Goshawk: Hunting Memory Corruptions via Structure-Aware and Object-Centric Memory Operation Synopsis

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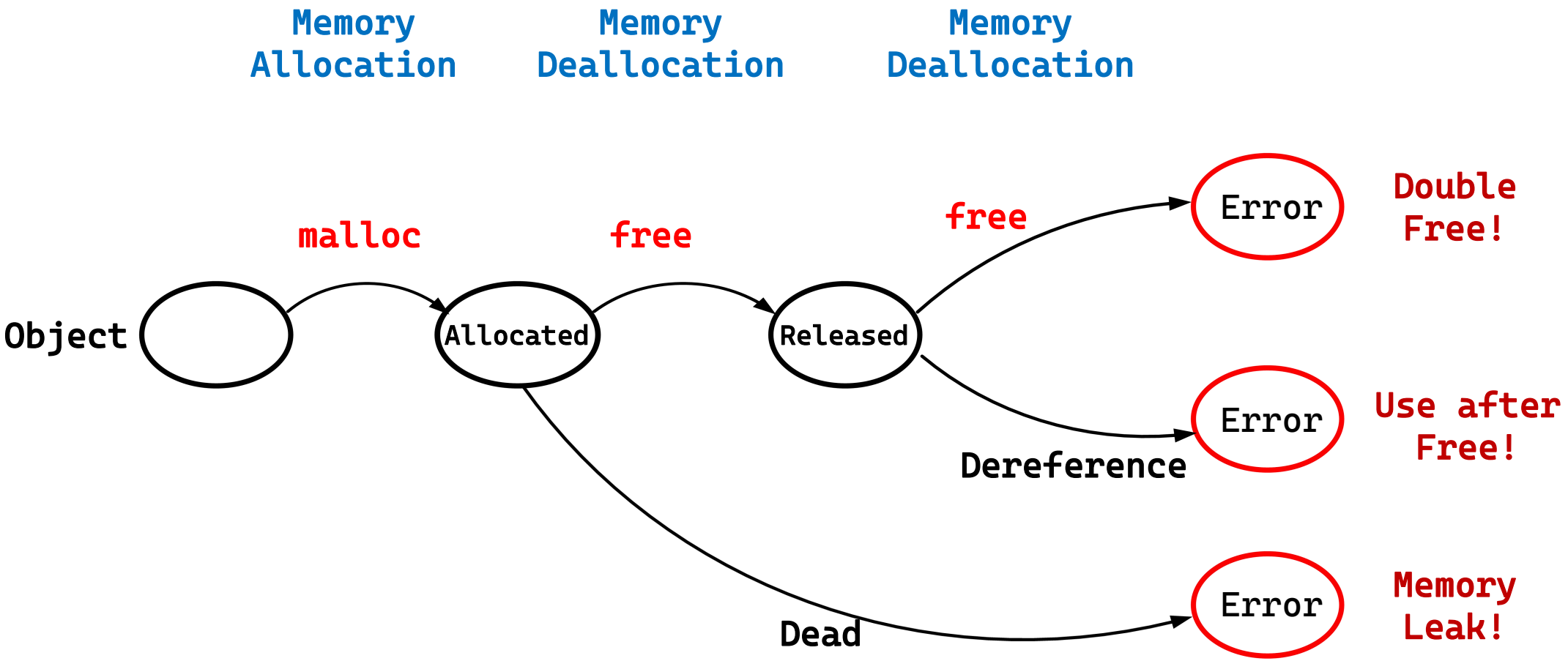
Outline

1. Motivation
2. Design
3. Evaluation
4. Conclusion

Memory corruption bugs detection routine



Custom Memory Management Functions

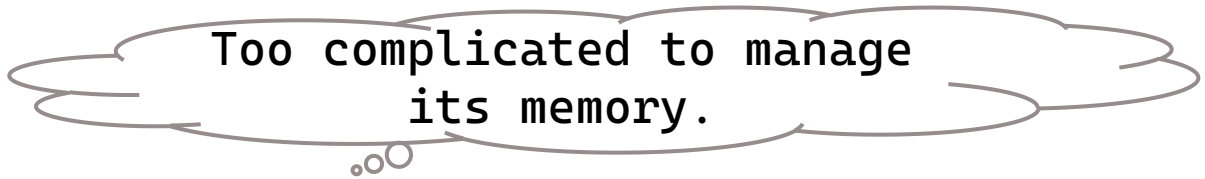
Structure Definition

```
struct sk_buff {
    union {
        struct {
            struct sk_buff              *next;
            struct sk_buff              *prev;

                union {
                    struct net_device   *dev;
                    unsigned long       dev_scratch;
                };
            };
            struct rb_node      rbnode;
            struct list_head    list;
    };
      …
};//205 lines, used more than 20,000 times
```

Structure Memory Management

```
1 void l2cap_create_connless_pdu(...)
2 {
3     struct sk_buff* skb;
4
5   ❶ skb = l2cap_sock_alloc_skb_cb(...);
6     ...
7   ❷ kfree_skb(skb);
8     ...
9 }
```



l2cap_sock_alloc_skb_cb()->bt_skb_send_alloc()->sock_alloc_send_skb()->
sock_alloc_send_pskb()->alloc_skb_with_frags()->alloc_skb()->__alloc_skb()->
napi_skb_cache_get()->kmem_cache_alloc_bulk()->__kmem_cache_alloc_bulk()-
>kmem_cache_alloc()

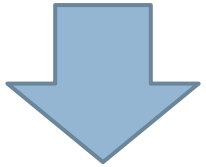
Complex Custom Memory Management Behaviors


```c
/*File: Linux/mm/dmapool.c*/
void *dma_pool_alloc(struct dma_pool *pool, gfp_t
                        mem_flags, dma_addr_t *handle)
{
     unsigned long flags;
     struct dma_page *page;
     size_t offset;
     void *retval;
     ...
     /*ALLOCATE OBJECT info*/
     page = pool_alloc_page(pool, mem_flags &
                                    (~__GFP_ZERO));
     if (!page)
           return NULL;
     retval = offset + page->vaddr;
     return retval;
}
```

```c
/*File: Linux/mm/dmapool.c*/
static struct dma_page *pool_alloc_page(struct
                        dma_pool *pool, gfp_t mem_flags)
{
     struct dma_page *page;

     page = kmalloc(sizeof(*page), mem_flags);
     if (!page)
           return NULL;

     page->vaddr = dma_alloc_coherent(pool->dev,
           pool->allocation,&page->dma, mem_flags);
      ...
     return page;
}
```

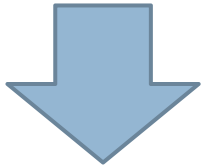


Feature 1: Multi-object and Structure nested allocation

Complex Custom Memory Management Behaviors


```
9       /*ALLOCATE OBJECT info*/
10    ❶ info = framebuffer_alloc(sizeof(struct hvfb_par),
11                                &hdev->device);
12      if (!info)
13              return -ENOMEM;
14      ...
15      ret = hvfb_getmem(hdev, info);
16
17      if (ret) {
18              pr_err("No memory for framebuffer\n");
19              goto error2;
20      }
21      ...
22  error2:
23      ...
24      /*DEALLOCATE OBJECT info*/
25    ❷ framebuffer_release(info);
26      ... //info->apertures double free!
27      return ret;
28  }
```

```
37      return info;
38  }
39  static int hvfb_getmem(struct hv_device *hdev, ...)
40  {
41      ...
42    ❸ info->apertures = alloc_apertures(1);
43      ...                 //info->apertures allocation
44      pdev = pci_get_device(...);
45      if (!pdev) {
46        ❹ kfree(info->apertures);//info->apertures free
47          return -ENODEV;
48      }
49  }
50  void framebuffer_release(struct fb_info *info)
51  {
52      if (!info) return;
53    ❺ kfree(info->apertures);
54      kfree(info);
55  }
```

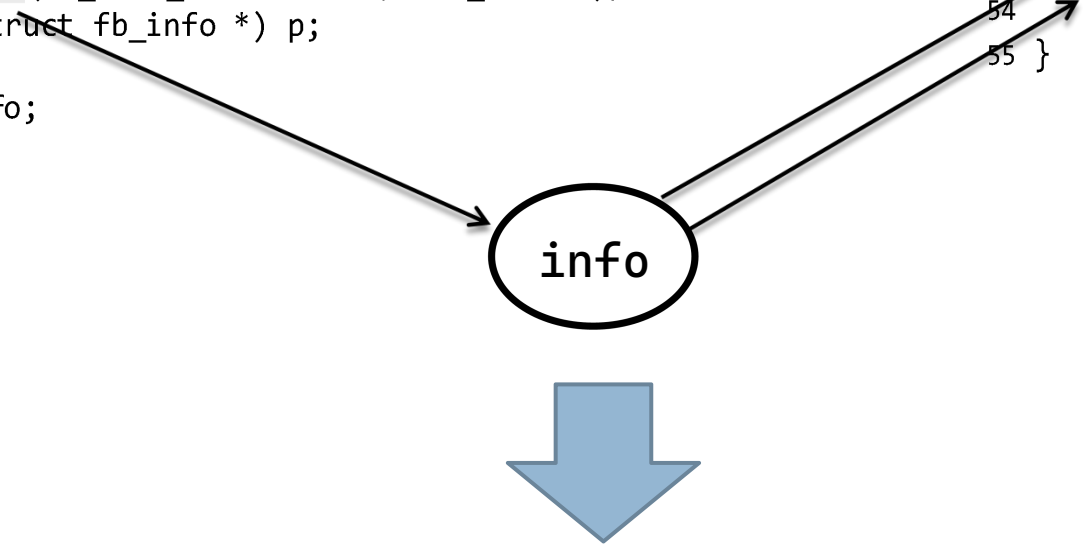


Feature 2: Require Stucture-aware deallocation

Complex Custom Memory Management Behaviors


```
29 struct fb_info *framebuffer_alloc(size_t size, ...)
30 {
31     struct fb_info *info;
32     char *p;
33     ...
34     p = kzalloc(fb_info_size + size, GFP_KERNEL);
35     info = (struct fb_info *) p;
36     ...
37     return info;
38 }
```

```
50 void framebuffer_release(struct fb_info *info)
51 {
52     if (!info) return;
53     kfree(info->apertures);
54     kfree(info);
55 }
```



Feature 3: Follow an Unpaired-use model

Objects & Challenges

Custom memory management functions

Traditional bug detection

How to fill the Gap?

```
l2cap_sock_alloc_skb_cb
pool_alloc_page
framebuffer_alloc
framebuffer_release
```

- Simple memory object
- Naive data flow tracking
- Paired-use model

- Multi-object allocation
- Structure nested allocation
- Structure-aware deallocation
- Unpaired-use model

MOS

Structure-aware and Object-centric Memory Operation Synopsis

MOS: Structure-aware and Object-centric Memory Operation Synopsis

Memory managemnt function interface

```
1  static struct dma_page *pool_alloc_page(struct
2                  dma_pool *pool, gfp_t mem_flags)
3  {
4      struct dma_page *page;
5
6      page = kmalloc(...);
9
10     page->vaddr = dma_alloc_coherent(...);
11     ...
12
13     return page;
14 }
```

Internal allocation/deallocation

Memory Operation Synopsis

MOS Representation:

```
{
```

Function name		Property
pool_alloc_page	:	Allocator

Memory object list		Object type
RetVal	:	struct dma_page*
RetVal->vaddr	:	void*

```
}
```

Object-centric **Structure-aware**

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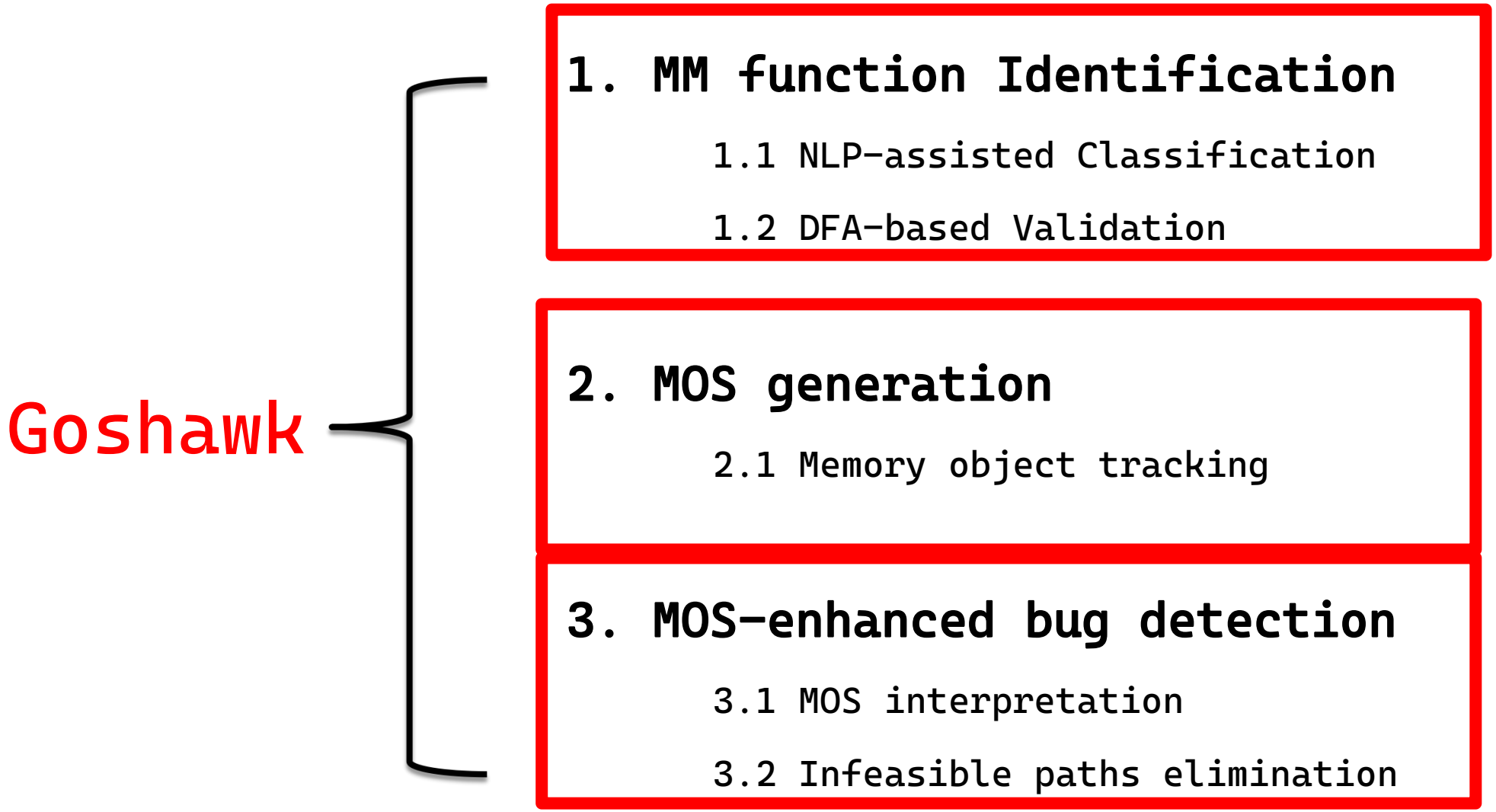
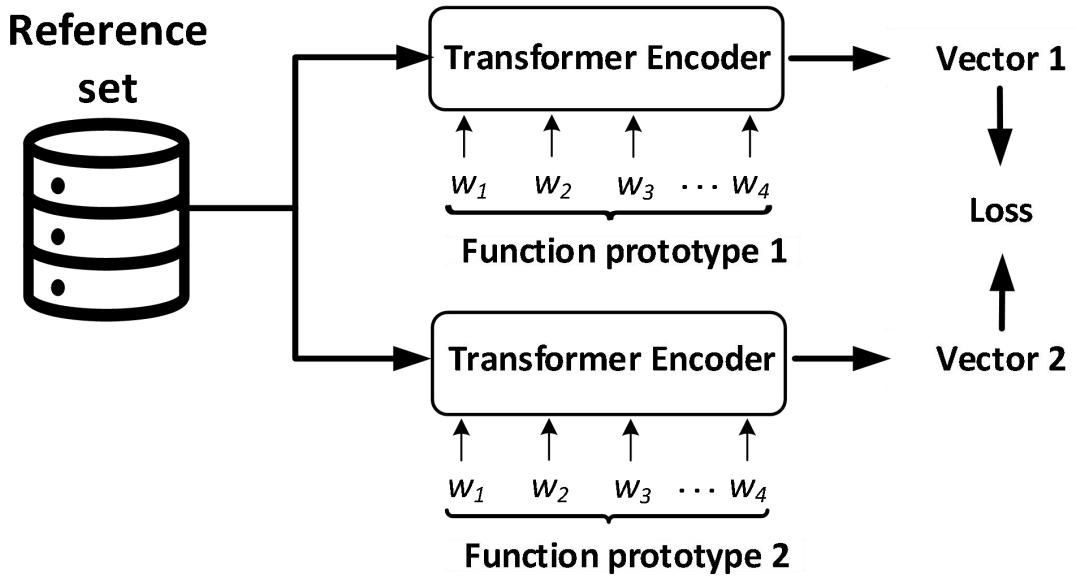
Goshawk: MOS-enhanced memory bugs detection system



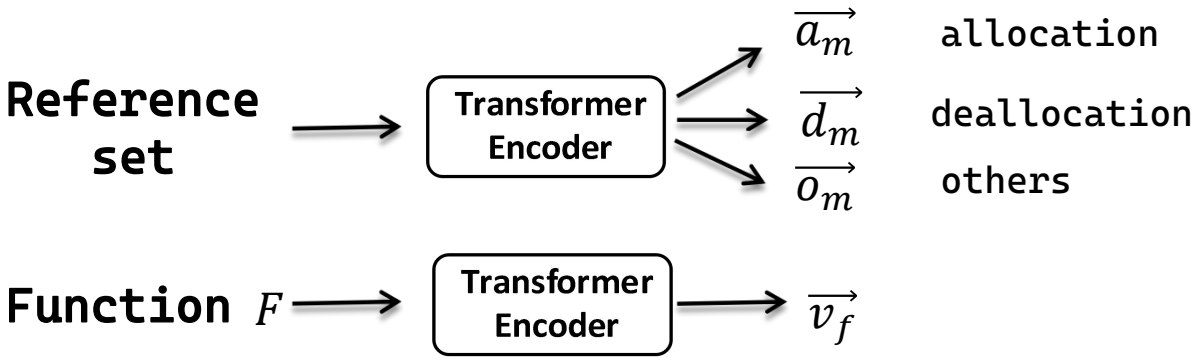
MM function Identification

NLP-assisted Classification

1. Segment and normalize function prototypes.
2. Convert function prototype into numeric vectors.
3. Compute the similarity with the reference set.



Siamese network training



$$Sim(F, X) = cosine(\overrightarrow{v_f}, \overrightarrow{x_m})$$

$$class(F) = \begin{cases} A, Sim(F, A) > max(Sim(F, D), Sim(F, O)) \\ D, Sim(F, D) > max(Sim(F, A), Sim(F, O)) \\ O, others \end{cases}$$

Function classification

MM function Identification

DFA-based Validation

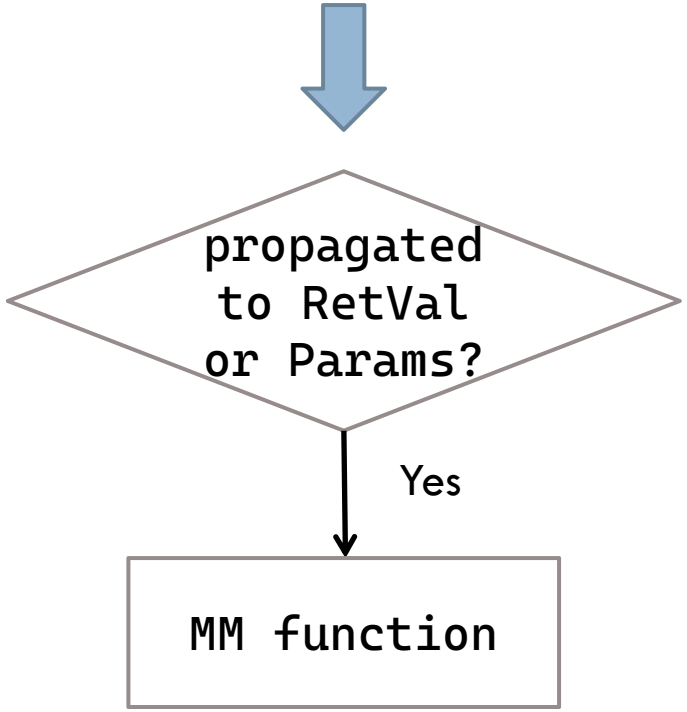
Interprocedural & backward analysis

```
1  static struct dma_page *pool_alloc_page(struct
2                  dma_pool *pool, gfp_t mem_flags)
3  {
4      struct dma_page *page;
5      page = kmalloc(...);
6      page->vaddr = dma_alloc_coherent(...);
7
8      return page;
9  }
10
11 static inline void *dma_alloc_coherent(...)
12 {
13     return dma_alloc_attrs(...);
14 }
15
16 void *dma_alloc_attrs(...)
17 {
18     cpu_addr = dma_direct_alloc(...);
19     return cpu_addr;
20 }
Official MM function set: kmalloc,...
```

❹ ❸ ❷ ❶

Official MM function set:

- collected from official documents
- 32 functions: *kmalloc*, *kfree*, *malloc*, *free*, *vmalloc*, *vfree*, etc.



MM function Identification

DFA-based Validation

Interprocedural & backward analysis

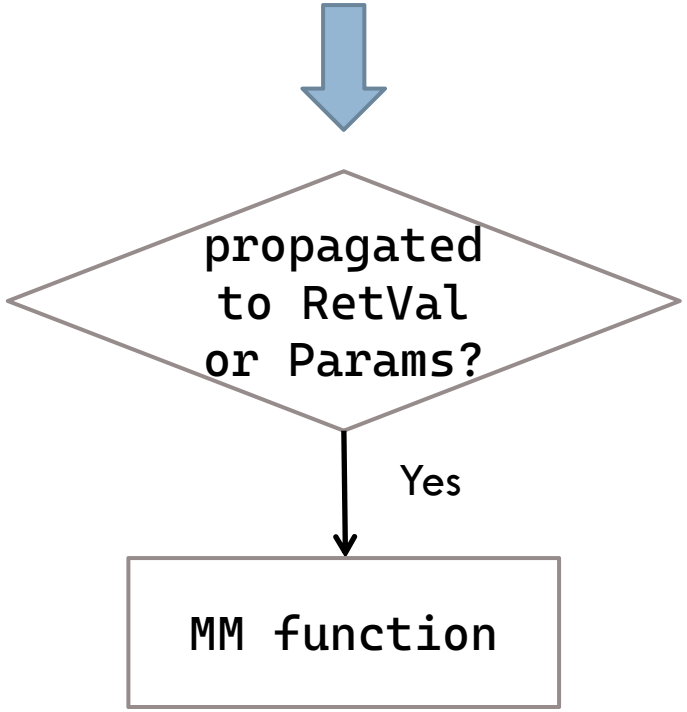
```
1  static void tpci200_uninstall(struct tpci200_board
2                                *tpci200)
3  {
4      tpci200_unregister(tpci200);
5      kfree(tpci200->slots);
6  }
7
8  static void tpci200_unregister(struct tpci200_board
9                                 *tpci200)
10 {
11     pci_iounmap(tpci200->info->pdev,
12                 tpci200->info->interface_regs);
13     pci_iounmap(tpci200->info->pdev,
14                 tpci200->info->cfg_regs);
15 }
16
17 void pci_iounmap(struct pci_dev *dev, void *addr)
18 {
19     ...
20     iounmap(addr);
21 }
```

❸ ❷ ❶

Official MM function set: kfree, iounmap, ...

Official MM function set:

- collected from official documents
- 32 functions: *kmalloc*, *kfree*, *malloc*, *free*, *vmalloc*, *vfree*, etc.



MOS Generation

Interprocedural & backward analysis

```
1  static struct dma_page *pool_alloc_page(struct
2                  dma_pool *pool, gfp_t mem_flags)
3  {
4      struct dma_page *page;
5      page = kmalloc(...);
6      page->vaddr = dma_alloc_coherent(...);
7
8      return page;
9  }
10
11 static inline void *dma_alloc_coherent(...)
12 {
13     return dma_alloc_attrs(...);
14 }
15
16 void *dma_alloc_attrs(...)
17 {
18     cpu_addr = dma_direct_alloc(...);
19     return cpu_addr;
20 }
Official MM function set: kmalloc,...
```

❹ ❸ ❷ ❶

Collected Data Flows

↓

Merge and abstract

↓

MOS Representation:

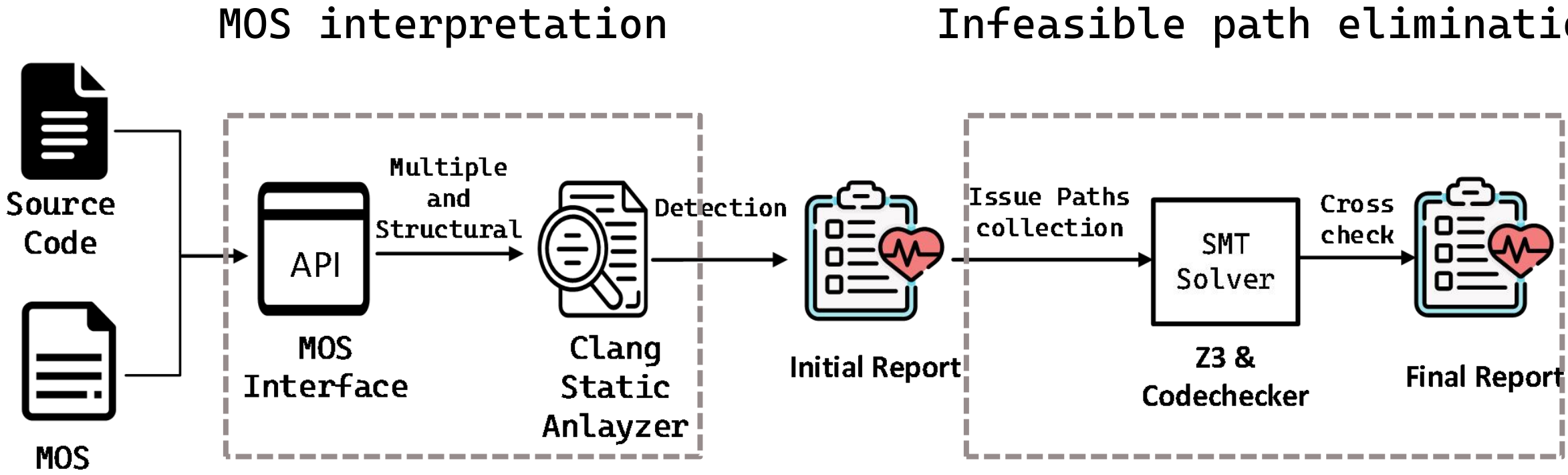
{

Function name		Property
pool_alloc_page	:	Allocator

Memory object list		Object type
RetVal	:	struct dma_page*
RetVal->vaddr	:	void*

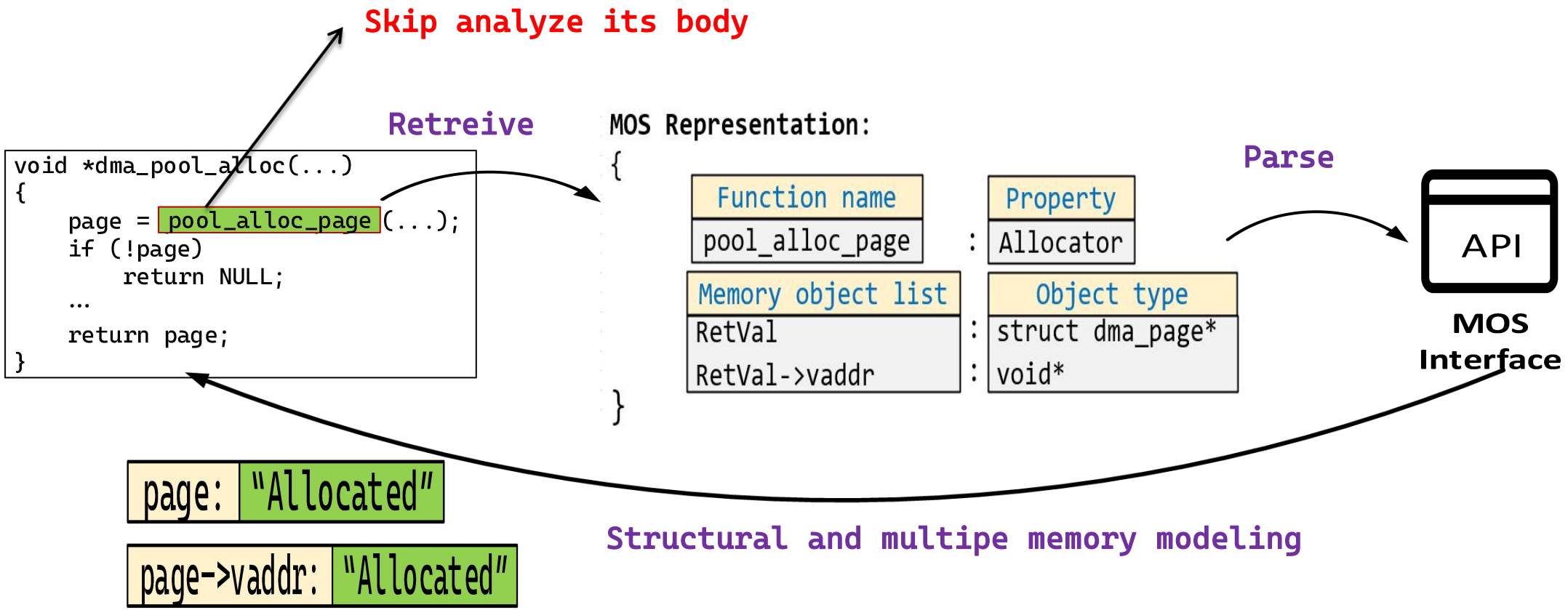
}

MOS-enhanced memory bugs detection



MOS-enhanced memory bugs detection

MOS interpretation



Infeasible paths elimination

```
1  static int hvfb_probe(struct hv_device *hdev,
2                const struct hv_vmbus_device_id *dev_id)
3  {
4       struct fb_info *info;
5
6       ❶ALLOCATE OBJECT info,info->apertures
7       info = framebuffer_alloc  (...);
9
10      ❷Deallocate OBJECT info->apertures
10       kfree(info->apertures);
11      info->status = Success ;
12
13 error2:
14
15      ❸Deallocate OBJECT info,info->apertures
16     framebuffer_release (info);
17
18      ❹info->apertures Double Free!
19 }
```

collect issue paths → CodeChecker with Z3 → cross check

```
1 void framebuffer_release(struct fb_info *info)
2 {
3       if ( info->status )
4             kfree(info->apertures);
5       kfree(info);
6 }
```

Infeasible Path !

Initial report

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1. Motivation
2. Design
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Overall Results

TABLE I
RESULTS OF CUSTOMIZED MEMORY MANAGEMENT FUNCTION IDENTIFICATION AND MEMORY BUG DETECTION IN POPULAR OPEN-SOURCE PROJECTS

Program	Version	Lines of Code	Number of Functions	Identified Allocators		Identified Deallocators		Detected Bugs		
				Primitive	Extended	Primitive	Extended	UAF	DF	Confirmed
Linux	5.12-rc2	20.1M	549K	2,916	1,805	1,812	4,266	32	17	40
FreeBSD	13.0.0	5.9M	99K	482	273	393	853	9	9	17
OpenSSL	3.0.0	456K	19K	93	15	134	193	1	8	9
Redis	6.2.1	149K	3K	51	9	28	41	1	0	1
Azure	2021_Ref01	661K	4.8K	126	7	58	177	0	4	1
QcloudE	3.1.8	86K	759	21	1	26	21	2	5	7
QcloudH	3.2.3	79K	638	20	1	25	21	2	2	4
Total	-	-	-	**3,709**	**2,111**	**2,476**	**5,572**	**47**	**45**	**79**

QcloudE refers to Qcloud IoT Explorer Device SDK and QcloudH refers to Qcloud IoT Hub Device SDK.
UAF: use-after-free bug; **DF**: double-free bug

- Identified more than 10,000 custom MM functions
- MM function identification is precise.
- Detected 92 new use-after-free and double-free bugs
- Achieves a low false positive.

	Allocator		Deallocator	
	Precision	Recall	Precision	Recall
w/o DFA	89.6%	91.0%	90.2%	97.0%
w/ DFA	100%	84.5%	100%	89.5%

Comparison with MallocChecker

TABLE II
COMPARISON WITH MALLOCCHECKER IN TERMS OF DETECTION EFFECTIVENESS AND EFFICIENCY (IN MINUTES)

	Goshawk		MalChk-S		MalChk-E	
	Bugs	Time	Bugs	Time	Bugs	Time
Linux	49	328.91	2	367.72	-	-
FreeBSD	18	20.84	5	19.73	6	664.76
OpenSSL	9	3.51	1	3.66	1	79.13
Redis	1	1.03	0	0.78	0	24.01
Azure	4	0.22	2	0.26	2	6.41
QcloudE	7	0.10	4	0.11	7	1.77
QcloudH	4	0.07	4	0.08	4	8.66
Presicion	**63.4%**		**20.6%**		**35.7%**	

MalChk-S : MallocChecker with AMD 3990x, 192G RAM.
MalChk-E : MallocChecker with Xeon 4126, 1T RAM.

Goshawk vs. MalChk-S:

- under the **same** experiment setting
- AMD 3990x, 192G RAM
- AD=5, AB=225,000, CTU=100

MalChk-E:

- more **extensive** experiment setting
- Xeon 4126, 1TG RAM
- AD=10, AB=2,250,000, CTU=20,000

AD: Analysis depth, AB: Analysis breadth, CTU: Cross translations units

Comparison with related works

TABLE IV
COMPARISON OF MM FUNCTION IDENTIFICATION IN THE LINUX KERNEL

Version	K-MELD		SinkFinder		Goshawk			
	A	D	A	D	A	D	MN	MD
v5.2.13	806	461	-	-	4,571	4,847	19	129
v4.19	-	-	256	182	4,396	4,704	8	46

A : # of allocators; **D** : # of deallocators;
MN : # of MM functions missed by NLP-assisted classification;
MD : # of MM functions missed by DFA based validation.

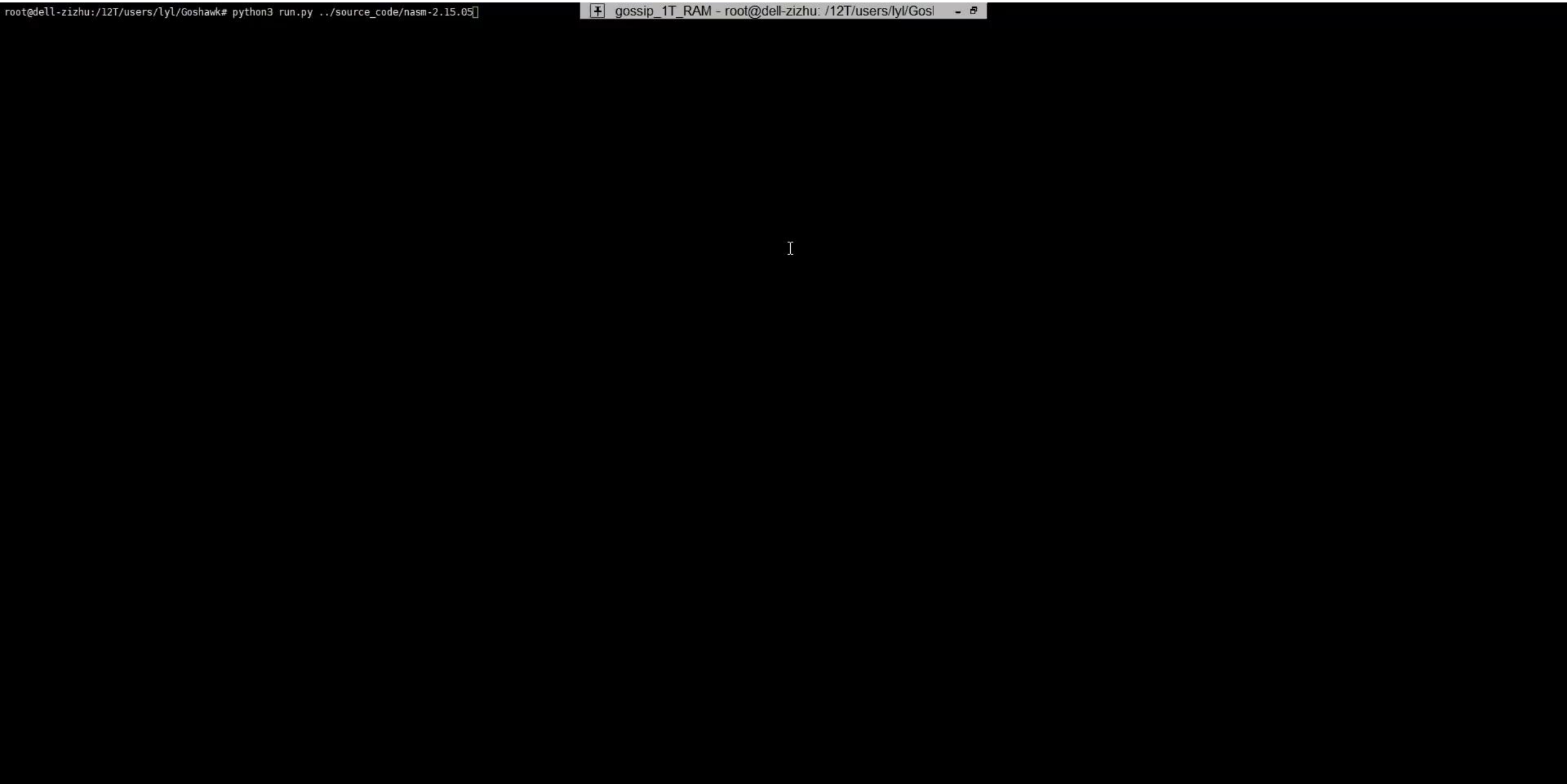
MM function identification:

- Outperforms by orders of magnitude
- Applicable to different scales codes

Bug detection:

- High coverage
- Less false warnings

Demonstration



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Conclusion

- MOS: a novel concept to enhance memory bug detection
- Goshawk: a easy-to-use bug detection tool
- Found 92 new bugs in Linux/BSD kernels, OpenSSL, Redis, etc.
- Found new bugs in CAIRO, Flite, NASM after our submission!

Download and try Goshawk by visiting https://goshawk.code-analysis.org/

Q&A
Thanks!