CSC 591
Systems Attacks and Defenses

Reverse Engineering

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Introduction

- Reverse engineering
  - process of analyzing a system
  - understand its structure and functionality
  - used in different domains (e.g., consumer electronics)

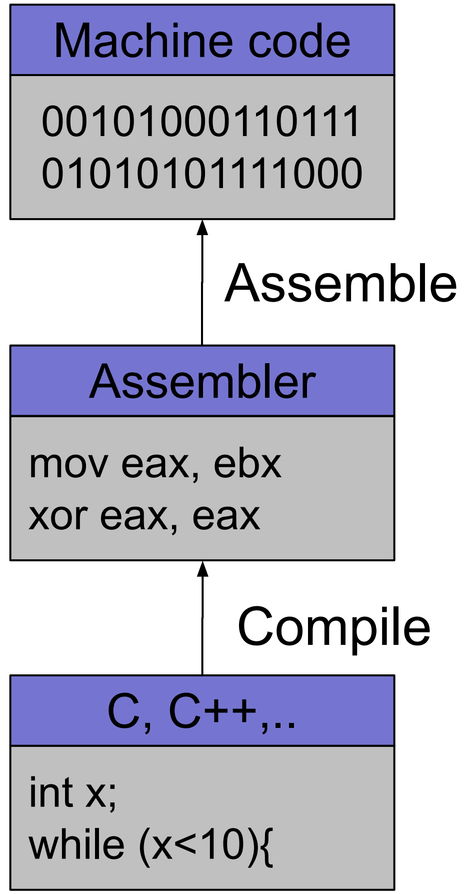
- Software reverse engineering
  - understand architecture (from source code)
  - extract source code (from binary representation)
  - change code functionality (of proprietary program)
  - understand message exchange (of proprietary protocol)

Software Engineering

First generation language

Second generation language

Third generation language



Software Reverse Engineering

First generation language

Machine code

```
00101000110111
01010101111000
```

↓ Disassemble

Second generation language

Assembler

```
mov eax, ebx
xor eax, eax
```

↓ De-compile

Third generation language

C, C++,..

```
int x;
while (x<10){
```

Going Back is Hard!

- Fully-automated disassemble/de-compilation of arbitrary machine-code is theoretically an **undecidable problem**

- Disassembling problems
  - hard to distinguish code (instructions) from data

- De-compilation problems
  - structure is lost
    - data types are lost, names and labels are lost
  - no one-to-one mapping
    - same code can be compiled into different (equivalent) assembler blocks
    - assembler block can be the result of different pieces of code

Why Reverse Engineering

- Software interoperability
  - Samba (SMB Protocol)
  - OpenOffice (MS Office document formats)
- Emulation
  - Wine (Windows API)
  - React-OS (Windows OS)
- Legacy software
  - Onlive
- Malware analysis
- Program cracking
- Compiler validation

Analyzing a Binary - Static Analysis

- Identify the file type and its characteristics
  - architecture, OS, executable format...
- Extract strings
  - commands, password, protocol keywords...
- Identify libraries and imported symbols
  - network calls, file system, crypto libraries
- Disassemble
  - program overview
  - finding and understanding important functions
    - by locating interesting imports, calls, strings...

Analyzing a Binary - Dynamic Analysis

- Memory dump
  - extract code after decryption, find passwords...
- Library/system call/instruction trace
  - determine the flow of execution
  - interaction with OS
- Debugging running process
  - inspect variables, data received by the network, complex algorithms..
- Network sniffer
  - find network activities
  - understand the protocol

Static Techniques

- Gathering program information
  - get some rough idea about binary (file)

```
linux util # file sil
sil: ELF 32-bit LSB executable, Intel 80386, version 1
(SYSV), for GNU/Linux 2.6.9, dynamically linked (uses s
hared libs), not stripped
```

  - strings that the binary contains (strings)

```
linux util # strings sil | head -n 5
/lib/ld-linux.so.2
_Jv_RegisterClasses
__gmon_start__
libc.so.6
puts
```

Static Techniques

- Examining the program (ELF) header (`elfsh`)
- `readelf`

```
[ELF HEADER]
[Object sil, MAGIC 0x464C457F]

Architecture        :       Intel 80386   ELF Version           :            1
Object type         :  Executable object  SHT strtab index      :           25
Data encoding       :      Little endian  SHT foffset           :         4061
PHT foffset         :                 52  SHT entries number    :           28
PHT entries number  :                  8  SHT entry size        :           40
PHT entry size      :                 32  ELF header size       :           52
Entry point         :          0x8048500  [_start]
{PAX FLAGS = 0x0}
PAX_PAGEEXEC        :           Disabled  PAX_EMULTRAMP         :  Not emulated
PAX_MPROTECT        :         Restricted  PAX_RANDMMAP          :    Randomized
PAX_RANDEXEC        :     Not randomized  PAX_SEGMEXEC          :       Enabled
```

Program entry point

Static Techniques

- Used libraries
  - easier when program is dynamically linked (ldd)

Interesting "shared" library used for (fast) system calls

```
linux util # ldd sil
        linux-gate.so.1 =>  (0xffffe000)
        libc.so.6 => /lib/libc.so.6 (0xb7e99000)
        /lib/ld-linux.so.2 (0xb7fcf000)
```

  - more difficult when program is statically linked

```
linux util # gcc -static -o sil-static simple.c
linux util # ldd sil-static
        not a dynamic executable
linux util # file sil-static
sil-static: ELF 32-bit LSB executable, Intel 80386, version 1
(SYSV), for GNU/Linux 2.6.9, statically linked, not stripped
```

Static Techniques

Looking at linux-gate.so.1

```
linux util # cat /proc/self/maps | tail -n 1
ffffe000-fffff000 r-xp 00000000 00:00 0          [vdso]
linux util # dd if=/proc/self/mem of=linux-gate.dso bs=4096 skip=1048574
 count=1 2> /dev/null
linux util # objdump -d linux-gate.dso | head -n 11

linux-gate.dso:     file format elf32-i386

Disassembly of section .text:

ffffe400 <__kernel_vsyscall>:
ffffe400:       51                      push   %ecx
ffffe401:       52                      push   %edx
ffffe402:       55                      push   %ebp
ffffe403:       89 e5                   mov    %esp,%ebp
ffffe405:       0f 34                   sysenter
```

Static Techniques

- Used library functions
  - again, easier when program is dynamically linked (nm -D)

```
linux util # nm -D sil | tail -n8
         U fprintf
         U fwrite
         U getopt
         U opendir
08049bb4 B optind
         U puts
         U readdir
08049bb0 B stderr
```

  - more difficult when program is statically linked

```
linux util # nm -D sil-static
nm: sil-static: No symbols
linux util # ls -la sil*
-rwxr-xr-x 1 root chris   8017 Jan 21 20:37 sil
-rwxr-xr-x 1 root chris 544850 Jan 21 20:58 sil-static
```

Static Techniques

Recognizing libraries in statically-linked programs

- Basic idea
  - create a checksum (hash) for bytes in a library function
- Problems
  - many library functions (some of which are very short)
  - variable bytes – due to dynamic linking, load-time patching, linker optimizations
- Solution
  - more complex pattern file
  - uses checksums that take into account variable parts
  - implemented in IDA Pro as: Fast Library Identification and Recognition Technology (FLIRT)

Static Techniques

- Program symbols
  - used for debugging and linking
  - function names (with start addresses)
  - global variables
  - use `nm` to display symbol information
  - most symbols can be removed with `strip`

- Function call trees
  - draw a graph that shows which function calls which others
  - get an idea of program structure

Static Techniques

Displaying program symbols

```
linux util # nm sil | grep " T"
080488c7 T __i686.get_pc_thunk.bx
08048850 T __libc_csu_fini
08048860 T __libc_csu_init
08048904 T _fini
08048420 T _init
08048500 T _start
080485cd T display_directory
080486bd T main
080485a4 T usage
linux util # strip sil
linux util # nm sil | grep " T"
nm: sil: no symbols
```

Static Techniques

- Disassembly
  - process of translating binary stream into machine instructions
- Different level of difficulty
  - depending on ISA (instruction set architecture)
- Instructions can have
  - fixed length
    - more efficient to decode for processor
    - RISC processors (SPARC, MIPS, ARM)
  - variable length
    - use less space for common instructions
    - CISC processors (Intel x86)

This will backfire in the future :)

Static Techniques

- Fixed length instructions
  - easy to disassemble
  - take each address that is multiple of instruction length as instruction start
  - even if code contains data (or junk), all program instructions are found

- Variable length instructions
  - more difficult to disassemble
  - start addresses of instructions not known in advance
  - different strategies
    - linear sweep disassembler
    - recursive traversal disassembler
  - disassembler can be desynchronized with respect to actual code

Static Techniques

- Linear sweep disassembler
  - start at beginning of code (.text) section
  - disassemble one instruction after the other
  - assume that well-behaved compiler tightly packs instructions
  - objdump -d uses this approach

Let's break LSD

```
#include <stdio.h>

int main() {
   printf("Hello, world!\n");
   return 0;
}
$ gcc hello.c -o hello
$ ./hello
Hello, world!
```

Objdump disassembly

```
0804840b <main>:
   804840b:       8d 4c 24 04             lea    0x4(%esp),%ecx
   804840f:       83 e4 f0                and    $0xfffffff0,%esp
   8048412:       ff 71 fc                pushl  -0x4(%ecx)
   8048415:       55                      push   %ebp
   8048416:       89 e5                   mov    %esp,%ebp
   8048418:       51                      push   %ecx
   8048419:       83 ec 04                sub    $0x4,%esp
   804841c:       83 ec 0c                sub    $0xc,%esp
   804841f:       68 c0 84 04 08          push   $0x80484c0
   8048424:       e8 b7 fe ff ff          call   80482e0 <puts@plt>
   8048429:       83 c4 10                add    $0x10,%esp
   804842c:       b8 00 00 00 00          mov    $0x0,%eax
   8048431:       8b 4d fc                mov    -0x4(%ebp),%ecx
   8048434:       c9                      leave
   8048435:       8d 61 fc                lea    -0x4(%ecx),%esp
   8048438:       c3                      ret
```

```
$ objdump -D hello
```

radare2 disassembly

```
[0x08048310]> pdf@main
/ (fcn) sym.main 46
|           0x0804840b    8d4c2404     lea ecx, [esp+0x4]
|           0x0804840f    83e4f0       and esp, 0xfffffff0
|           0x08048412    ff71fc       push dword [ecx-0x4]
|           0x08048415    55           push ebp
|           0x08048416    89e5         mov ebp, esp
|           0x08048418    51           push ecx
|           0x08048419    83ec04       sub esp, 0x4
|           0x0804841c    83ec0c       sub esp, 0xc
|           ; DATA XREF from 0x080484c0 (fcn.080484b8)
|           0x0804841f    68c0840408   push str.Helloworld ; 0x080484c0
|           ; CODE (CALL) XREF from 0x080482e6 (fcn.080482e6)
|           ; CODE (CALL) XREF from 0x080482f6 (fcn.080482f6)
|           ; CODE (CALL) XREF from 0x08048306 (fcn.08048306)
|           0x08048424    e8b7feffff   call 0x1080482e0 ; (sym.imp.puts)
|              sym.imp.puts(unk, unk, unk, unk)
|           0x08048429    83c410       add esp, 0x10
|           0x0804842c    b800000000   mov eax, 0x0
|           0x08048431    8b4dfc       mov ecx, [ebp-0x4]
|           0x08048434    c9           leave
|           0x08048435    8d61fc       lea esp, [ecx-0x4]
\           0x08048438    c3           ret
```

Let’s patch the program

```
$ radare2 -Aw hello
 [0x08048310]> 0x08048419
[0x08048419]> wx eb01   #(jmp 0x804841c)
```

We patched a 3-byte instruction with a 2-byte instruction. What is going to happen now with disassembly?!

Disassembly fails!

```
[0x08048310]> pdf@main
/ (fcn) sym.main 46
|           0x0804840b    8d4c2404     lea ecx, [esp+0x4]
|           0x0804840f    83e4f0       and esp, 0xfffffff0
|           0x08048412    ff71fc       push dword [ecx-0x4]
|           0x08048415    55           push ebp
|           0x08048416    89e5         mov ebp, esp
|           0x08048418    51           push ecx
|       ,=< 0x08048419    eb01         jmp loc.0804841c
|       |   0x0804841b    0483         add al, 0x83
|           0x0804841d    ec           in al, dx
|           0x0804841e    0c68         or al, 0x68
|           0x08048420    c0840408e8b. rol byte [esp+eax-0x14817f8], 0xff
|           0x08048428    ff83c410b800 inc dword [ebx+0xb810c4]
|           0x0804842e    0000         add [eax], al
|           0x08048430    008b4dfcc98d add [ebx-0x723603b3], cl
|           0x08048436    61           popad
|           0x08048437    fc           cld
\           0x08048438    c3           ret
```

Static Techniques

- Recursive traversal disassembler
  - aware of control flow
  - start at program entry point (e.g., determined by ELF header)
  - disassemble one instruction after the other, until branch or jump is found
  - recursively follow both (or single) branch (or jump) targets
  - not all code regions can be reached
    - indirect calls and indirect jumps
    - use a register to calculate target during run-time
  - for these regions, linear sweep is used
  - IDA Pro uses this approach

```
.text:0804840B ; int __cdecl main(int argc, const char **argv, const char **envp)
.text:0804840B                 public main
.text:0804840B main            proc near               ; DATA XREF: _start+17o
.text:0804840B var_4           = dword ptr -4
.text:0804840B argc            = dword ptr  0Ch
.text:0804840B argv            = dword ptr  10h
.text:0804840B envp            = dword ptr  14h
.text:0804840B                 lea     ecx, [esp+4]
.text:0804840F                 and     esp, 0FFFFFFF0h
.text:08048412                 push    dword ptr [ecx-4]
.text:08048415                 push    ebp
.text:08048416                 mov     ebp, esp
.text:08048418                 push    ecx
.text:08048419                 jmp     short loc_804841C
.text:08048419 ; ---------------------------------------------------------------------------
.text:0804841B                 db 4
.text:0804841C ; ---------------------------------------------------------------------------
.text:0804841C loc_804841C:                            ; CODE XREF: main+Ej
.text:0804841C                 sub     esp, 0Ch
.text:0804841F                 push    offset s        ; "Hello, world!"
.text:08048424                 call    _puts
.text:08048429                 add     esp, 10h
.text:0804842C                 mov     eax, 0
.text:08048431                 mov     ecx, [ebp+var_4]
.text:08048434                 leave
.text:08048435                 lea     esp, [ecx-4]
.text:08048438                 retn
.text:08048438 main            endp%
```

Dynamic Techniques

- General information about a process
  - /proc file system
  - /proc/<pid>/ for a process with pid <pid>
  - interesting entries
    - cmdline (show command line)
    - environ (show environment)
    - maps (show memory map)
    - fd (file descriptor to program image)

- Interaction with the environment
  - filesystem
  - network

Dynamic Techniques

- Filesystem interaction
  - `lsof`
  - lists all open files associated with processes
- Windows Registry
  - `regmon` (Sysinternals)
- Network interaction
  - check for open ports
    - processes that listen for requests or that have active connections
    - `netstat`
    - also shows UNIX domain sockets used for IPC
  - check for actual network traffic
    - `tcpdump`
    - ethereal/wireshark

Dynamic Techniques

- System calls
  - are at the boundary between user space and kernel
  - reveal much about a process' operation
  - `strace`
  - powerful tool that can also
    - follow child processes
    - decode more complex system call arguments
    - show signals
  - works via the ptrace interface

- Library functions
  - similar to system calls, but dynamically linked libraries
  - `ltrace`

Dynamic Techniques

- Execute program in a controlled environment
  - sandbox / debugger
- Advantages
  - can inspect actual program behavior and data values
  - (at least one) target of indirect jumps (or calls) can be observed
- Disadvantages
  - may accidentally launch attack/malware
  - anti-debugging mechanisms
  - not all possible traces can be seen

Dynamic Techniques

- Debugger
  - breakpoints to pause execution
    - when execution reaches a certain point (address)
    - when specified memory is access or modified
  - examine memory and CPU registers
  - modify memory and execution path

- Advanced features
  - attach comments to code
  - data structure and template naming
  - track high level logic
    - file descriptor tracking
  - function fingerprinting

Dynamic Techniques

- Debugger on x86 / Linux
  - use the `ptrace` interface

- `ptrace`
  - allows a process (parent) to monitor another process (child)
  - whenever the child process receives a signal, the parent is notified
  - parent can then
    - access and modify memory image (peek and poke commands)
    - access and modify registers
    - deliver signals
  - ptrace can also be used for system call monitoring

Dynamic Techniques

- Breakpoints
  - hardware breakpoints
  - software breakpoints

- Hardware breakpoints
  - special debug registers (e.g., Intel x86)
  - debug registers compared with PC at every instruction

- Software breakpoints
  - debugger inserts (overwrites) target address with an `int 0x03` instruction
  - interrupt causes signal SIGTRAP to be sent to process
  - debugger
    - gets control and restores original instruction
    - single steps to next instruction
    - re-inserts breakpoint

Anti-Disassembly

- Against static analysis (disassembler)
- Confusion attack
  - targets linear sweep disassembler
  - insert data (or junk) between instructions and let control flow jump over this garbage
  - disassembler gets desynchronized with true instructions

Anti-Disassembly

- Advanced confusion attack
  - targets recursive traversal disassembler
  - replace direct jumps (calls) by indirect ones (branch functions)
  - force disassembler to revert to linear sweep, then use previous attack

Anti-Debugging

- Against dynamic analysis (debugger)
  - debugger presence detection techniques
    - API based
    - thread/process information
    - registry keys, process names, …
  - exception-based techniques
  - breakpoint detection
    - software breakpoints
    - hardware breakpoints
  - timing-based and latency detection

Anti-Debugging

Debugger presence checks

- Linux
  - a process can be traced only once

```
if (ptrace(PTRACE_TRACEME, 0, 1, 0) < 0)
        exit(1);
```

- Windows
  - API calls

```
OutputDebugString()
IsDebuggerPresent()
```

    ... many more ...

  - thread control block
    - read debugger present bit directly from process memory

Anti-Debugging

Exception-based techniques

`SetUnhandledExceptionFilter()`

After calling this function, if an exception occurs in a process that is not being debugged, and the exception makes it to the unhandled exception filter, that filter will call the exception filter function specified by the `lpTopLevelExceptionFilter` parameter. [source: MSDN]

- Idea
  set the top-level exception filter, raise an unhandled exception, continue in the exception filter function

Anti-Debugging

Breakpoint detection

- detect software breakpoints
  - look for int 0x03 instructions

```
if ((*(unsigned *)((unsigned)<addr>+3) & 0xff)==0xcc)
    exit(1);
```

  - checksum the code

```
if (checksum(text_segment) != valid_checksum)
    exit(1);
```

- detect hardware breakpoints
  - use the hardware breakpoint registers for computation

Reverse Engineering

- Goals
  - focused exploration
  - deep understanding

- Case study
  - **copy protection mechanism**
  - program expects name and serial number
  - when serial number is incorrect, program exits
  - otherwise, we are fine

- Changes in the binary
  - can be done with hexedit or radare2

Reverse Engineering

- Focused exploration
  - bypass check routines
  - locate the point where the failed check is reported
  - find the routine that checks the serial number
  - find the location where the results of this routine are used
  - slightly modify the jump instruction
- Deep understanding
  - key generation
  - locate the checking routine
  - analyze the disassembly
  - run through a few different cases with the debugger
  - understand what check code does and develop code that creates appropriate keys

Malicious Code Analysis

Static analysis vs. dynamic analysis

- Static analysis
  - code is not executed
  - all possible branches can be examined (in theory)
  - quite fast
- Problems of static analysis
  - undecidable in general case, approximations necessary
  - binary code typically contains very little information
    - functions, variables, type information, …
  - disassembly difficult (particularly for Intel x86 architecture)
  - obfuscated code, packed code
  - self-modifying code

Malicious Code Analysis

- Dynamic analysis
  - code is executed
  - sees instructions that are actually executed
- Problems of dynamic analysis
  - single path (execution trace) is examined
  - analysis environment possibly not invisible
  - analysis environment possibly not comprehensive
- Possible analysis environments
  - instrument program
  - instrument operating system
  - instrument hardware

Malicious Code Analysis

- **Instrument program**
  - analysis operates in same address space as sample
  - manual analysis with debugger
  - Detours (Windows API hooking mechanism)

  - binary under analysis is modified
    - breakpoints are inserted
    - functions are rewritten
    - debug registers are used
  - not invisible, malware can detect analysis
  - can cause significant manual effort

Malicious Code Analysis

- **Instrument operating system**
  - analysis operates in OS where sample is run
  - Windows system call hooks

  - invisible to (user-mode) malware
  - can cause problems when malware runs in OS kernel
  - limited visibility of activity inside program
    - cannot set function breakpoints

- Virtual machines
  - allow to quickly restore analysis environment
  - might be detectable (x86 virtualization problems)

Malicious Code Analysis

- **Instrument hardware**
  - provide virtual hardware (processor) where sample can execute (sometimes including OS)
  - software emulation of executed instructions
  - analysis observes activity “from the outside”

  - completely transparent to sample (and guest OS)
  - operating system environment needs to be provided
  - limited environment could be detected
  - complete environment is comprehensive, but slower

  - Anubis uses this approach

Stealthiness

- One obvious difference between machine and emulator
  → time of execution

- Time could be used to detect such system
  → emulation allows to address these issues
  → certain instructions can be dynamically modified to return innocently looking results
  → for example, RTC (real-time clock) - `RDTSC` instruction

Challenges

- Reverse engineering is difficult by itself
  - a lot of data to handle
  - low level information
  - creative process, experience very valuable
  - tools can only help so much
- Additional challenges
  - compiler code optimization
  - code obfuscation
  - anti-disassembly techniques
  - anti-debugging techniques

GHIDRA

Ghidra

- Released in March 2019
- NSA
- open source
  - https://github.com/NationalSecurityAgency/ghidra
- In development for ~20 years
- Scripting in Java and Python
- Headless Analyzer
- https://github.com/NationalSecurityAgency/ghidra/wiki/files/recon2019.pdf

Your Security Zen

Jeff Bezos hack:

How Jeff Bezos' iPhone X Was Hacked

source: https://www.nytimes.com/2020/01/22/technology/jeff-bezos-hack-iphone.html

Your Security Zen

Google, Mozilla Ban Hundreds of Browser Extensions in Chrome, Firefox

source: https://threatpost.com/google-mozilla-ban-browser-extensions-chrome-firefox/152257/

Your Security Zen

After a decade of drama, Apple is ready to kill Flash in Safari once and for all

source: https://arstechnica.com/gadgets/2020/01/apple-seems-poised-to-end-adobe-flash-support-in-the-next-safari-release/

hackpack summer internships

- Bonus levels in assignments
- Good grade in this class
- Participate in hackpack meetings weekly and play CTFs

research during the summer

publish a research paper

WSPR lab

opportunity to see what a PhD looks like!