CS 290
Host-based Security and Malware

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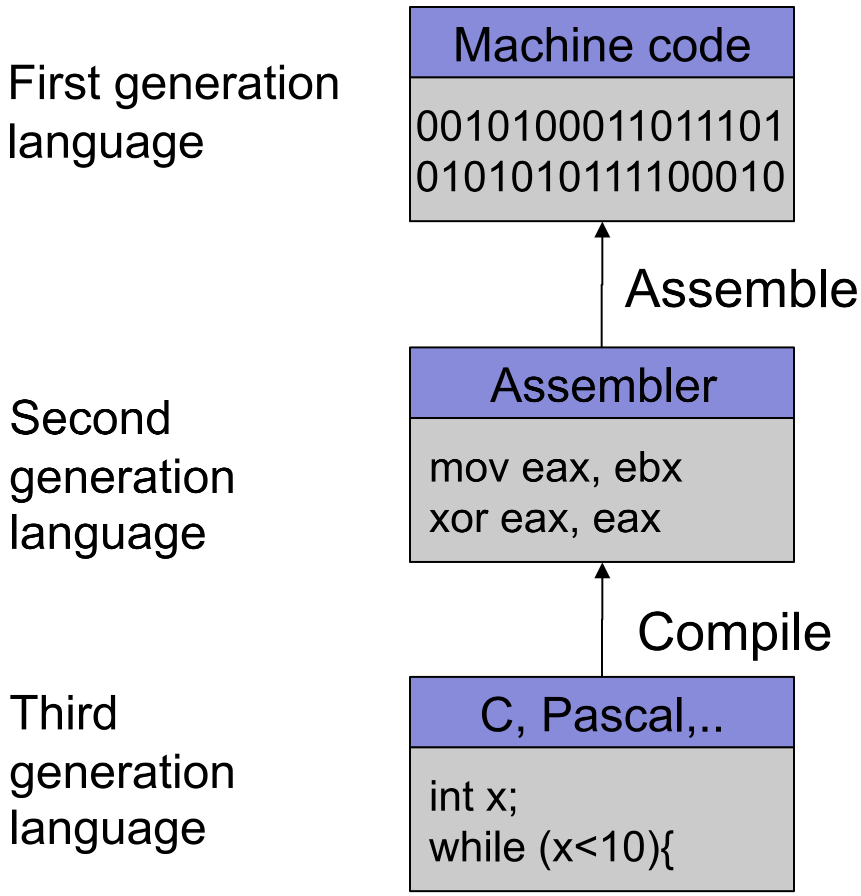
Reverse Engineering

Introduction

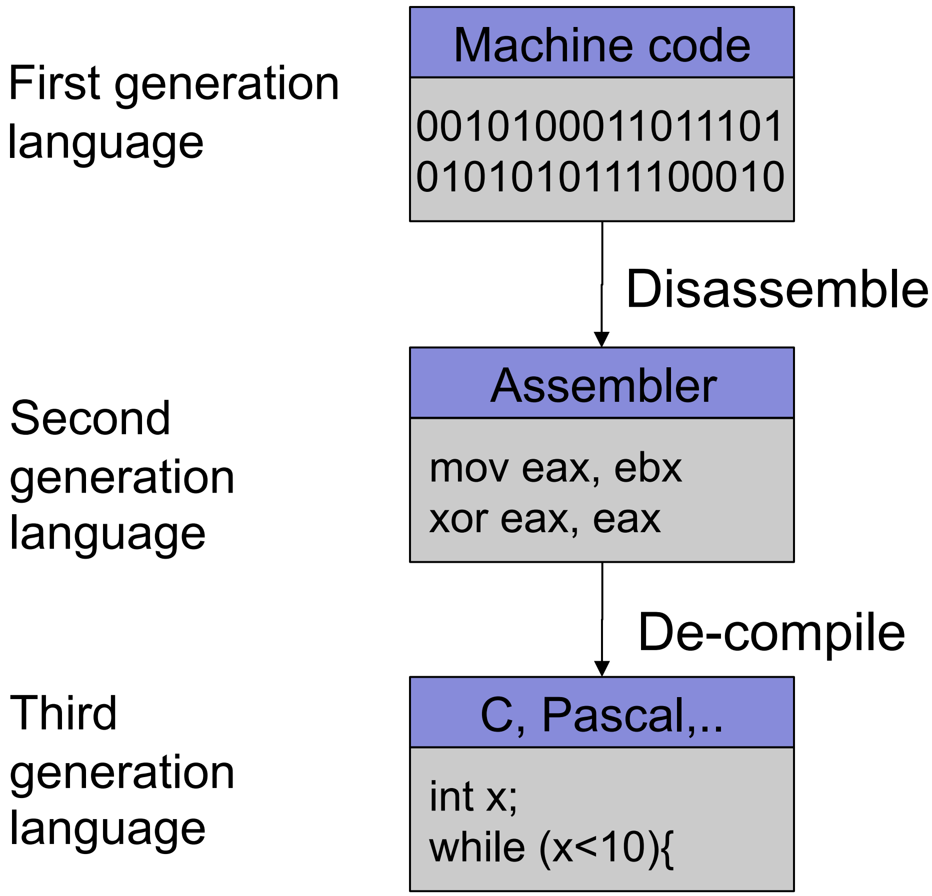
- Reverse engineering
  - process of analyzing a system
  - understand its structure and functionality
  - used in different domains (e.g., consumer electronics)

- 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



Software Reverse Engineering



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

<u>Static Analysis</u>

- 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

<u>Dynamic Analysis</u>

- 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
```

Program entry point

Static Techniques

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

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

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

  - 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

<u>Recognizing libraries in statically-linked programs</u>

- 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

<u>Displaying program symbols</u>

```
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

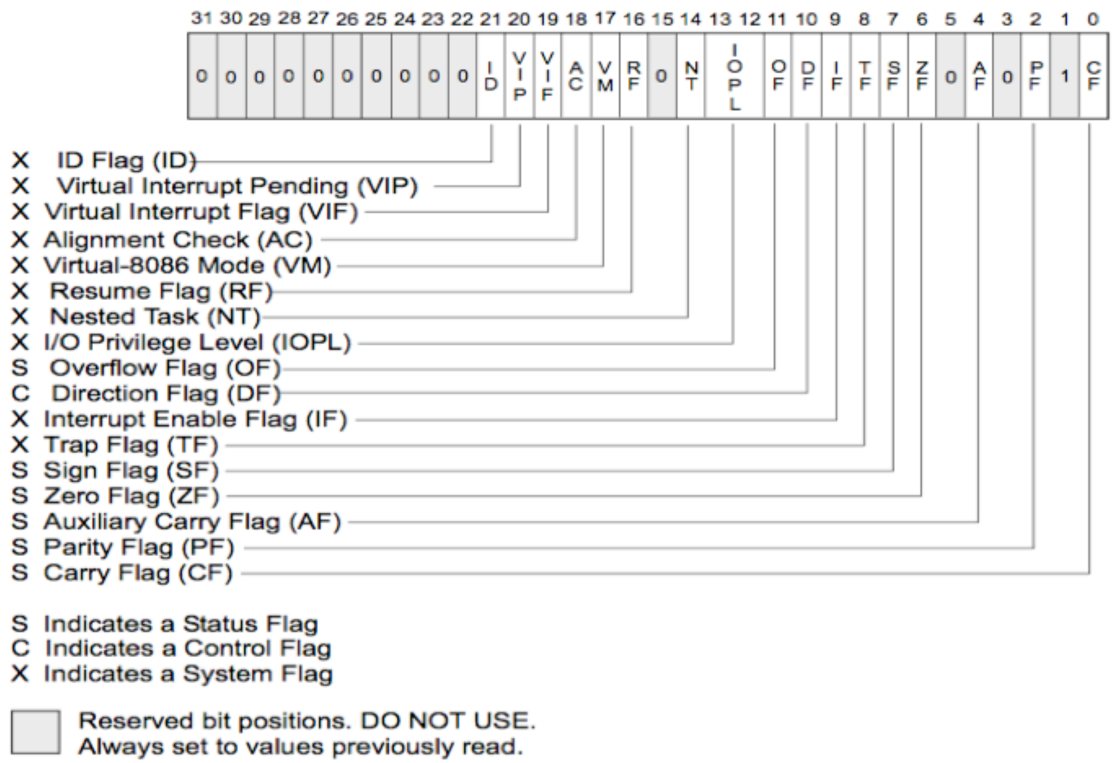
```
%esp    - stack pointer
%ebp    - frame pointer
%eip    - instruction pointer
```

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

_start:
mov $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

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

- `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
```

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`

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 attacks
  - 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)
  - detect tracing
    - a process can be traced only once

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

  - detect 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);
```

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, but faster
  - complete environment is comprehensive, but slower

  - Anubis uses this approach

Semantic Gap

- Analysis observes activity "from the outside"
  - how to relate instructions executed on processor
    with activity inside the operating system and sample?
  - must encode some knowledge about guest OS and processes
    - we chose to target MS Windows on Intel x86 machines
  - Qemu used as emulation environment

- Questions
  - how to identify which instructions belong to malware sample?
  - what to analyze?
  - how to implement analysis?

Tracking Malware Process

- Executed instructions must be assigned to correct process
  - make use of CR3 register
    - control register used for virtual memory management
    - holds physical address of the base of the page directory
    - unique for each process
    - ensures that virtual address spaces are disjoint
  - reloaded at every context switch

- Obtaining value of CR3 register
  - use small component inside operating system
  - extracts value from kernel task structure (EPROCESS)
  - process started in suspended state

Analysis Information

- Process interacts with operating system via system calls
  - needs OS for every interaction with environment
    - file system, network, registry, …
  - monitor system calls
  - unfortunately, on Windows, system calls largely undocumented and can change without notice
  - developers are supposed to use Windows API, which denotes a collection of stable, user-mode, shared libraries
  - of course, Windows API can be bypassed

→ we monitor Windows API calls and NT kernel calls

Analysis Report

- File activity
  - read, write, create, open, …
- Registry activity
- Service activity
  - start or stop of Windows services (via Service Manager)
- Process activity
  - start, terminate process, inter-process communication
- Network activity
  - API calls and packet logs

Analysis Implementation

- Windows API and kernel calls must be hooked *without* interfering with the program (and its memory)

- Can be implemented in straightforward fashion
  - compare address of instruction executed with function start address
  - Qemu allows to do this efficiently
  - start addresses extracted from library export tables

- Arbitrary addresses are possible
  - analysis has fine-grain control

Analysis Implementation

- Information about function invocation alone insufficient
  - we also want to know about arguments
- Callback invoked when “breakpoint” reached
  - allows us to extract argument values
  - semantic gap again, Anubis only knows about physical address space
  - appropriate read functions require argument type information (structure and size of arguments), similar to advanced debuggers
  - would be tedious to write by hand, automatic support desirable
- Callbacks are invoked on function call and function return

Argument Extraction

- Generate routines to extract argument values automatically
  - provide values directly to callback routine
  - requires knowledge about argument types

- Code generation component
  - processes Windows header files (read type definitions)
  - parameters may be `in` and `out` parameters (or both)
  - parameters may be of unknown length
    - zero-terminated strings
    - arrays where second parameters specifies length
  - headers files were manually augmented
  - complex structures (with pointers) are traversed automatically

Argument Extraction

- Problem
  - not all argument values need to present in physical memory
  - Anubis has only access to (emulated) physical memory
  - argument values could be swapped out
  - other problem are shared libraries that are not paged in
    - e.g., due to lazy evaluation

- Solution
  - make process access virtual address(es)
  - forces Windows to bring in memory (page fault handler)
  - Anubis has to (transparently) inject such access into process

Code Injection

- Modify control flow of target process
  - necessary to bring in paged out memory content
  - but also useful for calling arbitrary functions in context of target
- Calling functions
  - distinguish between open and create file (or registry key)
  - distinguish between files and directories
  - resolve unknown handles
- Can be easily done with Qemu
  - without modifying process' code
  - only problem is to push argument values onto process stack
  - dual problem to reading arguments, generator can be reused

Stealthiness

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

- Time could be used to detect our 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