Exploitations of Uninitialized Uses on macOS Sierra

Zhenquan Xu, Gongshen Liu,Tielei Wang, Hao Xu

Agenda

- Background & Introduction
- Vulnerability analysis & Exploitation
- Conclusion

Agenda

- **Background & Introduction**
- Vulnerability analysis & Exploitation
- Conclusion

Background

- Great tools have been developed to eliminate uninitialized use vulnerabilities :
  - Unisan : prevents kernel data leakage
  - STACKLEAK : prevents kernel stack data leakage
  - Split Kernel : same as STACKLEAK

PwnFest 2016

- Team up with Lokihardt for pwning Safari on macOS Sierra
  - Remote code execution in Safari by Lokihardt
  - Kernel code execution in Safari by us

SHANGHAI JIAO TONG UNIVERSITY

Fixed in macOS Sierra 10.12.3

- Released January 23, 2017
- CVE-2017-2357
- CVE-2017-2358

SHANGHAI JIAO TONG UNIVERSITY

Mitigations

- kASLR : kernel Address Space Layout Randomization
- W^X : Write XOR eXecute
- SMEP : Supervisor Mode Execution Protection
- SMAP : Supervisor Mode Access Protection

Agenda

- Background & Introduction
- **Vulnerability analysis & Exploitation**
- Conclusion

CVE-2017-2357

- The vulnerability lies in IOAudioFamily (<= 204.4)
- Source code:
  https://opensource.apple.com/source/IOAudioFamily/IOAudioFamily-204.4/
- The vulnerability is caused by partial initialization

Analysis

- Programs in the user space can register a notification port by calling IOConnectSetNotificationPort() on an IOAudioControlUserClient object

- Notification messages will be sent to the port when certain audio events occur afterwards

- IOAudioControlUserClient::registerNotificationPort() will be eventually invoked in the kernel

Analysis

```
IOReturn IOAudioControlUserClient::registerNotificationPort(mach_port_t port, UInt32 type, UInt32 refCon)
{
    ...
    if (notificationMessage == 0) {
        notificationMessage = (IOAudioNotificationMessage *)
          IOMallocAligned(sizeof(IOAudioNotificationMessage), sizeof (IOAudioNotificationMessage *));
        if (!notificationMessage) {
            return kIOReturnNoMemory;
        }
    }
    notificationMessage->messageHeader.msgh_bits = MACH_MSGH_BITS(MACH_MSG_TYPE_COPY_SEND, 0);
    notificationMessage->messageHeader.msgh_size = sizeof(IOAudioNotificationMessage);
    notificationMessage->messageHeader.msgh_remote_port = port;
    notificationMessage->messageHeader.msgh_local_port = MACH_PORT_NULL;
    notificationMessage->messageHeader.msgh_reserved = 0;
    notificationMessage->messageHeader.msgh_id = 0;
    notificationMessage->ref = refCon;
    ...
}
```

```
typedef struct _IOAudioNotificationMessage
{
    mach_msg_header_t  messageHeader;
    UInt32      type;
    UInt32      ref;
    void *      sender;
} IOAudioNotificationMessage;
```

notificationMessage is not zeroed out and *type* and *sender* is not initialized

Analysis

- IOAudioControlUserClient::sendChangeNotification() sends notification messages to userspace programs

```
void IOAudioControlUserClient::sendChangeNotification(UInt32 notificationType)
{
    if (notificationMessage) {
        kern_return_t kr;

      notificationMessage->type = notificationType;
        kr = mach_msg_send_from_kernel(&notificationMessage->messageHeader,
notificationMessage->messageHeader.msgh_size);
        if ((kr != MACH_MSG_SUCCESS) && (kr != MACH_SEND_TIMED_OUT)) {
            IOLog("IOAudioControlUserClient: sendRangeChangeNotification() failed - msg_send
returned: %d\n", kr);
        }
    }
}
```

SHANGHAI JIAO TONG UNIVERSITY

Analysis

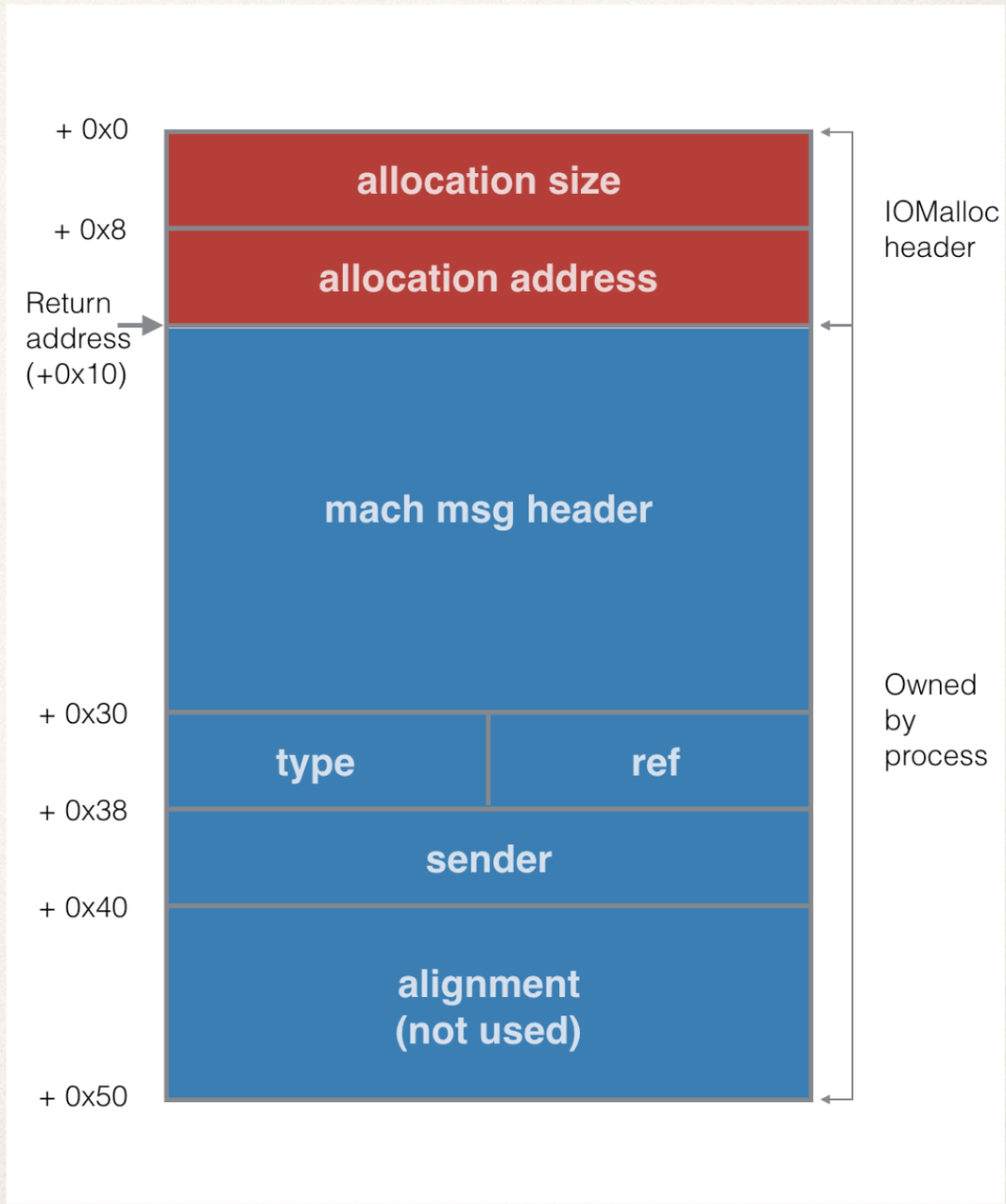
```
void IOAudioControlUserClient::sendChangeNotification(UInt32 notificationType)
{
    if (notificationMessage) {
        kern_return_t kr;

        notificationMessage->type = notificationType;
        kr = mach_msg_send_from_kernel(&notificationMessage->messageHeader,
notificationMessage->messageHeader.msgh_size);
        if ((kr != MACH_MSG_SUCCESS) && (kr != MACH_SEND_TIMED_OUT)) {
            IOLog("IOAudioControlUserClient: sendRangeChangeNotification() failed - msg_send
returned: %d\n", kr);
        }
    }
}
```

- *sender* is uninitialized (*notificationMessage* is partial initialized)
- the kernel sends a message with 8 bytes kernel heap data to the user space

SHANGHAI JIAO TONG UNIVERSITY

Exploitation

- *notificationMessage* is allocated via IOMallocAligned() which allocates a header structure to store metadata.
- *notificationMessage* is allocated in kalloc.80 zone
- *sender* is at +0x38



Exploitation

- Challenge 1: How to leak critical information such as kASLR slide
- Challenge 2: How to make the exploitation stable

Exploitation

```
class OSSerialize : public OSObject
{
    ...
private:
    char           * data;
    unsigned int     length;
    unsigned int     capacity;
    unsigned int     capacityIncrement;
    OSArray * tags;
    bool     binary;
    bool     endCollection;
    Editor editor;
    void * editRef;
    ...
}
```

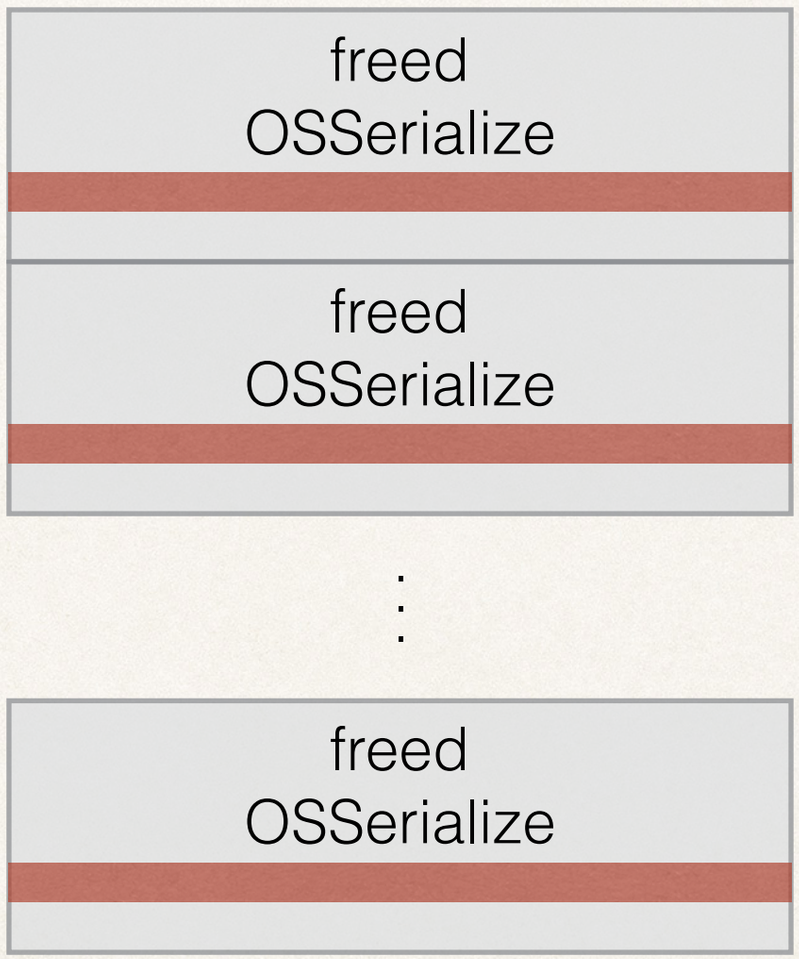
- The OSSerialize objects are allocated in kalloc.80
- The member at +0x38 is a function pointer
- *editor* is set to a kernel function in IORegistryEntryCreateCFProperties()

```
typedef const OSMetaClassBase * (*Editor)(
                        void* reference,
                        OSSerialize* s,
                        OSCollection* container,
                        const OSSymbol* name,
                        const OSMetaClassBase* value);
```

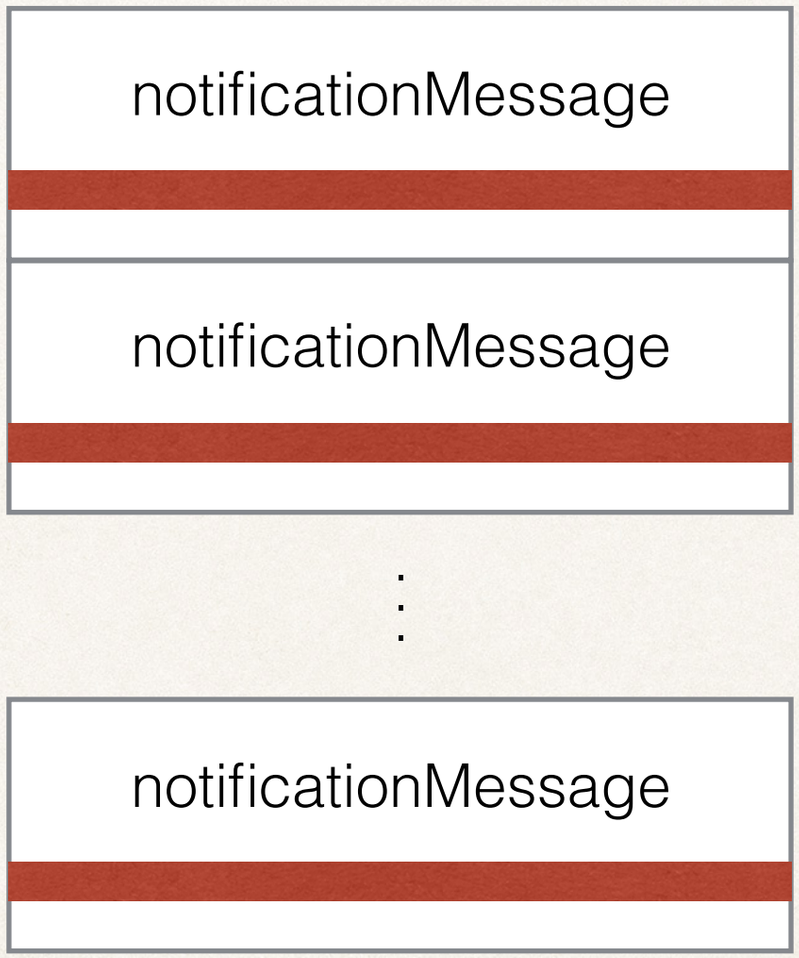
SHANGHAI JIAO TONG UNIVERSITY

Exploitation

Exploitation



Exploitation



Exploitation

- OSSerialize is allocated and deallocated within a function call (i.e. IORegistryEntryCreateCFProperties())

- We developed a new technique called “flashing memory”

- Allocate and deallocate OSSerialize objects very frequently

CVE-2017-2358

- The vulnerability lies in AMDRadeonXx000.kext (x may vary on different platforms)

- The vulnerability is caused by an uninitialized stack variable

- Accelerator is one of the devices that we can directly access in the WebContent sandbox

SHANGHAI JIAO TONG UNIVERSITY

Analysis

- Local variables *v46* and *v47* are not initialized
- *v46* and *v47* are passed to LookupResource()
- A vcall is invoked blindly on *v46* and *v47* then

```
__int64 __fastcall AMDRadeonX4000_AMDAccelShared::
     SurfaceCopy(IOAccelShared2 *this, __int64 a2,
     __int64 a3, __int64 a4)
{
  // local variable declaration
  ...
  IOAccelResource2 *v46; // [rsp+38h] [rbp-88h]@9
  void *v47; // [rsp+40h] [rbp-80h]@9
  ...
  // code
  ...
  IOAccelShared2::lookupResource(this, *(_DWORD *)(a2
        + 8), &v47);
  IOAccelShared2::lookupResource(this, *(_DWORD *)(a2
        + 4), (void **)&v46);
  v6 = -536870206;
  if ( !v47 || !v46 )
    goto LABEL_41;
  v12 = (*(__int64 (**)(void))(*(_QWORD *)v47 + 368LL
       ))();
  v13 = (*(__int64 (**)(void))(*(_QWORD *)v46 + 368LL
       ))();
  ...
}
```

always false

SHANGHAI JIAO TONG UNIVERSITY

Analysis

- *a2* is treated as an index into a resource array
- **a3* is set only when *a2* is valid and the corresponding resource object exists (*_RAX* != 0)

```
char __fastcall IOAccelNamespace::lookupId(
     IOAccelNamespace *this, unsigned int a2, void **
     a3)
{
  if ( *((_DWORD *)this + 6) <= a2 )
    return 0;
  _RAX = *(void **)(*((_QWORD *)this + 2) + 8LL * a2)
       ;
  if ( !_RAX )
    return 0;
  *a3 = _RAX;
  __asm { prefetcht0 byte ptr [rax] }
  return 1;
}
```

SHANGHAI JIAO TONG UNIVERSITY

Analysis

- *a2* is user's structure input
- We can supply an invalid id in the structure input
- PANIC

```
__int64 __fastcall AMDRadeonX4000_AMDAccelShared::
     SurfaceCopy(IOAccelShared2 *this, __int64 a2,
     __int64 a3, __int64 a4)
{
  // local variable declaration
  ...
  IOAccelResource2 *v46; // [rsp+38h] [rbp-88h]@9
  void *v47; // [rsp+40h] [rbp-80h]@9
  ...

  // code
  ...
  IOAccelShared2::lookupResource(this, *(_DWORD *)(a2
       + 8), &v47);
  IOAccelShared2::lookupResource(this, *(_DWORD *)(a2
       + 4), (void **)&v46);
  v6 = -536870206;
  if ( !v47 || !v46 )
    goto LABEL_41;
  v12 = (*(__int64 (**)(void))(*(_QWORD *)v47 + 368LL
       ))();
  v13 = (*(__int64 (**)(void))(*(_QWORD *)v46 + 368LL
       ))();
  ...
}
```

Exploitation

- The uninitialized value on kernel stack is random so we need to control the stack first

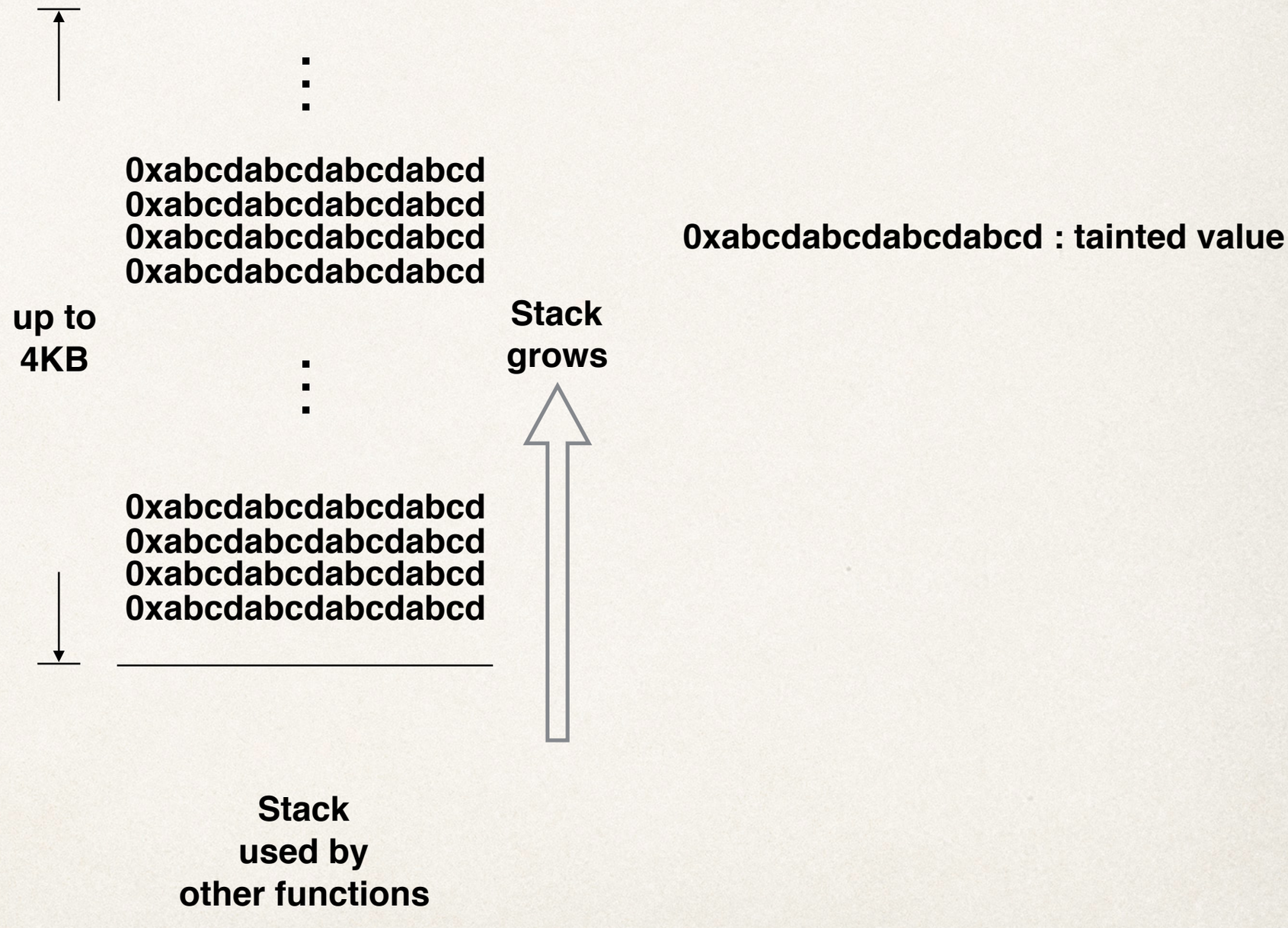
- A function (selector 7333) in the AGPM userclient can be used to taint the stack

- We are able to copy at most 4096 bytes of controlled, non-zero data onto kernel stack

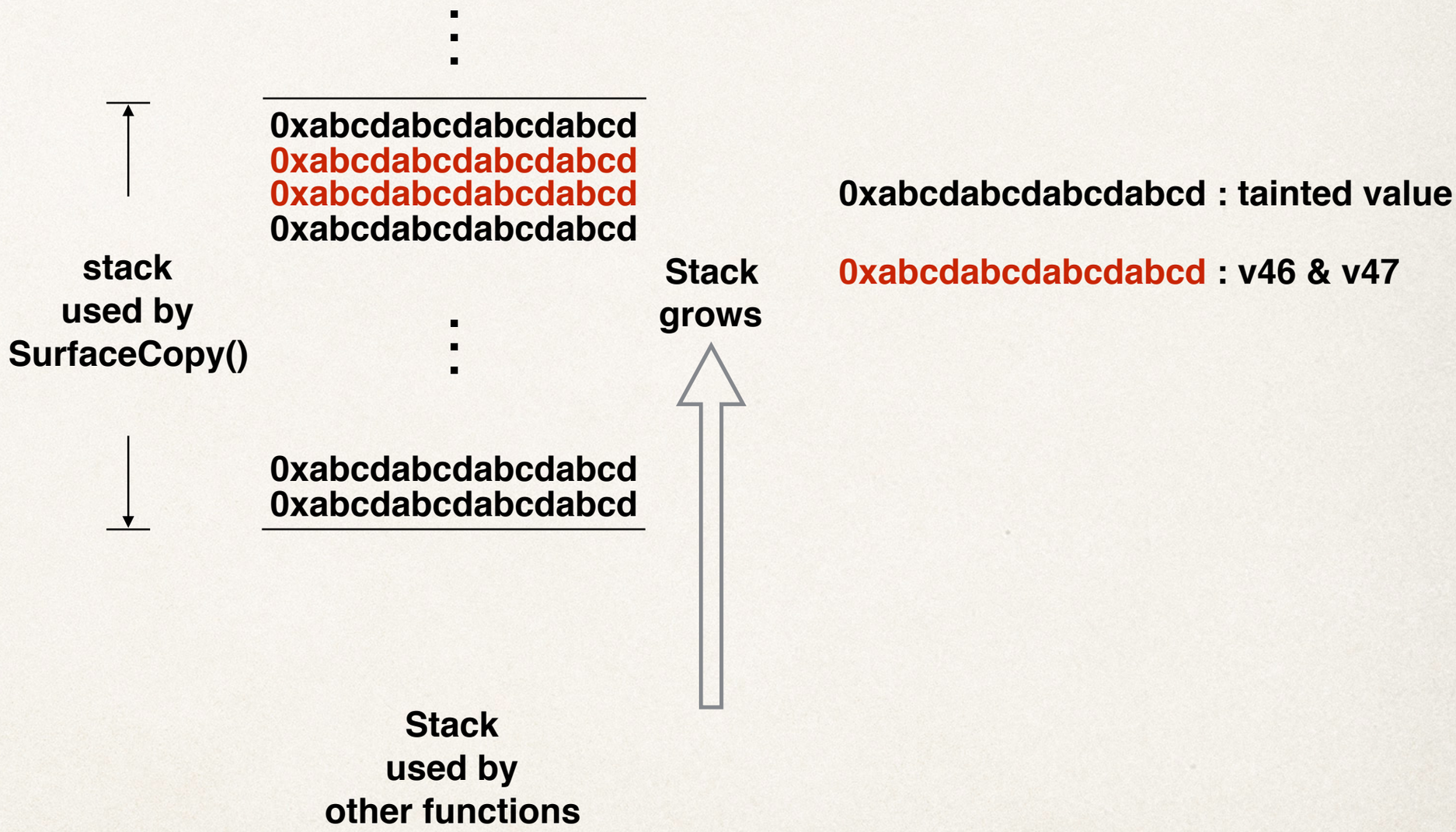
```
case 7333:
  kprintf("kAGPMSetPlimit plimit = %llu type = %s\n", *a2->scalarInput, a2->structureInput);
  v16 = (char *)&v22 - ((a2->structureInputSize + 1 + 15LL) & 0xFFFFFFFFFFFFFFF0LL);
  strncpy(v16, (const char *)a2->structureInput, a2->structureInputSize);
```

SHANGHAI JIAO TONG UNIVERSITY

Exploitation



Exploitation



Exploitation

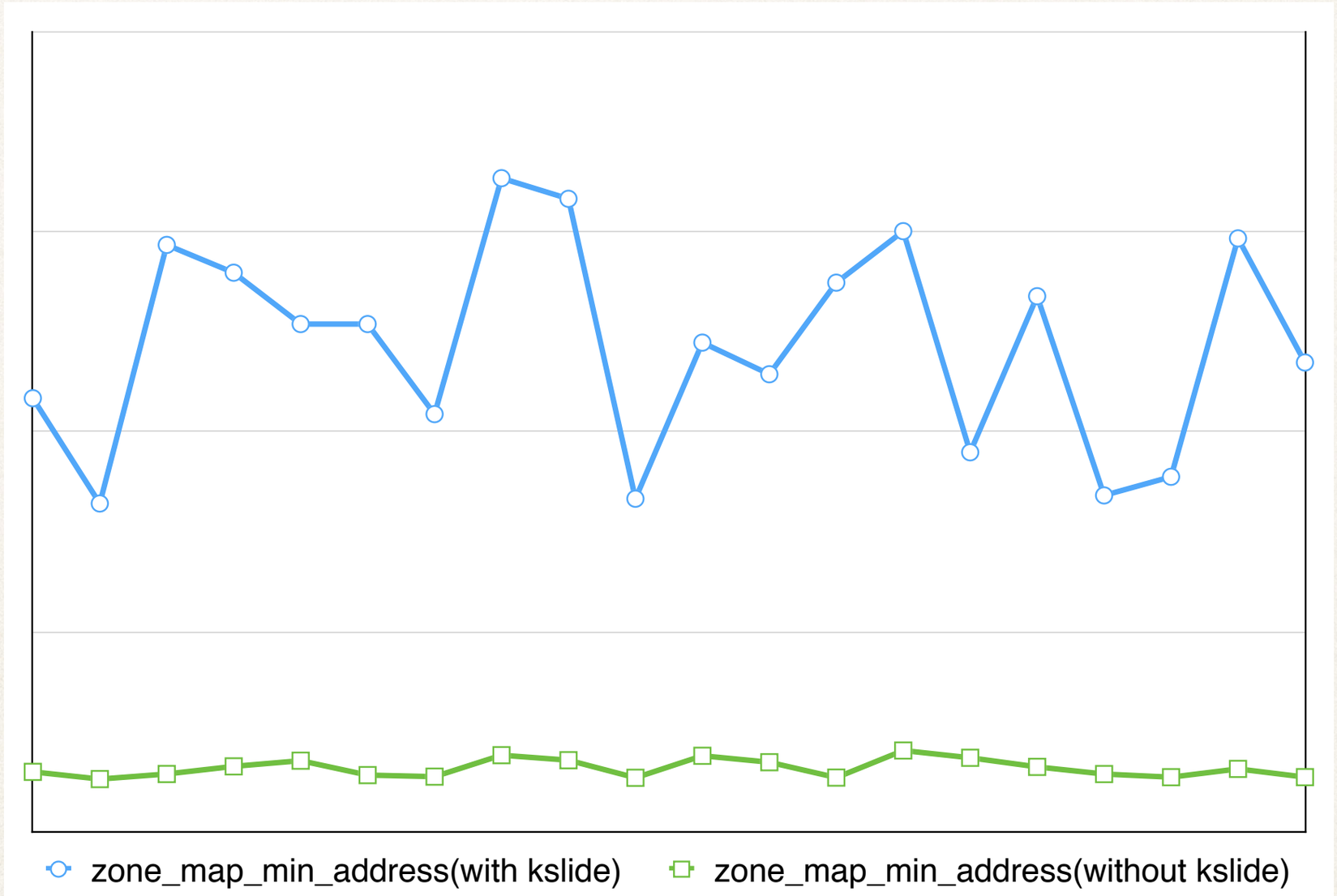
- What value should **0xabcdabcdabcdabcdabcd** be?
- We set **0xabcdabcdabcdabcdabcd** = the address of the object we fake on the heap

SHANGHAI JIAO TONG UNIVERSITY

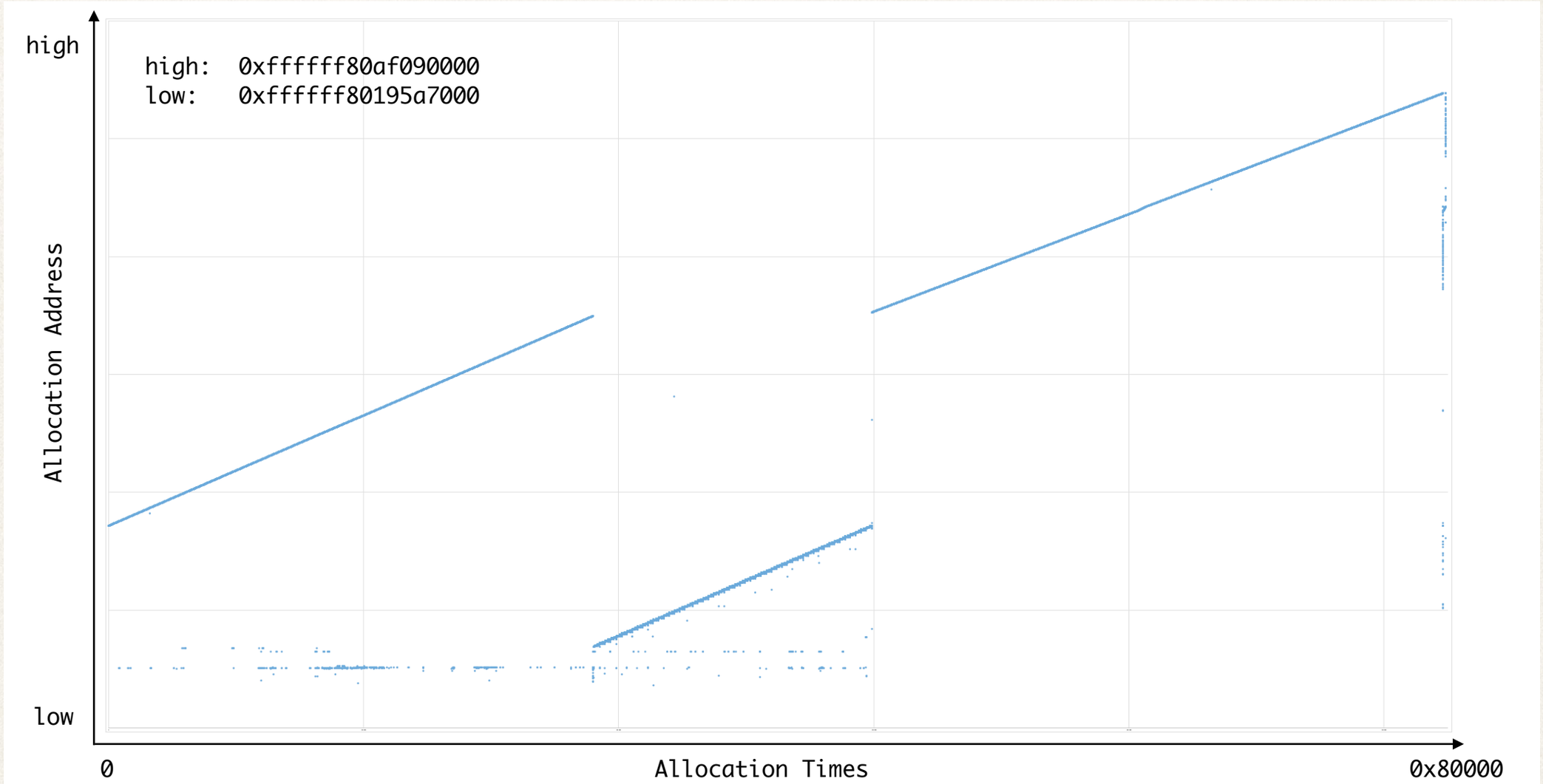
Exploitation

- How can we know the address of our fake objects?
- Spray several GBs of data on the heap
- Heap randomization is weak in the kernel
- User-controlled data at fixed, high address (we chose the address 0xffffff8060010110)

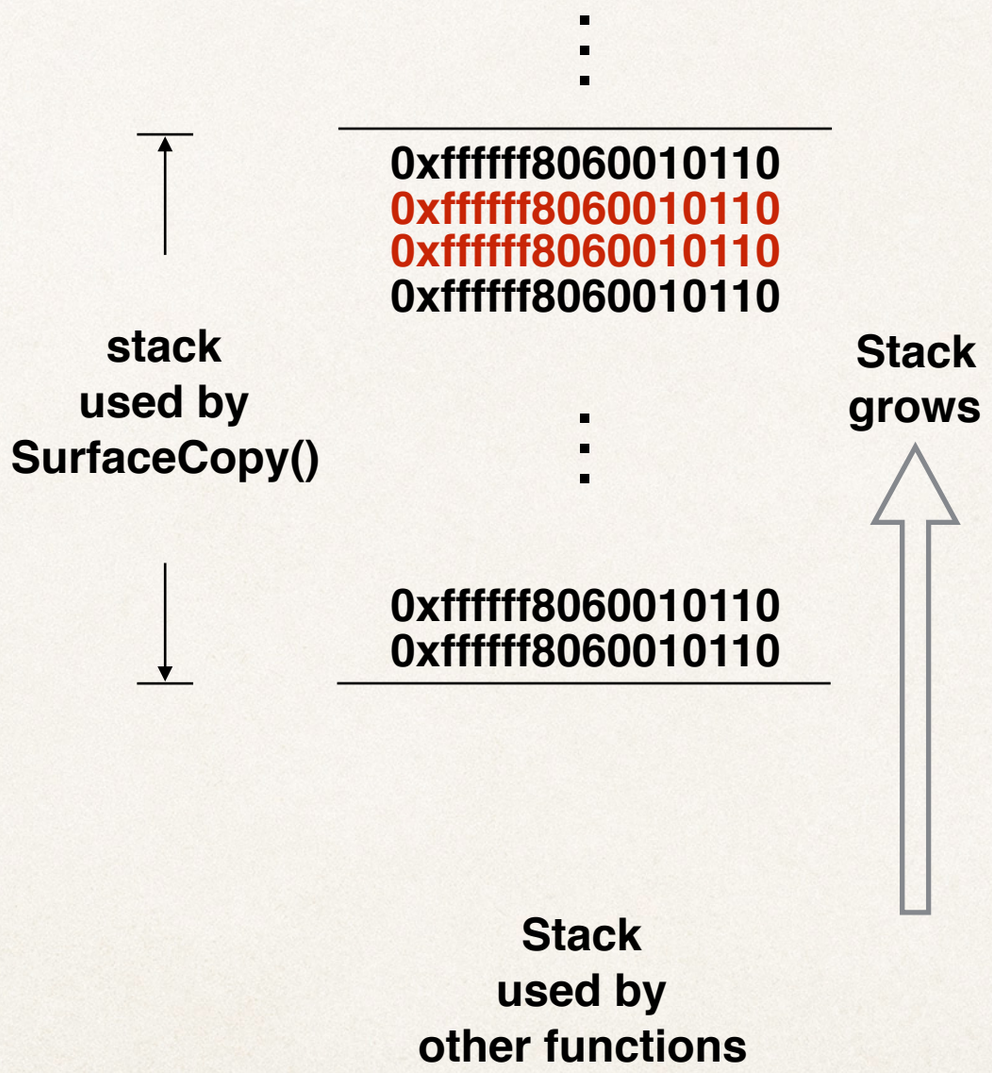
Exploitation



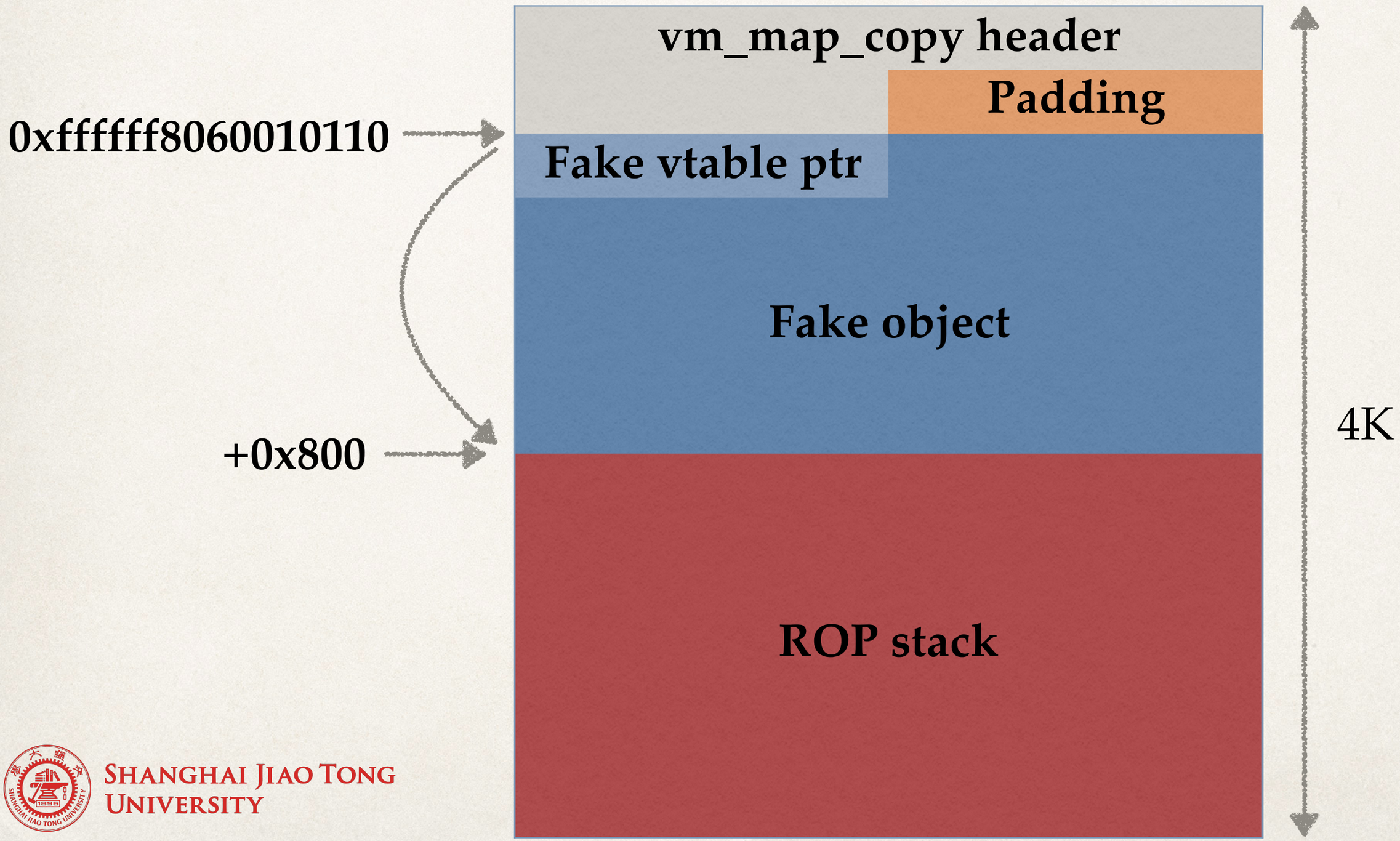
Exploitation



Exploitation



Exploitation



Exploitation

- Save registers
- Pivot the stack
- Disable SMEP & SMAP
- Return to SHELLCODE in the user space
- Re-enable SMEP & SMAP
- Call _thread_exception_return() to exit

SHANGHAI JIAO TONG UNIVERSITY

Agenda

- Background & Introduction
- Vulnerability analysis & Exploitation
- **Conclusion**

Conclusion

- New mitigations make exploitation more challenging but also encourage us to discover new exploit techniques
- Keep initialization in our mind while coding
- More effective tools for detecting uninitialized uses are still necessary

Credits

- Ian Beer
- qwertyoruiop
- Lokihardt
- INT 80 & windknown
- …

SHANGHAI JIAO TONG UNIVERSITY

Thank You For Your Attention

Q&A