Bochspwn Reloaded

Detecting Kernel Memory Disclosure with x86 Emulation and Taint Tracking

Mateusz “j00ru” Jurczyk

REcon 2017, Montreal

Alternative title (cheers Alex Ionescu!)

Memory Disclosure

Alternative title

KERNELBLEED

Agenda

- User ↔ kernel communication pitfalls in modern operating systems
- Introduction to Bochspwn Reloaded
  - Detecting kernel information disclosure with software x86 emulation
- Approaches, results and exploitation
  - Microsoft Windows
  - Linux
- Future work and conclusions

Bio

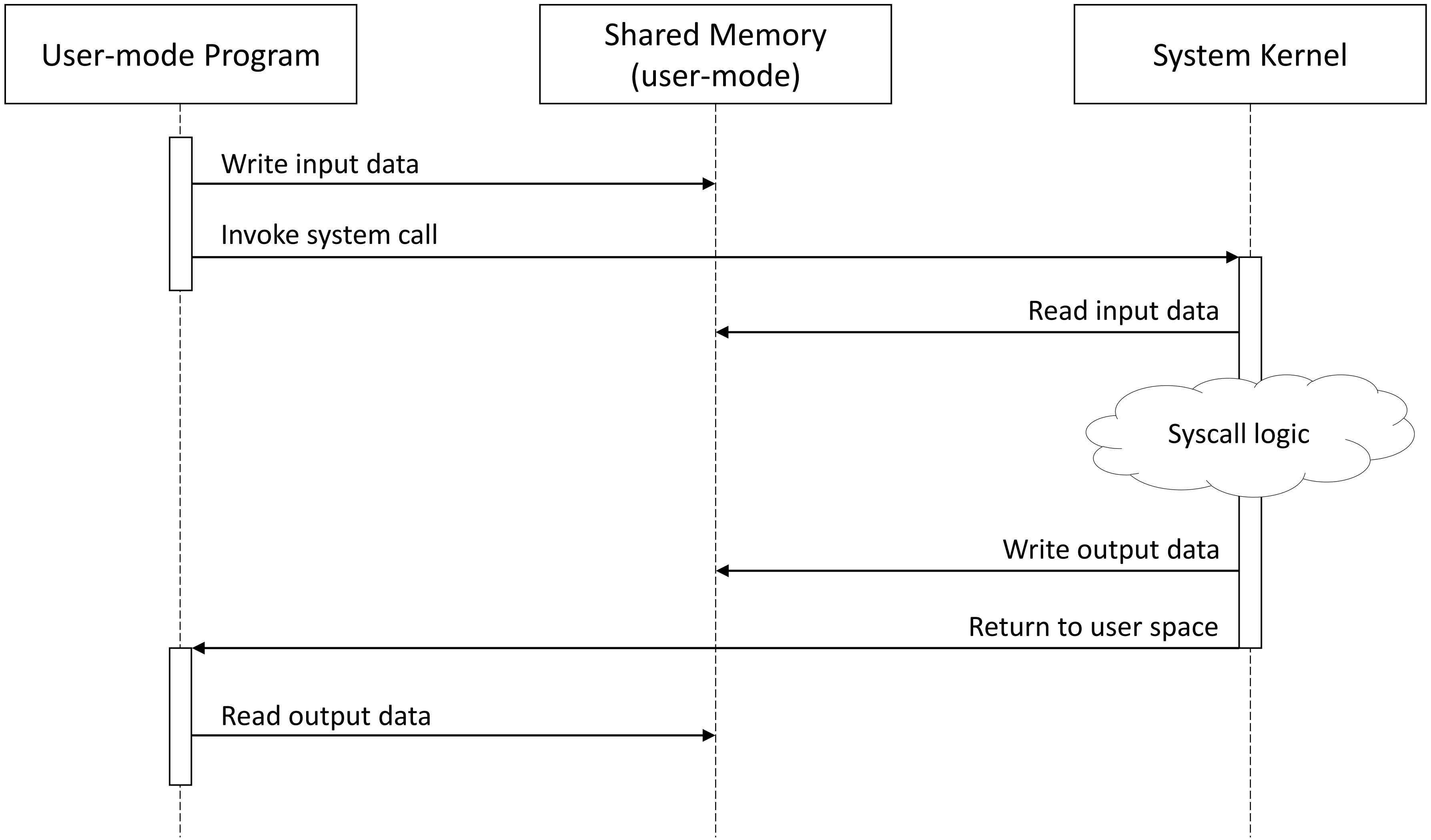
- Project Zero @ Google
- CTF Player @ Dragon Sector
- Low-level security researcher with interest in all sorts of vulnerability research and software exploitation.
- http://j00ru.vexillium.org/
- @j00ru

User ↔ kernel communication

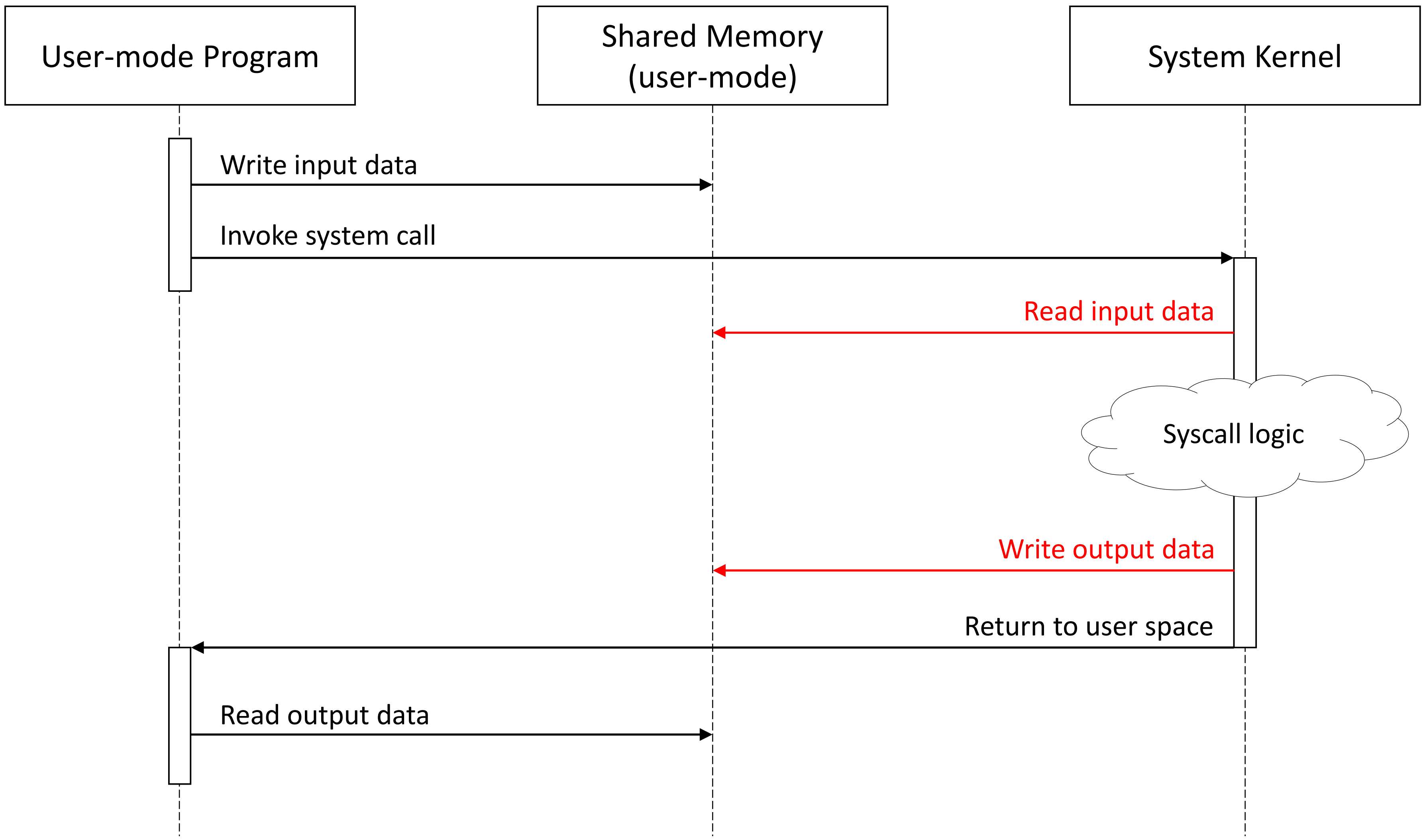
OS design fundamentals

- User applications run independently of other programs / the kernel.
- Whenever they want to interact with the system, they call into the kernel.
- Ring-3 memory is the i/o data exchange channel.
  - Also registers to a small extent.

Life of a system call



Life of a system call



In a perfect world...

- Within the scope of a single system call, each memory unit is:

  1. Read from at most once, securely.

     ... then ...

  2. Written to at most once, securely, only with data intended for user-mode.

In reality (double fetches)

*Read from **at most once**, securely.*

- Subject of the original *Bochspwn* study in 2013 with Gynvael Coldwind.
- Possible violation: *double* (or *multiple*) *fetches*, may allow race conditions to break code assumptions → buffer overflows, write-what-where conditions, arbitrary reads, other badness.
- Dozens (40+) vulnerabilities reported and fixed in Windows.
    - A few more just recently (CVE-2017-0058, CVE-2017-0175).

Kernel double fetches

Bochspwn: Exploiting Kernel Race Conditions Found via Memory Access Patterns

- Mateusz "j00ru" Jurczyk of Google Inc for reporting the Win32k Race Condition Vulnerability (CVE-2013-1258)
- Mateusz "j00ru" Jurczyk of Google Inc for reporting the Win32k Race Condition Vulnerability (CVE-2013-1259)
- Mateusz "j00ru" Jurczyk of Google Inc for reporting the Win32k Race Condition Vulnerability (CVE-2013-1260)
- Mateusz "j00ru" Jurczyk of Google Inc for repo
- Mateusz "j00ru" Jurczyk of Google Inc for repo
- Mateusz "j00ru" Jurczyk of Google Inc for repo
- Mateusz "j00ru" Jurczyk of Google Inc for repo
- Mateusz "j00ru" Jurczyk of Google Inc for repo
- Mateusz "j00ru" Jurczyk of Google Inc for reporting the Win32k Race Condition Vulnerability (CVE-2013-1266)
- Mateusz "j00ru" Jurczyk of Google Inc for reporting the Win32k Race Condition Vulnerability (CVE-2013-1267)

Identifying and Exploiting Windows Kernel Race Conditions via Memory Access Patterns

Bochspwn: Identifying 0-days via system-wide memory access pattern analysis

ility (CVE-2013-1268)
ility (CVE-2013-1269)
ility (CVE-2013-1270)
ility (CVE-2013-1271)
ility (CVE-2013-1272)
ility (CVE-2013-1273)
ility (CVE-2013-1274)
ility (CVE-2013-1275)
ility (CVE-2013-1276)
ility (CVE-2013-1277)

In reality (unprotected accesses)

Read from/written to at most once, ***securely****.*

- The kernel can almost never know if a user pointer is valid before actually operating on it.
  - All accesses must be guarded with try/except blocks.
  - This is well documented and understood, but...
- Failure to set up exception handling → unhandled exception → system crash.
  - Local authenticated DoS condition only, not fixed in bulletins by Microsoft.

Exception handler record

```
struct _EH3_EXCEPTION_REGISTRATION
{
  struct _EH3_EXCEPTION_REGISTRATION *Next;
  PVOID ExceptionHandler;
  PSCOPETABLE_ENTRY ScopeTable;
  DWORD TryLevel;
};
```

Microsoft C/C++ Compiler exception handling

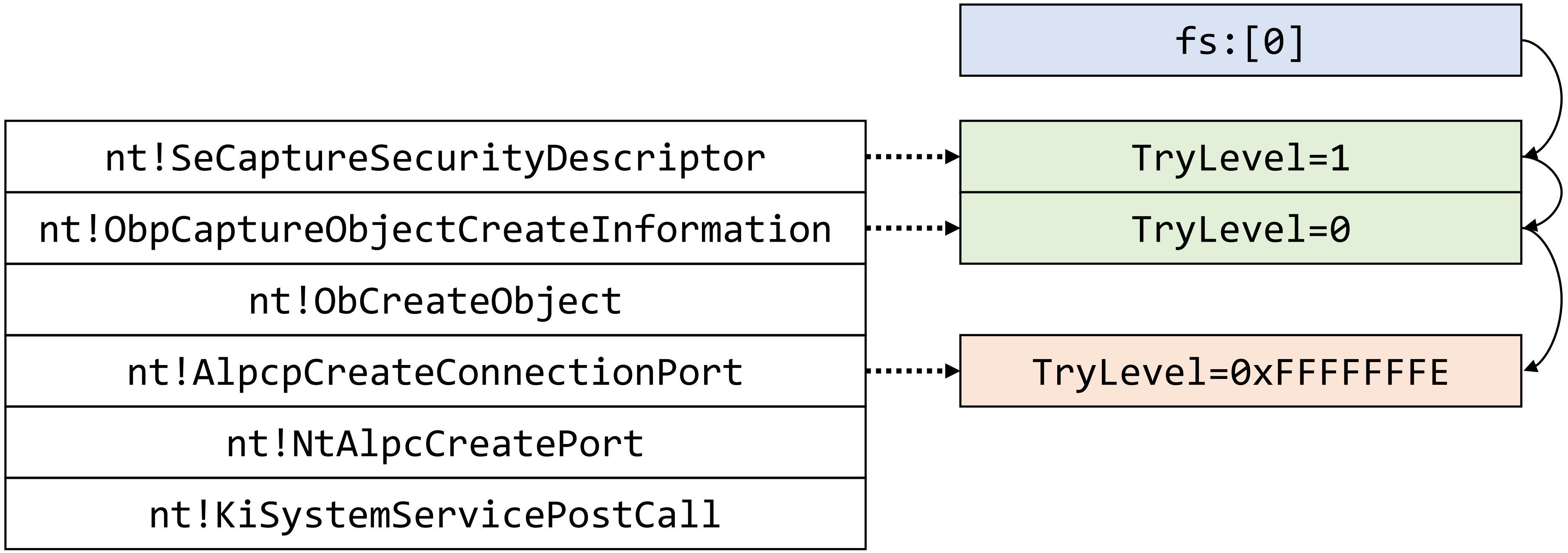
Exception handler #1 active

```
PAGE:00671CF3    mov    [ebp+ms_exc.registration.TryLevel], 1
PAGE:00671CFA    mov    eax, [ebp+var_2C]
PAGE:00671CFD    mov    ecx, [ebp+arg_14]
PAGE:00671D00    mov    [ecx], eax
PAGE:00671D02    mov    [ebp+ms_exc.registration.TryLevel], 0FFFFFFFEh
```

Write to user memory

Exception handler disabled

SEH chains on the stack



- If there are no positive TryLevel in the SEH chain at the time of a user-mode memory access, it may be used to trigger a BSoD.

Actual bugs found and documented

2017.04.24 Windows Kernel Local Denial-of-Service #5: win32k!NtGdiGetDIBitsInternal (Windows 7-10)

2017.04.03 Windows Kernel Local Denial-of-Service #4: nt!NtAccessCheck and family (Windows 8-10)

2017.03.07 Windows Kernel Local Denial-of-Service #3: nt!NtDuplicateToken (Windows 7-8)

2017.02.27 Windows Kernel Local Denial-of-Service #2: win32k!NtDCompositionBeginFrame (Windows 8-10)

2017.02.22 Windows Kernel Local Denial-of-Service #1: win32k!NtUserThunkedMenuItemInfo (Windows 7-10)

In reality (PreviousMode)

*Read from/written to at most once, **securely**.*

- There is a global variable in Windows called `PreviousMode`.
  - Indicates if the current kernel service was invoked from user-mode (`UserMode`) or the kernel (`KernelMode`).
- Accesses to user-mode memory while `PreviousMode=KernelMode` can indicate bugs.
  - Kernel code may trust data/pointers that should not be trusted.

In reality (double writes)

*Written to **at most once**, securely, ...*

- Why would the kernel write to a specific address more than once?
  - Code not realizing it's operating on user pointer and using it for temporary storage?
- What is stored in memory before the final write?
  - A normal synchronous user-mode client would never see that data.
- May indicate some strange/fishy behavior for follow-up analysis.

In reality (read-after-write)

*Read from [...] **then** written to [...]*

- Reading from user-space after already having written to it.
  - Again, why? Kernel code mistreating pointer as trusted / exclusive?
- What happens if we change it in between? Does the function make any assumptions?
- Another good indicator of interesting or sensitive areas of code.

In reality (other heuristics)

- **User-mode accesses with very deep callstacks.**
  - Such reads/writes should mostly occur in top-level syscall handlers.
  - The more nested the callstack, the less the code expects to be operating on ring-3 memory.
- **User-mode accesses with the first enabled exception handler very high up the callstack.**
  - Indicator of very broad try/except blocks.
  - Jumping across a number of functions back to the exception handler may leave dangling state in any of them.
- **Listing all user-mode accesses in general.**
  - Enumerating new attack surface.
  - Potentially useful in aiding other methods of bughunting, e.g. static analysis.

The subject of this talk

Written to at most once, securely,

only with data intended for user-mode

Writing data to ring-3

- System calls
  - Almost every single one on any system.
- IOCTLs
  - A special case of syscalls, but often have dedicated output mechanisms.
- User-mode callbacks
  - Specific to the graphical win32k.sys subsystem on Windows.
- Exception handling
  - Building exception records on the user-mode stack.

The easy problem – primitive types

```
NTSTATUS NtMultiplyByTwo(DWORD InputValue, LPDWORD OutputPointer) {
  DWORD OutputValue;

  if (InputValue != 0) {
    OutputValue = InputValue * 2;
  }

  *OutputPointer = OutputValue;
  return STATUS_SUCCESS;
}
```

Uninitialized if `InputValue == 0`

The easy problem – primitive types

- Disclosure of uninitialized data via basic types can and will occur, but:
  - is not a trivial bug for developers to make,
  - compilers will often warn about instances of such issues,
  - leaks only a limited amount of data at once (max 4 or 8 bytes on x86),
  - may be detected during development or testing, since they can be functional bugs.
- Not an inherent problem to kernel security.

The hard problem – structures and unions

```
typedef struct _SYSCALL_OUTPUT {
  DWORD Sum;
  DWORD Product;
  DWORD Reserved;
} SYSCALL_OUTPUT, *PSYSCALL_OUTPUT;

NTSTATUS NtArithOperations(DWORD InputValue, PSYSCALL_OUTPUT OutputPointer) {
  SYSCALL_OUTPUT OutputStruct;

  OutputStruct.Sum = InputValue + 2;
  OutputStruct.Product = InputValue * 2;

  RtlCopyMemory(OutputPointer, &OutputStruct, sizeof(SYSCALL_OUTPUT));
  return STATUS_SUCCESS;
}
```

Never initialized because „reserved”

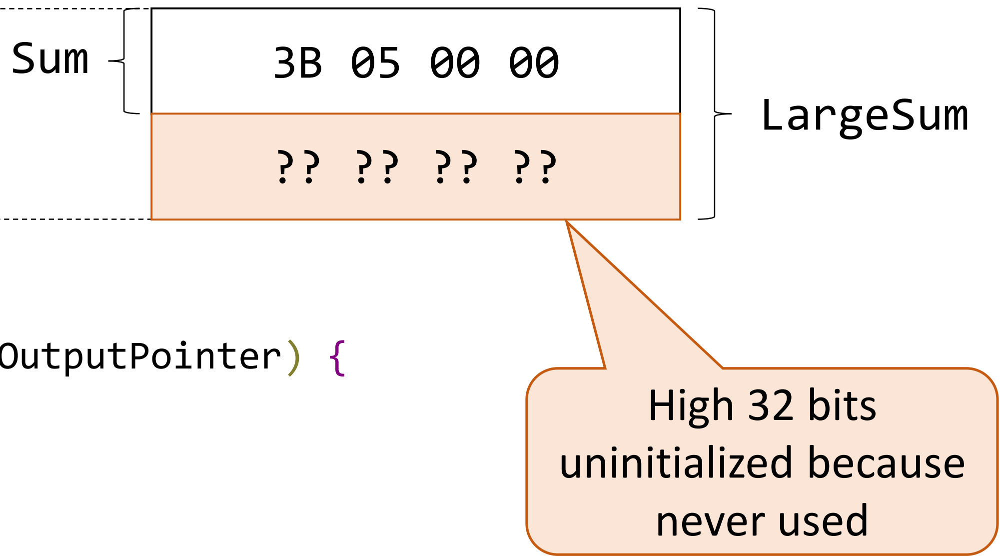
The hard problem – structures and unions

```
typedef union _SYSCALL_OUTPUT {
  DWORD Sum;
  QWORD LargeSum;
} SYSCALL_OUTPUT, *PSYSCALL_OUTPUT;

NTSTATUS NtSmallSum(DWORD InputValue, PSYSCALL_OUTPUT OutputPointer) {
  SYSCALL_OUTPUT OutputUnion;

  OutputUnion.Sum = InputValue + 2;

  RtlCopyMemory(OutputPointer, &OutputUnion, sizeof(SYSCALL_OUTPUT));
  return STATUS_SUCCESS;
}
```



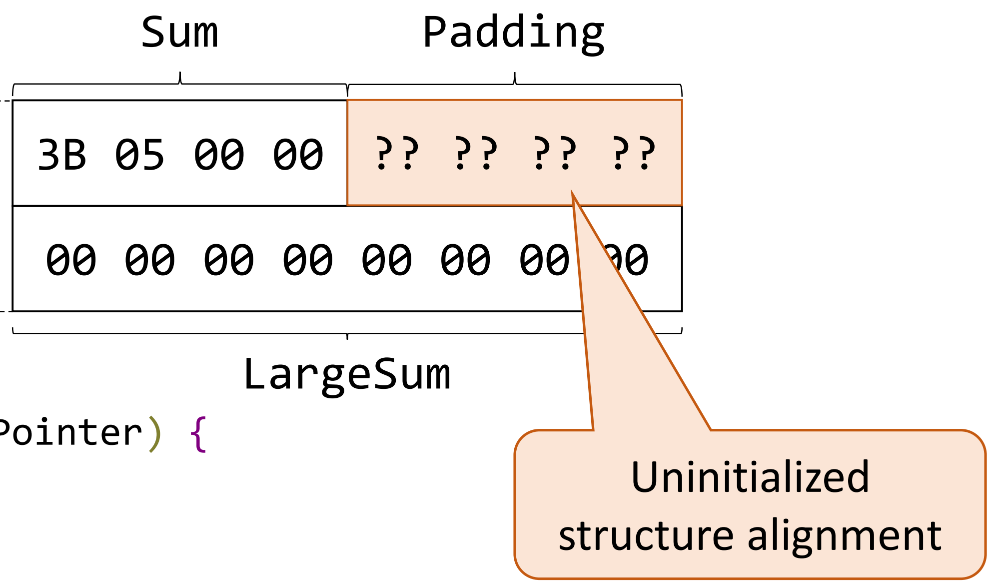
The hard problem – structures and unions

```c
typedef struct _SYSCALL_OUTPUT {
  DWORD Sum;
  QWORD LargeSum;
} SYSCALL_OUTPUT, *PSYSCALL_OUTPUT;

NTSTATUS NtSmallSum(DWORD InputValue, PSYSCALL_OUTPUT OutputPointer) {
  SYSCALL_OUTPUT OutputStruct;

  OutputStruct.Sum = InputValue + 2;
  OutputStruct.LargeSum = 0;

  RtlCopyMemory(OutputPointer, &OutputStruct, sizeof(SYSCALL_OUTPUT));
  return STATUS_SUCCESS;
}
```



The hard problem – structures and unions

- Structures and unions are almost always copied in memory entirely.
- With many fields, it’s easy to forget to set some of them.
    - or they could be uninitialized by design.
- Unions introduce holes for data types of different sizes.
- Compilers introduce padding holes to align fields in memory properly.
- Compilers have little insight into structures (essentially data blobs):
    - dynamically allocated from heap / pools.
    - copied in memory with `memcpy()` etc.

The hard problem – fixed-size arrays

```
43 3A 5C 57 69 6E 64 6F 77 73 5C 53 79 73 74 65 6D 33 32 00 ?? ?? ?? ?? ?? ??
?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ??
?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ??
?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ?? ??
```

Uninitialized unused region of array

```
NTSTATUS NtGetSystemPath(PCHAR OutputPath) {
  CHAR SystemPath[MAX_PATH] = "C:\\Windows\\System32";

  RtlCopyMemory(OutputPath, SystemPath, sizeof(SystemPath));
  return STATUS_SUCCESS;
}
```

The hard problem – fixed-size arrays

- Many instances of long fixed-size buffers used in user ↔ kernel data exchange.
  - Paths, names, identifiers etc.
  - While container size is fixed, the content length is usually variable, and most storage ends up unused.
- Frequently part of structures, which makes it even harder to only copy the relevant part to user-mode.
- May disclose huge continuous portions of uninitialized memory at once.

The hard problem – arbitrary request sizes

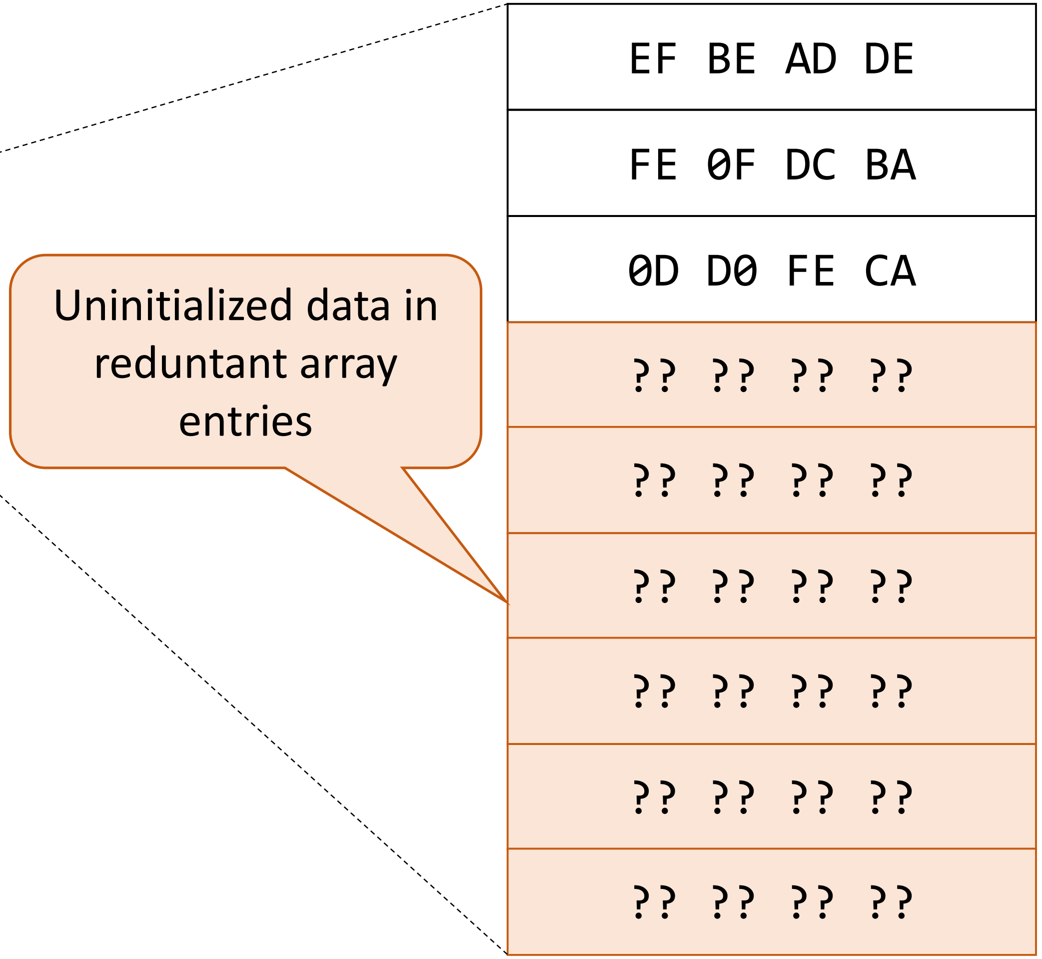
```
NTSTATUS NtMagicValues(LPDWORD OutputPointer, DWORD OutputLength) {
  if (OutputLength < 3 * sizeof(DWORD)) {
    return STATUS_BUFFER_TOO_SMALL;
  }

  LPDWORD KernelBuffer = Allocate(OutputLength);

  KernelBuffer[0] = 0xdeadbeef;
  KernelBuffer[1] = 0xbadc0ffe;
  KernelBuffer[2] = 0xcafed00d;

  RtlCopyMemory(OutputPointer, KernelBuffer, OutputLength);
  Free(KernelBuffer);

  return STATUS_SUCCESS;
}
```



The hard problem – arbitrary request sizes

- Common scheme in Windows – making allocations with user-controlled size and passing them back fully regardless of the amount of relevant data inside.
- May enable disclosure from both stack/heap in the same affected code.
  - Kernel often relies on stack memory for small buffers and falls back to pools for large ones.
- Often leads to large leaks of a controlled number of bytes.
  - Facilitates aligning heap allocation sizes to trigger collisions with specific objects in memory.
  - Gives significantly more power to the attacker in comparison to other bugs.

Extra factors: no automatic initialization

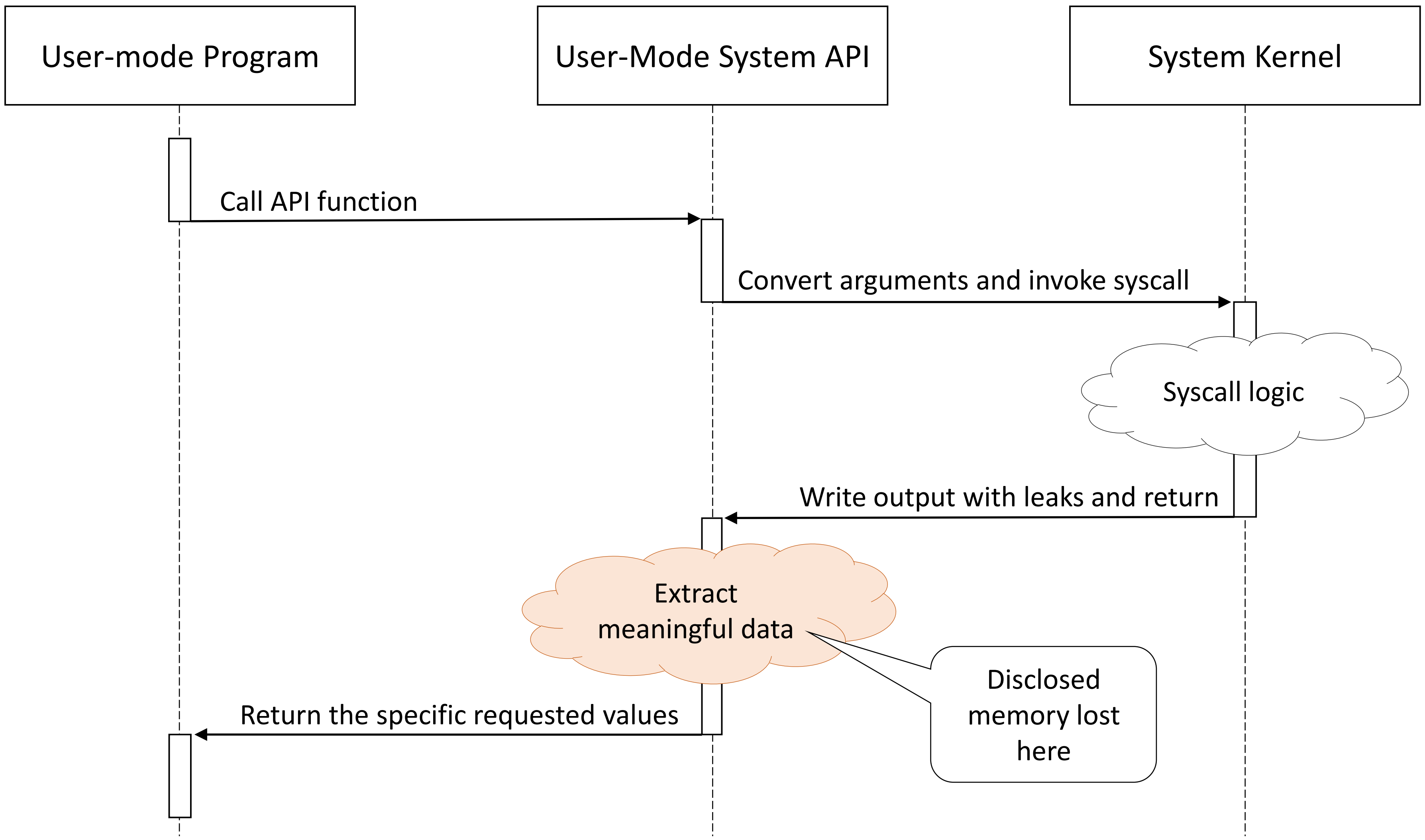
- Neither Windows nor Linux pre-initialize allocations (stack or heap) by default.
  - Exceptions from the rule mostly found in Linux: **`kzalloc()`**, **`__GFP_ZERO`**, **`PAX_MEMORY_STACKLEAK`** etc.
  - Buffered IOCTL I/O buffer is now always cleared in Windows since June 2017 (**new!**)
  - Resulting regions have old, leftover garbage bytes set by their last user.
- From MSDN:

> **Note** Memory that **ExAllocatePoolWithTag** allocates is uninitialized. A kernel-mode driver must first zero this memory if it is going to make it visible to user-mode software (to avoid leaking potentially privileged contents).

Extra factors: no visible consequences

- C/C++ don't make it easy to copy data securely between different security domains, but there's also hardly any punishment.
  - If the kernel discloses a few uninitialized bytes here and there, nothing will crash and likely no one will ever know (until now ☺).
- If a kernel developer is not aware of the bug class and not actively trying to prevent it, he'll probably never find out by accident.

Extra factors: leaks hidden behind system API



Severity and considerations

- „Just” local info leaks, no memory corruption or remote exploitation involved by nature.
- Actual severity depends on what we manage to leak out of the kernel.
- On the upside, most disclosures are silent / transparent, so we can trigger the bugs indefinitely without ever worrying about system stability.

Severity and considerations

- Mostly useful as a single link in a LPE exploit chain.
  - Especially with the amount of effort put into KASLR and protecting information about the kernel address space.
- One real-life example is a Windows kernel exploit found in the HackingTeam dump in July 2015 (CVE-2015-2433, MS15-080).
  - Pool memory disclosure leaking base address of win32k.sys.
  - Independently discovered by Matt Tait at P0, Issue #480.

Kernel-mode ASLR leak via uninitialized memory returned to usermode by NtGdiGetTextMetrics

Reported by matttait@google.com, Jul 10 2015

Stack disclosure benefits

- Consistent, immediately useful values, but with limited variety and potential to leak anything else:
  - Addresses of kernel stack, heap (pools), and executable images.
  - /GS stack cookies.
  - Syscall-specific data used by services previously invoked in the same thread.
  - Potentially data of interrupt handlers, if they so happen to trigger in the context of the exploit thread.

Heap disclosure benefits

- Less obvious memory, but with more potential to collide with miscellaneous sensitive information:
  - Addresses of heap, potentially executable images.
  - Possibly data of any active kernel module (disk, network, video, peripheral drivers).
    - Depending on heap type, allocation size and system activity.

Prior work (Windows)

1. **P0 Issue #480** (`win32k!NtGdiGetTextMetrics`, CVE-2015-2433), Matt Tait, July 2015
2. ***Leaking Windows Kernel Pointers***, Wandering Glitch, RuxCon, October 2016
   - Eight kernel uninitialized memory disclosure bugs fixed in 2015.
3. ***Win32k Dark Composition: Attacking the Shadow Part of Graphic Subsystem***, Peng Qiu and SheFang Zhong, CanSecWest, March 2017
   - Hints about multiple infoleaks in win32k.sys user-mode callbacks, no specific details.
4. ***Automatically Discovering Windows Kernel Information Leak Vulnerabilities***, fanxiaocao and pjf of IceSword Lab (Qihoo 360), June 2017

Prior work (Linux)

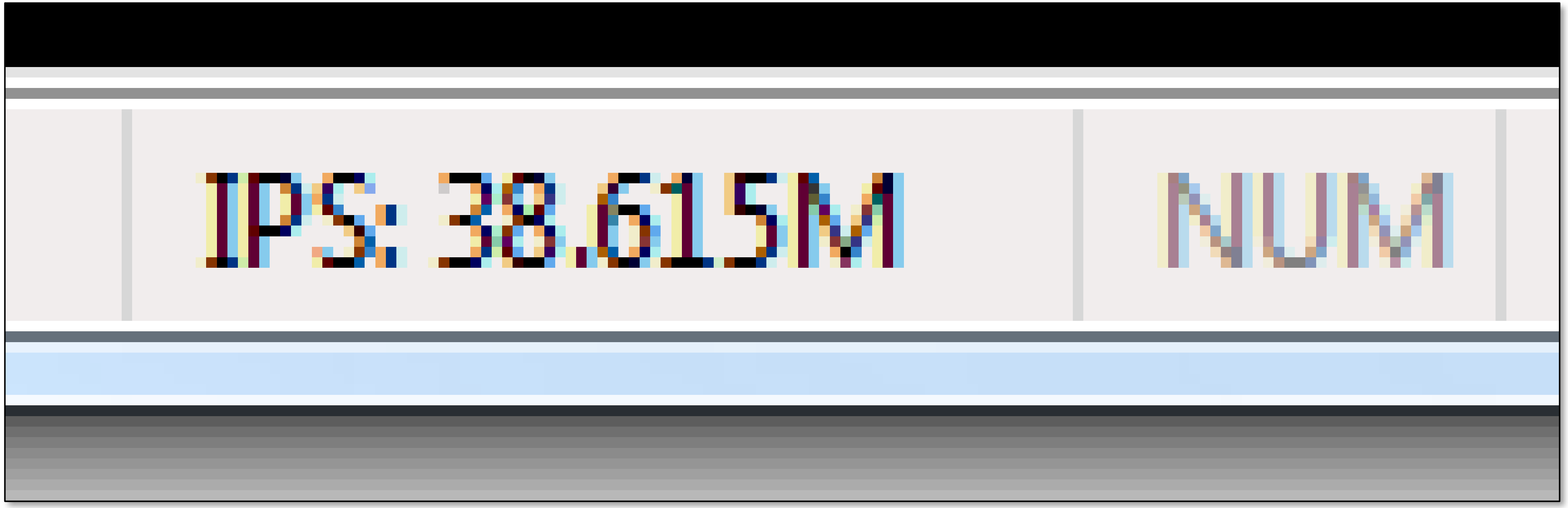
- In 2010, **Dan Rosenberg** went on a rampage and killed 20+ info leaks in various subsystems.
  - Some of the work mentioned in ***Stackjacking and Other Kernel Nonsense***, presented by Dan Rosenberg and Jon Oberheide in 2011.
- A number of patches submitted throughout the years by various researchers: Salva Peiró, Clément Lecigne, Marcel Holtmann, Kees Cook, Jeff Mahoney, to name a few.
- The problem seems to be known and well understood in Linux.

Bochspwn Reloaded design

bochs
think inside the bochs.

- Bochs is a full IA-32 and AMD64 PC emulator.
  - CPU plus all basic peripherals, i.e. a whole emulated computer.
- Written in C++.
- Supports all latest CPUs and their advanced features.
  - SSE, SSE2, SSE3, SSSE3, SSE4, AVX, AVX2, AVX512, SVM / VT-x etc.
- Correctly hosts all common operating systems.
- Provides an extensive instrumentation API.

Performance (short story)



Performance (long story)

- On a modern PC, non-instrumented guests run at up to **80-100M IPS**.
  - Sufficient to boot up a system in reasonable time (<5 minutes).
  - Environment fairly responsive, at between 1-5 frames per second.
- Instrumentation incurs a severe overhead.
  - Performance can drop to **30-40M IPS**.
    - still acceptable for research purposes.
  - Simple logic and optimal implementation is the key to success.

Bochs instrumentation support

- Instrumentation written in the form of callback functions plugged into Bochs through **BX_INSTR** macros, statically built into **bochs.exe**.
- Rich variety of event callbacks:
  - init, shutdown, before/after instruction, linear/physical memory access, exception, interrupt, ...
- Enables developing virtually any logic to examine or steer the whole operating system execution.
  - counting statistics, tracing instructions or memory accesses, adding metadata, altering instruction behavior, adding new instructions, ...

Bochs instrumentation callbacks

- BX_INSTR_INIT_ENV
- BX_INSTR_EXIT_ENV
- **BX_INSTR_INITIALIZE**
- **BX_INSTR_EXIT**
- BX_INSTR_RESET
- BX_INSTR_HLT
- BX_INSTR_MWAIT
- BX_INSTR_DEBUG_PROMPT
- BX_INSTR_DEBUG_CMD
- BX_INSTR_CNEAR_BRANCH_TAKEN
- BX_INSTR_CNEAR_BRANCH_NOT_TAKEN
- BX_INSTR_UCNEAR_BRANCH
- BX_INSTR_FAR_BRANCH
- BX_INSTR_OPCODE
- BX_INSTR_EXCEPTION
- BX_INSTR_INTERRUPT
- BX_INSTR_HWINTERRUPT
- BX_INSTR_CLFLUSH
- BX_INSTR_CACHE_CNTRL
- BX_INSTR_TLB_CNTRL
- BX_INSTR_PREFETCH_HINT
- **BX_INSTR_BEFORE_EXECUTION**
- **BX_INSTR_AFTER_EXECUTION**
- BX_INSTR_REPEAT_ITERATION
- **BX_INSTR_LIN_ACCESS**
- BX_INSTR_PHY_ACCESS
- BX_INSTR_INP
- BX_INSTR_INP2
- BX_INSTR_OUTP
- BX_INSTR_WRMSR
- BX_INSTR_VMEXIT

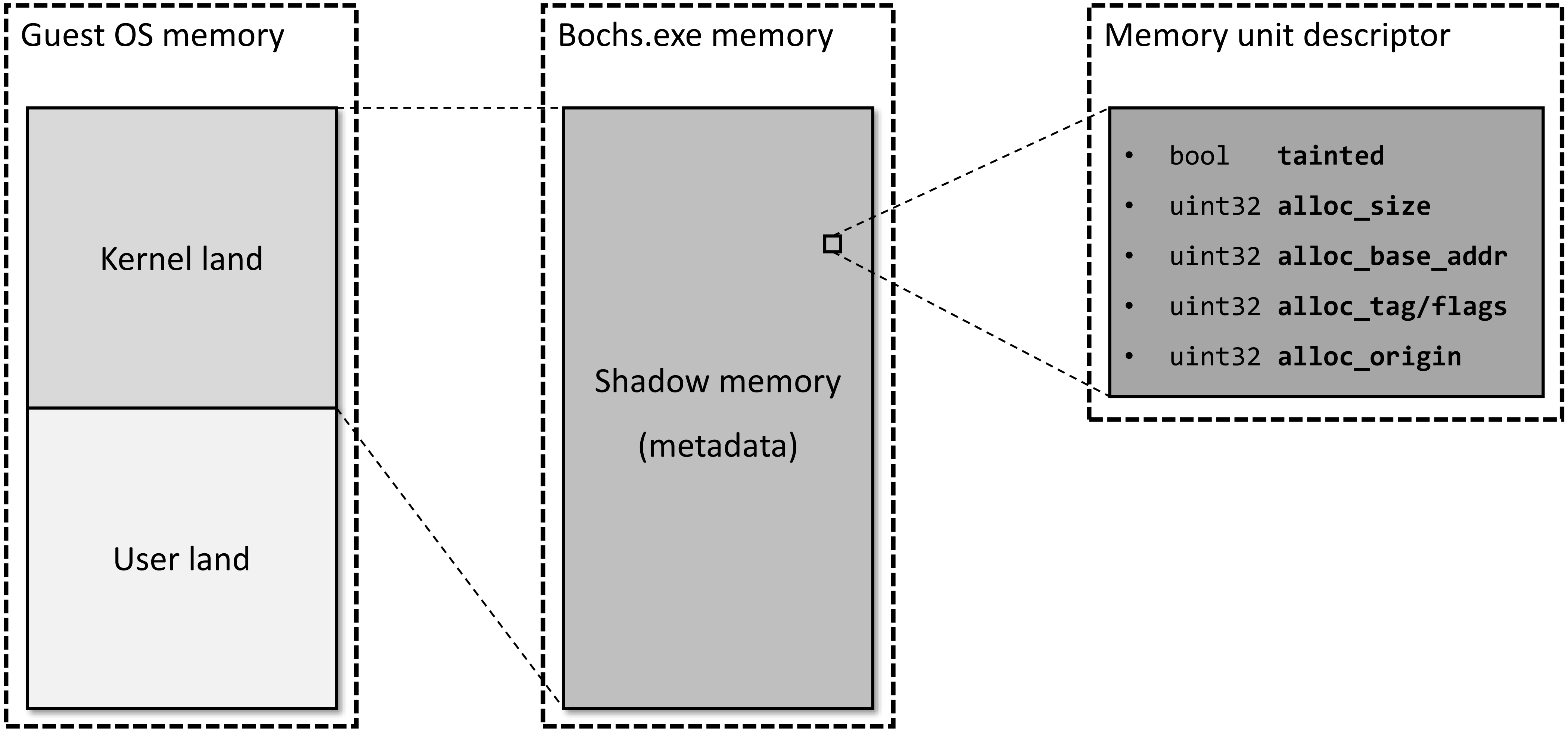
Core logic

- Taint tracking for the entire kernel address space.
- Required functionality:
  1. Set taint on new allocations (stack and heap).
  2. Remove taint on free (heap-only).
  3. Propagate taint in memory.
  4. Detect copying of tainted memory to user-mode.

Ancillary functionality

- Keep track of loaded guest kernel modules.
- Read stack traces on error to deduplicate bugs.
- Symbolize callstacks to prettify reports.
- Break into kernel debugger (attached to guest) on error.

Shadow memory representation



Shadow memory representation

- Linear in relation to the size of the guest kernel address space.
  - Only 32-bit guests supported at the moment.
  - Some information stored at 1-byte granularity, some at 8-byte granularity.
- Stores extra metadata useful for bug reports in addition to taint.
- Max shadow memory consumption:
  - Windows (2 GB kernel space) – **6 GB**
  - Linux (1 GB kernel space) – **3 GB**
  - Easily managable with sufficient RAM on the host.

Double-tainting

- Every time a region is tainted, corresponding guest memory is also padded with a special marker byte.
  - **`0xAA`** for heap and **`0xBB`** for stack areas.
- May trigger use-of-uninit-memory bugs other than just info leaks.
- Provides evidence that a bug indicated by shadow memory is real.
- Eliminates all false-positives, guarantees ~100% true-positive ratio.

Setting taint on stack

- Cross-platform, universal.
- Detect instructions modifying the ESP register:

```
ADD ESP, ...      SUB ESP, ...      AND ESP, ...
```

- After execution, if ESP decreased, call:

$$\texttt{set\_taint}(ESP_{old}, ESP_{new})$$

- Relies on the guest behaving properly, but both Windows and Linux do.

Setting taint on heap/pools (simplified)

- Very system specific.
- Requires knowledge of both the allocated address and request (size, tag / flags, origin etc.) at the same time.
- Then:

```
set_taint(address, address + size)
```

Removing taint on heap free

- Break on `free()` function prologue.
- Look up allocation size from shadow memory.
- Clear all taint and metadata for the whole region.

Taint propagation

- The hard part – detecting data transfers.
- Bochspwn only propagates taint for <REP> MOVS{B,D} instructions.
  - Typically used by memcpy() and its inlined versions across drivers.
  - Both source (ESI) and destination (EDI) addresses conveniently known at the same time.
  - We mostly care about copies of large memory blobs, anyway.
- Best effort approach
  - Moving taint across registers would require instrumenting dozens or hundreds of instructions instead of one, incurring a very significant CPU overhead for arguably little benefit.

Taint propagation

- If a memory access is not a result of `<REP> MOVS{B,D}`:
  - On *write*, clear the taint on the memory area (mark initialized).
  - On *read*, check taint. If shadow memory indicates uninitialized read, verify it with guest memory.
    - In case of mismatch (byte is not equal to the marker for whatever reason), clear taint.
    - If it's a real uninitialized read, we may report it as a bug if running in „strict mode".

Bug detection

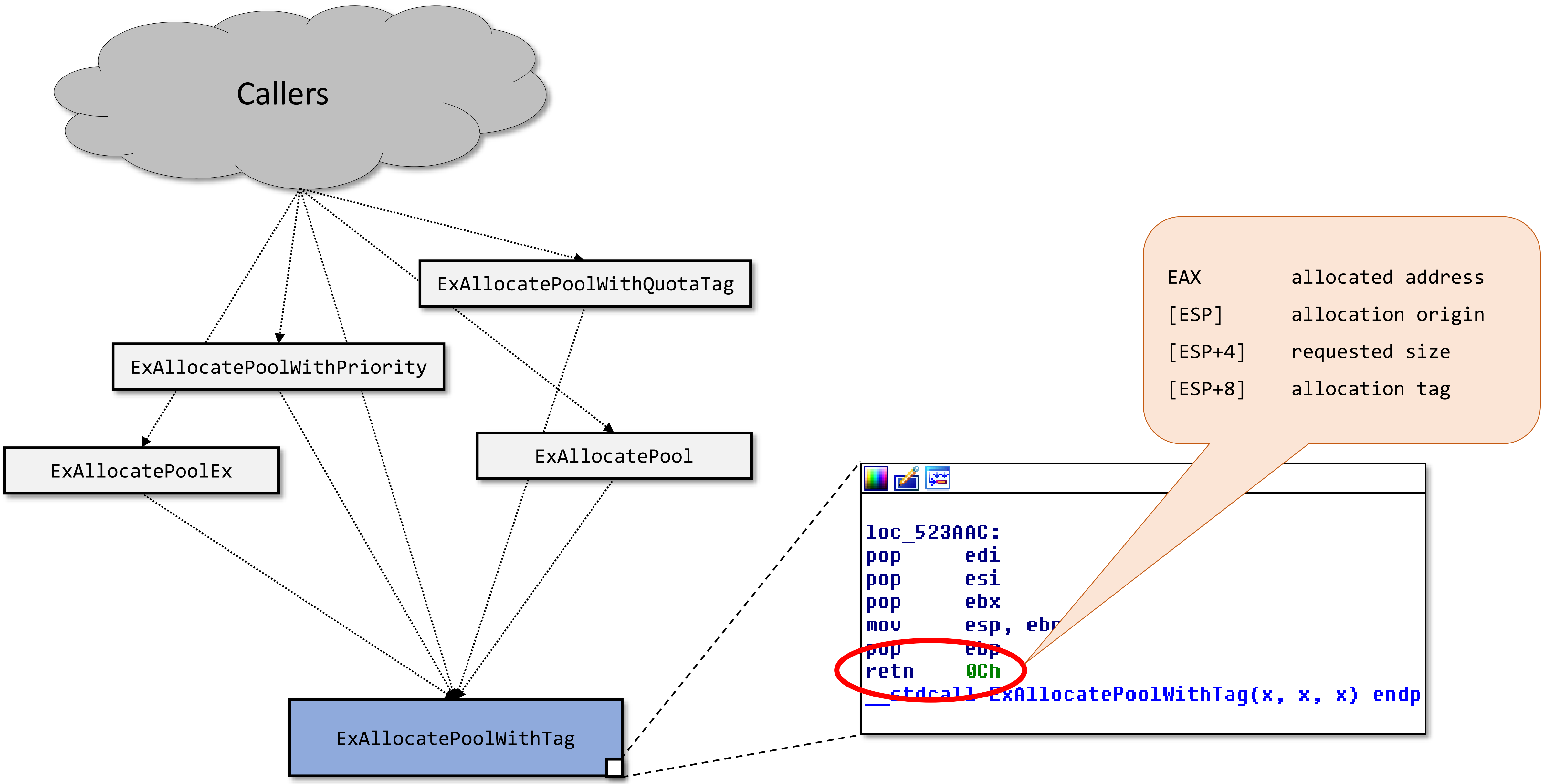
- Activated on <REP> MOVS{B,D} when ESI is in kernel-mode and EDI is in user-mode.
  - Copying an output data blob to user land.
  - If there is any tainted byte in the source memory region, report a bug.

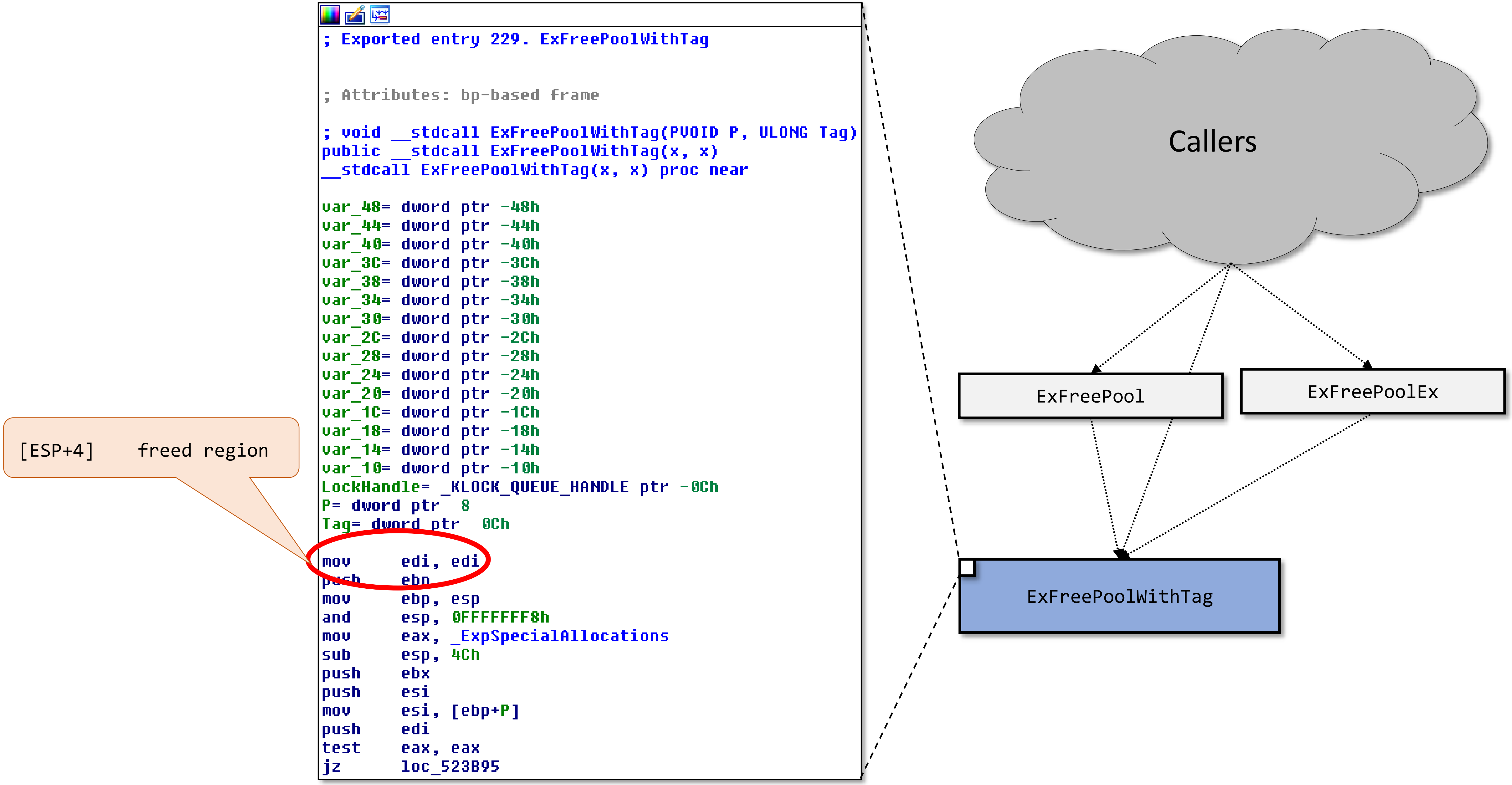
Let’s run it against some real systems

Bochspwn vs. Windows

(Un)tainting pool allocations

- A number of pool allocation routines in the kernel:
  - `ExAllocatePool`, `ExAllocatePoolEx`, `ExAllocatePoolWithTag`, `ExAllocatePoolWithQuotaTag`, `ExAllocatePoolWithTagPriority`
- All eventually call into one: **`ExAllocatePoolWithTag`**.
- STDCALL calling convention: arguments on stack, return value in EAX.
  - Both request (origin, size, tag) and output (allocated address) available at the same time.
- Similar for untaining freed regions.
- Extremely convenient for instrumentation.


Callers
ExAllocatePoolWithQuotaTag
ExAllocatePoolWithPriority
ExAllocatePoolEx
ExAllocatePool
ExAllocatePoolWithTag
loc_523AAC:
pop edi
pop esi
pop ebx
mov esp, ebp
pop ebp
retn 0Ch
__stdcall ExAllocatePoolWithTag(x, x, x) endp
EAX allocated address
[ESP] allocation origin
[ESP+4] requested size
[ESP+8] allocation tag


[ESP+4]   freed region
; Exported entry 229. ExFreePoolWithTag
; Attributes: bp-based frame
; void __stdcall ExFreePoolWithTag(PVOID P, ULONG Tag)
public __stdcall ExFreePoolWithTag(x, x)
__stdcall ExFreePoolWithTag(x, x) proc near
var_48= dword ptr -48h
var_44= dword ptr -44h
var_40= dword ptr -40h
var_3C= dword ptr -3Ch
var_38= dword ptr -38h
var_34= dword ptr -34h
var_30= dword ptr -30h
var_2C= dword ptr -2Ch
var_28= dword ptr -28h
var_24= dword ptr -24h
var_20= dword ptr -20h
var_1C= dword ptr -1Ch
var_18= dword ptr -18h
var_14= dword ptr -14h
var_10= dword ptr -10h
LockHandle= _KLOCK_QUEUE_HANDLE ptr -0Ch
P= dword ptr 8
Tag= dword ptr 0Ch
mov   edi, edi
push   ebp
mov   ebp, esp
and   esp, 0FFFFFFF8h
mov   eax, _ExpSpecialAllocations
sub   esp, 4Ch
push   ebx
push   esi
mov   esi, [ebp+P]
push   edi
test   eax, eax
jz   loc_523B95
Callers
ExFreePool
ExFreePoolEx
ExFreePoolWithTag

Optimized, specialized allocators

- `win32k!AllocFreeTmpBuffer` first tries to return a cached memory region (`win32k!gpTmpGlobalFree`) for allocations of ≤ 4096 bytes.
  - Called from ~55 locations, many syscall handlers.
  - Can be easily patched out to always use the system allocator.

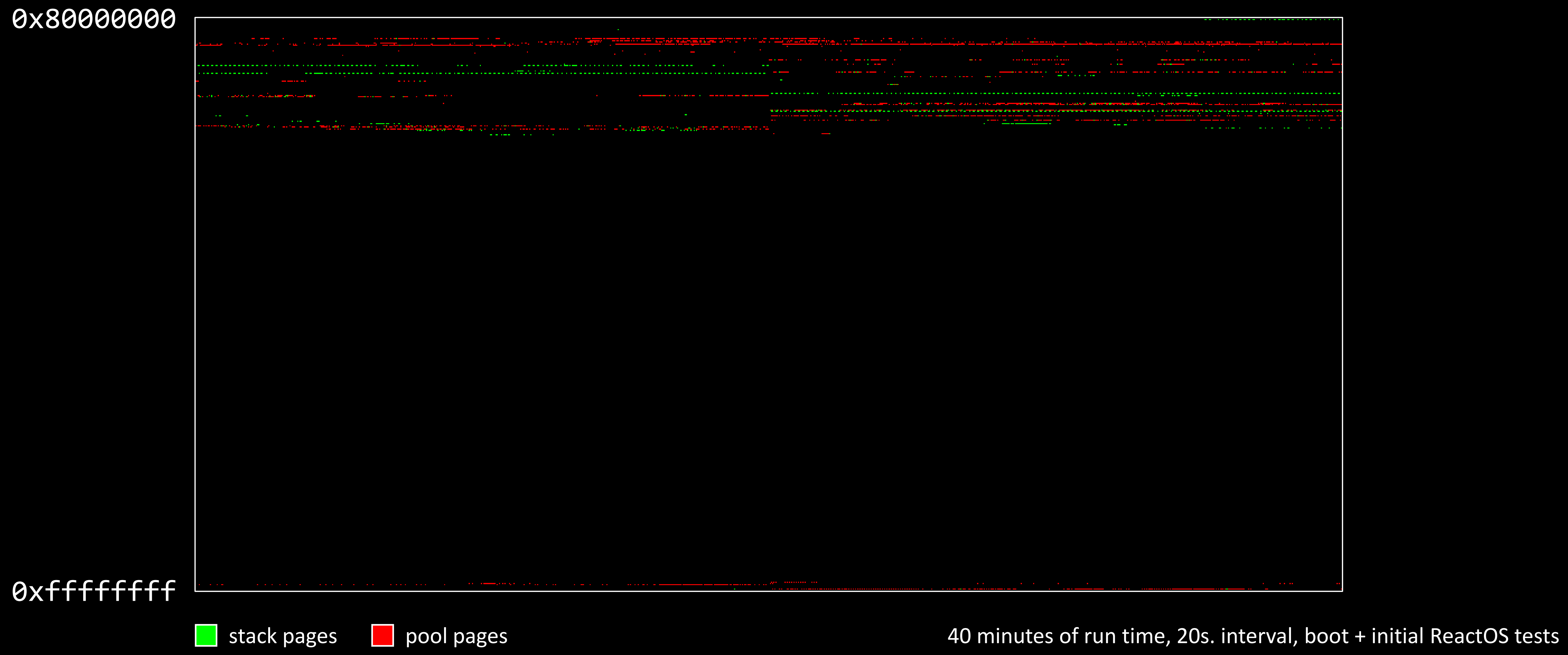
```
PVOID __stdcall AllocFreeTmpBuffer(unsigned int a1)
{
  PVOID result; // eax@2

  if ( a1 > 0x1000 || (result = InterlockedExchange(gpTmpGlobalFree, 0)) == 0 )
    result = AllocThreadBufferWithTag(a1, 'pmTG');
  return result;
}
```

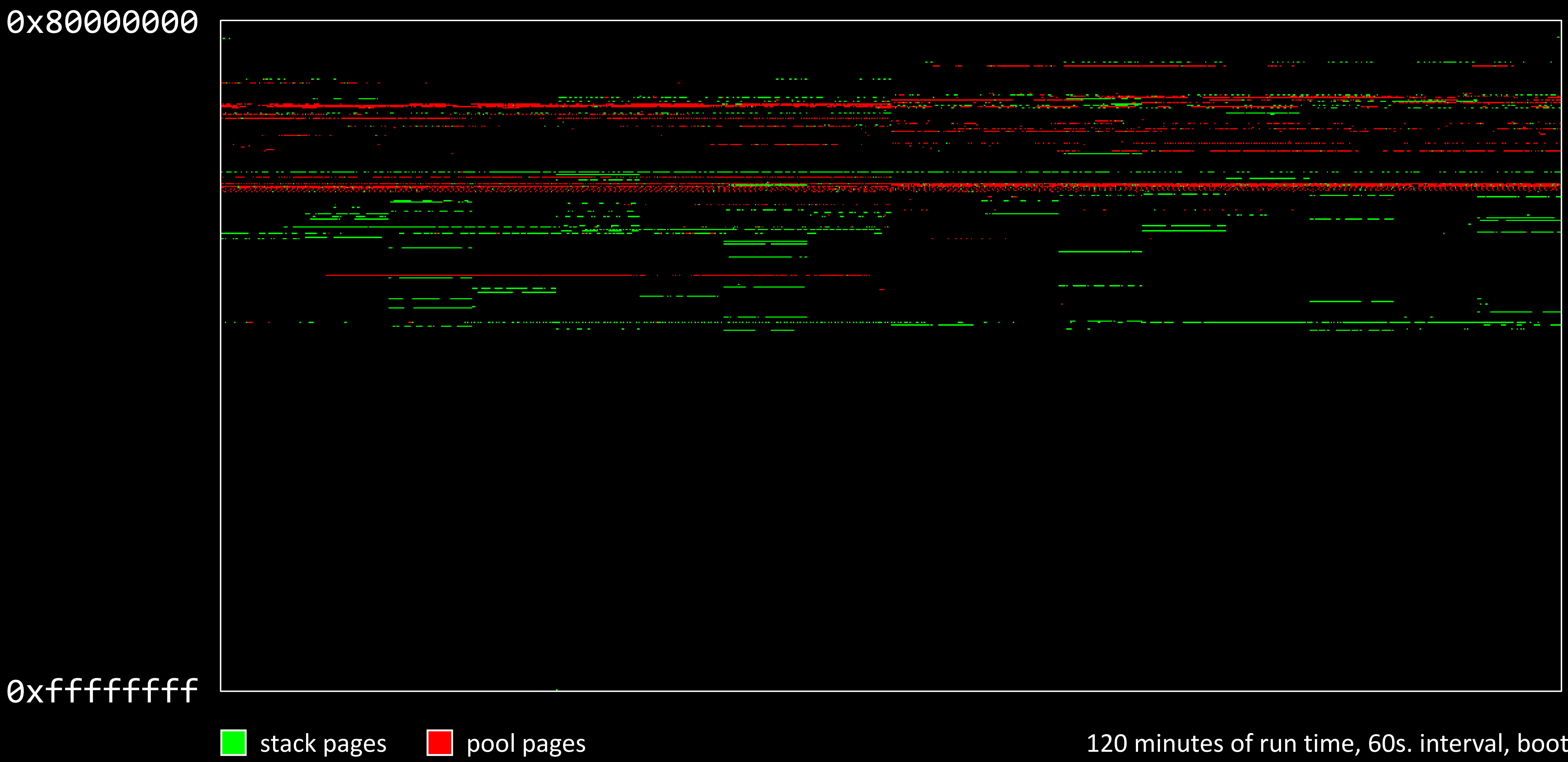
Propagating taint and detecting bugs

- The standalone **`memcpy()`** function in drivers is implemented mostly as **`rep movs`**.
  - Still some optimizations left which transfer data through registers.
  - All instances of `memcpy()` have the same signature – they can be patched to only use `rep movs` on disk or at run time in kernel debugger.
- Inlined memory copy is typically also compiled to `rep movs`.
- As a result, tracking most transfers of large data blobs works with Bochspwn's universal approach.

Windows 7 memory taint layout



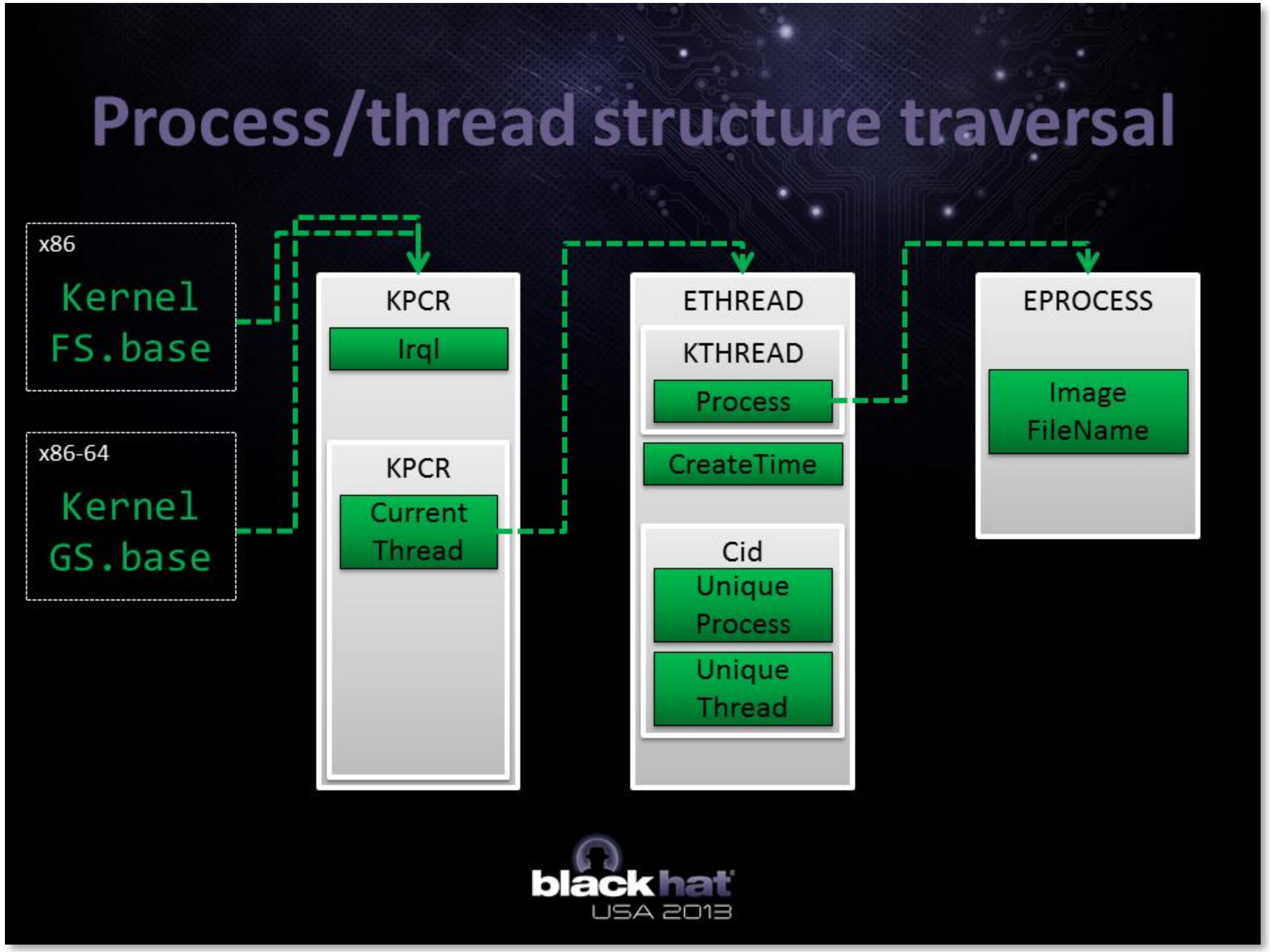
Windows 10 memory taint layout



120 minutes of run time, 60s. interval, boot + initial ReactOS tests

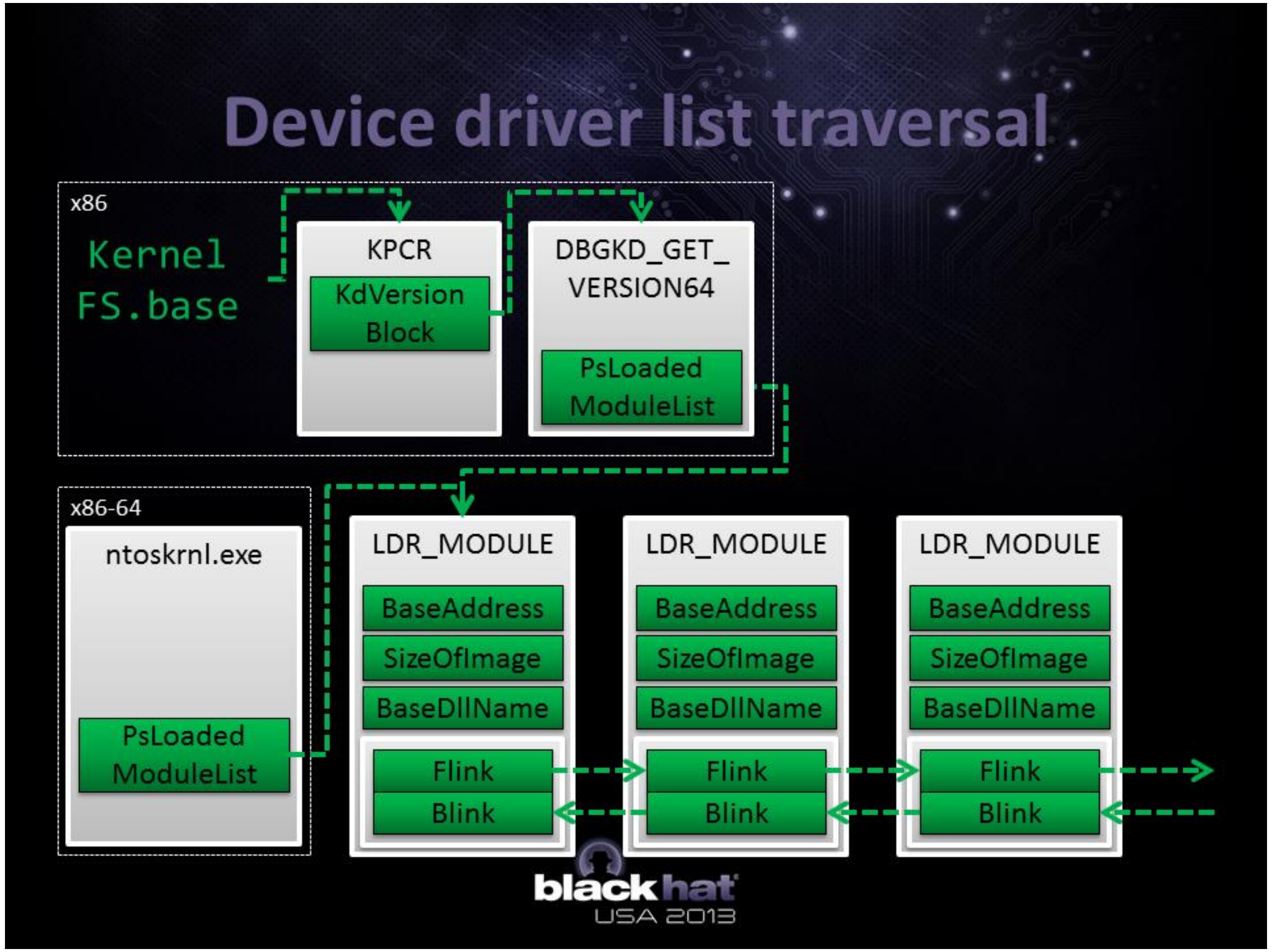
Keeping track of processes/threads

- Simple traversal of a kernel linked-list in guest virtual memory.
- Unchanged since original Bochspwn from 2013.



Keeping track of loaded kernel modules

- Simple traversal of a kernel linked-list in guest virtual memory.
- Unchanged since original Bochspwn from 2013.



Bochspwn report

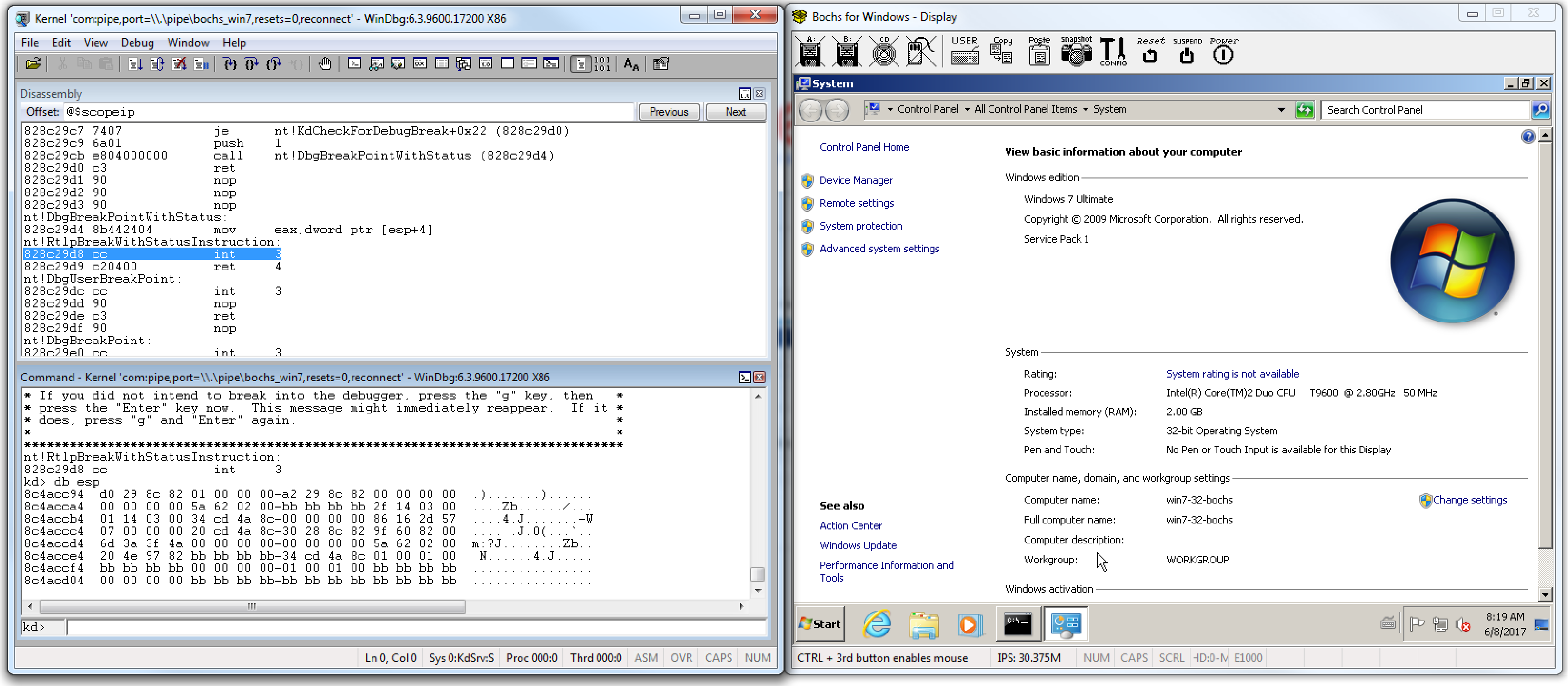
```
------------------------------ found uninit-access of address 94447d04
[pid/tid: 000006f0/00000740] {    explorer.exe}
       READ of 94447d04 (4 bytes, kernel--->user), pc = 902df30f
       [ rep movsd dword ptr es:[edi], dword ptr ds:[esi] ]
[Pool allocation not recognized]
Allocation origin: 0x90334988 ((000c4988) win32k.sys!__SEH_prolog4+00000018)
Destination address: 1b9d380
Shadow bytes: 00 ff ff ff Guest bytes: 00 bb bb bb
Stack trace:
 #0  0x902df30f ((0006f30f) win32k.sys!NtGdiGetRealizationInfo+0000005e)
 #1  0x8288cdb6 ((0003ddb6) ntoskrnl.exe!KiSystemServicePostCall+00000000)
```

Kernel debugger support

- Textual Bochspwn reports are quite verbose, but not always sufficient to reproduce bugs.
  - Especially for IOCTL / other complex cases, where function arguments need to be deeply inspected, kernel objects examined etc.
- Solution – attach WinDbg to the emulated guest kernel!
  - Easily configured, Bochs has support for redirecting COM ports to Windows pipes.
  - Of course slow, as everything working on top of Bochs, but workable. ☺

Breaking on bugs

- Attached debugger is not of much use if we can’t debug the system at the very moment of the infoleak.
- Hence: after the bug is logged to file, Bochspwn injects an INT3 exception in the emulator.
  - WinDbg stops directly after the offending **`rep movs`** instruction.
- Overall feels quite magical. ☺


Kernel 'com:pipe,port=\\.\pipe\bochs_win7,resets=0,reconnect' - WinDbg:6.3.9600.17200 X86
File Edit View Debug Window Help
Disassembly
Offset: @$scopeip
Previous
Next
828c29c7 7407 je nt!KdCheckForDebugBreak+0x22 (828c29d0)
828c29c9 6a01 push 1
828c29cb e804000000 call nt!DbgBreakPointWithStatus (828c29d4)
828c29d0 c3 ret
828c29d1 90 nop
828c29d2 90 nop
828c29d3 90 nop
nt!DbgBreakPointWithStatus:
828c29d4 8b442404 mov eax,dword ptr [esp+4]
nt!RtlpBreakWithStatusInstruction:
828c29d8 cc int 3
828c29d9 c20400 ret 4
nt!DbgUserBreakPoint:
828c29dc cc int 3
828c29dd 90 nop
828c29de c3 ret
828c29df 90 nop
nt!DbgBreakPoint:
Command - Kernel 'com:pipe,port=\\.\pipe\bochs_win7,resets=0,reconnect' - WinDbg:6.3.9600.17200 X86
* If you did not intend to break into the debugger, press the "g" key, then *
* press the "Enter" key now. This message might immediately reappear. If it *
* does, press "g" and "Enter" again. *
nt!RtlpBreakWithStatusInstruction:
828c29d8 cc int 3
kd> db esp
8c4acc94 d0 29 8c 82 01 00 00 00-a2 29 8c 82 00 00 00 00
8c4acca4 00 00 00 00 5a 62 02 00-bb bb bb bb 2f 14 03 00
8c4accb4 01 14 03 00 34 cd 4a 8c-00 00 00 86 16 2d 57
8c4accc4 07 00 00 00 20 cd 4a 8c-30 28 8c 82 9f 60 82 00
8c4accd4 6d 3a 3f 4a 00 00 00 00-00 00 00 00 5a 62 02 00
8c4acce4 20 4e 97 82 bb bb bb bb-34 cd 4a 8c 01 00 01 00
8c4accf4 bb bb bb bb 00 00 00 00-01 00 01 00 bb bb bb bb
8c4acd04 00 00 00 00 bb bb bb bb-bb bb bb bb bb bb bb bb
kd>
Ln 0, Col 0 Sys 0:KdSrv:S Proc 000:0 Thrd 000:0 ASM OVR CAPS NUM
Bochs for Windows - Display
USER Copy Paste Snapshot CONFIG Reset SUSPEND Power
System
Control Panel ▸ All Control Panel Items ▸ System
Search Control Panel
Control Panel Home
Device Manager
Remote settings
System protection
Advanced system settings
View basic information about your computer
Windows edition
Windows 7 Ultimate
Copyright © 2009 Microsoft Corporation. All rights reserved.
Service Pack 1
System
Rating: System rating is not available
Processor: Intel(R) Core(TM)2 Duo CPU T9600 @ 2.80GHz 50 MHz
Installed memory (RAM): 2.00 GB
System type: 32-bit Operating System
Pen and Touch: No Pen or Touch Input is available for this Display
Computer name, domain, and workgroup settings
Computer name: win7-32-bochs
Change settings
Full computer name: win7-32-bochs
Computer description:
Workgroup: WORKGROUP
See also
Action Center
Windows Update
Performance Information and Tools
Windows activation
Start
8:19 AM
6/8/2017
CTRL + 3rd button enables mouse IPS: 30.375M NUM CAPS SCRL HD:0-M E1000

Testing performed

- Instrumentation run on both Windows 7 and 10.
- Executed actions:
  - System boot up.
  - Starting a few default apps – **Internet Explorer**, **Wordpad**, **Registry Editor**, **Control Panel**, games etc.
  - Generating some network traffic.
  - Running ~800 **ReactOS unit tests** (largely improved since 2013).
- Kernel code coverage still a major roadblock for effective usage of full-system instrumentation.

Results!

Windows Kernel Information Disclosure Vulnerability	CVE-2017-8478	Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8479	Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8480	Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8481	Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8482	• fanxiaocao and pjf of IceSword Lab , Qihoo 360 • Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8483	Mateusz Jurczyk of Google Project Zero
Win32k Information Disclosure Vulnerability	CVE-2017-8484	Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8485	• fanxiaocao and pjf of IceSword Lab , Qihoo 360 • Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8488	Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8489	Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8490	
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8491	
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8492	

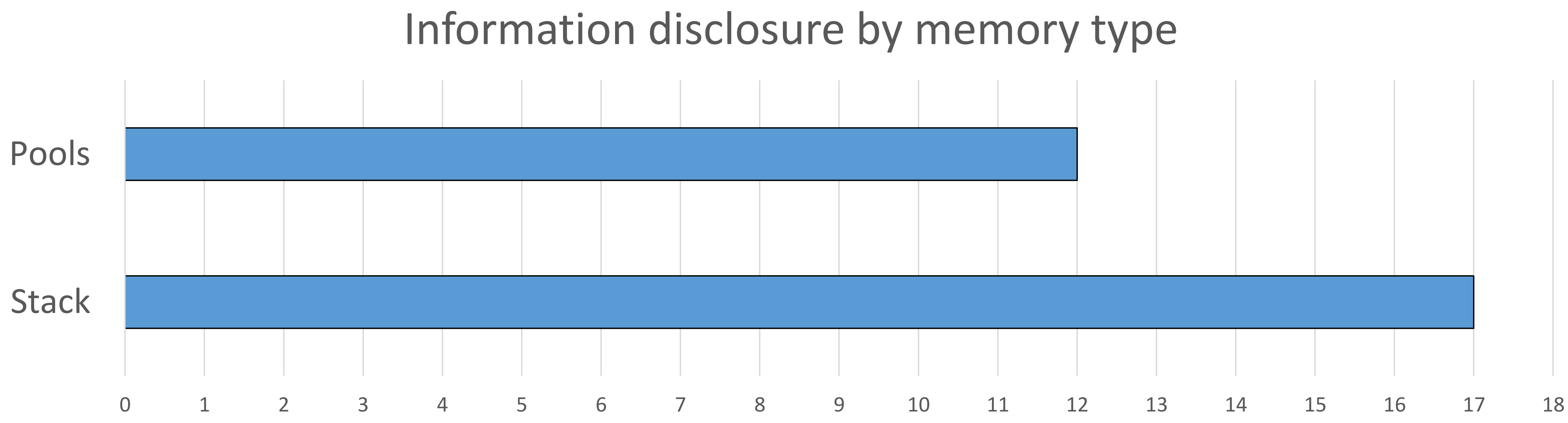
Windows Kernel Information Disclosure Vulnerability	CVE-2017-0175
Windows Kernel Information Disclosure Vulnerability	CVE-2017-0220
Win32k Information Disclosure Vulnerability	CVE-2017-0245
Windows Kernel Information Disclosure Vulnerability	CVE-2017-0258
Windows Kernel Information Disclosure Vulnerability	CVE-2017-0259

Windows Kernel Information Disclosure Vulnerability	CVE-2017-0167

Windows Kernel Information Disclosure Vulnerability	CVE-2017-0299	Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-0300	Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8462	Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8469	Mateusz Jurczyk of Google Project Zero
Win32k Information Disclosure Vulnerability	CVE-2017-8470	• fanxiaocao and pjf of IceSword Lab, Qihoo 360 • Mateusz Jurczyk of Google Project Zero
Win32k Information Disclosure Vulnerability	CVE-2017-8471	Mateusz Jurczyk of Google Project Zero
Win32k Information Disclosure Vulnerability	CVE-2017-8472	Mateusz Jurczyk of Google Project Zero
Win32k Information Disclosure Vulnerability	CVE-2017-8473	Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8474	• fanxiaocao and pjf of IceSword Lab , Qihoo 360 • Mateusz Jurczyk of Google Project Zero
Win32k Information Disclosure Vulnerability	CVE-2017-8475	Mateusz Jurczyk of Google Project Zero
Windows Kernel Information Disclosure Vulnerability	CVE-2017-8476	• fanxiaocao and pjf of IceSword Lab , Qihoo 360 • Mateusz Jurczyk of Google Project Zero
Win32k Information Disclosure Vulnerability	CVE-2017-8477	Mateusz Jurczyk of Google Project Zero

Summary of the results so far

- A total of **29 vulnerabilities** fixed by Microsoft in the last months (mostly June).



Summary – pool disclosures

Issue #	CVE	Component	Fixed in	Root cause	Number of leaked bytes
1144	CVE-2017-8484	win32k!NtGdiGetOutlineTextMetricsInternalW	June 2017	Structure alignment	5
1145	CVE-2017-0258	nt!SepInitSystemDacls	May 2017	Structure size miscalculation	8
1147	CVE-2017-8487	\Device\KsecDD, IOCTL 0x390400	June 2017	Unicode string alignment	6
1150	CVE-2017-8488	Mountmgr, IOCTL_MOUNTMGR_QUERY_POINTS	June 2017	Structure alignment	14
1152	CVE-2017-8489	WMIDataDevice, IOCTL 0x224000 (WmiQueryAllData)	June 2017	Structure alignment, Uninitialized fields	72
1153	CVE-2017-8490	win32k!NtGdiEnumFonts	June 2017	Fixed-size string buffers, Structure alignment, Uninitialized fields	6672
1154	CVE-2017-8491	Volmgr, IOCTL_VOLUME_GET_VOLUME_DISK_EXTENTS	June 2017	Structure alignment	8
1156	CVE-2017-8492	Partmgr, IOCTL_DISK_GET_DRIVE_GEOMETRY_EX	June 2017	Structure alignment	4
1159	CVE-2017-8469	Partmgr, IOCTL_DISK_GET_DRIVE_LAYOUT_EX	June 2017	Structure alignment, Different-size union overlap	484
1161	CVE-2017-0259	nt!NtTraceControl (EtwpSetProviderTraits)	May 2017	?	60
1166	CVE-2017-8462	nt!NtQueryVolumeInformationFile (FileFsVolumeInformation)	June 2017	Structure alignment	1
1169	CVE-2017-0299	nt!NtNotifyChangeDirectoryFile	June 2017	Unicode string alignment	2

Summary – stack disclosures

Issue #	CVE	Component	Fixed in	Root cause	Number of leaked bytes
1177	CVE-2017-8482	nt!KiDispatchException	June 2017	Uninitialized fields	32
1178	CVE-2017-8470	win32k!NtGdiExtGetObjectW	June 2017	Fixed-size string buffer	50
1179	CVE-2017-8471	win32k!NtGdiGetOutlineTextMetricsInternalW	June 2017	Uninitialized field	4
1180	CVE-2017-8472	win32k!NtGdiGetTextMetricsW	June 2017	Structure alignment, Uninitialized field	7
1181	CVE-2017-8473	win32k!NtGdiGetRealizationInfo	June 2017	Uninitialized fields	8
1182	CVE-2017-0245	win32k!xxxClientLpkDrawTextEx	May 2017	?	4
1183	CVE-2017-8474	DeviceApi (PiDqIrpQueryGetResult, PiDqIrpQueryCreate, PiDqQueryCompletePendedIrp)	June 2017	Uninitialized fields	8
1186	CVE-2017-8475	win32k!ClientPrinterThunk	June 2017	?	20
1189	CVE-2017-8485	nt!NtQueryInformationJobObject (BasicLimitInformation, ExtendedLimitInformation)	June 2017	Structure alignment	8
1190	CVE-2017-8476	nt!NtQueryInformationProcess (ProcessVmCounters)	June 2017	Structure alignment	4
1191	CVE-2017-8477	win32k!NtGdiMakeFontDir	June 2017	Uninitialized fields	104
1192	CVE-2017-0167	win32kfull!SfnINLPUAHDRAWMENUITEM	April 2017	?	20
1193	CVE-2017-8478	nt!NtQueryInformationJobObject (information class 12)	June 2017	?	4
1194	CVE-2017-8479	nt!NtQueryInformationJobObject (information class 28)	June 2017	?	16
1196	CVE-2017-8480	nt!NtQueryInformationTransaction (information class 1)	June 2017	?	6
1207	CVE-2017-8481	nt!NtQueryInformationResourceManager (information class 0)	June 2017	?	2
1214	CVE-2017-0300	nt!NtQueryInformationWorkerFactory (WorkerFactoryBasicInformation)	June 2017	?	5

Pool infoleak reproduction

- Use a regular VM with guest Windows.
- Find out which driver makes the allocation leaked to user-mode (e.g. win32k.sys).
- Enable **Special Pools** for that module, reboot.
- Start PoC twice, observe a repeated marker byte where data is leaked (changes between runs).

```
D:\>VolumeDiskExtents.exe
00000000: 01 00 00 00 39 39 39 39 ....9999
00000008: 00 00 00 00 39 39 39 39 ....9999
00000010: 00 00 50 06 00 00 00 00 ..P.....
00000018: 00 00 a0 f9 09 00 00 00 ........
```

```
D:\>VolumeDiskExtents.exe
00000000: 01 00 00 00 2f 2f 2f 2f ....////
00000008: 00 00 00 00 2f 2f 2f 2f ....////
00000010: 00 00 50 06 00 00 00 00 ..P.....
00000018: 00 00 a0 f9 09 00 00 00 ........
```

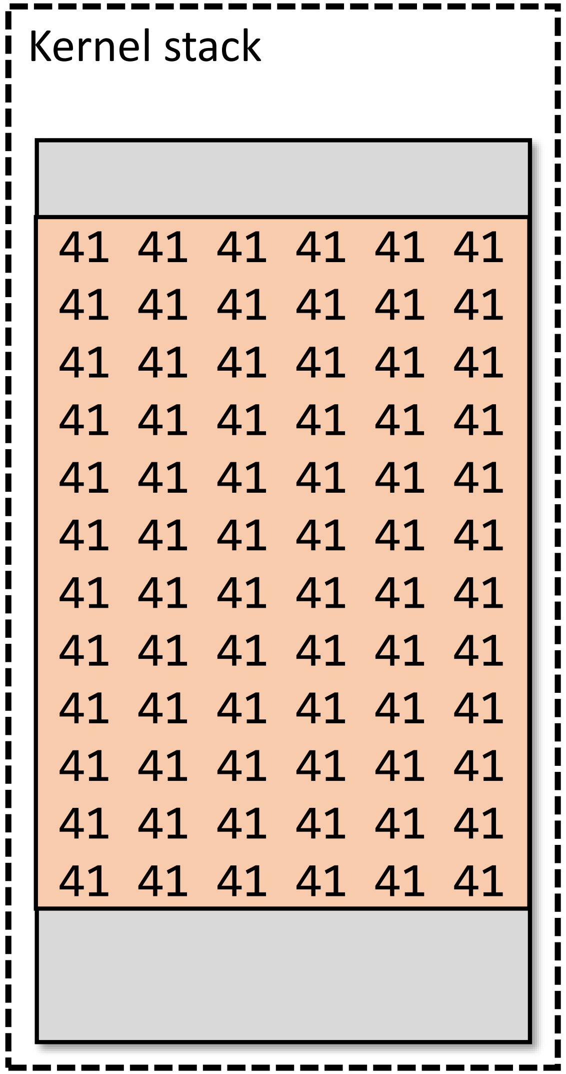
Stack infoleak reproduction

- More difficult, there is no official / documented way of padding stack allocations with marker bytes.
- In a typical scenario, it may not be obvious that/which specific bytes are leaked.
  - Non-volatile, non-interesting values (e.g. zeros) often occupy a large portion of the stack.
  - Observations could differ in Microsoft's test environment.
- Reliable proof of concept programs are highly desired.
  - To fully ensure that a bug is real also outside of Bochspwn environment.
  - To make the vendor's life easier with analysis.

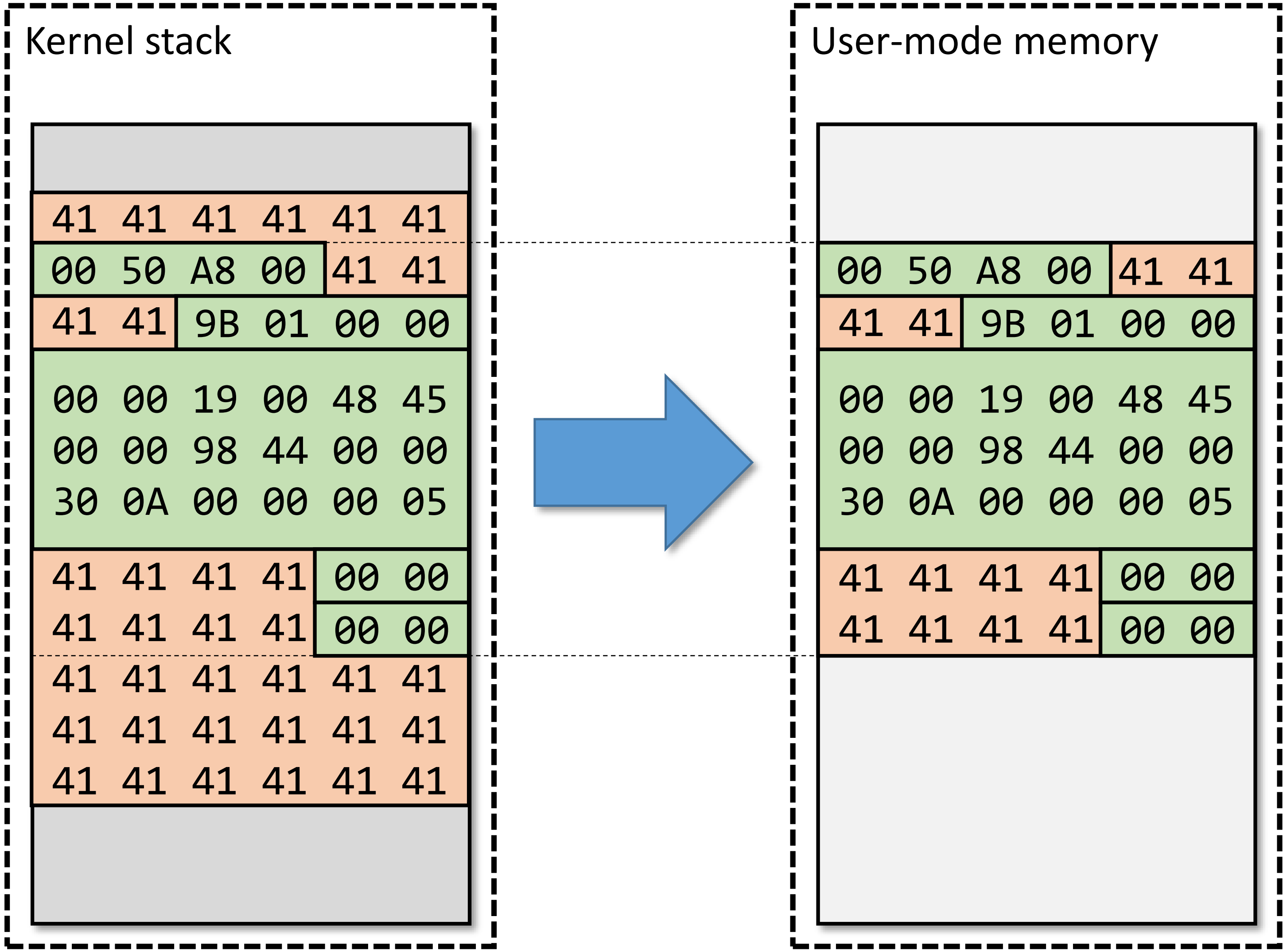
Stack spraying to the rescue

- A number of primitives exist in the Windows kernel to fill the kernel stack with controlled data.
  - Thanks to optimizations – local buffers used for „small” requests in many syscalls.
- Easy to identify: look for Nt* functions with large stack frames in IDA.
- My favorite: **`nt!NtMapUserPhysicalPages`**
  - Sprays up to 4096 bytes on x86 and 8192 bytes on x86-64.
  - Documented in „*nt!NtMapUserPhysicalPages and Kernel Stack-Spraying Techniques*” blog post in 2011.

1. Spray the kernel stack with an easily recognizable pattern.



2. Trigger the bug directly after, and observe the marker bytes at uninitialized offsets.



```
D:\>NtGdiGetRealizationInfo.exe
00000000: 10 00 00 00 03 01 00 00 ........
00000008: 2e 00 00 00 69 00 00 46 ....i..F
00000010: 41 41 41 41 41 41 41 41 AAAAAAAA
```

Quick digression: bugs without Bochspwn

- If *memory marking* can be used for bug demonstration, it can be used for discovery too.
- Basic idea:
  - Enable Special Pools for all common kernel modules.
  - Invoke tested system call twice, pre-spraying the kernel stack with a different byte each time.
  - Compare output in search of repeated patterns of differing bytes at common offsets.

Perfect candidate: NtQueryInformation*

```
NTSTATUS
NTAPI
NtQueryInformationProcess (
    IN HANDLE ProcessHandle,
    IN PROCESSINFOCLASS ProcessInformationClass,
    OUT PVOID ProcessInformation,
    IN ULONG ProcessInformationLength,
    OUT PULONG ReturnLength OPTIONAL
    );
```

Manually created

Brute-forced 0..255

Brute-forced 1..255

NtQueryInformationAtom
NtQueryInformationEnlistment
NtQueryInformationFile
NtQueryInformationJobObject
NtQueryInformationPort
NtQueryInformationProcess
NtQueryInformationResourceManager
NtQueryInformationThread
NtQueryInformationToken
NtQueryInformationTransaction
NtQueryInformationTransactionManager
NtQueryInformationWorkerFactory

Fruitful idea

Windows Kernel stack memory disclosure in nt!NtQueryInformationJobObject (information class 12)
Project Member Reported by mjurczyk@google.com, Mar 17

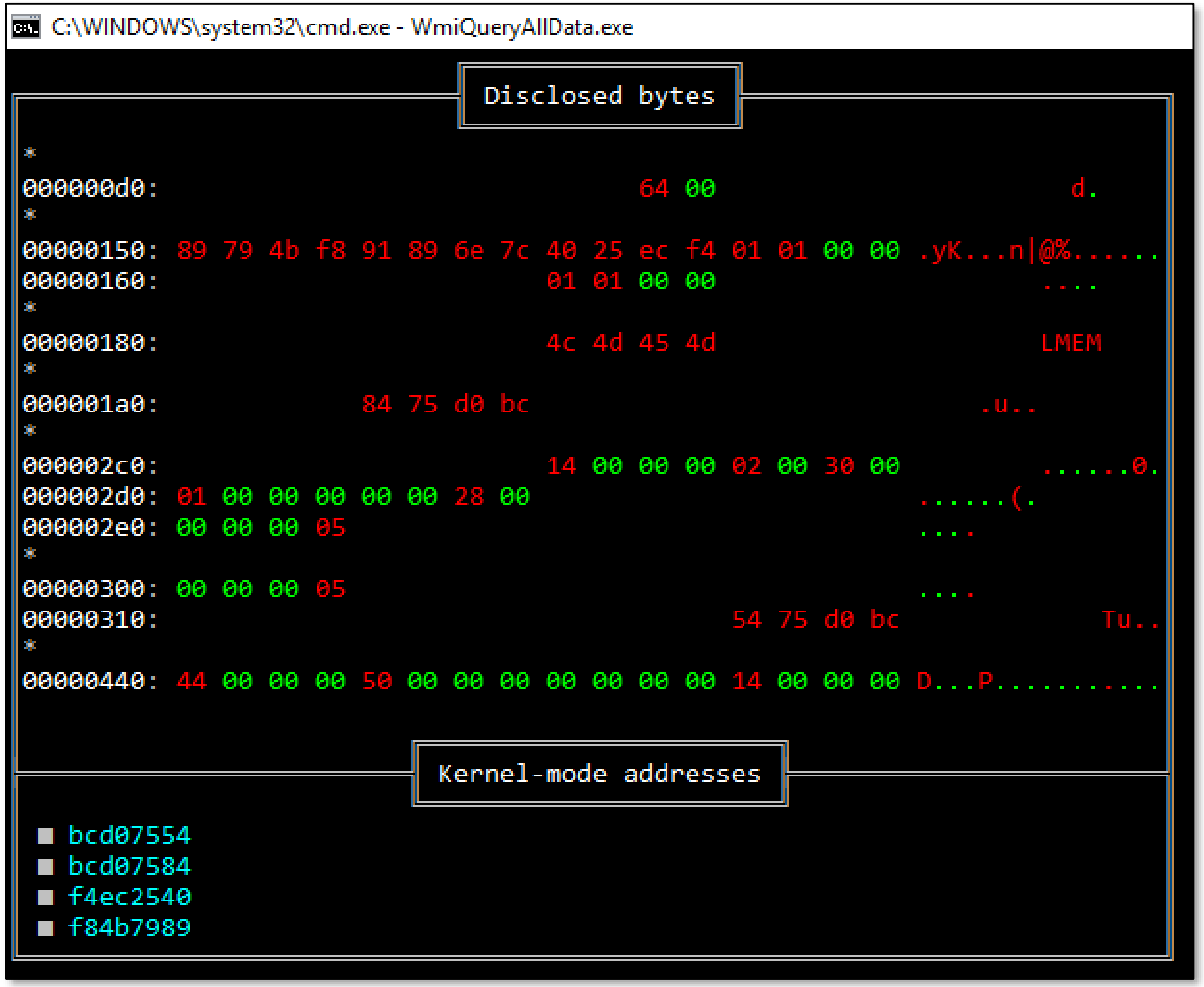
Windows Kernel stack memory disclosure in nt!NtQueryInformationJobObject (information class 28)
Project Member Reported by mjurczyk@google.com, Mar 17

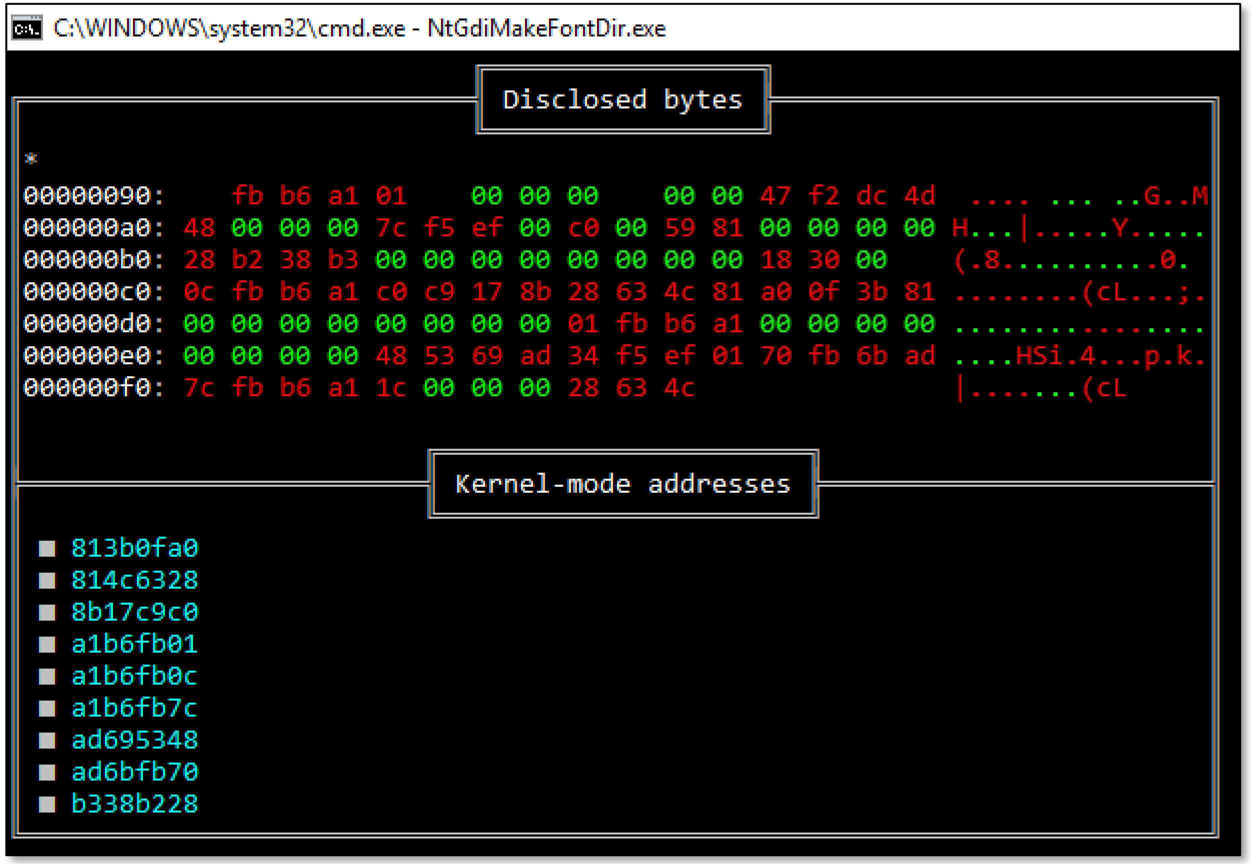
Windows Kernel stack memory disclosure in nt!NtQueryInformationTransaction (information class 1)
Project Member Reported by mjurczyk@google.com, Mar 17

Windows Kernel stack memory disclosure in nt!NtQueryInformationResourceManager (information class 0)
Project Member Reported by mjurczyk@google.com, Mar 20

Windows Kernel stack memory disclosure in nt!NtQueryInformationWorkerFactory (WorkerFactoryBasicInformation)
Project Member Reported by mjurczyk@google.com, Mar 21

Infoleak demos

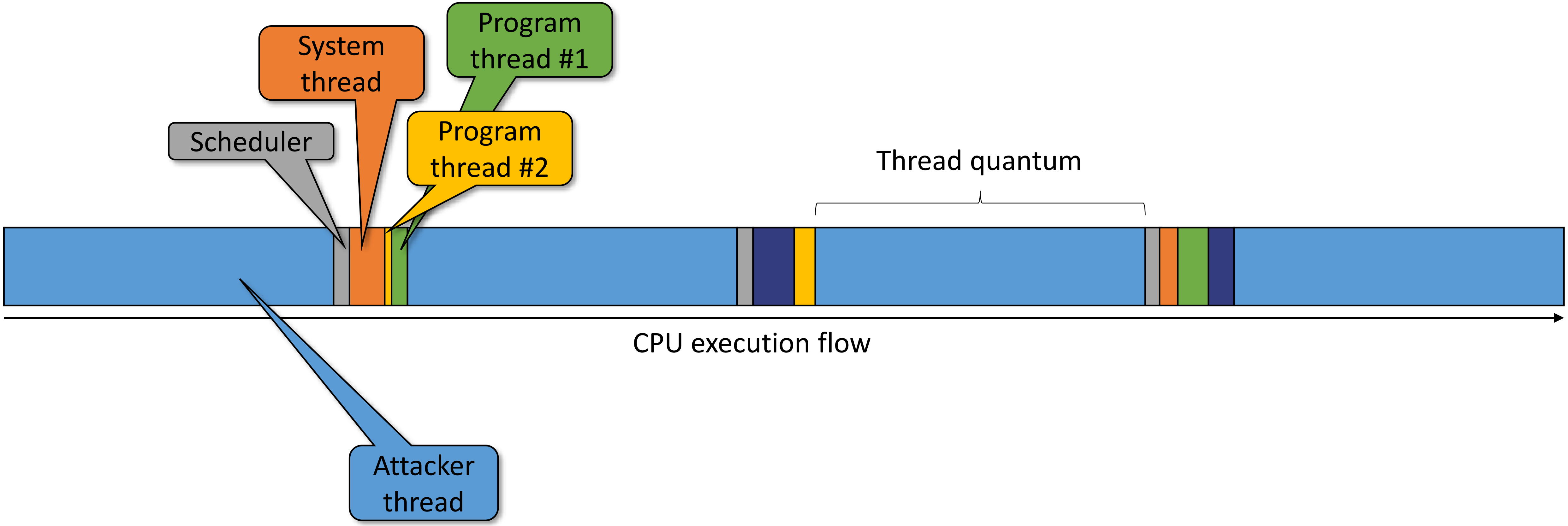


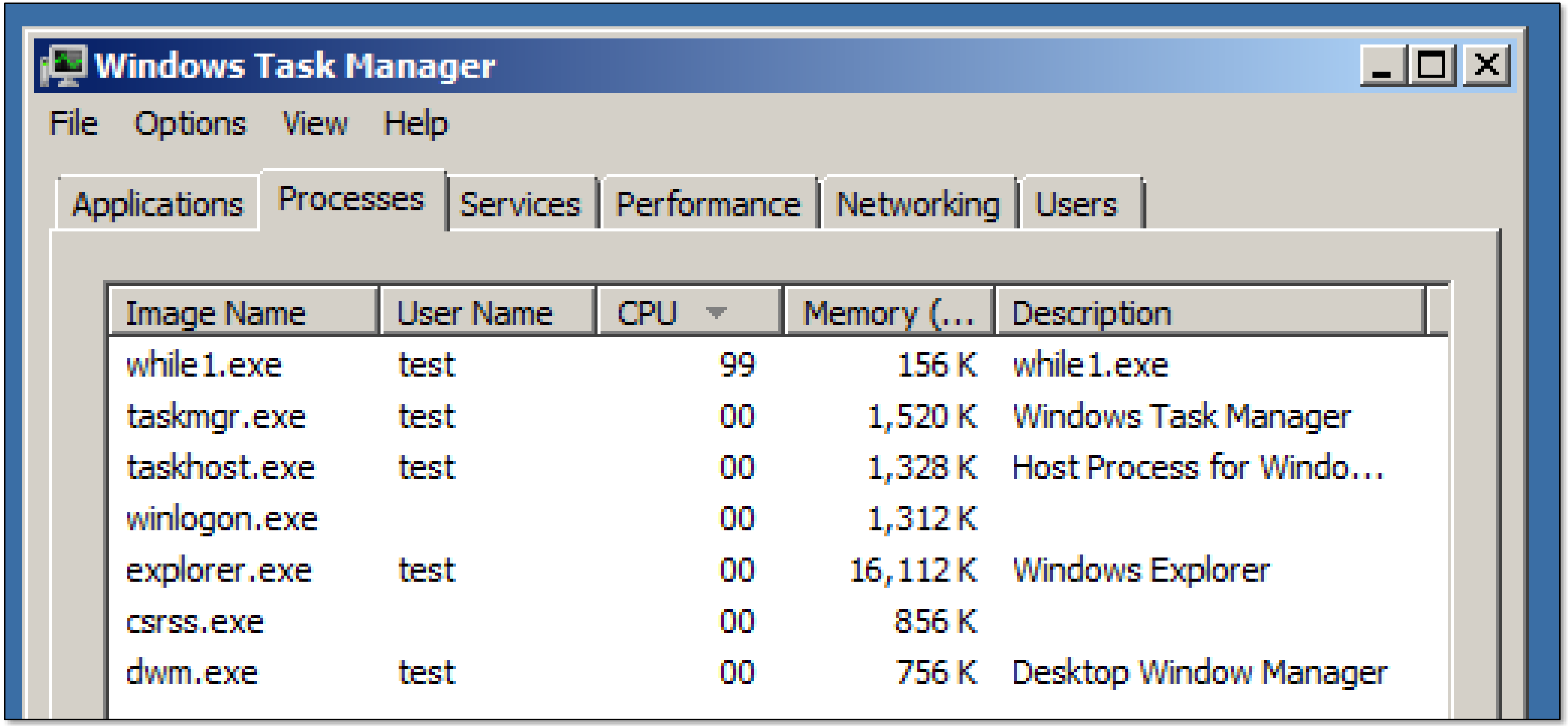


Sniffing on hardware activity

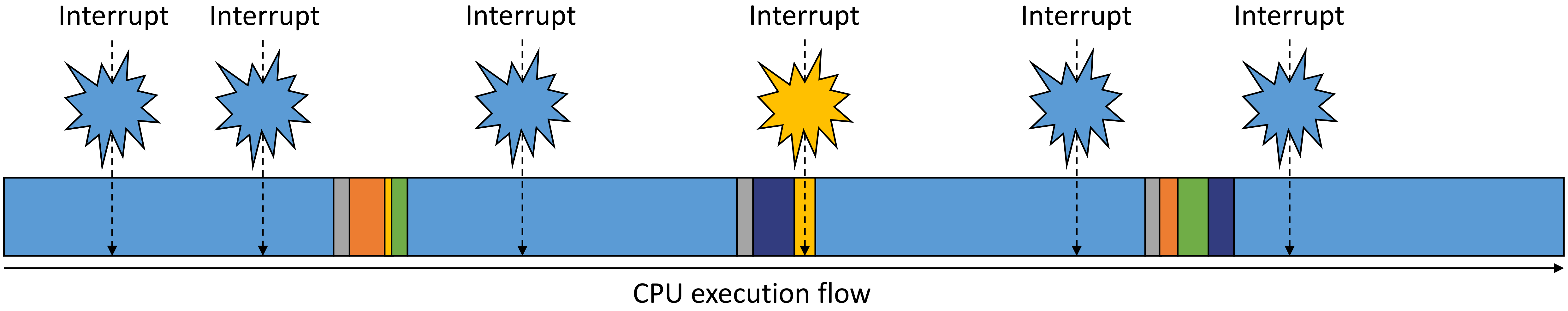
- On Windows 7, hardware interrupt handlers operate on the kernel stack of the currently active thread.
- The handlers may leave traces of sensitive data of what is going on in the system.
  - For example, characteristics of the actions performed by other users.
  - The information could be subsequently leaked with a stack disclosure vulnerability.
- Normally pretty unlikely to happen, but… CPU Time Spraying!

`while (1) { }`


System thread
Program thread #1
Scheduler
Program thread #2
Thread quantum
CPU execution flow
Attacker thread


Windows Task Manager
File Options View Help
Applications Processes Services Performance Networking Users
Image Name User Name CPU Memory (... Description
while1.exe test 99 156 K while1.exe
taskmgr.exe test 00 1,520 K Windows Task Manager
taskhost.exe test 00 1,328 K Host Process for Windo...
winlogon.exe 00 1,312 K
explorer.exe test 00 16,112 K Windows Explorer
csrss.exe 00 856 K
dwm.exe test 00 756 K Desktop Window Manager

```
while (1) { }
```


Interrupt
Interrupt
Interrupt
Interrupt
Interrupt
Interrupt
CPU execution flow

Exploitation algorithm

1. Clear the kernel stack (pad with zeros) with a stack-spraying primitive.
2. Actively consume some number of CPU cycles.
   - Just `for (int i = 0; i < N; i++) { }` for a well-adjusted N.
3. Disclose kernel stack memory with an infoleak bug.
4. Analyze the data for specific patterns and extract relevant information.

What interrupt should we target?

```
kd> !idt 91

Dumping IDT:

91:   85190058 i8042prt!I8042KeyboardInterruptService (KINTERRUPT 85190000)
```

i8042prt!I8042KeyboardInterruptService

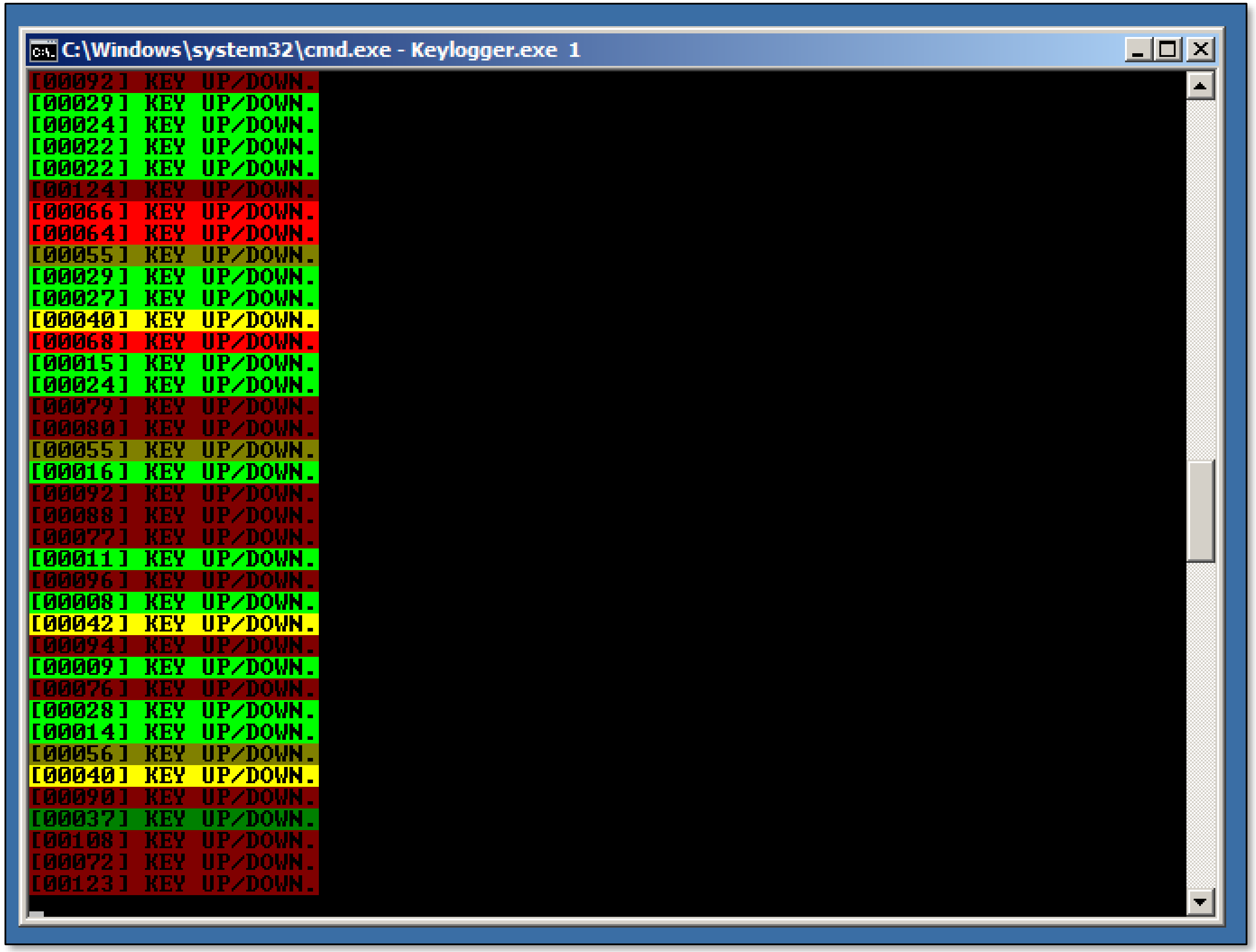
Scan code saved on the stack

```
loc_17581:
lea     eax, [ebp+var_1D]
push    eax
push    1
call    _I8xGetByteAsynchronous@8 ; I8xGetByteAsynchronous(x,x)
```

Keyboard sniffing obstacles

- The i8042prt.sys driver stores the detected scancode in several places on the stack in the interrupt handling code.
- However, all these locations seem to be overwritten later on (e.g. by `hal!HalEndSystemInterrupt`). ☹
- Even still, certain patterns can be recognized on the stack to identify the general key (un)press event.
- Windows 7 with a single CPU used in demo for simplicity.

Keyboard sniffing demo



Windows infoleak summary

- The problem seems to have remained almost completely unrecognized until just now (with a few exceptions).
  - The *invisibility* and non-obviousness of this bug class and no notion of privilege separation in C/C++ doesn't really help.
  - It's a fundamental issue, trivial to overlook but very difficult to get right in the code.

Windows infoleak summary

- Windows has a very loose approach to kernel→user data transfers.
- Tip of the iceberg, there may be many more instances of the bug lurking in the codebase.
  - Hundreds of `memcpy()` calls to user-mode exist, every one of them is a potential disclosure.
  - Especially those where size is user-controlled, but the amount of relevant data is fixed or otherwise limited.

Mitigation ideas (generic)

- Fully bug-proof: memset all stack and pool allocations when they are made/requested.
  - Would pretty much make the problem go away without any actual bug-fixing.
  - Easily implemented, but the overhead is probably too large?
  - Most kernel allocations don’t end up copied to user-mode, anyway.

That was fast!

Joseph Bialek
@JosephBialek

Follow

Anyone notice my change to the Windows IO Manager to generically kill a class of info disclosure? BufferedIO output buffer is always zero'd.

```
10046 00000001`4039329c 452be5        sub     r12d,r13d
10046 00000001`4039329f 458bc4        mov     r8d,r12d  // r8d = OutputBufferLength - InputBufferLength
10046 00000001`403932a2 418bcd        mov     ecx,r13d  // ecx = InputBufferLength
10046 00000001`403932a5 48034e18      add     rcx,qword ptr [rsi+18h] // rcx = SystemBuffer+InputBufferLength
10046 00000001`403932a9 33d2          xor     edx,edx
10046 00000001`403932ab e8e0fdcdff    call    ntoskrnl!memset (00000001`40073090)
```

Retweets 12 · Likes 8

8:59 PM - 15 Jun 2017

Mitigation ideas (generic)

- More realistic:
  - Clear the kernel stack post-syscall (a.k.a. PAX_MEMORY_STACKLEAK).
    - Prevents cross-syscall leaks, which are probably the majority.
  - Add a new allocator function clearing returned memory regions.
  - Detect which allocations end up copied to user-mode and clear only those (automatically or by adding `memset()` calls in code manually).

Mitigation ideas (bug-specific)

- With Windows source code, Microsoft could take the whole Bochspwn idea to the next level:
  - Adding instrumentation at compile time → access to much more semantic information, e.g. better taint propagation (full vs. just `memcpy`).
  - More code coverage → more bugs found.
  - Static analysis easier to use to guide dynamic approaches and vice versa.

Closing remarks

- The Bochspwn approach can be also used to detect *regular* use of uninitialized memory, but the results are much harder to triage:
  - LOTS of false positives.
  - Lack of source code makes it very difficult to determine if an access is a bug and what its impact is.
- Leaking specific sensitive data from pool disclosures seems like an interesting subject and still needs research. ☺

Bochspwn vs. Linux

Tainting heap allocations

- MUCH more complex than on Windows:
  - A number of allocators, public and internal, with many variants: **`kmalloc`**, **`vmalloc`**, **`kmem_cache_alloc`**.
  - Allocator functions have different declarations.
  - Passing arguments via registers (**`regparm=3`**) means request information is not available on RET instruction.
  - kmem_cache's have allocation sizes specified during cache creation.
  - kmem_cache's may have constructors (tainting at a different time then returning region to caller).
  - Allocators may return pointers ≤ 0x10 (not just NULL).

Variety of allocators (kmalloc/kmem_cache)

```
void *kmalloc(size_t, gfp_t);
void *__kmalloc(size_t, gfp_t);
void *kmalloc_order(size_t, gfp_t, unsigned int);
void *kmalloc_order_trace(size_t, gfp_t, unsigned int);
void *kmalloc_large(size_t, gfp_t);
void *kzalloc(size_t, gfp_t);
struct kmem_cache *kmem_cache_create(const char *, size_t, size_t,
unsigned long, void (*)(void *));
void *kmem_cache_alloc(struct kmem_cache *, gfp_t);
void *kmem_cache_alloc_trace(struct kmem_cache *, gfp_t, size_t);
```

Variety of allocators (vmalloc)

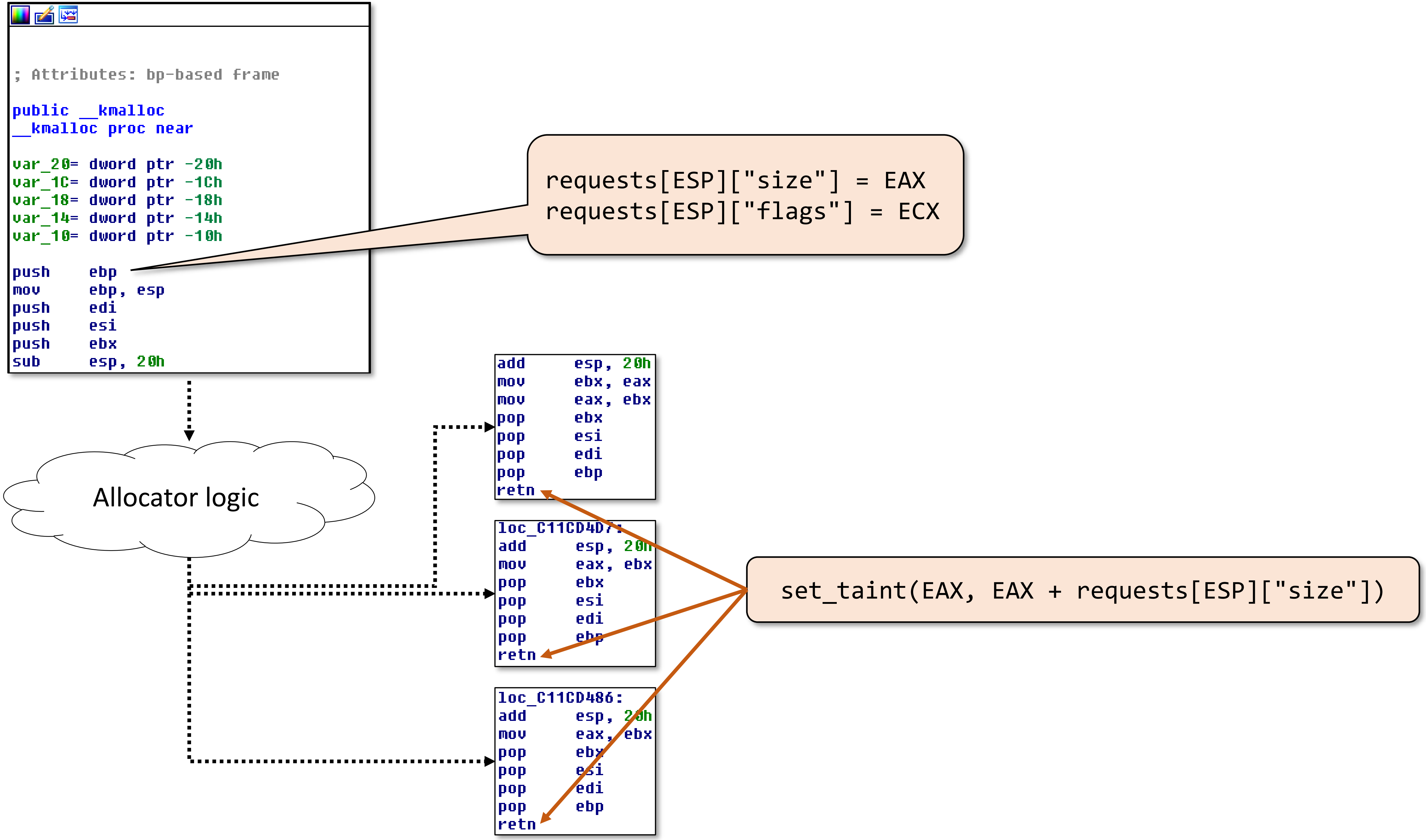
```
void *vmalloc(unsigned long);
void *vzalloc(unsigned long);
void *vmalloc_user(unsigned long);
void *vmalloc_node(unsigned long, int);
void *vzalloc_node(unsigned long, int);
void *vmalloc_exec(unsigned long);
void *vmalloc_32(unsigned long);
void *vmalloc_32_user(unsigned long);
void *__vmalloc(unsigned long, gfp_t, pgprot_t);
void *__vmalloc_node_range(unsigned long, unsigned long, unsigned long, unsigned long, gfp_t,
                           pgprot_t, unsigned long, int, const void *);
```

Variety of allocators

- Of course many of them call into each other, but in the end, we still had to hook into:
  - `__kmalloc`
  - `kmalloc_order`
  - `__kmalloc_track_caller`
  - `__vmalloc_node`
  - `kmem_cache_create`
  - `kmem_cache_alloc`
  - `kmem_cache_alloc_trace`
- ... and the corresponding `free()` routines, too.

regparm=3

- First three arguments to functions are passed through EAX, EDX, ECX.
  - Tried compiling the kernel without the option, but failed to boot. ☹
- Information about the allocation request and result is not available at the same time.
- Necessary to intercept execution twice: in the prologue and epilogue of the allocator.


; Attributes: bp-based frame
public __kmalloc
__kmalloc proc near
var_20= dword ptr -20h
var_1C= dword ptr -1Ch
var_18= dword ptr -18h
var_14= dword ptr -14h
var_10= dword ptr -10h
push ebp
mov ebp, esp
push edi
push esi
push ebx
sub esp, 20h
requests[ESP]["size"] = EAX
requests[ESP]["flags"] = ECX
Allocator logic
add esp, 20h
mov ebx, eax
mov eax, ebx
pop ebx
pop esi
pop edi
pop ebp
retn
add esp, 20h
mov eax, ebx
pop ebx
pop esi
pop edi
pop ebp
retn
loc_C11CD486:
add esp, 20h
mov eax, ebx
pop ebx
pop esi
pop edi
pop ebp
retn
set_taint(EAX, EAX + requests[ESP]["size"])

kmem_cache_{create,alloc}

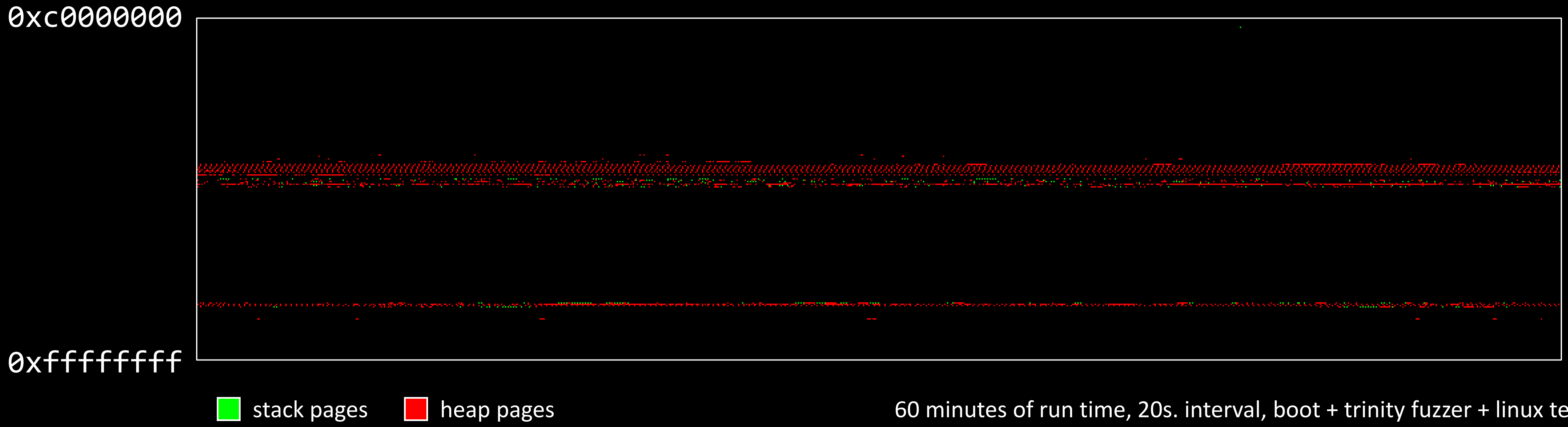
- Dedicated mechanism for quick allocation of fixed-sized memory regions (e.g. structs).
  - **`kmem_cache_create`** creates a cache object (receives size, flags, constructor).
  - **`kmem_cache_alloc`** allocates memory from cache.
  - **`kmem_cache_free`** frees a memory region from cache.
  - **`kmem_cache_destroy`** destroys the cache object.
- We need to:
  - Maintain an up-to-date list of currently active caches.
  - Break on cache constructors to set taint on memory.
  - Break on allocators to set other metadata (e.g. caller's EIP).

Propagating taint

- **CONFIG_X86_GENERIC=y** and **CONFIG_X86_USE_3DNOW=n** sufficient to compile `memcpy()` into a combination of `rep movs{d,b}`.

```
.text:C13CC43B                 mov     ebx, ecx
.text:C13CC43D                 mov     edi, eax
.text:C13CC43F                 shr     ecx, 2
.text:C13CC442                 mov     esi, edx
.text:C13CC444                 rep movsd
.text:C13CC446                 mov     ecx, ebx
.text:C13CC448                 and     ecx, 3
.text:C13CC44B                 jz      short loc_C13CC44F
.text:C13CC44D                 rep movsb
.text:C13CC44F
.text:C13CC44F loc_C13CC44F:                           ; CODE XREF: memcpy+1B↑j
.text:C13CC44F                 pop     ebx
.text:C13CC450                 pop     esi
.text:C13CC451                 pop     edi
.text:C13CC452                 pop     ebp
.text:C13CC453                 retn
.text:C13CC453 memcpy          endp
```

Ubuntu 16.04 memory taint layout



60 minutes of run time, 20s. interval, boot + trinity fuzzer + linux test project

Other useful CONFIG options

- **CONFIG_DEBUG_INFO=y** to enable debugging symbols.
- **CONFIG_VMSPLIT_3G=y** to use the 3G/1G user/kernel split.
- **CONFIG_RANDOMIZE_BASE=n** to disable kernel ASLR.
- **CONFIG_X86_SMAP=n** to disable SMAP.
- **CONFIG_HARDENED_USERCOPY=n** to disable sanity checks unnecessary during instrumentation.

Detecting bugs – copy_to_user

- Set **CONFIG_X86_INTEL_USERCOPY=n** to have `copy_to_user()` compiled to `rep movs{d,b}` instead of a sequence of `mov`.

```
.text:C13CCA2B                 mov     ebx, ecx
.text:C13CCA2D                 mov     edi, eax
.text:C13CCA2F                 mov     esi, edx
.text:C13CCA31                 cmp     ecx, 7
.text:C13CCA34                 jbe     short loc_C13CCA4E
.text:C13CCA36                 mov     ecx, edi
.text:C13CCA38                 neg     ecx
.text:C13CCA3A                 and     ecx, 7
.text:C13CCA3D                 sub     ebx, ecx
.text:C13CCA3F                 rep movsb
.text:C13CCA41                 mov     ecx, ebx
.text:C13CCA43                 shr     ecx, 2
.text:C13CCA46                 and     ebx, 3
.text:C13CCA49                 nop
.text:C13CCA4A                 rep movsd
.text:C13CCA4C                 mov     ecx, ebx
.text:C13CCA4E
.text:C13CCA4E loc_C13CCA4E:                           ; CODE XREF: __copy_from_user_ll_nocache_nozero+14↑j
.text:C13CCA4E                 rep movsb
.text:C13CCA50                 pop     ebx
.text:C13CCA51                 mov     eax, ecx
.text:C13CCA53                 pop     esi
.text:C13CCA54                 pop     edi
.text:C13CCA55                 pop     ebp
.text:C13CCA56                 retn
.text:C13CCA56 __copy_from_user_ll_nocache_nozero endp
```

Detecting bugs – put_user

- Linux has a macro to write values of primitive types to userland memory.
- No internal `memcpy()`, so such leaks wouldn't normally get detected.
- Each architecture has its own version of the macro, x86 too.
- Very difficult to modify the source to convert it to Bochspwn-compatible `rep movs`.
  - Various constructs passed as argument: constants, variables, structure fields, function return values etc.

The solution – temporary strict mode

```
#define __put_user(x, ptr) \
({                                  \
        __typeof__(*(ptr)) __x;     \
...
        __asm("prefetcht1 (%eax)"); \
        __x = (x);                  \
        __asm("prefetcht2 (%eax)"); \
...
```

1. Enable *strict mode* (for current ESP)

2. Evaluate expression written to userland

3. Disable *strict mode*

Strict mode

- **PREFETCH{1,2}** instructions are effectively NOPs in Bochs.
  - Can be used as markers in the code, or „hypercalls”.
- In between **PREFETCH1** and **PREFETCH2**, all reads of uninitialized memory are reported as kernel→user leaks, if ESP is unchanged.
  - The code block only contains evaluation of the expression being written to ring-3.
  - Verifying ESP prevents polluting logs with reports from function calls, thread preemptions etc.
- **365** such constructs added to the vmlinux used by Bochspwn.

Strict mode as seen in IDA

```
.text:C1027F72                 prefetcht1 byte ptr [eax]
.text:C1027F75                 mov     eax, [ebp+var_B4]
.text:C1027F7B                 mov     [ebp+var_AC], eax
.text:C1027F81                 prefetcht2 byte ptr [eax]
```

Sanitized

```
.text:C1035910                 prefetcht1 byte ptr [eax]
.text:C1035913                 mov     eax, [ebp+var_14]
.text:C1035916                 mov     edx, edi
.text:C1035918                 call    getreg
.text:C103591D                 mov     [ebp+var_10], eax
.text:C1035920                 prefetcht2 byte ptr [eax]
```

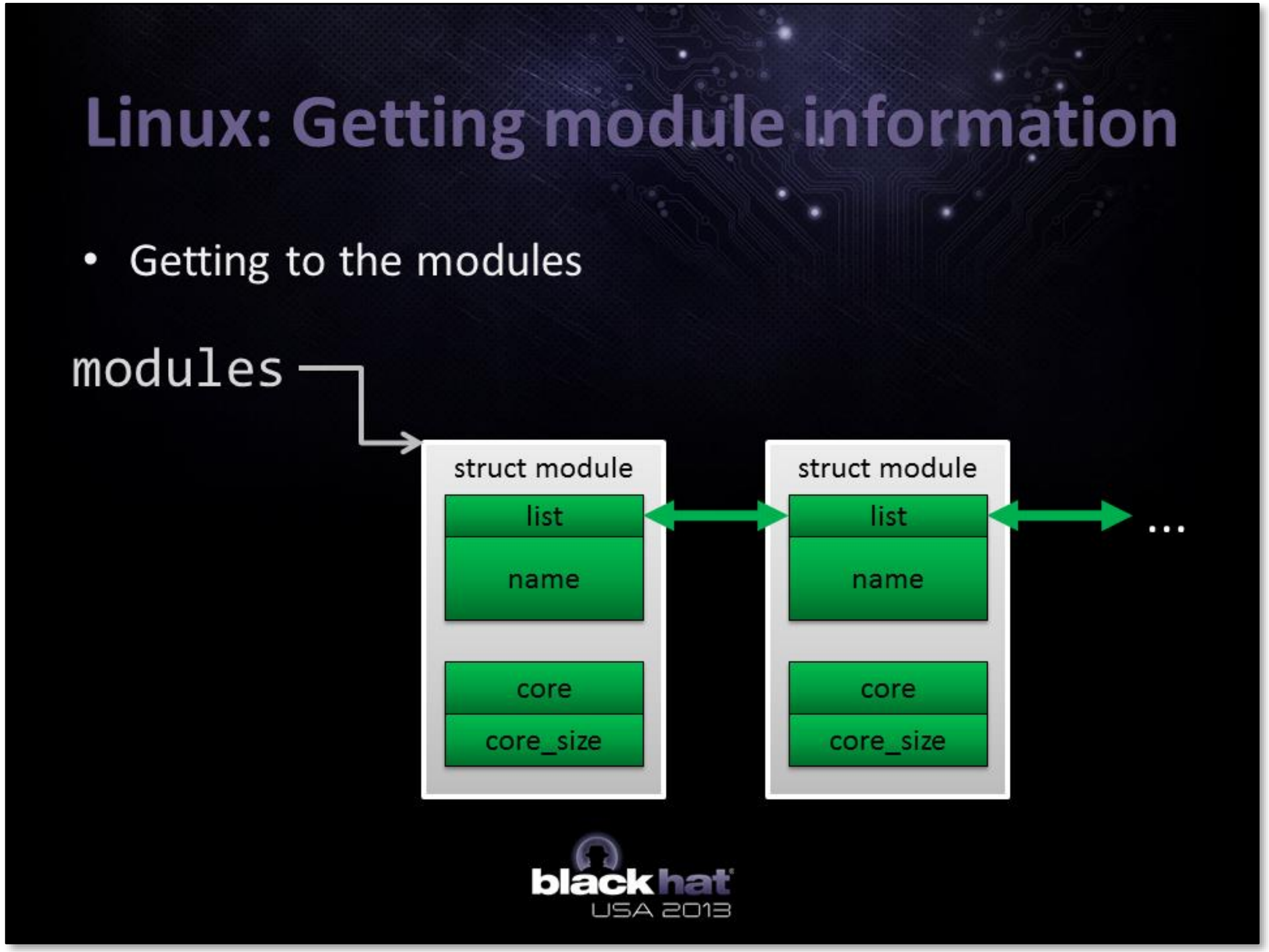
Sanitized

```
.text:C11ED784                 prefetcht1 byte ptr [eax]
.text:C11ED787                 mov     eax, [ebp+var_18]
.text:C11ED78A                 mov     edx, [ebp+var_14]
.text:C11ED78D                 mov     [ebp+var_10], eax
.text:C11ED790                 mov     [ebp+var_C], edx
.text:C11ED793                 prefetcht2 byte ptr [eax]
```

Sanitized

Keeping track of modules, symbolization etc.

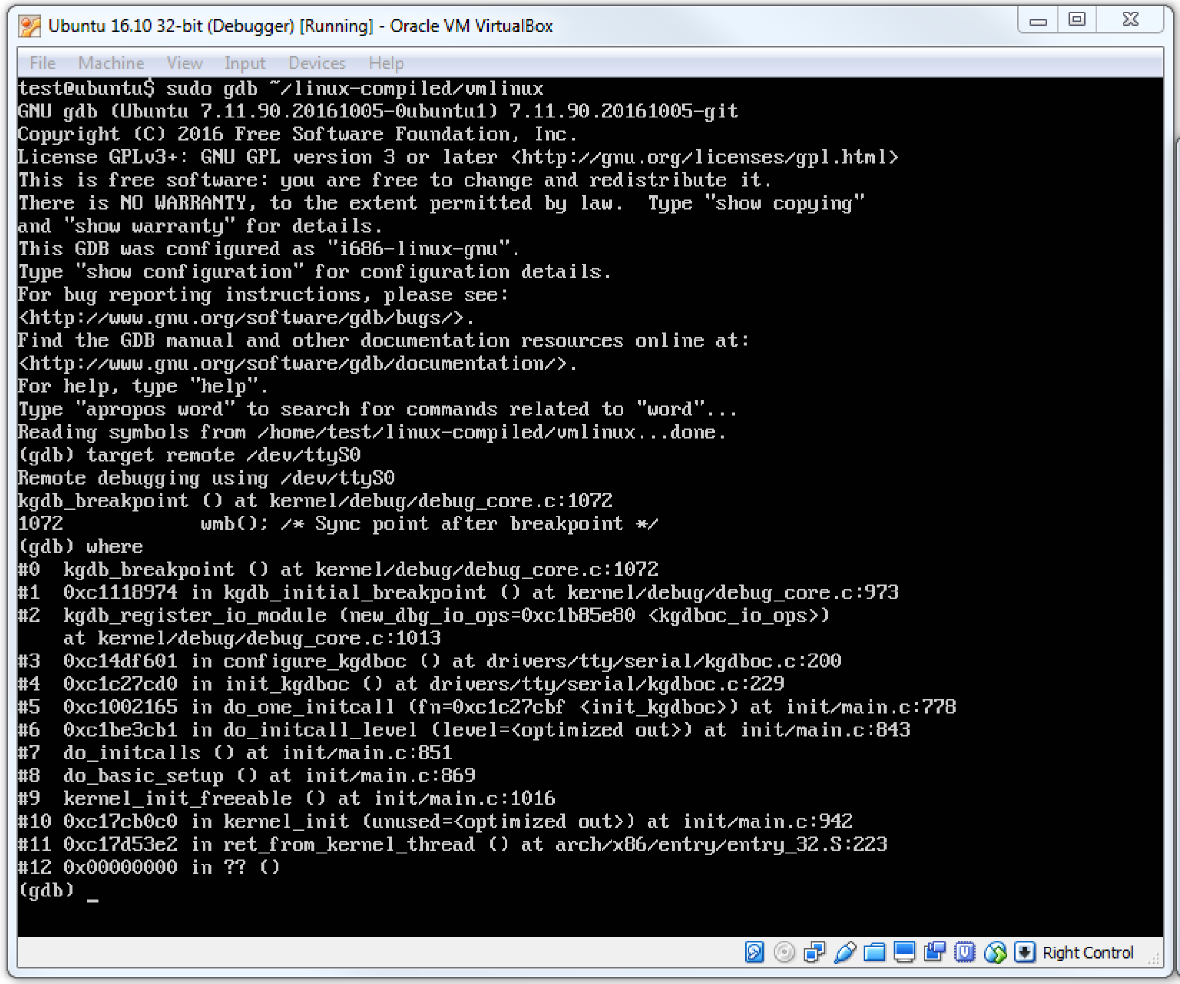
Again, simple logic unchanged since the 2013 Bochspwn.

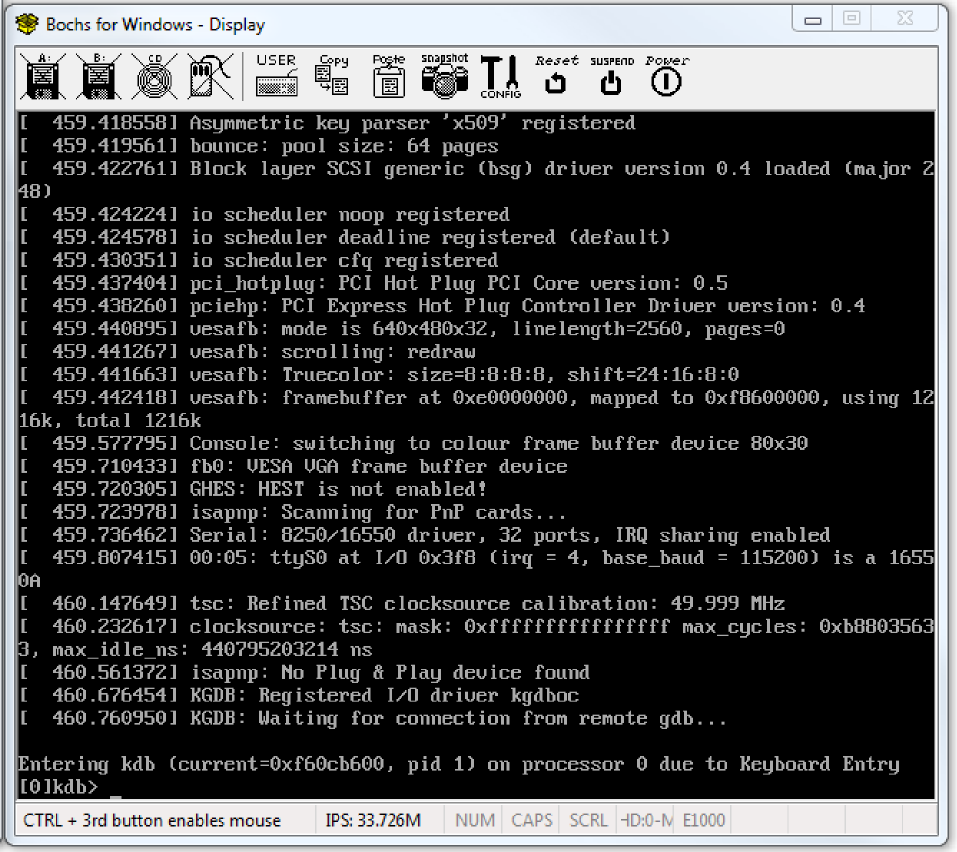


Bochspwn report

```
------------------------------ found uninit-access of address f5733f38
========== READ of f5733f38 (4 bytes, kernel--->kernel), pc = f8aaf5c5
                            [           mov edi, dword ptr ds:[ebx+84] ]
[Heap allocation not recognized]
Allocation origin: 0xc16b40bc: SYSC_connect at net/socket.c:1524
Shadow bytes: ff ff ff ff Guest bytes: bb bb bb bb
Stack trace:
#0  0xf8aaf5c5: llcp_sock_connect at net/nfc/llcp_sock.c:668
#1  0xc16b4141: SYSC_connect at net/socket.c:1536
#2  0xc16b4b26: SyS_connect at net/socket.c:1517
#3  0xc100375d: do_syscall_32_irqs_on at arch/x86/entry/common.c:330
  (inlined by) do_fast_syscall_32 at arch/x86/entry/common.c:392
```

Kernel debugging





Testing performed

- Instrumentation run on **Ubuntu 16.10 32-bit** (**kernel 4.8**).
- Executed actions:
  - System boot up.
  - Logging in via SSH.
  - Starting a few command-line programs and reading from **/dev** and **/proc** pseudo-files.
  - Running **Linux Test Project** (LTP) unit tests.
  - Running the **Trinity** + **iknowthis** system call fuzzers.
- Coverage-guided fuzzing with **Syzkaller** sounds like a perfect fit, but it doesn't actively support the x86 platform (currently only x86-64 and arm64).

Results!

Direct kernel→user disclosures

- Just **one** (1) minor bug!
- Disclosure of 7 uninitialized kernel stack bytes in the handling of specific IOCTLs in **`ctl_ioctl`** (`drivers/md/dm-ioctl.c`).
- **`/dev/control/mapper`** device, only accessible to root. ☹
- Issue discovered around April 20th, I was just about to report it a few days later, but...

author	Adrian Salido <salidoa@google.com>	2017-04-27 10:32:55 -0700
committer	Mike Snitzer <snitzer@redhat.com>	2017-04-27 13:55:13 -0400
commit	4617f564c06117c7d1b611be49521a4430042287 (patch)	
tree	f8005a09d0eb6827fd541e1c15d3fca1ff85c065	
parent	84ff1bcc2e25f1ddf5b350c4fa718ca01fdd88e9 (diff)	
download	linux-4617f564c06117c7d1b611be49521a4430042287.tar.gz	

2017-04-27 10:32:55 -0700

dm ioctl: prevent stack leak in dm ioctl call

```
When calling a dm ioctl that doesn't process any data
(IOCTL_FLAGS_NO_PARAMS), the contents of the data field in struct
dm_ioctl are left initialized.  Current code is incorrectly extending
the size of data copied back to user, causing the contents of kernel
stack to be leaked to user.  Fix by only copying contents before data
and allow the functions processing the ioctl to override.

Cc: stable@vger.kernel.org
Signed-off-by: Adrian Salido <salidoa@google.com>
Reviewed-by: Alasdair G Kergon <agk@redhat.com>
Signed-off-by: Mike Snitzer <snitzer@redhat.com>
```

Diffstat

-rw-r--r-- drivers/md/dm-ioctl.c 2

1 files changed, 1 insertions, 1 deletions

```
diff --git a/drivers/md/dm-ioctl.c b/drivers/md/dm-ioctl.c
index 0956b86..ddda810 100644
--- a/drivers/md/dm-ioctl.c
+++ b/drivers/md/dm-ioctl.c
@@ -1840,7 +1840,7 @@ static int ctl_ioctl(uint command, struct dm_ioctl __user *user)
 	if (r)
 		goto out;
 
-	param->data_size = sizeof(*param);
+	param->data_size = offsetof(struct dm_ioctl, data);
 	r = fn(param, input_param_size);
 
 	if (unlikely(param->flags & DM_BUFFER_FULL_FLAG) &&
```

Global strict mode

- Looks like Linux doesn't have any direct, trivially reachable infoleaks to user-mode...
- Bochspwn can be used to also detect use of uninitialized memory, not just leaks.
  - With source code, it's easy to analyze and understand each report.
- Let's try our luck there?

Use of uninitialized memory bugs

Location	Fixed	Patch sent	Found externally	Memory type
llcp_sock_connect in net/nfc/llcp_sock.c	Not yet	Yes	No	Stack
bind() and connect() handlers in multiple sockets (bluetooth, caif, iucv, nfc, unix)	Partially	Yes	No	Stack
deprecated_sysctl_warning in kernel/sysctl_binary.c	Yes	Yes	No	Stack
SYSC_epoll_ctl in fs/eventpoll.c	Yes	n/a	Yes	Stack
devkmsg_read in kernel/printk/printk.c	Yes, on 4.10+ kernels	n/a	Kind of (code area refactored)	Heap
dnrmg_receive_user_skb in net/decnet/netfilter/dn_rtmsg.c	Yes	Yes	No	Heap
nfnetlink_rcv in net/netfilter/nfnetlink.c	Not yet	Yes	No	Heap
ext4_update_bh_state in fs/ext4/inode.c	Not yet	n/a	Yes	Stack
nl_fib_lookup in net/ipv4/fib_frontend.c	Yes	n/a	Yes	Heap
fuse_release_common in fs/fuse/file.c	Yes	Yes	No	Heap
apply_alternatives in arch/x86/kernel/alternative.c	Yes	Yes	No	Stack
__bpf_prog_run in kernel/bpf/core.c	n/a	n/a	Yes	Stack
crng_reseed in drivers/char/random.c	n/a	n/a	No	Stack
unmapped_area_topdown in mm/mmap.c	n/a	n/a	No	Stack

Bonus: A local kernel DoS (NULL Pointer Dereference) while experimenting with another bug.

Results summary

- Even though the list is long, the bugs are mostly insignificant.
  - For example allow to answer „is an uninitialized byte on kernel stack equal to 0?"
  - One regular memory disclosure vulnerability in **AF_NFC**.
- False positives are bound to happen, and sometimes they are true positives that are just „working as intended".
- Good validation that the approach does work, but there just aren't more issues to be found.

KernelMemorySanitizer

- Linux kernel development is very rapid, bugs get fixed every day.
- Most collisions happened with **KMSAN**.
  - Currently under development by Alexander Potapenko.
  - Run-time instrumentation added by compiler to detect use of uninitialized memory.
  - Twin project of KernelAddressSanitizer, MemorySanitizer (for user-mode) and all other Sanitizers.
- The correct long-time approach to the problem in Linux.

Conclusions

- The Linux community has been on top of the problem for the last few years.
- Seemingly hardly any easy infoleaks left at all at this point.
    - Some uses of uninit memory, but even these are not trivial to find.
- Even when bugs show up, they are rather short-lived.
- Most remaining bugs should be swept off by KMSAN in the near future.

Future work

Future work for Bochspwn

- Run further iterations on Windows.
  - Triage and get a better understanding of some of the uninitialized reads detected by Bochspwn *strict-mode*.
- Look into improving code coverage.
  - Neverending story. Syzkaller does pretty well on Linux, no sensible equivalent for Windows.
- Improve taint propagation logic beyond just `rep movs`.
- Implement support for 64-bit guest systems.
  - Opens many doors – new bugs, more coverage, etc.

Future work for Bochspwn

- Taint-less approaches:
  - Poison stack and heap/pools with magic bytes, log all kernel→user writes with these bytes, review all reports for bugs.
    - Approach used (to an extent) by fanxiaocao and pjf.
  - Generalize for two or more such sessions with different marker bytes. For every write location which always has the marker at specific offset(s), that's a bug!
- Addresses the problem of non-ideal taint propagation (for other tradeoffs).

Other (crazy) ideas

- Recompilation or binary rewriting to make the kernels transfer data exclusively with `movs{b,d}` instructions? ☺
- Apply the concept to other data sinks than just user-mode memory.
  - Outgoing network traffic.
  - Output files saved by desktop applications.
- Other security domains? Inter-process communication, virtualization.

Thanks!

@j00ru

http://j00ru.vexillium.org/

j00ru.vx@gmail.com