All Software is Open Source

AN INTRODUCTION TO REVERSE ENGINEERING

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About me

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VECTRA®
SECURITY THAT THINKS

- Senior Security Researcher at *Vectra AI*
- Prior to that - Pentester/Secure Software Development Advocate with X-Force Ethical Hacking Team at *IBM Security*
- 25+ years in software design and development
- Ph.D. in Computer Science, CEH, OSCP, CISSP, CCSP
- *Interests*: reverse engineering, secure software development, CTFs
- Live in Ottawa, Canada; originally from Russia

Agenda

- What is Reverse Engineering
- Applications of RE
- What Can You Reverse and Why?
- Legal Issues
- Categories of RE
- Code Examples
- Tools
- Common Obstacles
- How to Practice
- General Strategies
- Resources

What is Reverse Engineering

Reverse Engineering (or *reversing*) - process of understanding how a device, system, piece of software works by examining it (without having access to original design specs, source code, etc.)

- Becomes necessary when the original design information is not available or intentionally withheld

- Humans have been doing RE forever
  - Many inventions in human history have been analyzed and copied

- All natural sciences are essentially RE
  - Nature doesn't come with a manual

- You have probably done RE in your life more than once
  - The toy you pulled apart as a kid to see what's inside
  - The clock you tried to fix (unsuccessfully)

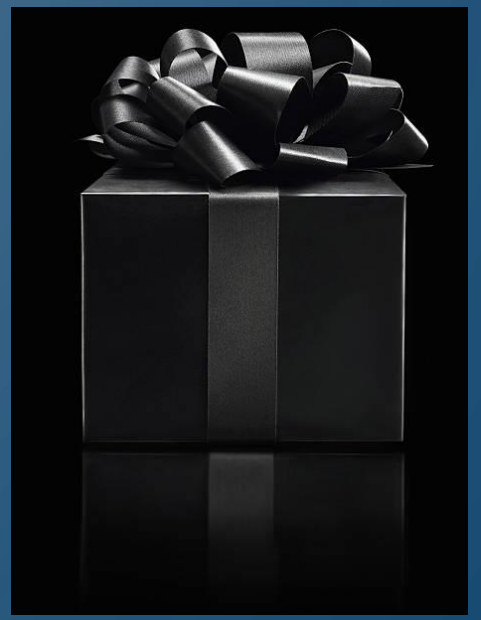
Modern Uses for RE

- Security/vulnerability research
- Pentesting
- Malware analysis
- Military/intelligence work
- Scientific research
- Commercial research/product compatibility
- Independent quality control
- Patent infringement detection
- ...and more

- We will talk about software RE
  - But that includes most hardware too - much of modern hardware is driven by software

Why Should You Do RE?

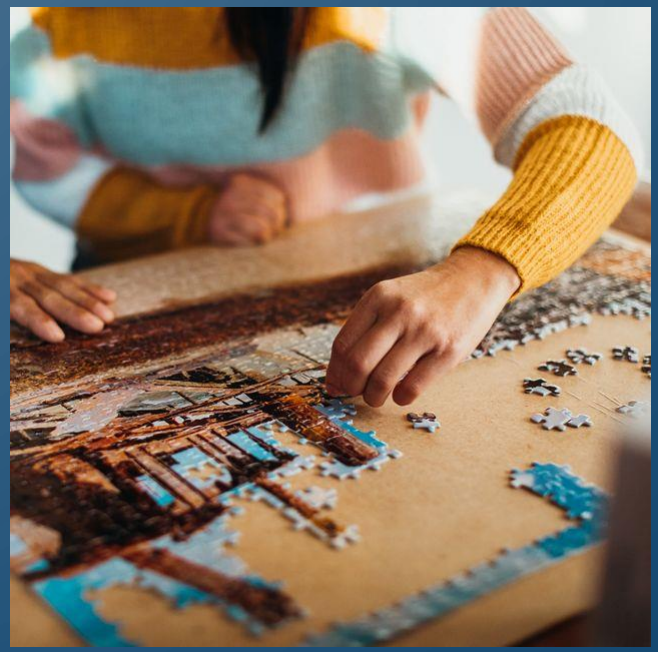
- A lot of software and hardware around us are "black boxes"
  - Documentation and architecture blueprints are scarce or withheld
- We want to be able to:
  - Analyze product for safety/quality
  - Analyze product for security/hidden backdoors
  - Recover legacy knowledge
  - Build compatible products
  - Patch in behavior changes or bug fixes
- RE gives you that power
  - *"When you know assembly - all software is open source" -- Unknown*



Why Should You Do RE? (cont.)

- Required skill if you are in Infosec
  - Vulnerability analysis (most CVEs require some RE)
  - Pentesting (analyzing customer software for holes)
  - Incident response (samples of ransomware, malware, phishing, C2, remote shells)

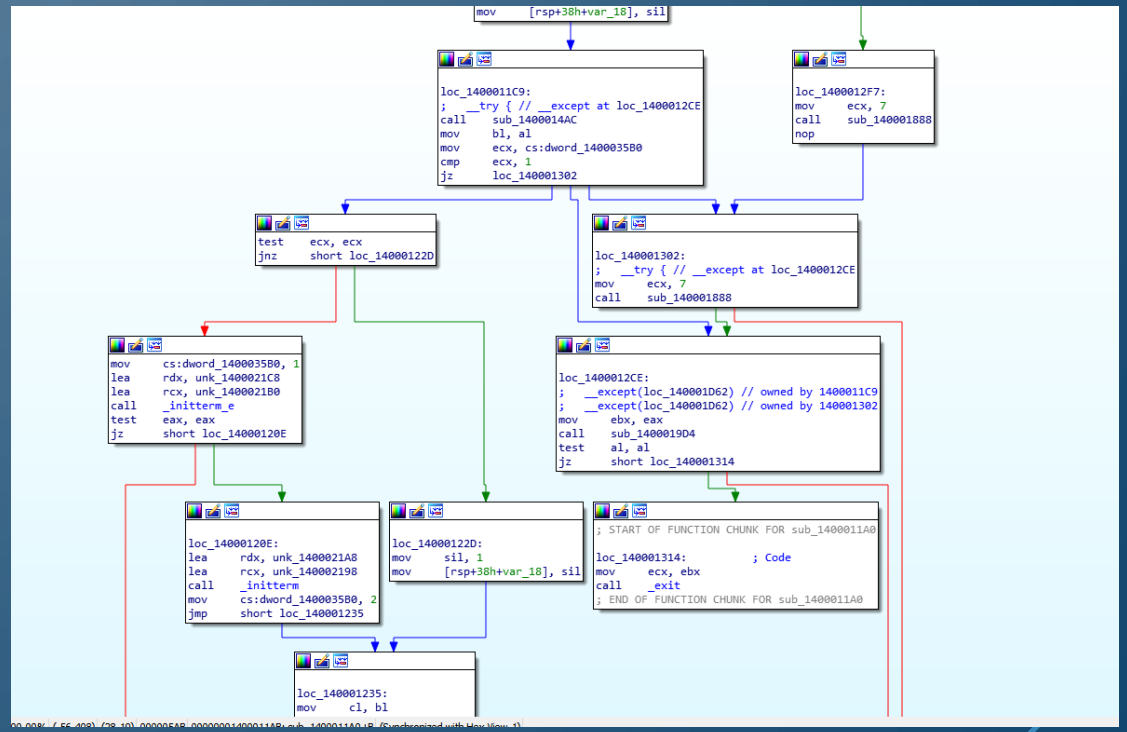
- RE can be lots of fun!
  - Gives you sense of discovery and accomplishment
  - You are overcoming challenges and discovering secrets
  - You will probably like it if you like:
    - Putting together puzzles
    - Solving crosswords
    - Geocaching
    - …



What Can You Reverse?

- Pretty much anything!

- Windows, macOS, Linux natively compiled executables
- Compiled Java, .Net, Python portable code
- iOS/Android apps
- Minified/obfuscated JavaScript and WASM
- Obfuscated PowerShell
- Obfuscated Office VBA
- Compiled automation scripts (AutoIt, AutoHotKey, etc...)
- BIOS/bootloaders
- Shellcode
- Hardware firmware
- …and the list goes on



Legality of RE

Big caveat - I'm not a lawyer, and this is not legal advice

- Is RE Legal? - It depends...

- Most license agreements contain anti-RE clauses
  - Vendors want to protect their intellectual property
  - Vendors want flaws to be harder to find

- Existing laws restrict RE
  - Digital Millennium Copyright Act (DMCA)
  - Computer Fraud and Abuse Act (CFAA)
  - Copyright law
  - EU Directive 2009/24
  - ...and others

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Legality of RE (cont.)

- You have more protection if you own the device or software you are reversing
- The Fair Use defense in Copyright Law
  - Using copyrighted works for good-faith security research is likely fair use
- Under DMCA legal owner of the program may RE it and circumvent its protection to achieve "interoperability"
- Intent and what you do with information discovered through RE is key

- For deeper analysis see this guide by Harvard Law School & EFF: https://clinic.cyber.harvard.edu/files/2020/10/Security_Researchers_Guide-2.pdf

Legality of RE: 3 Categories

Safe to do

- RE of non-commercial code or anything you yourself produce
- RE of commercial products done in private, without publishing or taking advantage of results
- Malware analysis

Tread carefully

- RE of commercial products for security research (bounty programs offer some protection)
- Publishing of limited reversed code/data as part of responsible vulnerability disclosure
- Publishing of tools based on RE discoveries
- Famous RE legal cases
  - Jon Lech Johansen arrested in 2000 for circumventing DVD copy protection; acquitted
  - Dmitry Sklyarov arrested after DEF CON in 2001 for circumventing Adobe protections; charges eventually dropped
- Even if what you are doing is not breaking the law, legal harassment is possible

Lawyer-up!

- Large-scale disclosure of discovered proprietary information, or (even worse) profiting from it
- Building compatible or competing products

Types of RE

- Data/communications analysis
  - Analysis of proprietary data formats (graphics, storage, databases)
  - Analysis of proprietary network protocols
  - Requires careful experimentation and use binary editors and capture tools
- Disassembly
  - Conversion of compiled binary to human-readable *machine* instructions
  - Native code (x86, ARM, MIPS, ...) and p-code (JVM, .Net, Python, ...)
- Decompilation
  - Attempt to recover original code from compiled binary
  - For native code results are spotty due to code optimizations; a C-like pseudocode is usually recovered
  - P-code is higher level and results are much better

Static vs. Dynamic Analysis

- Static involves analysis without execution
  - Helps where neither hardware nor emulators are available
  - Helps when debugging is not possible or anti-debugging measures are employed
- Dynamic is analysis though execution and debugging
  - Helps in cases of obfuscated/compressed/encrypted code and data
  - Helps confirm insight gleaned from static analysis
- Disassemblers and decompilers are often integrated with debuggers
- A combination approach often works best

Disassembly Example: C

- Consider a simple C example
- Compiled representation looks intimidating…

```c
#include <stdio.h>

// Password checker
int main( int argc, char *argv[] )  {

    // Secret password string
    char* password = "Sup3rSecretP4ssw0rd!!1";

    // Check the number of arguments
    if (argc == 2) {
        // Report success if the password matches
        if (!strcmp(argv[1],password)) {
            return 1;
        }
    }
    return 0;
}
```

```
00001000  48 83 EC 08 48 8B 05 DD 2F 00 00 48 85 C0 74 02  Hƒì.H‹.Ý/..H…Àt.
00001010  FF D0 48 83 C4 08 C3 00 00 00 00 00 00 00 00 00  ÿÐHƒÄ.Ã.........
00001020  FF 35 E2 2F 00 00 FF 25 E4 2F 00 00 0F 1F 40 00  ÿ5â/..ÿ%ä/....@.
00001030  FF 25 E2 2F 00 00 68 00 00 00 00 E9 E0 FF FF FF  ÿ%â/..h....éàÿÿÿ
00001040  FF 25 B2 2F 00 00 66 90 00 00 00 00 00 00 00 00  ÿ%²/..f.........
00001050  31 ED 49 89 D1 5E 48 89 E2 48 83 E4 F0 50 54 4C  1íI‰Ñ^H‰âHƒäðPTL
00001060  8D 05 8A 01 00 00 48 8D 0D 23 01 00 00 48 8D 3D  ..Š...H..#...H.=
00001070  C1 00 00 00 FF 15 66 2F 00 00 F4 0F 1F 44 00 00  Á...ÿ.f/..ô..D..
00001080  48 8D 3D A9 2F 00 00 48 8D 05 A2 2F 00 00 48 39  H.=©/..H..¢/..H9
00001090  F8 74 15 48 8B 05 3E 2F 00 00 48 85 C0 74 09 FF  øt.H‹.>/..H…Àt.ÿ
000010A0  E0 0F 1F 80 00 00 00 00 C3 0F 1F 80 00 00 00 00  à..€....Ã..€....
000010B0  48 8D 3D 79 2F 00 00 48 8D 35 72 2F 00 00 48 29  H.=y/..H.5r/..H)
000010C0  FE 48 89 F0 48 C1 EE 3F 48 C1 F8 03 48 01 C6 48  þH‰ðHÁî?HÁø.H.ÆH
000010D0  D1 FE 74 14 48 8B 05 15 2F 00 00 48 85 C0 74 08  Ñþt.H‹../..H…Àt.
000010E0  FF E0 66 0F 1F 44 00 00 C3 0F 1F 80 00 00 00 00  ÿàf..D..Ã..€....
000010F0  80 3D 39 2F 00 00 00 75 2F 55 48 83 3D F6 2E 00  €=9/...u/UHƒ=ö..
00001100  00 00 48 89 E5 74 0C 48 8B 3D 1A 2F 00 00 E8 2D  ..H‰åt.H‹=./..è-
00001110  FF FF FF E8 68 FF FF FF C6 05 11 2F 00 00 01 5D  ÿÿÿèhÿÿÿÆ../...]
00001120  C3 0F 1F 80 00 00 00 00 C3 0F 1F 80 00 00 00 00  Ã..€....Ã..€....
00001130  E9 7B FF FF FF 55 48 89 E5 48 83 EC 20 89 7D EC  é{ÿÿÿUH‰åHƒì ‰}ì
00001140  48 89 75 E0 48 8D 05 B9 0E 00 00 48 89 45 F8 83  H‰uàH..¹...H‰Eøƒ
00001150  7D EC 02 75 25 48 8B 45 E0 48 83 C0 08 48 8B 00  }ì.u%H‹EàHƒÀ.H‹.
00001160  48 8B 55 F8 48 89 D6 48 89 C7 E8 C1 FE FF FF 85  H‹UøH‰ÖH‰ÇèÁþÿÿ…
00001170  C0 75 07 B8 01 00 00 00 EB 05 B8 00 00 00 00 C9  Àu.¸....ë.¸....É
00001180  C3 66 2E 0F 1F 84 00 00 00 00 00 0F 1F 44 00 00  Ãf...„.......D..
00001190  41 57 4C 8D 3D 4F 2C 00 00 41 56 49 89 D6 41 55  AWL.=O,..AVI‰ÖAU
000011A0  49 89 F5 41 54 41 89 FC 55 48 8D 2D 40 2C 00 00  I‰õATA‰üUH.-@,..
000011B0  53 4C 29 FD 48 83 EC 08 E8 43 FE FF FF 48 C1 FD  SL)ýHƒì.èCþÿÿHÁý
000011C0  03 74 1B 31 DB 0F 1F 00 4C 89 F2 4C 89 EE 44 89  .t.1Û...L‰òL‰îD‰
000011D0  E7 41 FF 14 DF 48 83 C3 01 48 39 DD 75 EA 48 83  çAÿ.ßHƒÃ.H9ÝuêHƒ
000011E0  C4 08 5B 5D 41 5C 41 5D 41 5E 41 5F C3 0F 1F 00  Ä.[]A\A]A^A_Ã...
000011F0  C3 00 00 00 48 83 EC 08 48 83 C4 08 C3 00 00 00  Ã...Hƒì.HƒÄ.Ã...
```

Disassembly Example: C (cont.)

- But if we open the executable in a disassembler things look much clearer
- Even though you may not know assembly language you can get a rough idea of how C gets translated into it

```c
#include <stdio.h>

// Password checker
int main( int argc, char *argv[] )  {

    // Secret password string
    char* password = "Sup3rSecretP4ssw0rd!!1";

    // Check the number of arguments
    if (argc == 2) {
        // Report success if the password matches
        if (!strcmp(argv[1],password)) {
            return 1;
        }
    }
    return 0;
}
```

```
        PUSH    RBP
        MOV     RBP ,RSP
        SUB     RSP ,0x20
        MOV     dword ptr [RBP  + local_1c ],EDI
        MOV     qword ptr [RBP  + local_28 ],RSI
        LEA     RAX ,[s_Sup3rSecretP4ssw0rd!!1_00102004  ]
        MOV     qword ptr [RBP  + local_10 ],RAX => s_Sup3rSecretP
        CMP     dword ptr [RBP  + local_1c ],0x2
        JNZ     LAB_0010117a
        MOV     RAX ,qword ptr [RBP  + local_28 ]
        ADD     RAX ,0x8
        MOV     RAX ,qword ptr [RAX ]
        MOV     RDX => s_Sup3rSecretP4ssw0rd!!1_00102004,qword
        MOV     RSI => s_Sup3rSecretP4ssw0rd!!1_00102004,RDX
        MOV     RDI ,RAX
        CALL    strcmp
        TEST    EAX ,EAX
        JNZ     LAB_0010117a
        MOV     EAX ,0x1
        JMP     LAB_0010117f
LAB_0010117a:
        MOV     EAX ,0x0
LAB_0010117f:
        LEAVE
        RET
```

Decompilation Example: C

- With a decompiler we can get an even better picture of the code
- Quality of decompilation varies and depends on complexity of an application

```c
#include <stdio.h>

// Password checker
int main( int argc, char *argv[] )  {

    // Secret password string
    char* password = "Sup3rSecretP4ssw0rd!!1";

    // Check the number of arguments
    if (argc == 2) {
        // Report success if the password matches
        if (!strcmp(argv[1],password)) {
            return 1;
        }
    }
    return 0;
}
```

```c
undefined8 main(int param_1,long param_2)

{
  int iVar1;

  if ((param_1 == 2) &&
     (iVar1 = strcmp(*(char **)(param_2 + 8),"Sup3rSecretP4ssw0rd!!1" ), iVar1 == 0)) {
    return 1;
  }
  return 0;
}
```

Decompilation Example: Java

```java
import java.util.Base64;

public class re2 {
    // Testing for another password
    public static void main(String[] args) {
        if (args.length != 1) {
            System.out.println("Specify password on command line");
            return;
        }

        // The expected password is An0therH1dd3nP4ssword?!
        String encodedPassword = Base64.getEncoder().encodeToString(args[0].getBytes());
        if ("QW4wdGhlckgxZGQzblA0c3N3b3JkPyE=".equals(encodedPassword))
            System.out.println("Correct!");
        else
            System.out.println("Try again...");
    }
}
```

- Quality of decompilation of p-code language is much better

```java
import java.util.Base64;

public class re2 {
    public static void main(String[] strArr) {
        if (strArr.length != 1) {
            System.out.println("Specify password on command line");
            return;
        }
        if ("QW4wdGhlckgxZGQzblA0c3N3b3JkPyE=".equals(
                Base64.getEncoder().encodeToString(strArr[0].getBytes()))) {
            System.out.println("Correct!");
        } else {
            System.out.println("Try again...");
        }
    }
}
```

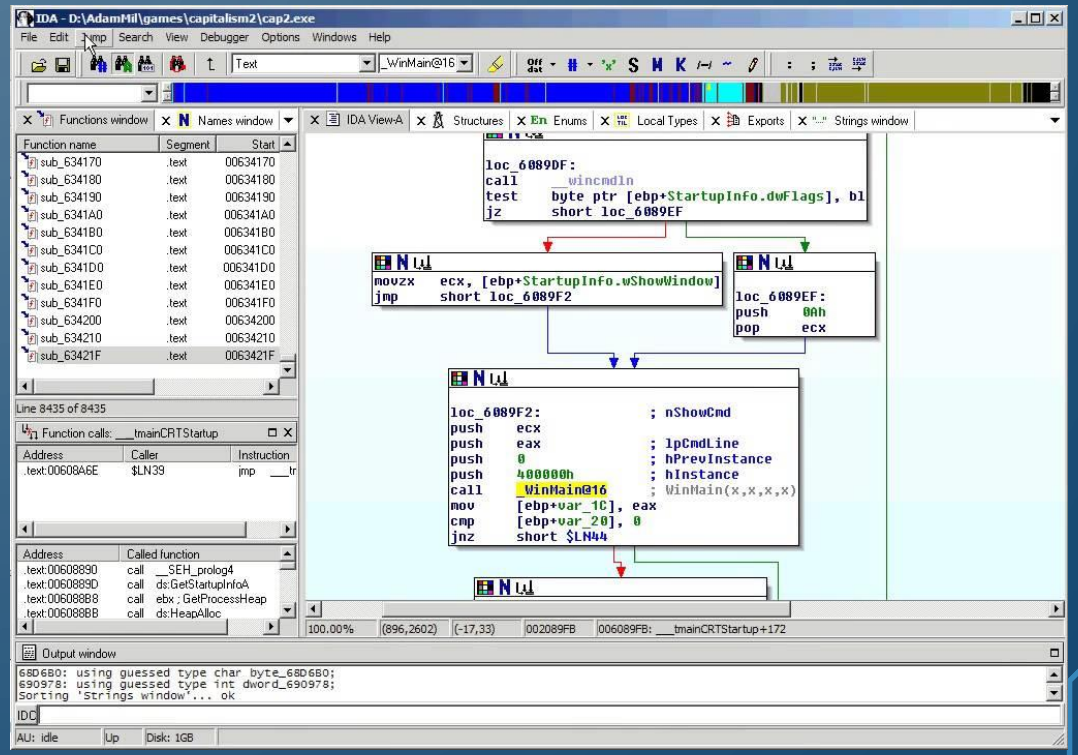
Decompilation Example: C#/.Net

```
using System;

namespace re3
{
    class re3
    {
        // This program will check if the password matches 'YetAn0th3rC00lPa55w0rd'
        static int Main(string[] args)
        {
            if ((args.Length != 1) || (args[0].Length != 22)) {
                Console.WriteLine("Supply password on command line");
                return 0;
            }

            // Load the expected password
            String key = args[0];

            // XOR against constant array
            byte[] xorArray = {0x82, 0xbe, 0xaf, 0x9a, 0xb5, 0xeb, 0xaf, 0xb3, 0xe8,
            0xa9, 0x98, 0xeb, 0xeb, 0xb7, 0x8b, 0xba, 0xee, 0xee, 0xac, 0xeb, 0xa9, 0xbf};
            for (int i = 0; i < xorArray.Length; i++)
                if (xorArray[i] != (Convert.ToByte(key[i]) ^ 0xDB)) {
                    Console.WriteLine("Wrong password!");
                    return 0;
                }

            Console.WriteLine("Correct!");
            return 1;
        }
    }
}
```

```
using System;

namespace re3
{
    internal class re3
    {
        private static int Main(string[] args)
        {
            int result;
            if (args.Length != 1 || args[0].Length != 0x16)
            {
                Console.WriteLine("Supply a password on command line");
                result = 0;
            }
            else
            {
                string text = args[0];
                byte[] array = new byte[]
                {
                    0x82,0xBE,0xAF,0x9A,0xB5,0xEB,0xAF,0xB3,0xE8,0xA9,0x98,
                    0xEB,0xEB,0xB7,0x8B,0xBA,0xEE,0xEE,0xAC,0xEB,0xA9,0xBF
                };
                for (int i = 0; i < array.Length; i++)
                {
                    if (array[i] != (Convert.ToByte(text[i]) ^ 0xDB))
                    {
                        Console.WriteLine("Wrong password!");
                        return 0;
                    }
                }
                Console.WriteLine("Correct!");
                result = 1;
            }
            return result;
        }
    }
}
```

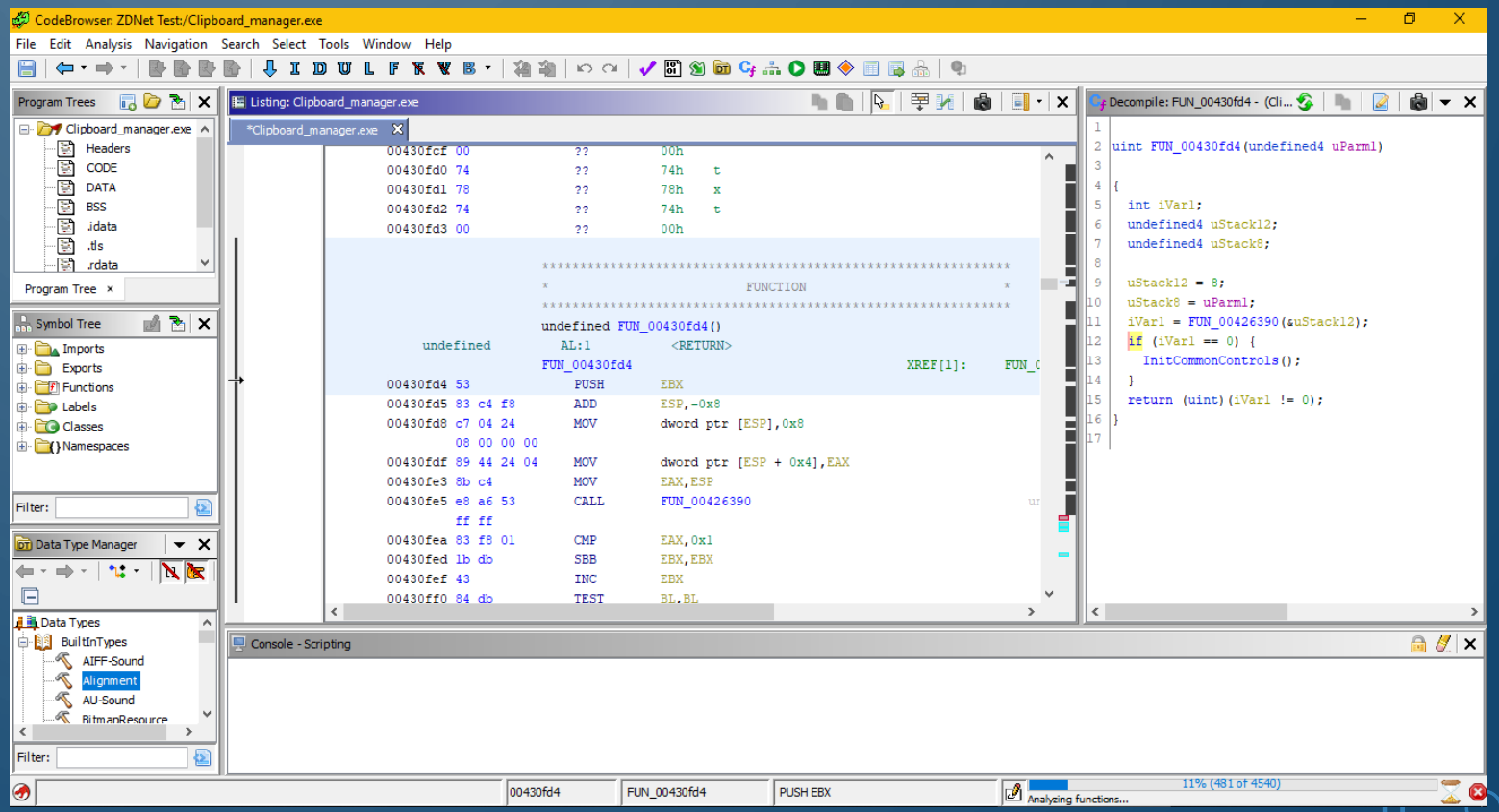
Tools: IDA Pro

- The ultimate RE tool
- Tons of support for many processors and environments
- Disassembler + Debugger
- +Decompiler add-on (Hex-Rays)
- Plugins, scripting, …
- Expensive - US$2K-4K
- …but there is a Free and a Home (US$365) version



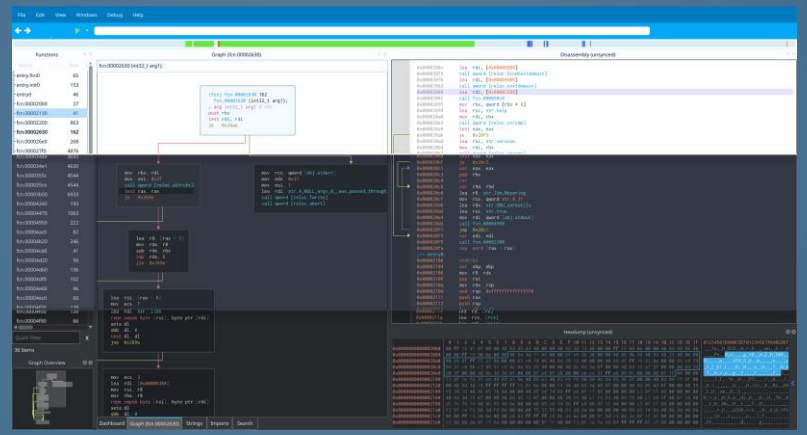
Tools: Ghidra

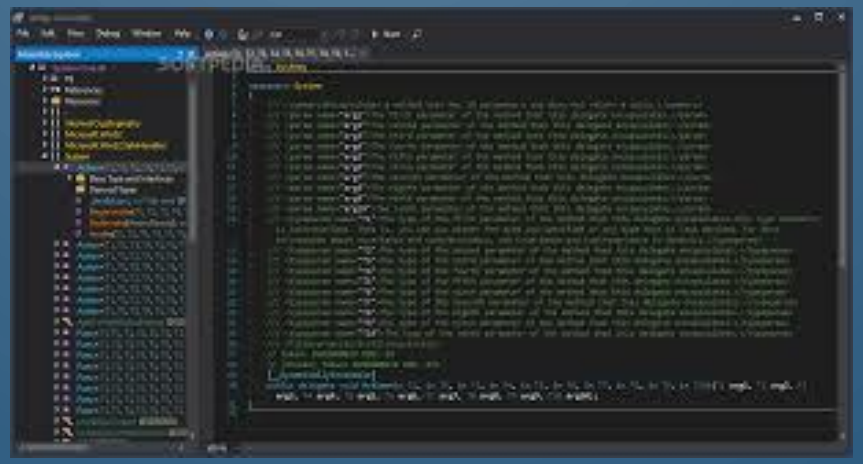
- Open-sourced by NSA (!)
- Many supported architectures
- Disassembler + Decompiler
- Now has a Debugger too
- Plugins, scripting, …



More Tools

- Complete frameworks
  - Radare2 (+ Cutter GUI)
  - Binary Ninja
- Decompilers
  - retdec
  - Snowman
- Debuggers
  - OllyDbg
  - EDB
  - x64dbg





- VMs
  - FlareVM
  - REMnux
- … and the list goes on

- .Net
  - dnSpy
  - ILSpy
- Java
  - JD-GUI
  - CFR
- Python
  - uncompyle6
- WASM
  - wasmdec

Obstacles: Information Lost in Compilation

- As part of compilation and optimizations code is made more difficult to reverse
- Lost:
  - Code comments
  - Meaningful names of functions and variables
  - Structure of data
  - Objects (e.g. C++)
- Variables move between stack and registers
- Execution flow constructs obscured (loops, conditional statements, exception handling, ...)
- Function inlining and embedding of libraries explodes body of code

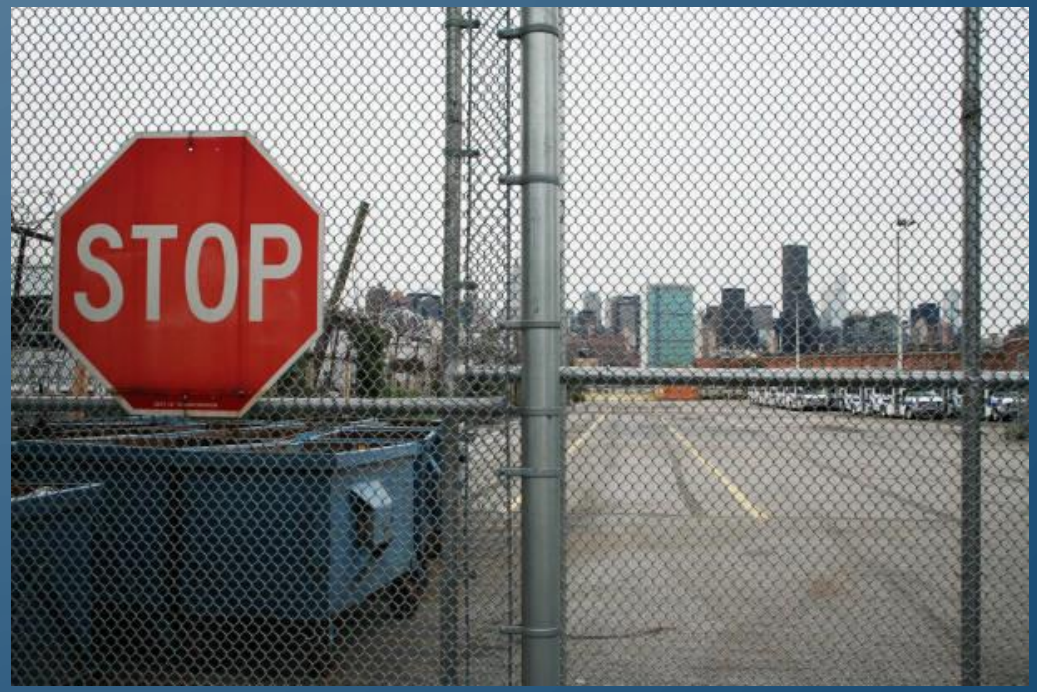
Obstacles: Counter-reversing Measures

- Software publishers know about RE and are not happy about it
- Many countermeasures are deployed to complicate analysis

- Obfuscation
  - Deliberate name obfuscation for scripting and p-code languages
  - Code minification
- Compression
  - Code and data compressed with "packers" (e.g. UPX)
- Encryption
  - Code and data decrypted at run time
  - Multiple nested levels and algorithms can be used

Obstacles: Counter-reversing Measures (cont.)

- Anti-disassembly
  - Jumps into the middle of instruction
  - False branches
  - Self-modifying code



- Anti-decompilation
  - Program flow intentionally obscured
    - Jump to register
    - Jumps through return
    - Call as a jump
  - Useless/dead code insertion
  - Extreme optimization
  - VM implementation (e.g. OISCs - Subleq, M/o/Vfuscator)

Obstacles: Counter-reversing Measures (cont.)

- Anti-debugging
  - Debugger detection
  - VM detection
  - Sporadic insertion of breakpoints
  - Use of debug handlers (e.g. PTRACE) for execution
  - Signal-based execution
  - SEH-based execution
  - Alarms and time-dependent code

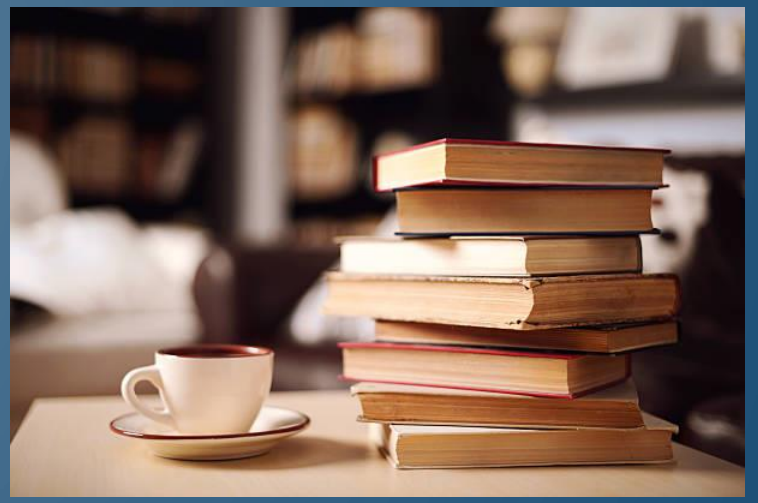
...and this is by no means an exhaustive list

Obstacles: Counter-reversing Measures (cont.)

- It's an arms race
  - Good debuggers and VMs can hide their presence to a degree
  - Disassemblers/decompilers can overcome some counter-measures
  - Deobfuscation/decompression tools are available

- Expect these challenges in your RE work
- They can all be overcome with adequate techniques and tools
- There is nothing out there that can't be analyzed and reversed, it just a question of time and effort

Practicing: L0 - Starting Out



- The only way to get good at RE is to study and practice

- Required skills
  - Beginner ability to write in a programming language
    - Most languages are fine, but C/C++ an asset
  - Basic knowledge of target computer architecture
    - Processor registers, machine language instructions, memory organization
  - General idea of compiler operation
    - It helps to understand how high-level language is translated into low-level (because you will be doing the reverse)
  - Attention to detail and patience

- You can learn as you go, but need basics to enjoy it and to make good progress

Practicing: L1 - Do-it-yourself Code Samples

- Write and compile a few primitive programs that use different aspects of the programming language
- Open compiled programs in a few decompilers and disassemblers
  - Study different tool features
  - Look at how compiled representation maps to original code
  - What code compiler adds to the executable (setup/teardown, function prologue/epilogue, library code)?
  - Try debugging
- This way you are taking one of the variables out of the equation, you know what the end result of your efforts should look like

Practicing: L2 - Crack-me's

- These are challenges designed by someone else
- Typically small applications that are hiding a secret ("flag")
- Go at your own pace

- Great resource - We Chall (http://www.wechall.net/)
- Directory of challenge sites (50+)
- Global scoreboard to gamify experience

Practicing: L3 - CTFs

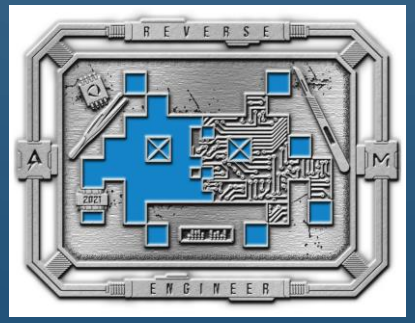
- Online and in-person competitions
- All levels (from beginner to pro)
- Occur all over the world regularly
- RE challenges are present in almost every CTF
- Typically 48-hour events
- Adds a time pressure to the experience (puts learning in over-drive! :))

- Recommended resource - CTF Time (https://ctftime.org/)
- A directory of online (and sometimes offline) CTFs
- Global scoreboard

Practicing: L4 - Flare-On

- Annual competition created by FireEye (http://flare-on.com/)
- The toughest RE competition in the world *(as far as I know - please let me know if you know of something better)*
- 10-12 challenges of increasing difficulty
- 40 days to complete them

- Windows, macOS, Linux, scripting, mobile, embedded, esoteric…
- Many challenges are based on real malware samples or malware techniques
- Finalists get a prize



General RE Strategies

- Make it an enjoyable experience
  - Requires a lot of time, patience and attention to detail
  - Make sure it's something you are motivated to do and enjoy
    - Solving a puzzle, finding a secret, trying to discover a bug...
- Keep your eyes on the prize
  - Fully understanding even an average application is unrealistic due to size
    - Simple application like Windows Notepad has ~13K machine instructions
  - Even if you had fully commented original source code it would take days and weeks
  - Focus on the information are looking for (algorithm, piece of data) and expand your understanding around that

General RE Strategies (cont.)

- Combine static and dynamic analysis
  - Actively use debugger for analysis - analyzing by hand is often too labor-intensive
  - Make the application do the heavy lifting (e.g. to bypass encryption and obfuscation algorithms)
  - Bypass problematic code, jump around
  - Make static analysis simpler by scripting some of the reversing work (e.g. decoding/decrypting data)

- Scripting for the win
  - Reversing requires a lot of processing
  - Take advantage of scripting to automate tasks
  - Use scripting available within tools

General RE Strategies (cont.)

- Look for the signs
  - Magic numbers
  - Common algorithms (hashing, encryption, ...)
  - Systems calls and library functions
  - There are tools and plugins to help
- Document, document, document
  - A lot of info is lost in compilation
  - Body of code is usually very large, and details are easy to forget
  - As you analyze the code:
    - Add names to functions and variables
    - Restore data structures and objects
    - Comment important code blocks
  - Rinse and repeat

Resources

- Lots of blogs, articles, writeups online
  - Google is your friend
- Conferences
  - REcon (held in Montreal and Brussels) https://recon.cx/
- Getting help online
  - Reverse Engineering Discord - https://discord.com/invite/weKN5wb *(invite may expire)*
  - https://www.reddit.com/r/ReverseEngineering/
  - https://reverseengineering.stackexchange.com/

Books

- Eilam, E. "Reversing: Secrets of Reverse Engineering"
- Yurichev, D. "Reverse Engineering for Beginners"
- Sikorski, M. "Practical Malware Analysis: The Hands-On Guide to Dissecting Malicious Software"
- Dang, B. "Practical Reverse Engineering: x86, x64, ARM, Windows Kernel, Reversing Tools, and Obfuscation"
- Eagle, C. "The IDA Pro Book, 2nd Edition: The Unofficial Guide to the World's Most Popular Disassembler"

Wrap-up

- A lot of software and hardware around us are "black boxes"
- RE allows you to look inside and understand how they work
- You can help make them more secure, build compatible solutions, and modify them in new ways based on RE knowledge
- Plenty of tools are available to help reverse any product out there
- As you learn more about it, I'm sure you will enjoy RE as a fun and intellectually-rewarding activity!

Q&A

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Slides can be found at https://github.com/0xd13a/presentations

Thank you!