Making Memory Account Accountable: Analyzing and Detecting Memory Missing-account bugs for Container Platforms

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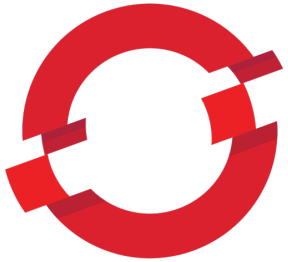
Outline

- Background and the problem
- Our contributions
- Exploitability and impact of missing-account bugs
  - Native runtimes & secure runtimes
  - CaaS platforms & FaaS platforms
- Automated bug detection
- Takeaways

Background

- OS-level virtualization (containers) is widely adopted in cloud platforms to virtualize and share hardware resources among different users.

OpenWhisk
(IBM Cloud functions)



Google GKE

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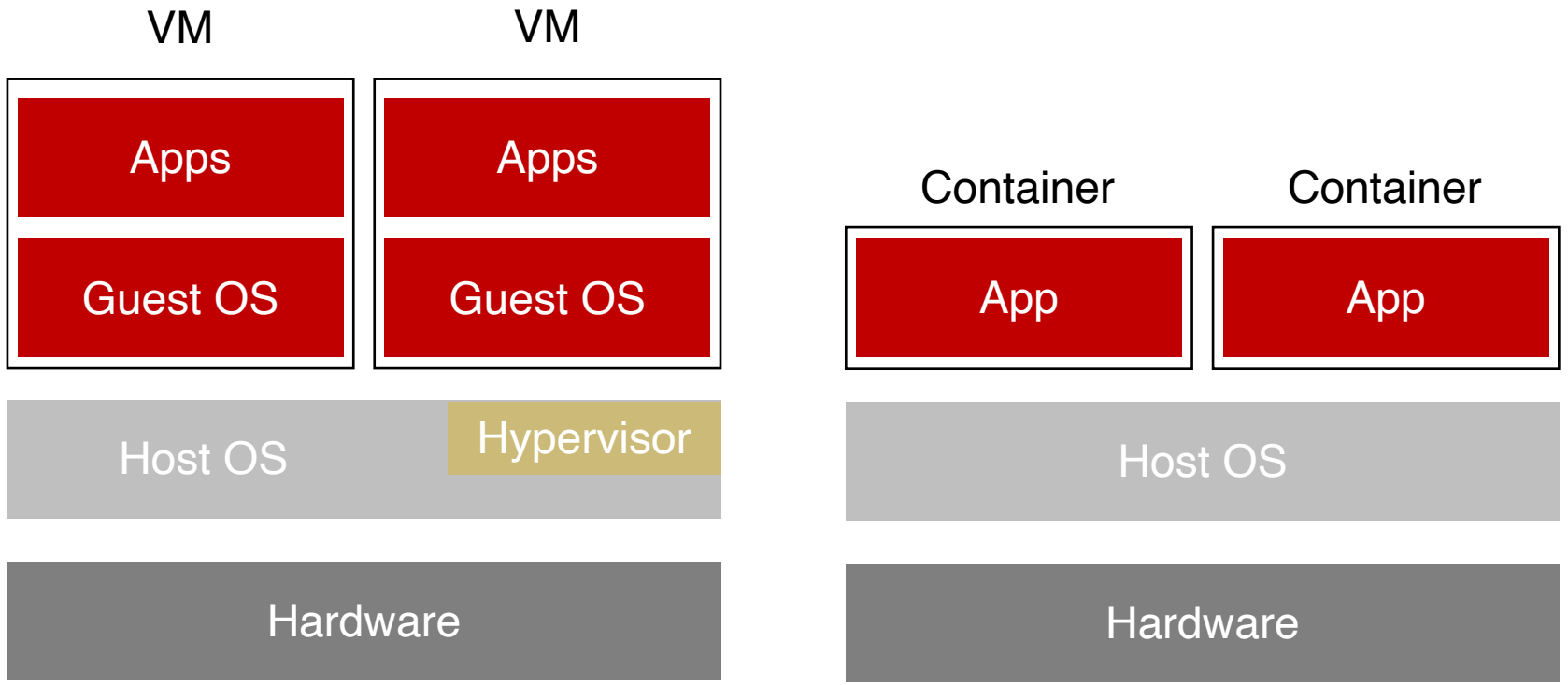
Background

- Compared with VM, OS-level virtualization (containers) is more lightweight and efficient. Different containers directly interact with the same host OS kernel.



Background (cont.)

- Memory usage accounting and limitation serves as the cornerstone for container techniques.

- Linux kernel proposes memory control groups (memcg) to account for and limit memory usage at per-process granularity.

- Our preliminary study shows that memcg is error-prone.
  - Numerous memory allocation sites in Linux kernel, which can be missed by memcg.
  - Accounting flags can be missing.
  - Existing bugs.

Problem

- Does memcg precisely account for memory usage? Does it miss any memory usage?
  - Memcg is not precise and it has missing-account bugs.
- What are the security impacts of memory missing-account bugs?
- How to efficiently discover these bugs in complex OS kernels?

Our Contribution

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- In-depth analysis of exploitability and impacts.
  - Memory missing-account bugs is exploitable on different container runtimes and container platforms.
  - The attack leads to DoS on the host nodes or even the whole cluster.
- Automated detection with new techniques.
  - Counter-based interface identification.
  - Alloc-charging mapping analysis.
  - Accounting flag analysis.
  - Dynamic validation.
- Community impact.
  - 53 exploitable missing-account bugs.
  - 37 confirmed, 18 patches merged.
  - 2 new CVEs.

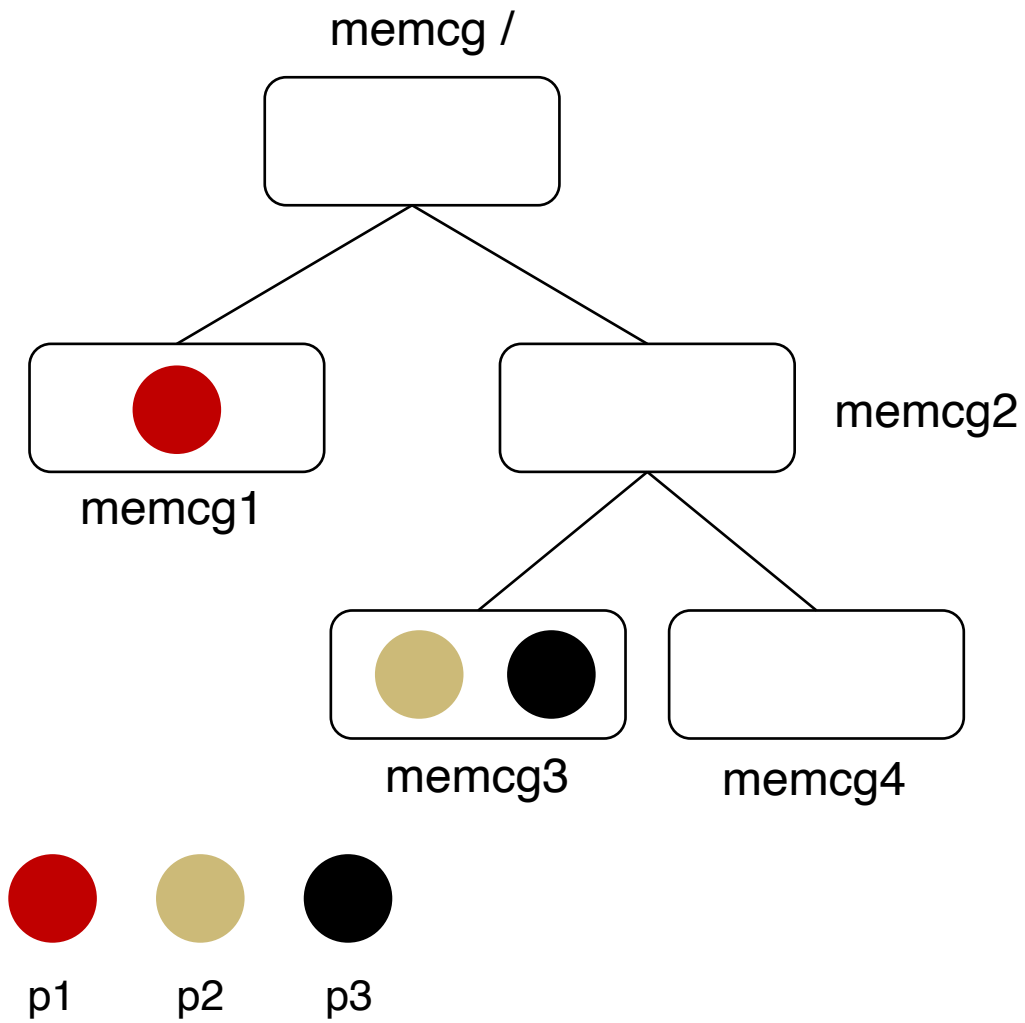
Memcg 101

- Memcg instances are organized as a tree.

  memcg1.usage = $MemUsage_{p1}$
  memcg3.usage = $MemUsage_{p2}$ + $MemUsage_{p3}$
  memcg2.usage = memcg3.usage + memcg4.usage

- Processes in the memcg receive OOM errors if the usage exceeds the limitation.

  usage(memcg) < max(memcg)



Memcg 101

- A memcg instance maintains page counters to record memory usage.

- After memory (de)allocation happens, the kernel invokes accounting interface to increase/decrease the page counters.

```
1  struct mem_cgroup {
2      ...
3      struct page_counter memory;/* Both v1 & v2 */
4      union {
5          struct page_counter swap;     /* v2 only */
6          struct page_counter memsw;     /* v1 only */
7      };
8      /* Legacy consumer-oriented counters */
9      struct page_counter kmem;     /* v1 only */
10     struct page_counter tcpmem;     /* v1 only */
11     ...
12 }
13 struct page_counter {
14     atomic_long_t usage;
15     ...
16     unsigned long max;
17     ...
18 }
19
20 bool page_counter_try_charge(struct page_counter *counter, unsigned
   ↪ long nr_pages, ...)
21 {
22     struct page_counter *c;
23     ...
24     new = atomic_long_add_return(nr_pages, &c->usage);
25     if (new > c->max) {
26         ...
27         goto failed;
28     }
29 }
```

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Attacking Native Runtimes

- We use Docker as the native runtime.
- The missing-account bug, CVE-2021-3759.

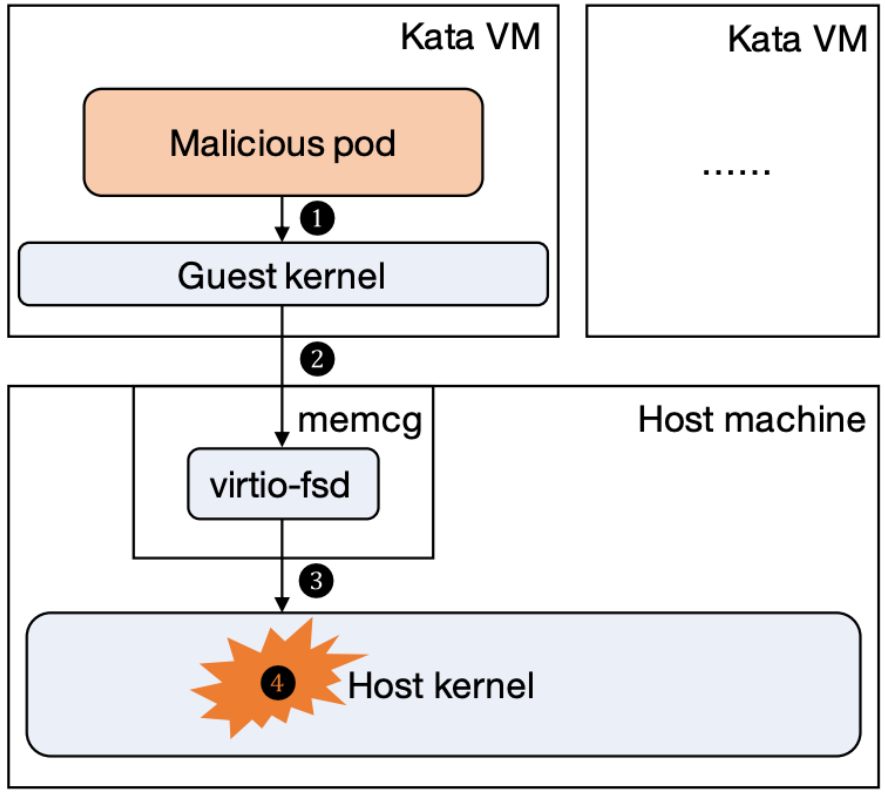
```
1   static struct sem_array *sem_alloc(size_t nsems)
2   {
3       struct sem_array *sma;
4
5       if (nsems > (INT_MAX - sizeof(*sma)) / sizeof(sma->sems[0]))
6           return NULL;
7
8       sma = kvzalloc(struct_size(sma, sems, nsems), GFP_KERNEL);
9       if (unlikely(!sma))
10          return NULL;
11
12      return sma;
13  }
```

GFP_KERNEL_ACCOUNT

- Impact: normal user in container can exhaust all 16 GB host memory, leading to system-wide OOM errors.

Attacking Secure Runtimes

- We use Kata Containers as the secure runtime.
- We exploit the POSIX lock missing-account bug, CVE-2022-0480.



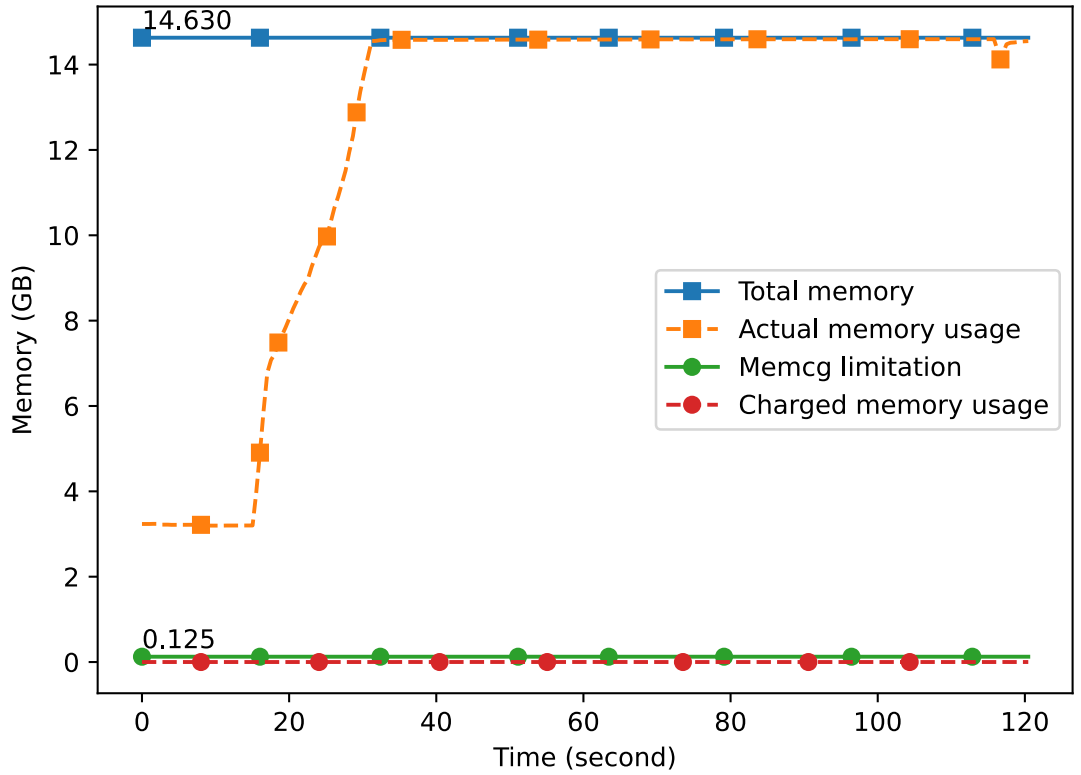
1. Attacker's pod allocates Posix locks by fcntl() syscall.
2. The guest kernel forwards the request to virtio-fsd daemon.
3. virtio-fsd allocates Posix locks on the host machine.
4. Missing-charged lock objects lead to memory exhaustion.

Attacking Secure Runtimes

- We use Kata Containers as the secure runtime.
- We exploit the POSIX lock missing-account bug, CVE-2022-0480.
- Impact: normal user in a Kata container can exhaust all 16 GB host memory, leading to system-wide OOM errors.

Attacking CaaS&FaaS Platforms

- We evaluate CVE-2021-3759 on OpenShift CaaS platform and OpenWhisk FaaS platform.



Attacking CaaS&FaaS Platforms

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- We evaluate CVE-2021-3759 on OpenShift CaaS platform and OpenWhisk FaaS platform.

- Impact.
  - For CaaS, the attacked node is crashed and all containers on it are down.
  - For FaaS, all worker nodes are crashed and all function run fails.

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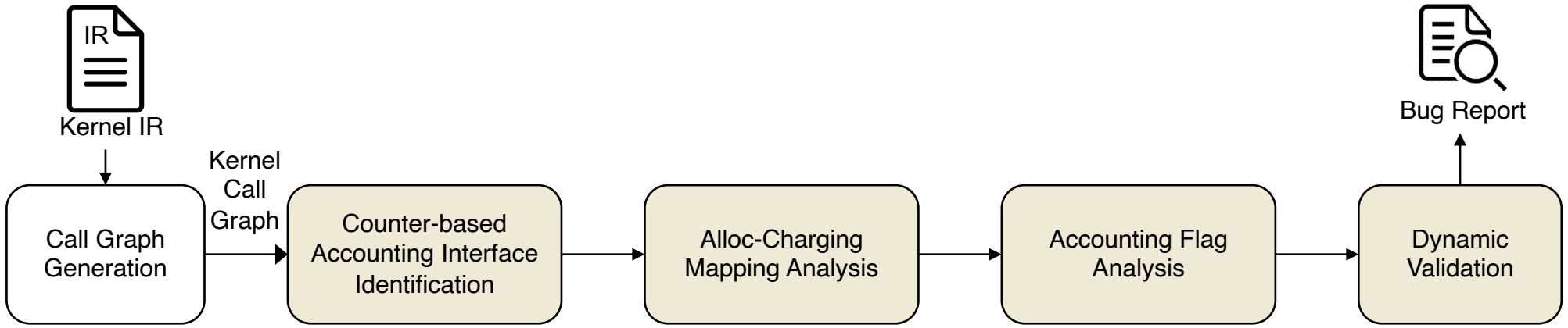
MANTA Analyzer

- Challenges:
  - Undocumented accounting interfaces.
  - Mapping memory allocation to accounting interface call among the complex execution paths.



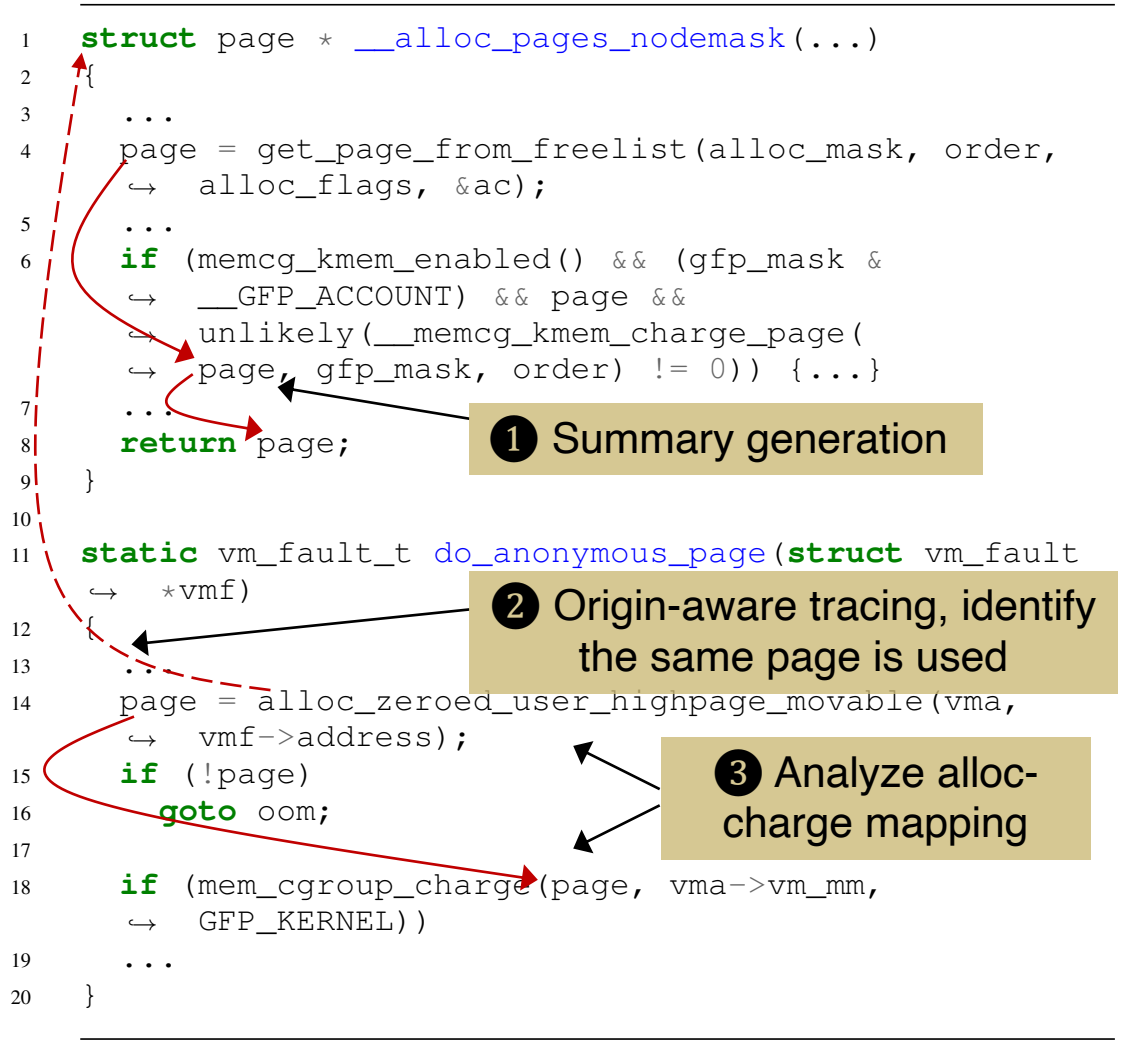
Accounting Interface Identification

- Our observation: all accounting interfaces finally increase/decrease the page counter.
- The traversal ends when it reaches out of memcg module.

```
1  bool page_counter_try_charge(struct page_counter *counter,
2                               unsigned long nr_pages, ...) {
3      struct page_counter *c;
4
5      for (c = counter; c; c = c->parent) {
6          long new;
7          new = atomic_long_add_return(nr_pages, &c->usage);
8          ......                                  page counter add
9      }
10     ......
11 }
12
13 int __memcg_kmem_charge_page(struct page *page, gfp_t gfp,
14                               int order) {
15     struct obj_cgroup *objcg;
16     int ret = 0;
17
18     objcg = get_obj_cgroup_from_current();
19     if (objcg) {
20         ret = obj_cgroup_charge_pages(objcg, gfp, 1 <<
           ↪  order);                                          Invoke
21         ......
22     }
23     ......
24 }
```

Alloc-Charging Mapping Analysis

- Our observation: pre-compute the summary of each function instead of recursively following the complex call chain.
- The summary generation is in a bottom-up order on call chains.
- MANTA raises a missing-account alarm for page that is not accounted nor escaped from current function.



Accounting Flag Analysis

- Bit-wise inter-procedural value tracing.

```
1  static int bpf_prog_load(...) {
2      ......
3      /* plain bpf_prog allocation */
4      prog = bpf_prog_alloc(bpf_prog_size(attr->insn_cnt),
       ↪  GFP_USER);
5      ......   missing-account!
6  }
7
8  struct bpf_prog *bpf_prog_alloc(unsigned int size, gfp_t
   ↪  gfp_extra_flags) {
9      gfp_t gfp_flags = GFP_KERNEL | __GFP_ZERO |
       ↪  gfp_extra_flags;
10     struct bpf_prog *prog;
11     int cpu;
12                          allocation site
13     prog = bpf_prog_alloc_no_stats(size, gfp_extra_flags);
14     if (!prog)
15         return NULL;
16                          allocation site
17     prog->stats = alloc_percpu_gfp(struct bpf_prog_stats,
       ↪  gfp_flags);
18     ......
19 }
```

Dynamic Validation

- For the 242 reported bugs, we further evaluate the triggerability from user space applications.

- Method: in-kernel instrumentation + user-space test cases.

  LTP test cases

  Common user-space tools (SeLinux, auditd, etc.)

  Manually developed test cases

Analysis Results

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- Analysis Results
  - Alerts: 242
  - Triggerable: 162
  - Exploitable & Reported: 53
  - Confirmed: 37
  - Patched: 18
  - Analysis precision: 66.9% (162/242)
- Impact analysis
  - 17 PoCs
  - 5 can exhaust more than 16GB host memory.

Bug ID	Source location	Function name	Allocation interface	Triggered by	Confirm Status	Patch Status
1	arch/x86/kernel/ldt.c:157	alloc_ldt_struct	kmalloc	clone	Confirmed	Merged
2	fs/eventfd.c:417	do_eventfd	kmalloc	eventfd	Pending	-
3	fs/eventpoll.c:1014	ep_alloc	kzalloc	epoll_create	Pending	-
4	fs/fcntl.c:899	fasync_alloc	kmem_cache_alloc	fcntl	Confirmed	Merged
5	fs/fs_context.c:234	alloc_fs_context	kzalloc	fsopen	Confirmed	Merged
6	fs/fs_context.c:634	legacy_init_fs_context	kzalloc	fsopen	Confirmed	Merged
7	fs/fsopen.c:100	fscontext_alloc_log	kzalloc	fsopen	Pending	-
8	fs/io-wq.c:1089	io_wq_create	kzalloc	io_uring_setup	Confirmed	Pending
9	fs/io-wq.c:1093	io_wq_create	kzalloc_node	io_uring_setup	Confirmed	Pending
10	fs/io-wq.c:1114	io_wq_create	kzalloc_node	io_uring_setup	Confirmed	Pending
11	fs/io_uring.c:1180	io_ring_ctx_alloc	kzalloc	io_uring_setup	Confirmed	Pending
12	fs/io_uring.c:1184	io_ring_ctx_alloc	kmem_cache_alloc	io_uring_setup	Confirmed	Pending
13	fs/io_uring.c:1197	io_ring_ctx_alloc	kmalloc	io_uring_setup	Confirmed	Pending
14	fs/io_uring.c:7254	__io_sqe_files_scm	kzalloc	io_uring_register	Pending	-
15	fs/io_uring.c:7507	alloc_fixed_file_ref_node	kzalloc	io_uring_register	Pending	-
16	fs/io_uring.c:7546	io_sqe_files_register	kzalloc	io_uring_register	Pending	-
17	fs/io_uring.c:7853	io_uring_alloc_task_context	kmalloc	io_uring_setup	Confirmed	Pending
18	fs/io_uring.c:8044	io_mem_alloc	__get_free_pages	io_uring_setup	Confirmed	Pending
19	fs/io_uring.c:9541	io_register_personality	kmalloc	io_uring_register	Pending	-
20	fs/locks.c:346	locks_alloc_lock	kmem_cache_zalloc	flock, fcntl	Confirmed	Merged
21	fs/locks.c:258	locks_get_lock_context	kmem_cache_alloc	flock	Confirmed	Merged
22	fs/namespace.c:177	alloc_vfsmnt	kmem_cache_zalloc	mount	Confirmed	Merged
23	fs/namespace.c:3267	alloc_mnt_ns	kzalloc	clone	Confirmed	Pending
24	fs/notify/group.c:121	fsnotify_alloc_group	kzalloc	inotify_init1	Confirmed	Merged
25	fs/notify/inotify/inotify_user.c:630	inotify_new_group	kmalloc	inotify_init1	Confirmed	Merged
26	fs/select.c:658	core_sys_select	kvmalloc	select	Confirmed	Merged
27	fs/signalfd.c:278	do_signalfd4	kmalloc	signalfd4	Pending	-
28	fs/timerfd.c:412	timerfd_create	kzalloc	timerfd_create	Pending	-
29	ipc/namespace.c:45	create_ipc_ns	kzalloc	clone	Confirmed	Pending
30	ipc/sem.c:514	sem_alloc	kvzalloc	semget	Confirmed	Merged
31	ipc/sem.c:1853	get_undo_list	kzalloc	semop	Confirmed	Merged
32	ipc/sem.c:1938	find_alloc_undo	kzalloc	semop	Confirmed	Merged
33	kernel/bpf/core.c:117	bpf_prog_alloc	alloc_percpu_gfp	bpf, prctl	Confirmed	Merged
34	kernel/bpf/core.c:85	bpf_prog_alloc_no_stats	__vmalloc	bpf, prctl	Confirmed	Merged
35	kernel/bpf/core.c:89	bpf_prog_alloc_no_stats	kzalloc	bpf, prctl	Confirmed	Merged
36	kernel/events/core.c:11142	perf_event_alloc	kzalloc	perf_event_open	Pending	-
37	kernel/events/core.c:4443	alloc_perf_context	kzalloc	perf	Pending	-
38	kernel/nsproxy.c:56	create_nsproxy	kmem_cache_alloc	setns	Confirmed	Pending
39	kernel/pid_namespace.c:90	create_pid_namespace	kmem_cache_zalloc	clone	Confirmed	Pending
40	kernel/seccomp.c:1481	init_listener	kzalloc	prctl	Pending	-
41	kernel/seccomp.c:565	seccomp_prepare_filter	kzalloc	prctl	Pending	-
42	kernel/signal.c:435	__sigqueue_alloc	kmem_cache_alloc	rt_sigqueueinfo	Confirmed	Merged
43	kernel/time/namespace.c:91	clone_time_ns	kmalloc	clone	Confirmed	Pending
44	kernel/time/namespace.c:97	clone_time_ns	alloc_page	clone	Confirmed	Pending
45	kernel/time/posix-timers.c:458	alloc_posix_timer	kmem_cache_zalloc	timer_create	Confirmed	Merged
46	kernel/user_namespace.c:105	create_user_ns	kmem_cache_zalloc	clone	Confirmed	Pending
47	mm/hugetlb.c:868	resv_map_alloc	kmalloc	memfd_create	Pending	-
48	mm/hugetlb.c:869	resv_map_alloc	kmalloc	memfd_create	Pending	-
49	mm/slab_common.c:245	create_cache	kmem_cache_zalloc	clone	Confirmed	Pending
50	net/core/net_namespace.c:423	net_alloc	kzalloc	clone	Pending	-
51	security/keys/key.c:277	key_alloc	kmem_cache_alloc	add_key	Confirmed	Pending
52	security/keys/key.c:282	key_alloc	kmemdup	add_key	Confirmed	Pending
53	security/keys/key.c:81	key_user_lookup	kzalloc	add_key	Confirmed	Pending

Takeaways

- It is hard to implement memory accounting correctly. Incorrect memory account can raise severe security threats.
  - DoS on native&secure runtimes.
  - DoS on CaaS&FaaS platforms.

- Static analysis is an effective way to find out and mitigate memory accounting bugs.
  - 53 reported bugs, 37 confirmed and 18 patches merged.

- We open source our tools and call upon more efforts on improving memcg.
  - https://github.com/ZJU-SEC/MANTA

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