CSC 405
Introduction to Computer Security

Reverse Engineering

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(Derived from slides by Chris Kruegel)

Introduction

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

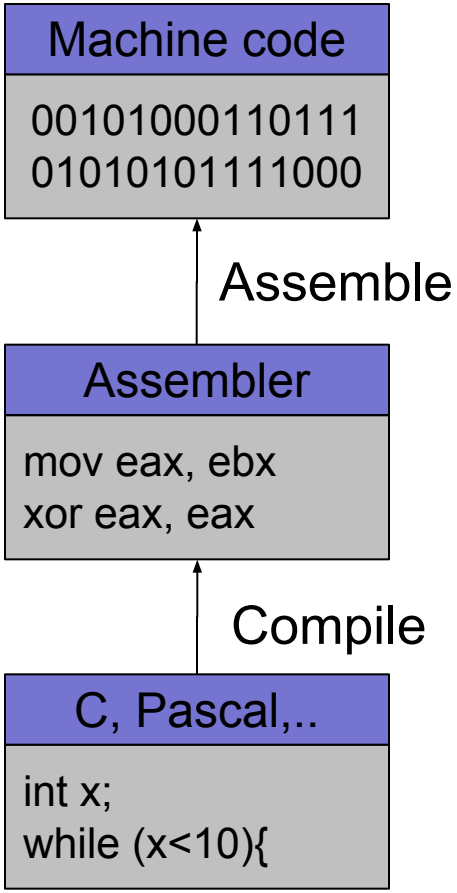
- Software reverse engineering
  - understand architecture (from source code)
  - extract source code (from binary representation)
  - change code functionality (of proprietary program)
  - understand message exchange (of proprietary protocol)

Software Engineering

First generation language

Second generation language

Third generation language



Software Reverse Engineering

First generation language

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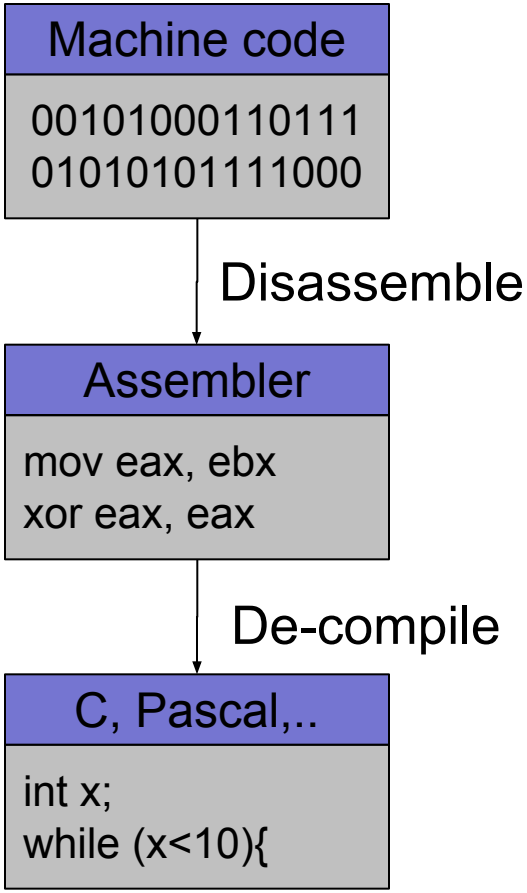


Going Back is Hard!

- 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)
- 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`)

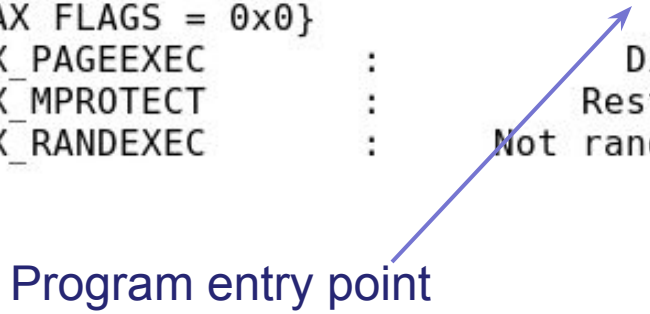
```
linux util # strings sil | head -n 5
/lib/ld-linux.so.2
_Jv_RegisterClasses
__gmon_start__
libc.so.6
puts
```

Static Techniques

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

```
[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
```



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)
  - variable length
    - use less space for common instructions
    - CISC processors (Intel x86)

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

Intel x86 Assembler Primer

- Assembler Language
  - human-readable form of machine instructions
  - must understand the hardware architecture, memory model, and stack

- AT&T syntax
  - mnemonic source(s), destination
  - standalone numerical constants are prefixed with a $
  - hexadecimal numbers start with 0x
  - registers are specified with %

Intel x86 Assembler Primer

- Registers
  - local variables of processor
  - six 32-bit general purpose registers
    - can be used for calculations, temporary storage of values, …

      `%eax, %ebx, %ecx, %edx, %esi, %edi`
  - several 32-bit special purpose registers

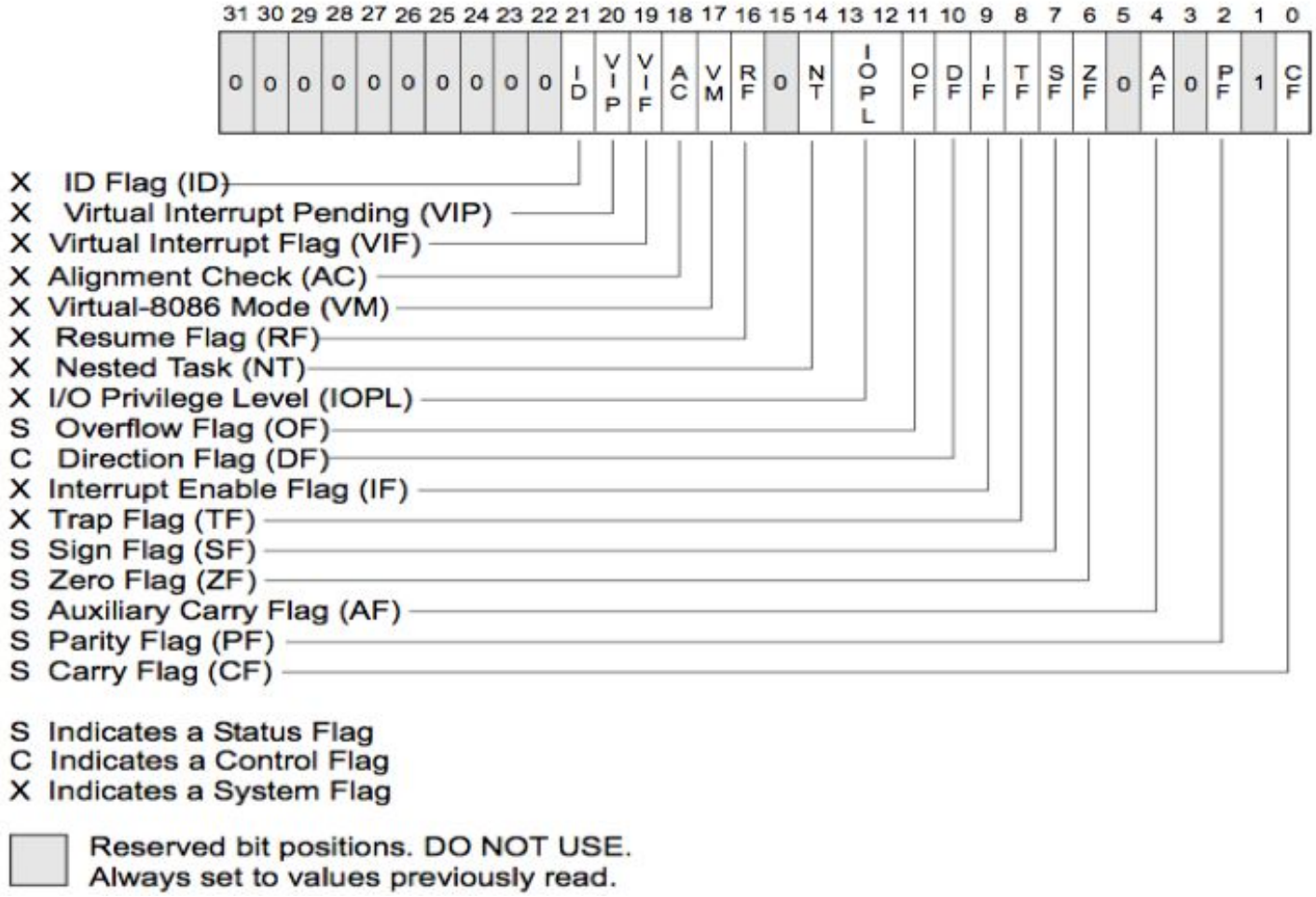
      `%esp- stack pointer`
      `%ebp- frame pointer`
      `%eip- instruction pointer`

- Important mnemonics (instructions)

  `mov` data transfer
  `add` / `sub` arithmetic
  `cmp` / `test` compare two values and set control flags
  `je` / `jne` conditional jump depending on control flags (branch)
  `jmp` unconditional jump

Intel x86 Assembler Primer

Status (EFLAGS) Register



Intel x86 Assembler Primer

- Status (EFLAGS) Register
  - used for control flow decision
  - set implicit by many operations (arithmetic, logic)

- Flags typically used for control flow
  - CF (carry flag)
    - set when operation “carries out” most significant bit
  - ZF (zero flag)
    - set when operation yields zero
  - SF (signed flag)
    - set when operation yields negative result
  - OF (overflow flag)
    - set when operation causes 2’s complement overflow
  - PF (parity flag)
    - set when the number of ones in result of operation is even

Intel x86 Assembler Primer

Instruction	Synonym	Jump condition	Description
jmp label		1	direct jump
jmp *operand		1	indirect jump
je label	jz	ZF	equal/zero
jne label	jnz	~ZF	not equal/zero
js label		SF	negative
jns label		~SF	non-negative
jg label	jnle	~(SF ^ OF) & ~ZF	greater than (signed)
jge label	jnl	(~SF ^ OF)	greater or equal (signed)
jl label	jnge	SF ^ OF	less than (signed)
jle label	jng	(SF ^ OF) | ZF	less or equal (signed)
ja label	jnbe	~CF & ~ZF	above (unsigned)
jae label	jnb	~CF	above or equal (unsigned)
jb label	jnae	CF	below (unsigned)
jbe label	jna	CF | ZF	below or equal (unsigned)

Intel x86 Assembler Primer

- When are flags set?
  - implicit, as a side effect of many operations
  - can use explicit compare / test operations
- Compare

  `cmp b, a` [note the order of operands]
  - computes (a – b) but does not overwrite destination
  - sets ZF (if a == b), SF (if a < b) [and also OF and CF]
- How is a branch operation implemented
  - typically, two step process

    first, a compare/test instruction

    followed by the appropriate jump instruction

Intel x86 Assembler Primer

- Program can access data stored in memory
  - memory is just a linear (flat) array of memory cells (bytes)
  - accessed in different ways (called addressing modes)

- Most general fashion
  - `address: displacement(%base, %index, scale)`

    where the result address is `displacement + %base + %index*scale`

- Simplified variants are also possible
  - use only displacement → direct addressing
  - use only single register → register addressing

Intel x86 Assembler Primer

- Stack
  - managed by stack pointer (%esp) and frame pointer (%ebp)
  - special commands (push, pop)
  - used for
    - function arguments
    - function return address
    - local arguments
- Byte ordering
  - important for multi-byte values (e.g., four byte long value)
  - Intel uses *little endian* ordering
  - how to represent `0x03020100` in memory?

```
0x040   0
0x041   1
0x042   2
0x043   3
```

Intel x86 Assembler Primer

```
# no input
# returns a status code, you can view it by typing echo $?
# %ebx holds the return code
.section .text
.globl _start

_start:
movl   $1, %eax    # This is the system call for exiting program
movl   $0, %ebx    # This value is returned as status
int    $0x80  # This interrupt calls the kernel, to execute sys call
```

Intel x86 Assembler Primer

- So how do we create the application?
  - we need to assemble and link the code
  - this can be done by using the assembler *as (or gcc)*

- Assemble

```
as exit.s –o exit.o |
  gcc –c –o exit.o exit.s
```

- Link

```
ld –o exit exit.o |
  gcc –nostartfiles –o exit exit.o
```

Intel x86 Assembler Primer

- `If` statement

```
#include <stdio.h>

int main(int argc, char **argv)
{
  int a;

  if(a < 0) {
    printf("A < 0\n");
  }
  else {
    printf("A >= 0\n");
  }
}
```

```
.LC0:
        .string "A < 0\n"
.LC1:
        .string "A >= 0\n"
.globl main
        .type   main, @function
main:
          [ function prologue ]
        cmpl    $0, -4(%ebp) /* compute: a - 0    */
        jns     .L2          /* jump, if sign bit
                                not set: a >= 0  */
        movl    $.LC0, (%esp)
        call    printf
        jmp     .L3
.L2:
        movl    $.LC1, (%esp)
        call    printf
.L3:
        leave
        ret
```

Intel x86 Assembler Primer

- `While` statement

```
#include <stdio.h>

int main(int argc, char **argv)
{
    int i;

    i = 0;
    while(i < 10)
    {
        printf("%d\n", i);
        i++;
    }
}
```

```
.LC0:
        .string "%d\n"
main:
        [ function prologue ]
        movl    $0, -4(%ebp)
.L2:
        cmpl    $9, -4(%ebp)
        jle     .L4
        jmp     .L3
.L4:
        movl    -4(%ebp), %eax
        movl    %eax, 4(%esp)
        movl    $.LC0, (%esp)
        call    printf
        leal    -4(%ebp), %eax
        incl    (%eax)
        jmp     .L2
.L3:
        leave
        ret
```

Intel x86 Assembler Primer

Task: Find the maximum of a list of numbers

- Questions to ask:
  - Where will the numbers be stored?
  - How do we find the maximum number?
  - How much storage do we need?
  - Will registers be enough or is memory needed?

- Let us designate registers for the task at hand:
  - %edi holds position in list
  - %ebx will hold current highest
  - %eax will hold current element examined

Intel x86 Assembler - Algorithm

- Check if `%eax` is zero (i.e., termination sign)
  - if yes, exit
  - if not, increase current position `%edi`
- Load next value in the list to `%eax`
  - we need to think about what addressing mode to use here
- Compare `%eax` (current value) with `%ebx` (highest value so far)
  - if the current value is higher, replace `%ebx`
- Repeat

Intel x86 Assembler - Code

```
.section .data
    data_items:
    .long 3,67,34,222,45,75,54,34,44,33,22,11,66,0
.section .text
.globl _start

_start:
  movl   $0, %edi          # Reset index
  movl   data_items(,%edi,4), %eax
  movl   %eax, %ebx        #First item is the biggest so far
```

Intel x86 Assembler - Code

```
start_loop:
  cmpl   $0, %eax
  je     loop_exit
  incl   %edi          # Increment edi
  movl   data_items(,%edi,4), %eax     # Load the next value
  cmpl   %ebx, %eax    # Compare ebx with eax
  jle    start_loop    # If it is less, just jump to the beginning
  movl   %eax, %ebx    # Otherwise, store the new largest number
  jmp    start_loop

loop_exit:
  movl   $1, %eax      # Remember the exit sys call? It is 1
  int    $0x80
```

Intel x86 Assembler Primer

- Functions
  - clearly, all larger programs need to be divided into functions
- x86 provides two operations
  - `call`
    - pushes address after call instruction on stack
    - jumps to target
  - `ret`
    - pops top of the stack
    - transfers control to that value
- A lot is filled in by the compiler
  - local and global variables
  - passing arguments between caller and callee

Intel x86 Assembler Primer

- Local variables
  - stored in the current stack frame
  - referenced relative to frame pointer (or stack pointer)

```
DIR *d;
d = opendir(s);
```

```
call 80484a8 <opendir@plt>
mov  %eax,0xfffffff0(%ebp)
```

- Global variables
  - referenced by absolute address (or offset to segment)

```
char *progname;
void usage() {
  char *s;
  s = progname;
```

```
mov  0x8049bbc,%eax
mov  %eax,0xfffffffc(%ebp)
```

Intel x86 Assembler Primer

- Function arguments
  - can be passed in different fashions, depending on the calling convention
- Calling conventions
  - cdecl
    use the stack to pass arguments, right to left, caller cleans stack
  - stdcall
    use the stack to pass arguments, right to left, callee cleans stack
  - fastcall
    pass first two arguments in registers, rest on stack (right to left)
- Argument access
  - with cdecl, use relative offset of base pointer
  - similar to local variables, but positive offset

Static Techniques

… after this x86 assembler digression, back to disassembling

- **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

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

Dynamic Techniques

- General information about 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
  - file system
  - network

Dynamic Techniques

- File system 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

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-disassemble techniques
  - anti-debugging techniques

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

```
jmp Label1
.short    0x4711

Label1:
```

```
8048000: 74 02              je 8048004
8048002: 47                 inc    %edi
     8048003: 11 90 90 90 90 90   adc %edx,0x90909090(%eax)
8048004:                    <Label1>
```

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`

Reverse Engineering

- Focused exploration
  - *bypass check routines*
  - locate the point where the failed check is reported
  - find the routine that checks the password
  - 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) - RTDSC instruction

Your Security Zen

- Hotel ransomed by hackers as guests locked out of rooms

One of Europe's top hotels has admitted they had to pay thousands in Bitcoin ransom to cybercriminals who managed to hack their electronic key system, locking hundreds of guests out of their rooms until the money was paid.

Source: http://www.thelocal.at/20170128/hotel-ransomed-by-hackers-as-guests-locked-in-rooms