syzbot

and the tale of thousand kernel bugs

Linux Security Summit 2018

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Agenda

- Kernel bug disaster
- What we are doing
- Where we need help

"Civilization runs on Linux" [1]

- Android (2e9 users)
- Cloud, servers
- Desktops, notebooks, chromebooks
- Cars
- Air/Car Traffic Control, Nuclear Submarines, Power Plants
- Large Hadron Collider, International Space Station
- ...
- Our coffee machines!

[1] from SLTS project which aims at maintaining kernel releases for 20+ years for industrial use

Security is Critical

- Protects privacy of 2 billion people
- Protects corp, government information
- Protects safety-critical systems
- The first line of defence for:
  - all incoming network packets
  - untrusted apps
  - VM guests
  - USB/NFC/Bluetooth (inserting a USB clicker into your notebook)
- Cars/phones/plants: stability and safety are also critical

Linux kernel is one of the most **security-critical** components in the world today.

Tip of The Iceberg

Bugs with logos and bold headlines

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Leading Linux distros dawdle as kernel flaw persists

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Code Execution Flaw Affected Linux Kernel Since 2005

Kernel has lots of bugs

453 CVEs in 2017 including:

- 169 code execution
- 125 gain privileges/information

But **lots** are unaccounted!

4100 "official" bug fixes in 2017 (again lots are unaccounted).

syzbot: continuous kernel fuzzing

For 12 months ~200 bugs/month:

- 1000 bugs in upstream kernel
- 1200 bugs in Android/ChromeOS/internal kernels

+1000 bugs reported manually before syzbot (~40 bugs/mo for 2 years)

= 3200 bugs

USB Stack State

Barely scratching the surface yielded 80+ externally triggerable bugs (18 CVEs).

Did not even get past handshake (WIP)

USB is not special. Flow of bugs is representative for any subsystem
(kvm, tcp, udp, rdma, sound, 9p, bpf, you name it)

USB drivers

- usb/core: memory corruption due to an out-of-bounds access in usb_destroy_configuration [fix] [CVE-2017-17558]
- usb/net/zd1211rw: possible deadlock in zd_chip_disable_rxtx
- usb/sound: use-after-free in __uac_clock_find_source [fix]
- usb/sound: slab-out-of-bounds in parse_audio_unit [fix]
- usb/media/em28xx: use-after-free in dvb_unregister_frontend [fix]
- usb/media/technisat: slab-out-of-bounds in technisat_usb2_rc_query
- usb/media/tm6000: use-after-free in tm6000_read_write_usb
- usb/net/qmi_wwan: divide error in qmi_wwan_probe/usbnet_probe [fix1, fix2] [CVE-2017-16649, CVE-2017-16650]
- usb/media/uvc: slab-out-of-bounds in uvc_probe
- usb/media/em28xx: use-after-free in em28xx_dvb_fini
- usb/media/em28xx: use-after-free in v4l2_fh_init
- usb/media/pvrusb2: WARNING in pvr2_i2c_core_done/sysfs_remove_group
- usb/sound/usx2y: WARNING in usb_stream_start [fix]
- usb/net/hfa384x: WARNING in submit_rx_urb/usb_submit_urb
- usb/media/dw2102: null-ptr-deref in dvb_usb_adapter_frontend_init/tt_s2_4600_frontend_attach
- usb/net/asix: kernel hang in asix_phy_reset
- usb/media/dtt200u: use-after-free in __dvb_frontend_free [fix] [CVE-2017-16648]
- usb/media/mxl111sf: trying to register non-static key in mxl111sf_ctrl_msg
- usb/media/au0828: use-after-free in au0828_rc_unregister
- usb/input/gtco: slab-out-of-bounds in parse_hid_report_descriptor [fix] [CVE-2017-16643]
- usb/core: slab-out-of-bounds in usb_get_bos_descriptor [fix] [CVE-2017-16535]
- usb/net/asix: null-ptr-deref in asix_suspend [fix] [CVE-2017-16647]
- usb/net/rt2x00: warning in rt2800_eeprom_word_index
- usb/irda: global-out-of-bounds in irda_qos_bits_to_value
- usb/media/imon: global-out-of-bounds in imon_probe/imon_init_intf0
- usb/sound: use-after-free in snd_usb_mixer_interrupt [fix] [CVE-2017-16527]
- usb/net/rtlwifi: trying to register non-static key in rtl_c2hcmd_launcher
- usb/net/prism2usb: warning in hfa384x_usbctlxq_run/usb_submit_urb
- usb/nfs/pn533: use-after-free in pn533_send_complete
- usb/media/imon: null-ptr-deref in imon_probe [fix] [CVE-2017-16537]
- usb/net/prism2usb: warning in hfa384x_drvr_start/usb_submit_urb

open (192):

Title	Repro	Count	Last	Reported
KASAN: slab-out-of-bounds Read in ntfs_attr_find	C	1	23d	22d
KASAN: slab-out-of-bounds Read in pfkey_add	C	769	1d06h	130d
KASAN: slab-out-of-bounds Write in process_preds	C	456	1h35m	13d
KASAN: stack-out-of-bounds Read in rdma_resolve_addr	C	3	26d	46d
KASAN: stack-out-of-bounds Read in update_stack_state	C	312	3h53m	62d
KASAN: stack-out-of-bounds Read in xfrm_state_find (5)	C	4	23d	23d
KASAN: stack-out-of-bounds Write in compat_copy_entries	syz	4	3h49m	3h57m
KASAN: use-after-free Read in __dev_queue_xmit	C	9	101d	111d
KASAN: use-after-free Read in __fput (2)		1	14d	5d17h
KASAN: use-after-free Read in __list_add_valid (5)	C	16	23d	30d
KASAN: use-after-free Read in __list_del_entry_valid (4)	C	16	23d	30d
KASAN: use-after-free Read in _decode_session4	C	3	25d	25d
KASAN: use-after-free Read in build_segment_manager	C	5	4d00h	4d16h
KASAN: use-after-free Read in ccid2_hc_tx_packet_recv		3	13d	22d
KASAN: use-after-free Read in cma_cancel_operation	C	8	5d02h	22d
KASAN: use-after-free Read in debugfs_remove (2)		1	4d02h	1d22h
KASAN: use-after-free Read in ip6_xmit	C	5174	33d	110d
KASAN: use-after-free Read in ip_defrag		1	115d	110d
KASAN: use-after-free Read in iput	C	2	7d13h	7d08h
KASAN: use-after-free Read in irq_bypass_register_consumer	C	292	7d01h	174d
KASAN: use-after-free Read in l2tp_session_create		119	31d	98d
KASAN: use-after-free Read in l2tp_session_register		4	21d	67d
KASAN: use-after-free Read in memcmp		1	88d	87d
KASAN: use-after-free Read in ntfs_read_locked_inode	C	1	20d	20d
KASAN: use-after-free Read in radix_tree_next_chunk	C	1637	5h11m	24d

Bug split

Use-after-free	18.5%
Heap-out-of-bounds	5.2%
Stack-out-of-bound	2.4%
Double-free	0.8%
Wild-access	4.8%
Uninit-memory	4.0%
GPF	20.2%
BUG/panic/div0	10.3%
deadlock/hang/stall	12.5%
WARNING	21.1%

Modest estimation: 500 security bugs (not counting DoS; very few have CVEs).

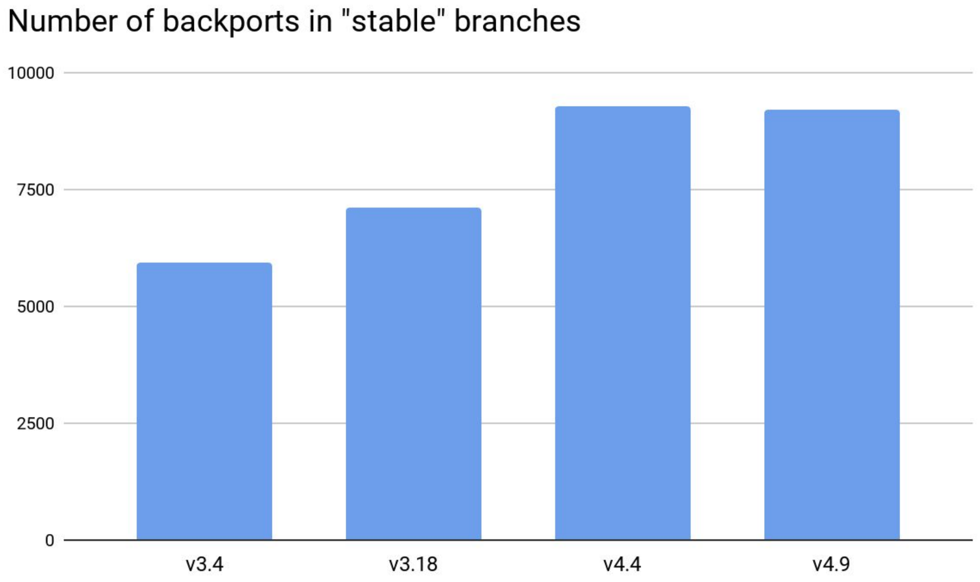
Exploit != use-after-free

- **"unresponsive" machine** -> full guest->host escape
  - page ref leak
  - CVE-2017-2596 / kvm: fix page struct leak in handle_vmon

- **WARNING** -> inter-VM/process info leaks
  - failure to restore registers
  - WARNING in __switch_to / WARNING in fpu__copy

- **stall** -> remote network DoS
  - lockup in udp[v6]_recvmsg
  - anything remotely triggerable is a concern

"Stable" releases



+ not backported fixes (700+)
+ not fixed upstream bugs (200+)
+ not found bugs (???)
+ not detectable yet bugs (???)
(info leaks, races)

Every "looks good and stable" release we produce contains >**20'000 bugs**.
No, not getting better over time.
No, this is not normal.

Distros State

End distros is what matters security-wise in the end.

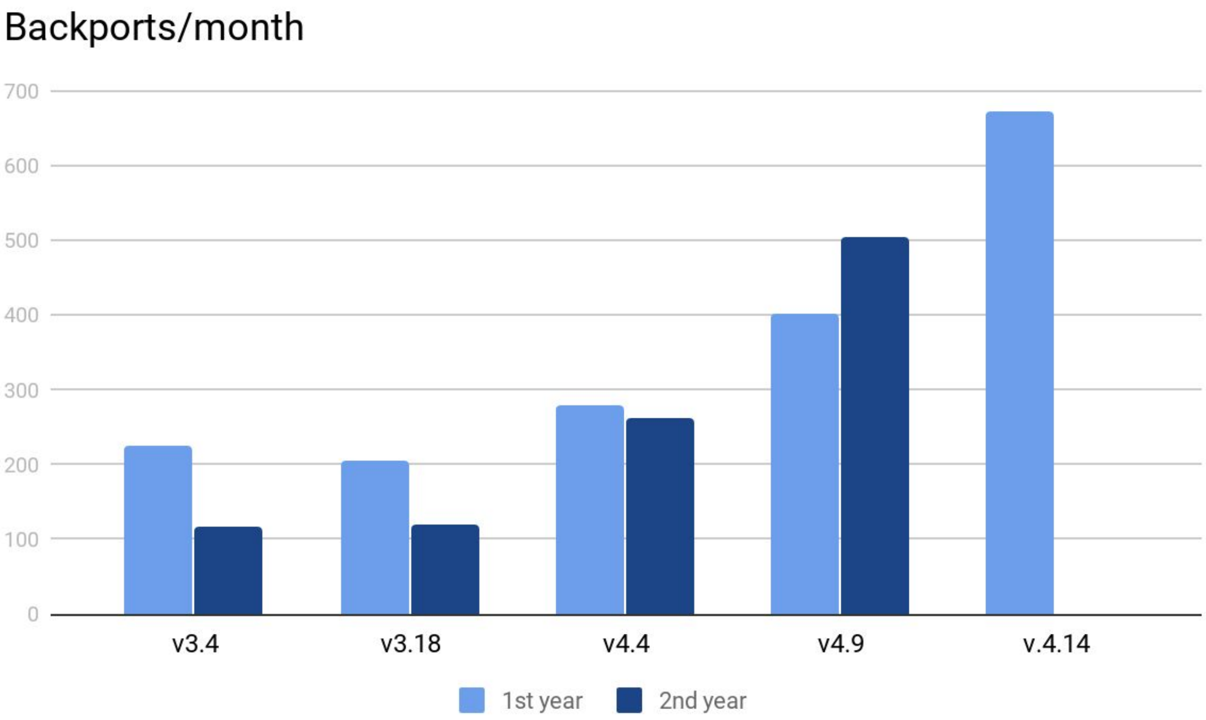
> `It isn't always possible for distributions to track the linux-stable tree or fully monitor the commits that flow into it.`

`CVE-2017-18344 discussion on linux-distros@`

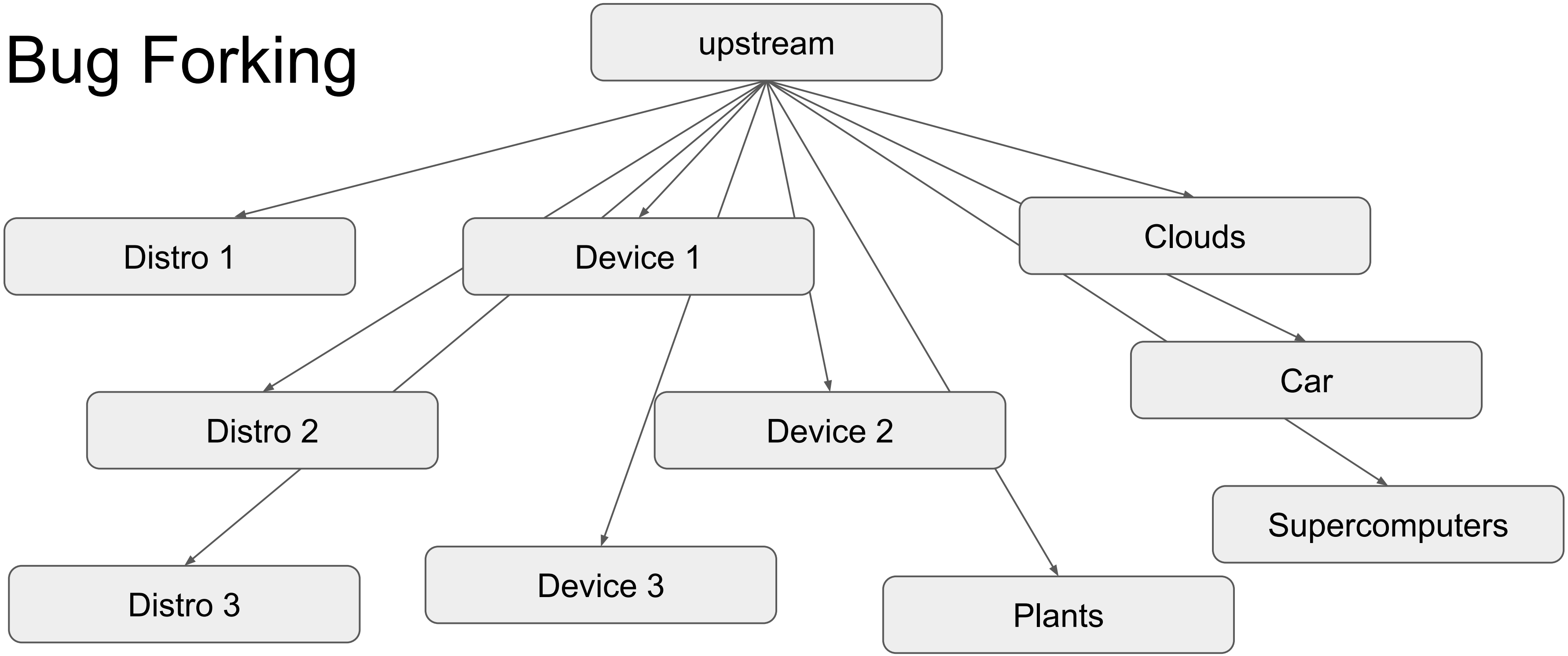
Stable process is not fully working, CVE process is not working.

Why?

"Stable" releases



Bug Forking



Each bug fork is effectively a new bug for most practical purposes.
Hundreds of thousands of bugs for Google. **Millions of bugs industry-wide**.

:(

Goal

Reduce bugs/release **100x**: 20'000 -> 200

Existing Defences Are Not Enough

- Attack surface reduction
  - large surface is still open
  - most subsystems are still relevant (USB for clients, namespaces for servers)

- Mitigations [1]
  - can't mitigate hundreds of arbitrary memory corruptions (assume there are few bugs)
  - don't mitigate lots of bug types (races, uninit memory, write what/where)
  - some are not backported/enabled (performance!)

[1] KASLR, REFCOUNT_FULL, STACKPROTECTOR, VMAP_STACK, SLAB_FREELIST_RANDOM, STRUCTLEAK, RANDSTRUCT, etc

Existing Defences Are Not Enough (2)

- Selinux/namespaces/fs-verity
  - logical protection: directly assume that kernel is not buggy ([1])
  - namespaces open even larger attack surface ([1], [2], [3], [4])

- Hiding buggy code "under root"
  - SELinux/AppArmor/IMA/module signing restrict root
  - root is **not** trusted on some systems (Android)
  - user still needs to do the thing, so they just issue sudo left and right

What we are doing

What we have

- bug detection:
  - KASAN
  - KMSAN
  - KTSAN
- bug discovery:
  - syzkaller
- systematic testing:
  - syzbot

KASAN (KernelAddressSANitizer)

- security "workhorse"
- Detects:
  - use-after-free
  - out-of-bounds on heap/stack/globals
- detects bugs at the point of occurrence
- outputs informative reports
- easy to use (`CONFIG_KASAN=y`)
- based on compiler instrumentation (gcc4.9+ or clang)
- fast: ~~2x slowdown, ~~2x memory overhead
- upstream in 4.3 kernel

KMSAN (KernelMemorySanitizer)

Detects uses of uninitialized values.

In the context of security:

- **information leaks** (local and remote) [easy to exploit: 1, 2]
- **control-flow subversion** [1]
- **data attacks** (uninit uid) [1, 2]

Not upstreamed yet (on github), work-in-progress.

Already found 50+ bugs.

KTSAN (KernelThreadSanitizer)

Detects **data races**.

Kernel data races represent **security threat**:

- TOCTOU (time-of-check-time-of-use) ([1])
- uninit/wrong credentials ([1])
- racy use-after-frees/double-frees ([1], [2], [3], [4])

Prototype on github, frozen due to lack of resources, found 20+ bugs.

Main obstacle: kernel is full of "benign" races (undefined behavior in C).

syzkaller

System call fuzzer:

- grammar-based
- coverage-guided
- unsupervised
- multi-OS/arch/machine

As compared to other kernel fuzzers:

- finds deeper bugs
- provides reproducers
- does regression testing
- scalable to large number of bugs

Syscall Descriptions

Declarative description of system calls:

```
open(file filename, flags flags[open_flags],
     mode flags[open_mode]) fd
read(fd fd, buf buffer[out], size len[buf])
close(fd fd)
```

Tests **only** what's described.

Programs

Descriptions allow to generate and mutate "programs" in the following form:

```
mmap(&(0x7f0000000000), (0x1000), 0x3, 0x32, -1, 0)
r0 = open(&(0x7f0000000000)="./file0", 0x3, 0x9)
read(r0, &(0x7f0000000000), 42)
close(r0)
```

syzbot: fuzzing automation

- continuous kernel/syzkaller build/update
- test machine management (qemu, GCE VMs, Android phones, ODROID, ...)
- bug deduplication and localization
- bug reporting/status tracking

syzkaller.appspot.com

We need YOU!

More Coverage

More syscall descriptions* -> more bugs. Coverage is not complete.

Poor environment setup: network devices, SELinux policies, etc.

CVE-2017-18017 (remote code exec): didn't test, didn't know netfilter exists
Android use-after-free (severity: high): don't test NSFS

Adding syzkaller descriptions is not hard.

* automatic interface extraction is not feasible (netlink, netfilter, images, string parsing, etc)

External Inputs

Injecting external inputs finds the most critical bugs. Need to test:

- Network packets (currently basic coverage via tun)
- USB
- NFC
- CAN
- Bluetooth
- Guest->host (emulation, vring, vsocks, hypercalls)
- Keyboard, mouse, touchscreen, mic, camera
- ...

Some may need better stubbing support, a-la tun.

Lots of bugs are unfixed

Hundreds of bugs are unfixed:

- Some are bad vulnerabilities
- Others affect stability or are DoS
- Rest harm syzkaller’s ability to uncover new vulnerabilities

Need help:

- Fixing bugs
- Triaging, routing, duping, closing fixed/obsolete

KASAN: manual checks

KASAN checks C accesses wrt `kmalloc()` size.

Does **not** check:

- asm accesses
- hardware accesses
- use-after-free with custom caches
- out-of-bounds with amortized growth

But can be checked with manual memory/access annotations:

```
kasan_check_write(p, size);
```

KASAN: manual checks: SKB

SKB: core networking data structure, holds packet data.

Uses proactive/amortized growth:

```
if (pskb_may_pull(skb, 2) {
    // can access skb->data[0-1], but not [2]
    if (pskb_may_pull(skb, 3) {
        // now can access bytes [0-2], but previous skb->data is invalidated
    }
}
```

Very easy to get wrong, bug nest: dozens of remotely-triggerable bugs.

Can make sense to do [strict/exact growth]() under KASAN.

KASAN: manual checks

Do **not** want KASAN annotations sprinkled everywhere.

But some "biggest bang for the buck" can be worthy:

- dma/i2c/spi/virtio?
- USB: something in URB?
- something in filesystems?
- ???

Other Tools

- **KMEMLEAK**: memory leak detector
  - in server context leaks are one of the worst bugs, remote leaks are remote DoS
  - has false positives -> no systematic testing -> bugs are not found/fixed

- **KUBSAN**: Undefined Behavior SANitizer
  - finds some intra-object overflows
  - invalid bools/enums (control flow hijacking)
  - overflows/invalid shifts (out-of-bound accesses)
  - needs cleanup, fixes face opposition

- **KTSAN**: data race detector
  - will find thousands of hard-to-localize bugs with actionable reports, but...
  - need to say NO to "benign data races" (undefined behavior in C)
  - all concurrent accesses need to be marked

Kernel Testing

Most bugs can be prevented with proper testing. We do need better testing:

- 20'000 bugs/release
- New bugs are introduced at high rate
- New bugs are backported to stable (1, 2, 3, 4, 5, 6, 7)
- Bugs are re-introduced (1, 2)
- Distros don't keep up

Development is slowed down:

- high reliance on manual labor
- delayed releases
- broken builds (bisection :()
- long fix latency (testing :()
- late feedback, reverts

Testing MUST be part of dev process

- Tests need to be easier to write, discover and run
  - userspace tests
  - in-kernel tests with hardware mocking (kunit)
- Tests for new functionalities, regression tests
- Automated continuous testing
- Integration into dev process, presubmit testing
- Use of all available tools (trivial bugs [1], [2], [3])

Thank you!

Q&A

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Backup

syzkaller coverage-guided algorithm

```
start with empty corpus of programs
while (true) {
    choose a random program from corpus and mutate it (or generate)
    execute and collect code coverage
    if (gives new coverage)
        add the program to corpus
}
```

Advantages:

- turns exponential problem into linear (more or less)
- inputs are reproducers
- corpus is perfect for regression testing

KMSAN: uses of uninit values

```
int x;
put_user(&x, user_ptr);            // reported



int y;
int x = y;                         // not reported
put_user(&x, user_ptr);            // reported
       (just assigning something to a variable does not make its value initialized)


int x = 0, y, z = 0;
if (foo) x = y + z;                // not reported
...
if (!foo) put_user(&x, user_ptr);// not reported
    (using uninit value in computations is not a  use, merely propagation)
```

HWASAN (HardWare assisted AddressSANitizer)

~KASAN, but with substantially smaller memory overhead (~10%).

Intended to be used on real devices (testing, canarying, maybe end users/prod).

Work-in-progress (patches mailed), only arm64 for now (requires TBI).

Will shine more with proper hardware implementation.

Hardware-assisted memory safety

1. We can't fix all bugs.

2. Some installations don't get timely updates (or at all).

Need better mitigations! SPARC ADI (or similar):

- Detect & mitigate most of use-after-free and out-of-bounds
- 1-5% CPU, 4-5% RAM overhead
- can actually make things faster:
  - don't need stack cookies, slab randomization, fortification, usercopy hardening, CFI, etc

KASAN Report (CVE-2013-7446)

```
BUG: KASan: use-after-free in remove_wait_queue
Write of size 8 by task syzkaller_execu/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
 sk_destruct+0x2e9/0x400 net/core/sock.c:1452
 ...
 SYSC_write fs/read_write.c:585
```

KMSAN report

```
BUG: KMSAN: uninit-value in ____nf_conntrack_find
Call Trace:
  ____nf_conntrack_find net/netfilter/nf_conntrack_core.c:539
  __nf_conntrack_find_get+0xc15/0x2190 net/netfilter/nf_conntrack_core.c:573
...
  __x64_sys_sendto+0x1a1/0x210 net/socket.c:1805
Uninit was stored to memory at:
  __nf_conntrack_confirm+0x2700/0x3f70 net/netfilter/nf_conntrack_core.c:793
  nf_conntrack_confirm include/net/netfilter/nf_conntrack_core.h:71
...
  __x64_sys_sendto+0x1a1/0x210 net/socket.c:1805
Uninit was created at:
  kmem_cache_alloc+0xad2/0xbb0 mm/slub.c:2739
  __nf_conntrack_alloc+0x166/0x670 net/netfilter/nf_conntrack_core.c:1137
  init_conntrack+0x635/0x2840 net/netfilter/nf_conntrack_core.c:1219
...
  __x64_sys_sendto+0x1a1/0x210 net/socket.c:1805
```

KTSAN Report (CVE-2015-7613)

```
ThreadSanitizer: data-race in ipc_obtain_object_check

Read at 0x123 of size 8 by thread 234 on CPU 5:
 ipc_obtain_object_check+0x7d/0xd0 ipc/util.c:621
 msq_obtain_object_check ipc/msg.c:90
 msgctl_nolock.constprop.9+0x208/0x430 ipc/msg.c:480
 SYSC_msgctl ipc/msg.c:538

Previous write at 0x123 of size 8 by thread 567 on CPU 4:
 ipc_addid+0x217/0x260 ipc/util.c:257
 newque+0xac/0x240 ipc/msg.c:141
 ipcget_public ipc/util.c:355
 ipcget+0x202/0x280 ipc/util.c:646
 SYSC_msgget ipc/msg.c:255

Also: locked mutexes, thread creation stacks, allocation stack, etc.
```

Say **No** to "Benign" Data Races

- Proving benignness is time consuming and impossible
- Allows automatic data race bug detection
- Makes code better documented

Proving Benignness

```
*p = (*p & 0xfffff) | v;
```

Option 1:

```
0: mov (%rdi),%rax
3: and $0xfffff,%eax
8: or %rax,%rsi
B: mov %rsi,(%rdi)
```

Option 2:

```
0: andq $0xfffff,(%rdi)
7: or %rsi,(%rdi)
```

This should be atomic, right?

```
void foo(int *p, int v)
{
    // some irrelevant code
    *p = v;
    // some irrelevant code
}
```

This should be atomic, right?

```
void foo(int *p, int v)
{
    // some irrelevant code
    *p = v;
    // some irrelevant code
}

void bar(int *p, int f)
{
    int tmp = *p & MASK;
    tmp |= f;
    foo(p, tmp);
}
```

This should be atomic, right?

```
void foo(int *p, int v)
{
     // some irrelevant code
     *p = v;
     // some irrelevant code
}

void bar(int *p, int f)
{
     int tmp = *p & MASK;
     tmp |= f;
     foo(p, tmp);
}
     after inlining:
*p = (*p & MASK) | f;
```

This should be atomic, right? Maybe

```
void foo(int *p, int v)
{
    // some irrelevant code
    *p = v;
    // some irrelevant code
}

void bar(int *p, int f)
{
    int tmp = *p & MASK;
    tmp |= f;
    foo(p, tmp);
}
    after inlining:
*p = (*p & MASK) | f;

0: andq $0xfffff,(%rdi)
7: or %rsi,(%rdi)
```

Based on Real Bug

```
--- a/fs/namespace.c
+++ b/fs/namespace.c
@@ -2212,7 +2212,7 @@ static int do_remount(struct path *path, int flags,
int mnt_flags,
                 lock_mount_hash();
                 mnt_flags |= mnt->mnt.mnt_flags &
                                                 ~MNT_USER_SETTABLE_MASK;
-                mnt->mnt.mnt_flags = mnt_flags;
+                WRITE_ONCE(mnt->mnt.mnt_flags, mnt_flags);
                 touch_mnt_namespace(mnt->mnt_ns);
                 unlock_mount_hash();
```

Temporary exposes mount without MNT_NOSUID, MNT_NOEXEC, MNT_READONLY flags.

Fragile

- Changing local computations can break such code
- Changing MASK from 0xfe to 0xff can break such code
- New compiler can break such code
- LTO can break such code