Windows Kernel Trap Handler and NTVDM Vulnerabilities – Case Study

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Introduction

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- Extremely into Windows NT internals
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What?

Case study of recent **NT Virtual DOS Machine** vulnerabilities in the Windows kernel fixed by the **MS13-063** bulletin.

Topics covered

- A brief history of Real mode, Virtual-8086 mode and Windows NTVDM
- Prior research
- Case study
    a. **CVE-2013-3196** (`nt!PushInt` write-what-where condition)
    b. **CVE-2013-3197** (`nt!PushException` write-what-where condition)
    c. **CVE-2013-3198** (`nt!VdmCallStringIoHandler` write-where condition)
    d. **0-day** (`nt!PushPmInterrupt` and `nt!PushRmInterrupt` Blue Screen of Death DoS)
- Conclusions and final thoughts

Why?

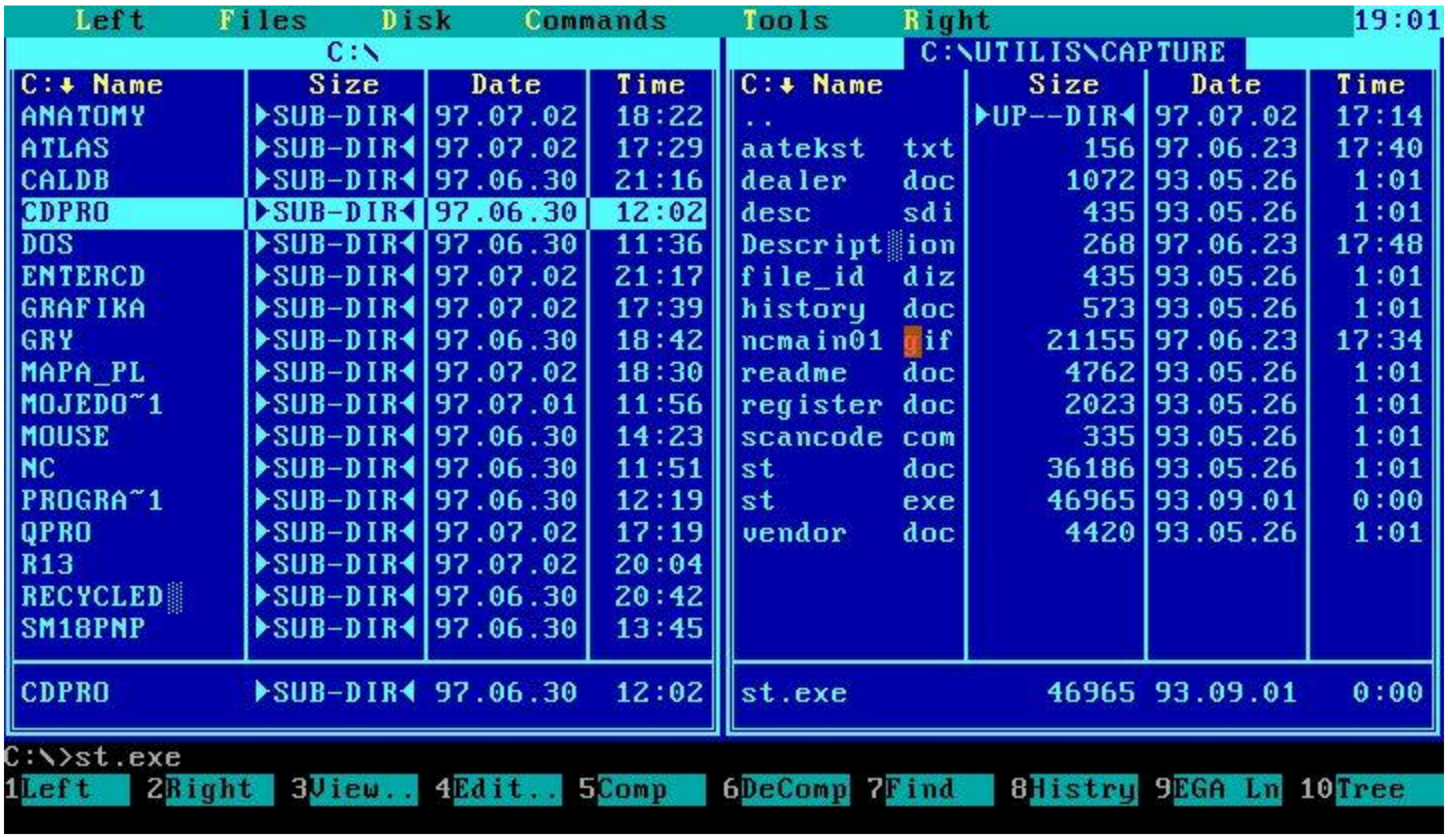
Operating system security is the last line of defense for client software security today.

e.g. see MWR Labs pwn2own 2013 Windows win32k.sys exploit write-up:

https://labs.mwrinfosecurity.com/blog/2013/09/06/mwr-labs-pwn2own-2013-write-up---kernel-exploit/

Real mode, Virtual-8086 mode and Windows

Back in the day…

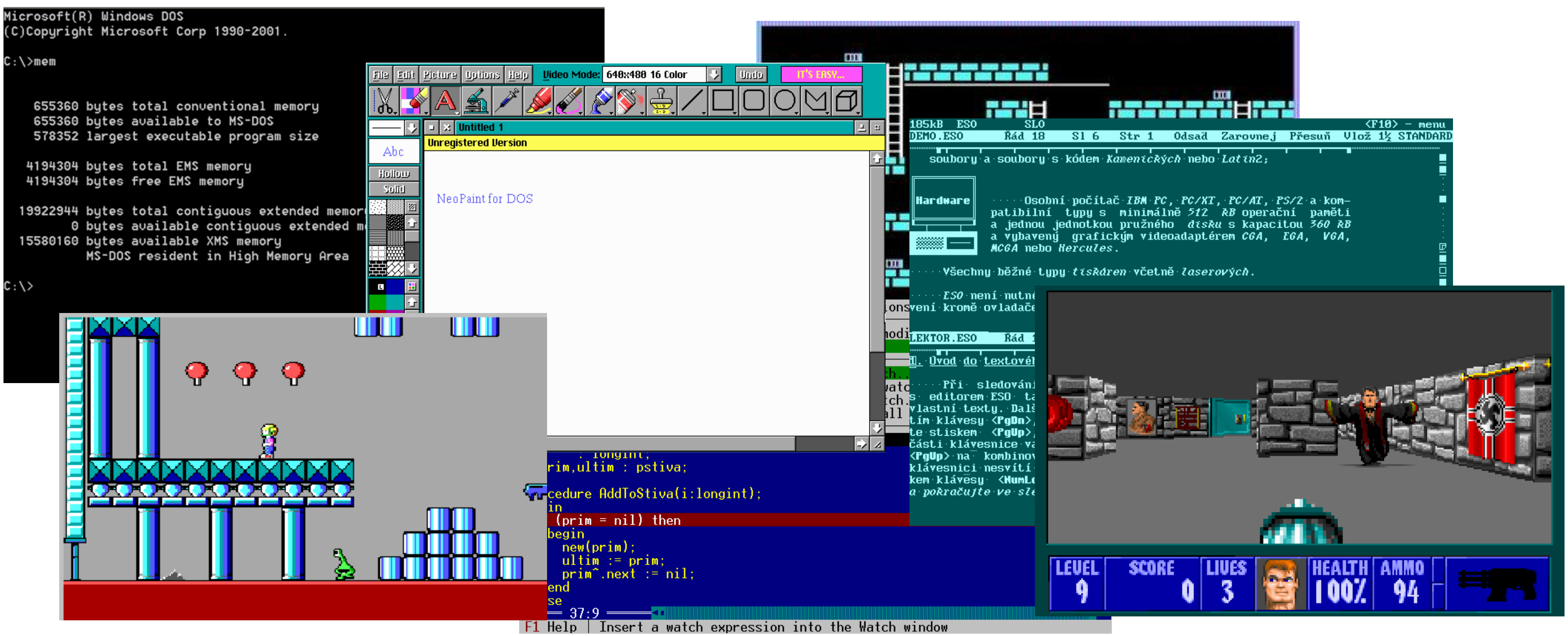


Real mode – the beginnings of x86

- First introduced in 1978 with the Intel 8086 CPU.
- Primary execution mode on x86 until ~1990.
- Key characteristics
  - Segmented addressing mode.
  - Addressable memory limited to 2^{20} (1 048 576) bytes = 1MB.
    - a little more with the A20 line enabled.
  - Limited execution context – eight general purpose 16-bit registers.
  - Lack of system security support.
    - no privilege level separation.
    - no memory protection.
    - no multitasking.

Real mode – the beginnings of x86

- Despite the architecture limitations, a number of programs were developed for 16-bit Real Mode.



Intel 80386 – the start of new era

- In 1985, Intel introduces a first CPU with full Protected mode.
  - Privilege level separation (rings 0-3)
  - Paging
  - Memory protection
  - Multitasking
  - Addressable memory extended to 2^{32} bytes (4GB)
- **NOT** backward compatible with Real mode.
  - Different CPU context, address width, instruction encoding and more.

Intel 80386 – the start of new era

- Protected mode was partially adopted by the Windows 3.1x and Windows 9x families.
  - *Hybrid* platforms, i.e. they switched back and forth between the 16-bit real and 32-bit protected modes.
- Windows NT 3.1 was the first fully 32-bit system released by Microsoft.
  - All further NT-family systems executed in Protected mode, until Long mode (64-bit) came along.

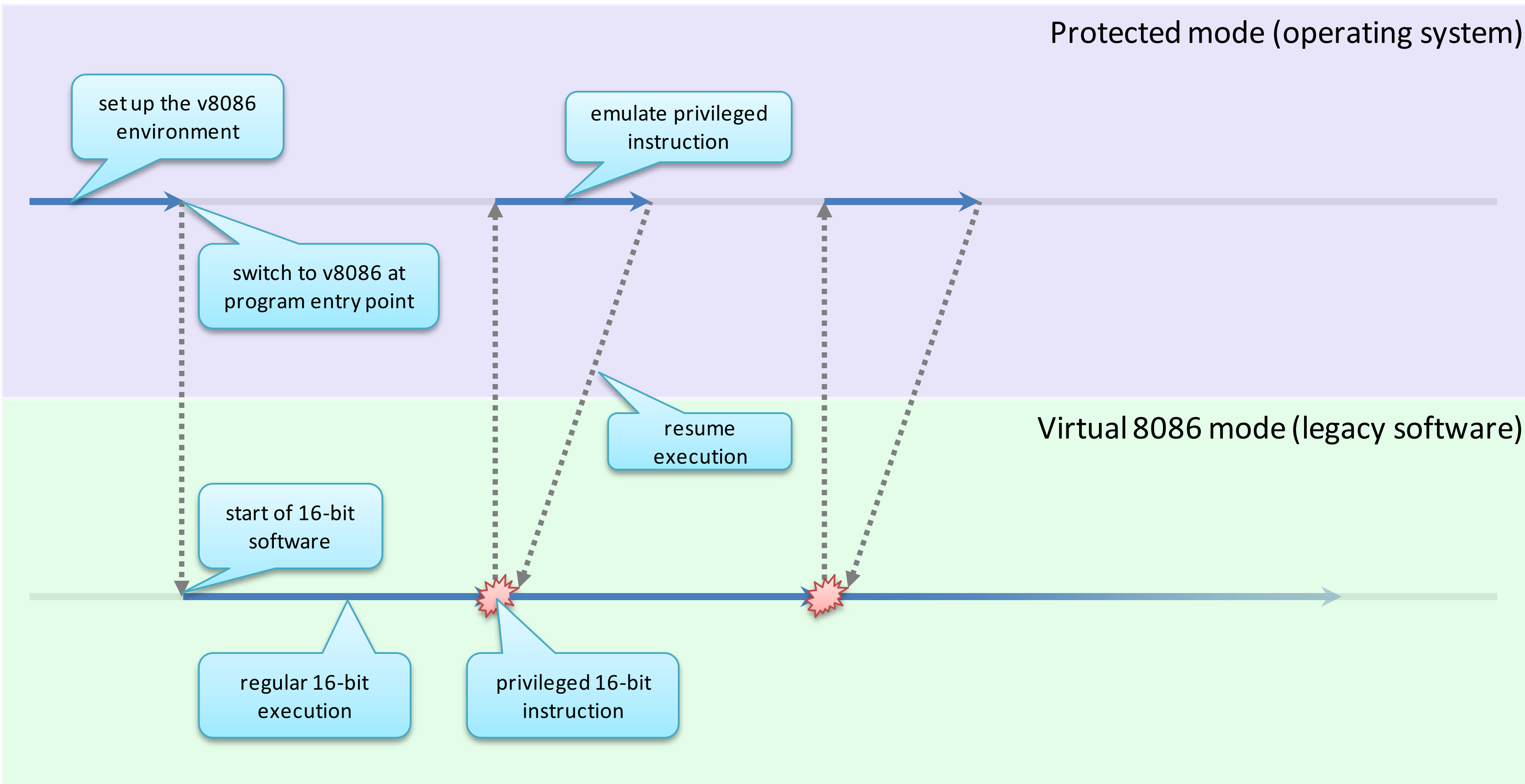
But hey…

… what about backward compatibility with all the DOS games and accounting software?

Basics of DOS compatibility

- Switching back to real mode to execute legacy software compromises 32-bit OS security.
- Effective solution: **Virtual 8086 mode**
  - Separate execution mode shipped by Intel as an integral part of Protected mode.
  - Designed specifically to enable secure execution of antique 16-bit programs within a “sandbox”.
  - Implements a trap-based “virtualization” environment.
    - From inside: analogous to actual Real mode.
    - From outside: managed by the operating system.

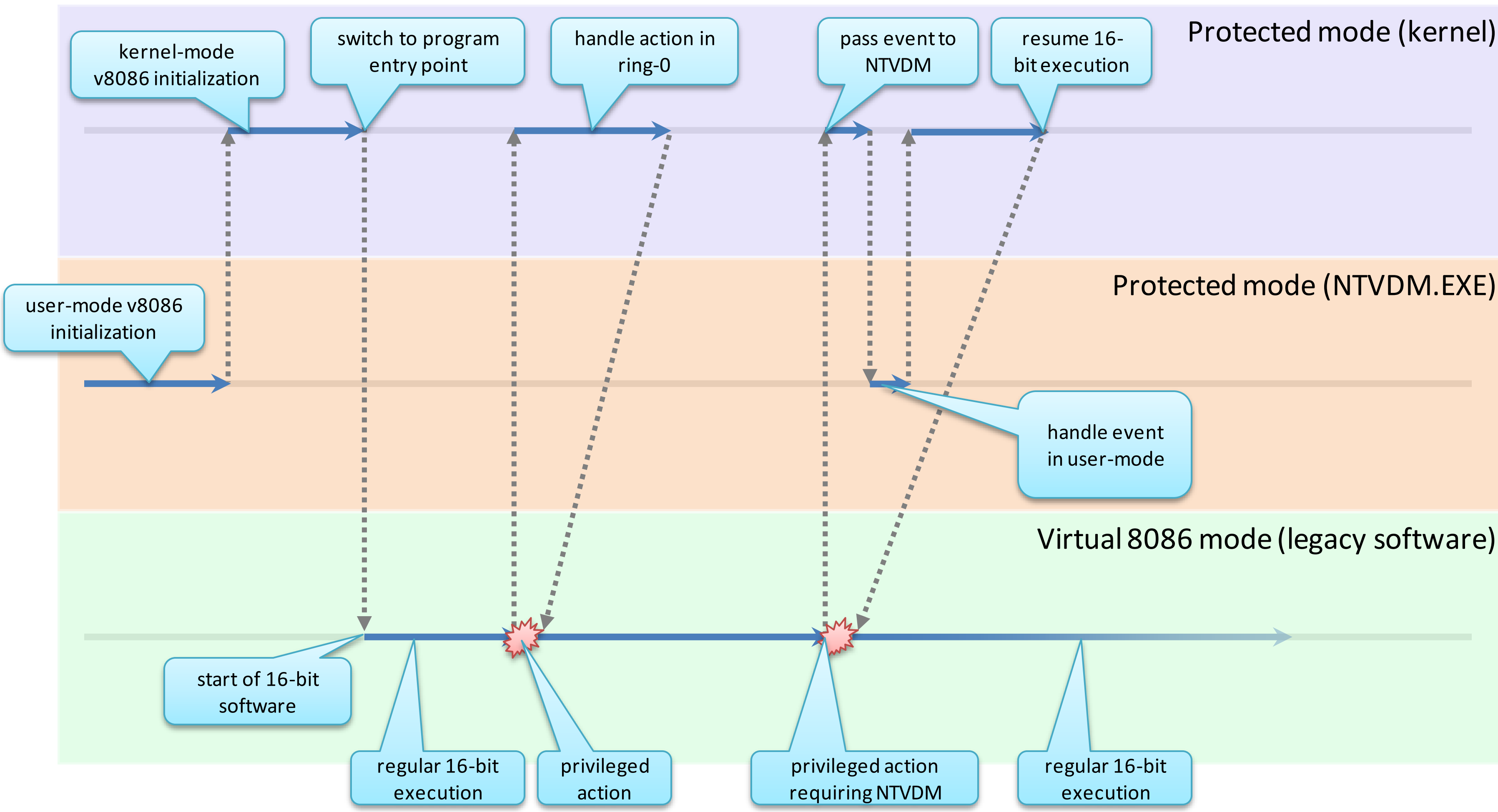
Legacy software execution flow in v8086



In Windows, things get more interesting

- Parts of the hypervisor are implemented directly in the kernel.
- All remaining functionality is handled by a user-mode NTVDM.EXE process.
  - As in "NT Virtual DOS Machine"
  - 32-bit host process for 16-bit apps.

Legacy software execution flow in Windows

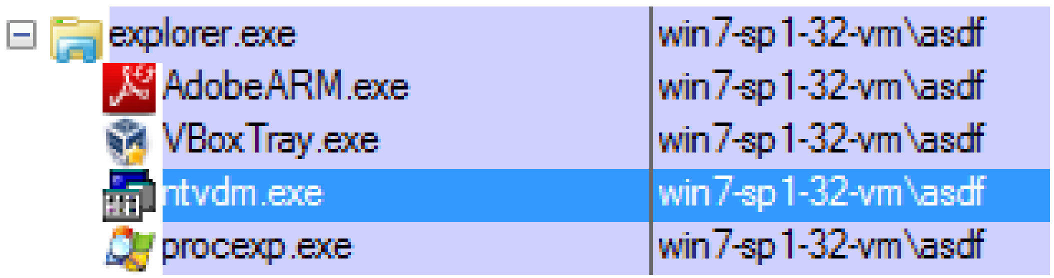


Kernel attack surface

- The NTVDM.EXE process is treated in a very special way by the Windows kernel.
  - Performance “hooks” in x86 trap handlers.
    - `KiTrap00`, `KiTrap01`, `KiTrap02`, `KiTrap03`, `KiTrap04`, `KiTrap05`, `KiTrap06`, `KiTrap07`, `KiTrap0b`, `KiTrap0c`, `KiTrap0d`, `KiTrap0e`, `KiTrap13`
  - Dedicated system calls in `ntoskrnl.exe`.
    - `nt!NtVdmControl`, …
  - Dedicated system calls in `win32k.sys`.
    - `win32k!NtUserInitTask`, …

Attack surface availability

- NTVDM.EXE is “special”, but runs with local user’s security token.



- User can run arbitrary 32-bit code within the subsystem via `OpenProcess()` and `CreateRemoteThread()`.
- Entire VDM – related attack surface is freely available to the local attacker.

Attack surface availability – problems

- Long mode doesn't support virtual-8086.
  - Consequently, VDM is eliminated from all x64 platforms.
    - … making the vector only suitable for 32-bit systems.
- Microsoft disabled NTVDM by default starting with Windows 8.
  - Globally re-enabling requires administrative rights (HKLM access)
  - Very good mitigation decision.
- Vulnerabilities still good for:
  - All 32-bit platforms up to and including Windows 7.
  - Windows 8 and 8.1 running DOS programs (e.g. some enterprises or DOS gamers' machines).

Prior research

Historical look at NTVDM security

Support for legacy 16-bit programs in Windows has a long history of vulnerabilities.

CVE-2004-0118: Windows VDM TIB Local Privilege Escalation

- **Discovered by:** Derek Soeder
- **Release date:** April 13, 2004
- **Affected platforms:** Windows NT 4.0 – Server 2003
- **Type:** Loading untrusted CPU context by the #UD trap handler.

CVE-2004-0208: Windows VDM #UD Local Privilege Escalation

- **Discovered by:** Derek Soeder
- **Release date:** October 12, 2004
- **Affected platforms:** Windows NT 4.0 – 2000
- **Type:** NULL Pointer Dereference due to uninitialized pointer in a non-typical order of `nt!NtVdmControl` calls.

CVE-2007-1206: Zero Page Race Condition Privilege Escalation

- **Discovered by:** Derek Soeder
- **Release date:** April 10, 2007
- **Affected platforms:** Windows NT 4.0 – Server 2003
- **Type:** Race condition in accessing a user-mode memory mapping with writable access triggered via `nt!NtVdmControl`.

CVE-2010-0232: Microsoft Windows #GP Trap Handler Local Privilege Escalation Vulnerability

- **Discovered by:** Tavis Ormandy
- **Release date:** January 19, 2010
- **Affected platforms:** Windows 2000 - 7
- **Type:** Kernel-mode stack switch caused by invalid assumptions made by the `nt!KiTrap0d` trap handler.

CVE-2010-3941: Windows VDM Task Initialization Vulnerability

- **Discovered by:** Tarjei Mandt
- **Release date:** December 15, 2010
- **Affected platforms:** Windows 2000 - 7
- **Type:** Double free condition caused by a vulnerability in `win32k!NtUserInitTask`.

CVE-2012-2553: Windows Kernel VDM use-after-free condition

- **Discovered by:** Mateusz “j00ru” Jurczyk
- **Release date:** December 18, 2012
- **Affected platforms:** Windows XP - 7
- **Type:** Use-after-free condition caused by a vulnerability in `win32k!xxxRegisterUserHungAppHandlers`.

Summary

- There have been all sorts of memory errors in each VDM-related component: the trap handlers, nt system calls and win32k.sys system calls.
- Having discovered that the security posture of trap handlers is miserable even in Windows 7 earlier this year, I decided to take a deeper look into them.
  - For some trap handler bugs from the past, see slides from my "Abusing the Windows Kernel" talk at NoSuchCon 2013.

Case study

CVE-2013-3196

(`nt!PushInt` write-what-where condition)

Word of introduction on #GP

- Interrupt 13 – General Protection Exception (#GP)
  - Triggered upon most security-related CPU events.
  - Primarily user-mode threads attempting to perform forbidden operations.
  - The list is extremely long, see Intel Manuals 3A, section "Interrupt 13".

General protection exception triggers

- Exceeding the segment limit when accessing the CS, DS, ES, FS, or GS segments.
- Exceeding the segment limit when referencing a descriptor table (except during a task switch or a stack switch).
- Transferring execution to a segment that is not executable.
- Writing to a code segment or a read-only data segment.
- Reading from an execute-only code segment.
- Loading the SS register with a segment selector for a read-only segment (unless the selector comes from a TSS during a task switch, in which case an invalid-TSS exception occurs).
- Loading the SS, DS, ES, FS, or GS register with a segment selector for a system segment.
- Loading the DS, ES, FS, or GS register with a segment selector for an execute-only code segment.
- Loading the SS register with the segment selector of an executable segment or a null segment selector.
- Loading the CS register with a segment selector for a data segment or a null segment selector.
- Accessing memory using the DS, ES, FS, or GS register when it contains a null segment selector.
- Switching to a busy task during a call or jump to a TSS.
- Using a segment selector on a non-IRET task switch that points to a TSS descriptor in the current LDT. TSS descriptors can only reside in the GDT. This condition causes a #TS exception during an IRET task switch.
- Violating any of the privilege rules described in Chapter 5, "Protection."
- Exceeding the instruction length limit of 15 bytes (this only can occur when redundant prefixes are placed before an instruction).
- Loading the CR0 register with a set PG flag (paging enabled) and a clear PE flag (protection disabled).
- Loading the CR0 register with a set NW flag and a clear CD flag.
- Referencing an entry in the IDT (following an interrupt or exception) that is not an interrupt, trap, or task gate.
- Attempting to access an interrupt or exception handler through an interrupt or trap gate from virtual-8086 mode when the handler's code segment DPL is greater than 0.
- Attempting to write a 1 into a reserved bit of CR4.
- Attempting to execute a privileged instruction when the CPL is not equal to 0 (see Section 5.9, "Privileged Instructions," for a list of privileged instructions).
- Writing to a reserved bit in an MSR.
- Accessing a gate that contains a null segment selector.
- Executing the INT *n* instruction when the CPL is greater than the DPL of the referenced interrupt, trap, or task gate.
- The segment selector in a call, interrupt, or trap gate does not point to a code segment.
- The segment selector operand in the LLDT instruction is a local type (TI flag is set) or does not point to a segment descriptor of the LDT type.
- The segment selector operand in the LTR instruction is local or points to a TSS that is not available.
- The target code-segment selector for a call, jump, or return is null.
- If the PAE and/or PSE flag in control register CR4 is set and the processor detects any reserved bits in a page-directory-pointer-table entry set to 1. These bits are checked during a write to control registers CR0, CR3, or CR4 that causes a reloading of the page-directory-pointer-table entry.
- Attempting to write a non-zero value into the reserved bits of the MXCSR register.
- Executing an SSE/SSE2/SSE3 instruction that attempts to access a 128-bit memory location that is not aligned on a 16-byte boundary when the instruction requires 16-byte alignment. This condition also applies to the stack segment.

Privileged instructions

- Privileged instructions can only be executed at `CPL=0`

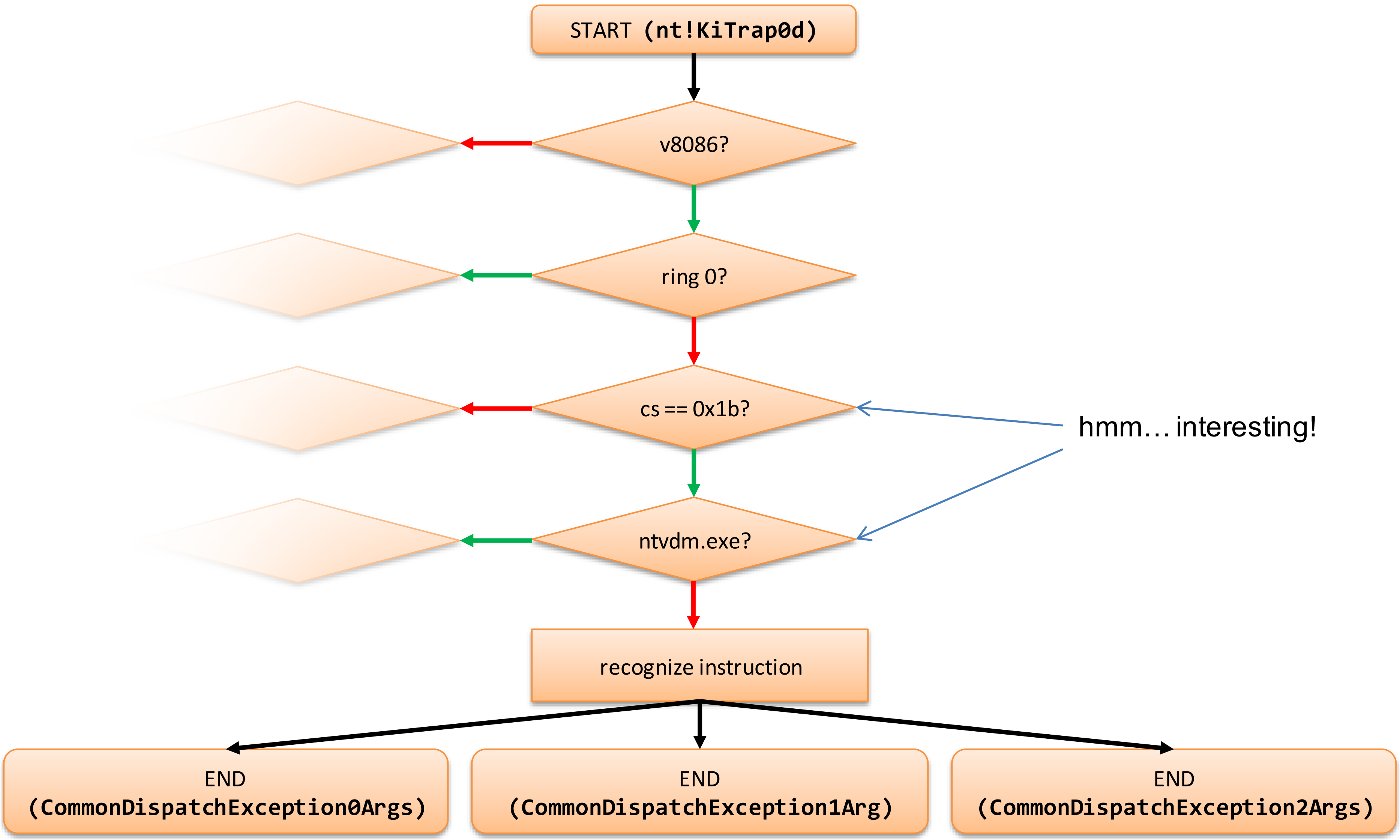
CLTS – Clear Task-Switched Flag	**MOV CRn** – Move Control Register
HLT – Halt Processor	**MOV DRn** – Move Debug Register
INVD - Invalidate Internal Caches	**MOV TRn** – Move Test Register
INVLPG - Invalidate TLB Entry	**MWAIT** - Monitor Wait
INVPCID - Invalidate Process-Context Identifier	**RDMSR** - Read from Model Specific Register
LGDT – Load GDT Register	**RDPMC** - Read Performance-Monitoring Counters
LIDT – Load IDT Register	**SYSEXIT** - Fast Return From Fast System Call
LLDT – Load LDT Register	**WBINVD** - Write Back and Invalidate Cache
LMSW – Load Machine Status	**WRMSR** - Write to Model Specific Register
LTR – Load Task Register	**XSETBV** - Set Extended Control Register
MONITOR - Set Up Monitor Address	

Sensitive instructions

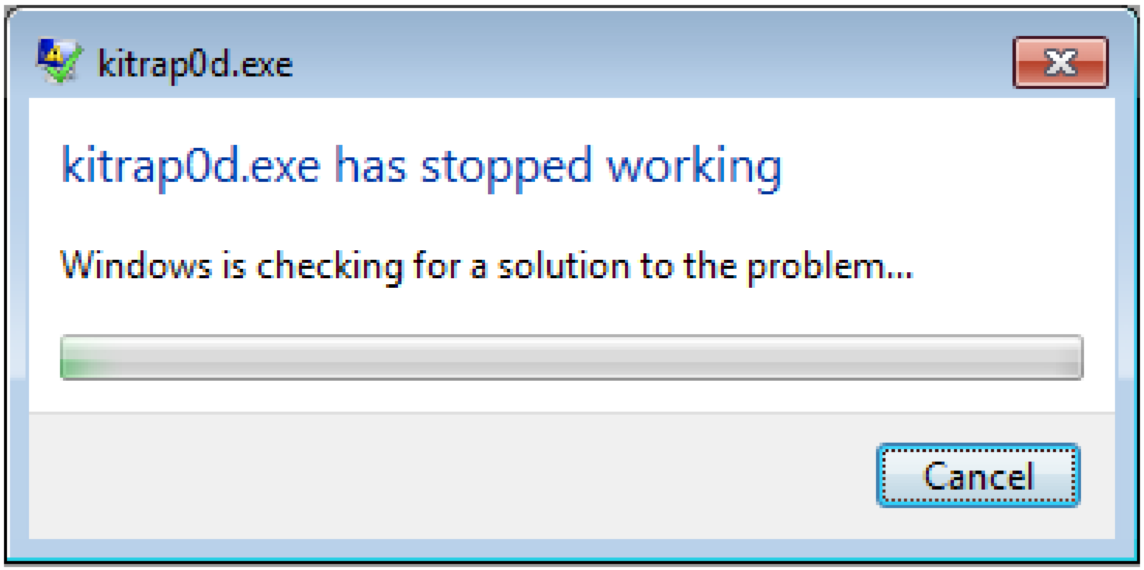
- Sensitive instructions can only be executed at `CPL ≤ IOPL`

IN – Input	**OUTS** – Output String
INS – Input String	**CLI** – Clear Interrupt-Enable Flag
OUT – Output	**STI** – Set Interrupt-Enable Flag

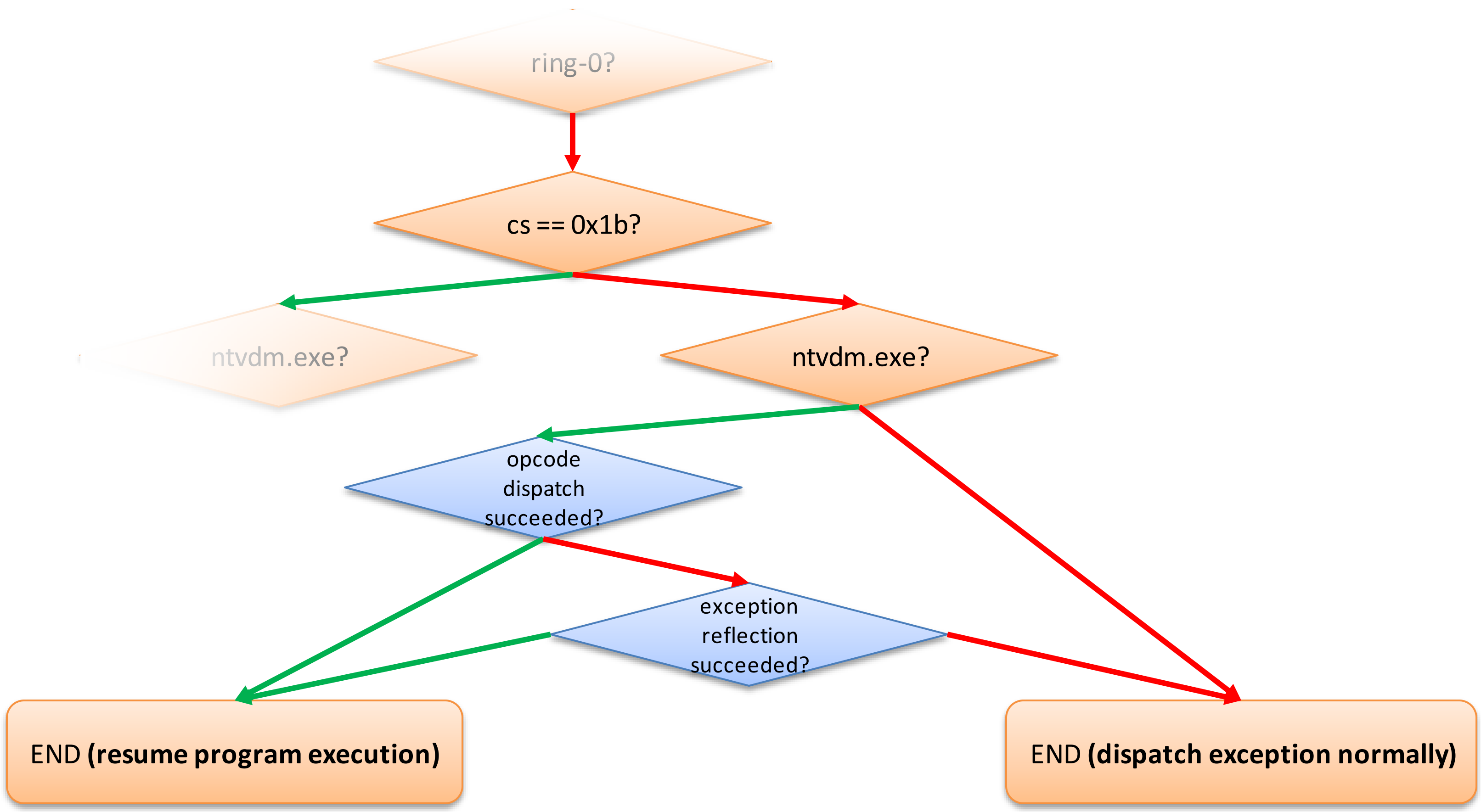
When ring-3 meets a privileged / sensitive instruction…



nt!CommonDispatchException

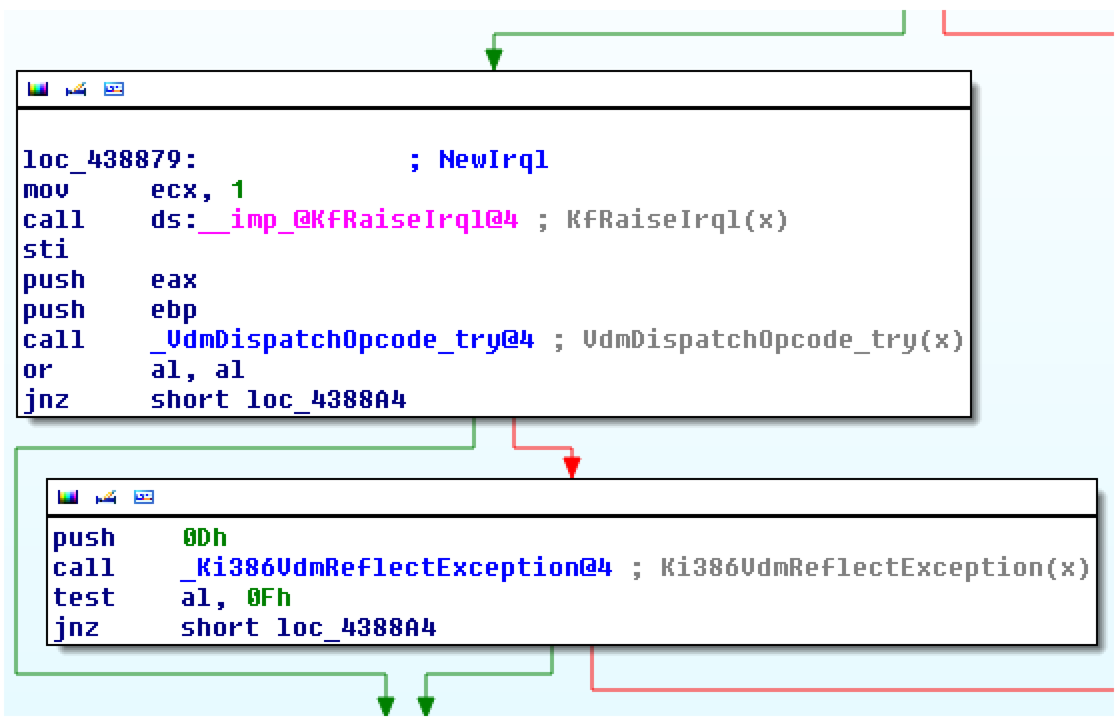


What are the other branches for?



VDM Opcode dispatching

- A special #GP handler branch is taken for two conditions:
  - `KTRAP_FRAME.SegCS != KGDT_R3_CODE`
  - The process is a VDM host.
- Part of DPMI (DOS Protected Mode Interface) support.



Inside nt!VdmDispatchOpcode_try()

```
PAGEDATA:00759100 ; int (__usercall *OpcodeDispatch)<eax>(int<ecx>, char<bl>, int<edi>, Reginfo *<esi>)
PAGEDATA:00759100 OpcodeDispatch  dd offset OpcodeInvalid ; DATA XREF: Ki386DispatchOpcode(x)+78↑r
PAGEDATA:00759100                                         ; OpcodeGenericPrefix+2B↑r
PAGEDATA:00759104                 dd offset Opcode0F
PAGEDATA:00759108                 dd offset OpcodeESPrefix
PAGEDATA:0075910C                 dd offset OpcodeCSPrefix
PAGEDATA:00759110                 dd offset OpcodeSSPrefix
PAGEDATA:00759114                 dd offset OpcodeDSPrefix
PAGEDATA:00759118                 dd offset OpcodeFSPrefix
PAGEDATA:0075911C                 dd offset OpcodeGSPrefix
PAGEDATA:00759120                 dd offset OpcodeOPER32Prefix
PAGEDATA:00759124                 dd offset OpcodeADDR32Prefix
PAGEDATA:00759128                 dd offset OpcodeINSB
PAGEDATA:0075912C                 dd offset OpcodeINSW
PAGEDATA:00759130                 dd offset OpcodeOUTSB
PAGEDATA:00759134                 dd offset OpcodeOUTSW
PAGEDATA:00759138                 dd offset OpcodeInvalid
PAGEDATA:0075913C                 dd offset OpcodeInvalid
PAGEDATA:00759140                 dd offset OpcodeINTnn
PAGEDATA:00759144                 dd offset OpcodeINTO
PAGEDATA:00759148                 dd offset OpcodeInvalid
PAGEDATA:0075914C                 dd offset OpcodeInvalid
PAGEDATA:00759150                 dd offset OpcodeINBimm
PAGEDATA:00759154                 dd offset OpcodeINWimm
PAGEDATA:00759158                 dd offset OpcodeOUTBimm
PAGEDATA:0075915C                 dd offset OpcodeOUTWimm
PAGEDATA:00759160                 dd offset OpcodeINB
PAGEDATA:00759164                 dd offset OpcodeINW
PAGEDATA:00759168                 dd offset OpcodeOUTB
PAGEDATA:0075916C                 dd offset OpcodeOUTW
PAGEDATA:00759170                 dd offset OpcodeLOCKPrefix
PAGEDATA:00759174                 dd offset OpcodeREPNEPrefix
PAGEDATA:00759178                 dd offset OpcodeREPPrefix
PAGEDATA:0075917C                 dd offset OpcodeCLI
PAGEDATA:00759180                 dd offset OpcodeSTI
PAGEDATA:00759184                 dd offset OpcodeInvalid
PAGEDATA:00759188                 dd offset OpcodeInvalid
```

What the heck… ?

Windows implements kernel-level emulation of sensitive 32-bit instructions executed within NTVDM.EXE!

What can go wrong?

There's 16-bit emulation, too!

Also invoked by nt!KiTrap0d, remember the first "v8086" branch?

```
PAGEDATA:0075921C                 dd offset Opcode0FV86
PAGEDATA:00759220                 dd offset OpcodeESPrefixV86
PAGEDATA:00759224                 dd offset OpcodeCSPrefixV86
PAGEDATA:00759228                 dd offset OpcodeSSPrefixV86
PAGEDATA:0075922C                 dd offset OpcodeDSPrefixV86
PAGEDATA:00759230                 dd offset OpcodeFSPrefixV86
PAGEDATA:00759234                 dd offset OpcodeGSPrefixV86
PAGEDATA:00759238                 dd offset OpcodeOPER32PrefixV86
PAGEDATA:0075923C                 dd offset OpcodeADDR32PrefixV86
PAGEDATA:00759240                 dd offset OpcodeINSBV86
PAGEDATA:00759244                 dd offset OpcodeINSWV86
PAGEDATA:00759248                 dd offset OpcodeOUTSBV86
PAGEDATA:0075924C                 dd offset OpcodeOUTSWV86
PAGEDATA:00759250                 dd offset OpcodePUSHFV86
PAGEDATA:00759254                 dd offset OpcodePOPFV86
PAGEDATA:00759258                 dd offset OpcodeINTnnV86
PAGEDATA:0075925C                 dd offset OpcodeINTOV86
PAGEDATA:00759260                 dd offset OpcodeIRETV86
PAGEDATA:00759264                 dd offset OpcodeNPXV86
PAGEDATA:00759268                 dd offset OpcodeINBimmV86
PAGEDATA:0075926C                 dd offset OpcodeINWimmV86
PAGEDATA:00759270                 dd offset OpcodeOUTBimmV86
PAGEDATA:00759274                 dd offset OpcodeOUTWimmV86
PAGEDATA:00759278                 dd offset OpcodeINBV86
PAGEDATA:0075927C                 dd offset OpcodeINWV86
PAGEDATA:00759280                 dd offset OpcodeOUTBV86
PAGEDATA:00759284                 dd offset OpcodeOUTWV86
PAGEDATA:00759288                 dd offset OpcodeLOCKPrefixV86
PAGEDATA:0075928C                 dd offset OpcodeREPNEPrefixV86
PAGEDATA:00759290                 dd offset OpcodeREPPrefixV86
PAGEDATA:00759294                 dd offset OpcodeCLIV86
PAGEDATA:00759298                 dd offset OpcodeSTIV86
PAGEDATA:0075929C                 dd offset OpcodeHLTV86
```

Quick summary

- Sensitive instructions executed in NTVDM.EXE don't cause immediate crash.
  - The #GP handler attempts to seamlessly emulate them.
  - Sounds extremely fishy and potentially error-prone!
- In May 2013, I was probably the only person who had decided to perform an extensive security review of the codebase.
  - It dates back to 1993 (Windows NT 3.1), so every bug found likely affected every 32-bit NT-family operating system out there.
- I reverse engineered each of the emulation handlers very carefully… ☺
  - If you have access to WRK, the functionality is found in `base\ntos\ke\i386\instemul.asm`

First vulnerability found in…

`nt!OpcodeINTnn`

An insight into nt!OpcodeINTnn()

```c
BOOLEAN OpcodeINTnn(PKTRAP_FRAME trap_frame, PVOID eip, Reginfo *reginfo) {
    if ((*(DWORD *)0x714 & 0x203) == 0x203) {
            VdmDispatchIntAck();
            return TRUE;
    }

    reginfo->RiEFlags = GetVirtualBits(trap_frame->EFlags);
    if (!SsToLinear(trap_frame->HardwareSegSs, reginfo)) {
            return FALSE;
    }

    PBYTE IntOperandPtr = eip + 1;
    if (IntOperandPtr - reginfo->RiCsBase > reginfo->RiCsLimit ||
        IntOperandPtr > MmHighestUserAddress) {
            return FALSE;
    }

    reginfo->RiEip = IntOperandPtr - reginfo->RiCsBase + 1;
    if (!PushInt(*IntOperandPtr, trap_frame, reginfo)) {
            return FALSE;
    }

    //
    // Set trap_frame->HardwareEsp, trap_frame->SegCs, trap_frame->EFlags
    // and trap_frame->Eip.
    //

    return TRUE;
}
```

quick dispatch, omitted

fill out stack fields in `Reginfo`

obtain the `INT imm8` operand

call `nt!PushInt()`

The Reginfo structure

- Internal, undocumented structure used internally for VDM instruction emulation.
- Stores parts of KTRAP_FRAME plus additional information.

```
00000000 Reginfo         struc ; (sizeof=0x38)
00000000
00000000 RiSegSs         dd ?
00000004 RiEsp           dd ?
00000008 RiEFlags        dd ?
0000000C RiSegCs         dd ?
00000010 RiEip           dd ?
00000014 RiTrapFrame     dd ?
00000018 RiCsLimit       dd ?
0000001C RiCsBase        dd ?
00000020 RiCsFlags       dd ?
00000024 RiSsLimit       dd ?
00000028 RiSsBase        dd ?
0000002C RiSsFlags       dd ?
00000030 RiPrefixFlags   dd ?
00000034 RiOperand       dd ?
00000038 Reginfo         ends
```

Inside nt!PushInt(), part 1.

```
BOOLEAN PushInt(ULONG int_no, PKTRAP_FRAME trap_frame, Reginfo *reginfo) {
     PVDM_TIB VdmTib;
     VDM_INTERRUPT *VdmInt;
     PVOID VdmEsp, NewVdmEsp;

     VdmTib = NtCurrentTeb()->Vdm;
     if (VdmTib >= MmUserProbeAddress) {
             return FALSE;
     }

     VdmInt = &VdmTib->VtInterruptTable[int_no];
     if (VdmInt >= MmUserProbeAddress) {
             return FALSE;
     }

     VdmEsp = trap_frame->HardwareEsp;
     if ((reginfo->RiSsFlags & SEL_TYPE_BIG) == 0) {
             VdmEsp = (USHORT)VdmEsp;
     }

     if (VdmInt->ViFlags & VDM_INT_32) {
             if (VdmEsp < 12) {
                     return FALSE;
             }

             NewVdmEsp = VdmEsp - 12;
     } else {
             if (VdmEsp < 6) {
                     return FALSE;
             }

             NewVdmEsp = VdmEsp - 6;
     }

     reginfo->RiEsp = NewVdmEsp;
```

load user-mode VDM_INTERRUPT structure from TEB for specified invoked interrupt.

decrement user-mode Esp by 6 or 12 depending on VDM_INTERRUPT flags.

Inside nt!PushInt(), part 2.

check that new Esp is within ss: limits

```
if (reginfo->RiSsFlags & SEL_TYPE_ED) {
    if (NewVdmEsp <= reginfo->RiSsLimit) {
        return FALSE;
    }
} else if (NewVdmEsp >= reginfo->RiSsLimit) {
    return FALSE;
}
```

write-what-where conditions

```
if (reginfo->ViFlags & VDM_INT_32) {
    *(DWORD *)(reginfo->RiSsBase + NewVdmEsp + 0) = reginfo->RiEip;
    *(DWORD *)(reginfo->RiSsBase + NewVdmEsp + 4) = trap_frame->SegCs;
    *(DWORD *)(reginfo->RiSsBase + NewVdmEsp + 8) = GetVirtualBits(reginfo->RiEFlags);
} else {
    *(WORD *)(reginfo->RiSsBase + NewVdmEsp + 0) = reginfo->RiEip;
    *(WORD *)(reginfo->RiSsBase + NewVdmEsp + 2) = trap_frame->SegCs;
    *(WORD *)(reginfo->RiSsBase + NewVdmEsp + 4) = GetVirtualBits(reginfo->RiEFlags);
}
```

Write-what-where condition

- Kernel emulates VDM instructions by manually crafting a trap frame on user stack.
  - Uses the full `ss:esp` user-mode address.
  - Didn’t perform address sanity checks (e.g. `ProbeForWrite`)
  - We could write 6 or 12 semi-controlled bytes into arbitrary kernel memory.

Reproduction – proof of concept

```
mov esp, 0xdeadbeef
int 0
```

- Above two instructions must be executed in the main `NTVDM.EXE` thread.
  - Vulnerability requires fully initialized VDM environment (`VdmTib` pointer in `TEB` and so forth). Also, `cs:` and `ss:` must point to custom LDT segments.
  - `Esp` can be any invalid kernel-mode address for the system to crash.
  - The `INT imm8` operand must be a kernel-mode trap (anything but `0x2a` - `0x2e`) to generate a #GP exception.

Reproduction – results

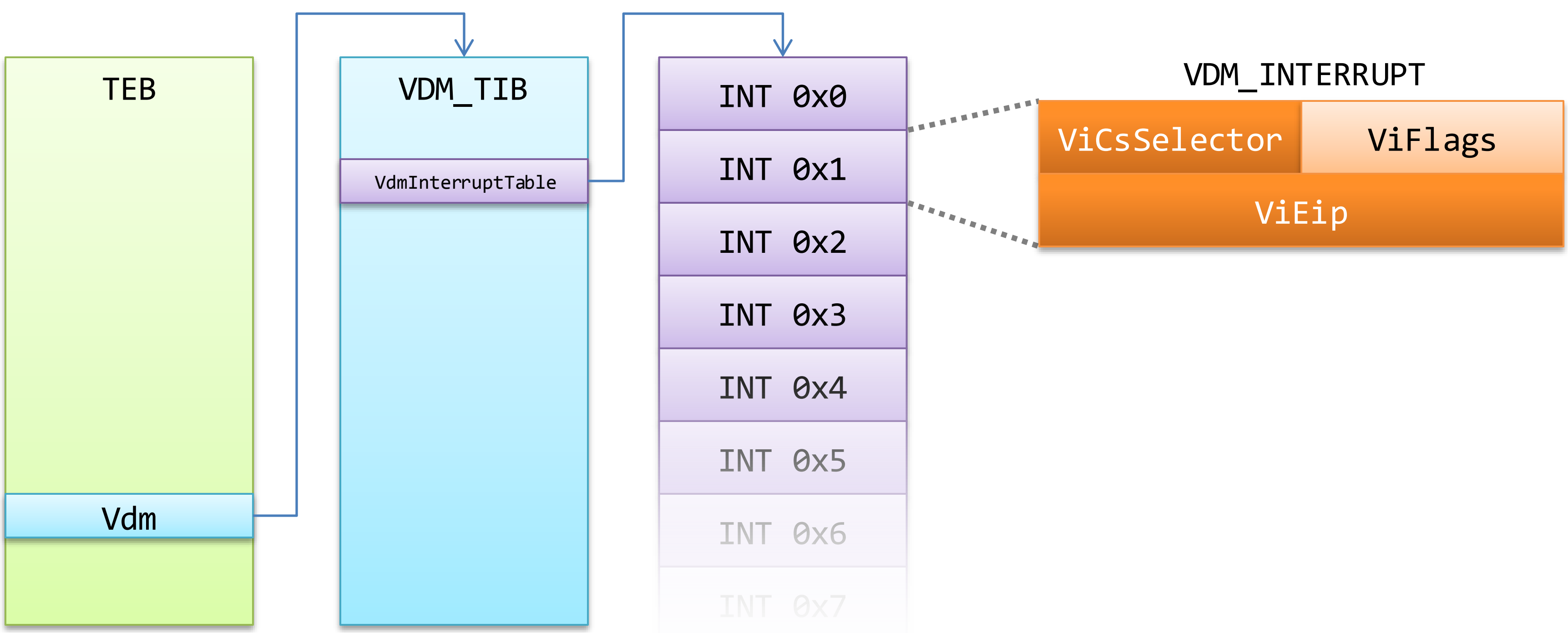
```
TRAP_FRAME:  a2ea4c24 -- (.trap 0xffffffffa2ea4c24)
ErrCode = 00000002
eax=024ef568 ebx=00000000 ecx=00000000 edx=6710140f esi=a2ea4cb8 edi=deadbee3
eip=82ab21a7 esp=a2ea4c98 ebp=a2ea4d34 iopl=0         nv up ei pl nz na po nc
cs=0008  ss=0010  ds=0023  es=0023  fs=0030  gs=0000             efl=00010202
nt!PushInt+0xa5:
82ab21a7 89143b          mov     dword ptr [ebx+edi],edx ds:0023:deadbee3=????????
Resetting default scope
```

Maintaining reliability

Just a write-what-where condition is not enough; we want to maintain control over the process.

nt!OpcodeINTnn - epilogue

- After a "trap frame" is created, the return `cs:eip` is transferred to:
  - `NtCurrentTeb()->Vdm->VtInterruptTable[int_no].ViCsSelector`
  - `NtCurrentTeb()->Vdm->VtInterruptTable[int_no].ViEip`



`nt!OpcodeINTnn` – epilogue cont'd.

All required structures are in user-mode.

If we properly initialize the `VdmInterruptTable` pointer,

we can control where execution goes after the exception.

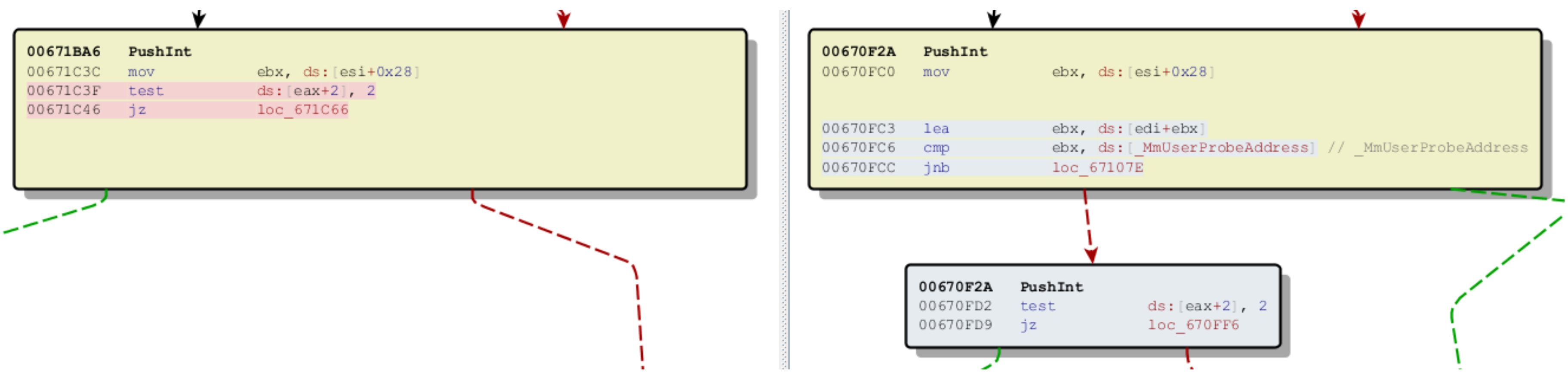
DEMO

Exploitation, affected versions

- Exploitation
  - One of the three *what* 32-bit values is the trap Eip.
  - Overwriting any kernel function pointer will do. I used the standard `nt!HalDispatchTable` method.
    - for this and all further demos during this presentation.
- Affected platforms: Windows NT 3.1 through Windows 8 32-bit.
  - exploitable on Vista+, see later.

Fix analysis

- Add three instructions to verify that ss:esp is within user space.



Case study

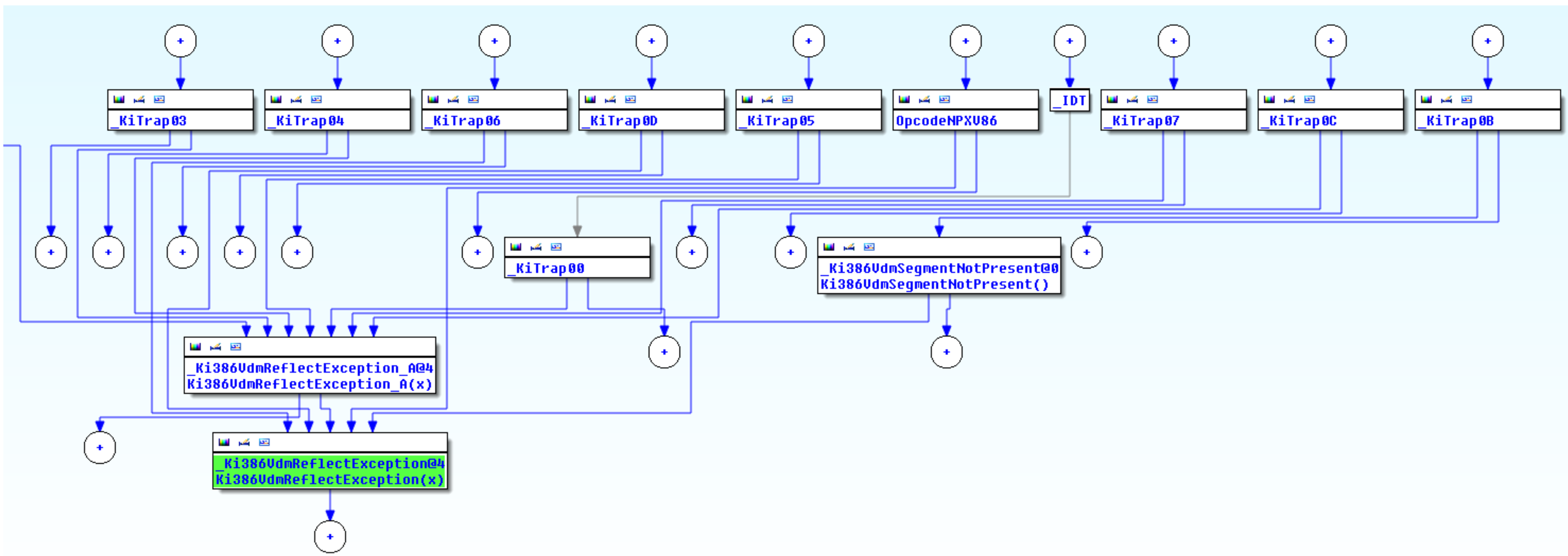
CVE-2013-3197

(`nt!PushException` write-what-where condition)

Exception handling in NTVDM.EXE

- It's not only `nt!KiTrap0d` that implements VDM-specific handling…
- All exception trap handlers do!
- Meet the `nt!Ki386VdmReflectException`.

nt!Ki386VdmReflectException proximity graph



Exception handling control flow

- For any regular process, each trap handler eventually redirects to `nt!CommonDispatchException`.
  - in most cases; sometimes the process is just terminated.
- Control is then transferred to user-mode `ntdll!KiUserExceptionDispatcher` via `KTRAP_FRAME` modification.
  - VEH handlers are invoked.
  - SEH handlers are invoked.
  - Original execution is resumed with `nt!NtContinue`.

Exception handling control flow cont'd.

- For VDM, the handlers first try to *reflect* the exception to the user-mode host process.
  - Create a "trap frame" on the user-mode stack.
  - Redirect execution to `cs:eip` specified in:
    - `NtCurrentTeb()->Vdm->VdmIntDescriptor[trap_no]->VfCsSelector`
    - `NtCurrentTeb()->Vdm->VdmIntDescriptor[trap_no]->VfEip`
  - This is achieved by a dedicated `nt!PushException` routine.

nt!PushException – trap frame creation code

```
if (NtCurrentTeb()->Vdm->VtDpmiInfo.VpFlags & 1) /* 32-bit frame */ {
    if (!CheckEsp(32, reginfo)) {
        return FALSE;
    }

    *(DWORD)(reginfo->RiSsBase + reginfo->RiEsp - 4)  = reginfo->RiSegSs;
    *(DWORD)(reginfo->RiSsBase + reginfo->RiEsp - 8)  = reginfo->RiEsp;
    *(DWORD)(reginfo->RiSsBase + reginfo->RiEsp - 12) = GetVirtualBits(reginfo->RiEFlags);
    *(DWORD)(reginfo->RiSsBase + reginfo->RiEsp - 16) = reginfo->RiSegCs;
    *(DWORD)(reginfo->RiSsBase + reginfo->RiEsp - 20) = reginfo->RiEip;
    *(DWORD)(reginfo->RiSsBase + reginfo->RiEsp - 24) = reginfo->RiTrapFrame->TsErrCode;
    *(DWORD)(reginfo->RiSsBase + reginfo->RiEsp - 28) = NtCurrentTeb()->Vdm->VtDpmiInfo.VpDosxFaultIretD >> 16;
    *(DWORD)(reginfo->RiSsBase + reginfo->RiEsp - 32) = NtCurrentTeb()->Vdm->VtDpmiInfo.VpDosxFaultIretD & 0xffff;
} else /* 16-bit frame */ {
    if (!CheckEsp(16, reginfo)) {
        return FALSE;
    }

    *(WORD)(reginfo->RiSsBase + reginfo->RiEsp - 2)   = reginfo->RiSegSs;
    *(WORD)(reginfo->RiSsBase + reginfo->RiEsp - 4)   = reginfo->RiEsp;
    *(WORD)(reginfo->RiSsBase + reginfo->RiEsp - 6)   = GetVirtualBits(reginfo->RiEFlags);
    *(WORD)(reginfo->RiSsBase + reginfo->RiEsp - 8)   = reginfo->RiSegCs;
    *(WORD)(reginfo->RiSsBase + reginfo->RiEsp - 10)  = reginfo->RiEip;
    *(WORD)(reginfo->RiSsBase + reginfo->RiEsp - 12)  = reginfo->RiTrapFrame->TsErrCode;
    *(DWORD)(reginfo->RiSsBase + reginfo->RiEsp - 16) = NtCurrentTeb()->Vdm->VtDpmiInfo.VpDosxFaultIret;
}
```

write-what-where condition

write-what-where condition

Write-what-where condition

- Again, the kernel writes data to a user-controlled ss:esp address with no sanitization.
- This enabled an attacker to write 16 or 32 semi-controlled bytes into arbitrary kernel memory.

Reproduction – proof of concept

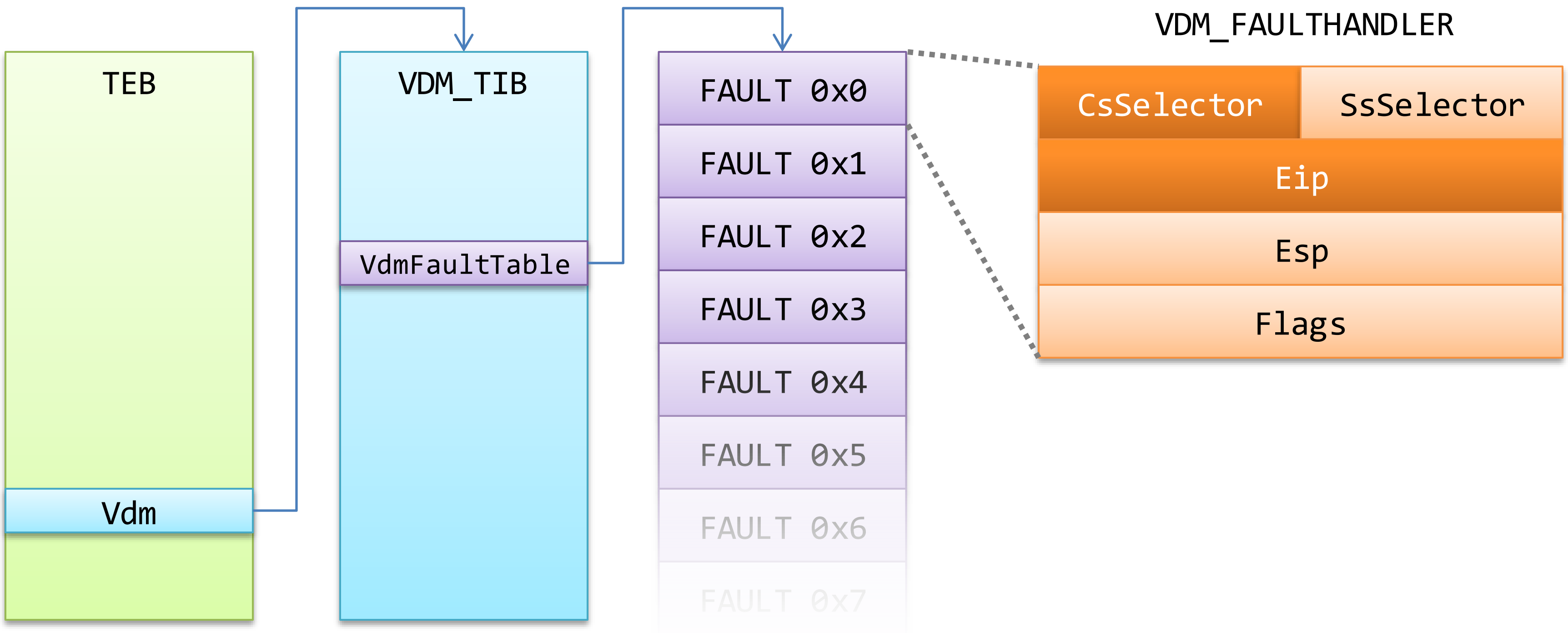
```
mov esp, 0xdeadbeef
xor ecx, ecx
div ecx
```

- Above three instructions must be executed in the main `NTVDM.EXE` thread.
  - Again, vulnerability requires fully initialized VDM environment (and custom `cs:`/`ss:` segments).
  - `Esp` can be any invalid kernel-mode address for the system to crash.
  - In the example, we trigger "Interrupt 0" (Divide Fault Exception). However, it is possible to trigger the vulnerability through the following trap numbers: {0, 1, 3, 4, 5, 6, 7, 0b, 0c, 0d}.

Reproduction – results

```
TRAP_FRAME:  8dd97c28 -- (.trap 0xffffffff8dd97c28)
ErrCode = 00000002
eax=000007f7 ebx=00000000 ecx=00000000 edx=deadbebf esi=8dd97ce4 edi=00000634
eip=82a874b5 esp=8dd97c9c ebp=8dd97d1c iopl=0         nv up ei ng nz na po nc
cs=0008  ss=0010  ds=0023  es=0023  fs=0030  gs=0000             efl=00010282
nt!PushException+0x150:
82a874b5 6689441a0e      mov     word ptr [edx+ebx+0Eh],ax ds:0023:deadbecd=????
Resetting default scope
```

Controlling execution afterwards



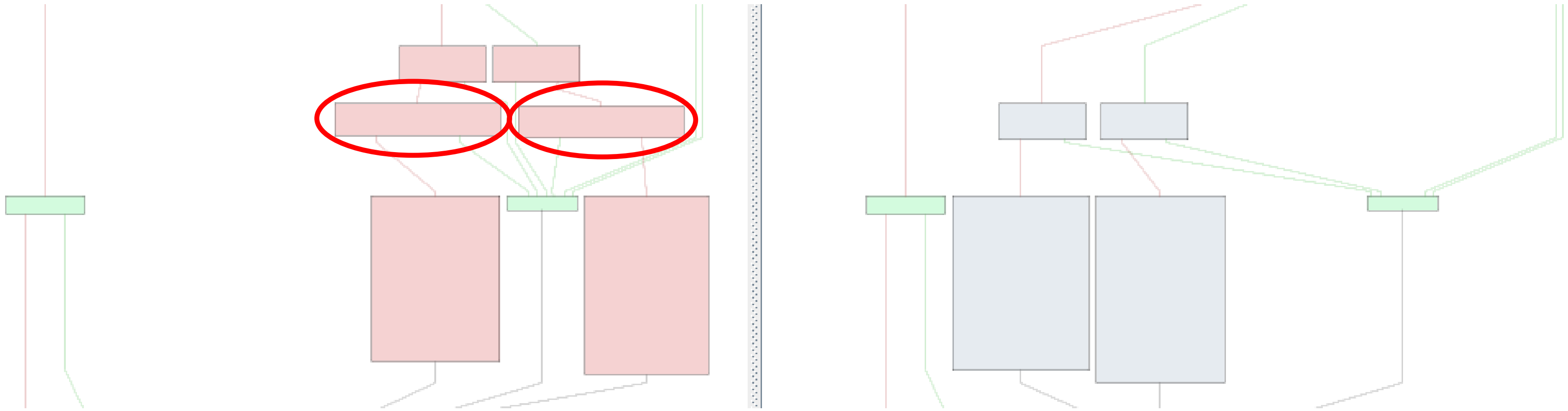
DEMO

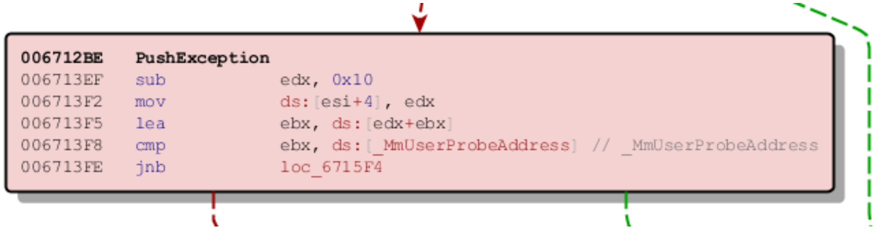
Exploitation, affected versions

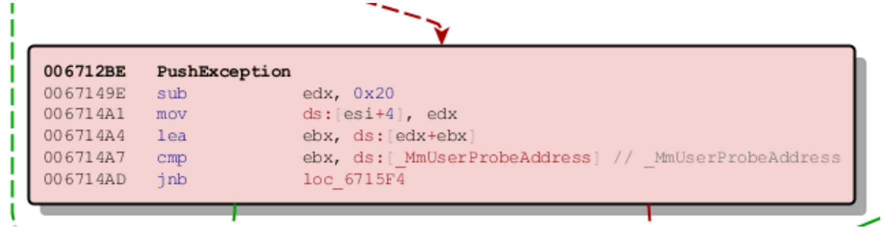
- Exploitation
  - One of the eight *what* 32-bit values is the trap Eip.
  - `nt!HalDispatchTable` a good candidate, again.
- Affected platforms: Windows NT 3.1 through Windows 8 32-bit.
  - exploitable on Vista+, see later.

Fix analysis

- Two `nt!MmUserProbeAddress` checks added for both 16 and 32-bit branches of the function.







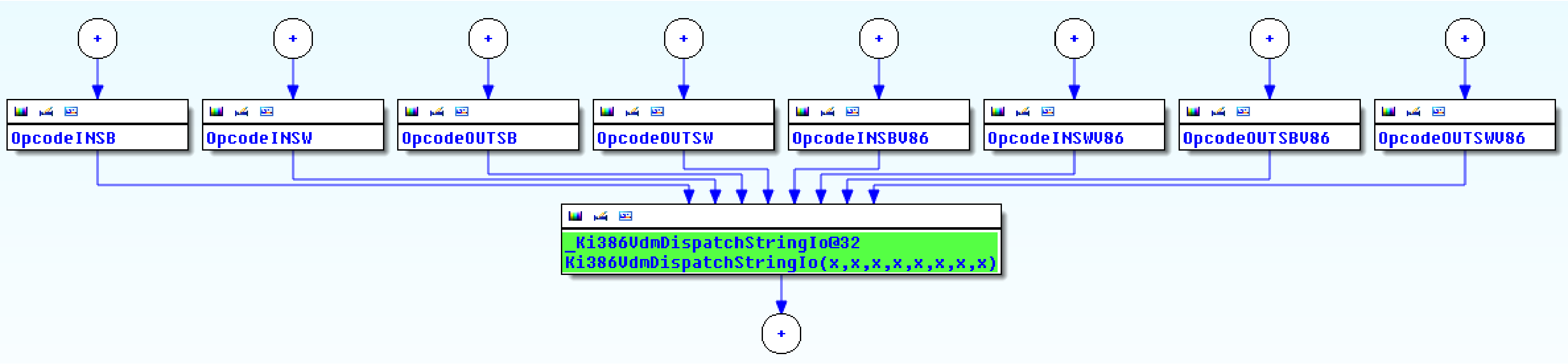
Case study

CVE-2013-3198

(`nt!VdmCallStringIoHandler` write-where condition)

Port I/O emulation

- In addition to privileged instructions, the kernel also emulates the Port I/O ones (both Virtual 8086 and Protected mode).
- For all I/O instruction handlers, the operation is processed by **`nt!Ki386VdmDispatchStringIo`**.



Port I/O emulation – references

- The Virtual 8086 mode port emulation functionality is quite complex, but virtually unknown and unused nowadays.
- Ivanlef0u wrote an **excellent** blog post detailing the inners of the mechanism, see “ProcessIoPortHandlers”.
  - Unfortunately in French (Google Translate works).
  - Who knows, maybe Ivan has known about the vulnerability for years. ☺

Port I/O emulation – kernel subsystem

- Device drivers can register VDM I/O handlers through `ZwSetInformationProcess(ProcessIoPortHandlers)`
  - Only accessible from ring-0, enforced by many routines along the way.
- The kernel module specifies following information about each handler through an internal structure:
  - I/O port range
  - “READ” or “WRITE”.
  - Access size (1, 2 or 4).
  - One-off or string access.
  - Pointer to a kernel-mode handler routine.

Port I/O emulation – kernel subsystem

Example of a kernel-mode handler declaration:

```
typedef NTSTATUS
(PDRIVER_IO_PORT_UCHAR *) (
    IN ULONG_PTR Context
    IN ULONG Port,
    IN UCHAR AccessMode,
    IN OUT Data PUCHAR
    );
```

Port I/O emulation – kernel subsystem

- So… *theoretically*, drivers can emulate physical devices for VDM.

-But do they?

(in a default Windows installation)

-No! well, sometimes…

Port I/O emulation – kernel subsystem

- There's no virtual devices registered by default…
- Except for **one** that I know of:
  - when switching a 16-bit app console to full screen, VIDEOPRT.SYS registers handlers for the VGA ports (`0x3b0` – `0x3df`)
  - only works on systems with the default video driver.
    - likely server workstations, unlikely user PCs.

I/O handler registration occurs here…

```
ChildEBP RetAddr  Args to Child
807b1738 82a55023 85886680 00000001 b06b1bf3 nt!Psp386InstallIoHandler
807b1994 828588a6 00000088 0000000d 807b1a40 nt!NtSetInformationProcess+0x7ad
807b1994 82857815 00000088 0000000d 807b1a40 nt!KiSystemServicePostCall
807b1a1c 91619f84 00000088 0000000d 807b1a40 nt!ZwSetInformationProcess+0x11
807b1a60 91616467 86a357f0 00000001 8597ae80 VIDEOPRT!pVideoPortEnableVDM+0x82
807b1ab4 82851c1e 86a357f0 86f32278 86f32278 VIDEOPRT!pVideoPortDispatch+0x360
807b1acc 9a5c45a2 fe915c48 fffffffe 00000000 nt!IofCallDriver+0x63
807b1af8 9a733564 86a35738 00230000 fe915c48 win32k!GreDeviceIoControlEx+0x97
807b1d18 828588a6 00000000 0130f294 00000004 win32k!NtGdiFullscreenControl+0x1100
807b1d18 77c77094 00000000 0130f294 00000004 nt!KiSystemServicePostCall
0130f25c 77ab6951 00670577 00000000 0130f294 ntdll!KiFastSystemCallRet
0130f260 00670577 00000000 0130f294 00000004 GDI32!NtGdiFullscreenControl+0xc
0130f28c 00672c78 00000088 0000003a 003bd0b0 conhost!ConnectToEmulator+0x6c
0130f3c0 0065f24d 00000001 003bd0b0 0130f4d4 conhost!DisplayModeTransition+0x40e
0130f458 7635c4e7 000e001c 0000003a 00000001 conhost!ConsoleWindowProc+0x419
```

Easy to initialize the handlers programatically

Switch the console to full screen and back with simple API calls:

```
SetConsoleDisplayMode(GetStdHandle(STD_OUTPUT_HANDLE),
  CONSOLE_FULLSCREEN_MODE, NULL);
SetConsoleDisplayMode(GetStdHandle(STD_OUTPUT_HANDLE),
  CONSOLE_WINDOWED_MODE, NULL);
```

Now, back to instruction emulation...

- `nt!Ki386VdmDispatchStringIo` works as follows:
    1. Locate a handler for the emulated operation using `nt!Ps386GetVdmIoHandler`.
    2. If it's a "READ", copy byte(s) from `ds:si` to kernel buffer.
    3. Invoke the I/O handler.
    4. If it's a "WRITE", copy byte(s) from kernel buffer to `es:di`.

Aaand the vulnerability is…

- You guessed it – neither `ds:si` nor `es:di` were validated prior to usage.
  - In Protected mode, segments can have 32-bit base addresses.
  - We could read from and write to arbitrary kernel memory by initializing `ds.base` and `es.base` adequately.

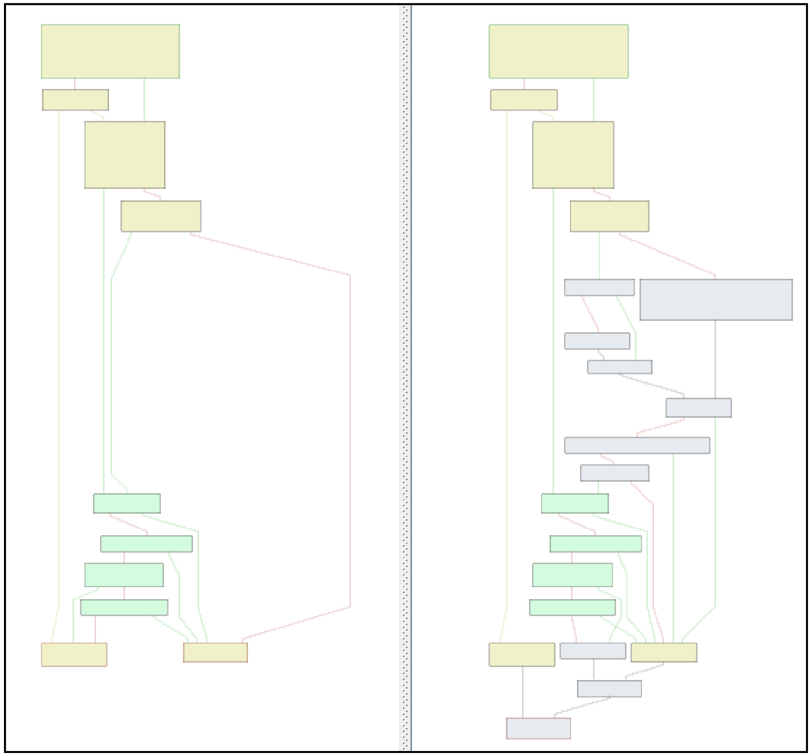
```
memcpy(&VdmStringIoBuffer, user_controlled, size);

memcpy(user_controlled, &VdmStringIoBuffer, size);
```

But wait…

- Can you even create an LDT entry with `Base >= MmUserProbeAddress`?
- The answer is found in the `nt!PspIsDescriptorValid` routine invoked during segment creation.
  - In all NT-family systems until and including Windows XP, there indeed was a `LDT_ENTRY.Base` sanity check.
  - However, it was removed from Vista and all further platforms!
    - Kernel code should **never** operate on user-provided segments, anyway.
    - See Derek Soeder's "Windows Expand-Down Data Segment Local Privilege Escalation" from 2004.

nt!PspIsDescriptorValid changes

- Ruben Santamarta noticed this back in 2010, see [“Changes in PspIsDescriptorValid”].
  - quote: *“Can you spot an exploitation vector? share it if so!“*
  - there you go! ☺



Exploitation steps

1. Set `cs:` to a custom LDT entry.
2. Create an LDT entry with *Base* in kernel address space and load it to `es:`.
3. Run the following instructions to write a `0x00` byte to specified location:

```
xor di, di
mov dx, 0x3b0
insb
```

4. ???
5. PROFIT!

Basic crash

```
TRAP_FRAME:  963889fc -- (.trap 0xffffffff963889fc)
ErrCode = 00000002
eax=aaaaaa00 ebx=00000001 ecx=fffffffd edx=00000003 esi=8297d260 edi=aaaaaaaa
eip=82854fc6 esp=96388a70 ebp=96388a78 iopl=0     vif nv up ei ng nz ac po cy
cs=0008  ss=0010  ds=0023  es=0023  fs=0030  gs=0000             efl=00090293
nt!memcpy+0x166:
82854fc6 8807            mov     byte ptr [edi],al         ds:0023:aaaaaaaa=??
Resetting default scope
```

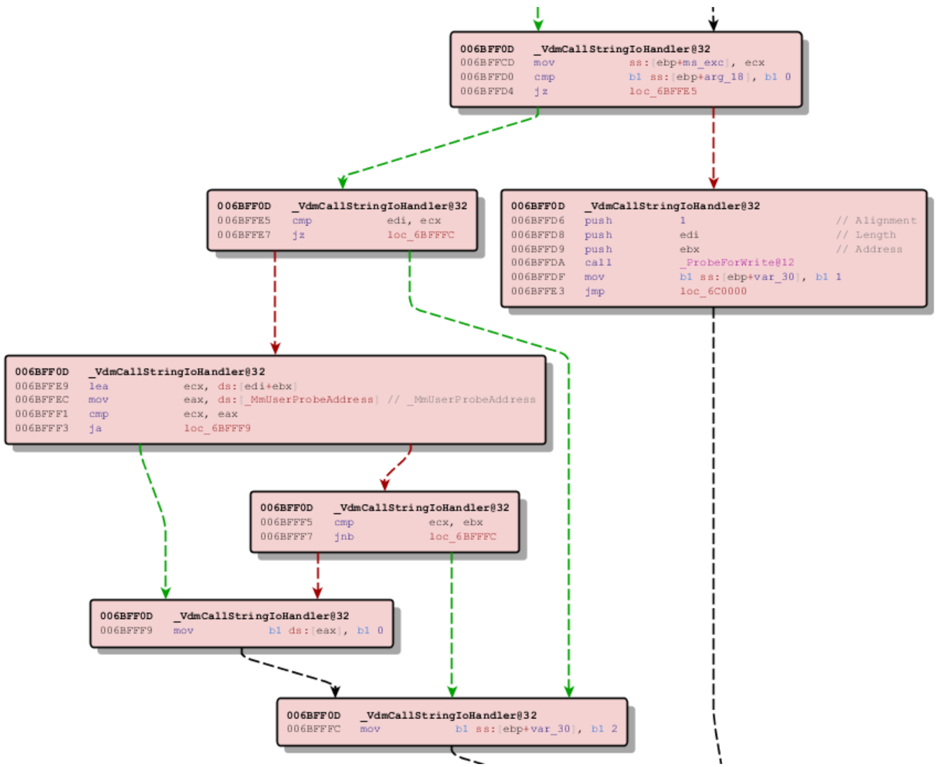
DEMO

Exploitation, affected versions

- Exploitation
  - We can zero-out any kernel function pointer.
  - NULL page already allocated by NTVDM.EXE for v8086.
- Affected platforms: Windows NT 3.1 through Windows 8 32-bit.
  - Only exploitable on Vista, Server 2008, 7, Server 2012 and 8 due to changes in LDT entry creation.

Fix analysis

- An inlined `ProbeForRead()` and regular `ProbeForWrite()` call added for the "READ" and "WRITE" port variants, respectively.



Case study

0-day

(`nt!PushPmInterrupt` and `nt!PushRmInterrupt` `Blue Screen of Death DoS`)

Hack all the nt!Push... functions!

PushException	006712BE
PushInt	00670F2A
PushPmInterrupt(x,x,x,x)	006F0023
PushRmInterrupt(x,x,x,x)	006EFE9C

`nt!PushException` was vulnerable...

`Nt!PushInt` was vulnerable...

what about the other two?

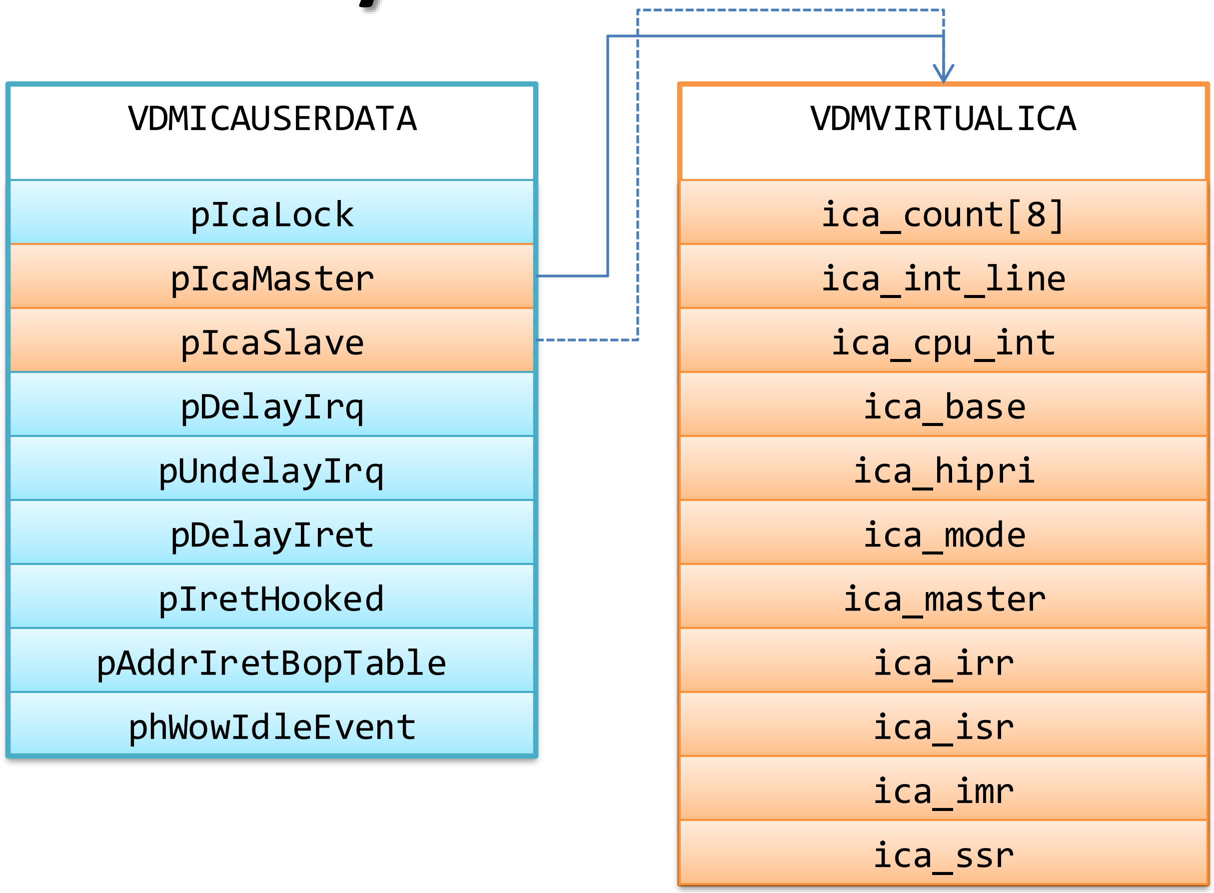
...

they are, too!

VDM interrupt dispatching basics

- In order to deliver interrupts to the Virtual 8086 mode environment, the kernel implements a virtual **Interrupt Controller Adapter (ICA).**
  - Emulates basic features of the Intel 8952A Priority Interrupt Controller.
  - Consists of two kernel-mode APIs: `nt!VdmpIcaAccept` and `nt!VdmpIcaScan`.
  - Uses two structures residing in user space of NTVDM.EXE: VDMICAUSERDATA and `VDMVIRTUALICA`.

ICA structure layout



- Both structures reside in ring-3 memory and thus are fully controlled.
- A pointer to the `VDMICAUSERDATA` structure is passed via the second `NtVdmControl(VdmInitialize, ...)` argument.

Reaching the vulnerable code

- Both routines can be reached with the following call chain:
   1. `nt!OpcodeINTnn`
   2. `nt!VdmDispatchIntAck`
   3. `nt!VdmDispatchInterrupts`
   4. `nt!Push{Pm,Rm}Interrupt`

Reaching the vulnerable code - requirements

First requirement:

`ds:[714h] & 0x203 = 0x203`

- `0x714` is a hardcoded address of a special NTVDM.EXE status dword.
  - Internally referenced to as `pNtVDMState`.
  - Resides within a writable NULL page and thus fully controlled.
- `0x203` = `VDM_INT_HARDWARE | VDM_INT_TIMER | VDM_VIRTUAL_INTERRUPTS`.
  - Essential for VDM to currectly dispatch interrupts under normal circumstances.
  - For exploitation, we can just forcefully set it with no side effects.
- Enforced by `nt!OpcodeINTnn` (otherwise, `nt!PushInt` is called).

Reaching the vulnerable code - requirements

Second requirement:

`IcaUserData->pIcaMaster->ica_irr = 0xff`

- First and foremost, `IcaUserData->pIcaMaster` must be a pointer to valid, zero-ed out memory.
- The `ica_irr` field is a bitmask which denotes available interrupt handling slots (1 = available).
- Enforced by `nt!VdmpIcaScan`.
  - Needed by the function (and later `nt!VdmIcaAccept`) to succeed.

Reaching the vulnerable code - requirements

Third requirement

`NtCurrentTeb()->Vdm->VtDpmiInfo.LockCount > 0`

- If `LockCount` at offset 1588 from the start of `VTM_TIB` is zero, `KTRAP_FRAME.HardwareSegSs` is loaded with a custom `ss:` selector from `VtDpmiInfo`.
  - We don't want to go into extra hassle, so just set to a non-zero value.
- Enforced by `nt!PushPmInterrupt`.

What now?

- We set up the necessary context and reached `nt!PushPmInterrupt` by invoking `INT nn`.
- What is the vulnerability, then?

Spot the bug!

controlled 16-bit value

controlled 32-bit value

```
PAGE:006F020E                 mov     ecx, [ebp+ica_base]
PAGE:006F0211                 shl     ecx, 3
PAGE:006F0214                 mov     eax, [edi+VtInterruptTable]
PAGE:006F0217                 add     eax, ecx
PAGE:006F0219                 mov     [ebp+local_var], eax
PAGE:006F021C                 add     eax, ecx
PAGE:006F021E                 mov     ecx, ds:_MmUserProbeAddress
PAGE:006F0224                 cmp     eax, ecx
PAGE:006F0226                 jb      short loc_6F022A
PAGE:006F0228                 mov     eax, ecx
PAGE:006F022A
PAGE:006F022A loc_6F022A:
PAGE:006F022A                 mov     al, [eax]
PAGE:006F022C                 mov     edi, [ebp+local_var]
PAGE:006F022F                 mov     ax, [edi]
```

Looks alright, eh?

Spot the bug!

controlled 16-bit value

controlled 32-bit value

```
PAGE:006F020E                mov     ecx, [ebp+ica_base]
PAGE:006F0211                shl     ecx, 3
PAGE:006F0214                mov     eax, [edi+VtInterruptTable]
PAGE:006F0217                add     eax, ecx
PAGE:006F0219                mov     [ebp+local_var], eax
PAGE:006F021C                add     eax, ecx
PAGE:006F021E                mov     ecx, ds:_MmUserProbeAddress
PAGE:006F0224                cmp     eax, ecx
PAGE:006F0226                jb      short loc_6F022A
PAGE:006F0228                mov     eax, ecx
PAGE:006F022A
PAGE:006F022A loc_6F022A:
PAGE:006F022A                mov     al, [eax]
PAGE:006F022C                mov     edi, [ebp+local_var]
PAGE:006F022F                mov     ax, [edi]
```

But… what is the ADD doing there?

Translated to C...

- The code adds `IcaUserData->pIcaMaster->ica_base * 8` **twice** to the validated pointer, but only **once** to the used one.
- Imagine:
  - `VtInterruptTable = 0xfff00010`
  - `ica_base = 0xffff`
- Then:
  - **Validated:** `0xfff00010 + (0xffff * 8) * 2 = 0x00000000`
  - **Used:** `0xfff00010 + (0xffff * 8) = 0xfff80008`

Practical exploitability

- The issue allows for reading from kernel addresses in the `0xfff80008` – `0xffffffff` range (last 128 pages).
- Unfortunately, the highest mapped memory region is `KUSER_SHARED_DATA` (528 pages from top).

```
0: kd> !address
[...]
c0000000 c1600000  1600000 ProcessSpace
c0800000 c1600000   e00000 Hyperspace
c1600000 ffc00000 3e600000 <unused>
ffc00000 ffdf0000   1f0000 HAL
ffdf0000 ffdf1000     1000 SystemSharedPage
ffdf1000 ffffffff   20f000 HAL
```

Practical exploitability

- The bug is currently believed to be non-exploitable.
  - HAL heap anyone?
  - Even if it was possible to map memory, it's still only a „READ”. ☹
  - Microsoft decided against releasing a bulletin.
- It can still crash your system!

Bugcheck log

```
TRAP_FRAME:  88c37b90 -- (.trap 0xffffffff88c37b90)
ErrCode = 00000000
eax=00000000 ebx=00000002 ecx=7fff0000 edx=fffffeff esi=88c37d34 edi=fff80008
eip=82b31e51 esp=88c37c04 ebp=88c37c50 iopl=0         nv up ei ng nz na pe cy
cs=0008  ss=0010  ds=0023  es=0023  fs=0030  gs=0000             efl=00010287
nt!PushPmInterrupt+0x20c:
82b31e51 668b07          mov     ax,word ptr [edi]        ds:0023:fff80008=????
Resetting default scope
```

DEMO

Considerations, affected versions

- It is interesting to think what type of high-level C mistake could have led to the vulnerable assembly.
  - Most likely a misuse of an internal `PROBE_*` macro.
  - I grepped for similar patterns in `nt` and `win32k.sys`, didn't find anything.
  - Maybe you'll have more luck!
- Affected platforms: Windows XP SP3 (at least) through Windows 8 32-bit.
  - Not fixed as of November 2013.

Conclusions

Final thoughts

- The bugs were of a very rare type: *write-what-where* in ntoskrnl.exe.
  - Nowadays almost unheard of.
  - Personal theory: Microsoft have excellent static code analysis tools, but assembly source is not covered.
- The major reason for all severe vulnerabilities was breaking one of the modern Windows kernel security assumptions.
  - Implicitly reading from / writing to memory using user-controlled segments.
  - Open question: are there possibly any other instances of the behavior?

Final thoughts

„If you wish to discover Windows kernel security issues, target code from the '90s"

point proven again.

- Often poorly written.
- Often poorly (or not at all) audited.
- Code from 20 years back is still the foundation of latest NT-family systems: Windows 8.1 and Server 2012.

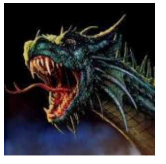
Final thoughts

- Security-wise, disabling VDM by default in Windows 8 was an **excellent** decision.
  - Likely tons of further 16-bit support vulnerabilities made useless.
  - Perhaps even never found due to lack of attacker incentive.
  - Additionally enabled MSFT to enforce NULL page protection on 64-bit and latest 32-bit platforms.
- Overall, I think it has been the most impactful kernel mitigation enabled thus far.
- Still, playing with the dark corners of the NT kernel was an exciting excercise. ☺

Final thoughts

Now, go and hack the kernel on your own!

Questions?



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