Windows Kernel Security

A Deep Dive into Two Exploits Demonstrated at Pwn2Own

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About me

SYNACKTIV

- **Thomas Imbert**
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  - Offensive security company
  - Pentest, Reverse engineering, Development, Incident response
  - Offices in France and we are hiring!

Agenda

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- Introduction to Pwn2Own contest
- Finding and exploiting a vulnerability in Cloud Filter (cldflt.sys)
- Advances in Windows Kernel mitigations
- Analysis of a second LPE in MSKS Server driver (mskssrv.sys)

Pwn2Own

Pwn2Own

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- **Ethical hacking contest organized by Zero Day Initiative (ZDI)**
- **Pwn2Own Vancouver 2023 in March**
  - Applications, virtualization, browsers, OS, Automotive: Tesla, …

Target	Prize	Master of Pwn Points
Ubuntu Desktop	$30,000	3
Microsoft Windows 11	$30,000	3
Apple macOS	$40,000	4

Pwn2Own – Windows entries

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- **One entry per target**
- **3 attempts of 10 minutes**
- **Two exploits developed:**
  - Standalone Windows LPE from unprivileged user
  - Windows LPE Add-on after VirtualBox escape

Available Add-on Prizes:

Add-on Prize	Prize	Master of Pwn Points
Escalation of privilege leveraging a Windows kernel vulnerability on the host operating system.	$50,000	5

Pwn2Own – Results

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- **Synacktiv entries:** Windows, macOS, Ubuntu, VirtualBox and Tesla

Cloud Filter

Incentives for picking cldflt.sys

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- **Pwn2Own requires vulnerability in kernel**
- **3 attempts of 10 minutes: long to trigger / unstable bugs works**

- **Idea: Pick a driver with a different interface than classic IOCTL**
  - Hopefully less reviewed / fuzzed

➢ **Filter communication port**

Filter Communication Port

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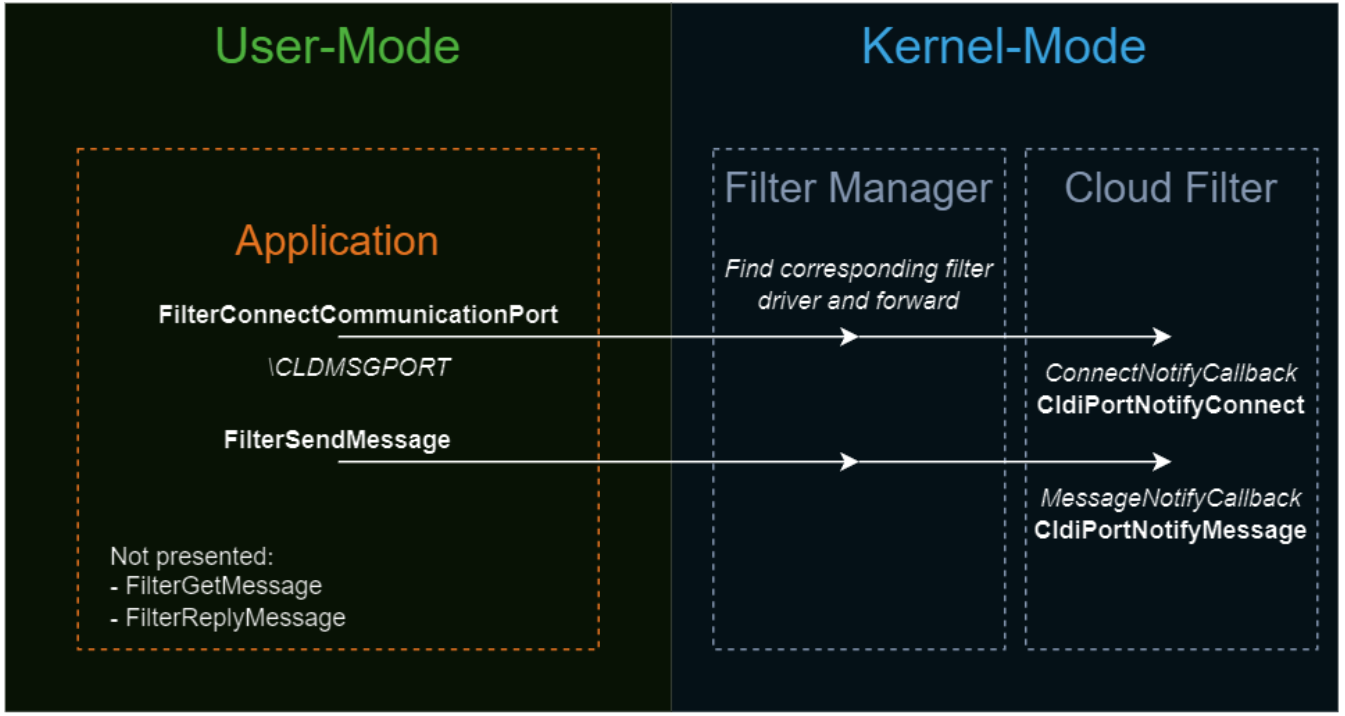
- **Communication mechanism between User and Kernel mode**
- **Port identified by a name, used by Filesystem Filter drivers**



Internally, it uses IOCTL and FSCTL to the Filter Manager (fltMgr.sys)

Incentives for picking cldflt.sys (2)

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- **Cloud Filter port**
  - One of the few interfaces reachable from unprivileged user
  - ~20 different messages (excluding FSCTL)
  - Asynchronous handling
  - Complex implementation
- **Quick manual review found a couple of race conditions**
  - Not exploitable or very hard to trigger

Cloud Filter (cldflt.sys)

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- **File System Minifilter driver**
- **Windows component: Cloud Files API**
  - Manage *placeholders* and *hydrate* them on access
  - Forward file access callbacks to user-mode sync provider process
  - Sync provider process synchronize files with remote cloud storage
- **Utilized by OneDrive**

Fuzzing – First steps

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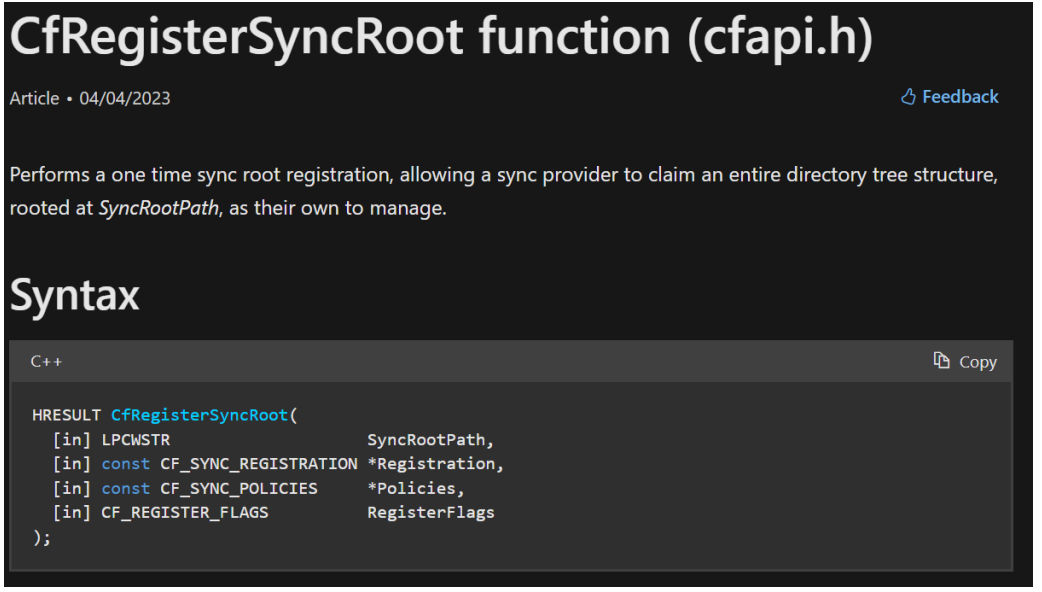
- **Manual review takes too long especially for Pwn2Own**
- **First, write a simple sync provider:**
  - Cloud Filter API documentation
  - Windows CloudMirror sample
  - James Forshaw, cldflt CVE PoC



CfRegisterSyncRoot function (cfapi.h)

Article • 04/04/2023 Feedback

Performs a one time sync root registration, allowing a sync provider to claim an entire directory tree structure, rooted at *SyncRootPath*, as their own to manage.

Syntax

C++ Copy

```
HRESULT CfRegisterSyncRoot(
  [in] LPCWSTR                    SyncRootPath,
  [in] const CF_SYNC_REGISTRATION *Registration,
  [in] const CF_SYNC_POLICIES     *Policies,
  [in] CF_REGISTER_FLAGS          RegisterFlags
);
```

Fuzzing – Writing the sync provider harness

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- Add a few files and directories placeholders (*CfCreatePlaceholders*)
- Implement basic support for callbacks (with random errors and mutations)

```
CF_CALLBACK_REGISTRATION Callback[14] = {
    CF_CALLBACK_TYPE_FETCH_DATA, FakeCallbackFetchData,
    CF_CALLBACK_TYPE_VALIDATE_DATA, FakeCallbackValidateData,
    CF_CALLBACK_TYPE_CANCEL_FETCH_DATA, FakeCallbackCancelData,
    CF_CALLBACK_TYPE_FETCH_PLACEHOLDERS, FakeCallbackFetchPlaceholder,
    CF_CALLBACK_TYPE_CANCEL_FETCH_PLACEHOLDERS, FakeCallbackCancelFetchPlaceholder,
    CF_CALLBACK_TYPE_NOTIFY_FILE_OPEN_COMPLETION, FakeCallbackOpenCompletion,
    CF_CALLBACK_TYPE_NOTIFY_FILE_CLOSE_COMPLETION, FakeCallbackCloseCompletion,
    CF_CALLBACK_TYPE_NOTIFY_DEHYDRATE, FakeCallbackDehydrate,
    CF_CALLBACK_TYPE_NOTIFY_DEHYDRATE_COMPLETION, FakeCallbackDehydrateCompletion,
    CF_CALLBACK_TYPE_NOTIFY_DELETE, FakeCallbackDelete,
    CF_CALLBACK_TYPE_NOTIFY_DELETE_COMPLETION, FakeCallbackDeleteCompletion,
    CF_CALLBACK_TYPE_NOTIFY_RENAME, FakeCallbackRename,
    CF_CALLBACK_TYPE_NOTIFY_RENAME_COMPLETION, FakeCallbackRenameCompletion,
    CF_CALLBACK_TYPE_NONE, NULL
};
```

- HsmFltPreACQUIRE_FOR_SECTION_SYNCHRONIZATION
- HsmFltPreCLEANUP
- HsmFltPreCREATE
- HsmFltPreDIRECTORY_CONTROL
- HsmFltPreFILE_SYSTEM_CONTROL
- HsmFltPreLOCK_CONTROL
- HsmFltPreMDL_READ
- HsmFltPreNETWORK_QUERY_OPEN
- HsmFltPrePREPARE_MDL_WRITE
- HsmFltPreQUERY_ALLOCATED_RANGES
- HsmFltPreQUERY_OPEN
- HsmFltPreREAD
- HsmFltPreSET_INFORMATION
- HsmFltPreWRITE

User-Mode callbacks called in response to kernel-mode callbacks of cldflt

Fuzzing – Filesystem fuzzing

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- **Write a client process to execute file system operations**
  - Open
  - Read
  - Write
  - Delete
  - Rename
  - List
  - …

```
AReadFile(base, L"\\PlacemeDir\\TEST2");
AListDirectory(base);
AReadFile(base, L"\\Placeme");
AMoveFile(base, L"\\Placeme", L"\\Placeme2");
AWriteFile(base, L"\\Placeme");
AReadFile(base, L"\\Placeme2");
ADeleteRawFile(base, L"\\Placeme2");
```

Generated operations

Fuzzing – Windows driver tips

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- **Attach a kernel debugger or configure kernel crash dump storage**
- **Configure Special Pool with verifier.exe to improve memory corruption detection**
  - Special Pool on ntoskrnl.exe, fltMgr.sys and cldflt.sys
  - Crash on Use-After-Free and Out-Of-Bounds access

Fuzzing – Crash analysis

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- **Got an interesting crash after a minute**

```
nt!IoCancelIrp+0x2b:
fffff802`713919cb c6434401        mov     byte ptr [rbx+44h],1 // 0x5c003a0043003244=??

PROCESS_NAME:  explorer.exe

STACK_TEXT:
nt!IoCancelIrp+0x2b
FLTMGR!FltCancelIo+0x20
cldflt!CldiStreamStartCountdownTimer+0x143
cldflt!CldiStreamRestartCountdownTimer+0x66
cldflt!CldStreamQueryProgress+0x141a
cldflt!CldiPortProcessQueryProgress+0x2b7
cldflt!CldiPortProcessFilterControl+0x4d
cldflt!CldiPortNotifyMessage+0x824
FLTMGR!FltpFilterMessage+0xda
...
nt!NtDeviceIoControlFile+0x56
nt!KiSystemServiceCopyEnd+0x28
ntdll!NtDeviceIoControlFile+0x14
FLTLIB!FilterpDeviceIoControl+0x136
FLTLIB!FilterSendMessage+0x31
cldapi!CfQueryProgress+0x3e7
```

The IRP object pointer (IoCancelIrp) seems to be corrupted with a wide string.

For curious reader: Special Pool did not catch the UAF because of the minute delay.

Vulnerability in Cloud Filter

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- **Each file operation is associated with a I/O request packet (IRP) in kernel**

- **The Filter Manager creates an IRP control object which saves the IRP and the callback data (*FLT_CALLBACK_DATA*) for each filesystem operation**

Vulnerability in Cloud Filter (2)

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- The Cloud Filter stores this FLT_CALLBACK_DATA on pending I/O (ex: user-mode callback not answering) in a global list.
- After a minute, if the request is still pending in the global list, the IRP is cancelled using *IoCancelIrp*.
- This prevents a sync provider to block file I/O indefinitely.

Vulnerability in Cloud Filter (3)

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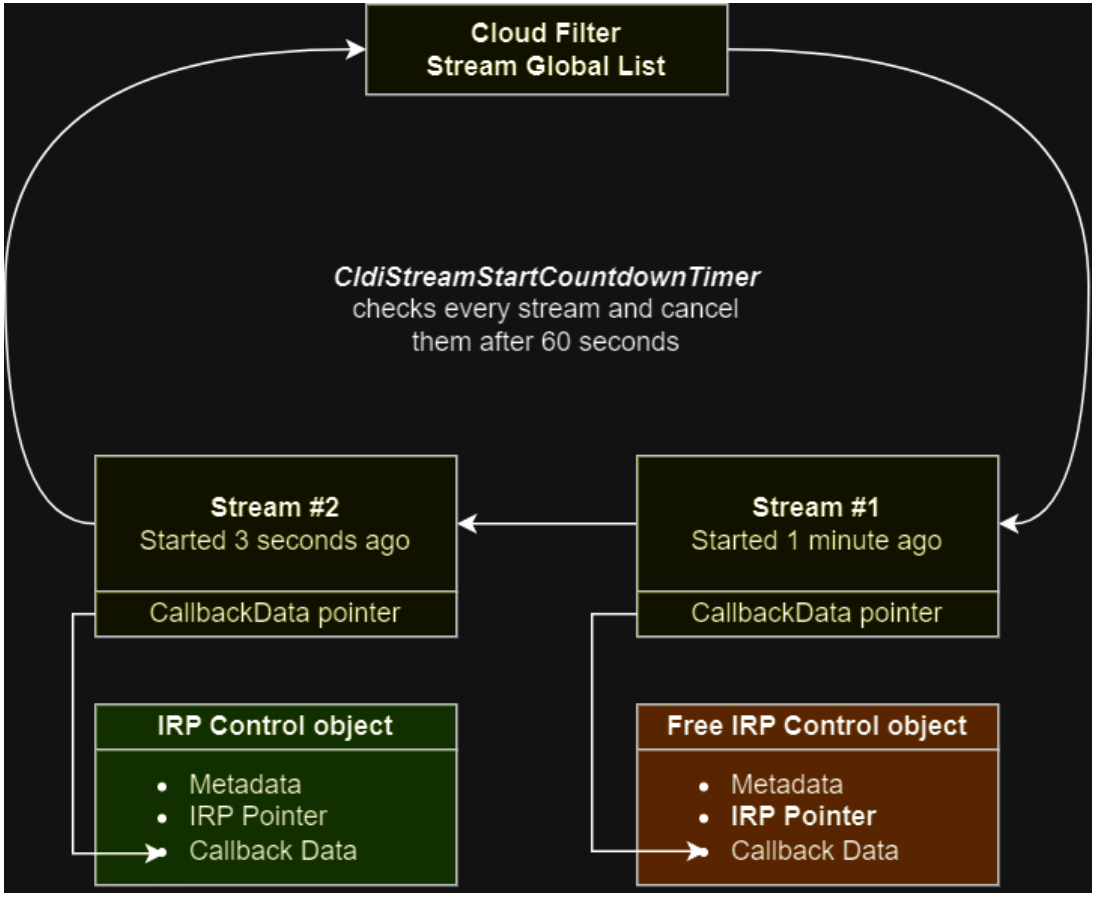
- **Vulnerability**

- The Cloud Filter Global List **is not cleared** properly if the sync provider die **but** the IRP control object **is freed**.



Use-After-Free Vulnerability

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- **The vulnerability is an Use-After-Free of the IRP Control Object allocated by FltMgr.sys in *FltpAllocateIrpCtrlInternal* on the NonPagedNx pool.**

- **To trigger the vulnerability, three processes are required:**
  - Sync provider never answering the file deletion (no *ACK_DELETE*)
  - Client process deleting a placeholder file
  - A scheduler starting both processes and killing them
    - Waiting 1 minute and calling *CfQueryProgress* to trigger the timer check

Vulnerability primitives

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- **If the UAF allocation content is controlled:**
  - Arbitrary IRP pointer passed to *IoCancelIrp*
    - **Arbitrary function call primitive**

```
BOOLEAN IoCancelIrp(PIRP Irp)
{ // Simplified
  KIRQL Irql = KeAcquireQueuedSpinLock(LockQueueIoCancelLock);
  Irp->Cancel = 1; // Arbitrary write byte with value 1
  PVOID CancelRoutinePtr = Irp->CancelRoutine;
  if ( CancelRoutinePtr )
  {
    CancelRoutinePtr(Irp->Tail.Overlay.CurrentStackLocation->DeviceObject, Irp); // Arbitrary function call
    return 1;
  }
}
```

Windows kernel exploitation 101

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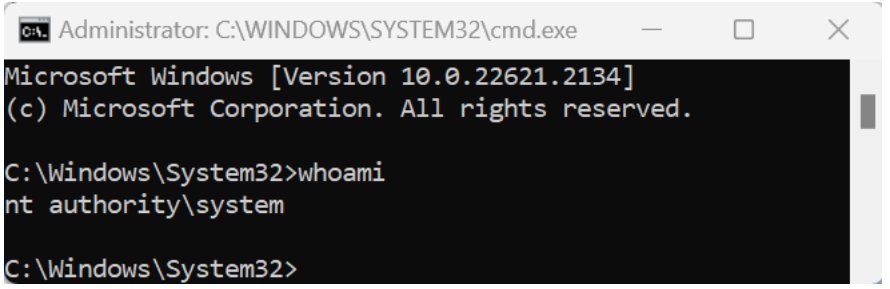
- **Goal:** Elevate our privileges to SYSTEM and run a command prompt
- **Data only technique:** Corrupt the current process TOKEN privileges
- **Require:** Arbitrary write and information leak of the TOKEN address



Windows kernel exploitation info

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- **No infoleak required:**
- **By design Windows API** *NtQuerySystemInformation* with *SystemExtendedHandleInformation* **discloses the TOKEN address**.
  - Note: Driver base address may be disclosed by *SystemModuleInformation* class.
  - It does not work in sandboxes.

Windows kernel exploitation info (2)

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- **Supervisor Mode Execution Protection (SMEP) and NX:**
  - Enabled, function pointer must point to executable kernel memory
- **Supervisor Mode Access Protection (SMAP):**
  - Not enabled in most situations, possible to forge fake objects in user-mode memory
- **Reuse allocation content:**
  - Spray *NonPagedNx* using Named Pipe data entries (size 0x588)

Windows kernel Control Flow Guard

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- **Control Flow Guard (CFG) validates indirect branch targets**
- **Arbitrary function call primitive is limited to valid targets**
  - _guard_dispatch_icall is called to check against a bitmap
- **Instead of ROP gadgets, jump on function gadgets**
  - First 2 function parameters are controlled
  - Chain allowed functions to control all parameters and achieve write primitive

Windows kernel CFG Chain

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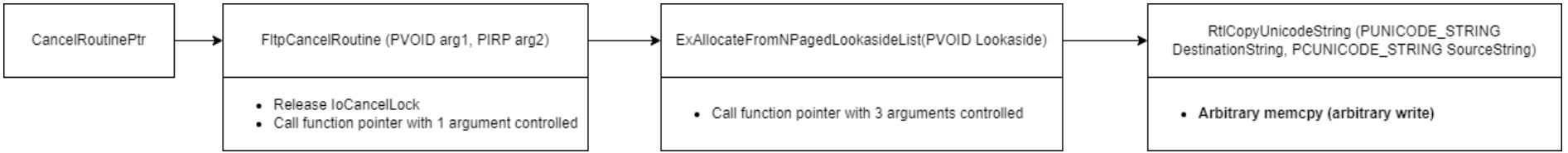
- **Assume, the IRP pointer in the UAF object is fully controlled and points to user mode memory**
- **Chain function gadget:**



Windows kernel CFG Chain (2)

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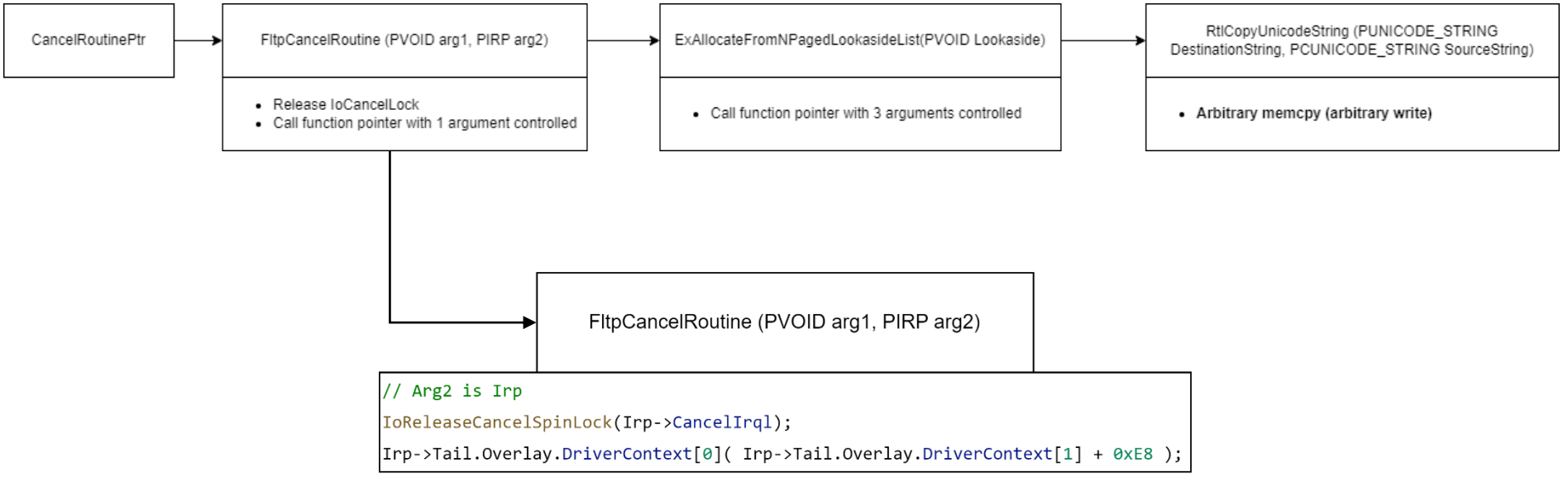

Windows kernel CFG Chain (3)

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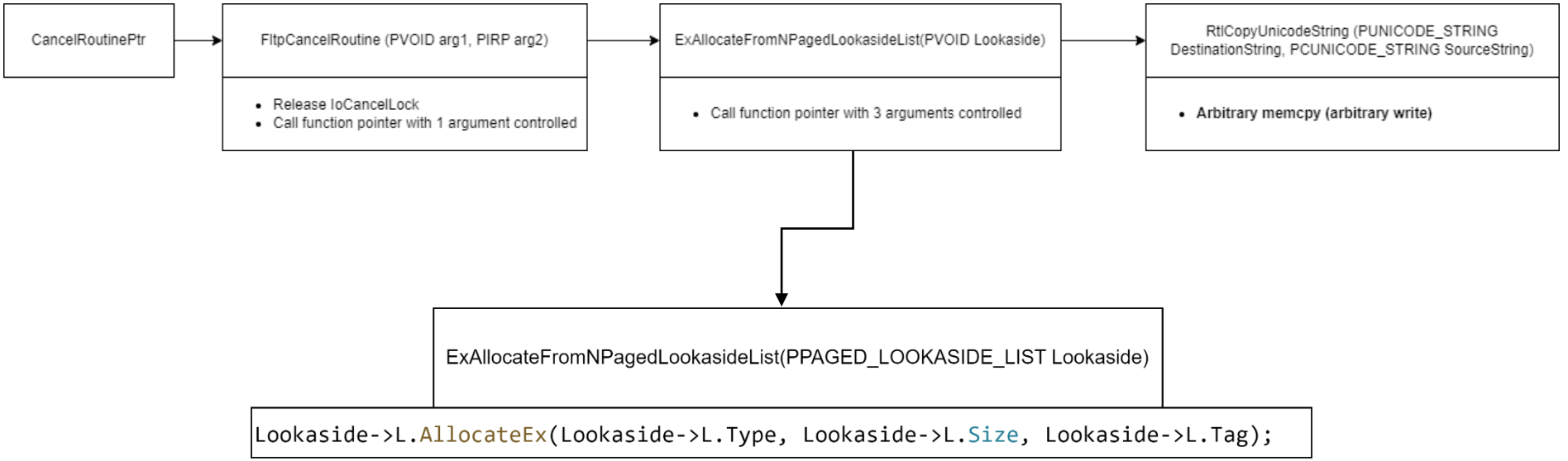

Windows kernel CFG Chain (4)

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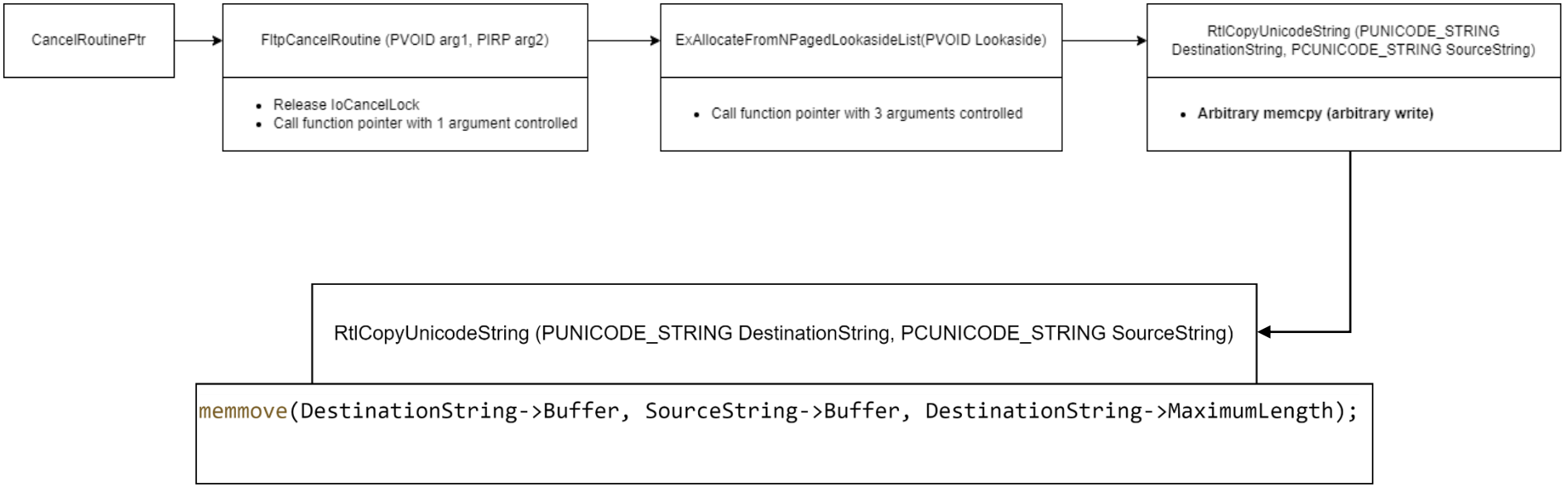

- **Arbitrary write achieved !**

Cloud Filter exploit

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- **Exploit steps:**
  - Prepare fake objects in user mode: *IRP, PAGED_LOOKASIDE_LIST, UNICODE_STRING*
  - Trigger the IRP control object free by killing the processes
  - Spray Named Pipe data entry to reuse the allocation (fake IRP points to UM)
  - Wait one minute and trigger UAF vulnerability
  - Verify token privileges are all granted thanks to the arbitrary write (gadgets chain)
  - Spawn a SYSTEM shell (*SeDebugPrivilege* used to control *winlogon* process)

Cloud Filter exploit notes

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- **Not very reliable**
  - But on fresh boot: >90%
- **Exploit takes between 1 and 6 minutes**
  - Issue: IRP control object is not always free, a lookaside list is used for performance
  - The vulnerability is played multiple times (8) to fill the lookaside list
- **Perfect for Pwn2Own** (3 attempts of 10 minutes with reboot)
- **Worked on second try at P2O !** (After a BSOD in the first attempt)

Cloud Filter timeline

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- **Manual review: 2 days**
- **Fuzzing: 1 day**
- **Root cause and reproduction: 3 days**
- **Exploit: 2 days**

Windows Kernel Mitigations

Will it work next year?

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- **Microsoft is actively working on mitigations to kill bug classes**
  - Zeroing most variables and pool allocations prevents uninitialized memory vulnerabilities
  - CastGuard: mitigates C++ type confusions
- **Also, Microsoft mitigates a few powerful exploit primitives:**
  - Thread *PreviousMode* overwrite
  - KASLR by design infoleak

KASLR infoleak future removal

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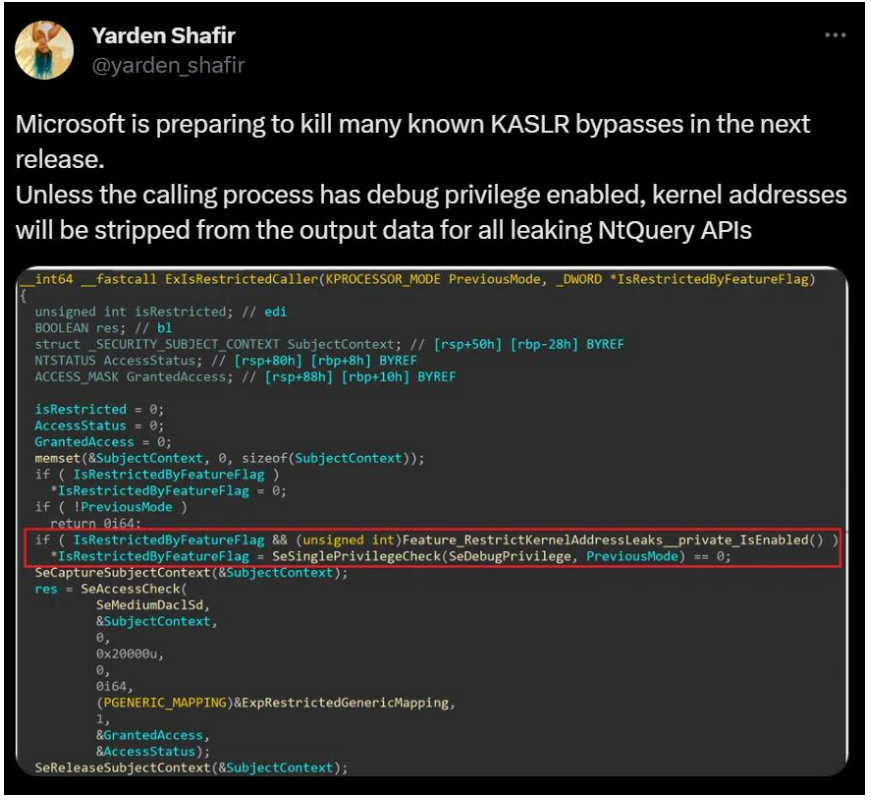
- **Thanks to Yarden and the security community, tracking changes on Insider builds:**

This mitigation would break the previous exploit.
The bug would then require a powerful infoleak of kernel driver bases to build the function gadgets chain.



Mitigation status

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- **SMAP:**
  - Enabled in functions (mostly interrupts) when the kernel is sure to never access user-mode memory
  - The UAF access runs at IRQL DISPATCH_LEVEL which is not supposed to access user-mode memory, but SMAP is not enabled and allow for easier exploit
- **CFG:**
  - Current kernel implementation quite limited, lack granularity and allow a lot of function targets (while user-mode has a more fine grained solution: XFG)

Both mitigations are hard or impossible to expand due to compatibility issues with 3rd party drivers.

Mitigation status (2)

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- **Control Flow Enforcement Technology (CET):**
  - Protect control-flow hijacking using a shadow stack and control transfer instructions
  - Not designed to prevent function gadgets chain
- **Hypervisor Protected Code Integrity (HVCI):**
  - Protect kernel integrity, prevent executing custom code in kernel
  - Not designed to detect data only attack on the token

Will it work next year? (2)

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- **Microsoft seems to focus on high impact scenarios**
  - Restricting attack surface of browser and application sandboxes
  - Reviewing and fuzzing remote services, hypervisor and kernel (ntoskrnl)
- **Local privilege escalation from unprivileged user**
  - Probably not high priority
  - KASLR infoleak hardening proves some efforts
- **Opinion: LPE will still be feasible with 1 kernel bug but it will require more work (or better bugs)**

MSKSSRV

Looking for another bug to exploit

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- **Objective: Find a stable bug to chain with VirtualBox exploit**
- **Reviewed random drivers for a quick win**
  - Pick a random driver in *System32\drivers* in IDA
  - Look for simple IOCTL issues
- **Found a couple of bugs in non-default drivers**
  - Optional features
  - Impossible to load without admin access

MSKSSRV – Introduction

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- **Part of Microsoft Streaming Service component**
- **Allow two processes to share content using Tx/Rx streams**
  - IOCTL interface
  - Streams are basically shared memory (*Section* object or UM mapping)
- **Driver automatically loaded on demand when opened**
  - No admin access required

```
DEFINE_GUIDSTRUCT("3C0D501A-140B-11D1-B40F-00A0C9223196", KSNAME_Server);
#define KSNAME_Server DEFINE_GUIDNAMED(KSNAME_Server)

HANDLE DeviceHandle;
KsOpenDefaultDevice(KSNAME_Server, GENERIC_READ | GENERIC_WRITE, &DeviceHandle);
```

MSKSSRV – Quick win

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- **Found this function reachable with user-mode inputs:**

```
__int64 __fastcall FsAllocAndLockMdl(void *InputField, ULONG InputField2, _MDL **pMdl)
{
  unsigned int status; // edi
  _MDL *Mdl; // rax
  _MDL *outMdl; // rbx

  status = 0;
  if ( InputField && InputField2 && pMdl )
  {
    Mdl = IoAllocateMdl(InputField, InputField2, 0, 0, 0i64);
    outMdl = Mdl;
    if ( Mdl )
    {
      MmProbeAndLockPages(Mdl, 0, IoWriteAccess);
      *pMdl = outMdl;
    }
    else
    {
      return 0xC000009A;
    }
  }
  else
  {
    return 0xC000000D;
  }
  return status;
}
```

MSKSSRV – Quick win (2)

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- **MmProbeAndLockPages invalid access mode**

```
void MmProbeAndLockPages(
  [in, out] PMDL            MemoryDescriptorList,
  [in]      KPROCESSOR_MODE AccessMode,
  [in]      LOCK_OPERATION  Operation
);
```

`[in] AccessMode`

The access mode in which to probe the arguments, either **KernelMode (0)** or **UserMode (1)**.

- *AccessMode* parameter sets to ***KernelMode*** access mode

```
10    Mdl = IoAllocateMdl(InputField, InputField2, 0, 0, 0i64);
11    outMdl = Mdl;
12    if ( Mdl )
13    {
14      MmProbeAndLockPages(Mdl, 0, IoWriteAccess);
```

Windows Parameter Probing

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- **Windows Kernel must validate pointers coming from user-mode**
  - Using probe functions, the pointers and size are validated
  - On Windows, the address is validated to be less than *0x7FFFFFFF0000*
  - Example API: *ProbeForRead / ProbeForWrite*

```
// MmProbeAndLockPages calls MiProbeAndLockPrepare which validates the address if AccessMode is set to UserMode
if ( AccessMode == UserMode )
{
    if ( !MdlLength
      || (MdlEndAddress = MdlLength + MdlVirtualAddress - 1, MdlEndAddress < MdlVirtualAddress)
      || MdlEndAddress > 0x7FFFFFFEFFFF )
    {
        return 0xC0000005i64;
    }
}
```

MSKSSRV – Quick win (3)

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- **Driver IOCTL accepts kernel mode pointer in MDL creation**
  - IOCTL 0x2F0408 – *FSRendezvousServer::PublishTx*
- **Memory Descriptor List (MDL)**
  - MDL is a kernel object describing one or more virtual memory ranges
  - MDL stores the physical addresses corresponding to the virtual ranges
  - MDL are used for I/O operations and DMA to map and lock memory

MSKSSRV – Vulnerability

SYNACKTIV

- **Driver IOCTL accepts kernel mode pointer in MDL creation**
  - IOCTL 0x2F0408 – *FSRendezvousServer::PublishTx*
- **Resulting MDL can be mapped to user-mode**
  - IOCTL 0x2F0410 – *FSRendezvousServer::ConsumeTx*
  - Arbitrary kernel virtual memory may be mapped to user-mode with read and write access
- **Arbitrary kernel read and write achieved !**

MSKSSRV – Exploit

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- **Same goal: corrupt the Token privileges**
- **Steps:**
  - Again, leverage by design KASLR infoleak to disclose Token address
  - Map the kernel page containing the Token to user-mode using the vulnerability
  - Overwrite the privileges bitfield to gain *SeDebugPrivilege*
  - Spawn a SYSTEM shell

```
uint8_t* UserModeMapping = MapToUserMode(GetTokenAddress());
memset(UserModeMapping + OFFSET_OF_TOKEN_PRIVILEGES, 0xFF, 0x10);
HANDLE winlogon = OpenWinlogonProcess();
SpawnProcessWithParentHandle(L"C:\\Windows\\System32\\cmd.exe", winlogon);
```

MSKSSRV – Exploit notes

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- **100% stable bug**
  - Missing probe are powerful bugs
  - Especially this one since it gives read and write access
- **Exploit takes less than 1 second**
- **Timeline: 1 day for manual review and exploit**
- **Worked on second try at P2O !** (Microsoft Defender blocked the first attempt)

DEMO

Conclusion

- **Pwn2Own is a great opportunity to challenge yourself**
  - Very fun and ethical contest
  - Large attack surface
  - Lots of Windows kernel exploitation documentation available online
  - Vulnerabilities have been fixed in June: CVE-2023-29360 & CVE-2023-29361
  - Try it!
- **Windows Kernel Security is slowly improving but still attackable with limited means**

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THANK YOU!