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Dynamic program analysis

for fun and profit

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Agenda:

- Dynamic analysis
- Overview of dynamic tools
- KASAN

Dynamic Tools Team

- Bug detection (user-space/kernel):
  - ASAN
  - MSAN
  - TSAN (C++, Go, Java)
  - KCSAN
  - LSAN
  - UBSAN
- Production hardening:
  - CFI
  - SafeStack
  - ShadowCallStack
  - HWASAN
  - Memory tagging (MTE)
  - GWP-ASan
  - KFENCE
- Bug provocation:
  - LibFuzzer (C++ [Go, Rust])
  - go-fuzz (Go)
  - syzkaller (kernels)
- Misc:
  - OSS-Fuzz
  - syzbot
  - SanitizerCoverage
  - KCOV
  - DFSAN

Why?

- **Bugs** == security issues
- **Bugs** == stability issues
- **Bugs** == low quality
- **Bugs** == wasted time
- **Bugs** == moving slow

Dynamic analysis == cost-effective way to find **bugs**

Dynamic program analysis -

analysis of the properties of a running program

Properties:

- bugs
- performance
- code coverage
- call graph
- data flow

Dynamic program analysis -

analysis of the properties of a **running program**

(properties that hold on a **single** execution)

Static program analysis -

analysis of the properties of **program code**

(properties that hold on **all** executions)

True Positive - report a real bug

False Positive - report not a bug

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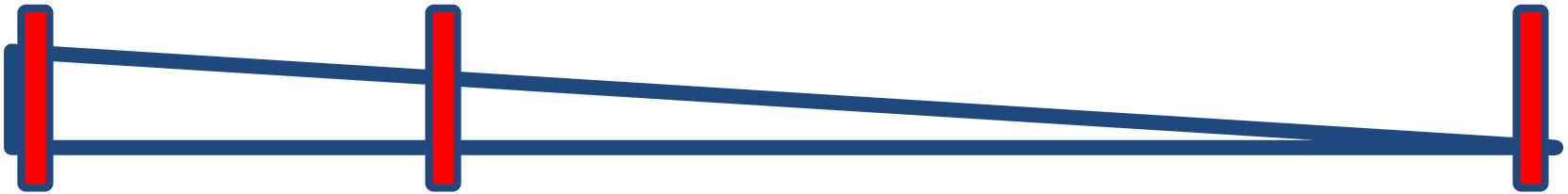
True Positives

No False Positives



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	Static Analysis	Dynamic Analysis
True Positives	+	—
No False Positives	—	+

Static Analysis

```
void func() {
   char* p = malloc(10);
   p[20] = 1; // OOB (out-of-bounds)
}
```

Static Analysis

```
void func(int index) {
   char* p = malloc(10);
   p[index] = 1; // OOB?
}
```

- unions
- arrays
- threads
- function pointers
- crypto algorithms
- ...

```
char* str = &buffer[offset];
int index = atoi(str);
func(index);
```

Dynamic Analysis

```
void func(int index) {
   char* p = malloc(10); // memorize size of *p
   p[index] = 1;         // if index >= size *p
}                        //     report bug
```

- doesn't matter how index was computed (atoi, unions, ...)
- never report a false positive
- always report the bug
- caveat: only on test that trigger the bug

	Warnings	Time (CPU/days)
clang --analyze*	10204	1.28
gcc -fanalyze*	461	0.24
Coccinelle	4526	1.5
Smatch*	405	1.8

* only analyze 1 configuration out of lots (12316 configs + different arches)

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☀️ Static

+ simpler, local bugs
+ more code coverage
+ faster, deterministic feedback

🌙 Dynamic

+ more complex bugs
+ no false positives
+ simper usage model

Getting coverage:

- tests (unit, system)
- fuzzing (syzkaller)
- development
- pre-production, mirror servers, dogfood clients
- production

Kernel tests:

- KUnit
- kselftests (tools/testing/selftests/*)
- out-of-tree suites:
  - Linux Test Project
  - xfstests
  - v4l2-compliance
  - ...

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DIY Tools

("Do It Yourself")

CONFIG_DEBUG_LIST=y

```
struct list_head {
    struct list_head *next;
    struct list_head *prev;
};

void __list_del_entry_valid(struct list_head *entry) {
#ifdef CONFIG_DEBUG_LIST
    BUG_ON(entry->next == LIST_POISON1);
    BUG_ON(entry->prev == LIST_POISON2);
    BUG_ON(entry->prev->next != entry);
    BUG_ON(entry->next->prev != entry);
#endif
}
```

CONFIG_DEBUG_LIST=y

```
list_del corruption, ffff88800771fe58->next is LIST_POISON1 (dead000000000100)
------------[ cut here ]------------
kernel BUG at lib/list_debug.c:45!
CPU: 0 PID: 1 Comm: swapper/0 Not tainted 5.11.0-rc7+ #74
RIP: 0010:__list_del_entry_valid+0xf/0x47 lib/list_debug.c:45
Call Trace:
 __list_del_entry include/linux/list.h:132 [inline]
 list_del include/linux/list.h:146 [inline]
 test_init+0x79/0x115 kernel/test.c:1040
 do_one_initcall+0x69/0x290 init/main.c:1223
 do_initcall_level init/main.c:1296 [inline]
 do_initcalls init/main.c:1312 [inline]
 do_basic_setup init/main.c:1332 [inline]
 kernel_init_freeable+0x1cd/0x249 init/main.c:1533
 kernel_init+0x10/0x1b1 init/main.c:1421
 ret_from_fork+0x1f/0x30 arch/x86/entry/entry_64.S:296
---[ end trace 1526104c6066be33 ]---
```

CONFIG_FORTIFY_SOURCE=y

```
char buf[10];
memset(buf, 0, size);


FORTIFY_INLINE void *memset(void *p, int c, size_t size)
{
    size_t p_size = __builtin_object_size(p);
    if (p_size < size)
        __write_overflow();
    return __underlying_memset(p, c, size);
}
```

BUG_ON(condition)
WARN_ON(condition)

```
void do_group_exit(int exit_code)
{
    BUG_ON(exit_code & 0x80); /* core dumps don't get here */
    ...
```

- DEBUG_LIST
- DEBUG_PLIST
- FORTIFY_SOURCE
- DEBUG_KOBJECT
- SCHED_STACK_END_CHECK
- HARDENED_USERCOPY
- HARDENED_USERCOPY_FALLBACK
- LOCKUP_DETECTOR
- SOFTLOCKUP_DETECTOR
- DETECT_HUNG_TASK
- WQ_WATCHDOG
- HARDLOCKUP_DETECTOR
- DEBUG_SG
- LOCKDEP
- PROVE_LOCKING
- DEBUG_ATOMIC_SLEEP
- PROVE_RCU
- RCU_EQS_DEBUG
- DEBUG_LOCK_ALLOC
- DEBUG_RT_MUTEXES
- DEBUG_SPINLOCK
- DEBUG_MUTEXES
- DEBUG_WW_MUTEX_SLOWPATH
- DEBUG_RWSEMS
- SND_DEBUG
- SND_PCM_XRUN_DEBUG

- DEBUG_OBJECTS
- DEBUG_OBJECTS_ENABLE_DEFAULT
- DEBUG_OBJECTS_FREE
- DEBUG_OBJECTS_PERCPU_COUNTER
- DEBUG_OBJECTS_RCU_HEAD
- DEBUG_OBJECTS_TIMERS
- DEBUG_OBJECTS_WORK
- DEBUG_PREEMPT
- DEBUG_DEVRES
- DEBUG_NOTIFIERS
- DEBUG_CREDENTIALS
- UBSAN_BOUNDS
- UBSAN_SHIFT
- DEBUG_VM
- DEBUG_VM_RB
- DEBUG_VM_VMACACHE
- DEBUG_VM_PGFLAGS
- DEBUG_VM_PGTABLE
- DEBUG_VIRTUAL
- DEBUG_KMAP_LOCAL_FORCE_MAP
- DEBUG_MEMORY_INIT
- PAGE_POISONING
- RING_BUFFER_VALIDATE_TIME_DELTAS
- DYNAMIC_DEBUG
- SND_CTL_VALIDATION
- DEBUG_PER_CPU_MAPS

- DEBUG_KMEMLEAK
- FAULT_INJECTION
- FAILSLAB
- FAIL_PAGE_ALLOC
- FAIL_MAKE_REQUEST
- FAIL_IO_TIMEOUT
- FAIL_FUTEX
- FAULT_INJECTION_DEBUG_FS
- FAULT_INJECTION_USERCOPY

- DEBUG_INFO
- DEBUG_BUGVERBOSE
- PRINTK_CALLER
- PANIC_ON_OOPS
- BUG_ON_DATA_CORRUPTION
- BOOTPARAM_HARDLOCKUP_PANIC
- BOOTPARAM_HUNG_TASK_PANIC
- BOOTPARAM_SOFTLOCKUP_PANIC
- panic_on_warn (command line)

```
$ scripts/decode_stacktrace.sh vmlinux < crash.log

  do_one_initcall (init/main.c:1223)
```

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KASAN

(KernelAddressSANitizer)

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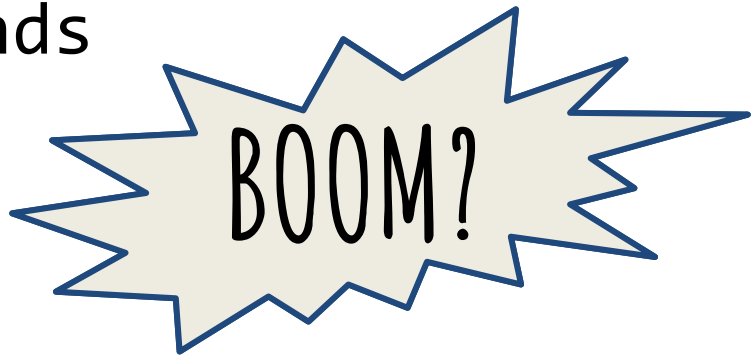
Pillars:

- no false positives
- work out of the box
- informative reports
- low overhead

KASAN:

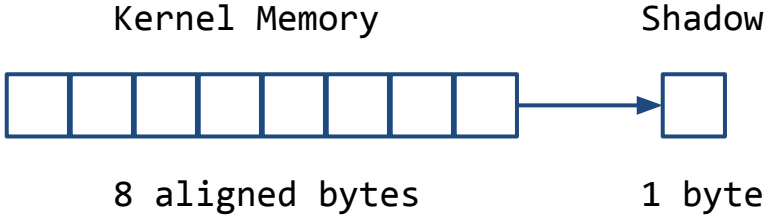
- Out-Of-Bounds
- Use-After-Free
- Heap, stack, globals
- CONFIG_KASAN=y

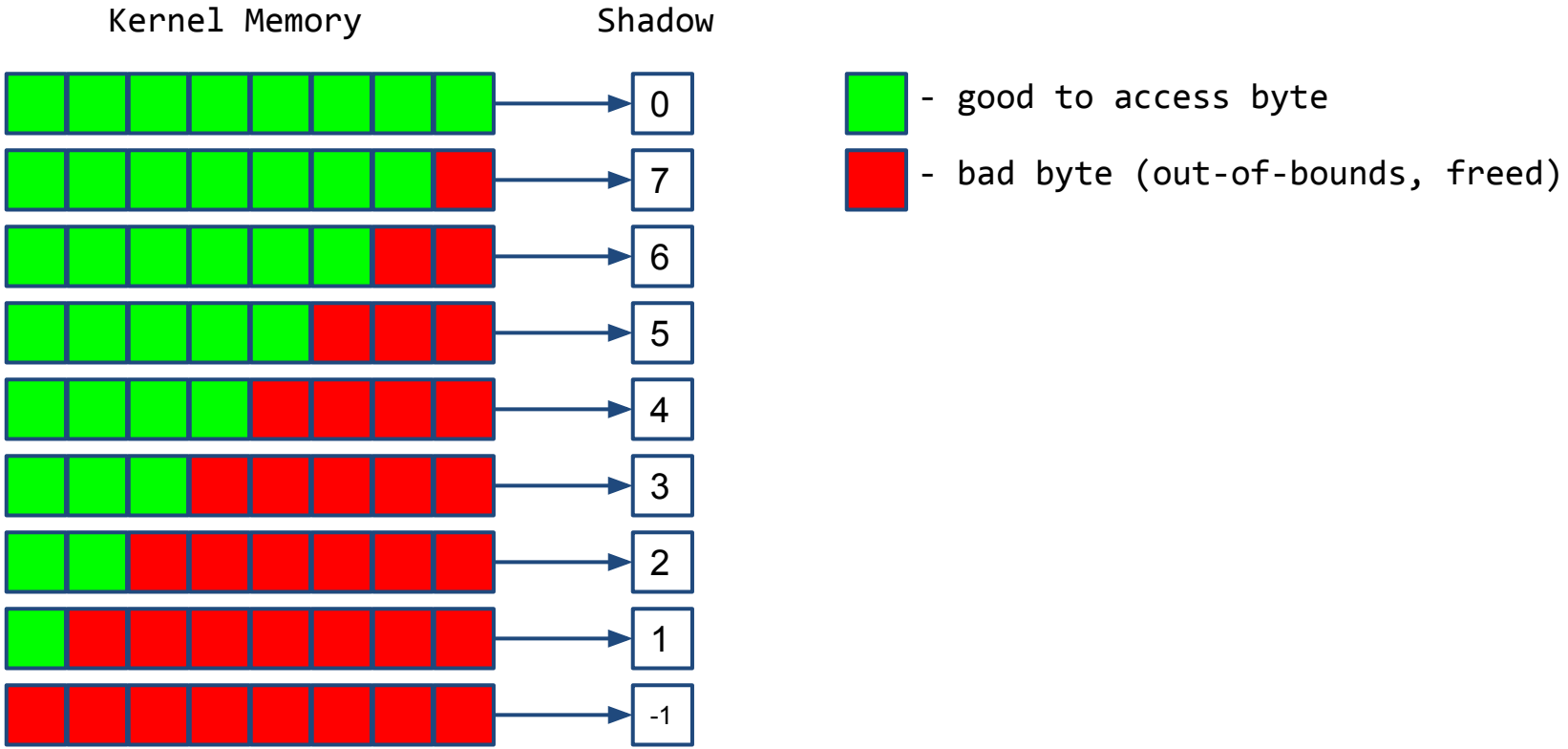
```
p = kmalloc(10);
p[20] = 1; // out-of-bounds


kfree(p);
p[0] = 1; // use-after-free
```

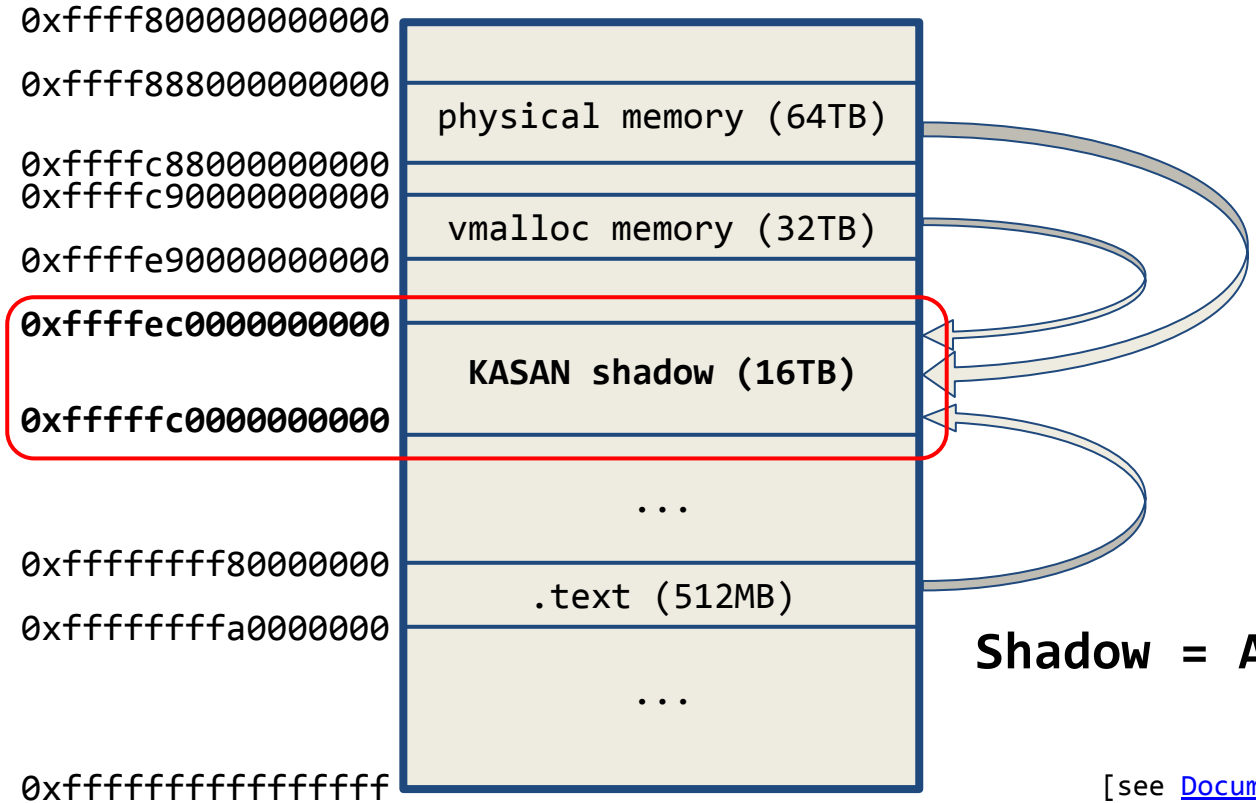


KASAN Report (CVE-2013-7446)

```
BUG: KASAN: use-after-free in remove_wait_queue
Write of size 8 by task syzkaller/10568

Call Trace:
 list_del include/linux/list.h:107
 __remove_wait_queue include/linux/wait.h:145
 remove_wait_queue+0xfb/0x120 kernel/sched/wait.c:50
 ...
 SYSC_exit_group kernel/exit.c:885

Allocated:
 kmem_cache_alloc+0x10d/0x140 mm/slub.c:2517
 sk_prot_alloc+0x69/0x340 net/core/sock.c:1329
 sk_alloc+0x33/0x280 net/core/sock.c:1404
 ...
 SYSC_socketpair net/socket.c:1281

Freed:
 kmem_cache_free+0x161/0x180 mm/slub.c:2745
 sk_prot_free net/core/sock.c:1374
 ...
 SYSC_write fs/read_write.c:585
```


Kernel Memory
Shadow
8 aligned bytes
1 byte

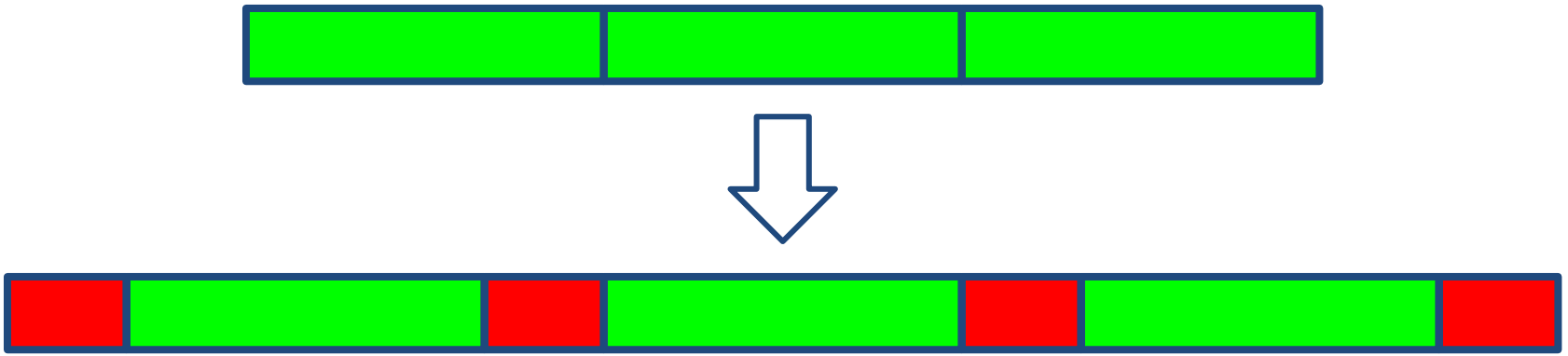

Kernel Memory
Shadow
0
7
6
5
4
3
2
1
-1
- good to access byte
- bad byte (out-of-bounds, freed)



Shadow = Addr/8 + Offset

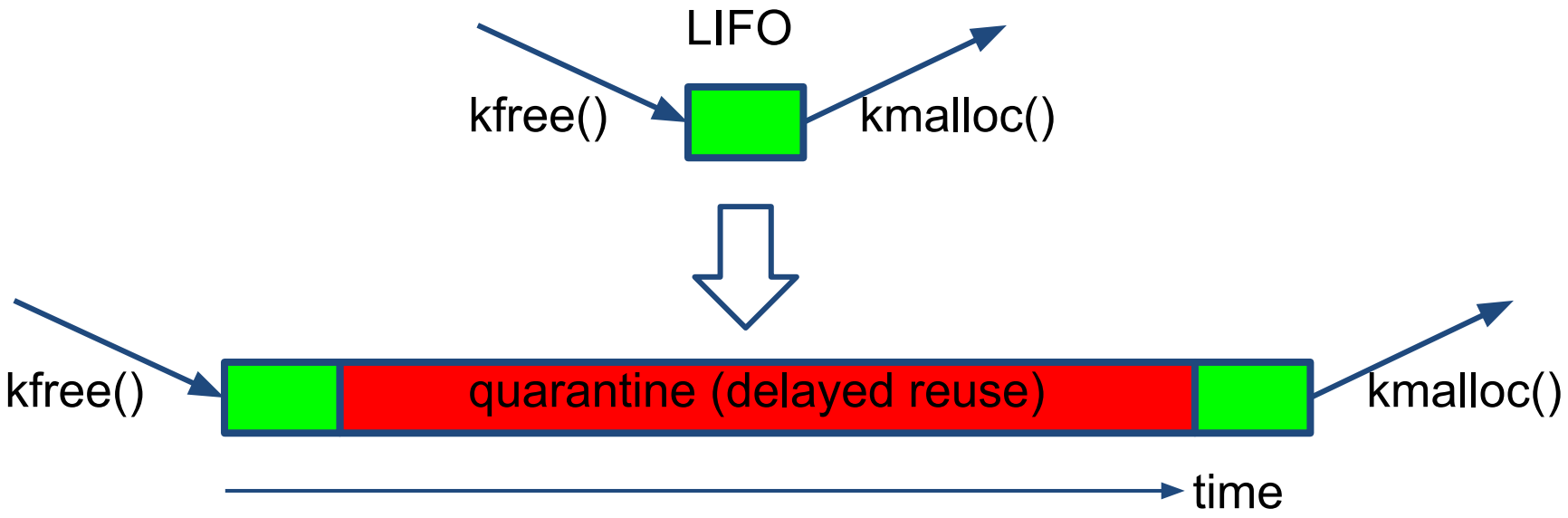
[see Documentation/x86/x86_64/mm.rst]

Red-zones around heap objects:



*compiler arranges red-zones for stack/globals

Quarantine for heap objects:



Compiler instrumentation:

```
shadow = p >> 3 + 0xdffffc0000000000;
if (*shadow)
    kasan_report8(p);
*p = 1;  // 8 bytes
```

Compiler instrumentation:

```
shadow = p >> 3 + 0xdffffc0000000000;
if (*shadow && *shadow <= ((p & 7) + N - 1))
   kasan_reportN(p);
*p = 1;  // N = 1, 2, 4 bytes
```

KASAN summary:

- shadow memory marks good/bad bytes
- red-zones (out-of-bounds)
- quarantine (use-after-free)
- shadow checks before memory accesses

- no false positives
  - by design
- work out of the box
  - just enable the config
- informative reports
  - alloc/free stacks
  - heap/stack/global object description
  - last call_rcu(), queue_work() stacks
- low overhead
  - ~~2x slowdown; ~~2x memory overhead

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How good is it?

https://syzkaller.appspot.com

open (863):

Title	Repro	Cause bisect	Fix bisect	Count	Last	Reported
BUG: soft lockup in ieee80211_tasklet_handler				5	15h27m	15h26m
WARNING in ieee802154_get_llsec_params				4	8h51m	19h46m
possible deadlock in io_link_timeout_fn				2	15h23m	19h46m
UBSAN: shift-out-of-bounds in detach_tasks				2	1d17h	19h46m
WARNING in hid_alloc_report_buf	C	unreliable		2	5d00h	1d01h
WARNING in ieee802154_del_seclevel				2	2d13h	1d23h
memory leak in __pskb_copy_fclone	C			1	3d18h	1d23h
memory leak in do_seccomp (2)	C			1	3d23h	1d23h
general protection fault in ieee802154_llsec_parse_key_id	C	inconclusive		4	3d02h	1d23h
KMSAN: kernel-infoleak in compat_drm_wait_vblank				3	10h12m	2d00h
WARNING in nbd_dev_add				1	2d13h	2d00h
memory leak in iget_locked	syz			1	4d08h	2d00h
memory leak in con_do_clear_unimap	C			1	2d20h	2d00h
KASAN: use-after-free Read in nbd_release	C	inconclusive		3	7h49m	2d00h
general protection fault in nbd_disconnect_and_put	C	unreliable		10	2h03m	2d00h
UBSAN: shift-out-of-bounds in nl802154_new_interface	C	inconclusive		17	18h33m	2d01h
INFO: rcu detected stall in __hrtimer_run_queues	C			18	13h30m	3d12h
KASAN: use-after-free Write in j1939_can_recv				1	7d23h	3d23h
WARNING in netlbl_cipsov4_add	C	inconclusive		105	3h13m	4d02h
KASAN: out-of-bounds Read in leaf_paste_entries	C	inconclusive		2	8d01h	4d03h
KASAN: use-after-free Read in ip6_pol_route (2)	C	done		2	9d07h	4d23h

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>5000 bugs reported

- KASAN: 1000
- KMSAN: 375
- KCSAN: 480
- LOCKDEP: 170
- WARNING+BUG: 1000
- NULL deref: 500

>3000 bugs fixed

>4500 LTS backports

sources: [1], [2], [3], [4]

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Dynamic tools are your friends!

- enable DEBUG_XXX, LOCKDEP, KASAN
- use during development
- insert BUG_ON / WARN_ON
- add/run tests
- scripts/decode_stacktrace.sh

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Bug fix - perfect first contribution!

syzkaller.appspot.com

Linux kernel Bug Fixing LF Mentorship program

Contributions are welcome!

bugzilla laundry list:

- [206267] KASAN: missed checks in copy_to/from_user
- [206269] KASAN: missed checks in ioread/write8/16/32_rep
- [199341] KASAN: misses underflow in memmove
- [203967] KASAN: incorrect alloc/free stacks for alloc_pages
- [199055] KASAN: poison skb linear data tail
- ...

Sanitizers in user-space!

- clang/gcc -fsanitize=address
  - use-after-free, out-of-bounds
- clang/gcc -fsanitize=thread
  - data races
- clang/gcc -fsanitize=memory
  - uses of uninit values
- clang/gcc -fsanitize=undefined
  - overflows, alignment, truncations, ...

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Thank you for joining us today!

We hope it will be helpful in your journey to learning more about effective and productive participation in open source projects. We will leave you with a few additional resources for your continued learning:

- The LF Mentoring Program is designed to help new developers with necessary skills and resources to experiment, learn and contribute effectively to open source communities.
- Outreachy remote internships program supports diversity in open source and free software
- Linux Foundation Training offers a wide range of free courses, webinars, tutorials and publications to help you explore the open source technology landscape.
- Linux Foundation Events also provide educational content across a range of skill levels and topics, as well as the chance to meet others in the community, to collaborate, exchange ideas, expand job opportunities and more. You can find all events at events.linuxfoundation.org.