POTUS: Probing Off-The-shelf USB drivers with Symbolic fault injection

James Patrick-Evans, Lorenzo Cavallaro, and Johannes Kinder

Royal Holloway, University of London

11th USENIX Workshop on Offensive Technologies – August 14-15, 2017

USB Device Drivers are a Problem

- Drivers are buggy
  - Drivers have 3-7 times higher number of bug reports than the core kernel
- Lots of old device drivers
  - OSs want to support as many devices as possible
- High privilege
  - Kernel modules run in ring 0

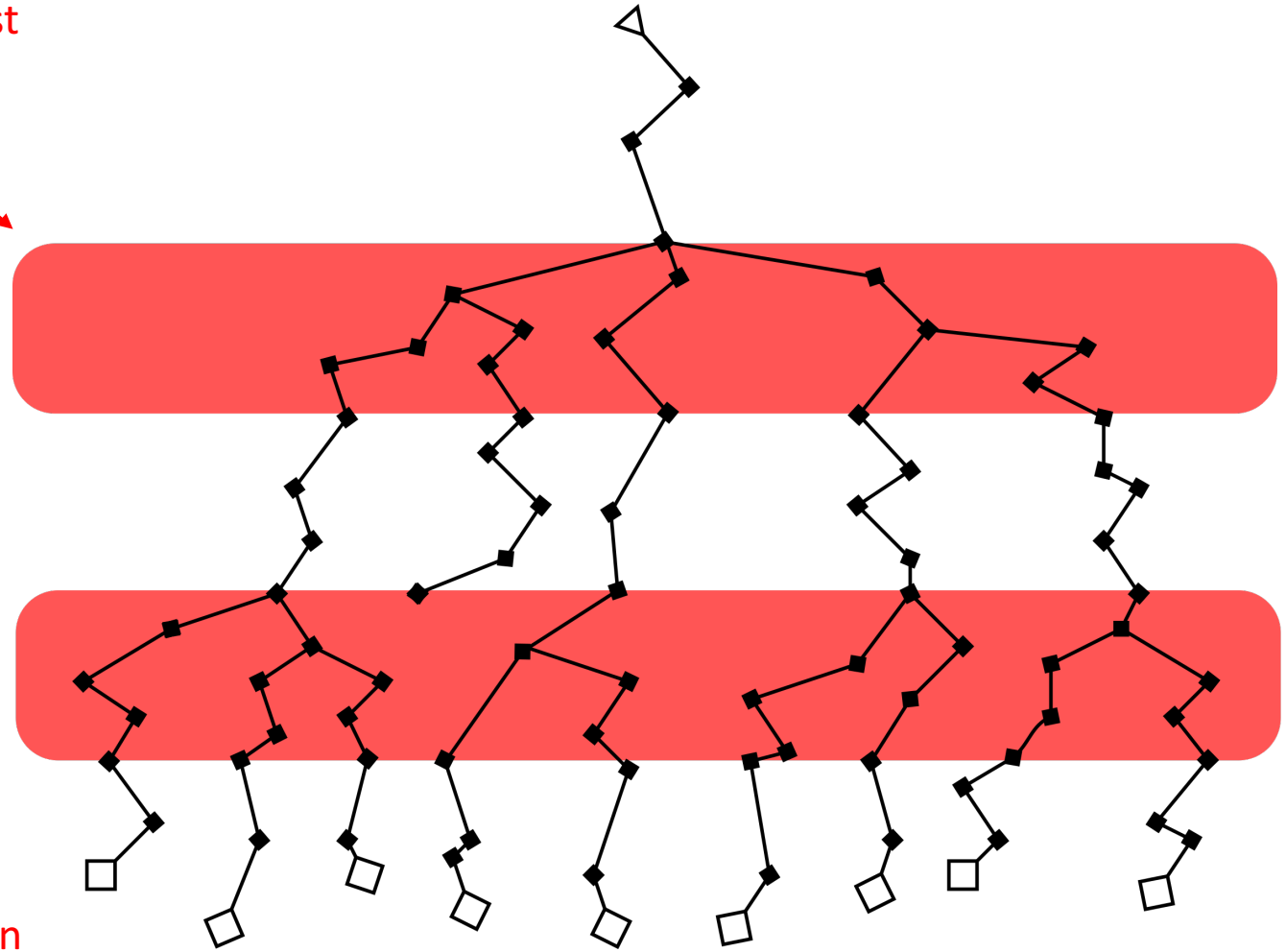
USB drivers present an easy attack vector for exploitation!

POTUS

- Semi-Automated testing framework for Linux USB device drivers
  - Fault Injection
  - Concurrency Fuzzing
  - Selective Symbolic Execution
- Emulate generic USB devices
- Detect memory errors and data races in the kernel

What is S2E?

Select module of interest
for symbolic execution



/usr/bin/cp

uas.ko

scsi.ko

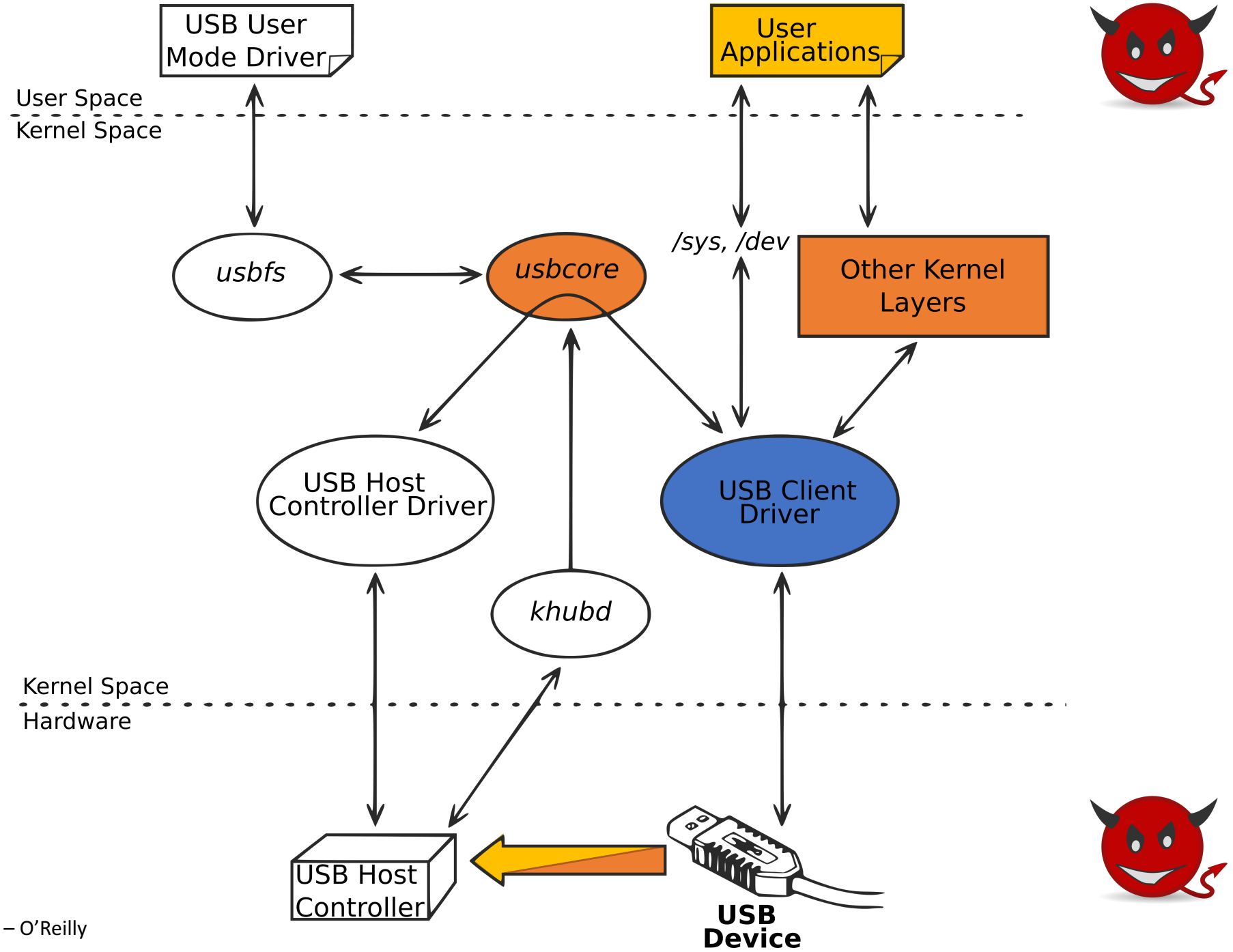
uas.ko

/usr/bin/cp

Select analysis plugins for
evaluation or path selection

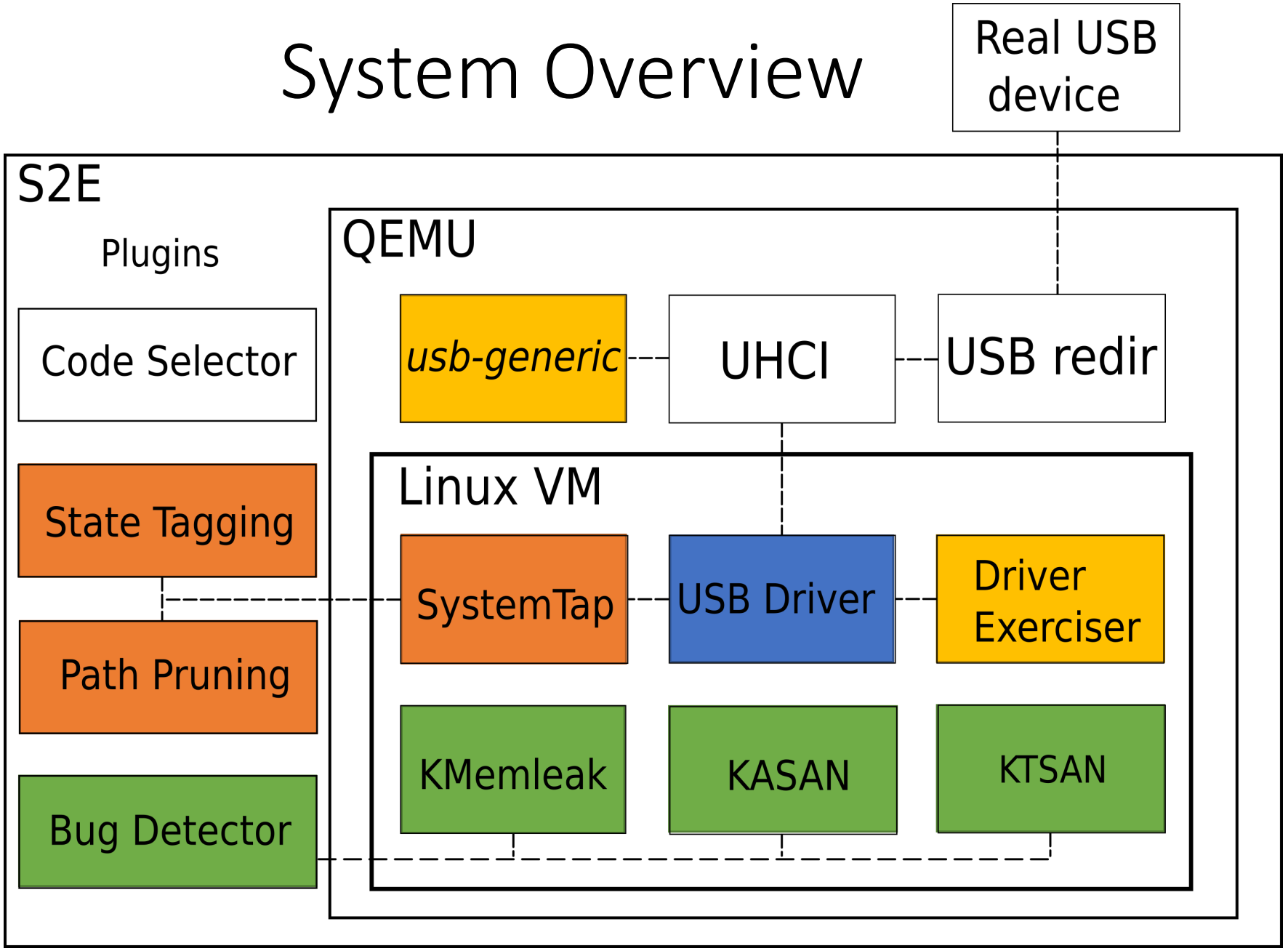
USB 101

- Master-Slave protocol, controlled by a Host Controller Interface (**HCI**)
- At the “software level” – communication is done via Universal Request Blocks (**URB**s)
- Transfer data to **endpoints** by scheduling **URB** transfers
- Devices identify by providing a set of **descriptors**



[1] Linux Device Drivers 3rd Edition – O'Reilly

System Overview



Symbolic Execution

Fault Injection

Concurrency Fuzzing

Error Detection

usb-generic

- Extended QEMU device model
- USB from JSON
  - String Descriptors
  - Device Descriptors
  - Interface Descriptors
  - Class Descriptors
  - Endpoint Descriptors

```
{
    bInterfaceNumber:       0,
    bNumEndpoints:          2,
    bInterfaceClass:        8,
    bInterfaceSubClass:     6,
    bInterfaceProtocol:     50,
     eps: [
        {
            bEndPointAddress: 1,
            bmAttributes:     1,
            wMaxPacketSize:   512
        },
        …
    ]
}
```

```
$ qemu-system-x86_64 -device usb-generic,cfg=config.json
```

Symbolic Execution

Fault Injection

Concurrency Fuzzing

Error Detection

usb-generic

- Host defined time, size and direction of URBs
- Inject symbolic or concrete data into **IN** requests, disregard data from **OUT** requests
- Inject delays and errors into URB requests by returning **STALL**, **NYET** and **NAK**
- Predefined routines for standard requests used during device enumeration e.g. **GET_DESCRIPTOR**

Symbolic Execution

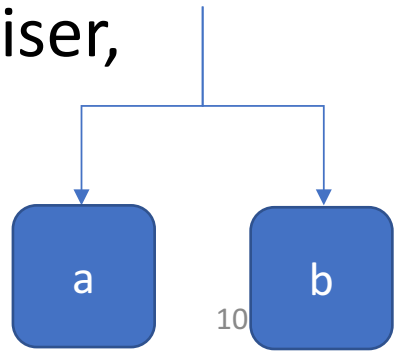
Fault Injection

Concurrency Fuzzing

Error Detection

Exercising Drivers

- Random **stress test** of interfaces exposed by drivers
- Expose concurrency errors by running operations simultaneously
- Pick an operation at random from a weighted tree which is performed on file descriptors
- Every time **sys_open** is called, **fork** the user space driver exerciser, operate on both file descriptors



Symbolic Execution

Fault Injection

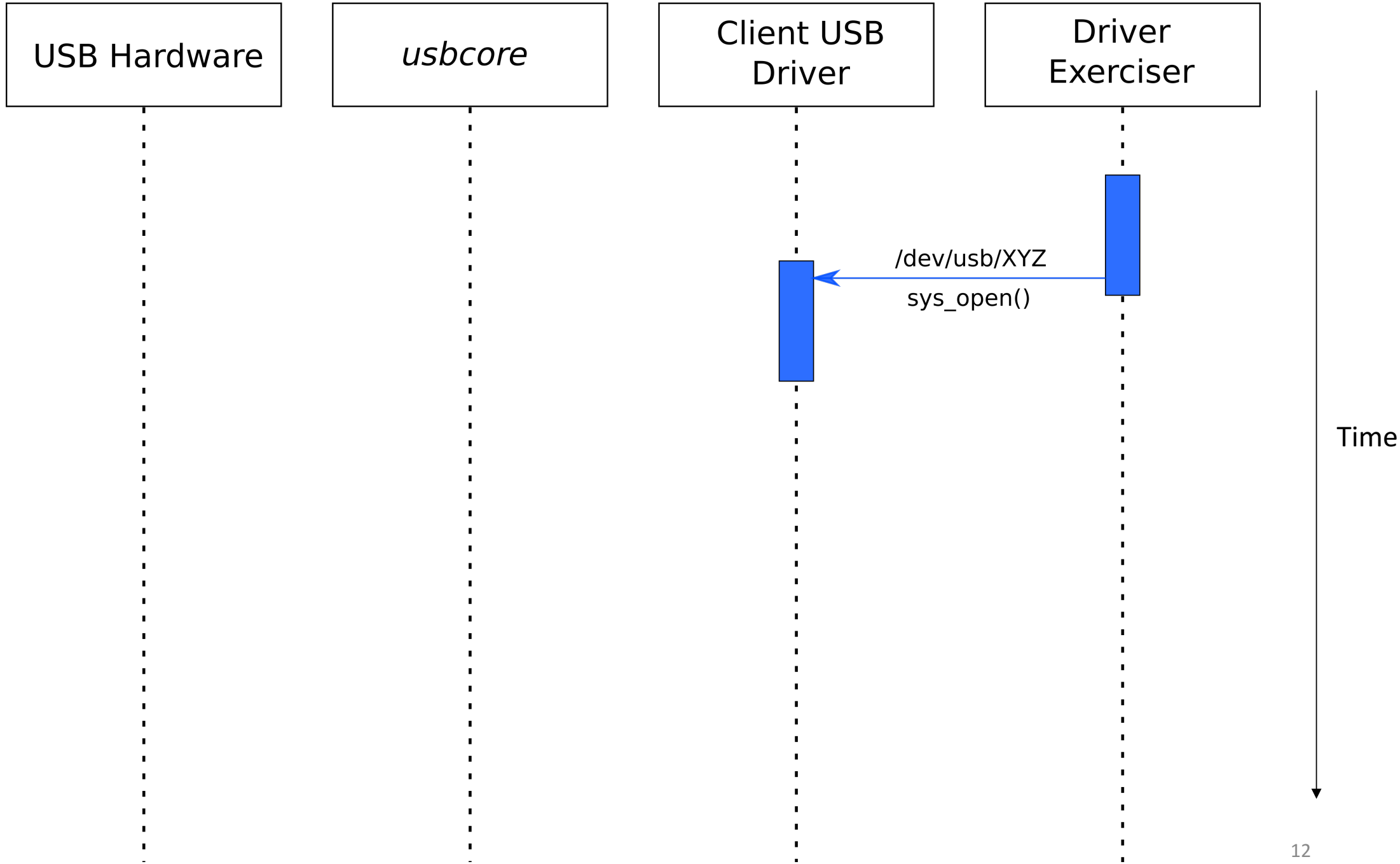
Concurrency Fuzzing

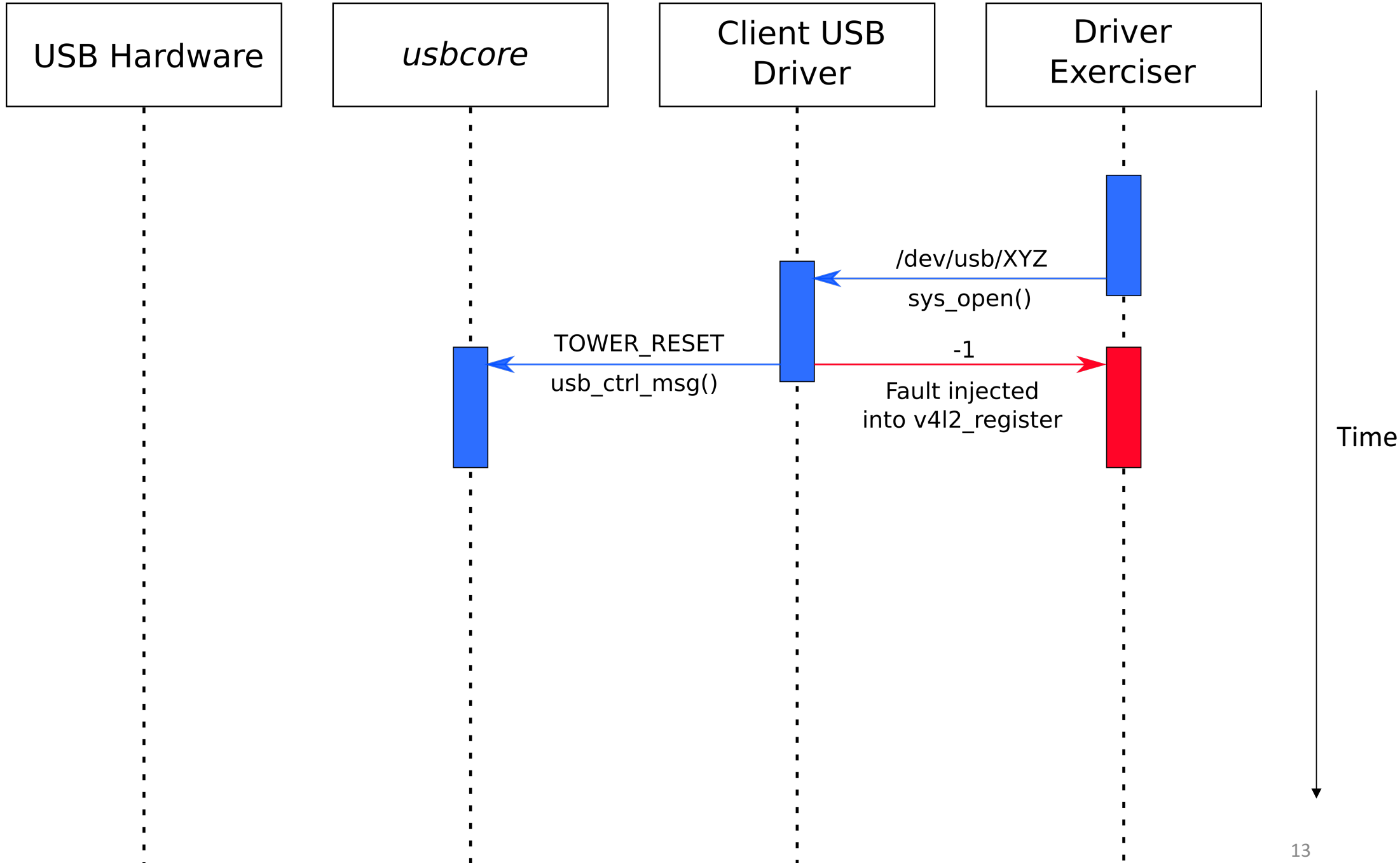
Error Detection

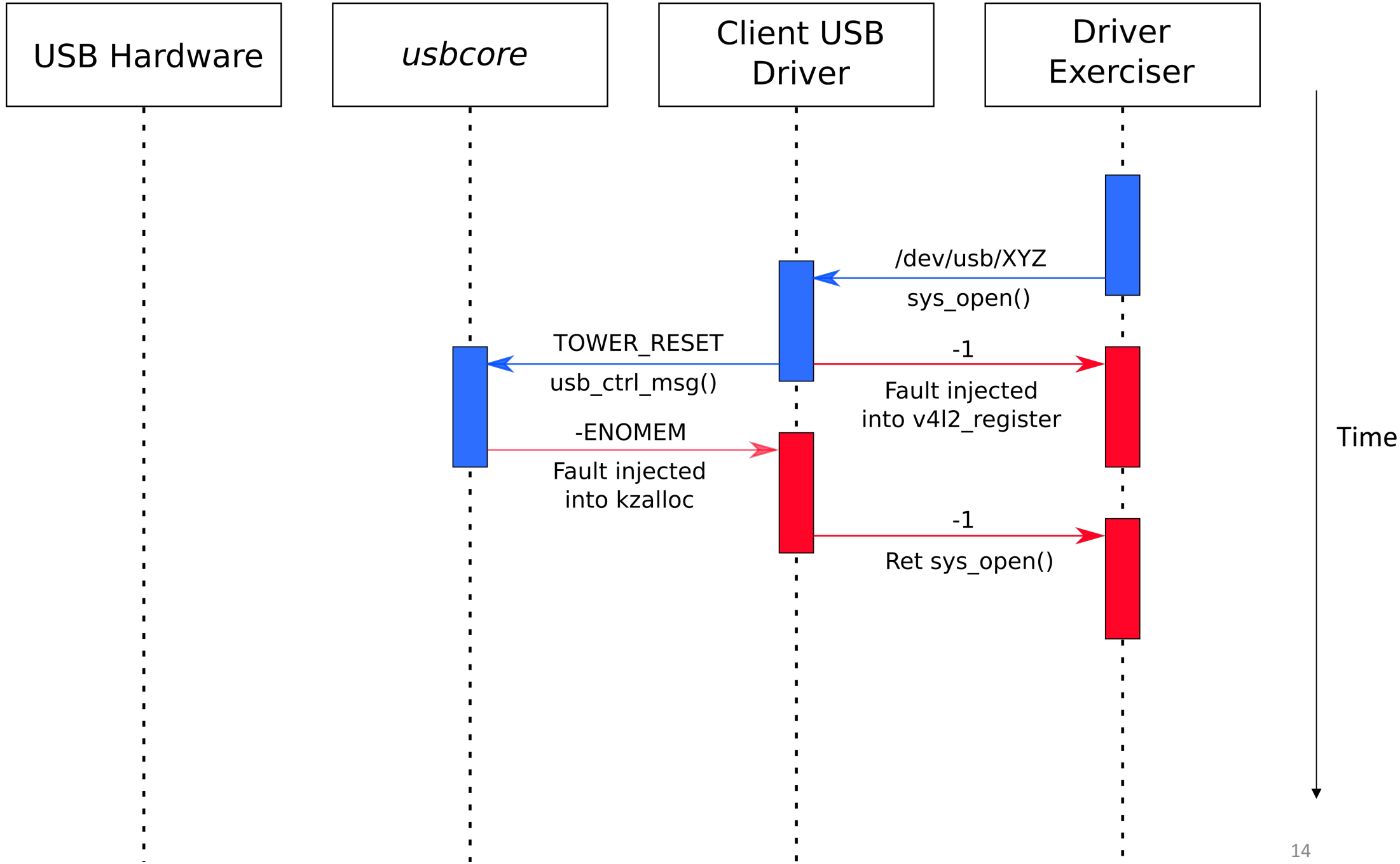
Injecting Faults

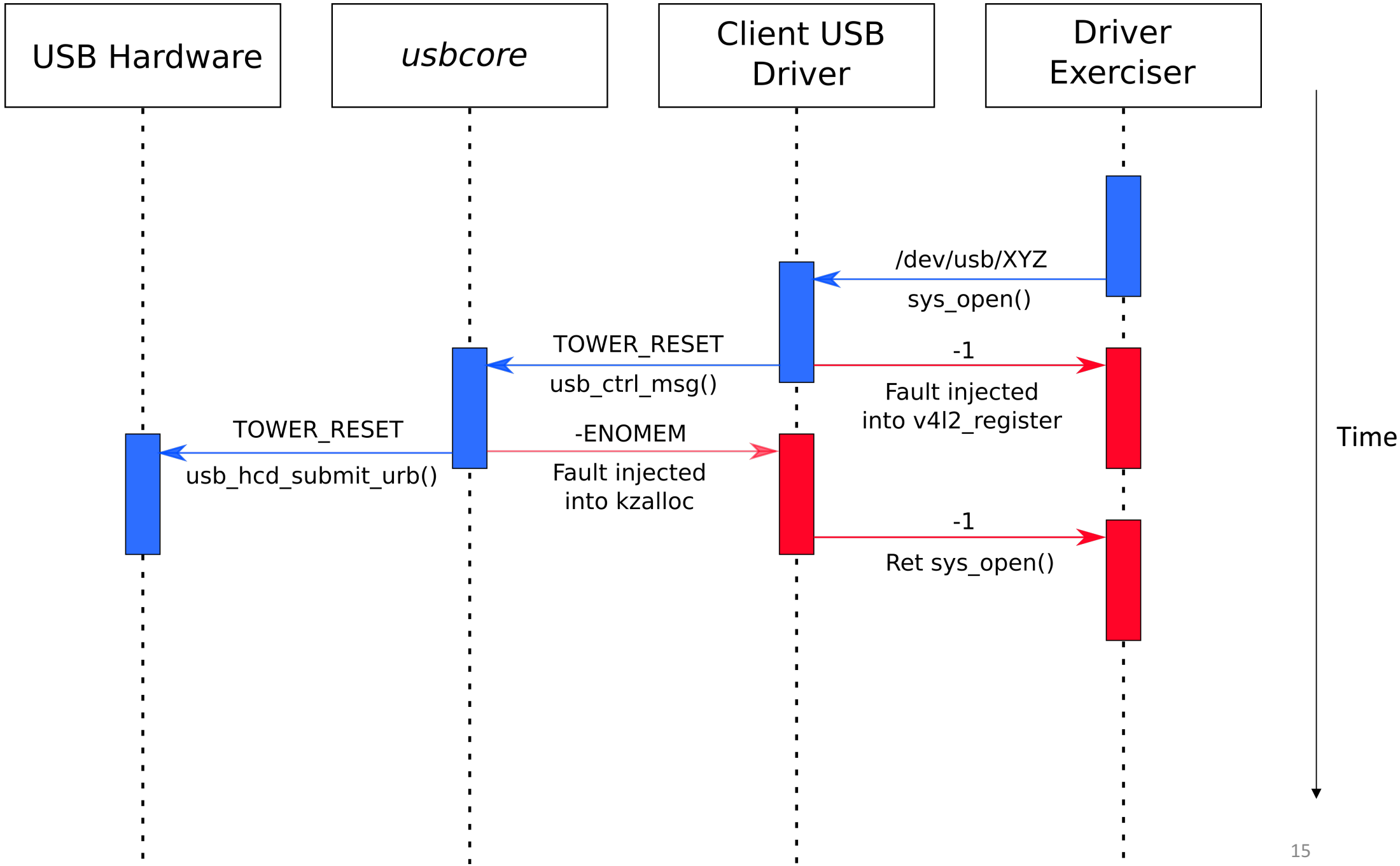
- **SystemTap** and kprobes kernel infrastructure
- Inject symbolic data and **symbolic faults**
- Typically, errors in the kernel are of the form **–ERRNO**
- Tapset libraries for hooking core kernel modules

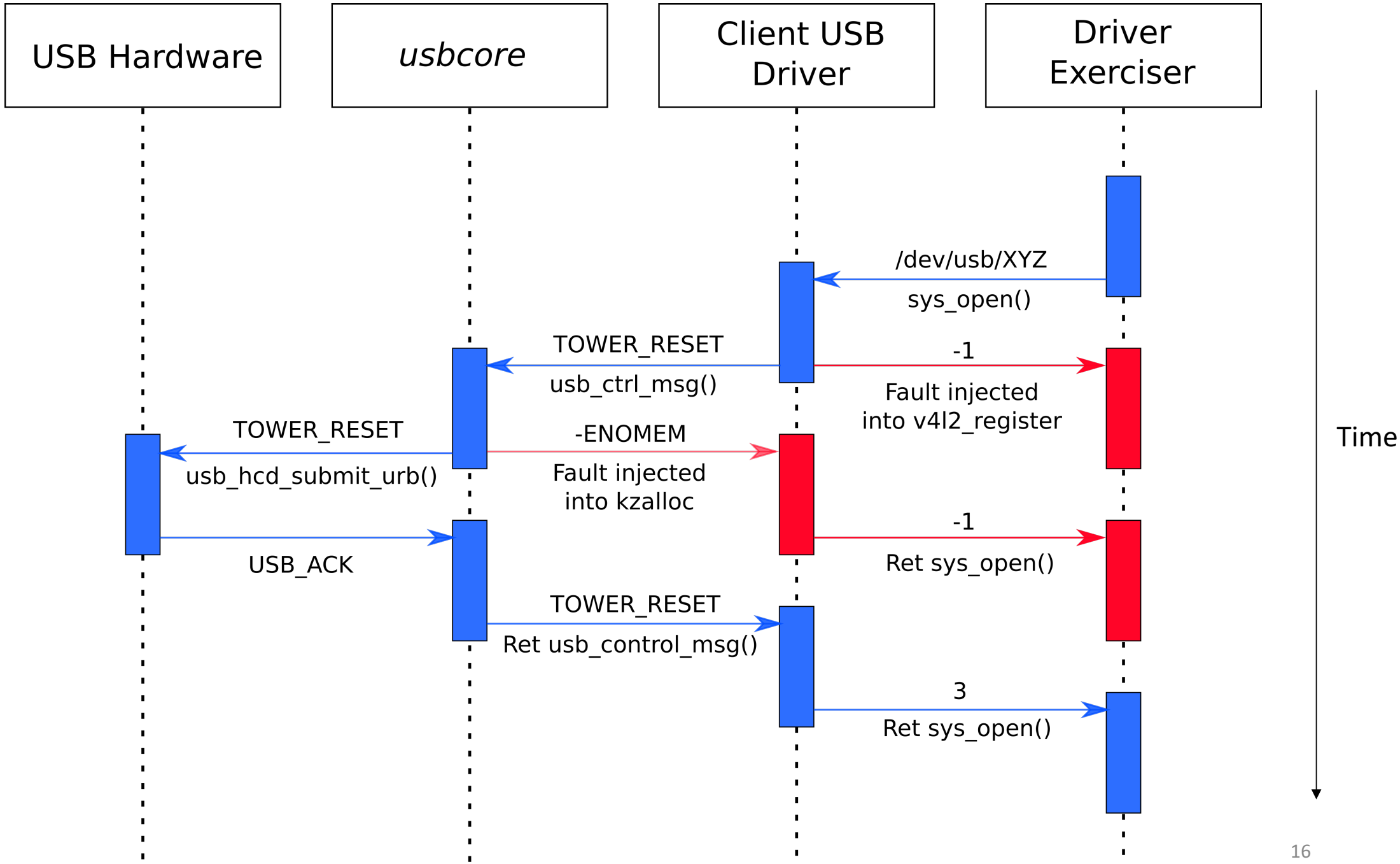
```
probe module("v4l2").function("video_register_device").return {
    child = s2e_fork()
    if (child) {
        s2e_log(__FUNC_NAME__ . " :: Injecting fault.\n")
        s2e_annotate(@FAULT_KEY, annotation + 1)
        video_unregister_device(@entry($vdev))
        $return = s2e_get_symb_fault(32)
```

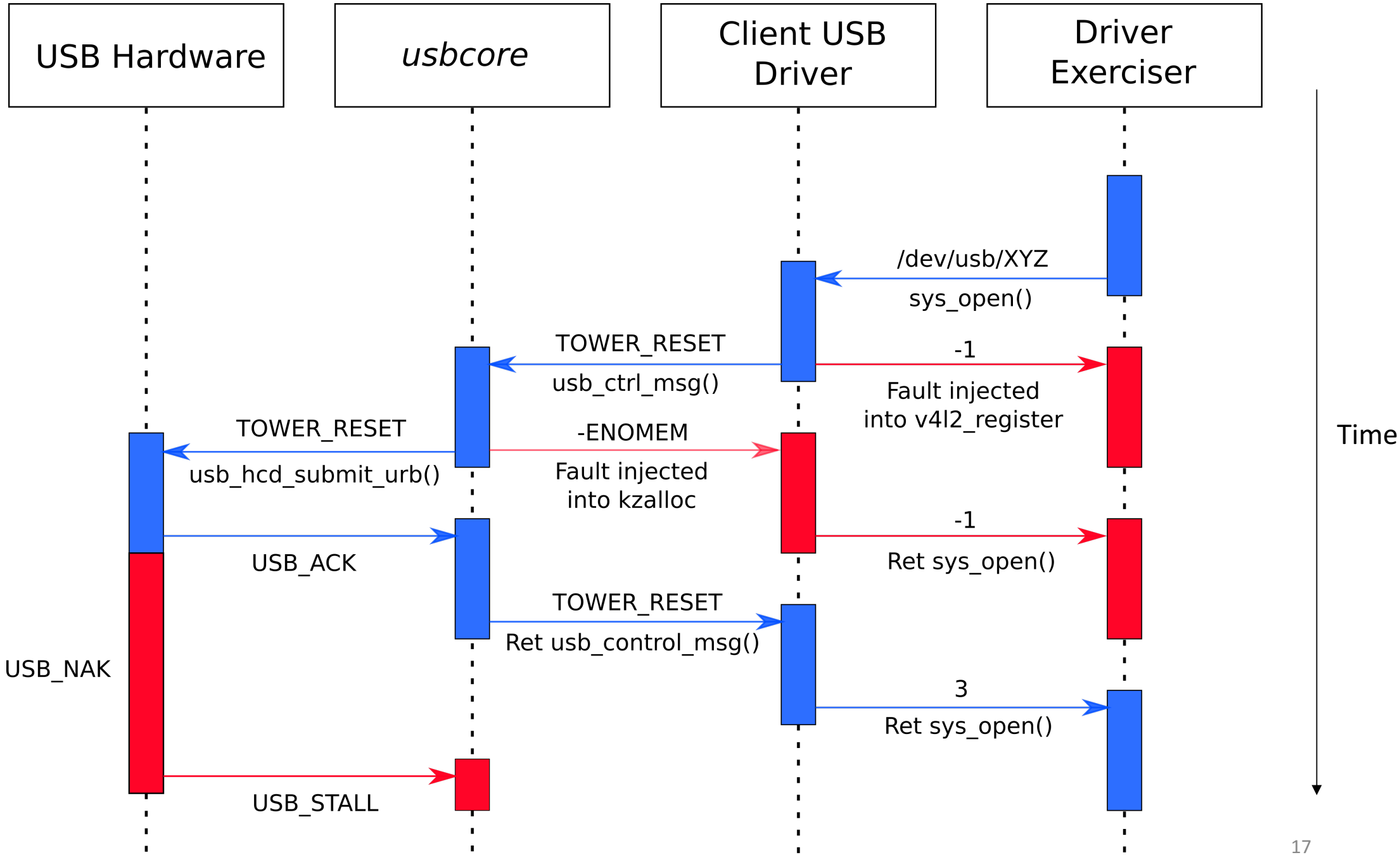

USB Hardware
usbcore
Client USB Driver
Driver Exerciser
/dev/usb/XYZ
sys_open()
Time


USB Hardware
usbcore
Client USB Driver
Driver Exerciser
/dev/usb/XYZ
sys_open()
TOWER_RESET
usb_ctrl_msg()
-1
Fault injected into v4l2_register
Time


USB Hardware
usbcore
Client USB Driver
Driver Exerciser
/dev/usb/XYZ
sys_open()
TOWER_RESET
usb_ctrl_msg()
-1
Fault injected into v4l2_register
-ENOMEM
Fault injected into kzalloc
-1
Ret sys_open()
Time


USB Hardware
usbcore
Client USB Driver
Driver Exerciser
/dev/usb/XYZ
sys_open()
TOWER_RESET
usb_ctrl_msg()
-1
Fault injected into v4l2_register
TOWER_RESET
usb_hcd_submit_urb()
-ENOMEM
Fault injected into kzalloc
-1
Ret sys_open()
Time


USB Hardware
usbcore
Client USB Driver
Driver Exerciser
/dev/usb/XYZ
sys_open()
TOWER_RESET
usb_ctrl_msg()
-1
Fault injected into v4l2_register
TOWER_RESET
usb_hcd_submit_urb()
-ENOMEM
Fault injected into kzalloc
USB_ACK
-1
Ret sys_open()
TOWER_RESET
Ret usb_control_msg()
3
Ret sys_open()
Time


USB Hardware
usbcore
Client USB Driver
Driver Exerciser
/dev/usb/XYZ
sys_open()
TOWER_RESET
usb_ctrl_msg()
-1
Fault injected into v4l2_register
TOWER_RESET
usb_hcd_submit_urb()
-ENOMEM
Fault injected into kzalloc
-1
Ret sys_open()
USB_ACK
TOWER_RESET
Ret usb_control_msg()
USB_NAK
3
Ret sys_open()
USB_STALL
Time

Airspy SDR

- Local DoS
- Present since 2013 or Linux 3.17 – 4.6
- *drivers/media/usb/airspy/airspy.c*
- CVE-2016-5400
- Debian/Ubuntu/Arch Linux

```
static int airspy_probe(struct usb_interface *intf, const struct usb_device_id *id)
{
    s = kzalloc(sizeof(struct airspy), GFP_KERNEL);
    ret = v4l2_device_register(&intf->dev, &s->v4l2_dev);

    /* Register controls */
    v4l2_ctrl_handler_init(&s->hdl, 5);
    s->lna_gain_auto = v4l2_ctrl_new_std(&s->hdl, &airspy_ctrl_ops,
            V4L2_CID_RF_TUNER_LNA_GAIN_AUTO, 0, 1, 1, 0);
       ...

    ret = video_register_device(&s->vdev, VFL_TYPE_SDR, -1);
    if (ret) {
        dev_err(s->dev, "Failed to register as video device (%d)\n",
                ret);
        goto err_unregister_v4l2_dev;
    }
       ...
    return 0;

err_free_controls:
    v4l2_ctrl_handler_free(&s->hdl);
err_unregister_v4l2_dev:
    v4l2_device_unregister(&s->v4l2_dev);
err_free_mem:
    kfree(s);
    return ret;
}
```

Can be triggered purely from hardware!

Lego USB Tower

- Local DoS or Local Privilege Escalation
- Present since 2002 or Linux 2.6 – 4.7
- *drivers/usb/misc/legousbtower.c*
- *CVE-2017-XXXX*
- *Debian/Ubuntu/Arch/Fedora/RHEL*

```
static int tower_probe (struct usb_interface *interface, const struct usb_device_id *id){
        ...
        /* we can register the device now, as it is ready */
        usb_set_intfdata (interface, dev);

        retval = usb_register_dev (interface, &tower_class);
      ...

      /* get the firmware version and log it */
      result = usb_control_msg (udev,
                                usb_rcvctrlpipe(udev, 0),
                                LEGO_USB_TOWER_REQUEST_GET_VERSION,
                                USB_TYPE_VENDOR | USB_DIR_IN | USB_RECIP_DEVICE,
                                0, 0, get_version_reply, sizeof(*get_version_reply),
                                1000);
      if (result < 0) {
              dev_err(idev, "LEGO USB Tower get version control request failed\n");
              retval = result;
              goto error;
      }
      ...
error:
      kfree(get_version_reply);
      tower_delete(dev);
      return retval;
}
```

```
static inline void tower_delete (struct lego_usb_tower *dev)
{
        tower_abort_transfers (dev);

        /* free data structures */
        usb_free_urb(dev->interrupt_in_urb);
        usb_free_urb(dev->interrupt_out_urb);
        kfree (dev->read_buffer);
        kfree (dev->interrupt_in_buffer);
        kfree (dev->interrupt_out_buffer);
        kfree (dev);
}
```

```
static ssize_t tower_write (struct file *file, const char __user *buffer,
                                        size_t count, loff_t *ppos)
{
    …
        bytes_to_write = min_t(int, count, write_buffer_size);
        dev_dbg(&dev->udev->dev, "%s: count = %zd, bytes_to_write = %zd\n",
                __func__, count, bytes_to_write);

        if (copy_from_user (dev->interrupt_out_buffer, buffer, bytes_to_write)) {
                retval = -EFAULT;
                goto unlock_exit;
        }
    …
}
```

Exploit – Lego USB Tower

- Can we build a UaF that is a **data-only** attack and will bypass **SMEP**, **SMAP** and PAX's **RAP**?

1. Inject maximum delay into REQUEST_GET_VERSION
2. Have user space call *sys_open()*
3. Wait for the 1 second timeout
4. Remap the *dev struct* in the general kernel cache
5. Change the values for *dev->interrupt_out_buffer*
6. Overwrite {,**fs**,**e**}{**u**,**g**}**id**
7. Repeat 5-6 to overwrite **capabilities**

Relaxed conditions to bypass KASLR and memory allocation!

Future Work

- Slow!
  - Interval URBs – *usb_fill_int_urb(…, $interval)*
  - State explosion due to $(\text{symbex}^{\text{faults}})^{\text{driver operations}}$
- Some paths we can't explore!
  - Concretization of data – real device may help
- usb-generic $\subseteq$ USB 2.0
  - USB On-The-Go (OTG), USB 3.0

Conclusion

- Abstract hardware interface
  - OS agnostic, CPU architecture agnostic
- Semi-Automated USB Driver Test Framework
  - Concurrency Fuzzing
  - Fault Injection
  - Selective Symbolic Execution
- Two 0-days in the Linux kernel, proof of concept for data-only LPE

Symbolic Execution

```
int myfunc(int x)
{
    int r = 0;

    if(x > 8){
        r = x - 7;
    }

    if(x < 5){
        r = x - 2;
    }

    return r;
}
```