PV204 Security technologies

Rootkits, reverse engineering of binary applications

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What is planned for this lecture?

- Rootkits (and defences)
- Reverse engineering (of binary applications)

K. Thompson – Reflections on Trusting Trust

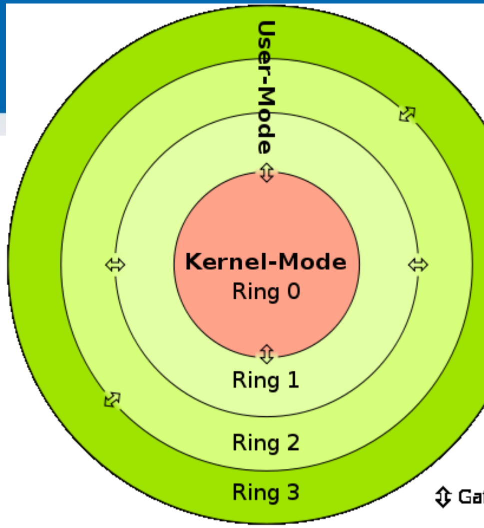
- Subverted C compiler (Turing Award Lecture, 1983)
  - Adds additional functionality for selected compiled programs
  - E.g., *login* cmd: log password or allow user with specific name
- Inspection of *login*'s source code will not reveal any issues
- Adds malicious functionality of compiler into binary of compiler compiled with already subverted compiler
  - Inspection of source code of compiler will not reveal any problem
- How can we detect modified *login* binary?
  - Expected hash, digital signatures, deterministic build…
  - What if signature verification tool is also modified?
- W32/Induc-A infected compiler for Delphi (2009)
  - Active at least a year before discovery

ROOTKITS

Rootkit definition

- Root-kit
  - *root* user *nix systems
  - *kit* set of tools to operate/execute commands
- Rootkit is piece or collection of software
  - Designed to enable access where it would be otherwise denied
  - Tries to hide(“cloak”) its presence in system
- Installed after obtaining privileged access
  - Privileged escalation, credentials compromise, physical access…
- Rootkit != exploit (rootkit usually installed after exploit)
- Rootkit is usually accompanied with additional payload
  - Payload does the actual (potentially malicious) work

Protection rings

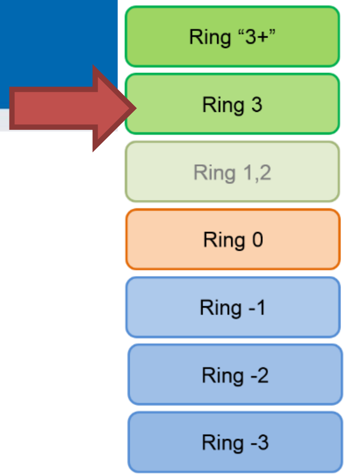


- Idea: introduce separate runtime levels
  - Crash in level X causes issue only in levels >=X
  - Direct support provided by CPU architectures (0/3)
    - Instructions which can be executed only in given ring
- Ring 3: unprivileged user programs
- Ring 2/1: device drivers (currently sparsely used)
- Ring 0: kernel programs
- Performance penalty associated with ring switching
  - In practice, only 3 and 0 are commonly used
- 0-3 Captures only rings/levels starting with OS
  - Levels -1/-2/-3 introduced for layers below OS

Rootkit		Ring level
Managed code rootkits	Ring “3+”	Managed code (runtime, JVM)
User-mode rootkits	Ring 3	User-mode
Kernel rootkits	Ring 1,2	Device drivers
Kernel rootkits	Ring 0	OS kernel, device drivers
Hypervisory-level rootkits	Ring -1	Hypervisory-level (VT-x, AMD-V)
SMM abuse, bootkits	Ring -2	System Management Mode, BIOS
FW/HW rootkits	Ring -3	Firmware, hardware

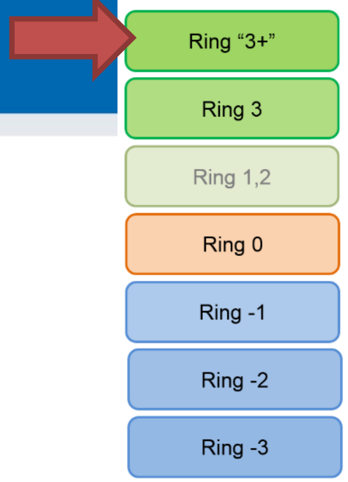
Principal ways of detection of rootkits

1. Detection running inside system, same or higher level
   - Flaws in rootkit cloaking, use of some side-channel leakage (of rootkit)
2. Detection running inside system, lower level
   - Not controlled by rootkit, rootkit cannot cloak itself
3. Detection via (offline) image of system / memory
   - Rootkit is not running => cannot cloak itself



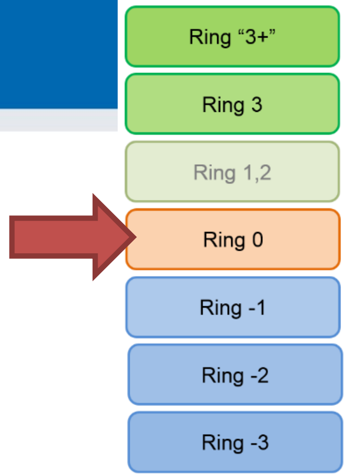
User-mode rootkits (Ring 3)

- Injects payload into other user applications
  – Injection of modified dlls (user app will use different CreateFile)
  – Modification of applications (modification of CreateFile)
- Interception of messages
  – RegisterWindowMessage()
- Function hooking
  – More generic hooks (SetWindowsHookEx()) – window manager
  – User application-specific hooks (plugins, example browser hook)
- File-system filters
  – Detect access to files by user application



Managed code rootkits (MCR) (Ring 3)

- Ring 3 (level for runtime / VM)
- Targets runtime environments for interpreted code
  - .NET VM, Java VM and Dalvik runtime…
- Large attack surface for MCR
  - Attacking runtime class libraries
  - Attacking JIT compiler
  - Abusing runtime instrumentation features
  - Extending language with malware API
  - Object-oriented malware (inside OO runtime)
- E. Metula: Managed Code Rootkits (Syngress)

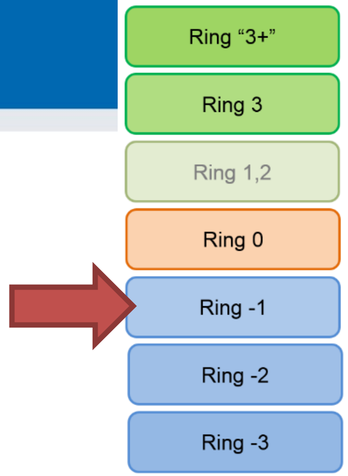


Kernel-mode rootkits (Ring 0)

- Runs with highest system privileges
  - Usually device drivers and loadable modules
  - Device drivers in MS Windows
  - Loadable kernel modules in Linux
- Direct kernel object manipulation
  - Data structures like list of processes…
  - System Service Descriptor Table (SSDT) hook [Microsoft]
  - System call table hook [Linux]
- Operating system may require mandatory drivers signing
  - More difficult to insert malicious driver
  - Still possible (compromised private keys: Stuxnet & Realtek's keys)

ROOTKITS BELOW OS LEVEL

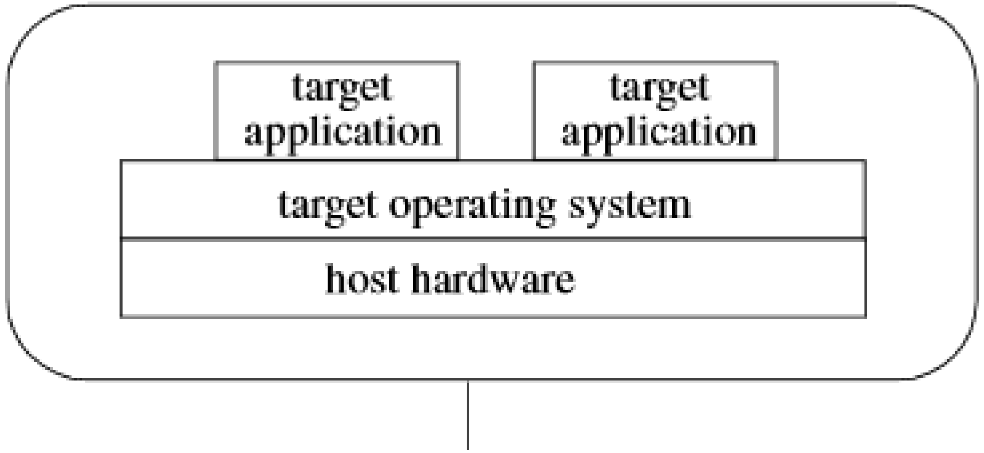
Hypervisory-level rootkits (Ring -1)



- Virtual-machine based rootkit (VMBR)
  - Type II hypervisors (VM on ordinary OS host)
- Based on CPU hardware virtualization features
  - Intel VT or AMD-V
- Rootkit hosts original system as virtual machine
  - And intercepts all relevant hardware calls
- Examples: SubVirt, BluePill (AMD-V, Intel VT-x)

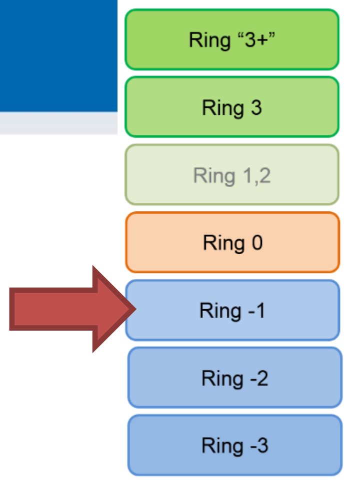
Hypervisory-level rootkits (Ring -1)

Before infection



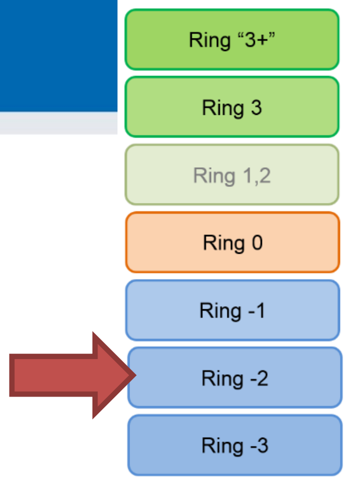
King et al: SubVirt: Implementing malware with virtual machines

Defense against hypervisory-level rootkits



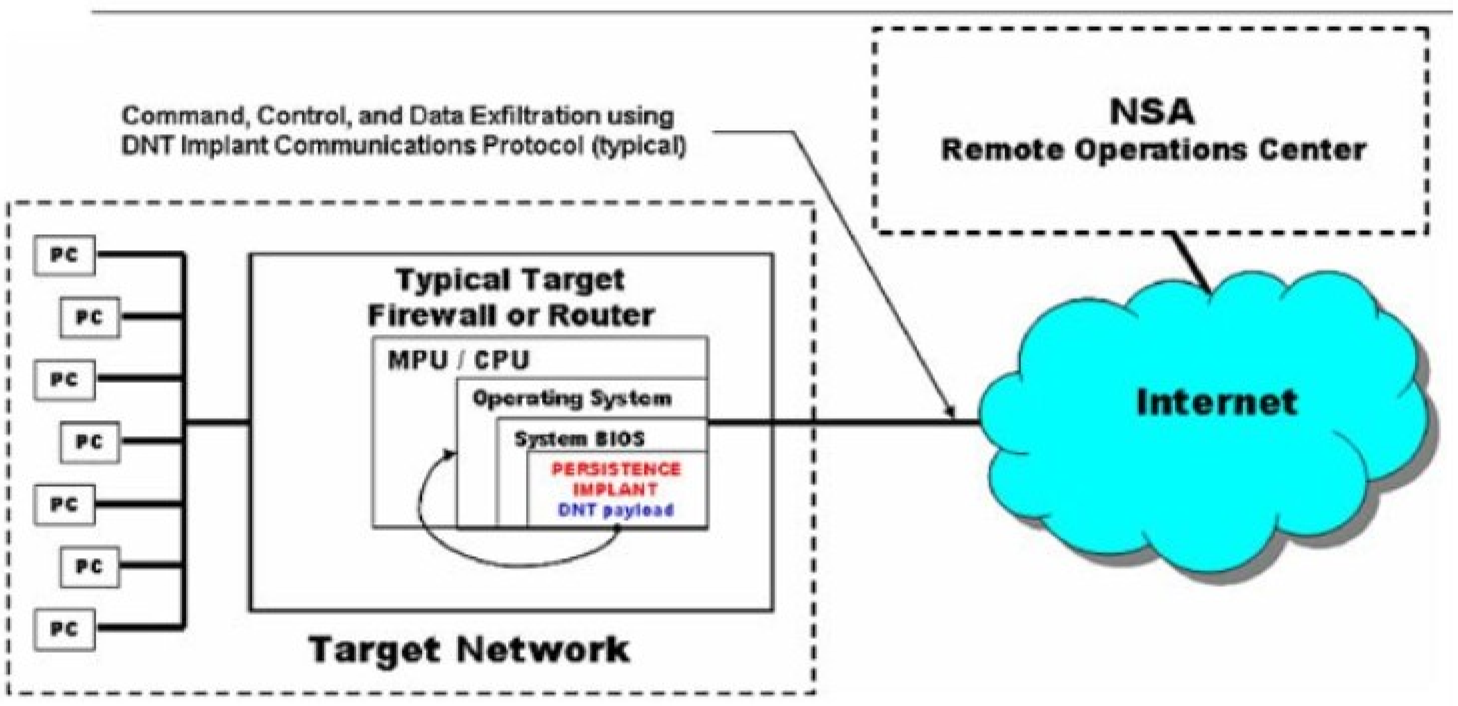
- Run detection/prevention on lower level
- Detect by timing differences of operations
  - System is emulated => side-channel info (timings…)
- Read and analyze HDD physical memory
  - After physical removal from (infected) computer
- Boot from safe medium (CD, USB, network boot)
  - inspect before VMBR loads
  - But VMBR can emulate shutdown / reboot
    - Physical power unplug recommended
- Trusted boot (based on TPM, lecture 07)

System Management Mode abuse (R.-2)



- System Management Mode (SMM)
  - x86 feature since Intel 386, all normal execution is suspended
  - Used for power management, memory errors, hardware-assisted debugger…
  - High-privilege mode (Ring -2)
- SMM entered via system management interrupt (SMI)
  - System cannot override or disable the SMI
- Target for rootkits
  - Modify memory, loaders, MBR…

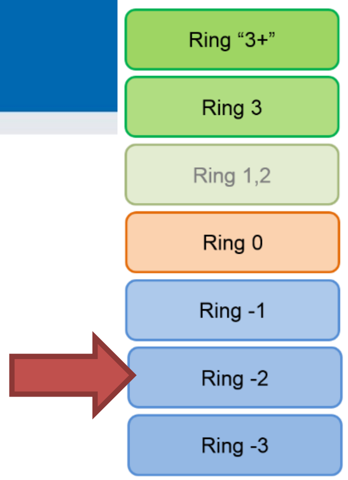
SMM Example: SOUFFLETROUGH implant



(TS//SI//REL) SOUFFLETROUGH Persistence Implant Concept of Operations

- https://en.wikipedia.org/wiki/NSA_ANT_catalog
- http://leaksource.info/2013/12/30/nsas-ant-division-catalog-of-exploits-for-nearly-every-major-software-hardware-firmware/

Bootkit rootkits (Ring -2)



- Bootkit = Rootkit + Boot capability
- Infect startup code
  - Master Boot Record (MBR)
  - Volume Boot Record (VBR)
  - Boot sector, BIOS routines…
- "Evil maid" attack
  - Can be used to attack full disk encryption
  - Assumption: user will left device physically unattended
  - Legitimate bootloader replaced (+ key capture)

Full-disk encryption compromise

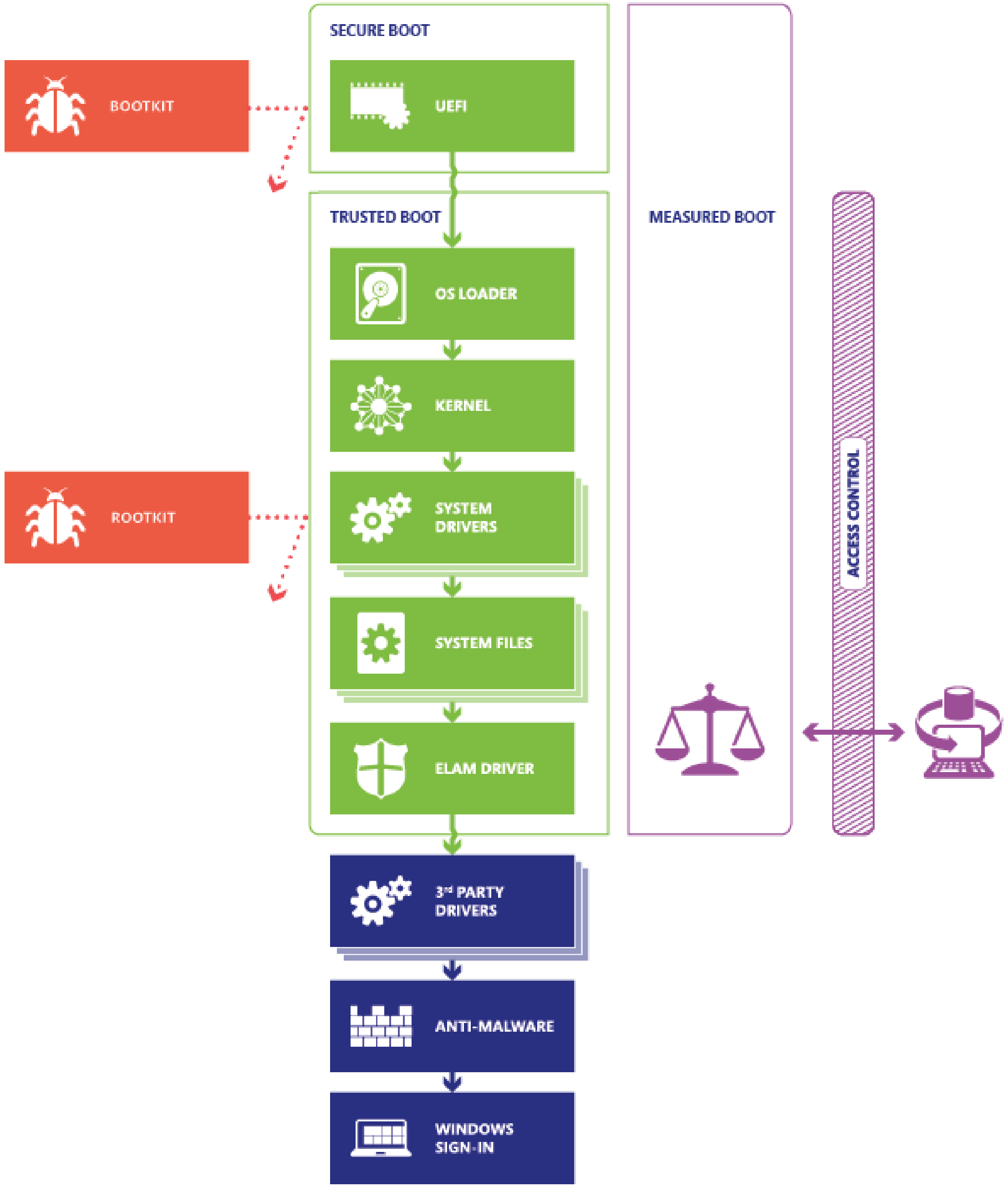
1. Full-disk encryption used to encrypt all data
2. Laptop powered down to prevent Coldboot or FireWire-based attacks (read key from memory)
3. Laptop left unattended ("Evil maid" enters)
   - USB used to read part of first sector of disk
   - If TrueCrypt/Bitlocker loader, then insert malicious bootloader
4. User is prompted with forged bootloader
   - Password is stored

- How to transfer saved password / data to attacker?
  - Second visit of Evil maid

http://theinvisiblethings.blogspot.co.uk/2009/10/evil-maid-goes-after-truecrypt.html

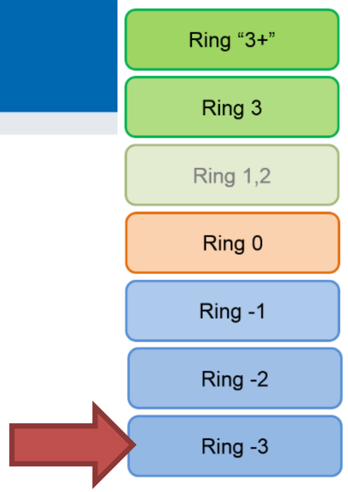
Bootkit defenses

- Prevention of physical access
  - Problematic for portable devices
- Trusted boot (static vs. dynamic root of trust)
  - Refer to Lecture 07 (Trusted boot)
  - But bootloader must authenticate itself to user
    - E.g., present image encrypted by key stored in TPM
    - Before user enters its password
- Defense by external verification of bootloader integrity
  - verify relevant unencrypted parts of disk (external USB)



http://technet.microsoft.com/en-US/windows/dn168167.aspx

Firmware / hardware rootkits (Ring -3)



- Persistent malware image in hardware
  - Network card, router, hard drive…
- Can run even after removal of device from target computer
  - Once device is powered again

LEGITIMATE USES

Legitimate uses of rootkits

- To whom is legitimacy measured?

- Hide true nature of network “honeypots”
- Protection of AV software against termination of inspected malware
- Anti-theft protections
- Digital rights management?

Sony BMG Extended copy protection

- Rootkit developed for (and approved) by Sony
  - Intended to limit possibility for disk copy
  - Users were not notified (silently installed after CD insert)
  - Digital rights management for Sony
  - To hide itself, any file starting with *sys* was hidden
- Detected by M. Russinovich's RootkitRevealer
  - After public disclose, other malware started to hide itself by naming its files as *sys* (user was already "infected")
- Sony released patch for removal (web-based uninstaller)
  - Even more serious flaw introduced (any visited page can install and run program)
  - Resulted in class-action lawsuit against Sony BMG

REVERSE ENGINEERING

Reverse engineering

- A process of knowledge or design extraction from final product (usually man-made)
- Engineering:
  - Mental model → blueprints/source-code → product/binary
- Reverse engineering (back engineering):
  - From product back to knowledge or design
  - Blueprints/source-code might be also recreated
- Not necessary/possible to perfectly recreate design
  - Engineering might be loose transformation
  - Back engineering might not be perfect/complete

Reverse engineering is general process
We will focus on software binaries only

Reverse engineering - legal issues

- Reverse engineering is legal when
  - Own binary without documentation
  - Anti-virus research, Forensics…
  - Interoperability, Fair use, education
- Problem with some copyright laws
  - not only selling circumvented content, but also attempt to circumvent is illegal (USA's DMCA)
- EFF Coders' Rights Project Reverse Engineering FAQ
  - Legal doctrines, Risky aspects, Selected decisions
  - https://www.eff.org/issues/coders/reverse-engineering-faq

How to start reverse engineering

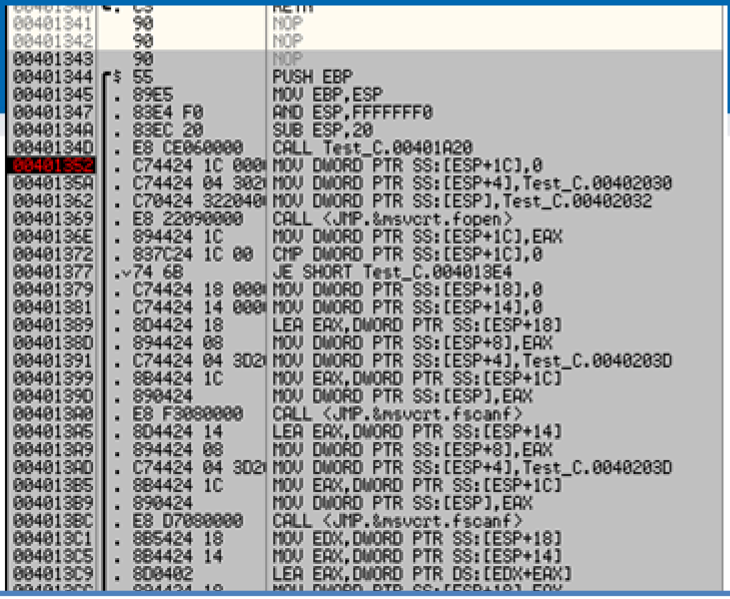
1. Learn basic concepts (compilers, memory, OS…)
2. See how source-code translates into binary
3. Try tools on simple examples (own code, tuts)
4. Utilize other knowledge (communication logs…)
5. Have fun! ☺

Basics

- Debugger vs. debugger with binary modification capabilities
  - E.g., Visual Studio vs. OllyDbg
- Disassembler vs. debugger
  - Static vs. dynamic code analysis
- Disassembler vs. decompiler
  - Native code → assembler → source code
- Native code vs. bytecode
  - Different instruction set, different execution model
- Registry-based vs. stack-based execution

Mixed source code/assembler in IDE

- Most current IDE supports mixed source code/assembler instructions mode (Visual Studio, QT Creator...)
  - Mode is usually available only during a debugging
  - Write simple code (e.g., if then else condition), insert breakpoint and start debugging
- Switch to mixed mode
  - Visual Studio→RClick→Go to disassembly
  - QTCreator→Debug→Operate by Instruction
- Easy way to learn how particular source code is translated into assembler code




```c
#include <stdio.h>
int main() {
    FILE* file = NULL;
    file = fopen("values.txt", "r");

    if (file) {
        int value1 = 0;
        int value2 = 0;
        fscanf(file, "%d", &value1)
        fscanf(file, "%d", &value2)

        value1 = value1 + value2;

        printf("Result: %d", value1)
    }
    fclose(file);
}
```

Original C source code

```
Dump of assembler code for function main:
        2               int main() {
0x00401344   <+0>:                  push    %ebp
0x00401345   <+1>:                  mov     %esp,%ebp
0x00401347   <+3>:                  and     $0xfffffff0,%esp
0x0040134a   <+6>:                  sub     $0x20,%esp
0x0040134d   <+9>:                  call    0x401a20 <__main>

        3               FILE* file = NULL;
0x00401352   <+14>:                 movl    $0x0,0x1c(%esp)

        4               file = fopen("values.txt", "r");
0x0040135a   <+22>:                 movl    $0x402030,0x4(%esp)
0x00401362   <+30>:                 movl    $0x402032,(%esp)
0x00401369   <+37>:                 call    0x401c90 <fopen>
0x0040136e   <+42>:                 mov     %eax,0x1c(%esp)

             ...

       17          }
0x004013f5   <+177>:                leave
0x004013f6   <+178>:                ret
          End of assembler dump.
```

Most common instructions/structures

- Most common ASM instructions
  - Load/Store from to registers: MOV, LEA
  - Arithmetic: ADD, INC…
  - Relational: CMP, TEST
  - Jumps: JMP, J*
  - Functions: CALL, RET
- Example of typical structures (C→ ASM)
  - Conditional jump, `for` loop, function call…
  - Familiarize via mixed source code/assembler in IDE
  - Be aware of debug/release differences

Compilation to bytecode (Java, C#)

- Source code compiled into intermediate bytecode
  - Java bytecode, .NET CLI ...
- Intermediate code interpreted by virtual machine
- Just-in-time compilation
  - Intermediate code is compiled by VM into native code
  - Improve performance significantly
  - Relevant for dynamic analysis, not for static analysis
- Usually easier to understand then assembler code

REGISTRY VS. STACK-BASED EXECUTION

Registry-based execution

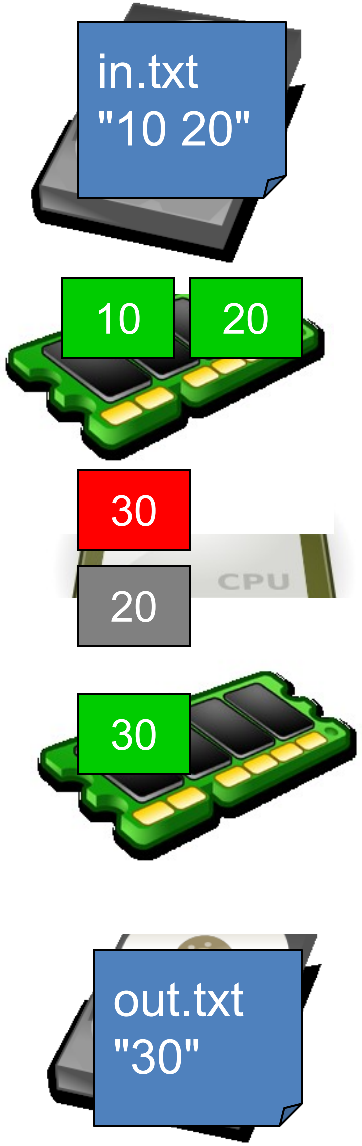
1. Values loaded (`mov`) from RAM to CPU registers
2. CPU operation (`add, inc, test`…) is executed
3. Resulting value is stored back (`mov`) to RAM

- Name of the registers
  - EAX 32bit, AX 16bit, AH/AL 8bit
  - EIP ... next address to execute (instruction pointer)
  - EBX ... usually loop counter
- Registers
  - Z – zero flag, C – carry flag, S – sign flag…

Add two numbers from file (HDD)

value = value + value2;

1. Read values from HDD into RAM memory
   - `fscanf(file, "%d", &value);`
2. Move value from RAM memory to CPU registry
   - `MOV    0x48(%esp),%eax`
   - `MOV    0x44(%esp),%edx`
3. Execute CPU instruction (e.g., ADD)
   - `ADD     %edx,%eax`
4. Transfer result from CPU register to RAM memory
   - `MOV    %eax, 0x48(%esp)`
5. Save result from RAM memory to file
   - `fprintf(file, "%d", value);`



Stack-based execution

- Bytecode contains sequence of operations
- Bytecode contains constants
- All intermediate values stored on stack
- Interpret:

1. Reads next operation from bytecode
2. Pop operand(s) for next operation from top of stack
3. Executes operation
4. Push result of operation on top of stack

- No registers are used
  - all operands for current operation at the top of the stack

Example: JavaCard bytecode

```
// ENCRYPT INCOMING BUFFER
  void Encrypt(APDU apdu) {
      byte[]     apdubuf = apdu.getBuffer();
      short      dataLen = apdu.setIncomingAndReceive();
      short      i;

      // CHECK EXPECTED LENGTH (MULTIPLY OF 64 bites)
      if ((dataLen % 8) != 0)
         ISOException.throwIt(SW_CIPHER_DATA_LENGTH_BAD);

      // ENCRYPT INCOMING BUFFER
      m_encryptCipher.doFinal(apdubuf, ISO7816.OFFSET_CDATA, dataLen,
                              m_ramArray, (short) 0);

      // COPY ENCRYPTED DATA INTO OUTGOING BUFFER
      Util.arrayCopyNonAtomic(m_ramArray, (short) 0, apdubuf,
                              ISO7816.OFFSET_CDATA, dataLen);

      // SEND OUTGOING BUFFER
      apdu.setOutgoingAndSend(ISO7816.OFFSET_CDATA, dataLen);
  }
```

Original JavaCard source code

```
.method  Encrypt(Ljavacard/framework/APDU;)V 129 {
 .stack 6;
 .locals 3;
 .descriptor     Ljavacard/framework/APDU;      0.10;
L0:    aload_1;
       invokevirtual 30;
       astore_2;
       aload_1;
       invokevirtual 42;
       sstore_3;
       sload_3;
       bspush 8;
       srem;
       ifeq L2;
L1:    sspush 26384;
       invokestatic 41;
       goto L2;
L2:    getfield_a_this 1;
       aload_2;
       sconst_5;
       sload_3;
       getfield_a_this 10;
       sconst_0;
       invokevirtual 43;
       pop;
       getfield_a_this 10;
       sconst_0;
       aload_2;
       sconst_5;
       sload_3;
       invokestatic 44;
       pop;
       aload_1;
       sconst_5;
       sload_3;
       invokevirtual 45;
       return;
}
```

Resulting JavaCard bytecode

Recovering information from binary executables

DISASSEMBLING

Disassembling of native binaries

- Reversing process of compilation
  - Back from native code to ASM
- Compilation/assembly is loose process:
  - Variable/function names
  - Unused structures
  - Performance optimization applied during compilation
- Wide range of native platforms
  - Differences in support and performance of disassemblers
- Bytecode is already on the level of “disassembled” binaries (usually easier to understand)

Structured code vs. sequence of executed ops

1. Structured code contains code for all branches
   – runnable binary/bytecode

- Information loss in compiled binary
  – Stripped metadata and debugging symbols
  – Compiler optimizations

2. Sequence of executed instructions only from the branches taken
   – E.g., power analysis of smart card with recognized operations
   – If loop was executed, then only linear sequence of instructions is observed corresponding to the number of loop iterations

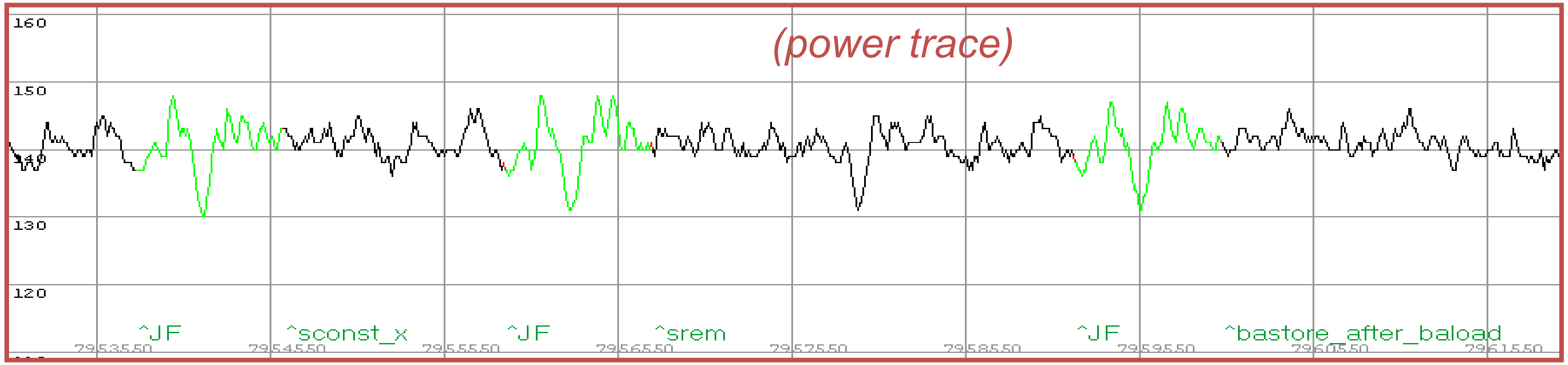
Structured code vs. sequence of executed ops

(source code)
m_ram1[0] = (byte) (m_ram1[0] % 1);

compiler

(bytecode)
getfield_a_this 0;
sconst_0;
baload;
sconst_1;
srem;
bastore;

oscilloscope



Bytecode reconstruction

(partial bytecode)
…; sconst_???; baload; sconst_???; srem; bastore;…

Tool: OllyDbg

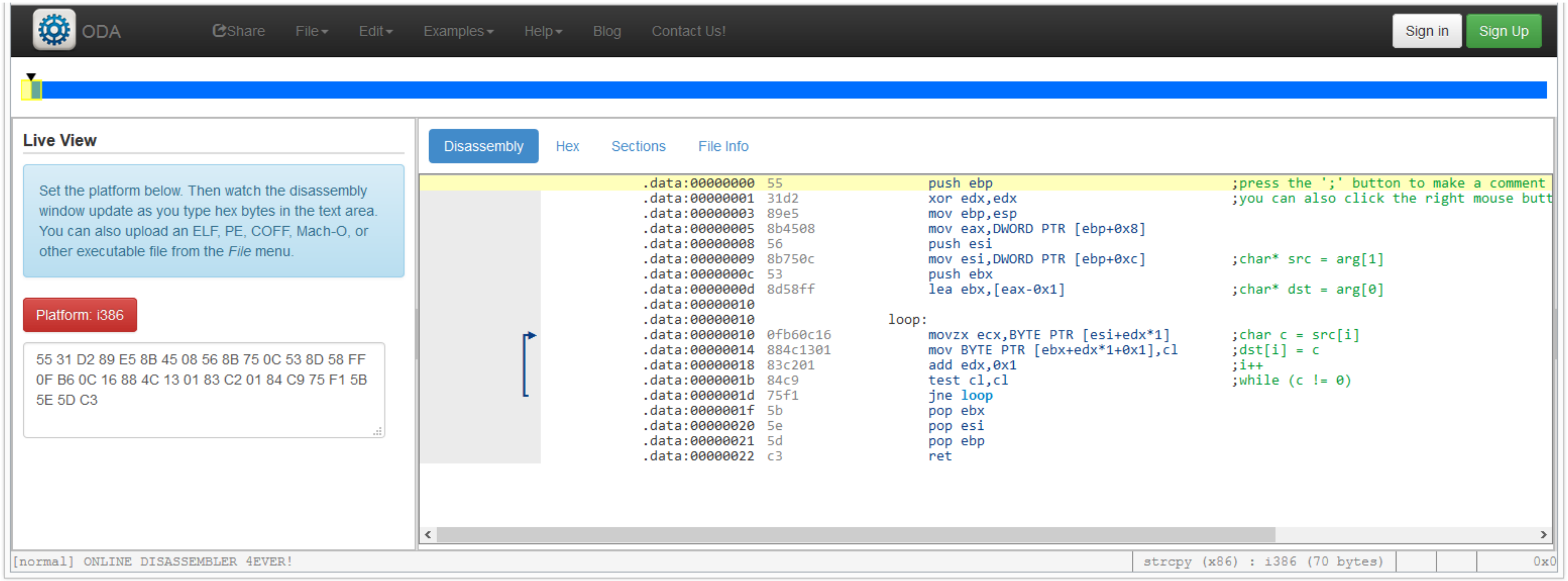
- Free disassembler and binary debugger
  - Works with Windows 32b binaries only
  - OllyDbg 64b version in development (but last update in 2014 ☹)
- Easy to start with, many tutorials
- Designed to make changes in binary easy
  - Change of jumps/data (valid PE is recreated)
- http://www.ollydbg.de/

Tool: IDA Pro

- Interactive Disassembler is legendary full-fledged disassembler with ability to disassemble many different platforms
- Free version available for non-commercial uses
  - http://www.hex-rays.com/idapro/idadownfreeware.htm
- Free version disassemble only Windows binaries
- Very nice visualization and debugger feature (similar as OllyDbg)

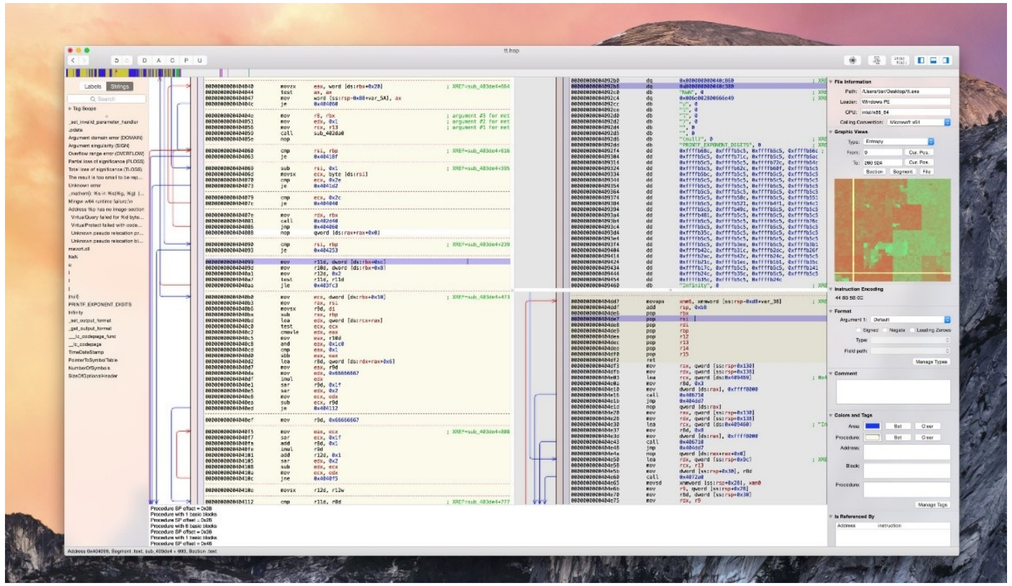
Tool: Online disassembler (ODA)

- https://www.onlinedisassembler.com/odaweb/



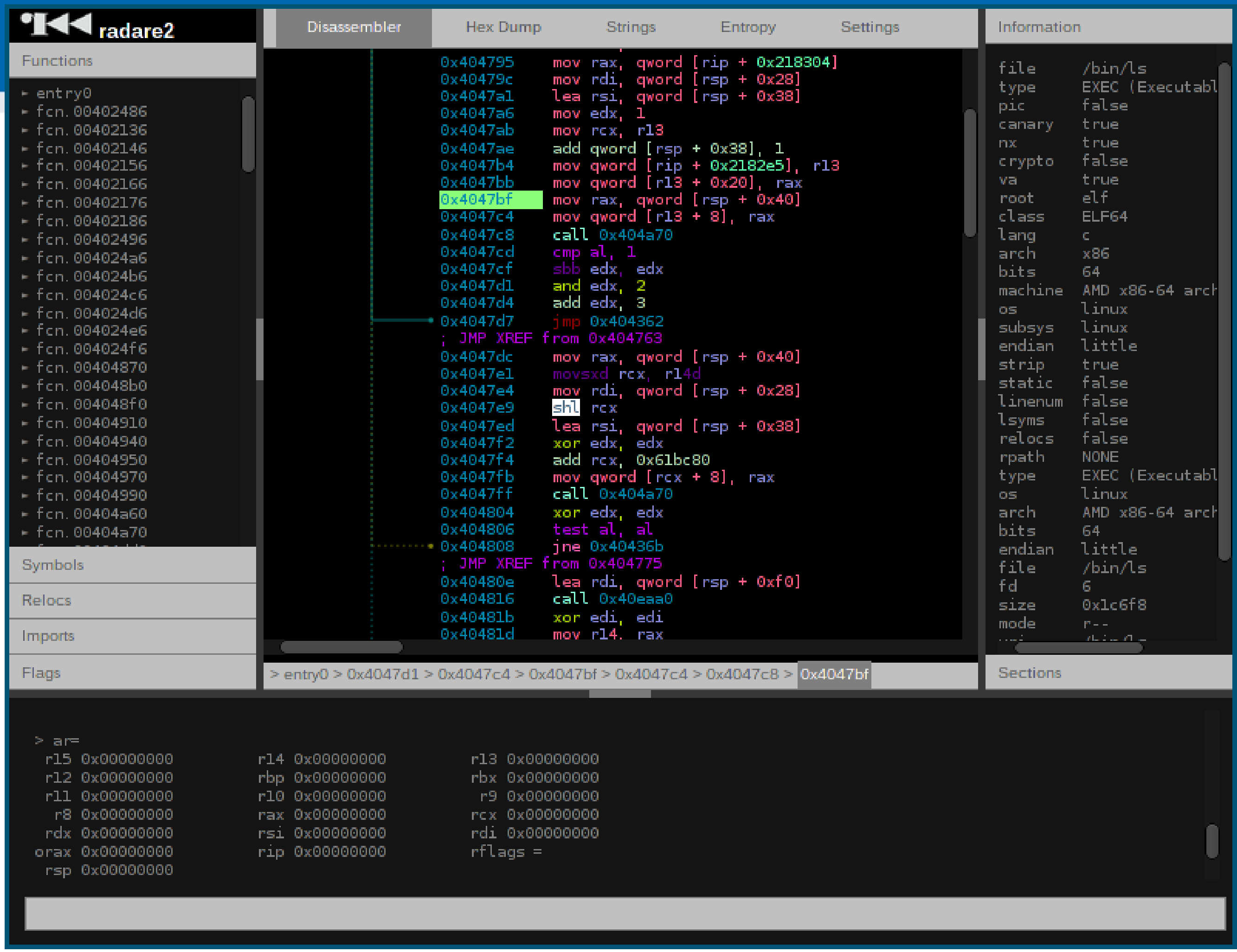
Tool: Hopper diassembler and debugger

- Linux and OS X reverse engineering tool
  - Older version supported Windows, but not anymore
- http://www.hopperapp.com
- Additional support for Objective-C



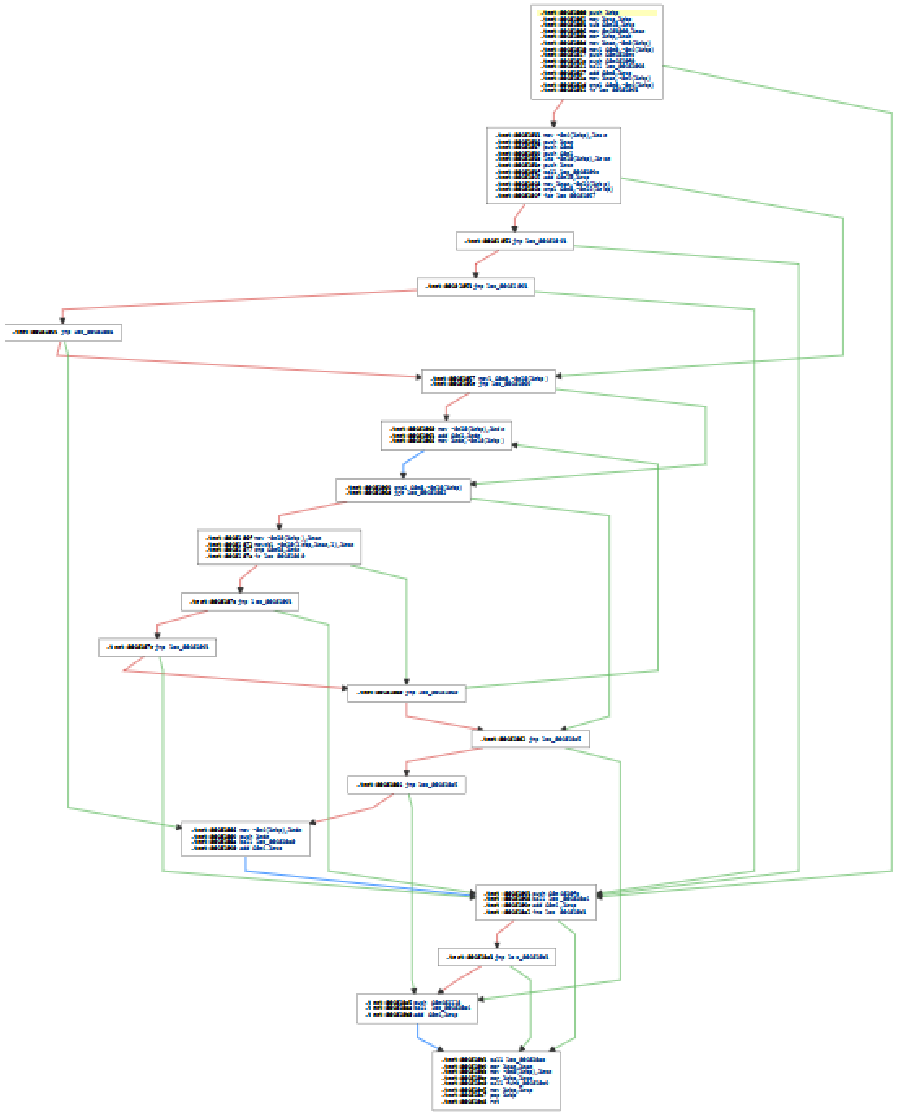
Radare

- https://www.radare.org/r/
- Multiplatform
- Very good support for multiple file formats and platforms
- (Unfair ☺) comparison with other tools
  - https://www.radare.org/r/cmp.html



Control flow graph

- Graph representation of control flow
- Separated functions/blocks
  - connection by jump instructions



Decompilation

- Native code decompilation
  - Decompiler produces source code from binary/ASM/bytecode code
  - Decompiler needs to do disassembling first and then try to create code that will in turn produce binary code you have at the beginning
  - Resulting code will NOT contain information removed during compilation (comments, function names, formatting...)
- Bytecode decompilation
  - usually much easier (more information preserved)
  - Mapping between source code and bytecode is less ambiguous
  - Compilation of decompiled bytecode produces similar bytecode

Decompiler tools

- C/C++
  - IDA
  - REC Studio 4.0, http://www.backerstreet.com/rec/rec.htm
  - Retargetable Decompiler, https://retdec.com/
  - Ghidra – diassembler by NSA https://github.com/NationalSecurityAgency/ghidra
- Java bytecode
  - DJ Java Decompiler, http://neshkov.com/dj.html
  - Java Decompiler, http://jd.benow.ca/
- .Net bytecode
  - dotPeek, https://www.jetbrains.com/decompiler/
  - ILSpy, http://ilspy.net/

Summary

- Several levels where rootkit can be placed (CPU rings)
- Rootkits cloaks itself and run malicious functionality
  - Detection on higher/same level difficult (but possible if cloaking is not perfect)
  - Try to detect on lower level (root is not "running")
  - Trusted boot (TPMs…) attempts to prevent/detect rootkit execution
- Reverse engineering of binaries
  - Compilation is lossy process (debug symbols, optimizations…)
  - Different platforms have different binaries (registry/stack-based execution, instructions, function calling conventions…)
  - Disassembling: binary -> assembler
  - Decompilation: assembler -> source code