Linux Kernel Debugging

Advanced Operating Systems 2020/2021

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Agenda – Debugging Scenarios

- **Debugging production kernels**
  - **Post-mortem analysis: interpreting kernel oops/panic output, creating and analyzing kernel crash dumps**
  - Kernel observability – dynamic debug, tracing, alt-sysrq dumps, live crash session
- Debugging during individual kernel development
  - Debug prints – `printk()` facilitiy
  - Debugger (`gdb`) support
- Finding (latent) bugs during collaborative development
  - Optional runtime checks configurable during build
  - Testing and fuzzing
  - Static analysis

Enterprise Linux Distro and Bugs (incl. Kernel)

- The software installation (e.g. ISO) itself is free (and open source, obviously)
- Customers pay for **support subscription**
  - Delivery of (tested by QA) package updates – fixing known bugs, CVE's… but not more!
  - **Getting reported bugs fixed**
    - Bugs specific to customer's workload, hardware, "luck", large number of machines…
    - Upstream will also fix reported bugs, but only with latest kernel and no effort guarantees
- Dealing with kernel bugs, e.g. crashes
  - Find out the root cause (buggy code) with limited possibilities (compared to local development)
    - Typically no direct access to customer's system or workload
    - Long turnarounds for providing a modified debug kernel and reproducing the bug
  - Write and deliver a fix (upstream first!) or workaround; fix goes to next update
    - Possibly a livepatch in some cases
  - Is a lot of fun ;-)

Kernel Oops - The Real World Example

- In September 2017, a customer reported a kernel **Oops**
  - Kernel detects an unexpected situation and reports it on the console(s)
    - Usually triggered by a CPU exception
    - The exception might be also triggered by an assertion in kernel code
  - Lots of (architecture-specific) information which may or may not be enough to find the root cause

- Kernel might survive an Oops and keep running
  - Kill just a single process, but that includes kernel threads
  - Possibly inconsistent state (locks that were locked are not unlocked…)
- Less serious kind of Oops: kernel **warning**, doesn't kill, just taints the kernel with **`W`** flag
  - Usually an assert-like condition for "this should not happen but should be able recover" situations
- Fatal oops (kernel **panic**) kills the system completely
  - Oops in interrupt context, `panic_on_oops`, `panic_on_taint` enabled, specific `panic()` calls
  - HW failure, critical memory allocation failure, init or idle task killed
  - May trigger crash dump if configured, or reboot automatically after set delay

Kernel Oops - The Real World Example

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G           E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_close+0x3e/0xb0
RSP: 0018:ffff880211337d88  EFLAGS: 00010202
RAX: fffffffffffffea RBX: fffffffffffffea RCX: 0000000000000006
RDX: 0000000000000000 RSI: 000000000000005c RDI: 0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Kernel Oops - The Real World Example

```
Stack:
 ffff88016d2319e0 ffff880158fea140 00007ffce0bf0000 ffffffff81127fa4
 ffff88008cecac80 ffff880211337dd8 ffff88016d2319e0 ffffffff811280f8
 0000000000000001 ffff88014c826088 ffff88008cecac80 0000000100000028
Call Trace:
 [<ffffffff81127fa4>] remove_vma+0x24/0x80
 [<ffffffff811280f8>] exit_mmap+0xf8/0x120
 [<ffffffff810602d9>] mmput+0x49/0x100
 [<ffffffff81065192>] exit_mm+0x122/0x160
 [<ffffffff81066f39>] do_exit+0x189/0x470
 [<ffffffff8106725d>] do_group_exit+0x3d/0xb0
 [<ffffffff810672e2>] sys_exit_group+0x12/0x20
 [<ffffffff81471df2>] system_call_fastpath+0x16/0x1b
 [<00007f29408be998>] 0x7f29408be997
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8b 33 48 8d bd 98 00 00 00 e8 7d ba
ff ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44 00 00 65 48 8b 04 25 00 a6 00
00 48 8b
RIP  [<ffffffff811e466e>] shm_close+0x3e/0xb0
 RSP <ffff880211337d88>
---[ end trace 3dad41c41965c82c ]---
```

Kernel Oops in Detail

```
------------[ cut here ]------------
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R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
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Kernel Oops in Detail – What Happened

```
------------[ cut here ]------------
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CPU 1
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                                    l auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)

                                    E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual

                                    >] shm_close+0x3e/0xb0

                                    0000000000000006
                                    0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
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Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Result of a `BUG( )` macro.

File + line translation enabled by `CONFIG_DEBUG_BUGVERBOSE` (implemented by `__bug_table` section on x86 - ~70-100kB)

Kernel Oops in Detail – What Happened

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid c ode: 0000 [#1] SMP
CPU 1
Module  : lp parport_pc af_packet st ide_cd_mod ide_core bridge st dev ext2 des_generic ecb
l auth_rpcgss sunrpc aut isc mperf vsock(FX)

E X 3.0.101-84-
>] shm_close+0x
0000000000000006
0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:00000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
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```

Result of a `BUG()` macro.

File + line translation enabled by `CONFIG_DEBUG_BUGVERBOSE` (implemented by `__bug_table` section on x86 - ~70-100kB)

The indicated line contains:

```
struct shmid_kernel *shp;
...
shp = shm_lock(ns, sfd->id);
BUG_ON(IS_ERR(shp));
```

This is essentially a hard assertion:
`if (<condition>) BUG()`

Kernel Oops in Detail – CPU Exception

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G           E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_close+0x3e/0xb0
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RDX: 0000000000000000 RSI: 000000000000005c RDI: 0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
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FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Kernel Oops in Detail – CPU Exception

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules l      d in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls      fs(X) nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
```

On x86_64, `BUG()` emits a standardized invalid opcode `UD2` (`0F 0B`) triggering a CPU exception.

The exception handler checks for `UD2` opcode and searches the `__bug_table` for details.

This reduces instruction cache footprint compared to `BUG()` being a call. Also prevents speculation into `BUG()` path.

```
E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual

>] shm_close+0x3e/0xb0

000000000000006
000000000000006
fff8804256a84d0
ffffff81a469c0
000000000000001
00) knlGS:0000000000000000

0000000001407e0
000000000000000
000000000000400
211336000, task ffff8801b49c8040)
```

Kernel Oops in Detail – CPU Exception

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.10
invalid opcode: 0000 [#1] SMP
CPU 1
Modules l      d in: lp parport_pc af_pa
md4 nls      fs(X) nfs fscache nfsd lockd nfs_a
<...>
```

```
E X 3.0.1
>] shm_cl
0000000000
0000000000006
fff8804256a84d0
ffffffff81a469c0
0000000000001
00) knlGS:0000000000000000

0000000001407e0
0000000000000
0000000000400
211336000, task ffff8801b49c8040)
```

On x86_64, BUG() emits a standardized invalid opcode UD2 (0F 0B) triggering a CPU exception.

The exception handler checks for UD2 opcode and searches the __bug_table for details.

This reduces instruction cache footprint compared to BUG() being a call. Also prevents speculation into BUG() path.

Since 4.11, the same trick is used for WARN(), WARN_ON() etc.

The UD0 opcode (0F FF) was used because some emulators terminate when they encounter UD2.

However turns out UD0 is not that well standardized (AMD vs Intel).

Kernel Oops in Detail – Error Code

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G           E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_close+0x3e/0xb0
RSP: 0018:ffff880211337d88  EFLAGS: 00010202
RAX: fffffffffffffea RBX: fffffffffffffea RCX: 0000000000000006
RDX: 0000000000000000 RSI: 000000000000005c RDI: 0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Kernel Oops in Detail – Error Code

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked i      o parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 c        nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[las
Supp

Pid:                                  X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Plat
RIP:                                 ] shm_close+0x3e/0xb0
RSP:
RAX:                                 0000000000000006
RDX:                                 0000000000000006
RBP:                                 ff8804256a84d0
R10:                                 ffffff81a469c0
R13:                                 0000000000000001
FS:                                  00) knlGS:0000000000000000
CS:
CR2:                                 0000000001407e0
DR0:                                 0000000000000000
DR3:                                 0000000000000400
Proc                                 11336000, task ffff8801b49c8040)
```

x86- and exception-specific error code (32-bit hex number). Not applicable to invalid opcode. Typically useful for page fault exceptions where it's a mask:

Bit 0 – Present
Bit 1 – Write
Bit 2 – User
Bit 3 – Reserved write
Bit 4 – Instruction fetch

(newer kernels decode this)

Kernel Oops in Detail – Counter and Config

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
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<...>
[last unloaded: ppa]
Supported: Yes, External

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Modules linked in: lp [illegible]ort_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 cifs(X) [illegible]cache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[last unloa
Supported:

Pid: 26341,                                    X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Platform/44
RIP: 0010:[                                  ] shm_close+0x3e/0xb0
RSP: 0018:f
RAX: ffffff                                  )0000000000006
RDX: 000000                                  )0000000000006
RBP: ffffff                                  ff8804256a84d0
R10: ffff88                                  fffff81a469c0
R13: ffff88                                  )0000000000001
FS:  00007f                                  ) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
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Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Oops counter, followed by state of selected important kernel config options:

PREEMPT
SMP
DEBUG_PAGEALLOC
KASAN
PTI/NOPTI

Kernel Oops in Detail – Kernel Modules

```
------------[ cut here ]------------
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invalid opcode: 0000 [#1] SMP
CPU 1
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CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
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Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Kernel Oops in Detail – Kernel Modules

```
------------[ cut here ]--------
kernel BUG at /usr/src/packages/
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport                                    ext2 des_generic ecb
md4 nls_utf8 cifs(X) nfs fs                                      sc mperf vsock(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tai                                 VMware Virtual
Platform/440BX Desktop Reference
RIP: 0010:[<ffffffff811e466e>]
RSP: 0018:ffff880211337d88  EFLA
RAX: fffffffffffffea RBX: fffff
RDX: 0000000000000000 RSI: 00000
RBP: ffffffff81a46920 R08: 00000
R10: ffff880192cecc00 R11: fffff
R13: ffff88008cecac80 R14: ffff8
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Modules (~drivers) and their taint flags:

- E – unsigned
- X – externally supported (SUSE)
- P – proprietary
- O – out-of-tree
- F – force-loaded
- C – staging/ tree module
- N – no support (SUSE)
- +/- – being loaded/unloaded

Last unloaded – insufficient cleanup?

Kernel Oops in Detail – Basic Info

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G          E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_close+0x3e/0xb0
RSP: 0018:ffff880211337d88  EFLAGS: 00010202
RAX: ffffffffffffffea RBX: ffffffffffffffea RCX: 0000000000000006
RDX: 0000000000000000 RSI: 000000000000005c RDI: 0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Kernel Oops in Detail – Basic Info

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G          E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_close+0x3e/0xb0
RSP: 001[illegible]ff880211337d88  EFLAGS: 00010202
RAX: f[illegible]fffffffea RBX: fffffffffffffea RCX: 0000000000000006
RDX: [illegible]000000 RSI: 000000000000005c RDI: 0000000000000006
[illegible]R09: ffff8804256a84d0
[illegible]R12: ffffffff81a469c0
[illegible]R15: 0000000000000001
[illegible]000(0000) knlGS:0000000000000000
[illegible]5003b
[illegible]CR4: 00000000001407e0
[illegible]DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Information about CPU, process in whose context the bug happened, exact kernel version, HW (or virtual host) platform.

Kernel Oops in Detail – Basic Info

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G          E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_close+0x3e/0xb0
RSP: 001[illegible]ff880211337d88  EFLAGS: 00010202
RAX: f[illegible]fffffffea RBX: ffffffffffffffea RCX: 0000000000000006
RDX: [illegible]000000 RSI: 000000000000005c RDI: 000000000000[illegible]
[illegible]R09: ffff8804256a
[illegible]R12: ffffffff81a4
[illegible]R15: 000000000000
[illegible]000(0000) knlGS:0
[illegible]5003b
[illegible]CR4: 00000000001407e0
[illegible]DR2: 000000000000000[illegible]
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 000000000000[illegible]00
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Information about CPU, process in whose context the bug happened, exact kernel version, HW (or virtual host) platform.

More process (task) details (addresses of related structures) Not printed in newer kernels.

Kernel Oops in Detail – Kernel taint flags

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G          E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_close+0x3e/0xb0
RSP: 0018:ffff880211337d88  EFLAGS: 00010202
RAX: ffffffffffffffea RBX: ffffffffffffffea RCX: 0000000000000006
RDX: 0000000000000000 RSI: 000000000000005c RDI: 0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Kernel Oops in Detail – Ker

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.1
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd nfs_ac
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G          E X 3.0.10
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_clo
RSP: 0018:ffff880211337d88  EFLAGS: 00010202
RAX: ffffffffffffffea RBX: ffffffffffffffea RCX: 00000000000
RDX: 0000000000000000 RSI: 000000000000005c RDI: 00000000000
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 00000000000
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 00000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Kernel taint flags:

POFCEX – same as per-module
G – no proprietary module (not P)
R – module was force-unloaded
D – there was an oops before
W – there was a warning before
L – soft-lockup has occurred before
B – bad page was encountered
K – kernel has been live patched
T – kernel structures randomized
M – system has reported a MCE
A – ACPI table was overriden
I – firmware bug workaround
S – “CPU out of spec”
X – distro-defined (auxiliary)
U – userspace-defined

Kernel Oops in Detail – instruction pointer

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G           E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_close+0x3e/0xb0
RSP: 0018:ffff880211337d88  EFLAGS: 00010202
RAX: ffffffffffffffea RBX: ffffffffffffffea RCX: 0000000000000006
RDX: 0000000000000000 RSI: 000000000000005c RDI: 0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Kerne n pointer

Which instruction was executing, translated to function name + offset / size.

May appear as different function from where BUG_ON( ) was reported, if the function containing BUG_ON( ) was inlined.

In newer kernel the raw value (address) was removed for security reasons (KASLR).

```
------------
kernel BUG a                                                    /shm.c:205!
invalid opco
CPU 1
Modules link                                                    tp llc joydev ext2 des_generic ecb
md4 nls_utf8                                                    bfs4 binfmt_misc mperf vsock(EX)
<...>
[last unload
Supported: Y

Pid: 26341, comm: <redacted> Tainted: G          E          1-84-default #1 VMware, Inc. VMware Virtual
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_close+0x3e/0xb0
RSP: 0018:ffff880211337d88  EFLAGS: 00010202
RAX: ffffffffffffffea RBX: ffffffffffffffea RCX: 0000000000000006
RDX: 0000000000000000 RSI: 000000000000005c RDI: 0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Kernel Oops in Detail – General Registers

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G           E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_close+0x3e/0xb0
RSP: 0018:ffff880211337d88  EFLAGS: 00010202
RAX: fffffffffffffea RBX: fffffffffffffea RCX: 0000000000000006
RDX: 0000000000000000 RSI: 000000000000005c RDI: 0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Kernel Oops in Deta

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd n
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted
Platform/440BX Desktop Reference Pl    rm
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811
RSP: 0018:ffff880211337d88  EFLAGS: 00010202
RAX: fffffffffffffea RBX: fffffffffffffea RCX: 0000000000000006
RDX: 0000000000000000 RSI: 000000000000005c RDI: 0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Values of the general registers at the trapping instruction. We can recognize kernel addresses:

FFFFFFFF8xxxxxxx – kernel code + data

FFFFFFFFAxxxxxxx – kernel modules code + data

FFFF88xxxxxxxxxx – direct mapped phys. mem.

FFFFEAxxxxxxxxxx – array of struct pages

RAX – small negative value, probably error code

```
shp = shm_lock(ns, sfd->id);
BUG_ON(IS_ERR(shp));
```

RAX probably result of `shm_lock()`

Crash Reference Card (64-bit)

Reg	Usage	Saved
RAX	Return value	no
RBX	Local variable	yes
RCX	Argument #4	no
RDX	Argument #3	no
RSI	Argument #2	no
RDI	Argument #1	no
RBP	(Stack base pointer)	yes
RSP	Stack pointer	yes

Reg	Usage	Saved
R8	Argument #5	no
R9	Argument #6	no
R10	Scratch registers	no
R11		no
R12	Local variables	yes
R13		yes
R14		yes
R15		yes

Virtual Memory Layout

0000000000000000 - 00007FFFFFFFFFFF	user space
DEAD0000xxxxxxxx	pointer poisons
FFFF800000000000 - FFFF87FFFFFFFFFF	hypervisor area
FFFF880000000000 - FFFFC7FFFFFFFFFF	direct mapping
FFFFC90000000000 - FFFFE8FFFFFFFFFF	vmalloc/ioremap
FFFFEA0000000000 - FFFFEAFFFFFFFFFF	vmemmap
FFFFFFFF80000000 - FFFFFFFF9FFFFFFF	kernel text+data
FFFFFFFFA0000000 - FFFFFFFFFFxxxxxx	kernel modules
FFFFFFFFFFxxxxxx - FFFFFFFFF5FFFFF	permanent fixmaps
FFFFFFFFF600000 - FFFFFFFFFFDFFFFF	vsyscalls (deprecated)

Calling Conventions

	Function	Syscall
1	RDI	RDI
2	RSI	RSI
3	RDX	RDX
4	RCX	R10
5	R8	R8
6	R9	R9
Return	RAX	RAX
RetHi	RDX	–
Syscall number:		RAX

Kernel Oops in Detail – Other Registers

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G           E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_close+0x3e/0xb0
RSP: 0018:ffff880211337d88  EFLAGS: 00010202
RAX: fffffffffffffea RBX: fffffffffffffea RCX: 0000000000000006
RDX: 0000000000000000 RSI: 000000000000005c RDI: 0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 00000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Kernel Oops in D

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_pa
md4 nls_utf8 cifs(X) nfs fscache nfsd
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted:
Platform/440BX Desktop Reference Platf
RIP: 0010:[<ffffffff811e466e>]  [<ffff
RSP: 0018:ffff880211337d88  EFLAGS: 00
RAX: ffffffffffffffea RBX: ffffffffffffffea RCX: 0
RDX: 0000000000000000 RSI: 000000000000005c RDI:                00006
RBP: ffffffff81a46920 R08: 0000000000000002 R09:                4256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R1:                 ffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Segment registers, and selected control registers:
FS – userspace thread-local storage
GS – kernel percpu base

CR0: enables protected mode, paging...
CR2: the faulting virtual address
CR3: physical address of top-level page table
CR4: a mask for enabling various extensions

DRx: x86 debug registers (only printed if not in default state)

Kernel Oops in Detail – Raw Stack Contents

```
Stack:
 ffff88016d2319e0 ffff880158fea140 00007ffce0bf0000 ffffffff81127fa4
 ffff88008cecac80 ffff880211337dd8 ffff88016d2319e0 ffffffff811280f8
 0000000000000001 ffff88014c826088 ffff88008cecac80 0000000100000028
Call Trace:
 [<ffffffff81127fa4>] remove_vma+0x24/0x80
 [<ffffffff811280f8>] exit_mmap+0xf8/0x120
 [<ffffffff810602d9>] mmput+0x49/0x100
 [<ffffffff81065192>] exit_mm+0x122/0x160
 [<ffffffff81066f39>] do_exit+0x189/0x470
 [<ffffffff8106725d>] do_group_exit+0x3d/0xb0
 [<ffffffff810672e2>] sys_exit_group+0x12/0x20
 [<ffffffff81471df2>] system_call_fastpath+0x16/0x1b
 [<00007f29408be998>] 0x7f29408be997
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8b 33 48 8d bd 98 00 00 00 e8 7d ba
ff ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44 00 00 65 48 8b 04 25 00 a6 00
00 48 8b
RIP  [<ffffffff811e466e>] shm_close+0x3e/0xb0
 RSP <ffff880211337d88>
---[ end trace 3dad41c41965c82c ]---
```

Kernel Oops in Detail – Raw Stack Contents

```
Stack:
 ffff88016d2319e0 ffff880158fea140 00007ffce0bf0000 ffffffff81127fa4
 ffff88008cecac80 ffff880211337dd8 ffff88016d2319e0 ffffffff811280f8
 0000000000000001 ffff88014c826088 ffff88008cecac80 0000000100000028
Call Trace:
 [<ffffffff81127fa4>] remove_vma+0x24/0x80
 [<ffffffff811280f8>] exit_mmap+0xf8/0x120
 [<ffffffff810602d9>] mmput+0x49/0x100
 [<ffffffff81065192>] exit_mm+0x122/0x160
 [<ffffffff81066f39>] do_exit+0x189/0x470
 [<ffffffff8106725d>] do_group_exit+0x3d/0xb0
 [<ffffffff810672e2>] sys_exit_group+0x12/0x20
 [<ffffffff81471df2>] system_call_fastpath+0x16/0x1b
 [<00007f29408be998>] 0x7f29408be997
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8b 33 48 8d bd 98 00 00 00 e8 7d ba
ff ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44 00 00 65 48 8b 04 25 00 a6 00
00 48 8b
RIP  [<ffffffff811e466e>] shm_close+0x3e/0xb0
 RSP <ffff880211337d88>
---[ end trace 3dad41c41965c82c ]---
```

Raw stack contents. Removed in 4.9. Decoded call trace more useful. Might sometimes contain values of variables that are not in registers.

Kernel Oops in Detail – Backtrace

```
Stack:
 ffff88016d2319e0 ffff880158fea140 00007ffce0bf0000 ffffffff81127fa4
 ffff88008cecac80 ffff880211337dd8 ffff88016d2319e0 ffffffff811280f8
 0000000000000001 ffff88014c826088 ffff88008cecac80 0000000100000028
Call Trace:
 [<ffffffff81127fa4>] remove_vma+0x24/0x80
 [<ffffffff811280f8>] exit_mmap+0xf8/0x120
 [<ffffffff810602d9>] mmput+0x49/0x100
 [<ffffffff81065192>] exit_mm+0x122/0x160
 [<ffffffff81066f39>] do_exit+0x189/0x470
 [<ffffffff8106725d>] do_group_exit+0x3d/0xb0
 [<ffffffff810672e2>] sys_exit_group+0x12/0x20
 [<ffffffff81471df2>] system_call_fastpath+0x16/0x1b
 [<00007f29408be998>] 0x7f29408be997
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8b 33 48 8d bd 98 00 00 00 e8 7d ba
ff ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44 00 00 65 48 8b 04 25 00 a6 00
00 48 8b
RIP  [<ffffffff811e466e>] shm_close+0x3e/0xb0
 RSP <ffff880211337d88>
---[ end trace 3dad41c41965c82c ]---
```

Kernel Oops in Detail –

```
Stack:
 ffff88016d2319e0 ffff880158fea140 00007ffc
 ffff88008cecac80 ffff880211337dd8 ffff880
 0000000000000001 ffff88014c826088 ffff88008ce
Call Trace:
 [<ffffffff81127fa4>] remove_vma+0x24/0x80
 [<ffffffff811280f8>] exit_mmap+0xf8/0x120
 [<ffffffff810602d9>] mmput+0x49/0x100
 [<ffffffff81065192>] exit_mm+0x122/0x160
 [<ffffffff81066f39>] do_exit+0x189/0x470
 [<ffffffff8106725d>] do_group_exit+0x3d/0xb0
 [<ffffffff810672e2>] sys_exit_group+0x12/0x20
 [<ffffffff81471df2>] system_call_fastpath+0x16/0x1b
 [<00007f29408be998>] 0x7f29408be997
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8b 33 48 8d bd 98 00 00 00 e8 7d ba
ff ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44 00 00 65 48 8b 04 25 00 a6 00
00 48 8b
RIP  [<ffffffff811e466e>] shm_close+0x3e/0xb0
 RSP <ffff880211337d88>
---[ end trace 3dad41c41965c82c ]---
```

Backtrace reconstructed by unwinding the stack, showing the return addresses from individual call frames.
Raw addresses were also removed in 4.9.
The downside is that multiple functions can have the same name. `gdb` will only show one symbol, `./scripts/faddr2line` is smarter

Functions from modules marked `[module]`
“?” would mean a pointer to function was found on stack but doesn't fit in the stack frame; could be leftover from previous execution, or unwinder failure.

How is stack unwinding implemented?

- “Guess”: All code lies in a designated range of addresses
  - There is a symbol table to convert addresses to individual function names
  - Every value on stack that looks like a pointer to this range can be a return address
  - Simple, but relatively slow and with many false positives (everything is marked “?”)
- Use `RBP` register when `CONFIG_FRAME_POINTER` is enabled
  - `RBP` will always point to the previous frame’s stored `RBP` value, and return address lies next to it
  - Simple pointer chasing plus collecting the return addresses
  - Fast, reliable, but maintaining `RBP` has performance impact on the kernel (5-10%)
- Using debuginfo to locate the stack frames from current `RIP` value
  - DWARF Call Frame Info (CFI) – DWARF unwinder was in mainline for a while, but then removed (slow, sometimes unreliable, requires assembler annotations)
  - ORC – uses custom unwinder data generated by `objtool` during build – since 4.14, also for reliable stack traces needed by some of the live patching consistency models
  - Relatively fast, reliable, no performance impact on the kernel (2-4 MB memory overhead)

Kernel Oops in Detail – Backtrace

```
Stack:
 ffff88016d2319e0 ffff880158fea140 00007ffce0bf0000 ffffffff81127fa4
 ffff88008cecac80 ffff880211337dd8 ffff88016d2319e0 ffffffff811280f8
 0000000000000001 ffff88014c826088 ffff88008cecac80 0000000100000028
Call Trace:
 [<ffffffff81127fa4>] remove_vma+0x24/0x80
 [<ffffffff811280f8>] exit_mmap+0xf8/0x120
 [<ffffffff810602d9>] mmput+0x49/0x100
 [<ffffffff81065192>] exit_mm+0x122/0x160
 [<ffffffff81066f39>] do_exit+0x189/0x470
 [<ffffffff8106725d>] do_group_exit+0x3d/0xb0
 [<ffffffff810672e2>] sys_exit_group+0x12/0x20
 [<ffffffff81471df2>] system_call_fastpath+0x16/0x1b
 [<00007f29408be998>] 0x7f29408be997
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8b 33 48 8d bd 98 00 00 00 e8 7d ba
ff ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44 00 00 65 48 8b 04 25 00 a6 00
00 48 8b
RIP  [<ffffffff811e466e>] shm_close+0x3e/0xb0
 RSP <ffff880211337d88>
---[ end trace 3dad41c41965c82c ]---
```

Kernel Oops in Detail – Backtrace

```
Stack:
 ffff88016d2319e0 ffff880158fea140 00007ffce0bf0000 ffffffff81127fa4
 ffff88008cecac80 ffff880211337dd8 ffff88016d2
 0000000000000001 ffff88014c826088 ffff88008ce
Call Trace:
 [<ffffffff81127fa4>] remove_vma+0x24/0x80
 [<ffffffff811280f8>] exit_mmap+0xf8/0x120
 [<ffffffff810602d9>] mmput+0x49/0x100
 [<ffffffff81065192>] exit_mm+0x122/0x160
 [<ffffffff81066f39>] do_exit+0x189/0x470
 [<ffffffff8106725d>] do_group_exit+0x3d/0xb0
 [<ffffffff810672e2>] sys_exit_group+0x12/0x20
 [<ffffffff81471df2>] system_call_fastpath+0x16/0x1b
 [<00007f29408be998>] 0x7f29408be997
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8b 33 48 8d bd 98 00 00 00 e8 7d ba
ff ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44 00 00 65 48 8b 04 25 00 a6 00
00 48 8b
RIP  [<ffffffff811e466e>] shm_close+0x3e/0xb0
 RSP <ffff880211337d88>
---[ end trace 3dad41c41965c82c ]---
```

Context matters! `shm_close()` is unlikely to be buggy by itself.

Here, task was exiting and cleaning up its memory layout – a list of vma's.
(see `/proc/pid/maps` for an example)
A vma was backed by shared memory segment, unregistering its usage led to BUG.

Kernel Oops in Detail – Code Listing

```
Stack:
 ffff88016d2319e0 ffff880158fea140 00007ffce0bf0000 ffffffff81127fa4
 ffff88008cecac80 ffff880211337dd8 ffff88016d2319e0 ffffffff811280f8
 0000000000000001 ffff88014c826088 ffff88008cecac80 0000000100000028
Call Trace:
 [<ffffffff81127fa4>] remove_vma+0x24/0x80
 [<ffffffff811280f8>] exit_mmap+0xf8/0x120
 [<ffffffff810602d9>] mmput+0x49/0x100
 [<ffffffff81065192>] exit_mm+0x122/0x160
 [<ffffffff81066f39>] do_exit+0x189/0x470
 [<ffffffff8106725d>] do_group_exit+0x3d/0xb0
 [<ffffffff810672e2>] sys_exit_group+0x12/0x20
 [<ffffffff81471df2>] system_call_fastpath+0x16/0x1b
 [<00007f29408be998>] 0x7f29408be997
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8b 33 48 8d bd 98 00 00 00 e8 7d ba
ff ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44 00 00 65 48 8b 04 25 00 a6 00
00 48 8b
RIP  [<ffffffff811e466e>] shm_close+0x3e/0xb0
 RSP <ffff880211337d88>
---[ end trace 3dad41c41965c82c ]---
```

Kernel Oops in Detail – C

```
Stack:
 ffff88016d2319e0 ffff880158fea140 00007ffce0bf0
 ffff88008cecac80 ffff880211337dd8 ffff88016d231
 0000000000000001 ffff88014c826088 ffff88008ceca
Call Trace:
 [<ffffffff81127fa4>] remove_vma+0x24/0x80
 [<ffffffff811280f8>] exit_mmap+0xf8/0x120
 [<ffffffff810602d9>] mmput+0x49/0x100
 [<ffffffff81065192>] exit_mm+0x122/0x160
 [<ffffffff81066f39>] do_exit+0x189/0x470
 [<ffffffff8106725d>] do_group_exit+0x3d/0xb0
 [<ffffffff810672e2>] sys_exit_group+0x12/0x20
 [<ffffffff81471df2>] system_call_fastpath+0x16/0x1b
 [<00007f29408be998>] 0x7f29408be997
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8b 33 48 8d bd 98 00 00 00 e8 7d ba
ff ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44 00 00 65 48 8b 04 25 00 a6 00
00 48 8b
RIP  [<ffffffff811e466e>] shm_close+0x3e/0xb0
 RSP <ffff880211337d88>
---[ end trace 3dad41c41965c82c ]---
```

A bunch of instructions around the `RIP`.
`RIP` position denoted by `< >`

Recall that `0F 0B` is opcode for `UD2`

We can disassemble the code listing by piping the oops into `./scripts/decodecode` in the kernel source tree.

Kernel Oops - `./scripts/decodecode` output

```
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8b 33 48 8d bd 98 00 00 00 e8 7d ba ff
ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44 00 00 65 48 8b 04 25 00 a6 00 00 48 8b
All code
========
   0:   8b 6b 08                mov    0x8(%rbx),%ebp
   3:   4c 8d a5 a0 00 00 00    lea    0xa0(%rbp),%r12
   a:   4c 89 e7                mov    %r12,%rdi
   d:   e8 0b 49 28 00          callq  0x28491d
  12:   8b 33                   mov    (%rbx),%esi
  14:   48 8d bd 98 00 00 00    lea    0x98(%rbp),%rdi
  1b:   e8 7d ba ff ff          callq  0xffffffffffffba9d
  20:   48 3d 00 f0 ff ff       cmp    $0xfffffffffffff000,%rax
  26:   48 89 c3                mov    %rax,%rbx
  29:   76 0a                   jbe    0x35
  2b:*  0f 0b                   ud2              <-- trapping instruction
  2d:   eb fe                   jmp    0x2d
  2f:   66 0f 1f 44 00 00       nopw   0x0(%rax,%rax,1)
  35:   65 48 8b 04 25 00 a6    mov    %gs:0xa600,%rax
  3c:   00 00
  3e:   48                      rex.W
  3f:   8b                      .byte 0x8b
```

Kernel Oops - ./scripts/decodecode output

```
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8
ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44
All code
========
   0:   8b 6b 08                mov    0x8(%rbx),%ebp
   3:   4c 8d a5 a0 00 00 00    lea    0xa0(%rbp),%r12
   a:   4c 89 e7                mov    %r12,%rdi
   d:   e8 0b 49 28 00          callq  0x28491d
  12:   8b 33                   mov    (%rbx),%esi
  14:   48 8d bd 98 00 00 00    lea    0x98(%rbp),%rdi
  1b:   e8 7d ba ff ff          callq  0xffffffffffffba9d
  20:   48 3d 00 f0 ff ff       cmp    $0xfffffffffffff000,%r
  26:   48 89 c3                mov    %rax,%rbx
  29:   76 0a                   jbe    0x35
  2b:*  0f 0b                   ud2              <-- trapping instruction
  2d:   eb fe                   jmp    0x2d
  2f:   66 0f 1f 44 00 00       nopw   0x0(%rax,%rax,1)
  35:   65 48 8b 04 25 00 a6    mov    %gs:0xa600,%rax
  3c:   00 00
  3e:   48                      rex.W
  3f:   8b                      .byte 0x8b
```

```
struct shmid_kernel *shp;
...
shp = shm_lock(ns, sfd->id);
BUG_ON(IS_ERR(shp));
```

`rdi` contained value of `ns`
`rsi` contained value of `sfd->id`
both might be lost now

Kernel Oops - ./scripts/decodecode output

```
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8
ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44
All code
========
   0:   8b 6b 08                mov    0x8(%rbx),%ebp
   3:   4c 8d a5 a0 00 00 00    lea    0xa0(%rbp),%r12
   a:   4c 89 e7                mov    %r12,%rdi
   d:   e8 0b 49 28 00          callq  0x28491d
  12:   8b 33                   mov    (%rbx),%esi
  14:   48 8d bd 98 00 00 00    lea    0x98(%rbp),%rdi
  1b:   e8 7d ba ff ff          callq  0xffffffffffffba9d
  20:   48 3d 00 f0 ff ff       cmp    $0xfffffffffffff000,%rax
  26:   48 89 c3                mov    %rax,%rbx
  29:   76 0a                   jbe    0x35
  2b:*  0f 0b                   ud2            <-- trapping instruction
  2d:   eb fe                   jmp    0x2d
  2f:   66 0f 1f 44 00 00       nopw   0x0(%rax,%rax,1)
  35:   65 48 8b 04 25 00 a6    mov    %gs:0xa600,%rax
  3c:   00 00
  3e:   48                      rex.W
  3f:   8b                      .byte 0x8b
```

```
struct shmid_kernel *shp;
...
shp = shm_lock(ns, sfd->id);
BUG_ON(IS_ERR(shp));
```

rax contains value of shp current, not lost

Kernel Oops - ./scripts/decodecode output

```
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8
ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44
All code
========
   0:   8b 6b 08                mov    0x8(%rbx),%ebp
   3:   4c 8d a5 a0 00 00 00    lea    0xa0(%rbp),%r12
   a:   4c 89 e7                mov    %r12,%rdi
   d:   e8 0b 49 28 00          callq  0x28491d
  12:   8b 33                   mov    (%rbx),%esi
  14:   48 8d bd 98 00 00 00    lea    0x98(%rbp),%rdi
  1b:   e8 7d ba ff ff          callq  0xffffffffffffba9d
  20:   48 3d 00 f0 ff ff       cmp    $0xfffffffffffff000,%rax
  26:   48 89 c3                mov    %rax,%rbx
  29:   76 0a                   jbe    0x35
  2b:*  0f 0b                   ud2            <-- trapping instruction
  2d:   eb fe                   jmp    0x2d
  2f:   66 0f 1f 44 00 00       nopw   0x0(%rax,%rax,1)
  35:   65 48 8b 04 25 00 a6    mov    %gs:0xa600,%rax
  3c:   00 00
  3e:   48                      rex.W
  3f:   8b                      .byte 0x8b
```

```
struct shmid_kernel *shp;
...
shp = shm_lock(ns, sfd->id);
BUG_ON(IS_ERR(shp));
```

Kernel Oops – Revisiting Register Values

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet st ide_cd_mod ide_core bridge stp llc joydev ext2 des_generic ecb
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd nfs_acl auth_rpcgss sunrpc autofs4 binfmt_misc mperf vsock(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G           E X 3.0.101-84-default #1 VMware, Inc. VMware Virtual
Platform/440BX Desktop Reference Platform
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff811e466e>] shm_close+0x3e/0xb0
RSP: 0018:ffff880211337d88  EFLAGS: 00010202
RAX: fffffffffffffea RBX: fffffffffffffea RCX: 0000000000000006
RDX: 0000000000000000 RSI: 000000000000005c RDI: 0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

Kernel Oops – Revisiting Register Values

```
------------[ cut here ]------------
kernel BUG at /usr/src/packages/BUILD/kernel-default-3.0.101/linux-3.0/ipc/shm.c:205!
invalid opcode: 0000 [#1] SMP
CPU 1
Modules linked in: lp parport_pc af_packet                                    eric ecb
md4 nls_utf8 cifs(X) nfs fscache nfsd lockd                                   ck(EX)
<...>
[last unloaded: ppa]
Supported: Yes, External

Pid: 26341, comm: <redacted> Tainted: G                                       ual
Platform/440BX Desktop Reference Plat
RIP: 0010:[<ffffffff811e466e>]  [<ffffffff8
RSP: 0018:ffff880211337d88  EFLAGS: 0001020
RAX: ffffffffffffffea RBX: ffffffffffffffea RCX: 0000000000000006
RDX: 0000000000000000 RSI: 000000000000005c RDI: 0000000000000006
RBP: ffffffff81a46920 R08: 0000000000000002 R09: ffff8804256a84d0
R10: ffff880192cecc00 R11: ffffffff81215a80 R12: ffffffff81a469c0
R13: ffff88008cecac80 R14: ffff880423c33740 R15: 0000000000000001
FS:  00007f2945893760(0000) GS:ffff88043fd00000(0000) knlGS:0000000000000000
CS:  0010 DS: 0000 ES: 0000 CR0: 000000008005003b
CR2: 00007f6941216960 CR3: 00000003f3bea000 CR4: 00000000001407e0
DR0: 0000000000000000 DR1: 0000000000000000 DR2: 0000000000000000
DR3: 0000000000000000 DR6: 00000000ffff0ff0 DR7: 0000000000000400
Process <redacted> (pid: 26341, threadinfo ffff880211336000, task ffff8801b49c8040)
```

RAX (and RBX) is the error value
`-22 == -EINVAL`
RDI is a `ns` pointer? definitely not
RSI is `shm->id`? could be?
RBP, R11, R12 – kernel code/static data
R09, R10, R13, R14 – kernel data

Kernel Oops in Detail – End of the Oops

```
Stack:
 ffff88016d2319e0 ffff880158fea140 00007ffce0bf0000 ffffffff81127fa4
 ffff88008cecac80 ffff880211337dd8 ffff88016d2319e0 ffffffff811280f8
 0000000000000001 ffff88014c826088 ffff88008cecac80 0000000100000028
Call Trace:
 [<ffffffff81127fa4>] remove_vma+0x24/0x80
 [<ffffffff811280f8>] exit_mmap+0xf8/0x120
 [<ffffffff810602d9>] mmput+0x49/0x100
 [<ffffffff81065192>] exit_mm+0x122/0x160
 [<ffffffff81066f39>] do_exit+0x189/0x470
 [<ffffffff8106725d>] do_group_exit+0x3d/0xb0
 [<ffffffff810672e2>] sys_exit_group+0x12/0x20
 [<ffffffff81471df2>] system_call_fastpath+0x16/0x1b
 [<00007f29408be998>] 0x7f29408be997
Code: 8b 6b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8b 33 48 8d bd 98 00 00 00 e8 7d ba
ff ff 48 3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44 00 00 65 48 8b 04 25 00 a6 00
00 48 8b
RIP  [<ffffffff811e466e>] shm_close+0x3e/0xb0
 RSP <ffff880211337d88>
---[ end trace 3dad41c41965c82c ]---
```

Kernel Oops in Detail – End of the Oops

```
Stack:
 ffff88016d2319e0 ffff880158fea140 00007ffce0bf0000 ffffffff81127fa4
 ffff88008cecac80 ffff880211337dd8 ffff88016d2319e0 ffffffff811280f8
 0000000000000001 ffff88014c826088 ffff88008cecac80 0000000100000028
Call Trace:
 [<ffffffff81127fa4>] remove_vma+0x24/0x80
 [<ffffffff811280f8>] exit_mmap+0xf8/0x120
 [<ffffffff810602d9>] mmput+0x49/0x100
                                    60
                                    70
                                    d/0xb0
                                    12/0x20
 [<f                 71df2>] system_call_fastpath+0x16/0x1b
 [<0                 408be998>] 0x7f29408be997
Code      0b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b 49 28 00 8b 33 48 8d bd 98 00 00 00 e8 7d ba
ff f      3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb fe 66 0f 1f 44 00 00 65 48 8b 04 25 00 a6 00
00 4      8b
RIP  [<ffffffff811e466e>] shm_close+0x3e/0xb0
 RSP <ffff880211337d88>
---[ end trace 3dad41c41965c82c ]---
```

RIP + RSP again in case the first ones scrolled away.

Kernel Oops in Detail – End of the Oops

```
Stack:
 ffff88016d2319e0 ffff880158fea140 00007ffce0bf0000 ffffffff81127fa4
 ffff88008cecac80 ffff880211337dd8 ffff88016d2319e0 ffffffff811280f8
 0000000000000001 ffff88014c826088 ffff88008cecac80 0000000100000028
Call Trace:
 [<ffffffff81127fa4>] remove_vma+0x24/0x80
 [<ffffffff811280f8>] exit_mmap+0xf8/0x120
 [<ffffffff810602d9>] mmput+0x49/0x100
                                    60
                                    70
                                    d/0xb0
                                    12/0x20
 [<f                71df2>] system_call_fastpath+0x16/0x
 [<0                408be998>] 0x7f29408be997
Code                0b 08 4c 8d a5 a0 00 00 00 4c 89 e7 e8 0b
ff f                3d 00 f0 ff ff 48 89 c3 76 0a <0f> 0b eb
00 4                8b
RIP  [<ffffffff811e466e>] shm_close+0x3e/0xb0
 RSP <ffff880211337d88>
---[ end trace 3dad41c41965c82c ]---
```

RIP + RSP again in case the first ones scrolled away.

First `oops_id` during uptime is random, then increased monotonically.

The intention is to recognize duplicate reports by sites such as `www.kerneloops.org`

What else can produce oops/panic?

- `BUG_ON()` as seen in the example – hard assertion
  - `WARN_ON[_ONCE]()` - soft assertion, unless `panic_on_warn` is enabled
- Memory paging related faults – check `CR2` register!
  - BUG: unable to handle kernel paging request
  - ... handle NULL pointer dereference (when `bad_addr < PAGE_SIZE`) – a structure's field might be accessed with non-zero offset
  - Corrupted page table (reserved bits set, etc.)
  - Kernel trying to execute `NX`-protected page
  - Kernel trying to execute/access userspace page (Intel SMEP/SMAP feature)
  - Failed bounds check in kernel mode (Intel MPX feature)
  - Kernel stack overflow
  - General protection fault, unhandled double fault
- FPU, SIMD exceptions from kernel mode

What else can produce oops/panic?

- Soft lockup
  - CPU spent over 20s in kernel without reaching a schedule point (in non-preemptive kernels)
  - A warning, unless related config or bootparam `softlockup_panic` enabled
    - Soft lockup can often recover, so not good idea to enable that in production, especially in a guest VM
- Hard lockup
  - CPU spent over 10s with disabled interrupts
  - Panic when `hardlockup_panic` is enabled
- Detection of both combines several generic mechanisms (for each CPU)
  - High priority kernel watchdog thread updates the soft lockup timestamp
  - High resolution timer (hrtimer) is configured to deliver periodic interrupts, the handler resets the hard lockup flag and wakes up the watchdog thread
  - It also reports soft lockup when the watchdog thread did not touch the soft lockup timestamp
  - Non-maskable interrupt (NMI) perf event reports hard lockup if hrtimer interrupts were not processed and hard lockup flag remains set

What else can produce oops/panic?

- Hung task check
  - `INFO: task … blocked for more than 120 seconds`
  - khungtaskd periodically processes tasks in uninterruptible sleep and checks if their switch count changed
- RCU stall detector
  - Detects when RCU grace period is too long (21s)
    - CPU looping in RCU critical section or disabled interrupts, preemption or bottom halves, no scheduling points in non-preempt kernels
    - RT task preempting non-RT task in RCU critical section
- Several other debugging config options (later)

Kernel Debugging – General Approach

- First, understand the immediate cause
  - Typically some unexpected/wrong value somewhere in memory
    - NULL pointer access, because certain structure's field was NULL/bogus
    - Page table corruption, SLAB corruption, strange lock value…
  - Here we know `shm_lock()` returned `-EINVAL`, but we don't know yet why
- Second, try to determine what could cause the value
  - Single bit flip? RAM error (yes, they do happen without ECC)
    - Often manifests as multiple different bugs from the same machine
  - Wrong use by upper layers? For example, SLAB corruption is almost never a bug in SLAB code, but e.g. result of double-free of a kernel object allocated from SLAB
  - Logical error in code? Race condition? Stray write?
- Note: no general and complete recipe
  - Mostly from own experience, or learn from others' analyses
  - Knowing the subsystem helps, still lots of staring into source code of the exact version

Why does shm_lock() return -EINVAL?

```
/*
 * shm_lock_(check_) routines are called in the paths where the rw_mutex
 * is not necessarily held.
 */
static inline struct shmid_kernel *shm_lock(struct ipc_namespace *ns, int id)
{
        struct kern_ipc_perm *ipcp = ipc_lock(&shm_ids(ns), id);

        if (IS_ERR(ipcp))
                return (struct shmid_kernel *)ipcp;

        return container_of(ipcp, struct shmid_kernel, shm_perm);
}
```

Why does `ipc_lock()` return `-EINVAL`?

```
/**
 * ipc_lock - Lock an ipc structure without rw_mutex held
 * @ids: IPC identifier set
 * @id: ipc id to look for
 *
 * Look for an id in the ipc ids idr and lock the associated ipc object.
 *
 * The ipc object is locked on exit.
 */

struct kern_ipc_perm *ipc_lock(struct ipc_ids *ids, int id)
{
        struct kern_ipc_perm *out;
        int lid = ipcid_to_idx(id);

        rcu_read_lock();
        out = idr_find(&ids->ipcs_idr, lid);
        if (out == NULL) {
                rcu_read_unlock();
                return ERR_PTR(-EINVAL);
        }
```

Why does `ipc_lock()` return `-EINVAL`?

```
        spin_lock(&out->lock);

        /* ipc_rmid() may have already freed the ID while ipc_lock
         * was spinning: here verify that the structure is still valid
         */
        if (out->deleted) {
                spin_unlock(&out->lock);
                rcu_read_unlock();
                return ERR_PTR(-EINVAL);
        }

        return out;
}
```

- Either `idr_find()` didn't find the `shmid`, or it was already deleted
- The oops report can't help anymore, need to inspect memory – **crash dump**

Obtaining crash dumps

- Several historical methods
  - diskdump, netdump, LKCD project…
  - Not very reliable (some parts of crashed kernel must still work) nor universal, needs dedicated server on same network etc.
  - Out of tree patches, included in old enterprise distros
- Current solution: kexec-based kdump
  - Crash kernel loaded into a boot-reserved memory area
    - Size specified as boot parameter, no universally good value, depends on hardware
  - On panic, kexec switches to the crash kernel without reboot
  - Memory of crashed kernel available as `/proc/vmcore`
  - Kdump utility can save to disk, network, filter pages...
    - `kexec (8), kdump (5), makedumpfile (8)`
- In VM guest environment, hypervisor dumps also possible

Analyzing kernel crash dumps

- gdb can be used to open ELF based dumps
  - But those are not easily compressed and filtered
- `gdb` has no understanding of kernel internals or virtual/physical mapping
  - There are some Python scripts under `scripts/gdb` in the Linux source
  - Can obtain per-cpu variables, dmesg, modules, tasks
- A better tool for Linux kernel crash dumps – `crash`
  - Created by David Anderson from Red Hat
  - Understands all dump formats – kdump (compressed), netdump, diskdump, xendump, KVM dump, s390, LKCD, ...
  - Understands some kernel internals: memory mapping, tasks, SLAB/SLUB objects, …
  - Can e.g. walk linked lists, pipe the output for further postprocessing
  - Extensible with Eppic – a C intepreter tailored to work with C structures stored in a dump, or Python (pykdump)

crash – disadvantages

- Uses gdb internally in a suboptimal way
  - Old version, embedded in the tool itself
  - Mostly by invoking some gdb command and postprocessing its output
- Backtraces are not using full potential of gdb
  - Not using debuginfo to print values of function parameters, local variables...
- Machine running crash must be of the same architecture as the machine that created the kernel dump
- pykdump works by executing crash commands and parsing their output

Invoking crash

- On core dump
  - `crash vmlinux.gz vmlinux.debug vmcore`
- On live system
  - `crash vmlinux.gz vmlinux.debug`

- Options
  - `-s` silent, output not paged to less
  - `-i file` execute commands from file
  - `--mod dir` search for module debuginfo in dir
  - `--minimal` only basic commands (for too broken dumps)

Invoking crash – welcome screen

```
      KERNEL: vmlinux.gz
   DEBUGINFO: vmlinux.debug
    DUMPFILE: vmcore
        CPUS: 8
        DATE: Thu Apr 10 16:07:34 2014
      UPTIME: 7 days, 03:17:51
LOAD AVERAGE: 0.01, 0.02, 0.05
       TASKS: 161
    NODENAME: lpapp114
     RELEASE: 3.0.101-0.7.17-default
     VERSION: #1 SMP Tue Feb 4 13:24:49 UTC 2014 (90aac76)
     MACHINE: x86_64  (2399 Mhz)
      MEMORY: 64 GB
       PANIC: "[615702.371868] kernel BUG at /usr/src/packages/BUILD/kernel-
default-3.0.101/linux-3.0/mm/slab.c:539!"
         PID: 58
     COMMAND: "kworker/6:1"
        TASK: ffff88080e03e680  [THREAD_INFO: ffff88080e040000]
         CPU: 6
       STATE: TASK_RUNNING (PANIC)
```

Invoking crash – help screen

```
crash> help

*               extend          log             rd              task
alias           files           mach            repeat          timer
ascii           foreach         mod             runq            tree
bpf             fuser           mount           search          union
bt              gdb             net             set             vm
btop            help            p               sig             vtop
dev             ipcs            ps              struct          waitq
dis             irq             pte             swap            whatis
eval            kmem            ptob            sym             wr
exit            list            ptov            sys             q
```

Basic crash commands

- `dmesg (log)` – same as the shell command
- `mod -t [mod]` – module taint flags
- `ps` – list processes (kernel/user), count by state, sort by last scheduled time…
- `dis [-l] [-r] [addr|sym]` – disassemble code
- `bt [task|pid] [-a]` – show backtrace(s)
  - `-l` – include file/line transition
  - `-FF` – translate addresses to symbols/slab objects

- Full input/output redirection/piping support

Basic crash commands

- `struct [-o] <name> [addr]` – print structure layout, offsets, values at address
- `rd [addr|symbol] [count]` – read/format raw memory contents
  - `wr` – write memory (for live systems)
- `search [-m mask] [value|expr|sym|string]`
  - search memory for given value (with optional mask)
- `kmem [-s] addr` – show info about the address
  - Is it a symbol? Slab object? Free page? Stack of a task?
- `vtop/ptov, pte` – address translation commands

crash - More complex inspection

- `list <addr>` – traverse objects via embedded list_head, print them out (as struct command does)
- `tree <root>` – traverse red-black or radix tree
- `foreach <command>` – apply one of a subset of commands on each task
- `dev, files, mount, ipcs, irq, net, swap, timer, runq, waitq`...
- `fuser [path|inode]` – who has a file open?

Using crash to solve our bug

- Recall, with the Oops and sources, we determined:
  - `shm_lock()` returned `-EINVAL` unexpectedly
  - Because `ipc_lock()` returned `-EINVAL` unexpectedly
  - Because `idr_find(shmid)` didn't find the `shmid`, or it was already deleted

- With crash, we want to find:
  - What was the `shmid` value?
    - Where was it obtained from?
  - Was it not found at all or was the object deleted?
    - Why?

crash – shm_close() disassembly

```
crash> dis -lr ffffffff811e466e
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 196
0xffffffff811e4630 <shm_close>:         push   %r12
0xffffffff811e4632 <shm_close+2>:       push   %rbp
0xffffffff811e4633 <shm_close+3>:       push   %rbx
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 198
0xffffffff811e4634 <shm_close+4>:       mov    0x98(%rdi),%rax
0xffffffff811e463b <shm_close+11>:      mov    0xa0(%rax),%rbx
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 200
0xffffffff811e4642 <shm_close+18>:      mov    0x8(%rbx),%rbp
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 202
0xffffffff811e4646 <shm_close+22>:      lea    0xa0(%rbp),%r12
0xffffffff811e464d <shm_close+29>:      mov    %r12,%rdi
0xffffffff811e4650 <shm_close+32>:      callq  0xffffffff81468f60 <down_write>
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 125
0xffffffff811e4655 <shm_close+37>:      mov    (%rbx),%esi
0xffffffff811e4657 <shm_close+39>:      lea    0x98(%rbp),%rdi
0xffffffff811e465e <shm_close+46>:      callq  0xffffffff811e00e0 <ipc_lock>
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 127
0xffffffff811e4663 <shm_close+51>:      cmp    $0xfffffffffffff000,%rax
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 125
0xffffffff811e4669 <shm_close+57>:      mov    %rax,%rbx
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 127
0xffffffff811e466c <shm_close+60>:      jbe    0xffffffff811e4678 <shm_close+72>
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 205
0xffffffff811e466e <shm_close+62>:      ud2
```

crash – shm_close() disassembly

```
crash> dis -lr ffffffff811e466e
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 1
0xffffffff811e4630 <shm_close>:         push   %r12
0xffffffff811e4632 <shm_close+2>:       push   %rbp
0xffffffff811e4633 <shm_close+3>:       push   %rbx
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 1
0xffffffff811e4634 <shm_close+4>:       mov    0x98(%rdi),%rax
0xffffffff811e463b <shm_close+11>:      mov    0xa0(%rax),%rbx
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 200
0xffffffff811e4642 <shm_close+18>:      mov    0x8(%rbx),%rbp
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 202
0xffffffff811e4646 <shm_close+22>:      lea    0xa0(%rbp),%r12
0xffffffff811e464d <shm_close+29>:      mov    %r12,%rdi
0xffffffff811e4650 <shm_close+32>:      callq  0xffffffff81468f60 <down_write>
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 125
0xffffffff811e4655 <shm_close+37>:      mov    (%rbx),%esi
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/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 127
0xffffffff811e466c <shm_close+60>:      jbe    0xffffffff811e4678 <shm_close+72>
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 205
0xffffffff811e466e <shm_close+62>:      ud2
```

Our goal here is to find whether some register contained `shmid` or a pointer to some structure that contains it (or pointer to a structure that has a pointer to another structure...)

crash – shm_close() disas

```
shm_close(struct vm_area_struct *vma)

vma pointer is in rdi
```

```
crash> dis -lr ffffffff811e466e
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 196
0xffffffff811e4630 <shm_close>:         push   %r12
0xffffffff811e4632 <shm_close+2>:       push   %rbp
0xffffffff811e4633 <shm_close+3>:       push   %rbx
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 198
0xffffffff811e4634 <shm_close+4>:       mov    0x98(%rdi),%rax
0xffffffff811e463b <shm_close+11>:      mov    0xa0(%rax),%rbx
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 200
0xffffffff811e4642 <shm_close+18>:      mov    0x8(%rbx),%rbp
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 202
0xffffffff811e4646 <shm_close+22>:      lea    0xa0(%rbp),%r12
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0xffffffff811e4655 <shm_close+37>:      mov    (%rbx),%esi
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0xffffffff811e4669 <shm_close+57>:      mov    %rax,%rbx
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 127
0xffffffff811e466c <shm_close+60>:      jbe    0xffffffff811e4678 <shm_close+72>
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 205
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crash – shm_close() disas

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/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 198
0xffffffff811e4634 <shm_close+4>:       mov    0x98(%rdi),%rax
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/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 200
0xffffffff811e4642 <shm_close+18>:      mov    0x8(%rbx),%rbp
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 202
0xffffffff811e4646 <shm_close+22>:      lea    0xa0(%rbp),%r12
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/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 127
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/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 205
0xffffffff811e466e <shm_close+62>:      ud2
```

```
shm_close(struct vm_area_struct *vma)
```

vma pointer is in `rdi`

```
struct file * file = vma->vm_file;
```

`file` pointer is in `rax`

crash – shm_close() disas

```
crash> dis -lr ffffffff811e466e
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 196
0xffffffff811e4630 <shm_close>:         push   %r12
0xffffffff811e4632 <shm_close+2>:       push   %rbp
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/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 198
0xffffffff811e4634 <shm_close+4>:       mov    0x98(%rdi),%rax
0xffffffff811e463b <shm_close+11>:      mov    0xa0(%rax),%rbx
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0xffffffff811e4642 <shm_close+18>:      mov    0x8(%rbx),%rbp
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0xffffffff811e4646 <shm_close+22>:      lea    0xa0(%rbp),%r12
0xffffffff811e464d <shm_close+29>:      mov    %r12,%rdi
0xffffffff811e4650 <shm_close+32>:      callq  0xffffffff81468f60 <down_write>
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0xffffffff811e4669 <shm_close+57>:      mov    %rax,%rbx
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/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 205
0xffffffff811e466e <shm_close+62>:      ud2
```

```
shm_close(struct vm_area_struct *vma)
```

vma pointer is in `rdi`

```
struct file * file = vma->vm_file;
```

`file` pointer is in `rax`

```
struct shm_file_data *sfd =
                    shm_file_data(file);
```

`sfd` pointer is in `rbx`

crash – shm_close() disas

```
crash> dis -lr ffffffff811e466e
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 196
0xffffffff811e4630 <shm_close>:         push   %r12
0xffffffff811e4632 <shm_close+2>:       push   %rbp
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0xffffffff811e463b <shm_close+11>:      mov    0xa0(%rax),%rbx
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 200
0xffffffff811e4642 <shm_close+18>:      mov    0x8(%rbx),%rbp
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 202
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0xffffffff811e464d <shm_close+29>:      mov    %r12,%rdi
0xffffffff811e4650 <shm_close+32>:      callq  0xffffffff81468f
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 125
0xffffffff811e4655 <shm_close+37>:      mov    (%rbx),%esi
0xffffffff811e4657 <shm_close+39>:      lea    0x98(%rbp),%rdi
0xffffffff811e465e <shm_close+46>:      callq  0xffffffff811e00e0
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 127
0xffffffff811e4663 <shm_close+51>:      cmp    $0xfffffffffffff000,%rax
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/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 127
0xffffffff811e466c <shm_close+60>:      jbe    0xffffffff811e4678 <shm_close+72>
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 205
0xffffffff811e466e <shm_close+62>:      ud2
```

`shm_close(struct vm_area_struct *vma)`

~~vma pointer is in rdi~~

`struct file * file = vma->vm_file;`

`file` pointer is in `rax (?)`

`struct shm_file_data *sfd = shm_file_data(file);`

`sfd` pointer is in `rbx`

`struct ipc_namespace *ns = sfd->ns;`
`down_write(&shm_ids(ns).rw_mutex);`
we just lost vma that was in `rdi`
we might have lost `*file` in `rax`

crash – shm_close() disas

```
crash> dis -lr ffffffff811e466e
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 196
0xffffffff811e4630 <shm_close>:         push   %r12
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/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 200
0xffffffff811e4642 <shm_close+18>:      mov    0x8(%rbx),%rbp
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 202
0xffffffff811e4646 <shm_close+22>:      lea    0xa0(%rbp),%r12
0xffffffff811e464d <shm_close+29>:      mov    %r12,%rdi
0xffffffff811e4650 <shm_close+32>:      callq  0xffffffff81468f60 <down
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 125
0xffffffff811e4655 <shm_close+37>:      mov    (%rbx),%esi
0xffffffff811e4657 <shm_close+39>:      lea    0x98(%rbp),%rdi
0xffffffff811e465e <shm_close+46>:      callq  0xffffffff811e00e0 <ipc_
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 127
0xffffffff811e4663 <shm_close+51>:      cmp    $0xfffffffffffff000,%rax
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 125
0xffffffff811e4669 <shm_close+57>:      mov    %rax,%rbx
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 127
0xffffffff811e466c <shm_close+60>:      jbe    0xffffffff811e4678 <shm_close+72>
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 205
0xffffffff811e466e <shm_close+62>:      ud2
```

```
shm_close(struct vm_area_struct *vma)

~~vma pointer is in rdi~~
```

```
struct file * file = vma->vm_file;

~~file pointer is in rax~~
```

```
struct shm_file_data *sfd =
                    shm_file_data(file);
```
sfd pointer is in rbx

```
shp = shm_lock(ns, sfd->id);
```
shm_lock(ns, id) is inlined and does:
```
struct kern_ipc_perm *ipcp =
    ipc_lock(&shm_ids(ns), id);
```
rsi has sfd->id which we want to know
rdi has &shm_ids(ns)
we definitely lost rax now

crash – shm_close() disas

```
crash> dis -lr ffffffff811e466e
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 196
0xffffffff811e4630 <shm_close>:         push   %r12
0xffffffff811e4632 <shm_close+2>:       push   %rbp
0xffffffff811e4633 <shm_close+3>:       push   %rbx
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 198
0xffffffff811e4634 <shm_close+4>:       mov    0x98(%rdi),%rax
0xffffffff811e463b <shm_close+11>:      mov    0xa0(%rax),%rbx
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 200
0xffffffff811e4642 <shm_close+18>:      mov    0x8(%rbx),%rbp
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 202
0xffffffff811e4646 <shm_close+22>:      lea    0xa0(%rbp),%r12
0xffffffff811e464d <shm_close+29>:      mov    %r12,%rdi
0xffffffff811e4650 <shm_close+32>:      callq  0xffffffff81468f60 <down_write>
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 125
0xffffffff811e4655 <shm_close+37>:      mov    (%rbx),%esi
0xffffffff811e4657 <shm_close+39>:      lea    0x98(%rbp),%rdi
0xffffffff811e465e <shm_close+46>:      callq  0xffffffff811e00e0 <ipc_lock>
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 127
0xffffffff811e4663 <shm_close+51>:      cmp    $0xfffffffffffff000,%rax
/usr/src/debug/kernel-default-3.0.101/linux-3.0/ipc/shm.c: 125
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0xffffffff811e466e <shm_close+62>:      ud2
```

```
shm_close(struct vm_area_struct *vma)

~~vma pointer is in rdi~~
```

```
struct file * file = vma->vm_file;

~~file pointer is in rax~~
```

```
struct shm_file_data *sfd =
                    shm_file_data(file);
~~sfd pointer is in rbx~~
```

we lost `sfd` in `rbx` :(

Getting the vma pointer

- We lost the `vma` pointer in `shm_close()` and all intermediate pointers leading to `shmid`
  - Checking `ipc_lock()` asm also showed that `shmid` gets quickly lost inside it
- There's a high chance some function up the call stack saved the `vma`, but how to find it without following more assembler?
  - `vma`'s (`struct vm_area_struct` objects) have a dedicated SLAB cache, and crash can mark these caches automatically in the backtrace

crash – rich backtrace with local data

```
crash> bt -FF
...
 #4 [ffff880211337cd0] invalid_op at ffffffff81472ddb
    [exception RIP: shm_close+62]
    RIP: ffffffff811e466e  RSP: ffff880211337d88  RFLAGS: 00010202
    RAX: ffffffffffffffea  RBX: ffffffffffffffea  RCX: 0000000000000006
    RDX: 0000000000000000  RSI: 000000000000005c  RDI: 0000000000000006
    RBP: ffffffff81a46920   R8: 0000000000000002   R9: ffff8804256a84d0
    R10: ffff880192cecc00  R11: ffffffff81215a80  R12: ffffffff81a469c0
    R13: ffff88008cecac80  R14: ffff880423c33740  R15: 0000000000000001
    ORIG_RAX: ffffffffffffffff  CS: 0010  SS: 0018
    ffff880211337cd8: 0000000000000001 [ffff880423c33740:signal_cache]
    ffff880211337ce8: [ffff88008cecac80:mm_struct] init_ipc_ns+160
    ffff880211337cf8: init_ipc_ns      ffffffffffffffea
    ffff880211337d08: apparmor_file_free_security [ffff880192cecc00:size-32]
    ffff880211337d18: [ffff8804256a84d0:idr_layer_cache] 0000000000000002
    ffff880211337d28: ffffffffffffffea 0000000000000006
    ffff880211337d38: 0000000000000000 000000000000005c
    ffff880211337d48: 0000000000000006 ffffffffffffffff
    ffff880211337d58: shm_close+62     0000000000000010
    ffff880211337d68: 0000000000010202 ffff880211337d88
    ffff880211337d78: 0000000000000018 shm_close+51
    ffff880211337d88: [ffff88016d2319e0:vm_area_struct] [ffff880158fea140:vm_area_struct]
    ffff880211337d98: 00007ffce0bf0000 remove_vma+36
 #5 [ffff880211337da0] remove_vma at ffffffff81127fa4
    ffff880211337da8: [ffff88008cecac80:mm_struct] ffff880211337dd8
    ffff880211337db8: [ffff88016d2319e0:vm_area_struct] exit_mmap+248
 #6 [ffff880211337dc0] exit_mmap at ffffffff811280f8
```

crash – rich backtrace with lo

```
crash> bt -FF
...
 #4 [ffff880211337cd0] invalid_op at ffffffff81472ddb
    [exception RIP: shm_close+62]
    RIP: ffffffff811e466e  RSP: ffff880211337d88  RFLAGS: 00010202
    RAX: ffffffffffffffea  RBX: ffffffffffffffea  RCX: 0000000000000006
    RDX: 0000000000000000  RSI: 000000000000005c  RDI: 0000000000000006
    RBP: ffffffff81a46920   R8: 0000000000000002   R9: ffff8804256a84d0
    R10: ffff880192cecc00  R11: ffffffff81215a80  R12: ffffffff81a469c0
    R13: ffff88008cecac80  R14: ffff880423c33740  R15: 0000000000000001
    ORIG_RAX: ffffffffffffffff  CS: 0010  SS: 0018
    ffff880211337cd8: 0000000000000001 [ffff880423c33740:signal_cache]
    ffff880211337ce8: [ffff88008cecac80:mm_struct] init_ipc_ns+160
    ffff880211337cf8: init_ipc_ns      ffffffffffffffea
    ffff880211337d08: apparmor_file_free_security [ffff880192cecc00:siz
    ffff880211337d18: [ffff8804256a84d0:idr_layer_cache] 000000000000
    ffff880211337d28: ffffffffffffffea 0000000000000006
    ffff880211337d38: 0000000000000000 000000000000005c
    ffff880211337d48: 0000000000000006 ffffffffffffffff
    ffff880211337d58: shm_close+62     0000000000000010
    ffff880211337d68: 0000000000010202 ffff880211337d88
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    ffff880211337db8: [ffff88016d2319e0:vm_area_struct] exit_mmap+248
 #6 [ffff880211337dc0] exit_mmap at ffffffff811280f8
```

```
remove_vma(vma) – vma in rdi
<remove_vma>:          push   %rbp
<remove_vma+1>:        push   %rbx
<remove_vma+2>:        mov    %rdi,%rbx
<remove_vma+5>:        sub    $0x8,%rsp
<remove_vma+9>:        mov    0x88(%rdi),%rax
<remove_vma+16>:       mov    0x18(%rdi),%rbp
<remove_vma+20>:       test   %rax,%rax
<remove_vma+23>:       je     <remove_vma+36>
<remove_vma+25>:       mov    0x8(%rax),%rax
<remove_vma+29>:       test   %rax,%rax
<remove_vma+32>:       je     <remove_vma+36>
<remove_vma+34>:       callq  *%rax
<remove_vma+36>:       mov    0x98(%rbx),%rdi
```

We enter shm_close() with vma in rbx, return address to remove_vma+36 on stack:

```
<shm_close>:           push   %r12
<shm_close+2>:         push   %rbp
<shm_close+3>:         push   %rbx
```

Our vma is ffff88016d2319e0, hooray!

crash – finally getting the shmid

```
crash> struct vm_area_struct.vm_file ffff88016d2319e0
  vm_file = 0xffff8800148fcb80

crash> struct file.private_data 0xffff8800148fcb80
  private_data = 0xffff8803f382cc60

crash> struct shm_file_data 0xffff8803f382cc60
struct shm_file_data {
  id = 13008988,
  ns = 0xffffffff81a46920 <init_ipc_ns>,
  file = 0xffff88037a645680,
  vm_ops = 0xffffffff816268a0 <shmem_vm_ops>
}
```

crash – checking existing shmid's with `ipcs`

- This checks the same structure that `ipc_lock()` was searching by `idr_find()`
  - No need to inspect it manually (a colleague did that, anyway)
- Our id 13008988 is indeed not there – was it freed too early, or was there a corruption?
  - The id 13008943 looks pretty close...

```
crash> ipcs -m
SHMID_KERNEL     KEY      SHMID      UID   PERMS BYTES      NATTCH
STATUS
ffff880424c74b90 00004dc4 98304      50016 760   40141728   1
...
ffff8803792ed0d0 000027b4 12976174   28900 740   4194480    24
ffff8803790f5790 000027c5 13008943   28900 740   20672      12
ffff880365da6b90 0000277a 13795376   28900 740   512000000  8519
ffff88039f3169d0 00002792 13828145   28900 740   54060      24
ffff880365d75b90 000027ae 13860914   28900 740   2076       24
ffff880365da6c90 000027ac 13893683   28900 740   535000     11
```

crash – checking suspicious shmid

```
crash> struct shmid_kernel ffff8803790f5790
struct shmid_kernel {
  shm_perm = {
…
    deleted = 0,
    id = 13008943,
    key = 10181,
…
  },
  shm_file = 0xffff88037a645680,
  shm_nattch = 12,
}
```

- Let's compare it with our `shm_file_data` – same file pointer **`0xffff88037a645680`**!
- One of the two objects here has most likely corrupted `id` field, but which one?

```
crash> struct shm_file_data 0xffff8803f382cc60
struct shm_file_data {
  id = 13008988,
  file = 0xffff88037a645680,
}
```

crash – which shmid is corrupted?

```
crash> search 0xffff88037a645680 # the shm_file pointer
```

The search returns a number of addresses that we can inspect:

- the `shmid_kernel ffff8803790f5790` with `shm_file` field
- two self-references (empty `list_head`)
- 12 objects from the `size-32` kmalloc cache
  - one is our `shm_file_data 0xffff8803f382cc60` with id 13008988
  - the other 11 appear to be correct `shm_file_data` structures with id 13008943
  - `shm_nattch == 12` – there should be 12 instances with id 13008943
- Conclusion: the `shmid_kernel` in the registry with id 13008943 is correct, the single `shm_file_data` with id 13008988 (that triggered BUG) is wrong
  - Note: it's often possible to cross-check data in kernel like this, as there are redundancies for functionality or performance reasons

What next?

- We found what exactly was wrong (first phase), but not why it was wrong
  - Doesn’t look like a RAM error. And catching stray writes done by kernel itself is very hard, especially from a crash dump.
  - The corrupted value was in object from `size-32` slab cache, shared by everyone calling `kmalloc()` with size between 17 and 32 bytes – overflow, use-after-free?
  - It only happened once. Further occurrences would show if this happens at the same place or randomly, and if there’s a pattern in the corruption itself.
- Indeed, other bug reports appeared later from same set of customer’s systems – crashes while reading `/proc/slabinfo` and other operation in SLAB due to broken lists of slab structures
  - crash will report some errors in those while running the kmem commands
  - Not an extensive integrity check of SLAB itself though
  - Manual checking would be tedious

crash-python

- An alternative to crash to overcome some of its limitations
  - Especially lack of rich stack traces, architecture dependency and complicated scripting
- Extend `gdb` Python API so that the whole gdb target can be provided by Python code
  - Originally patches from Linaro, adopted by SUSE colleagues
  - Use `libkdumpfile` and `libaddrxlat` libraries via their Python API to read vmcore files and translate virtual addresses to the dumped memory contents
  - Write `gdb` target on top (Linux tasks translate to `gdb`'s threads, etc.)
- All kernel-specific knowledge written in Python on top of gdb API for symbols, types and values
  - Implement equivalents to crash commands
  - Implement new commands to inspect kernel state – **SLAB/SLUB integrity checking**
  - Building blocks reusable for further ad-hoc scripting to help with a particular bug

crash-python applied on the bug

crash-python applied on the bug

- Several instances of a crash while reading `/proc/slabinfo` and other operation in SLAB due to broken lists of slab structures
- In several dumps, the minimal corruption of a doubly-linked list allowed to detect a corrupted pointer and compare it with an expected value
- Others were corrupted much more because they didn’t panic soon enough and the it was hard to point to the initial corruption

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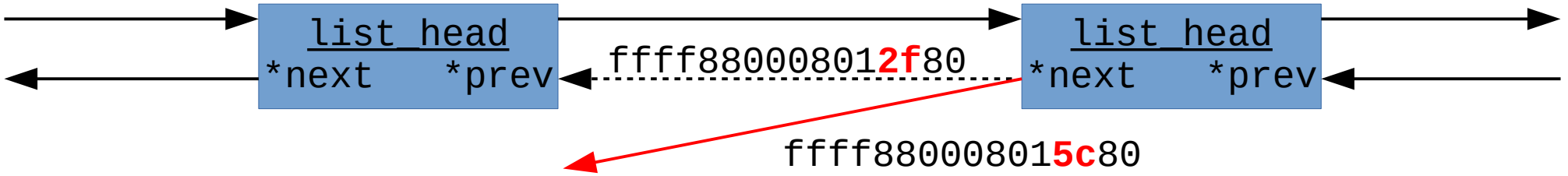

The Pattern Emerges...

- Turns out all the “simple” corruptions changed a byte `2f` to `5c`, and affected a `size-32` or `size-64` slab object
- For example, back to the `shmid` case:

```
crash> eval -b 13008943 # the expected value
hexadecimal: c6802f
    decimal: 13008943
      octal: 61500057
     binary:00000000000000000000000000000000000000011000110100000000101111
   bits set: 23 22 18 17 15 5 3 2 1 0

crash> eval -b 13008988 # the wrong value
hexadecimal: c6805c
    decimal: 13008988
      octal: 61500134
     binary:00000000000000000000000000000000000000011000110100000000101100
   bits set: 23 22 18 17 15 6 4 3 2
```

If In Doubt, Try ASCII (kudos to Michal Hocko)

- `2f` is `'/'`, `5c` is `'\'`
- Was somebody rewriting Linux filesystem paths to Windows?
  - The CIFS module (Samba client) has a function for that – `convert_delimiter()`, called by e.g. `cifs_build_path_to_root()`

```
static inline void convert_delimiter(char *path, char delim)
{
        int i;
        char old_delim;

        if (path == NULL)
                return;

        if (delim == '/')
                old_delim = '\\';
        else
                old_delim = '/';

        for (i = 0; path[i] != '\0'; i++) {
                if (path[i] == old_delim)
                        path[i] = delim;
        }
}
```

cifs_build_path_to_root() (v3.0.101)

```
char *cifs_build_path_to_root(struct smb_vol *vol, struct cifs_sb_info *cifs_sb,
                              struct cifs_tcon *tcon)
{
        int pplen = vol->prepath ? strlen(vol->prepath) : 0;
        int dfsplen;
        char *full_path = NULL;
...
        dfsplen = strnlen(tcon->treeName, MAX_TREE_SIZE + 1);
...
        full_path = kmalloc(dfsplen + pplen + 1, GFP_KERNEL);
        if (full_path == NULL)
                return full_path;

        if (dfsplen)
                strncpy(full_path, tcon->treeName, dfsplen);
        strncpy(full_path + dfsplen, vol->prepath, pplen);
        convert_delimiter(full_path, CIFS_DIR_SEP(cifs_sb));
        full_path[dfsplen + pplen] = 0; /* add trailing null */
        return full_path;
}
```

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}
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strlen() doesn't count trailing null

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+ 1 makes space for it, OK

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strncpy() copies trailing null but the given length excludes the byte where null is

too late, convert_delimiter() has already done the damage

The Bug’s (Upstream) History

- The bug was introduced upstream probably in 2011, kernel 3.1 (the commit was then backported to stable 3.0.x)
- The bug was fixed upstream in 2012, kernel 3.8, unknowingly (the commit intends to fix something else, much less critical)
  - This is a very common experience...
  - Upstream stable 3.2 was still maintained and vulnerable back in 2018, but CIFS maintainers didn’t respond to my report…
- Customer reported it only in 2017 – 6 years old bug
  - Needs a specific CIFS client/server settings, including frequent reconnect
  - Maybe it was reported previously, but happened just once and went unfixed
- Soon after we fixed our kernel, a different customer (with unpatched kernel) suddenly reported the same bug
  - Also a very common experience
  - Actually surprised that there was just one...

Debug prints

- `printk()` - send text to console/dmesg…
  - Including loglevels, from debugging to emergency
    - `printk(KERN_ERR “msg”), pr_err(), dev_err()`
- Correct implementation surprisingly nontrivial
  - Locking of buffers – what about printing from NMI?
  - Flooding slow consoles – printing task stalled
  - Timestamping/ordering from multiple CPUs
  - Prioritizing important info on panic
- Major rewrite addressing the above is ongoing for years now
- Printing very early during boot – `earlyprintk` setup needed
- `trace_printk()` – simpler, but output has to be captured later from the trace buffers

Dynamic debug prints

- The lowest level messages are actually compiled out when using `pr_debug()` and `dev_dbg()` wrappers
  - Unless `#define DEBUG` is active when compiling the file
  - Or `CONFIG_DYNAMIC_DEBUG` (dyndbg) is enabled
- With dyndbg, debug messages can be switched on/off at runtime via simple query language
  - `/sys/kernel/debug/dynamic_debug/control` or boot/modprobe parameters
  - Module, file, function, line (range), format string granularity
  - Flags to include func/line/module/thread id when printing
- Switching on/off uses live code patching (static keys) to minimize runtime impact (still, around 2% text size impact)
  - Ftrace uses the same mechanism for tracepoints

Live kernel debugging - `/proc/kcore`

- `/proc/kcore` enabled by CONFIG_PROC_KCORE
  - Provides virtual ELF “core dump” file
  - Usable by gdb, crash, **drgn** for read-only inspection
  - Printing values of global variables
  - Inspecting structures the same way as in a crash dump
- `/dev/kmem` – gone in 5.13 – could have bee configured read/write
  - crash can set variables and modify structures
- For full live debugging, we would need also to control execution, which is much trickier
  - Provide a server for gdb client that doesn't rely on the rest of the kernel functionality

Live kernel debugging - kgdb

- kgdb was merged in 2.6.26 (2008)
- Provides a server for remote gdb client
  - Over serial port – `CONFIG_KGDB_SERIAL_CONSOLE`
  - Over network using NETPOLL – not mainline (KDBoE)
- Enable on server
  - Boot with `kgdboc=ttyS0,115200`
  - `echo g > /proc/sysrq-trigger` or `kgdbwait` boot param
- Use from a client
  - `% gdb ./vmlinux`
  - `(gdb) set remotebaud 115200`
  - `(gdb) target remote /dev/ttyS0`
  - Allows limited gdb debugging similar to a userspace program

Live kernel debugging - kdb

- kdb is a frontend for kgdb that runs in the debugged kernel (no need for other client) – since 2.6.35 (2010)
- Provides a shell accessed via serial terminal, with optional PS/2 keyboard support
  - Enabled same way as the kgdb server
  - Switch between kdb/kgdb by `$3#33` and `kgdb`
- Provides some kernel-specific commands not available in pure gdb
- `lsmod, ps, ps A, summary, bt, dmesg, go, help`
  - Some can be executed from gdb – `monitor help`
  - Out of tree discontinued version seemed to be more capable
- KMS console support was proposed, but dropped

Live debugging - User-Mode Linux (UML)

- Special pseudo-hardware architecture
  - Otherwise compatible with the target architecture
- Running Linux kernel as a user space process
  - Originally a virtualization effort
- Useful for debugging and kernel development
  - A plain standard gdb can be used to attach to the running kernel
  - Guest threads are threads of the UML process
    - Slightly more complicated to follow processes
- Recommended environment for running KUnit tests

Magic SysRq hot keys

- Operator's intervention to the running system
  - For dealing with hangs or security issues
- Can be enabled/disabled by `/proc/sys/kernel/sysrq`
  - `Alt+SysRq+H` – show help
  - Invoke crash, reboot, shutdown, kill processes, OOM killer
  - Reset nice level of all real-time processes
  - Sync, remount read-only, freeze filesystems
  - Dump registers, tasks, stacks, memory stats, locks taken, armed timers, sleeping tasks, ftrace buffer
  - **R**aising **E**lephants **I**s **S**o **U**tterly **B**oring or **R**eboot **E**ven **I**f **S**ystem **U**tterly **B**roken
    - Raw keyboard, Send SIGTERM to all processes, Send SIGKILL to all processes, Sync data to disk, Remount all filesystems read-only, Reboot
- Can be activated also from console (`/proc/sysrq-trigger`) or via network

Kernel debugging config options

- Kernel can be built with additional debugging options enabled
  - Extra checks that can catch errors sooner, or provide extra information, at the cost of CPU and/or memory overhead
  - Can also hide errors such as race conditions...
- Many of them under “Kernel hacking” in `make menuconfig`
  - Others placed in the given subsystem/driver
- Useful when hunting a particular bug, but mainly for regression testing
- Some now intended also for production kernels, can be compiled in but inactive unless enabled with a boot parameter
  - Again, using static keys to minimize overhead when not enabled

Kernel debugging config options

- `DEBUG_LIST` – catch some list misuses, poisoning
- `DEBUG_VM` – enable `VM_BUG_ON()` checks
- **`PAGE_OWNER`** – track who allocated and freed which pages in order to find a memory leak or double free
- **`DEBUG_PAGEALLOC`** – unmap (or poison) pages after they are freed
- `DEBUG_SLAB` – detect some cases of double free, or use-after-free (by poisoning), buffer overflow (red-zoning)
- **`SLUB_DEBUG`** – the SLUB variant can enable/disable debugging at boot for individual caches
  - Extra sanity checks, poisoning, red zoning, alloc/free tracking, tracing
- `DEBUG_KMEMLEAK` – detect leaks with a conservative garbage collection based algorithm
- **`KFENCE`** – low-overhead sampling based detection of overflow, use-after-free, invalid-free for slab objects

Kernel debugging config options

- KASAN – Find out of bounds accesses and use-after-free bugs using shadow memory (~valgrind) or sw/hw tags
  - GENERIC - Instrument each access to check shadow memory
    - Cost is 1/8 memory and 3x slower performance, needs new enough GCC or Clang
  - SW_TAGS – embeds tags to pointers, checks by instrumentation
    - Only slab and page allocations, arm64 with Top Byte Ignore, Clang, 1/16 memory
  - HW_TAGS – arm64 with Memory Tagging Extension, checks by hardware
    - Also slab and page allocations, only reports first bug, then disables itself
- UBSAN – Find out presence of undefined behavior (per C standard)
- KCSAN – dynamic race detector, based on compile-time instrumentation
  - Detect situations with two plain memory accesses to same place, one write
  - Needs GCC or Clang 11+, inserts soft watchpoints and stalls

Kernel debugging config options

- `DEBUG_STACKOVERFLOW` – check if random corruption involving struct thread_info is caused by too deep call chains
- `DEBUG_SPINLOCK` and others for different locks – catch missing init, freeing of live locks, some deadlocks
- `LOCK_STAT` – for lock contention, perf lock
- `PROVE_LOCKING` – a.k.a. “lockdep” - mechanism for online proving that deadlocks cannot happen and report that deadlock can occur before it actually does
- Various subsystem specific options that enable both `KERN_DEBUG` `printk()`’s and extra checks

Kernel Fuzzing

- Try to trigger bugs by exposing the program to various inputs (i.e. chains of syscalls in the case of kernel)
- trinity – mostly random syscalls and parameters, only avoids known invalid input (flags) to not waste time on it
- syzkaller – unsupervised coverage-guided fuzzer from Google
  - For Akaros, FreeBSD, Fuchsia, gVisor, Linux, NetBSD, OpenBSD, Windows.
  - More efficient in finding corner-cases, but needs instrumentation
  - Often can generate a short reproducer with the report
- syzbot - https://syzkaller.appspot.com/
  - CI for automated fuzzing, reporting and tracking of found bugs
  - Linux: 3078 fixed, 978 open, 5529 invalid
  - Often used with debug options enabled, such as KASAN, UBSAN, lockdep...

Kernel testing (CI) initiatives

- Developers can’t possibly test their code in all possible architectures and configurations
- Automated testing and reporting very useful for development (linux-next) and stabilization (rc versions)
- LKP (Linux Kernel Performance) a.k.a. 0-day bot by Intel – tests linux-next, developer git trees, patches on mailing lists, replies with bug reports, sometimes proposed fixes
- kernelci.org by Linaro – for various ARM SoCs
- “Hulk Robot” used in Huawei

Linux Kernel Static Analysis

- Sparse – semantic checker for types and locks relying on attributes
  - Types – bitwise, kernel, user, iomem
  - Locks – acquire, release, must_hold
- Smatch – built upon sparse, can report e.g. missing NULL checks, array overflow
- Coccinelle – allows finding code matching a pattern as well as changing it
- Coverity – proprietary static analysis tool, scans Linux for free, but limited access to results

Thank you.