Automatically Diagnosing Use-after-free Bugs via Reference Miscounting Detection on Binaries

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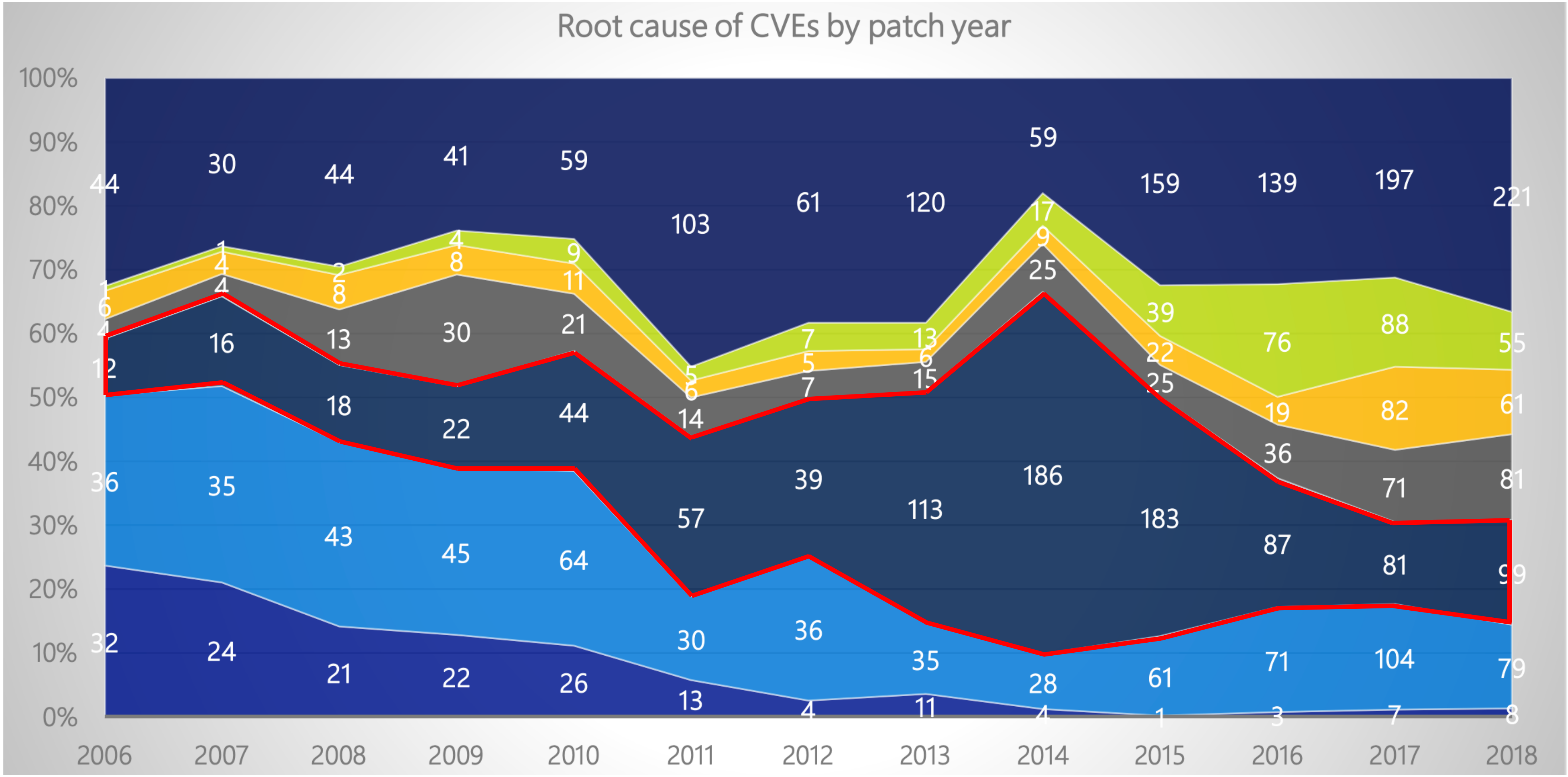
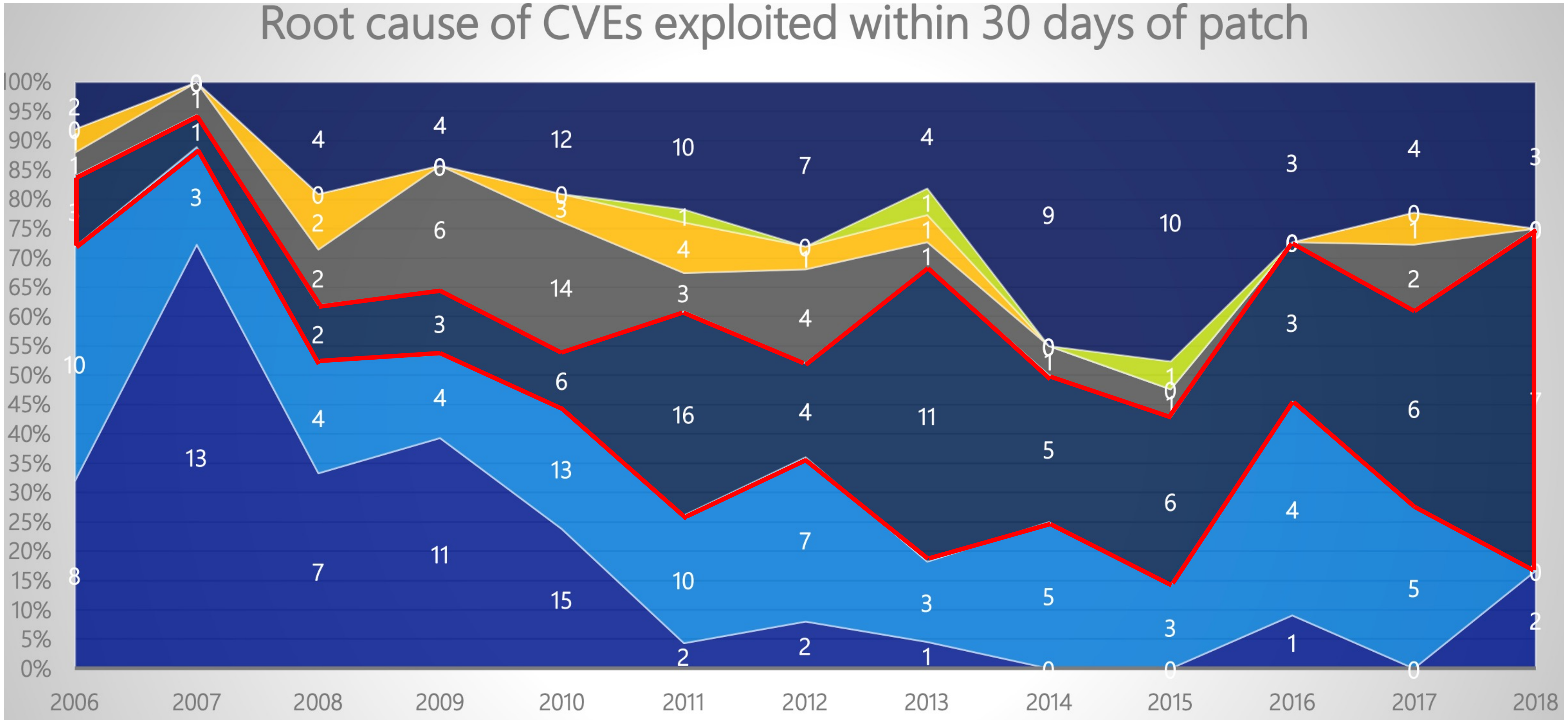
Use-after-free (UAF): **consistently popular**



Matt Miller. Trends, Challenges, And Strategic Shifts In The Software Vulnerability Mitigation Landscape. BluHat IL. 2019

Use-after-free (UAF): **highly exploitable**



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Root causes of UAF bugs

- UAF: use a dangling pointer after the referred object is freed
- (Illegally use) a dangling pointer after the referred object is freed
  - dangling use
  - *DangNull [NDSS'15], pSweeper [CCS'18], ASAN [ATC'12], …*
- Use a dangling pointer after the referred object is (illegally freed)
  - premature free
  - no existing work

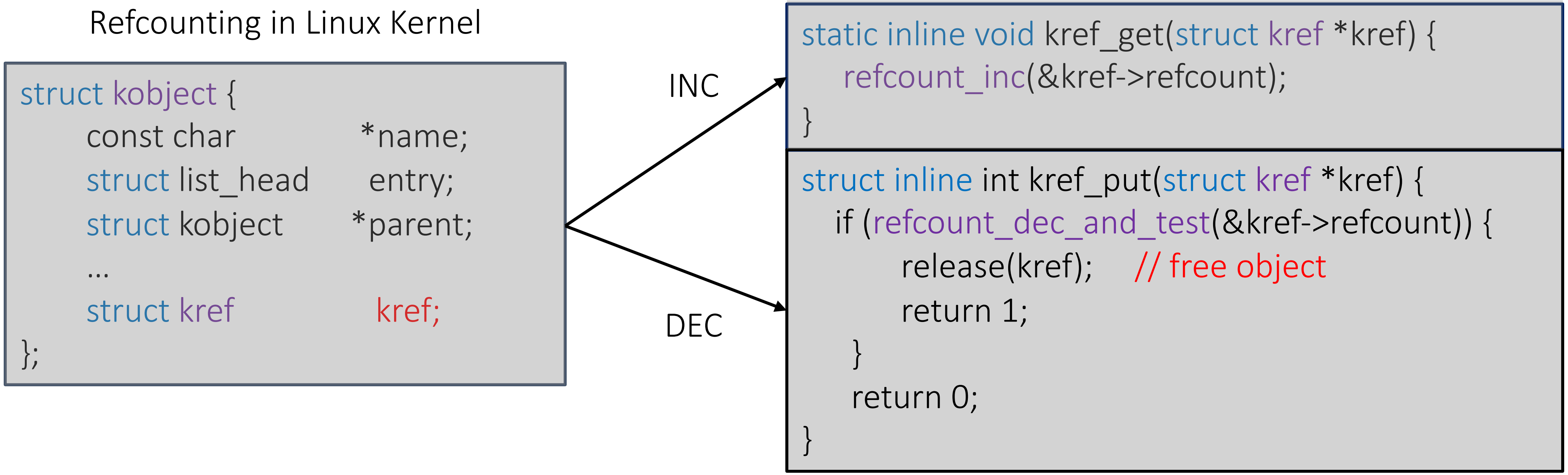
Our work: FreeWill

- Automatic diagnose premature-free caused UAF bugs
    - identify *reference miscounting* as a common reason
    - detect reference miscounting operations
    - suggest possible patches
- Evaluations on large programs/systems
    - 76 bugs from Linux/MacOS, Python/PHP, Chrome/Firefox/IE
        - confirm 48 miscouting, 16 dangling usage
    - complete analysis within 15 minutes
    - 56 patch suggestions

Reference counting for memory management

- Associate a counter for each heap object
- Create a new reference => increase the counter
- Destroy an existing reference => decrease the counter
  - if counter reaches 0, free the object

Refcounting in Linux Kernel



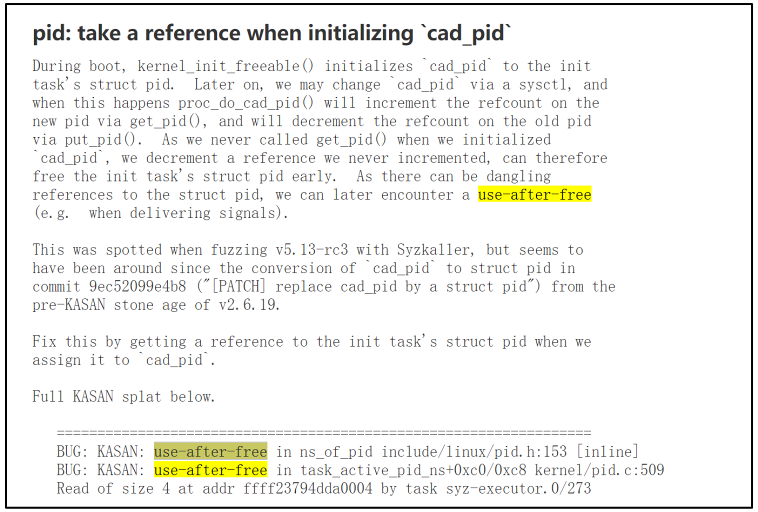
```
struct kobject {
        const char            *name;
        struct list_head       entry;
        struct kobject        *parent;
        …
        struct kref            kref;
};
```

```
static inline void kref_get(struct kref *kref) {
    refcount_inc(&kref->refcount);
}
```

```
struct inline int kref_put(struct kref *kref) {
   if (refcount_dec_and_test(&kref->refcount)) {
         release(kref);     // free object
         return 1;
    }
    return 0;
}
```

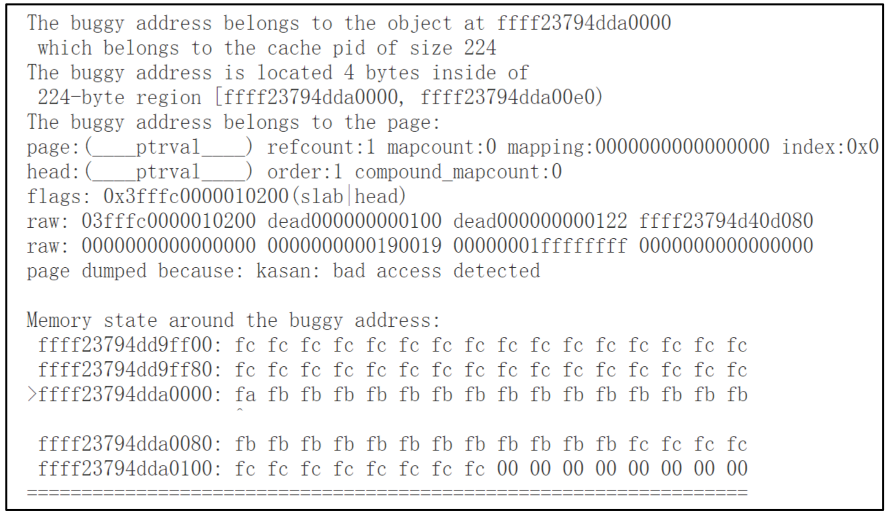
Reference miscounting

- Miss decrements for destroyed references
  - never free (memory leak)
- Miss increments for newly created references
  - premature free (finally use-after-free)

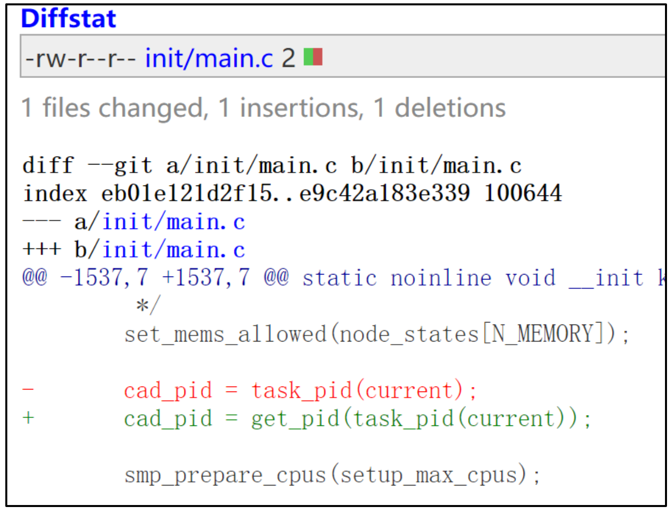


pid: take a reference when initializing `cad_pid`

```
During boot, kernel_init_freeable() initializes `cad_pid` to the init
task's struct pid.  Later on, we may change `cad_pid` via a sysctl, and
when this happens proc_do_cad_pid() will increment the refcount on the
new pid via get_pid(), and will decrement the refcount on the old pid
via put_pid().  As we never called get_pid() when we initialized
`cad_pid`, we decrement a reference we never incremented, can therefore
free the init task's struct pid early.  As there can be dangling
references to the struct pid, we can later encounter a use-after-free
(e.g.  when delivering signals).

This was spotted when fuzzing v5.13-rc3 with Syzkaller, but seems to
have been around since the conversion of `cad_pid` to struct pid in
commit 9ec52099e4b8 ("[PATCH] replace cad_pid by a struct pid") from the
pre-KASAN stone age of v2.6.19.

Fix this by getting a reference to the init task's struct pid when we
assign it to `cad_pid`.

Full KASAN splat below.

  ==================================================================
  BUG: KASAN: use-after-free in ns_of_pid include/linux/pid.h:153 [inline]
  BUG: KASAN: use-after-free in task_active_pid_ns+0xc0/0xc8 kernel/pid.c:509
  Read of size 4 at addr ffff23794dda0004 by task syz-executor.0/273
```



```
The buggy address belongs to the object at ffff23794dda0000
 which belongs to the cache pid of size 224
The buggy address is located 4 bytes inside of
 224-byte region [ffff23794dda0000, ffff23794dda00e0)
The buggy address belongs to the page:
page:(____ptrval____) refcount:1 mapcount:0 mapping:0000000000000000 index:0x0
head:(____ptrval____) order:1 compound_mapcount:0
flags: 0x3fffc0000010200(slab|head)
raw: 03fffc0000010200 dead000000000100 dead000000000122 ffff23794d40d080
raw: 0000000000000000 0000000000190019 00000001ffffffff 0000000000000000
page dumped because: kasan: bad access detected

Memory state around the buggy address:
 ffff23794dd9ff00: fc fc fc fc fc fc fc fc fc fc fc fc fc fc fc fc
 ffff23794dd9ff80: fc fc fc fc fc fc fc fc fc fc fc fc fc fc fc fc
>ffff23794dda0000: fa fb fb fb fb fb fb fb fb fb fb fb fb fb fb fb
                   ^
 ffff23794dda0080: fb fb fb fb fb fb fb fb fb fb fb fb fc fc fc fc
 ffff23794dda0100: fc fc fc fc fc fc fc fc 00 00 00 00 00 00 00 00
==================================================================
```



Diffstat

-rw-r--r-- init/main.c 2 🟩🟥

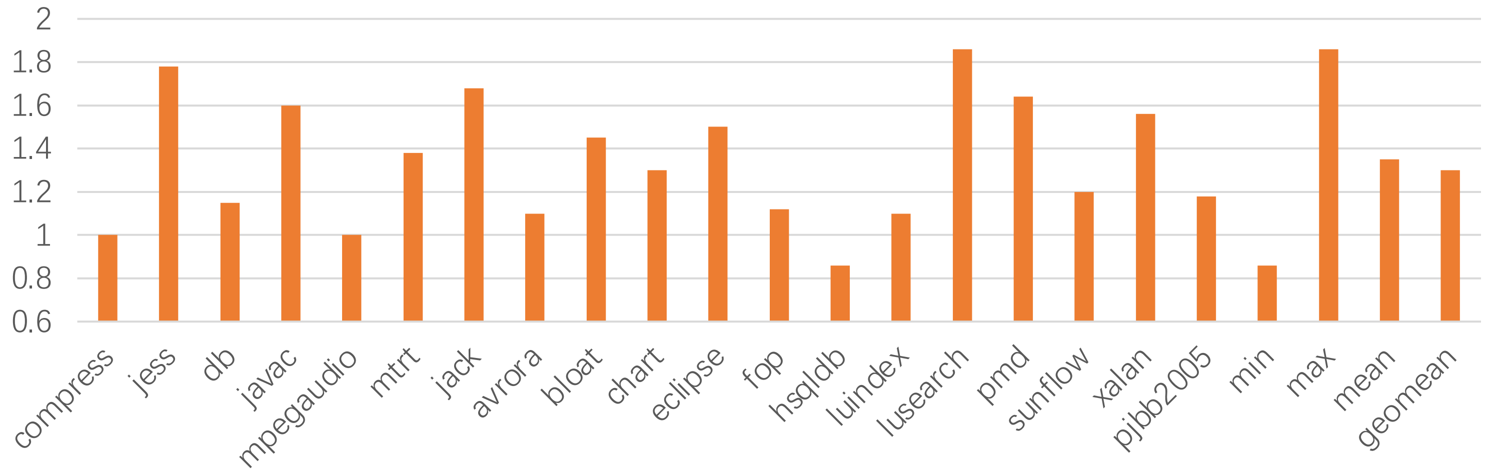
1 files changed, 1 insertions, 1 deletions

```
diff --git a/init/main.c b/init/main.c
index eb01e121d2f15..e9c42a183e339 100644
--- a/init/main.c
+++ b/init/main.c
@@ -1537,7 +1537,7 @@ static noinline void __init k
 	 */
 	set_mems_allowed(node_states[N_MEMORY]);

-	cad_pid = task_pid(current);
+	cad_pid = get_pid(task_pid(current));

 	smp_prepare_cpus(setup_max_cpus);
```

Linux Kernel Commit-0711F0D7050
(2021-06-04)

Challenge of detection: not all missed refcounting are bad

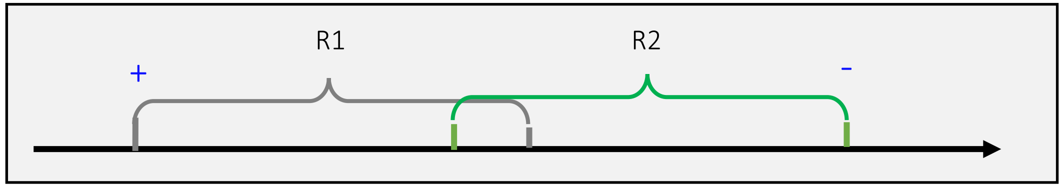
- Refcounting brings ***performance*** overhead (up to 30%)



Rifat Shahriyar, Stephen M. Blackburn, and Daniel Frampton. Down For The Count? Getting Reference Counting Back In The Ring. In ACM SIGPLAN Notices, volume 47, pages 73–84. ACM, 2012.

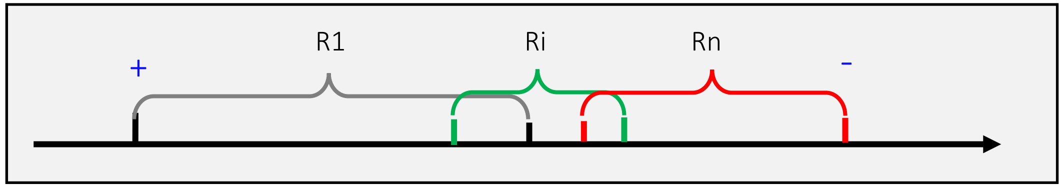
- Programmers ***intentionally omit*** refcounting operations
  - complicated rules guiding the omission
- Which missed refcounting is at fault?

Legal refcounting-omission rules



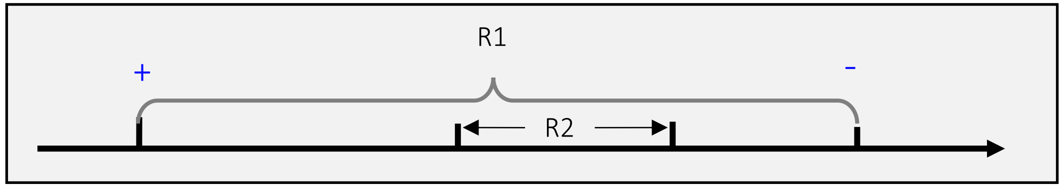
overlapping rule

- Safe to omit R1--, R2++



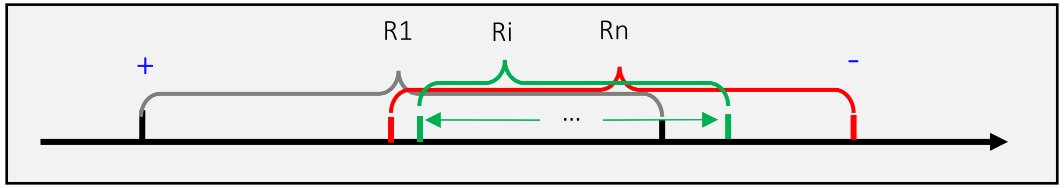
transmitting-overlapping rule

- Safe to omit R1--, Ri++, Ri--, Rn++



containing rule

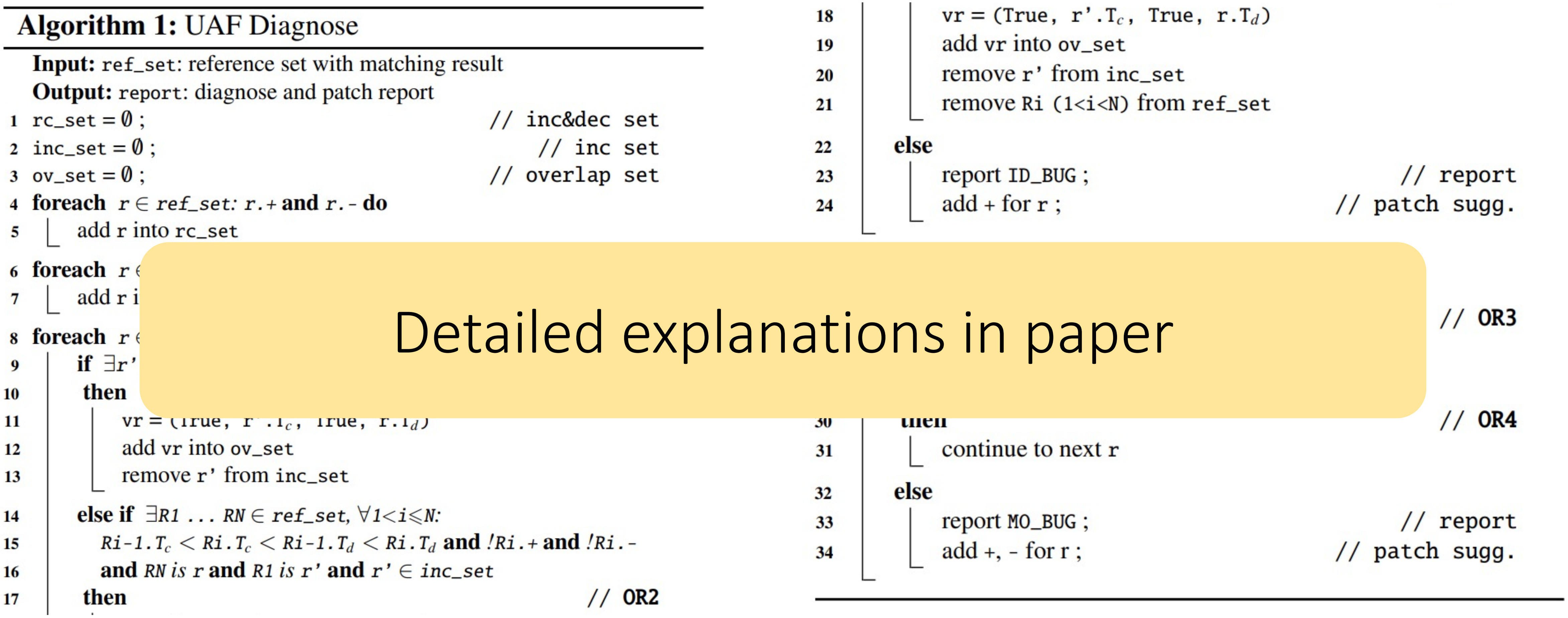
- Safe to omit R2++ & R2--



overlapping-containing rule

- Safe to omit R1--, Ri++ & Ri--, Rn++

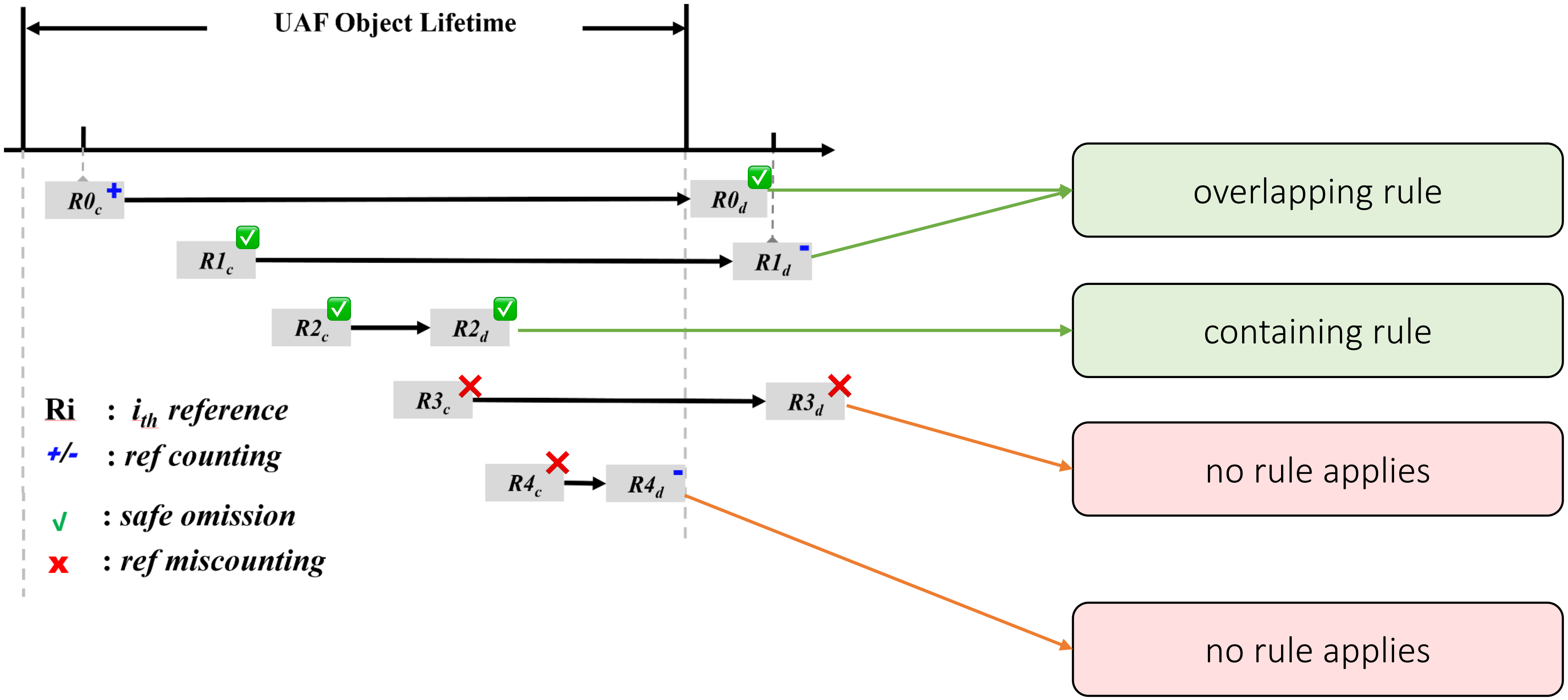
Bug diagnosis algorithm



```
Algorithm 1: UAF Diagnose
Input: ref_set: reference set with matching result
Output: report: diagnose and patch report
rc_set = ∅ ;                                   // inc&dec set
inc_set = ∅ ;                                  // inc set
ov_set = ∅ ;                                   // overlap set
foreach r ∈ ref_set: r.+ and r.- do
    add r into rc_set
foreach r ∈
    add r i
foreach r ∈
    if ∃r'
    then
        vr = (True, r'.$T_c$, True, r.$T_d$)
        add vr into ov_set
        remove r' from inc_set
    else if ∃R1 ... RN ∈ ref_set, ∀1<i⩽N:
      Ri-1.$T_c$ < Ri.$T_c$ < Ri-1.$T_d$ < Ri.$T_d$ and !Ri.+ and !Ri.-
      and RN is r and R1 is r' and r' ∈ inc_set
    then                                       // OR2
        vr = (True, r'.$T_c$, True, r.$T_d$)
        add vr into ov_set
        remove r' from inc_set
        remove Ri (1<i<N) from ref_set
    else
        report ID_BUG ;                        // report
        add + for r ;                          // patch sugg.
                                               // OR3
    then                                       // OR4
        continue to next r
    else
        report MO_BUG ;                        // report
        add +, - for r ;                       // patch sugg.
```

Detailed explanations in paper

Bug diagnosis

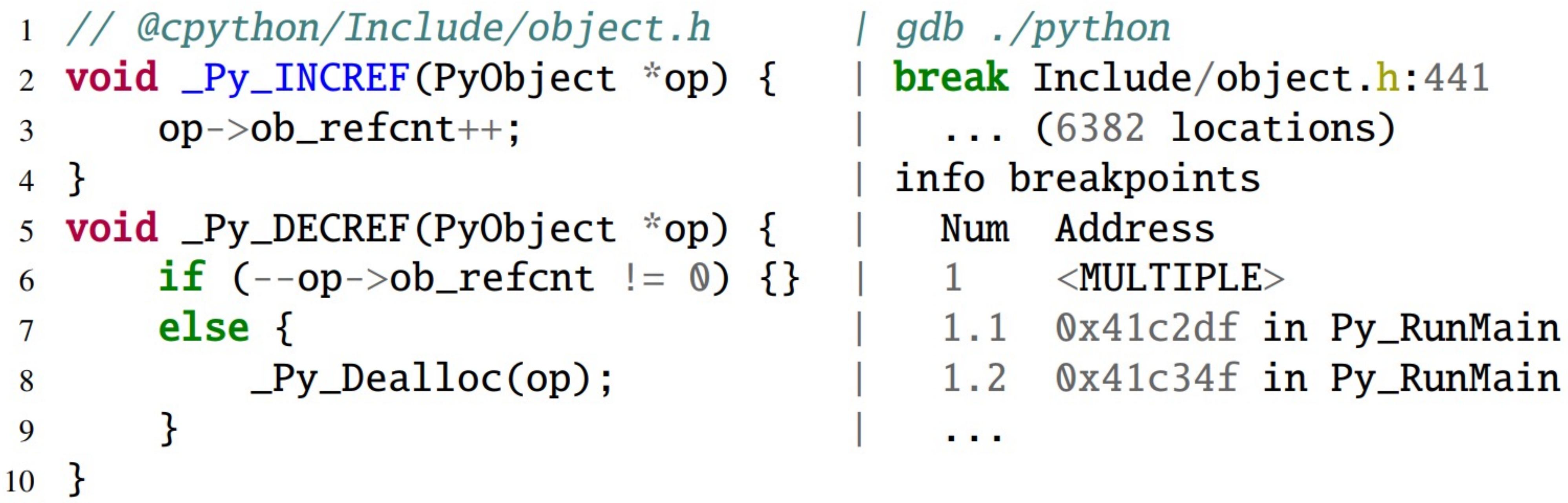


Challenges of **binary-level** diagnosis

- C1: identify reference/refcounting operations
- C2: correlate refcounting to reference creation/destruction

Reference/refcounting detection (w/ source)

- Detecting with debug info and annotation

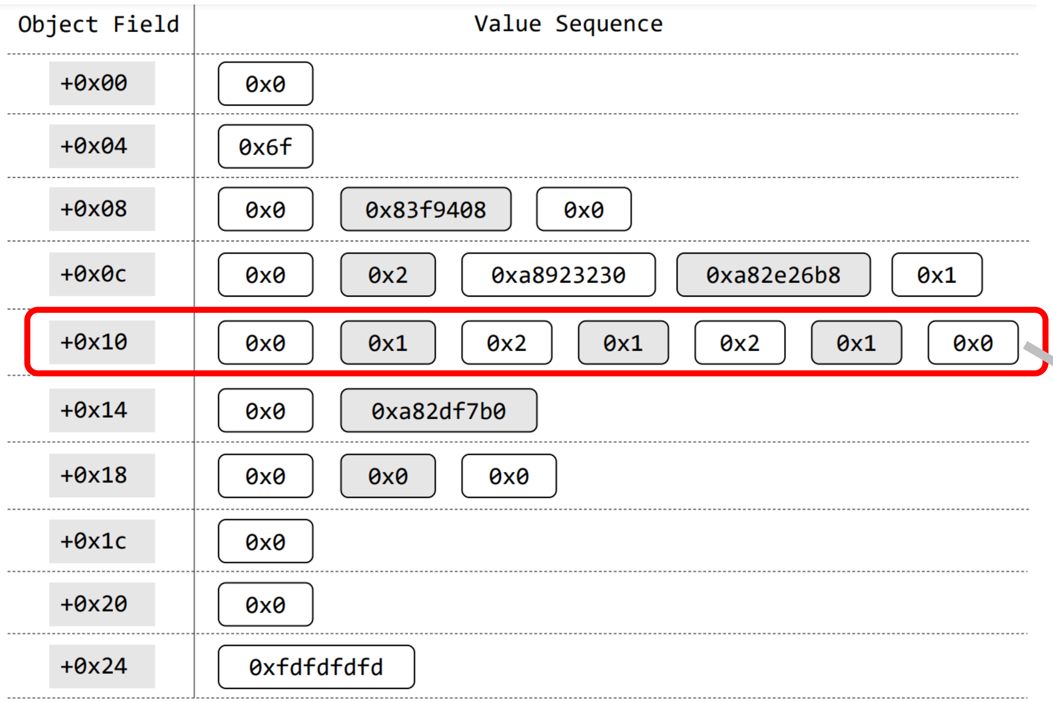


```
// @cpython/Include/object.h        | gdb ./python
void _Py_INCREF(PyObject *op) {     | break Include/object.h:441
    op->ob_refcnt++;                |   ... (6382 locations)
}                                   | info breakpoints
void _Py_DECREF(PyObject *op) {     |   Num  Address
    if (--op->ob_refcnt != 0) {}    |   1    <MULTIPLE>
    else {                          |   1.1  0x41c2df in Py_RunMain
        _Py_Dealloc(op);            |   1.2  0x41c34f in Py_RunMain
    }                               |   ...
}
```

Reference Counting in Python 3.9

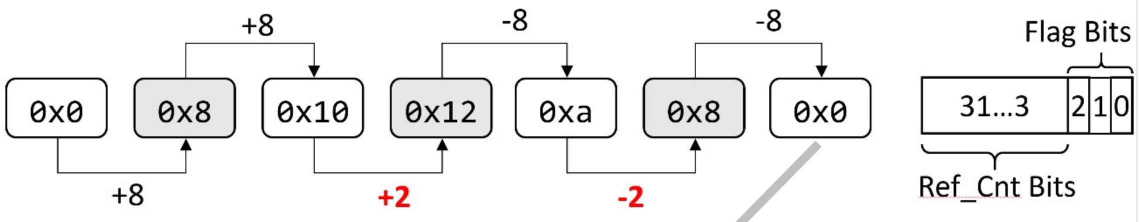
Reference/refcounting detection (w/o source)

- (H1) fix-step changing
  - data-flow analysis
- (H2) control-dependent free
  - control-flow analysis



Object Field	Value Sequence
+0x00	0x0
+0x04	0x6f
+0x08	0x0 0x83f9408 0x0
+0x0c	0x0 0x2 0xa8923230 0xa82e26b8 0x1
+0x10	0x0 0x1 0x2 0x1 0x2 0x1 0x0
+0x14	0x0 0xa82df7b0
+0x18	0x0 0x0 0x0
+0x1c	0x0
+0x20	0x0
+0x24	0xfdfdfdfd

A Python Object Value Sequence

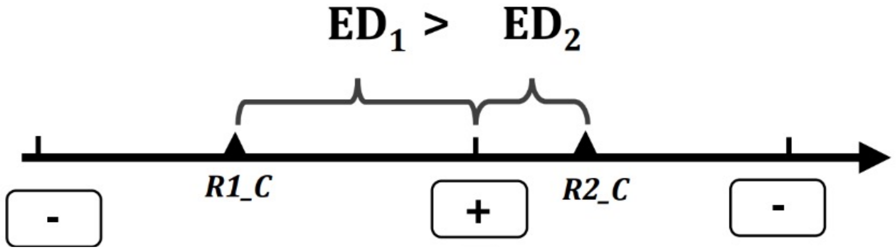


False Negatives (IE-CTreeNode Object)

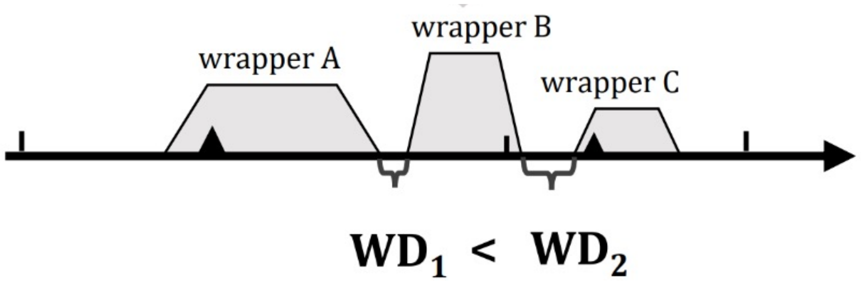
```
if (value == 0)
free(…);
```

Refcounting & reference correlation

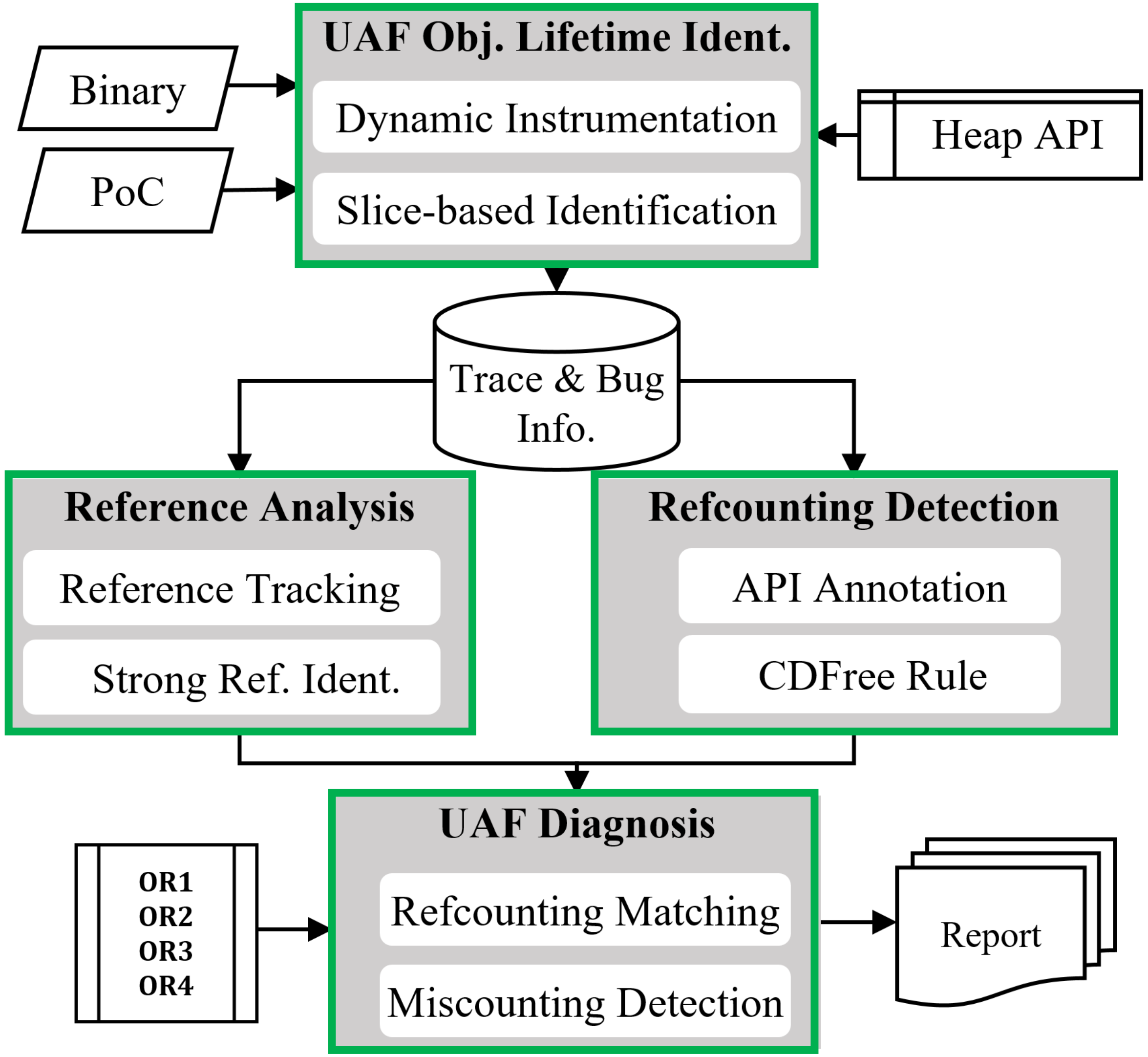
- Based on execution distance (ED)



- Based on wrapper distance (WD)



FreeWill architecture



Evaluation

- Q1: accuracy of root cause diagnosis
- Q2: efficacy of patch suggestion
- Q3: accuracy of reference & refcounting detection

- 76 UAF bugs
  - 32 from Chrome, Firefox and IE
  - 21 from Linux and MacOS
  - 23 from Python and PHP

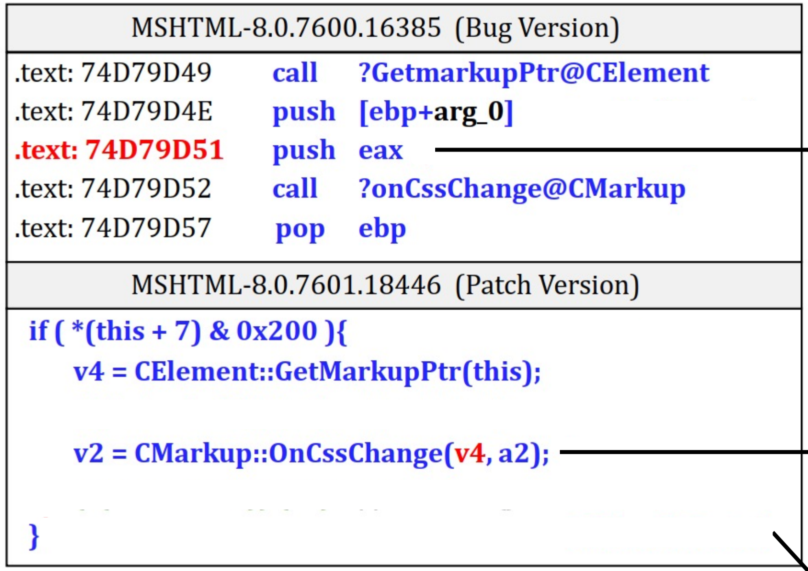
Q1: diagnosis (76 bugs)

- 48 bugs caused by reference miscounting
  - 36 bugs - programmers fail to count the reference (no INC, no DEC)
  - 12 bugs - only decrease but no increase (no INC, has DEC)
- 18 bugs caused by dangling use

Dataset	**Web Browser (32)**			**Kernel (21)**		**Script Engine (23)**	
	IE	**Chrome**	**Firefox**	**Linux**	**MacOS**	**Python**	**PHP**
no INC, no DEC	14	0	0	6	2	10	4
no INC, has DEC	0	0	0	6	3	2	1
dangling use	4	6	4	2	1	0	2
null-deref	0	0	1	1	0	3	0

Q2: patch suggestions

- 56 out of 71 patch suggestions matched with official ones



```
MSHTML-8.0.7600.16385  (Bug Version)
.text: 74D79D49      call   ?GetmarkupPtr@CElement
.text: 74D79D4E      push   [ebp+arg_0]
.text: 74D79D51      push   eax
.text: 74D79D52      call   ?onCssChange@CMarkup
.text: 74D79D57      pop    ebp

MSHTML-8.0.7601.18446  (Patch Version)
 if ( *(this + 7) & 0x200 ){
     v4 = CElement::GetMarkupPtr(this);

     v2 = CMarkup::OnCssChange(v4, a2);

 }
```

Patch Suggestion (CVE-2014-1776)

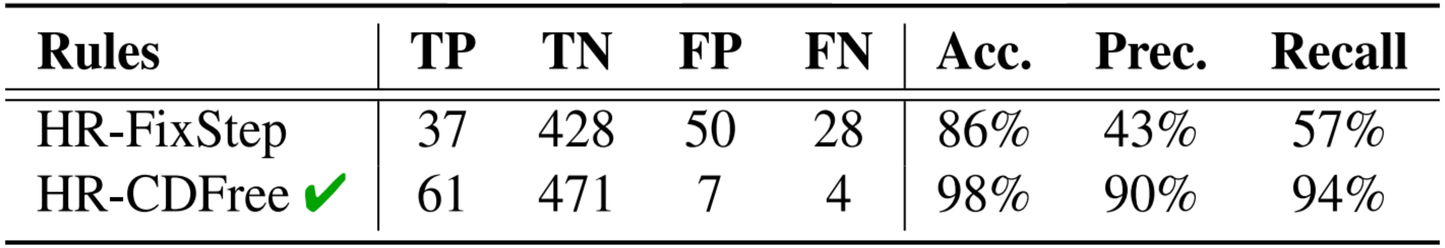
Diagnose: PUSH creates a new reference, but no refcounting.

Patch: add increment and decrement to argument

Official patch: call AddRef() and Release() to increase and decrease the refcount of argument

Q3: reference & refcounting detection

- On average, each UAF object has 2000 references
- Along one trace, 543 objects created, 65 refcounted
- Accuracy of counter detection



Rules	TP	TN	FP	FN	Acc.	Prec.	Recall
HR-FixStep	37	428	50	28	86%	43%	57%
HR-CDFree ✓	61	471	7	4	98%	90%	94%

Conclusion: FreeWill

- Diagnosing UAF bugs due to premature free
  - identify *reference miscounting* as a common reason
  - automatically detect reference miscounting
  - suggest possible patches
- Evaluation on large programs/systems
  - complete analysis within 15 minutes
  - 56 patch suggestions

Thanks & Questions

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