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Detecting Missed Security Operations Through Differential Checking of Object-based Similar Paths

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Background

Background

Reference count operation

Security check

Initialization

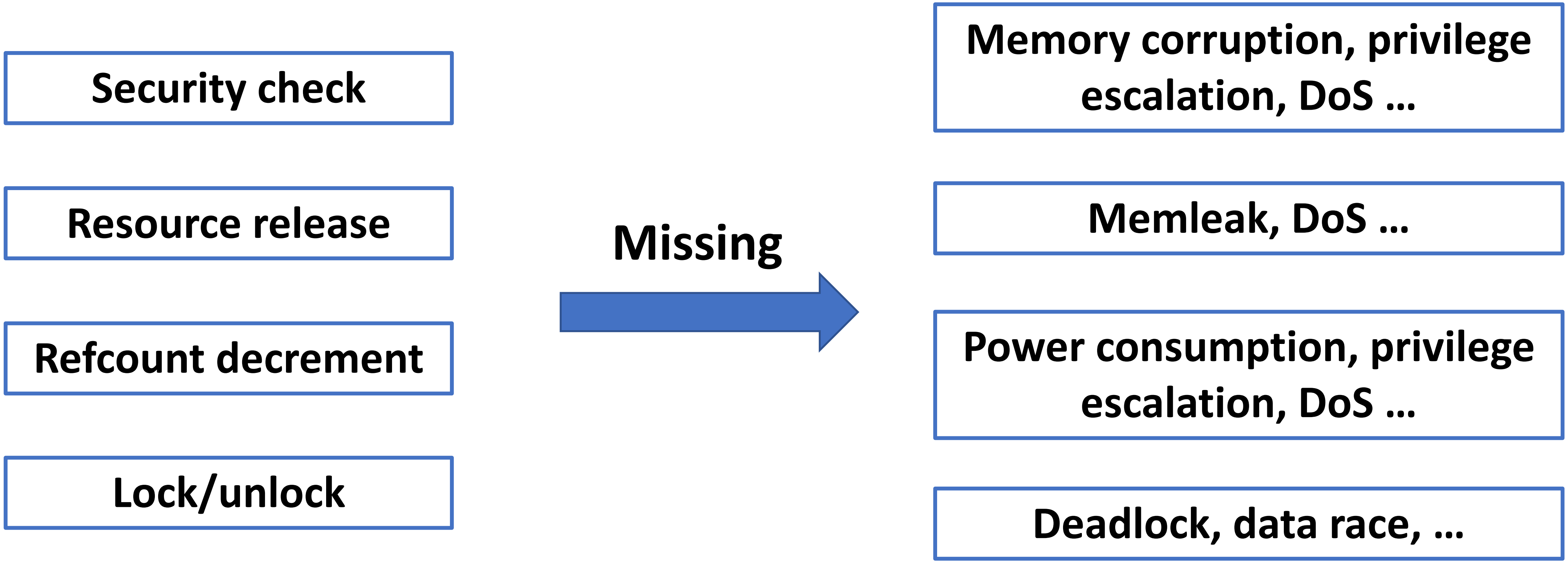
Lock

Security operations are widely used in large-scale programs

Resource release

Background

- **Missing security operations could lead to many security issues**



Security check

Resource release

Refcount decrement

Lock/unlock

Missing

Memory corruption, privilege escalation, DoS …

Memleak, DoS …

Power consumption, privilege escalation, DoS …

Deadlock, data race, …

61% vulnerabilities in the NVD are caused by missing security operations!

Background

How to determine whether the missed security operations are indeed necessary？

Cross-checking

- **High level idea**
  - Collect a substantial number of similar code pieces.
  - Check the behaviors of security operations across the similar code pieces.
  - The majority is correct.

- **Limitations**
  - Sufficient code pieces are required to enable cross-checking.
  - The granularity of code piece is hard to control.
  - The majority is not always correct.

Insight

- **A security operation usually focuses on one critical object.**

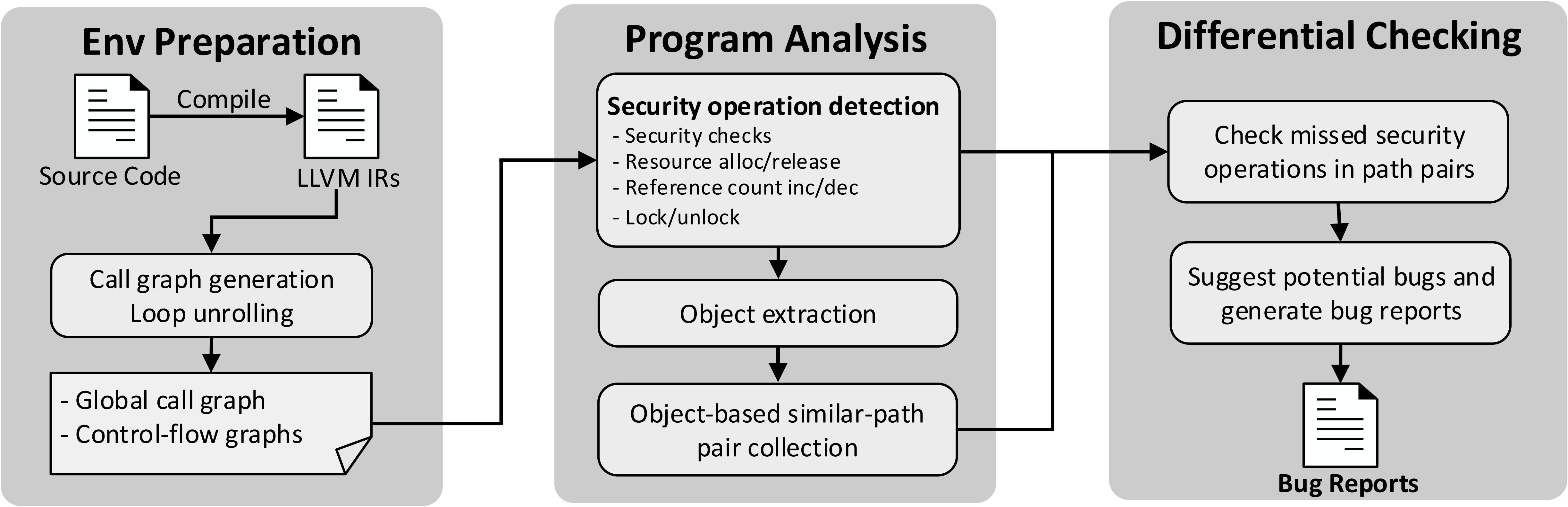
- **The similarity of code pieces should be based on the particular object.**
  - Object-based similar path pair.
  - It takes only 2 paths to enable inconsistency analysis and bug detection.
  - Fine-grained and robust.

System Design

Overview

IPPO (Inconsistent Path Pairs as a bug Oracle)

- Statically detect bugs caused by missed security operations.
- LLVM-based intra-procedural static analyzer.



Security Operation Detection

Security check

FILE: drivers/dma/dma-jz4780.c

```
…
854.   jzdma = devm_kzalloc(dev, struct_size(jzdma, chan,
855.                        soc_data->nb_channels), GFP_KERNEL);
856.   if (!jzdma)
857.       return -ENOMEM;
…
```

Lock/unlock

FILE: arch/x86/platform/uv/uv_irq.c

```
…
161.   mutex_lock(&uv_lock);
…
175.   mutex_unlock(&uv_lock);
…
```

Refcount inc/dec

FILE: drivers/net/ethernet/intel/e1000e/ethtool.c

```
…
161.   pm_runtime_get_sync(netdev->dev.parent);
…
175.   pm_runtime_put_sync(netdev->dev.parent);
…
```

Resource alloc/release

FILE: drivers/platform/x86/dell/dell-wmi-sysman/biosattr-interface.c

```
…
124.   buffer = kzalloc(buffer_size, GFP_KERNEL);
…
141.   kfree(buffer);
…
```

Extracting Objects

Security check

FILE: drivers/dma/dma-jz4780.c

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Lock/unlock

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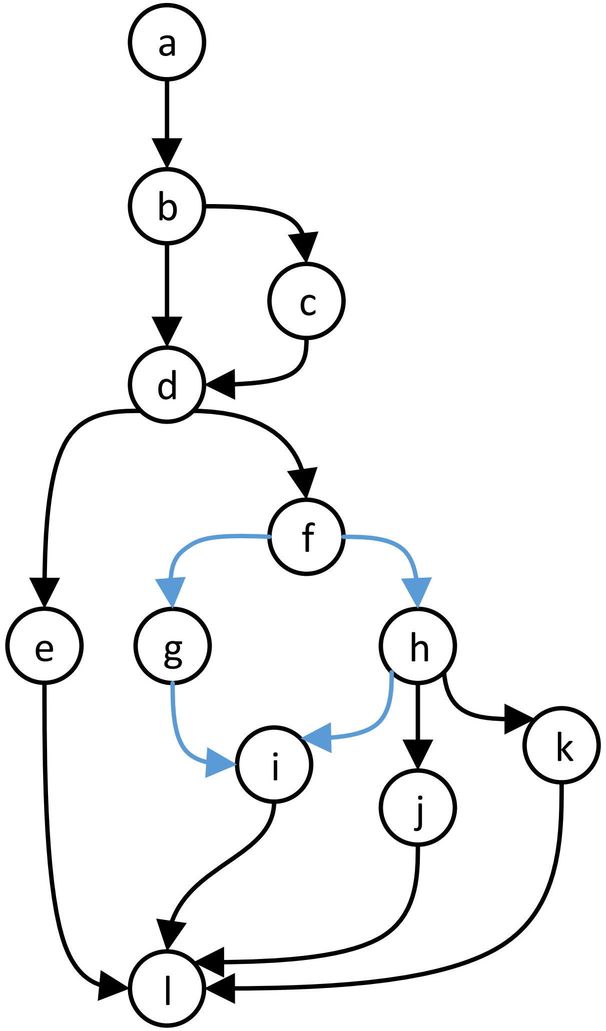
Object-based Similar Path Pair

- Rules for constructing object-based similar path pair (OSPP)

- **Rule 1**
  - The two paths start at the same block and end at the same block in CFG.

- **Challenge: path explosion in large functions**



Object-based Similar Path Pair

- **Rules for constructing object-based similar path pair (OSPP)**

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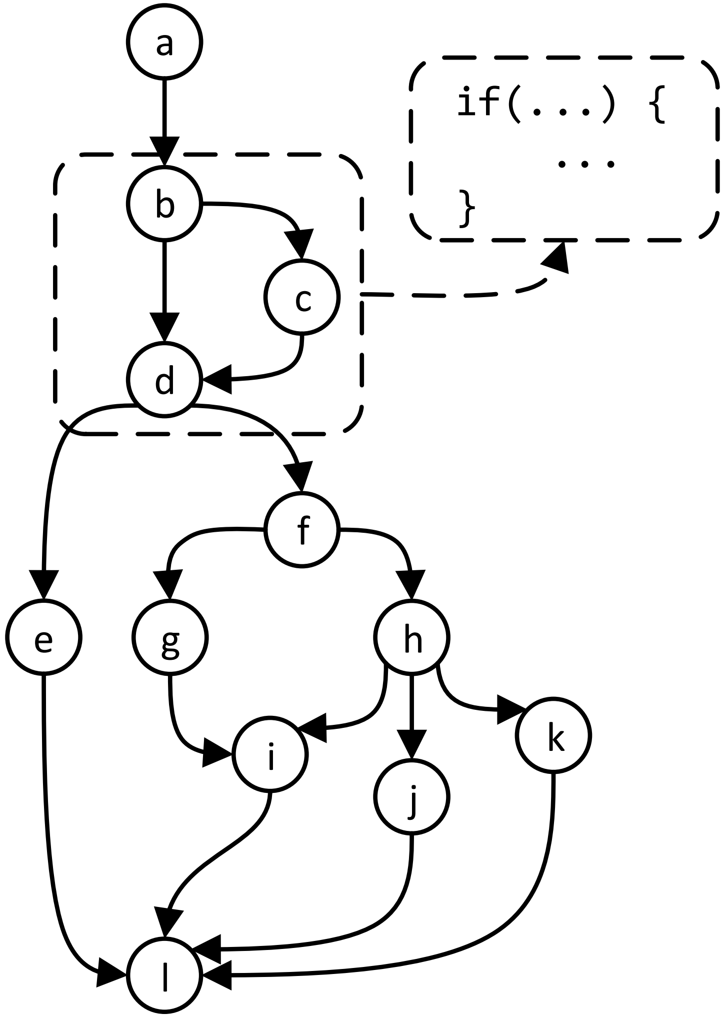
  - **Challenge: path explosion in large functions**

Root cause: The redundant common messages



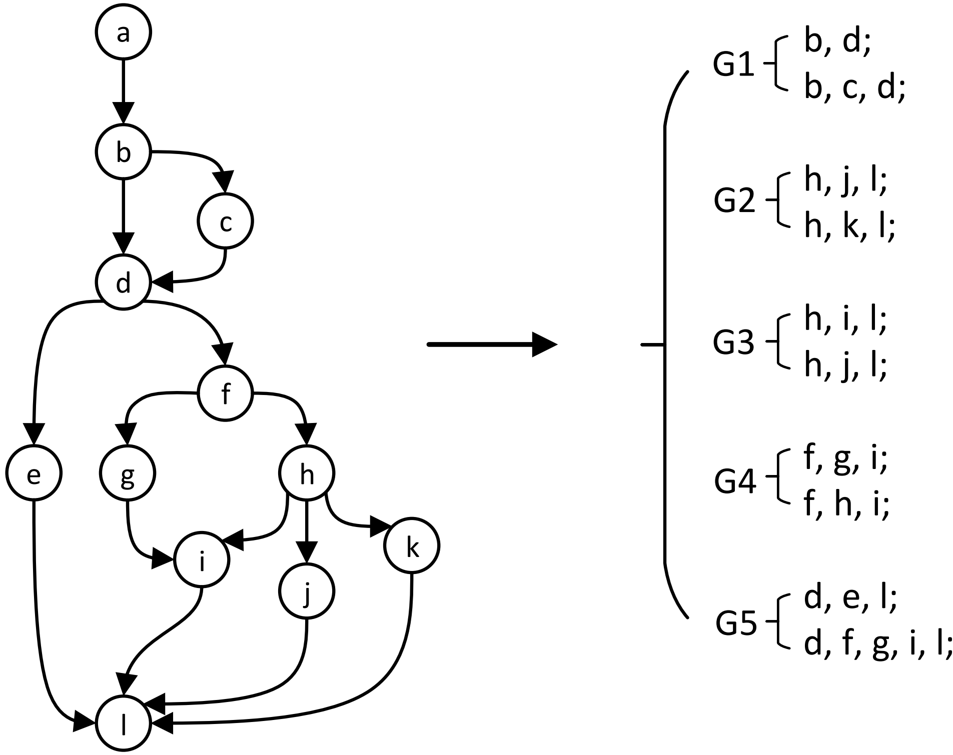
Object-based Similar Path Pair

- Rules for constructing object-based similar path pair (OSPP)

  - **Rule 1**
    - The two paths start at the same block and end at the same block in CFG.

  - **Challenge:** path explosion in large functions

  - **Our solution:** reduced similar path (RSP)
    - Only collect paths that share no common basic blocks besides the start block and the end block.



G1 { b, d; b, c, d;

G2 { h, j, l; h, k, l;

G3 { h, i, l; h, j, l;

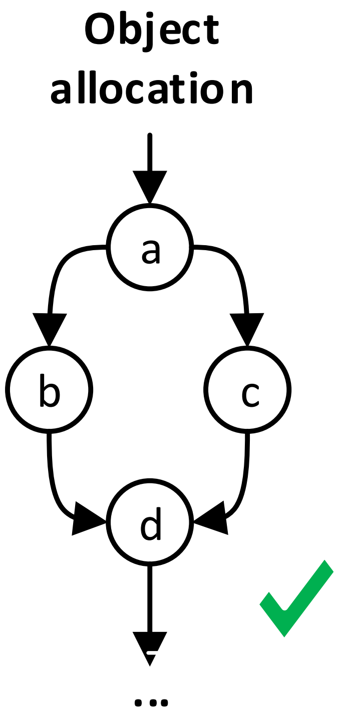
G4 { f, g, i; f, h, i;

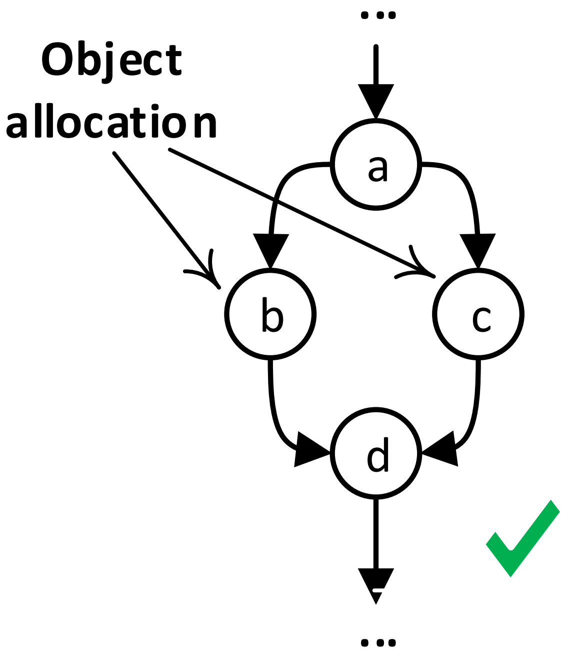
G5 { d, e, l; d, f, g, i, l;

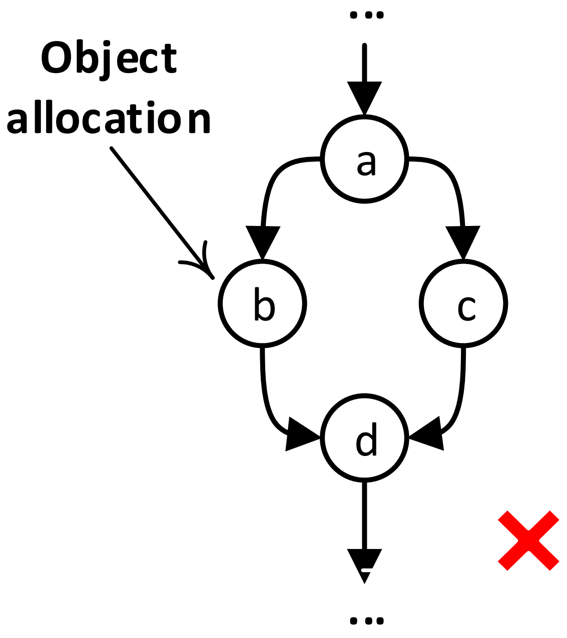
Object-based Similar Path Pair

- **Rules for constructing object-based similar path pair (OSPP)**

- **Rule 2**
  - The object has the same state in two paths.





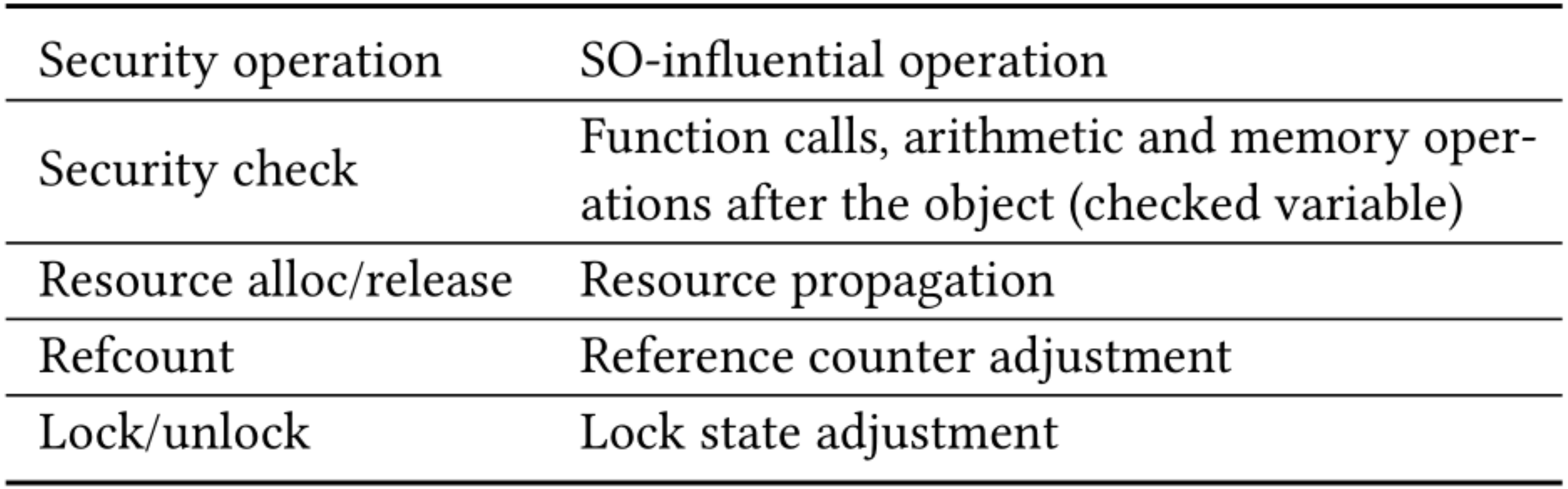


Object-based Similar Path Pair

Rules for constructing object-based similar path pair (OSPP)

- **Rule 3**
  - The object has the same ***security operation-influential operations*** against the object.

Table 1: SO-influential operations.



Security operation	SO-influential operation
Security check	Function calls, arithmetic and memory operations after the object (checked variable)
Resource alloc/release	Resource propagation
Refcount	Reference counter adjustment
Lock/unlock	Lock state adjustment

Object-based Similar Path Pair

- **Rules for constructing object-based similar path pair (OSPP)**

- **Rule 4**
  - The two paths have the same set of pre- and post-conditions against the object.

Pre-condition:

The branch condition of a path pair. → *Must be object irrelevant*

Post-condition:

The return values of a path pair. → *A pair of normal paths or a pair of error handing paths*

Object-based Similar Path Pair

➢ **Rules for constructing object-based similar path pair (OSPP)**

- **Challenge:** how to efficiently collect path pairs that satisfy the post-condition of Rule 4?

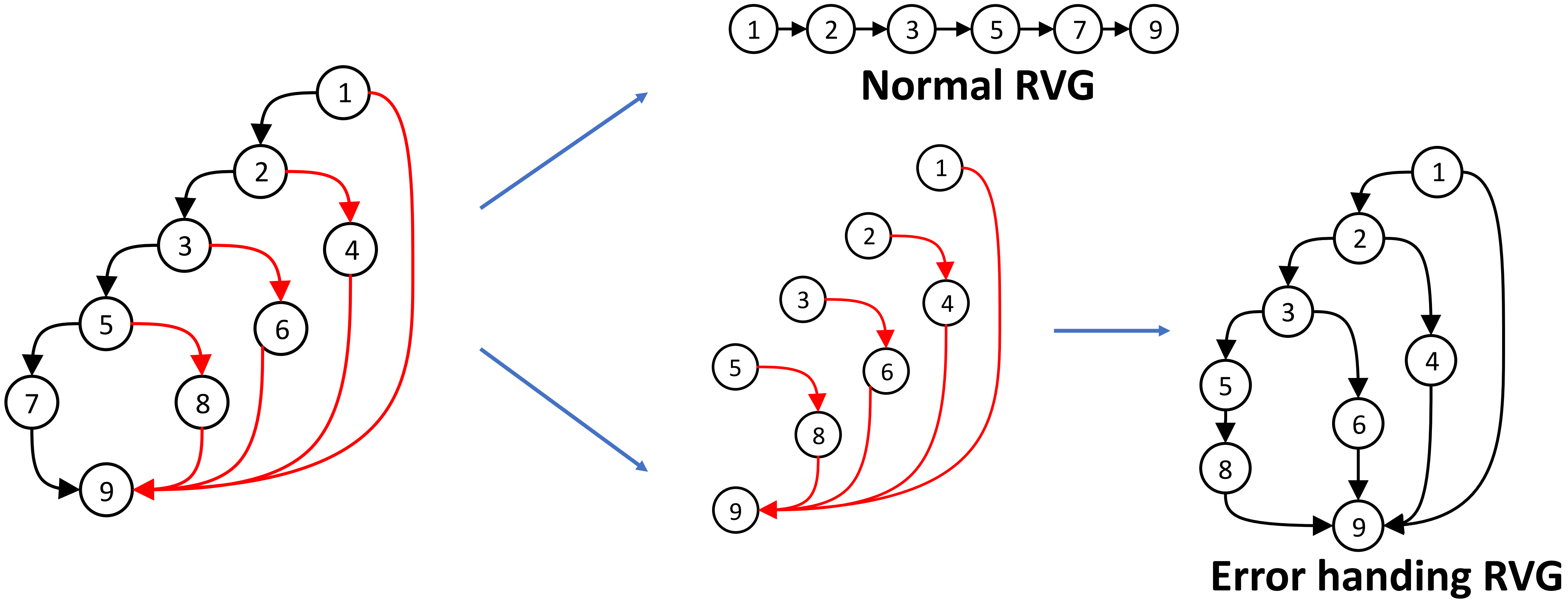
- **Our solution:** **graph partitioning**
  - Divide the CFG into 2 sub-CFGs:
  - Paths in each sub-CFG share the same return value

➢ Return value-based graphs (RVGs)

Object-based Similar Path Pair

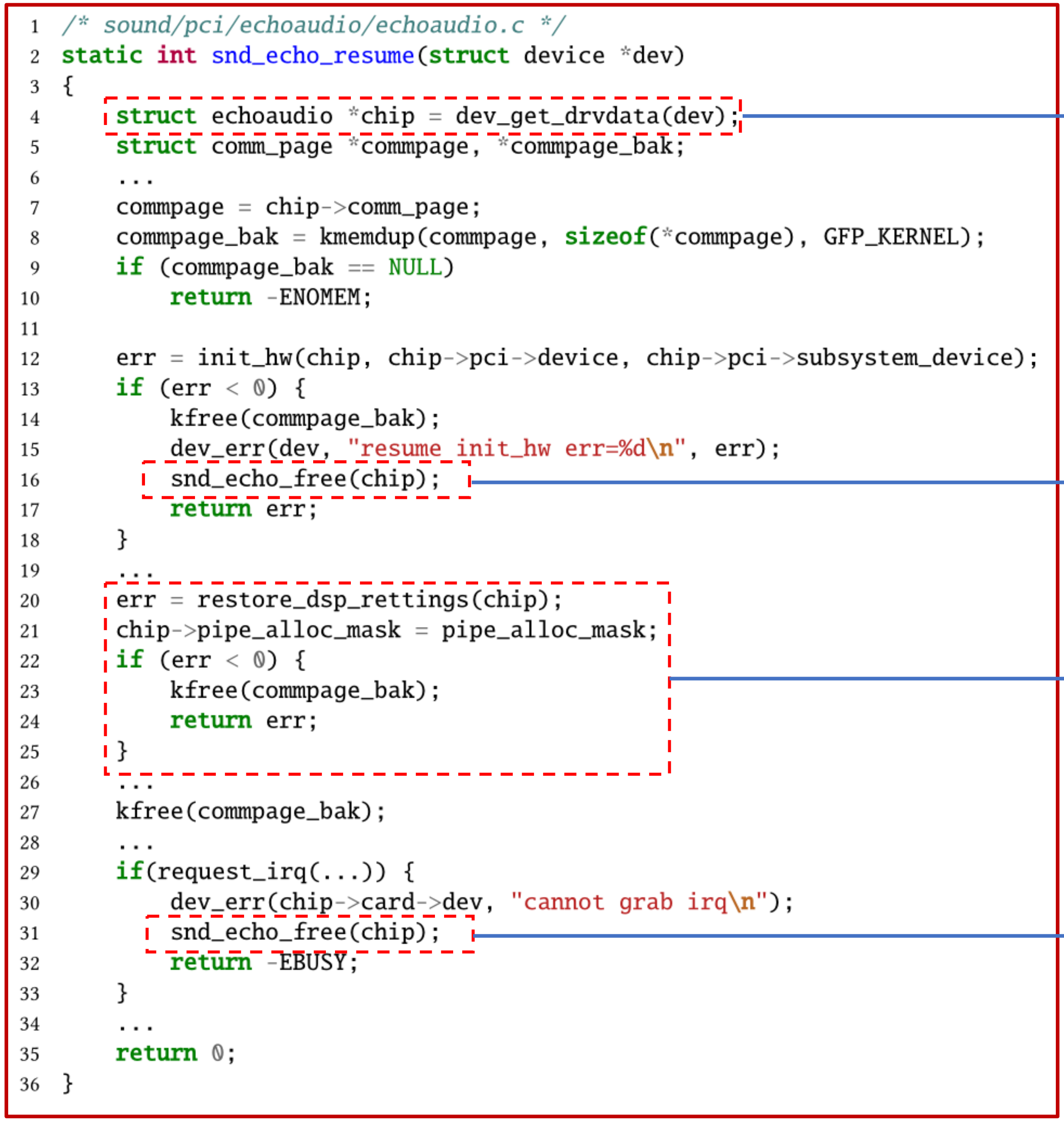
- Rules for constructing object-based similar path pair (OSPP)

  - Generating return value-based graphs



Case Study

A Double-free Bug Found by IPPO



```c
/* sound/pci/echoaudio/echoaudio.c */
static int snd_echo_resume(struct device *dev)
{
    struct echoaudio *chip = dev_get_drvdata(dev);
    struct comm_page *commpage, *commpage_bak;
    ...
    commpage = chip->comm_page;
    commpage_bak = kmemdup(commpage, sizeof(*commpage), GFP_KERNEL);
    if (commpage_bak == NULL)
        return -ENOMEM;

    err = init_hw(chip, chip->pci->device, chip->pci->subsystem_device);
    if (err < 0) {
        kfree(commpage_bak);
        dev_err(dev, "resume init_hw err=%d\n", err);
        snd_echo_free(chip);
        return err;
    }
    ...
    err = restore_dsp_rettings(chip);
    chip->pipe_alloc_mask = pipe_alloc_mask;
    if (err < 0) {
        kfree(commpage_bak);
        return err;
    }
    ...
    kfree(commpage_bak);
    ...
    if(request_irq(...)) {
        dev_err(chip->card->dev, "cannot grab irq\n");
        snd_echo_free(chip);
        return -EBUSY;
    }
    ...
    return 0;
}
```

Resource allocation of object *chip*

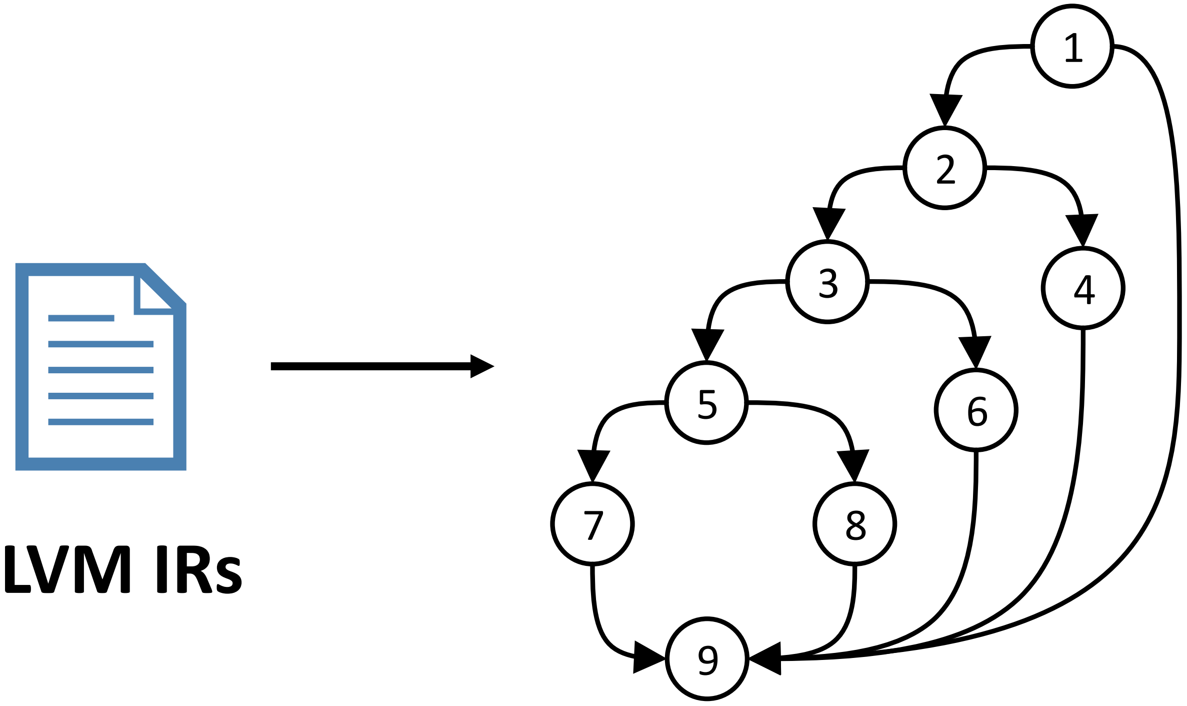
Resource release of object *chip*

Missing release against *chip* in the error handing path

Resource release of object *chip*

Workflow of IPPO

- **Security operation detection & error edges identification**

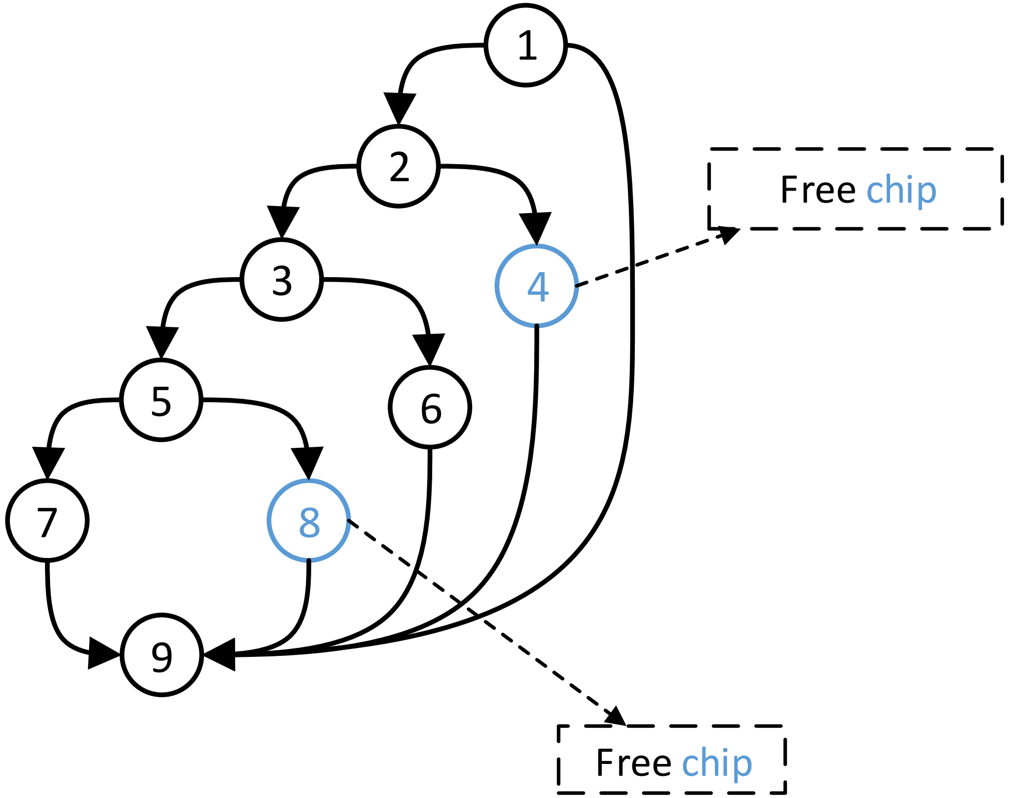


Control flow graph

Workflow of IPPO

- **Security operation detection & error edges identification**

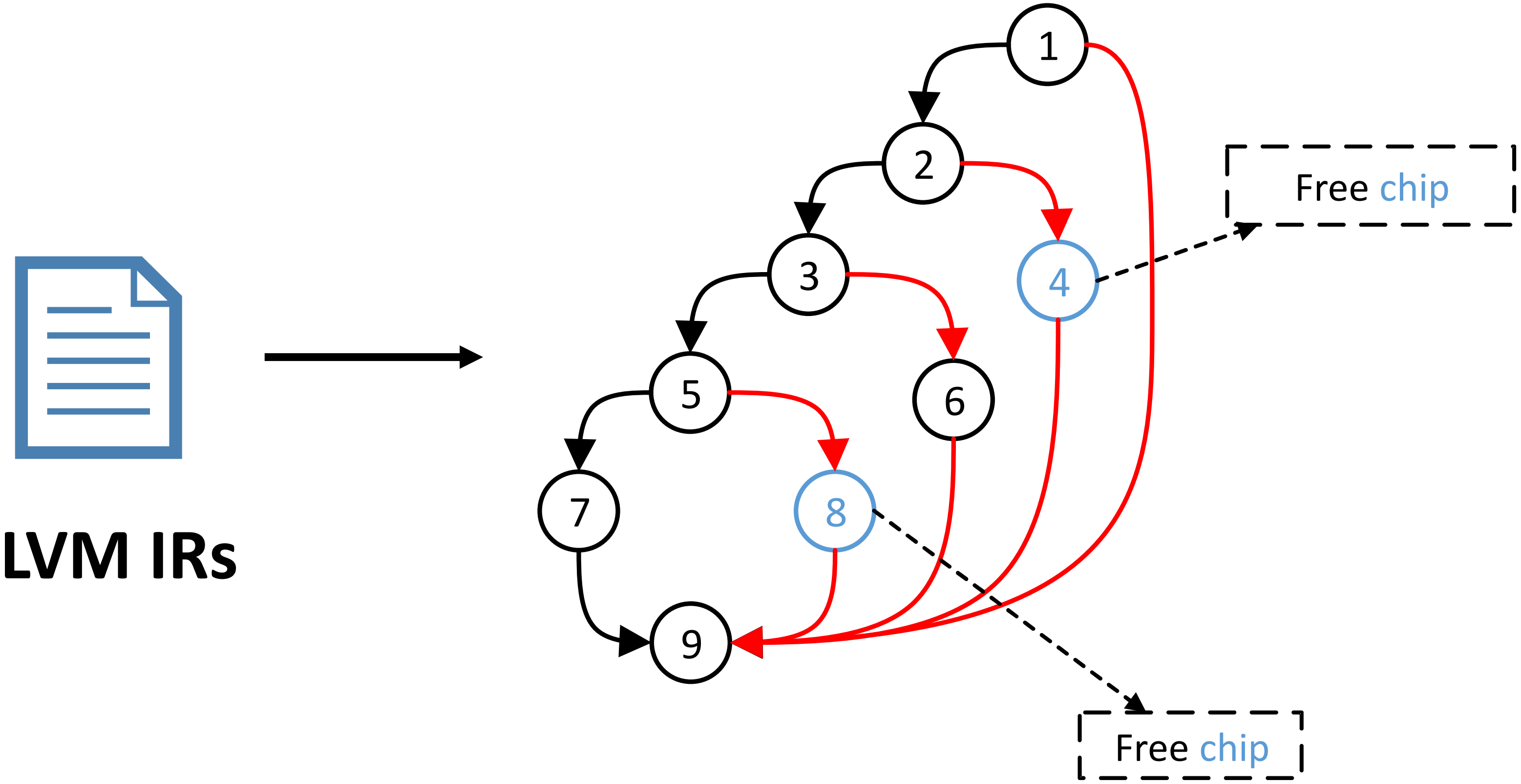
LLVM IRs



Control flow graph

Workflow of IPPO

- **Identify error edges**

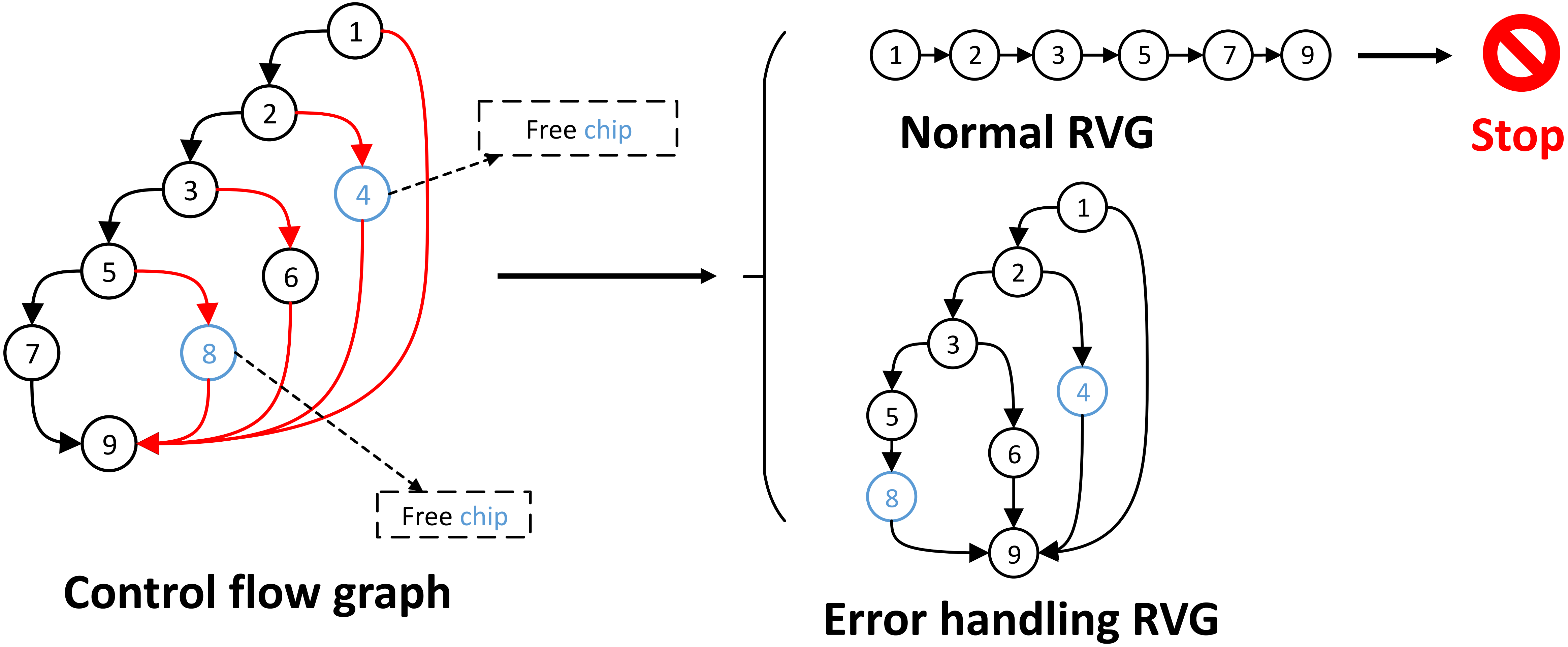


LLVM IRs

Control flow graph

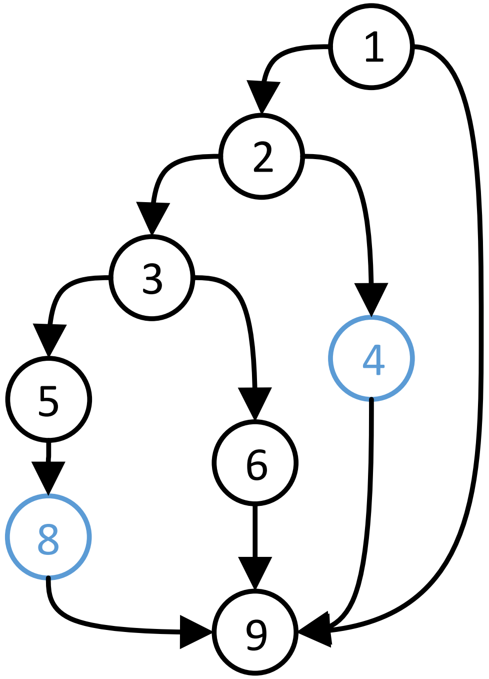
Workflow of IPPO

- **Generate return value-based graphs**



Workflow of IPPO

- **Collect reduced similar paths (RSPs)**



RSP 1
③ - ⑤ - ⑧ - ⑨
③ - ⑥ - ⑨

RSP 2
② - ③ - ⑤ - ⑧ - ⑨
② - ④ - ⑨

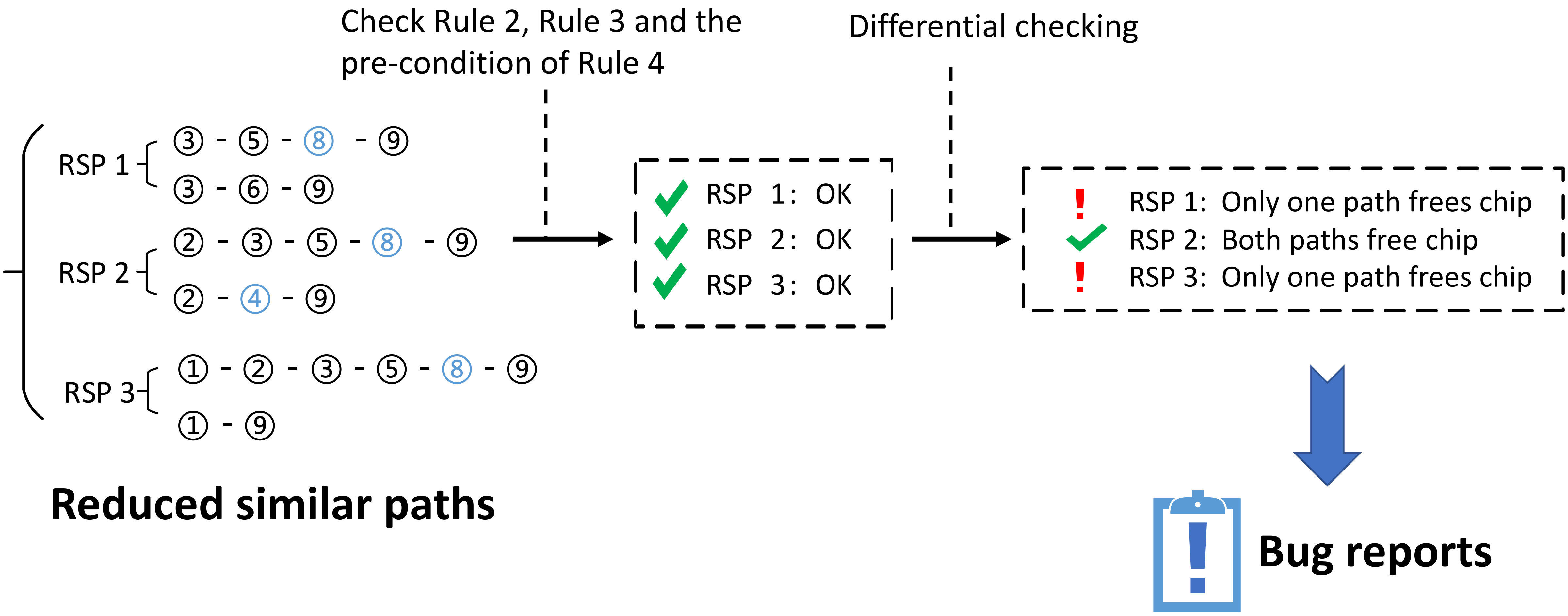
RSP 3
① - ② - ③ - ⑤ - ⑧ - ⑨
① - ⑨

Error handling RVG

Reduced similar paths

Workflow of IPPO

➢ OSPP rules checking & differential checking



Check Rule 2, Rule 3 and the pre-condition of Rule 4

Differential checking

RSP 1
③ - ⑤ - ⑧ - ⑨
③ - ⑥ - ⑨

RSP 2
② - ③ - ⑤ - ⑧ - ⑨
② - ④ - ⑨

RSP 3
① - ② - ③ - ⑤ - ⑧ - ⑨
① - ⑨

✓ RSP 1: OK
✓ RSP 2: OK
✓ RSP 3: OK

! RSP 1: Only one path frees chip
✓ RSP 2: Both paths free chip
! RSP 3: Only one path frees chip

Reduced similar paths

Bug reports

Evaluation

Experimental Setting

Environment

- Use a laptop with 16 GB RAM and Intel Core i7 CPU with six cores
- Use Clang-9.0

Targets

- Linux kernel v5.8
- FreeBSD 12
- OpenSSL 3.0.0-alpha6
- PHP 8.0.8

Bug Findings

- ➢ **Only focus on missed *return value checks, refcount decrement, resource release*, and *unlock*.**
- ➢ **Complete the whole analysis in 2 hours.**

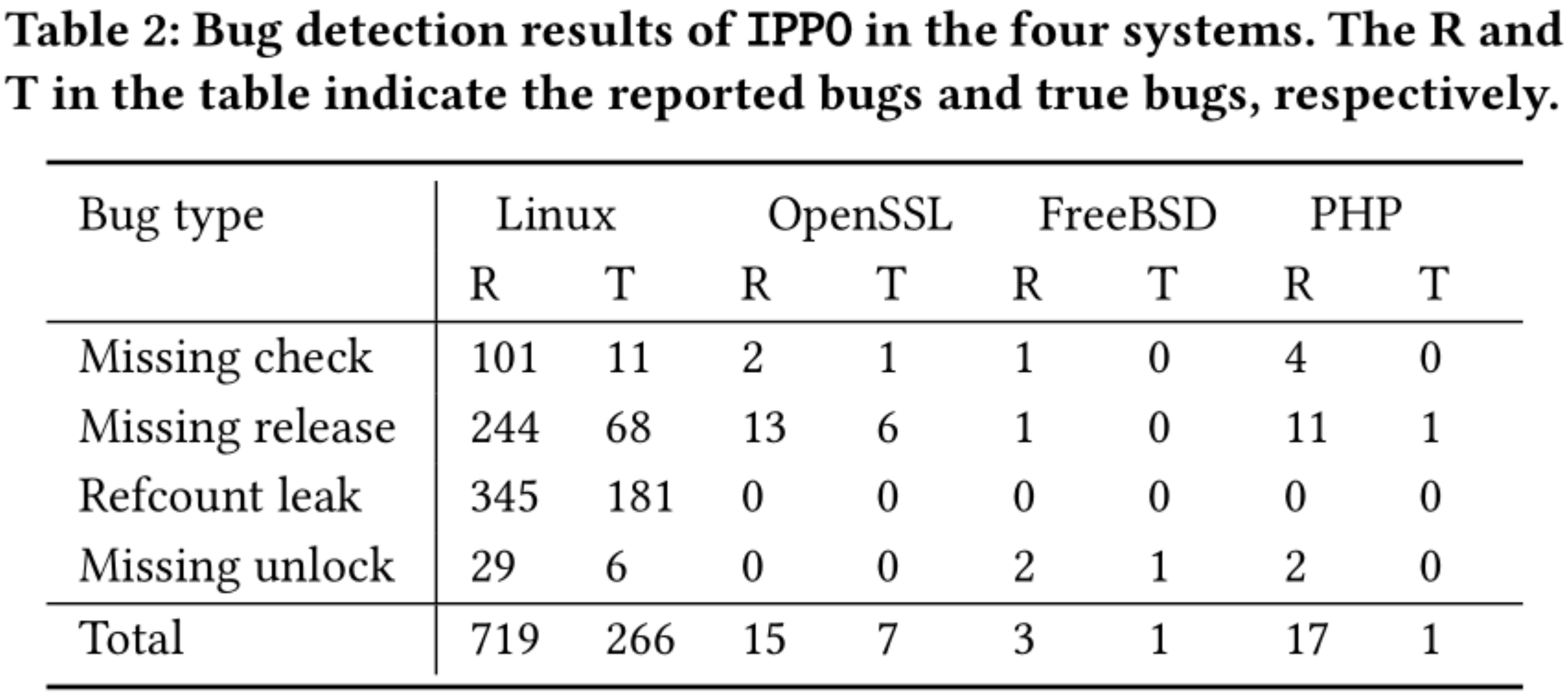


Table 2: Bug detection results of IPPO in the four systems. The R and T in the table indicate the reported bugs and true bugs, respectively.

Bug type	Linux		OpenSSL		FreeBSD		PHP	
	R	T	R	T	R	T	R	T
Missing check	101	11	2	1	1	0	4	0
Missing release	244	68	13	6	1	0	11	1
Refcount leak	345	181	0	0	0	0	0	0
Missing unlock	29	6	0	0	2	1	2	0
Total	719	266	15	7	3	1	17	1

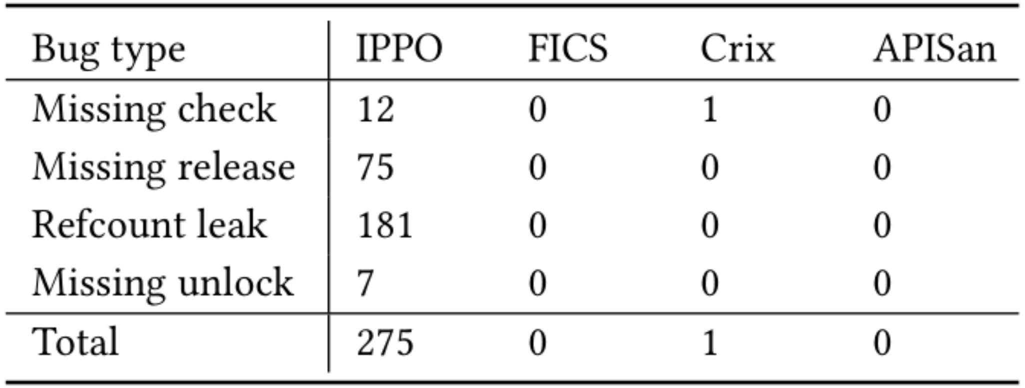
275 valid bugs.

161 are previous unknown.

136 have been fixed by our patches or reports.

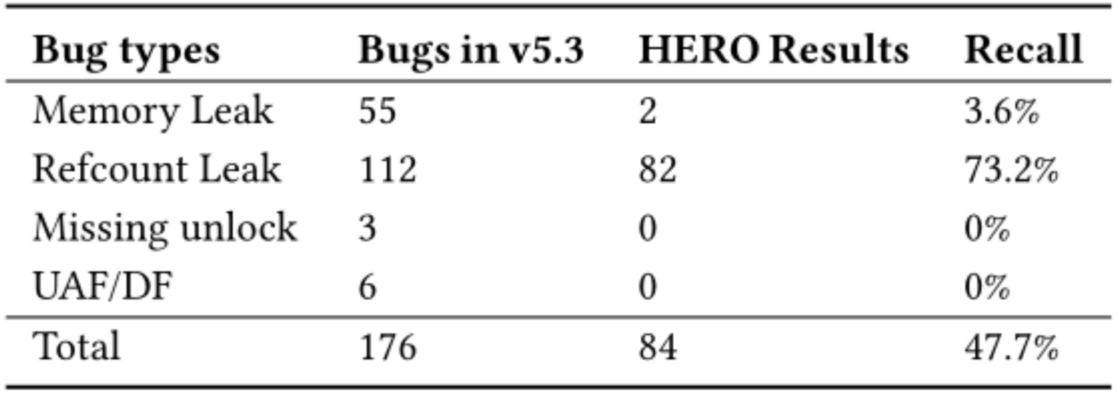
Comparison with Other Tools

- **Comparison with cross-checking tools**



Bug type	IPPO	FICS	Crix	APISan
Missing check	12	0	1	0
Missing release	75	0	0	0
Refcount leak	181	0	0	0
Missing unlock	7	0	0	0
Total	275	0	1	0

- **Comparison with pairing analysis tool: HERO**



Bug types	**Bugs in v5.3**	**HERO Results**	**Recall**
Memory Leak	55	2	3.6%
Refcount Leak	112	82	73.2%
Missing unlock	3	0	0%
UAF/DF	6	0	0%
Total	176	84	47.7%

IPPO is a promising complementation with existing tools.

Limitation & Discussion

➢False positives

- Unexpected pre-condition.
- Imprecise data-flow analysis.
- Imperfect error path analysis.
- Imperfect security operation detection.
- ……

➢False negatives

- Imperfect security operation detection.
- ……

➢Supporting inter-procedural analysis

- Model inter-procedural object-based similar paths.

Conclusion

- **Missing security operations is common in real-world programs, and could cause various security issues.**

- **We presented IPPO: a framework to detect missed security operations.**
  - Object-based similar path pairs.
  - Reduced similar path.
  - Return value-based sub-CFG.

- **We evaluated IPPO on 4 real-world programs.**
  - Find 161 new bugs.
  - IPPO could effectively detect bugs that missed by existing tools

Q&A

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