```
___________________________.
|;;|                     |;;||
|[]|---------------------|[]||
|;;|                     |;;||
|;;|   --------------    |;;||
|;;|   | COMP6447 |      |;;||
|;;|   --------------    |;;||
|;;|     printf(x)       |;;||
|;;|                     |;;||
|;;|_____________________|;;||
|;;;;;;;;;;;;;;;;;;;;;;;;;;;||
|;;;;;;_______________ ;;;;;||
|;;;;;|  ___          |;;;;;||
|;;;;;| |;;;|         |;;;;;||
|;;;;;| |;;;|         |;;;;;||
|;;;;;| |;;;|         |;;;;;||
|;;;;;| |;;;|         |;;;;;||
|;;;;;| |___|         |;;;;;||
\_____|_______________|_____||
 ~~~~~^^^^^^^^^^^^^^^^^~~~~~~
```

Formatting your strings

- wtf is a format string?
- how do they work?
- history lesson
- how 2 haq them?
- live exploit demo
- case study
- questions / practical exercises

What is a format string?????

- new class of vulns disclosed in early 2000's
- kind of a **big deal** (remote root code exec - hell yes!)
- easy to find (**grep** / static checks)
- issue previously known, considered **harmless**

WHITEPAPER:

"Format String Attacks"

by Tim Newsham

Sep 2000

tutorial on how to use the man page

FORMAT FUNCTION (ANSI C)

- **converts data types to human readable strings**
- accepts **variable number of arguments**
- one of which is the **‘format string’**
- used pretty much **everywhere**

```
#include <stdio.h>

int printf(const char *format, ...);

int fprintf(FILE *stream, const char *format, ...);

int sprintf(char *str, const char *format, ...);

int snprintf(char *str, size_t size, const char *format, ...);
```

How a format string works

FORMAT STRING PROCESSING:

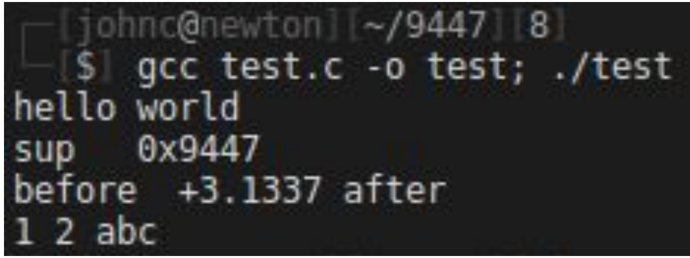
- not % - copied unchanged into output stream
- %   - fetch next argument from stack, output conversion

%<flags><width><precision><modifier><type>

printf(“sup %#8x\n”, 37959);

printf(“before %+8.2lf after\n”, 3.1337);

printf(“%d %x %s”, 1, 2, “abc\n”);



tldr

A format string has some **prebuilt** functions for converting types to strings:

- %d - take argument as **integer** and print it
- %c - take argument as **char** and print it
- %p - take argument as a **pointer** and print it
- %s - take argument as a **pointer**, dereference it, print array of chars

moar

Contains some less familiar functionality

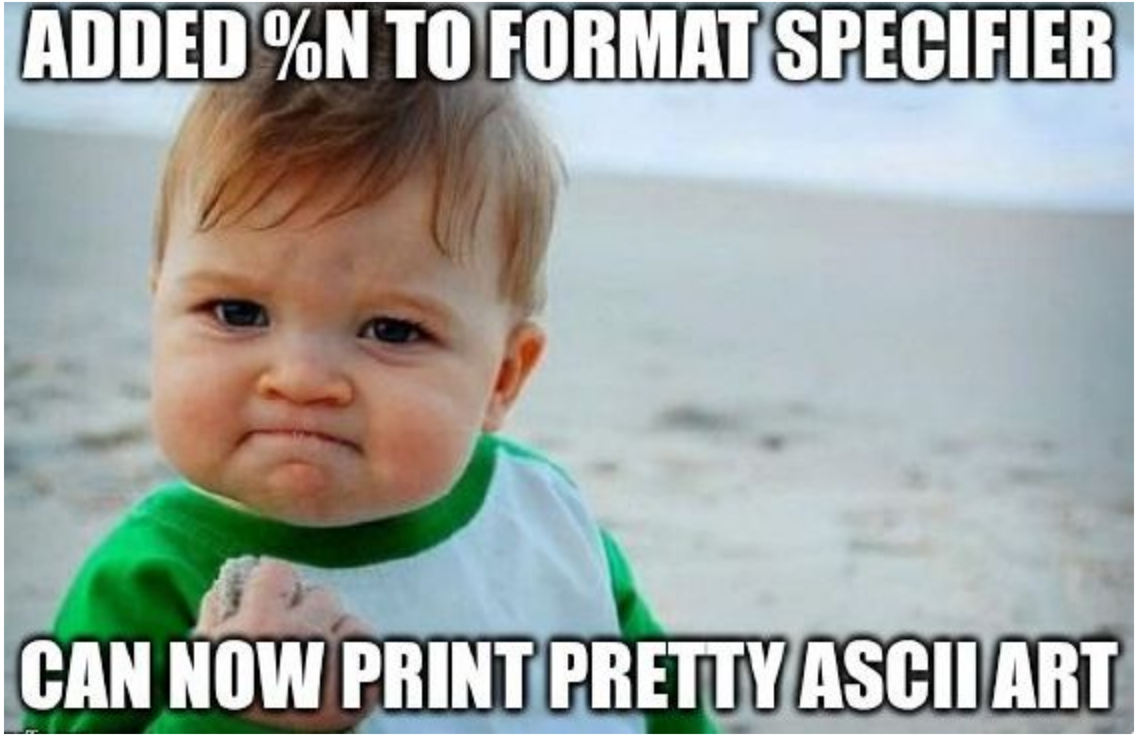
- %x - take argument as **integer** and print it in hexadecimal
- %n - ???

What the %n

According to man page:

- The **number of characters written so far** is stored into the integer **pointed** to by the corresponding **argument**.

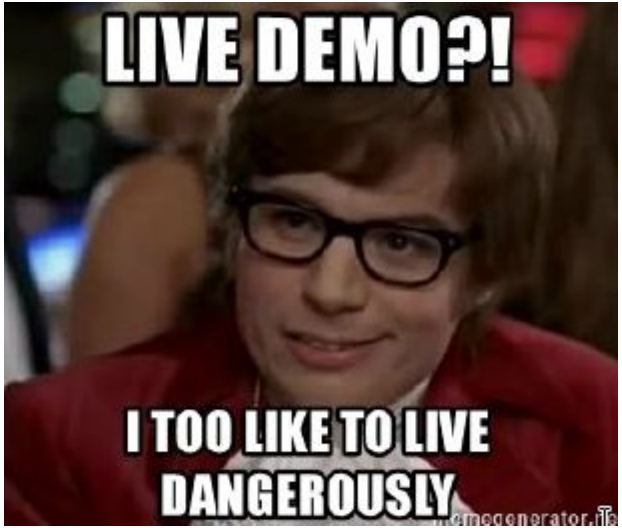
Ruh roh.. So printf doesn’t just print to output… It can also store ints in memory ??


ADDED %N TO FORMAT SPECIFIER
CAN NOW PRINT PRETTY ASCII ART

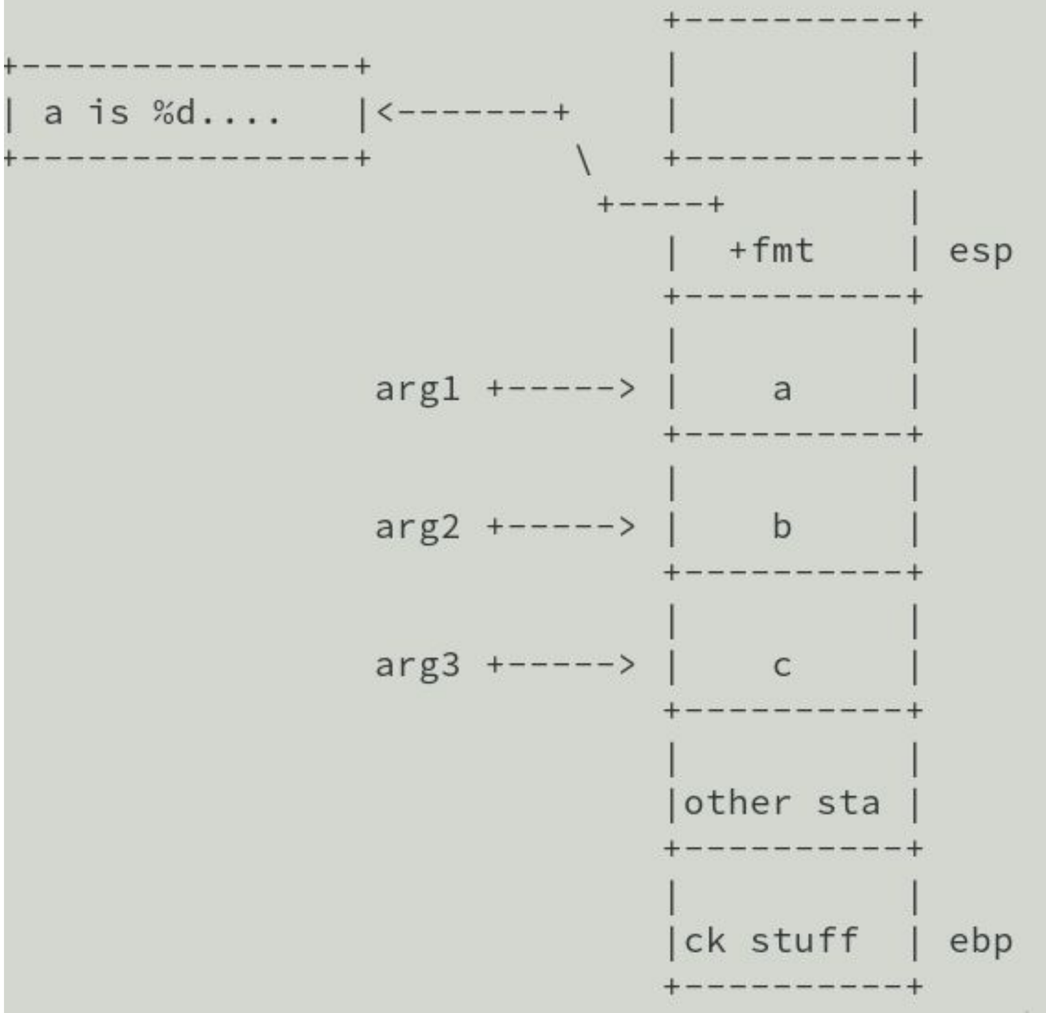
Why %n is used

```
int main(){
  int var = 1;
  int n;
  printf("%s: %nFoo\n","hello",&n);
  printf("%*sBar\n",n,"");
}
```

First lets jump into binaryninja and see how a printf call works...



- How does printf know the number of arguments



What could go wrong here?

take a look at the following,

--

printf(“%s”, userStr);   // good

printf(userStr);   // bad

--

what could go wrong here?

Questions to ask everytime you learn something new

- What do you expect to happen when you enter
  - “Adam”
  - “14”
  - “%d”
  - “%s”

Cool story bro

Format string vulns are really useful. They can be used for:

- Crashing programs/servers
    - Because its fun
- Leaking information
    - Eg: Stack canaries, memory addresses, other secrets in memory
- Overwriting Variables (:-O)
- Dumping entire process memory
    - Don’t have access to the binary locally to test? No worries...

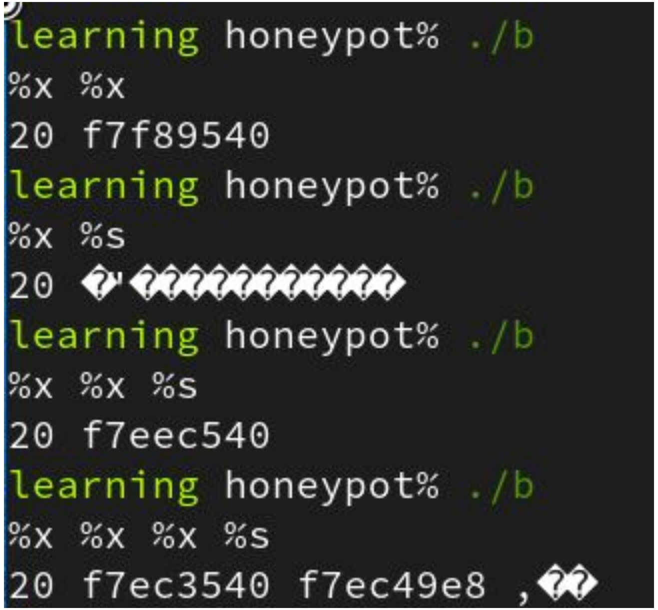
Crashing

```
learning honeypot% ./b
%x %x %x %x
20 f7f63540 f7f649e8 f7f62e24
learning honeypot% ./b
%s
[1]    7101 segmentation fault (core dumped)  ./b
learning honeypot% ./b
%n
[1]    7137 segmentation fault (core dumped)  ./b
```

Arbitrary reads

can be used to map out entire process space

may need to pad (e.g. with A’s) to get alignment right



How do i read **any** address?

- %s reads from a pointer on the **stack**
- It would be nice if you could put your own pointer on the **stack**
- Wait… havn’t we needed to do this every week?
    - If you just put 4 bytes in your buffer
    - And tell printf to treat them as a pointer
    - .. it will
- Payload looks like
    - `\x12\x34\x45\x78 %s`
    - This doesn’t work because our buffer isn’t the first thing on the stack..

Your buffer is on the stack.

You just need a way to tell printf, to look at it

```
+-------------+
|             |
|             |
+-------------+
|             |   esp
|  fmt        |
+-------------+
|             |
|   ...       |
+-------------+
|    ...      |
|             |
+-------------+
|   ...       |
|             |
+-------------+

     ...
+-------------+
|             |
|  YOUR       |
+-------------+
|             |
|  BUFFER     |
+-------------+
|             |   ebp
|             |
+-------------+
```

Let’s learn how to leak abritrary addresses

This thing we are doing is called a **memory read primitive**

How a format string works

```
What is the flags?
What is the modifier?
```

```
%<flags><width><precision><modifier><type>
```

Back to demo

- What does
    - %x
    - %1$x
    - %2$x
    - %14$x
- How do we deal with weird stack offsets/padding

Arbitrary write

- Can overwrite useful numbers
    - What happens if we write over a function pointers?
    - Or a return address

Tldr; use %n to write the number of bytes to some pointer

- Can select **what pointer** to write with (we just learnt this)
- We can select **how many** bytes to overwrite (we will see this soon)
- We can select **what bytes** to write

I want to write 100 to 0x12345678

Payload looks like

- ‘\x78\x45\x34\x12 %n’
  - This only writes the number 5 to the address (why?)
- ‘\x78\x45\x34\x12 AA…..AAAAAA %n’
  - This works fine. But what if our buffer is small
  - What if i want to write the number 10000000?
- We need a better way
  - That way is the width modifier
    - %<flags><width><precision><modifier><type>
- ‘Demo time’
  - What does %100x do
  - What does ‘\x78\x45\x34\x12 **%95x**%n’ do

Okay.

What happens if I want to write a really big number. Like **0x8040129…**

I can’t print that many characters out.. It would take two long (lets demo this?)

Write one or two byte(s) at a time…

%**hh**n

%**h**n

Man page

- **hh**
  - A following integer conversion corresponds to a signed char or unsigned char argument
  - When used with %n, writes only 1 bytes
- **h**
  - A following integer conversion corresponds to a short int or unsigned short int argument
  - When used with %n, writes only 2 bytes

Chaining together multiple small writes

- Goal is to write 0xAABBCCDD to address 0x12345678
- First write
  - 0xAA to address 0x1234567**8**
- Second write
  - 0xBB to address 0x1234567**9**
- Third write
  - 0xCC to address 0x1234567**A**
- Fourth write
  - 0xDD to addres 0x1234567**B**

Exploit looks like

\x78\x45\x34\x12\x79\x56\x35\x12…%150x%12$hhn%1392x%13$hhn...

Remember that hhn only writes 1 byte

What happens if I do two writes

In the first write I write 0xFF, and the second one I want to write 0x01

By the time the second write starts, 0xFF characters have already been printed…

<addr1><addr2>%247x%4$n%??x%5$n

Take advantage of overflows: 0xFF + 0x2 = 0x01

0x02 + 0x100 = 0x02 (if the answer is 1 byte long :P)

Where can I write

Lots of fun places to write to

- PLT / GOT
- dtors
- C lib hooks (__malloc_hook, __free_hook, etc)
- __atexit handlers
- Function ptrs, jump tables

What is the GOT? - Global Offset Table

- `every lib function has entry (addr of real function)`
- `initially contains address of RTL`
- `RTL resolves real address and replaces entry on first call`
- `independent and writeable (sometimes)`
- `Tldr its a cache for function calls`
- pwndbg command `got`.

```
(gdb) x/i 0x08048501
   0x8048501 <main+84>: call   0x8048380 <exit@plt>
(gdb) x/i 0x8048380
   0x8048380 <exit@plt>:        jmp    *0x804a018
(gdb) x/a 0x804a018
0x804a018 <exit@got.plt>:       0xb7e537f0 <__GI_exit>
(gdb)
```

```
┌[johnc@newton][~/9447][0]
└[$] objdump --dynamic-reloc foo

foo:     file format elf32-i386

DYNAMIC RELOCATION RECORDS
OFFSET   TYPE              VALUE
080497b4 R_386_GLOB_DAT    __gmon_start__
080497c4 R_386_JUMP_SLOT   printf
080497c8 R_386_JUMP_SLOT   __gmon_start__
080497cc R_386_JUMP_SLOT   exit
080497d0 R_386_JUMP_SLOT   strlen
080497d4 R_386_JUMP_SLOT   __libc_start_main
080497d8 R_386_JUMP_SLOT   snprintf
```

What to write?

So we know we can

- Leak any memory address
- Write to any memory address

So what do we write?

- Well, if we know a function that pops a shell.. We can overwrite a function pointer (such as GOT) ..
- If theres no good win functions, we can write **shellcode**, and overwrite a function pointer to **point to the stack** :O

Case study 2012

```
sudo_debug(int level, const char *fmt, …)

va_list ap;

char *fmt2;

if (level > debug_level)

  return

easprintf(&fmt2, “%s: %s\n”, getprogname(), fmt);

va_start(ap, fmt);

vfprintf(stderr, fmt2, ap);

va_end(ap);

efree(fmt2);
```

Case study 2012

```
sudo_debug(int level, const char *fmt, …)

va_list ap;

char *fmt2;

if (level > debug_level)

  return

easprintf(&fmt2, “%s: %s\n”, getprogname(), fmt);

va_start(ap, fmt);

vfprintf(stderr, fmt2, ap);

va_end(ap);

efree(fmt2);
```

Theres a lot of format string functions...

Which of these **don’t** use format strings?

- printf
- sprintf,
- scanf
- sscanf,
- vprintf
- syslog

My tips

- Dont do guess work
  - Research the addresses
  - Research the correct offsets
  - Your payload should work first try if you do the right research into the binary
- Guess and check won’t really work here like it did last week
- Try to solve the problem one step at a time, ask simple questions
  - Where is the vulnerable function called
  - How can you control the paramater to it?
  - How can you use this to create a read primitive?
  - How can you use this to create a write primitive? (usually very similar to above)
  - Where do you want to write to?
  - What do you want to write there?
- Mark Dowd: “I’ll never stop to be amazed by the amount of effort people put in to not understand things”

questions?

```
 ___________________________.
|;;|                     |;;||
|[]|---------------------|[]||
|;;|    -------------    |;;||
|;;|   | COMP6447 |      |;;||
|;;|    -------------    |;;||
|;;|   midterm exam      |;;||
|;;|                     |;;||
|;;|_____________________|;;||
|;;;;;;;;;;;;;;;;;;;;;;;;;;;||
|;;;;;;_______________ ;;;;;||
|;;;;;|  ___          |;;;;;||
|;;;;;| |;;;|         |;;;;;||
|;;;;;| |;;;|         |;;;;;||
|;;;;;| |;;;|         |;;;;;||
|;;;;;| |;;;|         |;;;;;||
|;;;;;| |___|         |;;;;;||
\_____|_______________|_____||
 ~~~~~^^^^^^^^^^^^^^^^^~~~~~~
```

Midsem exam is next week!!!!!!!!!

Exciting

Be prepared. Will be 3 pwn challenges.

- Will have 36 hours to **start** the exam.
- Will have 2 hours to **do** the exam.

3 flags = full marks. Content up to this week

Cheating is not advised

Try your best!

```
___________________________.
|;;|                     |;;||
|[]|---------------------|[]||
|;;|    --------------   |;;||
|;;|                     |;;||
|;;|   | COMP6447 |      |;;||
|;;|    --------------   |;;||
|;;|  use protection     |;;||
|;;|                     |;;||
|;;|_____________________|;;||
|;;;;;;;;;;;;;;;;;;;;;;;;;;;||
|;;;;;;_______________ ;;;;;||
|;;;;;|  ___          |;;;;;||
|;;;;;| |;;;|         |;;;;;||
|;;;;;| |;;;|         |;;;;;||
|;;;;;| |;;;|         |;;;;;||
|;;;;;| |;;;|         |;;;;;||
|;;;;;| |___|         |;;;;;||
\_____|_______________|_____ |
 ~~~~~^^^^^^^^^^^^^^^^^~~~~~~
```

Protections

Two types of memory protections

1. Stop you corrupting memory
   a. Stack reordering / random padding
   b. Stack canary
   c. FORTIFY
   d. RELRO
   e. Writing good code
   f. Testing :D
2. Stop you gaining code exec after memory corruption
   a. ASLR/PIE Randomisation
   b. NX
   c. Pointer Authentication
   d. Hypervisor magic stuff

Bypassing these

- Some can’t be bypassed
- Always situational
    - No one size fits all solution

Finding if these are enabled?

checksec from pwntools or pwndbg

```
aslr honeypot% checksec a.out
[!] Could not populate PLT: ERROR: fail to load the dynamic library.
[*] '/home/honeypot/moreappropiatename/comp6447/2020/lectures/4/aslr/a.out'
    Arch:     i386-32-little
    RELRO:    Partial RELRO
    Stack:    No canary found
    NX:       NX enabled
    PIE:      No PIE (0x8048000)
```

```
aslr honeypot% gcc -m32 ./test.c -pie -z relro -z now -fstack-protector-all
aslr honeypot% checksec a.out
[!] Could not populate PLT: ERROR: fail to load the dynamic library.
[*] '/home/honeypot/moreappropiatename/comp6447/2020/lectures/4/aslr/a.out'
    Arch:     i386-32-little
    RELRO:    Full RELRO
    Stack:    Canary found
    NX:       NX enabled
    PIE:      PIE enabled
```

ASLR

How it works

- Whenever a new process executes, **every memory region** gets an **ASLR slide**
    - This is a **random** number, that is **aligned** to a boundary (ie: final byte is 00)
    - Everything within the memory region is relatively the same, only thing that moves is the base
- This is system wide. Can't be disabled on a per program basis

What it tries to do

- Increase entropy, you need to now guess xx bits to get a correct address
    - Brute forceable in 32 bit computers (**don't** try this in this course)
    - Not brute forceable in 64 bit computers

How to solve? Leak an address, **requires information leak vulnerability**

```
aslr honeypot% cat test.c
#include <stdio.h>

int main(int argc, char *argv[], char *envp[]) {
  int a = 0;
  printf("%p\n", &a);
}
aslr honeypot% repeat 5 ./a.out
0xff85c16c
0xffc683bc
0xfffe66dc
0xffabfcac
0xff892c5c
```

Position Independent Execution (PIE)

Similar to ASLR, but affects the text/code region of a program.

- Program specific, the program needs to be compiled with this option enabled
  - Program can't contain jumps to static addresses anymore, everything has to be relative
  - GCC usually sets **EBX** to be the base of the binary, and offsets global variables from that
- If ASLR is disabled system wide, this is disabled
  - 1 way relationship, this has no effect on ASLR, ASLR has an effect on this

Solution to this: Same as ASLR, leak an address, or use a different memory region (ie: put shellcode on the stack, don't need to defeat PIE)

```
aslr honeypot% cat test.c
#include <stdio.h>

int main(int argc, char *argv[], char *envp[]) { printf("%p\n", main); }
aslr honeypot% repeat 5 ./a.out
0x566511ad
0x566451ad
0x565cf1ad
0x565b91ad
0x566271ad
```

Even with ASLR/PIE. Memory regions are ordered

```
pwndbg> vmmap
LEGEND: STACK | HEAP | CODE | DATA | RWX | RODATA
0x565ef000 0x565f0000 r--p     1000 0      /home/honeypot/moreappropiatename/comp6447/2020/lectures/4/aslr/a.out
0x565f0000 0x565f1000 r-xp     1000 1000   /home/honeypot/moreappropiatename/comp6447/2020/lectures/4/aslr/a.out
0x565f1000 0x565f2000 r--p     1000 2000   /home/honeypot/moreappropiatename/comp6447/2020/lectures/4/aslr/a.out
0x565f2000 0x565f3000 r--p     1000 2000   /home/honeypot/moreappropiatename/comp6447/2020/lectures/4/aslr/a.out
0x565f3000 0x565f4000 rw-p     1000 3000   /home/honeypot/moreappropiatename/comp6447/2020/lectures/4/aslr/a.out
0xf7daf000 0xf7dcc000 r--p    1d000 0      /usr/lib/libc-2.31.so
0xf7dcc000 0xf7ef6000 r-xp   12a000 1d000  /usr/lib/libc-2.31.so
0xf7ef6000 0xf7f5c000 r--p    66000 147000 /usr/lib/libc-2.31.so
0xf7f5c000 0xf7f5d000 ---p     1000 1ad000 /usr/lib/libc-2.31.so
0xf7f5d000 0xf7f5f000 r--p     2000 1ad000 /usr/lib/libc-2.31.so
0xf7f5f000 0xf7f61000 rw-p     2000 1af000 /usr/lib/libc-2.31.so
0xf7f61000 0xf7f65000 rw-p     4000 0
0xf7f7b000 0xf7f7f000 r--p     4000 0      [vvar]
0xf7f7f000 0xf7f81000 r-xp     2000 0      [vdso]
0xf7f81000 0xf7f82000 r--p     1000 0      /usr/lib/ld-2.31.so
0xf7f82000 0xf7fa0000 r-xp    1e000 1000   /usr/lib/ld-2.31.so
0xf7fa0000 0xf7fab000 r--p     b000 1f000  /usr/lib/ld-2.31.so
0xf7fab000 0xf7fac000 r--p     1000 29000  /usr/lib/ld-2.31.so
0xf7fac000 0xf7fad000 rw-p     1000 2a000  /usr/lib/ld-2.31.so
0xffb80000 0xffba1000 rw-p    21000 0      [stack]
```

Even with ASLR/PIE. Memory regions are ordered

```
pwndbg> vmmap
LEGEND: STACK | HEAP | CODE | DATA | RWX | RODATA
0x565ef000 0x565f0000 r--p     1000 0      /home/honeypot/moreappropiatename/comp6447/2020/lectures/4/aslr/a.out
0x565f0000 0x565f1000 r-xp     1000 1000   /home/honeypot/moreappropiatename/comp6447/2020/lectures/4/aslr/a.out
0x565f1000 0x565f2000 r--p     1000 2000   /home/honeypot/moreappropiatename/comp6447/2020/lectures/4/aslr/a.out
0x565f2000 0x565f3000 r--p     1000 2000   /home/honeypot/moreappropiatename/comp6447/2020/lectures/4/aslr/a.out
0x565f3000 0x565f4000 rw-p     1000 3000   /home/honeypot/moreappropiatename/comp6447/2020/lectures/4/aslr/a.out
0xf7daf000 0xf7dcc000 r--p    1d000 0      /usr/lib/libc-2.31.so
0xf7dcc000 0xf7ef6000 r-xp   12a000 1d000  /usr/lib/libc-2.31.so
0xf7ef6000 0xf7f5c000 r--p    66000 147000 /usr/lib/libc-2.31.so
0xf7f5c000 0xf7f5d000 ---p     1000 1ad000 /usr/lib/libc-2.31.so
0xf7f5d000 0xf7f5f000 r--p     2000 1ad000 /usr/lib/libc-2.31.so
0xf7f5f000 0xf7f61000 rw-p     2000 1af000 /usr/lib/libc-2.31.so
0xf7f61000 0xf7f65000 rw-p     4000 0
0xf7f7b000 0xf7f7f000 r--p     4000 0      [vvar]
0xf7f7f000 0xf7f81000 r-xp     2000 0      [vdso]
0xf7f81000 0xf7f82000 r--p     1000 0      /usr/lib/ld-2.31.so
0xf7f82000 0xf7fa0000 r-xp    1e000 1000   /usr/lib/ld-2.31.so
0xf7fa0000 0xf7fab000 r--p     b000 1f000  /usr/lib/ld-2.31.so
0xf7fab000 0xf7fac000 r--p     1000 29000  /usr/lib/ld-2.31.so
0xf7fac000 0xf7fad000 rw-p     1000 2a000  /usr/lib/ld-2.31.so
0xffb80000 0xffba1000 rw-p    21000 0      [stack]
```

Look for patterns

- 0x565... = Binary base with **PIE enabled*****
- 0x804… = Binary base with **PIE disabled*****
- 0xf7f… = Library base***
- 0xff… = Stack base***

*** (usually on 32 bit linux systems)

Non executable stack / NX / W^X

- Reads how it does
- Can’t write code then execute it by default
  - Never have a memory region which is both writeable and executable
- Set my compiler, enforced by hardware
- If you try to execute non executable code, you will die (or crash)

How to bypass?

- ROP/RET2code/RET2libc
  - We will learn this in upcoming weeks

RELRO?

A technique to harden ELF binaries using **Relocation R**ead-**O**nly

- TLDR; makes the GOT read only.

Comes in two parts. Partial and Full RELRO

Partial is pretty useless. GOT is still writeable.

Full is where GOT becomes read only

Solution: **Write somewhere else**

Fortify?

- Used to combat things like format string exploits
- Does a lot
    - causes some **lightweight checks** to be performed to detect some **buffer overflow** errors when employing various string and memory manipulation functions
        - memcpy, memset, stpcpy, strcpy, strncpy, strcat, strncat, **sprintf, snprintf, vsprintf, vsnprintf**, gets, etc
- Important thing it does
    - Only allows %n when fmt string is in readonly memory

Pointer Authentication (PAC)

A new technique introduced in ARM 8.3

- PAC is new and increasingly difficult to bypass
  - https://googleprojectzero.blogspot.com/2019/02/examining-pointer-authentication-on.html
- its purpose is to detect pointers created by an external entity.
- When you want to jump to address X, you jump to a signed version of the address
  - That address/code is calculated from three values:
    - the pointer itself
    - a secret key hidden in the process context
    - and a third value like the current stack pointer.
  - The secret key is intended to make it impossible for an attacker to generate valid codes, while the stack pointer can help prevent the reuse of a valid, signed pointer should one leak to the attacker
- Not something you have to worry about in the course (maybe in life though ;))

From now

ASLR will be enabled in wargames

As will other protections. (check with checksec)