There's a party at ring0...

(...and you're invited)

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Introduction

- All systems make some assumptions about kernel security.
  - Sometimes a single kernel flaw can break the entire security model.
  - The sandboxing model in Google Chrome and Android makes us even more dependent on kernel security.
- We've been involved in finding, fixing and mitigating some fascinating kernel bugs, and we want to share some of our work.
- We're going to discuss some of the ways to protect the kernel from malicious userland code, and mitigate unknown kernel vulnerabilities.

The Kernel as a Target

Local Privilege Escalation*

- You have arbitrary code execution on a machine
- You want to escalate (or change) privileges
- What can you target?
  - Processes with more/other privileges (Running deamons, suid binaries you can execute on Unix)
  - The kernel
    - Big code base
    - Performs complex, error-prone tasks
    - Responsible for the security model of the system

The Linux kernel as a local target

- The Linux kernel has been a target for over a decade
- Memory / memory management corruption vs. logical bug

- The complexity of a kernel makes for more diverse and interesting logical bugs

- Fun logical bugs include:
  - ptrace() / suidexec (Nergal, CVE-2001-1384)
  - ptrace() / kernel threads (cliph / Szombierski, CVE-2003-0127)
  - /proc file give-away (H00lyshit, CVE-2006-3626)
  - prctl suidsafe (CVE-2006-2451)

Linux kernel mm corruption bugs

- Tend to be more interesting and diverse than userland counterpart
  - Complexity of memory management
  - Interesting different paradigm (the attacker finely controls a full address space)

- cliph / ihaquer do_brk() (CVE-2003-0961)
- cliph / ihaquer / Devine / others "Lost-VMA"-style bugs (check isec.pl)
- Couple of "classic" overflows
- Null (or to-userland) pointer dereferences

Escapes through the kernel

- Exploiting the kernel is often the easiest way out of:
    - chroot() jails
    - Mandatory access control
    - Container-style segregation (vserver etc..)
- Using those for segregation, you mostly expose the full kernel attack surface
    - Virtualization is a popular alternative

- MAC makes more sense in a full security patch such as grsecurity.

Windows and local kernel bugs

- Traditionally were not considered relevant on Windows
- Changed somewhat recently
  - Increased reliance on domain controls
  - Use of network services
  - Introduction of features like protected mode / integrity levels

- This has changed in the last few years and Windows is roughly in the same situation as Linux now
  - With a bit less focus on advanced privilege separation and segregation (Lacks MAC for instance)

Remotely exploitable kernel bugs

- Published exploits are still quite rare for Linux.
- Notable exceptions
  - Wifi drivers (big attack surface, poorly written code)
    - See few exploits by Stéphane Duverger, sgrakkyu or Julien
    - Read Stéphane's paper
  - *s*grakkyu's impressive SCTP exploit
    - (Read his article co-written with twiz in Phrack)
  - Few others

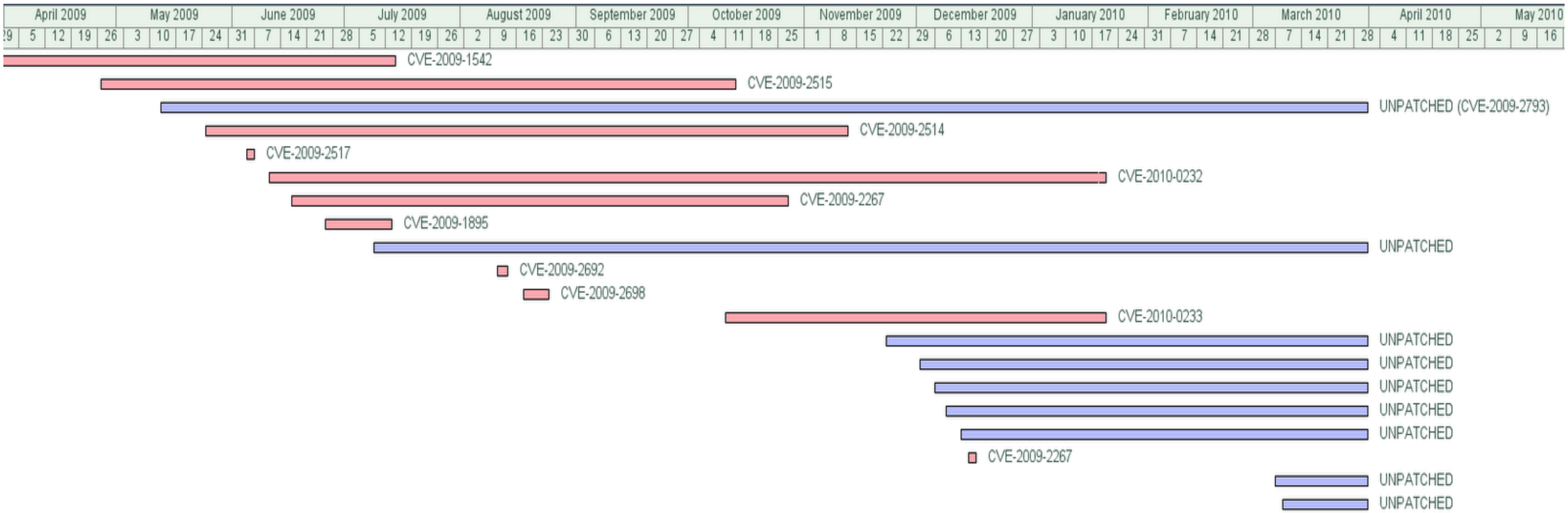
Remotely exploitable kernel bugs (2)

- Have been quite popular on Windows for at least 6/7 years
  - Third party antivirus and personal firewall code
  - GDI-related bugs
  - TCP/IP stack related ones (Neel Mehta et al.)
  - Immunity's SMBv2 exploit

- Web browsers changed the game
  - The threat model for in-kernel GDI is now different
  - See also the remotely exploitable NVidia drivers bug on Linux
  - Stay tuned...

Some bugs from the last year

Timeline*


April 2009
May 2009
June 2009
July 2009
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September 2009
October 2009
November 2009
December 2009
January 2010
February 2010
March 2010
April 2010
May 2010
CVE-2009-1542
CVE-2009-2515
UNPATCHED (CVE-2009-2793)
CVE-2009-2514
CVE-2009-2517
CVE-2010-0232
CVE-2009-2267
CVE-2009-1895
UNPATCHED
CVE-2009-2692
CVE-2009-2698
CVE-2010-0233
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CVE-2009-2267
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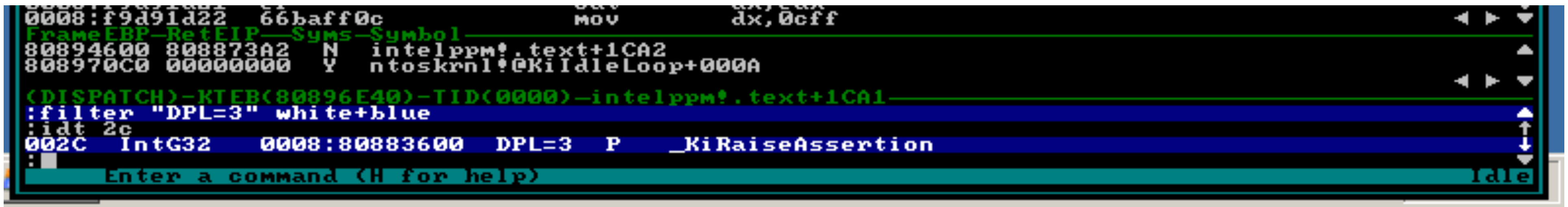
Exposing Kernel Attack Surfaces

- There are many entrypoints for attackers to expose kernel attack surface, apart from system calls there are also
  - Ioctls, devices, kernel parsers
  - Filesystems, network protocols
  - Fonts, Bitmaps, etc. (primarily Windows)
  - Executables formats (COFF, ELF, a.out, etc.)
  - And so on.

- Perhaps one under appreciated entrypoint is dpl3 interrupt handlers, so we decided to take a look.

Windows 2003 KiRaiseAssertion Bug

- In Windows Server 2003, Microsoft introduced a new dpl3 (accessible to ring3 code) IDT entry (KiRaiseAssertion in the public symbols).



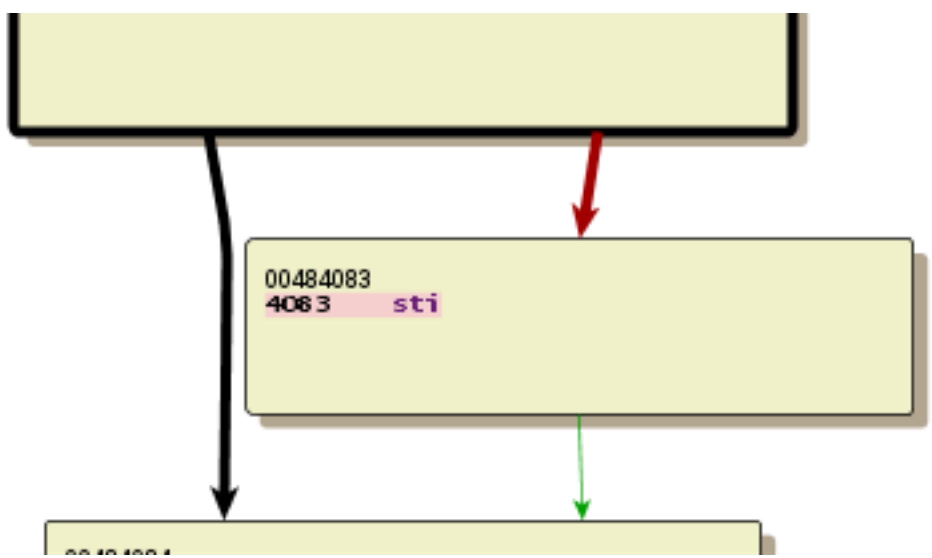
- This makes int 0x2c roughly equivalent to RaiseException (STATUS_ASSERTION_FAILED).
- I've never seen this feature used, but analysis revealed an interesting error; interrupts were not enabled before the exception dispatch!
- This bug has two interesting characteristics...

Windows 2003 KiRaiseAssertion Bug

- Tiny exploit (4 bytes)...

```
00000000  31E4          xor esp,esp
00000002  CD2C          int 0x2c
```

- Tiny patch (1 byte)...



Page Fault Exceptions

- A page fault exception occurs when code:
  - Attempts to access a non-present page
  - Has insufficient privilege to access a present page
  - Various other paging related errors

The handler is passed a set of flags describing the error:

  - `I/D` - Instruction / Data Fetch
  - `U/S` - User / Supervisor Mode
  - `W/R` - Read / Write access
  - `P` - Present / Not present

Supervisor Mode

- If the processor is privileged when the exception occurs, the supervisor bit is set
- Operating system kernels use this to detect when special conditions occurs
  - This could mean a kernel bug is encountered
  - Oops, BugCheck, Panic, etc
  - Or some other unusual low-level event
- Can also happen in specific situations (copy-from-user etc...)
- If the processor can be tricked into setting the flag incorrectly, ring3 code can confuse the privileged code handling the interrupt

VMware Invalid #PF Code

- By studying the machine state while executing a Virtual-8086 mode task, we found a way to cause VMware to set the supervisor bit for user mode page faults
- Far calls in Virtual-8086 mode were emulated incorrectly
  - When the cs:ip pair are pushed onto the stack, this is done with supervisor access
  - We were able to exploit this to gain ring0 in VMware guests
- The linux kernel checks for a magic CS value to check for PNPBIOS support
  - But... in Virtual-8086 mode we must be permitted any value cs

Exploiting Incorrect U/S Bit

- We can exploit this error :-)
- We mmap() our shellcode at NULL, then enter vm86 mode.
    - mmap_min_addr was beginning to gain popularity at the time we were working on this, so we bypassed that as well (CVE-2009-1895)
- When we far call with a non-present page at ss:sp, a #PF is delivered.
- Because we can spoof arbitrary cs, we set a value that the kernel recognises as a PNPBIOS fault.
- The kernel tries to call the PNPBIOS fault handler.
- But because this is not a real fault, the handler will be NULL.
- => r00t

Exploiting Incorrect U/S Bit

- Triggering this issue was simple, we used a code sequence like this:

```
vm.regs.esp = 0xDEADBEEF;
vm.regs.eip = 0x00000000;
vm.regs.cs = 0x0090;
vm.regs.ss = 0xFFFF;

CODE16("call 0xaabb:0xccdd", code, codesize);

memcpy(REAL(vm.regs.cs, vm.regs.eip), code, codesize);

vm86(Vm86Enter, &vm);
```

More Page Fault Fun

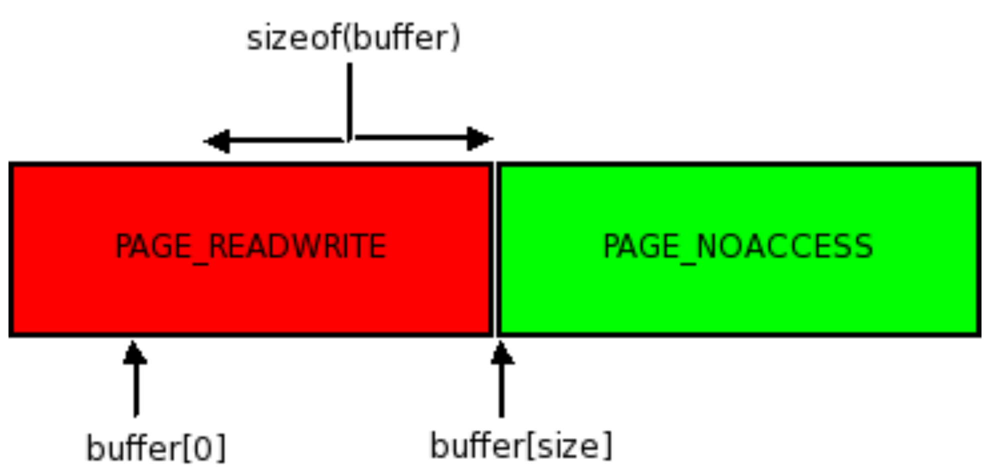
- If the kernel ever trusts data from userspace, a security issue may exist.

- However, it's worth remembering that it's not just the data that users control, it's also the presence or absence of data.

- By claiming to have more data available than we really do, we can reach lots of unusual error paths.
    - This is especially true on Windows where the base system types are large inter-dependent structures.
- We found an interesting example of this problem on Windows NT, resulting in a privilege escalation.
- MS10-015, a double-free in NtFilterToken()

Windows NT NtFilterToken() Bug

- NtFilterToken() is the system service that makes routines like CreateRestrictedToken() work.
- NtFilterToken() would pass a (void **) to a helper routine, which would be used to store the captured data.
- I can force the capture to fail by claiming the SID is bigger than it really is, and forcing the structure to straddle a page boundary.



Windows NT NtFilterToken() Bug

- On error, the helper routine releases but doesn't reset the (void **) parameter, which NtFilterToken() will release again!
- The kernel detects a double free and BugChecks, so we only get one attempt to exploit this...
- We need to get the buffer reallocated a small window. This is possible, but unfortunately is unavoidably unreliable.

Example Code: http://bit.ly/b9tPqn

Windows NT TTF Parsing Vulnerability

"Moving [...] the GDI from user mode to kernel mode has provided improved performance without any significant decrease in system stability or reliability."

(Windows Internals, 4th Ed., Microsoft Press)

- GDI represents a significant kernel attack surface, and is perhaps the most easily accessible remotely.
- We identified font parsing as one of the likely weak points, and easily accessible via Internet Explorer's `@font-face` support.
- This resulted in perhaps our most critical discovery, remote ring0 code execution when a user visits a hostile website (even for unprivileged or protected mode users).

Windows NT TTF Parsing Vulnerability

- The font format supported by Internet Explorer is called EOT (Embedded OpenType), essentially a trivial DRM layer added to TTF format fonts.
- EOT also defines optional sub-formats called CTF and MTX (in which we also identified ring3 vulnerabilities, see MS10-001 and others), but are essentially TTF with added compression and reduced redundancy.
  - See http://www.w3.org/Submission/2008/SUBM-EOT-20080305/
- EOT also adds support for XOR encryption, and other advanced DRM techniques to stop you pirating Comic Sans.
- The t2embed library handles reconstructing TTF files from EOT input, including decryption and so on, at which point GDI takes over.

Windows NT TTF Parsing Vulnerability

- We found multiple integer errors when GDI parses TTF directories (these directories simply describe the position of each table in the file).
- This code is executed at ring0, and was essentially unchanged since at least NT4.
- Microsoft wasn't alone, most other implementations we tested were vulnerable, but as the decoder ran at ring0 on Microsoft platforms, the impact was far more serious.

NULL pointer dereferences*

- To-userland pointer dereferences
  - If at any time the kernel trusts data in user space, privilege escalation is likely

- NULL dereferences are a common error
  - Common initialization value / error-returned as pointers
  - NULL is a special value in C, but has no special meaning to the underlying hardware on x86

NULL pointer dereferences

- Interestingly, they used to not be exploitable in Linux 2.0 / i386
  - Segmentation was used
  - A dereferenced pointer without a segment override would not reach userland
  - Wrong pointer dereferences didn't become "to-userland" pointer dereferences
  - thus their destination would be harder to control
- Interesting threads in ~2004/2005, where many Linux kernel developers did not understand the security consequences
- Was still the case for some of them until recently
- Will talk about mmap_min_addr later

Linux kernel sock_sendpage

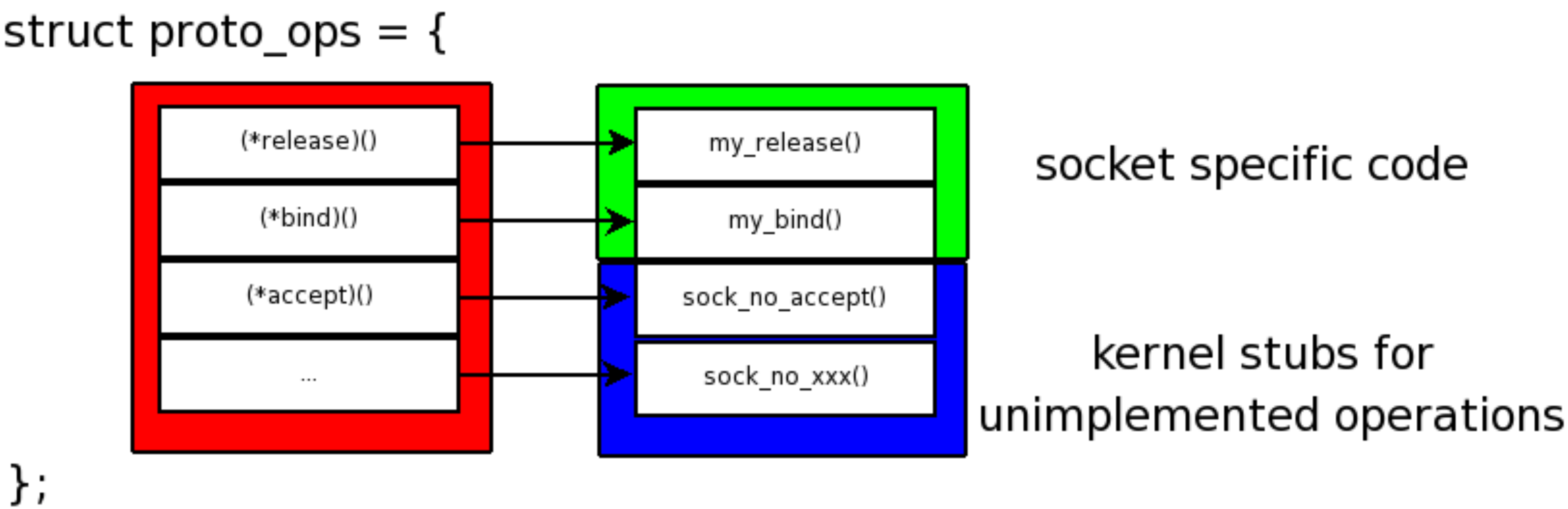
- CVE-2009-2692, found it last August
- Affected all 2.4 and 2.6 kernels to date
- Every major distribution shipped vulnerable kernels
- NULL function pointer dereference
- Trivial to exploit

Linux kernel sock_sendpage

- Every socket in the Linux kernel has a set of function pointers associated with it called *proto_ops* (Protocol Operations).
- Implement the various operations that can be performed on a socket, e.g. accept, bind, shutdown, and so on.
- The general socket management code doesn't have to know about the underlying transport or protocol, because this is all abstracted away.

Linux kernel sock_sendpage

- The proto_ops definition is available in include/linux/net.h



Linux kernel sock_sendpage

- Drivers implement the operations they support and point operations they don't support to pre-defined kernel stubs
- This model is very fragile if you add a new operation:
  - You need to update all drivers and point the new operation to a stub (or implement it)
  - It's a lot of code to update, including macros used for initialization

Linux kernel sock_sendpage

When sock_sendpage() was added, it assumed the corresponding proto_ops field would always be correctly initialized

```
static ssize_t sock_sendpage(struct file *file, struct page *page,
           int offset, size_t size, loff_t *ppos, int more)
{
  struct socket *sock;
  int flags;

  sock = file->private_data;

  flags = !(file->f_flags & O_NONBLOCK) ? 0 : MSG_DONTWAIT;
  if (more)
    flags |= MSG_MORE;

  return sock->ops->sendpage(sock, page, offset, size, flags);
}
```

Linux kernel sock_sendpage

- Unfortunately, a lot of drivers did not get properly updated
- The SOCKOPS_WRAP macro had a bug
  - Used by many drivers to initialize proto_ops
  - Making them vulnerable in any case

- .sendpage was implicitly initialized to NULL for many drivers
- And sock_sendpage() would start executing code at NULL
- Map your shellcode at NULL and it'll get executed

- We wrote a trivial exploit that we shared with vendors

Linux udp_sendmsg()

- CVE-2009-2698, released in August
- It's possible to trigger a codepath in udp_sendmsg() that will result in calling ip_append_data() with a NULL routing table

- This time, it's a data NULL pointer dereference
  - An attacker will control kernel's data (rtable) through address NULL
  - Still exploitable

Linux fasync use after free*

- Drivers which want to provide asynchronous IO notification have a linked list of fasync_struct containing fds (and the corresponding *file* structure) to notify
- The same *file* structure could be in multiple fasync_struct lists
    - Most notably a special one for locked files
- If the *file* was locked, and then closed, a logical bug would remove the *file* structure only from the special locked files linked list and free the file structure
- The driver would still have a reference to this freed *file* structure

- Gabriel Campana wrote an exploit
    - Tricky to make it reliable

NetBSD's Iret #GP handling failure*

- An inter-privilege iret can fail before the privilege switch occurs
- For instance, if restored EIP is past the code segment limit
  - #GP will occur
  - ... while in kernel mode
  - No privilege switch occurs, so no stack switch
  - No saved stack information on the trap frame
- But NetBSD expects a full trap frame
- Due to the non executable stack emulation, this can happen during a legitimate program's execution

Windows NT #GP Trap Handler Bug*

- After discovering these fun bugs in interrupt handlers, we audited the remaining interrupt handlers.
- One section of code in KiTrap0D (the name of the #GP trap handler in the public symbols) appeared to trust the contents of the trap frame.
- The code itself is a component of the Virtual-8086 monitor, introducing lots of fun special cases that few people are familiar with.
- It took another two weeks of research to figure out how to reach the code and write a reliable exploit, but the end result was a fascinating and ancient vulnerability in the core of Windows NT.

BIOS Calls and Sensitive Instructions

- If you can remember programming MS-DOS, you'll be familiar with int 0x21 to invoke system services.
- BIOS calls were then used to interact with hardware, most people will remember int 0x10 was used for video related services.
- In Virtual-8086 mode, these services are intercepted by the monitor code.
- "Sensitive Instructions" is the term given by Intel to any action in Virtual-8086 mode that real mode programs expect to be able to perform, but cannot be permitted in protected mode.
- These actions trap, and the kernel is given an opportunity to decide how to proceed.

Windows NT #GP Trap Handler Bug

- The design of the Virtual-8086 monitor in Windows NT has barely changed since it's original implementation in the early nineties.
- In order to support BIOS service routines, a stub exists in the #GP trap handler that restores execution context from the trap frame.
- Access to this code is authenticated, but by magic values that I knew we could forge from our work on vmware.
- However, There were several hurdles we needed to overcome before we could reach this code, but each one was an interesting exercise.

Windows NT #GP Trap Handler Bug

- The Virtual-8086 monitor is exposed via the undocumented system service NtVdmControl().
  - This call is authenticated, a process is required to have a flag called VdmAllowed in order to access it.
- We found that the VdmAllowed flag can only be set with SeTcbPrivilege (which is only granted to the most privileged code).
- We were able to defeat this check by requesting the NTVDM subsystem, and then using CreateRemoteThread() to execute within the authorised subsystem process.
- Now that we were authorised to access NtVdmControl(), we could try to reach the vulnerable code...

Windows NT #GP Trap Handler Bug

- The vulnerable code was guarded by a test for a specific cs:eip pair in the trap frame.
- We can forge trap frames by making iret fail, but we still can't request iret return into arbitrary code segments, as this would be an obvious privilege escalation (rpl0).
- But...cs loses it's special meaning in Virtual-8086 mode, which is guaranteed to always be cpl3, so it's reasonable to request any value.
- We still need to cause iret to #GP, we did this by setting eflags.TF=1, when returning. This is considered "sensitive", and we get #GP instead.
- This is poorly documented by Intel, but is self-evident from experimentation.

Automation and fuzzing

System Call Exploration

- On Windows, the system call interface is complex, unstable, unsupported and undocumented.
  - It's also vast, with ~1400 entries (cf. Linux ~300).
- They are designed to only ever be called by Microsoft code.
- Rarely see exposure to malformed parameters, so simple fuzzing will generally expose interesting bugs.
- The parameters are often complex objects, multiple levels deep with large inter-dependencies. Pathological parameters will often reach rarely exercised code.
- Of course, the kernel also parses fonts, pixmaps, and other complex formats all at ring0...
  - All excellent fuzz candidates!

System Call Fuzzing

- Trivial fuzzing will find Windows bugs.
- Fuzzing will find Linux bugs, but the task is not so trivial.

- We've developed some interesting techniques for fuzzing on Linux, and have had some success finding minor bugs.

Protecting the kernel and its attack surface

TPE (trusted path executables)*

- A reasonably old concept to prevent local privilege escalation
- Aims to prevent gaining arbitrary code execution in the first place
- A naïve way of doing it on Linux was to mount user-writable PATHs "noexec"
    - Easy bypass by going through the dynamic loader
    - grsecurity had a good gid/uid based one for years
    - Now *could* actually works ("noexec" prevents file mappings as PROT_EXEC)
- This approach is gaining popularity on the Windows platform (white listing)

TPE (drawbacks)

- "Arbitrary code execution" should not only mean "arbitrary opcodes"
  - You can exploit lots of bugs from a Python or Ruby interpreter
- gdb
- The threat model is changed for many binaries
  - a local vulnerability in 'nethack' now becomes useful
  - or those zsh / make vulnerabilities

- Of course, useless if the attacker already has arbitrary code execution
  - Browser sandbox
  - OpenSSH / vsftpd 'privilege-separated' sandbox

Sandboxing and attack surface reduction

- Ideally, a process could opt-out from some kernel features it does not require
- Linux does not have any real "discretionary privilege dropping facility"
  - Most of the focus is on Mandatory Access Control
  - Programmer defined vs. Administratively defined policies debate
- Windows has more privilege-dropping like features (control over tokens)
  - But still nothing to really protect the kernel's attack surface

Options are limited

- On Linux, things such as chroot() to an empty directory remove a small chunk of attack surface
    - cf. Chrome's Linux suid sandbox design
- ptrace() based sandbox
    - Good choice but slow (and not trivial to get right)
- SECCOMP-based sandbox
    - Chrome Linux' future ?

- If we can't protect the kernel let's reduce it's privileges
    - Virtualization is an interesting alternative for seggregation

UDEREF

- Unexpected to userland pointer dereferences are an issue
- We've mentioned Linux/i386 used to have separate logical address space for Kernel/Userland
  - The Kernel's segment descriptors bases were above PAGE_OFFSET
- PaX' UDEREF makes data segments expand-down, limit them above PAGE_OFFSET
- KERNEXEC takes care of the code segment

- What to do on AMD_64 ?
  - No segmentation
  - Full address space switching (Xen does it) ?

mmap_min_addr

- mmap_min_addr is a pragmatic attempt to tackle this problem portably
  - Focusing on NULL pointers dereferences
- system-wide minimum address that can be used in a process
- process with CAP_SYS_RAWIO capability have an exception

- This has been plagued with many bugs in the past
- In much better shape now
  - We've found one bypass using personalities and suid binaries
  - Another one we need to investigate

mmap_min_addr personalities bypass

- CVE-2009-1895
- SVr4 maps page 0 as read-only, some programs depend on this behaviour
  - To make porting programs easier, Linux supports a SVr4 personality
- The personality is per process and is kept on execve()
  - We could get this personality and execute a setuid binary
  - The process gets CAP_SYS_RAWIO since it executes as root now
  - thanks to this capability the mmap_min_addr check succeeds and a page is mapped at zero in the address space

mmap_min_addr personalities bypass

- We now have a process we don't control with a page mapped at zero
- Can we regain control of the process ?
- We were looking for a binary that would drop privileges, and let us regain control without going through execve
- We found one: pulseaudio

Other kernel protection

- From PaX
    - RANDKSTACK
    - KERNEXEC
    - Permission tightening
        - Data in kernel non executable
        - Make some sensitive structures read-only
    - Misc
        - Reference counters overflow
        - Slab object size checks

Conclusion

- There are lots of bugs to find in kernels
  - And the attack surface is growing in general
  - And easier to reach from remote
- Their exploitation difficulty goes from very easy to very challenging
- It's hard to get rid of the kernel's attack surface
  - Remains even in systems designed with security in mind
  - May evolve soon
- Userland exploitation prevention is maturing
  - Kernel exploitation prevention is immature
  - And current sandboxing techniques make the kernel an ideal target

Thanks!

- Questions ?

Bonus Slides

Windows Virtual Path Parsing

- MS10-21 fixed an interesting bug parsing virtual paths.
- A core routine handling virtualized keys made some invalid assumptions about virtualized registry keys.
- A typical path would something like `L"\\Registry\\user\\S-x-y-z"`
- A registry key can be nested arbitrarily deep.
- But we found a routine that assumed every path would contain at least five path seperators!
- This is simply not the case...

Windows Virtual Path Parsing

```
while (MaxDirectories) {
    if (*CurrentChar == '\\') {
      if (--MaxDirectories == 0)
        break;
    } else {
        CurrentChar++;
        Count++;
    }
}
```

Windows Virtual Path Parsing

- This assumption can be broken by simply setting the VirtualTarget flag on a key that does not have five path components.

```
// Set Virtual Target
Virt.VirtualTarget = 1;
// http://msdn.microsoft.com/en-us/library/cc512139%
28VS.85%29.aspx
ReturnCode = NtSetInformationKey(KeyHandle,
KeySetVirtualizationInformation, &Virt, sizeof
(KEY_SET_VIRTUALIZATION_INFORMATION));
```

Windows Virtual Path Parsing

- It's not immediately clear why anyone would make this error.
- Not even an inexperienced Windows developer would believe an arbitrary registry key would conform to these rules.
- Matthieu Suiche pointed out that VirtualStore keys do conform to these rules, and so it's likely Microsoft simply didn't test with any other keys.

MiCreatePagingFileMap() Vulnerability

- MiCreatePagingFileMap() contained an interesting optimisation in PAE kernels.
- This routine accepts a PLARGE_INTEGER parameter, and is the kernel code responsible for things like CreateFileMapping().
- We noticed that part of the routine realised the parameter was 64bits, and part assumed it was 32bits.
- We could bypass the sanity checks by hiding bits in the upper dword.
- This results in an obvious heap overflow, a minimal testcase would be something like this.

```
CreateFileMappingA(NULL, NULL, PAGE_WRITECOPY, 0x6c, 0, NULL);
```