Finding File System Crash Consistency Bugs Through Fuzzing and Verification

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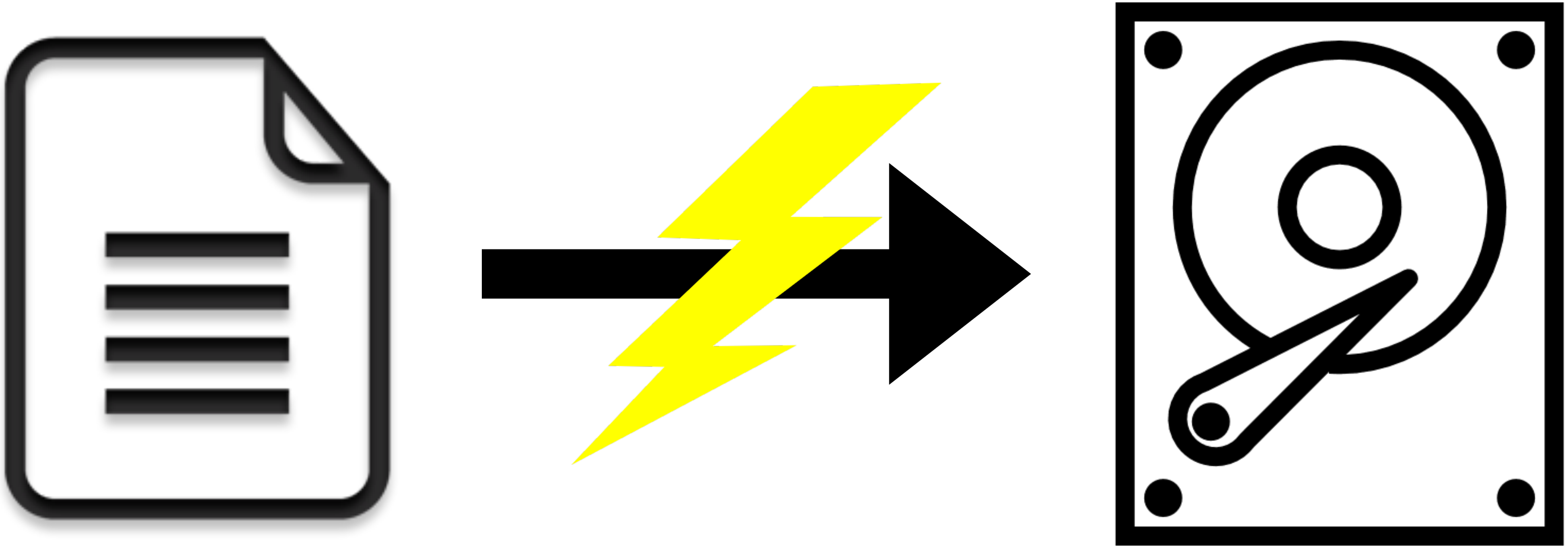


Example crash consistency bug

```
mkdir(A);fsync(A);CRASH!
```

Output of `ls –l` in parent directory:

Expected:

```
total 0
drwxr-xr-x 2 root root 4096 Nov  9 08:23 A
```

Actual:

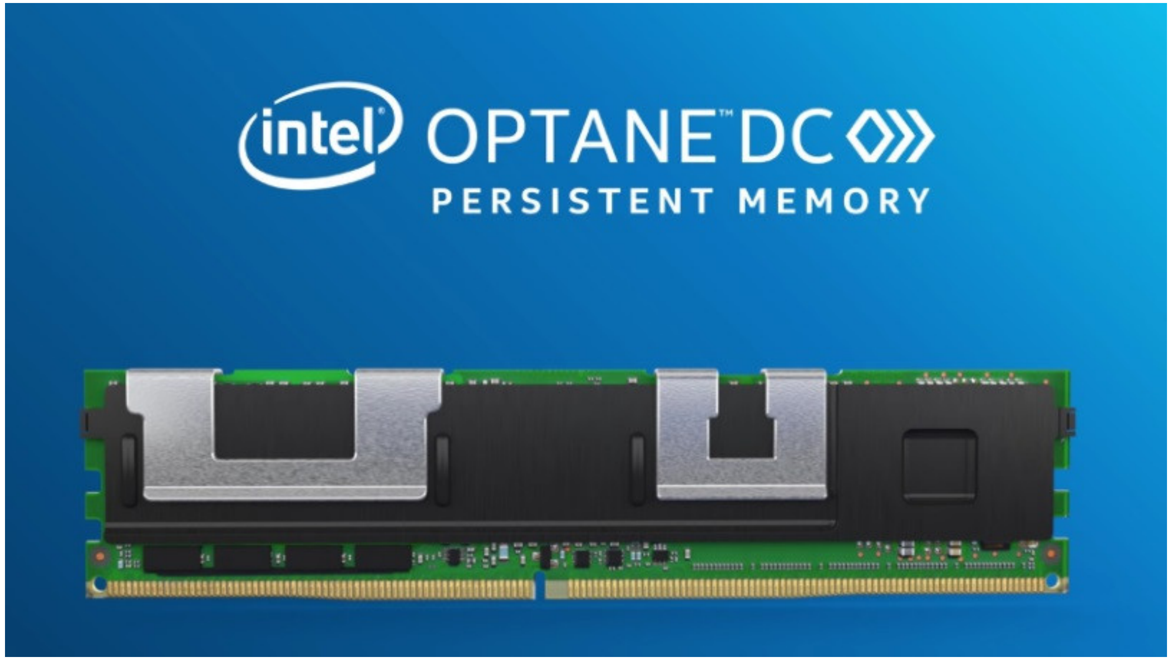
```
ls: cannot access 'A': Input/output error
total 0
d????????? ? ? ? ? ? A
```

Projects

1. Fuzzing for persistent memory file system crash consistency bugs
2. Ext4 journal verification

Persistent memory (PM)

- Non-volatile
- Similar performance to DRAM
- Byte-addressable
- High capacity
- File systems: NOVA, SplitFS, Strata, ext4-DAX…



General approach

- Based on CrashMonkey+ACE (OSDI'18)
- Record-and-replay approach
  1. Run a workload that accesses the file system
  2. Record writes to persistent media via file system
  3. Replay writes up to simulated crash point
  4. Check consistency
- Some new challenges…

Challenges

- How to log writes?
  - CrashMonkey: intercept block I/O by mounting FS on wrapper block device
- PM writes are made via memory load/store interface
- Data must be explicitly flushed or bypass cache with special assembly instructions to guarantee durability Key issue: **no software layer at which to intercept writes**

Challenges

- What types of programs should we test on?
- Few known bugs, little existing work

The NOVA team was aware of **one** crash-consistency bug in their file system

Current approach

- Observation: most writes/flushes to PM in file systems are made by a small set of central library functions
- Loadable kernel module to automatically instrument PM writer functions
- Baseline: tests from ACE
- Found 4 bugs in NOVA with ACE-generated test cases!
  - All confirmed and fixed in main NOVA repo

NOVA crash consistency bugs

- NULL pointer dereference in recovery procedure on 1 core due to bug in per-CPU metadata access
  - **Made crash recovery impossible** on single core machines
- **`fsync`'ed directory inaccessible** due to missing flush on an inode field after `mkdir`
- **File system unwritable** due to lack of flush of updated inumber information after `mkdir`
- **New directory unreadable and undeletable** due to lack of flush on inode valid field after `mkdir`

Next steps

- Fuzzing
  - Generate new test programs based on past programs that exposed bugs
  - Syzkaller (Linux kernel fuzzer) for generating syntactically valid sequences of file system calls

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File system verification

- Can we formally prove that a file system has no crash consistency bugs?
- Some prior work
  - FSCQ (SOSP '15)
  - Yggdrasil (OSDI '16)
- Problem: no work on verifying *existing* file systems

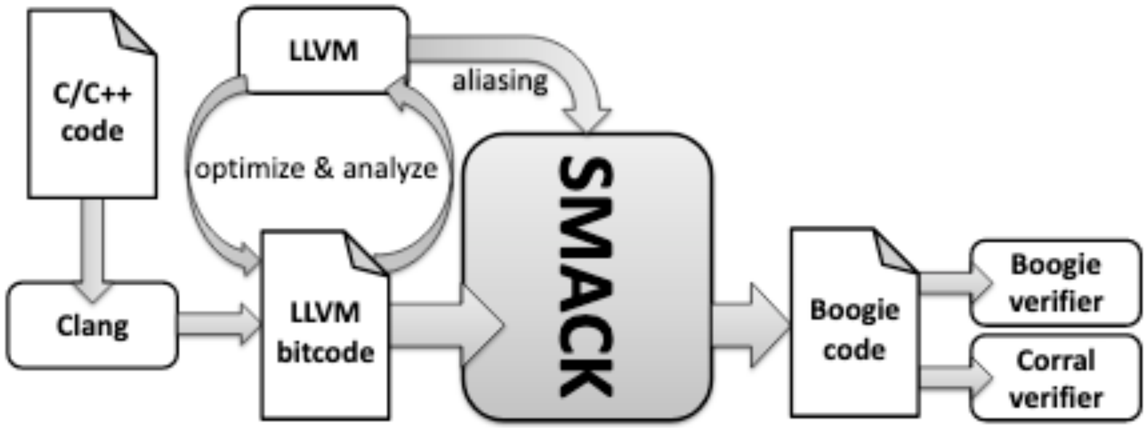
Very quick verification background

- Hoare triples: {P} S {Q}
  - For a precondition P, a statement S, and a postcondition Q: assume P and execute S.
  - If Q always holds, the triple is *valid*
- Hoare triples form basis of deductive program verification
- Can specify a program using Hoare triples and check correctness using SMT solver

Our goal: formally verify Linux's JBD2 journaling system

Current approach

- Exploring both bounded model checking and full deductive verification
- One possible workflow:
  - Boogie: intermediate verification language
  - Corral: bounded verifier
  - SMACK: C → Boogie translator



Challenges

- How best to model on disk state?
- How to reduce amount of manual effort?
- Is bounded verification feasible?
- Is full verification feasible?

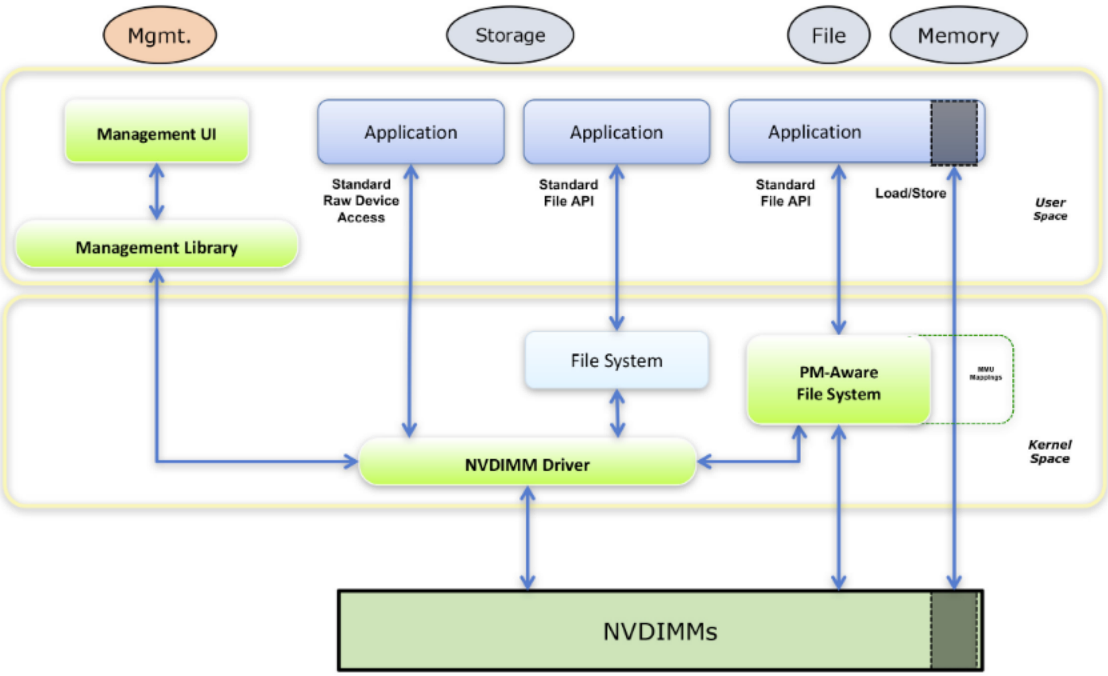
Conclusion

- Crash consistency bugs can have serious consequences in real file systems
  - PM file systems
  - Mature systems like ext4
- Exploring 2 approaches to finding bugs
  - Record-and-replay + fuzzing for PM file systems
  - Formal verification of ext4 journal

Supplemental slides

Writing to PM

- x86
  - CLWB: flush a cache line to persistent memory
  - SFENCE: enforces order in which memory stores become globally visible
  - CLWB+SFENCE: enforces order in which data is made durable in PM



No CLWB → data is not guaranteed to be persisted!

Very quick ext4 background

- Ext4: most widely used Linux file system
- Uses a *journal* (JBD2) to ensure crash consistency
  - Make a note of new operations in journal before actually executing them
  - If we crash, replay journal onto the main FS

Transaction 1 start	Some data	Some more data	Transaction 1 end	Transaction 2 start	…

Corral

- Reachability problem: for a control flow graph, does there exist a path from the initial state to the error state?
    - I.e., is there an execution that establishes the presence of an error?
    - In general, recursively enumerable and undecidable
- Reachability is decidable for *bounded* programs

Corral

- Takes a recursion bound from the user
- Statically inlines loops and recursive procedures up to provided bound
- Inlined program can be verified as though it is a program with no loops
  - Makes verification decidable because all possible executions can now be explored