HFL: Hybrid Fuzzing on the Linux Kernel

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Software Security Analysis

- Random fuzzing
  - **Pros**: Fast path exploration
  - **Cons**: Strong branch conditions e.g., *if(i == 0xdeadbeef)*

- Symbolic/concolic execution
  - **Pros**: Generate concrete input for strong branch conditions
  - **Cons**: State explosion

Hybrid Fuzzing in General

- Combining ***traditional fuzzing*** and ***concolic execution***
  - *Fast exploration* with fuzzing (*no state explosion*)
  - *Strong branches are handled* with concolic execution
- State-of-the-arts
  - Intriguer [CCS’19], DigFuzz [NDSS’19], QSYM [Sec’18], etc.
  - Application-level hybrid fuzzers

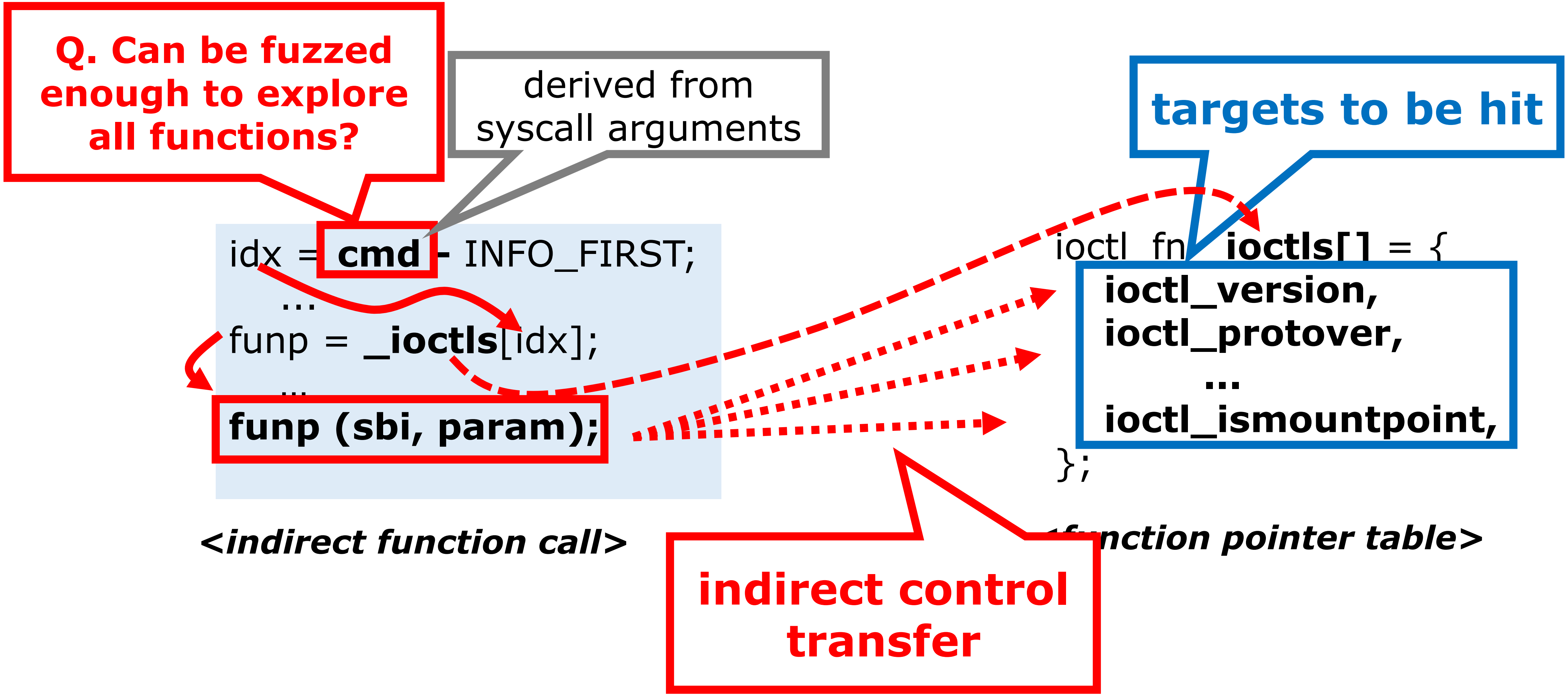
Kernel Testing with Hybrid Fuzzing

- Software vulnerabilities are critical threats to OS

Q. Is hybrid-fuzzing good enough for kernel testing?

more bugs in kernels.
  - A huge number of specific branches e.g., CAB-Fuzz[ATC’17], DIFUZE[CCS’17]

Challenge 1: Indirect Control Transfer



Challenge 2: System Call Dependencies

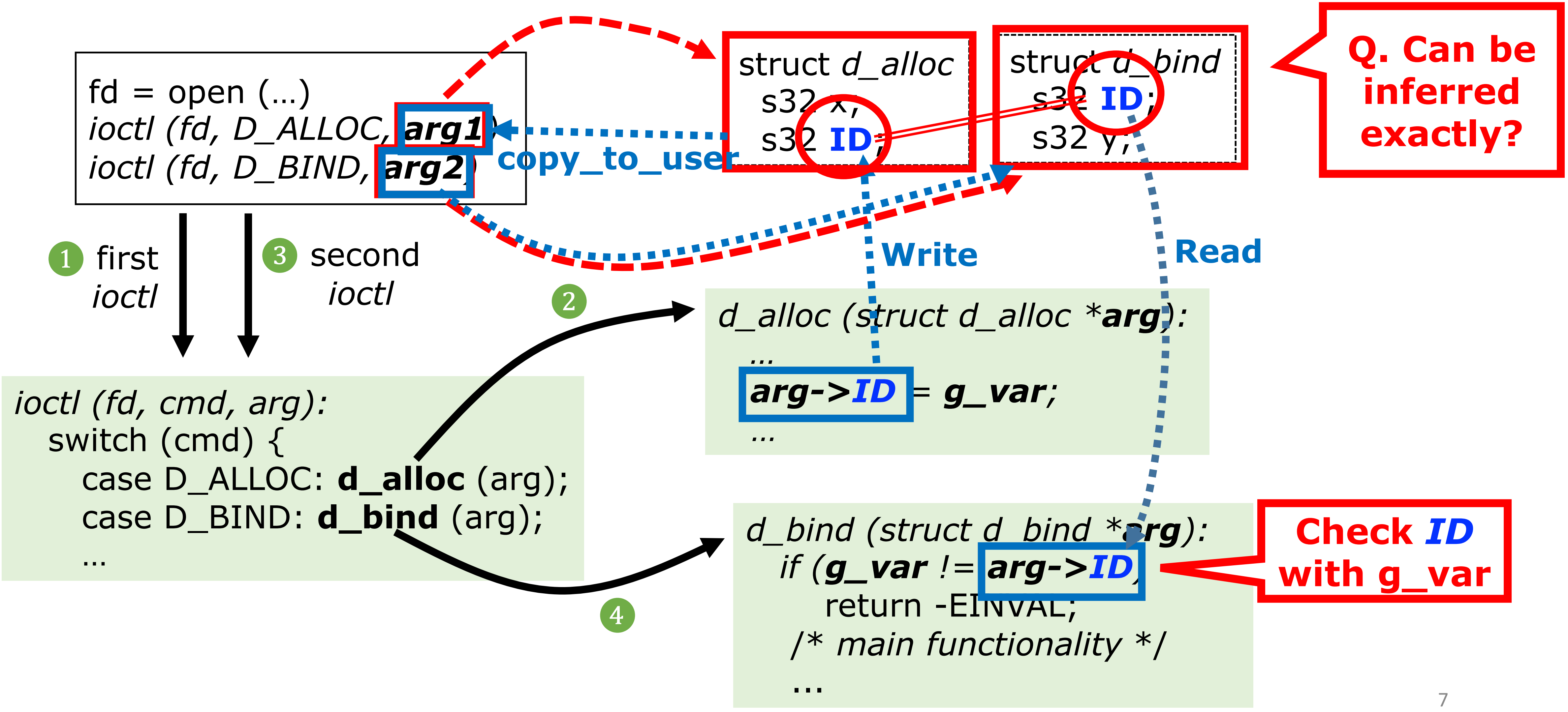
explicit syscall dependencies

*<u>**int**</u> **open** (const char *pathname, int flags, mode_t mode)*
*ssize_t **write** (<u>**int fd**</u>, void *buf, size_t count)*

***ioctl** (int fd, unsigned long req, void *argp)*
***ioctl** (int fd, unsigned long req, void *argp)*

Q. What dependency behind?

Example: System Call Dependencies



Challenge 3: Complex Argument Structure

unknown type

ioctl (int fd, unsigned long cmd, ***void *argp****)*

write (int fd, ***void *buf****, size_t count)*

unknown type

Example: Nested Arguments Structure

ioctl (fd, USB_X, ***arg****)*

syscall

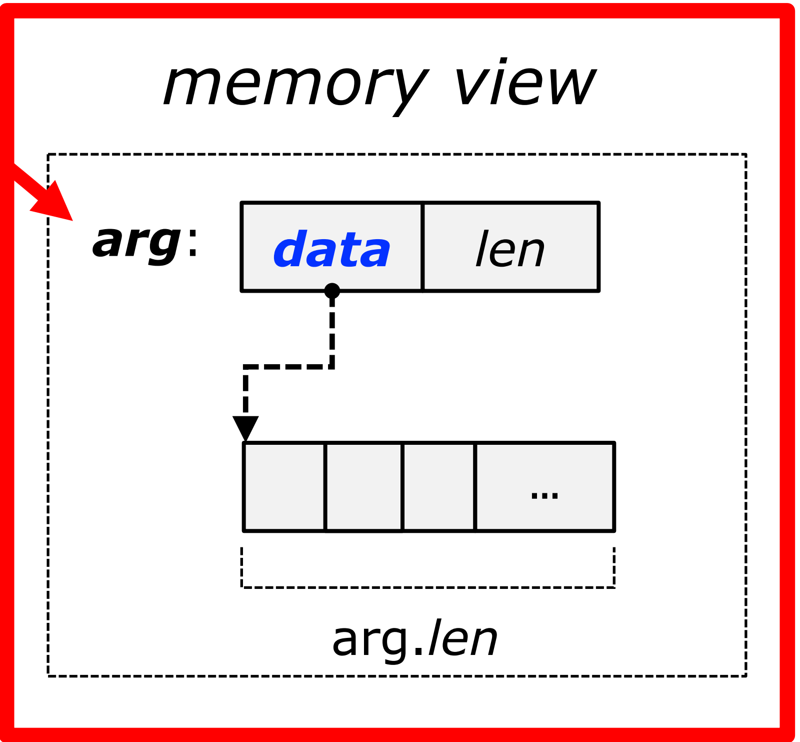
struct *usbdev_ctrl*:
    void ****data***;
    unsigned ***len***;

```
struct usbdev_ctrl ctrl;
uchar *tbuf;
    …
copy_from_user (&ctrl, arg, sizeof(ctrl))
    …
copy_from_user (tbuf, ctrl.data, ctrl.len)

/* do main functionality */
    …
```

dst addr

src addr



Q. Can be inferred exactly?

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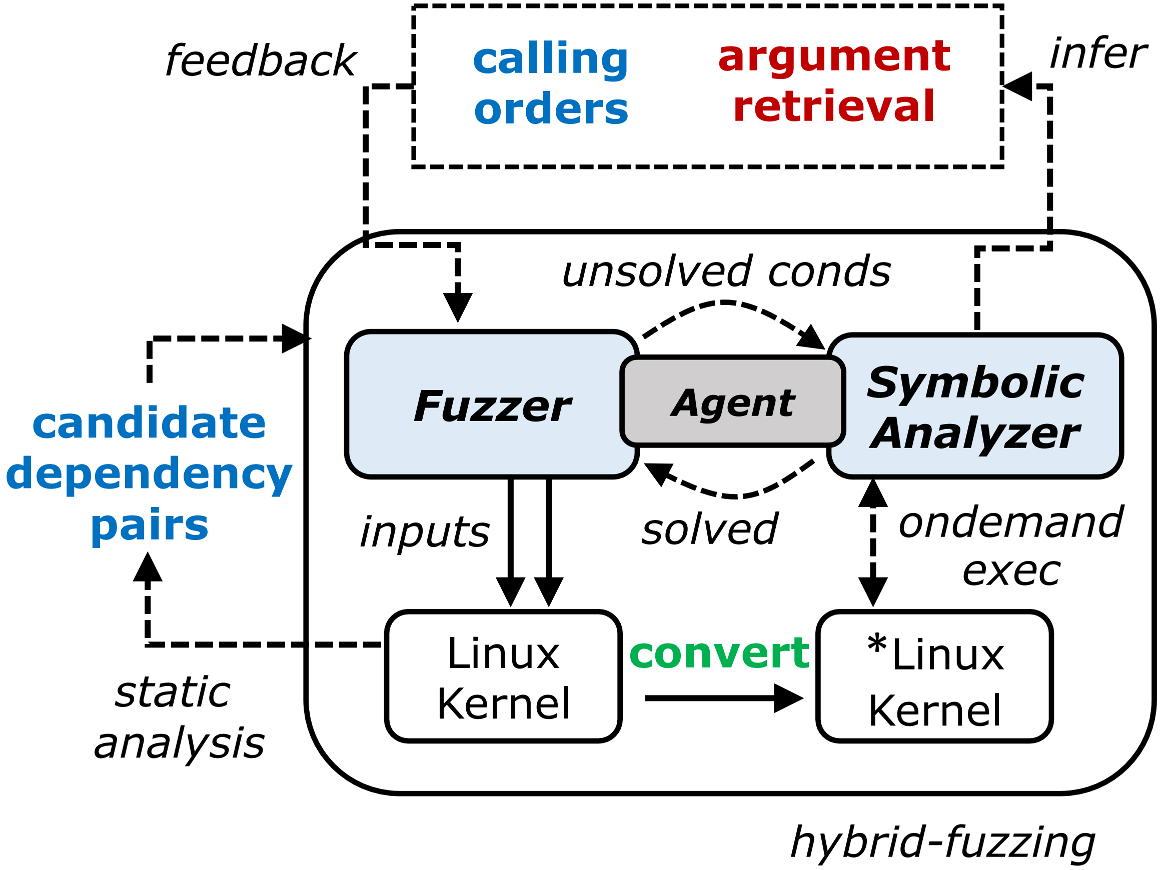


- The *first* hybrid kernel fuzzer
  - Handling the challenges

1. *Implicit control transfer*
   - ***Convert to direct control-flow***
2. *System call dependencies*
   - ***Infer system call dependency***
3. *Complex argument structure*
   - ***Infer nested argument structure***

- Coverage-guided/system call fuzzer
- Hybrid fuzzing
  - Combining fuzzer and symbolic analyzer
  - *Agent* act as a glue between the two components

1. Conversion to Direct Control-flow

<Before>

```
idx = cmd – INFO_FIRST;
    …
funp = _ioctls[idx];
    …
funp (sbi, param);
```

Compile time conversion:
***direct* control transfer**

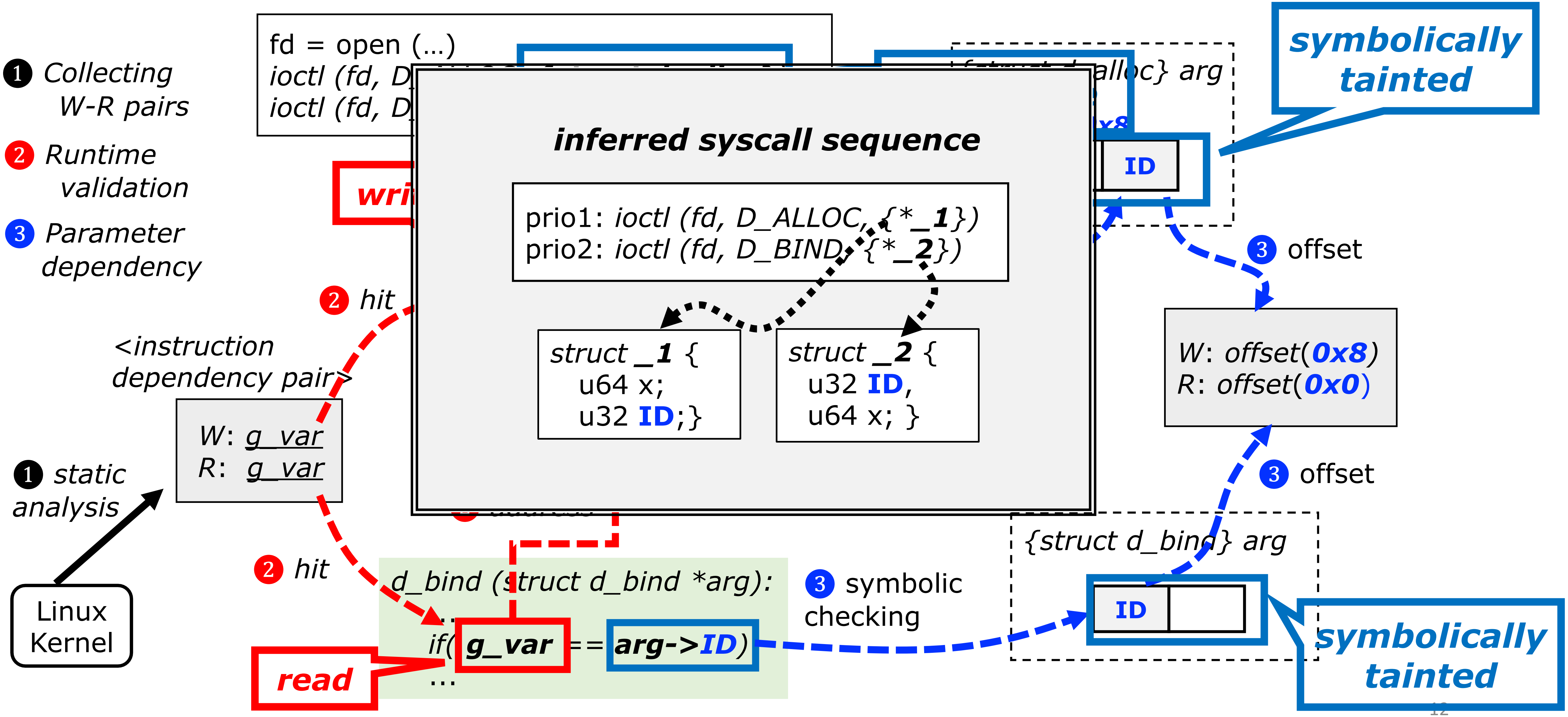
```
ioctl_fn _ioctls[] = {
    ioctl_version,
    ioctl_protover,
        …
    ioctl_ismountpoint,
};
```

functions

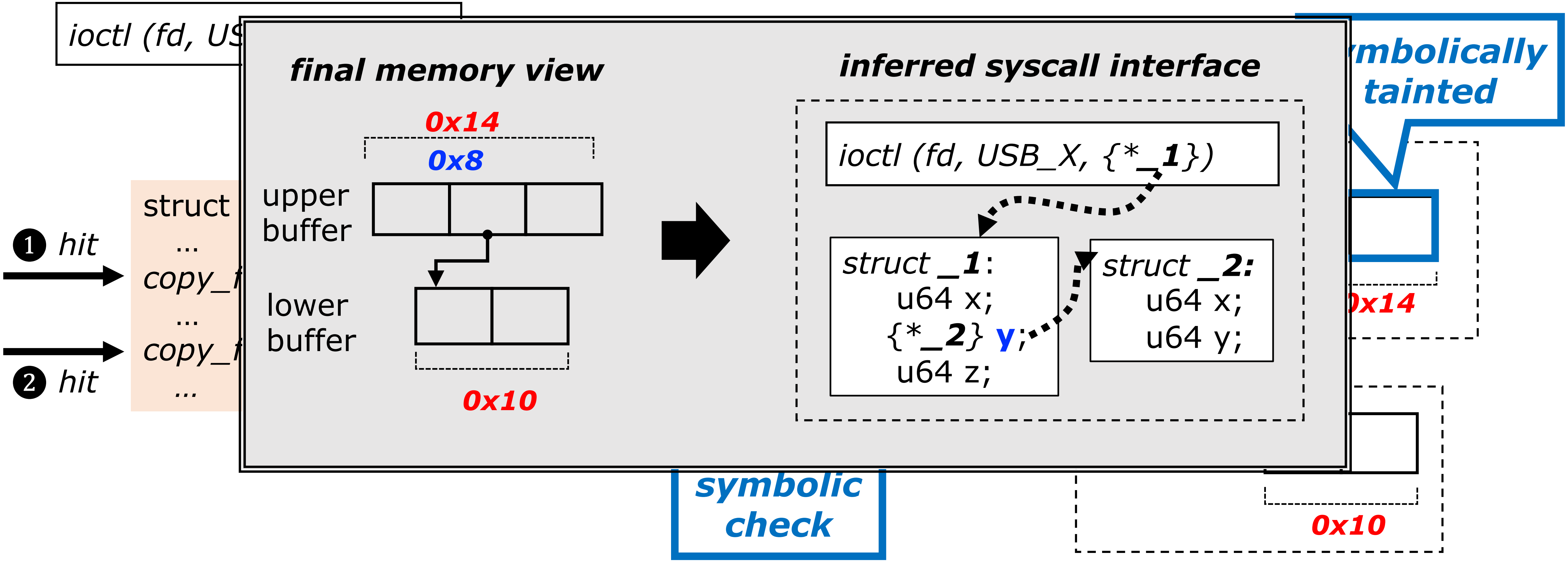
<After>

```
idx = cmd – INFO_FIRST;
    …
funp = _ioctls[idx];
    …
if (cmd == IOCTL_VERSION)
    ioctl_version (sbi, param);
else if (cmd == IOCTL_PROTO)
    ioctl_protover (sbi, param);
  …
    ioctl_ismountpoint (sbi, param)
```

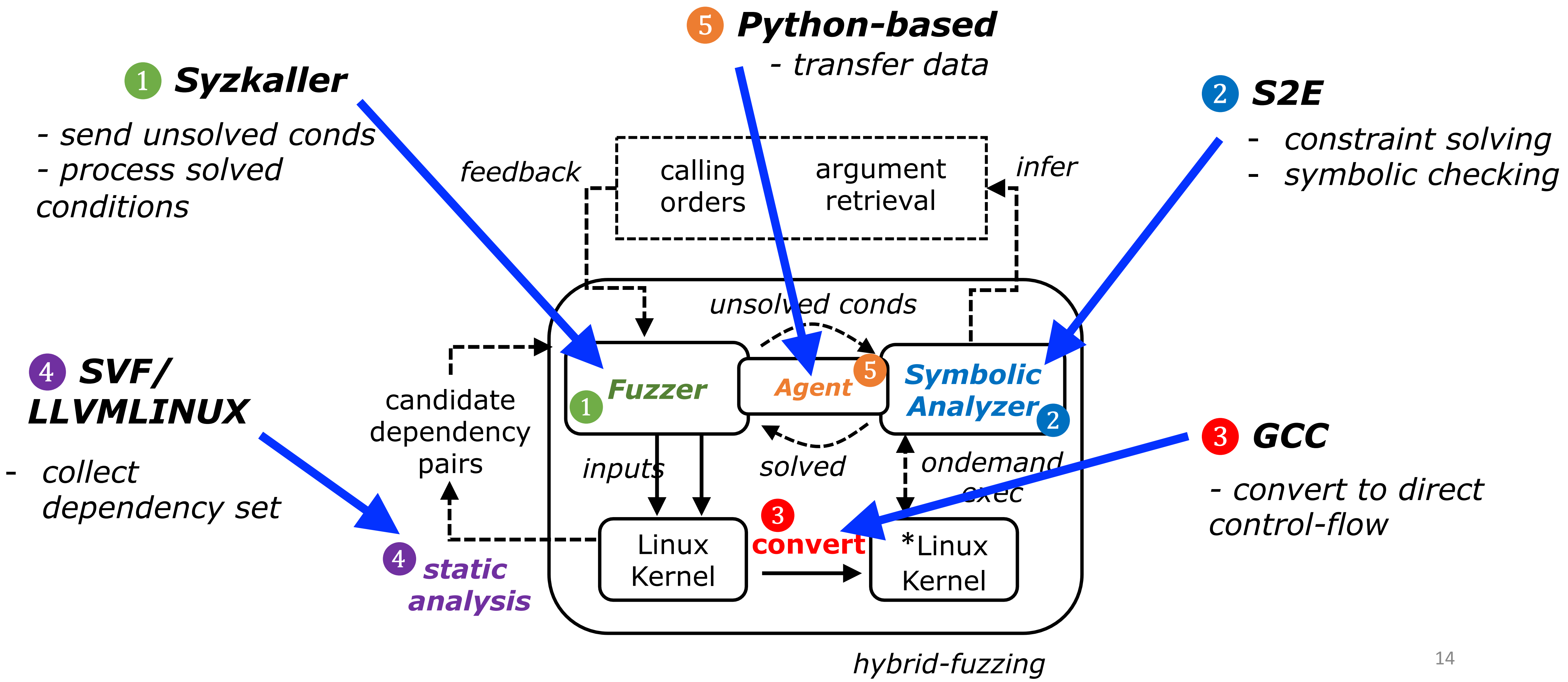
2. Syscall Dependency Inference



3. Nested Argument Format Retrieval



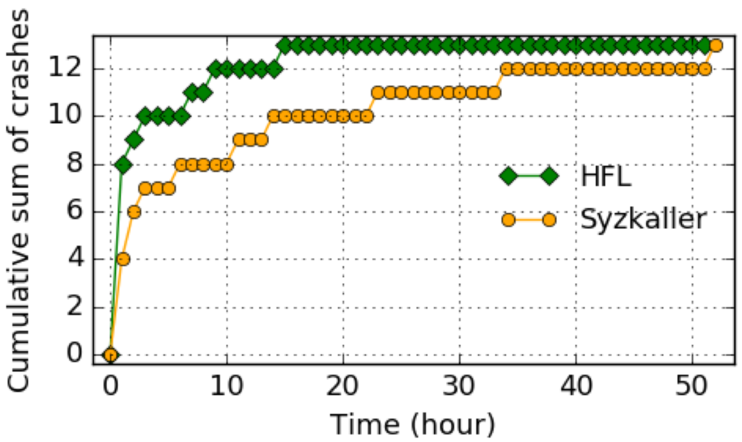
Implementation



Vulnerability Discovery

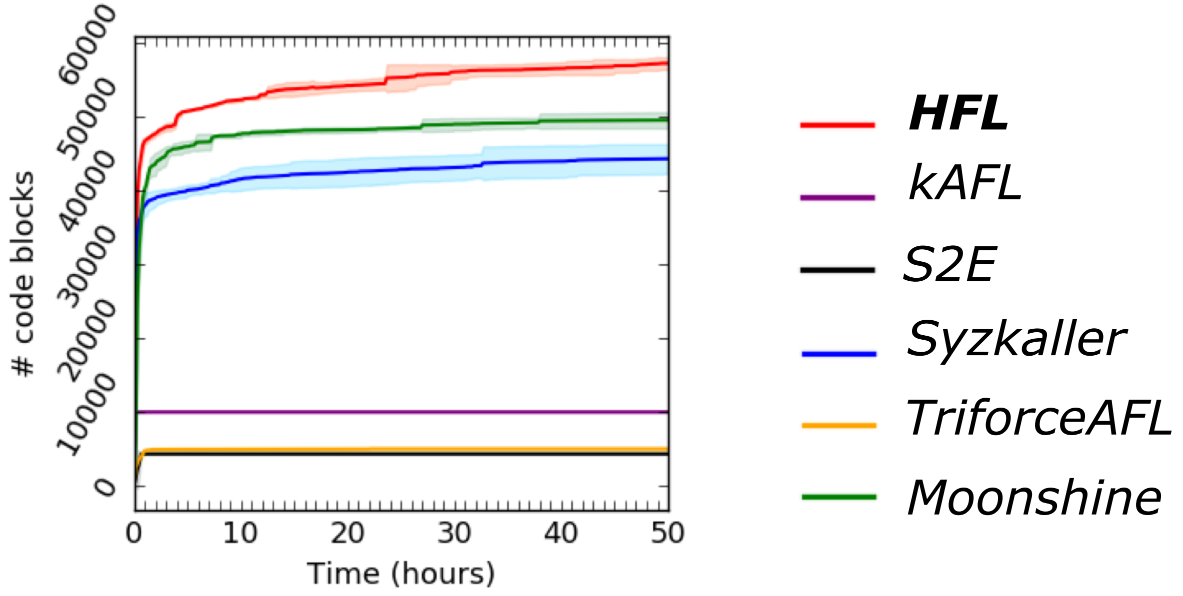
- Discovered new vulnerabilities
  - ***24 new vulnerabilities*** found in the Linux kernels
    - 17 confirmed by Linux kernel community
  - UAF, integer overflow, uninitialized variable access, etc.

- Efficiency of bug-finding capability
  - 13 known bugs for HFL and Syzkaller
  - They were all found by HFL ***3x*** faster than Syzkaller



Code Coverage Enhancement

- Compared with state-of-the-art kernel fuzzers
  - *Moonshine [Sec’18], kAFL [CCS’17], etc.*
- *KCOV*-based coverage measurement
- HFL presents coverage improvement over the others
  - *Ranging from **15%** to **4x***



Case Study: Syscall Dependency

Handled by hybrid feature

1st ioctl

```c
long ppp_ioctl(struct file *fi
    ...
    switch (cmd) {
    // 1. write dependency
    // [syscall]: ioctl(fd, PPP
    // [NOTE]: VAL is written to untyped syscall argu
    case PPPNEWUNIT:
        // allocate an VAL to unit
        err = ppp_create_interface(net, file, &unit);
        if (err < 0)
            break;
        // write the VAL toward userspace
        if (put_user(unit, arg))
            break;
        ...
    // 2. read dependency
    // [syscall]: ioctl(fd, PPPIOCCONNECT, {VAL}->un
    // [NOTE]: VAL is read from untyped syscall argu
    case PPPCONNECT:
        // read VAL from userspace
        if (get_user(unit, arg))
            break;
        ppp = ppp_find_unit(pn, unit); // ...
        // [FAIL]: return if (untyped) value dependen
        if (!ppp)
            goto out;

        /* main connection procedure */
        ...
}
```

prio1: ioctl(fd, PPPNEWUNIT, ID)
prio2: ioctl(fd, PPPCONNECT, ID)

a var

ID written to arg

Handled by hybrid feature

2nd ioctl

Read ID from arg

check ID

FAIL!!

SUCCESS!!

Covered by syscall dependency inference

Conclusion

- HFL is the *first* hybrid kernel fuzzer.
- HFL addresses the crucial challenges in the Linux kernel.
- HFL found 24 new vulnerabilities, and presented the better code coverage, compared to state-of-the-arts.

Thank you