A Syscall Journey in the Windows Kernel

Alice included in Windows Internals
2022-03-24 5423 words 26 minutes

CONTENTS

The analysis on this post was made from a Windows 10 x64 bits. If you are trying to compare the content of this post on a lower Windows version *you will be disappointed* since changes were made in Windows 10.

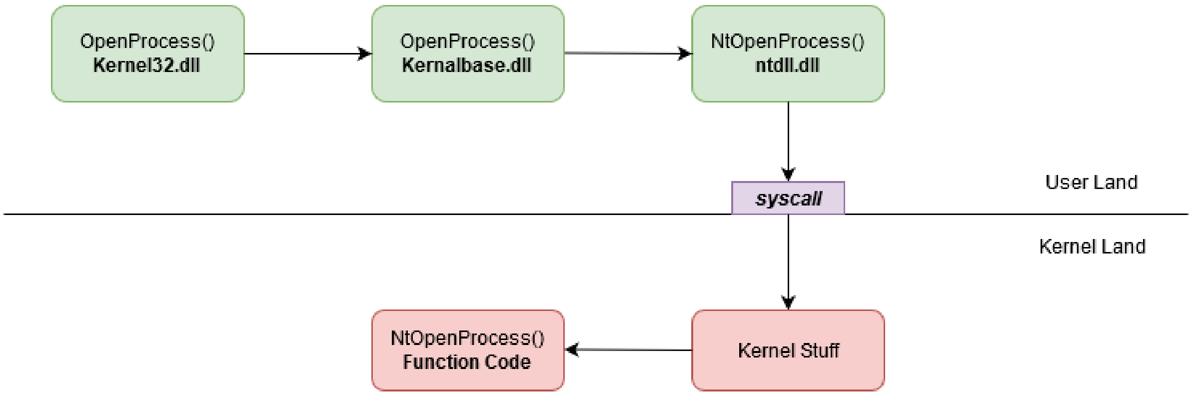
In my last post dedicated to the different ways to retrieve Syscall ID, I explained quickly how direct syscalls were performed in User Mode and remained vague about how it was processed in Kernel Mode.

In this post, we will focus on how syscall numbers are processed in the Kernel and how the kernel routines related to the syscall numbers are retrieved and executed.

Previously in the User Mode

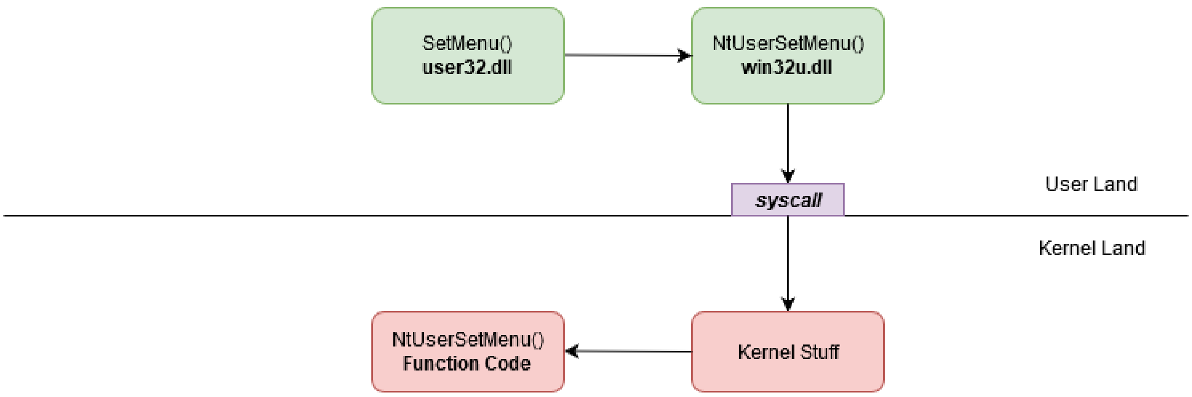
When a program needs to interact with other processes, memory, drives or the file system it uses the Windows API functions in `Kernel32.dll`. However, to interact with the Windows GUI, a program will use functions located in `user32.dll` and `gdi32.dll`.

Some of these functions can be seen as wrappers for direct syscalls to the Kernel. For instance, if you perform an `OpenProcess()` the execution will be:



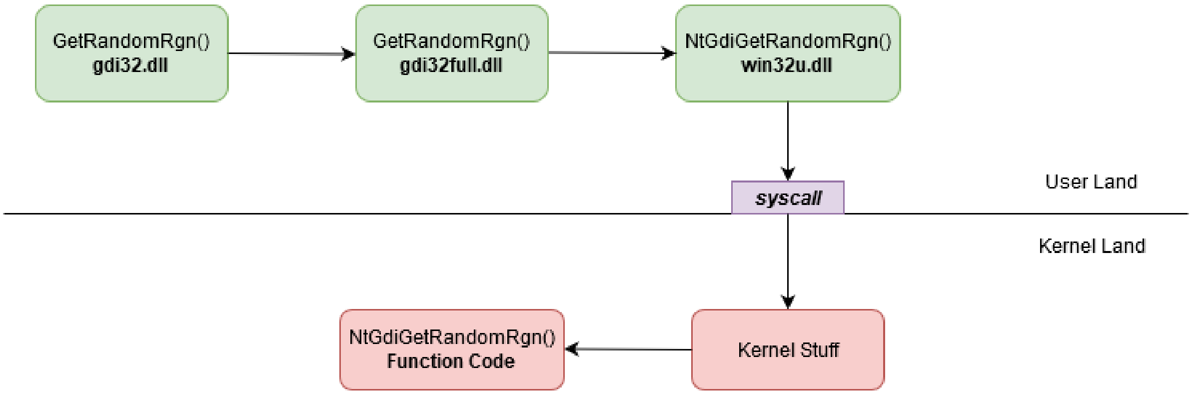
OpenProcess direct syscall

If you perform a `SetMenu()` the execution will be:



OpenProcess direct syscall

Finally, if you perform a `GetRandomRgn()` the execution will be:



OpenProcess direct syscall

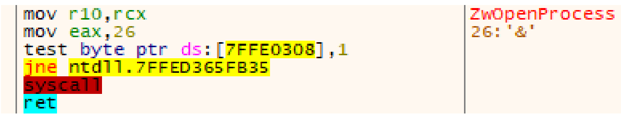
In the native windows execution flow, direct syscalls are performed via `Nt*` and `Zw*` functions that can be found in `ntdll.dll` or by `NtUser*` and `NtGdi*` functions that can be found in `win32u.dll`.

Small warning here, not all the `Kernel32`, `user32` and `gdi32` functions end up in direct syscall.

The "real" code of `Nt*`, `Zw*`, `NtUser*` and `NtGdi*` function runs in Kernel Mode.

In this post, `Nt*` and `Zw*` functions will be called `Native functions`. `NtUser*` and `NtGdi*` functions will be called `GUI functions`.

A direct syscall looks like this:



OpenProcess direct syscall

The code of a direct syscall is also called `syscall stub`.

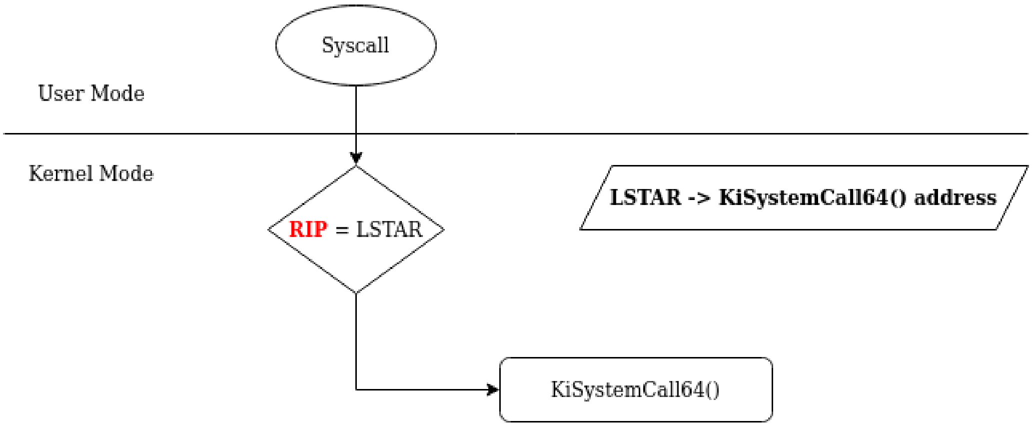
The purpose of the `syscall stub` is to forward the execution flow of the function to the related code in the Kernel (the `kernel routine`). It's the last step in User Mode. This transfer of execution is done by the assembly instruction `syscall`.

The only difference between `syscall stub` is the number moved in EAX. This number is called `syscall ID` or `syscall number` or `system service number (SSN)`.

It allows the Kernel to retrieve the function code related to this identifier. Syscall identifiers are unique on a system and linked to a single function. ***They can change between different OS versions or service packs.***

Welcome My Son, Welcome To The Machine Kernel[1]

On a 64 bits system, When the `syscall` instruction is executed the address in the `LSTAR` register is put in the `RIP` register.



`RIP` is the register that store the next address to be executed in the workflow.

For the `LSTAR` register, it's only purpose is to store the address of the first function executed in Kernel-Mode after a `syscall` instruction. The `LSTAR` register is one of many others registers called MSR (Model Specific Registers).

The value of the `LSTAR` register is set at the boot time.

We can see the value in `LSTAR` by using Windbg in Kernel Debug mode. In the system, `LSTAR` is identified as `msr[c0000082]`.

To read his value, we use the command `rdmsr` (read MSR).

```
lkd> rdmsr c0000082 //
msr[c0000082] = fffff807`403ca140
lkd> ln  fffff807`403ca140

(fffff807`403ca140)   nt!KiSystemCall64Shadow   |  (fffff807`403ca16d)   nt!KiSystemCall64ShadowCommon
```

After the execution of the `syscall` instruction in User Mode, we **switch into the Kernel Mode**.

From here to the execution of the related kernel routine, the following functions will be executed (pretty much in this order) :

- `KiSystemCall64Shadow` or `KiSystemCall64` (if the Meltdown mitigation is not activated);
- `KiSystemServiceUser` ;
- `KiSystemServiceStart` ;
- `KiSystemServiceRepeat` ;
- `KiSystemServiceGdiTebAccess` ;
- `KiSystemServiceCopyStart` (not executed all the time);
- `KiSystemServiceCopyEnd` .

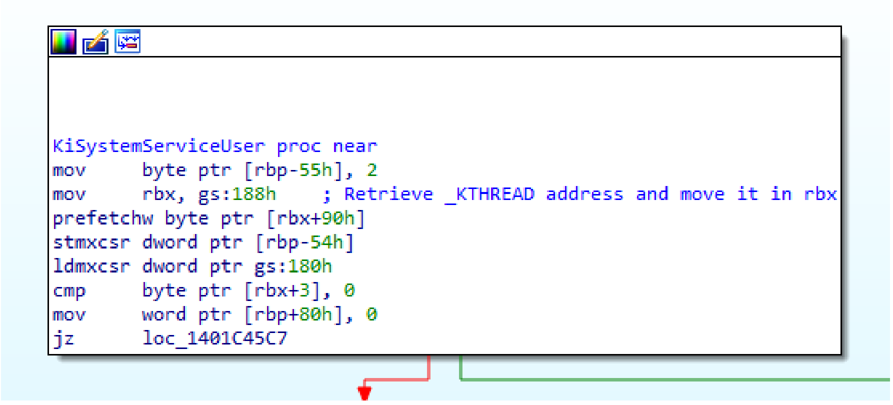
In this post we will only focus on `KiSystemServiceUser`, `KiSystemServiceStart`, `KiSystemServiceRepeat` and `KiSystemServiceCopyEnd` functions. We will also focus on specific Kernel structures used during the syscall number processing.

Retrieving the Kernel Thread with KiSystemServiceUser()

After the execution of the first function of the workflow (`KiSystemCall64`), `KiSystemServiceUser()` is the next one.

One of the important things happening in this function is the retrieval of the `KTHREAD structure` address of the current thread.

To do so, the instruction `mov rbx, gs:188h` is used.



get KThread

But what is this instruction? In the kernel of x64 bits systems, `gs:0` contains a pointer to the `_KPCR` structure. KPCR stands for `Kernel Processor Control Region`.

```
lkd> dt nt!_KPCR
   +0x000 NtTib             : _NT_TIB
   +0x000 GdtBase           : Ptr64 _KGDTENTRY64
   +0x008 TssBase           : Ptr64 _KTSS64
   +0x010 UserRsp           : Uint8B
   +0x018 Self              : Ptr64 _KPCR
   +0x020 CurrentPrcb       : Ptr64 _KPRCB
   +0x028 LockArray         : Ptr64 _KSPIN_LOCK_QUEUE

   +0x030 Used_Self         : Ptr64 Void
   +0x038 IdtBase           : Ptr64 _KIDTENTRY64
   +0x040 Unused            : [2] Uint8B
   +0x050 Irql              : UChar
   +0x051 SecondLevelCacheAssociativity : UChar
   +0x052 ObsoleteNumber    : UChar
   +0x053 Fill0             : UChar
   +0x054 Unused0           : [3] Uint4B
   +0x060 MajorVersion      : Uint2B
   +0x062 MinorVersion      : Uint2B
   +0x064 StallScaleFactor : Uint4B
   +0x068 Unused1           : [3] Ptr64 Void
   +0x080 KernelReserved    : [15] Uint4B
   +0x0bc SecondLevelCacheSize : Uint4B
   +0x0c0 HalReserved       : [16] Uint4B
   +0x100 Unused2           : Uint4B
   +0x108 KdVersionBlock    : Ptr64 Void
   +0x110 Unused3           : Ptr64 Void
   +0x118 PcrAlign1         : [24] Uint4B
   +0x180 Prcb              : _KPRCB
```

The `_KPCR` structure is used to store processor specific data. At the end of the structure (offset `0x180h`), we can see another structure called `_KPRCB` (Kernel Processor Control Block).

Like `_KPCR`, this structure contains processor specific data but it also **contains pointers to the current, next and idle thread schedule for execution.**

The target offset was `gs:188h`. So, if the end of `_KPCR` is at `180h`, our value is at the offset `0x008h` of `_KPRCB`.

```
lkd> dt nt!_KPRCB
   +0x000 MxCsr            : Uint4B
   +0x004 LegacyNumber     : UChar
   +0x005 ReservedMustBeZero : UChar
   +0x006 InterruptRequest : UChar
   +0x007 IdleHalt         : UChar
   +0x008 CurrentThread    : Ptr64 _KTHREAD

   +0x010 NextThread       : Ptr64 _KTHREAD

   +0x018 IdleThread       : Ptr64 _KTHREAD

   ....
```

the value at `0x008h` is a pointer to the `_KTHREAD` structure of the current thread!

So by getting the value in `gs:188h`, we can indeed retrieve the KTHREAD address of the current thread.

The KTHREAD structure contains a lots of crucial informations needed by the Kernel for thread execution/management. It can be viewed as the Kernel version of the `TEB` (Thread Environment Block). **Fun fact, the address of the TEB is stored in the KTHREAD!**

```
   lkd> dt nt!_KTHREAD
   +0x000 Header           : _DISPATCHER_HEADER

   +0x018 SListFaultAddress : Ptr64 Void
   ....
   +0x080 SystemCallNumber : Uint4B
   +0x084 ReadyTime        : Uint4B
   +0x088 FirstArgument    : Ptr64 Void
   ....
   +0x0f0 Teb              : Ptr64 Void
   ....
```

At the end of `KiSystemServiceUser()`, two values are initialized in the KTHREAD structure.

```
loc_1401C45C7:
mov     rax, [rbp-50h]
mov     rcx, [rbp-48h]
mov     rdx, [rbp-40h]
sti
mov     [rbx+88h], rcx  ; move address of the FirstArgument in _KTHREAD.FirstArgument
mov     [rbx+80h], eax  ; move the SystemCallNumber in _KTHREAD.SystemCallNumber
db      66h, 66h, 66h, 66h, 66h, 66h
nop     word ptr [rax+rax+00000000h]
KiSystemServiceUser endp
```

Set SystemCall number and address of the first argument

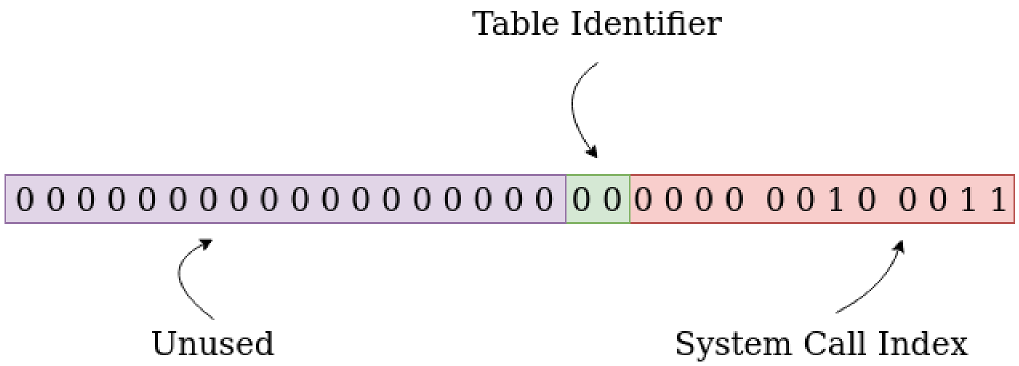
We know by now that `rbx` stores the KTHREAD address of the current thread.

If we check the related offsets, we can see that `0x080` is the **SystemCallNumber** field and `0x088` is the **FirstArgument** field (*cf. KTHREAD structure above*).

The secrets of the Syscall Number and KiSystemServiceStart()

The `System Call Number` or `System Service Number` contains more information that it seems.

Actually, it contains 2 informations. The `Table Identifier` and the `System Call Index`.



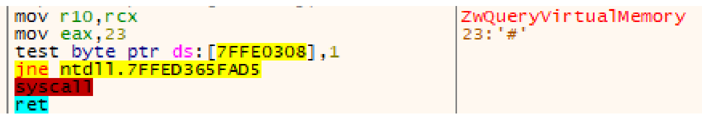
Informations in the Syscall Number 23h (NtQueryVirtualMemory)

In the first 12 bits [0 to 11] of this numbers (to read from the right to the left), it's where the `System Call Index` is stored. In the bits 12 to 13 the `Table Identifier` is stored. The rest of the bits are unused.

Even if theoretically, the 2 bits dedicated to the `Table Identifier` can generate 4 values, today (in Windows 10 and 11) the values on the `Table Identifier` can only be `00` or `01`.

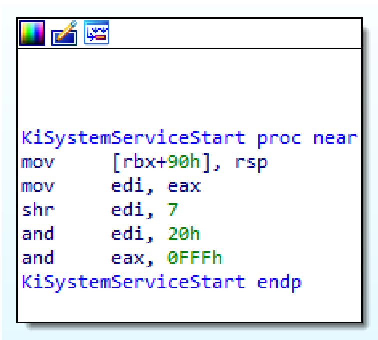
The purpose of the function `KiSystemServiceStart()` is to **extract these informations** from the `System Call Number`.

Remember that our `System Call Number` is stored in the `eax` register.



Function NtQueryVirtualMemory()

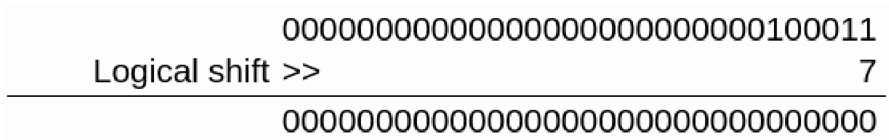
Now, let's take a look on what this function is actually doing.



The function KiSystemServiceStart()

If we take as example the function `NtQueryVirtualMemory()`, the `System Call Number` associated is `23h`

```
mov edi,eax     // edi = 23h = 0010 0011
shr edi, 7      // We shift edi 7 bits to the righ
t
```



Shift 7 bits to the right

The value of `edi` is now `0000 0000` or `00h`. Then, we extract the table identifier:

```
and edi, 20h    // edi = 00h
```

$$
\begin{array}{r}
000000 \\
\text{AND } 100000 \\
\hline
000000
\end{array}
$$

Extract table index

For `NtQueryVirtualMemory()` the Table Identifier is `00h`.

Now we extract the `System Call Index` from `eax`

```
and eax, 0FFFh  // eax = 23h
```

$$
\begin{array}{r}
000000100011 \\
\text{AND } 111111111111 \\
\hline
000000100011
\end{array}
$$

Extract SSN

The `System Call Index` for NtQueryVirtualMemory() is `23h`.

So basically, nothing change except that we have now the `Table Identifier` in the `edi` register and the `System Call Index` in `eax`. Well, that's kind of true. But let's take another example not from `ntdll`.

```
mov r10,rcx                          NtUserSetMenu
mov eax,1496
test byte ptr ds:[7FFE0308],1
jne win32u.7FFECFE4A305
syscall
ret
```

Function NtUserSetMenu()

For the function `NtUserSetMenu()` of `win32u.dll` the `System Call Number` is `1496h`.

```
mov edi, eax    // edi = 1496h = 0001 0100 1001 0110
shr edi, 7      // Shift bits to the right
```

$$
\begin{array}{lr}
 & 00000000000000000001010010010110 \\
\text{Logical shift >>} & 7 \\
\hline
 & 00000000000000000000000000101001
\end{array}
$$

Shift 7 bits to the right

The value of `edi` is now `0000 0000 0010 1001` or `29h`. Then, we extract the table identifier:

```
and edi, 20h    // edi = 29h
```

$$
\begin{array}{r}
101001 \\
\text{AND } 100000 \\
\hline
100000
\end{array}
$$

Extract table index

For `NtUserSetMenu()` the table identifier is `20h`.

Now we extract the `System Call Index` from `eax`

```
and eax, 0FFFh  // eax = 1496h
```

```
    1010010010110
AND 0111111111111
-----------------
    0010010010110
```

Extract SSN

The `System Call Index` for `NtUserSetMenu()` is `496h`.

Today in Windows 10 and 11, the initial value on the `Table Identifier` can only lead to the results `20h` or `00h`. This can be predicted just by looking at the `Syscall Number`.

If the number is between `1000h` and `1FFFh` the `Table Identifier` will be `20h`. This format of `Syscall Number` can be found on `win32u.dll`. **These functions are related to the Windows GUI.**

If the `Syscall Number` is between `0h` and `FFFh` the `Table Identifier` will be `00h`. This format of `Syscall Number` can be found on `ntdll.dll`. **These functions are related to Native functions.**

We will see in detail in the next chapter why the `Table Identifier` value is important.

Check and find with KiSystemServiceRepeat()

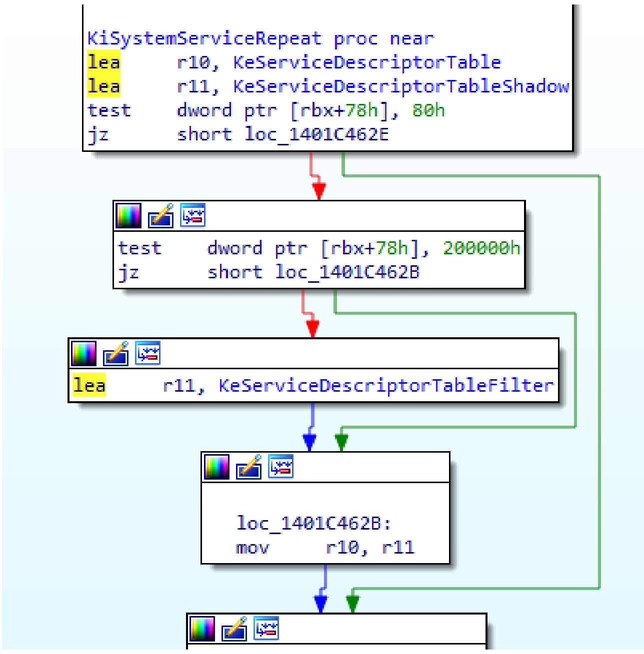
Friendly warning, this section is quite complex. I suggest you read it completely once to grasp the general idea and then read it a second time to pay attention to the detail.

The `KiSystemServiceRepeat()` function is the heart of the System call processing in the kernel.

It's purpose is to:

- check if the syscall is related to a GUI function;
- choose the right `System Descriptor Table`;
- retrieve the address of the kernel routine related to the `System Call Index`.

Let's start the analysis of this function!



We can see that the address of 2 structures are loaded in `r10` and `r11`. These structures named `KeServiceDescriptorTable` and `KeServiceDescriptorTableShadow` are generally called `Service Descriptor Table` (SDT).

`Service Descriptor Table` always contains 4 `SYSTEM_SERVICE_TABLE` structure.

```
typedef struct tag_SERVICE_DESCRIPTOR_TABLE {
    SYSTEM_SERVICE_TABLE item1;
    SYSTEM_SERVICE_TABLE item2;
    SYSTEM_SERVICE_TABLE item3;
    SYSTEM_SERVICE_TABLE item4;
} SERVICE_DESCRIPTOR_TABLE;
```

And a `SYSTEM_SERVICE_TABLE` contains 4 elements:

```
typedef struct tag_SYSTEM_SERVICE_TABLE {
    PULONG      ServiceTable;
    PULONG_PTR  CounterTable;
    ULONG_PTR   ServiceLimit;
    PBYTE       ArgumentTable;
} SYSTEM_SERVICE_TABLE;
```

In this function the elements `ServiceTable` and `ServiceLimit` of the `SYSTEM_SERVICE_TABLE` will be used.

00 Synthesis break

- We have two `Service Descriptor Table` named `KeServiceDescriptorTable` and `KeServiceDescriptorTableShadow`
- The `Service Descriptor Table` contains 4 `SYSTEM_SERVICE_TABLE`
- `SYSTEM_SERVICE_TABLE` are composed by 4 elements but for us only `ServiceTable` and `ServiceLimit` will be useful.

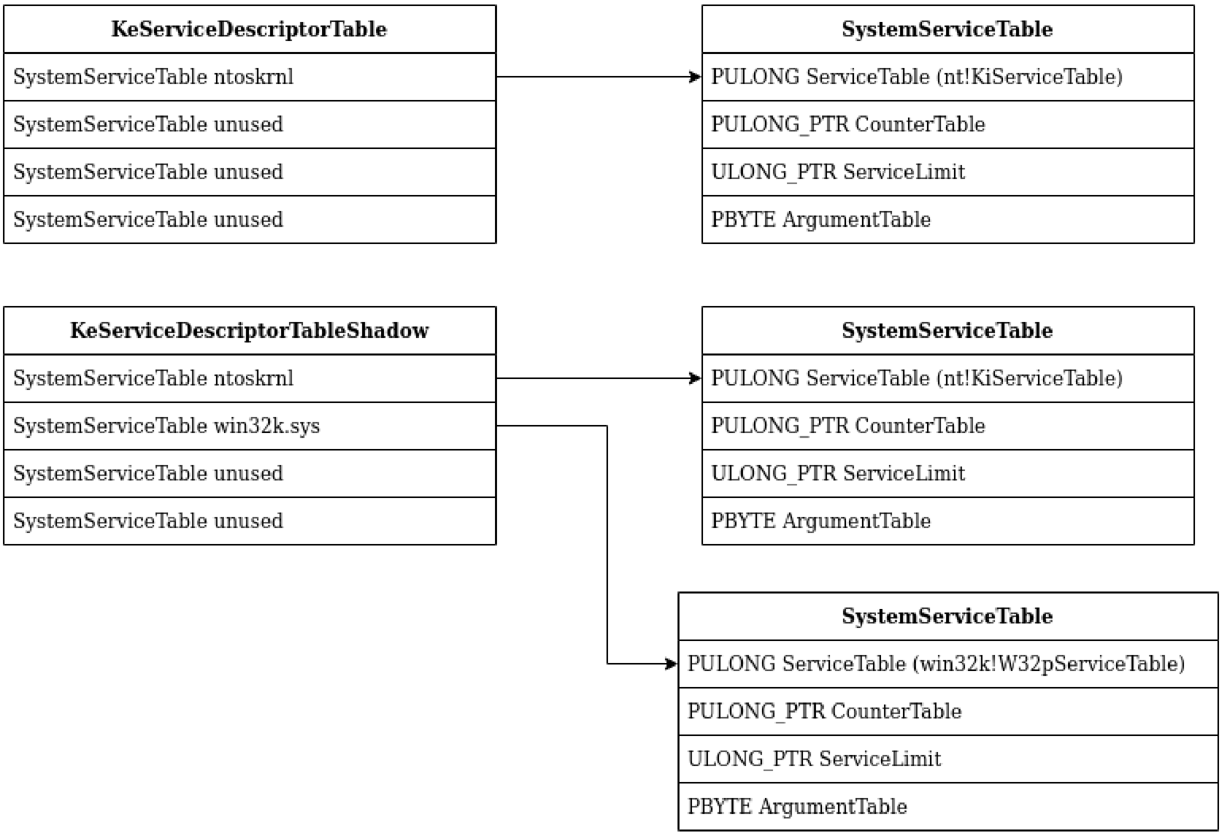
In the Kernel memory the `KeServiceDescriptorTable` look like this:

```
lkd> dps nt!KeServiceDescriptorTable
fffff803`23e04880  fffff803`23ca8450 nt!KiServiceTable
fffff803`23e04888  00000000`00000000
fffff803`23e04890  00000000`000001cf
fffff803`23e04898  fffff803`23ca8b90 nt!KiArgumentTable
fffff803`23e048a0  00000000`00000000
fffff803`23e048a8  00000000`00000000
fffff803`23e048b0  00000000`00000000
fffff803`23e048b8  00000000`00000000
fffff803`23e048c0  fffff803`23bd7280 nt!KiBreakpointTrapShadow
fffff803`23e048c8  fffff803`23bd7300 nt!KiOverflowTrapShadow
fffff803`23e048d0  fffff803`23bd7d00 nt!KiRaiseSecurityCheckFailureShadow

fffff803`23e048d8  fffff803`23bd7d80 nt!KiRaiseAssertionShadow
fffff803`23e048e0  fffff803`23bd7e00 nt!KiDebugServiceTrapShadow
fffff803`23e048e8  fffff803`23bd9140 nt!KiSystemCall64Shadow
fffff803`23e048f0  fffff803`23bd8e00 nt!KiSystemCall32Shadow
fffff803`23e048f8  00000000`00000000
```

And `KeServiceDescriptorTableShadow` look like this:

```
lkd> dps nt!KeServiceDescriptorTableShadow
fffff803`23ded980  fffff803`23ca8450 nt!KiServiceTable
fffff803`23ded988  00000000`00000000
fffff803`23ded990  00000000`000001cf
fffff803`23ded998  fffff803`23ca8b90 nt!KiArgumentTable
fffff803`23ded9a0  fffff1d5`938cb000 win32k!W32pServiceTable
fffff803`23ded9a8  00000000`00000000
fffff803`23ded9b0  00000000`000004da
fffff803`23ded9b8  fffff1d5`938cc84c win32k!W32pArgumentTable

fffff803`23ded9c0  00000000`00111311
fffff803`23ded9c8  00000000`00000000
fffff803`23ded9d0  ffffffff`80000018
fffff803`23ded9d8  00000000`00000000
fffff803`23ded9e0  00000000`00000000
fffff803`23ded9e8  00000000`00000000
fffff803`23ded9f0  00000000`00000000
fffff803`23ded9f8  00000000`00000000
```

The following figure is a graphic representation of the 2 `Service Descriptor Table`



After the initialization of `r10` and `r11` with SDTs, we can see that a test is performed with the instruction:

```
test dword ptr [rbx+78h], 80h
```

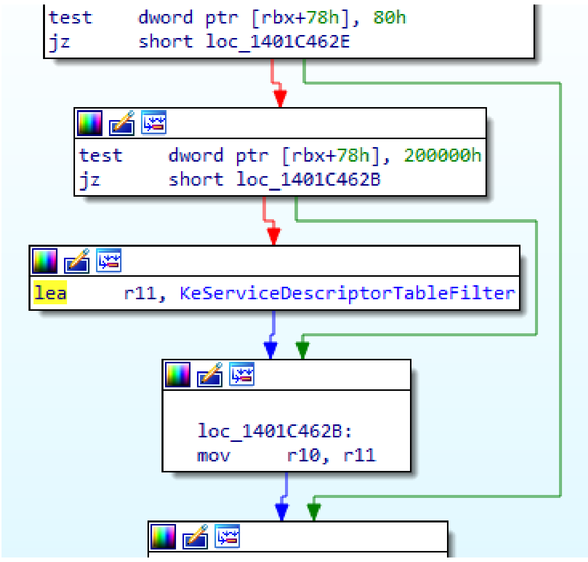
Earlier we saw that `rbx` contains the KTHREAD of the current thread. If we check at the offset `78h` of the KTHREAD structure we find this :

```
   +0x078 UserIdealProcessorFixed : Pos 0, 1 Bit
   +0x078 ThreadFlagsSpare : Pos 1, 1 Bit
   +0x078 AutoAlignment    : Pos 2, 1 Bit
   +0x078 DisableBoost     : Pos 3, 1 Bit
   +0x078 AlertedByThreadId : Pos 4, 1 Bit
   +0x078 QuantumDonation  : Pos 5, 1 Bit
   +0x078 EnableStackSwap  : Pos 6, 1 Bit
   +0x078 GuiThread        : Pos 7, 1 Bit
   +0x078 DisableQuantum   : Pos 8, 1 Bit
   +0x078 ChargeOnlySchedulingGroup : Pos 9, 1 Bit
   +0x078 DeferPreemption  : Pos 10, 1 Bit
   +0x078 QueueDeferPreemption : Pos 11, 1 Bit
   +0x078 ForceDeferSchedule : Pos 12, 1 Bit
   +0x078 SharedReadyQueueAffinity : Pos 13, 1 Bit
   +0x078 FreezeCount      : Pos 14, 1 Bit
   +0x078 TerminationApcRequest : Pos 15, 1 Bit
   +0x078 AutoBoostEntriesExhausted : Pos 16, 1 Bit
   +0x078 KernelStackResident : Pos 17, 1 Bit
   +0x078 TerminateRequestReason : Pos 18, 2 Bits
   +0x078 ProcessStackCountDecremented : Pos 20, 1 Bit
   +0x078 RestrictedGuiThread : Pos 21, 1 Bit
   +0x078 VpBackingThread  : Pos 22, 1 Bit
   +0x078 EtwStackTraceCrimsonApcDisabled : Pos 23, 1 Bit
   +0x078 EtwStackTraceApcInserted : Pos 24, 8 Bits
   +0x078 ThreadFlags      : Int4B
```

The purpose of this instruction is to check if the `GuiThread` flag is set. If the flag is set then following instruction will be executed.

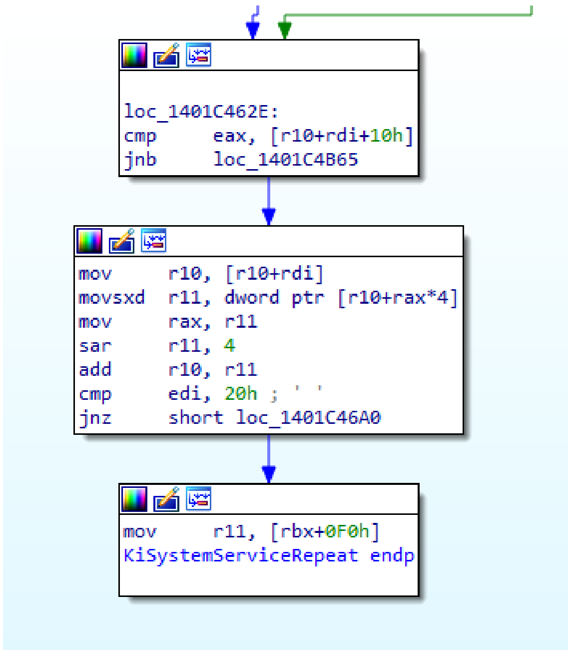
```
test dword ptr [rbx+78h], 200000h
```

If the flag is not set then it jumps above all this part.



However, **the first time that the thread will executes this routine the `GuiThread` flag is not be set.** Why? Because the Kernel doesn't know yet that if the current thread is processing a GUI function or not.

So for now the flag is not set and we are taking the jump to end up in this code:



It's checking if the value of `eax` is above the value at the address `[r10+rdi+10h]`

Let's take a breath and use what we already know.

- `eax` contains the `System Call Index` extracted ealier in `KiSystemServiceStart()`
- `rdi` contains the `Table Identifier` extracted ealier in `KiSystemServiceStart()`. It's value is `20h` or `00h`
- `r10` contains the address of `KeServiceDescriptorTable` (it as been initialized at the beginning of this function)
- `10h` it just 16 in hexadecimal.

Ok so it looks like our `System Call Index` is compared with something in the `KeServiceDescriptorTable`.

If our syscall is related to a GUI function, we then have

`[KeServiceDescriptorTable+20h+10h]` if not we have `[KeServiceDescriptorTable+00h+10h]`.

Ok. Fine.

Let's come back to what a `Service Descriptor Table` look like. A `Service Descriptor Table` contains 4 `SYSTEM_SERVICE_TABLE` structure and for `KeServiceDescriptorTable` in memory it look like this:

```
lkd> dps nt!KeServiceDescriptorTable
fffff803`23e04880  fffff803`23ca8450 nt!KiServiceTable
fffff803`23e04888  00000000`00000000
fffff803`23e04890  00000000`000001cf
fffff803`23e04898  fffff803`23ca8b90 nt!KiArgumentTable
fffff803`23e048a0  00000000`00000000
fffff803`23e048a8  00000000`00000000
fffff803`23e048b0  00000000`00000000
fffff803`23e048b8  00000000`00000000
fffff803`23e048c0  fffff803`23bd7280 nt!KiBreakpointTrapShadow
fffff803`23e048c8  fffff803`23bd7300 nt!KiOverflowTrapShadow
fffff803`23e048d0  fffff803`23bd7d00 nt!KiRaiseSecurityCheckFailureShadow

fffff803`23e048d8  fffff803`23bd7d80 nt!KiRaiseAssertionShadow
fffff803`23e048e0  fffff803`23bd7e00 nt!KiDebugServiceTrapShadow
fffff803`23e048e8  fffff803`23bd9140 nt!KiSystemCall64Shadow
fffff803`23e048f0  fffff803`23bd8e00 nt!KiSystemCall32Shadow
fffff803`23e048f8  00000000`00000000
```

So for a GUI function (Table Identifier at `20h`) the formula is `[KeServiceDescriptorTable+20h+10h]` -> `[23e04880+20h+10h]` -> `[23e048b0]`. We can see that at this address the value is `0h`.

```
lkd> dps nt!KeServiceDescriptorTable
fffff803`23e04880  fffff803`23ca8450 nt!KiServiceTable
fffff803`23e04888  00000000`00000000
fffff803`23e04890  00000000`000001cf
fffff803`23e04898  fffff803`23ca8b90 nt!KiArgumentTable
fffff803`23e048a0  00000000`00000000
fffff803`23e048a8  00000000`00000000
fffff803`23e048b0  00000000`00000000 <- [KeServiceDescriptorTable+20h+10h
]
fffff803`23e048b8  00000000`00000000
....
```

However, if our syscall is a Native function the Table Identifier will be `00h` and the formula `[KeServiceDescriptorTable+00h+10h]` -> `[23e04880+00h+10h]` -> `[23e04890]`. We can see that at this address the value is `1CFh`.

```
lkd> dps nt!KeServiceDescriptorTable
fffff803`23e04880  fffff803`23ca8450 nt!KiServiceTable
fffff803`23e04888  00000000`00000000
fffff803`23e04890  00000000`000001cf <- [KeServiceDescriptorTable+00h+10h
]
fffff803`23e04898  fffff803`23ca8b90 nt!KiArgumentTable
....
```

So basically the third item of the `SYSTEM_SERVICE_TABLE` is checked. This item is the `ServiceLimit` and it indicates the number elements in the `ServiceTable`.

```
typedef struct tag_SYSTEM_SERVICE_TABLE {
    PULONG      ServiceTable;
    PULONG_PTR  CounterTable;
    ULONG_PTR   ServiceLimit;
    PBYTE       ArgumentTable;
} SYSTEM_SERVICE_TABLE;
```

The `ServiceTable` item of the `SYSTEM_SERVICE_TABLE` is an array of `relative value address` (RVA). Each element of this array is linked to a kernel routine function.

So we have our `System Call Index` in `eax` checked against the number of RVA in the `ServiceTable`. What does it mean.

It checks if the `System Call Index` is valid (aka in the limit of the `ServiceTable` array) !

01 Synthesis break

> - the `GuiThread` flag of the current thread KTHREAD structure is checked. However, Since it's the first time we are executing this routine with this thread it's set to 0.
> - the `System Call Index` is compared to the number of elements in the `ServiceTable` of the first `SYSTEM_SERVICE_TABLE` in `KeServiceDescriptorTable`.

But wait a minute ! If we have a GUI function like `NtUserSetMenu()`. Its `Sytem Call Index` is `496h` ! So the check will be `496h > 0h` and our `System Call Index` will be considered invalid (aka the jump taken)!

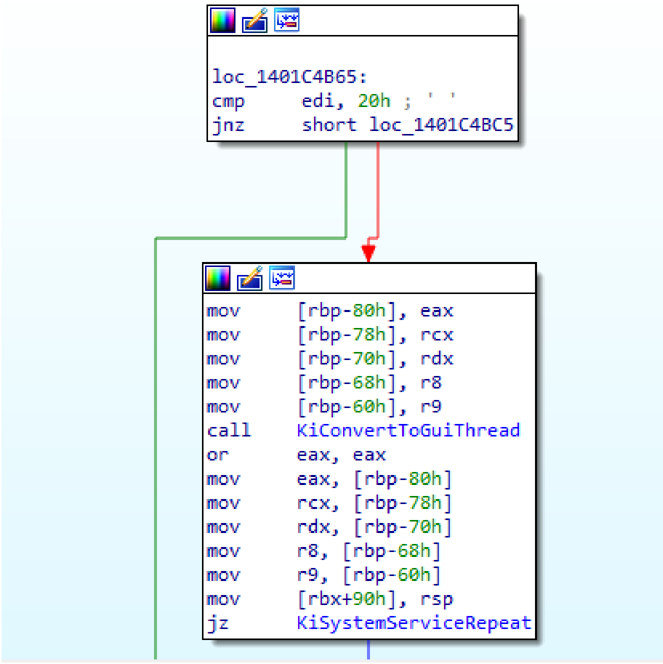
Yes that's true !

If we are in the case of `NtQueryVirtualMemory()`, then it's not a GUI function. So in this case the check will be if `23h (the System call Index of the function) > 1CFh`. Since `23h` is below `1CFh` the jump is not taken and the execution will continue in this function.

However, in the case of `NtUserSetMenu()`, `496h > 00h`. So here the jump to `loc_1401C4B65` will be taken.

For the exercise let's imagine that we are in the case of `NtUserSetMenu()` and that it's the first time that this thread is processing a GUI function.

In this case the jump to `loc_1401C4B65` will take us here:



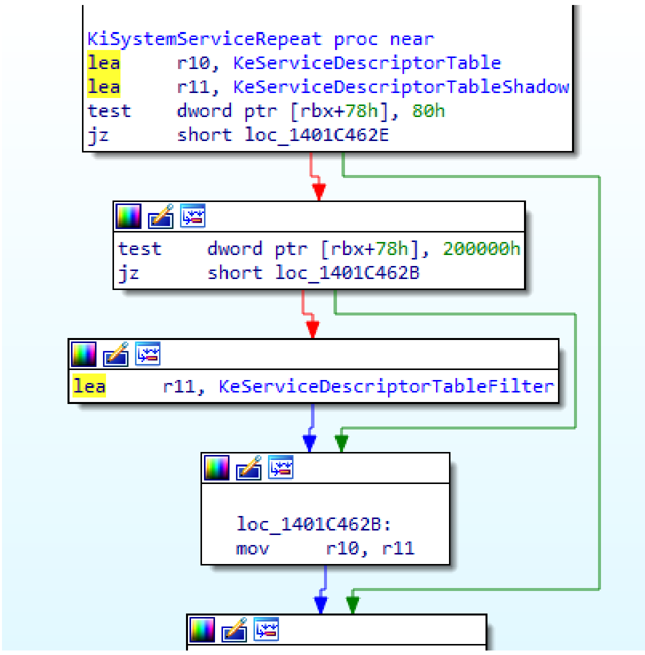
As we can see the first instruction is to check if `edi` is `20h`. But by now we know what this means! It means that it's a check to see if we are processing a GUI function.

We can see 2 others functions `KiConvertGuiThread` and `KiSystemServiceRepeat`.

So here it will be simple. If `edi` is indeed `20h` it means that we are processing a GUI function and we need to convert our current thread in a GUI Thread via the function `KiConvertGuiThread` and then go back to `KiSystemServiceRepeat`.

But if `edi` is not `20h`, it means that our syscall is not from a GUI function and that the `System Call Index` is out of range of the `ServiceTable`. So in this the last case, the routine it basically exiting the syscall processing workflow.

So if we are in the case of `NtUserSetMenu()`, our current thread is convert into a GUI Thread an we come back at the beginning of `KiSystemServiceRepeat()`.



This time the `GuiThread` flag checked with `test dword ptr [rbx+78h], 80h` will be set, the jump taken and the following instruction executed

```
test dword ptr [rbx+78h], 200000h
```

Now another flag in the KTHREAD of the current thread is checked. This time it's the `RestrictedGuiThread` flag.

```
   +0x078 UserIdealProcessorFixed : Pos 0, 1 Bit
   +0x078 ThreadFlagsSpare : Pos 1, 1 Bit
   +0x078 AutoAlignment    : Pos 2, 1 Bit
   +0x078 DisableBoost     : Pos 3, 1 Bit
   +0x078 AlertedByThreadId : Pos 4, 1 Bit
   +0x078 QuantumDonation  : Pos 5, 1 Bit
   +0x078 EnableStackSwap  : Pos 6, 1 Bit
   +0x078 GuiThread        : Pos 7, 1 Bit
   +0x078 DisableQuantum   : Pos 8, 1 Bit
   +0x078 ChargeOnlySchedulingGroup : Pos 9, 1 Bit
   +0x078 DeferPreemption  : Pos 10, 1 Bit
   +0x078 QueueDeferPreemption : Pos 11, 1 Bit
   +0x078 ForceDeferSchedule : Pos 12, 1 Bit
   +0x078 SharedReadyQueueAffinity : Pos 13, 1 Bit
   +0x078 FreezeCount       : Pos 14, 1 Bit
   +0x078 TerminationApcRequest : Pos 15, 1 Bit
   +0x078 AutoBoostEntriesExhausted : Pos 16, 1 Bit
   +0x078 KernelStackResident : Pos 17, 1 Bit
   +0x078 TerminateRequestReason : Pos 18, 2 Bits
   +0x078 ProcessStackCountDecremented : Pos 20, 1 Bit
   +0x078 RestrictedGuiThread : Pos 21, 1 Bit
   +0x078 VpBackingThread  : Pos 22, 1 Bit
   +0x078 EtwStackTraceCrimsonApcDisabled : Pos 23, 1 Bit
   +0x078 EtwStackTraceApcInserted : Pos 24, 8 Bits
   +0x078 ThreadFlags       : Int4B
```

If this flag is set the value of `r10` will be the address of `KeServiceDescriptorTableFilter` if not it will be `KeServiceDescriptorTableShadow`.

So from here it seems that **for Native functions *KeServiceDescriptorTable* will be used** and **for GUI functions it will be *KeServiceDescriptorTableFilter* or *KeServiceDescriptorTableShadow***.

Before Windows 10 only two `Service Descriptor Table` existed. `KeServiceDescriptorTable` and `KeServiceDescriptorTableShadow`.

Since Windows 10 the `KeServiceDescriptorTableFilter` table was introduced.

Because GUI functions processed by the kernel are often targeted for exploit research, Microsoft decided to introduce this new table to reduce the attack surface. You can find information about it on a very interesting Google Project Zero blog post here

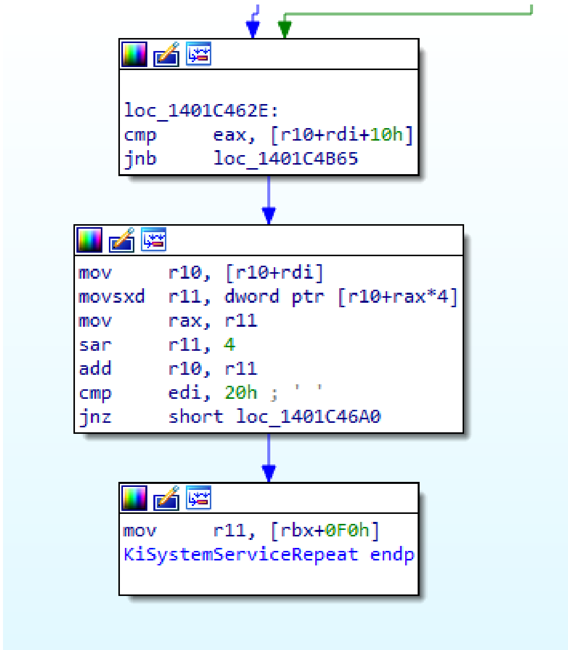
There is very few information about this table. Here's what we can found about it in the book `Windows Internals Part 1`.

> **Filter Win32k System Call:** This filters access to the Win32k kernel-mode subsystem driver only to certain API allowing simple GUI and Direct X access, mitigating many of the possible attacks, without completely disabling availability of the GUI/GDI Services.
>
> This [filtering] is set through an internal process creation attribute flag, which can define one out of three possible sets of Win32k filters that are enabled. However, because the filter sets are hard-coded, this mitigation is reserved for Microsoft internal usage.

02 Synthesis break

- We followed the case of `NtUserSetMenu()` executed by a thread that has never executed a GUI function before
- Our thread has been converted into a GUI thread so the flag `GuiThread` is now set
- According to the value of the flag `RestrictedGuiThread` the value of `r10` is now `KeServiceDescriptorTableFilter` or `KeServiceDescriptorTableShadow`
- `KeServiceDescriptorTableFilter` was introduced in Windows 10 and exist to reduce the attack surface on GUI functions
- `KeServiceDescriptorTable` is used for Native functions

Now let's take a look at the second part of this function



Last time we were here, we saw that if we were in the case of a GUI function the jmp to `loc_1401C4B65` was taken.

But now we have taken this jump and the value of `r10` is now the address of `KeServiceDescriptorTableFilter` or `KeServiceDescriptorTableShadow`.

To simplify, we will say that in this case, our process is not protected with `Win32k filters` so the `KeServiceDescriptorTableShadow` is used.

Lets take a look at `KeServiceDescriptorTableShadow` in memory again:

```
lkd> dps nt!KeServiceDescriptorTableShadow
fffff803`23ded980  fffff803`23ca8450 nt!KiServiceTable
fffff803`23ded988  00000000`00000000
fffff803`23ded990  00000000`000001cf
fffff803`23ded998  fffff803`23ca8b90 nt!KiArgumentTable
fffff803`23ded9a0  fffff1d5`938cb000 win32k!W32pServiceTable
fffff803`23ded9a8  00000000`00000000
fffff803`23ded9b0  00000000`000004da
fffff803`23ded9b8  fffff1d5`938cc84c win32k!W32pArgumentTable

fffff803`23ded9c0  00000000`00111311
fffff803`23ded9c8  00000000`00000000
fffff803`23ded9d0  ffffffff`80000018
fffff803`23ded9d8  00000000`00000000
fffff803`23ded9e0  00000000`00000000
fffff803`23ded9e8  00000000`00000000
fffff803`23ded9f0  00000000`00000000
fffff803`23ded9f8  00000000`00000000
```

So if we calculate our magic formula again -> `[r10+rdi+10h]` ->

`[KeServiceDescriptorTableShadow+20h+10h]` -> `[23ded980+20h+10h]` -> `[23ded9b0]`. We can see that at this address the value is `4DAh`.

```
lkd> dps nt!KeServiceDescriptorTableShadow
fffff803`23ded980  fffff803`23ca8450 nt!KiServiceTable
....
fffff803`23ded9a0  fffff1d5`938cb000 win32k!W32pServiceTable
fffff803`23ded9a8  00000000`00000000
fffff803`23ded9b0  00000000`000004da <- [KeServiceDescriptorTableShadow+20h+10h
]
fffff803`23ded9b8  fffff1d5`938cc84c win32k!W32pArgumentTable
....
```

And now we are good to go! Because the `System Call Index` of `NtUserSetMenu()` is `496h` and `496h < 4DAh` the jump is not taken and we can follow the rest of the function workflow. **We are in the range of the `W32pServiceTable` `System Service Table`**.

```
mov     r10, [r10+rdi]
movsxd  r11, dword ptr [r10+rax*4
]
mov     rax, r11
sar     r11, 4
add     r10, r11
cmp     edi, 20h ; ' '
```

Let's take a new breathe.

So what we know:

- `r10` is the address of our `System Descriptor Table` which in our case will be `KeServiceDescriptorTable` for `NtQueryVirtualMemory()` and `KeServiceDescriptorTableShadow` for `NtUserSetMenu()`
- `rdi` is the `Table Identifier`. `00h` for `NtQueryVirtualMemory()` and `20h` for `NtUserSetMenu()`
- `rax` is the `System Call identifier`. `23h` for `NtQueryVirtualMemory()` and `496h` for `NtUserSetMenu()`

So. Step by step.

```
mov     r10, [r10+rdi]

// For NtQueryVirtualMemory()   -> [KeServiceDescriptorTable+00h]
// For NtUserSetMenu()          -> [KeServiceDescriptorTableShadow+20h
]
```

If we check in memory this values, we found that for `NtQueryVirtualMemory()` `r10` will be the address of the `KiServiceTable`.

```
lkd> dps nt!KeServiceDescriptorTable
803`23e04880  fffff803`23ca8450 nt!KiServiceTable <- [KeServiceDescriptorTable+00h
]
803`23e04888  00000000`00000000
803`23e04890  00000000`000001cf
803`23e04898  fffff803`23ca8b90 nt!KiArgumentTable
....
```

And for `NtUserSetMenu()`, `r10` will be the address of `W32pServiceTable`.

```
lkd> dps nt!KeServiceDescriptorTableShadow
803`23ded980  fffff803`23ca8450 nt!KiServiceTable
803`23ded988  00000000`00000000
803`23ded990  00000000`000001cf
803`23ded998  fffff803`23ca8b90 nt!KiArgumentTable
803`23ded9a0  fffff1d5`938cb000 win32k!W32pServiceTable <- [KeServiceDescriptorTableShadow+20h
]
803`23ded9a8  00000000`00000000
803`23ded9b0  00000000`000004da
803`23ded9b8  fffff1d5`938cc84c win32k!W32pArgumentTable
803`23ded9c0  00000000`00111311
....
```

The notation `nt!` means that the address is in the module `ntoskrnl.exe`. `win32k!` means that this address is located in the driver `win32k.sys`.

Here we can definitly see that GUI functions and Native functions are not at all in the same part of the kernel.

The next instruction then

```
movsxd  r11, dword ptr [r10+rax*4]

// For NtQueryVirtualMemory()    -> [nt!KiServiceTable + 23h*4h]
// For NtUserSetMenu()           -> [win32k!W32pServiceTable + 496h*4h
]
```

Here in `r11` will store a value from a `Service Table`. `Service Table` are also called `System Service Dispatch Table` (SSDT).

> **ASM Time**
>
> The `movsxd` is a `mov` that allows to preserve the sign extension when a smaller register is copied into a 64-bit register. It is done by filling the extra bits with the sign extension.
>
> In a word if you are copying a negative number from a 32 bits register like ecx in a 64 bits register like rax **the value will stay negative**.

Remember when earlier we said that `Service Table` was an array of `Relative Virtual Address` related to kernel routine? Well it’s here that is happening. `rax` is our `System Call Index`, and what is really useful to find stuff in array? And index! So here we are searching in the appropriate `Service Table` the `RVA` of our function.

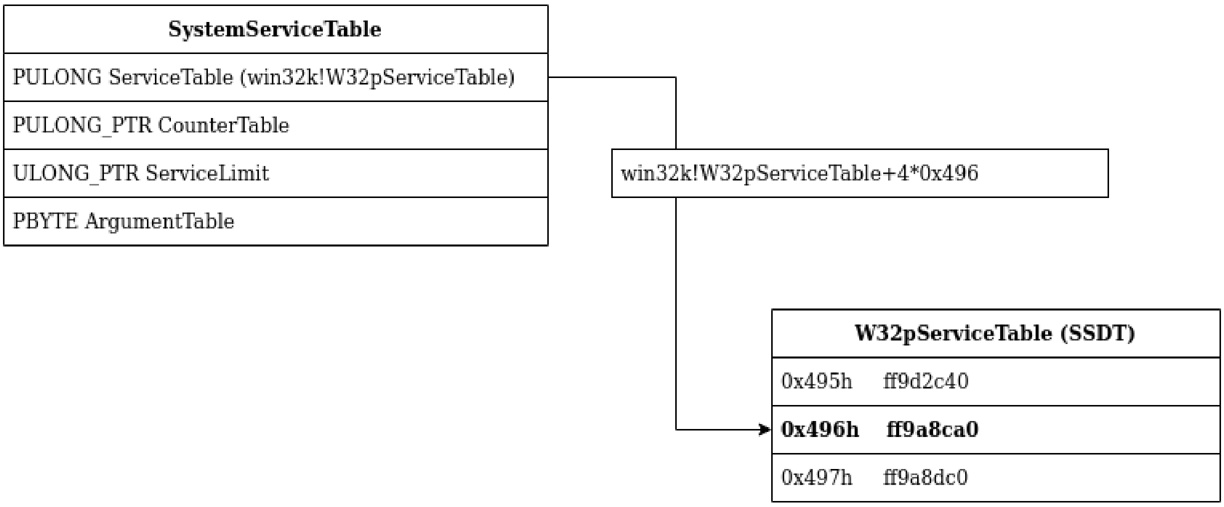
For `NtQueryVirtualMemory()`

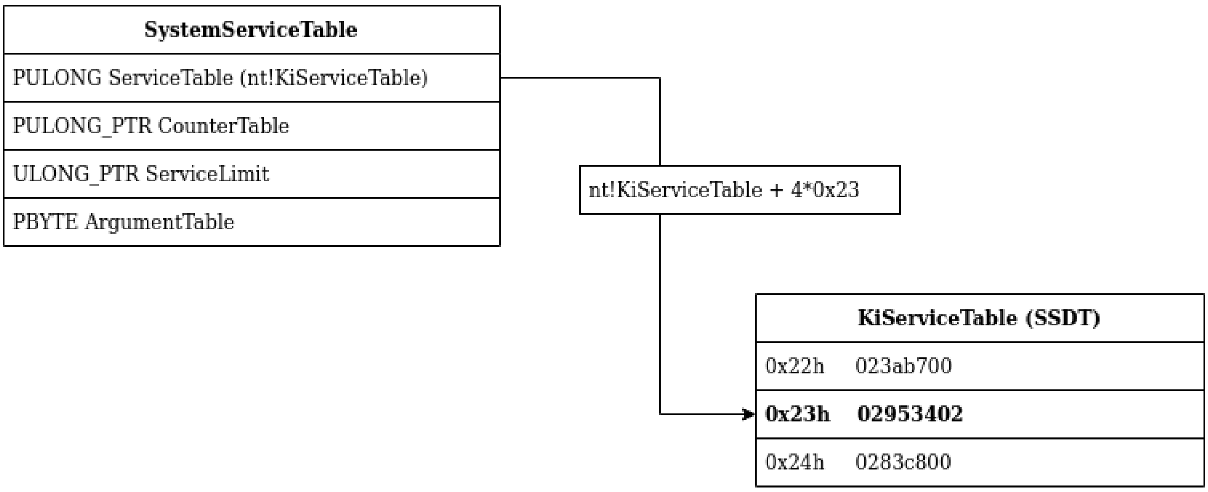
```
lkd> dd /c1 nt!KiServiceTable+4*0x23 L1
fffff803`23ca84dc  02953402
```

For `NtUserSetMenu()`

```
lkd> dd /c1 W32pServiceTable+4*0x496 L1
fffff1d5`938cc258  ff9a8ca0
```

And the multiplication by 4? Well, it’s just that in this array each item is 4 bytes long.





So let's look at the next instructions.

```
mov     rax, r1
1
sar     r11, 4
```

It seems that we are saving our `RVA` in `rax` and we are performing on it (the `RVA`) an arithmetic shift of 4 bits to the right.

For the case of `NtQueryVirtualMemory()`, an arithmetic shift of 4 bits to the right on the `RVA` `02953402h` will result in `295340h`

00000010100101010011010000000010
Arithmetic shift >> 4

00000000001010010101001101000000

	unsigned	signed
hex	295340	295340

For the case of `NtUserSetMenu()` an arithmetic shif of 4 bits to the right on the `RVA` `ff9a8ca0h` will result in `-65736`

```
                    11111111100110101000110010100000
Arithmetic shift >>                                4
---------------------------------------------------
                    11111111111110011010100011001010
```

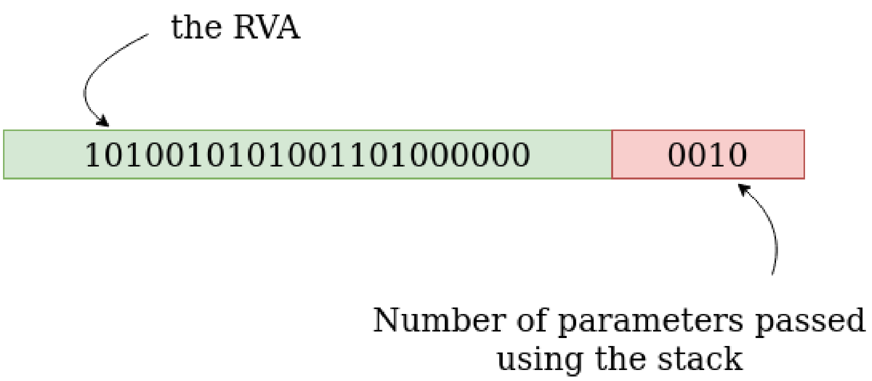
	unsigned	signed
hex	FFF9A8CA	-65736

> **ASM Time**
>
> Arithmetic shift right (`sar`) are often used for signed integers. Like `movsxd` it allows to preserve the sign extension.
>
> For `ff9a8ca0h` the most significant bit (aka the last bit on the left) is set. So we are dealing with a negative number.

But why the `RVA` is shifted 4 bits to the right? It's because the data retieved in the `SSDT` actually contains 2 things.

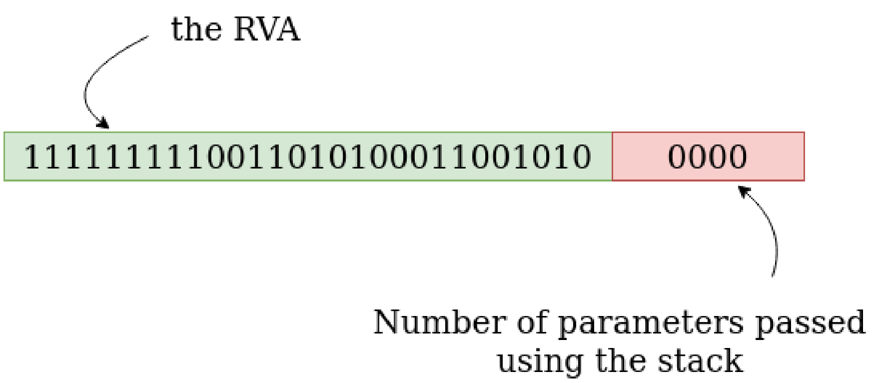
The 4 first bits is the number of parameters that are passed using the stack, the rest is our RVA. So by shifting 4 bits to the right, we are retrieving the real value of our `RVA` .

Below you can find the representation of the entry associated to `NtQueryVirtualMemory()` in the `SSDT` .



Representation of `02953402` .

And here the representation of the entry associated to `NtUserSetMenu()` .



Representation of `ff9a8ca0` .

As we can see, the number of parameters passed using the stack is 2 for `NtQueryVirtualMemory()` and 0 for `NtUserSetMenu()` .

Let's see the prototype of this functions to check the number of parameters used by them.

For `NtUserSetMenu()`:

```
NtUserSetMenu(
 HWND hWnd,
 HMENU hMenu,
 BOOL bRepaint);
```

For `NtQueryVirtualMemory()`:

```
NtQueryVirtualMemory(
 HANDLE ProcessHandle,
 PVOID BaseAddress,
 MEMORY_INFORMATION_CLASS MemoryInformationClass,
 PVOID Buffer,
 ULONG Length,
 PULONG ResultLength);
```

But Wait a minute! For `NtUserSetMenu()` there is 3 parameters and for `NtQueryVirtualMemory()` there is 6!

Yes. But remember, I said "number of parameters **passed using the stack**". What what does this mean?

Well, unlike in 32 bits where all the parameters of the function are passed using the stack. In Windows 64 bits systems, the first 4 parameters are passed using, in this order, the following registers:

- `RCX`;
- `RDX`;
- `R8`;
- `R9`.

The rest of the parameters are **passed using the stack**.

And in our case? Well, `NtUserSetMenu()` is using 3 parameters, so they will be passed using the `RCX`, `RDX` and `R8` registers. Here the stack will not be involved, hence the 0 parameters passed using the stack in `ff9a8ca0`.

`NtQueryVirtualMemory()` is using 6 parameters, the first 4 will be passed using the `RCX`, `RDX`, `R8` and `R9` registers. And the two last parameters will be passed using the stack, hence the 2 parameters passed using the stack in `02953402`

03 Synthesis break

> - We retrieved the address of the `System Service Dispatch Table` and stored it in `r10`
> - Using the `System Service Dispatch Table` array we found the `RVA` related to our functions by using our `System Call Index`
> - We performed a arithmetic shift right of 4 bits on our `RVA` to retrieve the "real value" of the `RVA` and remove the part with the number of parameters passed using the stack. Then we stored it in `r11`
> - The code uses instruction used for signed integer such as `movsxd` and `sar`
> - For Native functions, we use a `System Service Dispatch Table` located in `ntoskrnl`. For GUI functions, we use a `System Service Dispatch Table` located in the driver `win32k.sys`

Now we add our `RVA` to the address of our `System Service Dispatch Table`.

```
add     r10, r11 // r10 = SSDT, r11 = RVA
```

Let's take a look to what's located at this address.

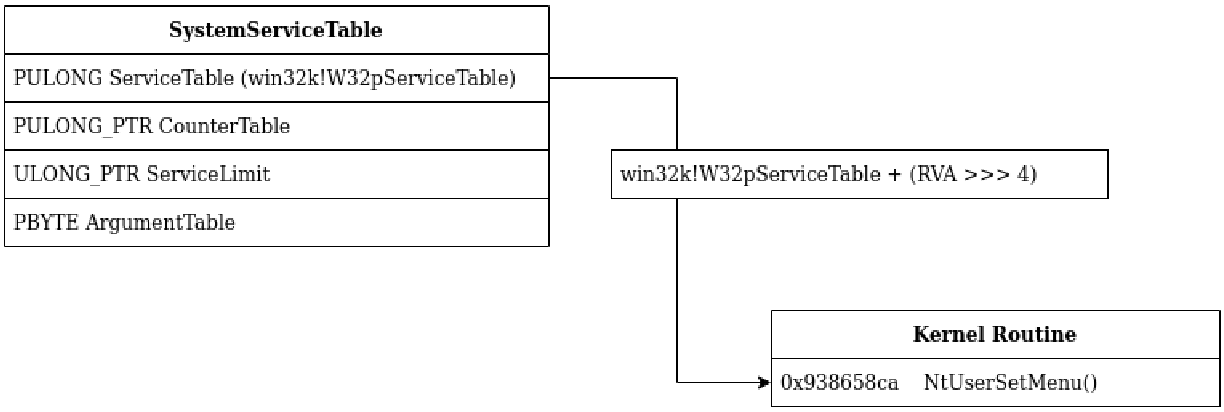
For the case of `NtQueryVirtualMemory()`:

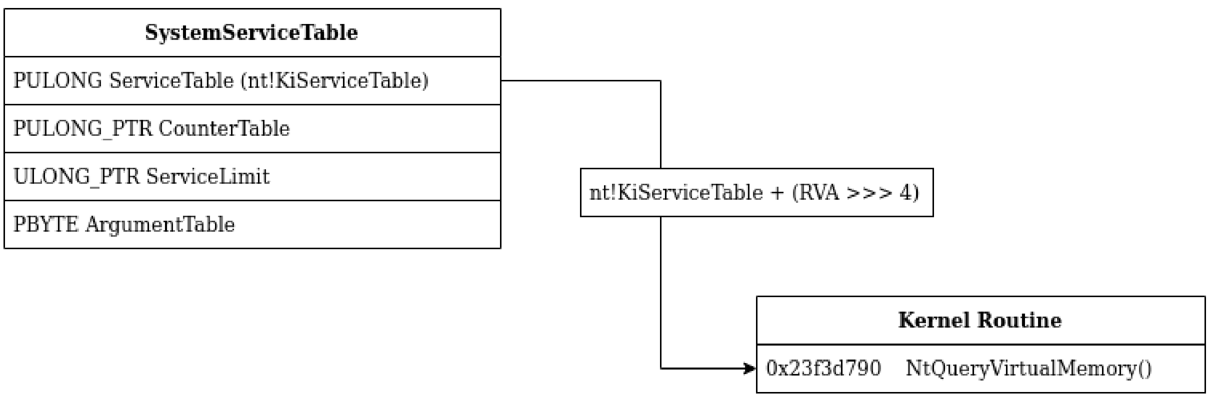
```
lkd> u nt!KiServiceTable + 00295340 L1
nt!NtQueryVirtualMemory:
fffff803`23f3d790 4883ec48        sub     rsp,48h
```

For the case of `NtUserSetMenu()`:

```
lkd> u W32pServiceTable +  (-65736) L1
win32k!NtUserSetMenu:
fffff1d5`938658ca 48ff2587730500  jmp     qword ptr [win32k!_imp_NtUserSetMenu (fffff1d5`938bcc58)]
```

Hourra! It seems that we found the addresses of our functions in the kernel!!!





What about the Filter Table ?

Let's check the function `NtUserSetMenu()` but this time in the `KeServiceDescriptorTableFilter` table.

```
lkd> dd /c1 win32k!W32pServiceTableFilter+4*0x496 L1
ffff9487`c926df88  ffd2b100

lkd> ? (ffd2b100>>>4)
Evaluate expression: 268249872 = 00000000`0ffd2b10

lkd> dd /c1 win32k!W32pServiceTableFilter+ffffffff`fffd2b10 L1
ffff9487`c923f840  48ec8348

lkd> u win32k!W32pServiceTableFilter+ffffffff`fffd2b10 L1
win32k!stub_UserSetMenu:
ffff9487`c923f840 4883ec48        sub     rsp,48h
```

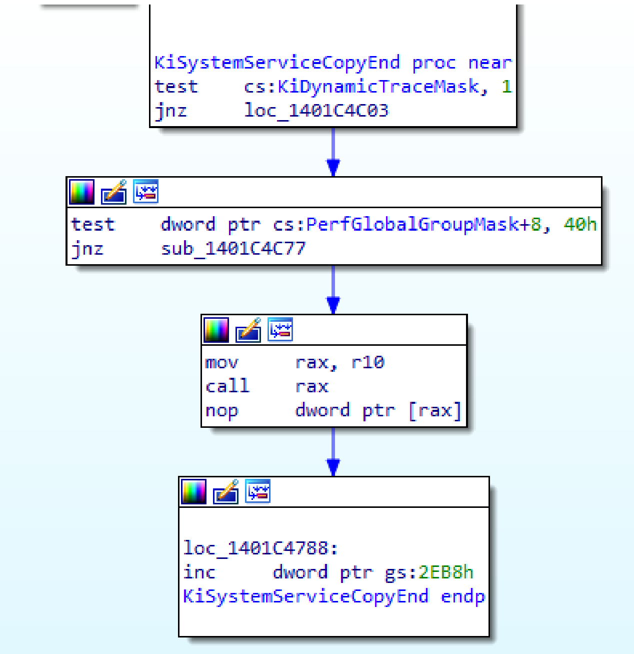
The name of the function here is different. The function is called `stub_UserSetMenu` instead of `NtUserSetMenu`.

Why? We can find the answers in the book `Windows Internals Part 2`.

> The only material difference between the Filter entries is that they point to system calls in Win32k.sys **with names like stub_UserGetThreadState, while the real array [SSDT not filtered] points to NtUserGetThreadState.** The former stubs will **check if Win32k.sys filtering enabled for this system call**, based, in part, on the filter set that's been loaded for the process.
>
> Based on this determination, **they will either fail the call and return STATUS_INVALID_SYSTEM_SERVICE if the filter set prohibits it or end up calling the original function** (such as NtUserGetThreadState), with potential telemetry if auditing is enabled.

The execution of the Kernel routine via KiSystemServiceCopyEnd()

The next functions executed after `KiSystemServiceRepeat()` are `KiSystemServiceGdiTebAccess()` and under certain condition `KiSystemServiceCopyStart`. Then we end up here in `KiSystemServiceCopyEnd()`, the end of the road.



The interesting part for us is

```
mov   rax, r10

call  rax
```

In the previous chapter, we saw that the address of our Kernel routine was put in `r10`. Well as we can see it here, `r10` is moved in `rax` and `rax` is executed.

So that's it. The code of our functions in the Kernel is called here, in `KiSystemServiceCopyEnd()`!

Wrapping it up

In a nutshell, the workflow we learn in this post:

- `syscall` instruction: Performed in User-Mode. Put the address in the `LSTAR` register in `RIP` leading to the execution of the kernel function `KiSystemCall64[Shadow]()`
- `KiSystemServiceUser()`: Retrieve the `KTHREAD structure` address of the current thread
- `KiSystemServiceStart()`: Extract the `Table Identifier` and the `System call Index` from the `System Call Number` stored in `eax`.
- `KiSystemServiceRepeat()`: The heart of the System call processing in the kernel. Check if the syscall is related to a GUI function, choose the right `System Descriptor Table` and finally retrieve the address of the kernel routine related to the `System Call Index` by using the `System Service Dispatch Table`.
- `KiSystemServiceCopyEnd()` : Execute the Kernel routine.

> **Security Note:**
>
> At this point you may think "Ok, so I just have to make a malicious driver and place hooks on the `LSTAR` register or in the `SSDT` to hijack the kernel workflow". Well, there was a time when this was possible. Actually, it was a way for EDR or AV to perform analysis (like today with hooks in DLLs).
>
> However, it's not possible anymore. To prevent this kind of change, Microsoft invented the `Kernel Patch Protection` (KPP) also known as `Patch Guard` (PG). With `KPP`, any attempt to patch the `SSDT` or `LSTAR` will lead to a a `BSOD` (blue screen of death).

I hope, you enjoyed this quick overview on how syscall are processed in the Kernel.

Thanks

Thanks to Aurélien Denis for the proofreading! And thanks to @am0nsec for reminding me the part about the number of arguments passed using the stack stored in the `SSDT` values.

Sources

- System Service Descriptor Table - SSDT
- The Quest for the SSDTs
- Windows Internals, Part 1, 7th Edition by Pavel Yosifovich, Mark E. Russinovich, Alex Ionescu, David A. Solomon
- Windows Internals, Part 2, 7th Edition by Andrea Allievi, Alex Ionescu, Mark E. Russinovich, David A. Solomon
- Practical Reverse Engineering: x86, x64, ARM, Windows Kernel, Reversing Tools, and Obfuscation by Bruce Dang, Alexandre Gazet, Elias Bachaalany, Sébastien

Josse

1. https://www.youtube.com/watch?v=lt-udg9zQSE ↩

Updated on 2022-03-24

Kernel, System Calls, Windows Internals