GhostRace: Exploiting and Mitigating Speculative Race Conditions

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VUSec

IBM Research | Zurich

In This Talk

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- Speculative Race Condition

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- Inter-Process Interrupt Storming

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- Gadget Scanner (1200+)

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- Speculative Race Condition
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- Gadget Scanner (1200+)
- PoC Exploit (12KB/s)




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- Speculative Race Condition
- Inter-Process Interrupt Storming
- Gadget Scanner (1200+)
- PoC Exploit (12KB/s)
- Mitigation (5%)

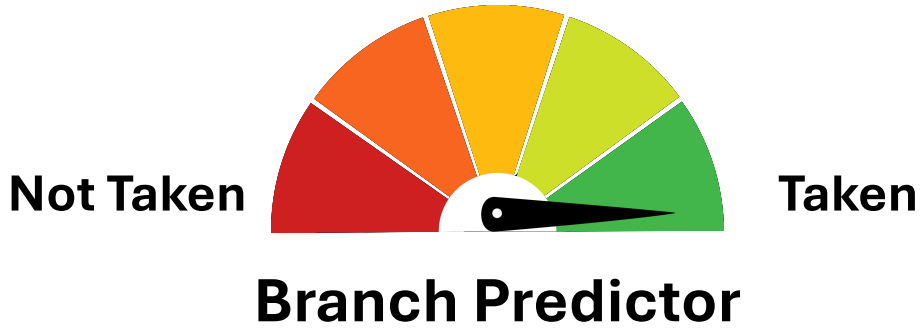




Background

Spectre v1

```
if (condition){
    ...
}
```

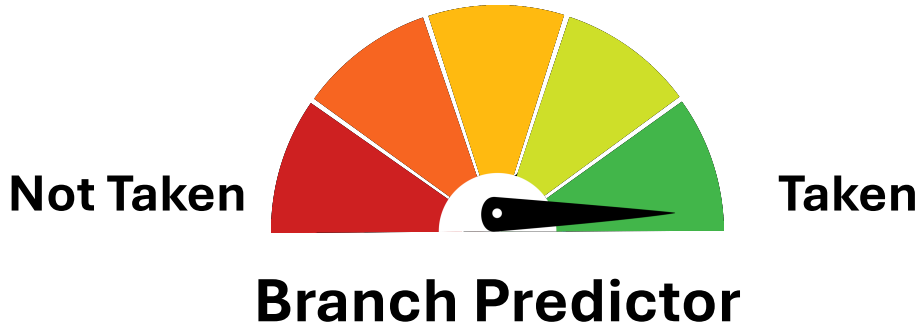


Background

Spectre v1

Conditional Branch Misprediction

```
if (condition){
    ...
}
```



Background

Concurrency Bugs

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Concurrency Bugs

SHARED DATA

```
struct A{

  struct B* Bptr;
}
```

```
struct B{
  void (*fptr)(...);
  void *arg;
}
```

Background

Concurrency Bugs

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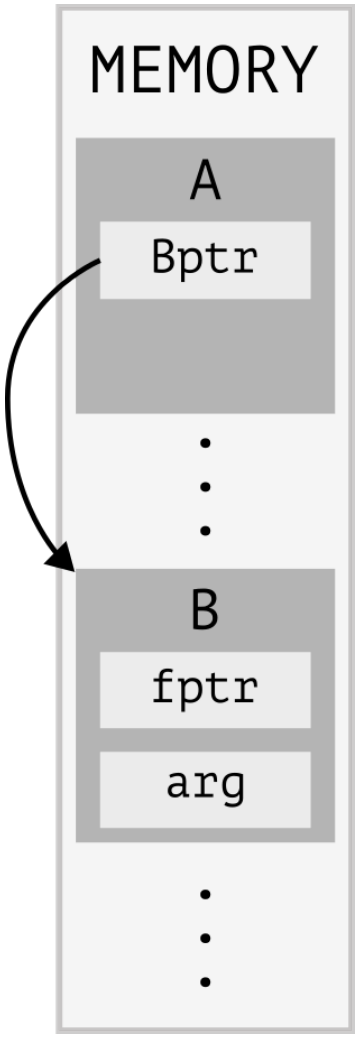

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Concurrency Bugs

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```
struct A{
   struct B* Bptr;
}
```

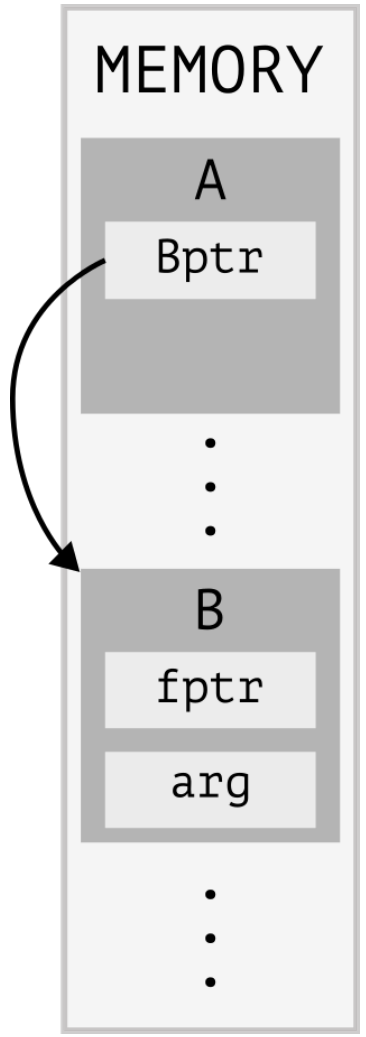
```
struct B{
  void (*fptr)(...);
  void *arg;
}
```

THREAD 1

```
func(A_ptr){

  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;

}
```



Background

Concurrency Bugs

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struct A{
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```
struct B{
  void (*fptr)(...);
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}
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  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;

}
```
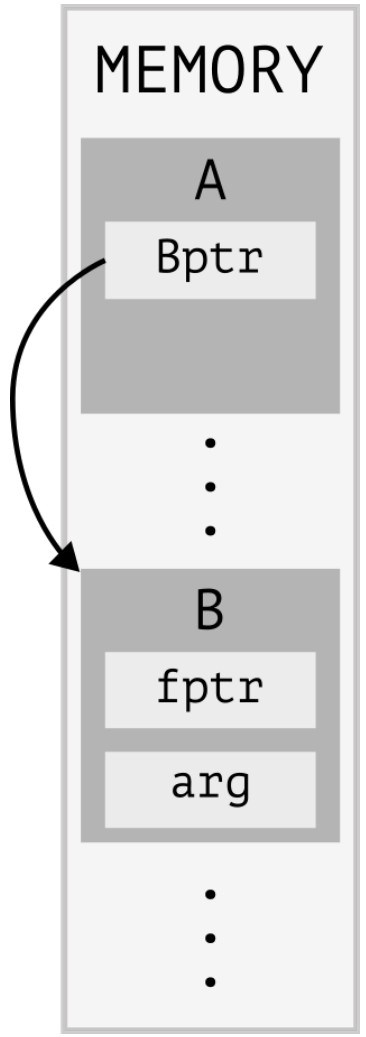

THREAD 2

```
func(A_ptr){

  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;

}
```



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Concurrency Bugs

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```
struct A{
   struct B* Bptr;
}
```

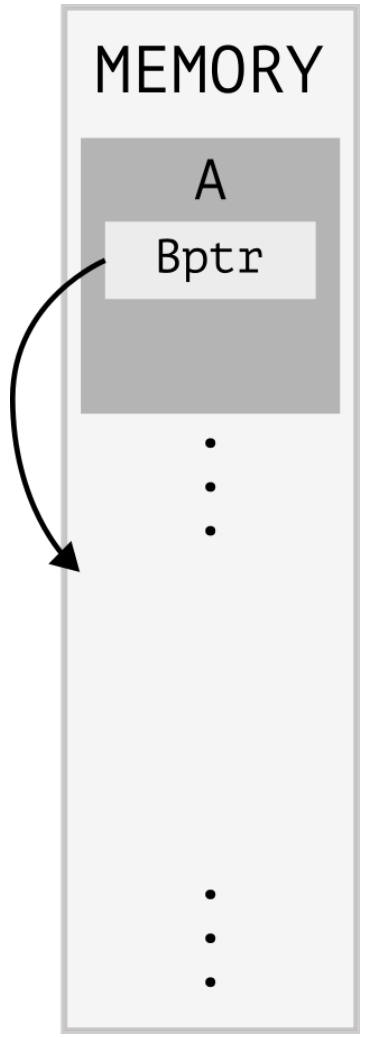
```
struct B{
  void (*fptr)(...);
  void *arg;
}
```

THREAD 1

```
func(A_ptr){

  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;

}
```

THREAD 2

```
func(A_ptr){

  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;

}
```



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Concurrency Bugs

SHARED DATA

```
struct A{
   struct B* Bptr;
}
```

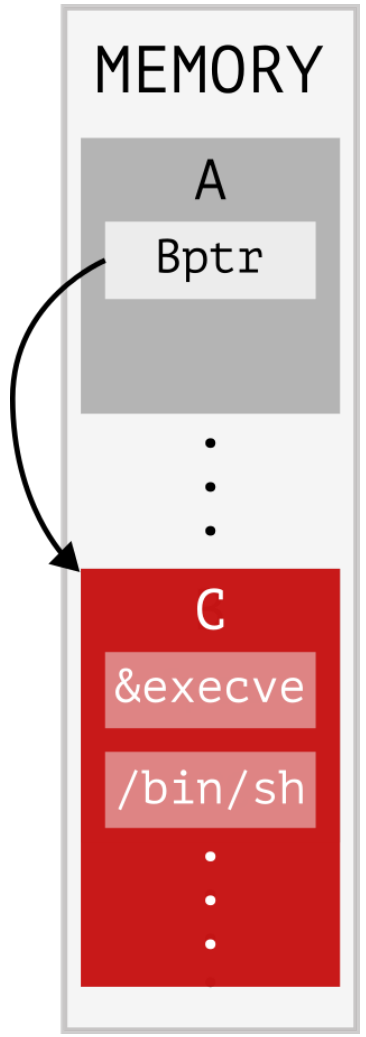
```
struct B{
  void (*fptr)(...);
  void *arg;
}
```

THREAD 1

```
func(A_ptr){

  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;

}
```

THREAD 2

```
func(A_ptr){

  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;

}
```



Concurrent Use-After-Free Attack

SHARED DATA

```
struct A{
   struct B* Bptr;
}
```

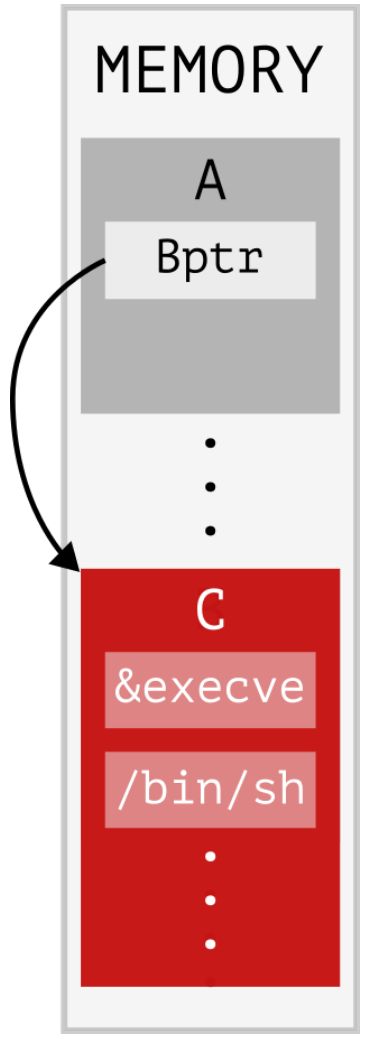
```
struct B{
  void (*fptr)(...);
  void *arg;
}
```

THREAD 1

```
func(A_ptr){

  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;

}
```

THREAD 2

```
func(A_ptr){

  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;

}
```



Background

Concurrency Bugs

SHARED DATA

```
struct A{
  struct mutex m;
  struct B* Bptr;
}
```

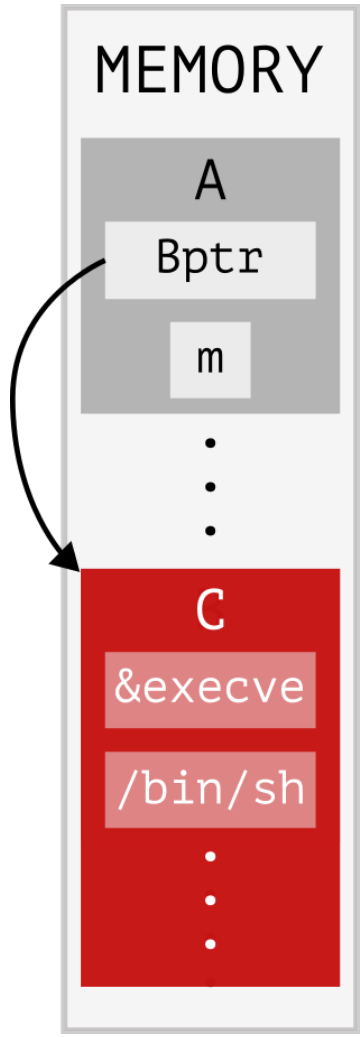
```
struct B{
  void (*fptr)(...);
  void *arg;
}
```

THREAD 1

```
func(A_ptr){
  mutex_lock(&Aptr->m);
  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;
  mutex_unlock(&Aptr->m);
}
```

THREAD 2

```
func(A_ptr){
  mutex_lock(&Aptr->m);
  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;
  mutex_unlock(&Aptr->m);
}
```



Background

Concurrency Bugs

SHARED DATA

```
struct A{
  struct mutex m;
  struct B* Bptr;
}
```

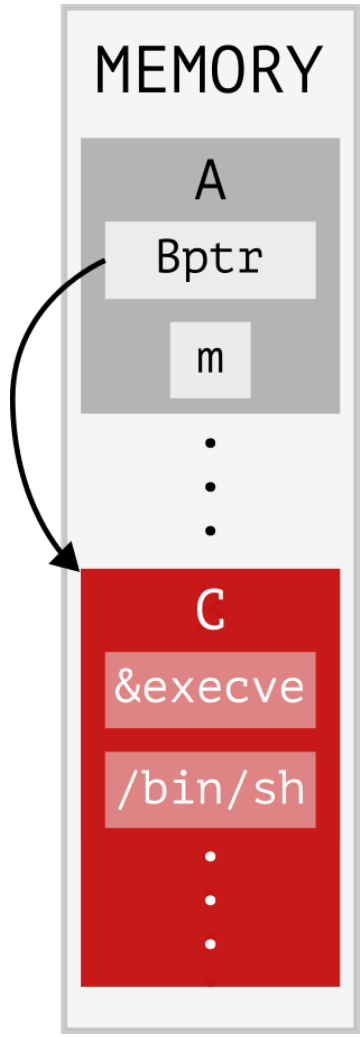
```
struct B{
  void (*fptr)(...);
  void *arg;
}
```

THREAD 1

```
func(A_ptr){
  mutex_lock(&Aptr->m);
  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;
  mutex_unlock(&Aptr->m);
}
```

THREAD 2

```
func(A_ptr){
  mutex_lock(&Aptr->m);
  if(Aptr->Bptr->fptr){
    Aptr->Bptr->fptr(arg);
  }
  kfree(Aptr->Bptr);
  Aptr->Bptr = NULL;
  mutex_unlock(&Aptr->m);
}
```



Race Free Critical Region

SHARED DATA

```
struct A{
   struct mutex m;
   struct B* Bptr;
}
```

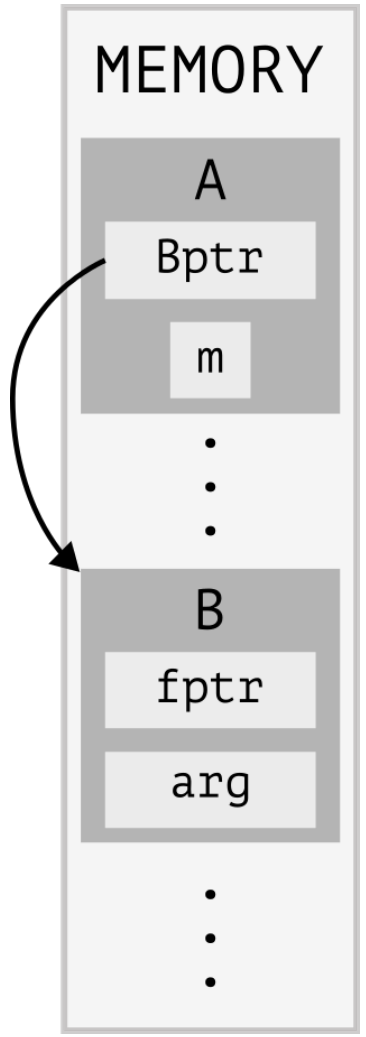
```
struct B{
  void (*fptr)(...);
  void *arg;
}
```

THREAD 1

```
func(A_ptr){
  mutex_lock(&Aptr->m);
   if(Aptr->Bptr->fptr){
      Aptr->Bptr->fptr(arg);
   }
   kfree(Aptr->Bptr);
   Aptr->Bptr = NULL;
  mutex_unlock(&Aptr->m);
}
```

THREAD 2

```
func(A_ptr){
  mutex_lock(&Aptr->m);
   if(Aptr->Bptr->fptr){
      Aptr->Bptr->fptr(arg);
   }
   kfree(Aptr->Bptr);
   Aptr->Bptr = NULL;
  mutex_unlock(&Aptr->m);
}
```



Real Example

NFC Gadget

SHARED DATA

```
struct nfc_hci_dev {
   ...
   struct mutex msg_tx_mutex;
   ...
   struct hci_msg* cmd_pending_msg;
   ...
}
```

```
struct hci_msg {
   ...
   void (*cb)(...);
   void *cb_context;
   ...
}
```

THREAD 1

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

THREAD 2

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

How do synchronization primitives behave during speculative execution?

How do synchronization primitives behave during speculative execution?

What are the security implications for modern operating systems?

Objective

SHARED DATA

```
struct nfc_hci_dev {
   ...
   struct mutex msg_tx_mutex;
   ...
   struct hci_msg* cmd_pending_msg;
   ...
}
```

```
struct hci_msg {
   ...
   void (*cb)(...);
   void *cb_context;
   ...
}
```

THREAD 1

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

THREAD 2

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

Objective

Speculatively Hijack The Control-Flow

```
struct nfc_hc
   ...
   struct mute
   ...
   struct hci_
   ...
}
```

```
) {
...);
ntext;
```

THREAD 1

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
        hdev->cmd_pending_msg->
        cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

THREAD 2

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
        hdev->cmd_pending_msg->
        cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

UAF Attack Challenges

SHARED DATA

```
struct nfc_hci_dev {
   ...
   struct mutex msg_tx_mutex;
   ...
   struct hci_msg* cmd_pending_msg;
   ...
}
```

```
struct hci_msg {
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   void (*cb)(...);
   void *cb_context;
   ...
}
```

THREAD 1

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

THREAD 2

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

UAF Attack Challenges

1. Bypass The Sync. Primitive

SHARED DATA

```
struct nfc_hci_dev {
   ...
   struct mutex msg_tx_mutex;
   ...
   struct hci_msg* cmd_pending_msg;
   ...
}
```

```
struct hci_msg {
   ...
   void (*cb)(...
   void *cb_contex
   ...
}
```

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```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

THREAD 2

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

UAF Attack Challenges

1. Bypass The Sync. Primitive

2. Create an Exploitation Window

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```
struct nfc_hci_dev {
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   struct mutex msg_tx_mutex;
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   ...
}
```

```
struct hci_msg {
   ...
   void (*cb)(...
   void *cb_contex
   ...
}
```

THREAD 1

```
fc_hci_msg_tx_work(hdev){
 ...
 mutex_lock(&hdev->msg_tx_mutex);
 if(hdev->cmd_pending_msg->cb){
    hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
 }
 kfree(hdev->cmd_pending_msg);
 hdev->cmd_pending_msg = NULL;
 ...
 mutex_unlock(&hdev->msg_tx_mutex);
}
```

THREAD 2

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
        hdev->cmd_pending_msg->
        cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

UAF Attack Challenges

1. Bypass The Sync. Primitive

2. Create an Exploitation Window

3. Reallocate The Freed Memory With a Malicious Object

```
struct nfc_hci
  ...
  struct mute
  ...
  struct hci_
  ...
}
```

```
msg {
)(...
_contex
```

```
fc_hci_msg_tx_work(hdev){
...
mutex_lock(&hdev->msg_tx_mutex);
if(hdev->cmd_pending_msg->cb){
   hdev->cmd_pending_msg->cb(
     hdev->cmd_pending_msg->
     cb_context, NULL, -ETIME);
}
kfree(hdev->cmd_pending_msg);
hdev->cmd_pending_msg = NULL;
...
mutex_unlock(&hdev->msg_tx_mutex);
}
```

```
nfc_hci_msg_tx_work(hdev){
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  mutex_lock(&hdev->msg_tx_mutex);
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     hdev->cmd_pending_msg->cb(
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```
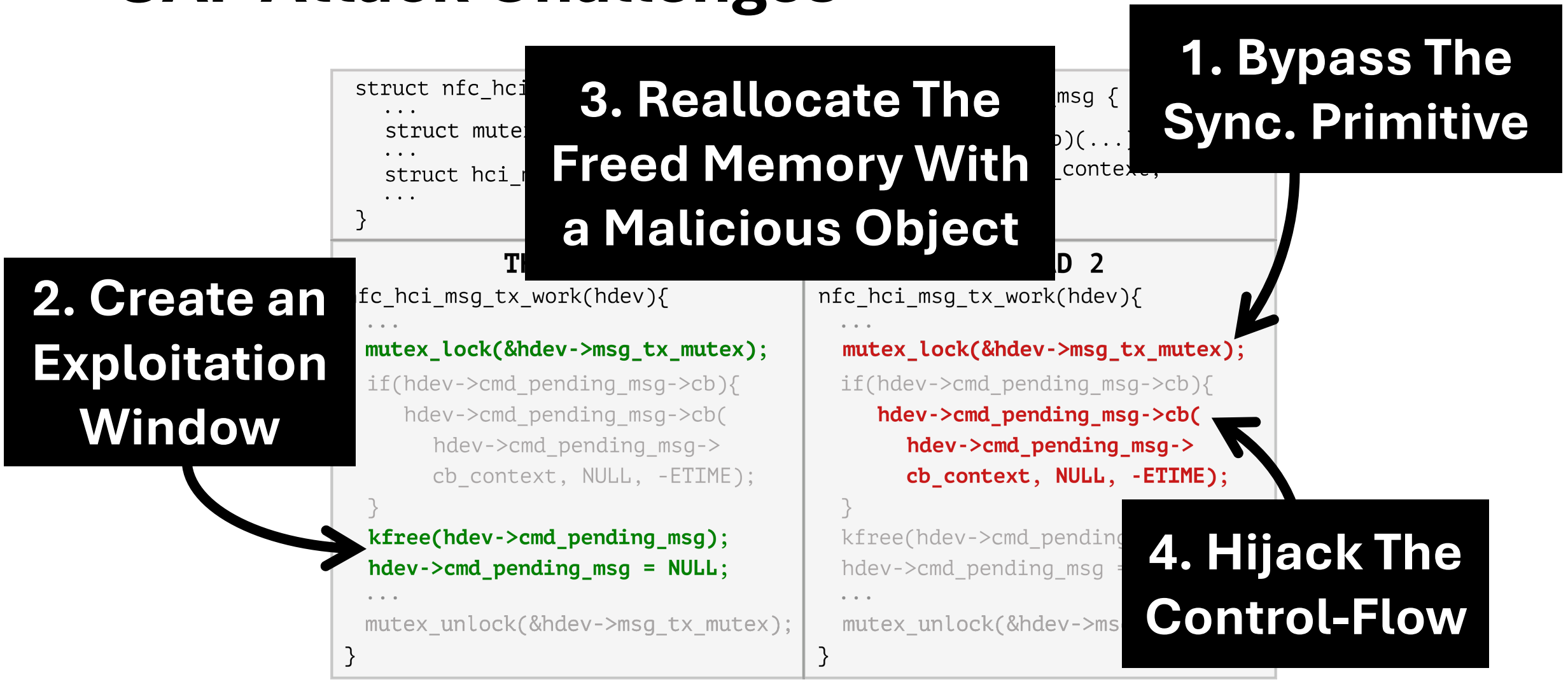

UAF Attack Challenges



UAF Attack Challenges

1. Bypass The Sync. Primitive

2. Create an Exploitation Window

SHARED DATA

```
struct nfc_hci_dev {
   ...
   struct mutex msg_tx_mutex;
   ...
   struct hci_msg* cmd_pending_msg;
   ...
}
```

```
struct hci_msg {
   ...
   void (*cb)(...
   void *cb_contex
   ...
}
```

THREAD 1

```
fc_hci_msg_tx_work(hdev){
 ...
 mutex_lock(&hdev->msg_tx_mutex);
 if(hdev->cmd_pending_msg->cb){
    hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
 }
 kfree(hdev->cmd_pending_msg);
 hdev->cmd_pending_msg = NULL;
 ...
 mutex_unlock(&hdev->msg_tx_mutex);
}
```

THREAD 2

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
        hdev->cmd_pending_msg->
        cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

UAF Attack Challenges

1. Bypass The Sync. Primitive

SHARED DATA

```
struct nfc_hci_dev {
   ...
   struct mutex msg_tx_mutex;
   ...
   struct hci_msg* cmd_pending_msg;
   ...
}
```

```
struct hci_msg {
   ...
   void (*cb)(...
   void *cb_contex
   ...
}
```

THREAD 1

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

THREAD 2

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

Synchronization Primitives

Synchronization Primitives

Mutex lock on x86 arch:

- Conditional branch

```
void mutex_lock(struct mutex *lock){
  ...
  if (!__mutex_trylock_fast(lock))
    if (atomic_long_try_cmpxchg_acquire(&lock, ...))
```

Synchronization Primitives

Mutex lock on x86 arch:

- Conditional branch
- A series of inlined function calls

```
void mutex_lock(struct mutex *lock){
  ...
  if (!__mutex_trylock_fast(lock))
    if (atomic_long_try_cmpxchg_acquire(&lock, ...))
      ↳arch_atomic_long_try_cmpxchg_acquire(&lock, , ...)
        ↳arch_atomic_try_cmpxchg_acquire(&lock, , ...)
          ↳arch_atomic_try_cmpxchg(&lock, , ...)
            ↳arch_try_cmpxchg((&lock, , ...)
              ↳__raw_try_cmpxchg(ptr, ...)({
```

Synchronization Primitives

Mutex lock on x86 arch:

- Conditional branch
- A series of inlined function calls
- Atomic compare and exchange

```
void mutex_lock(struct mutex *lock){
  ...
  if (!__mutex_trylock_fast(lock))
    if (atomic_long_try_cmpxchg_acquire(&lock, ...))
      ↳arch_atomic_long_try_cmpxchg_acquire(&lock, , ...)
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                  asm volatile(
                      "lock cmpxchgq %2, %1"
                      : "=a" (ret), "+m" (*ptr)
                      : "r" (new), "0" (old)
                      : "memory"
                      );
                })
      return true;
  ...
}
```

Synchronization Primitives

Mutex lock on x86 arch:

- Conditional branch
- A series of inlined function calls
- Atomic compare and exchange

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void mutex_lock(struct mutex *lock){
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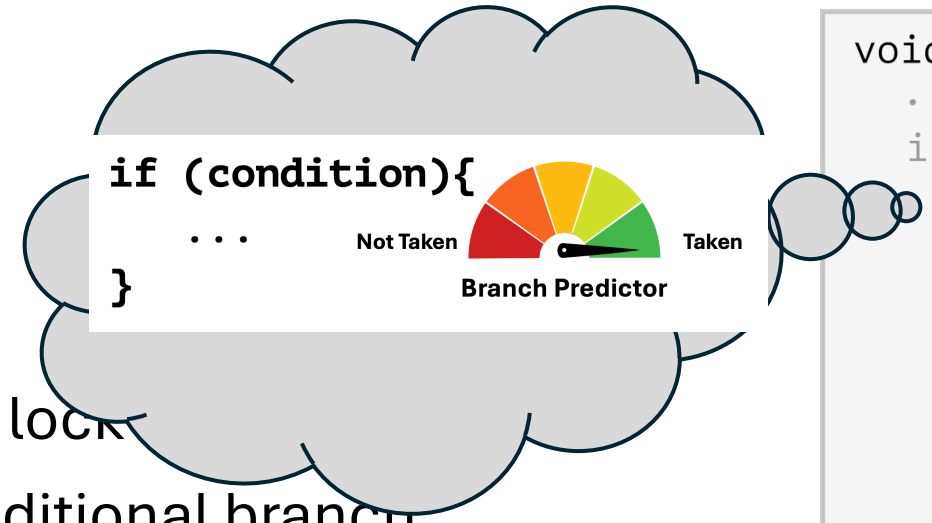
                      : "memory"
                      );
})
```

Atomic != Serializing

Synchronization Primitives



Mutex lock

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- A series of inlined function calls
- Atomic compare and exchange

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```
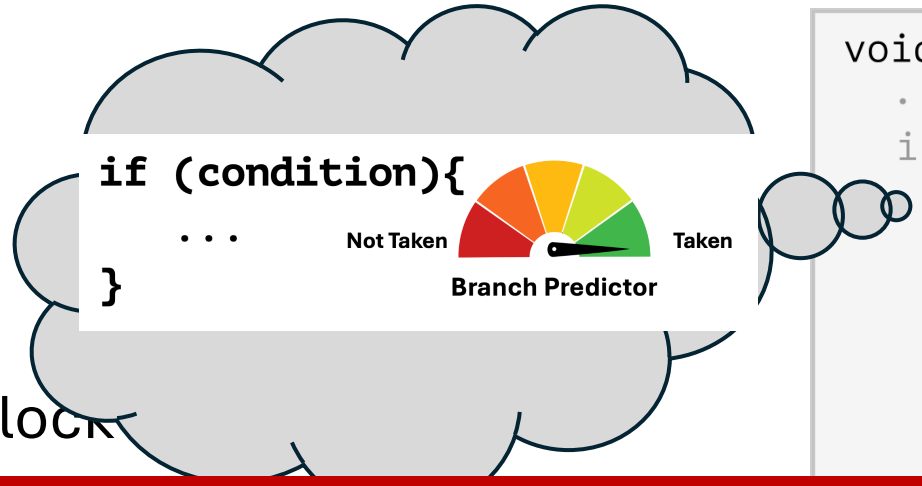

Atomic != Serializing

Synchronization Primitives



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                  : "r" (new), "0" (old)
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                  );
})
```

Speculative Race Condition

UAF Attack Challenges

1. Bypass The Sync. Primitive:
Speculative Race Condition

SHARED DATA

```
struct nfc_hci_dev {
   ...
   struct mutex msg_tx_mutex;
   ...
   struct hci_msg* cmd_pending_msg;
   ...
}
```

```
struct hci_
   ...
   void (*cb
   void *cb_
   ...
}
```

THREAD 1

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
        hdev->cmd_pending_msg->
        cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

THREAD 2

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
        hdev->cmd_pending_msg->
        cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

UAF Attack Challenges

1. Bypass The Sync. Primitive:
Speculative Race Condition

2. Create an Exploitation Window

SHARED DATA

```
struct nfc_hci_dev {
   ...
   struct mutex msg_tx_mutex;
   ...
   struct hci_msg* cmd_pending_msg;
   ...
}
```

```
struct hci_
   ...
   void (*cb
   void *cb_
   ...
}
```

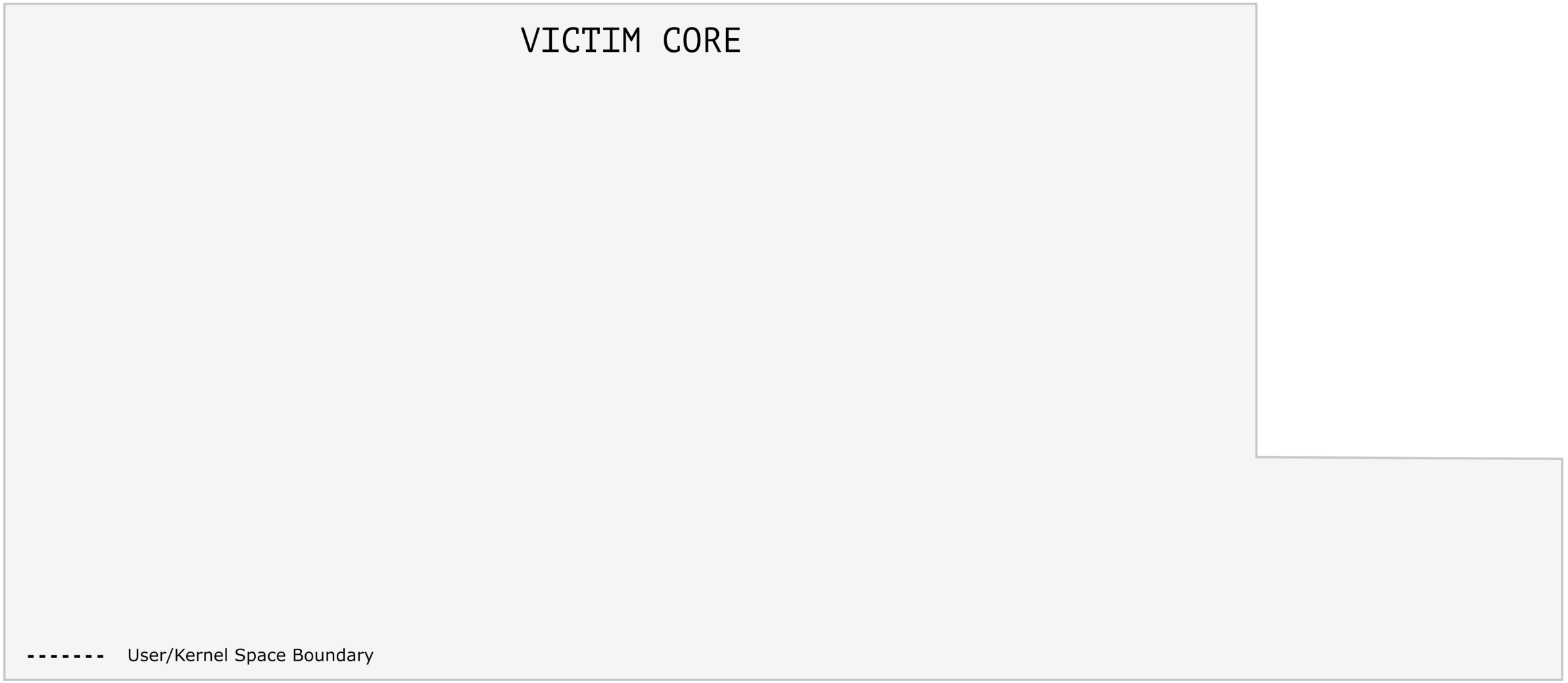
THREAD 1

```
fc_hci_msg_tx_work(hdev){
 ...
 mutex_lock(&hdev->msg_tx_mutex);
 if(hdev->cmd_pending_msg->cb){
    hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
 }
 kfree(hdev->cmd_pending_msg);
 hdev->cmd_pending_msg = NULL;
 ...
 mutex_unlock(&hdev->msg_tx_mutex);
}
```

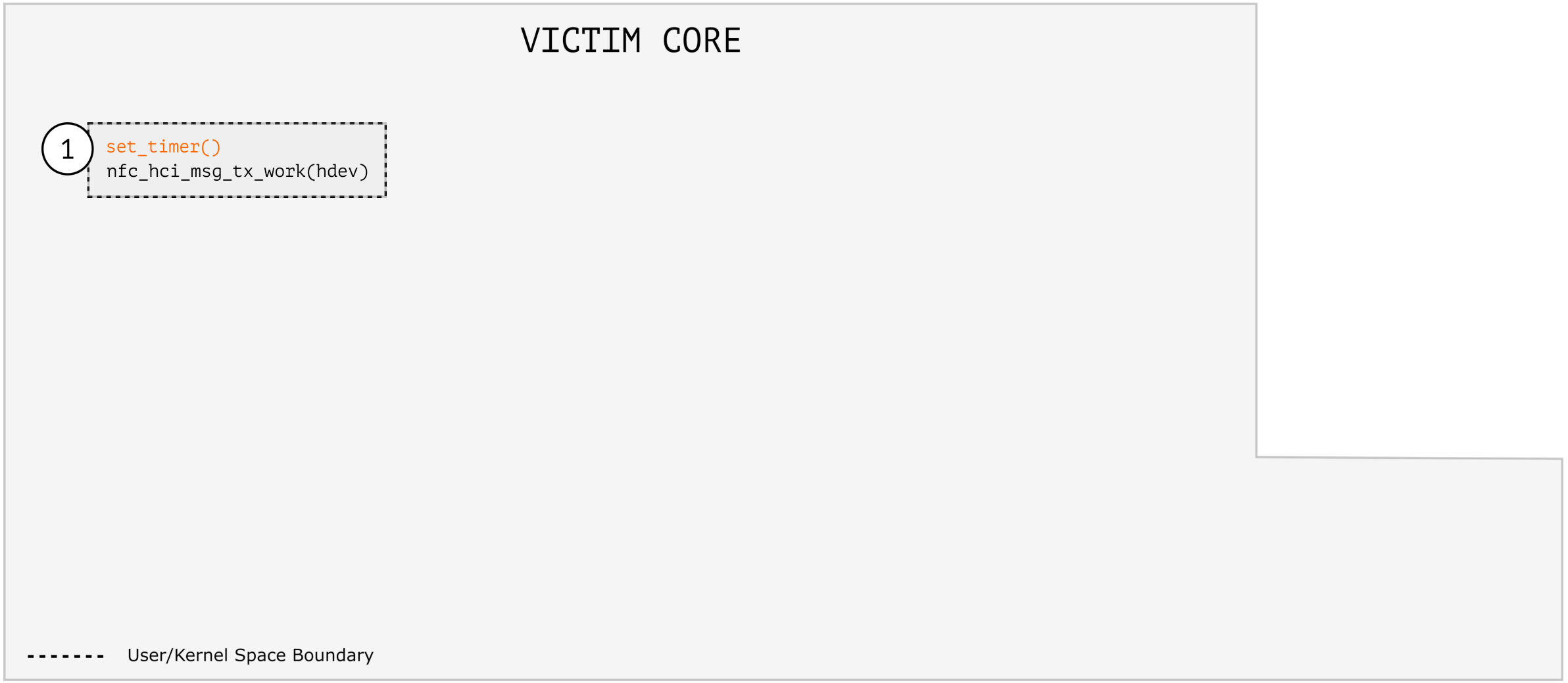
THREAD 2

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
        hdev->cmd_pending_msg->
        cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

Creating UAF Exploitation Window



Creating UAF Exploitation Window



Creating UAF Exploitation Window

VICTIM CORE

1 `set_timer()`
`nfc_hci_msg_tx_work(hdev)`

```
nfc_hci_msg_tx_work(hdev){
  ...
  mutex_lock(&hdev->msg_tx_mutex);
  if(hdev->cmd_pending_msg->cb){
     hdev->cmd_pending_msg->cb(
       hdev->cmd_pending_msg->
       cb_context, NULL, -ETIME);
  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```

------- User/Kernel Space Boundary

Creating UAF Exploitation Window

VICTIM CORE

1 `set_timer()`
`nfc_hci_msg_tx_work(hdev)`

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nfc_hci_msg_tx_work(hdev){
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  }
  kfree(hdev->cmd_pending_msg);
  hdev->cmd_pending_msg = NULL;
  ...
  mutex_unlock(&hdev->msg_tx_mutex);
}
```
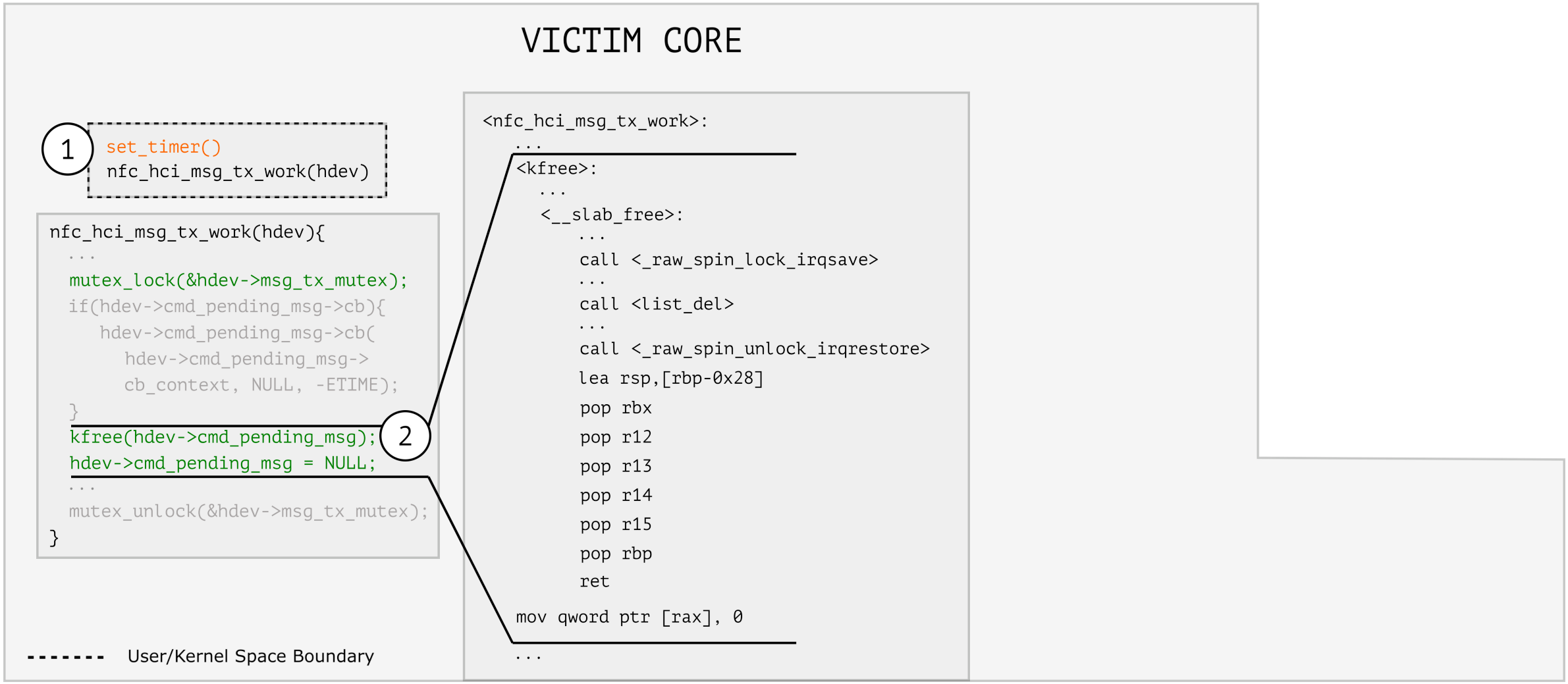

2

------- User/Kernel Space Boundary

Creating UAF Exploitation Window



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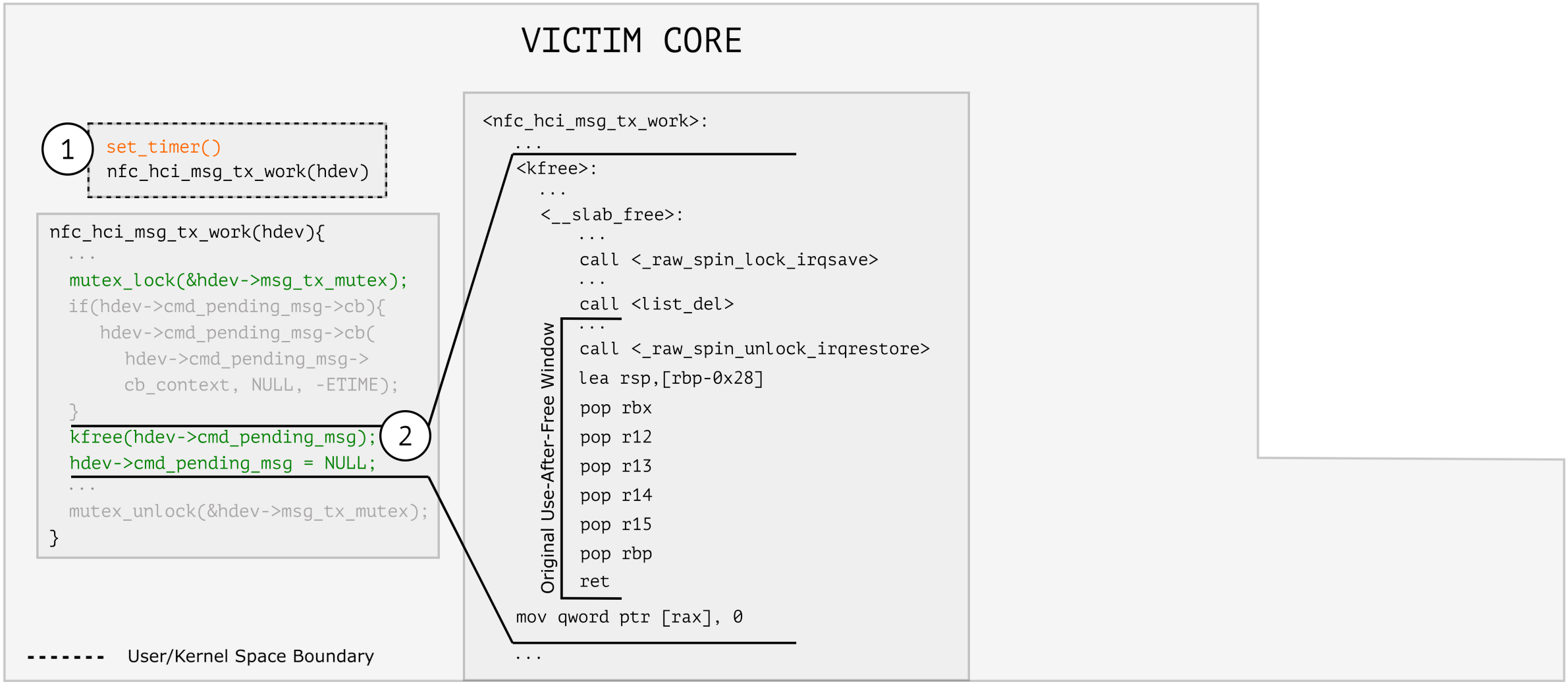

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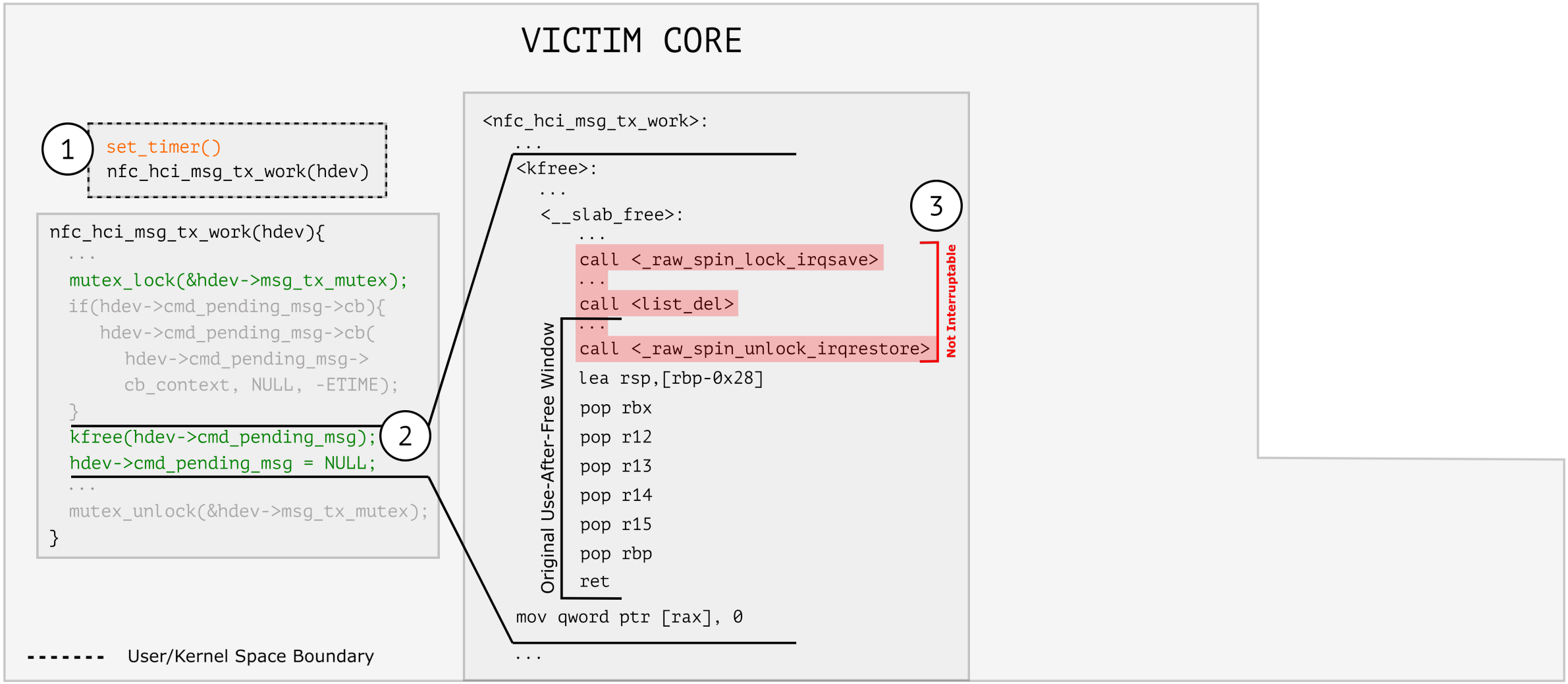

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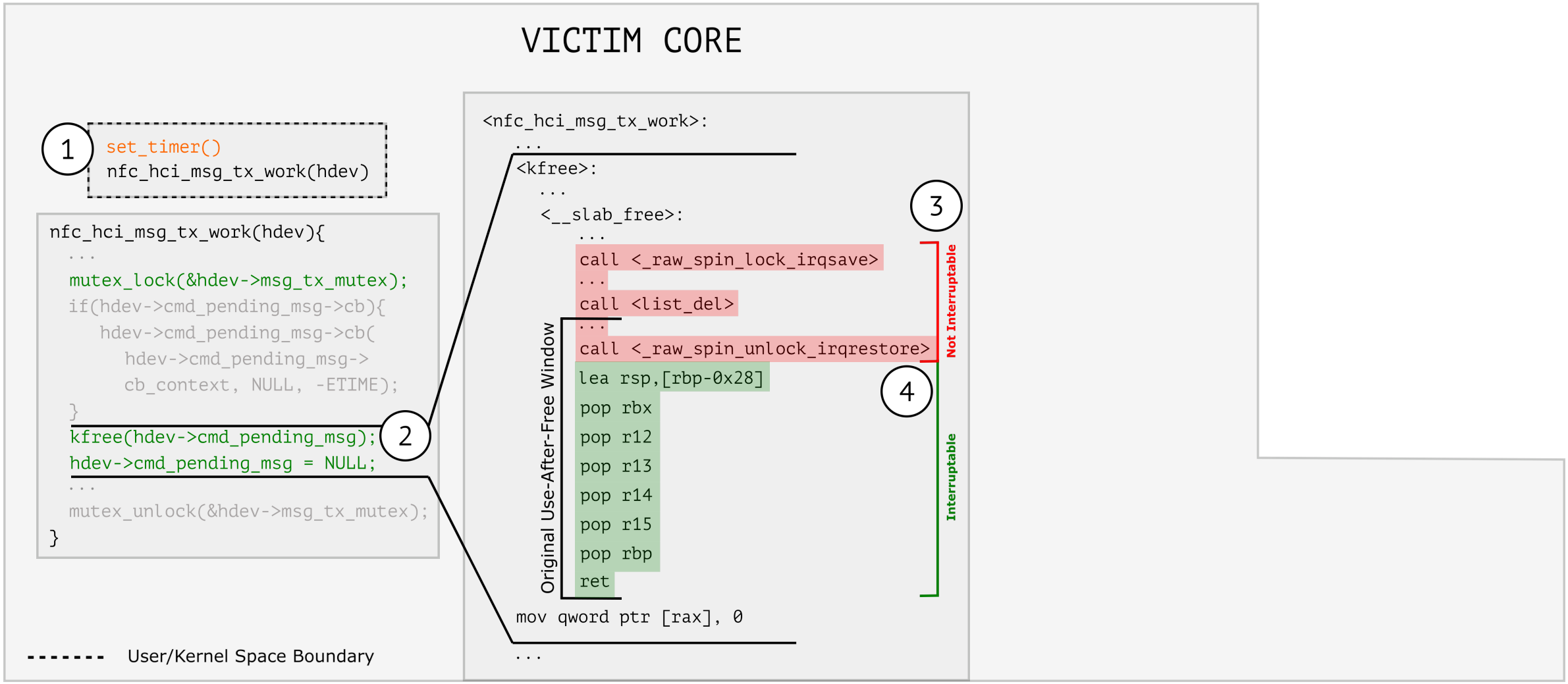
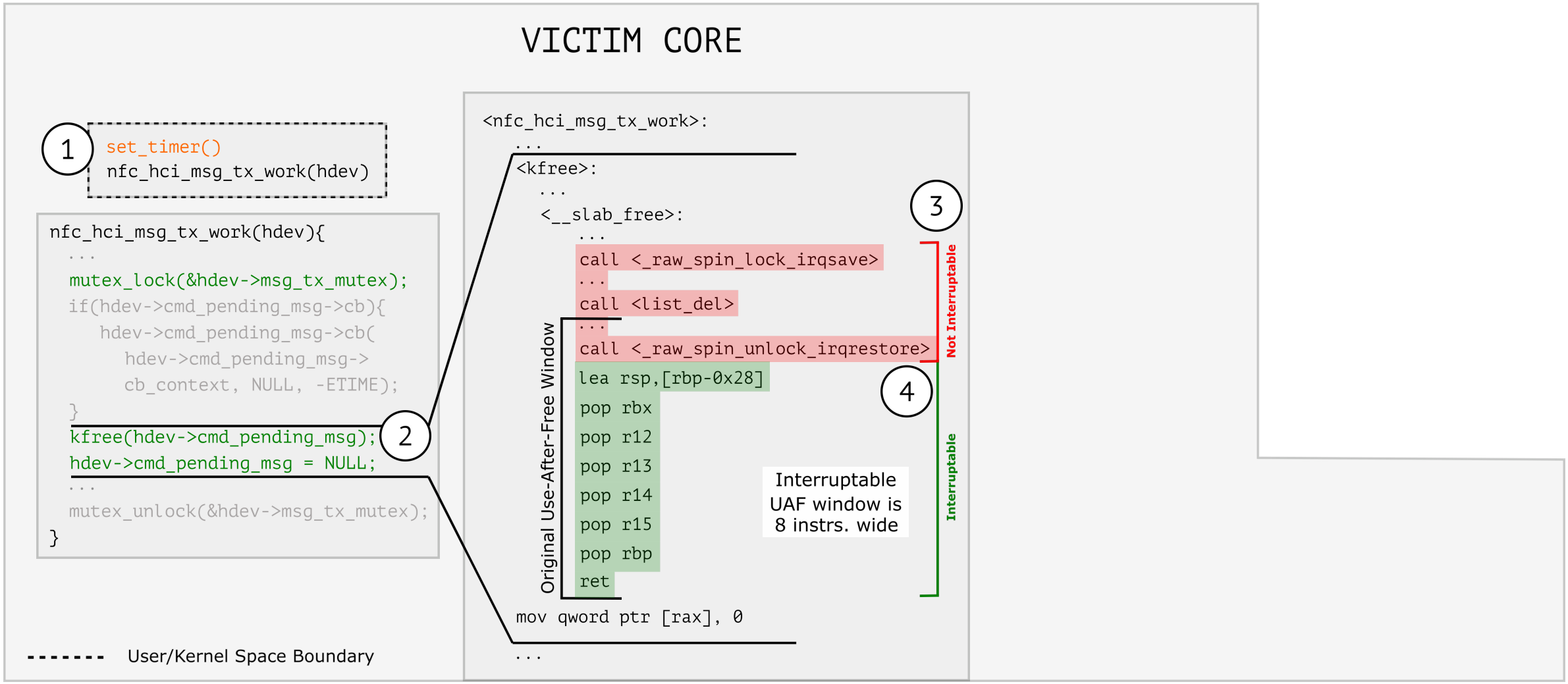


Creating UAF Exploitation Window



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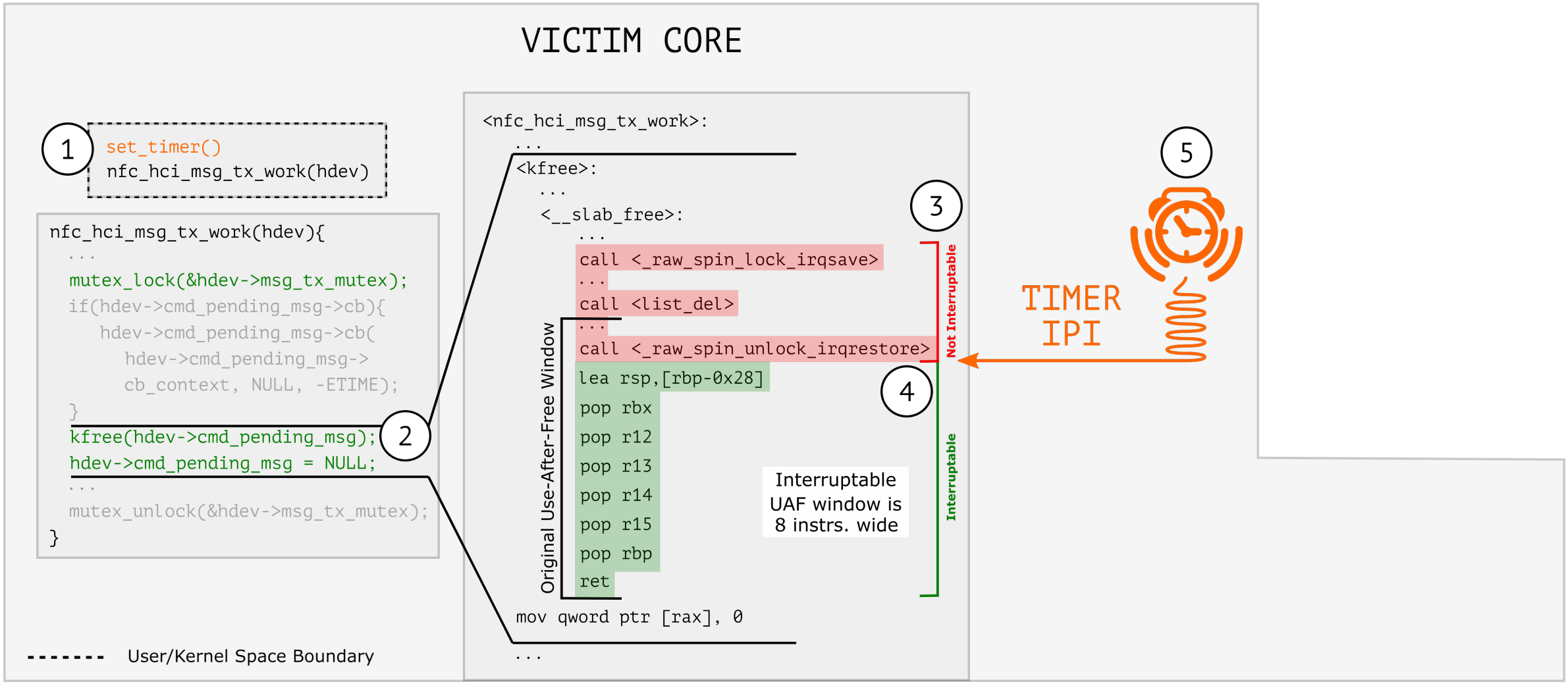

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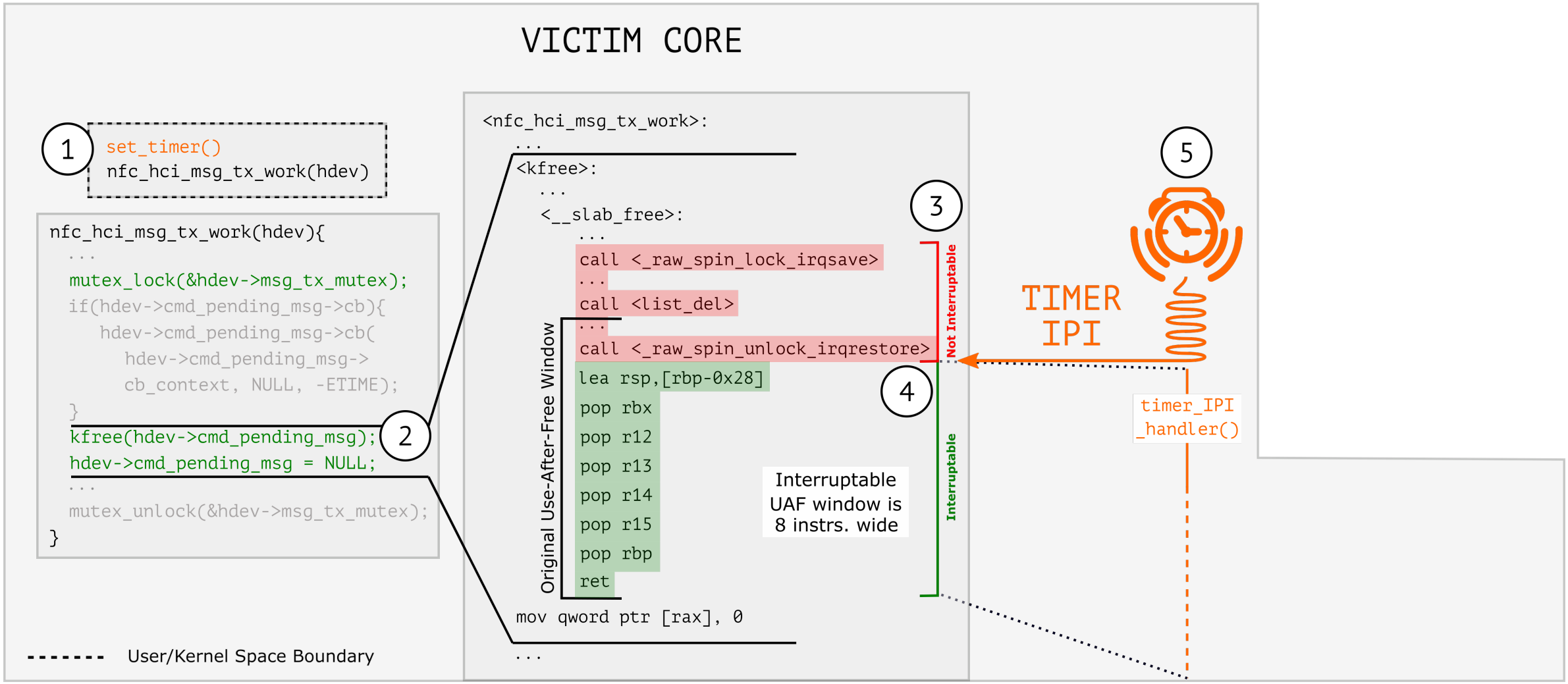

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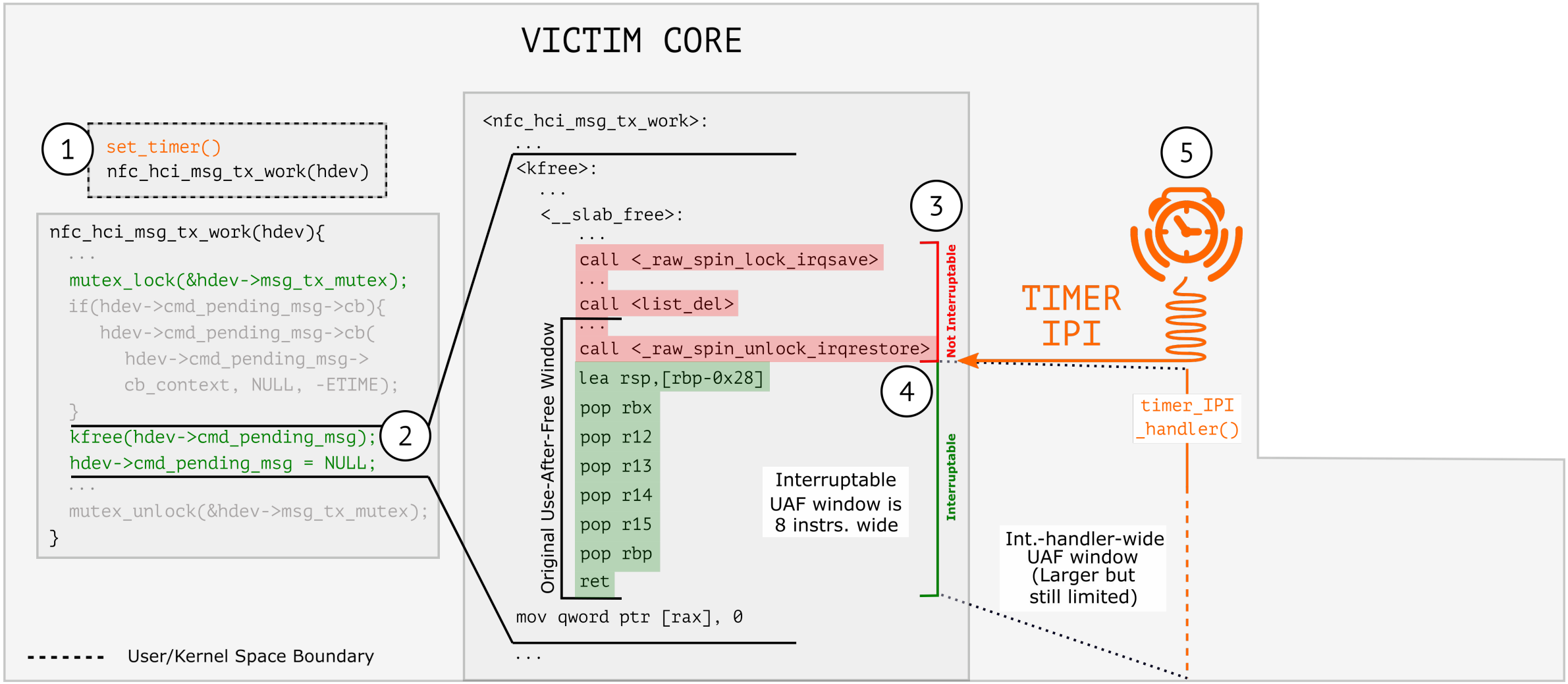

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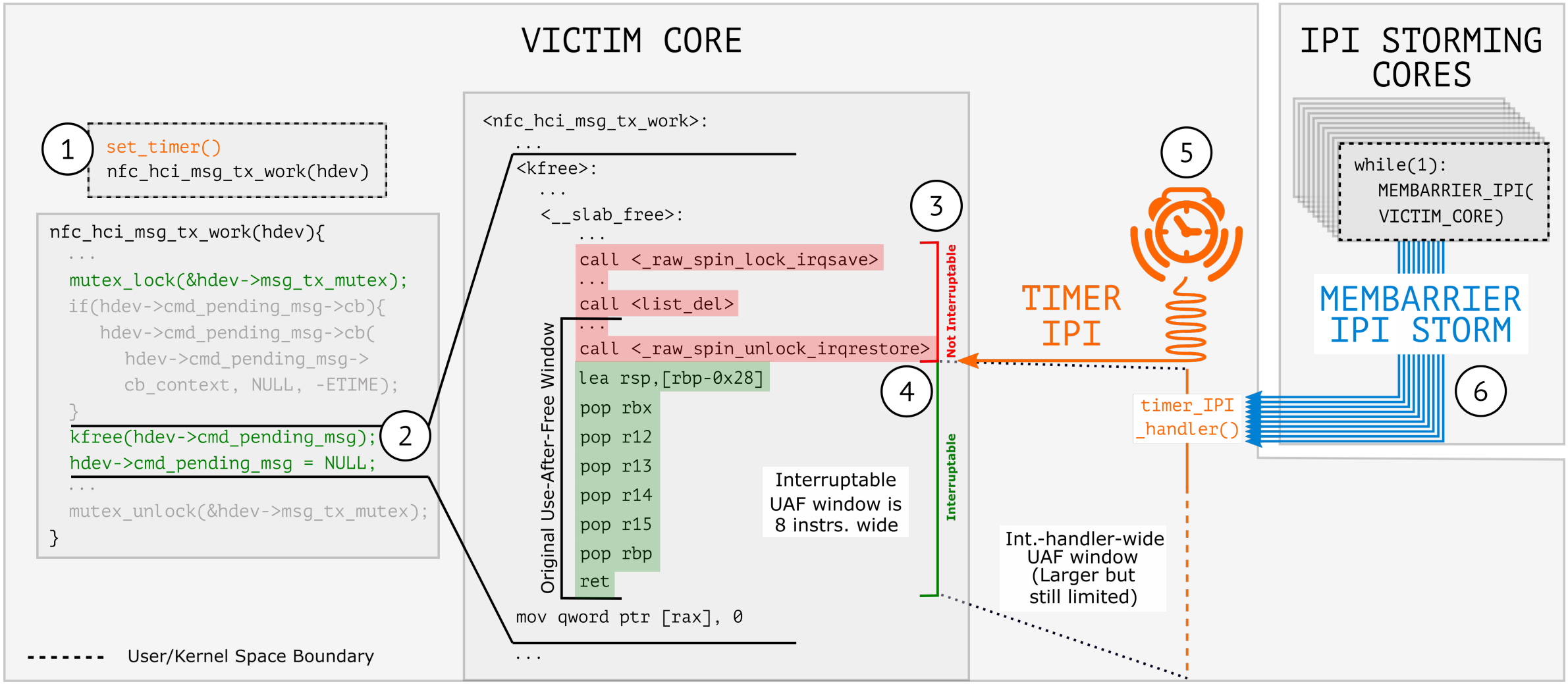

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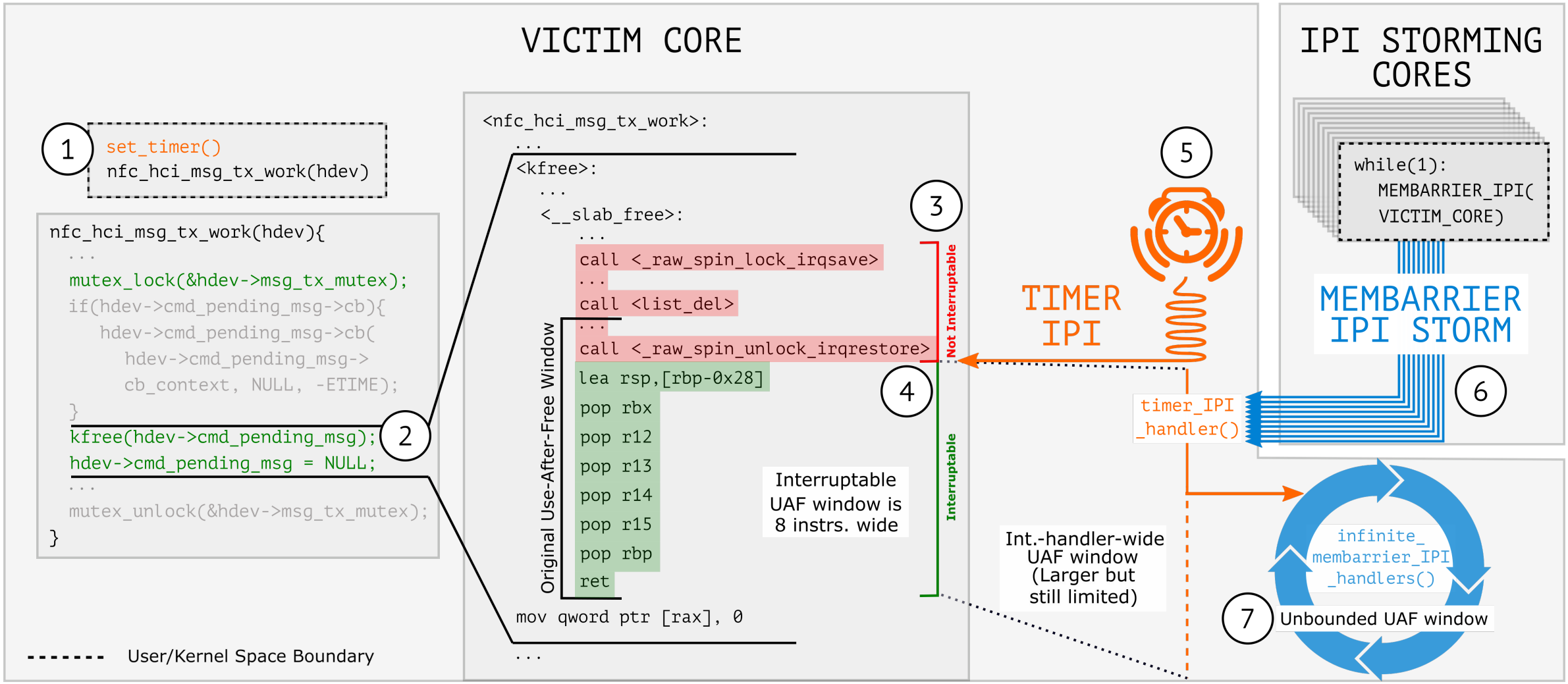

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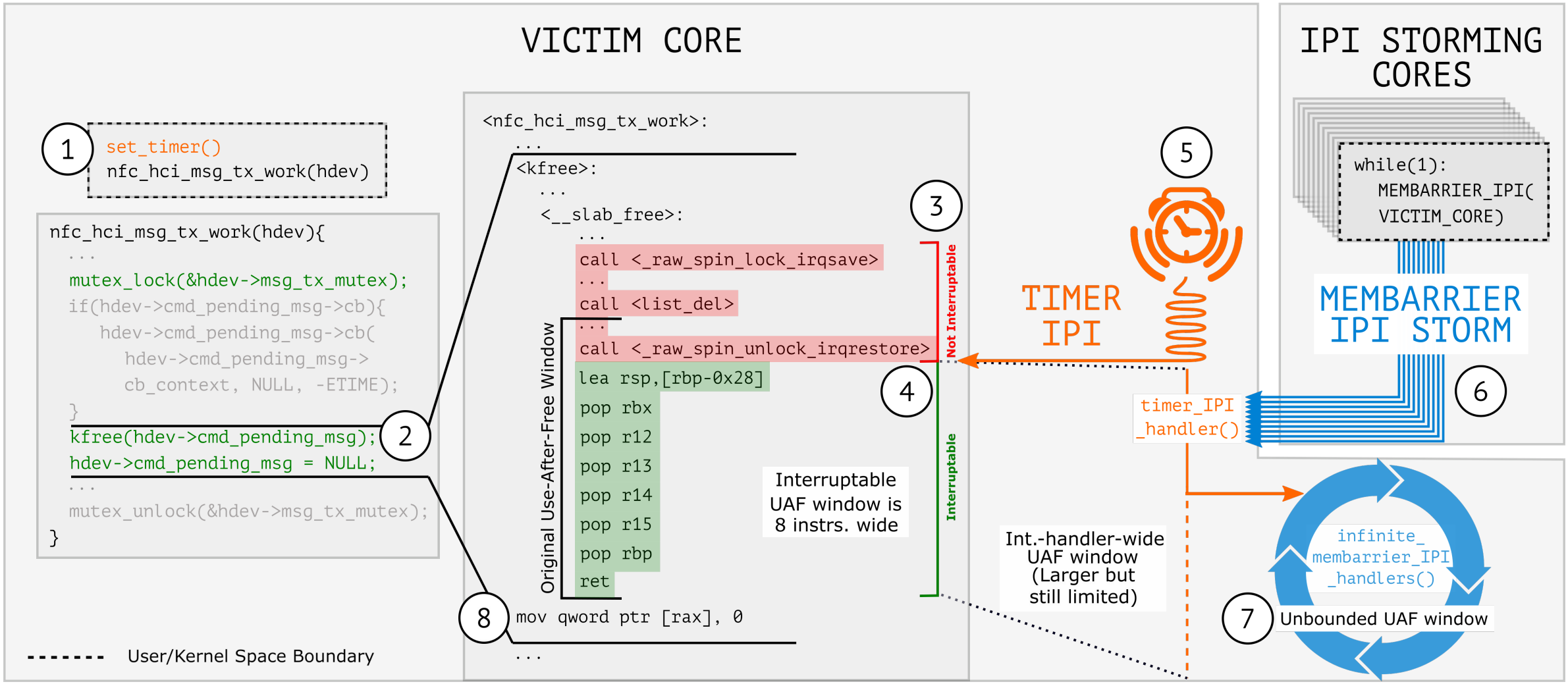

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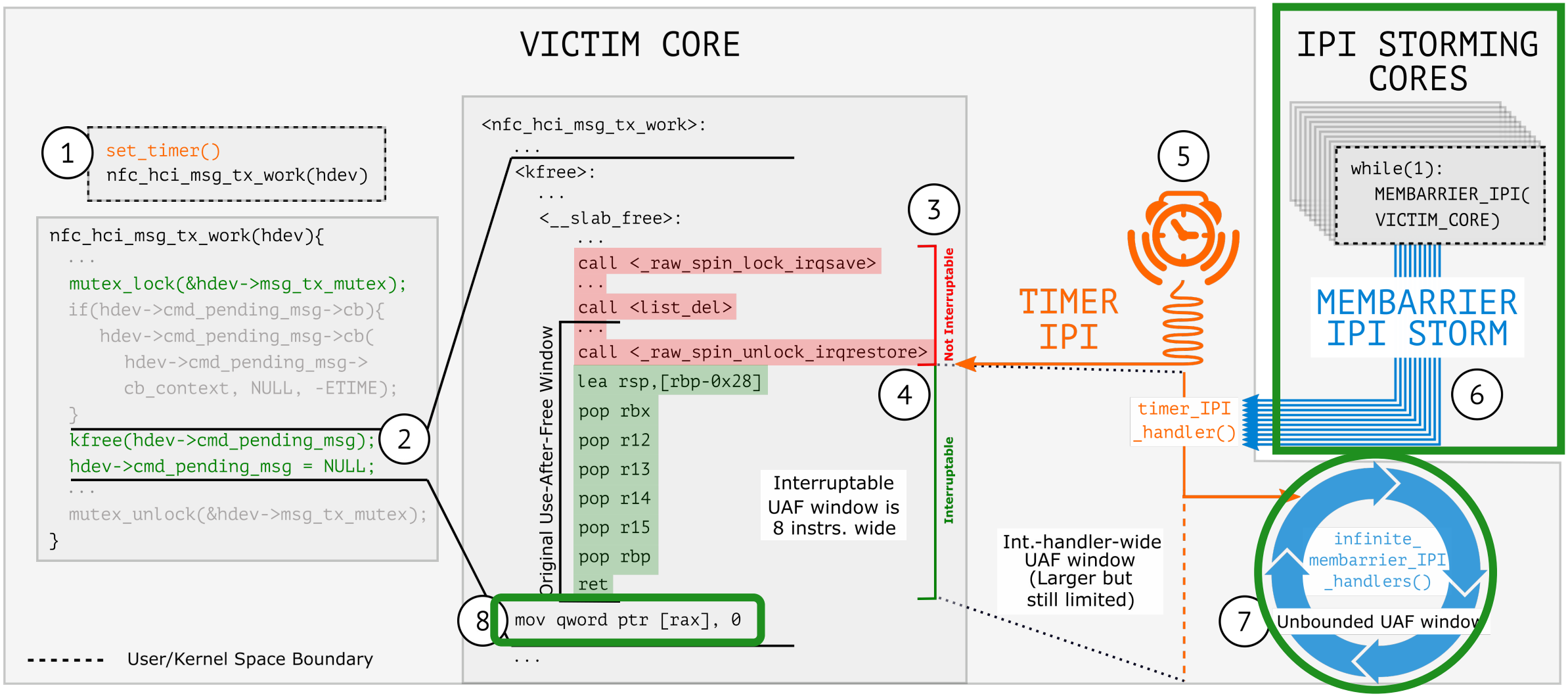

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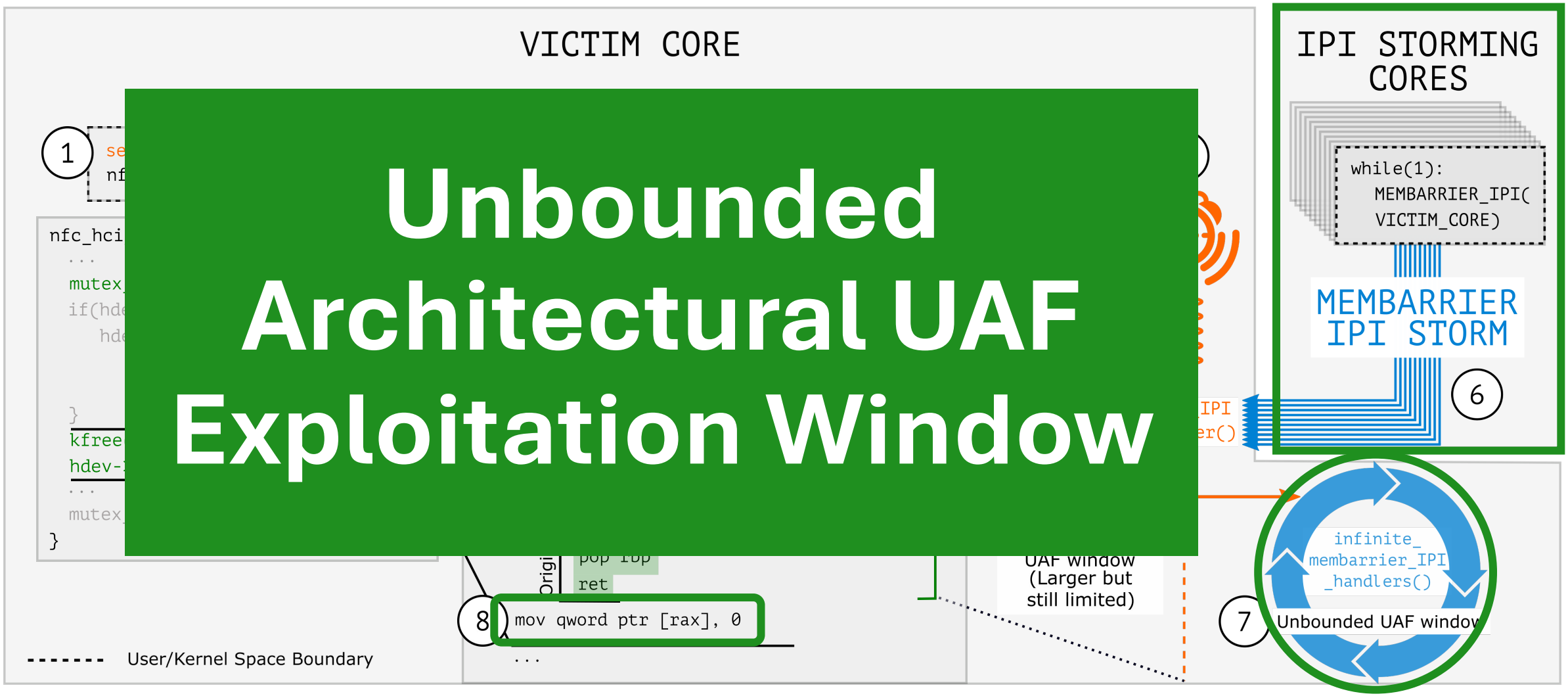

UAF Attack Challenges

1. Bypass The Sync. Primitive:
Speculative Race Condition

2. Create an Exploitation Window:
IPI Storming

SHARED DATA

```
struct nfc_hci_dev {
   ...
   struct mutex msg_tx_mutex;
   ...
   struct hci_msg* cmd_pending_msg;
   ...
}
```

```
struct hci_
   ...
   void (*cb
   void *cb_
   ...
}
```

THREAD 1

```
i_msg_tx_work(hdev){

x_lock(&hdev->msg_tx_mutex);
dev->cmd_pending_msg->cb){
dev->cmd_pending_msg->cb(
  hdev->cmd_pending_msg->
  cb_context, NULL, -ETIME);
 }
 kfree(hdev->cmd_pending_msg);
 hdev->cmd_pending_msg = NULL;
 ...
 mutex_unlock(&hdev->msg_tx_mutex);
}
```

THREAD 2

```
nfc_hci_msg_tx_work(hdev){
 ...
 mutex_lock(&hdev->msg_tx_mutex);
 if(hdev->cmd_pending_msg->cb){
    hdev->cmd_pending_msg->cb(
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      cb_context, NULL, -ETIME);
 }
 kfree(hdev->cmd_pending_msg);
 hdev->cmd_pending_msg = NULL;
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```

UAF Attack Challenges

1. Bypass The Sync. Primitive:
Speculative Race Condition

3. Reallocate The Freed Memory:
msgsnd syscall

2. Create an Exploitation Window:
IPI Storming

4. Hijack The Control-Flow:
Speculatively Execute A Controlled Disclosure Gadget

```
struct nfc_
   ...
   struct m
   ...
   struct h
   ...
}
```

```
t hci_
id (*cb
id *cb_
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  cb_context, NULL, -ETIME);
}
kfree(hdev->cmd_pending_msg
hdev->cmd_pending_msg = NUL
...
mutex_unlock(&hdev->msg_tx_
}
```

THREAD 2

```
nfc_hci_msg_tx_work(hdev){
...
mutex_lock(&hdev->msg_tx_mutex);
if(hdev->cmd_pending_msg->cb){
   hdev->cmd_pending_msg->cb(
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```

Speculative Concurrent Use-After-Free Attack

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}
```

THREAD 2

```
nfc_hci_msg_tx_work(hdev){
...
mutex_lock(&hdev->msg_tx_mutex);
if(hdev->cmd_pending_msg->cb){
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```

Linux Kernel Attack Surface

Linux Kernel Attack Surface

- Gadget scanner using the Coccinelle patching engine

Linux Kernel Attack Surface

- Gadget scanner using the Coccinelle patching engine
- Statically analyzed Linux v5.15.83

Linux Kernel Attack Surface

- Gadget scanner using the Coccinelle patching engine
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Identified 1283 Speculative Concurrent Use-After-Free Gadgets

Mitigating Speculative Race Conditions

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void mutex_lock(struct mutex *lock){
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  if (!__mutex_trylock_fast(lock))
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                        : "memory"
                        );
                })
      return true;
  ...
}
```

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                })
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  ...
}
```

Mitigating Speculative Race Conditions

LMBench:
Geomean
≈5%

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                })
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  ...
}
```

GhostRace: Exploiting and Mitigating Speculative Race Conditions

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- Speculative Race Condition

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- Speculative Race Condition

- Inter-Process Interrupt Storming

GhostRace: Exploiting and Mitigating Speculative Race Conditions

- Speculative Race Condition
- Inter-Process Interrupt Storming
- Gadget Scanner (1200+)

GhostRace: Exploiting and Mitigating Speculative Race Conditions

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- PoC Exploit (12KB/s)




GhostRace: Exploiting and Mitigating Speculative Race Conditions

- Speculative Race Condition
- Inter-Process Interrupt Storming
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GhostRace: Exploiting and Mitigating Speculative Race Conditions

- Speculative Race Condition
- Inter-Process Interrupt Storming
- Gadget Scanner (1200+)
- PoC Exploit (12KB/s)
- Mitigation (5%)





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