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Systematic Testing of Fault Handling Code in Linux Kernel

Alexey Khoroshilov
Andrey Tsyvarev

ISP RAS
Institute for System Programming of the Russian Academy of Sciences

Fault Handling Code

```
821             error = filemap_write_and_wait_range(VFS_I(ip)->i_mapping,
822                                                  ip->i_d.di_size, newsize);
823             if (error)
824                     return error;
...
852     tp = xfs_trans_alloc(mp, XFS_TRANS_SETATTR_SIZE);
853     error = xfs_trans_reserve(tp, &M_RES(mp)->tr_itruncate, 0, 0);
854     if (error)
855             goto out_trans_cancel;
...
925 out_unlock:
926     if (lock_flags)
927             xfs_iunlock(ip, lock_flags);
928     return error;
929
930 out_trans_abort:
931     commit_flags |= XFS_TRANS_ABORT;
932 out_trans_cancel:
933     xfs_trans_cancel(tp, commit_flags);
934     goto out_unlock;
```

Fault Handling Code

DOING
WHAT YOU LIKE
IS **FREEDOM**

Fault Handling Code

DOING
WHAT YOU LIKE
IS **FREEDOM**

LIKING
WHAT YOU DO
IS **HAPPINESS**

Fault Handling Code

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Fault Handling Code

- Is not so fun
- Is really hard to keep all details in mind

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Fault Handling Code

- Is not so fun
- Is really hard to keep all details in mind
- Practically is not tested
- Is hard to test even if you want to
- **Bugs seldom(never) occurs**

  => low pressure to care

Why do we care?

- It beats someone time to time
- Safety critical systems
- Certification authorities

How to improve situation?

- Managed resources
  - \+ No code, no problems
  - – Limited scope
- Static analysis
  - \+ Analyzes all paths at once
  - – Detects prescribed set of consequences (mostly local)
  - – False alarms
- Run-time testing
  - \+ Detects even hidden consequences
  - \+ Almost no false alarms
  - – Tests are needed
  - – Specific hardware may be needed (for drivers testing)

Run-Time Testing of Fault Handling

- Manually targeted test cases
  - \+ The highest quality
  - – Expensive to develop and to maintain
  - – Not scalable
- Random fault injection on top of existing tests
  - \+ Cheap
  - – Oracle problem
  - – No any guarantee
  - – When to finish?

Systematic Approach

- Hypothesis:
  - Existing test lead to deterministic control flow in kernel code
- Idea:
  - Execute existing tests and collect all potential fault points in kernel code
  - Systematically enumerate the points and inject faults there

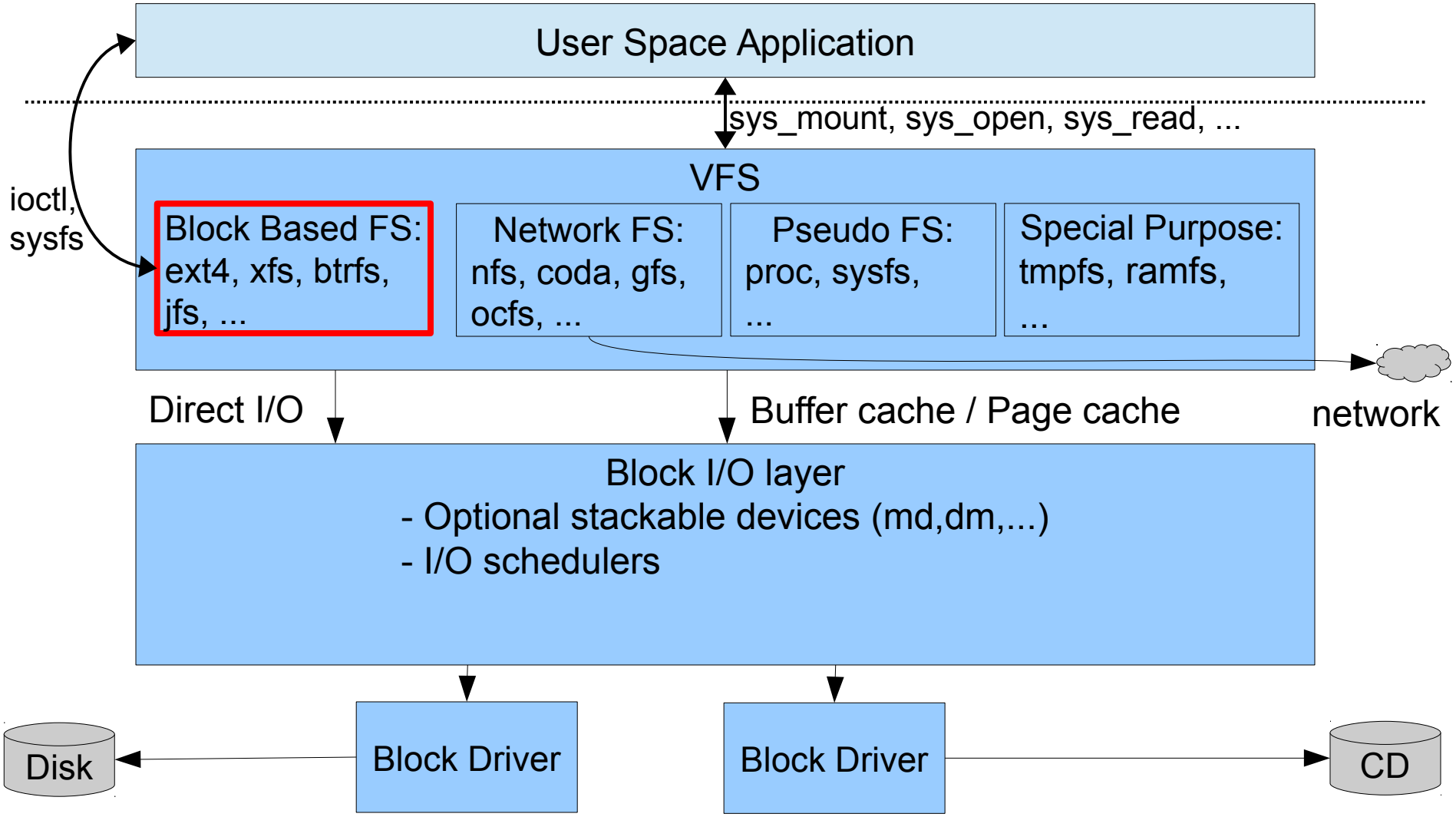
Experiments – Outline

- Target code
- Fault injection implementation
- Methodology
- Results

Experiments – Target

- Target code: file system drivers
- Reasons:
  - Failure handling is more important than in average
    - Potential data loss, etc.
  - Same tests for many drivers
  - It does not require specific hardware
  - Complex enough

Linux File System Layers



File System Drivers - Size

File System Driver	Size, LoC
JFS	18 KLOC
Ext4	37 KLoC *with jbd2*
XFS	69 KLoC
BTRFS	82 KLoC
F2FS	12 KLoC

File System Driver – VFS Interface

- file_system_type
- super_operations
- export_operations
- inode_operations
- file_operations
- vm_operations
- address_space_operations
- dquot_operations
- quotactl_ops
- dentry_operations

~100 interfaces in total

FS Driver – Userspace Interface

File System Driver	ioctl	sysfs
JFS	6	-
Ext4	14	13
XFS	48	-
BTRFS	57	-

FS Driver – Partition Options

File System Driver	mount options	mkfs options
JFS	12	6
Ext4	50	~30
XFS	37	~30
BTRFS	36	8

FS Driver – On-Disk State

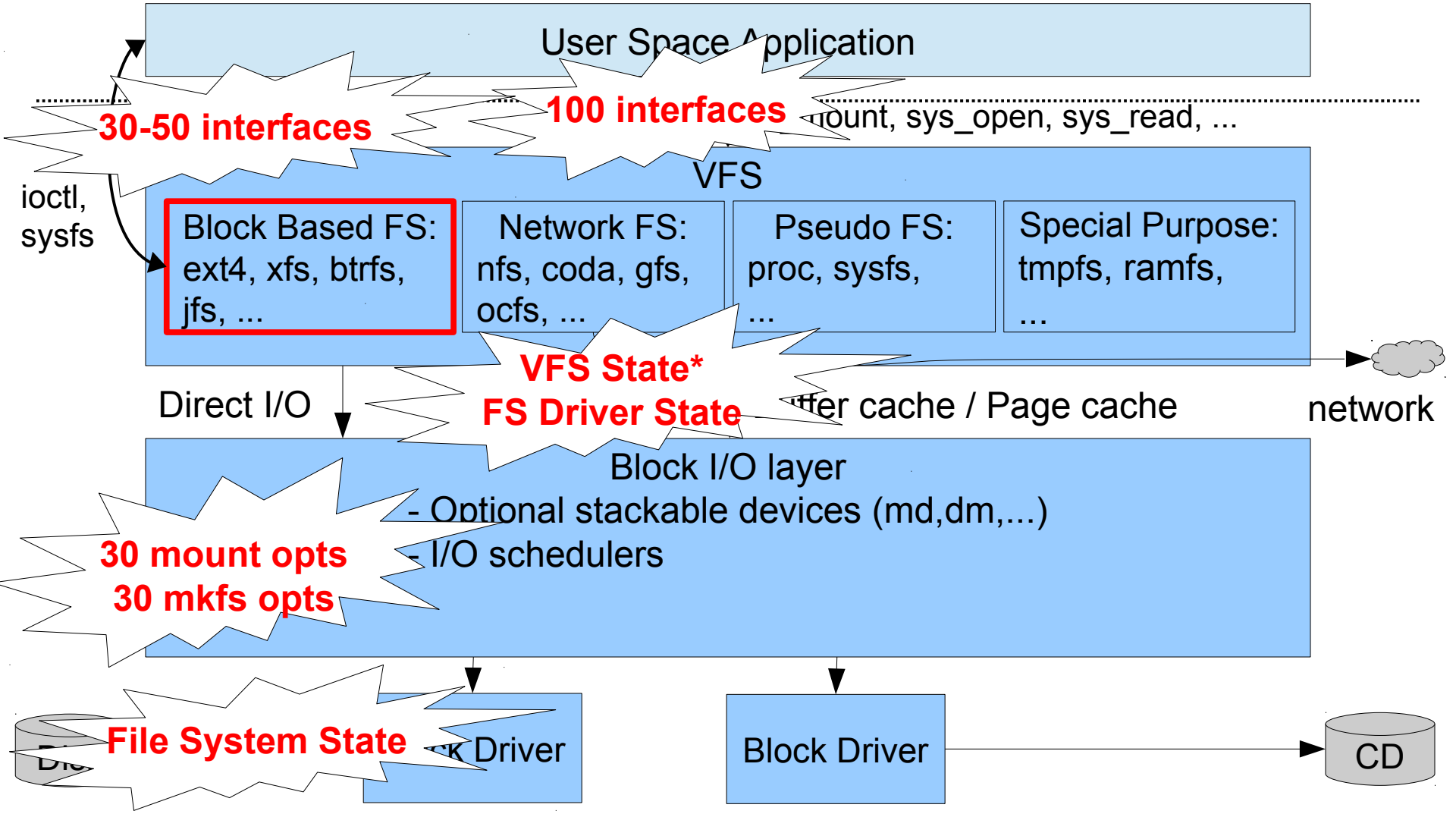
File System Hierarchy

* File Size
* File Attributes
* File Fragmentation
* File Content (holes,...)

FS Driver – In-Memory State

- Page Cache State
- Buffers State
- Delayed Allocation
- ...

Linux File System Layers



FS Driver – Fault Handling

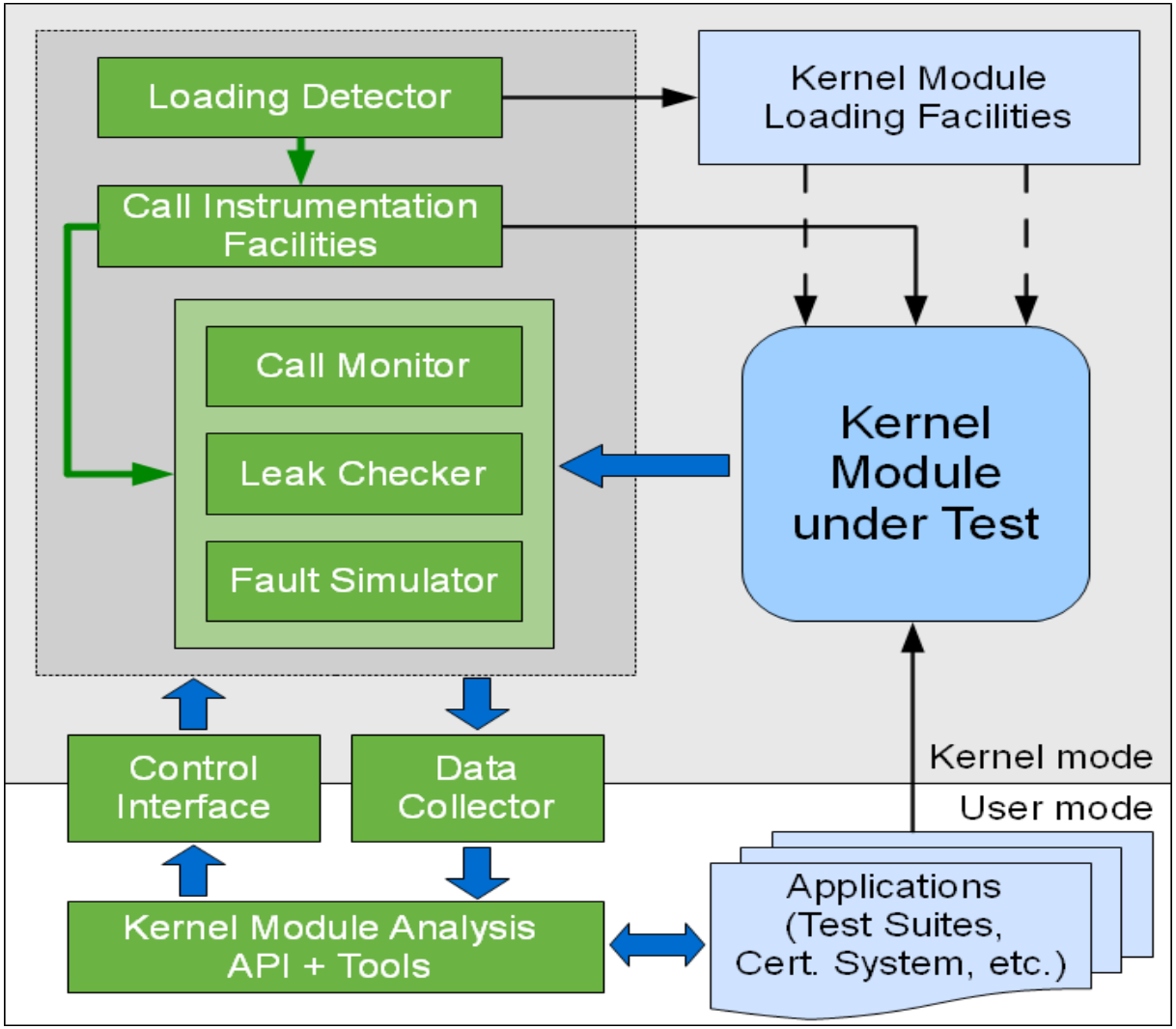
- Memory Allocation Failures
- Disk Space Allocation Failures
- Read/Write Operation Failures

Fault Injection - Implementation

- Based on KEDR framework*
  - intercept requests for memory allocation/bio requests
    - to collect information about potential fault points
    - to inject faults
  - also used to detect memory/resources leaks

(*) http://linuxtesting.org/project/kedr

KEDR Workflow



http://linuxtesting.org/project/kedr

Experiments – Tests

- 10 deterministic tests from xfstests*
  - generic/
    - 001-003, 015, 018, 020, 053
  - ext4/
    - 002, 271, 306
- Linux File System Verification** tests
  - 180 unit tests for FS-related syscalls / ioctls
  - mount options iteration

(*) git://oss.sgi.com/xfs/cmds/xfstests
(**) http://linuxtesting.org/spruce

Experiments – Oracle Problem

- Assertions in tests are disabled
- Kernel oops/bugs detection
- Kernel assertions, lockdep, memcheck, etc.
- KEDR Leak Checker

Experiments – Methodology

- Collect source code coverage of FS driver on existing tests
- Collect source code coverage of FS driver on existing tests with fault simulation
- Measure an increment

Methodology – The Problem

- If kernel crashes code, coverage results are unreliable

Methodology – The Problem

- If kernel crashes code, coverage results are unreliable
- As a result
  - Ext4 was analyzed only
  - XFS, BTRF, JFS, F2FS, UbiFS, JFFS2 crashes and it is too labor and time consuming to collect reliable data

Experiment Results

Systematic Approach

- Hypothesis:
  - Existing test lead to deterministic control flow in kernel code
- Idea:
  - Execute existing tests and collect all potential fault points in kernel code
  - Systematically enumerate the points and inject faults there

Complete Enumeration

	Fault points	Expected Time
Xfstests (10 system tests)	270 327	2,5 years
LFSV (180 unit tests*76 mount options)	488 791	7 months

Possible Idea

- Unit test structure
  - Preamble
  - **Main actions**
  - Checks
  - Postamble
- What if account fault points inside main actions?

Complete Enumeration

	Fault points	Expected Time
Xfstests (10 system tests)	270 327	2,5 years
LFSV (180 unit tests)	488 791	7 months
LFSV (180 unit tests) – main part only	9 226	1,5 hours

- that gives 311 new lines of code covered
- i.e. 18 seconds per line

Another Idea

- Automatic filtering
  - e.g. by Stack Trace of fault point

LFSV Tests

	Increment *new lines*	**Time** *min*	**Cost** *seconds/line*
LFSV without fault simulation	-	110	-
LFSV – main only – no filter	311	92	18
LFSV – main only – stack filter	266	2	0.45
LFSV – whole test – no filter		*unfeasible*	
LFSV – whole test – stack filter	333	4	0.72

Main-only vs. Whole

+ 2-3 times more cost effective
– Manual work =>
  - expensive
  - error-prone
  - unscalable

+ More scalable
+ Better coverage

Unit tests vs. System tests

	Increment *new lines*	**Time** *min*	**Cost** *second/line*
LFSV – whole test – stack filter	333	4	0.72
LFSV – whole test – stackset filter	354	9	1.53
Xfstests – stack filter	423	90	13
Xfstests – stackset filter	451	237	31

+ 10-30 times more cost effective

+ Better coverage

Systematic vs. Random

	Increment *new lines*	**Time** *min*	**Cost** *second/line*
Xfstests without fault simulation	-	2	-
Xfstests+random(p=0.01,repeat=200)	380	152	24
Xfstests+random(p=0.02,repeat=200)	373	116	19
Xfstests+random(p=0.05,repeat=200)	312	82	16
Xfstests+random(p=0.01,repeat=400)	451	350	47
Xfstests+stack filter	423	90	13
Xfstests+stackset filter	451	237	31

Systematic vs. Random

+ 2 times more cost effective
+ Repeatable results
– Requires more complex engine
+ Cover double faults
– Unpredictable
– Nondeterministic

No.	Type	Brief	Added on	Accepted	Status
F0010	Crash	f2fs: Possible use-after-free when umount filesystem	2014-09-08	https://lkml.org/lkml/2014/7/21/198 commit	Fixed in kernel 3.17-rc1
F0009	Crash	ext4: Destruction of ext4_groupinfo_caches during one mount causes BUG_ON for other mounted ext4 filesystems	2014-05-12	https://lkml.org/lkml/2014/5/12/147 commit	Fixed in kernel 3.16-rc1
F0008	Crash	f2fs: BUG_ON() is triggered in recover_inode_page() when mount valid f2fs filesystem	2014-04-18	https://lkml.org/lkml/2014/4/14/189 commit	Fixed in kernel 3.17-rc1
F0007	Crash	f2fs: f2fs unmount hangs if f2fs_init_acl() fails during mkdir syscall	2014-02-17	https://lkml.org/lkml/2014/2/6/18 commit	Fixed in kernel 3.15-rc1
F0006	Deadlock	f2fs: a deadlock in mkdir if ACL is enabled	2013-10-28	https://lkml.org/lkml/2013/10/26/163 commit	Fixed in kernel 3.12-rc3
F0005	Crash	ext4: system hangs after failure in ext4_mb_new_preallocation()	2013-07-01	https://lkml.org/lkml/2013/5/5/64 commit	Fixed in kernel 3.10-rc3
F0004	Deadlock	ext4: deadlocks after allocation failure in ext4_init_io_end()	2013-06-04	https://lkml.org/lkml/2013/5/13/426 commit	Fixed in kernel 3.10-rc3
F0003	Crash	jfs: Several bugs in jfs_freeze() and jfs_unfreeze()	2013-05-24	https://lkml.org/lkml/2013/5/24/76 commit	Fixed in kernel 3.10-rc3
F0002	Crash	ext4: NULL dereference in ext4_calculate_overhead()	2012-11-28	https://lkml.org/lkml/2012/11/28/354 commit	Fixed in kernel 3.8-rc1
F0001	Crash	ext4: NULL pointer dereference in mount_fs() because of ext4_fill_super() wrongly reports success	2012-11-08	https://bugzilla.kernel.org/show_bug.cgi?id=48431 commit	Fixed in kernel 3.8-rc1

XFS bug

```
[ 3143.894108] Start: fsim.spruce.common.-L_SPRUCE_XFS:.utime.UtimeNormalNotNull.kmalloc.2
[ 3143.894110] KEDR FAULT SIMULATION: forcing a failure
[ 3143.894116] CPU: 0 PID: 7127 Comm: fs-driver-tests Tainted: G        W  O   3.17-generic #1
[ 3143.894118] Hardware name: innotek GmbH VirtualBox/VirtualBox, BIOS VirtualBox 12/01/2006
[ 3143.894119]  ffff8800701e7be0 ffff8800701e7b98 ffffffff8169b4a1 0000000000000001
[ 3143.894185]  ffff8800701e7bc8 ffffffffa022fbcf ffffffffa022fb25 ffff8800701e7fd8
[ 3143.894188]  ffff880082421a80 0000000000008250 ffff8800701e7c18 ffffffffa023f610
[ 3143.894190] Call Trace:
[ 3143.894197]  [<ffffffff8169b4a1>] dump_stack+0x4d/0x66
[ 3143.894202]  [<ffffffffa022fbcf>] kedr_fsim_point_simulate+0xaf/0xc0 [kedr_fault_simulation]
[ 3143.894208]  [<ffffffffa023f610>] kedr_repl_kmem_cache_alloc+0x40/0x90 [kedr_fsim_cmm]
[ 3143.894230]  [<ffffffffa02401d3>] kedr_intermediate_func_kmem_cache_alloc+0x73/0xd0 [kedr_fsim_cmm]
[ 3143.894264]  [<ffffffffa038b497>] kmem_zone_alloc+0x77/0x100 [xfs]
[ 3143.894277]  [<ffffffffa038fbd7>] xlog_ticket_alloc+0x37/0xe0 [xfs]
[ 3143.894288]  [<ffffffffa038fd39>] xfs_log_reserve+0xb9/0x220 [xfs]
[ 3143.894299]  [<ffffffffa0389e35>] xfs_trans_reserve+0x2b5/0x2f0 [xfs]
[ 3143.894311]  [<ffffffffa037ad9f>] xfs_setattr_nonsize+0x19f/0x610 [xfs]
[ 3143.894328]  [<ffffffffa037b63d>] xfs_vn_setattr+0x2d/0x80 [xfs]
[ 3143.894334]  [<ffffffff811d9581>] notify_change+0x231/0x380
[ 3143.894337]  [<ffffffff811ed97b>] utimes_common+0xcb/0x1b0
[ 3143.894339]  [<ffffffff811edb1d>] do_utimes+0xbd/0x160
[ 3143.894340]  [<ffffffff811edc2f>] SyS_utime+0x6f/0xa0
[ 3143.894343]  [<ffffffff816a49d2>] system_call_fastpath+0x16/0x1b
[ 3143.894369]
[ 3143.894380] =============================================
[ 3143.894382] [ BUG: lock held when returning to user space! ]
[ 3143.894384] 3.17-generic #1 Tainted: G        W  O
[ 3143.894386] ---------------------------------------------
[ 3143.894388] fs-driver-tests/7127 is leaving the kernel with locks still held!
[ 3143.894390] 1 lock held by fs-driver-tests/7127:
[ 3143.894392]  #0:  (sb_internal){.+.+.+}, at: [<ffffffffa0389a44>] xfs_trans_alloc+0x24/0x40 [xfs]
[ 3143.894410] LFSV: Fatal error was arisen.
```

XFS bug

```
528 int
529 xfs_setattr_nonsize(
530         struct xfs_inode        *ip,
531         struct iattr            *iattr,
532         int                     flags)
533 {
…
600         tp = xfs_trans_alloc(mp, XFS_TRANS_SETATTR_NOT_SIZE);
601         error = xfs_trans_reserve(tp, &M_RES(mp)->tr_ichange, 0, 0);
602         if (error)
603                 goto out_dqrele;
604
605         xfs_ilock(ip, XFS_ILOCK_EXCL);
…
723 out_trans_cancel:
724         xfs_trans_cancel(tp, 0);
725         xfs_iunlock(ip, XFS_ILOCK_EXCL);
726 out_dqrele:
727         xfs_qm_dqrele(udqp);
728         xfs_qm_dqrele(gdqp);
729         return error;
```

Conclusions

- Fault handling in file systems is not in good shape
- Research should be continued
- First conclusions:
  - Fault simulation in unit tests is much more cost effective
  - Systematic tests are more cost effective than random ones

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Thank you!

Alexey Khoroshilov
khoroshilov@linuxtesting.org
http://linuxtesting.org/

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