Anatomy of a Remote Kernel Exploit

(Dartmouth Edition)

Dan Rosenberg

Who am I?

- Security consultant and vulnerability researcher at Virtual Security Research in Boston
  - App/net pentesting, code review, etc.
  - Published some bugs
  - Rooted a few Android phones
  - Focus on Linux kernel
  - Research on kernel exploitation and mitigation

Agenda

- Motivation
- Challenges of remote exploitation
- Prior work
- Case study: ROSE remote stack overflow
  - Exploitation
  - Backdoor
- Future work

Motivation

Why am I giving this talk?

Why Remote Kernel Exploits?

- Instant root
  - No need to escalate privileges
- Remote userland exploitation is hard!
  - Full ASLR + NX/DEP
  - Sandboxing
  - Reduced privileges

Goals of This Talk

- Explore operating system internals from perspective of an attacker
- Discuss kernel data structures and subsystems
- Exploit development methodology
- Individual bugs vs. exploit techniques
- Discuss next steps for kernel hardening

Challenges of Remote Kernel Exploitation

Wait, so you mean this is kind of hard?

Warning: Fragile

- Consequence of failed remote userland exploit:
  - Crash application/service, wait until restarted
  - Crash child process, try again immediately
- Consequence of failed remote kernel exploit:
  - Kernel panic, game over

Lack of Environment Control

- Typical local kernel exploit:
  - Can trigger allocation of heap structures
  - Can trigger calling of function pointers
  - High amount of information leakage available to local users

- Remote kernel exploit:
  - ?

Primer: Process vs. Interrupt Context

- Systems calls occur in “process context”:
  - Kernel is executing code, but is associated with userland process
  - Has credentials, network/filesystem namespace, etc.

- On Linux, asynchronous events (e.g. network data) occur in “interrupt context”:
  - Network driver generates hardware interrupt
  - Kernel dispatches data to appropriate softirq handler
  - No userland process associated with execution
  - On Linux, associated with softirqd kernel thread

Escape From Interrupt Context

- End goal: userland code execution (remote shell)
  - How do we get there?
  - No process backing execution

- Need to transition
  - Interrupt context to process context to userland

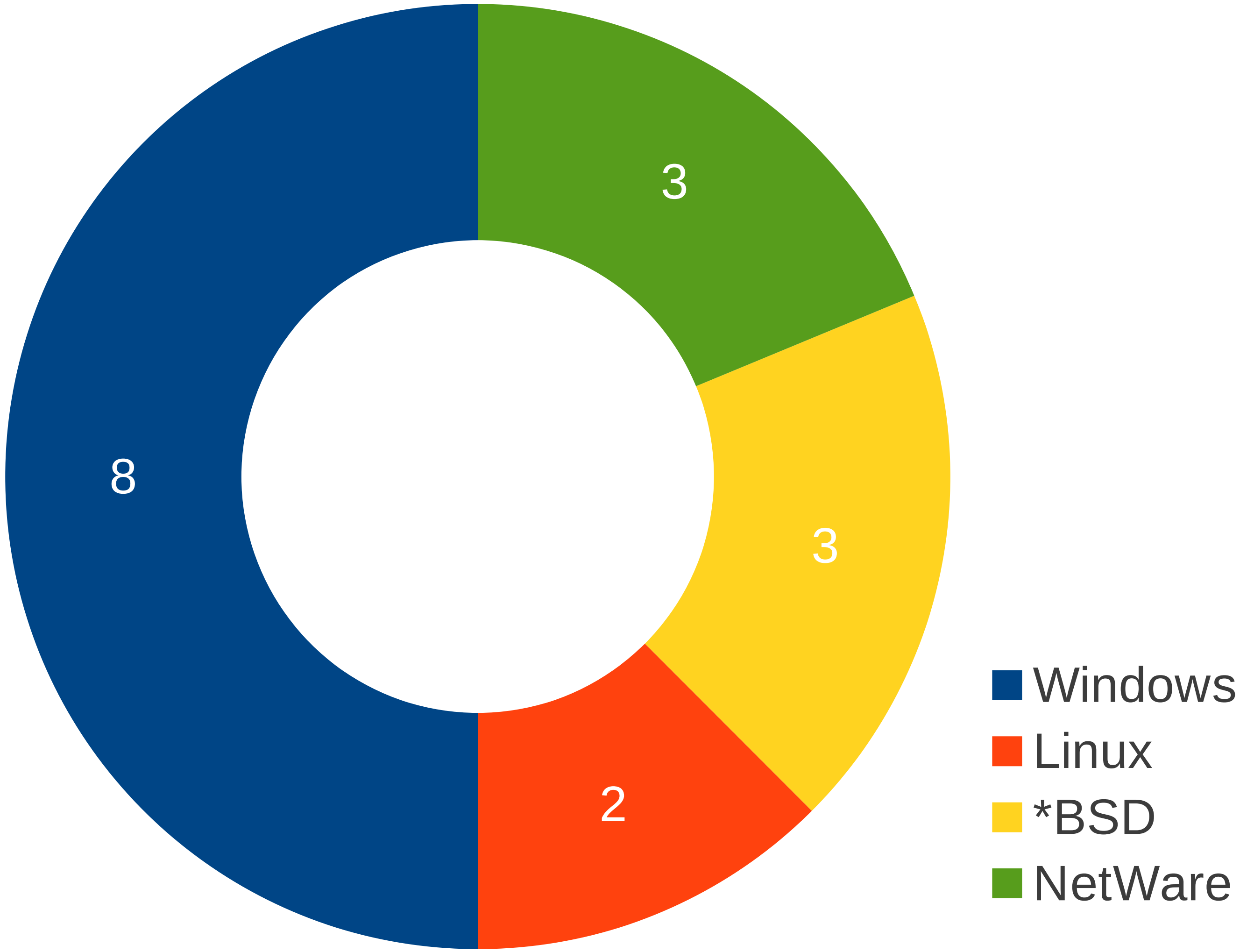
Prior Work

What's been done before?

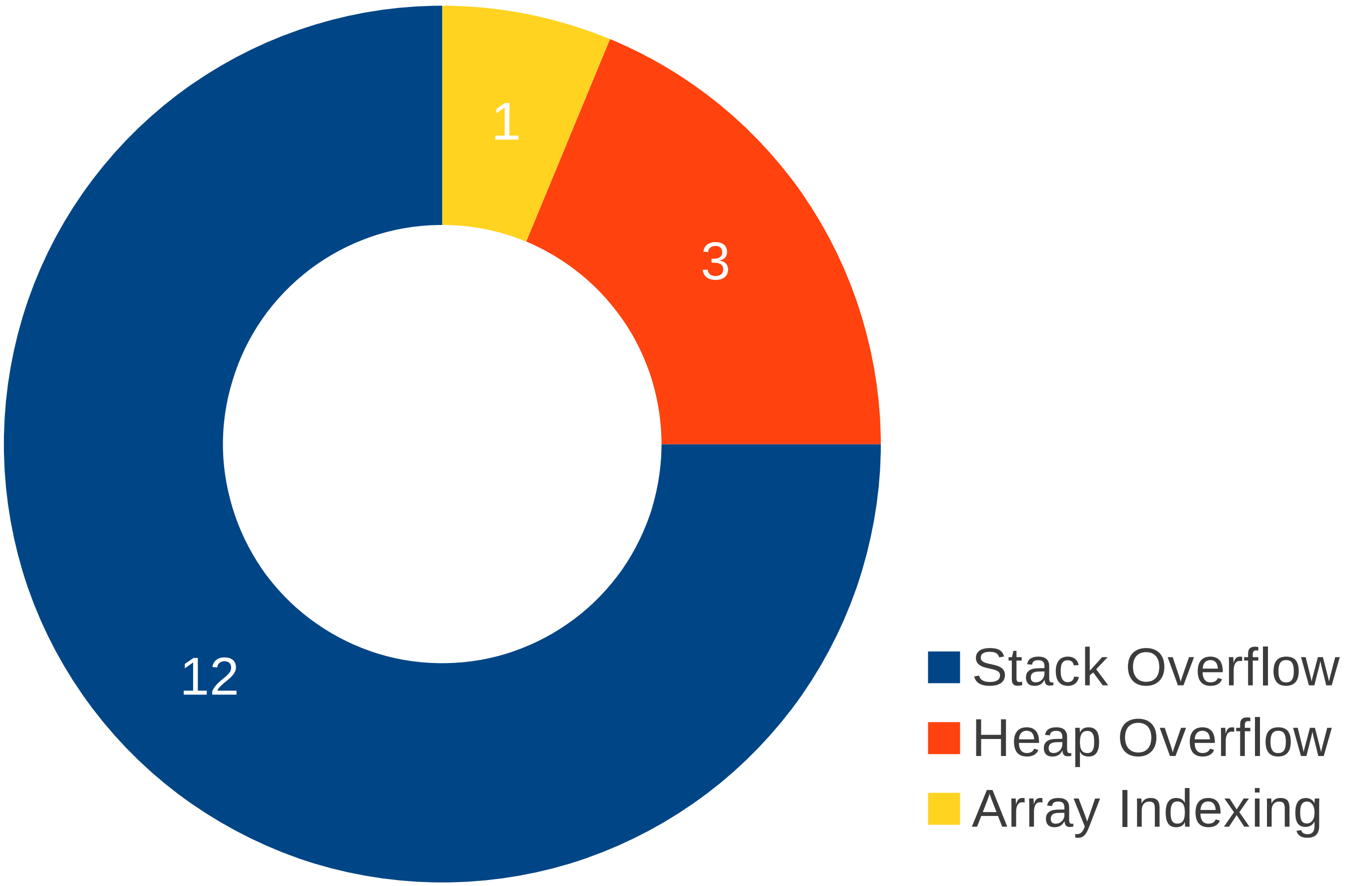
A Few Statistics

- 18 known exploits for 16 vulnerabilities
  - 19 authors
  - 9 with full public source code
  - 3 with partial or PoC source
- Wide range of platforms
  - Solaris and OS X still need some remote love

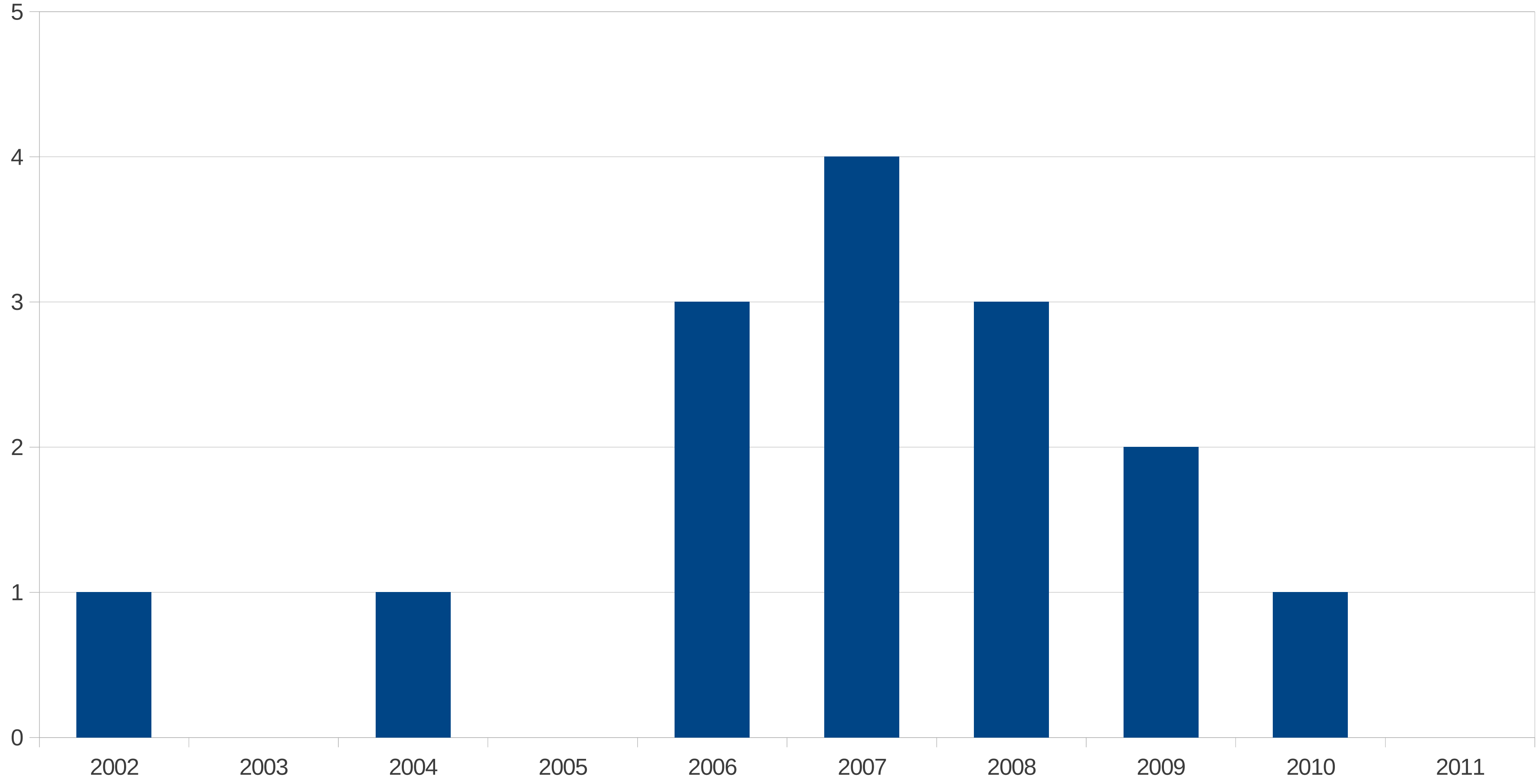
By Operating System



By Vulnerability Class



By Year



Highlights

- Barnaby Jack: Step into the Ring 0 (August 2005)
  - First publication on remote kernel exploitation
  - Transition to userland and kernel backdoor
- Sinan Eren: GREENAPPLE (May 2006)
  - First remote kernel exploit in Immunity CANVAS

Highlights (cont.)

- hdm, skape, Johnny Cache (November 2006)
  - Broadcom, Dlink, and Netgear wifi drivers
  - First remote kernel exploits in Metasploit
- Alfredo Ortega, Gerardo Richarte: OpenBSD IPv6 mbuf overflow (April 2007)
  - First public remote kernel heap overflow
  - Bypasses userland NX

Primer: NX (Non-Executable Pages)

- Pages have permissions: read, write, execute
  - Initially, on Intel chips, page table entries only supported read and write flags
  - Read implied executable

- Before long, realized this was a bad idea
  - Malicious data can be executed as code!

- NX is implemented using 63^{rd} bit of page table entry:
  - Natively supported on 64-bit platforms
  - Supported on PAE CPUs (need hardware + software)
  - Emulated in userland by kernel

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Highlights (cont.)

- Kostya Kortchinsky: MS08-001 (January 2008)
  - Immunity CANVAS
  - First publicized remote Windows kernel pool overflow

- sgrakkyu: sctp-houdini (April 2009)
  - First remote Linux sl*b overflow
  - Introduced vsyscall trick to transition from interrupt context to userland

Primer: Linux Virtual Syscalls

- On x86-64 machines, Linux supports "virtual syscalls"
  - Three system calls that can be implemented entirely in userland: gettimeofday, getcpu, time
- Trapping to kernel mode is relatively expensive
  - Check CPL, switch stack, store trap frame, reload %cs and %ss
- Faster to just stay in userland
- "vsyscall" page accomplishes this by mapping a page exported by the kernel into every userland process

So What Was That Trick?

- Sgrakkyu realized this is a good attack vector
- vsyscall page is a shadowed mapping: read-write version in kernel memory, read-execute in user memory
- In interrupt context, we can write into the kernel mapping of this page, overwriting a virtual syscall
- Now every userland process will execute our userland shellcode whenever they call a virtual syscall!

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Observations

- Majority stack overflows, but none dealt with NX kernel stack
  - Let's fix that
- No Linux interrupt context stack overflows
  - sgrakkyu and twiz showed us how in Phrack 64, let's do it in real life
- Wireless drivers suck
  - Six 802.11 remote kernel exploits

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Building the Exploit

Or: How I Learned to Stop Worrying and Love the Ham

Target: 32-bit x86 PAE Kernel

- Kernel has NX support (CONFIG_DEBUG_RODATA)
  - Only enforced on PAE (32-bit) or 64-bit kernels
- Can't execute first-stage shellcode on kernel stack
- Can't introduce code into userspace without proper page permissions
- No vsyscall trick for easy transitions

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Test Setup

- Attacker and victim VMs (Ubuntu 10.04)
- Debugging using KGDB over virtual serial port (host pipe)
- BPQ (AX.25 over Ethernet)
- Except for glue code, exploit written entirely in x86 assembly

Famous Last Words

Debian Security Advisory DSA-2240-1:

Dan ~~Rosenburg~~ reported two issues in the Linux implementation of the Amateur Radio X.25 PLP (Rose) protocol. A remote user can cause a **denial of service** by providing specially crafted facilities fields.

Intro to ROSE

- Rarely used amateur radio protocol
- Provides network layer on top of AX.25's link layer
- Uses 10-digit addresses and AX.25 callsigns
- Static routing only

CVE-2011-1493

- On initiating a ROSE connection, parties exchange facilities (supported features)
- FAC_NATIONAL_DIGIS allows host to provide list of digipeaters
- Parsing for this field reads length value from frame and copies digipeater addresses without bounds checking, causing a stack overflow

Sad Code :-(

```
...
l = p[1];
...
else if (*p == FAC_NATIONAL_DIGIS) {
  fac_national_digis_received = 1;
  facilities->source_ndigis = 0;
  facilities->dest_ndigis   = 0;
  for (pt = p + 2, lg = 0 ; lg < l ; pt += AX25_ADDR_LEN, lg += AX25_ADDR_LEN) {
    if (pt[6] & AX25_HBIT)
      memcpy(&facilities->dest_digis[facilities->dest_ndigis++], pt, AX25_ADDR_LEN);
    else
      memcpy(&facilities->source_digis[facilities->source_ndigis++], pt, AX25_ADDR_LEN);
  }
}
...
```

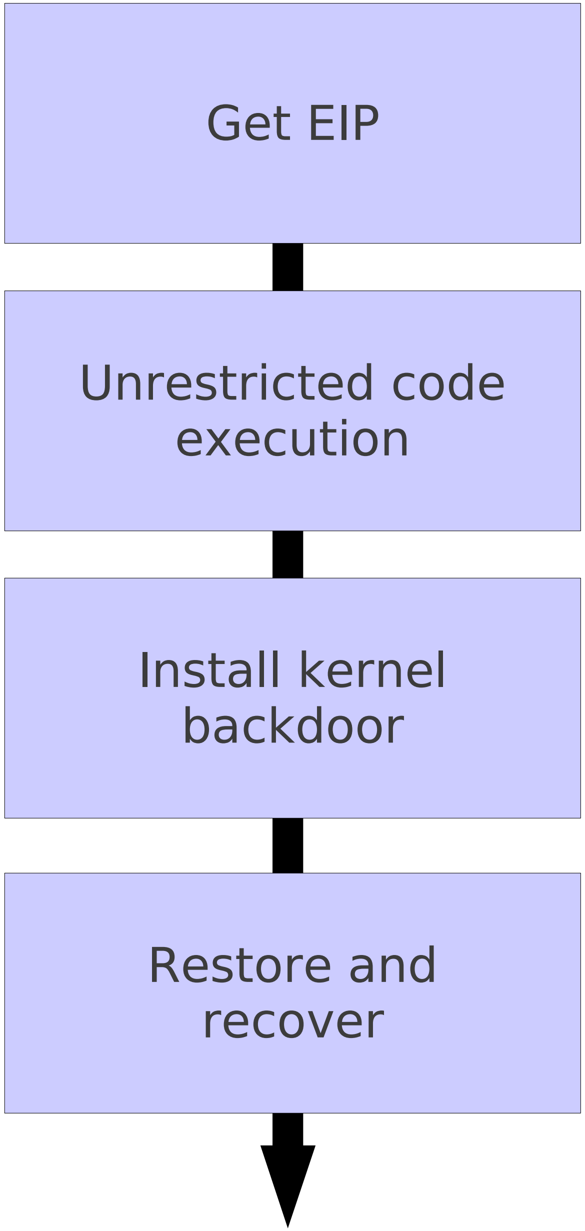
Constraint #1

- The seventh byte of an AX.25 address is AND'd with AX25_HBIT (0x80) if it's a destination digipeater
  - Otherwise, treated as a source digipeater

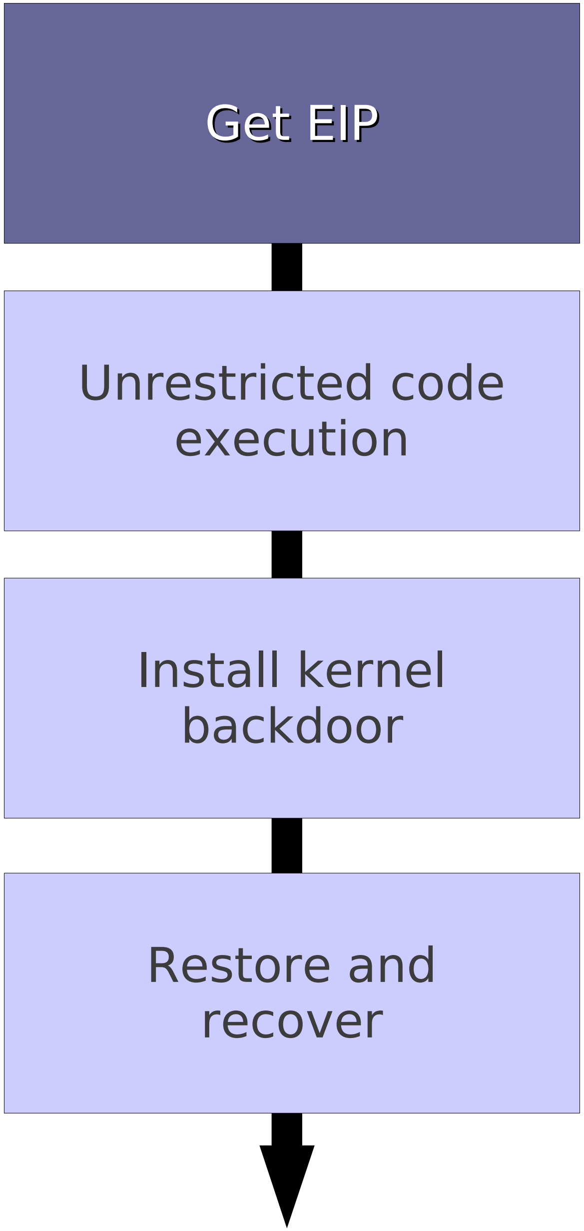
- Every seventh byte of our payload needs to be consistently greater or less than 0x80, or we'll copy into the wrong array

- Requires manual tweaking

Plan of Attack



Triggering the Bug



- Fairly trivial
- Modify ROSE facilities output functions to craft frame with overly large length field for FAC_NATIONAL_DIGIS, followed by lots of NOPs (0x90)

Evil ROSE Frame

ROSE header	Facilities Total Length = XX	0x00	FAC_NATIONAL	FAC_NATIONAL_DIGIS	len = 0xff	0x9090...

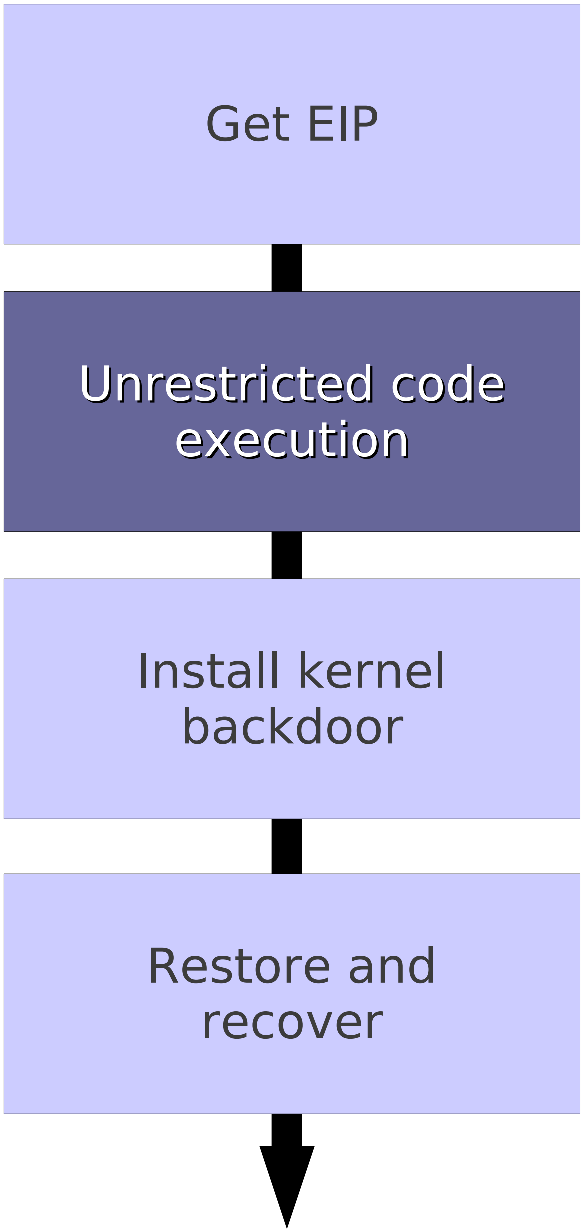
Got EIP

- Recompile ROSE module, reload, and use rose_call to initiate connection to target

- Overflowed softirq stack (interrupt handler)

```
Program received signal SIGSEGV,
Segmentation fault.
[Switching to Thread 1456]
0x90909090 in ?? ()
(gdb) i r
eax            0x0    0
ecx            0xde3a5f3c -566599876
edx            0x296  662
ebx            0x90909090 -1869574000
esp            0xd11e199c 0xd11e199c
ebp            0x90909090 0x90909090
esi            0x90909090 -1869574000
edi            0x90909090 -1869574000
eip            0x90909090 0x90909090
eflags         0x10286    [ PF SF IF RF ]
cs             0x60   96
ss             0x68   104
ds             0x9090007b -1869610885
es             0x9090007b -1869610885
fs             0xffff 65535
gs             0xffff 65535
```

How to Execute Code?



- Traditionally, return into shellcode on stack
- Problem 1: we don't know where we are
  - Trampolines are easy
- Problem 2: softirq stack is non-executable

Primer: Registers

- x86-32 has several general purpose registers:
  - %eax, %ebx, %ecx, %edx, %esi, %edi

- Some have "traditional" uses
  - %eax is return code
  - %ecx is a counter
  - %esi/%edi are source and destination of copy

- Special registers: %esp (stack pointer), %ebp (frame pointer), %eip (instruction pointer)

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Primer: Calling Convention

- How do we invoke functions?
  - Traditionally, put arguments on stack (%esp), and issue a “call” instruction

- Different in kernel mode:
    - First argument in %eax
    - Second in %edx
    - Third in %ecx
    - Others on stack

Primer: ROP

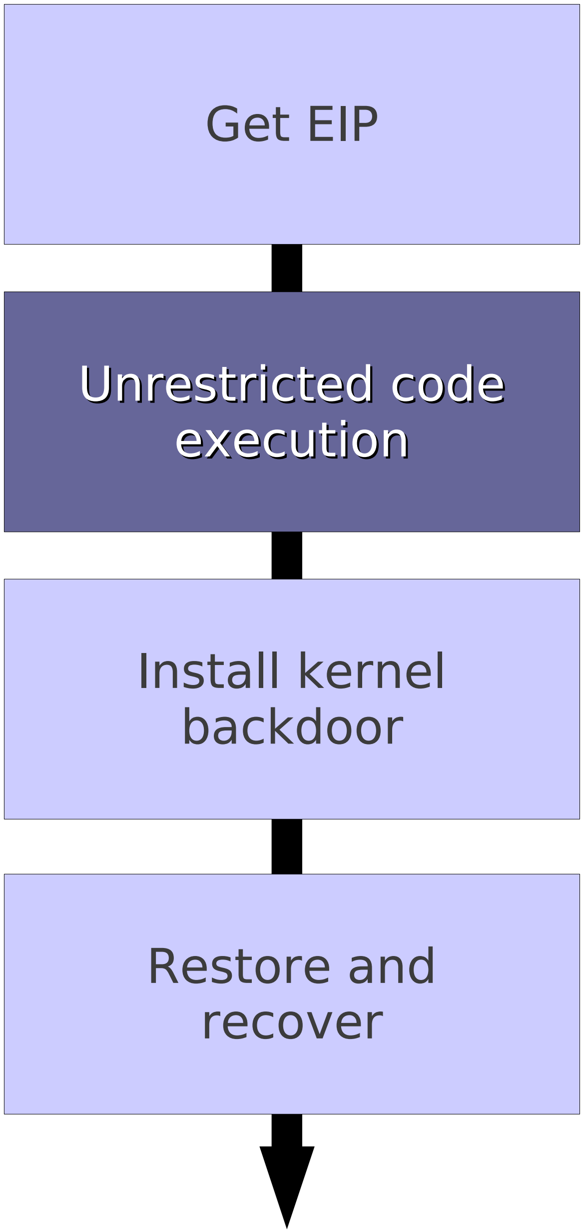
- We control the return address and data at %esp
- Each return will direct execution to address at stack pointer and increment it
- Chain together function epilogues ("gadgets") to perform arbitrary computation
- Relies on homogeneity of distribution (binary) kernels and lack of randomization
  - Choose gadgets that are more likely to appear in constant locations across kernels

Making our Stack Executable

- Kernel has nice function to do this for us:
  - `set_memory_x()`
- Calling convention has arguments in registers
- ROP stub steps:
  - Load (%esp & ~0xfff) into %eax
  - Load 4 into %edx
  - Call `set_memory_x()`
  - Jump into stack

```
static unsigned long rop_stub[] = {
/*1*/   PUSH_ESP_POP_EAX,
/*4*/   0xffffffff,
        0xffffffff,
/*3*/   0xffffffff,

        ALIGN_EAX,
/*2*/   0xffffffff,
        0xffffffff,

/*1*/   RET,

/*4*/   POP_EDX,
        0x00000004,
/*3*/   0xffffffff,
        0xffffffff,
/*2*/   0xffffffff,
        0xffffffff,

/*1*/   RET,

/*4*/   SET_MEMORY_X,
        JMP_ESP,
};
```

Overcoming Space Constraints



- We now have traditional shellcode executing on the softirq stack!
- Problem: length is limited to 0xff (255), minus what we've already used
- Not enough room for a useful payload

Needle in a Haystack

- Full ROSE frame is intact somewhere on the kernel heap
- Pointer to a memory region containing our socket data lives on the stack
- Walk up the stack, following kernel heap pointers
- Search general area for tag included in ROSE frame
- Mark it executable and jump to it

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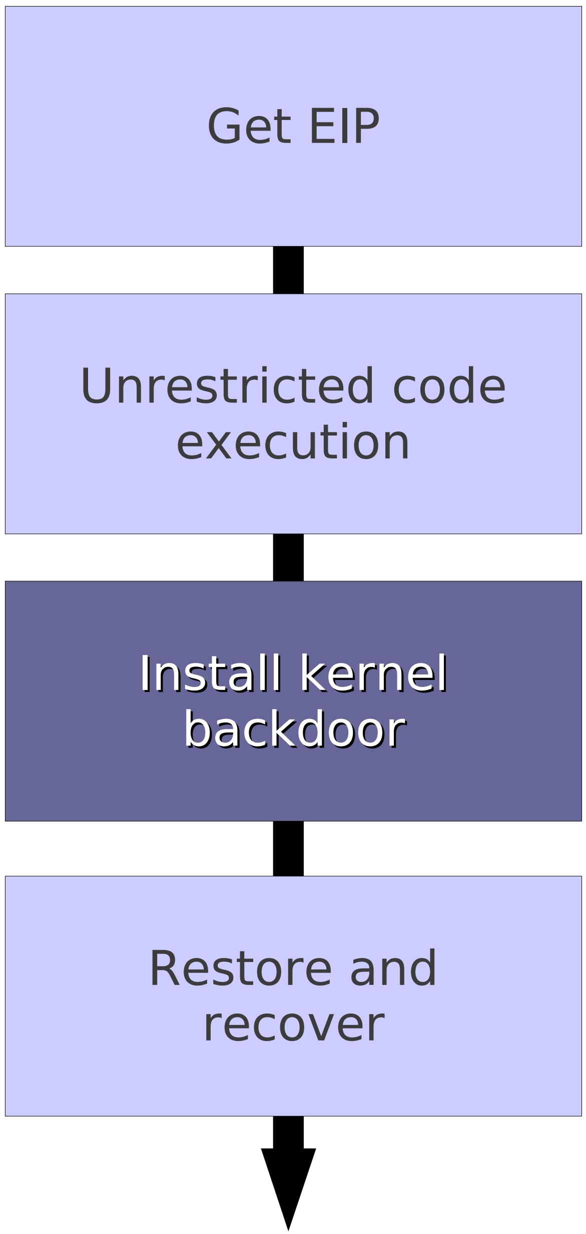
What Now?



- We can execute arbitrary-length payloads now!
- Goal: install kernel backdoor in ICMP handler

Primer: Linux Networking

- What happens when network data is received?
- Hardware magic happens, driver layer (linux/drivers/net) receives low-level frame
- Driver identifies “this is an IP packet”, sends to network layer (linux/net/ipv{4,6})
- Network layer checks “what protocol is this” (TCP, UDP, ICMP, etc.) and dispatches to appropriate protocol handler (linux/net/*)

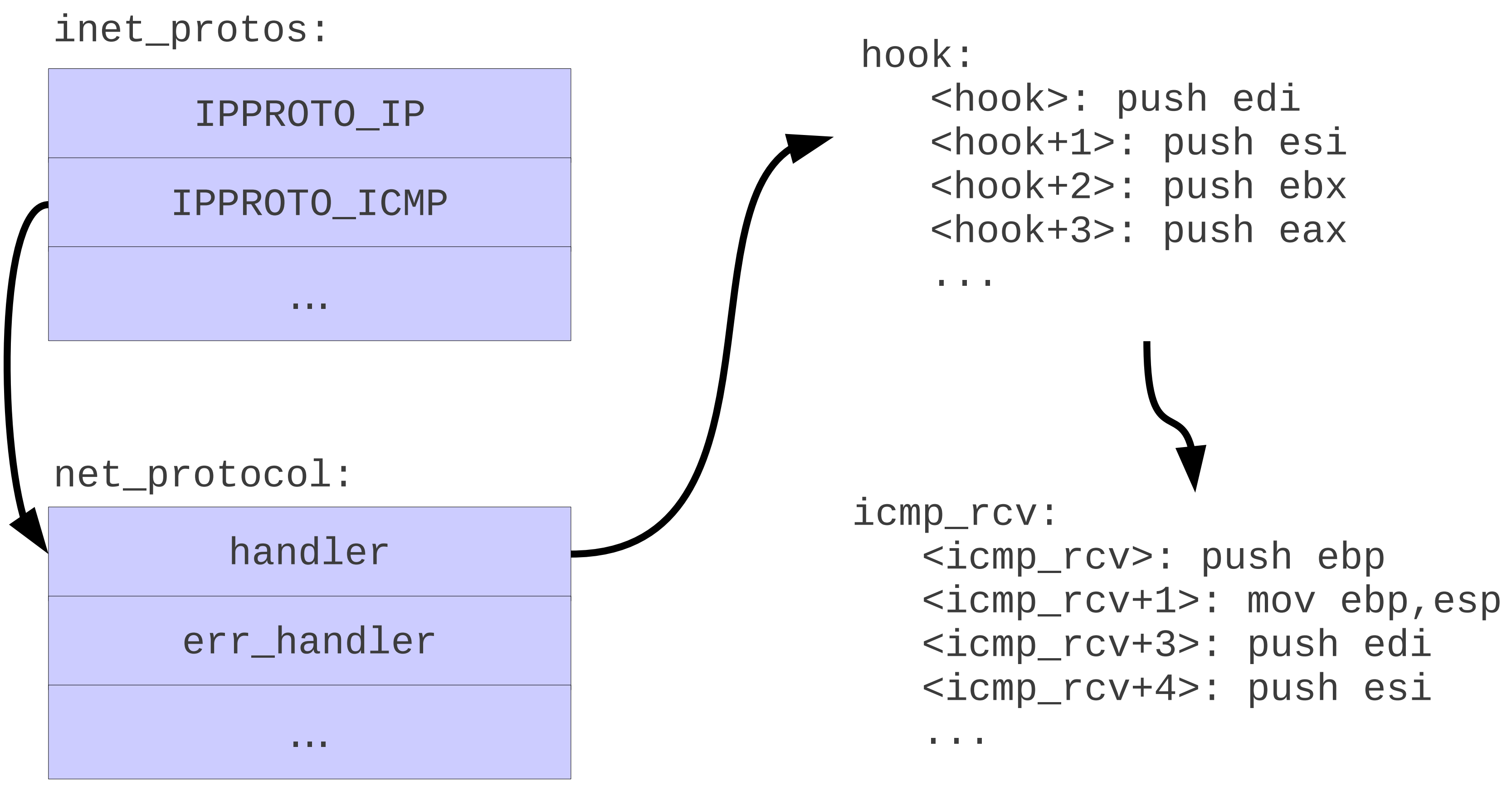
Protocol Handlers

```
/* Array of network protocol structure */
const struct net_protocol __rcu
*inet_protos[MAX_INET_PROTOS] __read_mostly;


/* Definition of network protocol structure */
struct net_protocol {
        int   (*handler)(struct sk_buff *skb);
        void (*err_handler)(struct sk_buff *skb, u32 info);
        ...
};


/* Standard well-defined IP protocols.  */
enum {
  IPPROTO_IP = 0,   /* Dummy protocol for TCP */
  IPPROTO_ICMP = 1, /* Internet Control Message Protocol */
  ...
};
```

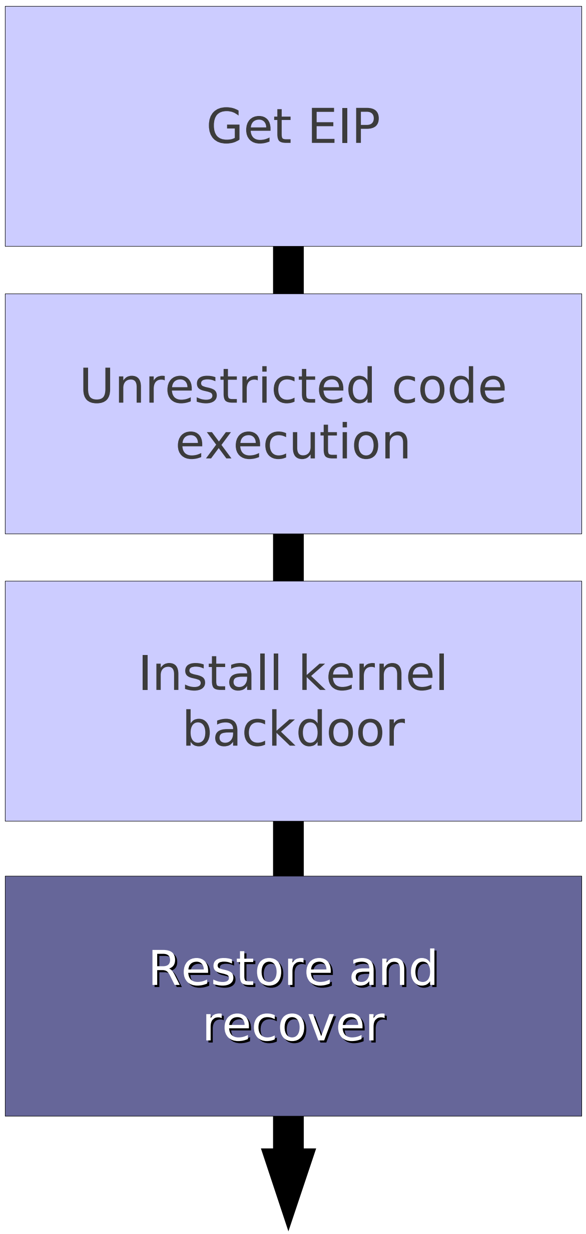
Hooking ICMP

- Storage on softirq stack
  - Already executable, safe, persistent
- Copy hook and address of original ICMP handler
  - We'll need this later
- Handler is in read-only memory
  - Flip write-protect bit in %cr0 register
- Write address of our hook into ICMP handler function pointer

Hooked In


inet_protos:
IPPROTO_IP
IPPROTO_ICMP
…
net_protocol:
handler
err_handler
…
hook:
<hook>: push edi
<hook+1>: push esi
<hook+2>: push ebx
<hook+3>: push eax
...
icmp_rcv:
<icmp_rcv>: push ebp
<icmp_rcv+1>: mov ebp,esp
<icmp_rcv+3>: push edi
<icmp_rcv+4>: push esi
...

Time to Rebuild...



- We've destroyed large portions of the softirq stack
- How can we keep the kernel running?

Cleaning Up the Locks

- ROSE protocol is holding two spinlocks
  - If we don't release these, the ROSE stack will deadlock soon
- Problem: ROSE is a module, we don't know where the locks live

Needle in a Haystack, Again

- Global `modules` variable: linked list of loaded kernel modules

- A plan!
  - Follow linked list until we find ROSE module
  - Read `module` structure, find start of .data section
  - Scan .data section for byte pattern of two consecutive spinlocks (distinctive signature)
  - Release them

Preemption Woes

- Preemption count must be consistent with what the kernel is expecting, or scheduler will...

...complain and fix it for you?!

```
if (unlikely(prev_count != preempt_count())) {
        printk(KERN_ERR "huh, entered softirq %u %s %p"
               "with preempt_count %08x,"
               " exited with %08x?\n", vec_nr,
               softirq_to_name[vec_nr], h->action,
               prev_count, preempt_count());
        preempt_count() = prev_count;
}
```

- Let's avoid that warning...

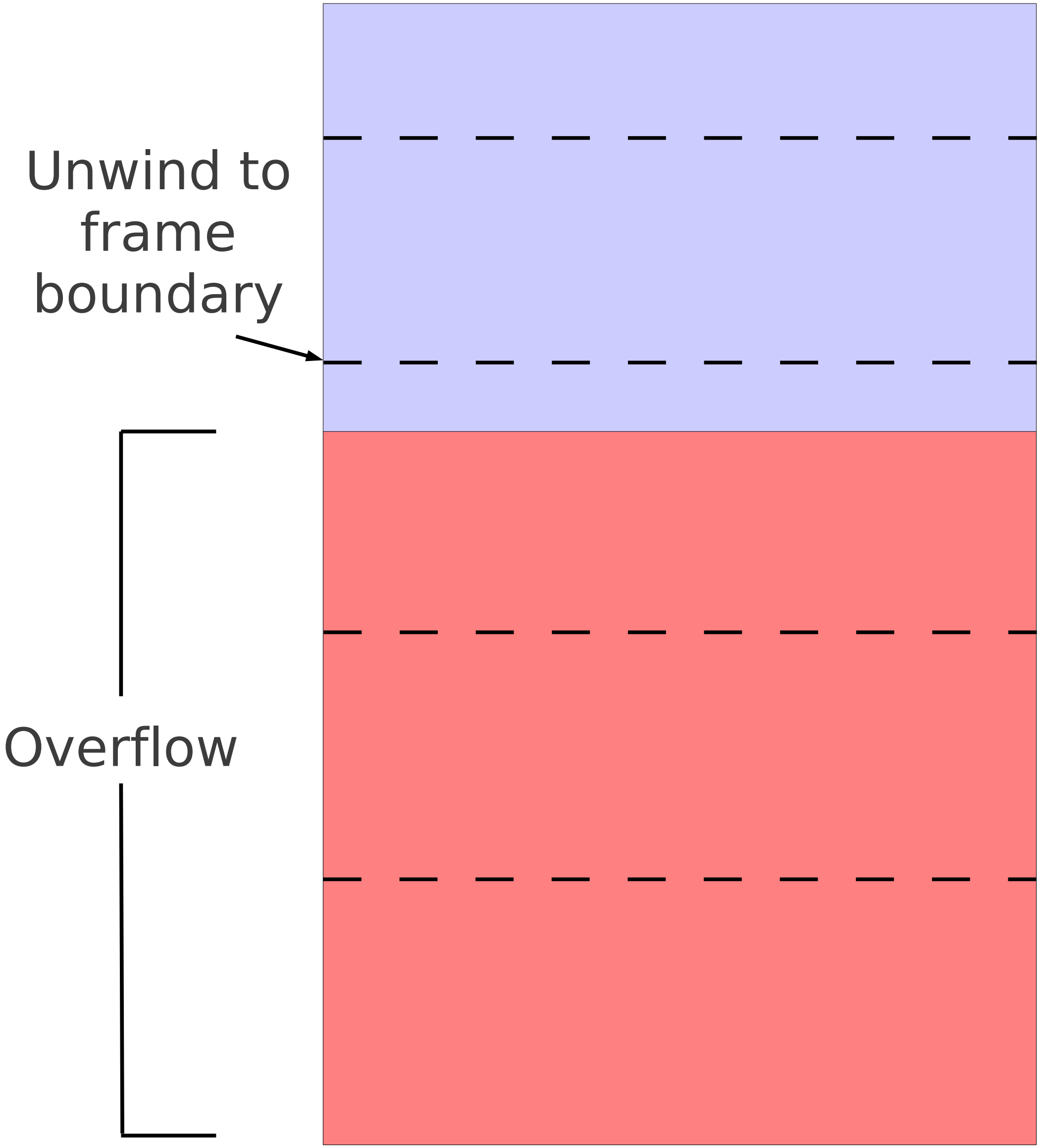
Has Anybody Seen a Preemption Count?

- Preempt count lives at known location in `thread_info` struct, at base of kernel stack:

```
struct thread_info {
   struct task_struct *task; /* main task structure */
   struct exec_domain *exec_domain; /* execution domain */
   __u32 flags;           /* low level flags */
   __u32 status;          /* thread synchronous flags */
   __u32 cpu;             /* current CPU */
   int preempt_count;     /* 0 => preemptable,
                             <0 => BUG */
   ...
};
```

- Decrement it and we're done

Unwinding the Stack



- Stack is partially corrupted from overflow
- Need to restore it to recoverable state
- Walk up stack from current location until we match a signature of a known good state
- Adjust ESP to good state, and return

Refresher: What Have We Achieved?

- Trigger the overflow, gain control of EIP
- Leverage ROP to mark softirq stack executable, jump into shellcode
- Search for intact ROSE frame on kernel heap, mark executable, jump into it
- Install kernel backdoor by hooking ICMP handler
- Do some necessary cleanup and unwind stack for safe return from softirq

Kernel Backdoors for Fun and Profit

(Insert "backdoor" joke)

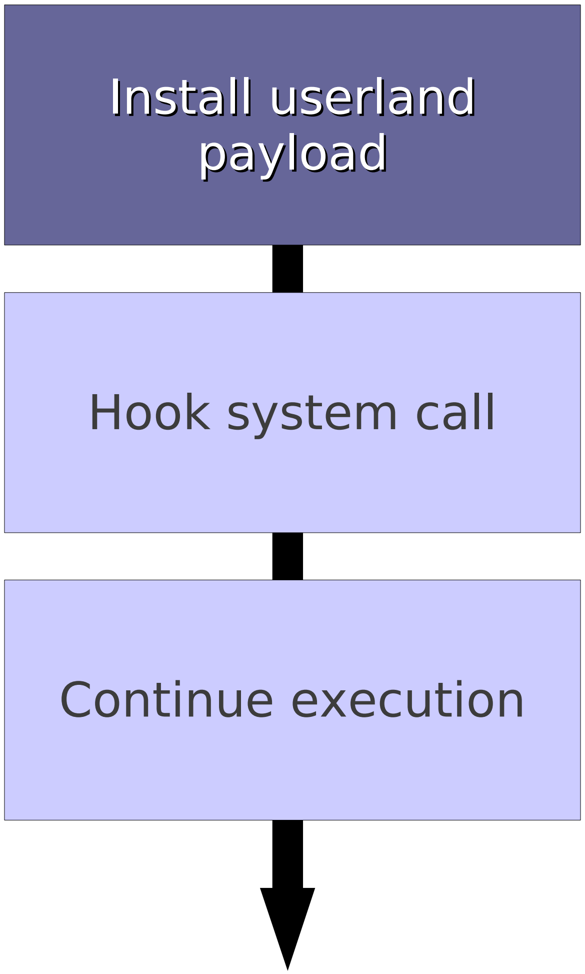
What About That Backdoor Part?

- Whenever an ICMP packet is received, our hook is called
- Check for magic tag in ICMP header
- Two distinct types of packets
  - “Install” packets contain userland shellcode
  - “Trigger” packets cause shellcode to execute
- May be sent independently
  - Install payload, trigger it repeatedly at later date

Backdoor Strategy

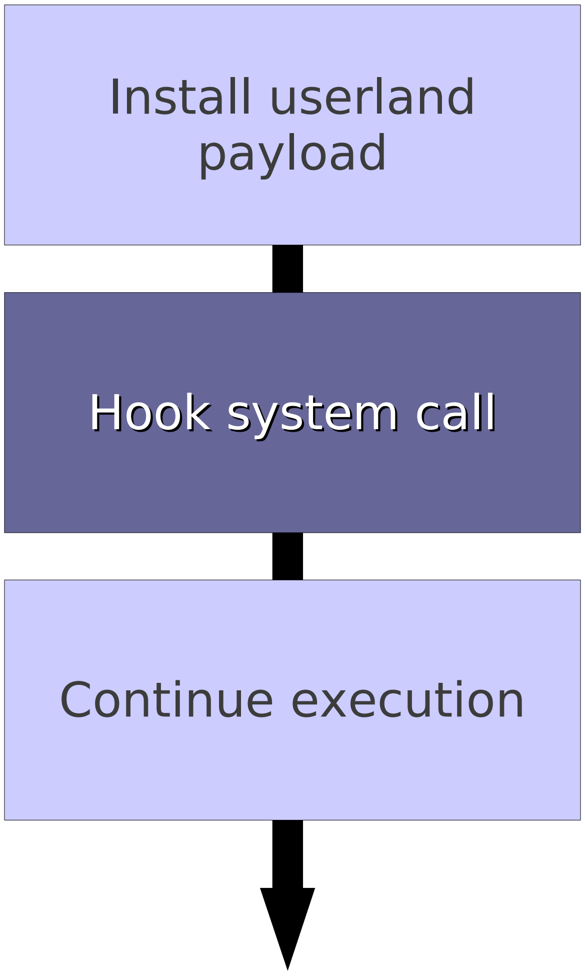
- Problem: ICMP handler also runs in softirq context
  - Want userland code execution
- Phase 1: transition to kernel-mode process context
- Phase 2: hijack userland control flow

Backdoor Phase I



- Check for magic tag and packet type
- If “install” packet, copy userland payload into safe place (softirq stack)

Transition to Process Context



- If “trigger” packet, need to transition to process context
- Easiest way: hook system call

Primer: System Calls

- Userland process invokes a system call (read, write, fork, etc.)
- Traditional mechanism is `int 0x80` (more recently everything uses `systenter/syscall`)
- Index into Interrupt Descriptor Table, check privileges
- Invokes handler specified by IDT (syscall entry point)
- Syscall entry point parses arguments, indexes into syscall table, and calls appropriate system call handler

System Call Hijacking

- How to find system call table at runtime?
  - `sidt` instruction retrieves IDT address
  - Find handler for INT 0x80 (syscall)
  - Scan function for byte pattern calling into syscall table
- Read-only syscall table
  - More flipping write-protect bit in %cr0
- Store original syscall handler for later, write address of hook into syscall table

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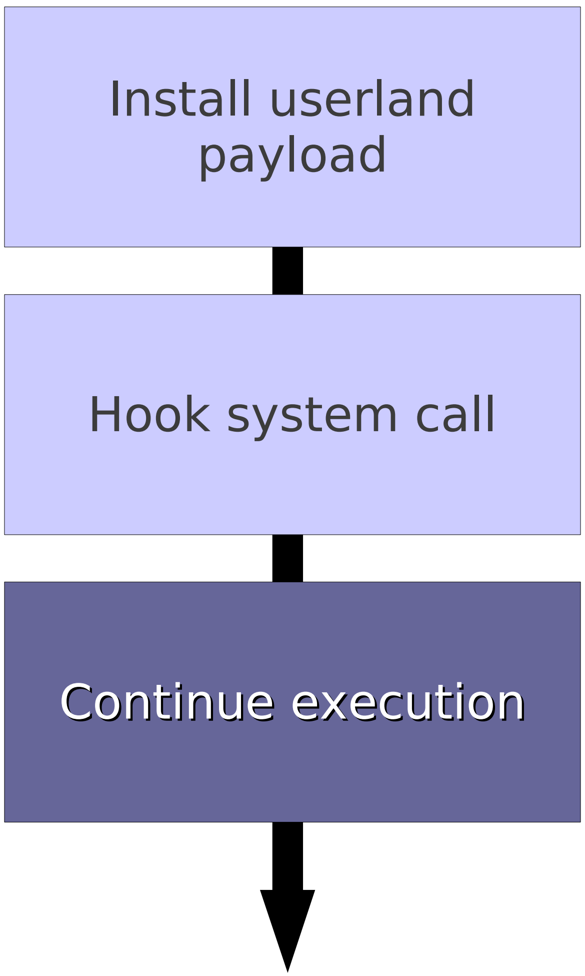
Carry On…

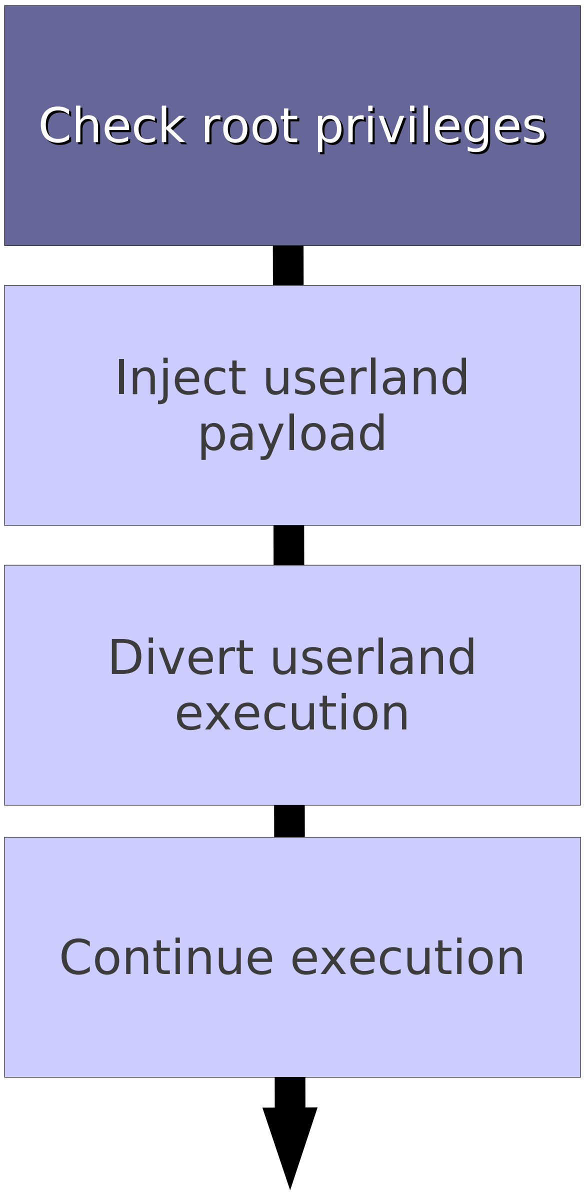


- Want working ICMP stack
- Call original ICMP handler

Backdoor Phase 2

- We've copied userland payload to kernel memory
- Some process comes along and calls our hooked system call...
- Need to hijack process for userland code execution

Only Root, Please



- Only interested in root processes
- How to verify?
  - `thread_info → task_struct → cred`
  - Unstable, annoying…

System Calls from Kernel Mode?

- System calls are extremely useful abstractions
  - Friendly interface, kernel does most of the work
- Poll: is it possible to call system calls via `INT 0x80` from kernel mode?
  - Tally your votes...

System Calls from Kernel Mode!

- Most system calls will work when called from kernel

- Stack switch only occurs on inter-PL interrupts
  - Based on CPL vs. DPL of GDT descriptor
  - Happens on `int` and `iret`

- When called from kernel mode, just an ordinary intra-PL interrupt

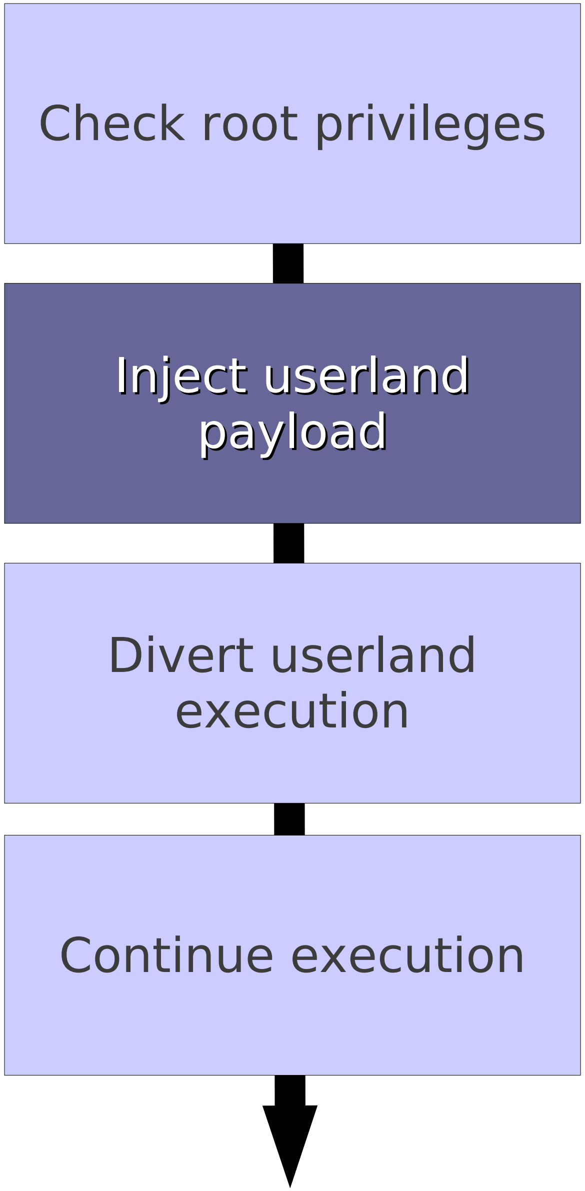
Exceptions (No Pun Intended)

- Doesn't work quite right with some system calls
  - Some require `pt_regs` (per-thread register) structure
  - Assumptions about state of stack at time of system call
- fork, execve, iopl, vm86old, sigreturn, clone, vm86, rt_sigreturn, sigaltstack, vfork

Checking for Root

- Easy: load %eax with 0x18 (getuid), INT 0x80
- Check %eax (return code) for 0
- If not zero, call original syscall handler for hooked function
- If zero, unhook syscall and continue payload

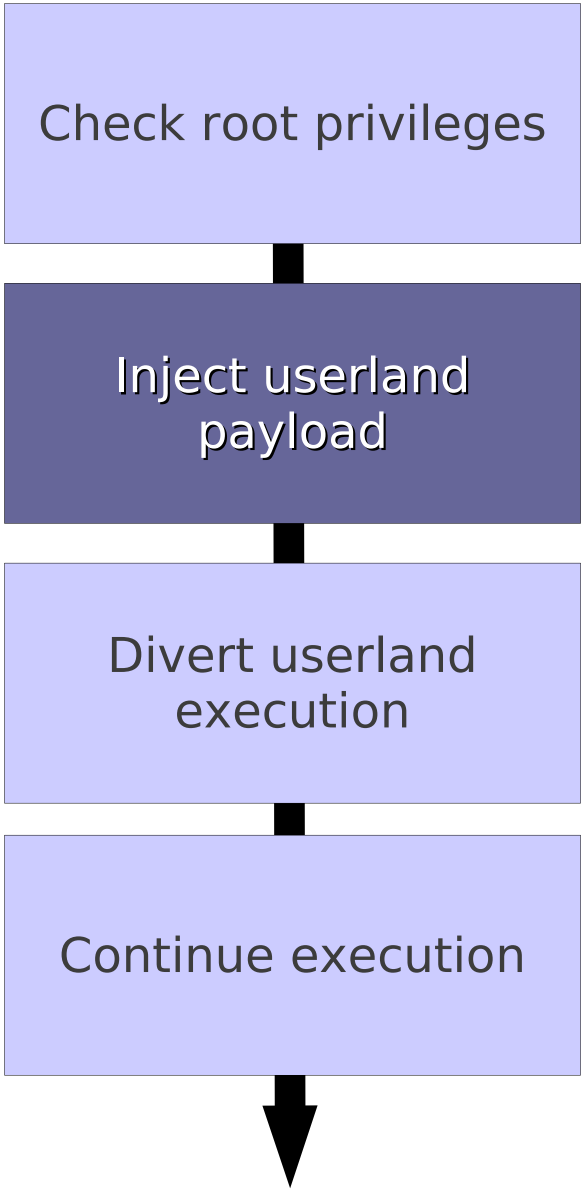
Lethal Injection



- Kernel stack contains pointer to saved userland %esp

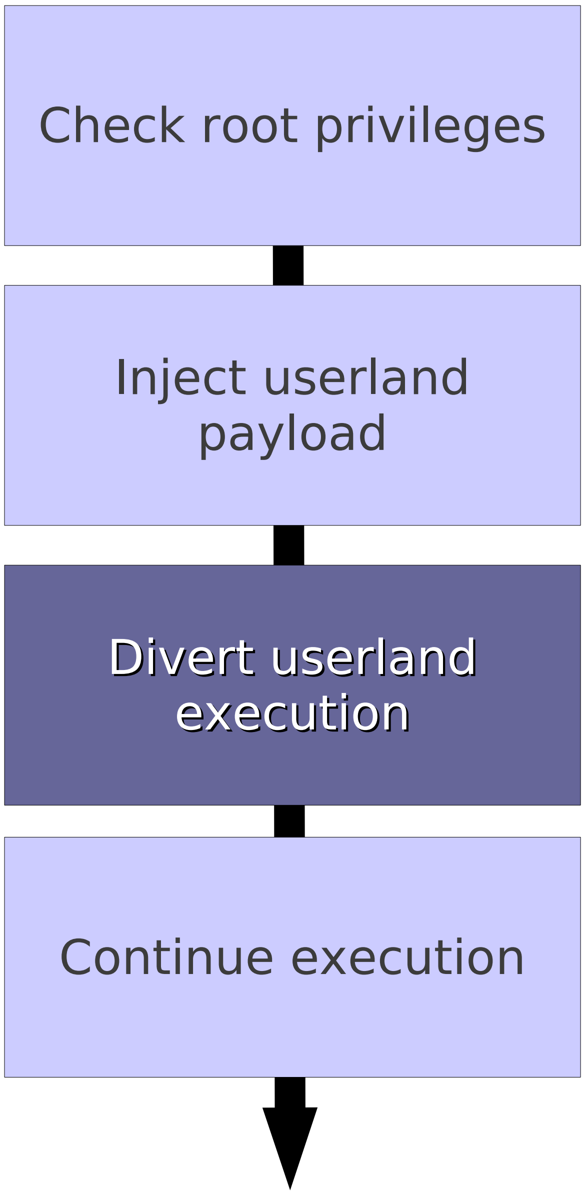
- Copy userland payload from kernel memory to userland stack

Let it Run...



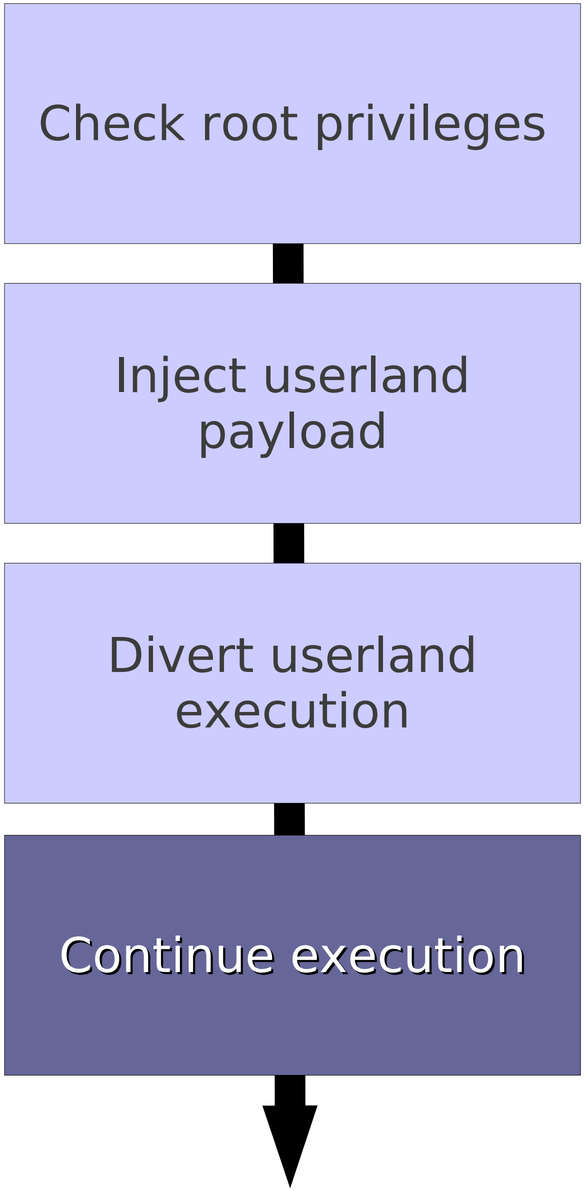
- Userland stack is non-executable (NX)
- Call `mprotect` syscall via INT 0x80 to mark userland stack executable

It's a Diversion!



- Need to redirect userland control flow
- Kernel stack contains pointer to saved userland %eip
- Give original saved %eip to userland shellcode for later
- Overwrite pointer with address of payload on userland stack

Keep on Running



- Want hijacked process to keep running
- Jump to original handler for hijacked system call

Userland Payloads

- Use your imagination!
  - Connect-back root shells work just fine
- Payloads are prefixed with stub that keeps hijacked process running
  - Fork new process
  - Child runs shellcode
  - Parent jumps to original saved %eip

ROSE Exploitation Demo

Future Work

No, this isn't a perfect exploit.

Hard-Coding

- Advantages over signatures / fingerprinting
  - Reliability vs. portability

- On PAE kernel, ROP gadgets seem unavoidable
  - Minimize number of ROP gadgets
  - Minimize hard-coding of other data structures

- On non-PAE kernel, situation is better
  - Can survive with one JMP ESP (if you know saved EIP offset)
  - Partial overwrites or spraying possible

Future Work: Offense

- Remote fingerprinting of kernel
  - Automatic generation of ROP gadgets

- Exploiting other packet families
  - IrDA, Bluetooth, X.25?

- Finding that TCP/IP bug that breaks the Internet

Future Work: Defense

- Randomize kernel base at boot
  - Prevents code reuse (e.g. ROP) remotely in absence of remote kernel memory disclosure

- Fuzz and audit networking protocols more rigorously

- Inline functions that alter page permissions directly (prevent easy ROP)

- Policies on preventing page permission modification after initialization

Thanks To…

- Ralf Baechle
- Nelson Elhage
- Kees Cook
- twiz, sgrakkyu

Questions?

E-mail: drosenberg@vsecurity.com

Twitter: @djrbliss

Company:

http://www.vsecurity.com

Personal:

http://www.vulnfactory.org

Exploit code:

https://github.com/djrbliss/rose-exploit