Linux Memory Analysis Workshop – Session 1

Andrew Case

Who Am I?

- Security Analyst at Digital Forensics Solutions
  - Also perform wide ranging forensics investigations
- Volatility Developer
- Former Blackhat, SOURCE, and DFRWS speaker
- Computer Science degree from UNO
- GIAC Certified Forensics Analyst (GCFA)

Format of this Workshop

- I will be presenting the Linux kernel memory analysis capabilities of Volatility
- Along the way we will be seeing numerous examples of Linux kernel source code as well as Volatility's plugins source code
- Following along with me while I use Volatility to recover data will get you the most out of this workshop

Setting up Your Environment

Agenda for Today's Workshop

1. **Recovering Vital Runtime Information**
2. Investigating Live CDs (Memory Analysis)
3. Detecting Kernel Rootkits

Agenda for This Hour

- Memory Forensics Introduction
- Recovering Runtime Information
  - Will discuss kernel internals necessary to recover processes, memory maps, loaded modules, etc
  - Will discuss how these are useful/relevant to forensics & IR
  - We will be recovering data with Volatility as we go
- Q&A / Comments

Memory Forensics Introduction

Introduction

- Memory analysis is the process of taking a memory capture (a copy of RAM) and producing higher-level objects that are useful for an investigation
- A memory capture has the entire state of the operating system as well as running applications
  - Including all the related data structures, variables, etc

The Goal of Memory Analysis

- The higher level objects we are interested in are in-memory representations of C structures, custom data structures, and other variables used by the operating system
- With these we can recover processes listings, filesystem information, networking data, etc
- This is what we will be talking about throughout the workshop

Information Needed for Analysis

- The ability to:
  1. Locate needed data structures in memory
  2. Model those data structures offline
  3. Report their contents

Locating Data Structures

- To locate static data structures, we use the *System.map* file
  - Contains the name and address of every static data structure used in the kernel
  - Created in the kernel build process by using *nm* on the compiled *vmlinux* file

Modeling Data Structures

- The parts of the Linux kernel we care about are written in C
- All data structures boil down to C structures
- These have a very simple in-memory representation (next slide)

C Structures in Memory

- Source Code:

```
struct blah {
        int i;
        char c;
        short s;      };
struct blah *b =
malloc(…);
```

- In Memory:
  - Lets say we have an instance of ‘b’ at 0x0
  - Then:

b->i goes from 0x0 to 0x4

b->c goes from 0x4 to 0x5

b->s goes from 0x5 to 0x7

Modeling Structures

- During analysis we want to automatically model each C structure of interest
- To do this, we use Volatility's *dwarfparse.py*:
  - Builds a profile of C structures along with members, types, and byte offsets
  - Records offsets of global variables
- Example structure definition

```
'ClassObject': [ 0xa0, {      Class name and size
'obj': [0x0, ['Object']],     Member name, offset,
                              and type
```

Introducing Volatility

Volatility

- Most popular memory analysis framework
  - Written in Python
  - Open Source
  - Supports Windows {XP, Vista, 7, 2003, 2008}
  - Support Linux 2.6.9 to 2.6.3x on Intel and ARM
- Allows for analysis plugins to be easily written
- Used daily in real forensics investigations
- Will be the framework used in this workshop

Volatility Object Manager

- Once we have a model of a kernel's data structures (profiles) we can then just rely on Volatility
- Its object manager takes care of parsing the struct definitions, including types, and then providing them as requested
  - Example on next slide

Example Plugin Code

- Accessing a structure is as simple as knowing the type and offset

  intval = obj.Object(“int”, offset=intOffset, ..)

- Volatility code to access ‘descriptor’ of an ‘Object’:

  o = obj.Object("Object", offset=objectAddress, ..)

  c = obj.Object("ClassObject", offset=**o.clazz**, …)

  desc = linux_common.get_string(**c.descriptor**)

Volatility Address Spaces

- Address spaces are used to translate virtual addresses to offsets within a memory capture
  - Same process used to translate to physical addresses on a running OS
- Plugin developers simply need to pass the given address space to functions that need it
  - Manual change only required to access userland (will see an example in a bit)

Current Address Spaces

- x86 / x64
- Arm (Android)
- Firewire
- Windows Hibernation Files
- Crash Dumps
- EWF Files

Recovering Runtime Information

Runtime Information

- This rest of this session is focused on orderly recovery of data that was active at the time of the memory capture
- We will be discussing how to find key pieces of information and then use Volatility to recover them

Information to be Recovered

- Processes
- Memory Maps
- Open Files
- Network Connections
- Network Data
- Loaded Kernel Modules

Recovering Process Information

- Each process is represented by a *task_struct*
- Once a *task_struct* is located, all information about a process can be quickly retrieved
  - Possible to do it through other methods, but much more convoluted

Locating Processes – Method 1

- *init_task* is the symbol for the *task_struct* of "swapper", the PID 0 process
  - Statically initialized
- task_struct->tasks holds a linked list of all active processes
  - NOT threads! (more on this later)
  - Simply walking the list gives us a process listing

Locating Processes – Method 2

- Newer kernels have a Process ID (pid) namespace
- The hash table can be located through *init_pid_ns* and then enumerated
- These hash tables are used to populate */proc/<pid>*

Wanted Per-Process Information

- Name and Command Line Arguments
- UID/GID/PID
- Starting/Running Time
- Parent & Child Processes
- Memory Maps & Executable File
- Open Files
- Networking Information

Needed *task_struct* Members

- Name
  - char comm[TASK_COMM_LEN]; // 16
  - Command line arguments in later slides
- User ID / Group ID
  - Before 2.6.29
    - *uid* and *gid*
  - Since 2.6.29
    - struct cred *cred;
    - cred->uid and cred->gid

task_struct Members Cont.

- Parent Process
  - struct task_struct *real_parent;
- Child processes
  - struct list_head children; /* list of my children */
- Process times
  - utime, stime, start_time, real_starttm

Recovery with Volatility

- Option 1:
  - In: *volatility/plugins/linux_task_list_ps.py*
  - Walks the task_struct->*tasks* list
- Option 2:
  - In: *volatility/plugins/linux_task_list_psaux.py*
  - Reads command line invocation from userland
    - Will cover algorithm after discussing memory management structures

Process Gathering Demo/Hands On

- Will be using:
  - *linux_task_list_ps*
  - *linux_task_list_psaux*

Process Memory Maps

- Viewed on a running system within */proc/<pid>/maps*
- Lists all mappings within a process including:
  - Mapped file, if any
  - Address range
  - Permissions

Accessing the Mappings

- Each mapping is stored as a *vm_area_struct*
- Stored in two places:
  - task_struct->mm->mm_rb
    - Red black tree of mappings
  - task_struct->mm->mmap
    - List of mappings ordered by starting address

Needed Members of vm_area_struct

- unsigned long *vm_start*, *vm_end*
  - The starting and ending addresses of the mapping
- vm_area_struct *vm_next*
  - The next vma for the process (linked list from mm->mmap)
- struct file *vm_file*
  - If not NULL, points to the mapped file (shared library, open file, main executable, etc)

Recovery with Volatility

- Listing mappings implemented in *volatility/plugins/linux_proc_maps.py*
- Analyzing specific mappings implemented in *volatility/plugins/linux_dump_maps.py*
  - Can specify by PID or address

Getting the Command Line Args

- Each processes' *mm_struct* contains a number of variables that hold the address of the .text, .data, heap, stack, and command line args
- Command line args:
  - Beginning address stored in *arg_start*
  - End address stored in *arg_end*
  - Arguments are stored in a list of null terminated "strings"

Using ->mm to get **argv

```
# switch pgd (address space)
tmp_dtb = self.addr_space.vtop(task.mm.pgd)
# create new address space
proc_as =
    self.addr_space.__class__(self.addr_space.base,
    self.addr_space.get_config(), dtb = tmp_dtb)
# read in command line argument buffer
argv = proc_as.read(task.mm.arg_start,
    task.mm.arg_end - task.mm.arg_start)
```

Gathering Open Files

- Want to emulate */proc/<pid>/fd*
- task_struct->files->fdt->fd is array of *file* structures
- Each array index is the file descriptor number
- If an index is non-NULL then it holds an open file
- Use *max_fds* of the *fdt* table to determine array size

Information Per-File

- Path information stored in the *f_dentry* and *f_vfsmnt* members
  - To get full path, need to emulate *__d_path* function
- Inode information stored in *f_dentry* structure
  - Contains size, owner, MAC times, and other metadata
- Recovering file contents in-memory requires use of the *f_mapping* member
  - Come back for session 2!

Memory Maps and Open Files Demo

- Memory Maps
  - Listing process mappings
  - Acquiring the stack and heap from interesting processes
- Open Files
  - Lists open files with their file descriptor number

Networking Information

- The kernel contains a wealth of useful information related to network activity
- This info is immensely helpful in a number of forensics and incident response scenarios

Netstat Plugin

- Used to emulate the *netstat* command
- This information is found on a running machine found in these */proc/net/* files:
  - tcp/tcp6
  - udp/udp6
  - unix
- We find open sockets by enumerating open files of processes and then finding those which are socket file descriptors

Volatility's linux_netstat.py

```
openfiles = lof.linux_list_open_files.calculate(self)

# for every open file
for (task, filp, _i, _addr_space) in openfiles:

    d = filp.get_dentry() # the files dentry

    if filp.f_op  == self.smap["socket_file_ops"] or
    filp.d.d_op == self.smap["sockfs_dentry_operations"]:
            # it is a socket, can get the protocol information
            iaddr = d.d_inode
            skt = self.SOCKET_I(iaddr)
            inet_sock = obj.Object("inet_sock", offset = skt.sk, …)
```

ARP Cache

- Emulates *arp -a*
- The ARP cache stores recently discovered IP and MAC address pairs
  - It is what facilities ARP poisoning
- Recovery of this cache provides information on other machines the target machine was communicating with

Recovering the ARP Cache

- Implemented in *linux_arp.py*
- This code walks the *neigh_tables* and their respective *hash_buckets* to recover *neighbor* structures
- These contain the device name, mac address, and corresponding IP address for each entry

Routing Table

- Emulates *route -n*
- The routing table stores routing information for every known gateway device and its corresponding subnet
- The *linux_route* plugin recovers this information

Routing Cache

- Emulates *route –C*
- This cache stores recently determined source IP and gateway stores
- A great resource to determine recent network activity on a computer

Network Recovery Demo/Hands On

- Many plugins!

Dmesg

- The simplest plugin in all of Volatility
- Simply locates and prints the kernel debug buffer

Dmesg Plugin Code

```
ptr_addr = self.smap["log_buf"]

# the buffer
log_buf_addr = obj.Object("long", offset = ptr_addr, vm =
    self.addr_space)

# its length
log_buf_len = obj.Object("int", self.smap["log_buf_len"], vm =
    self.addr_space)

# read in the buffer
yield linux_common.get_string(log_buf_addr, self.addr_space,
    log_buf_len)
```

Loaded Kernel Modules

- Want to emulate the *lsmod* command
- Each module is represented by a *struct module*
- Each active module is kept in the *modules* list
- We can simply walk the list to recover all needed information

Information Per Module

- char *name*[MODULE_NAME_LEN]
  - The name of the module
- void *module_init*
  - .text + .data of init functions
- void *module_core*
  - .text + .data of core functions
- symtab/strtab
  - Symbol and string tables
- struct list_head *list*
  - Entry within the list of loaded modules

Recovery with Volatility

- In: *volatility/plugins/linux_lsmod.py*
- Volatility code:

```
mods_addr = self.smap["modules"]
modules =  obj.Object("list_head",offset=mods_addr,)
for module in
    linux_common.walk_list_head("module", "list",
    modules, …):
        yield module
```

Questions/Comments?

- Please fill out the feedback forms!
- Contact:
  - andrew@digdeeply.com
  - @attrc

Linux Memory Analysis Workshop – Session 2

Andrew Case

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Setting up Your Environment

Agenda for Today's Workshop

1. Recovering Vital Runtime Information
2. **Investigating Live CDs Through Memory Analysis**
3. Detecting Kernel Rootkits

Agenda for This Hour

- Discuss Live CDs and how they disrupt the normal forensics process
- Present research that enables traditional investigative techniques against live CDs
- We will be recovering files and data as we go along
- Q&A / Comments

Introducing Volatility

Volatility

- Most popular memory analysis framework
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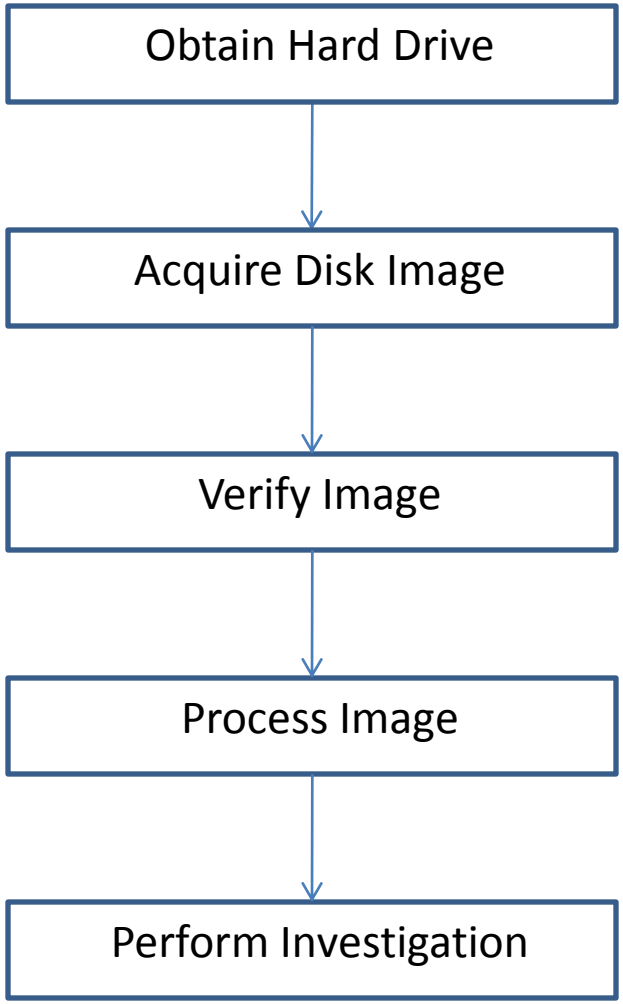
Live CD Introduction

Normal Forensics Process



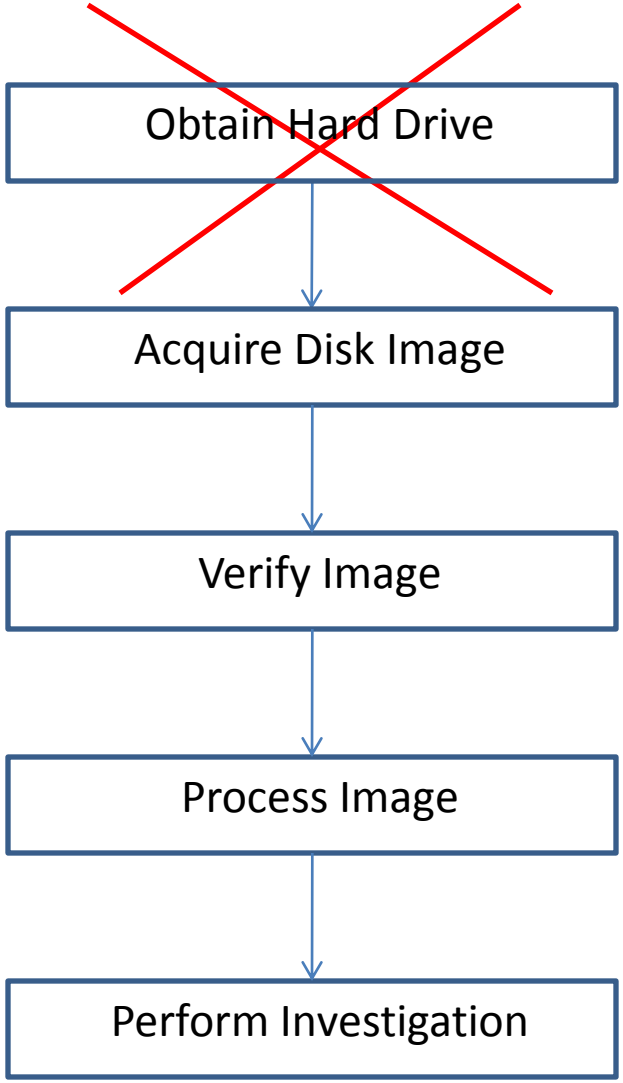
Traditional Analysis Techniques

- Timelining of activity based on MAC times
- Hashing of files
- Indexing and searching of files and unallocated space
- Recovery of deleted files
- Application specific analysis
  - Web activity from cache, history, and cookies
  - E-mail activity from local stores (PST, Mbox, …)

Problem of Live CDs

- Live CDs allow users to run an operating system and all applications entirely in RAM
- This makes traditional digital forensics (examination of disk images) impossible
- All the previously listed analysis techniques cannot be performed

The Problem Illustrated



No Disks or Files, Now What?

- All we can obtain is a memory capture
- With this, an investigator is left with very limited and crude analysis techniques
- Can still search, but can't map to files or dates
  - No context, hard to present coherently
- File carving becomes useless
  - All fragmented in memory
- Good luck in court

People Have Caught On…

- The Amnesic Incognito Live System (TAILS) [1]
  - "No trace is left on local storage devices unless explicitly asked."
  - "All outgoing connections to the Internet are forced to go through the Tor network"
- Backtrack [2]
  - "ability to perform assessments in a purely native environment dedicated to hacking."

What It Really Means…

- Investigators without deep kernel internals knowledge and programming skill are basically hopeless
- It is well known that the use of live CDs is going to defeat most investigations
  - Main motivation for this work
  - Plenty anecdotal evidence of this can be found through Google searches

What is the Solution?

- Memory Analysis!
  - It is the only method we have available…
- This Analysis gives us:
  - The complete file system structure including file contents and metadata
  - Deleted Files (Maybe)
  - Userland process memory and file system information

Recovering the Filesystem

Goal 1: Recovering the File System

- Steps needed to achieve this goal:
  1. Understand the in-memory filesystem
  2. Develop an algorithm that can enumerate directory and files
  3. Recover metadata to enable timelining and other investigative techniques

The In-Memory Filesystem

- AUFS (AnotherUnionFS)
  - http://aufs.sourceforge.net/
  - Used by TAILS, Backtrack, Ubuntu 10.04 installer, and a number of other Live CDs
  - Not included in the vanilla kernel, loaded as an external module

AUFS Internals

- Stackable filesystem
  - Presents a multilayer filesystem as a single one to users
  - This allows for files created after system boot to be transparently merged on top of read only CD
- Each layer is termed a branch
  - In the live CD case, one branch for the CD, and one for all other files made or changed since boot

Walkthrough

- Explore AUFS on a running system

AUFS Userland View of TAILS

```
# cat /proc/mounts
    aufs / aufs rw,relatime,si=4ef94245,noxino
    /dev/loop0 /filesystem.squashfs squashfs
    tmpfs /live/cow tmpfs
    tmpfs /live tmpfs rw,relatime
# cat /sys/fs/aufs/si_4ef94245/br0
   /live/cow=rw
# cat /sys/fs/aufs/si_4ef94245/br1
   /filesystem.squashfs=rr
```

Mount points relevant to AUFS

The mount point of each AUFS branch

Forensics Approach

- No real need to copy files from the read-only branch
  - Just image the CD
- On the other hand, the writable branch contains every file that was created or modified since boot
  - Including metadata
  - No deleted ones though, more on that later

Linux Internals

Struct Dentry

- Represents a directory entry (directory, file, …)
- Contains the name of the directory entry and a pointer to its inode structure
- Members used:
  - *d_inode* – pointer to inode structure
  - *d_name* – name of file

Struct Inode

- FS generic, in-memory representation of a disk inode
- Contains address_space structure that links an inode to its file's pages
- Also provides metadata:
  - MAC Times
  - Size
  - Owner
  - more…

Struct Address_Space

- Links physical pages together into something useful
- Holds the search tree of the struct *page*s for a file
  - This pages then lead to physical pages

Linux Internals Overview II

- Page Cache
  - Used to store *struct page* structures that correspond to physical pages
  - address_space structures contain linkage into the page cache that allows for ordered enumeration of all physical pages pertaining to an inode
- Tmpfs
  - In-memory filesystem
  - Used by TAILS to hold the writable branch

Enumerating Directories

- Once we can enumerate directories, we can recover the whole filesystem
- Not as simple as recursively walking the children of the file system's root directory
- AUFS creates hidden dentrys and inodes in order to mask branches of the stacked filesystem
- Need to carefully interact between AUFS and tmpfs structures

Directory Enumeration Algorithm

1) Walk the super blocks list until the “aufs” filesystem is found
   - This contains a pointer to the root dentry
2) For each child dentry, test if it represents a directory

   If the child is a directory:
   - Obtain the hidden directory entry (next slide)
   - Record metadata and recurse into directory

   If the child is a regular file:
   - Obtain the hidden inode and record metadata

Getting the Superblock

```
# get a reference the list of super blocks
sbptr = obj.Object("Pointer", offset =
        self.smap["super_blocks"], …)
# the list
sb_list = obj.Object("list_head", offset = sbptr.v(),…)
# walk the list and find “aufs”
for sb in walk_list_head("super_block","s_list", sb_list,
    if sb.s_id.startswith("aufs"):
        return sb.s_root
```

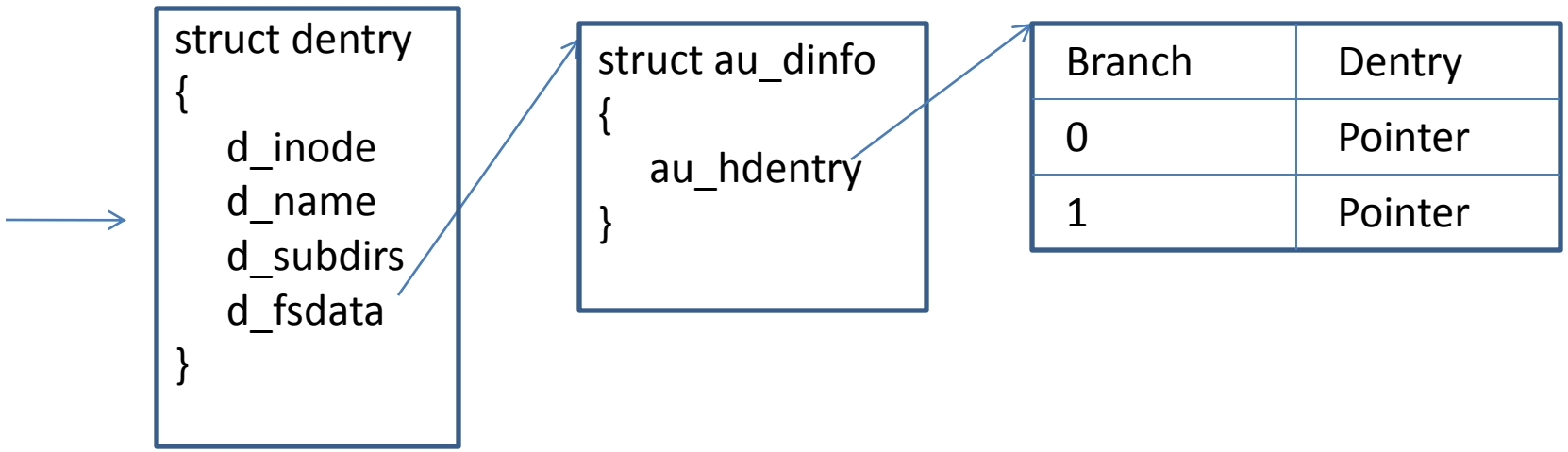
The Initial Code

```
# walk the directory and get the hidden dentry
def calculate(self):
    # get the superblock
    root_dentry = self.get_aufs_sb()
    # walk every dentry
    for dentry in walk_list_head("dentry", "d_u",
            root_dentry.d_subdirs, ...):
            h_dentry = self.get_h_dentry(dentry, 0)
```

Obtaining a Hidden Directory

- Each kernel dentry stores a pointer to an *au_dinfo* structure inside its *d_fsdata* member

- The *di_hdentry* member of *au_dinfo* is an array of *au_hdentry* structures that embed regular kernel dentrys



get_h_dentry(dentry)

```
# the hidden “fsdata” pointer
dinfo = obj.Object("au_dinfo",
offset=dentry.d_fsdata,

# get the array of hidden dentrys
dentry_array = obj.Object("Array",
offset=dinfo.di_hdentry,  "au_hdentry", count=2)

# grab the hidden dentry at branch ‘index’
h_dentry = dentry_array[index].hd_dentry
```

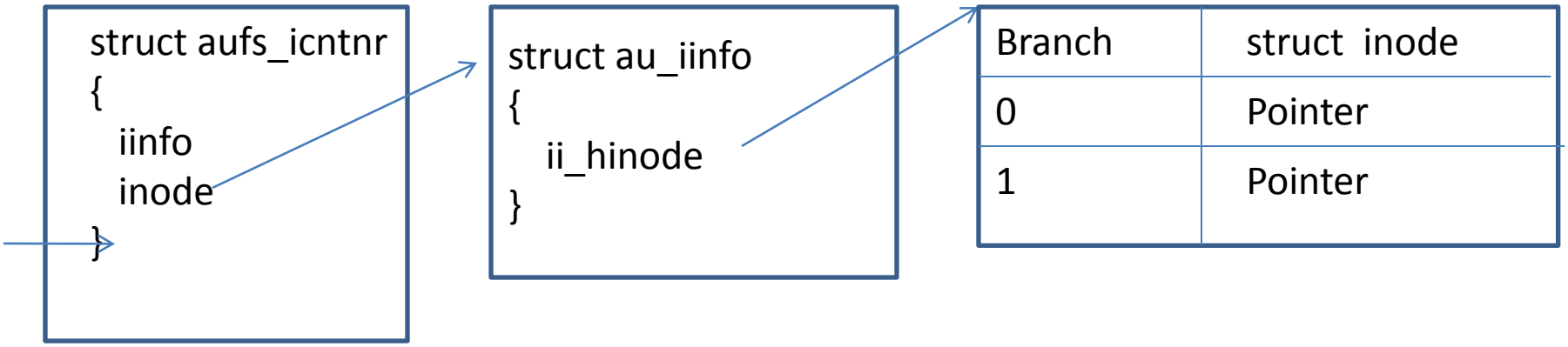
Obtaining Metadata

- All useful metadata such as MAC times, file size, file owner, etc is contained in the hidden inode
- This information is used to fill the *stat* command and *istat* functionality of the Sleuthkit
- Timelining becomes possible again

Obtaining a Hidden Inode

- Each aufs controlled inode gets embedded in an *aufs_icntnr*

- This structure also embeds an array of *au_hinode* structures which can be indexed by branch number to find the hidden inode of an exposed inode



Demo/Hands-On

- Will recover the filesystem structure and metadata
- Will examine with a few FS analysis tools
- Will discuss how to keep forensically sound and discuss limitations

Goal 2: Recovering File Contents

- The size of a file is kept in its inode's *i_size* member
- An inode's *page_tree* member is the root of the radix tree of its physical pages
- In order to recover file contents this tree needs to be searched for each page of a file
- The lookup function returns a *struct page* which leads to the backing physical page

Recovering File Contents Cont.

- Indexing the tree in order and gathering of each page will lead to accurate recovery of a whole file
- This algorithm assumes that swap isn't being used
  - Using swap would defeat much of the purpose of anonymous live CDs
- Tmpfs analysis is useful for every distribution
  - Many distros mount /tmp using tmpfs, shmem, etc

Goal 3: Recovering Deleted Info

- Discussion:
  1. Formulate Approach
  2. Discuss the *kmem_cache* and how it relates to recovery
  3. Attempt to recover previously deleted file and directory names, metadata, and file contents

Approach

- We want orderly recovery
- To accomplish this, information about deleted files and directories needs to be found in a non-standard way
  - All regular lists, hash tables, and so on lose track of structures as they are deleted
- Need a way to gather these structures in an orderly manner
  - *kmem_cache* analysis to the rescue!

Recovery though *kmem_cache* analysis

- A *kmem_cache* holds all structures of the same type in an organized manner
  - Allows for instant allocations & deallocations
  - Used for handling of process, memory mappings, open files, and many other structures
- Implementation controlled by allocator in use
  - SLAB and SLUB are the two main ones

kmem_cache Internals

- Both allocators keep track of allocated and previously de-allocated objects on three lists:
  - *full*, in which all objects are allocated
  - *partial,* a mix of allocated and de-allocated objects
  - *free,* previously freed objects*
- The free lists are cleared in an allocator dependent manner
  - SLAB leaves free lists in-tact for long periods of time
  - SLUB is more aggressive

kmem_cache Illustrated

- */proc/slabinfo* contains information about each current kmem_cache
- Example output:

# name	*<active_objs>*	*<num_objs>*
task_struct	*101*	*154*
mm_struct	*76*	*99*
filp	*901*	*1420*

The difference between *num_objs* and *active_objs* is how many free objects are being tracked by the kernel

Recovery Using *kmem_cache* Analysis

- Enumeration of the lists with free entries reveals previous objects still being tracked by the kernel
  - The kernel does not clear the memory of these objects
- Our previous work has demonstrated that much previously de-allocated, forensically interesting information can be leveraged from these caches [4]

Recovering Deleted Filesystem Structure

- Both Linux kernel and aufs directory entries are backed by the *kmem_cache*
- Recovery of these structures reveals names of previous files and directories
  - If *d_parent* member is still in-tact, can place entries within file system

Recovering Previous Metadata

- Inodes are also backed by the *kmem_cache*
- Recovery means we can timeline again
- Also, the dentry list of the AUFS inodes still have entries (strange)
  - This allows us to link inodes and dentrys together
  - Now we can reconstruct previously deleted file information with not only file names & paths, but also MAC times, sizes, inode numbers, and more

Recovering File Contents – Bad News

- Again, inodes are kept in the *kmem_cache*
- Unfortunately, page cache entries are removed upon deallocation, making lookup impossible
  - A large number of pointers would need to stay in-tact for this to work
- This removes the ability to recover file contents in an orderly manner
- Other ways may be possible, but will require more research

Summary of File System Analysis

- Can completely recover the in-memory filesystem, its associated metadata, and all file contents
- Ordered, partial recovery of deleted file names and their metadata is also possible
- Traditional forensics techniques can be made possible against live CDs
  - Making such analysis accessible to all investigators

Questions/Comments?

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Linux Memory Analysis Workshop – Session 3

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Who Am I?

- Security Analyst at Digital Forensics Solutions
  - Also perform wide ranging forensics investigations
- Volatility Developer
- Former Blackhat, SOURCE, and DFRWS speaker
- Computer Science degree from UNO
- GIAC Certified Forensics Analyst (GCFA)

Format of this Workshop

- I will be presenting the Linux kernel memory analysis capabilities of Volatility
- Along the way we will be seeing numerous examples of Linux kernel source code as well as Volatility's plugins source code
- Following along with me while I use Volatility to recover data will get you the most out of this workshop

Agenda for Today's Workshop

1. Recovering Vital Runtime Information
2. Investigating Live CDs Through Memory Analysis
3. **Detecting Kernel Rootkits**

Agenda for This Hour

- This session will be a walkthrough of kernel-mode rootkits under Linux
- We will discussing the techniques used by rootkits to stay hidden and how the Volatility modules uncover them
- I will also be presenting previously never disclosed rootkit techniques developed for this workshop
- Q&A / Comments

Introducing Volatility

Volatility

- Most popular memory analysis framework
  - Written in Python
  - Open Source
  - Supports Windows {XP, Vista, 7, 2003, 2008}
  - Support Linux 2.6.9 to 2.6.3x on Intel and ARM
- Allows for analysis plugins to be easily written
- Used daily in real forensics investigations
- Will be the framework used in this workshop

Volatility Object Manager

- Once we have a model of a kernel's data structures (profiles) we can then just rely on Volatility
- Its object manager takes care of parsing the struct definitions, including types, and then providing them as requested
  - Example on next slide

Example Plugin Code

- Accessing a structure is as simple as knowing the type and offset

  intval = obj.Object(“int”, offset=intOffset, ..)

- Volatility code to access ‘descriptor’ of an ‘Object’:

  o = obj.Object("Object", offset=objectAddress, ..)

  c = obj.Object("ClassObject", offset=**o.clazz**, …)

  desc = linux_common.get_string(**c.descriptor**)

Volatility Address Spaces

- Address spaces are used to translate virtual addresses to offsets within a memory capture
  - Same process used to translate to physical addresses on a running OS
- Plugin developers simply need to pass the given address space to functions that need it
  - Manual change only required to access userland (will see an example in a bit)

Current Address Spaces

- x86 / x64
- Arm (Android)
- Firewire
- Windows Hibernation Files
- Crash Dumps
- EWF Files

Linux Kernel-Mode Rootkits

Introduction

- I promise not to bore you with information from ~2002 Phrack articles…
- Rootkits target two types of data:
  1. Static
     - Easy to implement and easy to detect
  2. Dynamic
     - Harder to implement and harder to detect

Static-Data Altering Rootkits

- These rootkits target data structures that are easy to modify, but are also effective at hiding activity
- Common technique types include:
  - Directly overwriting instructions in memory (.text)
  - Overwriting the system call & interrupt descriptor tables
  - Overwriting members of global data structures

Type 1: Overwriting .text

- Very popular as its easy to implement and makes hiding data easy
- Rootkits alter running instructions for a few reasons:
  - To gain control flow
  - To filter data (add, modify, delete) to stay hidden
  - To implement “triggers” so that userland code can make requests

Detecting Code Overwrites

- The compiled code of the kernel is static
  - One exception is covered next
- The compiled kernel (*vmlinux*) is an ELF file
  - All functions, including their name, instructions, and size can be gathered from debug information
- This information can then be compared to what is in memory
- Any alteration points to malicious (or broken) software

SMP Alternatives

- There is one circumstance when runtime modifications happen in the Linux kernel
- When the computer first boots and only one processor is active, all multi-core synchronization primitives are NOP'ed out
- When more than one CPU comes online, the kernel then has to rewrite these instructions with their SMP-safe counterparts to maintain concurrency

SMP Alts. Cont.

- These alternative instructions are kept for performance reasons
  - No reason to get, set, and check SMP locks if only one CPU is active
- The alternative instructions and their target location are stored within the vmlinux file
- We can gather this information and use it for accurate .text modification checking

Type 2: System Call & IDT Overwriting

- To avoid being detected when overwriting .text, rootkits started modifying the tables used to service system calls and interrupts
- This allows for a rootkit's code to easily filter the data received and returned by native kernel functions

Attack Examples

- Overwrite the *read* system call and filter out the rootkit's logging data unless a specific register contains a magic value
- Overwrite the *stat* system call to hide files from userland anti-rootkit applications
- Many more possibilities…

Detecting These Attacks

- The IDT and the system call table are simply C arrays
- They can be copied from the clean *vmlinux* file and then compared to the values in memory
- Will easily detect that the table has been altered and which entries were modified

Type 3: Overwriting Data Structures

- Popularized by the *adore*[1] rootkit, this attack overwrites function pointers of global data structures to filter information
- Adore overwrites the *readdir* member of the *file_operations* structure for the *proc* and root filesystems
  - The replacement function filters out files on a pattern used by the rootkit, effectively hiding them from userland

Other Common Attacks

- Overwriting structure members used to display information through */proc*
  - Info files in */proc* use the *seq_operations* interface
  - Hijacking the *show* member of this structure allows for trivial filtering of information
- Possible targets
  - Loaded modules list
  - Networking connections (netstat)
  - Open files (lsof)

Detecting these Attacks

- We take a generic approach
- During the profile creation stage, we filter for a number of commonly targeted structure types
  - For variables found, we then copy the statically set values of each member that may be hijacked
- This ensures that all instances of those structures are checked for malicious tampering

Targeted Structure Types

- *file_operations*
- *inode_operations*
- *vm_operations_struct*
- *address_space_operations*
- Operation structures used by */proc*

Hands On

- We will look at a memory image infected with a rootkit that uses a number of static-data altering techniques
- Volatility will show us the data structures infected

Dynamic-Data Modification Rootkits

- Rootkits that modify dynamic data are much more interesting than those that alter static data
  - Require more skill on part of the rootkit developer
  - Require more complicated analysis and detection capabilities on the detector
- Cannot be detected by using System.map or vmlinux
  - Need deep parsing of in-kernel data structures

Attacks & Defenses

- The rest of this session will cover attacks and defense related to dynamic data altering
  - Most of these attacks are new (developed for this workshop) to highlight the stealth ability of these types of attacks
- But first, we need to learn about the *kmem_cache*
  - Will be used extensively by our detection mechanisms

The *kmem_cache*

- The *kmem_cache* is a facility that provides a consistent and fast interface to allocate/de-allocate objects (C structures) of the same size
- The implementation of each cache is provided by the system allocator
  - SLAB and SLUB are the two main ones

kmem_cache Internals

- Both allocators keep track of allocated and previously de-allocated objects on three lists:
  - *full*, in which all objects are allocated
  - *partial,* a mix of allocated and de-allocated objects
  - *free,* previously freed objects*
- The free lists are cleared in an allocator dependent manner
  - SLAB leaves free lists in-tact for long periods of time
  - SLUB is more aggressive

kmem_cache Illustrated

- */proc/slabinfo* contains information about each current kmem_cache
- Example output:

# name	*<active_objs>*	*<num_objs>*
task_struct	*101*	*154*
mm_struct	*76*	*99*
filp	*901*	*1420*

The difference between *num_objs* and *active_objs* is how many free objects are being tracked by the kernel

Utilizing the *kmem_cache*

- All of the allocated objects backed by a particular cache can be found on the *full* and *partial* lists
  - The one caveat is SLUB without debugging on
  - Every distro checked enables SLUB debugging
  - Might be possible to find all references even with debugging off

The Idea Behind the Detection

- Dynamic-data rootkit methods work by removing structures from lists, hash tables, and other data structures
- To detect this tampering, we can take a particular cache instance and use this as a cross-reference to other stores
- Any structure in the *kmem_cache* list, but not in another, is hidden
  - Inverse holds as well

Why the Detection Works

- *All* instances of a structure must be backed by the caches
- These caches work similar to an immutable store:
  - Structures of the specific type cannot be hidden from it
- A few possible attack scenarios exist, but will not work undetected

Detection Subversion Scenarios

1. Allocating outside the cache
   - Will be detected by the inverse comparisons
2. Allocating in the cache and then removing from it
   - Very difficult to do and will result in detection as with scenario #1
3. Allocating in the cache and then setting the entry as free
   - The structure will be overwritten on next allocation

Our First New Attack

- The first developed attack was hiding processes from */proc*
- A number of rootkit detection systems work by trying to enumerate */proc/[1-65535]* and then compare the output to *ps*
- The numbered proc directories are backed by their respective PID namespace and number

Process Background

- All tasks are allocated from the *task_struct_cachep*
- Tasks are represented by a *task_struct*
- It is possible to remove a *task_struct* from the structures */proc* uses to fill */proc/<fd>/* while still allowing it to run

The Attack

- As simple as removing from the namespace
- Code, where *p* is the *task_struct* we want to hide:

```
pid = p->pids[PIDTYPE_PID].pid; // get the pid ref
detach_pid(p, PIDTYPE_PID);      // take out of PID
                                 //  group
```

- The process will no longer show up in */proc/<pid>* lookups

Detection

- We gather processes from a number of places before comparing to those in the cache
  - Implemented in *linux_check_processes.py*

1) Each *task_struct* holds a pointer into the *tasks* list
2) The run queue, where scheduled processes wait to execute
3) The PID cache, where we just removed our process from

Hands-on/Demo

- We will now investigate hidden processes and look at the corresponding Volatility detection code

Next Attack: Memory Maps

- The next attack hides memory maps from */proc/<pid>/maps*
  - This file is used to list every mapped address range in a process
- Each mapping is represented by a *vm_area_struct* and they are kept in two places:
  - The *mmap* list of the processes' *mm_struct*
  - The *mm_rb* tree of the *mm_struct*

mm_struct and *vm_area_struct*

- mm_struct
  - Used to represent the memory management structures of a process
- vm_area_struct
  - Represents a single memory mapping within a process

The Attack

- Inspection of a *maps* file makes attacks such as shared library injection very noticeable
  - The full path of the mapped binary plus its data and code sections will be visible
- To hide maps, we need to:
  - Remove the *vma* from the *mmap* lists
  - Fixup the structures that account for paging
- This will hide the map and allow for the targeted process to exit cleanly

Detection

- Implemented in: linux_check_mappings.py
- The first step is to gather all active VMAs for a process so they can be compared against those in the cache
- The problem is that the VMAs are anonymous
  - No immediate linkage to a specific process

Detection Cont.

- To work around this, we rely on the fact that *vma*s keep a back pointer to their owning *mm_struct* in the *vm_mm* member
- Using this, we can gather all the *vma*s for a specific process and then compare against the cache
- Can you think of a bypass in this detection?

Preventing Malware Tampering

- Since we rely on *vm_mm,* malware could try to avoid this detection by changing *vm_mm*
- Possible attempts:
  1. Set *vm_mm* to some invalid value (NULL, etc)
  2. Set *vm_mm* to another processes's *mm_struct*
- Will still be detected:
  - All *mm_struct*s are also in a *kmem_cache*
  - Comparing the list of *vm_mm* values to this cache will reveal avoidance attempts

Next Attack: Open files

- The */proc/<pid>/fd* directory contains a symlink per open file
  - The symlink name is the file descriptor number
- Used by a number of utilities (lsof) and anti-rootkit applications to detect files being accessed
- To remain stealthy, this directory listing needs to be filtered

The Attack

- A processes' file descriptors are stored in an array of *file* structures indexed by file descriptor number
- All non-null indexes are treated as open files
  - NULL entries are skipped

The Hiding Code

```
idx = loop_counter; // the file desc to test
file = p->files->fdt->fd[idx]; // the file struct
if (file)
{
   fn = d_path(…); // get the full path of file
   if(!IS_ERR(fn) &&
   strcmp(fn,"/tmp/hidefile.txt"))
         fdt->fd[i] = NULL;
}
```

Detection

- As with the process detection algo, finding all open files requires gathering from a number of sources:
  - The (non-hidden) open files per-process
  - The *vm_file* structures used to memory map files
  - All swap files
- We then compare these against the *filp_cachep kmem_cache*

Demo

- Will demo showing detection of dynamic modification of:
  - Mappings
  - Open Files

Questions/Comments?

- Please fill out the feedback forms!
- Contact:
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References

[1] http://lwn.net/Articles/75991/