ER-π: Exhaustive Interleaving Replay for Testing Replicated Data Library Integration

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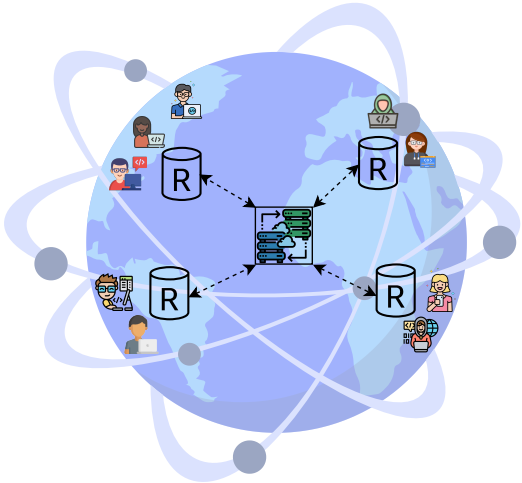
Table of Contents

Replicated Data System (RDS)



+ High availability
+ Low latency
+ Partition tolerance
+ Scalability

RDS in Practice

Domains

Platforms

Azure

ORACLE
GOLDEN GATE

APACHE hadoop

Middleware Designs

- CRDT
- MRDT
- ECRO

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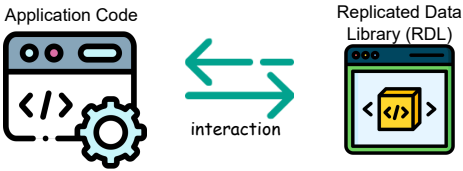
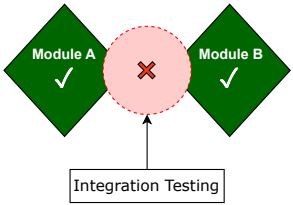
Integrating RDL and Testing the Integration



App ⇔ RDL Interaction



Problem Context

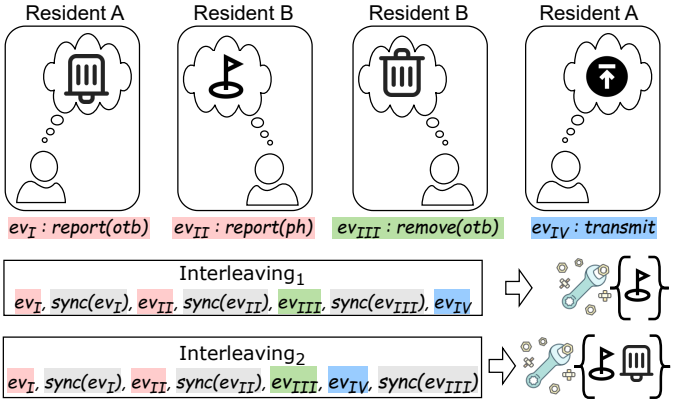
Application developers often:

- misunderstand RDL properties [1]
- hold incorrect assumptions [2]

Goals:

- ✗ Test RDL Design
- ✗ Test RDL Implementation
- ✔ Test RDL Integration

Motivating Scenario



Challenges

- Non-deterministic distributed execution
- Subtle bugs in some interleavings [3]
- Exhaustive replay for bug reproduction
- Combinatorial explosion of interleavings
- Impractical exhaustive replay

Solution Overview

ER-π—a middleware for exhaustive integration testing of RDL-based applications.

1. Detects distributed events raised from the app–RDL interactions.
2. Generates and persists all possible interleavings.
3. Reduces the problem space via *four* novel pruning algorithms.
4. Replays interleavings to reproduce bugs.

Pruning Algorithms

1. Event Grouping
2. Replica Specific
3. Event Independence
4. Failed Ops

Event Grouping

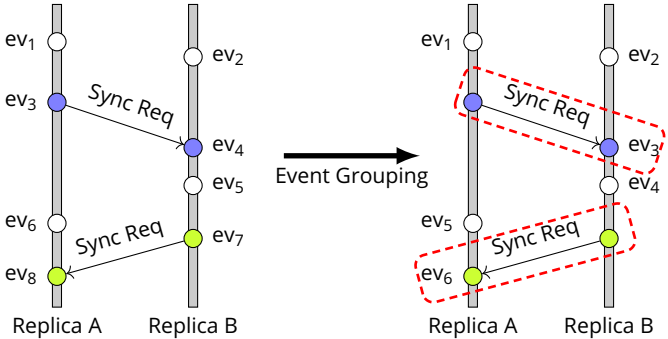


Figure: Grouping Events to Reduce Their Total #

Replica Specific

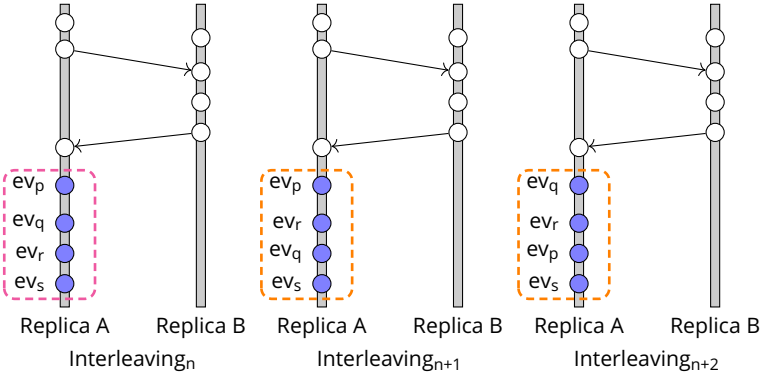
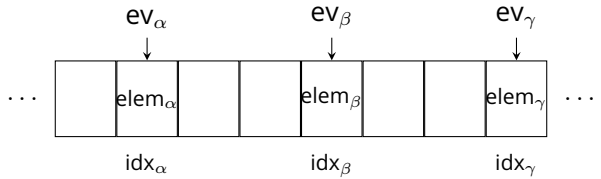


Figure: Replica B-specific Pruning

Event Independence



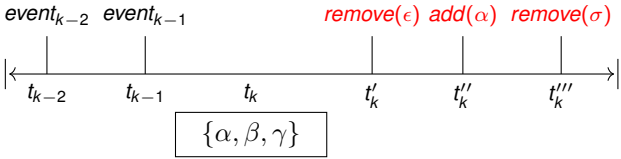
If Explored: {...ev_α, ev_β, ev_γ...}

Consider Explored: {...ev_α, ev_γ, ev_β...}

Consider Explored: {...ev_β, ev_α, ev_γ...}

Figure: Event Independence Pruning

Failed Ops



If Explored: {...*remove*(ϵ), *add*(α), *remove*(σ)...}

Consider Explored: {...*remove*(ϵ), *remove*(σ), *add*(α)...}

Consider Explored: {...*add*(α), *remove*(ϵ), *remove*(σ)...}

Figure: Failed Ops Pruning

Motivating Example Revisited

1. ev_I : *report*(*otb*)
2. *sync*(ev_I)
3. ev_{II} : *report*(*ph*)
4. *sync*(ev_{II})
5. ev_{III} : *remove*(*otb*)
6. *sync*(ev_{III})
7. ev_{IV} : *transmit*

7 Events $\equiv$ 5040 Interleavings

- Sync event causally depends on the corresponding update event
  - i) $(ev_I, sync(ev_I)) \Rightarrow ev'_I$
  - ii) $(ev_{II}, sync(ev_{II})) \Rightarrow ev'_{II}$
  - iii) $(ev_{III}, sync(ev_{III})) \Rightarrow ev'_{III}$
  - iii) ev_{IV} : *transmit*

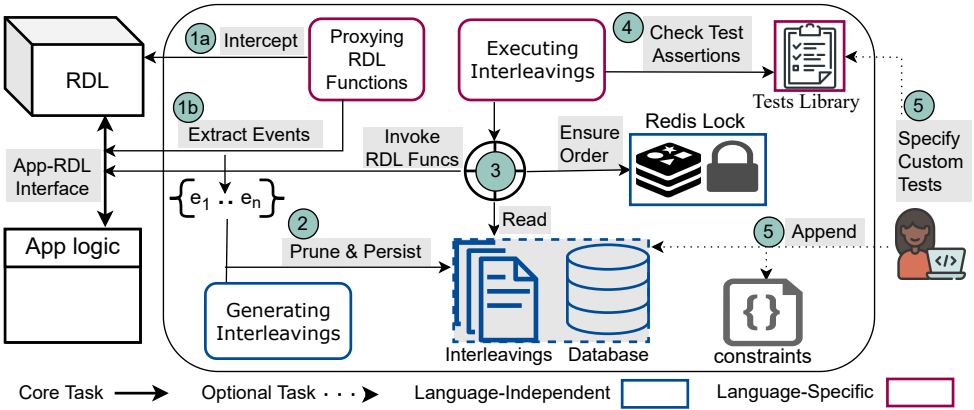
4 events $\equiv$ 24 Interleavings

- $\{ev_{IV}, \underbrace{\{ev'_I, ev'_{II}, ev'_{III}\}}_{3!=6}\} \rightarrow$ Problems: $\{\} \Rightarrow$ 1 Interleaving

Total Interleavings: $24 - 5 = 19$

Problem Space Reduction: $\lfloor \frac{5040}{19} \rfloor = 265\times$

System Components and Workflow



Implementation

Language-

- Specific Components: Go($\approx$ 300), JavaScript($\approx$ 280), and Java($\approx$ 415)
- Agnostic Components: C++($\approx 2K$)

Distributed Lock: Redis Lock [4]

Research Questions

- ✓ RQ1: Reproducing Bugs
- ✓ RQ2: Recognizing Misconceptions
- ✓ RQ3: Reducing Problem Space

RQ1: Reproducing Bugs

BugName	Issue#	#Events	Status	Reason
1. Roshi-1	18	9	closed	misconception
2. Roshi-2	11	10	closed	RDL issue
3. Roshi-3	40	21	closed	misconception
4. OrbitDB-1	513	12	open	—
5. OrbitDB-2	512	8	open	—
6. OrbitDB-3	1153	15	closed	misuse
7. OrbitDB-4	583	18	closed	misconception
8. OrbitDB-5	557	24	closed	misconception
9. ReplicaDB-1	79	10	closed	misuse
10. ReplicaDB-2	23	14	closed	misconception
11. Yorkie-1	676	17	open	—
12. Yorkie-2	663	22	closed	misconception

Table: Bug benchmarks. ``#Events''—# of interleaved events. ``Status''—if the bug is closed by library developers. ``Reason''—what causes the bug.

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RQ2: Recognizing Misconceptions

1. The underlying network ensures causal delivery [5].
2. The order of List elements is always consistent [5].
3. Moving items in a List doesn't cause duplication [6].
4. Sequential IDs are always suitable for creating new items in a to-do list [6].
5. Multiple replicas in different regions mathematically resolve to the same state without coordination [7, 2].

RQ3: Reducing Problem Space

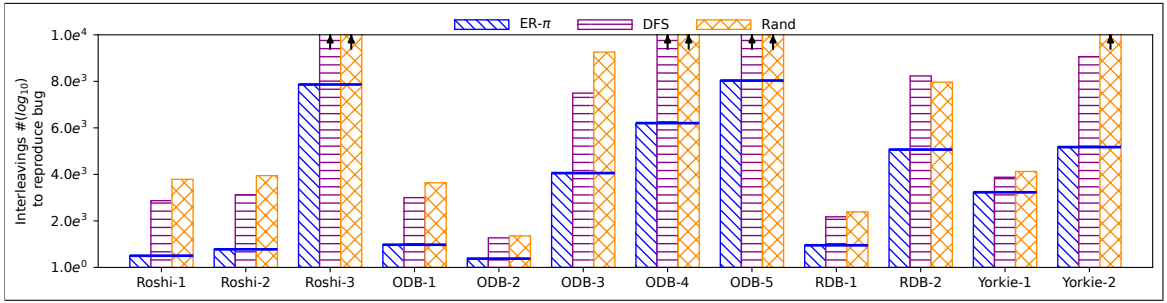

Figure: Number of Interleavings Explored to Reproduce Bug

RQ3: Reducing Problem Space

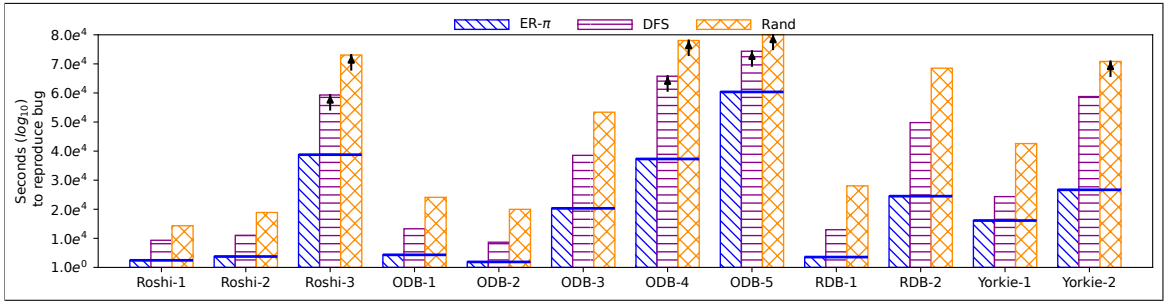

Figure: Time Required to Reproduce Bug

Limitations

- SUT comprises distinct RDL and business logic components
- Pruning algorithms assume eventual consistent RDLs
- Interfacing with RDLs relies on robust proxying support

Insights and Implications

Key Insights

- Non-deterministic interleavings can cause subtle bugs
- Misconceptions about App-RDL interactions are common
- Exhaustive interleaving replay is feasible with effective pruning
- Middleware for integration testing can benefit RDL applications

Implications

- Middleware for replaying interleavings is useful, even without pruning
- Testing RDL-based applications requires tools like ER-π
- Future RDL design should strive to minimize usage misconceptions

Summary

ER-π—a middleware for exhaustive integration testing of RDL-based applications.

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4. Replays interleavings to reproduce bugs.

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