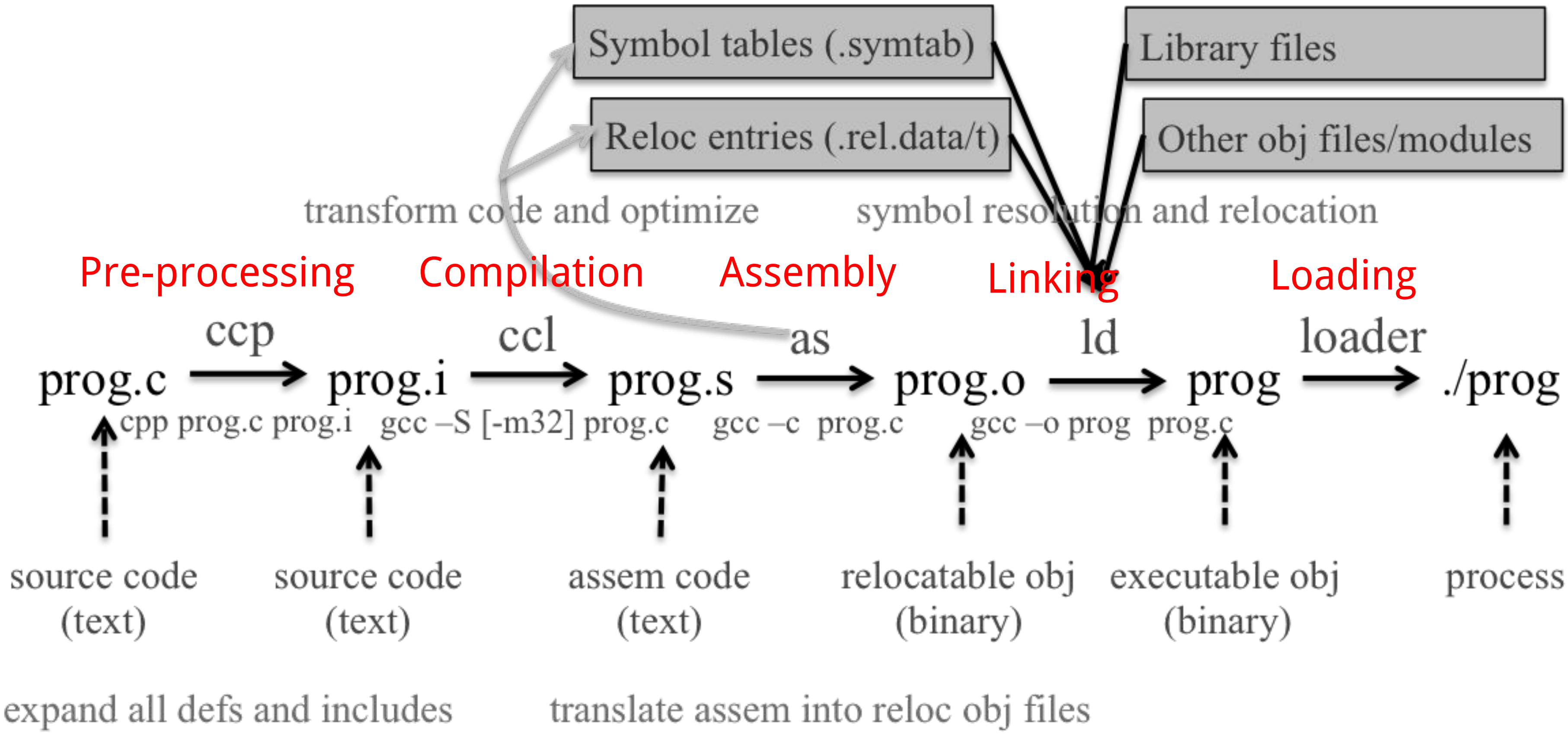
Agenda

1. Background knowledge
   a. Compiler, linker, loader
   b. x86 and x86-64 architectures and ISA
   c. ARM ISA
   d. Linux fundamentals
      i. Linux file permissions
      ii. Set-UID programs
      iii. Memory map of a Linux process
      iv. System calls
      v. Piping
      vi. Environment and Shell variables
      vii. ELF files
      viii. Reverse engineering tools

Background Knowledge: Compiler, linker, and loader

From a C program to a process



A Shell in a Nutshell

```
int pid = fork();

if (pid == 0) {
    // I am the child process

    exec("ls"); }
else if (pid == -1)
{
    // fork failed
}
else {
    // I am the parent; continue my business being a cool program
    // I could wait for the child to finish if I want
}
```

https://github.com/kamalmarhubi/shell-workshop

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.

1. Copying the command-line arguments on the stack
2. Initializing registers (e.g., the stack pointer)
3. Jumping to the program entry point (_start)

Compiling a C program behind the scene (add_32 add_64)

add.c

```c
#include "add.h"

#define BASE 50

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

add.h

```c
#ifndef ADD_H
#define ADD_H

int add(int, int);

#endif
```

main.c

```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
```

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

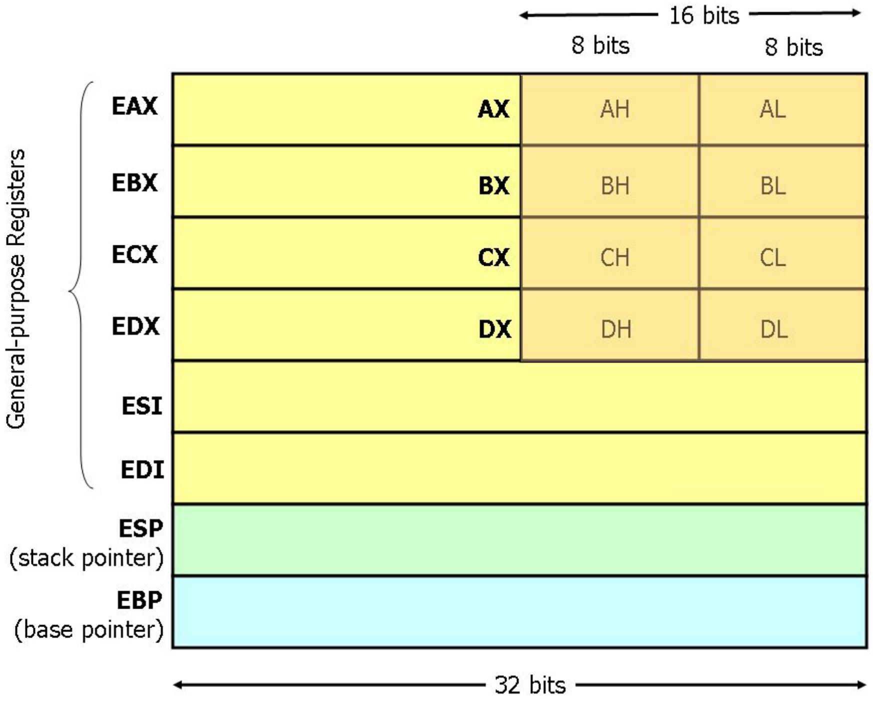
Address 0	0x12
Address 1	0x34
Address 2	0x56
Address 3	0x78

Base Registers

There are

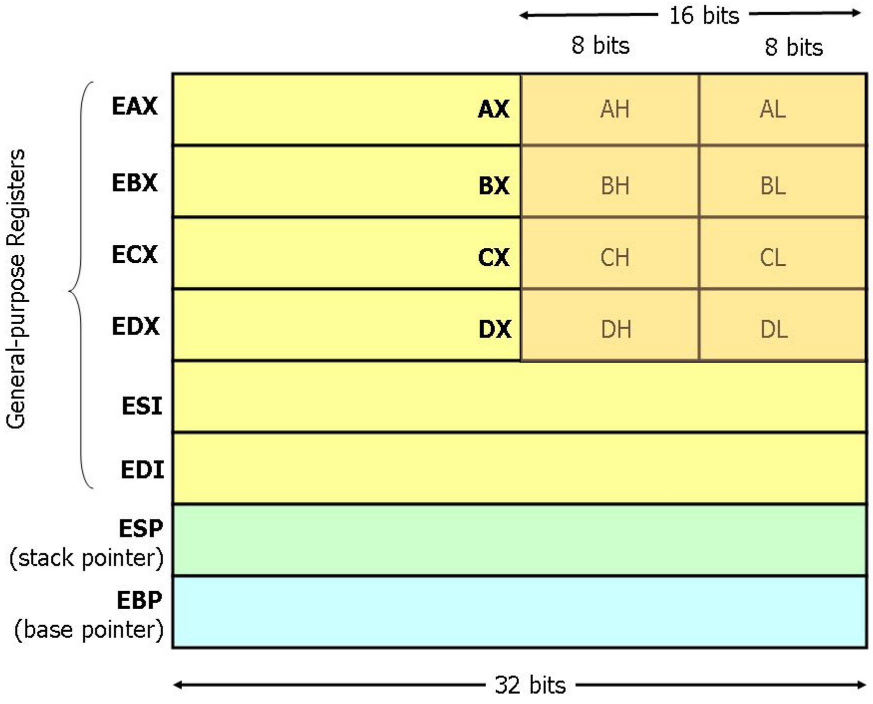
- Eight 32-bit “general-purpose” registers,
- One 32-bit EFLAGS register,
- One 32-bit instruction pointer register (eip), and
- Other special-purpose registers.

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.

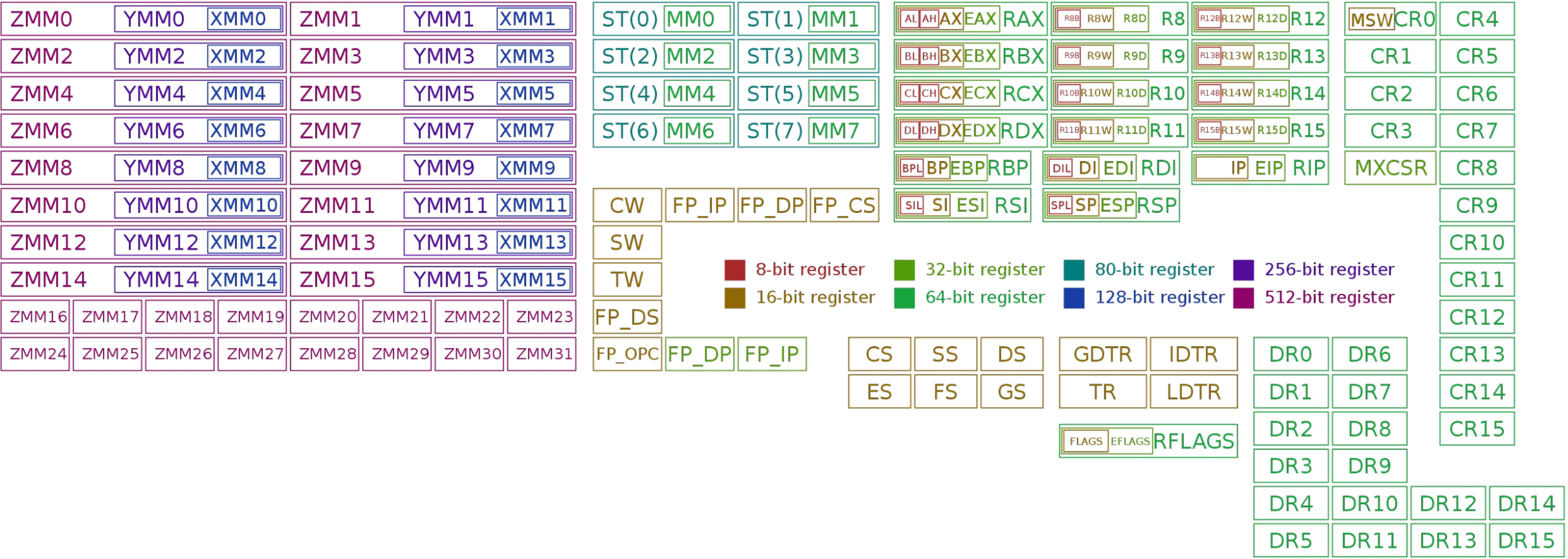
We will be interested in, at most, the bits

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



https://en.wikipedia.org/wiki/X86

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>

In Intel syntax the first operand is the destination

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)

Square bracket [] represents memory location.

mov [eax], ebx Copy 4 bytes from register EBX into memory address specified in 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 2n 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

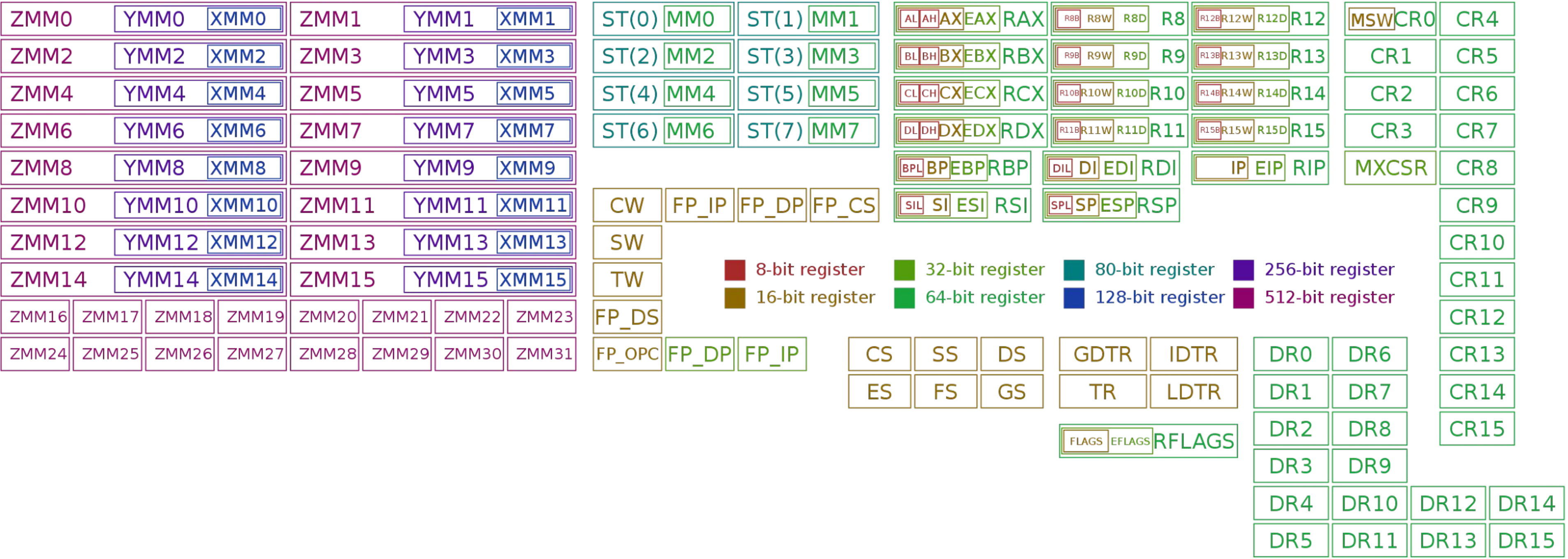
leave — Releases the function frame set up by an earlier ENTER instruction.

Equivalent to:

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

Background Knowledge: x86-64/amd64 architecture

Registers on x86 and x86-64



https://en.wikipedia.org/wiki/X86

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;
}
```

```
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));
}
```

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

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

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
```

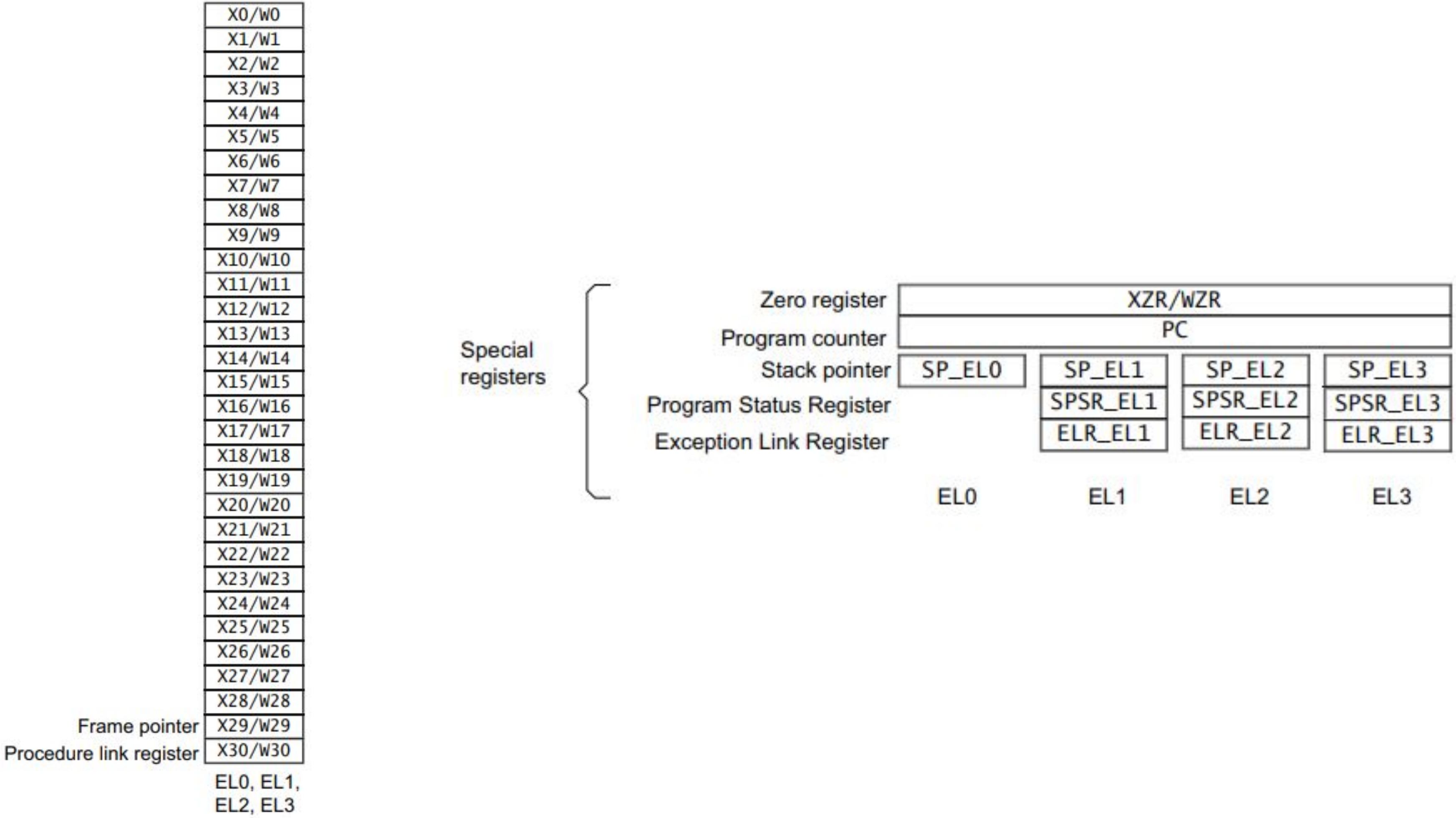
x86-64

```
0000000000001220 <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
```

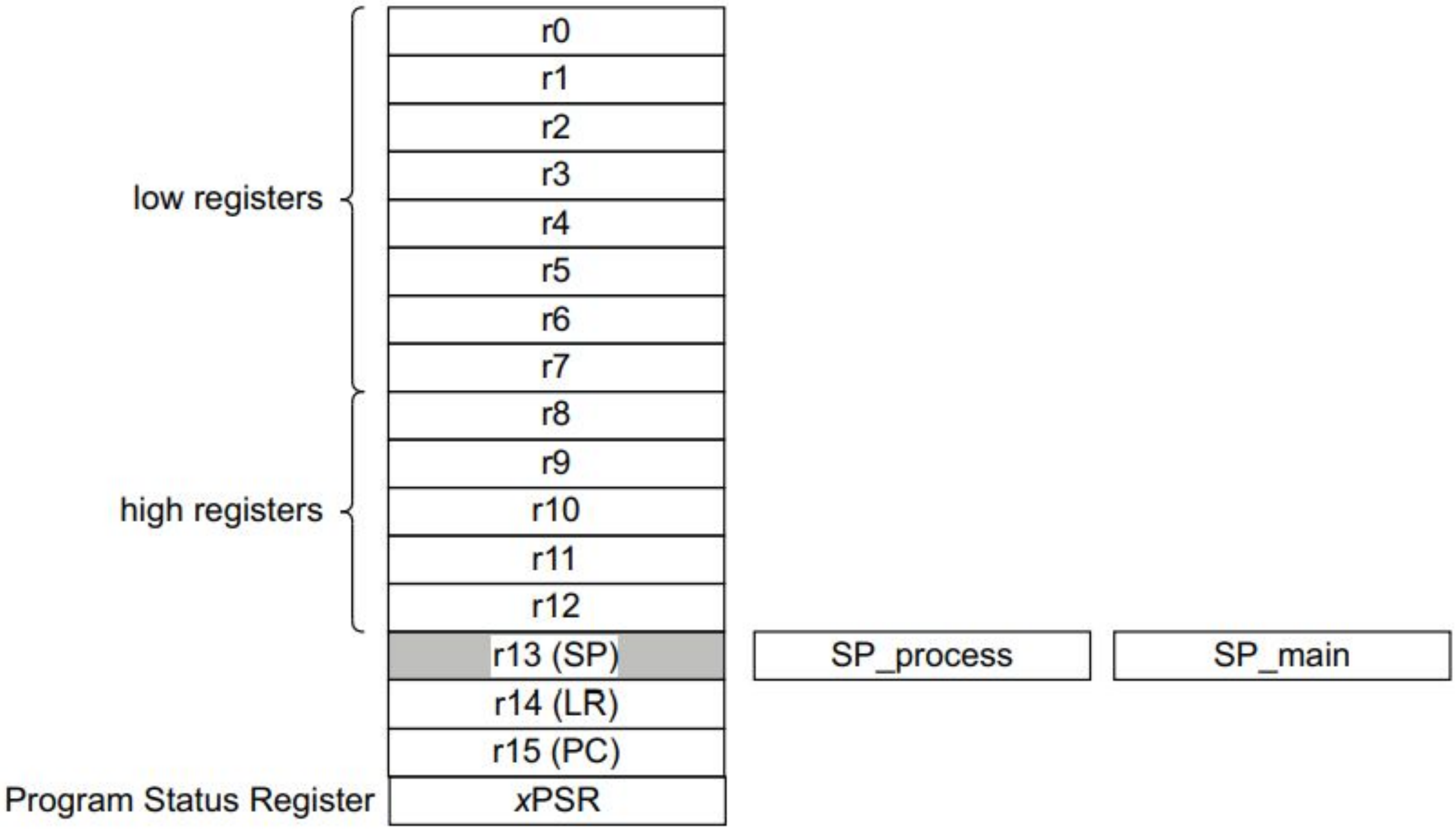
```
objdump -M intel -d ladd_32
objdump -M intel -d ladd_64
```

Background Knowledge:
ARM Cortex-A/M Architecture

Cortex-A 64 bit



Cortex-M 32 bit



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 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 the 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  ETjOlBjXkAMXVJs-630x390.jpg
-rw-r--r--  1 ziming ziming      8980 Aug 16  2018  examples.desktop
```

Permissions for owner, group, and others

```
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-rw-rw-r--  1 ziming ziming    742772 Oct 29  2019  14-P2P.pdf
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```

Link count

```
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-rw-r--r--  1 ziming ziming      8980 Aug 16  2018  examples.desktop
```

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

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Group

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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  ETjOlBjXkAMXVJs-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
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  ETjOlBjXkAMXVJs-630x390.jpg
-rw-r--r--  1 ziming ziming      8980 Aug 16  2018  examples.desktop
```

Last modify time

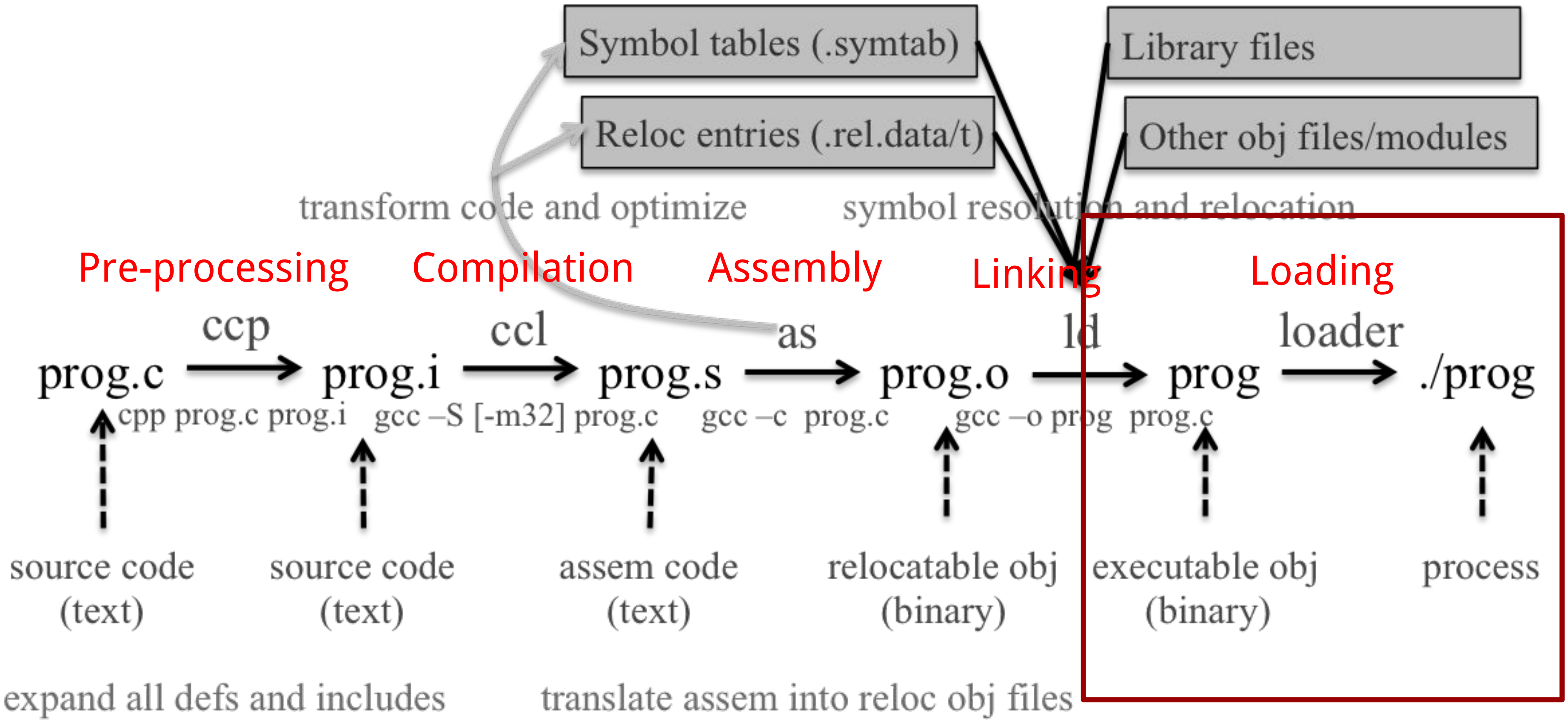
```
ziming@ziming-ThinkPad:~$ ls -l
total 530336
-rw-rw-r--  1 ziming ziming    742772 Oct 29  2019 14-P2P.pdf
-rw-rw-r--  1 ziming ziming     32956 Mar 21 23:21 19273679_G.webp
-rw-rw-r--  1 ziming ziming     94868 Mar 21 23:20 200320_brigham.jpg
-rw-r--r--  1 ziming ziming       700 Nov 18  2019 2.txt
-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 ETjOlBjXkAMXVJs-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 ETjOlBjXkAMXVJs-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 bzcat
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       6 Jul  4  2019 bzfgrep ->
-rwxr-xr-x  1 root root    3642 Jul  4  2019 bzgrep
-rwxr-xr-x  3 root root   34888 Jul  4  2019 bzip2
-rwxr-xr-x  1 root root   14328 Jul  4  2019 bzip2recov
lrwxrwxrwx  1 root root       6 Jul  4  2019 bzless ->
-rwxr-xr-x  1 root root    1297 Jul  4  2019 bzmore
-rwxr-xr-x  1 root root   35064 Jan 18  2018 cat
-rwxr-xr-x  1 root root   14328 Apr 21  2017 chacl
-rwxr-xr-x  1 root root   63672 Jan 18  2018 chgrp
-rwxr-xr-x  1 root root   59608 Jan 18  2018 chmod
-rwxr-xr-x  1 root root   67768 Jan 18  2018 chown
-rwxr-xr-x  1 root root   10312 Jan 22  2018 chvt
-rwxr-xr-x  1 root root  141528 Jan 18  2018 cp
-rwxr-xr-x  1 root root  157224 Nov  5  2019 cpio
-rwxr-xr-x  1 root root  121432 Jan 25  2018 dash
-rwxr-xr-x  1 root root  100568 Jan 18  2018 date
-rwxr-xr-x  1 root root   76000 Jan 18  2018 dd
-rwxr-xr-x  1 root root   84776 Jan 18  2018 df
-rwxr-xr-x  1 root root  133792 Jan 18  2018 dir
-rwxr-xr-x  1 root root   72000 Mar  5 12:23 dmesg
```

```
-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 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 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
```

Example: rdsecret

main.c

```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);
```

```c
 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);
}
```

Why do we need Set-UID programs?

Many system tasks require **privileged access**, but should be safely usable by **unprivileged users**.

Examples:

- Changing your password (passwd)
- Mounting devices
- Modifying system configuration
- Managing network settings

Running all user programs as root would be disastrous for security.

Why do we need Set-UID programs?

Unix introduces **setuid programs**:

- A program file is marked with a special bit (setuid)
- When executed, the process runs with the **file owner's privileges**
- Commonly owned by root

This allows:

Temporary privilege elevation for a specific task

Microsoft Windows’ solution

Windows does **not** use file-based privilege elevation.

Instead, it uses:

- **Access tokens**
- **User Account Control (UAC)**
- **Privilege separation with services**

Typical pattern:

1. User program runs unprivileged
2. Requests privileged action
3. Windows service (running as SYSTEM/Admin) performs the action after approval

Privilege is controlled by the **OS security subsystem**, not the executable file.

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

```
ziming@ziming-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 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]                   NULL             0000000000000000  00000000
       0000000000000000  0000000000000000           0     0     0
  [ 1] .interp           PROGBITS         0000000000000318  00000318
       000000000000001c  0000000000000000   A       0     0     1
  [ 2] .note.gnu.propert NOTE             0000000000000338  00000338
       0000000000000020  0000000000000000   A       0     0     8
  [ 3] .note.gnu.build-i NOTE             0000000000000358  00000358
       0000000000000024  0000000000000000   A       0     0     4
  [ 4] .note.ABI-tag     NOTE             000000000000037c  0000037c
       0000000000000020  0000000000000000   A       0     0     4
  [ 5] .gnu.hash         GNU_HASH         00000000000003a0  000003a0
       00000000000000e4  0000000000000000   A       6     0     8
  [ 6] .dynsym           DYNSYM           0000000000000488  00000488
       0000000000000d08  0000000000000018   A       7     1     8
  [ 7] .dynstr           STRTAB           0000000000001190  00001190
       000000000000064c  0000000000000000   A       0     0     1
  [ 8] .gnu.version      VERSYM           00000000000017dc  000017dc
       0000000000000116  0000000000000002   A       6     0     2
  [ 9] .gnu.version_r    VERNEED          00000000000018f8  000018f8
       0000000000000070  0000000000000000   A       7     1     8
  [10] .rela.dyn         RELA             0000000000001968  00001968
       0000000000001350  0000000000000018   A       6     0     8
  [11] .rela.plt         RELA             0000000000002cb8  00002cb8
       00000000000009f0  0000000000000018  AI       6    25     8
  [12] .init             PROGBITS         0000000000004000  00004000
       000000000000001b  0000000000000000  AX       0     0     4
  [13] .plt              PROGBITS         0000000000004020  00004020
       00000000000006b0  0000000000000010  AX       0     0     16
```

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)

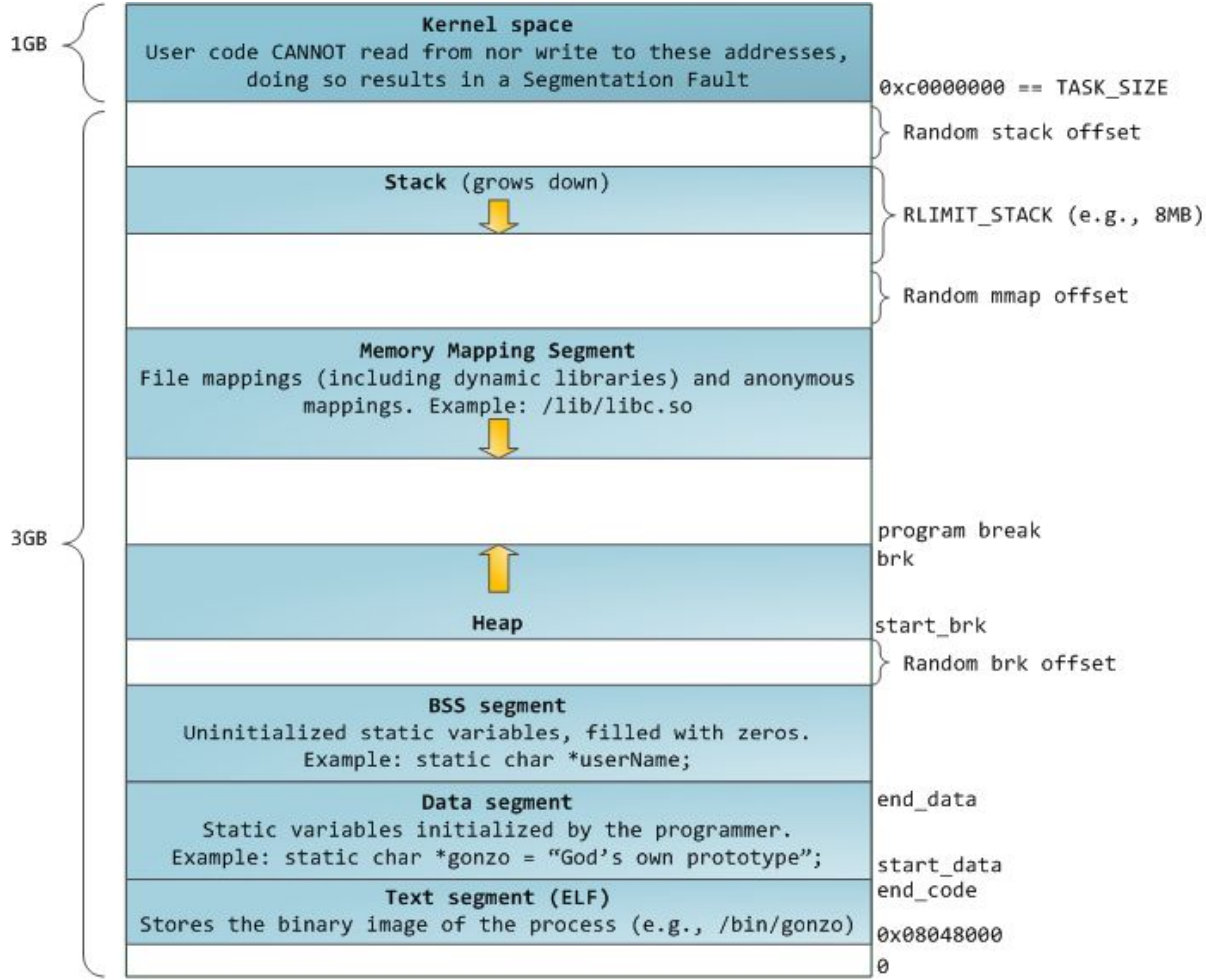
Each process in a multi-tasking OS runs in its own memory sandbox.

This sandbox is the **virtual address space**.

- In 32-bit mode is a 4GB block of memory addresses.
- On modern Linux x86-64 systems, the CPU supports 64-bit virtual addresses, but Linux actually uses only 48 bits (and on newer systems up to 57 bits with 5-level paging).

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-me
mory/

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
```

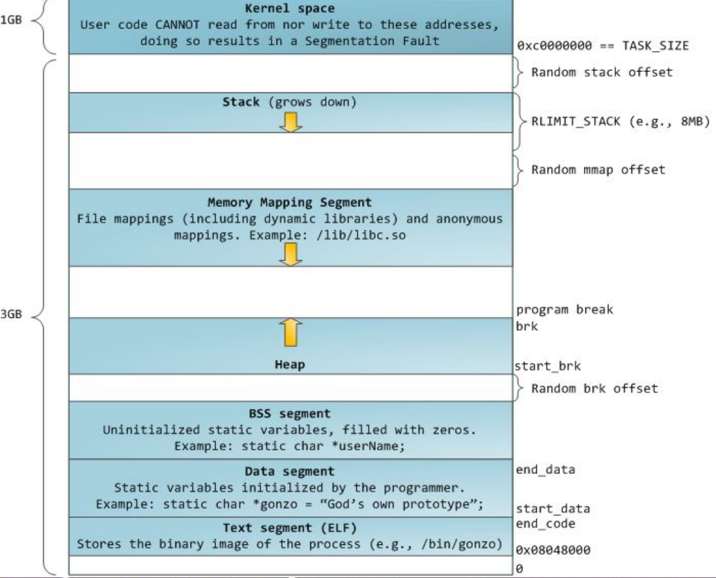
/proc/pid_of_process/maps

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 libc-2.27.so
f7f4b000 rw-p 001d7000 103:02  2883591    4   4   4          4         4        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
f7f75000 rw-p 00000000  00:00        0    8   8   8          8         8        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         0        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 ld-2.27.so
f7fa3000 rw-p 00026000 103:02  2883587    4   4   4          4         4        0              0              0               0    0       0      0 ld-2.27.so
ffef3000 rw-p 00000000  00:00        0  132  12  12         12        12        0              0              0               0    0       0      0 [stack]
                                       ==== === === ========== ========= ======== ============== ============== =============== ==== ======= ======
                                       2372 988 988        988        60        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]
ffffffffff600000 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 KB
```

Background Knowledge: System Calls

What are System Calls?

When a process needs to invoke a kernel service, it invokes a procedure call in the operating system interface using special instructions (not a **call** instruction in x86). Such a procedure is called a system call.

The system call enters the kernel; the kernel performs the service and returns. Thus a process alternates between executing in user space and kernel space.

System calls are generally not invoked directly by a program, but rather via wrapper functions in glibc (or perhaps some other library).

Popular System Call

On Unix, Unix-like and other POSIX-compliant operating systems, popular system calls are open, read, write, close, wait, exec, fork, exit, and kill.

Many modern operating systems have hundreds of system calls. For example, Linux and OpenBSD each have over 300 different calls, FreeBSD has over 500, Windows 7 has close to 700.

Glibc interfaces

Often, but not always, the name of the wrapper function is the same as the name of the system call that it invokes.

For example, glibc contains a function chdir() which invokes the underlying "chdir" system call.

Tools: strace & ltrace

```
ctf@misc_firstflag_64:/$ strace ./misc_firstflag_64
execve("./misc_firstflag_64", ["./misc_firstflag_64"], 0x7fffffffe680 /* 17 vars */) = 0
access("/etc/suid-debug", F_OK)         = -1 ENOENT (No such file or directory)
brk(NULL)                               = 0x555555559000
arch_prctl(0x3001 /* ARCH_??? */, 0x7fffffffe5a0) = -1 EINVAL (Invalid argument)
fcntl(0, F_GETFD)                       = 0
fcntl(1, F_GETFD)                       = 0
fcntl(2, F_GETFD)                       = 0
access("/etc/suid-debug", F_OK)         = -1 ENOENT (No such file or directory)
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=47355, ...}) = 0
mmap(NULL, 47355, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7ffff7fbf000
close(3)                                = 0
openat(AT_FDCWD, "/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0\360q\2\0\0\0\0\0"..., 832) = 832
pread64(3, "\6\0\0\0\4\0\0\0@\0\0\0\0\0\0\0@\0\0\0\0\0\0\0@\0\0\0\0\0\0\0"..., 784, 64) = 784
pread64(3, "\4\0\0\0\20\0\0\0\5\0\0\0GNU\0\2\0\0\300\4\0\0\0\3\0\0\0\0\0\0\0", 32, 848) = 32
pread64(3, "\4\0\0\0\24\0\0\0\3\0\0\0GNU\0\t\233\222%\274\260\320\31\331\326\10\204\276X>\263"..., 68, 880) = 68
fstat(3, {st_mode=S_IFREG|0755, st_size=2029224, ...}) = 0
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7ffff7fbd000
pread64(3, "\6\0\0\0\4\0\0\0@\0\0\0\0\0\0\0@\0\0\0\0\0\0\0@\0\0\0\0\0\0\0"..., 784, 64) = 784
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mmap(NULL, 2036952, PROT_READ, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7ffff7dcb000
mprotect(0x7ffff7df0000, 1847296, PROT_NONE) = 0
mmap(0x7ffff7df0000, 1540096, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x25000) = 0x7ffff7df0000
mmap(0x7ffff7f68000, 303104, PROT_READ, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x19d000) = 0x7ffff7f68000
mmap(0x7ffff7fb3000, 24576, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x1e7000) = 0x7ffff7fb3000
mmap(0x7ffff7fb9000, 13528, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0x7ffff7fb9000
close(3)                                = 0
arch_prctl(ARCH_SET_FS, 0x7ffff7fbe540) = 0
mprotect(0x7ffff7fb3000, 12288, PROT_READ) = 0
mprotect(0x555555557000, 4096, PROT_READ) = 0
mprotect(0x7ffff7ffc000, 4096, PROT_READ) = 0
munmap(0x7ffff7fbf000, 47355)           = 0
fstat(1, {st_mode=S_IFCHR|0620, st_rdev=makedev(0x88, 0), ...}) = 0
brk(NULL)                               = 0x555555559000
brk(0x55555557a000)                     = 0x55555557a000
write(1, "Congratulations on getting your "..., 45Congratulations on getting your first flag!!
) = 45
openat(AT_FDCWD, "/flag", O_RDONLY)     = -1 EACCES (Permission denied)
write(1, "Error: Cannot open the flag file"..., 36Error: Cannot open the flag file!!!
) = 36
exit_group(0)                           = ?
+++ exited with 0 +++
```

misc/firstflag

main.c

```
int main(int argc, char *argv[])
{
  printf("Congratulations on getting your first flag!!\n");
  print_flag();
}
```

flag.h

```
int print_flag()
{
        FILE *fp = NULL;
        char buff[MAX_FLAG_SIZE] = {0};

        fp = fopen("/flag", "r");

        if (fp == NULL)
        {
            printf("Error: Cannot open the flag file!!!\n");
            return 1;
        }

        fread(buff, MAX_FLAG_SIZE - 2, 1, fp);
        printf("The flag is: %s\n", buff);
        fclose(fp);
        return 0;
}
```

Tools: strace & ltrace

```
ctf@misc_firstflag_64:/$ strace ./misc_firstflag_64
execve("./misc_firstflag_64", ["./misc_firstflag_64"], 0x7fffffffe680 /* 17 vars */) = 0
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fcntl(0, F_GETFD)                        = 0
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pread64(3, "\4\0\0\0\20\0\0\0\5\0\0\0GNU\0\2\0\0\300\4\0\0\0\3\0\0\0\0\0\0\0", 32, 848) = 32
pread64(3, "\4\0\0\0\24\0\0\0\3\0\0\0GNU\0\t\233\222%\274\260\320\31\331\326\10\204\276X>\263"..., 68, 880) = 68
fstat(3, {st_mode=S_IFREG|0755, st_size=2029224, ...}) = 0
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pread64(3, "\6\0\0\0\4\0\0\0@\0\0\0\0\0\0\0@\0\0\0\0\0\0\0@\0\0\0\0\0\0\0"..., 784, 64) = 784
pread64(3, "\4\0\0\0\20\0\0\0\5\0\0\0GNU\0\2\0\0\300\4\0\0\0\3\0\0\0\0\0\0\0", 32, 848) = 32
pread64(3, "\4\0\0\0\24\0\0\0\3\0\0\0GNU\0\t\233\222%\274\260\320\31\331\326\10\204\276X>\263"..., 68, 880) = 68
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mprotect(0x7ffff7df0000, 1847296, PROT_NONE) = 0
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mmap(0x7ffff7f68000, 303104, PROT_READ, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x19d000) = 0x7ffff7f68000
mmap(0x7ffff7fb3000, 24576, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x1e7000) = 0x7ffff7fb3000
mmap(0x7ffff7fb9000, 13528, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0x7ffff7fb9000
close(3)                                 = 0
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mprotect(0x7ffff7fb3000, 12288, PROT_READ) = 0
mprotect(0x555555557000, 4096, PROT_READ) = 0
mprotect(0x7ffff7ffc000, 4096, PROT_READ) = 0
munmap(0x7ffff7fbf000, 47355)            = 0
fstat(1, {st_mode=S_IFCHR|0620, st_rdev=makedev(0x88, 0), ...}) = 0
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brk(0x55555557a000)                      = 0x55555557a000
write(1, "Congratulations on getting your "..., 45Congratulations on getting your first flag!!
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openat(AT_FDCWD, "/flag", O_RDONLY)      = -1 EACCES (Permission denied)
write(1, "Error: Cannot open the flag file"..., 36Error: Cannot open the flag file!!!
) = 36
exit_group(0)                            = ?
+++ exited with 0 +++
```

Execve - first system call
Access - check file permission
Brk - check data segment/heap
Arch_prctl - set architecture-specific thread state
Fcntl - manipulate file descriptor
Openat - similar to open
Fstat - get file status
Mmap - map files or devices into memory
Close
Read
Pread64 - similar to read
Mprotect - set protection on a region of memory
Munmap - map files or devices into memory
Write
Exit_group

Use “man 2 syscall_name” to check out its usage

Making a System Call in x86/64 Assembly

On x86/x86-64, most system calls rely on the software interrupt.

A software interrupt is caused either by an exceptional condition in the processor itself, or a special instruction (the **int 0x80** instruction or **syscall** instruction).

For example: a divide-by-zero exception will be thrown if the processor's arithmetic logic unit is commanded to divide a number by zero as this instruction is in error and impossible.

Making a System Call in x86 Assembly (INT 0x80)

x86 (32-bit)

Compiled from Linux 4.14.0 headers.

NR	syscall name	references	%eax	arg0 (%ebx)	arg1 (%ecx)	arg2 (%edx)	arg3 (%esi)	arg4 (%edi)	arg5 (%ebp)
0	restart_syscall	man/ cs/	0x00	-	-	-	-	-	-
1	exit	man/ cs/	0x01	int error_code	-	-	-	-	-
2	fork	man/ cs/	0x02	-	-	-	-	-	-
3	read	man/ cs/	0x03	unsigned int fd	char *buf	size_t count	-	-	-
4	write	man/ cs/	0x04	unsigned int fd	const char *buf	size_t count	-	-	-
5	open	man/ cs/	0x05	const char *filename	int flags	umode_t mode	-	-	-
6	close	man/ cs/	0x06	unsigned int fd	-	-	-	-	-
7	waitpid	man/ cs/	0x07	pid_t pid	int *stat_addr	int options	-	-	-
8	creat	man/ cs/	0x08	const char *pathname	umode_t mode	-	-	-	-
9	link	man/ cs/	0x09	const char *oldname	const char *newname	-	-	-	-
10	unlink	man/ cs/	0x0a	const char *pathname	-	-	-	-	-
11	execve	man/ cs/	0x0b	const char *filename	const char *const *argv	const char *const *envp	-	-	-
12	chdir	man/ cs/	0x0c	const char *filename	-	-	-	-	-
13	time	man/ cs/	0x0d	time_t *tloc	-	-	-	-	-
14	mknod	man/ cs/	0x0e	const char *filename	umode_t mode	unsigned dev	-	-	-
15	chmod	man/ cs/	0x0f	const char *filename	umode_t mode	-	-	-	-

https://chromium.googlesource.com/chromiumos/docs/+/master/constants/syscalls.md#x86-32_bit

Making a System Call in x86 Assembly

```
xor    eax,eax
push   eax
push   0x68732f2f
push   0x6e69622f
mov    ebx,esp
push   eax
push   ebx
mov    ecx,esp
mov    al,0xb
int    0x80
```

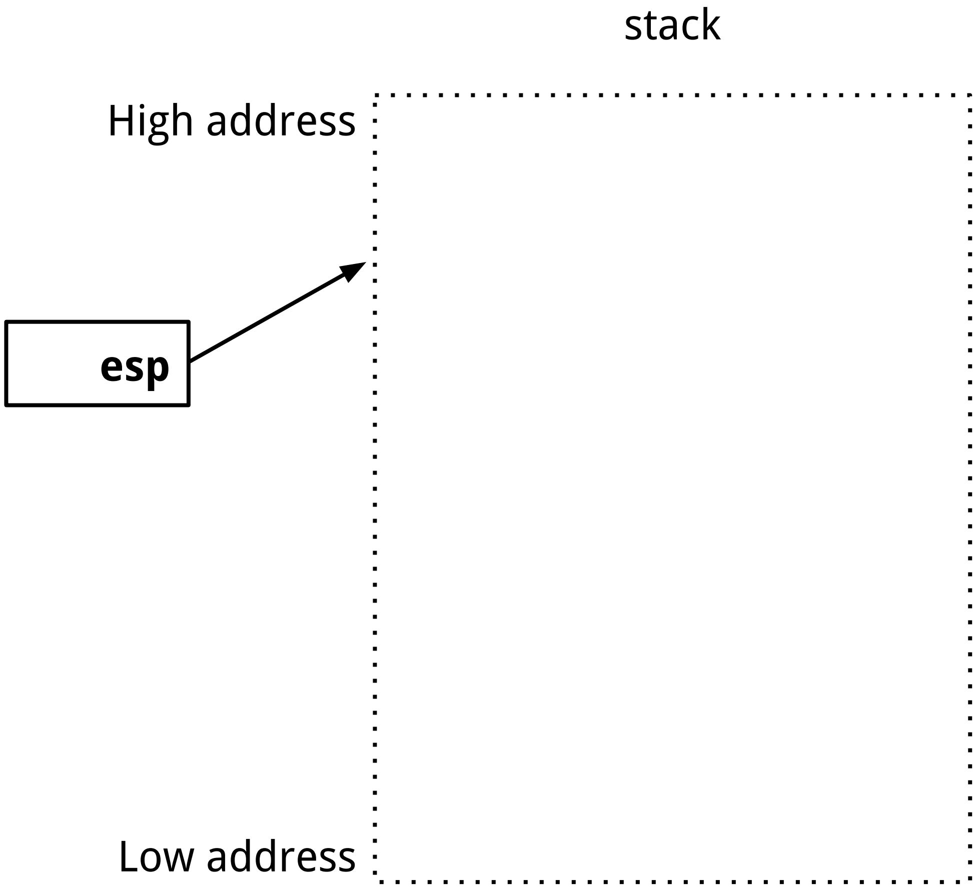
Dec	Hx	Oct	Char	Dec	Hx	Oct	Html	Chr	Dec	Hx	Oct	Html	Chr	Dec	Hx	Oct	Html	Chr
0	0	000	NUL (null)	32	20	040		Space	64	40	100	@	@	96	60	140	`	`
1	1	001	SOH (start of heading)	33	21	041	!	!	65	41	101	A	A	97	61	141	a	a
2	2	002	STX (start of text)	34	22	042	"	"	66	42	102	B	B	98	62	142	b	b
3	3	003	ETX (end of text)	35	23	043	#	#	67	43	103	C	C	99	63	143	c	c
4	4	004	EOT (end of transmission)	36	24	044	$	$	68	44	104	D	D	100	64	144	d	d
5	5	005	ENQ (enquiry)	37	25	045	%	%	69	45	105	E	E	101	65	145	e	e
6	6	006	ACK (acknowledge)	38	26	046	&	&	70	46	106	F	F	102	66	146	f	f
7	7	007	BEL (bell)	39	27	047	'	'	71	47	107	G	G	103	67	147	g	g
8	8	010	BS (backspace)	40	28	050	(	(	72	48	110	H	H	104	68	150	h	h
9	9	011	TAB (horizontal tab)	41	29	051	)	)	73	49	111	I	I	105	69	151	i	i
10	A	012	LF (NL line feed, new line)	42	2A	052	*	*	74	4A	112	J	J	106	6A	152	j	j
11	B	013	VT (vertical tab)	43	2B	053	+	+	75	4B	113	K	K	107	6B	153	k	k
12	C	014	FF (NP form feed, new page)	44	2C	054	,	,	76	4C	114	L	L	108	6C	154	l	l
13	D	015	CR (carriage return)	45	2D	055	-	-	77	4D	115	M	M	109	6D	155	m	m
14	E	016	SO (shift out)	46	2E	056	.	.	78	4E	116	N	N	110	6E	156	n	n
15	F	017	SI (shift in)	47	2F	057	/	/	79	4F	117	O	O	111	6F	157	o	o
16	10	020	DLE (data link escape)	48	30	060	0	0	80	50	120	P	P	112	70	160	p	p
17	11	021	DC1 (device control 1)	49	31	061	1	1	81	51	121	Q	Q	113	71	161	q	q
18	12	022	DC2 (device control 2)	50	32	062	2	2	82	52	122	R	R	114	72	162	r	r
19	13	023	DC3 (device control 3)	51	33	063	3	3	83	53	123	S	S	115	73	163	s	s
20	14	024	DC4 (device control 4)	52	34	064	4	4	84	54	124	T	T	116	74	164	t	t
21	15	025	NAK (negative acknowledge)	53	35	065	5	5	85	55	125	U	U	117	75	165	u	u
22	16	026	SYN (synchronous idle)	54	36	066	6	6	86	56	126	V	V	118	76	166	v	v
23	17	027	ETB (end of trans. block)	55	37	067	7	7	87	57	127	W	W	119	77	167	w	w
24	18	030	CAN (cancel)	56	38	070	8	8	88	58	130	X	X	120	78	170	x	x
25	19	031	EM (end of medium)	57	39	071	9	9	89	59	131	Y	Y	121	79	171	y	y
26	1A	032	SUB (substitute)	58	3A	072	:	:	90	5A	132	Z	Z	122	7A	172	z	z
27	1B	033	ESC (escape)	59	3B	073	;	;	91	5B	133	[	[	123	7B	173	{	{
28	1C	034	FS (file separator)	60	3C	074	<	<	92	5C	134	\	\	124	7C	174			|
29	1D	035	GS (group separator)	61	3D	075	=	=	93	5D	135	]	]	125	7D	175	}	}
30	1E	036	RS (record separator)	62	3E	076	>	>	94	5E	136	^	^	126	7E	176	~	~
31	1F	037	US (unit separator)	63	3F	077	?	?	95	5F	137	_	_	127	7F	177	&#127;	DEL

Source: www.LookupTables.com

http://shell-storm.org/shellcode/files/shellcode-827.php

Making a System Call in x86 Assembly

```
xor    eax,eax
push   eax
push   0x68732f2f
push   0x6e69622f
mov    ebx,esp
push   eax
push   ebx
mov    ecx,esp
mov    al,0xb
int    0x80
```



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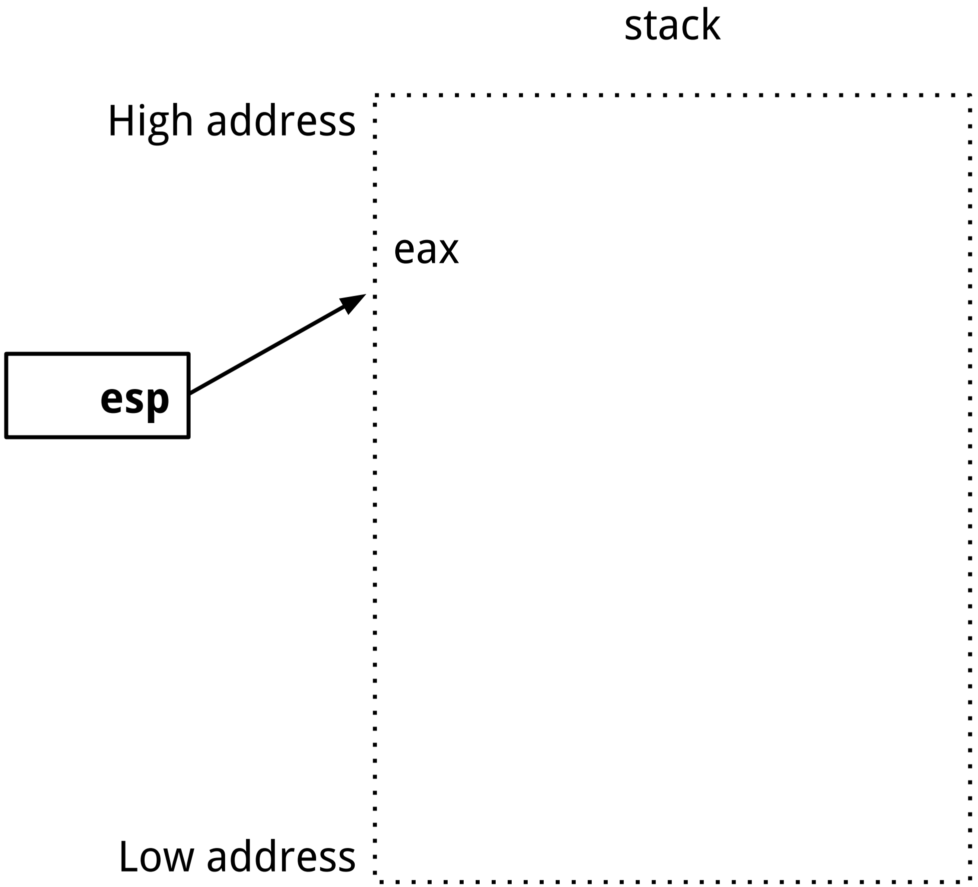

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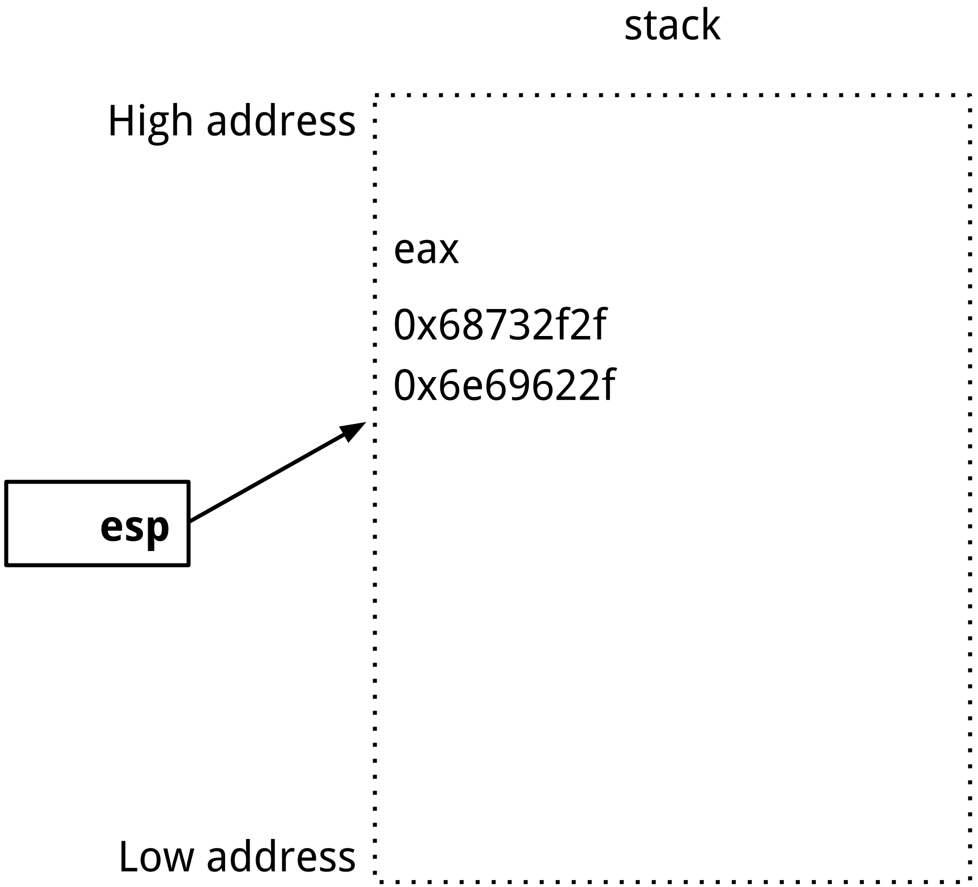

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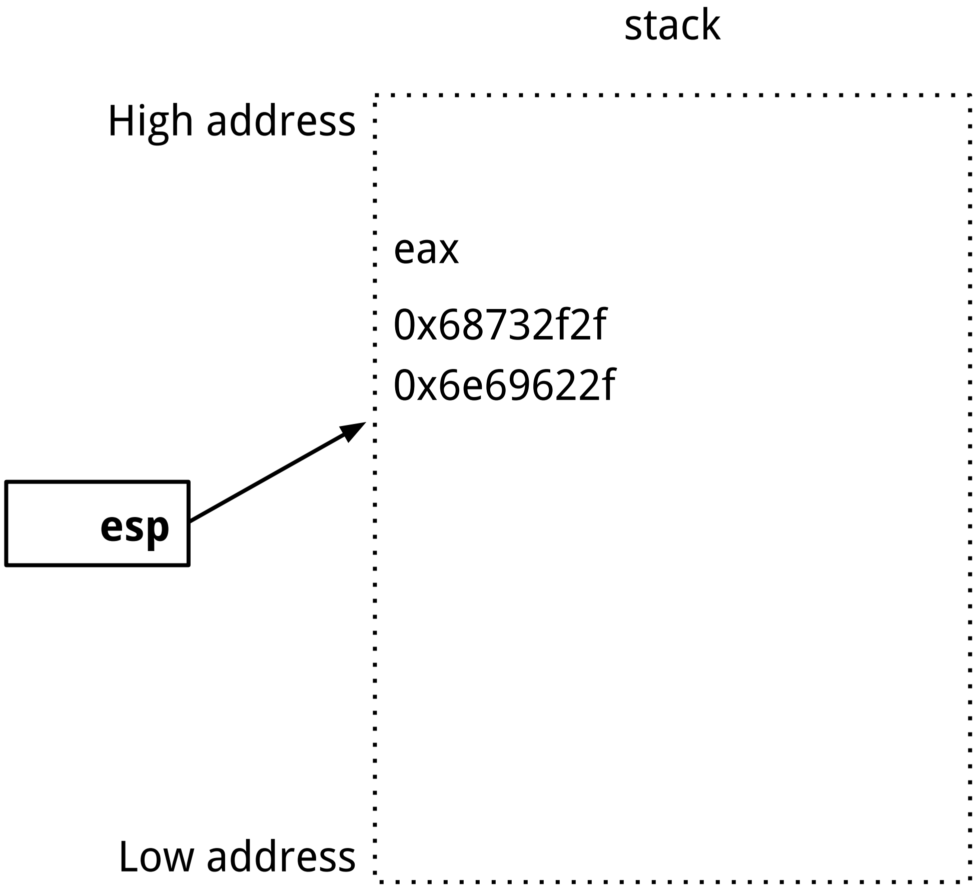
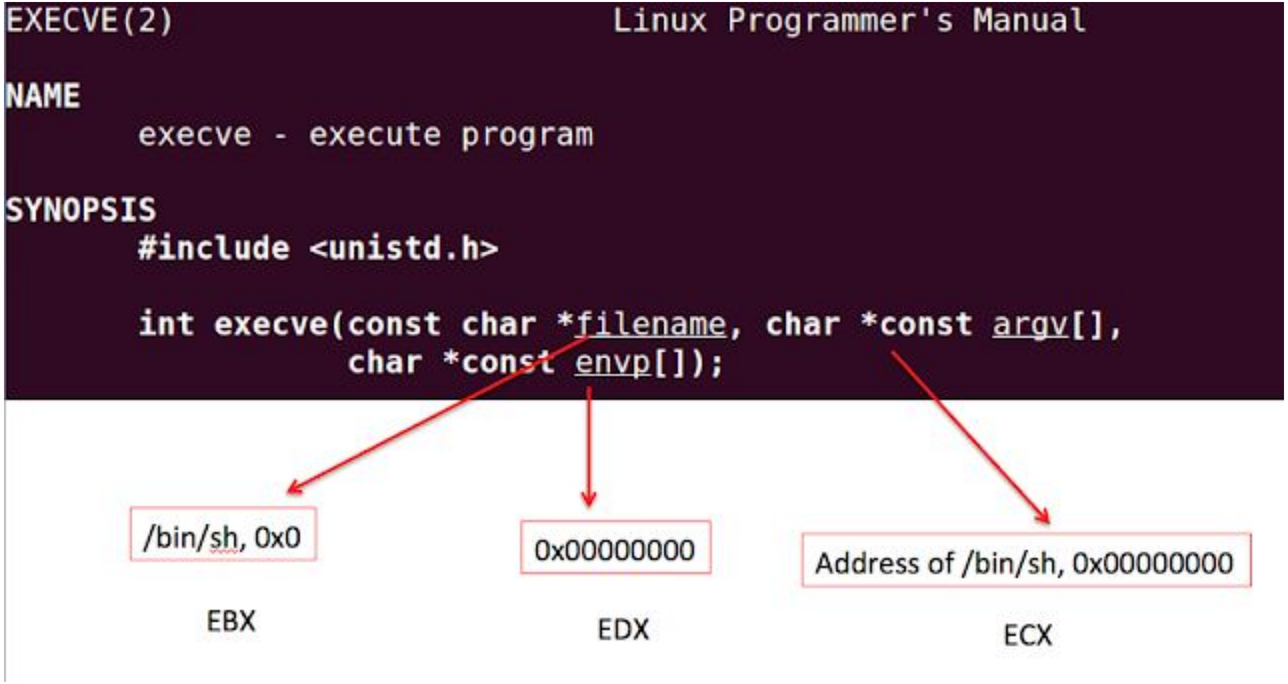
push   0x68732f2f
push   0x6e69622f
mov    ebx,esp
push   eax
push   ebx
mov    ecx,esp
mov    al,0xb
int    0x80
```



Making a System Call in x86 Assembly



execve("/bin/sh", address of string "/bin/sh", 0)

Making a System Call in x86_64 (64-bit) Assembly

x86_64 (64-bit)

Compiled from Linux 4.14.0 headers.

NR	syscall name	references	%rax	arg0 (%rdi)	arg1 (%rsi)	arg2 (%rdx)	arg3 (%r10)	arg4 (%r8)	arg5 (%r9)
0	read	man/ cs/	0x00	unsigned int fd	char *buf	size_t count	-	-	-
1	write	man/ cs/	0x01	unsigned int fd	const char *buf	size_t count	-	-	-
2	open	man/ cs/	0x02	const char *filename	int flags	umode_t mode	-	-	-
3	close	man/ cs/	0x03	unsigned int fd	-	-	-	-	-
4	stat	man/ cs/	0x04	const char *filename	struct __old_kernel_stat *statbuf	-	-	-	-
5	fstat	man/ cs/	0x05	unsigned int fd	struct __old_kernel_stat *statbuf	-	-	-	-
6	lstat	man/ cs/	0x06	const char *filename	struct __old_kernel_stat *statbuf	-	-	-	-
7	poll	man/ cs/	0x07	struct pollfd *ufds	unsigned int nfds	int timeout	-	-	-
8	lseek	man/ cs/	0x08	unsigned int fd	off_t offset	unsigned int whence	-	-	-
9	mmap	man/ cs/	0x09	?	?	?	?	?	?
10	mprotect	man/ cs/	0x0a	unsigned long start	size_t len	unsigned long prot	-	-	-
11	munmap	man/ cs/	0x0b	unsigned long addr	size_t len	-	-	-	-
12	brk	man/ cs/	0x0c	unsigned long brk	-	-	-	-	-
13	rt_sigaction	man/ cs/	0x0d	int	const struct sigaction *	struct sigaction *	size_t	-	-

https://chromium.googlesource.com/chromiumos/docs/+/master/constants/syscalls.md#x86-32_bit

Making a System Call in x86_64 (64-bit) Assembly

NR	syscall name	references	%rax	arg0 (%rdi)	arg1 (%rsi)	arg2 (%rdx)	arg3 (%r10)	arg4 (%r8)	arg5 (%r9)
59	execve	man/ cs/	0x3b	const char *filename	const char *const *argv	const char *const *envp	-	-	-

```
push rax
xor rdx, rdx
xor rsi, rsi
mov rbx,'/bin//sh'
push rbx
push rsp
pop rdi
mov al, 59
syscall
```

SYSTEM AND LIBRARY CALLS EVERY PROGRAMMER NEEDS TO KNOW

LINUX SYSTEM PROGRAMMING

O'REILLY®

ROBERT LOVE

Background Knowledge:
Piping

Channels of Communication for Linux Process

Every process in Linux has three initial, standard channels of communication:

- Standard Input (stdin, fd=0) is the channel through which the process takes input. For example, your shell uses Standard Input to read the commands that you input.
- Standard Output (stdout, fd=1) is the channel through which processes output normal data, such as the flag when it is printed to you in previous challenges or the output of utilities such as *ls*.
- Standard Error (stderr, fd=2) is the channel through which processes output error details. For example, if you mistype a command, the shell will output, over standard error, that this command does not exist.

Examples

Redirecting output > or 1>

echo hi > asdf *echo hi 1> asdf*

Appending output >>

echo hi >> asdf

Redirecting errors 2>

/challenge/run 2> errors.log

Redirecting input <

rev < messagefile

Channels of Communication for Linux Process

- Process can also take input from command line arguments

ls -al

cat /flag

cat 1.txt 2.txt 3.txt

Pipe

The | (pipe) operator. Standard output from the command to the left of the pipe will be connected to (piped into) the standard input of the command to the right of the pipe.

echo hello-world | wc -c

Background Knowledge:
Environment and Shell Variables

Environment and Shell Variables

Environment and Shell variables are a set of dynamic **named values**, stored within the system that are used by applications launched in shells.

KEY=value
KEY="Some other value"
KEY=value1:value2

The names of the variables are case-sensitive (UPPER CASE).
Multiple values must be separated by the colon : character.
There is no space around the equals = symbol.

Environment and Shell Variables

Environment variables are variables that are available system-wide and are inherited by all spawned child processes and shells.

Shell variables are variables that apply only to the current shell instance. Each shell such as zsh and bash, has its own set of internal shell variables.

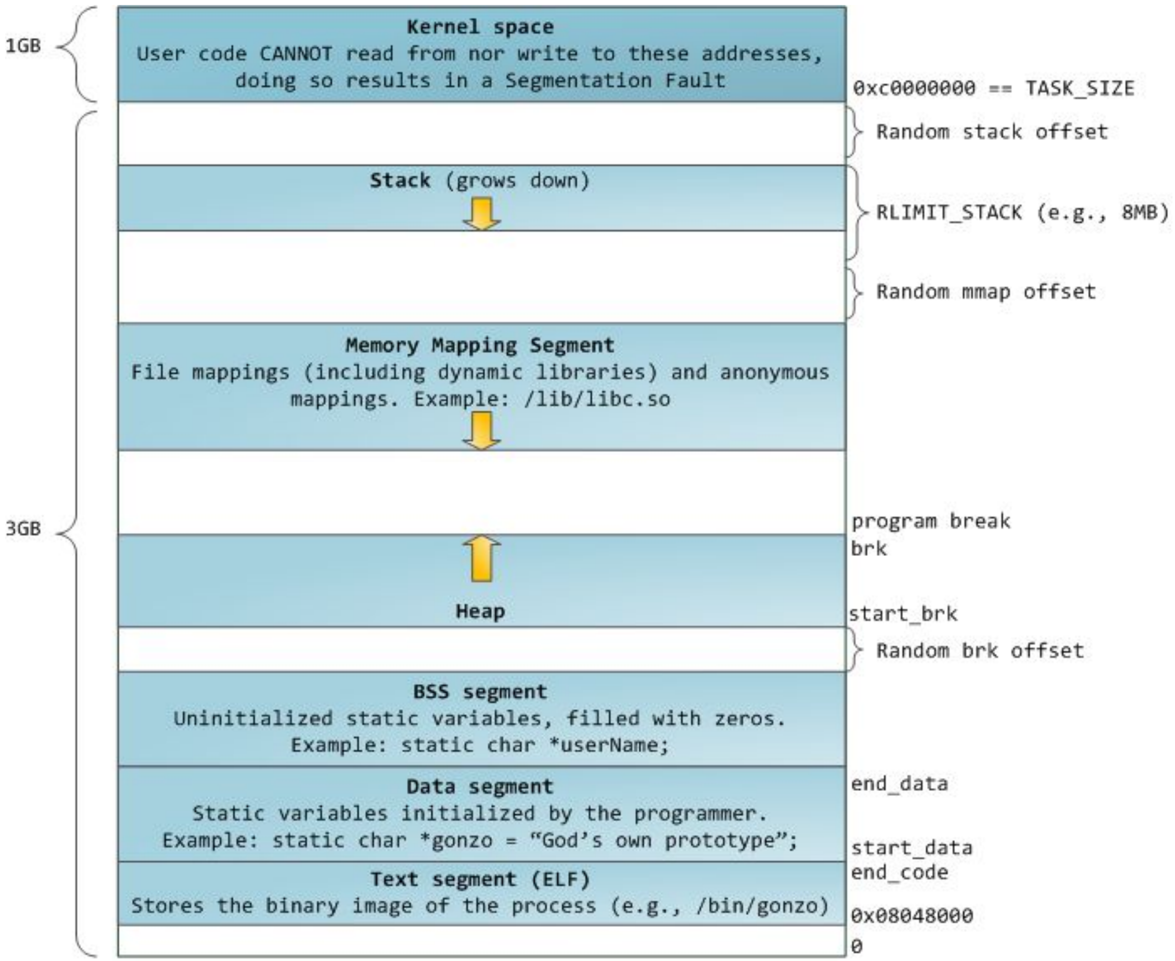
Common Environment Variables

USER - The current logged in user.
HOME - The home directory of the current user.
EDITOR - The default file editor to be used. This is the editor that will be used when you type edit in your terminal.
SHELL - The path of the current user's shell, such as bash or zsh.
LOGNAME - The name of the current user.
PATH - A list of directories to be searched when executing commands.
LANG - The current locales settings.
TERM - The current terminal emulation.
MAIL - Location of where the current user's mail is stored.

Commands

env – The command allows you to run another program in a custom environment without modifying the current one. When used without an argument it will print a list of the current environment variables.
printenv – The command prints all or the specified environment variables.
set – The command sets or unsets shell variables. When used without an argument it will print a list of all variables including environment and shell variables, and shell functions.
unset – The command deletes shell and environment variables.
export – The command sets environment variables

The environment variables live towards the top of the stack, together with command line arguments.

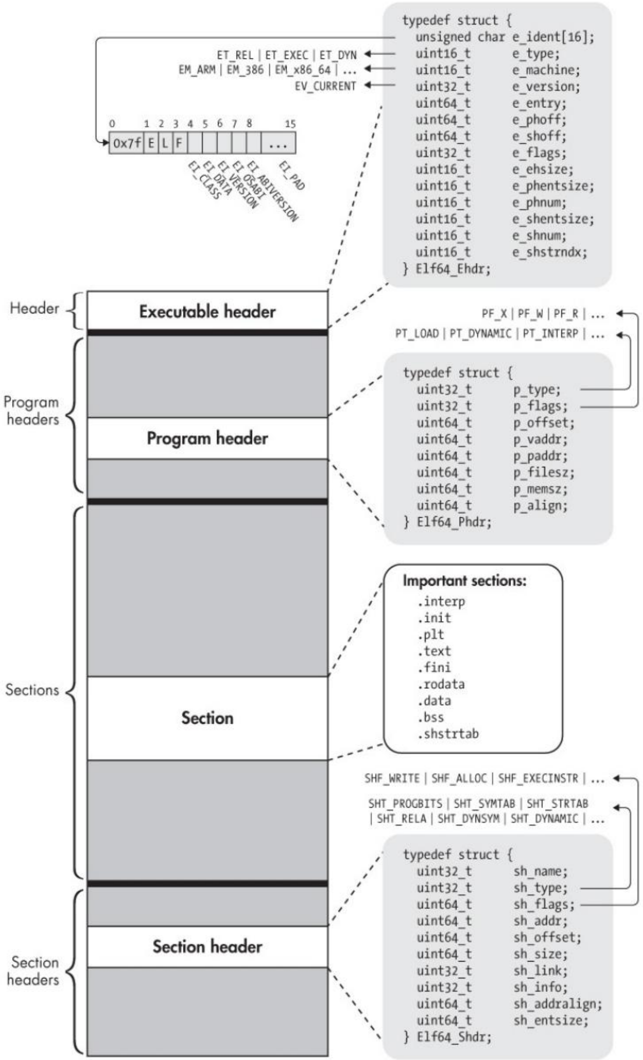


Background Knowledge:
Executable and Linkable Format (ELF)

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).



- Executable (a.out), object files (.o), shared libraries (.a), even core dumps.
- Four *types* of components: an **executable header**, a series of (optional) **program headers**, a number of **sections**, and a series of (optional) **section headers**, one per section.

Executable Header

```
typedef struct {
  unsigned char e_ident[16];   /* Magic number and other info      */ 0x7F ELF ..
  uint16_t      e_type;        /* Object file type Executable, obj, dynamic lib */
  uint16_t      e_machine;     /* Architecture x86-64, Arm         */
  uint32_t      e_version;     /* Object file version              */
  uint64_t      e_entry;       /* Entry point virtual address      */
  uint64_t      e_phoff;       /* Program header table file offset */
  uint64_t      e_shoff;       /* Section header table file offset */
  uint32_t      e_flags;       /* Processor-specific flags         */
  uint16_t      e_ehsize;      /* ELF header size in bytes         */
  uint16_t      e_phentsize;   /* Program header table entry size  */
  uint16_t      e_phnum;       /* Program header table entry count */
  uint16_t      e_shentsize;   /* Section header table entry size  */
  uint16_t      e_shnum;       /* Section header table entry count */
  uint16_t      e_shstrndx;    /* Section header string table index*/
} Elf64_Ehdr;
```

readelf -h a.out

```
→  add readelf -h /bin/ls
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 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
```

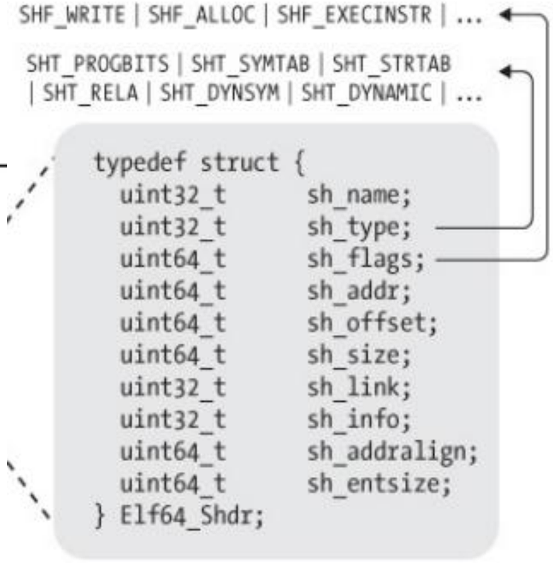
Sections

The code and data in an ELF binary are logically divided into contiguous non-overlapping chunks called sections. The structure of each section varies depending on the contents.

The division into sections is intended to provide a convenient organization for use by the ***linker***.

Section Header Format

```
typedef struct {
  uint32_t  sh_name;       /* Section name (string tbl index)   */
  uint32_t  sh_type;       /* Section type                      */
  uint64_t  sh_flags;      /* Section flags                     */
  uint64_t  sh_addr;       /* Section virtual addr at execution */
  uint64_t  sh_offset;     /* Section file offset               */
  uint64_t  sh_size;       /* Section size in bytes             */
  uint32_t  sh_link;       /* Link to another section           */
  uint32_t  sh_info;       /* Additional section information    */
  uint64_t  sh_addralign;  /* Section alignment                 */
  uint64_t  sh_entsize;    /* Entry size if section holds table */
} Elf64_Shdr;
```



Each section is described by its section header.

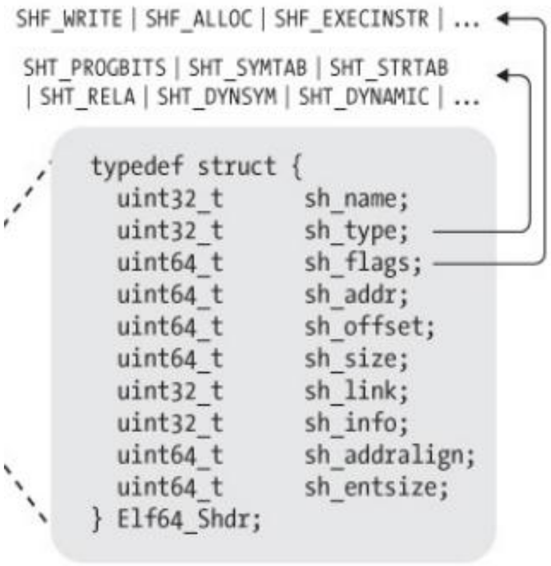
readelf -S a.out

sh_flags

SHF_WRITE: the section is writable at runtime.

SHF_ALLOC: the contents of the section are to be loaded into virtual memory when executing the binary.

SHF_EXECINSTR: the section contains executable instructions.



```
→ add readelf -S add
There are 31 section headers, starting at offset 0x385c:

Section Headers:
  [Nr] Name              Type            Addr     Off    Size   ES Flg Lk Inf Al
  [ 0]                   NULL            00000000 000000 000000 00      0   0  0
  [ 1] .interp           PROGBITS        000001b4 0001b4 000013 00   A  0   0  1
  [ 2] .note.gnu.build-i NOTE            000001c8 0001c8 000024 00   A  0   0  4
  [ 3] .note.gnu.propert NOTE            000001ec 0001ec 00001c 00   A  0   0  4
  [ 4] .note.ABI-tag     NOTE            00000208 000208 000020 00   A  0   0  4
  [ 5] .gnu.hash         GNU_HASH        00000228 000228 000020 04   A  6   0  4
  [ 6] .dynsym           DYNSYM          00000248 000248 0000a0 10   A  7   1  4
  [ 7] .dynstr           STRTAB          000002e8 0002e8 0000bb 00   A  0   0  1
  [ 8] .gnu.version      VERSYM          000003a4 0003a4 000014 02   A  6   0  2
  [ 9] .gnu.version_r    VERNEED         000003b8 0003b8 000040 00   A  7   1  4
  [10] .rel.dyn          REL             000003f8 0003f8 000040 08   A  6   0  4
  [11] .rel.plt          REL             00000438 000438 000020 08  AI  6  24  4
  [12] .init             PROGBITS        00001000 001000 000024 00  AX  0   0  4
  [13] .plt              PROGBITS        00001030 001030 000050 04  AX  0   0 16
  [14] .plt.got          PROGBITS        00001080 001080 000010 10  AX  0   0 16
  [15] .plt.sec          PROGBITS        00001090 001090 000040 10  AX  0   0 16
  [16] .text             PROGBITS        000010d0 0010d0 000259 00  AX  0   0 16
  [17] .fini             PROGBITS        0000132c 00132c 000018 00  AX  0   0  4
  [18] .rodata           PROGBITS        00002000 002000 000025 00   A  0   0  4
  [19] .eh_frame_hdr     PROGBITS        00002028 002028 000054 00   A  0   0  4
  [20] .eh_frame         PROGBITS        0000207c 00207c 00014c 00   A  0   0  4
  [21] .init_array       INIT_ARRAY      00003ed0 002ed0 000004 04  WA  0   0  4
  [22] .fini_array       FINI_ARRAY      00003ed4 002ed4 000004 04  WA  0   0  4
  [23] .dynamic          DYNAMIC         00003ed8 002ed8 0000f8 08  WA  7   0  4
  [24] .got              PROGBITS        00003fd0 002fd0 000030 04  WA  0   0  4
  [25] .data             PROGBITS        00004000 003000 000008 00  WA  0   0  4
  [26] .bss              NOBITS          00004008 003008 000004 00  WA  0   0  1
  [27] .comment          PROGBITS        00000000 003008 00002a 01  MS  0   0  1
  [28] .symtab           SYMTAB          00000000 003034 000490 10     29  47  4
  [29] .strtab           STRTAB          00000000 0034c4 00027d 00      0   0  1
  [30] .shstrtab         STRTAB          00000000 003741 000118 00      0   0  1
Key to Flags:
  W (write), A (alloc), X (execute), M (merge), S (strings), I (info),
  L (link order), O (extra OS processing required), G (group), T (TLS),
  C (compressed), x (unknown), o (OS specific), E (exclude),
  p (processor specific)
```

readelf -S a.out

Sections

.init: executable code that performs initialization tasks and needs to run before any other code in the binary is executed.

.fini: code that runs after the main program completes.

.text: where the main code of the program resides.

Sections

.rodata section, which stands for “read-only data,” is dedicated to storing constant values. Because it stores constant values, .rodata is not writable.

The default values of initialized variables are stored in the .data section, which is marked as writable since the values of variables may change at runtime.

the .bss section reserves space for uninitialized variables. The name historically stands for “block started by symbol,” referring to the reserving of blocks of memory for (symbolic) variables.

Dynamic linking

Dynamic linking ***reduces binary size*** by offloading code to system libraries, such as libc, instead of embedding it within each executable.

For example, ELF files link to the system’s puts() rather than including their own.

This not only saves space but also allows users to ***update libraries independently of binaries***.

https://ir0nstone.gitbook.io/notes/binexp/stack/aslr/plt_and_got

Lazy Binding (.plt, .got, .got.plt Sections)

Binding at Load Time: When a binary is loaded into a process for execution, the dynamic linker resolves references to functions located in shared libraries. The addresses of shared functions were not known at compile time.

In reality - Lazy Binding: many of the relocations are typically not done right away when the binary is loaded but are deferred until the first reference to the unresolved location is actually made.

Lazy Binding (.plt, .got, .got.plt Sections)

Lazy binding in Linux ELF binaries is implemented with the help of two special sections, called the Procedure Linkage Table (.plt) and the Global Offset Table (.got).

.plt is a code section that contains executable code. The PLT consists entirely of stubs of a well-defined format, dedicated to directing calls from the .text section to the appropriate library location.

.got.plt is a data section.

Lazy Binding (.plt, .got, .got.plt Sections)

When you call puts() in C and compile it as an ELF executable, it is not actually puts() - instead, it gets compiled as puts@plt.

Because the program doesn't know where puts() actually is - so it jumps to the PLT entry of puts instead.

Lazy Binding (.plt, .got, .got.plt Sections)

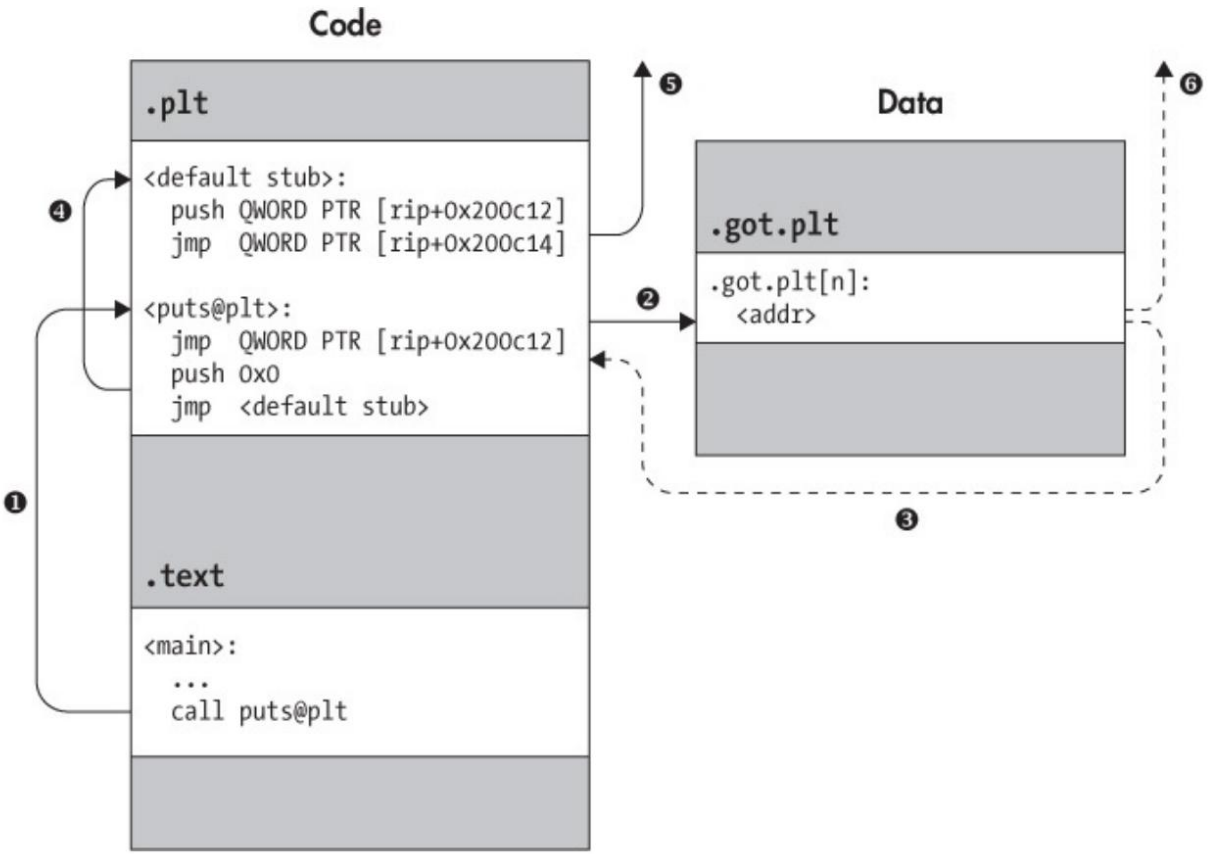
puts@plt does some very specific things:

- If there is a GOT entry for puts, it jumps to the address stored there.
- If there isn't a GOT entry, it will resolve it and jump there.

The GOT is a massive table of addresses; these addresses are the actual locations in memory of the libc functions. puts@got, for example, will contain the address of puts in memory.

When the PLT gets called, it reads the GOT address and redirects execution there. If the address is empty, it coordinates with the ld.so (also called the dynamic linker/loader) to get the function address and stores it in the GOT.

Dynamically Resolving a Library Function Using the PLT



Takeaways

Calling the PLT address of a function is equivalent to calling the function itself

- The use of the first point is clear - if we have a PLT entry for a desirable libc function, for example system, we can just redirect execution to its PLT entry and it will be the equivalent of calling system directly; no need to jump into libc

The GOT address contains addresses of functions in libc, and the GOT is within the binary

- It will always be a constant offset away from the base. Therefore, if PIE is disabled or you somehow leak the binary base, you know the exact address that contains a libc function's address. If you perhaps have an arbitrary read, it's trivial to leak the real address of the libc function and therefore bypass ASLR.

Example: Debug misc/lazyb

```
0028| 0xffffc63c --> 0xf7dccee5 (<__libc_start_main+245>:       add    esp,0x10)
[------------------------------------------------------------------------------]
Legend: code, data, rodata, value
0x56556207 in main ()
gdb-peda$ si
[----------------------------------registers-----------------------------------]
EAX: 0x5655701e ("Second call to printf.")
EBX: 0x56559000 --> 0x3efc
ECX: 0xffffffff
EDX: 0xffffffff
ESI: 0xf7f99000 --> 0x1ead6c
EDI: 0xf7f99000 --> 0x1ead6c
EBP: 0xffffc638 --> 0x0
ESP: 0xffffc61c ("\fbUV\036pUV\344\306\377\377\354\306\377\377\345aUVP\306\377\377")
EIP: 0x56556070 (<puts@plt>:    endbr32)
EFLAGS: 0x296 (carry PARITY ADJUST zero SIGN trap INTERRUPT direction overflow)
[-------------------------------------code-------------------------------------]
   0x56556060 <__cxa_finalize@plt>:     endbr32
   0x56556064 <__cxa_finalize@plt+4>:   jmp    DWORD PTR [ebx-0x10]
   0x5655606a <__cxa_finalize@plt+10>:  nop    WORD PTR [eax+eax*1+0x0]
=> 0x56556070 <puts@plt>:       endbr32
   0x56556074 <puts@plt+4>:     jmp    DWORD PTR [ebx+0xc]
   0x5655607a <puts@plt+10>:    nop    WORD PTR [eax+eax*1+0x0]
   0x56556080 <__libc_start_main@plt>:  endbr32
   0x56556084 <__libc_start_main@plt+4>:        jmp    DWORD PTR [ebx+0x10]
[------------------------------------stack-------------------------------------]
0000| 0xffffc61c ("\fbUV\036pUV\344\306\377\377\354\306\377\377\345aUVP\306\377\377")
0004| 0xffffc620 --> 0x5655701e ("Second call to printf.")
0008| 0xffffc624 --> 0xffffc6e4 --> 0xffffc893 ("/home/ziming/Dropbox/myTeaching/Software Security UB 2021 Fall/code/lazybinding/lazyb")
0012| 0xffffc628 --> 0xffffc6ec --> 0xffffc8e9 ("COLORTERM=truecolor")
0016| 0xffffc62c --> 0x565561e5 (<main+24>:     add    ebx,0x2e1b)
0020| 0xffffc630 --> 0xffffc650 --> 0x1
0024| 0xffffc634 --> 0x0
0028| 0xffffc638 --> 0x0
[------------------------------------------------------------------------------]
Legend: code, data, rodata, value
0x56556070 in puts@plt ()
gdb-peda$
[----------------------------------registers-----------------------------------]
EAX: 0x5655701e ("Second call to printf.")
EBX: 0x56559000 --> 0x3efc
ECX: 0xffffffff
EDX: 0xffffffff
ESI: 0xf7f99000 --> 0x1ead6c
EDI: 0xf7f99000 --> 0x1ead6c
EBP: 0xffffc638 --> 0x0
ESP: 0xffffc61c ("\fbUV\036pUV\344\306\377\377\354\306\377\377\345aUVP\306\377\377")
EIP: 0x56556074 (<puts@plt+4>:  jmp    DWORD PTR [ebx+0xc])
EFLAGS: 0x296 (carry PARITY ADJUST zero SIGN trap INTERRUPT direction overflow)
[-------------------------------------code-------------------------------------]
   0x56556064 <__cxa_finalize@plt+4>:   jmp    DWORD PTR [ebx-0x10]
   0x5655606a <__cxa_finalize@plt+10>:  nop    WORD PTR [eax+eax*1+0x0]
   0x56556070 <puts@plt>:       endbr32
=> 0x56556074 <puts@plt+4>:     jmp    DWORD PTR [ebx+0xc]
 | 0x5655607a <puts@plt+10>:    nop    WORD PTR [eax+eax*1+0x0]
 | 0x56556080 <__libc_start_main@plt>:  endbr32
 | 0x56556084 <__libc_start_main@plt+4>:        jmp    DWORD PTR [ebx+0x10]
 | 0x5655608a <__libc_start_main@plt+10>:       nop    WORD PTR [eax+eax*1+0x0]
 |->   0xf7e1fcd0 <__GI__IO_puts>:      endbr32
       0xf7e1fcd4 <__GI__IO_puts+4>:    push   ebp
       0xf7e1fcd5 <__GI__IO_puts+5>:    mov    ebp,esp
       0xf7e1fcd7 <__GI__IO_puts+7>:    push   edi
                                                                  JUMP is taken
[------------------------------------stack-------------------------------------]
0000| 0xffffc61c ("\fbUV\036pUV\344\306\377\377\354\306\377\377\345aUVP\306\377\377")
0004| 0xffffc620 --> 0x5655701e ("Second call to printf.")
0008| 0xffffc624 --> 0xffffc6e4 --> 0xffffc893 ("/home/ziming/Dropbox/myTeaching/Software Security UB 2021 Fall/code/lazybinding/lazyb")
0012| 0xffffc628 --> 0xffffc6ec --> 0xffffc8e9 ("COLORTERM=truecolor")
0016| 0xffffc62c --> 0x565561e5 (<main+24>:     add    ebx,0x2e1b)
0020| 0xffffc630 --> 0xffffc650 --> 0x1
0024| 0xffffc634 --> 0x0
0028| 0xffffc638 --> 0x0
[------------------------------------------------------------------------------]
Legend: code, data, rodata, value
0x56556074 in puts@plt ()
gdb-peda$
[0] 0:gdb*
```

GDB Cheatsheet:

https://darkdust.net/files/GDB%20Cheat%20Sheet.pdf

Section View (Section Header)
vs.
Segment View (Program Header)

The program header table provides a segment view of the binary, as opposed to the section view provided by the section header table.

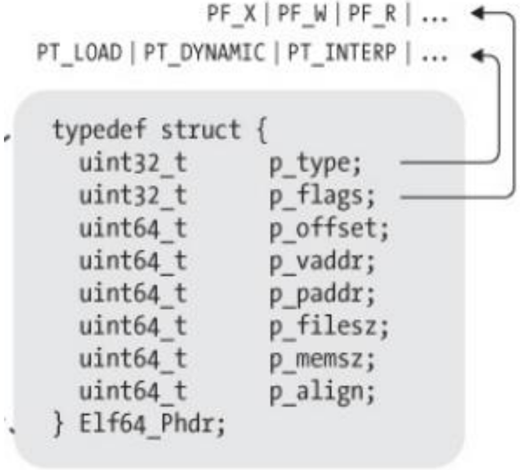
The section view of an ELF binary is meant for static linking purposes.

The segment view is used by the operating system and dynamic linker when loading an ELF into a process for execution to locate the relevant code and data and decide what to load into virtual memory.

Segments are simply a bunch of sections bundled together.

Program Header Format

```
typedef struct {
  uint32_t  p_type;   /* Segment type             */
  uint32_t  p_flags;  /* Segment flags            */
  uint64_t  p_offset; /* Segment file offset      */
  uint64_t  p_vaddr;  /* Segment virtual address  */
  uint64_t  p_paddr;  /* Segment physical address */
  uint64_t  p_filesz; /* Segment size in file     */
  uint64_t  p_memsz;  /* Segment size in memory   */
  uint64_t  p_align;  /* Segment alignment        */
} Elf64_Phdr;
```



Each section is described by its section header.

```
readelf -l a.out
```

```
→ add readelf -l add

Elf file type is DYN (Shared object file)
Entry point 0x1160
There are 12 program headers, starting at offset 52

Program Headers:
  Type           Offset   VirtAddr   PhysAddr   FileSiz MemSiz  Flg Align
  PHDR           0x000034 0x00000034 0x00000034 0x00180 0x00180 R   0x4
  INTERP         0x0001b4 0x000001b4 0x000001b4 0x00013 0x00013 R   0x1
      [Requesting program interpreter: /lib/ld-linux.so.2]
  LOAD           0x000000 0x00000000 0x00000000 0x00458 0x00458 R   0x1000
  LOAD           0x001000 0x00001000 0x00001000 0x00344 0x00344 R E 0x1000
  LOAD           0x002000 0x00002000 0x00002000 0x001c8 0x001c8 R   0x1000
  LOAD           0x002ed0 0x00003ed0 0x00003ed0 0x00138 0x0013c RW  0x1000
  DYNAMIC        0x002ed8 0x00003ed8 0x00003ed8 0x000f8 0x000f8 RW  0x4
  NOTE           0x0001c8 0x000001c8 0x000001c8 0x00060 0x00060 R   0x4
  GNU_PROPERTY   0x0001ec 0x000001ec 0x000001ec 0x0001c 0x0001c R   0x4
  GNU_EH_FRAME   0x002028 0x00002028 0x00002028 0x00054 0x00054 R   0x4
  GNU_STACK      0x000000 0x00000000 0x00000000 0x00000 0x00000 RW  0x10
  GNU_RELRO      0x002ed0 0x00003ed0 0x00003ed0 0x00130 0x00130 R   0x1

 Section to Segment mapping:
  Segment Sections...
   00
   01     .interp
   02     .interp .note.gnu.build-id .note.gnu.property .note.ABI-tag .gnu.hash .dynsym .dynstr .gnu.version .gnu.version_r .rel.dyn .rel.plt
   03     .init .plt .plt.got .plt.sec .text .fini
   04     .rodata .eh_frame_hdr .eh_frame
   05     .init_array .fini_array .dynamic .got .data .bss
   06     .dynamic
   07     .note.gnu.build-id .note.gnu.property .note.ABI-tag
   08     .note.gnu.property
   09     .eh_frame_hdr
   10
   11     .init_array .fini_array .dynamic .got
→ add
[0] 0:zsh*
```

Background Knowledge:
Manual Binary Analysis Tools

Tools for this class

file
readelf
strings
nm
objdump
GDB
[optional] IDA Pro
[optional] ghidra
[optional] Binary Ninja

GDB Cheat Sheet

Start gdb using:
gdb <binary>
Pass initial commands for gdb through a file
gdb <binary> –x <initfile>

To start the program and breakpoint at main()
start <argv>

To start the program and breakpoint at _start
starti <argv>

To run the program without breakpoint
r <argv>
Use another progrom’s output as stdin in GDB:
r <<< $(python2 -c "print '\x12\x34'*5")

GDB Cheat Sheet

Set breakpoint at address:
b *0x80000000

Set breakpoint at beginning of a function:
b main

....
b <filename:line number>
b <line number>

Disassemble 10 instructions from an address:
x/10i 0x80000000

Exam 15 dword (w) from an address; show hex (x):
x/15wx 0x80000000

Exam 3 qword (g) from an address; show hex (x):
x/3gx 0x80000000

GDB Cheat Sheet

To show breakpoints
info b

To remove breakpoints
clear <function name>
clear *<instruction address>
clear <filename:line number>
clear <line number>

GDB Cheat Sheet

Use “examine” or “x” command
x/32xw <memory location> to see memory contents at memory location, showing 32 hexadecimal words
x/5s <memory location> to show 5 strings (null terminated) at a particular memory location
x/10i <memory location> to show 10 instructions at particular memory location

See registers
info reg

Step an instruction
si

GDB Script

Use “examine” or “x” command
x/32xw <memory location> to see memory contents at memory location, showing 32 hexadecimal words
x/5s <memory location> to show 5 strings (null terminated) at a particular memory location
x/10i <memory location> to show 10 instructions at particular memory location

See registers
info reg

Step an instruction
si

Shell Cheat Sheet

Run a program and use another program’s output as a parameter

```
program $(python2 -c "print '\x12\x34'*5")
```

Python3

```
python3 -c "import sys; sys.stdout.buffer.write(b'\x90'*20)"
```

Reading

1. https://iq.thc.org/how-does-linux-start-a-process