Using lightweight formal methods to validate a key-value storage node in Amazon S3

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Outline

- Introduction and ShardStore
- Validating a Storage System
- Conformance Checking
- Checking Crash Consistency
- Checking Concurrent Executions
- Other Properties
- Experience and Lessons

Introduction and ShardStore

ShardStore and S3

- The core of S3 are storage node servers
- ShardStore — new key-value storage node
    - 40k lines of code in Rust
    - Crash consistency and concurrency in the implementation
    - Slowly rolling out to replace previous version

Validation goals

- Functional API correcteness

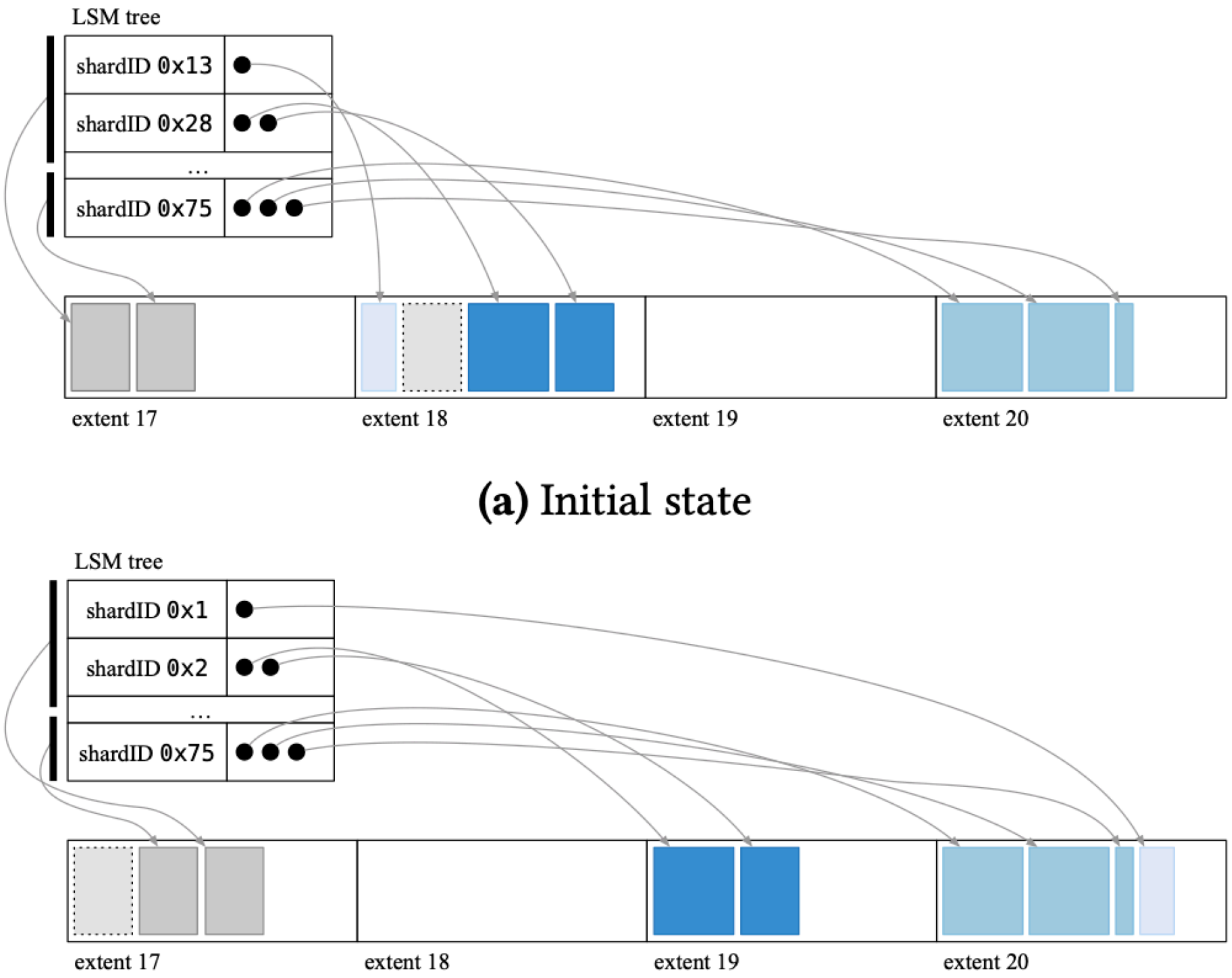
- Crash consistency of on disk data

- Concurrent correctness of API calls and background tasks

Soundness-correctness trade-off — willing to accept weaker guarantees than formal methods

ShardStore

- Log-Structured Merge Tree (LSM)
- Data in chunks, chunks in extents
- More than one log complicates crash consistency
- Garbage collection (GC) in the background



(a) Initial state

(b) After reclamation of extent 18 and LSM-tree flush

Figure 1. ShardStore's on-disk layout

Validating a Storage System

Properties

- Focus on durability and consistency
- Performance and availability is out of scope
- Additional safety properties — undefined behavior, bounds checking, etc

Results must outlive involvement of formal methods experts and be supported by development team in the future

=> lightweight approach to formal methods

Three views on durability

		Section
Sequential	Crash-free	“4 Conformance Checking”
Sequential	With crashes	“5 Checking Crash Consistency”
Concurrent	Crash-free	“6 Checking Concurrent Executions”
Concurrent	With crashes	Out of scope

Reference model

- Executable specification with the same interface in Rust
- 1% of the size of the implementation
- For simplicity omits implementation failures (IO, resource exhaustion, etc)
- Also used as a mock for unit tests, to help keep it up-to-date

Conformance Checking

Property-based testing

- Implementation code refines the model
- Argument bias to steer into interesting states
- Default to random selection, only bias if have quantitative evidence of the benefit
- Code coverage to identify blind spots in tests

Failure injection

- Fail-stop crash
    - Covered in “5 Checking Crash Consistency”
- Disk IO error
    - Relax check against the model
- Resource exhaustion
    - Out of scope for property-based testing

Checking Crash Consistency

Write path

Crash consistency is the primary motivation for this effort

Every put operation has three steps:

1. Write chunked data to an extent
2. Write index entry in the LSM tree
3. Update LSM tree metadata to point to new on-disk index data

Dependency graph

- Inspired by soft updates
- IO scheduler respects dependencies
- Next append only issued if dependency is persisted

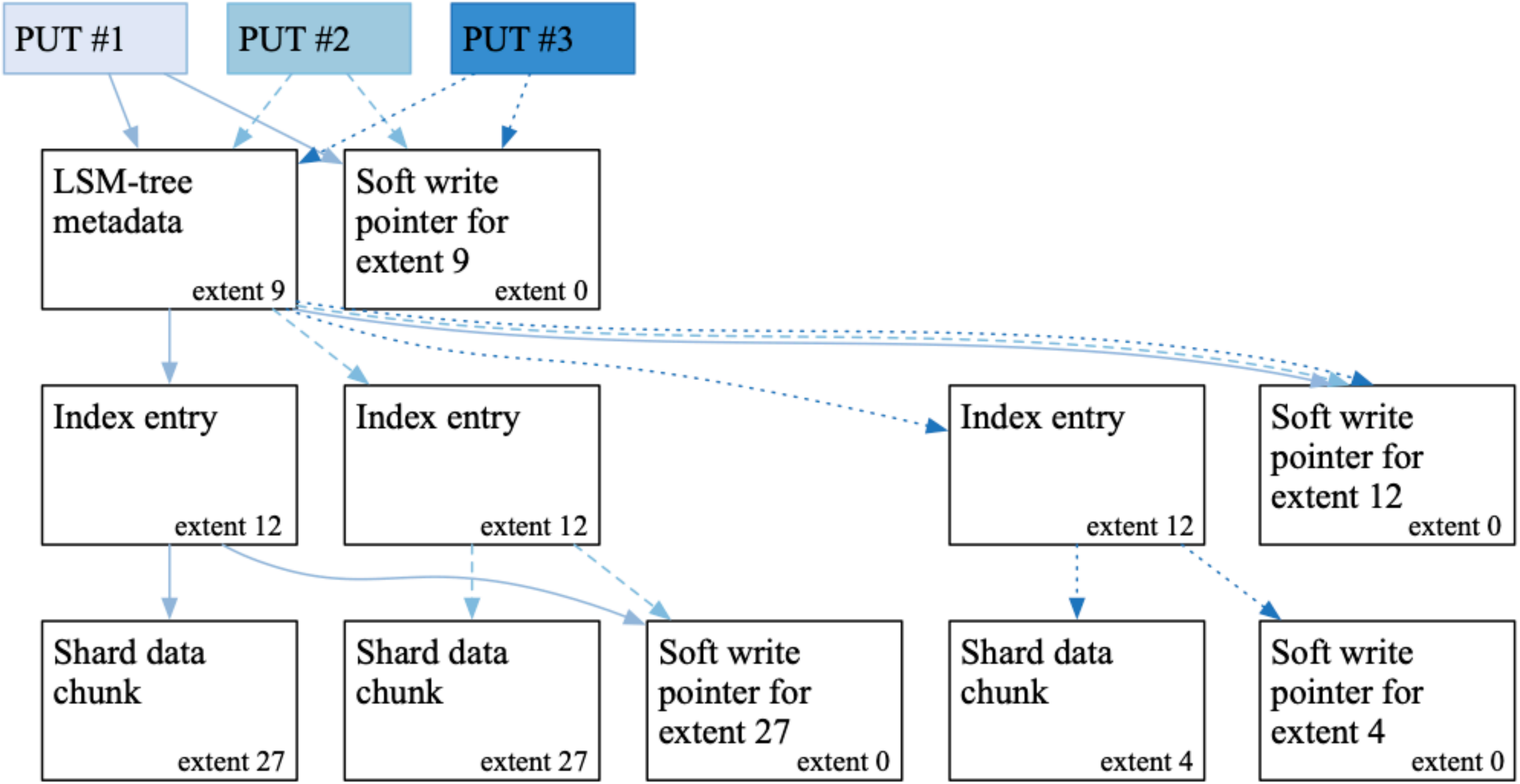


Figure 2 (a) Dependency Graph

Two properties

Persistence — if dependency is persisted, it should be visible after the crash

Forward progress — after non-crash shutdown every operation’s dependency is persistent

Extending property-based testing

- Add new operations to model (e.g. DirtyReboot, IndexFlush)
- Adding block-level crash states proved to be slow and did not uncover new bugs
    - Block level crashes are not used by default

Checking Concurrent Executions

Checking Concurrent Executions

Checking for linearizability

Hand-written harness to validate key properties

- Loom model checker for Rust with sound model checking (slow)
- Shuttle model checker with probabilistic algorithms (faster)

Loom and Shuttle offer a soundness-scalability trade-off

Other Properties

Other properties

- Undefined behavior
  - Miri interpreter for Rust
  - Rust compiler dynamic analysis tools
- Serialization
  - Crux symbolic execution engine to prove panic-freedom
  - Fuzzing

Experience and Lessons

Experience

- Developing the reference model took ~ 2 x 9 months of FM experts
- Non-experts contributed 18% of the model code so far

Benefits:

- Early detection is a great
- Continuous integration/validation keeps the model up-to-date

Limitations

- Hard to evaluate coverage by property-based tests
- Accidental complexity gluing with S3 not covered
- Huge API surface — not everything is covered

Testing distributed systems

Curated list of resources on testing distributed systems
https://asatarin.github.io/testing-distributed-systems/

The end

Contacts

- Follow me on Twitter @asatarin
- https://www.linkedin.com/in/asatarin/
- https://asatarin.github.io/

References

- Self reference for this talk (slides, video, etc)
- "Using lightweight formal methods to validate a key-value storage node in Amazon S3" paper
- Talk at SOSP 2021
- Blog post from Murat Demirbas