The Windows Notification Facility

The Most Undocumented Kernel Attack Surface Yet

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About Gabrielle Viala

- Gaby - @pwissenlit on twitter
- Reverse engineer at Quarkslab
- Playing with the Windows Internals
- Member of the BlackHoodie organization board
- Quite new in the field so I don't have much record yet ;)

About Alex Ionescu

- VP of EDR Strategy and Founding Architect at CrowdStrike
- Co-author of *Windows Internals 5th-7th Editions*
- Reverse engineering NT since 2000 – was lead kernel developer of ReactOS
- Instructor of worldwide Windows internals classes
- Author of various tools, utilities and articles
- Conference speaker at SyScan, Infiltrate, Offensive Con, Black Hat, Blue Hat, Recon, …
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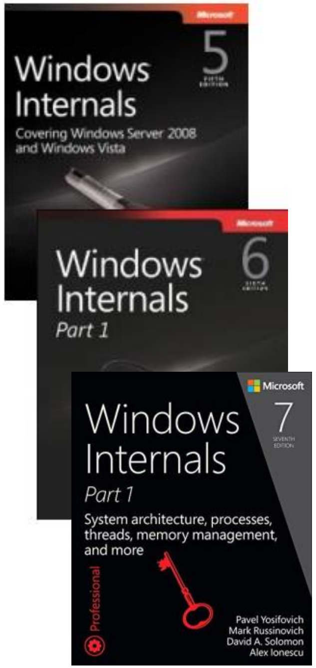

Talk Outline

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WNF Internals & APIs

What is WNF?

- The Windows Notification Facility is a *pubsub* (Publisher/Subscriber) user/kernel notification mechanism that was added in **Windows 8**, in part to solve some long-standing design constraints in the OS, as well as to serve as a basis for Mobile-based/App-centric Push Notifications similar to iOS/Android
- Its key differentiator is that it is a *blind* (basically, registration-less) model which allows for *out-of-order* subscription vs. publishing
  - By this, we mean that a consumer can subscribe to a notification even before the notification has been published by its producer
  - And that there is no requirement for the producer to 'register' the notification ahead of time
- On top of this, it also supports persistent vs. volatile notifications, monotonically increasing unique change stamp IDs, payloads of up to 4KB for each notification event, a thread-pool-based notification model with group-based serialization, and a security model that is both *scope* based and implements Windows Security Descriptors through the standard DACL/SACL mechanism [Run-On Sentence Pwnie Award]

Why does WNF exist?

- The canonical example is a driver wanting to know if the volumes have been mounted for RW access yet
  - To indicate this, `Autochk` (Windows' `fsck`) signals an event called `VolumesSafeForWriteAccess`
    - But to signal an event, you need to first create it
- However, how can we know if `Autochk` has run, before `Autochk` has created the event for us wait on?
  - Ugly solution: Sit in a `sleep()` loop checking for the presence of the event – once the event is known to exist, wait on it
- After a Windows application exits, all handles are closed – and once an object has no handles, it is destroyed
  - So who would event keep the event around?
- Without WNF, the solution is to have the kernel create the event before any drivers can load, and have `Autochk` *open* it like a consumer would, but instead, be the one to signal it instead of waiting on it

WNF State Names

- In the WNF world, a state name is a 64-bit number – but there's a trick to it – it has an encoded structure
- A state name has a *version,* a *lifetime*, a *scope,* a *data permanence* flag*,* and a *unique sequence* number

```
typedef struct _WNF_STATE_NAME_INTERNAL
{
    ULONG64 Version:4;
    ULONG64 NameLifetime:2;
    ULONG64 DataScope:4;
    ULONG64 PermanentData:1;
    ULONG64 Unique:53;
} WNF_STATE_NAME_INTERNAL, *PWNF_STATE_NAME_INTERNAL;
```

- This data is only accessible if we XOR the 64-bit number with a magic constant:

```
#define WNF_STATE_KEY 0x41C64E6DA3BC0074
```

State Name Lifetime

- A WNF state name can be *well-known, permanent, persistent*, or *temporary* (`WNF_STATE_NAME_LIFETIME`)
- The first-three lifetimes are related to the registry location where the state information will be kept
  - Well-known names live in `HKLM\SYSTEM\CurrentControlSet\Control\Notifications`
  - Permanent names live in `HKLM\SOFTWARE\Microsoft\Windows NT\CurrentVersion\Notifications`
  - Persistent names live in `HKLM\SOFTWARE\Microsoft\Windows NT\CurrentVersion\VolatileNotifications`
- Cannot *register* a well-known name – these are relied upon by the kernel and must be <u>provisioned in the registry</u>
- Permanent and persistent names require SeCreatePermanentPrivilege, just like global named objects
  - Persistent names persist <u>beyond process (registrar’s) exit</u> while *permanent* names persist <u>beyond reboot</u>

State Scopes

- The data scope determines the first security boundary around a WNF state name – who has access/visibility to it
  - A state name's can have *system scope, session scope, user scope, process scope* or *machine scope*
  - Other than providing a security boundary, WNF scopes can also be used to provide *instantiated data* for the same name
  - Kernel bypasses state access checks, while TCB-privilege allows cross-scope access of WNF state names
- System and machine scoped names are global – there is no scope identifier (they use a different *scope map*)
- Session scoped names use the session ID as the identifier
- User scoped names use the user SID as the identifier
- Process scoped names use the EPROCESS object address as the identifier

Sequence Numbers

- To guarantee uniqueness, each state name has a unique 51-bit sequence number associated with it
  - Well-known names have a 4-character *family* tag with the remainder 21 bits used as the unique identifier
  - Permanent names have an increasing sequence number seeded off the registry value "`SequenceNumber`"
  - Persistent names and volatile names share an increasing sequence number seeded off a runtime global value
- This data is then managed on a per-silo (container) basis and available in `PspHostSiloGlobals->WnfSiloState`
- Internally, within Microsoft, each WNF name then has a 'friendly' identifier that is used in code – sometimes this is stored in a global sharing the same name
  - `nt!WNF_BOOT_DIRTY_SHUTDOWN` – `0x1589012fa3bc0875` => `0x544f4f4200000801`
  - BOOT1, Well-Known Lifetime, System Scope, Version 1

Registering a WNF State Name

- Other than well-known names, as previously mentioned, a WNF state name can be registered at runtime:

```
NTSTATUS
ZwCreateWnfStateName (
  _Out_ PWNF_STATE_NAME StateName,
  _In_ WNF_STATE_NAME_LIFETIME NameLifetime,
  _In_ WNF_DATA_SCOPE DataScope,
  _In_ BOOLEAN PersistData,
  _In_opt_ PCWNF_TYPE_ID TypeId, // This is an optional way to get type-safety
  _In_ ULONG MaximumStateSize, // Cannot be above 4KB
  _In_ PSECURITY_DESCRIPTOR SecurityDescriptor // *MUST* be present
);
```

- Can also use `ZwDeleteWnfStateName` to delete the registered state name (other than for well-known ones)

Publishing WNF State Data

- To modify WNF state name data, the following system call can be used

```
NTSTATUS
ZwUpdateWnfStateData (
  _In_ PCWNF_STATE_NAME StateName,
  _In_reads_bytes_opt_(Length) const VOID* Buffer,
  _In_opt_ ULONG Length, // Must be less than MaximumSize when registered
  _In_opt_ PCWNF_TYPE_ID TypeId, // Optionally, for type-safety
  _In_opt_ const PVOID ExplicitScope, // Process handle, User SID, Session ID
  _In_ WNF_CHANGE_STAMP MatchingChangeStamp, // Expected current change stamp
  _In_ LOGICAL CheckStamp // Enforce the above or silently ignore it
);
```

- Can also use `ZwDeleteWnfStateData` to wipe the current state data buffer

Consuming WNF Data

- To query WNF state name data, the following system call can be used instead – most parameters are like *update*

```
NTSTATUS
ZwQueryWnfStateData(
  _In_ PCWNF_STATE_NAME StateName,
  _In_opt_ PCWNF_TYPE_ID TypeId,
  _In_opt_ const VOID* ExplicitScope,
  _Out_ PWNF_CHANGE_STAMP ChangeStamp,
  _Out_writes_bytes_to_opt_(*BufferSize, *BufferSize) PVOID Buffer,
  _Inout_ PULONG BufferSize // Can be 0 to receive the current size
);
```

- The real power, however, is that both the Update and Query APIs don't actually need a <u>registered</u> state name
  - If the name is non-temporary, and the caller has sufficient access, the name instance can be live-registered!

WNF Notifications

- So far, we've assumed that the consumer knows *when* to call the API – but there are 'blocking' reads as well
  - This works using a notification system, closer to a true pub-sub model
- First, the process must register an event (`ZwSetWnfProcessNotificationEvent`)
  - Then use `ZwSubscribeWnfStateChange`, specifying an event mask -> receive a subscription ID on output
    - 1 -> Data Arrival 10 -> Name Destroyed (these are called *data notifications*)
    - 2 -> Data Subscriber Arrived, 4 -> Meta Subscriber Arrived, 8 -> Generic Subscriber Arrived (these are called *meta* notifications)
  - Then, wait on the event that was registered
  - Whenever it is signaled, `ZwGetCompleteWnfStateSubscription`, which returns an `WNF_DELIVERY_DESCRIPTOR`
- But these low-level APIs have a problem (thanks Gabi!) – only a single per-process notification event can exist

High Level API

- When it comes to notifications, things get complicated – so Rtl provides a simpler interface:

```
NTSTATUS
RtlSubscribeWnfStateChangeNotification (
  _Outptr_ PWNF_USER_SUBSCRIPTION* Subscription,
  _In_ WNF_STATE_NAME StateName,
  _In_ WNF_CHANGE_STAMP ChangeStamp,
  _In_ PWNF_USER_CALLBACK Callback,
  _In_opt_ PVOID CallbackContext,
  _In_opt_ PCWNF_TYPE_ID TypeId,
  _In_opt_ ULONG SerializationGroup,
  _In_opt_ ULONG Unknown);
```

- Uses single `Ntdll.dll`-managed event queue with a callback system – no need for using any system calls

Notification Callback

- Behind the scenes, the contents of the `WNF_DELIVERY_DESCRIPTOR` are converted into the callback parameters

```
typedef NTSTATUS (*PWNF_USER_CALLBACK) (
  _In_ WNF_STATE_NAME StateName,
  _In_ WNF_CHANGE_STAMP ChangeStamp,
  _In_opt_ PWNF_TYPE_ID TypeId,
  _In_opt_ PVOID CallbackContext,
  _In_ PVOID Buffer,
  _In_ ULONG BufferSize);
```

- For each registration, an entry is entered into the `RtlpWnfProcessSubscriptions` global pointer, which has a `LIST_ENTRY` of `WNF_NAME_SUBSCRIPTION` structures (we will play with these a bit later)
  - Each one of these, in turn, has a `LIST_ENTRY` of `WNF_USER_SUBSCRIPTION` structures, with the callback and context

Kernel API

- WNF also provides almost identical functionality to kernel-mode callers as well, both through the exported system calls (which can be used from a driver) as well as through high-level APIs in the executive runtime
- `ExSubscribeWnfStateChange` -> Given state name, mask, and a callback + context, receives subscription handle
    - Callbacks receive the signaled name, event mask, change stamp, <u>but not the buffer or its size</u>
- `ExQueryWnfStateData` receives the subscription handle, and reads the currently active state data
    - Each callback ends up calling this to actually get the data associated with the notification
- For both kernel and user-mode subscriptions, WNF creates a `WNF_SUBSCRIPTION` data structure to track it
    - But some fields won't be filled out for user-mode – like the Callback/Context – since this is in `Ntdll.dll` struct instead

WNF Data Structures

WNF Name Instance

- WNF events are identified in memory as name instances
- Stores all the information related to the event

```
typedef struct _WNF_NAME_INSTANCE
{
            WNF_CONTEXT_HEADER Header;
            EX_RUNDOWN_REF RundownProtection;
            RTL_BALANCED_NODE TreeLinks;
            WNF_STATE_NAME_INTERNAL StateName;
            PWNF_SCOPE_INSTANCE ScopeInstance;
            struct
            {
                ULONG MaxStateSize;
                PWNF_TYPE_ID TypeId;
                PSECURITY_DESCRIPTOR SecurityDescriptor;
            } StateNameInfo;
            ULONG64 StateDataLock;
            PWNF_STATE_DATA StateData;
            WNF_CHANGE_STAMP CurrentChangeStamp;
            HANDLE KeyHandle;
            EX_PUSH_LOCK StateSubListLock;
            LIST_ENTRY StateSubscriptionListHead;
            LIST_ENTRY TemporaryNameListEntry;
            PEPROCESS CreatorProcess;
            ULONG64 NumberOfSubscribers;
} WNF_NAME_INSTANCE, *PWNF_NAME_INSTANCE;
```

WNF Name Instance

- WNF events are identified in memory as name instances
- Stores all the information related to the event

```
typedef struct _WNF_CONTEXT_HEADER
{
            CSHORT NodeTypeCode;
            CSHORT NodeByteSize;
} WNF_CONTEXT_HEADER, *PWNF_CONTEXT_HEADER;
```

- `Header.NodeTypeCode: 0x903`

```
typedef struct _WNF_NAME_INSTANCE
{
            WNF_CONTEXT_HEADER Header;
            EX_RUNDOWN_REF RundownProtection;
            RTL_BALANCED_NODE TreeLinks;
            WNF_STATE_NAME_INTERNAL StateName;
            PWNF_SCOPE_INSTANCE ScopeInstance;
            struct
            {
                ULONG MaxStateSize;
                PWNF_TYPE_ID TypeId;
                PSECURITY_DESCRIPTOR SecurityDescriptor;
            } StateNameInfo;
            EX_PUSH_LOCK StateDataLock;
            PWNF_STATE_DATA StateData;
            WNF_CHANGE_STAMP CurrentChangeStamp;
            HANDLE KeyHandle;
            EX_PUSH_LOCK StateSubListLock;
            LIST_ENTRY StateSubscriptionListHead;
            LIST_ENTRY TemporaryNameListEntry;
            PEPROCESS CreatorProcess;
            ULONG NumberOfDataSubscribers;
} WNF_NAME_INSTANCE, *PWNF_NAME_INSTANCE;
```

WNF Name Instance

- WNF events are identified in memory as name instances
- Stores all the information related to the event

```c
typedef struct _WNF_STATE_DATA
{
        WNF_CONTEXT_HEADER Header;
        ULONG MaxDataSize;
        ULONG DataSize;
        WNF_CHANGE_STAMP ChangeStamp;
} WNF_STATE_DATA, *PWNF_STATE_DATA;
```

- Actual data is just under the structure…
- `Header.NodeTypeCode:` **`0x904`**

```c
typedef struct _WNF_NAME_INSTANCE
{
        WNF_CONTEXT_HEADER Header;
        EX_RUNDOWN_REF RundownProtection;
        RTL_BALANCED_NODE TreeLinks;
        WNF_STATE_NAME_INTERNAL StateName;
        PWNF_SCOPE_INSTANCE ScopeInstance;
        struct
        {
            ULONG MaxStateSize;
            PWNF_TYPE_ID TypeId;
            PSECURITY_DESCRIPTOR SecurityDescriptor;
        } StateNameInfo;
        EX_PUSH_LOCK StateDataLock;
        PWNF_STATE_DATA StateData;
        WNF_CHANGE_STAMP CurrentChangeStamp;
        HANDLE KeyHandle;
        EX_PUSH_LOCK StateSubListLock;
        LIST_ENTRY StateSubscriptionListHead;
        LIST_ENTRY TemporaryNameListEntry;
        PEPROCESS CreatorProcess;
        ULONG NumberOfDataSubscribers;
} WNF_NAME_INSTANCE, *PWNF_NAME_INSTANCE;
```

WNF Scope Instance

- Represents a WNF scope in memory
- Got a “list” of name instances available for the scope
    - Actually RTL_AVL_TREE for quick look up ;)
- `Header.NodeTypeCode:` **`0x902`**

```
typedef struct _WNF_SCOPE_INSTANCE
{
    WNF_CONTEXT_HEADER Header;
    EX_RUNDOWN_REF RundownProtection;
    WNF_DATA_SCOPE DataScope;
    ULONG InstanceIdSize;
    PVOID InstanceIdData;
    LIST_ENTRY ResolverListEntry;
    EX_PUSH_LOCK Lock;
    RTL_AVL_TREE NameSet;
    PVOID PermanentDataStore;
    PVOID VolatileDataStore;
} WNF_SCOPE_INSTANCE, *PWNF_SCOPE_INSTANCE;
```

```
typedef enum _WNF_DATA_SCOPE
{
    WnfDataScopeSystem = 0x0,
    WnfDataScopeSession = 0x1,
    WnfDataScopeUser = 0x2,
    WnfDataScopeProcess = 0x3,
    WnfDataScopeMachine = 0x4,
} WNF_DATA_SCOPE;
```

WNF Scope Map

- Keeps track of the available scopes
- Bound to a silo
  - **EJOB->ServerSiloGlobals.WnfSiloState.ScopeMap**
  - If no silo exist, may be found with **nt!PspHostSiloGlobals**
- Header.NodeTypeCode: **0x901**

```
typedef struct _WNF_SCOPE_MAP
{
    WNF_CONTEXT_HEADER Header;
    PWNF_SCOPE_INSTANCE SystemScopeInstance;
    PWNF_SCOPE_INSTANCE MachineScopeInstance;
    struct
    {
        WNF_SCOPE_MAP_ENTRY WnfScopeTypeSystem;
        WNF_SCOPE_MAP_ENTRY WnfScopeTypeSession;
        WNF_SCOPE_MAP_ENTRY WnfScopeTypeUser;
        WNF_SCOPE_MAP_ENTRY WnfScopeTypeProcess;
        WNF_SCOPE_MAP_ENTRY WnfScopeTypeMachine;
    } ByDataScope;
} WNF_SCOPE_MAP, *PWNF_SCOPE_MAP;
```

```
typedef struct _WNF_SCOPE_MAP_ENTRY
{
        EX_PUSH_LOCK Lock;
        LIST_ENTRY MapEntryHead;
}WNF_SCOPE_MAP_ENTRY, *PWNF_SCOPE_MAP_ENTRY;
```

WNF Subscription

- Created when a component subscribes an event
- Header.NodeTypeCode: **0x905**

```
typedef enum _WNF_SUBSCRIPTION_STATE
{
    WNF_SUB_STATE_QUIESCENT = 0x0,
    WNF_SUB_STATE_READY_TO_DELIVER = 0x1,
    WNF_SUB_STATE_IN_DELIVERY = 0x2,
    WNF_SUB_STATE_RETRY = 0x3,
} WNF_SUBSCRIPTION_STATE;
```

```
typedef struct _WNF_SUBSCRIPTION
{
    WNF_CONTEXT_HEADER Header;
    EX_RUNDOWN_REF RundownProtection;
    ULONG64 SubscriptionId;
    LIST_ENTRY ProcessSubscriptionListEntry;
    PEPROCESS Process;
    PWNF_NAME_INSTANCE NameInstance;
    WNF_STATE_NAME_INTERNAL WnfStateName;
    LIST_ENTRY StateSubscriptionListEntry;
    PVOID CallbackRoutine;
    PVOID CallbackContext;
    WNF_CHANGE_STAMP CurrentChangeStamp;
    ULONG DeliveryOption;
    LIST_ENTRY PendingSubscriptionListEntry;
    WNF_SUBSCRIPTION_STATE SubscriptionState;
    ULONG SubscribedEventSet;
    ULONG SignaledEventSet;
} WNF_SUBSCRIPTION, *PWNF_SUBSCRIPTION;
```

WNF Process Context

- Keeps track of all the structures involved with a process
- Accessible via
  - `EPROCESS.WnfContext`
  - `nt!ExpWnfProcessesListHead`
- `Header.NodeTypeCode:` **`0x906`**

```
typedef struct _WNF_PROCESS_CONTEXT
{
    WNF_CONTEXT_HEADER Header;
    PEPROCESS Process;
    LIST_ENTRY WnfProcessesListEntry;
    struct
    {
        PWNF_SCOPE_INSTANCE WnfScopeTypeSession;
        PWNF_SCOPE_INSTANCE WnfScopeTypeUser;
        PWNF_SCOPE_INSTANCE WnfScopeTypeProcess;
    } ImplicitScopeInstances;
    EX_PUSH_LOCK NameInstanceListLock;
    LIST_ENTRY TemporaryNamesListHead;
    EX_PUSH_LOCK SubscriptionListLock;
    LIST_ENTRY ProcessSubscriptionListHead;
    EX_PUSH_LOCK PendingQueueLock;
    LIST_ENTRY DeliveryPendingListHead;
    PKEVENT NotificationEvent;
} WNF_PROCESS_CONTEXT, *PWNF_PROCESS_CONTEXT;
```

WNF User vs. Kernel Subscriber

- How to handle the “single per-process notification event” issue?
  - High level APIs work with a set of userland structures to multiplex the subscriptions!
- `WNF_SUBSCRIPTION_TABLE` object keeps track of all the different subscriptions
  - `Header.NodeTypeCode:` **`0x914`**

```
typedef struct _WNF_SUBSCRIPTION_TABLE
{
    WNF_CONTEXT_HEADER Header;
    SRWLOCK NamesTableLock;
    LIST_ENTRY NamesTable;
    LIST_ENTRY SerializationGroupListHead;
    [...]
    PTP_TIMER Timer;
    ULONG64 TimerDueTime;
} WNF_SUBSCRIPTION_TABLE, *PWNF_SUBSCRIPTION_TABLE;
```

WNF User vs. Kernel Subscriber

- Userland subscription used for the whole process context
- Specific to a name instance with at least one subscriber
- `Header.NodeTypeCode:` **`0x912`**

```
typedef struct _WNF_NAME_SUBSCRIPTION
{
    WNF_CONTEXT_HEADER Header;
    ULONG64 SubscriptionId;
    WNF_STATE_NAME_INTERNAL StateName;
    WNF_CHANGE_STAMP CurrentChangeStamp;
    LIST_ENTRY NamesTableEntry;
    PWNF_TYPE_ID TypeId;
    SRWLOCK SubscriptionLock;
    LIST_ENTRY SubscriptionsListHead;
    ULONG NormalDeliverySubscriptions;
    ULONG ReliableDeliverySubscriptions;
    ULONG NotificationTypeCount[5];
    PWNF_DELIVERY_DESCRIPTOR RetryDescriptor;
    ULONG DeliveryState;
    ULONG64 ReliableRetryTime;
} WNF_NAME_SUBSCRIPTION, *PWNF_NAME_SUBSCRIPTION;
```

WNF User vs. Kernel Subscriber

- Userland subscription for a specific subprocess consumer
- Multiple WNF_USER_SUBSCRIPTION's can be linked to a WNF_NAME_SUBSCRIPTION
  - Enables different sub-subscribers to register a callback for the same event
- `Header.NodeTypeCode:` **`0x914`**

```
typedef struct _WNF_USER_SUBSCRIPTION
{
    WNF_CONTEXT_HEADER Header;
    LIST_ENTRY SubscriptionsListEntry;
    PWNF_NAME_SUBSCRIPTION NameSubscription;
    PVOID Callback;
    PVOID CallbackContext;
    ULONG64 SubProcessTag;
    ULONG CurrentChangeStamp;
    ULONG DeliveryOptions;
    ULONG SubscribedEventSet;
    PWNF_SERIALIZATION_GROUP SerializationGroup;
    ULONG64 UserSubcriptionCount;
    [...]
    HANDLE ThreadId;
}WNF_USER_SUBSCRIPTION, *PWNF_USER_SUBSCRIPTION;
```

Analyzing with Tools & WinDbg

Fixing !wnf

- Native windbg command line for displaying information about the wnf structures
- Doesn’t work out of the box
  - Relies on private symbols…. :/
- Can be “fixed” by adding the structure definition to ntkrnlmp and ntdll PDBs (thanks Alex for the protip!)

```
cl /c ntDef.c /Zi /Fdntkrnlmp.pdb /Gz  /D "_AMD64_"  /I "c:\program files (x86)\windows
kits\10\include\[version]\km"
```

- But not totally finished (some errors still occur sometime)…
  - Some ugly patches are also needed

WinDBG Custom Extension

- Basically does the same things as !wnf command

- Does not rely on private symbols and should (hopefully) work smoothly

```
kd> !wnfhelp
[WnfDbg] extension commands help:
 > !wnfsm [Address]                        = Displays the structure of a _WNF_SCOPE_MAP object.
                                                The address can either be a scope map or an eprocess (in case of multiple silo).
                                                If no address are provided, it will search for the generic scope map with nt!PspHostSiloGlobals.
 > !wnfsi [Address] [0/1/2]                = Displays the structure of a _WNF_SCOPE_INSTANCE object.
 > !wnfsilist <Address> [0/1/2]            = List all the scope instances in a list_entry.
 > !wnfni [Address] [0/1/2]                = Displays the structure of a _WNF_NAME_INSTANCE object.
 > !wnfnilist <Address> [0/1/2]            = List all the name instances in a list_entry.
 > !wnfsd <Address>                        = Displays the structure of a _WNF_STATE_DATA object and dump the data.
 > !wnfsub [Address] [0/1/2]                      = Displays the structure of a _WNF_SUBSCRIPTION object.
 > !wnfsublist <address> [offsetList] [0/1/2]     = List all the subscriptions in a list_entry
                                                    [offsetList] indicates the offset of the list to parse in the subscription.
                                                    By default, it will parse ProcessSubscriptionListEntry.
                                                    If the address provided is the base address of a list_entry, it will parse this list.
 > !wnfctx [Address] [0/1/2]                 = Displays the structure of a _WNF_PROCESS_CONTEXT object.
 > !wnfctxlist [Address] [0/1/2]             = Displays the structure of a _WNF_SCOPE_INSTANCE object.
                                               If no address is provided, it will list the process contexts pointed by nt!ExpWnfProcessesListHead
 > !wnfctxhead                               = Prettyprints the list head pointed by nt!ExpWnfProcessesListHead
 > !wnfname <StateName>                          = Displays the WNF state name information.
 > !wnfwhat <Address>                            = Determines the type of the structure at the provided address and dumps its structure.
 > !wnfhelp                                      = meh... >_>'

  - For most of these commands, the inputted address can either be the base address of the object or the base of a list_entry in the structure.
  - Specify the verbosity level with 0, 1 or 2.
```

WnfCom

- (Small) python module that can be used to communicate via WNF
  - Enables reading and writing data for existing name instances
  - Can also create a temporary state name (server style ☺)
  - Got a “client” side that is notified anytime an update happens for a specific name instance
- Easy peasy to use:

```
>>> from wnfcom import Wnfcom
>>> wnfserver = Wnfcom()
>>> wnfserver.CreateServer()
[SERVER] StateName created: 41c64e6da5559945
>>> wnfserver.Write(b“potato soup")
Encoded Name: 41c64e6da5559945, Clear Name: 6e99931
        Version: 1, Permanent: No, Scope: Machine,
Lifetime: Temporary, Unique: 56627
State update: 11 bytes written
```

```
>>> from wnfcom import Wnfcom
>>> wnfclient = Wnfcom()
>>> wnfclient.SetStateName("41c64e6da5559945")
>>> wnfclient.Listen()
[CLIENT] Event registered: 440
[CLIENT] Timestamp: 0x1 Size: 0xb
 Data:
00000000: 70 6F 74 61 74 6F 20 73  6F 75 70
potato soup
```

WnfDump

- Command-line C utility that can be used to discover information about WNF state names
  - -d ➔ **D**ump all WNF state names using registry-based enumeration, displaying vital information
    - Add –v ➔ **V**erbose output, which includes a hexdump of the WNF state data
    - Add –s ➔ **S**ecurity descriptors, which includes an SDDL string of the WNF state name's permissions
  - -b ➔ **B**rute-force temporary WNF state names (will show how we do this soon)
  - -i ➔ Show **i**nformation about a specific single WNF state name
  - -r ➔ **R**ead a particular WNF state name
  - -w ➔ **W**rite data into a particular WNF state name
  - -n ➔ Register for **n**otifications as a subscriber for the given WNF state name

WNF Attack Surface

The 0-byte Write

- Initially, wanted to check if Read/Write access was allowed to a particular state name by trying to write 0 bytes
  - If write succeeds, assume Write access is granted
- Turns out this is quite naïve:
  - Writing 0 bytes essentially overwrites any data that may have been previously stored and not yet consumed
    - If this is persistent data, it’s even worse…
  - It also updates the change stamp
    - Meaning anyone pushing updates with *enforce* enabled will get a failure to update the data
- So the shell died… and I could no longer re-launch it
  - Rebooted – black screen after logon ☹

The Privileged Disclosure

- When reading the thousands of WNF state names that exist on the system, I noticed several that had interesting-looking buffers
  - Including some that had what looked to be like pointers or other privileged data
- I did several repros on multiple machines and in some cases discovered heap, stack, and other privileged information data/information disclosures across privilege boundaries
  - Submitted case(s) last week with MSRC – which is why we can't share tools today ☹
- The main underlying problem is the same as you've seen in past research from j00ro, taviso, and others…
  - Certain WNF state names contain encoded data structures with various padding/alignment issues
  - Or in certain cases, bona fide uninitialized memory (such as due to `sizeof` misuse or other scenarios)

The Modern App Launcher Blocker

- Once a certain WNF state name is written to, no modern app launches work anymore for the duration of the boot session
  - A reboot fixes this
- After the disaster with "*just writing a zero*", I basically decided to try "fuzzing" by writing arbitrary data into each WNF state name that I could enumerate/get access to
  - Some of you know that I'm not a fuzzer person – so I had no smart generation algorithm and no logging/auditing enabled to see what writes caused what
  - I just wrote garbage everywhere/anywhere
  - And then I couldn't launch apps anymore
- Something worth looking into ☺

The Crashing Service

- Very similar finding to the one on the previous slide, using the same methodology, but running as Administrator (since we know that's not a boundary)
- In this case I got a service to crash (NULL pointer dereference)
  - Probably not exploitable beyond a DoS
  - I was hoping to get a kernel driver to crash (or something more interesting)
- Because I wasn't mutating my data, I just want to stress this was baby's first incompetent "fuzzer" 101
  - You might be able to find actual serious issues with a better approach
- At the time, I also only looked at well-known state names – not persistent, permanent or temporary ones

Discovering State Names and Permissions

- The first approach was to discover all the possible state names that could perhaps be manipulated maliciously
- For well-known names, permanent names, and persisted names, this is doable by enumerating the registry keys
  - We can then associate friendly names with the well-known names if we obtain Microsoft’s database
    - There are a few places where this can be found ☺
  - Then, we can also look in the registry for their security descriptor (this is the first thing in the data buffer)
- The security descriptor is a bit tricky because it doesn’t have an Owner or Group, so technically it’s ‘invalid’
  - We manually fix this up to address the problem with a fake owner/group
- But for temporary names – they’re not in the registry, and only kernel has the data structures for them (!wnf)

Discovering Volatile Names

- Volatile names are actually not that hard to brute force
  - The version is always 1
  - The lifetime is `WnfTemporaryStateName`
  - The permanent flag is always zero (temporary names can't have permanent data)
  - The scope is one of the 4 possible scopes
  - But the sequence number is 51 bits, Alex!
- Well…. recall that sequence numbers are *monotonically increasing*
  - And for volatile names, the sequence is reset to 0 each boot
- So we can use `ZwQueryWnfStateNameInformation` with the `WnfInfoStateNameExist` class up to ~1M…

Brute Forcing Security Descriptors

- Volatile state names only have security descriptors in kernel memory – no way to query this without !wnf
- But we can infer if we have read access by trying to read ☺
- We can infer write access by trying to write!
  - But you saw how well that went
- So there's a trick: remember that we can enforce a *matching change stamp*
  - Set this to 0xFFFFFFFF – the match check is made ***after*** the access check, so the error value leaks the writeable state
- Doesn't give us the whole security descriptor, but we can run the tool at different privileges to get some idea of AC/Low IL/User/Admin/SYSTEM

Covert Side Channel

Using “empty” WNF State Names

- There are many Well-Known WNF State Names that are unused on most systems – especially the ones related to XBOX or CELL families
  - A single registry is provisioned for all Windows SKUs, which is what allows this to happen
  - As long as some of these have maximum sizes that are large enough (some use 4K!), we can stash arbitrary data there
- Using a well-known name has the advantage that no registration needs to happen – one less API to call
  - However, if the state name is truly never used – the change stamp will reveal that it was written to (by not being 0)
    - This requires reading the data at least once though, and you *could* overflow the change stamp
- The perfect well-known name to use would have a liberal security descriptor allowing World/Everyone RW as well as AppContainer (ALL_APPLICATION_PACKAGES) or even some Edge Low Privilege App Container (LPAC)

Creating custom WNF State Names

- The other option is creating a custom WNF state name and perhaps using a volatile name and/or an explicitly scoped name to avoid detection/enumeration by simpler user-mode based tools (if they even know about WNF)
  - Can leverage “Type ID”s which are GUIDs to essentially make it impossible to read/write to the state ID without having the right “type”
- The disadvantage is that someone could intercept/hook the creation of the state name through the API…
  - But of course, recall that the pub/sub model means that you can ‘make up’ a correct state name when calling Query/Update and avoid going through that path at all
    - Albeit this won’t work with temporary names since that wouldn’t make sense (the sequence number would never match)
- Yet another option is re-using non-well known state names that you can infer/enumerate on your own and re-use for side-channel purposes
  - For example, each process has a “Wake Channel”, which is a WNF state

EDR/AM Visibility Options

- Given that WNF can be used this way (and many others…), what options does an EDR/AV product have?
- There are no documented (or undocumented) notifications/callbacks when WNF is being used in kernel-mode
- But… there is ETW tracing for WNF!
  - `PERFINFO_LOG_TYPE_WNF_(UN)SUBSCRIBE, CALLBACK, PUBLISH, NAME_RUNDOWN`
  - `EVENT_TRACE_GROUP_WNF (0xD00)`
  - `WnfGuid {42695762-EA50-497A-9068-5CBBB35E0B95}`
- However, only used if the Rtl* Publish/Query/Subscribe are used – not the system calls
- Hooking the user-mode NTDLL exports/system calls seems to be the only way – and will likely cause issues

Interesting/Sensitive WNF State Names

Inferring System State and User Behavior with WNF

- Some WNF IDs can be used because the reveal interesting information about the machine state:
  - `WNF_WIFI_CONNECTION_STATUS` – Wireless connection status (many more interesting WNF* IDs)
  - `WNF_BLTH_BLUETOOTH_STATUS` – Similar, but for Bluetooth (also `WNF_TETH_TETHERING_STATE`)
  - `WNF_UBPM_POWER_SOURCE` – Indicates battery power vs. AC adapter (`WNF_SEB_BATTERY_LEVEL` has battery level)
  - `WNF_CELL_*` – On Windows Phone (lol), has information such as network, number, signal strength, EDGE vs 3G, etc.
- Others can be used to infer user behaviors
  - `WNF_AUD_CAPTURE/RENDER` – Indicates (including the PID) the process that is capturing/playing back audio
  - `WNF_TKBN_TOUCH_EVENT` – Indicates each mouse click, keyboard press, or touch screen press
  - `WNF_SEB_USER_PRESENT` / `WNF_SEB_USER_PRESENCE_CHANGED` – Utilizes Windows' own user-presence learning

Avoiding Standard Notification APIs

- Even in situations where certain user actions already have documented APIs for receiving a notification, these APIs may generate event log/EDR/audit data
- Corresponding WNF IDs may exist (and sometimes may even be more descriptive) for the same actions
- For example, `WNF_SHEL_(DESKTOP)APPLICATION_(STARTED/TERMINATED)` provides information on both modern application launches (including the actual package name that was launched) through DCOM, as well as regular Win32 application launches
  - As long as the applications were created through `ShellExecute` (and/or interactively through Explorer.exe or CLI)
- Other examples are when there is a user-mode API, but no kernel-mode equivalent
  - `WNF_EDGE_LAST_NAVIGATED HOST` – Indicates each URL the user types in (or clicks on) in Edge
  - `WNF_SHEL_LOCKSCREEN_ACTIVE` – Indicates the lock screen is active

Controlling the System with WNF

- Some WNF IDs can be written to in order to effect change on the system
  - `WNF_FSRL_OPLOCK_BREAK` receives a list of PIDs (and the number/size) and terminates each of them!
  - There is a similar API for waiting on the process(es) to exit/resume instead
- Others we haven't quite figured out yet, but look pretty interesting
  - `WNF_SHEL_DDC_(WNS/SMS)_COMMAND` – The buffer size is 4KB which indicates potential for parsing bugs
- In a similar vein, there are also certain WNF IDs that indicate that certain things should happen/be done
  - `WNF_CERT_FLUSH_CACHE_TRIGGER` – Flushes the certificate store
  - `WNF_BOOT_MEMORY_PARTITIONS_RESTORE` – Stores the original memory partitions
  - `WNF_RTDS_RPC_INTERFACE_TRIGGER_CHANGED` – Potentially starts RPC-Interface Trigger Started Services

Using WNF to Change System State

Dumping Kernel/User Subscribers

- All subscriptions done by a process are in the `WNF_PROCESS_CONTEXT` as a `LIST_ENTRY` of `WNF_SUBSCRIPTION`
  - Kernel subscriptions are basically owned by the System process
- We can use !list to dump the `Callback` and `CallbackContext` in `WNF_SUBSCRIPTION` for the System Process
  - Note that in some cases, the *event aggregator* (CEA.SYS) is used which hides the real callback(s) in the context
- We can repeat this for user-mode processes as well, but the `Callback` will be NULL, as these are user subscribers
  - So we need to attach to user-space, get the `RtlpWnfProcessSubscriptions` table, go over the `WNF_NAME_SUBSCRIPTION’s` and then for each one, dump the list of `WNF_USER_SUBSCRIPTION` structures, each of which has a callback
  - Unfortunately, this symbol is a *static* which means that it is not in public symbols (but can be found by disassembling)
  - Certain user-mode callbacks also use the *event aggregator* (`EventAggregation.dll`) which stores callback in context

Signaling Arbitrary Subscribers & Changing State

- By dumping all of these subscribers, we get a pretty good overview of all of the different pieces of code that will execute if particular WNF state names are updated (assuming access rights allow the attacker to do so)
  - These are the places where you want to look for parsing bugs in the incoming data structure/buffer
  - As well as the places where there might be hidden logic bugs due to certain states not being expected to be present
    - Or at the very least, changes in the behavior of certain components which may be unwanted
- A very good example of unwanted/interesting change of behavior is using the Windows Feature Store to modify insider preview settings
  - I was going to talk about this here, but Rafael Riviera beat me to it and published an amazing tool called mach2
  - And also dumped/documented all of the preview settings for each build
- Check out mach2 on GitHub – a great example of misusing WNF for unintended effects ☺

Interesting Insider Settings

- HVSIContainerForOffice
- AndromedaStore
- CnnAntiSpoofingDataCollection
- DeepInferno
- DevModeInternal
- DisableAppcontainerFixups
- FailFastTreeParent, FailFastOnWrongThreadContext
- HcsSecurityMitigation
- HvciEverywhereInsiderOptIn
- VmmsVirtualMachineAppContainerLaunch
- VmChipsetLoadFirmwareFromFile, VmChipsetPackageStagingFirmware

Injecting Code with WNF

- Common techniques for injecting code into other processes include
  - `WriteProcessMemory` – directly injecting code
  - File Mappings (Section Objects) – mapping a section object into the target, or writing into an already-mapped section
  - Atom Objects – storing data into an atom and then having the target request the atom data
  - Window Messages – using messages such as `WM_COPYDATA` and DDE messages to cause the target process to get data
  - GUI Objects – Changing the title of a Window (or that of its class) to data we wish to have in the target's memory
- Using WNF provides yet another way of transferring data into a target process
  - Either by re-using one of its existing WNF IDs that it reads (especially if it's stored in a persistent fashion in the process)
  - Or by directing the process to call `Rtl/ZwQueryWnfStateData` on a particular WNF ID of interest

Modifying Callbacks/Contexts for Code Redirection

- Injecting memory is one part of the problem, but to redirect control flow, common solutions include
  - APCs
  - Remote Threads
  - Changing Thread Context
  - Modifying the “*window long*” of a window to get a custom callback/context associated with the window handler
- Another approach, however, can be to parse the `WNF_USER_SUBSCRIPTION`’s of a remote process (and these are linked to `WNF_NAME_SUBSCRIPTION`’s, which are linked off the `RtlpWnfProcessSubscriptions`)
  - The callback function can be changed (be wary of CFG) and then the WNF payload + size will be parameters 5 and 6
  - Alternatively, the callback context can be changed (which is often a V-Table or has another embedded function pointer)

Conclusion

Key Takeaways

- The Windows Notification Facility is an extremely interesting, well-designed addition to the Windows 8+ kernel
  - It provides lots of useful functionality to various system applications, services, and drivers
  - It also acts as the basis for more advanced functionality and notification frameworks
- Unfortunately, it is highly undocumented, and provides no real visibility into its behavior
  - Other than a WinDBG extension which doesn't work since the WNF symbols are private
  - And some limited ETW events that only work for one particular set of callers
  - Its ability to persist data across reboots also makes it even more interesting for misuse
- There is no magic intellectual property in WNF internals – Microsoft should publish the symbols to make !wnf work, and provide additional ETW-based visibility into the kernel

Key Takeaways (cont)

- WNF has grown beyond just providing notifications
  - Did its designer really mean for it to be used as a way to kill processes from kernel-mode?
  - Should it really be used to store PII and every URL ever visited in a world-readable WNF state name?
  - Do teams that use WNF at Microsoft fully understand the implications, boundaries, etc?
    - Such as needing to initialize memory and treating data the same way you'd treat system call parameters
- Because it can be used to transfer data from one boundary to another, and because callbacks are involved, both parsing errors as well as code redirection/injection attacks are possible using more novel techniques than usual
  - Obviously, this implies permissions to exist in the first place, so this is an EDR-evasion technique more than anything
- How long until we start seeing WNF state names with pointers in them? :-/
- Defenders – start fuzzing, building visibility tools, and poking at WNF – at the very least, you'll have fun!

Future Research

- A big chunk of WNF events all start with `SEB_` which represents the System Events Broker
  - `SystemEventsBrokerServer.dll` and `SystemEventsBrokerClient.dll` are the user-mode high-level APIs
  - It may be that some of these SEB events are then internally parsed by SEB's clients, masking some true consumers
- Many of the registered kernel-mode and user-mode callbacks are owned by `CEA.SYS` or `EventAggregation.dll`
  - These are part of the "Event Aggregation Library", which allows you to have start/stop callbacks when a certain set of events have accumulated above a certain threshold, or multiple WNF events are happening at the same time, or in a given sequence, or when at least one out of a group of WNF events have occurred
    - Essentially a finite state machine around WNF event IDs that callers can register for
    - So the real consumers are hidden behind the event aggregation library
- Once MSRC is done with analysis, will release all of these tools so that you can play with them!

THANK YOU!

Q & A