Updated Analysis of PatchGuard on Microsoft Windows 10 RS4

A use case of REVEN, the Timeless Analysis Tool

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Abstract

**Since Windows 64b, PatchGuard has been of great interest in Windows security.
For most iterations of its development, several people have analyzed its main mechanisms and internals which, many times, led to a functional bypass. Researchers seem to agree on one thing: bypassing PatchGuard will always be theoretically possible since it runs at the same level as a driver. Which seems true, theoretically.
That said, just like vulnerability exploit isn't about NOP-sled anymore, bypassing PatchGuard isn't about hooking KeBugCheck anymore.**

This paper will present a complete overview of PatchGuard mecanisms, from the initialization to the Blue Screen Of Death, and insights about how we implemented a driver able to disable it.

Especially, this research has been conducted using timeless analysis with Tetrane's tool REVEN. Not a single debugger was used during this entire analysis.

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I - Introduction

This paper will present a complete overview of PatchGuard mechanisms, from the initialization to the Blue Screen Of Death, and insights about how we implemented a driver able to disable it.
In this introduction we will first have a few words about timeless analysis, then we will see what PatchGuard is about and an overview of how it works, and our approach to analyze it.

A - Few words about Timeless Analysis with REVEN

For this research we used timeless analysis. Since most don't know what it is, I guess it's good to present it in a few words.
Where a classic debugger can give you the state at a specific instruction and can only go forward in execution, Timeless Analysis is a mechanisms that allows you to time-travel through the execution of your entire system and instantly retrieve the full state of the system (Full memory, User and Kernel, Hardware Events, any process/thread).

Timeless Analysis workflow consists in several steps:

- Recording the full execution of the virtual machine (more than 10 billions instructions is ok)
- Replaying the recorded scenario on a simulated CPU
- Analysing the produced trace as in any debugger, but time-travel

For PatchGuard, this allowed us to record only once the initialization and the Blue Screen Of Death and work with it all along this research. With a classical debugger, one would have to set a lot of breakpoints just to be able to circumvent anti-debug checks, and a lot more to observe specific states of the system. Furthermore, as PatchGuard basically encrypt itself when it's not running, we could easily retrieve the full decrypted state of it.

See more informations about REVEN awesome functionnalities at VII - B in this article, and visit our website and blog at www.tetrane.com and blog.tetrane.com. Don't hesitate to contact us and enjoy the read!

B - What's PatchGuard

PatchGuard, originally named « Kernel Patch Protection », is a Windows mechanism that aim to defend the kernel against patches. Here is a statement from Microsoft FAQ:

« Because patching replaces kernel code with unknown, untested code, there is no way to assess the quality or impact of the third-party code... An examination of Online Crash Analysis (OCA) data at Microsoft shows that system crashes commonly result from both malicious and non-malicious software that patches the kernel. »

Patching the kernel has never been supported by Microsoft because it can cause a number of negative effects. From the vendor point of view, PatchGuard forced them to stop using undocumented structures to proceed with their detection mechanisms. And from malware writers point of view, PatchGuard prevents Rootkits from being persistent and difficult to detect or remove. As such, PatchGuard is of great interest from an attacker perspective.

C - How does it work?

PatchGuard will check many structures and code area from the kernel that can be used by an attacker/vendor to perform sensitive operations. As said before, an attacker can hook some structures such as the Interrupt

Descriptor Table (IDT) or other structures, and PatchGuard will prevent this by performing checks. For example, a non-exhaustive list of checked structures include:

- IDT/GDT
- Debug routines
- Loaded module list
- PatchGuard code and structure itself
- etc.

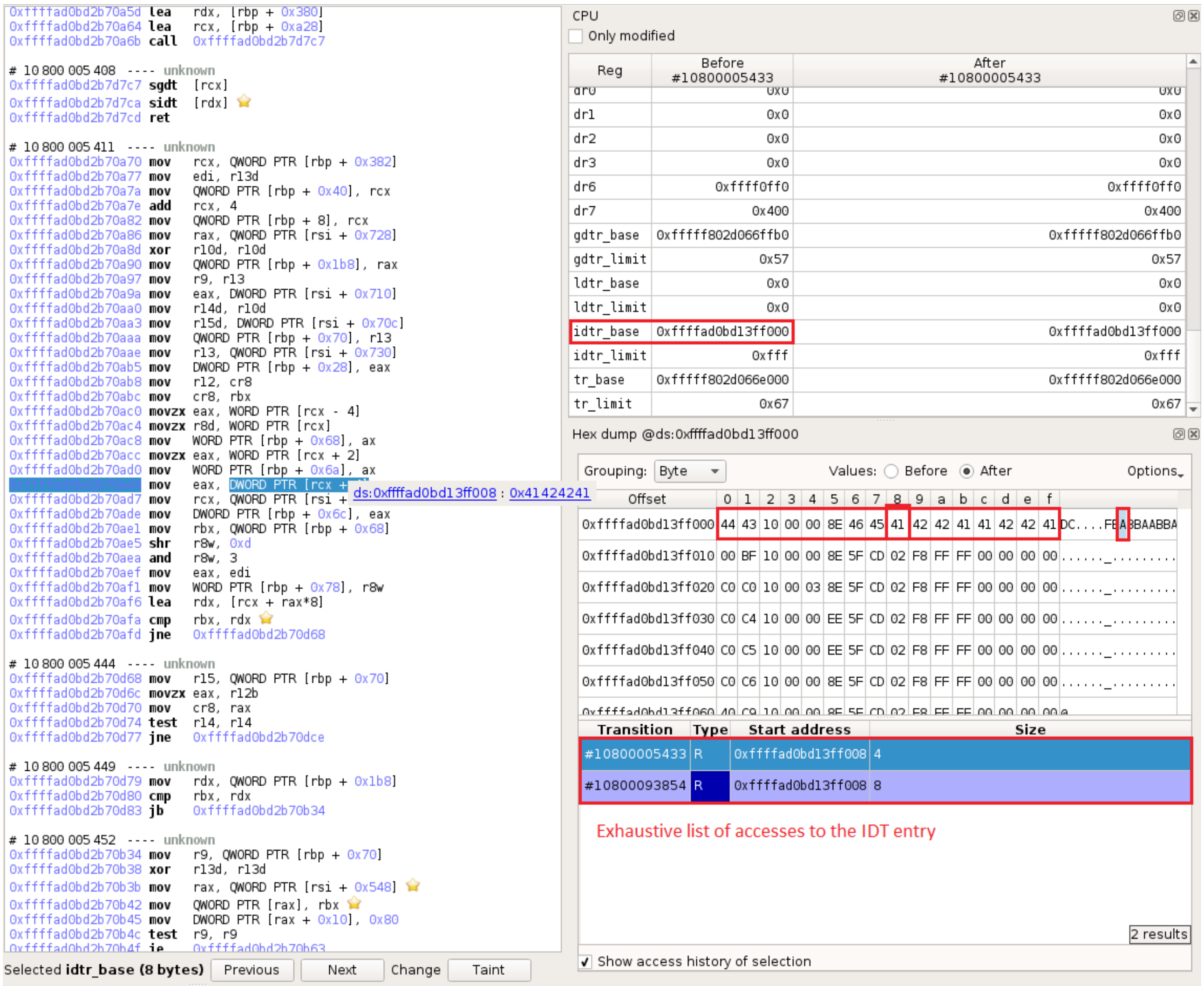
An unexhaustive list is also available on the MSDN in the BugCheck 0x109 page.

The basic idea behind PatchGuard is that it will compute the checksum of sensitive structures regularly during the execution time of the system, and will compare it with the one obtain at boot time, before any user driver load. If a modification is detected, then PatchGuard will trigger a Blue Screen Of Death (BSOD) with the BugCheck code 0x109 (CRITICAL_STRUCTURE_CORRUPTION), considering that the system is compromised.

Now, since PatchGuard runs at the same level than any driver, it will always be possible to disable it, as long as you can find it. And this is where PatchGuard is complicated. Because it has to hide itself from an attacker, PatchGuard uses many mechanisms that will be described in this paper. This is important because it also defines how we successfully disabled it (with some limitations not really related to PatchGuard), by looking for each and every places a PatchGuard context could be.

D - Our approach: Timeless debugging

To analyze PatchGuard we first developped a driver to patch the IDT. Then with REVEN, the Timeless Analysis tool from Tetrane, we recorded both the initialization of PatchGuard and the process of triggering the BSOD. For instance, here is how we can use memory history on the patched IDT to get the list of memory accesses to this area, showing the instructions responsible for the check:



By using this Memory History feature, this allowed us to quickly find the checksum algorithm and the encryption key used to randomize it.
We then discovered the decrypted in-memory PatchGuard context structure, used by PatchGuard to hold information and perform checks.

After analysing many entries we got a good overview of how main mechanisms of PatchGuard work and we were able to continue this analysis with both static analysis and Timeless Debugging to observe the execution workflow.

II - Initialization

In this part we will describe how PatchGuard initialize its contexts and verification mechanisms. It is mostly done by KiFilterFiberContext. KiFilterFiberContext were originally named this way to mislead analysts, but it is a well known function now.

A - Call to KiFilterFiberContext

The initialization of PatchGuard is performed mostly by KiFilterFiberContext. This function is called at the beginning of the boot, before any user driver load. KiFilterFiberContext is called in two manners, that are detailed hereafter.

1 - Triggering an exception in KiAmd64SpecificState

The initialization of PatchGuard uses an exception handler as an obfuscation method. Triggering voluntarely a division error, the exception handler is executed and the patchguard initialization function is called. This mechanism is visible at the beginning of the boot process.

Here are the faulty instructions we can see with REVEN:

```
        0xfffff803c98dabd1    movzx edx, byte ptr [rip - 0x4f3255] ; KdDebuggerNotPresent
        0xfffff803c98dabd8    movzx eax, byte ptr [rip - 0x51ee66] ; KdPitchDebugger
        0xfffff803c98dabdf    or    edx, eax
        0xfffff803c98dabe1    mov   ecx, edx
        0xfffff803c98dabe3    neg   ecx
        0xfffff803c98dabe5    sbb   r8d, r8d
        0xfffff803c98dabe8    and   r8d, 0xffffffee
        0xfffff803c98dabec    add   r8d, 0x11
        0xfffff803c98dabf0    ror   edx, 1
        0xfffff803c98dabf2    mov   eax, edx
        0xfffff803c98dabf4    cdq
        0xfffff803c98dabf5    divide error while executing idiv r8d
```

What's interesting here is that the two values used to compute the division are actually known symbols: KdDebuggerNotPresent & KdPitchDebugger. These two values are used to determine if a debugger is attached or not. As such, if a debugger is present then PatchGuard isn't initialized.

In a normal scenario, these two variables are set to 1, which gives at the idiv instruction the values rax=0x80000000, rdx=0x80000000 and r8d=0xffffffff. The idiv instruction computation is the following:

```
        [edx:eax] / r8d
i.e.    0x8000000080000000 / 0xffffffff
```

As defined in the AMD64 documentation, * *If a positive result is greater than 7FFFFFFFH or a negative result is less than 80000000H* *, then a divide error is triggered. In this case, both operands are negative which should give a positive result, but the result of this division is 0x80000001, hence the divide error.

As soon as the divide error is triggered the function KiDivideErrorFault is executed, which proceeds to dispatch the exception to the rightful handler. In this case, the handler is only a stub for the KiFilterFiberContext function:

```
; Exception handler for KiInitAmd64SpecificState
0xfffff803c98f1d1c push  rbp
0xfffff803c98f1d1e sub   rsp, 0x20
0xfffff803c98f1d22 mov   rbp, rdx
0xfffff803c98f1d25 xor   ecx, ecx
0xfffff803c98f1d27 call  0xfffff803c98a0bb0

; KiFilterFiberContext - ntoskrnl.exe
0xfffff803c98a0bb0 mov   qword ptr [rsp + 8], rbx
[...]
```

The callstack we got from REVEN is the following:

```
KiFilterFiberContext
KiInitAmd64SpecificState_ExceptionHandler
__C_Specific_Handler
RtlpExecuteHandlerForException
RtlDispatchException
KiDispatchException
KiExceptionDispatch
KiDivideErrorFault
KeInitAmd64SpecificState                // Triggers a page fault
PipInitializeCoreDriversAndElam
IopInitializeBootDrivers
IoInitSystemPreDrivers
IoInitSystem
```

KiFilterFiberContext is known to be responsible for calling the initialization procedure with specifics arguments to create Patchguard contexts.
One thing to notice here is that one of the argument is hard-coded to 0, which gives a hint about the fact that it is probably called elsewhere. As a matter of fact, another initialization has already been documented and points to the function ExpLicenseWatchInitWorker.

2 - ExpLicenseWatchInitWorker

This function is called before KeInitAmd64SpecificState, in the boot process. Here is the callstack:

```
KiFilterFiberContext
ExpLicenseWatchInitWorker
ExInitSystemPhase2
Phase1InitializationDiscard
Phase1Initialization
```

The ExInitSystemPhase2 is also responsible for calling the function ExpGetNtProductTypeFromLicenseValue, which is clearly related to the Microsoft license verification.

What's interesting in this case is the fact that ExpLicenseWatchInitWorker will call KiFilterFiberContext, but only with a low probability. Many mechanisms of PatchGuard uses random values (with the instruction rdtsc) to decide things and in this case, it is used to decide whether or not KiFilterFiberContext should be called, with a probability of 4%.

Several points, and one in particular are to be noted in this function.

- The first thing to notice is once again, this function includes some checks for the presence of a debugger and the safe boot mode.
- The second thing, not especially related to PatchGuard is the fact that the return value of this function is the random value generated by the rdtsc instruction, multiplied by a constant value 0x51eb851f

(this is actually a constant to optimize a division). If we only suppose that the function is called by ExInitSystemPhase2, this random returned value is later used as an index if InitIsWinPEMode is true:

```
    mov al, r15b              ; eax is NOT zero extended here
    loc_1408EAFBB
    inc rax
    cmp [rcx + rax*2], di     ;RAX is the following: [0000.0000][RAND][r15b]
    jnz loc_1408EAFBB
```

a - Structure passed to KiFilterFiberContext

KiFilterFiberContext, this time, is called with a structure. This structure is build from values fetched from the PRCB (Process Register Control Block), from the HalReserved field, along with the pointer to KiFilterFiberContext:

```
        0xfffff803c98dedda mov   rax, qword ptr [rip - 0x46d3a1]           ; KPRCB
        0xfffff803c98dede1 mov   r11, qword ptr [rax + 0x78]               ; HalReserved[6]
        0xfffff803c98dede5 mov   rbx, qword ptr [rax + 0x70]               ; HalReserved[5]
        0xfffff803c98dede9 and   qword ptr [rax + 0x78], 0
        0xfffff803c98dedee and   qword ptr [rax + 0x70], 0
```

As one can see, these fields are cleaned right after.

Here is a pseudo code of ExpLicenseWatchInitWorker:

```
DWORD64 ExpLicenseWatchInitWorker()
{
    KiFilterParam = Prcb.HalReserved[6]; // &KiServiceTablesLocked
    pKiFilterFiberContext = Prcb.HalReserved[5]; // &KiFilterFiberContext

    Prcb.HalReserved[6] = 0;
    Prcb.HalReserved[5] = 0;

    if (InitSafeBootMode != 0 | KUSER_SHARED_DATA.KdDebuggerEnabled >> 1)
    {
        return rand_stuff
    }
    if(random(0,100) ≤ 4)
        KiFilterFiberContext(pKiFilterFiberParam);
}
```

These two pointers are set at the very beginning of the boot, in the function KiLockServiceTable, it comes from the following callstack:

```
    KiLockServiceTable
    KeCompactServiceTable
    KiInitializeKernel
    KiSystemStartup
```

Two things are to be explained from this function. The first one it how it puts the two pointers in the HalReserved field, and the second one is the function it calls right at the beginning of it.

i - KiLockServiceTable: Filling the HalReserved[] field

To "obfuscate" its control flow, KiLockServiceTable uses once again an exception handler, but instead of triggering a fault, it calls directly the handler by fetching a pointer to it with RtlLookupExceptionHandler. The handler itself is only a stub to the function KiFatalExceptionFilter, which we analyzed:

The first HalReserved field to be filled is the 6th:

```
    lea     rbx, KiServiceTablesLocked
    [...]
    mov     [rsi+(_KPRCB_.HalReserved[6])], rbx
```

This function KiServiceTablesLocked is a misleading name as it holds a structure instead. This structure is a parameter given to the KiFilterFiberContext function. As such, it is already named it KI_FILTER_FIBER_PARAM in literature.

A prototype for this structure is the following:

```
typedef struct _KI_FILTER_FIBER_PARAM
{
    CHAR  code_prefetch_rcx_retn[4];           // prefetchw byte ptr [rcx]; retn;
    CHAR  padding[4];                          // Align
    PVOID pPsCreateSystemThread;
    PVOID Pg_Method3StubToCheckRoutine_sub_1402CD680;
    PVOID pKiBalanceSetManagerPeriodicDpc;
}KI_FILTER_FIBER_PARAM, *PKI_FILTER_FIBER_PARAM;
```

Details about this structure will be given later since it involve a deep explanation about mechanisms used to trigger checks routines.

ii - KiLockServiceTable: Checksums initializations

KiLockServiceTable calls right at the beginning the function KiLockExtendedServiceTable, which is also a PatchGuard related function. It is used to perform a checksum of either several sections or a checksum of the function table entries. Both results are set in two globals (qword_1403AD4B8 and qword_1403AD4C8) that will be used later, during the context initialization process.
These checksum mechanisms itself will be explained later in this article.

B - KiFilterFiberContext

As previously seen, KiFilterFiberContext can be called either with an argument (KI_FILTER_FIBER_PARAM structure pointer) or with NULL (most of the cases, from KiAmd64SpecificState). Its main job is to call the context initialization routine with specifics arguments. These arguments will mainly determine which method to use to trigger a PatchGuard check. Since this main initialization function is already known, a common name is KiInitializePatchGuardContext (from literature).

1 - Quick Overview

Here is a pseudo code of KiFilterFiberContext:

```
KiFilterFiberContext(PKI_FILTER_FIBER_PARAM pKiFilterFiberParam)
{

    AntiDebug();
    rand1_10 = __rdtsc() % 10;
    rand2_1 = rand1_10 > 6;
    rand3_6 = __rdtsc() % 6;
    rand4_13 = __rdtsc() % 13;
```

```
// First initialize a global in memory, this will be explained
if(!g_pGlobalCtx
  && !pKiFilterFiberParam
  && !KpgApiRegistered)
  if(PsIntegrityCheckEnabled)
  {
    Notify_Callback("TV", Pg_TVCallback_CheckRoutine_sub_1401825A0, &KpgApiConsumerRanges)
    if ( KpgApiConsumerRanges )
        KpgApiRegistered = 1;
  }

// Now initialize a first context
result = KiInitPatchGuardContext(
            rand3_13,
            rand2_6,
            rand2_1 + 1,
            pKiFilterFiberParam,
            1)

if (result)
{
    if (rand1_10 < 6)
    {
        rand5_13 = __rdtsc() % 13;

        // Get a random value < 6 but different from rand3_6
        rand6_6 = __rdtsc() % 6;
        while ( rand6_6 == rand3_6)
        {
            rand6_6 = __rdtsc() % 6;
        }

        // Initialize a second context
        result = KiInitPatchGuardContext(
                    rand5_13,
                    rand6_6,
                    rand2_1 + 1,
                    pKiFilterFiberParam,
                    0);
    }
    if(result)
    {
        if(!g_pGlobalCtx
            && !pKiFilterFiberParam
            && (KiSwInterruptPresent()>=0)
            && KpgApiRegistered)
        {
            localvar = 8;
            if(KiSwInterruptPresent() >= 0)
            {
                localvar = 0;
            }

            // Initialize a Third context
            result = KiInitPatchGuardContext(0, 7, 1, 0, localvar);
        }
        if(result && !pKiFilterFiberParam)
        {
            // Zero stuff
            memset(&KpgKernelExtents, 0, 24);
            KpgProtectedFunctionExtentsSupported = 0;
            KpgDisabledTimerMethods = 0;
            KpgProcessListOverflowLock = 0;
            dword_1403AD510 = 0;
            qword_140904080 = 0;
        }
    }
}
```

```
AntiDebug();

return result;
```

This function is slightly more complicated than previous version of it from Windows 8.1 but still, the main idea remains the same: using mostly random values as arguments, KiInitPatchGuardContext is called up to three times ; the first time occurs no matter what, the second with only a 50 % chance, and the third time, with a new method, is quite special, occurs most of the time, and will be described in this article. One other new thing is the notification of a callback named « TV », which comes from an other binary.

C - Initialization of PatchGuard contexts

Most of the initialization methods depend on the KiInitPatchGuardContext, which arguments decide how checks will be triggered, but other mechanisms exist. In this section, we will describe what is a PatchGuard context, and describe the multiple methods PatchGuard uses to hide itself in the system. If many of these methods are already known, but not all, we will try to describe them with care since this is the base of the code we developped to disable PatchGuard completely.

1 - PatchGuard context: Definition

In literature, a PatchGuard context used to describe the huge structure that is used by PatchGuard to perform checks. But with time, we can see that when researchers says « I found a PatchGuard context », they don't talk about the structure but more of an « instance » of PatchGuard, which basically means the combination of a method and a structure ; the method being how checks are initialized and triggered, and the structure being the entire amount of data used by PatchGuard to perform checks.

a - Structure

To analyze its content and initialization we analyzed most of the accesses done to its fields and correlated it with the KiInitPatchGuardContext function.

Hereafter are some explanations of some interesting fields in this structure. This isn't exhaustive and much detailed but it give a hint of what can be found whithin this structure.

It is mainly separated in three sections. The first one, of size 0x928 is the one holding the core content of PatchGuard mechanisms. The second one is more of a data recipient, that will keep original data for later use. And the third part holds information about data to check.

i - First part

- **CmpAppendDllSection**

The very beginning of the PatchGuard context structure holds the code of the function CmdAppendDllSection. This code is copied directly in the structure at 0x1408929CC, and will be used later when the integrity check is triggered by PatchGuard. Its main job is to decrypt (xor) the rest of the PatchGuard context structure with a randomly generated key. With the memory history of accesses and time-travel debugging we easily find that the key is generated at 0x1408A8291. For methods using DPC, this key is passed as DeferredContext argument. If we take the example of function PopThermalZoneDpc, the KiProcessExpiredTimerList will call it with the DeferredContext in rdx.

- **Nt API pointers**

Next part of the structure holds many function pointers (more than 100) from ntoskrnl API. These pointers are kept this way so that PatchGuard routines can use them independently from a relocation, and for some of them to be able to copy them (just like CmdAppendDllSection). This makes sense because the main verification routine actually doesn't use directly the ntos function but instead a full copy of it copied in executable memory.

Most of these pointer are initialized near 0x140892AC4:

```
    sti
    lea     rax, ExAcquireResourceSharedLite
    mov     [r14+pg_ctx_rs4.ntoskrnl_ExAcquireResourceSharedLite_0xe8], rax
    lea     rax, ExAcquireResourceExclusiveLite
    mov     [r14+pg_ctx_rs4.ntoskrnl_ExAcquireResourceExclusiveLite_0xf0], rax
    lea     rax, ExAllocatePoolWithTag
    mov     [r14+pg_ctx_rs4.ntoskrnl_ExAllocatePoolWithTag_0xf8], rax
    [...]
```

Most of these function have known symbols and are common Windows Kernel routines, yet a few of them are unamed routines directly related to PatchGuard. For example at 0x1401812E0, the function is only here to call directly the deferred routine entry of a DPC, which is used by PatchGuard at some point.

- **Pointer to Global Variables their Values**

Many references to global variables are stored and used. For example it holds two values originally held by globals KiWaitAlways and KiWaitNever at offsets 0x4e0 and 0x5b8. These values are initialized randomly at boot time and we will see later that these per-boot random values are used to encode and decode PatchGuard DPC pointers. An other example of interesting global is the one that holds a pointer to an other PatchGuard context structure, at offset 0x5f8. This pointer is used multiple times as a clean backup of a structure. It is also the structure pointed by this global that is send in case of a KeBugCheck, as one can see in the KiMarkBugCheckRegion:

```
    mov     rcx, cs:Pg_GlobalCtx_qword_14045E208
    test    rcx, rcx
    jz      short loc_1401812BD
    mov     edx, 928h                    // Size of the PatchGuard structure
    call    IoAddTriageDumpDataBlock
```

- **Common variables**

System related variables:
In this category we can find variables such as Ntoskrnl and Hal base addresses, the current PRCB, the maximum virtual addressing size, and else. We can also find the Initialization Vector used with checksums of critical structures, or the shift value used to derive the Initialization vector at each block iteration. Both these values are initialized randomly with rdtsc at 0x1408937A0. In the same way, the checksum of the PatchGuard context is stored in itself. To detect any corruption it is firstly computed during the initialization and compared to runtime computed checksums at the beginning of each check routines.

- **Runtime variables**

Some fields are also used as runtime variables to keep track of check routine states. We can find for example the total amount of data checked for what one can call a "check session". As explained previously with the third argument to KiInitPatchGuardContext, it is incremented after each critical structure checksum by the size of it, and compared to a maximum. The data necessary for the the scheduling method is temporary stored in the context structure, such as DPC structure, ETHREAD pointers so that it can calls function like KiInsertQueueApc. One can also find parameters that are passed to KeBugCheck in case of a detected corruption, or the scheduling method, passed as parameter to KiInitPatchGuardContext.

- **Flags**

One of the main flag is the one located at offset 0x828.
It is used as a bitmap representing booleans, such as (Non-exhaustive list):

```
        BIT 6  0x40                     Only one processor
        BIT 8  0x100                    Use of KiDpcDispatch
        BIT 9  0x200                    Use of KiTimerDispatch
        BIT 15 0x8000                   Use of KeSetEvent
        BIT 18 0x40000                  Related to the ntoskrnl routines checksum
        BIT 20 0x100000                 Should DR7 be cleared
        BIT 24 0x1000000                loc_1402F4907
        BIT 27 0x8000000                Should PTE be restored loc_1402F117F
        BIT 28 0x10000000               Scheduling method 7, use of KiInterruptThunk
        BIT 30 0x40000000               loc_1408A836F Again, scheduling method 7
        BIT 31 0x80000000               Result of KiSwInterruptPresent
```

Other flags exists, but we didn't analyzed all of them.

ii - Second part

The second part of the structure holds data that will be kept for later use.

- **PTE save**

In Windows 10 RS4, exactly 20 entries are saved in the structure. These entries are saved because it mitigate a bypass. We will see later that these PTE are restored just before triggering KeBugCheck.

- **Critical Kernel routines save**

For the same reason PTE are saved, the entire code of critical kernel is saved right after. For Windows 10 RS4, here are the routines with their respective offset in the structure:

```
     Hal        HaliHaltSystem_0x930
     Ntosrknl   KeBugCheckEx_0x940
     Ntoskrnl   KeBugCheck2_0x950
     Ntoskrnl   KiBugCheckDebugBreak_0x960
     Ntoskrnl   KiDebugTrapOrFault_0x970
     Ntoskrnl   RtlpBreakWithStatusInstruction_OR_DbgBreakPointWithStatus_0x980
     Ntoskrnl   RtlCaptureContext_0x990
     Ntoskrnl   StartOfChunckFor_KeQueryCurrentStackInformation_0x9a0
     Ntoskrnl   KeQueryCurrentStackInformation_0x9b0
     Ntoskrnl   KiSaveProcessorControlState_0x9c0
     Ntoskrnl   memcpy_OR_memmove_0x9d0
     Ntoskrnl   IoSaveBugCheckProgress_0x9e0
     Ntoskrnl   KeIsEmptyAffinityEx_0x9f0
     Ntoskrnl   VfNotifyVerifierOfEvent_0xa00
     Ntoskrnl   _guard_check_icall_0xa10
     Ntoskrnl   KeGuardDispatchICall_0xa20
     Ntoskrnl   g_pxHalHaltSystem_0xa30
```

Once again we will see later that these functions are restored just before triggering KeBugCheck. All these function comes with their respective size so the restore routine knows how much to rewrite. The code itself is stored later in the structure. Something interesting is that the last "function" is actually only a pointer to xHalHaltSystem.

iii - Third part

To keep track of what structure needs to be checked, PatchGuard uses an array of structures that holds the necessary information for each checks.

- **Critical structure for checks**

Here is a prototype of one structure

```
struct pg_crit_struct_check_data
{
    ULONG64 KeBugCheckType_0x0; // 0x2 for IDT, 0x3 for GDT, etc.
    ULONG64 pData_0x8;
    ULONG32 szData_0x10;
    ULONG32 hash_0x14;
    ULONG64 specific[3];
};
```

The KeBugCheckType is used to distinguish structures type. A non-exhaustive list is available in the MSDN documentation as this information is given along with the KeBugCheck issued by PatchGuard (see documentation for BugCheck 0x109: CRITICAL_STRUCTURE_CORRUPTION).

Next there is both a pointer to the data to be check coupled with the size to be checked. The important value is the checksum result. This checksum is computed during the initialization of PatchGuard and will be used as reference when PatchGuard will check the integrity of the corresponding structure.
Finally, the last entries from this structure are specific to the data that has to be checked. For example, for the IDT check case, this specific value will hold the target processor which has been used to execute. In general, this means that this structure can differ regarding the checked structure, and indicates that the check code isn't exactly the same for all structures.

- **Relative entries in the PatchGuard context structure**

These structures are stored in an array in the PatchGuard context structure. Several entries exist in the first part of the PatchGuard context structure to use this array:

```
0x680: Total count of critical structure in the array
0x684: Offset to next critical structure data to checksum
0x6a8: Offset to the first critical structure data
0x6ac: Current count of checked structure
```

These information are important and used by PatchGuard in its check algorithm.

2 - PatchGuard context: Initialization

PatchGuard context are mostly initialized by KiInitPatchGuardContext. This function is actually unnamed but is known in literature. We will see in this section that other methods exists to initialize PatchGuard context, and in some cases, some independant way of checking the system are set up.

a - KiInitPatchGuardContext: Method 0, 1, 2, 3, 4, 5, 7

As stated, this function is responsible for the initialization of most PatchGuard contexts. The choice of which method is to be used is done regarding the argument given to this function. These argument are mostly randomly choosen, as we described in the KiFilterFiberContext overview. In this section we will go through argument given to this function that will describe how PatchGuard checks are initialized and triggered after.

Here are the argument given to this function:

- - Arg 1: Index for DPC method
- - Arg 2: Scheduling method

- - Arg 3: Random value used to determine the maximum size to be checked
- - Arg 4: Pointer to the structure from ExpLicenseWatchInitWorker (only 4 % chance)
- - Arg 5: Boolean to decide whether or not the integrity of nt routines has to be checked

In our case, the most important arguments are the 2nd one (the method used to schedule a check) and the 4th one (that allows more scheduling methods). In KiFilterFiberContext, a random value is given as an index for the second argument, which will decide what method should be used. In this section we will first describe the different method that KiInitPatchGuardContext may initialize combined with the 4th argument regarding the method. Then we will have a quick look at other arguments.

i - Method 0 – Inserting a timer, linked with a DPC

The main idea with this method is that PatchGuard will initialize a PatchGuard Context structure and a DPC (Deferred Procedure Call), and set it in a timer structure. The timer is then queued with KeSetCoalescableTimer, around 0x1408A8920. The timer will fire the DPC from the first argument between 2' to 2'10" following the call. This timer isn't periodic, and has to be restored at the end of the check routine but we will see this later in this article. The TolerableDelay parameter is a random value between 0 and 0.001 second.

ii - Method 1 and 2 – Hidden DPC

When the 2nd parameter to KiInitPatchGuardContext is 1 or 2, PatchGuard initialize a context structure and a DPC structure, but instead of using a timer, hides it in the kernel structure PRCB (Process Register Control Block). What is interesting with this method is that legit function from the system are actually responsible for queuing the DPC.

- **AcpiReserved**

For method 1, the pointer to the DPC is hidden in the field AcpiReserved from the PRCB:

```
loc_1408A890C:
mov     rax, [rsp+2238h+KPRCB_var_308]
mov     [rax+_KPRCB_.AcpiReserved], r8 ; DPC initialized by PatchGuard
jmp     loc_1408A89CE
```

It is queued in HalpTimerDpcRoutine, and check that at least two minutes have elapsed between each check. To keep count of when the last queue occured, it uses the global variable HalpTimerLastDpc. This global variable is initialized in HalpTimerSchedulePeriodicQueries, and its value is taken from the global variable at 0xFFFFF78000000014, which is related to the uptime (of the machine I think, but i'm not sure of this). HalpTimerDpcRoutine is called when a certain ACPI event occurs, e.g. transitioning to idle state.

- **HalReserved**

For method 2, the pointer to the DPC is hidden in the field HalReserved from the PRCB:

```
loc_1408A88F8:
mov     rax, [rsp+2238h+KPRCB_var_308]
mov     [rax+(_KPRCB_.HalReserved+38h)], r8 ; DPC initialized by PatchGuard
jmp     loc_1408A89CE
```

Side note: Recall that this field (but entry of this array), is also used to keep a pointer to structure KI_FILTER_FIBER_PARAM when KiFilterFiberContext is called from ExpLicenseWatchInitWorker.
It is queued by HalpMcaQueueDpc, also with a 2 minutes minimum period, and checks are done when HAL timer clock interrupt occurs (see HalpTimerClockInterrupt/HalpTimerAlwaysOnClockInterrupt).

iii - Method 3 – System Thread

This case needs a pointer to a KI_FILTER_FIBER_PARAM structure, which has only a 4 % chance to happen (from the function ExpLicenseWatchInitWorker, explained at II - A - 2 - a). An overview of this structure has already been shown previously, but recall that it holds a pointer to the PsCreateSystemThread function. This pointer is used to create a new system thread in the function sub_1408A9518 (that we conveniently name Pg_InitMethod3SystemThread), with the function sub_1402CD680 (offset 0x10 in the KI_FILTER_FIBER_PARAM structure, which is a stub to the verification routine, so we conveniently name it Pg_Method3StubToCheckRoutine_sub_1402CD680) as a StartAddress. Pg_InitMethod3SystemThread is called directly in KiInitPatchGuardContext at 0x1408A5B88.

One interesting thing to note is the elegant obfuscation that is added. The idea is that some bypasses used to target the entry StartAddress and Win32StartAddress from the ETHREAD structure to identify a PatchGuard thread, so in Windows 10 they modified these entries with common function pointers:
Right after the thread creation, PatchGuard acquires a pointer to the corresponding ETHREAD (without lock, just sayin') and modifies both fields StartAddress and Win32StartAddress:

```
lea     rcx, Pg_FuncArray_off_1408F71E0
mov     rcx, [rcx+rax*8] ; rax is a random value
mov     rax, [rsp+0A8h+var_68]
mov     [rax+ETHREAD_.anonymous_1.anonymous_0.StartAddress], rcx
mov     [rax+ETHREAD_.Win32StartAddress], rcx
```

To do so it first get a random value between 0 and 7 and fetch a function pointer in an array in memory at offset Pg_FuncArray_off_1408F71E0. Here is the content of this array:

index	Function name
0	KeBalanceSetManager
1	KeSwapProcessOrStack
2	ExpWorkerThread
3	PopIrpWorker
4	FsRtlWorkerThread
5	EtwpLogger
6	Pg_Method3StubToCheckRoutine_sub_1402CD680

Only the last entry is the right one, which means that there is only one out of seven chance that fileds StartAddress and Win32StartAddress in the ETHREAD structure are correct.

iv - Method 4 – Asynchronous Procedure Call

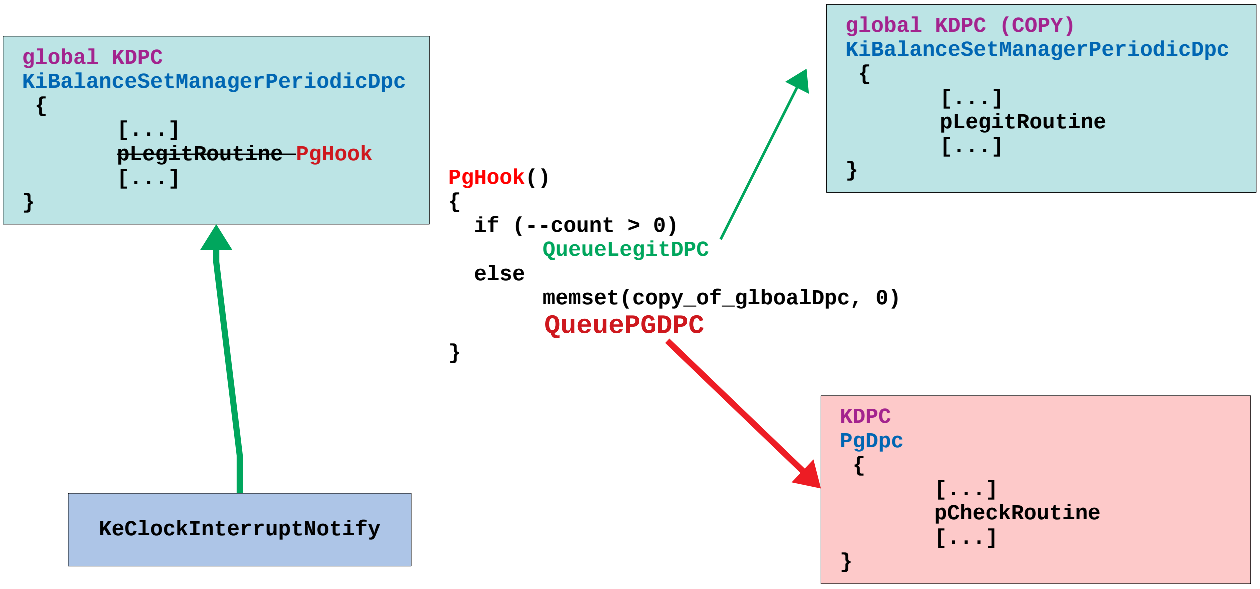
The fourth method initializes a PatchGuard Context structure and an APC structure, and directly inserts it to an existing system thread. The NormalRoutine argument is set to xHalTimerWatchdogStop, which is actually just a « ret 0 » instruction. The KernelRoutine is set to KiDispatchCallout which will call the verification routine in a way, and the RundownRoutine is NULL..
These arguments are set at 0x14089555B (initialization of function pointers in the context structure) and 0x1408A8734 (preparing the arguments for KiInsertQueueApc call).

The way it choose which thread to attach to is done using PsEnumProcessThreads with the callback Pg_IsStartAddressPopIrpWorkerControl_sub_1408A9B70, which job is to query the thread start address and compare the result with PopIrpWorkerControl. If such thread is to be found, then a pointer to the ETHREAD structure is stored at offset 0x830 into the PatchGuard context structure, and is later copied into the KAPC structure given to KeInsertQueueApc.

v - Method 5 – Hook a regular DPC

Just like method 3 (using a system thread), this method requires a valid KI_FILTER_FIBER_PARAM structure, otherwhise KiInitPatchGuardContext will fallback to method 0.
For this method, the last entry of the structure is used, which is a pointer to the global variable KiBalanceSetManagerPeriodicDpc. This variable holds a KDPC structure and its DPC routines are initialized in the function KiInitSystem. What is elegant in this method is that it is actually a legit DPC, that is queued by the system every second or so by KeClockInterruptNotify, at 0x1400619b6; and PatchGuard hook this legit DPC so that every 120 queues (actually, like many other method, a random value between 120 and 130 times), the PatchGuard DPC is queued instead of the legit one.

Here is a diagram simplifying this mechanism code:



If the PatchGuard DPC is to be queued, then it first proceed to clear the copy of the global DPC, and let the verification routine setting it back at the end of the check.

vi - Method 7 – the new weird one.

(No, there is no method 6, I don't have any explanation for that.)
At first sight, this method does... nothing. Well, almost nothing. It actually does two things. The first thing is it initializes a DPC to be queued, but clears it right after so never queues it. The second is it initializes a global PatchGuard context structure, which will be available through a global pointer for the system. This global PatchGuard context structure is actually in cleartext in memory, and remains at the end of the initialization function. In this part we will describe what we found especially for the DPC that isn't used.

- **Unused DPC**

When the index 7 is given to KiInitPatchGuardContext, many specific branches are taken. Especially, a DPC is initialized and the routine is defined as one of the KiInterruptThunk functions, or one of the KiMachineCheckControl functions. KiInterruptThunk and KiMachineCheckControl are both a set of 16 stubs, respectively to the function FsRtlTruncateSmallMcb and KiDecodeMcaFault, that in turn will call the check routine FsRtlMdlReadCompleteDevEx. In the initialization function KiInitPatchGuardContext, it is the KiInterruptThunk function that is used, but we will see later that some references to KiMachineCheckControl exist in other PatchGuard routines.
To use this function array, a random value from 0 to 0xf is generated (rdtsc & 0xf), and then used as an index in these stubs. Even though 16 stubs are available for each function, there are only two different types of stub:one clears the DR7 (debug register) before calling the check routine and the other doesn't.

Here are the two different stubs for the KiInterruptThunk function:

```
33 C0                                    xor     eax, eax
90                                       nop
90                                       nop
90                                       nop
E9 F6 AF 12 00                           jmp     FsRtlTruncateSmallMcb
66 0F 1F 44 00 00                        align   10h
```

```
33 C0                                    xor      eax, eax
0F 23 F8                                 mov      dr7, rax
E9 E6 AF 12 00                           jmp      FsRtlTruncateSmallMcb
66 0F 1F 44 00 00                        align 10h
```

Both or the exact same size, thanks to NOP instructions.
These two stubs are repeated 8 times, and the random value is used to picks one of them. For the KiMachineCheckControl function, stubs are almost the same with the difference in that KiDecodeMcaFault is called instead of FsRtlTruncateSmallMcb.

Now, as we said before, the problem with this method is that it doesn't seem to do anything more. Other methods use the DPC by coupling it with a timer or putting it somewhere in memory so that the system can queue it at some point, but this one doesn't. Here is a technical analysis to detail our finding. Even though it doesn't proove that there is no path whatsoever that may queue this DPC, it will show some of our research regarding this method.

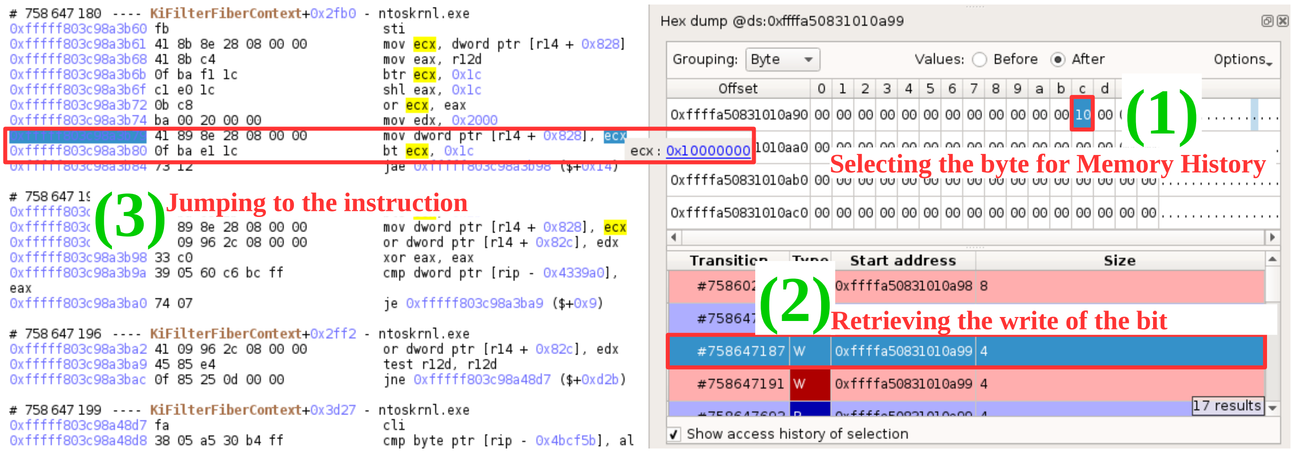
Technical analysis:
Using Reven as a time-travel debugger, we followed the execution for this initialization to find why there is no handler for this method.

- First Check: test the flag with 0x10000000

Starting from the block that randomly choose the KiInterruptThunk stub, we find a check on a flag right before at 1408A8308:

```
        test     [rsp+2238h+flag_828_on_stack_var_140], 10000000h
```

Let's analyze where this flag comes from.
This flag comes from the PatchGuard context and we can use the memory history to find out where it comes from. Going through several memcpy with the Memory History feature from reven, we find that this flag is set at 0x140891B60. Here is a screenshot of how Memory History can be used to find this:



Using the same method multiple times, here is a summary of the results for the flag 0x10000000.

As seen in the screenshot, here is the piece of code that is responsible for setting the flag:

```
        mov     ecx, [r14+pg_ctx_rs4.multiple_flag_0x828]
        mov     eax, r12d
        btr     ecx, 1Ch
        shl     eax, 1Ch
        or      ecx, eax
        mov     edx, 2000h
        mov     [r14+pg_ctx_rs4.multiple_flag_0x828], ecx
```

It is set regarding the value of r12d. With the time travel debugging again we find that this register is set at 0x140891707:

```
        mov     r12d, dword ptr [rsp+2238h+var_bIsMethod7_2158];
```

Again, using the Memory History feature on this stack memory location, we find that it has been set at 140890A13:

```
        cmp     esi, 7
        mov     rdi, 0CCCCCCCCCCCCCCCDh
        cmovz   ebx, r12d       ; r12 = 1
        mov     dword ptr [rsp+2238h+var_bIsMethod7_2158], ebx
```

Here esi contains the scheduling method, which is 7. The last piece of data is r12 but statically we easily find this it is hardcoded to 1 independently from the control flow.

- Second check: Test the flag with 0x40000000

Next there is another check to decide whether or not the method dispatcher should be taken:

```
        test    [rsp+2238h+flag_828_on_stack_var_140], 40000000h
```

In the recording of the initialization, this flag is set and the method dispatcher isn't executed.

Using the same mechanism as for the 0x10000000 flag, we find that the flag 40000000h is set at 0x140893BC9:

```
        cmp     esi, 7
        jnz     short loc_140893BEC
        mov     eax, [r14+pg_ctx_rs4.multiple_flag_0x828]
        and     eax, 0FBFFFFF7h
        bts     eax, 1Eh
        mov     [r14+pg_ctx_rs4.multiple_flag_0x828], eax
```

Again, esi contains the scheduling method, which is 7. The flag is directly set and there is no modification of it afterwards.

- Third check: From a stack variable, without correlation to method 7

By following the trace of the execution, we find another last decisive check at 0x1408A8C81 that will decide whether or not the function KeSetEvent should be called with specifics arguments:

```
        mov     rax, [rsp+2238h+var_21E8]
        test    rax, rax
        jz      short loc_1408A8CAF
```

This jump is taken and the KeSetEvent isn't called.
Again with Memory History, we find the origin of this stack area at 0x1408A5B9F:

```
        mov     [rsp+2238h+ var_bIsMethod7_21E8], r11
```

This memory area may be not NULL if the scheduling method is 3 (PsCreateSystemThread) and if the setup of the new thread succeeded. If so, this stack variable holds a pointer to the StartContext argument given to PsCreateSystemThread, that we will describe later, but the basic idea is that the new thread will wait on this object and KeSetEvent will notify it.

- Quick conclusion

The whole PatchGuard context is right after completely zeroed (including the previously chosen DPC routine) and the execution properly exit the function.

We showed that the two firsts checks are directly linked to the scheduling method passed as the second argument to KiInitPatchGuardContext, and even though it doesn't proove that no path can lead to the real setup of the method, it shows that there is no obvious flag or random value to do so.

- ## Global PatchGuard Context initialization

As we mentionned before, when the index 7 is given to KiInitPatchGuardContext, a global PatchGuard context structure is also initialized. This global PatchGuard context can be accessed through a global pointer, located at 0x14045E208. Many mechanisms are different, such as checksum that are not performed with the usual algorithm but with some SHA256 related algorithm. We didn't analyzed these mechanisms specifically since the idea remains the same.
The fact that this call to KiInitPatchGuardContext with index 7 occurs all of the time is important because it also mean that this initialization is important, and the fact is that this global PatchGuard context is actually used by other new methods (compared to Windows 8.1).

This end the description of different methods that can be used by PatchGuard to initialize a context. At this point we can describe other arguments given to KiInitPatchGuardContext.

vii - KiInitPatchGuardContext: Other arguments

We stated before that the most important arguments to KiInitPatchGuardContext where the second one (index used as a method) and the fourth (pointer to KI_FILTER_FIBER_PARAM, from the 4 % chances function ExpLicenseWatchInitWorker). This small part is to describe the other arguments.

- **Argument 1: DPC Routine pointer**

As we described that several methods used a DPC structure to hide PatchGuard and queue it at some point, it is important to note that the verification routine isn't set as is in the DPC. The DPC will actually contain a pointer to a function that is known to unqueue DPC, and will perform specific operation when the DPC is actually a PatchGuard one.
The first argument is an index to choose a routine randomly, and this routine will be set as on of these functions:

Index	Routine
0	CmpEnableLazyFlushDpcRoutine
1	ExpCenturyDpcRoutine
2	ExpTimeZoneDpcRoutine
3	ExpTimeRefreshDpcRoutine
4	CmpLazyFlushDpcRoutine
5	ExpTimerDpcRoutine
6	IopTimerDispatch
7	IopIrpStackProfilerDpcRoutine
8	KiBalanceSetManagerDeferredRoutine
9	PopThermalZoneDpc
10	KiTimerDispatch OR KiDpcDispatch
11	KiTimerDispatch OR KiDpcDispatch
12	KiTimerDispatch OR KiDpcDispatch

For the last routines KiTimerDispatch and KiDpcDispatch, if the second argument is less than 3 then KiTimerDispatch is used, otherwise (greater or equal than 3) KiDpcDispatch is used. This choice is made at 0x1408A50CA.

As one can see in the previous pseudo code of KiFilterFiberContext, this first parameter is chosen randomly except for the last call to KiInitPatchGuardContext where it is 0 - CmpEnableLazyFlushDpcRoutine, but we will see that in this case it isn't used by the initialization routine. The switch between these 12 routines can be seen near 0x1408A5AA9.

- **Argument 3: Random value to determine the total size of data to check**

This random value can be one or two (as one can see in KiFilterFiberContext). It is used to divide the hardcoded value 0x140000 and the result is immediatly set into the PatchGuard context structure at offset 0x6cc. This value is used to determine the maximum size of data (in bytes) to checksum at each PatchGuard check. The main idea is that PatchGuard use a list of structures to check the integrity and after each checksum a counter is incremented by the size of the data. While the total amount of checked data is less than the maximum previously defined, PatchGuard proceeds with the next structure to check in its list. This mechanism will be explained more in detail in the Verification Routine section.

- **Argument 5: Boolean for ntosrknl functions integrity check**

This argument is a boolean to decide whether or not ntoskrnl functions checksum should be performed. The check is done at 140894183:

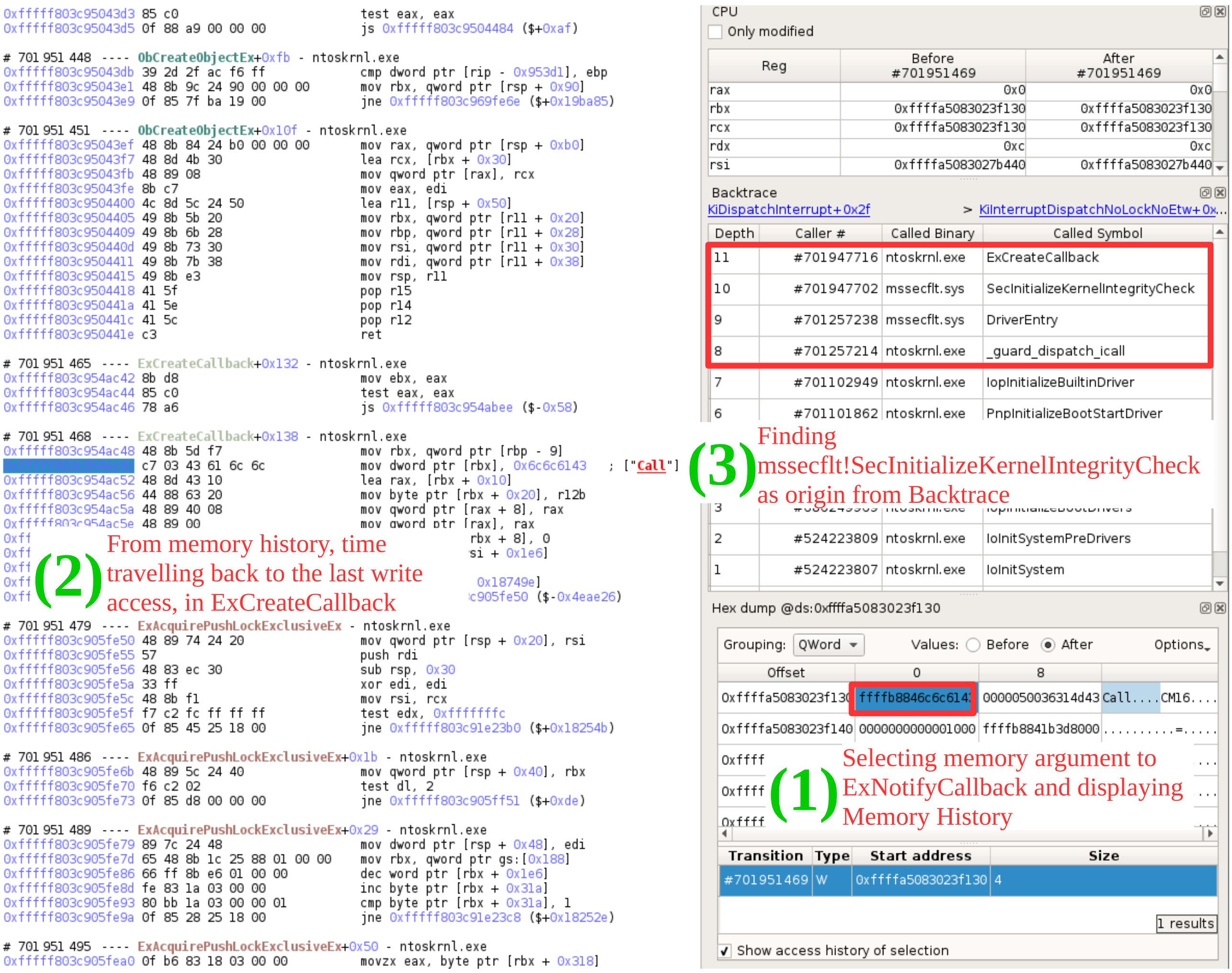
```
mov     eax, [rsp+2238h+arg_20_var_2140]
and     eax, r13d;                                   r13 is hardcoded to 1
mov     dword ptr [rsp+2238h+arg20_copy_var_2170], eax
jz      loc_1408943C4
```

The checksum result is then stored in the PatchGuard context as every other Windows Kernel structures that are to be checked by PatchGuard. In KiFilterFiberParam, one can see that this parameter is True only for the first call to KiInitPatchGuardContext.

This end the initialization methods that may come from KiInitPatchGuardContext, now we will describe other methods initialized directly, or doesn't use any context structure at all.

b - « TV » callback, first time linking PatchGuard to mssecflt.sys

KiFilterFiberContext is a rather small function and we can easily see the notification of a callback. This callback cannot be found in ntoskrnl, but we can see that it takes a function pointer (sub_1401825A0, renamed Pg_TVCallback_CheckRoutine_sub_1401825A0) as an argument. It could be rather difficult to find where it comes from. From the KiFilterFiberContext function we notice that there is no call to ExRegisterCallback, which means that the object callback already exists and has been created previously during the boot. With timeless analysis we instantly discover that this callback is initialized in the binary mssecflt.sys in the function SecInitializeKernelIntegrityCheck:


(1) Selecting memory argument to ExNotifyCallback and displaying Memory History
(2) From memory history, time travelling back to the last write access, in ExCreateCallback
(3) Finding mssecflt!SecInitializeKernelIntegrityCheck as origin from Backtrace

The callback function is named SecKernelIntegrityCallback. It is initialized in SecInitializeKernelIntegrityCheck which is called directly from the driver entry routine of mssecflt.sys. Here is the call stack (that you can also see in the screenshot above) for SecInitializeKernelIntegrityCheck, which shows that it comes from the IoInitSystem function:

```
        SecInitializeKernelIntegrityCheck
        mssecflt.sys DriverEntry
        _guard_dispatch_icall
        IopInitializeBuiltinDriver
        PnpInitializeBootStartDriver
        PipInitializeCoreDriversByGroup
        PipInitializeCoreDriversAndElam
        IopInitializeBootDrivers
        IoInitSystemPreDrivers
        IoInitSystem
```

The callback function itself is SecKernelIntegrityCallback. It is a very small routine that simply put the function pointer into a global variable:

```
    [...] // Tracing and Logging related actions
    g_qword_1C0013428 = &Pg_TVCallback_CheckRoutine_sub_1401825A0; // Pointer from the notification
                                                                    // function argument
    *KpgApiConsumerRanges = SecProtectedRanges;
```

We can also see that it will set the value of the global variable KpgApiConsumerRanges (passed as parameter) to SecProtectedRanges.

Having a quick look at Pg_TVCallback_CheckRoutine_sub_1401825A0 indicates that it is one of the PatchGuard check routine, as it look very much like FsRtlMdlReadCompleteDevEx. A difference can be noted though: the scheduling method isn't reset at the end of the routine.
There is no specific initialization more than this callback for this method, as, as we mentionned earlier, it uses the global PatchGuard context structure. How this function is called is detailed later in this article.

c - KiSwInterruptDispatch

Just like the callback method, this method isn’t initialized per se, as it uses the global PatchGuard context structure from method 7. It is also a new method and is called by KiSwInterrupt function, which is an IDT function. We will describe its trigger mechanism later in this paper. We can see some references to KiSwInterrupt in KiFilterFiberContext, that are related.

d - Some breadcrumbs: CcInitializeBcbProfiler

PatchGuard uses an hidden way to perform checks with CcInitializeBcbProfiler. This function starts by computing the checksum of a random ntoskrnl routine. Then it sets up a DPC with the routine CcBcbProfiler, and with some bonus data in the DPC. Here is the structure passed as parameter:

```
struct pg_CcInitializeBcbProfiler
{
    KDPC_ kdpc;
    KTIMER timer;
    ULONG64 res_RtlpLookupPrimaryFunctionEntry_0x80; //  0D1B71759
    ULONG64 hardcoded_140000000h_0x88;
    ULONG32 func_size_0x90;
    ULONG32 padding_0x94;
    ULONG64 checksum_function_0x98;
    ULONG64 random_1_0xa0;
```

```
    ULONG32 random_2_0xa8;
    ULONG32 bool_CcBcbProfiler_or_sub_140499010_0xac;

    ULONG64 bKiAreCodePatchesAllowed_0xb0;
    struct _LIST_ENTRY_ workitem_List_0xb8;
    void* workitem_WorkerRoutine_psub_140499010_0xc8 /* function */;
    void* workitem_Parameter_pCurrentStruct_0xd0;
};
```

Note that this structure contains everything to compute again the checksum of the random routine:

- Pointer to the Function entry
- Base address of the image (added to the RVA to get the VA)
- Size of the function
- Checksum
- Random values used at seed for the checksum

The DPC is queued with KeSetCoalescableTimer, like in the initialization function with a DueTime set between 2' and 2'10". Next, routine CcBcbProfiler either queue the workitem from the parameter with sub_1404099010 (that we convieniently rename Pg_CcBcbProfilerTwin_sub_140499010) as WorkerRoutine, or continue its execution.

Except for the WorkItem part, routines Pg_CcBcbProfilerTwin_sub_1404099010 and CcBcbProfiler are almost identical, and the main objective is to perform the integrity check of the random ntoskrnl function and compare the result with the one stored in the structure. Both functions sets up again the timer with KeSetCoalescableTimer afterwards.

e - Some breadcrumbs: PspProcessDelete

Some pieces of integrity verification can also be found in specific places, such as PspProcessDelete. This function does more than just deleting a process as in the middle of it, an integrity check will be performed on the KeServiceDescriptorTable and its shadow twin KeServiceDescriptorTableShadow.
This integrity check is independant, as it doesn't need any PatchGuard context structure or dedicated thread. It is just a small piece of verification that one can find in the middle of system code. Note that the original checksum for both table, along with the Initialization Vector and the shift value necessary to compute the checksum, are available in global variable, in a way that if an attacker wants to patch an entry of the Descriptor Table (Shadow or not), then computing again the checksum and replacing the original one is completely feasible.
This checksum occurs regarding a random value generated at 0x1401ecd55, with KiQueryUnbiaisedInterruptTime, so that it is not launched too many times (The interval hasn't been reversed yet but we can see that the result is computed with an addition of 288e9 and a random value). This timer is stored at 0x1403DB100. The checksum results for these structures are stored at 0x1403DB108, 0x1403DB110 and 0x1403DB118. The IV is stored at 0x1403DB0F0 and the shift value is stored at 0x1403DB0F8. If one of these checksum fails, then a KeBugCheck is triggered through a Dpc inserted with KiSchedulerDpc.
The initialization of these checksums is performed in CmpInitDelayRefKCBEngine.
To disable this method, one can just patch the timer to infinity or compute again the checksum of the modified table (and get its hook protected by PatchGuard, which is nice).

f - Some breadcrumbs: KiInitializeUserApc

Just like PspProcessDelete, this function hide an autonomous piece of code to check the integrity for the IDT. The timer to define whether or not a check should be performed is stored at 0x1403DB1C0, the IV at 0x1403DB1B0 and the shift value at 0x1403DB1B0. The original checksum is stored at 0x1403DB1B8. Identically, if a modification is detected, the code inject a DPC with KiSchedulerDpc which will call KeBugCheck.
Just like the PspProcessDelete case, to disable this method, one can just set the timer to infinity or compute again the checksum of the modified IDT (and get its hook protected by PatchGuard, which is nice).

g - Other call to KiInitPatchGuardContext

An other call to KiInitPatchGuardContext can be seen with cross-references, from the exception handler of KiVerifyXcpt15. This routine belong to an array of function pointers named KiVerifyXcptRoutines, it is called multiple times (defined by the constant KiVerifyPass, 0xA) in KiVerifyScopesExecute.
This method hasn't been analyzed much yet, but the thing is that KiInitPatchGuardContext so that method 0 is used to create a context (the timer injected with KeSetCoalescableTimer), so no new method to disable.

III - Triggering a check

We have seen previously multiple methods used to setup some contexts, now this section concerns how these contexts are triggered. Depending on each methods, the process may vary.

A - DPC execution

The most famous way for PatchGuard to trigger a check is to use DPC. The routine set as DeferredRoutine are picked among the following:

0	CmpEnableLazyFlushDpcRoutine
1	ExpCenturyDpcRoutine
2	ExpTimeZoneDpcRoutine
3	ExpTimeRefreshDpcRoutine
4	CmpLazyFlushDpcRoutine
5	ExpTimerDpcRoutine
6	IopTimerDispatch
7	IopIrpStackProfilerDpcRoutine
8	KiBalanceSetManagerDeferredRoutine
9	PopThermalZoneDpc
10	KiTimerDispatch OR KiDpcDispatch
11	KiTimerDispatch OR KiDpcDispatch
12	KiTimerDispatch OR KiDpcDispatch

From index 0 to 9, functions use an exception handler to fire the check. KiTimerDispatch and KiDpcDispatch call the DPC directly without using the exception trick. Also, note that method 5 uses KiBalanceSetManagerDeferredRoutine all the time.

1 - Non-Canonical DeferredContext pointer

When one of these functions is called, the first objective is to determine whether or not the DPC stacked is a PatchGuard DPC or a usual DPC, as these functions have a nominal usage. All of these function take a DPC structure pointer as parameter and it will be used to determine if the DPC comes from PatchGuard or not.

The check is done regarding the argument KDPC.DeferredContext, whether it has a canonical address or not. (Namely, whether or not the pointer start with 0xffffxxxxxxxxxxxx or not) This check is rather simple. Here is a simple snippet of code that can be used to check if a DeferredContext has a canonical address:

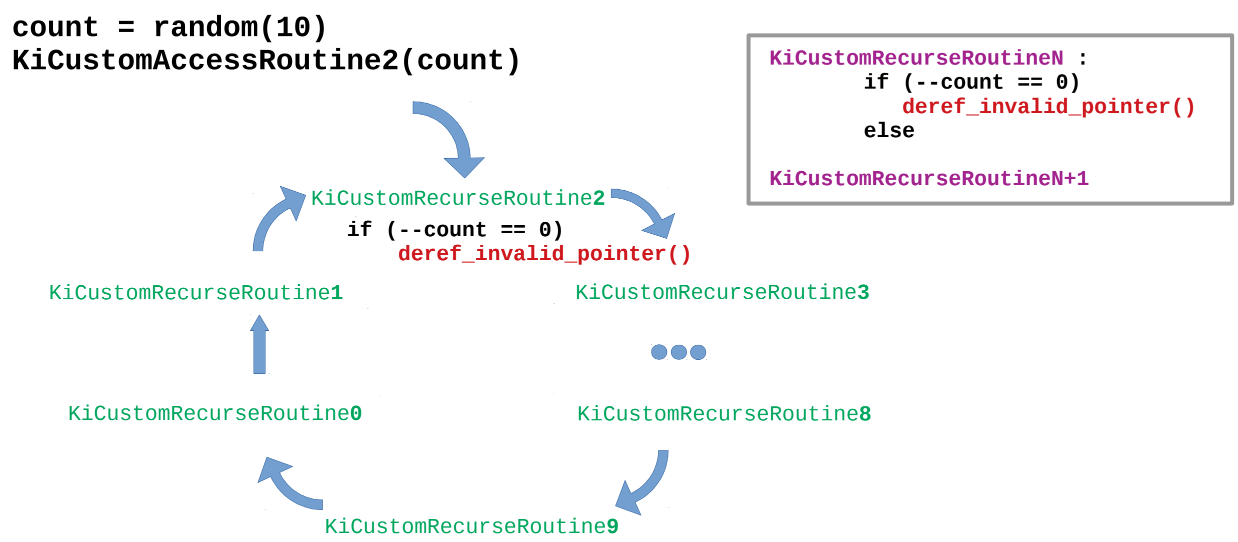
```
is_patchguard_context PROC
    mov     rdx, rcx
    sar     rdx, 2fh
    inc     rdx
    cmp     rdx, 1
    jbe     ctx_is_not_patchguard
    mov     rax, 1 ; patchguard
    ret
ctx_is_not_patchguard:
    xor     rax, rax
    ret
is_patchguard_context ENDP
```

If the aforementionned DeferredContext parameter has a non-canonical address, then the function KiCustomAccessRoutineX (X depending on the function called) is called, to lead to what we may call « the russian roulette trick.

2 - Triggering the exception handler: The Russian roulette trick

KiCustomAccessRoutineX will then call KiCustomRecurseRoutineX with two parameters: a counter and the non-canonical DeferredContext. The counter is obtained from the last two bits from the deferred context, plus one.

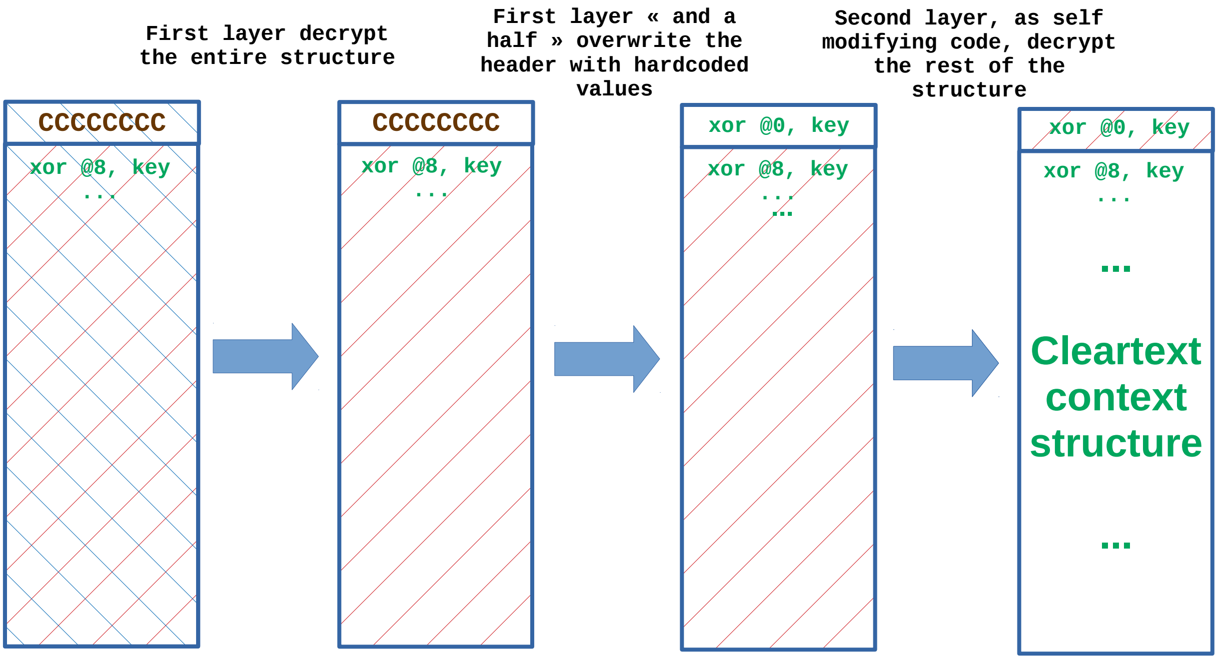
KiCustomRecurseRoutineX is a set of 10 circular function doing a simple task: Decrementing the counter and while it's different from zero, call the next function. Here is a diagram that illustrate this mechanism:



The idea is that until the counter is zero, PatchGuard will keep decrementing it and eventually, an invalid pointer will be dereferenced. Depending of each original function, a combination of try/except/finally handler will eventually lead to the decryption of the PatchGuard context structure. This mechanism looks like pulling the trigger of a gun with one bullet until it shoot, hence the « Russian roulette » comparison.

3 - PatchGuard context decryption

The exception handler is responsible for decrypting the first layer of the PatchGuard context structure. There are roughly two layer of decryption, and one small trick. Here is an overly simplified diagram of each layer, followed by the explanation of each part:



a - First layer

The first layer of decryption targets the whole context structure.
There are multiple different code to do so which is summarized in the following list:

Idx	Routine	1st layer encryption
0	CmpEnableLazyFlushDpcRoutine	Method 1
1	ExpCenturyDpcRoutine	Method 1
2	ExpTimeZoneDpcRoutine	Method 1
3	ExpTimeRefreshDpcRoutine	Method 2
4	CmpEnableLazyFlushDpcRoutine	Method 1
5	ExpTimerDpcRoutine	Method 2
6	IopTimerDispatch	Method 2
7	IopIrpStackProfilerDpcRoutine	Method 1
8	KiBalanceSetManagerDeferredRoutine	Method 1
9	PopThermalZoneDpc	Method 2

10-12	KiTimerDispatch	Method 1 with hardcoded key?
10-12	KiDpcDispatch	No 1st layer encryption

These encryption/decryption routines use random values from KiWaitNever and KiWaitAlways. KiWaitNever and KiWaitAlways are two global variables holding random values, generated at boot time and used by KiInitPatchGuardContext to encrypt the PatchGuard context structure. This is interesting because it means that an attacker that want to interact with the structure must know the position of these global variables and to do so, must have both the ntoskrnl version and corresponding symbols information.

b - First layer... and a half

Before applying the second layer of decryption, PatchGuard rewrite four bytes at the very beginning of the PatchGuard structure. These bytes actually represent the code that will decrypt the context through the third layer of decryption (CmdAppendDllSection), as self modifying code. This rewrite is done using hard coded values, and for each routine the code is different. Just to give you an idea, here are a few methods used.

```
- ExpCenturyDpcRoutine rewrites four bytes one by one:
   mov     byte ptr [r11], 2Eh
   mov     byte ptr [r11+1], 48h
   mov     byte ptr [r11+2], 31h
   mov     byte ptr [r11+3], 11h ; pg_ctx PROLOGUE
```

```
- PopThermalZoneDpc uses the xor of two hardcoded values:
   *pg_ctx = 0x0AD1B6FF5 ^ 0x0BC2A27DB ; = 0x1131482E
```

```
- ExpTimeZoneDpcRoutine rewrites directly a DWORD32 and rotate it after:
   mov     qword ptr [rbp+38h], 31482E11h
   mov     rdx, [rbp+38h]
   shl     edx, 18h
   mov     rcx, [rbp+38h]
   shr     rcx, 8
   or      rcx, rdx
   mov     [rbp+38h], rcx ; 0x1131482E
```

At this point there is no assumption about why it is done this way. The usage of XOR is typical of Just-In-Time code, and since the code around is not very clear this is a possibility. Otherwise, these "tricks" were introduced volontarely to prevent some magic values to be searchable in the code, but it doesn't sound like something difficult to overcome.

c - Second and last layer

The code for the second layer of decryption is actually held in the first part of the PatchGuard context, and it is called directly at the end of the previous decryption layer called. Recall that this code is copied directly from CmdAppendDllSection, and start by multiple xor instructions to decrypt itself. We can separate this decryption process in two parts:

Here is a snippet of the trace for the first part that we can see with timeless analysis as it rewrites its own instruction (as seen with REVEN):

```
// rcx points to 0xffffce80c3f00058, which is the current instruction

0xffffce80c3f00058  2e 48 31 11       xor   qword ptr cs:[rcx], rdx
0xffffce80c3f0005c  48 31 51 08       xor   qword ptr [rcx + 8], rdx
0xffffce80c3f00060  48 31 51 10       xor   qword ptr [rcx + 0x10], rdx
0xffffce80c3f00064  48 31 51 18       xor   qword ptr [rcx + 0x18], rdx
0xffffce80c3f00068  48 31 51 20       xor   qword ptr [rcx + 0x20], rdx
[...]
```

The first xor instruction here rewrite both itself and decrypt the very next instruction.
The second part is the decryption loop for the whole context structure (as seen with REVEN):

```
0xffffce80c3f000d7          xor    qword ptr [rdx + rcx*8 + 0xc0], rax
0xffffce80c3f000df          ror    rax, cl
0xffffce80c3f000e2          btc    rax, rax
0xffffce80c3f000e6          loop   0xffffce80c3f000d7
```

4 - Passing control to the verification routine

Once this decryption is over, the context structure is ready to use. Two functions are called one after another.

The first one is called directly from the data in the structure (see previously, the second part of the structure). It is a copy of sub_1402F5270, and do two things:

- Verify the PatchGuard context structure integrity and the integrity of 47 routines or parts of routines that are critical to PatchGuard. For example, the first code to be checked is the epilogue of ExpWorkerThread calling KeBugCheck2 at 0x1401FAFF8:

```
or      [rsp+38h+var_18], 0FFFFFFFFFFFFFFFFh
mov     r9, rbx          ; BugCheckParameter3
mov     r8, rdi          ; BugCheckParameter2
mov     edx, 5           ; BugCheckParameter1
mov     ecx, 0E4h        ; BugCheckCode
call    KeBugCheckEx
```

  The second check is the exception handler of ExpWorkerThread (unwind), and the last check is KelpiGenericCall.
  If PatchGuard detects a modification then it will enter the process to trigger the KeBugCheck. We will describe shortly after the main algorithm used to check the integrity and the process of triggering KeBugCheck.

- Initialize a WORK_QUEUE_ITEM structure (see 0x1402F5BE1). The WorkerRoutine is picked out of three stub that will call a verification routine as a WorkItem. The three stubs are:
  - A random stub picked from KiMachineCheckControl array, if the seventh method is used (already described previously). In this case the field Parameter points to the PatchGuard context;
  - The copy of FsRtlUninitializeSmallMcb in the PatchGuard context structure. In this case the Parameter is also the PatchGuard context

- sub_1401812E0, which is only a stub to call the deferred routine from a DPC passed as a parameter. In this case the DPC parameter is setup to be slightly encrypted and is also a pointer to KiMachineCheckControl. The associated field Parameter is the aforementionned DPC.

Note that the condition checked to decide if the third stub has to be chosen isn't clear at the moment. It checks the presence of an unknown struct at offset 0x8a0 in the context structure.

The second call is actually a jump, to ExQueueWorkItem. Obviously, the previously initialized WORK_QUEUE_ITEM is passed as parameter and the verification routine can start once a Worker thread process the new item.

For the DPC method, this conclude the mechanism that is used to pass control to the verification routine. The other method that we will describe hereafter are mostly subset of this mechanism.

B - System Thread method

As we described before, the third method used by PatchGuard creates a system thread in function Pg_InitMethod3SystemThread. This function is called directly in KiInitPatchGuardContext.

1 - Triggering the Exception Handler

PsCreateSystemThread is called through the exception handler of Pg_InitMethod3SystemThread.

For this case we saw a piece of code that we don’t really understand:
At 0x1408940E8 in KiInitPatchGuardContext, the instruction CPUID is called:

```
mov     eax, 80000008h  ; Virtual and physical address sizes
cpuid
```

This will returns the largest virtual and physical address sizes. The result is stored in the PatchGuard context at offset 0x7b8 and used in Pg_InitMethod3SystemThread:

```
;   __try { ;__except at loc_1408A982B

[...]

mov     al, byte ptr [rsi+pg_ctx_rs4.max_virt_address_size_0x7b8]
dec     al ; 0x40 => 0x3f
movzx   r11d, al ; r11 = 0x3f
mov     ebx, 3Fh
sub     ebx, r11d ; rbx = 0

[...]

div     rbx ; May trigger the error
```

If the maximum virtual address size is 0x40, then rbx is 0 at the division instruction, and will trigger the exception. This is very unusual since x86_64 only use 0x30 bits to address the virtual memory so we don't really know why this is placed here.

It seems that the actual fault is triggered a few instruction later when dereferrencing a "random" register near 0x1408A97DD.

This part is not very clear to us, at it is very difficult to record and debug this mechanism. It may lack some information or may be wrong...

2 - New Thread

The thread is then created at 0x1408A9837. Recall that the structure KI_FILTER_FIBER_PARAM contains a pointer to PsCreateSystemThread; this pointer is used by PatchGuard to create the new thread. The StartContext parameter given to PsCreateSystemThread is a pointer to a new type of structure which can be defined as follow:

```
struct pg_StartContext
{
    ULONG64 pEvent_0x00; Just a pointer to the event in the very
                       ; same structure
    ULONG64 bRandom_ShouldRunKeRundownApcQueues_0x08; set at 0x1408A970B
    ULONG64 unknown_0x10;
    KEVENT_ event_0x18;
};
```

The event object is initialized before the exception handler in the function Pg_InitMethod3SystemThread and one of the first thing the newly created thread does in Pg_Method3StubToCheckRoutine_sub_1402CD680 is waiting on this object to be signaled, with KeWaitForSingleObject. This event is notified at the end of the KiInitPatchGuardContext, so almost right after being initialized. Note that there is no timeout (set to 0) for the first time this method is used.

Function Pg_InitMethod3SystemThread returns a pointer to the structure and the event is notified at the end of KiInitPatchGuardContext at 0x1408A8CA7. Then the whole decryption and check process may start.

3 - Decryption process

The decryption process is basically the same as the one used by DPCs: a two stages decryption with an additional hard-coded prologue. The first stage uses KiWaitNever and KiWaitAlways and the second stage is performed by CmpAppendDllSection's copy, just like in the DPC case, which eventually calls the verification routine.

4 - Post verification for this case only

Once the verification routine ended, the context is restored to a waiting state with either KeDelayExecutionThread or KeWaitForSingleObject, but this time with a timeout set between 2' and 2'10". This is important because when looking for PatchGuard threads in the disabling driver, this is the kind of places we have to look into.

C - APC insertion

As explained in the first part, the fourth method insert an APC in a system thread queue. Especially, the system thread must have, as a StartAddress (entry in the ETHREAD structure) a pointer to PopIrpWorkerControl.
The KernelRoutine parameter given to KiInsertQueueApc is KiDispatchCallout.
Just like DPC and system thread method, it uses a two stage decryption routine and rewrite the first part of the context with an hard coded xor value. This method is quite immediate since APC delivery is fast, but for each of the previous methods a wait is performed in the verification to ensure that a minimum amount of time has elapsed, between 2' and 2'10".

D - Global variable call

Recall that KiFilterFiberContext notify a callback, that itself places a pointer to the check routine Pg_TVCallback_CheckRoutine_sub_1401825A0 in a global variable from mssecflt.sys. This method uses the global PatchGuard context structure, initialized by KiInitPatchGuardContext when the second argument is 7.
The fact that this global PatchGuard structure is in cleartext in memory imply that there is no need to decrypt and hide the decryption process for this method. This method therefore calls directly the check routine.
Hereafter is an analysis of conditions that are used to trigger a check.

Statically, we only find one reference that will call the function pointer stored in the global variable, in the function SecKernelIntegrityCheck.

The check routine can be called up to five times until the returned status differs from STATUS_MORE_PROCESSING_REQUIRED. Here is the pseudo code responsible for the call:

```
i = 0
while i < 5:
    if(Pg_TVCallback_CheckRoutine_sub_1401825A0() != STATUS_MORE_PROCESSING_REQUIRED):
        break
    i++
```

By analyzing cross-references to this function we find that it may be called from several path. We can sort out two main possibilities for a call:

- The first one is from SecDetInitializeTimers. This path may come from the SecMessage (called by SecCreatePort) and SecDetInitialize;
- The second one is from SetGetProcessContextWithAssertion, which is the most interesting as it may be called from many callback functions such as:
  SecPreCleanup, SecSendFileDeleteEvent, SecSendFileModifyEvent, SecPreWrite, SecPostCreate, SecPostSetInfo, SecRegisterRegCallback, RegPostRenameKey, SecObHandleOpenProcessCallback, and so on.

For example, the path for SecSendFileModifyEvent is the following:

```
    SecSendFileModifyEvent
        if(EtwEventEnabled(Microsoft_Windows_SECHandle, Event 7))
            SecSendFileModifyOrDeleteEvent
```

```
                SecGetProcessContextWithAssertions
                    SecDetPerformImmediateAssertions
                        SecKernelIntegrityImmediateCheck
                            SecQueueIntegrityCheck
                                SecDeferredIntegrityCheck  // as inserted APC
                                    SecKernelIntegrityCheck
                                        Pg_TVCallback_CheckRoutine_sub_1401825A0();qword_1C0013428
```

The call to Pg_TVCallback_CheckRoutine_sub_1401825A0 has nothing special like the other methods. It goes almost straightforward to checks and we will see later that the code responsible for modifying the behaviour of PatchGuard regarding the method isn't present in this version of the check routine.

E - KiSwInterruptDispatch method

Just like the method from the global variable, this method uses the global PatchGuard context structure, which is in cleartext. This means that there is no decryption process and the verification routine is called directly at some point in KiSwInterrupt.

F - Breadcrumbs

Breadcrumbs methods are quite special as they work by themselve. They don't use specific code to trigger their checks, but as we've seen before, they are not executed all of the time. For the CcInitializeBcbProfiler, as we described either queue a workitem with the twin function or continue its own execution. And for the two other piece of verification code from PspProcessDelete and KiInitializeUserApc, both of these function don't rely on any specific mechanism other than a timer (not the structure TIMER, just a counter of time) stored in a global variable.

IV - Verification routines

Even though the historical and main verification routine is FsRtlMdlReadCompleteDevEx, we showed previously that other ones exists depending on the triggering method used. Here is a brief overview of these functions:

- FsRtlMdlReadCompleteDevEx: The historical verification routine. One of the biggest routine in ntoskrnl (more than 12ko in Windows 10 RS4), this function is used by most methods from KiFilterFiberContext. As such, it includes the code to verify kernel structures but also the code to handle different triggering methods, e.g. to specifically schedule again the next check.
- Pg_TVCallback_CheckRoutine_sub_1401825A0: This function looks very much like FsRtlMdlReadCompleteDevEx. We showed previously that it was called from a global variable set up from KiFilterFiberContext. Because there is no specific method to call this function (we saw that it was related to Security Events in mssecflt.sys), there is no specific code to handle method and no need to settle back the next check context.
- CcBcbProfiler/Pg_CcBcbProfilerTwin_sub_140499010: We saw that these two routines are used only to check a randomly choosen routine from ntoskrnl

This section will mainly describe FsRtlMdlReadCompleteDevEx. As a matter of fact, Pg_TVCallback_CheckRoutine_sub_1401825A0 looks very much like a subset of it, and the couple CcBcbProfiler/s Pg_CcBcbProfilerTwin_sub_140499010 are quite small and we already provided an overview of their functionnalities.

FsRtlMdlReadCompleteDevEx can be summed up into multiple parts:

1. Prologue
2. Check of structures
3. Epilogue (two possible outcomes)

A - Prologue

Following sections are placed sequentially regarding the flow of execution that we carefully followed with REVEN and Timeless Analysis.
To summarize, here are the main steps that will be described:

1. Checksum the pg_ctx part 1, 2 and 3, with comparison
2. Re-Encrypt part 1
3. Checksum of part 2 and 3, to save
4. Wait
5. Decrypt back part 1
6. Checksum of part 2 and 3, with comparison
7. Checksum of part 1 (0x618 bytes), with comparison
8. Set the affinity thread

1 - Checksum the pg_ctx part 1, 2 and 3, with comparison

At this point the full PatchGuard context structure is in plain text in memory. PatchGuard proceeds to check the integrity of the whole structure and compare the result with the one stored before the context decryption, initialized in KiInitPatchGuardContext.
Before this checksum is performed, variable data is saved on the stack and cleared from the structure so the checksum remains the same. It will be restored afterwards. This includes values like the checksum of the context (obviously, collision in the hash algorithm aren't in the scope of PatchGuard)), or structures like the WorkItem.

2 - Re-Encrypt part 1

Because PatchGuard shouldn't let its context in plain-text in memory, it proceeds to re-encrypt its first part. At this point I'm not sure why the rest of if isn't encrypted back.

3 - Checksum of part 2 and 3

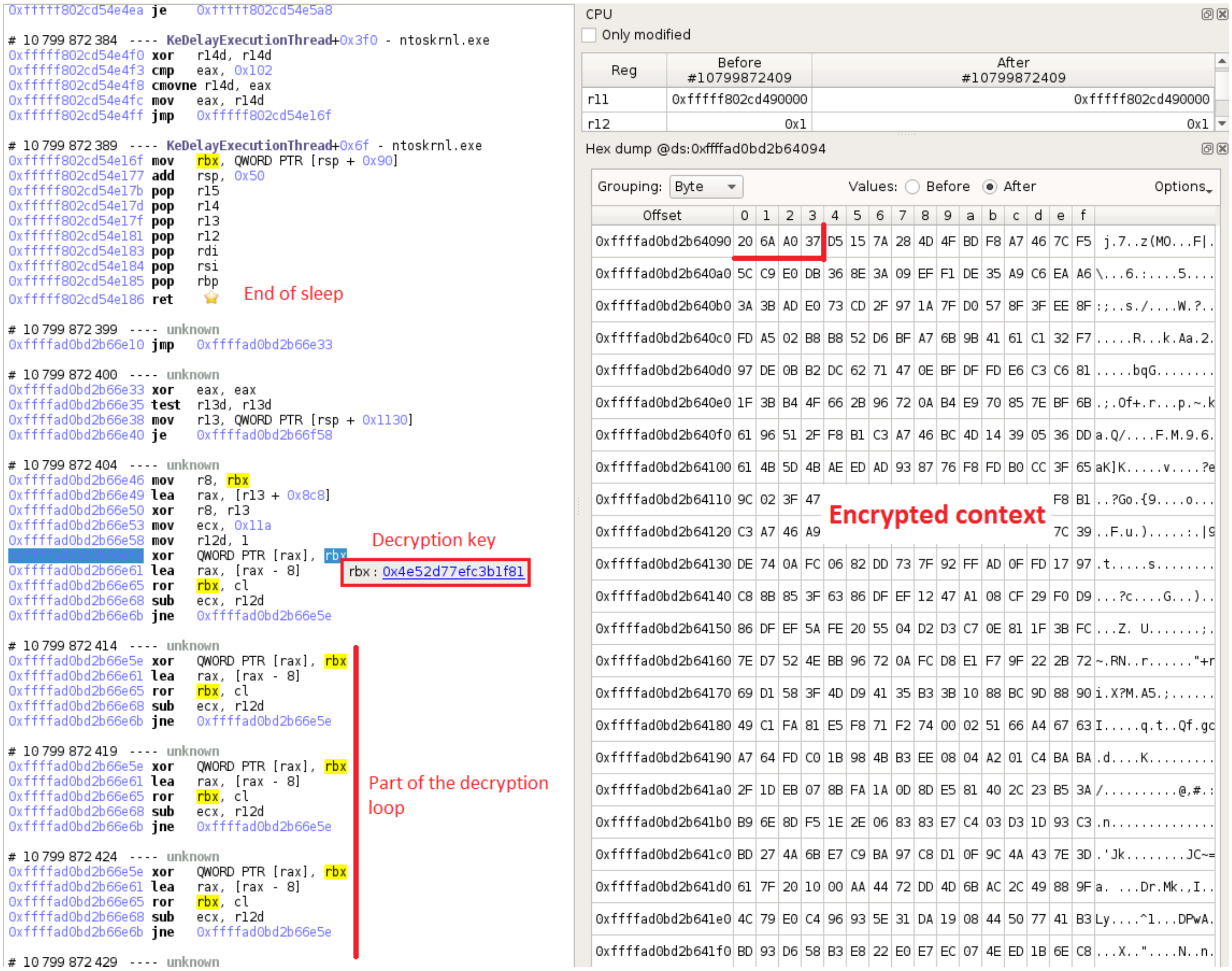
PatchGuard perform another checksum, of part 2 and 3 from the context. Recall that these parts contain the full code of some nt routines, along with an array containing information for each critical structure to be verified later.
These part won't be re-encrypted by PatchGuard before the wait.

4 - Wait

The wait (sleep) ensure that at least two minutes have elapsed between two checks. It can be performed with three different methods:

- Unamed function sub_140182390, (named SelfEncryptWaitAndDecrypt in literature)
- KeWaitForSingleObject
- KeDelayExecutionThread

For example, we can easily see with REVEN the method used by the wait before re-decrypting the structure:



The choice of which routine to use is done regarding information contained in the context, from KiInitPatchGuardContext.

- For SelfEncryptWaitAndDecrypt it is a boolean at offset 0x8f8 in the PatchGuard context structure, initially set at 0x1408948DE. If this boolean is not set then PatchGuard check for an object that can come from 0x5d0 or Ox890.
- At offset 0x890, it may be an Event object (initialized at 0x140895AF4) or a Timer initialized at 0x140895B12. At 0x5d0 it is a global variable event, which is named in ntoskrnl: KiStackProtectNotifyEvent. This event is picked regarding the first bit of the flag at offset 0x82c.
- If none of these objects are picked by PatchGuard then a classical timer is set with KeDelayExecutionThread.

Each of these function are called with a Timeout or DueTime, set between 2' and 2'10". The KeWaitForSingleObject is specific as it can immediatly return since the object may already have been signaled. This might be the case if the object is a Timer object (initialized and set in KiInitPatchGuardContext between 2' and 2'10"), or the global event KiStackProtectNotifyEvent, which may be signaled at 0x140165B44, in KeBalanceSetManager. On the other hand the Event object initialized in KiInitPatchGuardContext doesn't seem to be signaled at any time but this is not a problem since a timeout is passed as a parameter to KeWaitForSingleObject.

SelfEncryptWaitAndDecrypt (sub_140182390), as its name (from Satoshi Tanda) stands for, does more than just waiting. It adds another layer of encryption, that basically do what the main function does: Re-encrypt the context, trigger the wait with a KeDelayExecutionThread, then decrypt back the context once the wait is over.

Now, this wait is important because it gives details about where a PatchGuard context may be sleeping at some point, which is useful to disable it in our driver.

5 - Decrypt back the first part of the context

Once back in the main function, the first part of the context is decrypted back. Nothing to be added here.

6 - Checksum of part 2 and 3, with comparison

To ensure that no modification occured on part 2 and 3 during the wait, a checksum of these part is performed again and the result is compared to the one obtained before the wait. The original checksum was previously stored in a register, and pushed/poped on the stack by the wait routine. This mean that it is probably very difficult to find it and modify it.

7 - Checksum of part 1, with comparison

Last step is the checksum of the first part, but all of it, only the 0x618 first bytes. It is compared to the original one computed during the context initialization in KiInitPatchGuardContext. This original checksum result is stored at offset 0x8b8 in the structure.
Note that the first 0x618 bytes of the structure contains the function pointers used by PatchGuard, but no hashes nor variables.

8 - Setting the Thread Affinity group

Since PatchGuard uses multiple threads and checks some structure that may be processor-specific, this last part of the prologue define the processor on which the check will run. To do so, it first retrieves the SessionId previously set in KiInitPatchGuardContext. Then it will generate a random value between 0 and the total amount of process on the system. Instead of picking a random PID, PatchGuard prefers to loop and fetch the n-th process, n being the random value.
Next PatchGuard will attach to this process and fetch its Group Affinity. But it will not directly use it for its own. It will get a random value between 0 and the amount of processor that may run this thread. In other words, it will perform an Hamming weigth on the bitmap representing the affinity. Then with the random value n, it will select the n-th processor (obtained with a loop with KeEnumerateNextProcessor) and set the new affinity to this processor.
For example, if a thread may run on processor 1, 2 and 6, then PatchGuard will choose a random value 0 <= n < 3 and set its System affinity to n with KeSetSystemGroupAffinityThread.

Hereafter is a pseudo code:

```
rand = random(0, n_processes)
res_process = PsGetNextProcess()
while(rand != 0)
{
    res_process = PsGetNextProcess(res_process)
}
n_proc = hamming_weight(AffinityMask(res))
PgAffinity = random(0, n_proc)
KeSetSystemGroupAffinityThread(PgAffinity)
```

B - Kernel Structure Integrity Checks

In this part we will first present the main algorithm and detail a practical use-case we recorded with timeless analysis, where we modified the IDT structure and observed the BSOD.

1 - Main algorithm

First recall some entries from the PatchGuard context structure:

- In the third part of the structure is an array of structure holding information necessary for the check, including a pointer to the data to check, its size, its type and of course the checksum computed during initialization
- The offset to the first element of this array
- The maximum amount of data to be checked for one round of PatchGuard checks
- A size counter of currently checked data
- A counter of currently checked data structure
- etc.

With these information the algorithm sounds pretty clear but lets detail it:

- First the type of data is used in a small dispatcher. This first dispatcher is actually here to define the next structure that will be checked after the current one. As a matter of fact, in most case the next one will be picked but in some case, for example for a type "0x1c: Driver object corruption" or "0x1e: Modification of module padding", then the next item to analyze is different. This first check is important because it will decide whether or not it has to perform some preliminary checks or operations.

- Next the "huge" chunk proceed to verify the integrity of the selected structure. For nominal data area, this mechanisms is quite simple as PatchGuard proceeds with the checksum and compare it with the original one, but for more specific structures some preparation may be necessary.

- Once this verification is done, PatchGuard increments the total amount of data checked and compares it with the maximum defined. Recall that this maximum depends in KiInitPatchGuardContext from the

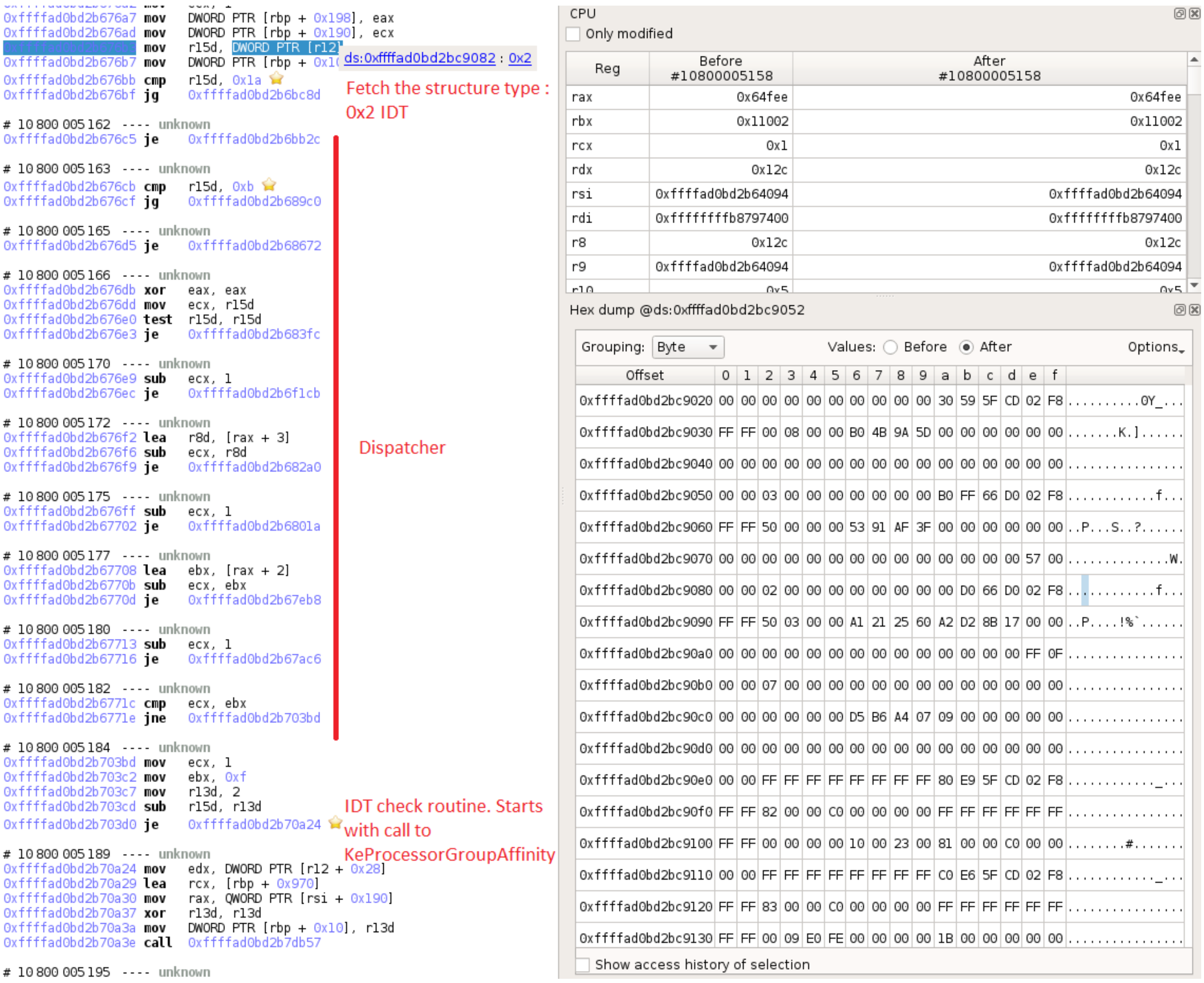
3rd parameter. If the total amount isn't reached, then PatchGuard proceeds with the next entry in the array of critical data structures.

Next part detail the example of the IDT check.

2 - Practical use-case: IDT verification with timeless debugging

To check the IDT PatchGuard goes through some preliminary steps. We followed these steps with timeless analysis. As previously stated PatchGuard starts by dispatching the type of the bugcheck, at 0x1402DFE99. For the IDT the type is 0x2, and the dispatcher goes to 0x1402E9B9E.

The first part of the check is what we defined previously as « specific » to different structure. Here is the first dispatcher that can be seen with REVEN when PatchGuard fetch the structure type:



Since the IDT is processor bound, and pointed to by the idtr register, selecting the right processor is necessary to control the specific processor that PatchGuard will check. This information is stored in the check structure (see II - C - 1 - a - iii) at offset 0x28 for the IDT (initialized at 0x1408a2130). Note that the information stored in this structure may vary regarding the structure. PatchGuard therefore proceeds to initialize a KAFFINITY structure with this information and call KeSetSystemGroupAffinityThread to set the execution of its thread on the selected processor, and call KeGetIdtGdt to fetch the idtr and gdtr values.

Then the check is splitted in two part: the first part handle the KxUnexpectedInterrupt functions, and the second the Interrupt Dispatcher Table itself.

For the first part, which is still considered as « specific » operations, the code fetches the address of KxUnexpectedInterrupt0 in the PatchGuard context and iterates on entries (recall that KxUnexpectedInterrupt0 is actually an array of functions). For each entry, it disables all external interrupt (set CR8 to 0xf), then if it matches with the respective KxUnexpectedInterrupt(s) entry, it calls KiGetInterruptObjectAddress to get the KINTERRUPT object and check if its type is 0 to proceed with other checks. CR8 is then restored to its original value, to enable interrupts back.
This check then uses RtlSectionTableFromVirtualAddress to check three things:

- whether the address belongs to a discardable image (IMAGE_SCN_MEM_DISCARDABLE);
- whether the address belongs to the mapping of ntoskrnl.exe;
- whether it belongs to one of the exported functions of ntoskrnl.exe (using RtlLookupFunctionEntry).

For the second part, PatchGuard simply checksums the table pointed by the IDT register, the same way it does with most structures. Once the hash computation is over, PatchGuard restores the previous processor affinity using KeRevertToUserGroupAffinityThread, and compares the obtained hash with the one stored in memory.

C - Epilogue

The epilogue of the check routine can be separated in two part, obviously: the one that happens when a modification is detected, and the one that happens when everything is fine. To analyze this part we followed carefully the control flow with REVEN for the IDT case.

1 - Everything's fine, go home and be safe!

After the final hash comparison of a structure, as stated before, if the total amount of data checked is below the maximum defined in KiInitPatchGuardContext, then PatchGuard proceeds with the next structure from the array. Otherwise, it will re-arm the PatchGuard context for later use. This goes through multiple steps yet these aren't really different from the initialization ones.
For methods 0, 1, 2, 4 and 5 the code is almost identical to the one from KiInitPatchGuardContext regarding the method used:

1. KeSetCoalescableTimer is called directly
2. DPC is stored in KPRCB.AcpiReserved
3. DPC is stored in KPRCB.HalReserved
4. APC is inserted with KeInsertQueueApc

5. DPC was already set in a global variable

The third method, which is the creation of a system thread, is rearmed but not in the same main function. Recall that it is called in Pg_Method3StubToCheckRoutine_sub_1402CD680. Once the verification routine is done, a small dispatcher choose between KeDelayExecutionThread or KeWaitForSingleObject.

- If KeDelayExecutionThread is chosen, a the usual timeout between 2' and 2'10" is set.
- If KeWaitForSingleObject is used, the same timeout of 2' is set this time. Recall that the first time it was called, no timeout was provided, only an event that was notified through KeSetEvent at the end of KiInitPatchGuardContext for the seventh method. But in this case, with one out of two chance (per boot), the event is reset and, unless we missed something, will never be set anymore since the notification occurs in the initialization routine.

For the seventh method, nothing is done at all, the code go straight to the end of the check routine. As we stated before, this method is cleared right after the beginning of the initialization so we don't really know what it does here.

2 - Die you filthy wild patch

Once the checksum is over, for the IDT case PatchGuard first restores the previous affinity for the current thread. Then the comparison is performed between the computed hash and the original one from KiInitPatchGuardContext. And if a modification is detected, the BSOD is triggered after some meticulous actions.

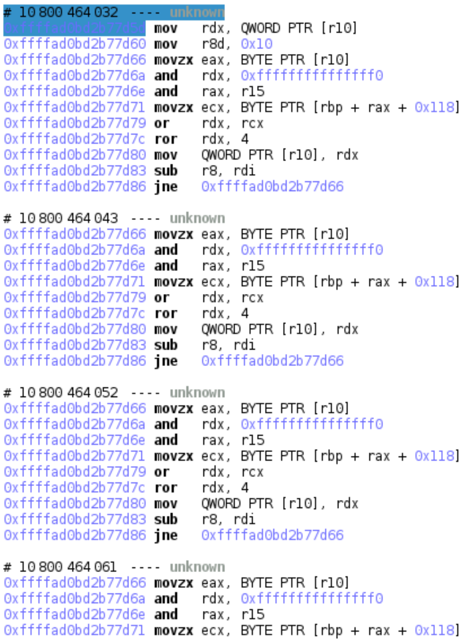
a - Checksum, Encryption and verifications

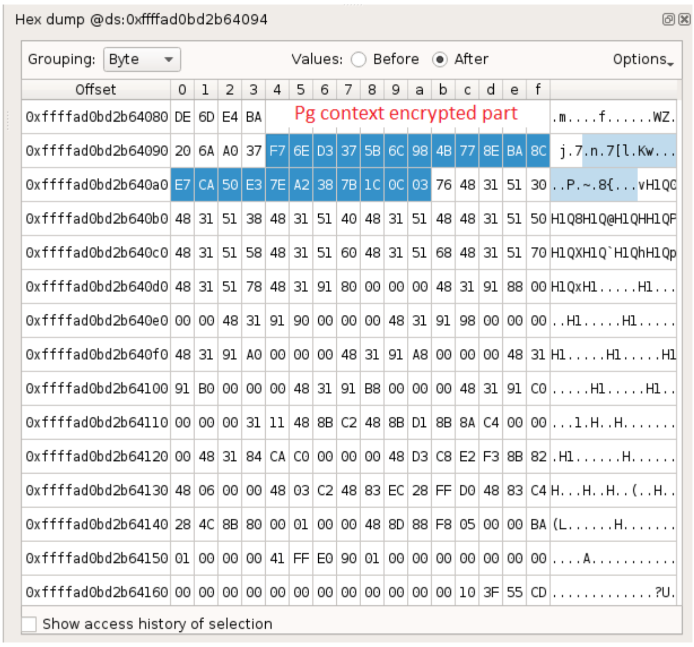
The first step is related to the PatchGuard context. PatchGuard starts by computing the checksum of the full structure. To do so, it must first put it in a "common" state where volatile values are cleared or set to specific state. So PatchGuard proceeds to save values on the stack and clear them from the context. This includes:

- Checksum of the full context structure (part 1,2,3) at offset 0x658 which is zeroed
- Total size of checked data at offset 0x6c8, which is set to the size of the first part of the context (just like in the initialization)
- Workitem at offset 0x638, saved on the stack, and zeroed from the context

Then the checksum for the full structure is performed.
Once this is done, the workitem is restored in the context from the stack and the checksum result is stored at 0x658. Note that this checksum isn't compared to the previous one, but it doesn't seem to be that critical.

Next PatchGuard proceeds to reencrypt the very beginning of the PatchGuard context, which is the code of CmpAppendDllSection. There is no obvious reason for this encryption especially since the rest of the structure remains in clear text for now. Here is what can be seen with REVEN in the middle of the re-encryption process. In this view, one can see the PatchGuard context structure being re-encrypted step by step, the selected part being the newly encrypted data and the rest of it the data that is encrypted right after:





b - Restore Sensitive data

The next part of post detection process is the rewrite of sensitive data, especially used in the mechanism of calling KeBugCheck. Instead of checking the integrity (which we suppose may already have been compromised), PatchGuard prefers to rewrite PTE and Windows critical routines. These rewrites will prevent an attacker from hooking PatchGuard at this moment, as the hook will be re-written with original values.

i - PTE rewrite

Recall that in the initialization function KiInitPatchGuardContext, PTE were saved in the context structure. Here is a snippet:

```
[...]
ULONG64 pointer_to_PTE_0x1_0xa40;        //  ffff8140a0502f80
ULONG64 saved_value_for_PTE_1_0xa48;        //  0000000001008063
ULONG64 pointer_to_PTE_0x2_0xa50;        //  ffff8140a05f0078
ULONG64 saved_value_for_PTE_2_0xa58;       //  0000000001009063
[...]
```

To restore these PTE, PatchGuard first fetches a SpinLock with KeAquireSpinLockForDpc from the context to safely manipulate this data, then it iterates over these PTE and rewrites the system's one with these values.

One interesting mechanism here is the use of a "trick":

```
mov   rcx, cr4
test  cl, cl
jns   0xffffad0bd2b7863c ; // (not taken)
mov   rax, rcx
btr   rax, 7 ; //   PGE Page Global Enabled
```

```
mov   cr4, rax
mov   cr4, rcx
```

It uses a "side effect" of the "mov cr4" instruction to flush the TLB. The Intel documentation specifies that when modifying any of the paging flags, all TLB entries are flushed, including global entries. Here the modified bit is the 7th, which is the PGE - Page Global Enabled.

ii - Critical Routines rewrite

The next part of the rewrite handles the critical routines to execute the BugCheck. For example, routines such as KeBugCheckEx, KeBugCheck, or KeIsEmptyAffinityEx are rewritten. In the PatchGuard context, the information is stored as an array of pairs (pFunction, size_of_routine), starting at offset 0x930, and the entire code of each routine is stored after the PTE entries at offset 0xb80.

Here is a sample of this array from the context structure:

```
[...]
ULONG64 ntoskrnl_KeBugCheckEx_0x940;                // fffff803fba40650 0x197650
ULONG64 size_ntoskrnl_KeBugCheckEx_0x948;           //  0000000000000120
ULONG64 ntoskrnl_KeBugCheck2_0x950;                 // fffff803fbaf8660 0x24f660
ULONG64 size_ntoskrnl_KeBugCheck2_0x958;            //  0000000000000de0
ULONG64 ntoskrnl_KiBugCheckDebugBreak_0x960;        // fffff803fbaf97a0 0x2507a0
ULONG64 size_ntoskrnl_KiBugCheckDebugBreak_0x968;   //  00000000000000b5
[...]
```

iii - One more anti-debug

With many anti-debug all along the execution, here is probably the last one, and is simply a rewrite of the DbgPrint routine with 0xC3, which is a « ret » instruction. There is no explanation for this rewrite as DbgPrint doesn't seem to be a good target but maybe at some point an attacker can hook DbgPrint to prevent the BSOD.

iv - Clear some entries

PatchGuard clears two offsets from the context structure, which are 0x610 (KxUnexpectedInterrupt0 or KiIsrThunkShadow), and 0x690. We don't known the reason of this, since the checksum has already been computed, but these values are volatiles.

v - KeBugCheckEx or SdpbCheckDll

Almost at the end of the verification routine, PatchGuard will call KeGuardCheckICall with KeBugCheckEx as argument. But, once again a small change is easily visible with timeless analysis: if the scheduling method used is 7, then KeGuardCheckICall is rewritten in KiInitPatchGuardContext function, at 0x140895C2B, along with KeGuardDispatchICall:

```
lea     rax, KeGuardCheckICall
sub     eax, ebx
```

```
    test    edi, edi
    jz      short loc_140895C3D
    mov     byte ptr [rax+r12], 0C3h ; // ret instruction
```

This mean that if method used is not 7, then SdpbCheckDll is called instead of KeBugCheckEx.

SdpbCheckDll is a stub to KeBugCheckEx but starts by clearing the thread stack, obtained from ETHREAD.InitialStack, before jumping to KeBugCheck. Note that if the current thread is executing a DPC (check KPCRB.DpcRoutineActive), then PatchGuard will check if the current stack is the one from the Dpc (pointed to by KPCRB.DpcStack). In this case, the DpcStack is cleared instead of the ETHREAD.InitialStack.

This can be observed at 0x1402F1139:

```
    mov     rax, gs:20h
    mov     r15, gs:188h
    mov     rsi, [rax+2E50h]; DpcStack
    mov     al, [rax+2E6Ah];  DpcRoutineActive
    test    al, al
    jz      short loc_1402F117B
    lea     rax, [rbp+2278h+pg_ctx_var_2100];// just a pointer to the first
                                            ;// element on the stack
    cmp     rax, rsi
    ja      short loc_1402F117B ;    // Above the stack limit?
    lea     rax, [rsi-6000h] ;       // Stack is supposed to be 0x6000
    lea     rcx, [rbp+2278h+pg_ctx_var_2100]
    cmp     rcx, rax
    jnb     short loc_1402F117F ;    // Below the stack limit?

    loc_1402F117B:
    mov     rsi, [r15+ETHREAD_.Tcb.InitialStack]
```

Then PatchGuard simply proceeds to jump to KeBugCheckEx.

V - Disabling PatchGuard

During this analysis we implemented a driver that is able to disable all PatchGuard context that we know of. The idea behind this disabling driver is that we consider that at any time, PatchGuard is either sleeping from the initialization method (for example as a DPC in a timer), or waiting in the middle of a verification routine (as one can say, an already launched check), at one of the multiple sleeps we can find in the middle of check routines.

Here is a list of contexts we have to disable:

- Already launched contexts: This include all threads that are waiting in the middle of verification routines
- Method 0: Timer set with a DPC
- Method 1: Pointer to DPC set in PRCB AcpiReserved field
- Method 2: Pointer to DPC set in PRCB HalReserved field
- Method 3: System Thread launched at initialization time
- Method 4: APC injected in a system thread
- Method 5: Regular DPC hooked by PatchGuard
- Method from global pointer in mssecflt.sys
- Method from KiSwInterruptDispatch
- Breadcrumbs CcInitializeBcbProfiler: Function to check one specific Nt routine, sleeps between each check
- Breadcrumbs PspProcessDelete: Piece of code that check the KeServiceDescriptorTable
- Breadcrumbs KiInitializeUserApc: Piece of code that check the IDT

This section aim to explain which method can be used to disable each context.

A - Limitations

Even though we don't think that we missed some things related to PatchGuard, **we didn't implemented this bypass to support multi-core.** This is a lot of work and not really related to PatchGuard itself, and our tests shows that problems comes from APC injection problems.

Also, one huge precondition is the fact that the disabling code only works for **one specific kernel version**, as we use a lot of hard coded values and offsets.

B - Disable already launched contexts

To disable already launched context we implemented a code that will loop through system threads and unwind their call stack. With pointers of return addresses, combined with the known location of each sleeps in the middle of verification routines, we were able to find each one of them.

Once we found these threads, we used two methods to disable them. The first one is to set their timer to infinity, and the second one is to inject an APC that will perform an « infinite » sleep with KeDelayExecutionThread.

Note that this code disables already launched PatchGuard context but also method 3 and 4 as they are launched almost right after being initialized, along with the CcInitializeBcbProfiler method.

C - Disable Timers from method 0

Timers queued by method 0 can easily be found thanks to the deferred context that has a non-canonical pointer. This way, we were able to find them and set the DueTime to infinity. Going through each timer is important as method 0 can queue multiple contexts.

D - Disable hidden DPC pointer from method 1 and 2

Recall that method 1 and 2 set pointers to DPC in the PRCB structure. To disable them, we just have to clear these entries from the structure. If the checks are already launched then previous disable will take care of them.

E - Disable the hook from method 5

This method is pretty straightforward to disable as one just have to restore the original DeferredRoutine in the global DPC.

F - Disable the global pointer from mssecflt.sys

Now that's where things gets tricky. At first sight one could think that just clearing the pointer to the global PatchGuard context would work: one of the first checks performed in the verification routine is whether or not this context is set, and if so, just exit properly. But since the global PatchGuard context is also used by KiSwInterruptDispatch, we must ensure that it's also working for this other method. And it's not, since it will dereference the pointer at the beginning of the check routine, so we have to be more tricky.

At this point, there is one thing to realize: the global PatchGuard context isn't checked anymore. These two methods don't check the context themselve before using it, the other method did, and we disabled them, so basically, at this point, modifying the global PatchGuard context structure is open-bar. We just have to look for something to modify.

For the method from the global pointer of mssecflt, we can see that a check is performed almost at the beginning: (pseudo code)

```
if(pg_ctx.already_checked_struct_count > VALUE)
       exit_properly()
```

Since we can freely modify the PatchGuard context structure, we can just set the entry to a « big » number (0xffff for example) and it will exit properly.

G - Disable the KiSwInterruptDispatch method

Just like the method from the global pointer in mssecflt.sys, this method uses the global PatchGuard context structure, that we can freely modify at this point of the disabling process.

One of the first check that is performed is the following one:

```
if(ExAllocatePoolWithTag(pg_ctx.sha256_state_size + sizeof(ctx))
       exit_properly()
```

To take this branch we can just set the entry sha256_state_size to a huge value so that ExAllocatePoolWithTag fails and PatchGuard exits properly. We used 0xffffffffffffffff – sizeof(ctx) - 1

H - Disable Breadcrumbs – KeServiceDescriptorTable check

We showed that this method uses many global variables. Among others the original hash, and all the information needed to compute it so an attacker can modify the table and compute the new hash so PatchGuard « protect » the attacker's hook. Or, to disable it, the attacker can just set the timer to infinity as it is also stored in a global variable near the hash.

I - Disable Breadcrumbs – IDT check

Just like the KeServiceDescriptorTable check, one can either compute again the hash to make the hook protected by PatchGuard, or simply disable this check by setting the timer to infinity, as it is also stored in a global variable near the hash.

VI - Conclusion

A - Few words

Microsoft PatchGuard is a very interesting piece of software, and we showed that the tricks it uses to hide itself really increase the amount of efforts an attacker have to deploy to disable it. As such, the more different initialization methods it uses directly imply more work for an attacker.
That said, PatchGuard isn't really obfuscated as Warbird or other mechanisms with huge virtual machine are. This is probably done this way to keep good system performances.

In this case we showed that analyzing Patchguard with Reven does not require setting breakpoints or bypassing anti-debug technique. Generally speaking, since Reven allows instant time travel in memory, it is very time saving when trying to analyze a complicated structure such as the PatchGuard context. It was very helpful to analyze the general workflow of the detection routine. Furthermore, since each and every instruction is replayed, it is possible to exhaustively analyze all actions performed by any program on the system.

Now, even though the model is to hide mechanisms and triggering methods, we showed that we were able to analyze them at the point we were able to disable them. Especially, we instantly found that the new method (compared to Windows 8.1) came from mssecflt.sys, thanks to timeless analysis. Disabling it was just a few lines of code after that.

B - Remarks about this work

This paper tend to be exhaustive, but really, there is still plenty of mechanisms I didn't look into. I don't think though that they induce some context I didn't see. For example, one can have a deeper look at KiVerifyXcpt and MceDispatch. There is also the method 7 that does « nothing », but maybe we missed something. And so on. Please feel free to contact me about this (@_YouB_).

Regarding the results, as we stated, our disabling code doesn't work for multi-core system yet. As this problem doesn't look like it's related to reversing PatchGuard per se, we haven't spend time on it yet.
On one core system, our code successfully disabled PatchGuard every time we tested it (several dozen of times). This doesn't mean that we handled every single use case, but at this point we're pretty confident about it.

About releasing the source code and the analyzed PatchGuard context structure. Right now I didn't contacted Microsoft. This is in our TODO list for sure but we don't want to be illegal in any way.

C - References

Here are major information sources related to PatchGuard, that I have used/read:

1. Satoshi Tanda, « PgResearch », https://github.com/tandasat/PgResarch/ 2014, last accessed 26/02/2019. // (true goldmine)
2. Ermolov, Shishkin, « Microsoft Windows 8.1 Kernel Patch Protection Analysis », 2014, Positive Technologies
3. Skape, « Bypassing PatchGuard on Windows x64 », Uninformed, 2005
4. Skywing, « PatchGuard Reloaded – A brief (!!) Analysis of PatchGuard Version 3 », Uninformed, 2007
5. zer0mem (Peter Hlavaty), « How to boost PatchGuard: it's all about gong fu! », www.zer0mem.sk/?p=271, 2013, last accessed 26/02/2019

I don't quote people from online help that answered very old questions but they really helped me a lot. Some special thanks are in the presentation too.

VII - About Tetrane and REVEN technology

A - TETRANE

TETRANE is a highly specialized software development firm created in 2011 and based in France. TETRANE develops REVEN Axion, a software reverse engineering analysis and debugging solution.
The timeless analysis concept at the core of REVEN Axion provides in-depth information about real program behavior to hunt, analyze, and identify software bugs as well as to aid in accurate understanding of highly sophisticated code bases, including malware and other malicious code. TETRANE also maintains training and expertise on complex hardware and software architectures. As of December 2018, TETRANE has 14 full-time employees, including 10 R&D engineers and PhDs.

TETRANE's mission is to reduce the time it takes to understand and handle software bugs and malware, thus giving customers a crucial competitive advantage.

Innovation: Innovation is the key to our success.Breakthrough innovation means taking risks, so we continue to imagine and explore new technological areas. We promote change, and are confident in our ability to shape the future. The only real failure is the refusal to try.
Professionalism & Excellence: We strive to exceed our customers' expectations because we want them to succeed. The work we do is serious, but our passion makes it fun.
We work with teams of experts all around the world to ensure you're getting the quality you deserve.
Trust: We operate in sensitive environments, so we earn the trust of our customers through the quality of our products; we keep their trust through our loyalty to them.
Team: Our strength as a team comes from the belief that every member matters. We learn from each other, value individual skills, and are all striving together to deliver high-quality solutions.

To learn more about TETRANE, please visit: https://www.tetrane.com

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+1 (415) 513-7474
contact[AT]tetrane.com

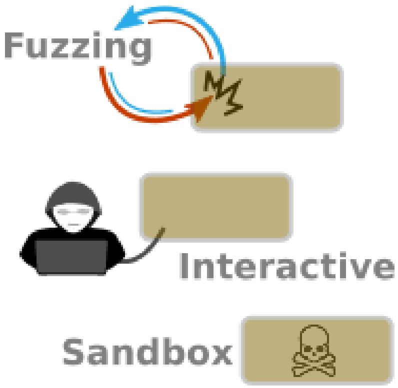
B - TETRANE's technology

TETRANE's Timeless Analysis captures a time slice of a **full system execution (CPU, Memory, Hardware Events)** to provide unique analysis features that speed up and scale your reverse engineering process.

A simple workflow to unleash your RE Power with Timeless Analysis. Quickly identify the root-cause, assess the exploitability, and bypass packers or crypto, triage, etc. All of this is done through a GUI or API.

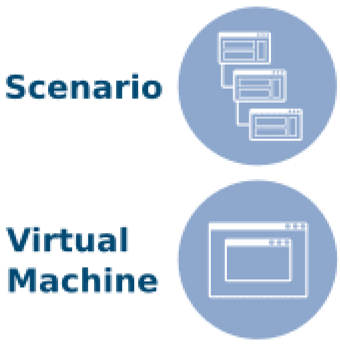
1 - Example of workflow

a - Identify the scenario you want analyzed



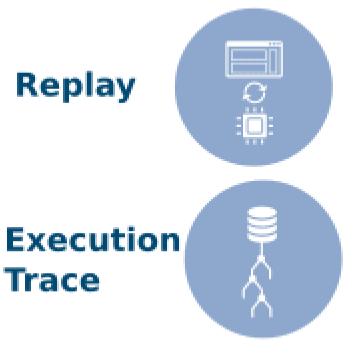
Identify the crash, the event, or just the time slice you want to capture. It can be from a manual execution, triggered in a fuzzing process, or from a malware sandbox

b - Capture the full system execution



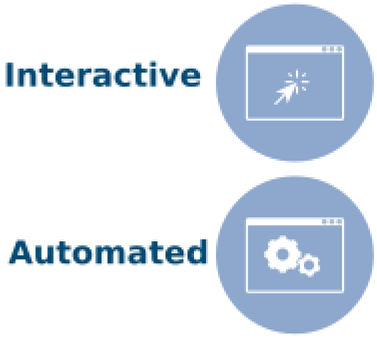
Capture the execution within a VM (Vbox or QEMU). The whole process can be automated or done manually. TETRANE captures the overall system (CPU, memory, I/O) including kernel execution. You have now captured all you need and avoided the multiple executions typically required when using a debugger.

c - Generate the trace



The full trace is generated once and for all. It extends the pure execution by generating additional data to profive features like state of art data tainting, memory history, instant search, etc.

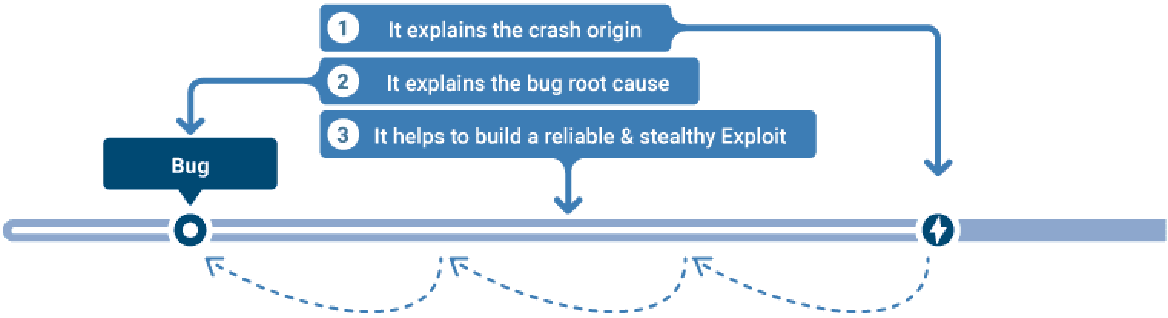
d - Analyze interactively or automatically



Identify the root cause, assess the exploitability, and write a reliable exploit. No matter what your reverse engineering goal is, you will love investigating through our GUI and the scripts we build on top of our API. Integrated with tools like IDA, WinDbg and Wireshark, you can seamlessly mix all of their capabilities.

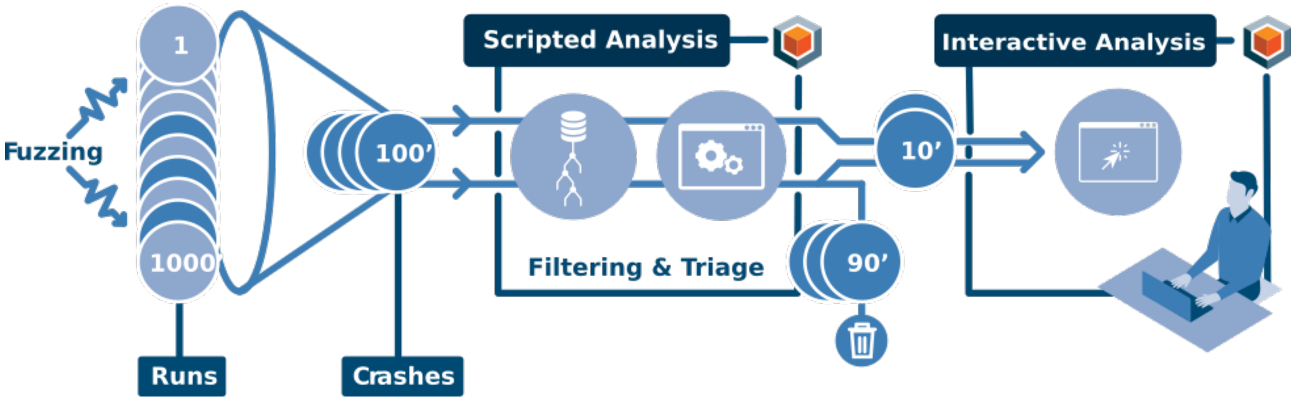
2 - Unprecedented Speed for Vulnerability Analysis

Immediately locate the crash origin and start investigating with **Memory History** and **Data Tainting**, both backwards and forwards.



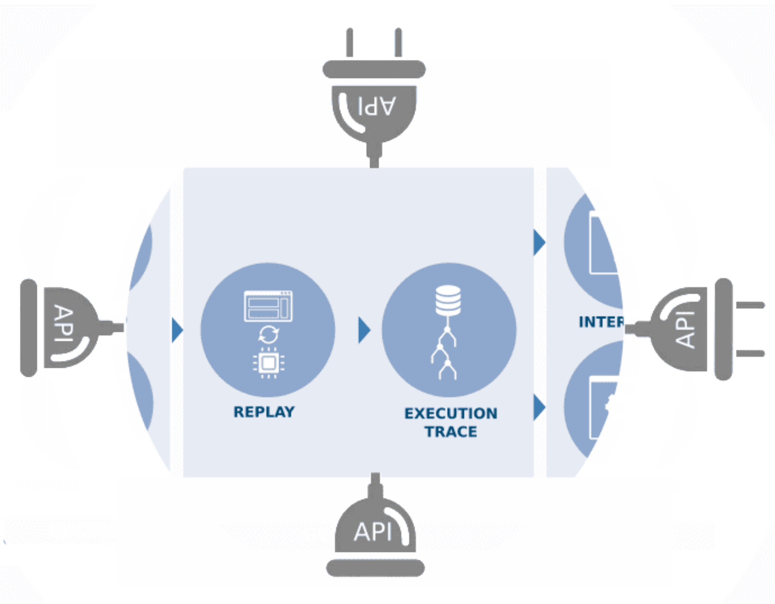
3 - Automate Triage at Scale

Looking to increase the throughput of your reverse engineering process? Automate the investigation of all crashes resulting from fuzzing to focus your security researchers on high-value cases.



4 - Build your own Reverse Engineering Platform

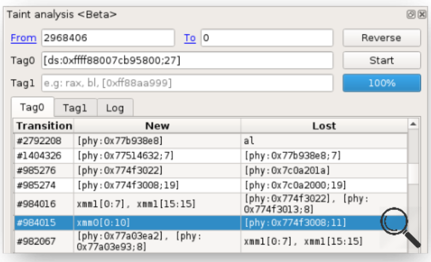
Whatever your goal is, everyone can benefit from a faster process, a deeper analysis, and a solution that helps address any cyber security talent shortages. Build your own platform to automate your workflow, pre-process results, and integrate it with tools like IDA Pro, Wireshark, or WinDbg. Build your own scripts or integration with the Python API.



5 - Unique capabilities to assess vulnerabilities

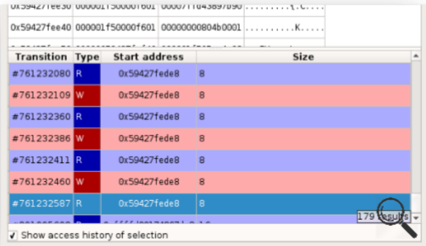
Get to the root cause quickly, assess if a vulnerability is exploitable, bypass complex malware protections, and get full visibility of the kernel as well as multi-process software.

a - Data tainting



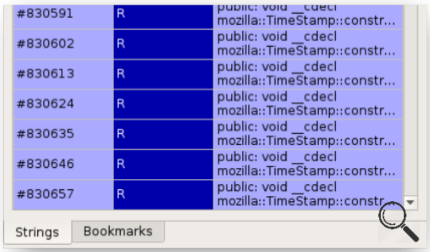
The state of art taint analysis automates the task of following targeted data from memory buffers and registers. When performing a backward taint, you will be able to find the origin of the tainted data. The taint view follows the data flow in the trace, either forward or backward, system wide, and through billions of instructions.

b - Memory History



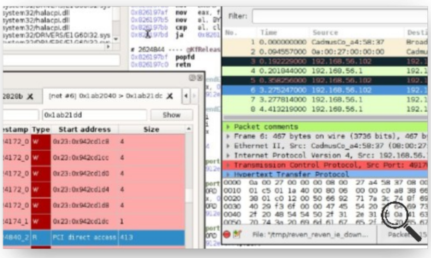
Instantly view the exhaustive access history of a selected memory buffer through billions of instructions.

c - String View



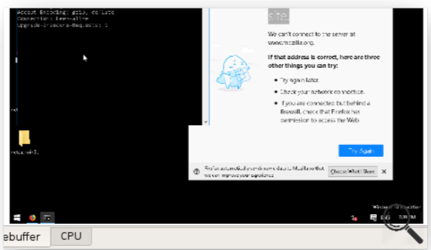
Find and see dynamic strings as easily as you do with static strings. This could be the data recieved from the network, decrypted text or encrypted CnC URL from malware. If it's in clear text at anytime of execution in memory, you will see it in seconds.

d - Integrated with RE Tools



Python API and seamless integration with IDA, Windbg, Wireshark, GDB, Volatility, and more.

e - Framebuffer view



You can review what was on the screen at any point in time.

- END -