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# Binary Reverse Engineering

## with Ghidra

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# Outline

- 1 Introduction
  - Disassembling
  - Basic Blocks and Control Flow Graphs
  - Functions and Call Graphs
- 2 Getting started with Ghidra
  - Navigation
  - Finding `main/WinMain`
  - Improving Ghidra's output
- 3 Dynamic Analysis
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    - ASLR and other settings
  - Synchronizing static and dynamic analysis
  - Code Coverage
  - Pwntools
  - Patching and Instrumentation
- 4 Practice time!

# Reversing

How can we know what a program *really* does?

In particular, a **binary program, without anything else**

No source code, no documentation, no symbols, ...

**Reverse engineering** (AKA *reversing*) consists in attempting to understand how a device/process/piece-of-software accomplishes a task

- in our case, **what a program does, and how**
- can we just use ChatGPT/CoPilot/*some Large Language Model*...?

# Reversing challenges

- low-level languages
- often, no “symbols”; i.e. meaningful names
- (almost) no type information
- no class/module/namespace boundaries
- code and data can be mixed, and they usually do
- difficulty in adding/changing/removing instructions
- ...

With some effort and the right tools, **we'll break programs apart to learn how they work and what they do.**

An old saying goes:

*Once you speak machine code, then every program becomes open-source* 😊

# Beware

We always reverse engineer programs that have been explicitly written to be reversed (the so-called “crackmes”, and some CTF-like challenges), open-source software or malware

- It is not easy to find detailed and practical advice about the legal boundaries of reversing copyrighted software in EU, US, ... worldwide
- As far as I understand (but I am not a lawyer), in EU you are allowed to reverse engineer a program for **private purposes or to understand its interfaces to allow another program to interface with it**

## Never run unknown files

Unless you're 100% confident they are safe

Exercises/assignments, not clearly marked as malware, are safe (AFAIK 😊)

# Static vs Dynamic Analysis

Broadly speaking, we can split our methods/tools into

- **Dynamic analysis:** we run the binary and analyze it, or log its behavior, as it executes
  - often simpler, can observe runtime states
  - can be harmful; e.g., malware
  - not everything is necessarily apparent
  - for each run you observe *that* particular execution, and might miss *interesting* parts of the code; e.g.

```
if (random()==0xcafebabe) { /* interesting stuff */ }
```

- **Static analysis:** we reason about the binary without running it
  - you can analyze the whole binary in one go
  - you don't need a CPU/system that can run such a binary
  - (obviously, almost) no knowledge of runtime states
  - can be difficult to pinpoint *interesting* parts

# First approach: identification/integrity checking

How can we check the “identity” of a file?

Hash functions: controlla l'hash, ma possono essere manipolati, utilizzando certi metodi  
diversi file possono avere lo stesso hash

Linux/WSL `md5sum`, `sha*sum`, ...

Windows HashMyFiles [https://www.nirsoft.net/utils/hash\\_my\\_files.html](https://www.nirsoft.net/utils/hash_my_files.html)

...

→ `sample{1,2}.elf`



# Format and strings

The first approach usually consists in checking

## Formats

- `file`
- `magika` <https://github.com/google/magika>
- `diec` <https://github.com/horsicq/Detect-It-Easy>
- `polyfile` <https://github.com/trailofbits/polyfile>
- ...
- when in doubt, hex editors (e.g., `ImHex`  
<https://github.com/WerWolv/ImHex>)

## Strings

- `strings`; in Windows, *SysInternals Suite*  
<https://docs.microsoft.com/en-us/sysinternals> or inside the MS Store
- `floss` <https://github.com/mandiant/flare-floss>
- ...

# Executable specific tools

ELF `hte`, `readelf`, `objdump`, `nm`, ...

- XELFViewer

<https://github.com/horsicq/XELFViewer>

PE `hte`, `dumpbin.exe`, ...

- PE Bear

<https://github.com/hasherezade/pe-bear>

- PE Studio

<https://www.winitor.com/download>

- XPEViewer

<https://github.com/horsicq/XPEViewer>

- ...

# Linux: beware of 32-bit executables in modern distros

Modern **Linux distros do not ship 32-bit libraries** by default; e.g., on 64-bit Ubuntu systems, you need to add those:

- `sudo dpkg --add-architecture i386`
- `sudo apt update`
- `sudo apt install libc6-dbg:i386`

**A (simpler) alternative seems to be installing the package `gcc-multilib`**

Other distributions should provide analogous packages.

## CTFs and Flags

All challenge descriptions are *tongue in cheek*: don't take them too seriously 😊 (but read them carefully, since they may contain hints)

In these exercises, *flags* are strings in the format `BASC{...}`.

*A flag is trapped inside a restricted area, protected by a super-secure password. Will you find it?*

→ `restricted_area_v1`

## Demo/exercise: restricted-area v2.0

*We fixed all vulnerabilities of the previous version.*

*This program doesn't accept any password, so you can't guess them! Ahahah*

*Can you still manage to get the flag?*

→ `restricted_area_v2`

Can you find the flag... with the tools discussed so far?

To go deeper, we need to look at the code...

# How could we analyse/reverse machine code?

- 1 Disassemble, i.e. decoding bytes into assembler instructions
- 2 Group instructions into (basic) blocks and functions
- 3 Abstract into graphs
  - control-flow graphs describe the structure of functions
  - call graphs describe the relationships between functions
  - code/data cross references help in understanding dependencies and find interesting (starting) points, to explore further
- 4 Decompile, i.e. *trying* to recover corresponding C code

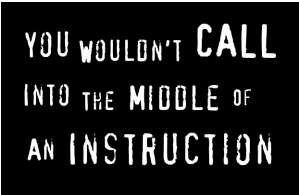
The general goal is inferring higher-level semantics, by giving meaningful names, and adding comments

- e.g. “increment variable counter” instead of `ADD [RSP-0x1C], 1`  
or “call function ask\_password” instead of `CALL 0x61a4be0032`

# Disassembling

Disassembling might sound boring and trivial, however... [ACvdV<sup>+</sup>16, JZL<sup>+</sup>20]

- How do you distinguish between *code* and *data*?
  - E.g., compilers may embed data inside code sections
- Instructions could be *overlapped* [JLH13, LD03]



YOU WOULDN'T CALL  
INTO THE MIDDLE OF  
AN INSTRUCTION

<https://twitter.com/awesomekling/status/1369178264716120065>

- Code can be *encrypted/packed/obfuscated/...*

# Types of disassemblers

## Static disassemblers can be split into

- **Linear sweep**
  - start at the beginning
    - disassemble the first instruction
    - then the following one,
    - and so on
  - no attempt to understand the control flow
- **Recursive traversal**
  - focus on of control flow
  - start at the entry point
    - if non-branch, continue to the next instruction
    - if branch, continue to possible targets

→ `asm-examples/tricky_disasm/tricky.asm`



# Basic Blocks

**Basic blocks** are sequences of instructions in which

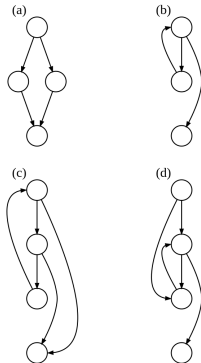
- flow of control enters at the beginning
- leaves at the end, without branching (except at the end)

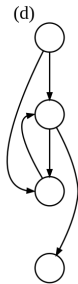
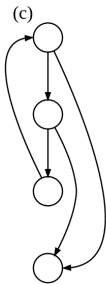
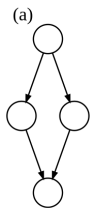


# Control flow graph

A **Control Flow Graph** captures the execution paths that can take place inside a function

- the **nodes** are basic blocks
- **edges** represent potential **control flow paths**
  - back edges represent loops





- a** an if-then-else
- b** a while loop
- c** a loop with two exits, e.g. while with an if...break in the middle
- d** a loop with two entry points, e.g. goto into a while or for loop

[https://en.wikipedia.org/wiki/Control\\_flow\\_graph](https://en.wikipedia.org/wiki/Control_flow_graph)

# CFG Construction challenges

## Problematic constructs are:

- **indirect jump instructions**; mainly used to implement switch statements. [MM16] handles various kinds of jump tables with a backward intraprocedural dataflow analysis; e.g.:

Instruction	Jump target analysis
mov %ebp,0xf8(%rsp)	$0 \leq \%rdx == 0xf8(\%rsp) == \%ebp \leq 5$
cmp \$0x5,%ebp ja 43a4ab	$0 \leq \%ebp \leq 5$
lea 0x525e8f(%rip),%rax lea -0x302(%rip),%rcx	$\%rax = 0x9602a0, \%rcx = 0x43a116$ $JTT = 0x43a116 + [0x9602a0 + \%rdx \times 8]$
movslq 0xf8(%rsp),%rdx	$\%rdx == 0xf8(\%rsp)$
add (%rax,%rdx,8),%rcx	$JTT = \%rcx + [\%rax + \%rdx \times 8]$
jmpq *%rcx	$JTT = \%rcx$

- **non-returning functions**; e.g. `exit` or `abort`. If not recognized, a nonexistent control flow is assumed from a non-returning call to its next block

# CFG Partitioning challenges

Functions can share BBs, their code can be non-contiguous

---

```
35110db510 <__write>:
35110db510    cmpl $0x0,0x2b8199(%rip)
35110db517    jne 35110db529
35110db519 <__write_nocancel>:
35110db519    mov $0x1,%eax
...
35110db526    jae 35110db559
35110db528    retq
35110db529    sub $0x8,%rsp
...
35110db556    jae 35110db559
35110db558    retq
35110db559    mov 0x2b2a48(%rip),%rcx
...
35110db56c    jmp 35110db558
```

---

**Figure 9: Functions sharing code and non-contiguous functions example from libc.** The code in blue is shared by both functions. `__write_nocancel` is also a non-contiguous function, which is separated by the code from `__write`.

From: [MM16]

## Tail calls: 2 or 3 functions?

---

```
BZFILE* BZ_API (BZ2_bzdopen) (int fd, char * mode)
{ return bzopen_or_bzdopen(NULL,fd,mode,1);}
BZFILE* BZ_API (BZ2_bzopen) (char *path, char * mode)
{ return bzopen_or_bzdopen(path,-1,mode,0);}

```

---

```
// entry point of bzopen_or_bzdopen, but no function symbol
351f40baa0  mov %rbx,-0x30(%rsp)
...
351f40bd70 <BZ2_bzdopen>:
351f40bd70  mov %rsi,%rdx          // set mode
351f40bd73  mov $0x1,%ecx          // set open_mode
351f40bd78  mov %edi,%esi          // set fd
351f40bd7a  xor %edi,%edi          // set path
351f40bd7c  jmpq 351f40baa0
...
351f40bd90 <BZ2_bzopen>:
351f40bd90  mov %rsi,%rdx          // set mode
351f40bd93  xor %ecx,%ecx          // set open_mode
351f40bd95  mov $0xffffffff,%esi   // set fd
351f40bd9a  jmpq 351f40baa0

```

---

**Figure 10: A tail call example from bzip2.** BZ2\_bzdopen and BZ2\_bzopen both perform a tail call to the internal function bzopen\_or\_bzdopen, which does not have a function symbol.

# Finding function entry points (without symbols)

Without complete symbols, identifying function entry points becomes significantly more difficult; you can tackle this issue by

- recognizing *function prologue patterns*; however, difficult to
  - adapt to variations in compilers and optimization levels
  - detect non-standard/hand-written functions
- parsing `.eh_frame` section  
[https://bitlackeys.org/#eh\\_frame](https://bitlackeys.org/#eh_frame)
- using the CFG; see e.g. [ASB17]

(non-inlined) library functions are somewhat easier to detect:

- in dynamically linked programs, function names cannot be omitted
  - tricky programs may play with `dlsym/GetProcAddress` and/or *offsets*
- in statically linked programs we can try *fingerprinting* known functions [JRM11]

# Call graphs

Once you have identified functions, then it can be useful representing **relationships between functions** in a **Call Graph**

- each node represents a function
- each edge  $(f, g)$  indicates that  $f$  calls  $g$ 
  - A cycle indicates recursive calls
- can be computed statically or dynamically
  - E.g. a profiler could produce a dynamic call graph
- a static call graph **represents every possible run**
  - computing the exact static call graph is an undecidable problem
  - static call graph algorithms are generally **overapproximations**
    - when function pointers or virtual methods are invoked, a combination of *dataflow* and *data type* analysis can limit the set of potential *targets*
    - if the program loads code modules dynamically at runtime, there is no way to be sure that the control flow graph is complete



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# Getting started

- A highly extensible application for software reverse engineering
  - Official site: <https://ghidra-sre.org/>  
You find there binaries and installation guide
  - Guides/tutorials
    - docs/GhidraClass, inside Ghidra installation directory
    - these slides 😊
    - (paid, excellent) [The Ghidra Book](https://nostarch.com/GhidraBook)  
<https://nostarch.com/GhidraBook>
    - (free) [“Hands-on Reversing with Ghidra”](https://vimeo.com/728095141)  
by Jeremy Blackthorne @ Ringzer0 Training 2022  
<https://vimeo.com/728095141>
- script snippets: <https://github.com/Hack0vert/GhidraSnippets>
- The main, closed-source, alternatives are:
    - *IDA Pro* <https://hex-rays.com/ida-pro/>
    - *Binary Ninja* <https://binary.ninja/>

# The environment

Let's use Ghidra to analyze `restricted_area_v1` ...

- Projects
  - Loaders
  - Tools → Code Browser
- Auto-analysis (with/w.o. the PDB file)
- Window handling/layout

# Shortcuts and suggested options

Shortcut to remember:

- F1
- F4 while the mouse is over any toolbar icon or menu item

Suggested key bindings (*Edit* → *Tool Options...* → *Key Bindings*):

- ESC/shift-ESC for *Previous/Next location in History*
- X/ctrl-X for *Find References To* and *Show References To Address*

Moreover, you may consider to set “Left” for *Mouse Button Activate* in *Listing Fields* → *Cursor Text Highlight*

# Symbol views

- *Symbol table* displays a tabular view of each symbol
  - *Symbol reference* display reference information for selected symbol, and type of reference
    - RW read/write data access
    - Read read-only data access
    - Write write-only data access
    - Data general data access
    - Branch conditional jump
    - Jump unconditional jump
    - Call subroutine/function call
    - Unknown all other reference types
- *Symbol tree* hierarchical view

## Imported functions

These views are useful to quickly look at imports/exports

# Default labels

## Default label prefixes

- Common

**FUN** a function

**DAT** a data item (AKA “global variable”)

**LAB** code (usually, some jump-target inside a function)

- Others

**SUB** code that has at least one call to it (but it doesn't seem a proper function)

**EXT** an external entry point

**OFF** the associated address is *offcut*, i.e. inside of an instruction or data item

**UNK** none of the above

You can **change/assign a label** with **L**

# Navigation

Views are synchronized

- **G** to jump to address/label (wildcards)/expression
- toolbar: next/previous
  - location
  - selected/highlighted range
  - code-unit
- double-click on label/address in the code browser
- click on names in *Functions/...*  
(when enabled, otherwise double-click)

“next”/“previous” meaning for I/D/U

When searching for Instructions/Data/Undefined items, Ghidra will skip all contiguous items of the same type. Then, it will search for the item.

- inside *Listing*
  - c call
  - j jump
  - \* pointer
  - w write
  - r read
- in *Reference to ...* views



To display incoming and outgoing calls:

- *Function Call Graph*
- *Function Call Trees*

Search...

**Program Memory** performs searching for byte patterns in program memory

**Program Text** searches for text strings in various parts of the listing

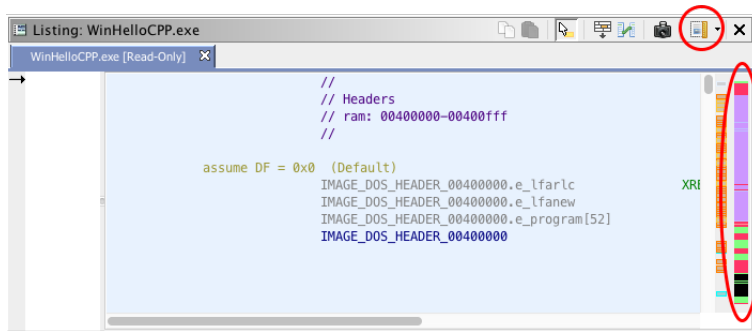
- supports wildcards but not full regular-expressions

**For Strings** finds potential strings within the program memory

**For ...** find scalars, instruction patterns, ...

# Bars

- Navigation marker area (right-click to see/select categories)
- Overview bars
  - Entropy
  - Overview



# Columns and Column-filters

- Some windows let you choose the columns and their filters (e.g. *Functions* and *Defined Strings*)
- Filters can be saved and reused later

## Other views

- *Bytes* (click on its settings for adding “columns”)
- *Defined data*
- *Defined strings*

### View synchronization

Views are synchronized, you can make snapshots/independent-views with the “camera”

# Startup code

When we analyzed `restricted_area_v1`, Ghidra found and jumped to `main`. Let's check `v2` out...

Most executables share the same startup code, which

- ① initializes the CRT
  - in Windows the very first thing is initializing the security cookie
- ② calls the main function (`main` or `WinMain`)
  - saving the return value `v`
- ③ cleans up the CRT
- ④ exits with exit-value `v`

The executable entry-point is called `entry`

## entry

If Ghidra does not name `entry` automatically, you can find the entry-point by navigating the ELF/PE-header (see *Program trees* → *Headers*)

# Linux/Windows: main

According to the C standard,

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

however, a common extension is

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

## Decompiler Parameter ID analysis

While generally useful (but expensive: turned-off by default for large programs), this analysis can be misleading when looking for `main/WinMain` because it can “hide” parameters, at call site, that are unused by the function

# Windows: WinMain

[https://learn.microsoft.com/en-us/windows/win32/learnwin32/winmain--the-application-entry-point:](https://learn.microsoft.com/en-us/windows/win32/learnwin32/winmain--the-application-entry-point)

```
int __stdcall WinMain(  
    [in] HINSTANCE hInstance,  
    [in] HINSTANCE hPrevInstance,  
    [in] LPSTR      lpCmdLine,  
    [in] int        nShowCmd  
);
```

- `hInstance` is actually the `module load-address`
- `hPrevInstance` is always 0 (it is from the 16-bit days)
- `pCmdLine` contains the command-line arguments as a Unicode string
- `nCmdShow` is a flag that says whether the main application window will be minimized/maximized/...



# Linux: the address of main

[https://refspecs.linuxbase.org/LSB\\_3.1.0/LSB-generic/LSB-generic/baselib---libc-start-main-.html](https://refspecs.linuxbase.org/LSB_3.1.0/LSB-generic/LSB-generic/baselib---libc-start-main-.html):

In Gdb we can ...

- start
- b \_\_libc\_start\_main
- c
- find out its first parameter
  - 32 bits: p \*(void \*\*)(esp+4)
  - 64 bits: p \$rdi

# Comments

Comments can be added to any instruction/data-item, with ; (semicolon)

Five categories:

**End-of-line (EOL)** Displayed to the right of the instruction

**Pre** Displayed above the instruction and in decompiled code

**Post** Displayed below the instruction

**Plate** Displayed as a block header above the instruction, and in decompiled view.  
Plate comments are automatically surrounded by '\*'s

**Repeatable** Displayed to the right of the instruction if there is no EOL comment.  
These are also displayed at the “from” address of a reference (if there is no EOL or repeatable comment defined at that address)

# Constants

- convert
- set equate

Note: decompiler and listing views are not “synchronized” as conversions/equates go

LLMs can be leveraged to improve the decompiler output; some notable Ghidra plugins/scripts are:

- GhidrOllama  
<https://github.com/lr-m/GhidrOllama>  
that allows you to use any Ollama Models <https://ollama.com/library> *offline*
- DAILA  
<https://github.com/mahaloz/DAILA>  
AFAIK needs an internet connection to leverage OpenAI's GPT, etc.

Interesting video: *Your Teammate Isn't Human: Mixing Decompilation and AI for Modern Reverse Engineering*

<https://www.youtube.com/watch?v=HbrebQiFLDs>

# Calling conventions

Both `function1` and `function2` takes three integers and print a simple calculation.

Let's find out what

→ `function1` and

→ `function2` do by ...

- ① running them, and guessing
- ② using Ghidra decompiler/function graph

... and we're back to restricted-area!

- Can you find the address of `main`?
- Identify the function that prints the flag

Why such a function is not called? Can we do something about it?

Two possibilities are:

- altering the control flow by using a debugger
- patching the machine code

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# Dynamic Analysis tools

We can observe the execution of a program at many different levels; e.g.,

## Linux

- `strace [-f] [-e ...]`
- `ltrace` — some versions don't work with eagerly-bind executables; check with: `readelf --dynamic ... | grep NOW`

Try: `ltrace -e strcmp ./restricted_area_v1` # same for v2

- `gdb + GEF`

## Windows

- `Process Monitor` from the *Sysinternals Suite*
- `Tiny Tracer` [https://github.com/hasherezade/tiny\\_tracer](https://github.com/hasherezade/tiny_tracer)
- `x64dbg`

... and even making our custom analyses by leveraging instrumentation frameworks



**Debuggers** are software (or hardware) that permit to get an insight into **what a program/system is doing**, by

- **pausing the execution** at specific places
  - optionally, when some conditions are met
- **showing the contents of registers and memory**
- **resuming** the execution
- ...

# Symbols and debug information

Programs and libraries can include

- **Symbols**, mapping names to memory addresses. For instance, they allow you to find in which function the *instruction-pointer* is, ...
- Full **debug information**, that allow a debugger to match machine code to its corresponding source-level constructs

Released programs typically don't, but they rely on standard libraries...

# Symbols in Linux

Libc symbols are distributed separately

- in Ubuntu, `libc6-db` and `libc6-db:i386`
- in `gdb` (or `~/.gdbinit`) use:  
`set debug-file-directory /usr/lib/debug`  
then,
- `info address symbol` shows where data for symbol is stored
- `info symbol addr` prints the name of symbol stored at *addr*

You can also use `addr2line(1)` to read symbol information

Compiling with `-g/-ggdb` adds **debug information** using DWARF [Eag12]  
(<https://dwarfstd.org/>)

- to dump DWARF information, `dwarfdump`; e.g. `-1` prints the association between PCs and source lines  
→ `c-examples/buggy_factorial`

# Symbols in Windows

Symbol information can be downloaded from a **symbol server**

- official one: `https://msdl.microsoft.com/download/symbols`
- you can set the environment value `_NT_SYMBOL_PATH` to something like:  
`srv*your-cache-path*server-url`; e.g.  
`setx _NT_SYMBOL_PATH ^`  
`srv*c:\sym*https://msdl.microsoft.com/download/symbols`
- x64dbg set the server in: **Options → Preferences → Misc**
- `symchk.exe` from Windows SDK, and 3<sup>rd</sup>-party utilities, can download symbols and store them in the cache

With MS's compiler, `/DEBUG` add **debugging information**:

- 1 The linker puts these information into a **program database (PDB)** file
- 2 The **executable/DLL** contains the **path** of the corresponding PDB
- 3 A **debugger** reads the **embedded name** and uses the PDB

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  - Patching and Instrumentation
- 4 Practice time!

Let's open three times each `restricted_area_v{1,2}` in the debugger.

Obviously, the code is different for `v1/2`, but you should notice something else. . .

*In order to prevent an attacker from reliably jumping to, for example, a particular exploited function in memory, ASLR randomly arranges the address space positions of key data areas of a process, including the base of the executable and the positions of the stack, heap and libraries*

`https://en.wikipedia.org/wiki/Address\_space\_layout\_randomization`

# Memory map

You can synchronize the static and dynamic addresses by setting the **Image Base** from the **Memory Map**

- however, there other ways. . .



# Useful settings

- You can disable ASLR by

Linux using the command `setarch`; for instance:

```
setarch $(uname --machine) --addr-no-randomize bash
```

Windows resetting the flag `IMAGE_DLLCHARACTERISTICS_DYNAMIC_BASE` (0x40) in the field `DllCharacteristics` of the `PE_IMAGE_OPTIONAL_HEADER` (e.g., by using `PE Bear`)

- Windows 10+ implement parallel loading by creating a thread pool of worker threads when the process initializes. You can set registry key

```
HKLM\Software\Microsoft\Windows NT\CurrentVersion\Image File Execution  
Options\your-program.exe\MaxLoaderThreads
```

to 1, to avoid having multiple threads around

# Restricted area, again!

Let's solve `restricted_area_v2` with the help of a debugger

*Volatility is a tendency to change quickly, as it happens with the flag of this challenge.*

*No, this is not a forensics challenge.*

*Can you be fast enough to catch the flag?*

→ volatility

# Synchronizing static and dynamic analysis

Two different approaches:

- Ret-Sync, which allows you to use any debugger
- Ghidra “internal” debugger; some shortcomings/limitations at the moment

- **ret-sync** stands for *Reverse-Engineering Tools SYNChronization*
- plugins **to synchronize a debugging session with a disassembler**

`https://github.com/bootleg/ret-sync`

# Remote debugging

Ret-sync can be configured via its “.ini” `.sync` file

```
[INTERFACE]
host=...
port=...
```

To enable remote-debugging:

- 1 find the IP address of the computer running Ghidra
  - typically, Ghidra is run on the host and the debugger inside a VM
  - in VMware, the host-only network (VMnet1) allows you to access an isolated virtual network, completely contained within the host system
- 2 then, create the configuration file and copy it to both:
  - the user's home directory of the debugger machine  
`c:\users\user\.sync`
  - the user's home directory or the Ghidra project folder (`.../project.rep/.sync`) of the Ghidra machine

# Ret-sync bugs

Sometimes ret-sync doesn't work properly with gdb 😞

The following workaround, in the `.sync` file (inside the Ghidra project folder; i.e., `.../project.rep/.sync`), seems to solve the problems:

- set `use_raw_addr=true` under section `[GENERAL]`

# Ret-sync shortcuts in Ghidra

Most important are:

- F2** Set breakpoint at cursor address

- Ctrl-F2** Set hardware breakpoint at cursor address

- Alt-F3** Set one-shot breakpoint at cursor address

- Ctrl-F3** Set one-shot hardware breakpoint at cursor address

- Alt-F2** Translate (rebase in debugger) current cursor address

- F5** Go

- F10** Step over

- F11** Step into



# Code Coverage

- To collect coverage data DrCov, leveraging *DynamoRio*:  
`drrun.exe -t drcov -- program`
  - A similar tool for Intel Pin can be found inside <https://github.com/gaasedelen/lighthouse> the project that inspired Cartographer and Lightkeeper
- To analyze/visualize, *Cartographer*: <https://github.com/nccgroup/Cartographer>
  - another, similar, project is: <https://github.com/WorksButNotTested/lightkeeper>

```
UVar2 = (UINT)unaff_RBX;
uVar4 = __srt_initialize_crt(1);
if ((char)uVar4 == '\0') {
    FUN_140001db0(7);
}
else {
    bVar1 = false;
    uVar9 = 0;
    uVar4 = __srt_acquire_startup_lock();
    UVar2 = (UINT)CONCAT71((int7) {(ulonglong)unaff_RBX >> 0}, (char)uVar4);
    if (DAT_140022af0 != 1) {
        if (DAT_140022af0 == 0) {
            DAT_140022af0 = 1;
            uVar5 = FUN_1400089a4((undefined **)&DAT_1400172c8, (undefined **)&DAT_140017300);
            if ((int)uVar5 != 0) {
                return 0xff;
            }
        }
        FUN_140008960((undefined **)&DAT_1400172b0, (undefined **)&DAT_1400172c0);
        DAT_140022af0 = 2;
    }
    else {
        bVar1 = true;
        uVar9 = 1;
    }
}
```

# Pwntools

Pwntools is a

- CTF framework and
- exploit development library

written in Python

<https://github.com/Gallopsled/pwntools>

Demo/exercise:

→ bomb (local and “remote”)

# Tubes: pwnlib.tubes

- `process`
- `sock`
  - `remote`
  - `listen`
- `ssh`
- ...

various methods to interact:

- `send*[after]`
- `recv*`
  - `clean`  
returns all buffered data from a tube by calling `recv` with a low timeout until it fails
- `interactive`  
prints a prompt, and simultaneously reads & writes

<https://docs.pwntools.com/en/stable/tubes.html#module-pwnlib.tubes>

# Context

Many settings controlled via `context`, such as

- `os`: target OS, see `pwnlib.context.ContextType.oses`
- `arch`: architecture; see `pwnlib.context.ContextType.architectures`
- `bits` / `endian`: bit-width/endianness
- `log_level`: logging level; default `logging.INFO`

## `context.binary`

The easiest way to *automagically* set all context values is assigning the property `binary`; e.g.:

```
context.binary = './my-binary'
```

(you can also assign an ELF object, which we'll encounter in a few slides)

# Packing and unpacking of strings

```
>>> p8(0), p16(0), p32(0), p64(0)
(b'\x00', b'\x00\x00', b'\x00\x00\x00\x00',
 b'\x00\x00\x00\x00\x00\x00\x00\x00')
>>> p32(0xdeadbeef)
b'\xef\xbe\xad\xde'
>>> p32(0xdeadbeef, endian='big')
b'\xde\xad\xbe\xef'
>>> hex(u32(b'\xbe\xba\xfe\xca'))
'0xcafebabe'
```

<https://docs.pwntools.com/en/stable/util/packing.html>

## Endianness

context-aware; can be overridden in the parameters

# Magic Command-Line Arguments

Settings, when run in `from pwn import *` mode, can be specified by

- adding **UPPERCASE arguments** to the command-line; those arguments are extracted, and removed from `sys.argv`
- using **environment variables, prefixed by `PWNLIB_`**

For instance, to enable more **verbose debugging**:

```
$ PWNLIB_DEBUG=1 python exploit.py
$ python exploit.py DEBUG
```

Then, for instance, to switch between a local/remote target:

```
if args.REMOTE: # equivalent to: args['REMOTE']
    io = remote('exploitme.com', 4141)
else:
    io = process('./pwnable')
```

See <https://docs.pwntools.com/en/stable/args.html>

# Assemble and Disassemble

```
>>> asm('nop')
'\x90'
>>> asm('mov eax, 0xdeadbeef').hex()
'b8efbeadde'
>>> asm('mov eax, 0').hex()
'b800000000'
>>> print(disasm(unhex('6a0258cd80'))))
0:    6a 02                push    0x2
2:    58                  pop     eax
3:    cd 80              int     0x80
```



# ELF parsing and patching

class ELF members:

- `sym[bols]` is a *dotdict* of name to address for symbols
  - `prog.symbols['printf']` can be simplified to:  
`prog.symbols.printf`  
`prog.sym.printf`
- `got` is a *dotdict* of name to address for GOT entries
- `plt` is a *dotdict* of name to address for PLT entries
  - for an imported function *f*, `elf.plt.f == elf.symbols.f`
- `search(string, writable = False)` → a generator  
search the virtual address space for the specified string
- `(dis)asm` to (dis)assembly using virtual addresses
- `read/write/save`
- ...

To create an ELF from assembly/bytes: `ELF.from_assembly`, and `ELF.from_bytes`

<https://docs.pwntools.com/en/stable/elf/elf.html>

# Interfacing with GDB

Example:

```
p = gdb.debug(args=..., gdbscript=...)
```

`gdb` is run in a **new terminal**, executing the `gdbscript`

- if `tmux` detected, defaults to new pane; if you want to change that: `context.terminal = ['tmux', 'new-window']`  
`context.terminal = ['tmux', 'split-window', '-h']`
- if `Gnome terminal` doesn't work automatically, you can try:  
`context.terminal = ['gnome-terminal', '--window', '--', 'bash', '-c']`

See <https://docs.pwntools.com/en/stable/gdb.html> and  
<https://docs.pwntools.com/en/stable/context.html>

# And much more...

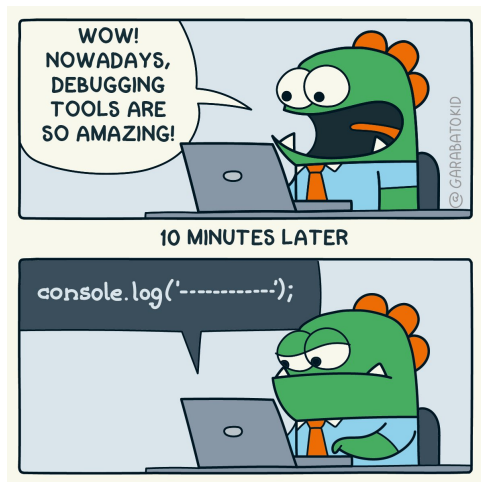
- finding ROP gadgets
- preparing format string payloads
- generating Python scripts (`pwn template ...`)
- ...

**RTFM** <https://docs.pwntools.com/en/stable/index.html>

## Jupyter notebooks/PyCharm

to use pwntools inside some environments, you need to set the variable `PWNLIB_NOTERM`; e.g.  
`PWNLIB_NOTERM=1 jupyter notebook`

# Debuggers



<https://twitter.com/garabatokid/status/1192753360497197056>

# Introduction

**Instrumentation** means inserting **new code** into a **program** or a **process**, to

- **observe** and/or
- **change**

**its behavior.**

- **Easy with source programs**
  - manually
  - automatically; for instance, in gcc you can use:
    - `-fsanitize=address` to instrument memory access instructions to detect out-of-bounds and use-after-free bugs
    - `-pg/-finstrument-functions` to generate profiling code
    - ...
- **Interesting on (stripped) binaries** 😊

Let's consider three scenarios:

- ① Replacing existing code/AKA “patching”
  - This can also be seen as “removing”, since we can overwrite with NOPs
- ② Inserting/removing code in the middle of existing one
- ③ Adding new code “somewhere”

# Replacing existing code

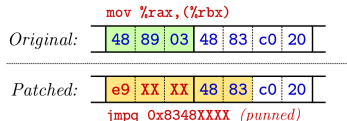
It's *relatively easy to replace* existing instructions, as long as

- 1 the new code fits into the space of the old one
- 2 jump targets are preserved

Examples of safe transformations are:

- “NOPping” annoying checks (anti-analysis? 😊)
- transforming conditional jumps to unconditional ones
- changing constant operands
- ...

**e9patch** [DGR20] relaxes the former constraint by “punning” bytes following an instruction. I.e., those bytes are used both as the last bytes of the inserted jump *and* the bytes for following instructions



# Inserting/removing code

Inserting new (or removing old) code is extremely hard, quoting [And18]:

*... new code will shift existing code to different addresses, thereby breaking references to that code. It's practically impossible to locate and patch all existing references after moving ...*

So, manually patching it's possible, but *tough* ... interesting read:

Did Microsoft just manually patch their equation editor executable? Why yes, yes they did. (CVE-2017-11882)



# Instrumentation framework

For more complex scenarios, there are **Instrumentation frameworks**

- tools for building program analysis tools
- they allow you to choose what to instrument and how

We can't cover them now; the most prominent are **Frida** <https://www.frida.re/>:

- “Unlocking secrets of proprietary software using Frida” @ NDC 2018  
<https://www.youtube.com/watch?v=QC2jQI7GLus>
- “The engineering behind the reverse engineering” @ OSDC 2015  
<https://www.youtube.com/watch?v=uc1mbN9EJKQ>

and Intel's **Pin** <https://www.intel.com/software/pintool>

## Restricted area, again *and again!*

Let's solve `restricted_area_v2` by patching the executable

## Demo/exercise: restricted-area v3.0

We promise this is the last variant!

→ `restricted_area_v3`

...you know what to do, don't you? 😊

Start the server by running:

`restricted_area_v3_run_server.sh`

The server listen at port 6001/tcp, that can be reached by running:

`nc 127.0.0.1 6001`

# Outline

## 1 Introduction

- Disassembling
- Basic Blocks and Control Flow Graphs
- Functions and Call Graphs

## 2 Getting started with Ghidra

- Navigation
- Finding `main/WinMain`
- Improving Ghidra's output

## 3 Dynamic Analysis

- Debuggers
  - ASLR and other settings
- Synchronizing static and dynamic analysis
- Code Coverage
- Pwntools
- Patching and Instrumentation

## 4 Practice time!

## Exercises:

- `math_is_4_fun`
- `minions`, port 6002
- `jurassic_park`
- `slow_printer`
- `easter_egg`
- `lucky-numb3rs`, port 6003
- `the_maze`, port 6004
- `unbreakable_aes`

## Demo/exercise:

- `pacman4console`

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