Simulating Failure Recovery *In Situ* for Production Distributed Systems

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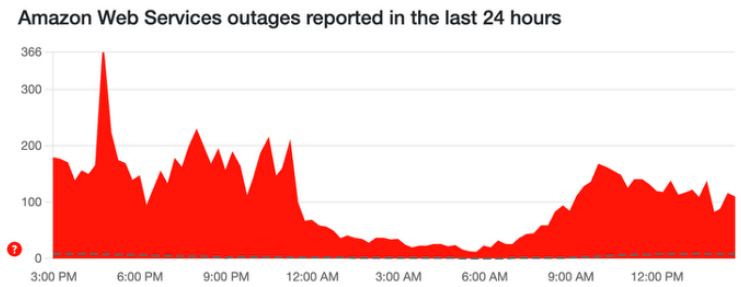
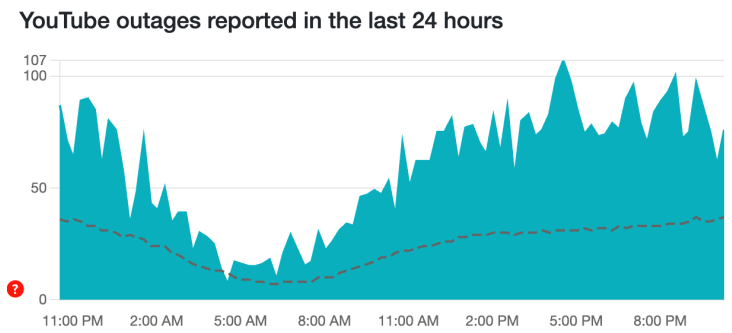
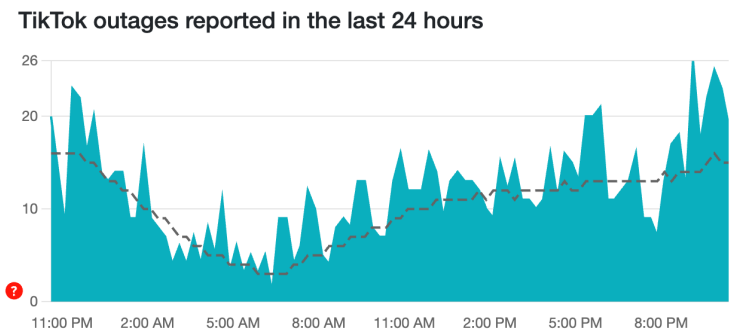
nsdi '26

University of Virginia

Failures are inevitable in cloud systems

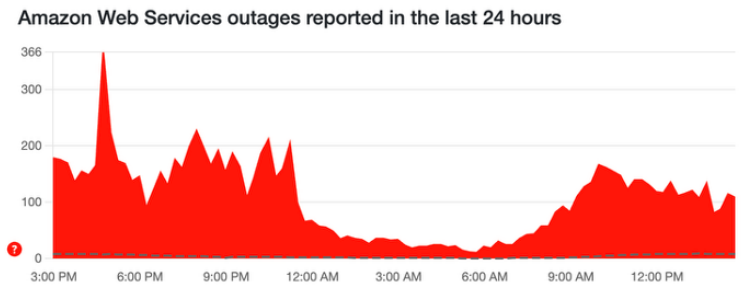


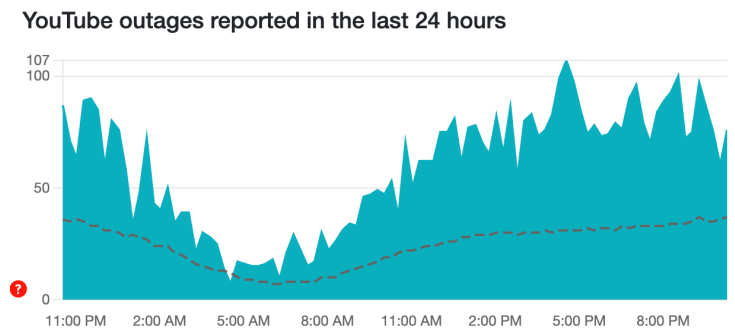


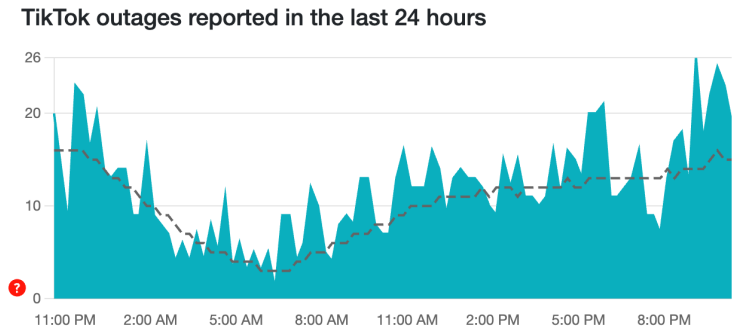


Statistics from downdetector.com

Failures are inevitable in cloud systems







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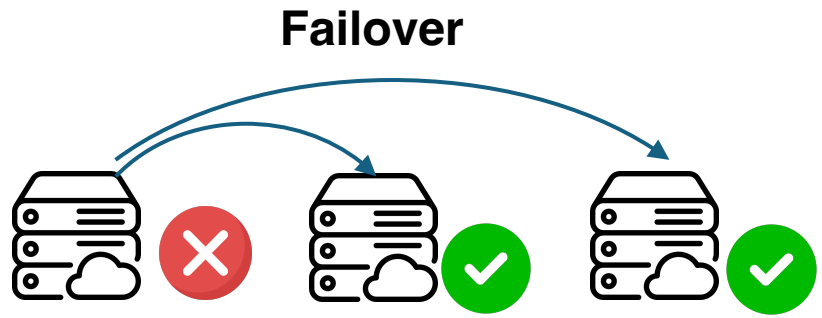
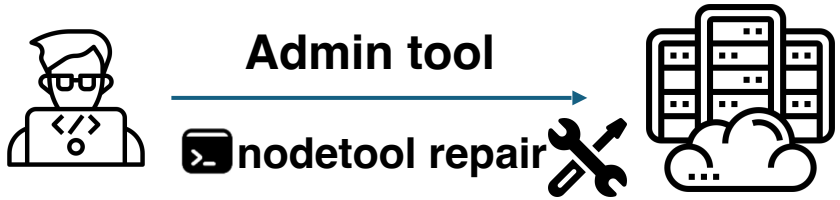
Correct recovery is critical





Ironically, recovery itself is error-prone in production

- Recovery failures: incorrect recovery actions that **fail to alleviate** failures, or even **amplify** consequences

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Kubernetes Liveness and Readiness Probes: How to Avoid Shooting Yourself in the Foot [1]

Nov 4, 2018

I expand on these ideas in my presentation Kubernetes Probes: How to Avoid Shooting Yourself in the Foot.

kubernetes

[1] https://blog.colinbreck.com/kubernetes-liveness-and-readiness-probes-how-to-avoid-shooting-yourself-in-the-foot/

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Kubernetes Liv
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Summary of Windows Azure Service Disruption on Feb 29th

its standard autonomic failure recovery operations for a server in the HI state, the FC will service heal any VMs that were assigned to the failed server by reincarnating them to other servers. In a case like this, when the VMs are moved to available servers the leap day bug will reproduce during GA initialization, resulting in a cascade of servers that move to HI.

kubernetes

Azure

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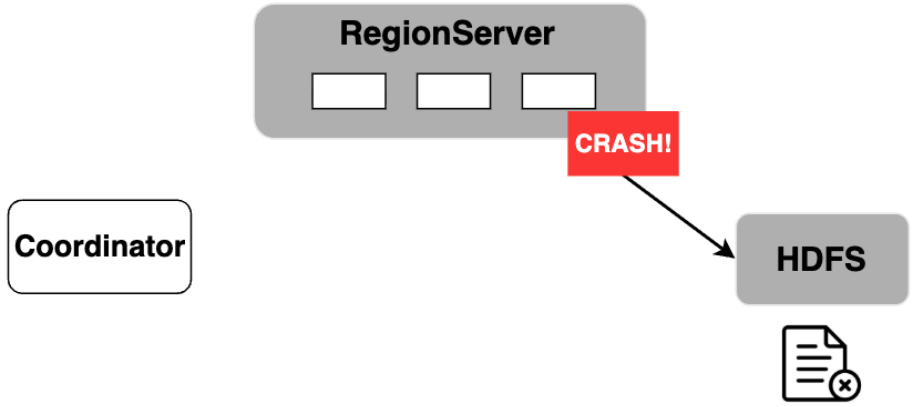
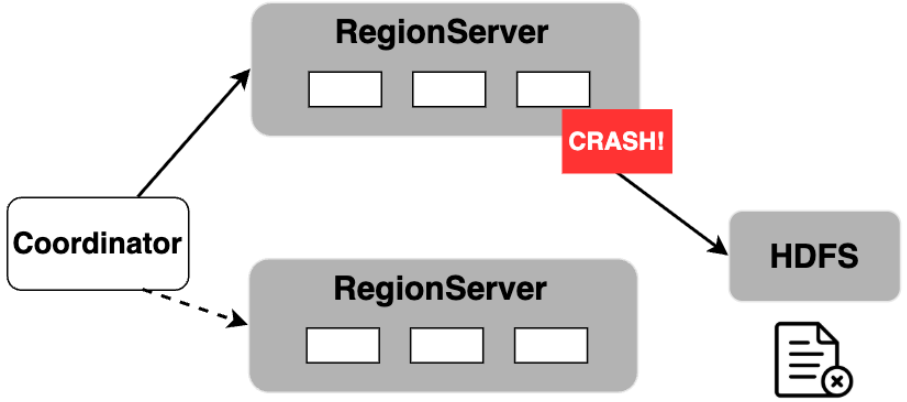
[2] https://azure.microsoft.com/en-us/blog/summary-of-windows-azure-service-disruption-on-feb-29th-2012/

A real-world recovery failure in HBase production clusters



(1) RegionServer crashed while replicating a buggy log file

A real-world recovery failure in HBase production clusters



(1) RegionServer crashed while replicating a buggy log file

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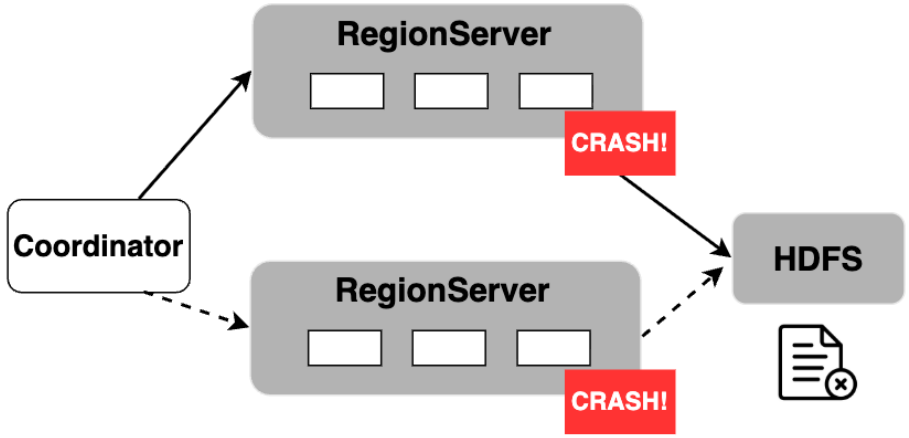
A real-world recovery failure in HBase production clusters



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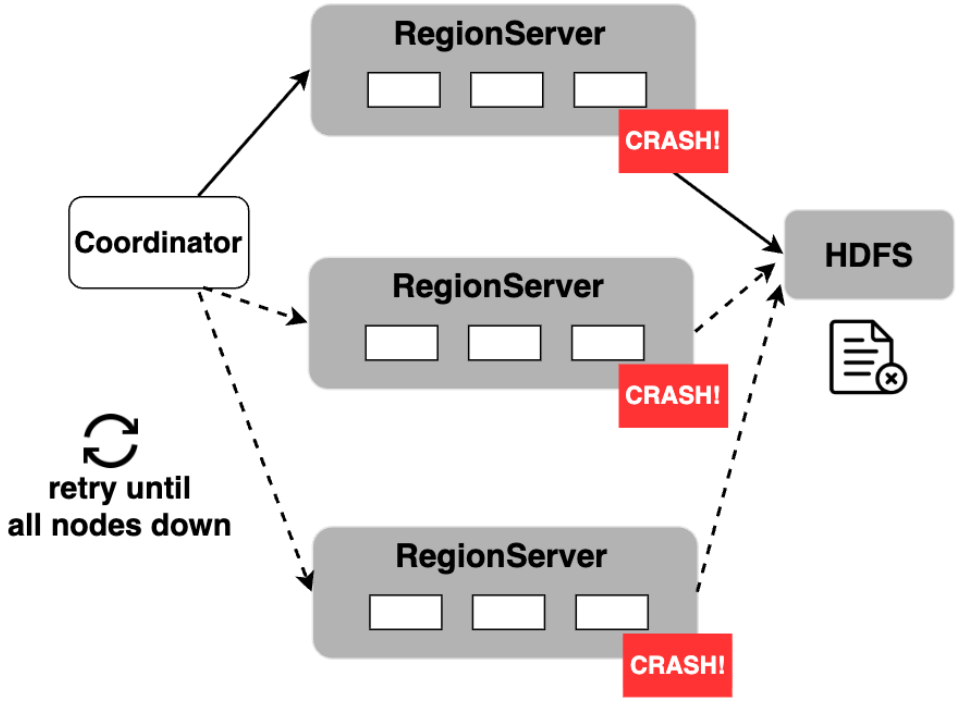
(3) RegionServer crashed again due to the resumed replication task!

A real-world recovery failure in HBase production clusters



(1) RegionServer crashed while replicating a buggy log file

(2) Coordinator initiated the recovery

(3) RegionServer crashed again due to the resumed replication task!

Without proper checking, recovery can become a deadly source of new failures!

(4) The whole cluster would be down with cascading failures**!**

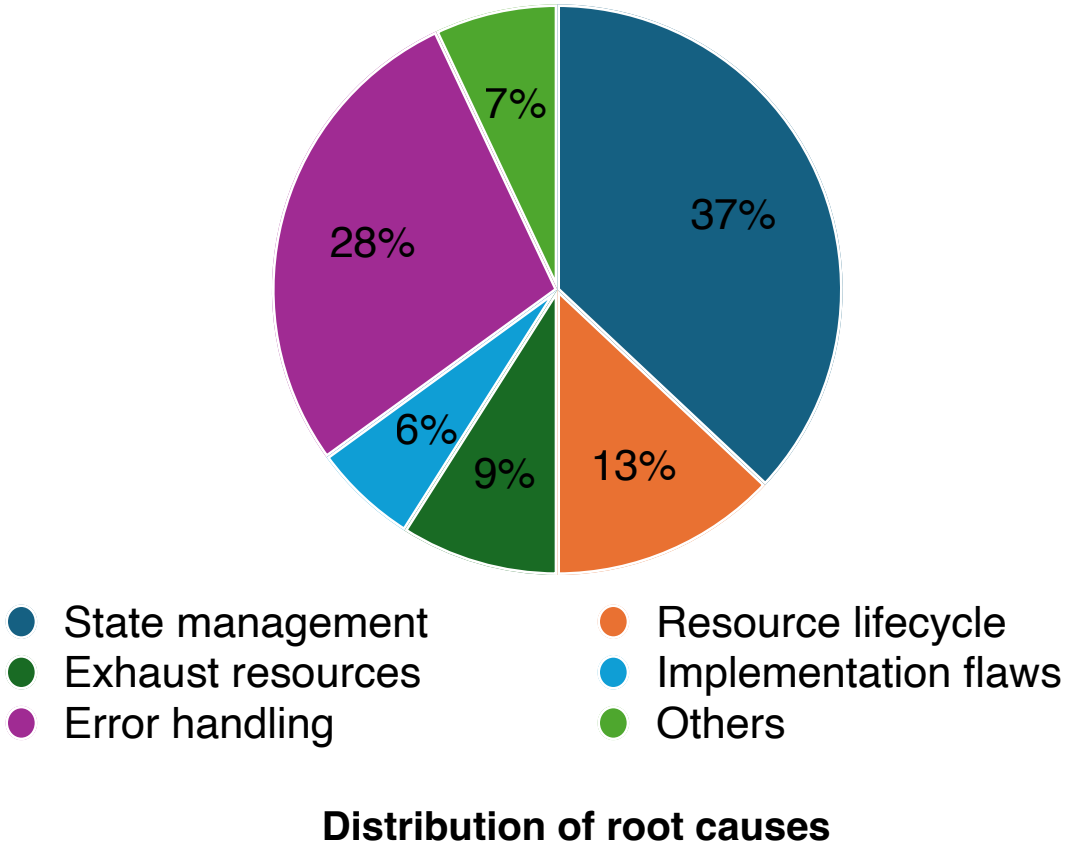
Failure study

- We studied **75** production incidents induced by recovery from **8 systems**
  - Recovery failures are **prevalent**
  - Recovery failures often lead to **severe consequences**

Software	Lang.	Category	Date	Sampled
HDFS	Java	File Sys.	2014-2024	10
HBase	Java	Database	2010-2025	15
YARN	Java	Resource Mgr.	2014-2025	5
TiDB	Go	Database	2019-2025	5
Kafka	Scala	Streaming	2017-2024	10
Cassandra	Java	Database	2011-2024	15
RabbitMQ	Erlang	Message Bkr.	2016-2024	5
Mesos	C++	Resource Mgr.	2015-2022	10

Study findings (selected)

- Finding 1: The root causes of recovery failures are diverse



Distribution of root causes

Study findings (selected)

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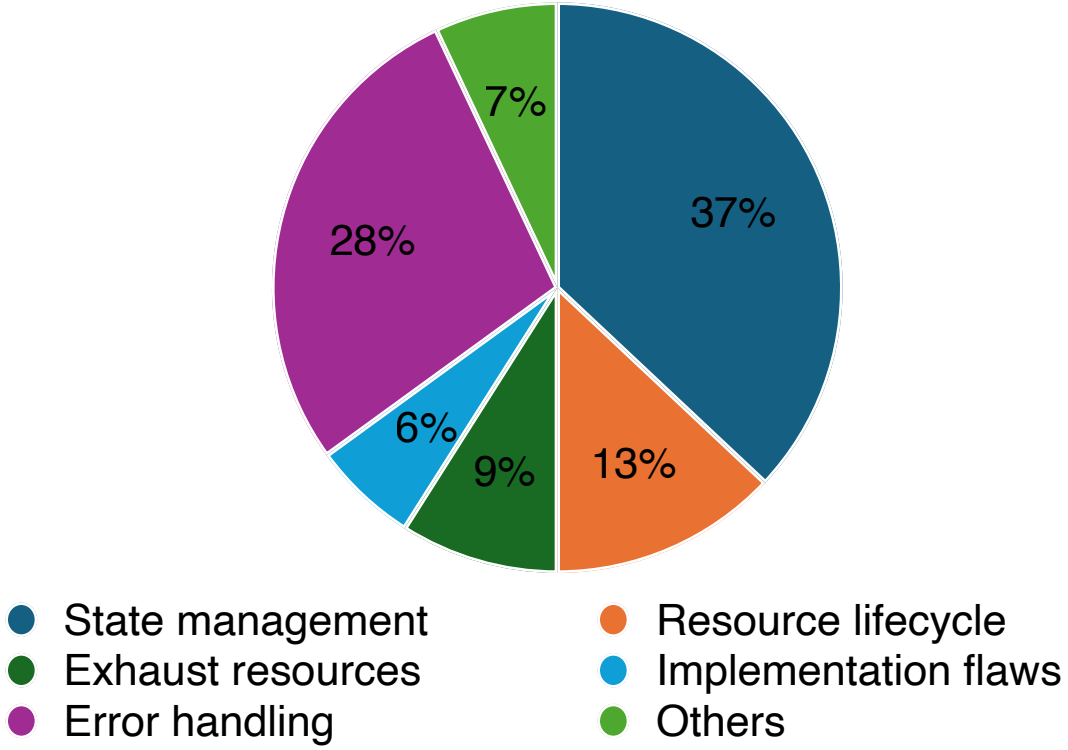
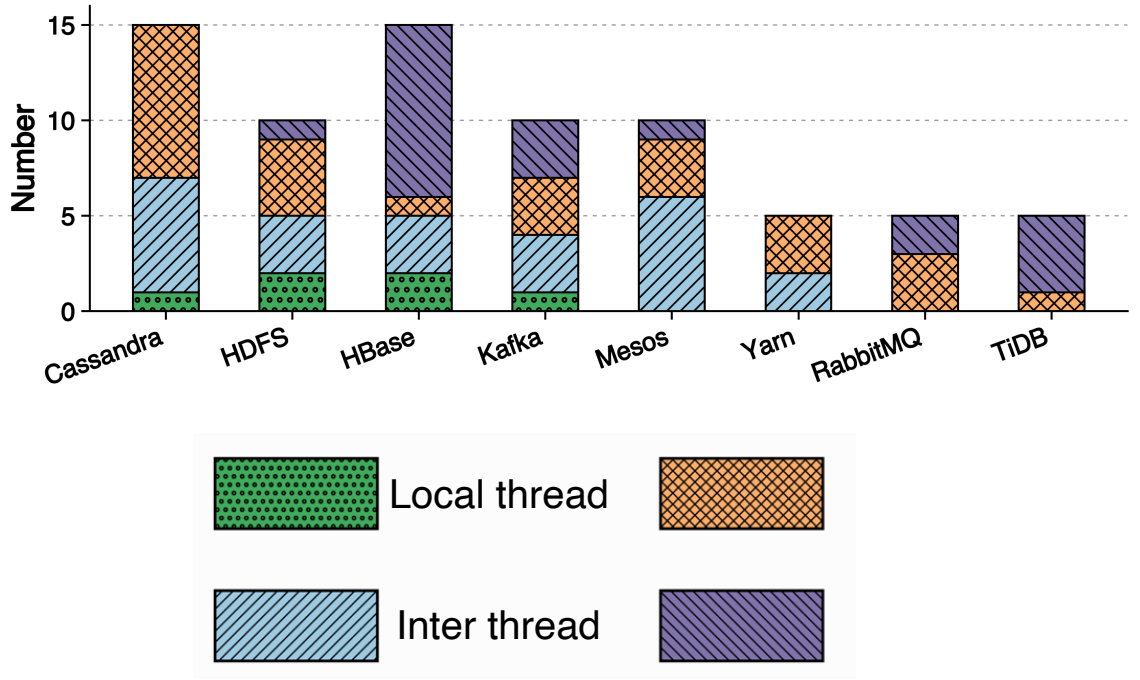


Distribution of root causes

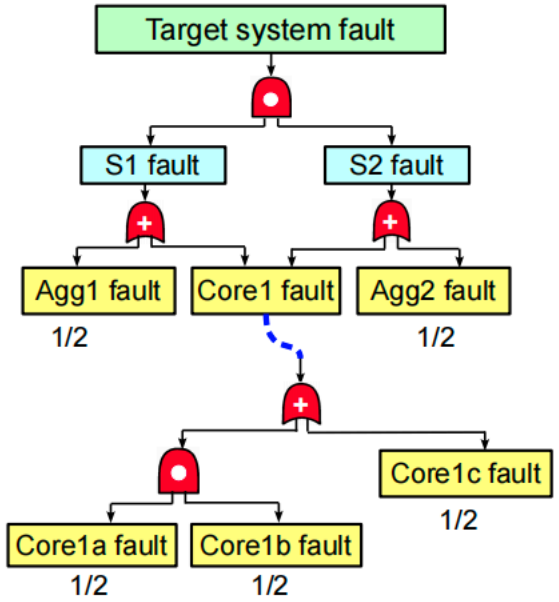
- Finding 2: Most recovery failures (92%) manifest beyond local thread scope



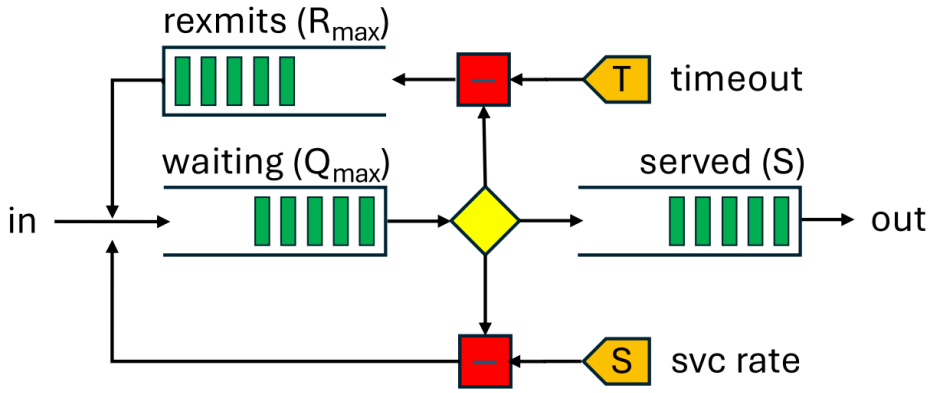
Distribution of the scope of recovery failures

Existing work

- **Offline** approaches model the system or test before deployment
  - Miss **low-level implementation bugs**
  - Miss **issues caused by dynamic interactions** (Finding 1, Finding 2)



CloudCanary [NSDI'20]



Metastability [HotNets'25]

Existing work

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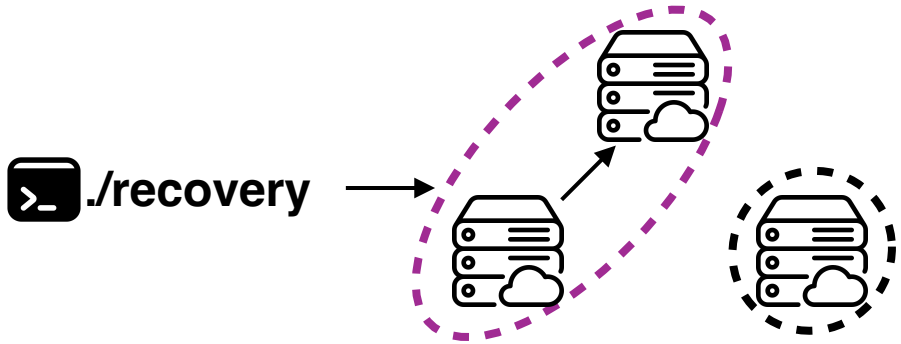
- **Online** approaches predict failures using runtime information
  - Different node setups and workloads could cause **inaccuracy**
  - Lack built-in **safety mechanism**



Narya [OSDI'20]

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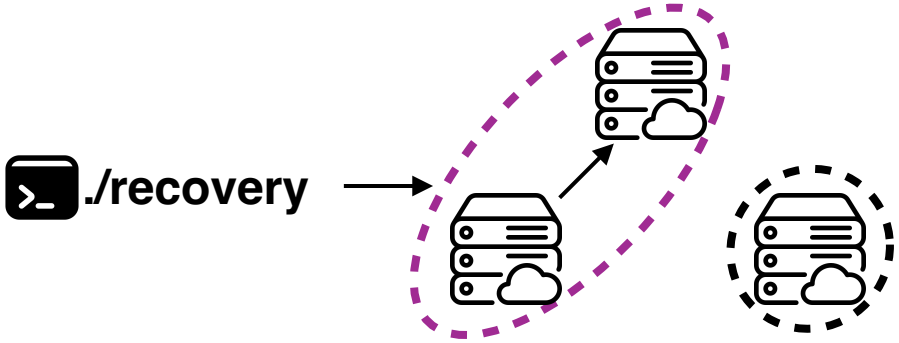
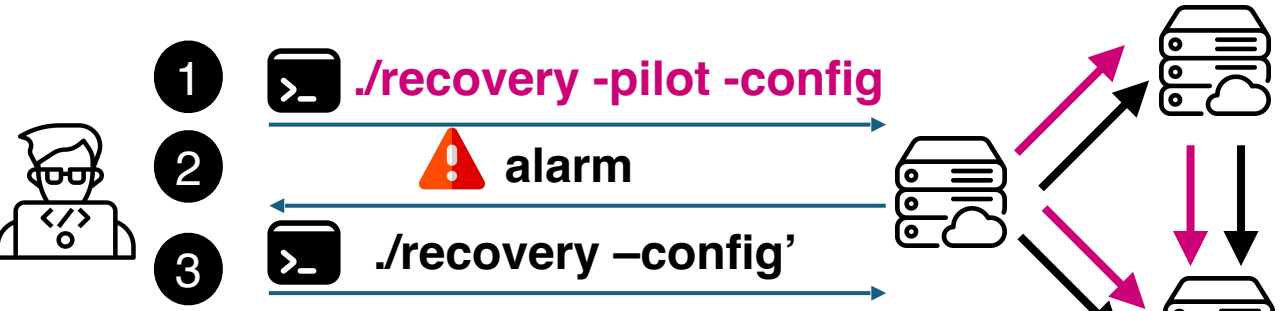


Narya [OSDI'20]

Can we simulate recovery accurately and safely?

Pilot Execution

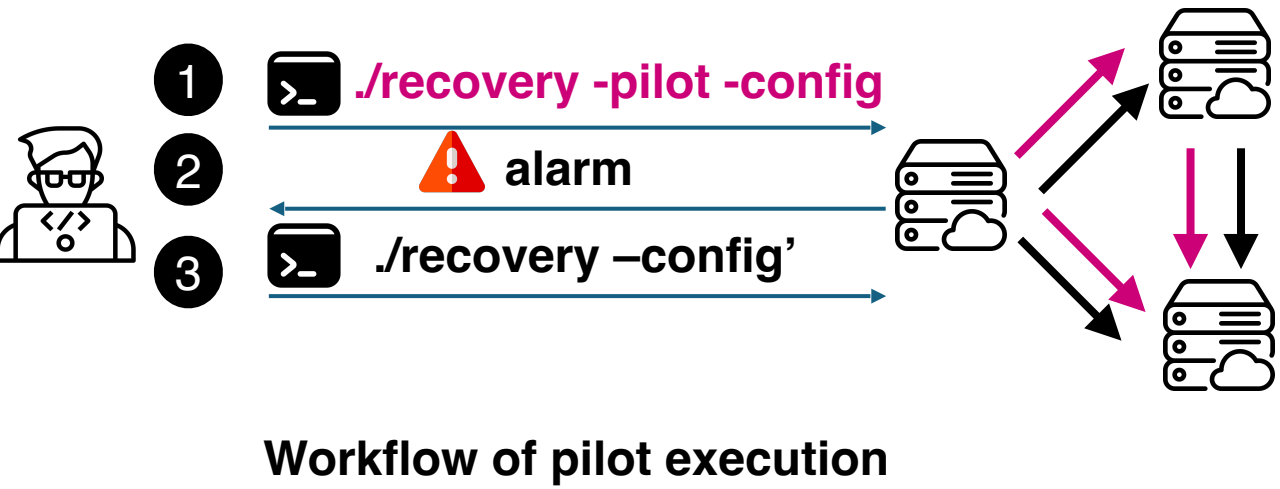
- Preview recovery before committing it, so operators can validate its consequences



Workflow of pilot execution

Pilot Execution

- Preview recovery before committing it, so operators can validate its consequences



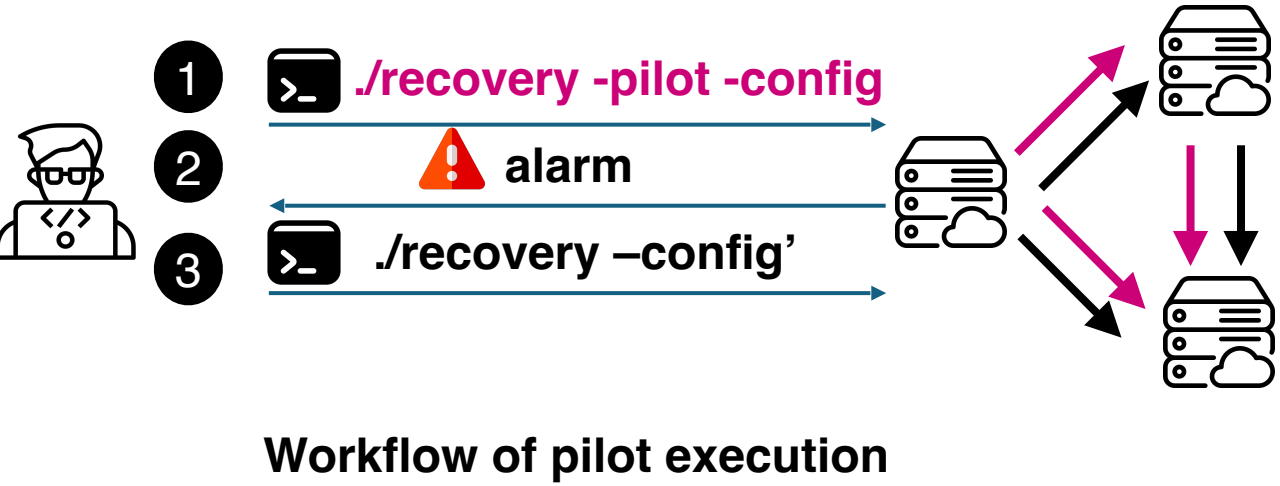
Workflow of pilot execution

Speculative execution treats early execution as an optimization

Pilot execution treats early execution as a safety check for recovery

Pilot Execution

- Preview recovery before committing it, so operators can validate its consequences

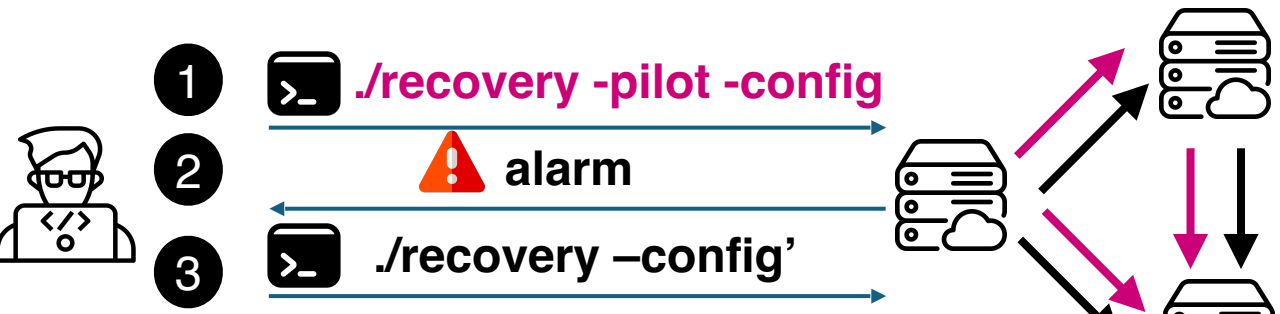


Workflow of pilot execution

Challenge1
Run in production without disruption

Pilot Execution

- Preview recovery before committing it, so operators can validate its consequences

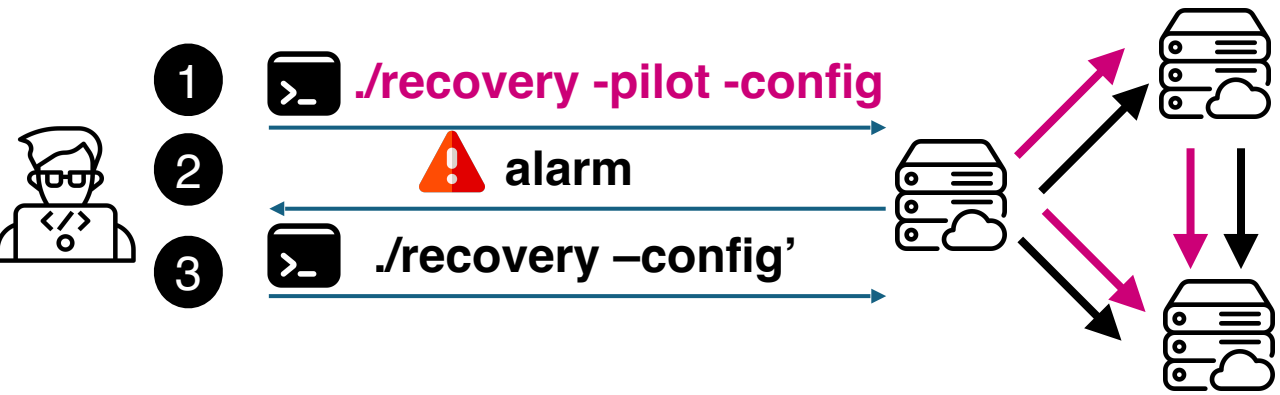


Workflow of pilot execution

Challenge1
Run in production without disruption
Isolate simulation with phantom threads

Pilot Execution

- Preview recovery before committing it, so operators can validate its consequences



Workflow of pilot execution

Challenge1
Run in production without disruption
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Challenge 2
Simulate recovery in distributed environment

Pilot Execution

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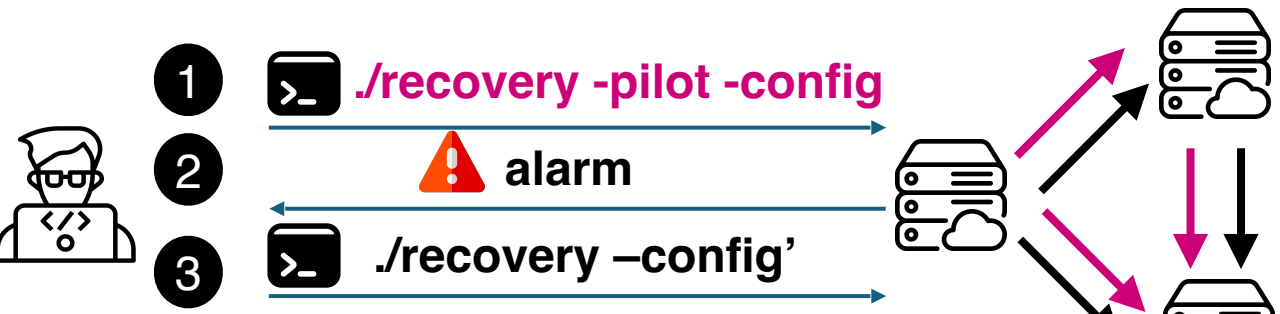


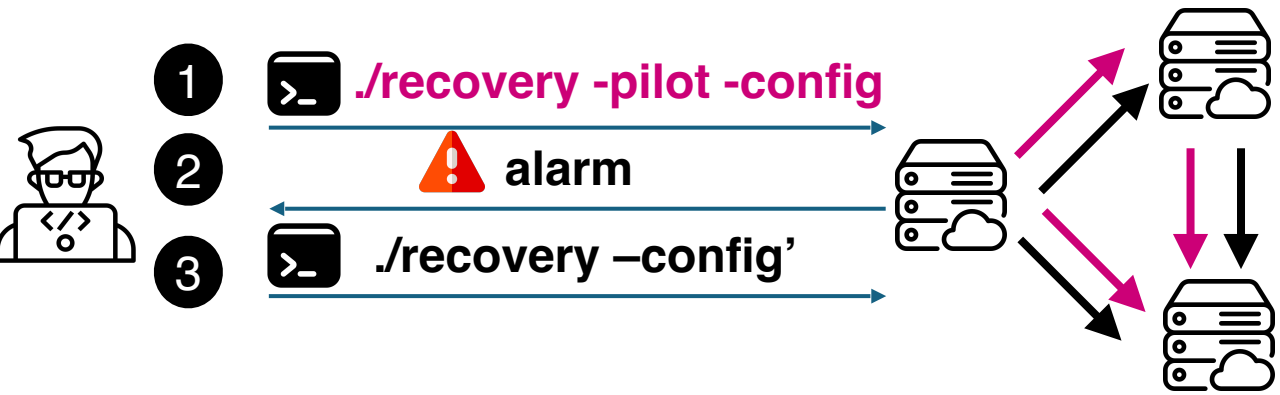
Workflow of pilot execution

Challenge1
Run in production without disruption
Isolate simulation with phantom threads

Challenge 2
Simulate recovery in distributed environment
Propagate execution with tracked metadata

Pilot Execution

- Preview recovery before committing it, so operators can validate its consequences



Workflow of pilot execution

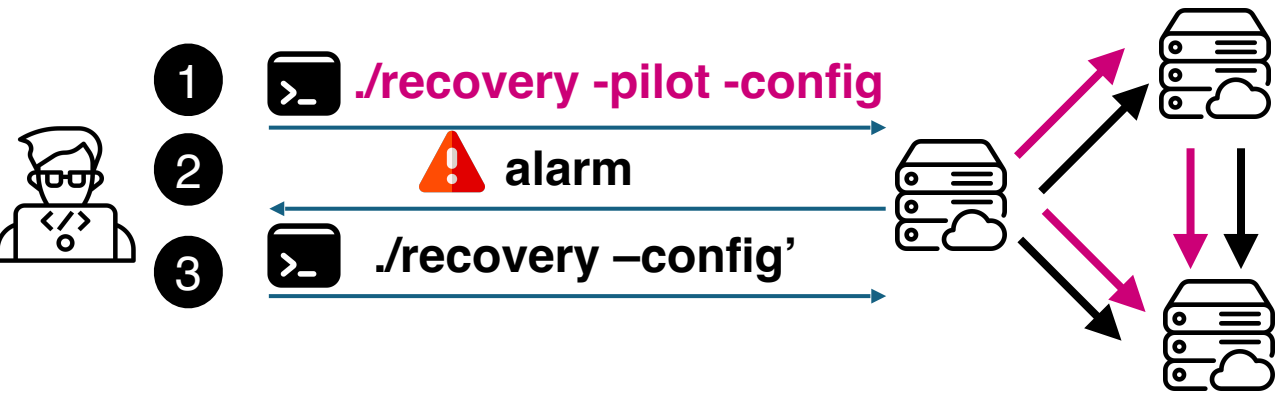
Challenge1
Run in production without disruption
Isolate simulation with phantom threads

Challenge 2
Simulate recovery in distributed environment
Propagate execution with tracked metadata

Challenge 3
Limit delay to the original recovery

Pilot Execution

- Preview recovery before committing it, so operators can validate its consequences



Workflow of pilot execution

Challenge1
Run in production without disruption
Isolate simulation with phantom threads

Challenge 2
Simulate recovery in distributed environment
Propagate execution with tracked metadata

Challenge 3
Limit delay to the original recovery
Accelerate original recovery with caching

Challenge 1 Pilot execution should not disrupt production environment

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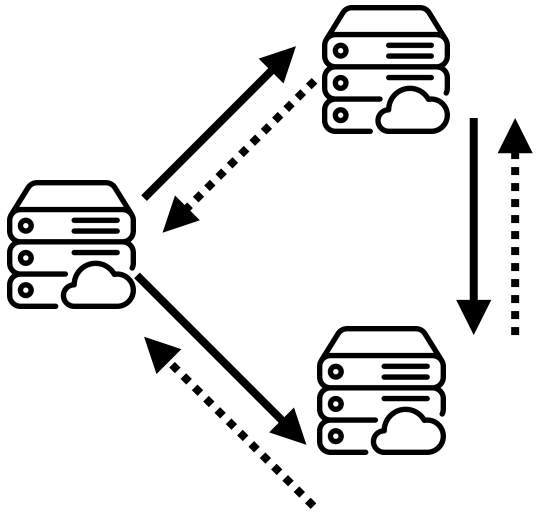
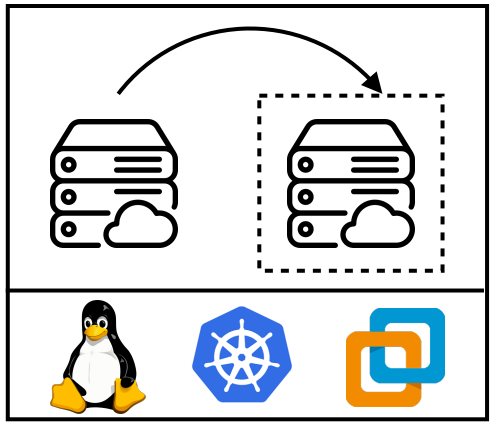
- Recovery spans distributed side effects, making rollback hard to implement
- Virtualization provides isolation, but incurs high overhead and weakens fidelity



Transactional rollback



Isolate recovery in virtualized environment

Challenge 1 Pilot execution should not disrupt production environment

- Recovery spans distributed side effects, making rollback hard to implement
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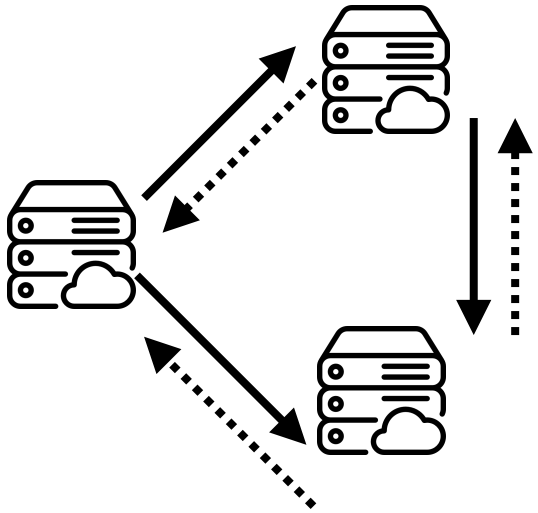
- **In-Situ simulation**: Use dedicated threads for pilot execution



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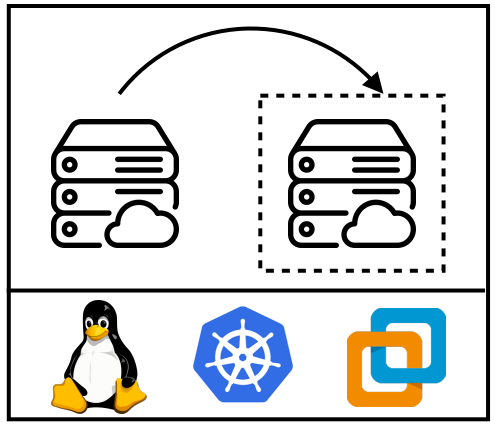

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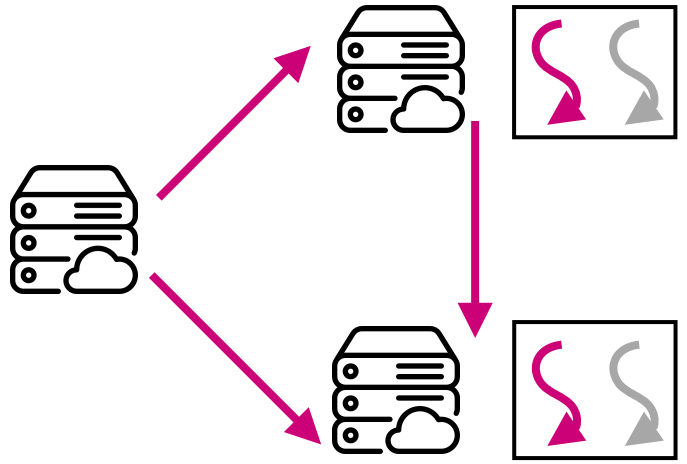
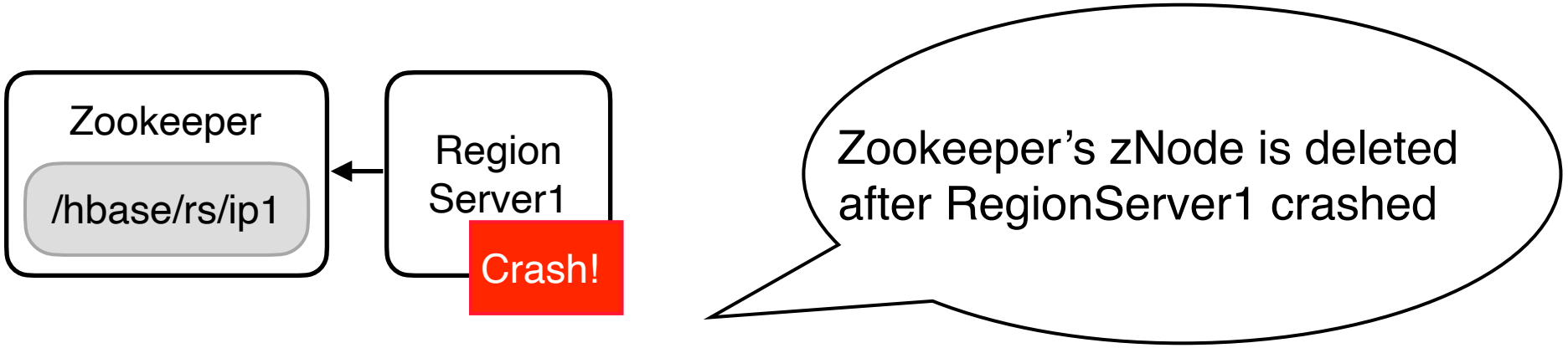


In-Situ simulation

Initiate phantom threads

- Instrument the recovery entry point to launch pilot execution



Initiate phantom threads

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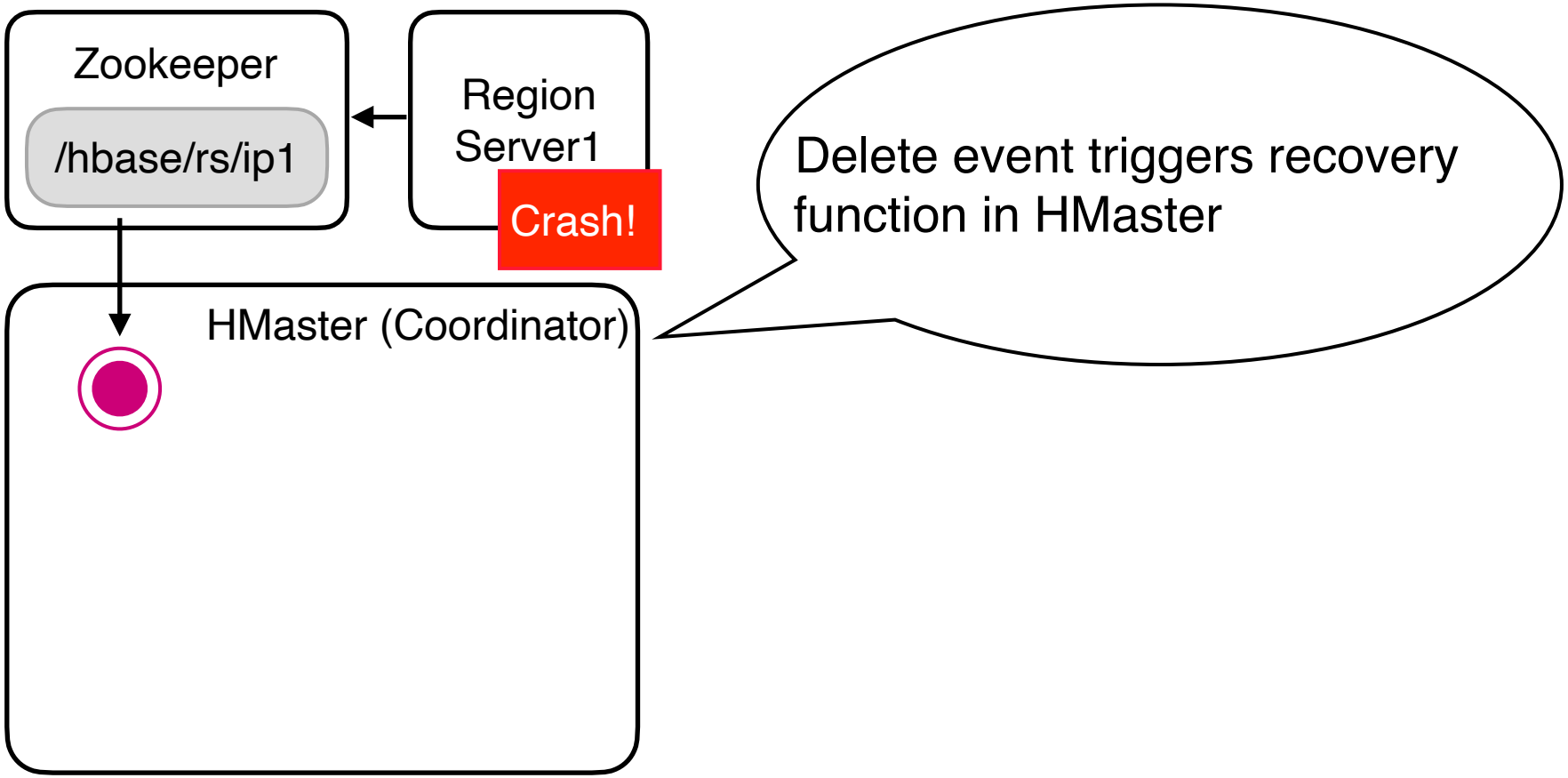

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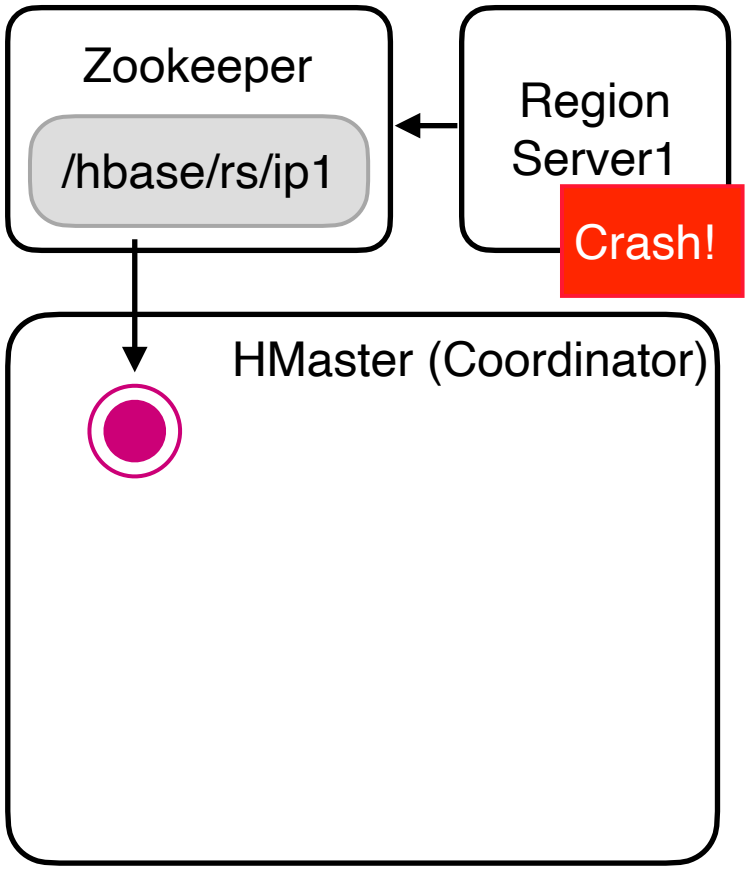

Entry point of HBase recovery

```
@ZooKeeperCallback
public void failover() {
  transferQueue(server);
  this.server = getFailoverTarget();
  //…
  File.write(path, content);
  ZooKeeperClient.deleteNode(path);
  //…
}
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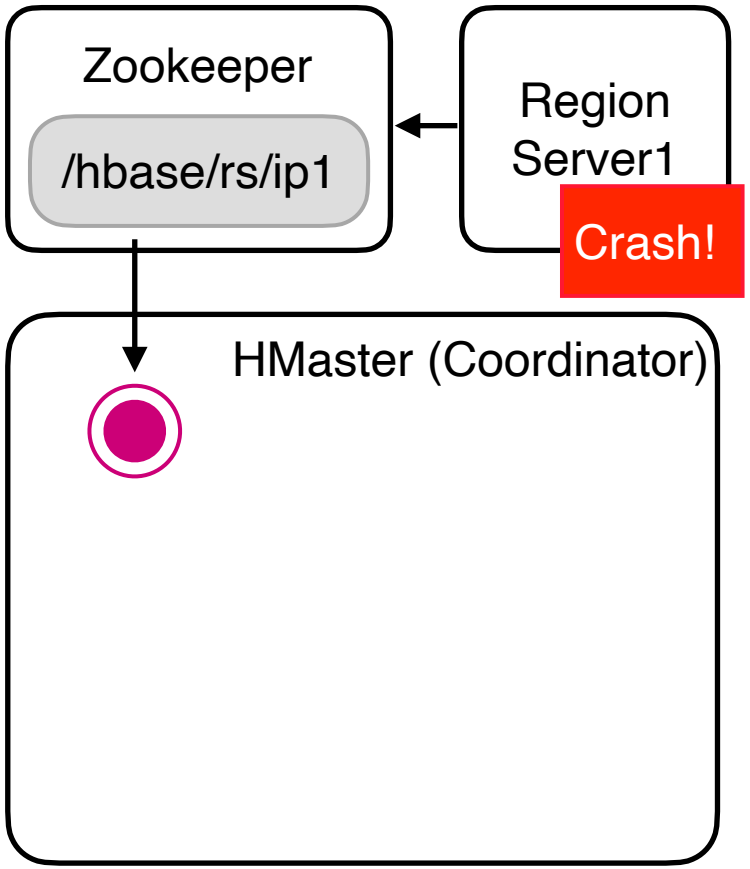

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Divert into pilot execution

Initiate phantom threads

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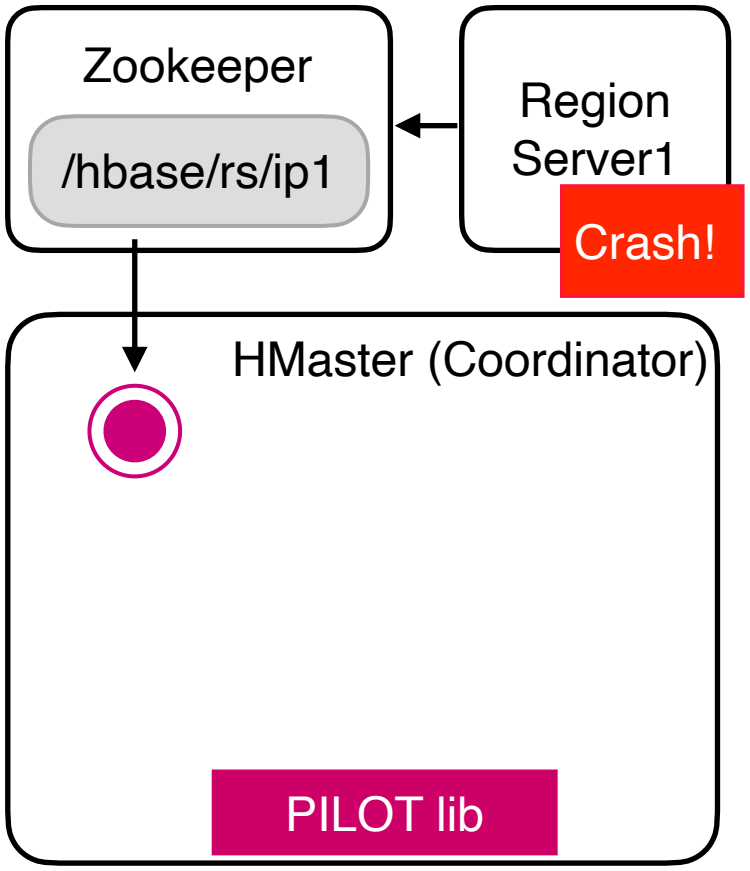

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+            Pilot.report(id);
+            return;
+        }
+    }
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Initiate phantom threads

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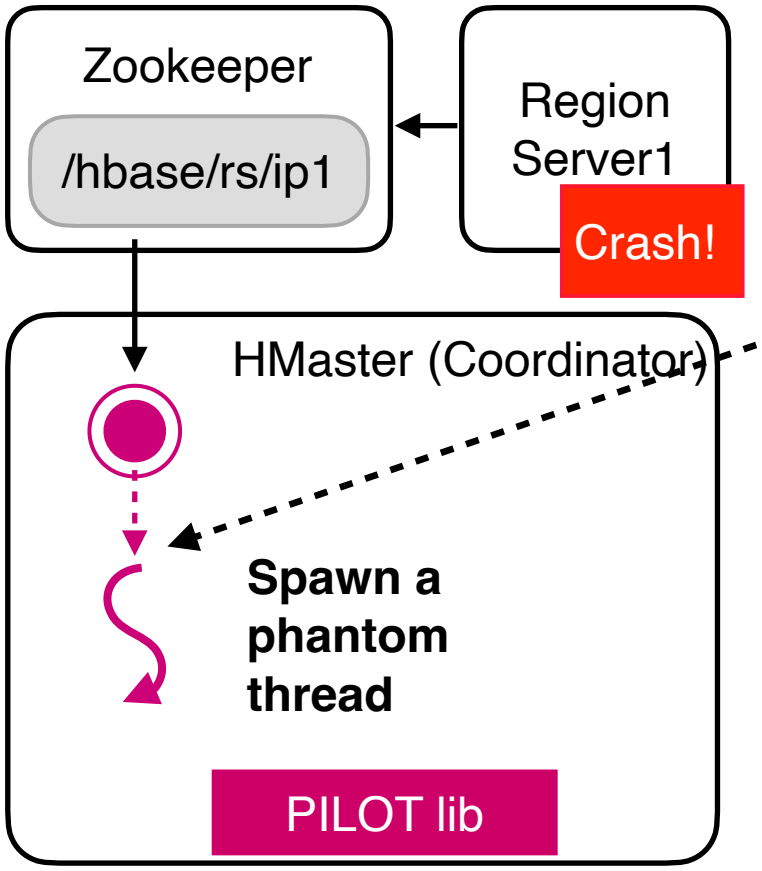

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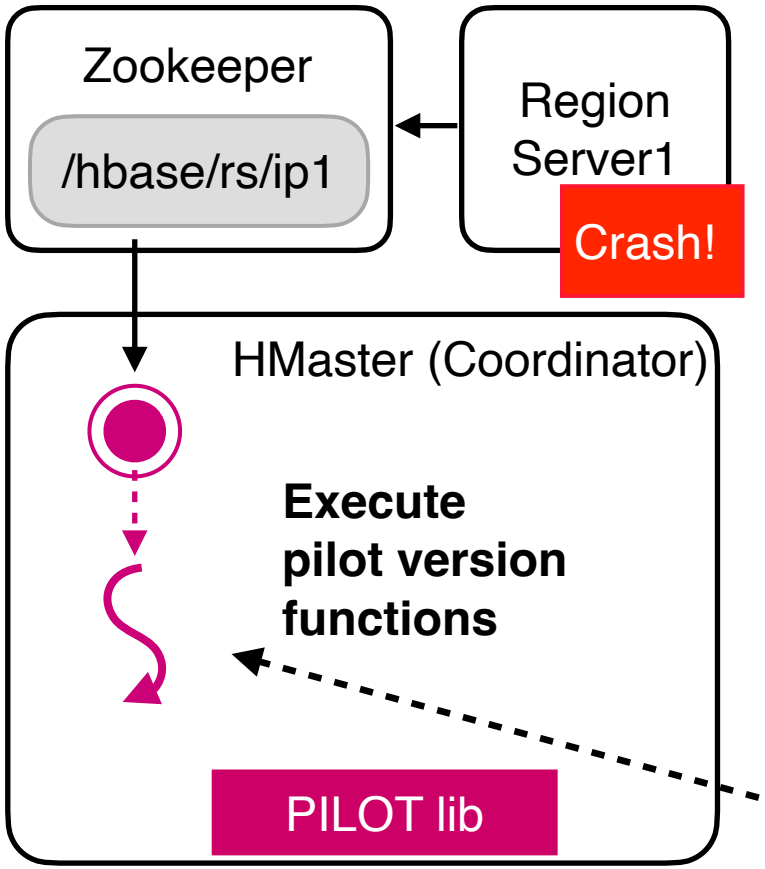

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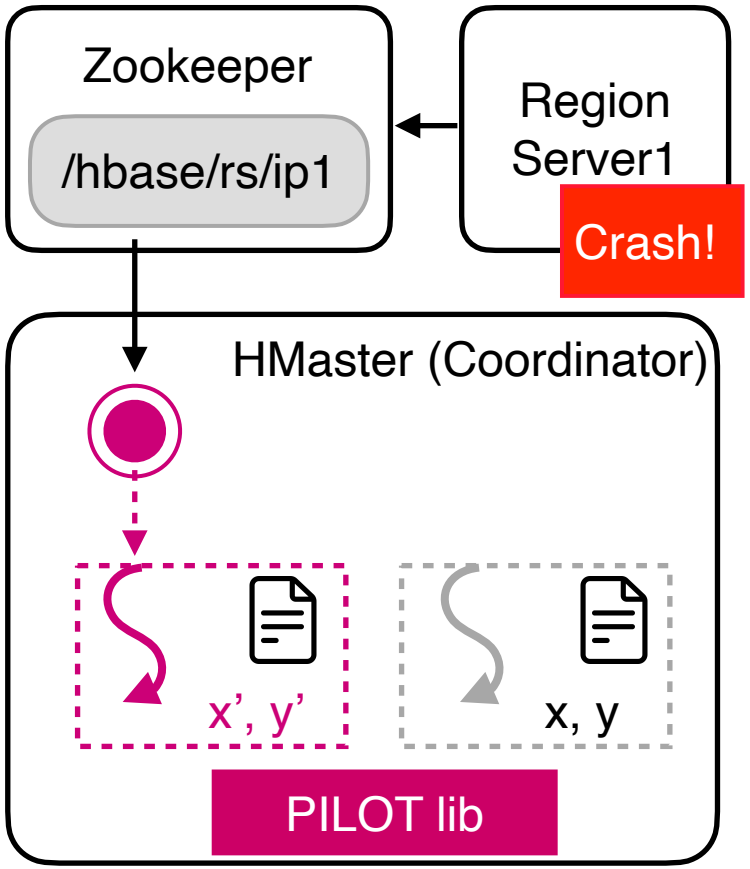
Isolate phantom threads

- Isolate side effects with pilot functions



(1) State Isolation with Recursive Redirection

```
public class NodeFailoverWorker {
    public Server server;

    public void failover() {
        transferQueue(server);
        server = getFailoverTarget();
    }
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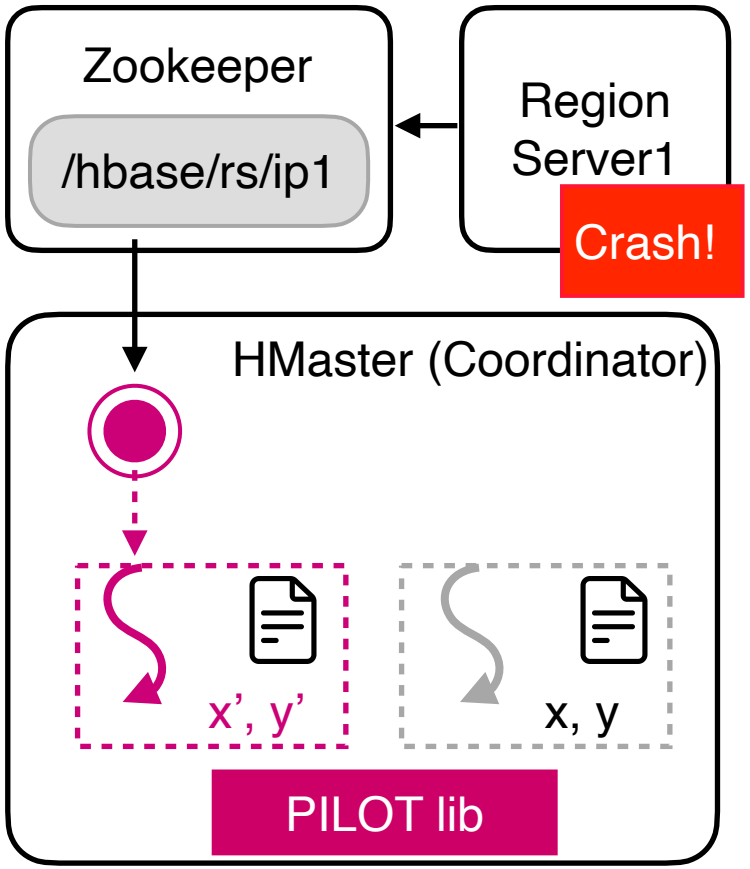
Isolate phantom threads

- Isolate side effects with pilot functions



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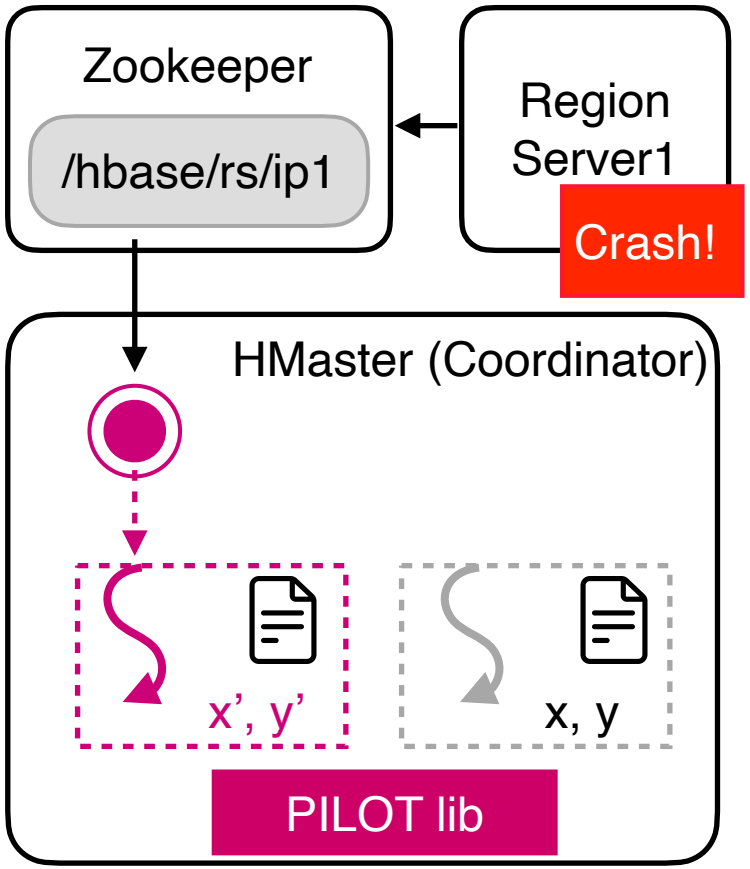
+   public Server server$pilot;

    public void failover() {
        transferQueue(server);
        server = getFailoverTarget();
    }
}
```

Isolate phantom threads

- Isolate side effects with pilot functions



(1) State Isolation with Recursive Redirection

```
public class NodeFailoverWorker {
    public Server server;
+   public Server server$pilot;

+   public void failover$pilot() {
+       server$pilot =
+           PilotUtil.copy(server);
        transferQueue(server);
        server = getFailoverTarget();
    }
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Isolate phantom threads

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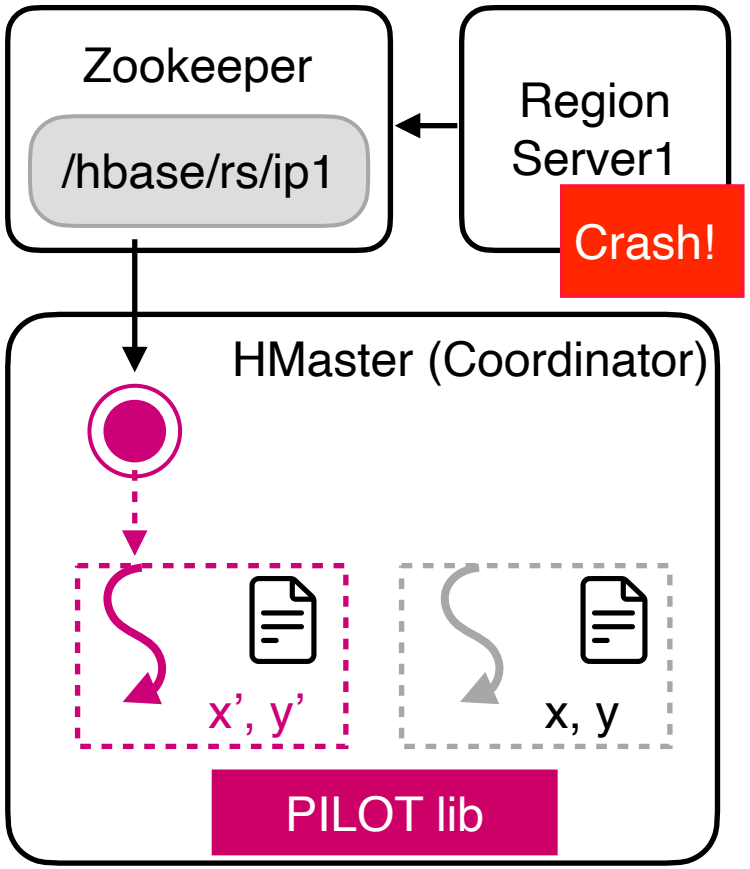

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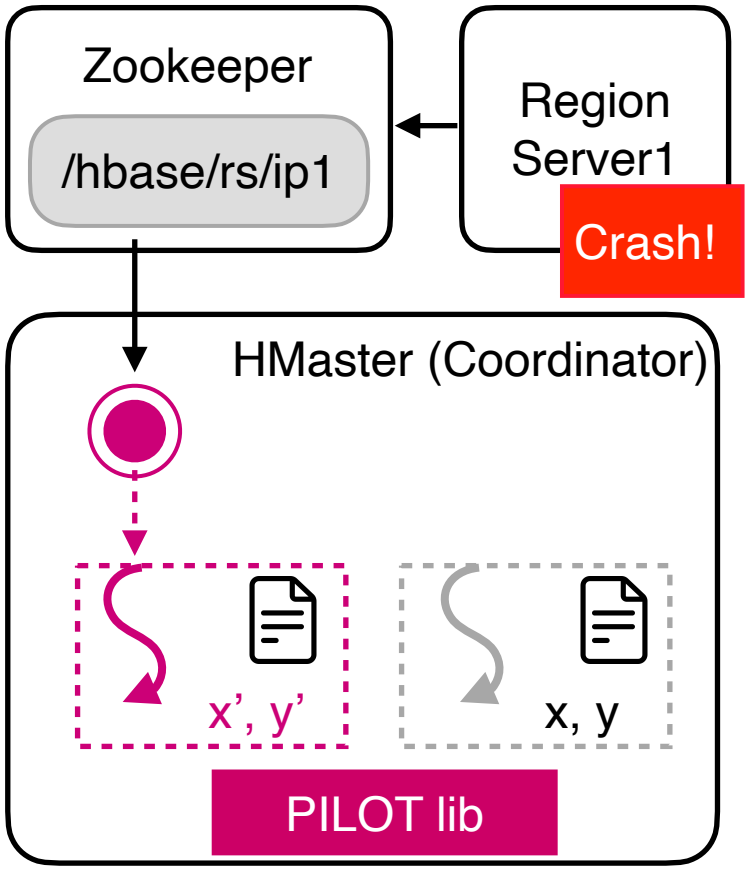


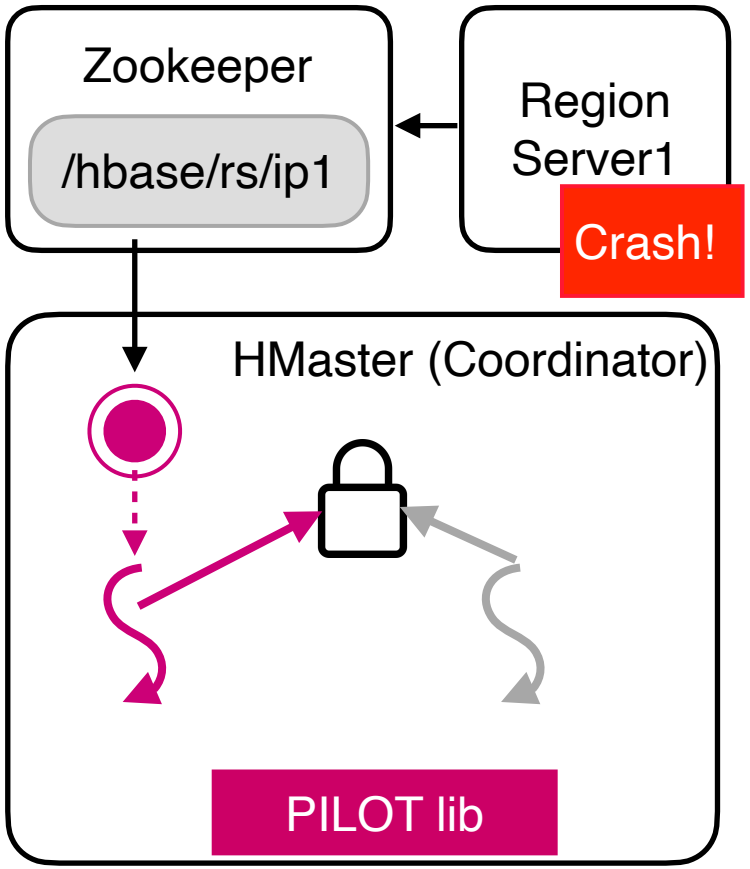
(1) State Isolation (2) I/O (3) Third-Party Service

```
public class NodeFailoverWorker {
    public Server server;
+   public Server server$pilot;

+   public void failover$pilot() {
+       server$pilot =
+           PilotUtil.copy(server);
-       transferQueue(server);
-       server = getFailoverTarget();
+       transferQueue$pilot(server);
+       server$pilot =
+           getFailoverTarget$pilot();
    }
}
```

Manage phantom threads

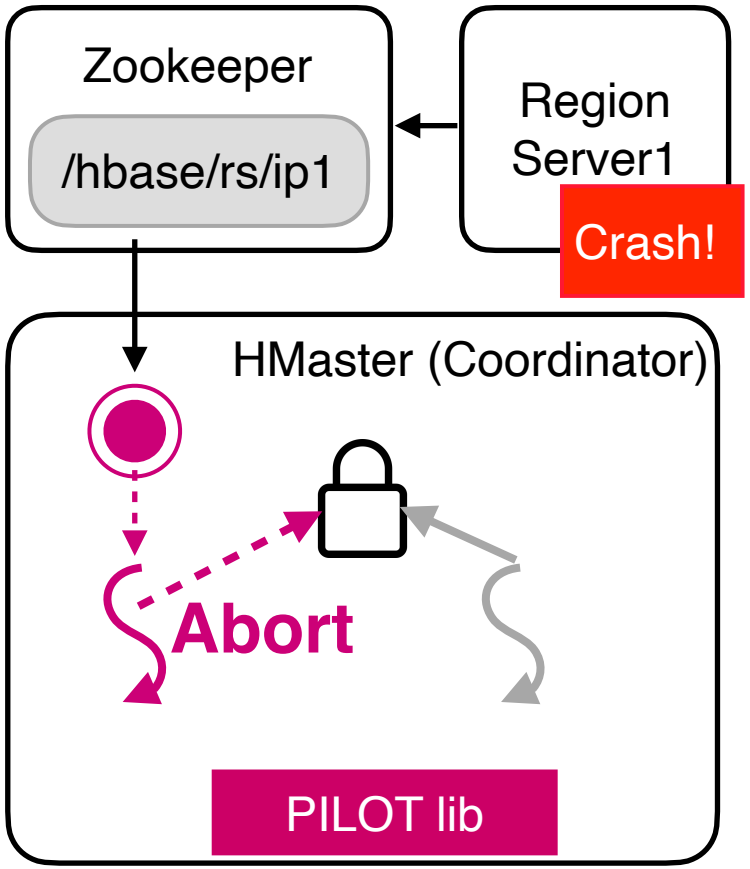
- Avoid disrupting production



- Phantom threads and original threads may compete

Manage phantom threads

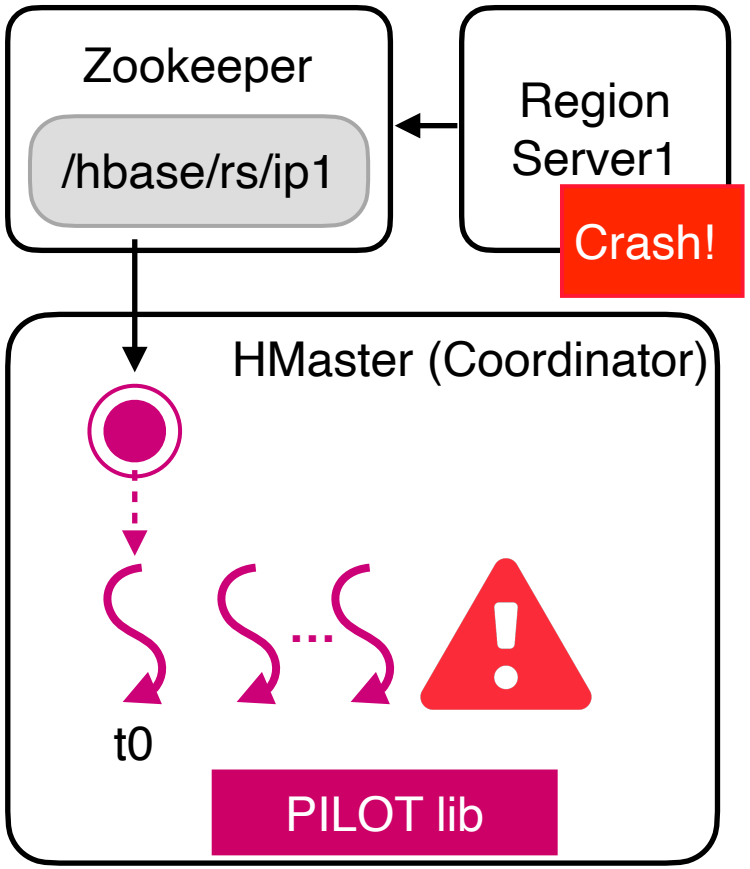
- Avoid disrupting production



- Phantom threads and original threads may compete
  - Phantom threads always yield to original threads

Manage phantom threads

- Avoid disrupting production



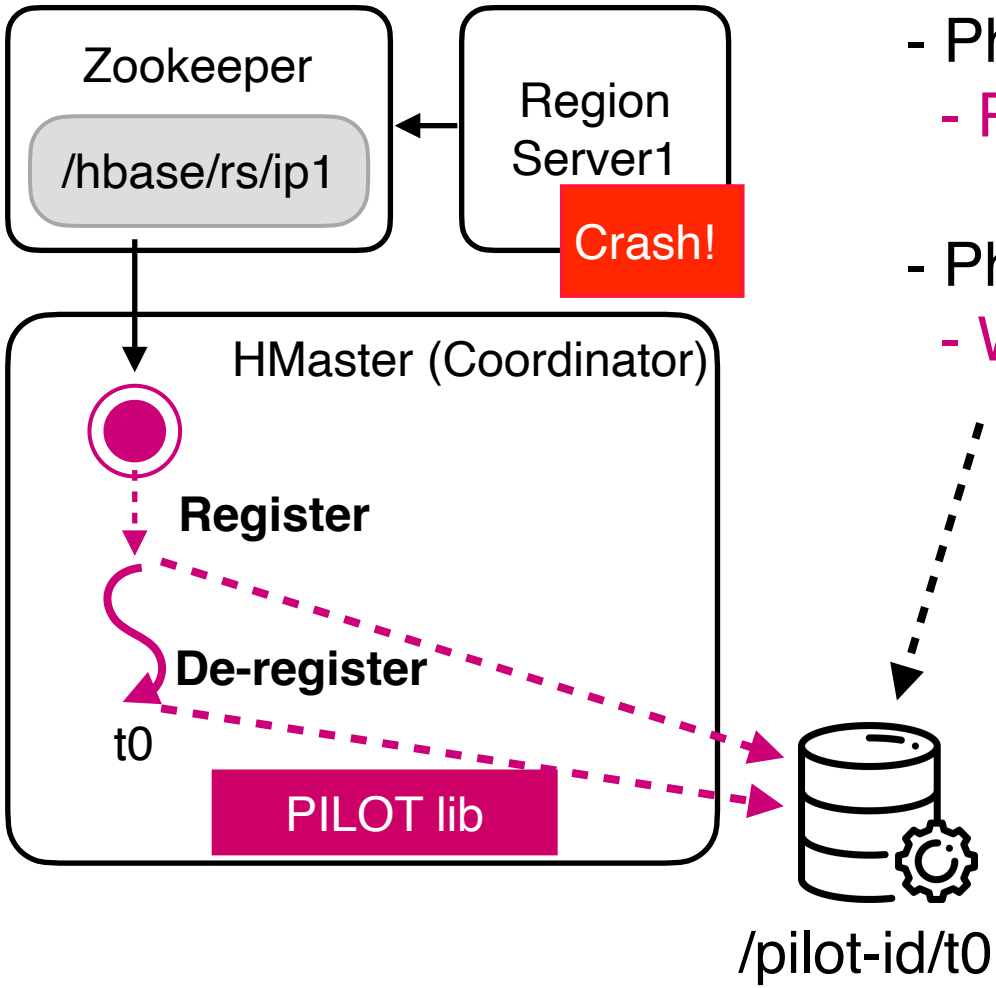
/pilot-id/t0

- Phantom threads and original threads may compete
  - Phantom threads always yield to original threads

- Phantom threads may leak or outlive the pilot run

Manage phantom threads

- Avoid disrupting production

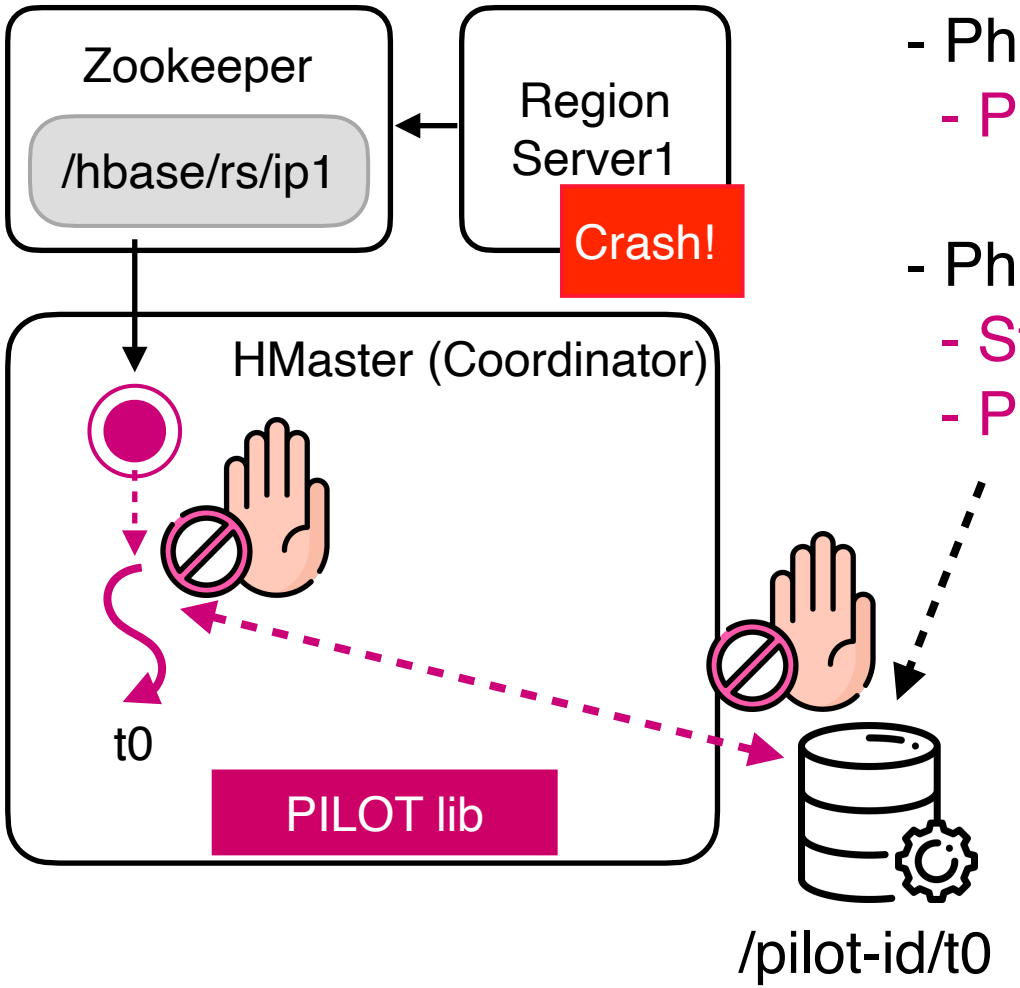


- Phantom threads and original threads may compete
  - Phantom threads always yield to original threads

- Phantom threads may leak or outlive the pilot run
  - Watch status registry to check if finished or not

Manage phantom threads

- Avoid disrupting production

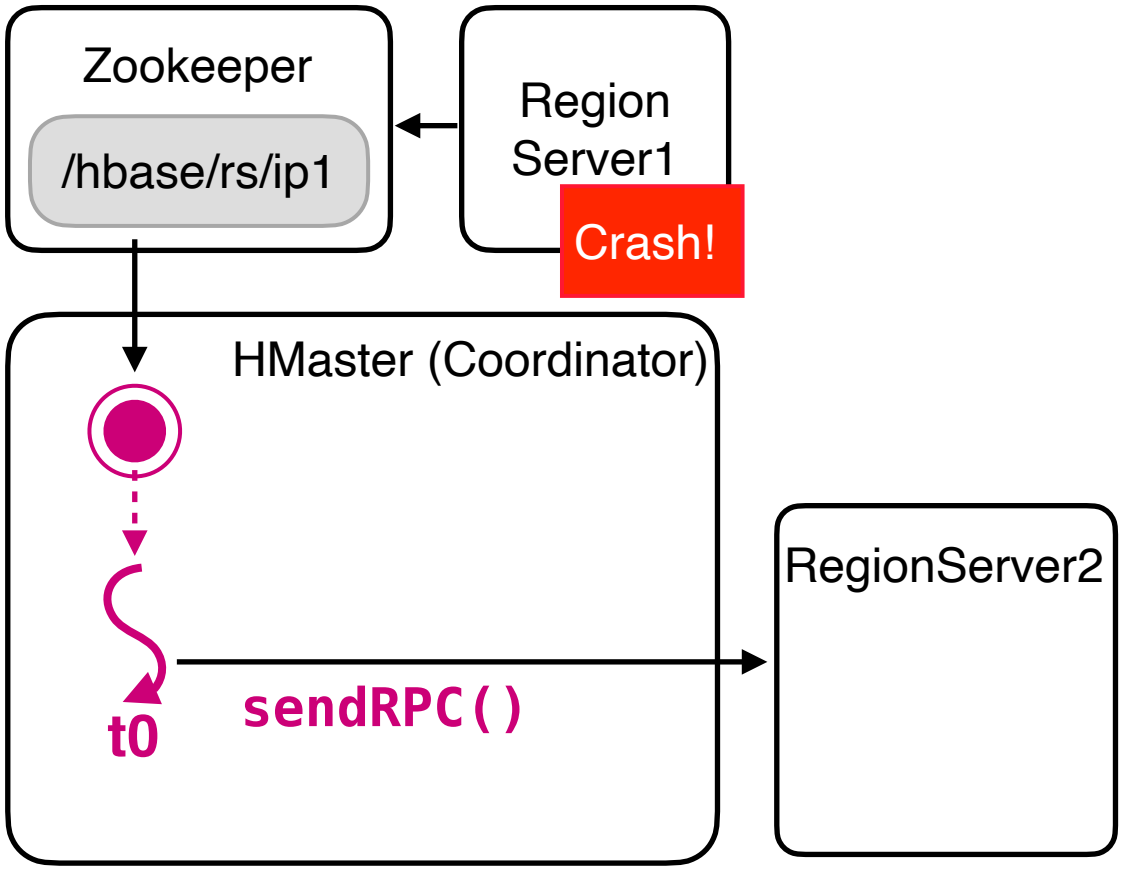


- Phantom threads and original threads may compete
  - Phantom threads always yield to original threads

- Phantom threads may leak or outlive the pilot run
  - Status registry can trigger cleanup callbacks
  - Prevent storms of phantom threads

Challenge 2 Simulate recovery in distributed environment

- **Recovery includes a lot of inter-thread and inter-process interactions**
  - e.g. RPC, async executor, condition variable, etc…

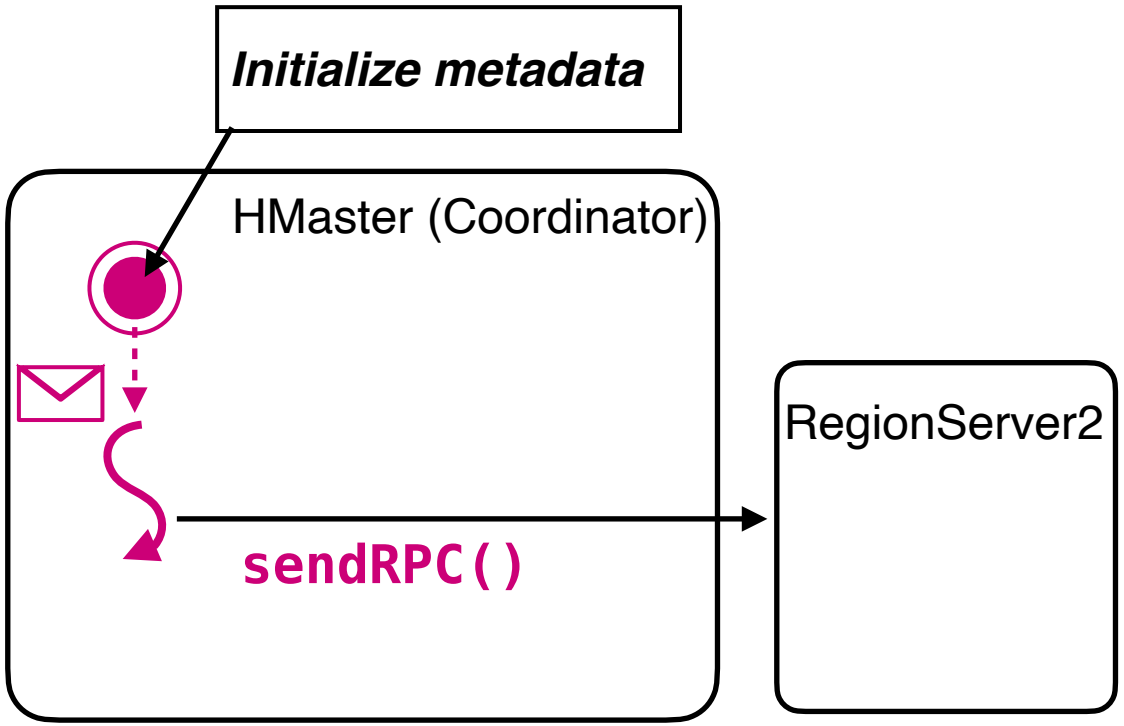


How to handle propagation?

```
public void failover$pilot() {
 Region region = getRegion();
 sendRPC(region);
}
```

Challenge 2 Simulate recovery in distributed environment

- **Recovery includes a lot of inter-thread and inter-process interactions**
  - e.g. RPC, async executor, condition variable, etc…
- **How to ensure the whole recovery process is simulated by phantom threads?**
  - **Propagate pilot execution with tracked metadata**



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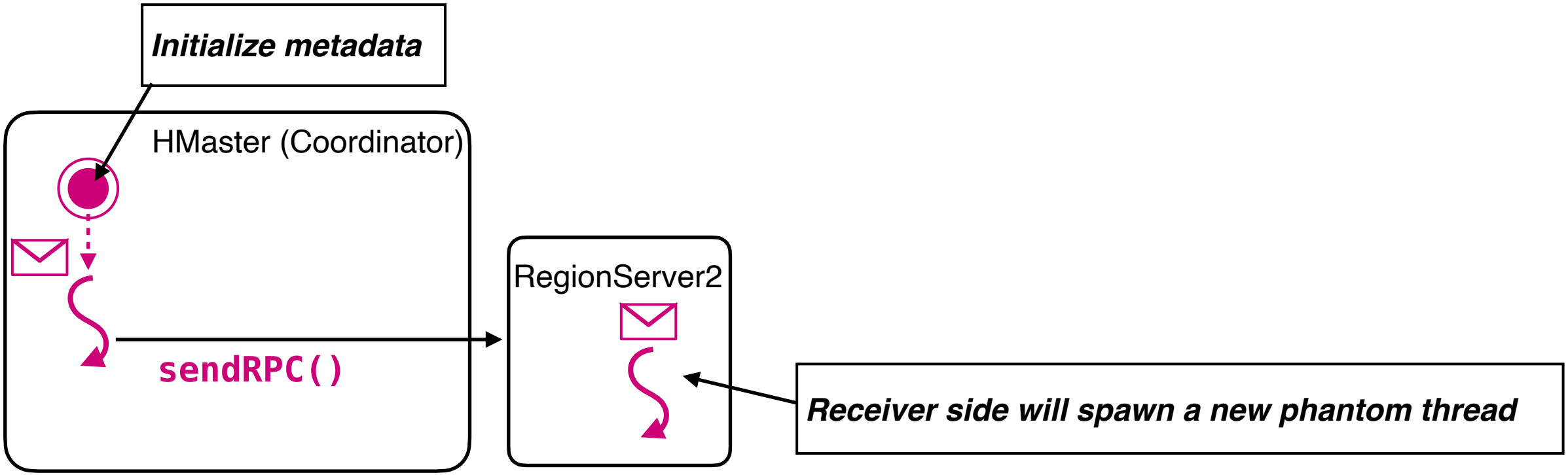

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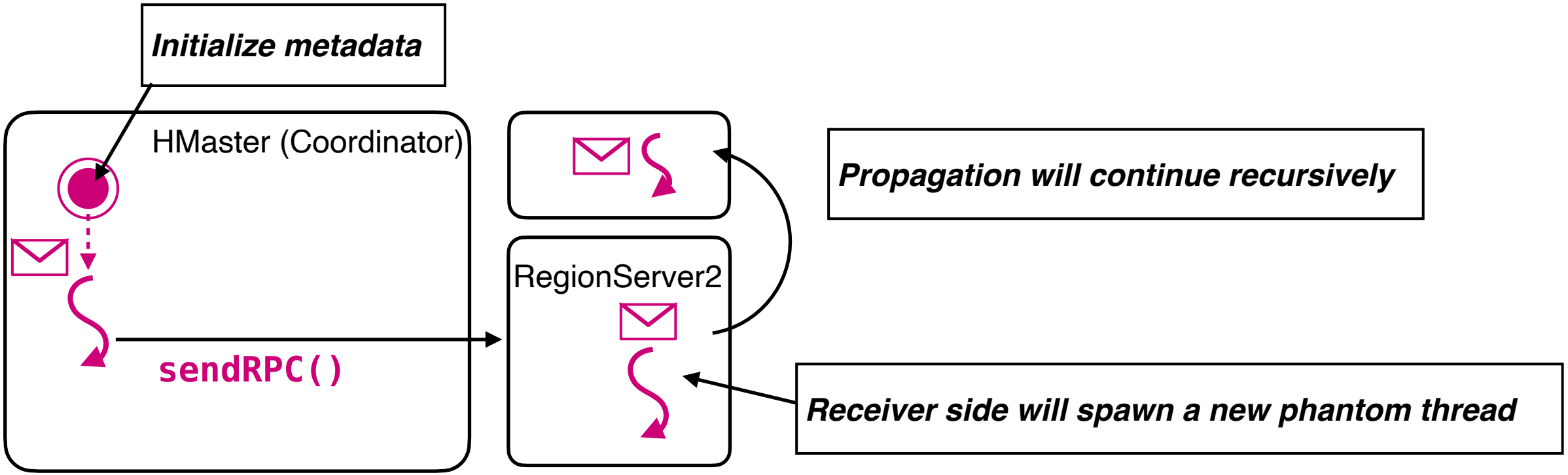
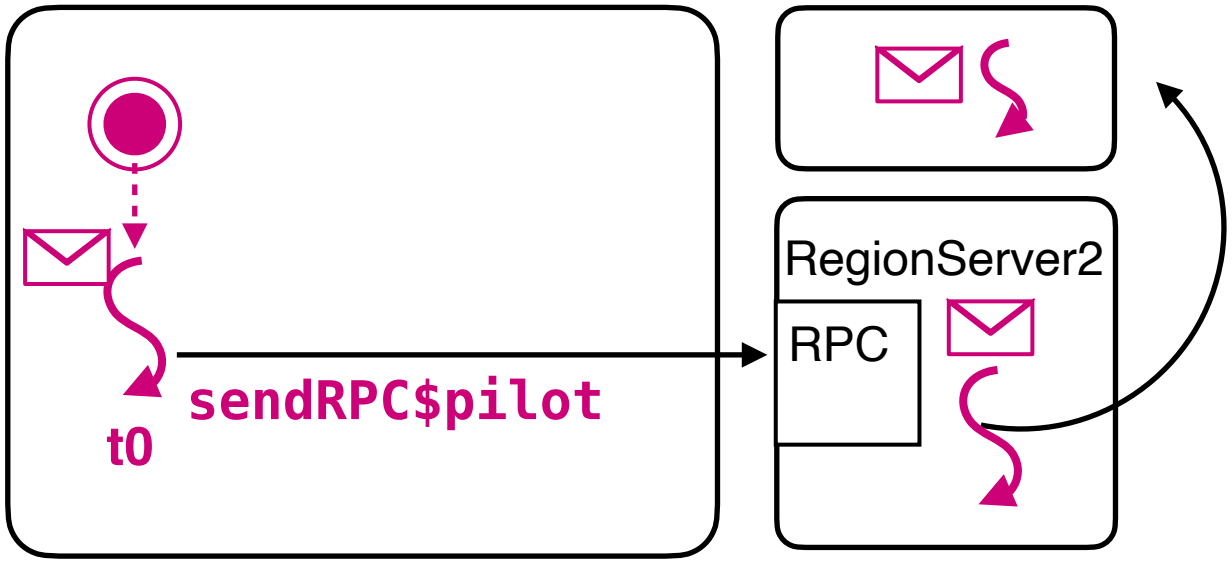


Propagate execution with the tracked metadata

- **PilotContext: Pilot Run ID (Global Identifier) + Span metadata**
  - Tracing infrastructure already supports common propagation scenarios

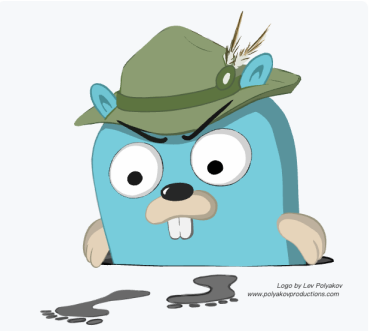


OpenTelemetry

slack join chat → | Unit Tests passing | codecov 97% | Project+Community stats
license scan passing | openssf scorecard 8.2 | openssf best practices silver
CLOMonitor Report A | Artifact Hub jaegertracing

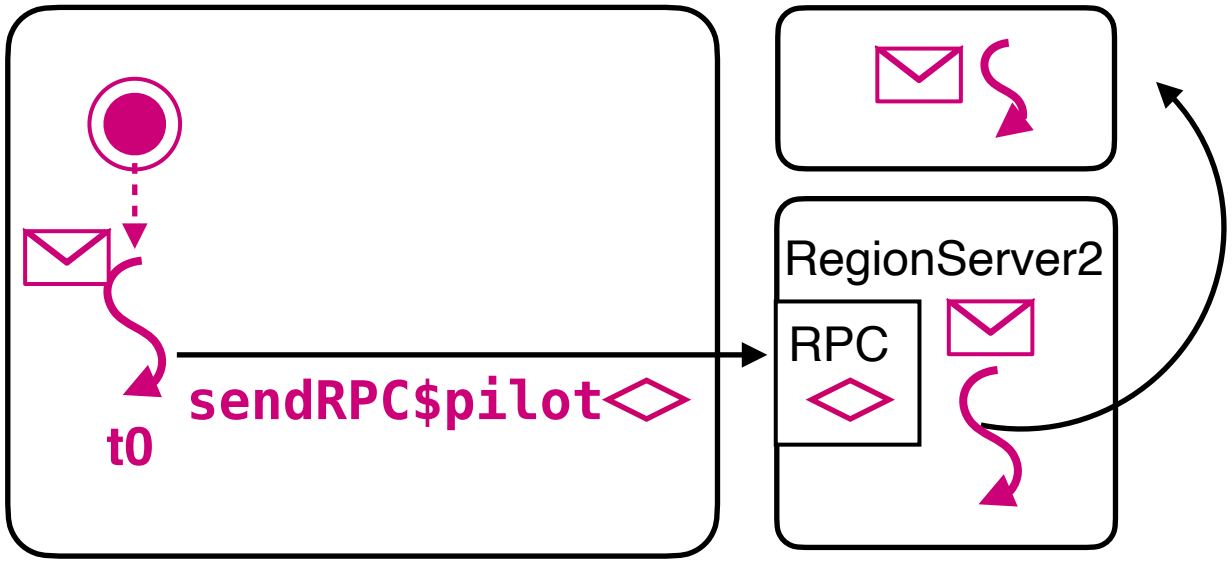
CLOUD NATIVE COMPUTING FOUNDATION
GRADUATED PROJECT

Jaeger - a Distributed Tracing System



Propagate execution with the tracked metadata

- **PilotContext: Pilot Run ID (Global Identifier) + Span metadata**
  - Tracing infrastructure already supports common propagation scenarios
  - Our instrumentation piggybacks on existing tracing frameworks with hooks ◇



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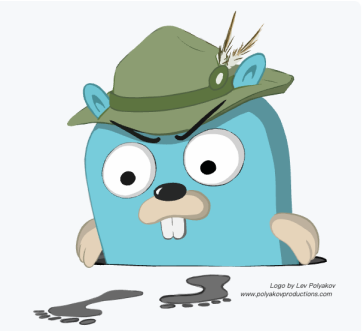
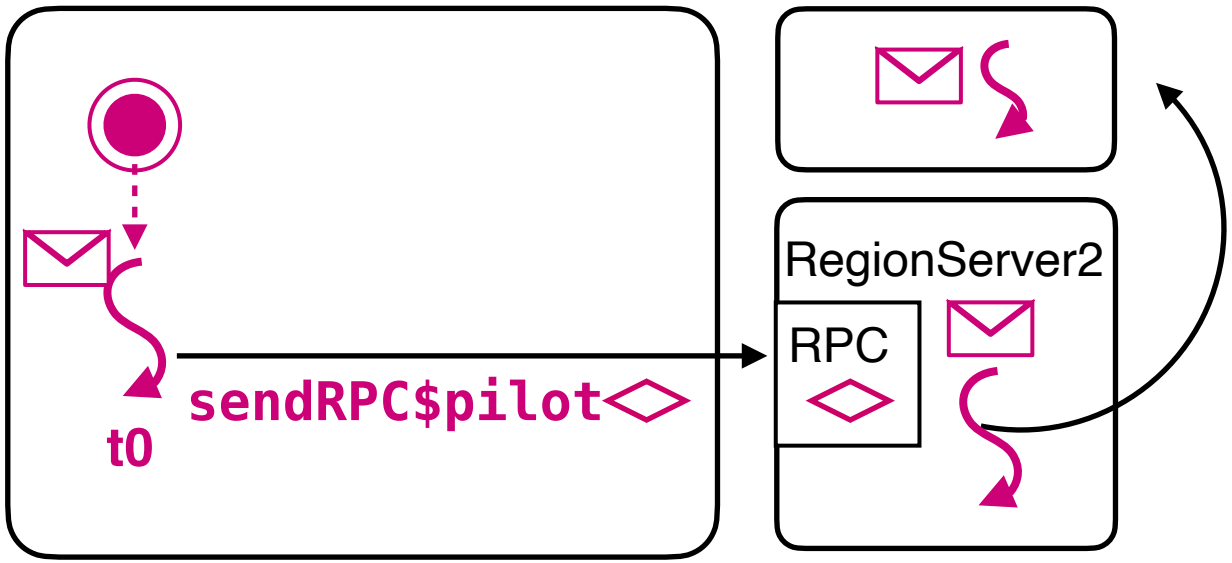
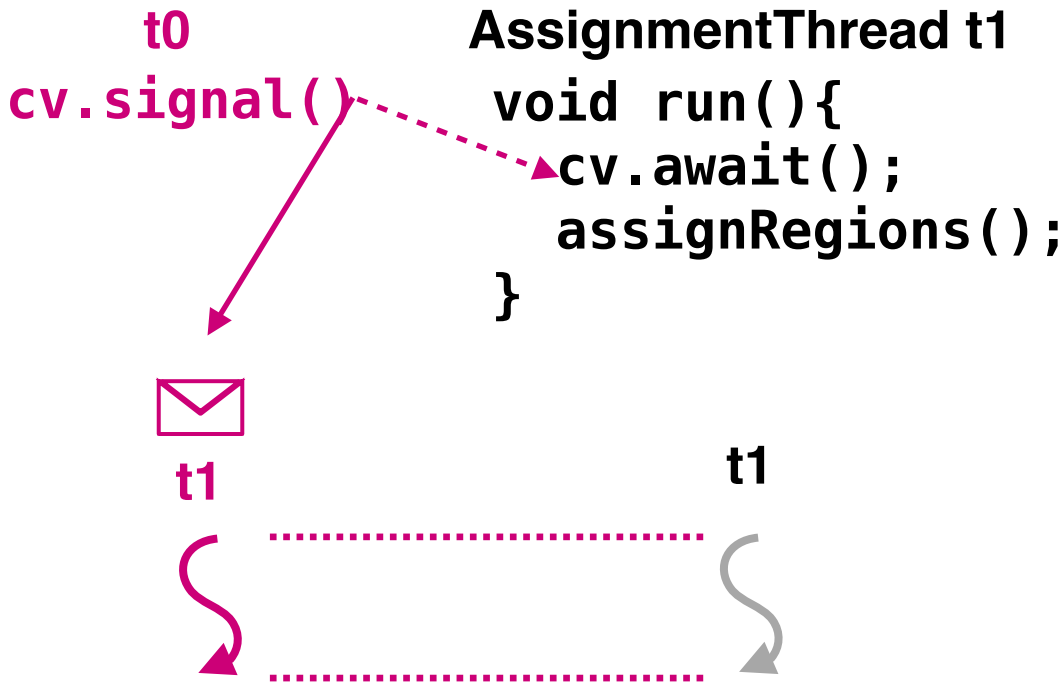


Propagate execution with the tracked metadata

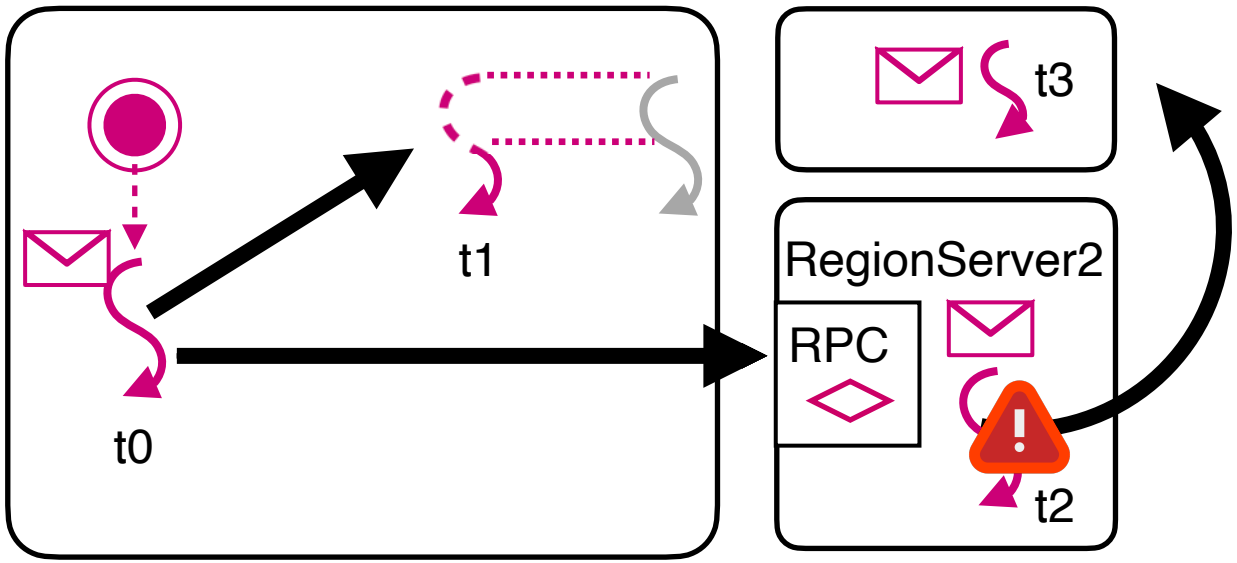
- **PilotContext: Pilot Run ID (Global Identifier) + Span metadata**
  - For some cases (e.g., cond vars), we simulate the affected behavior explicitly





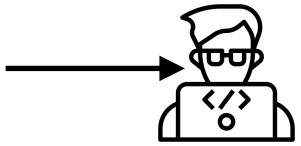
Propagate execution with the tracked metadata

- **PilotContext: Pilot Run ID (Global Identifier) + Span metadata**
  - Span relationship and alarm will be provided to the operator



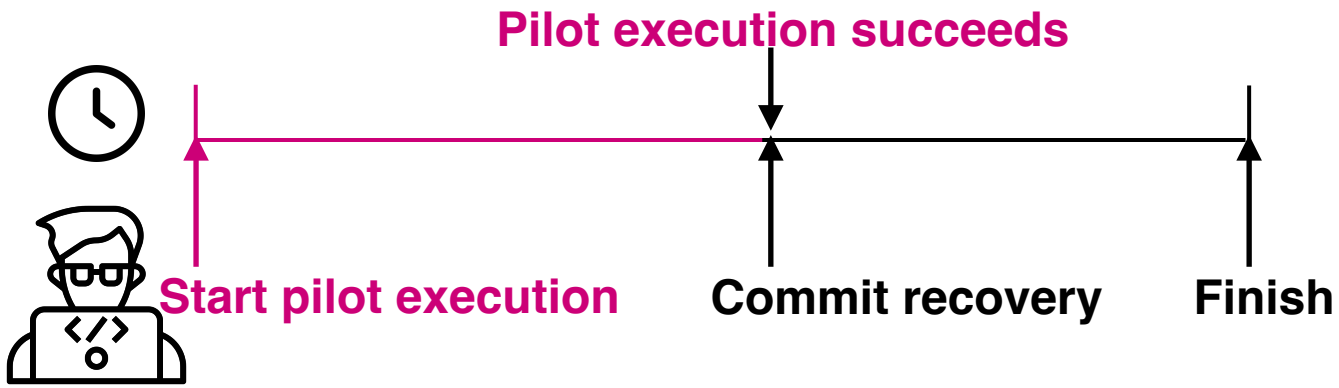

```
catch(IOException e){
-Runtime.halt();
+Pilot.report();
}
```

Alarm: t2 crashes with WAL-xxx



Challenge 3 Avoid delaying original recovery

-Without optimization, end-to-end recovery time will be doubled



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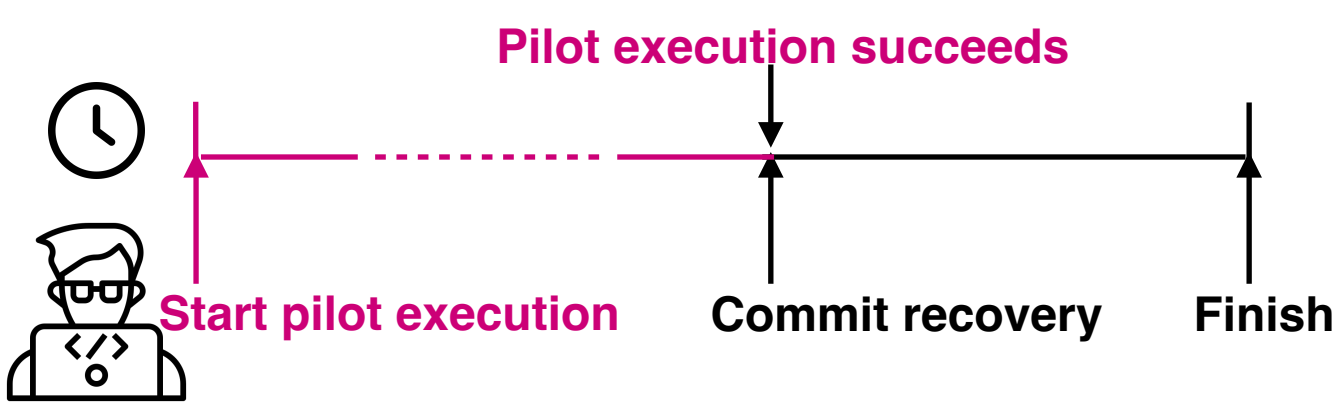

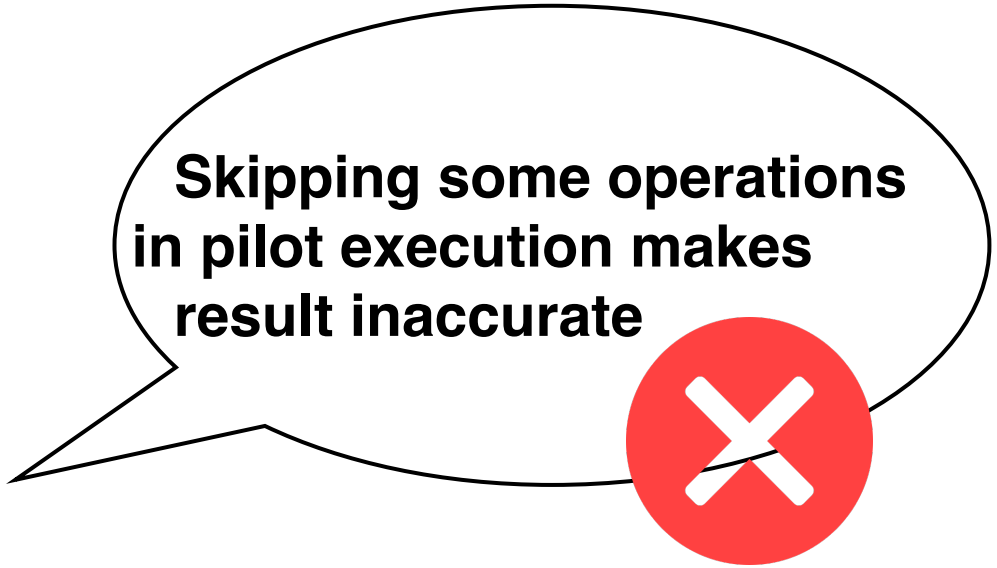

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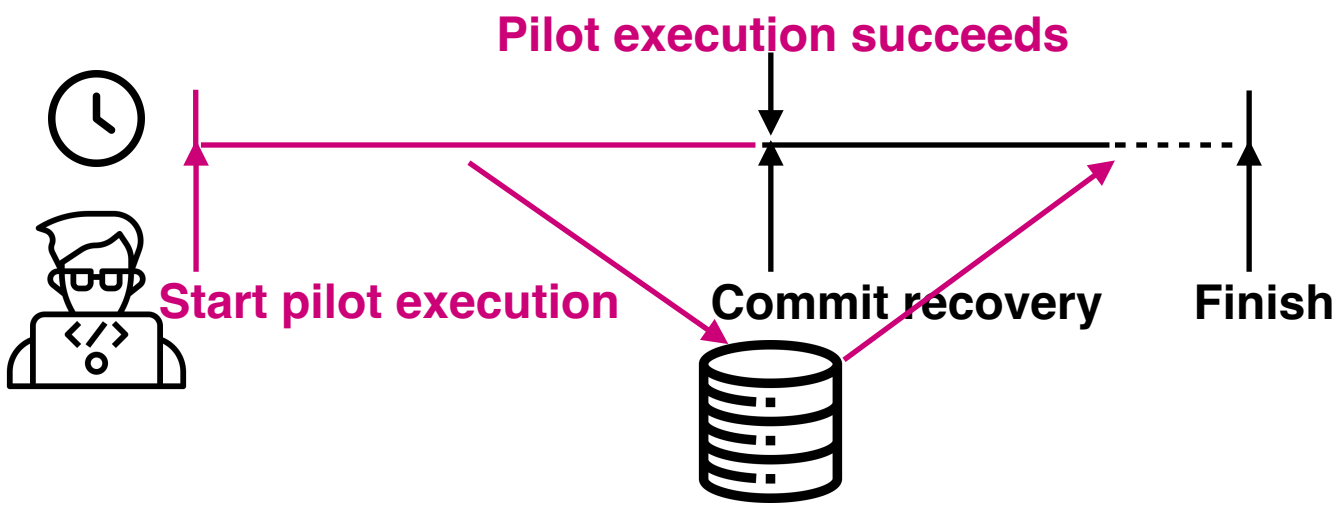

Pilot lib caches I/O and compute-intensive results

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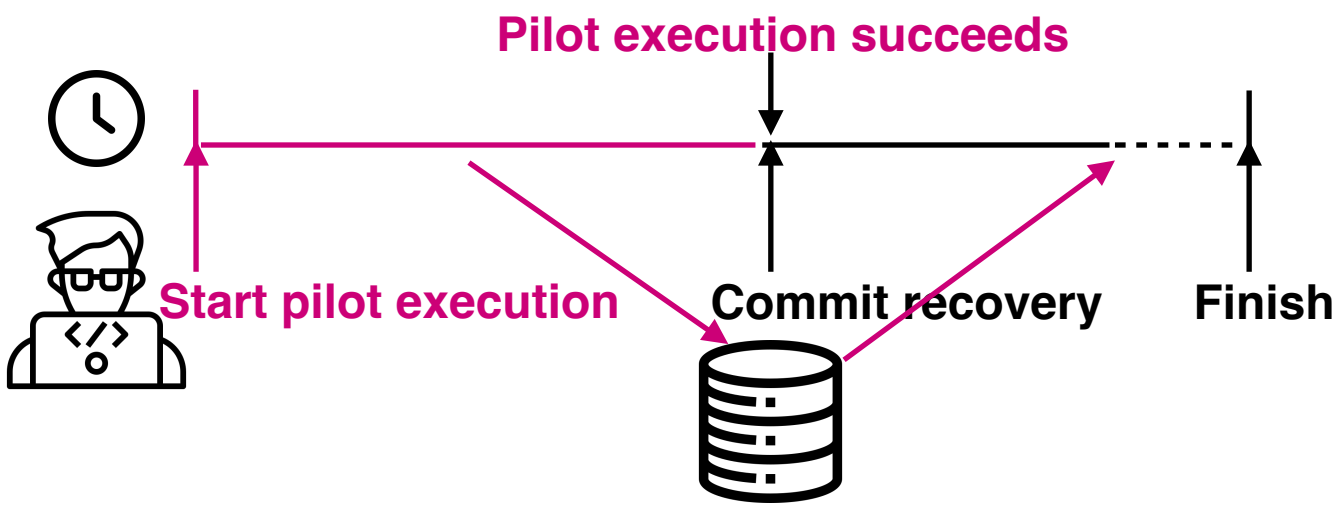
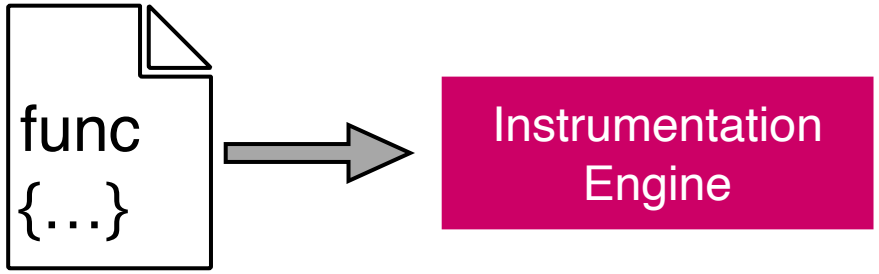


Pilot lib caches I/O and compute-intensive results

-Solution: accelerate original recovery with caching

PILOT: System Support for Pilot Execution

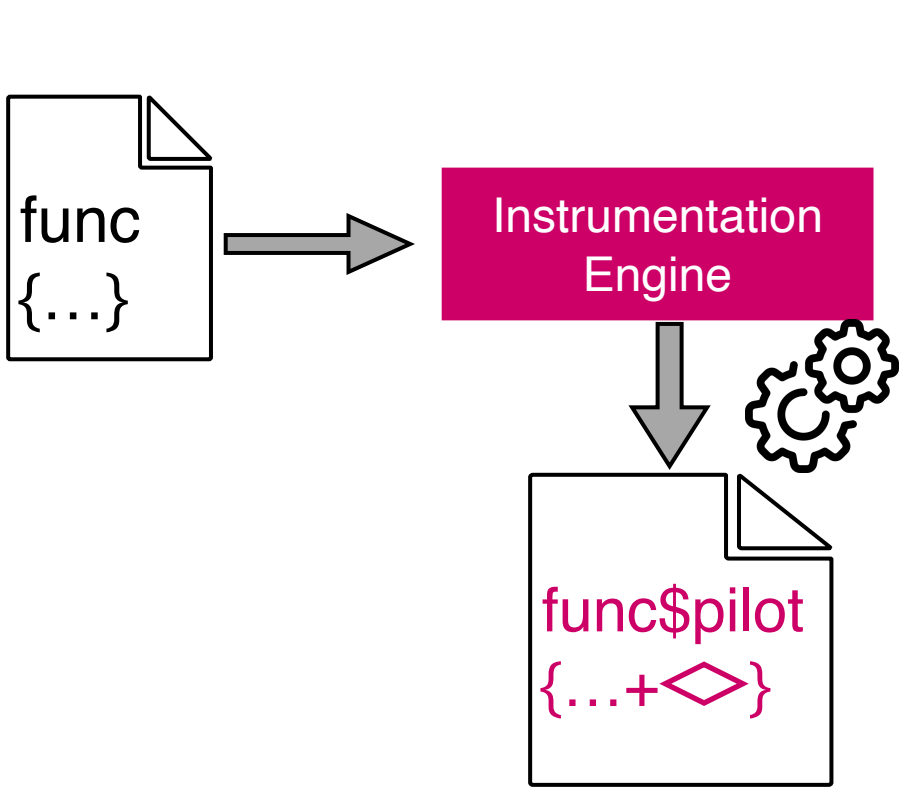
- We implement PILOT, a framework that makes pilot execution easy to adopt for existing distributed systems
- PILOT contains an **instrumentation engine** and a **runtime library**



Offline

PILOT: System Support for Pilot Execution

- PILOT contains an **instrumentation engine** and a **runtime library**
- Instrumentation generate pilot version functions and add hooks



Offline

PILOT: System Support for Pilot Execution

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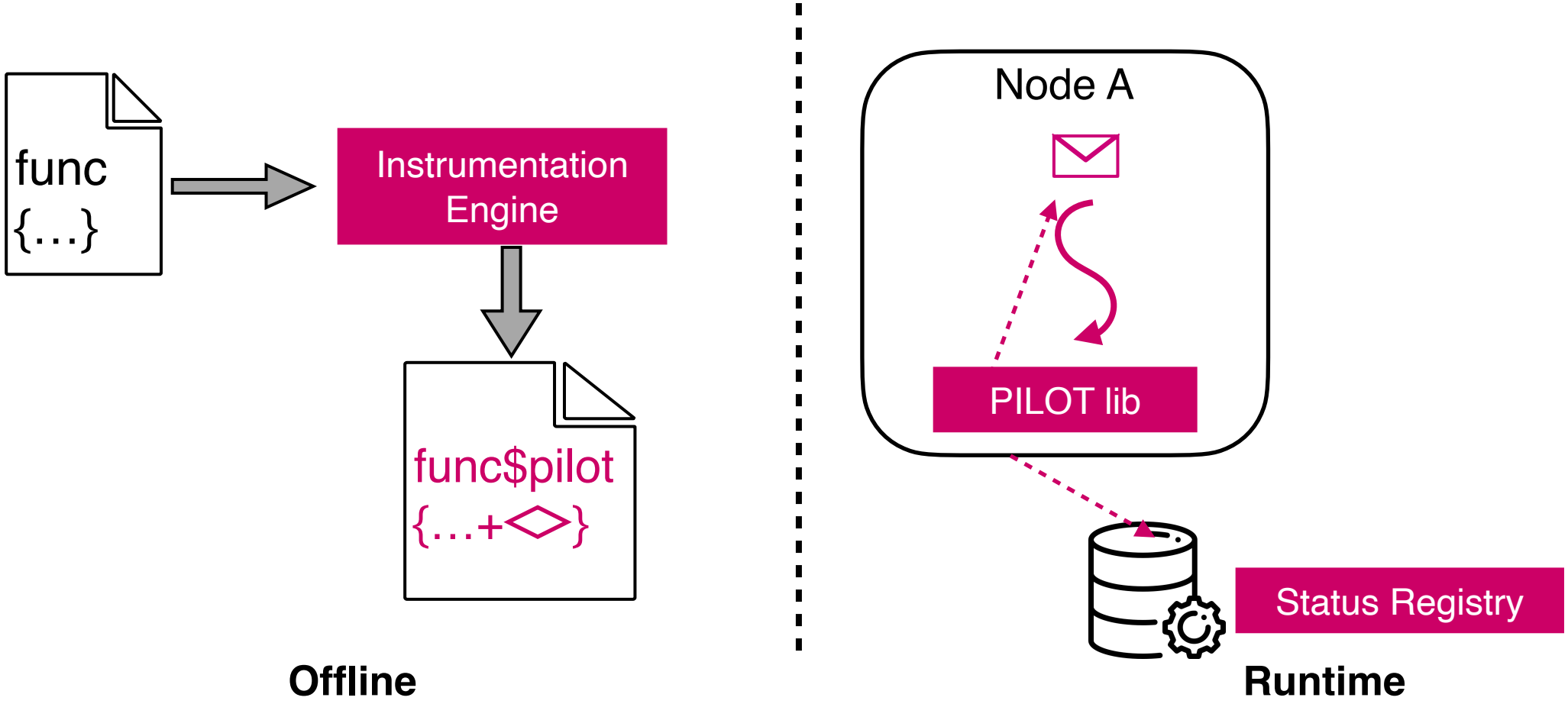
- PILOT runtime library **propagates** and **manages** pilot execution



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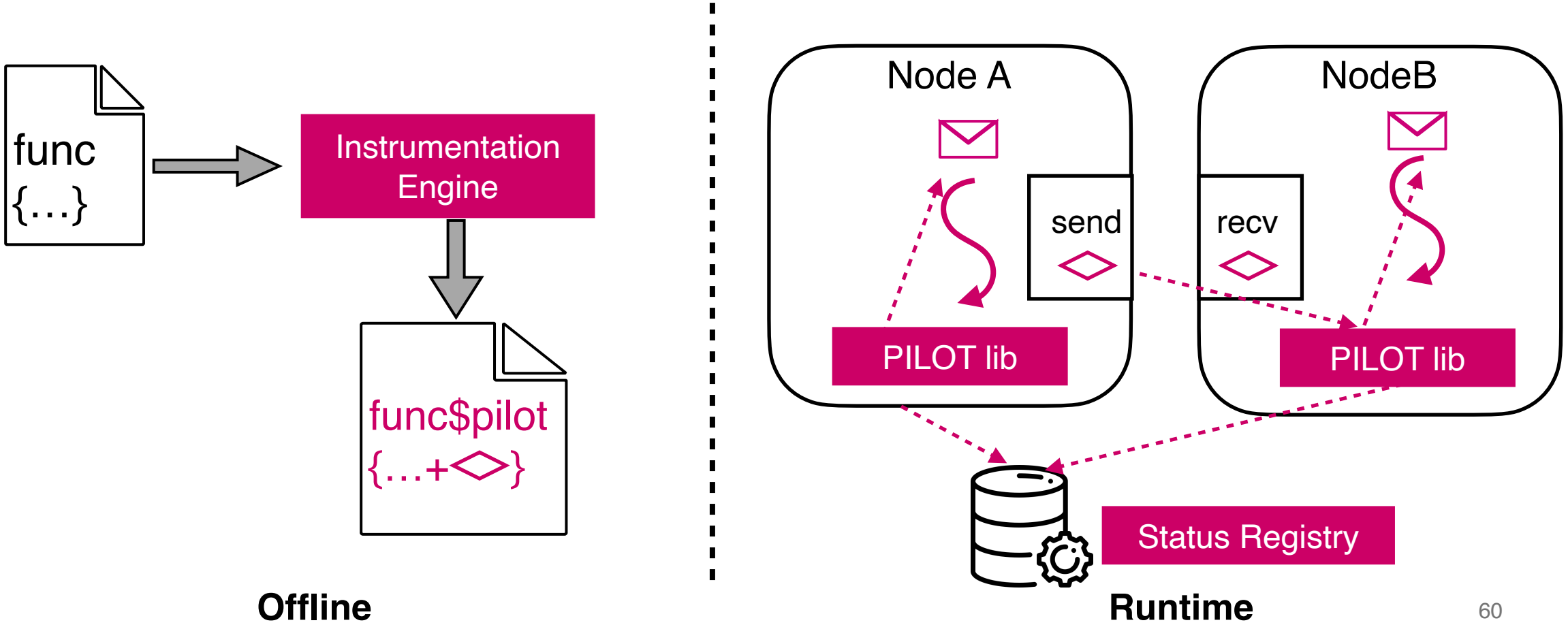


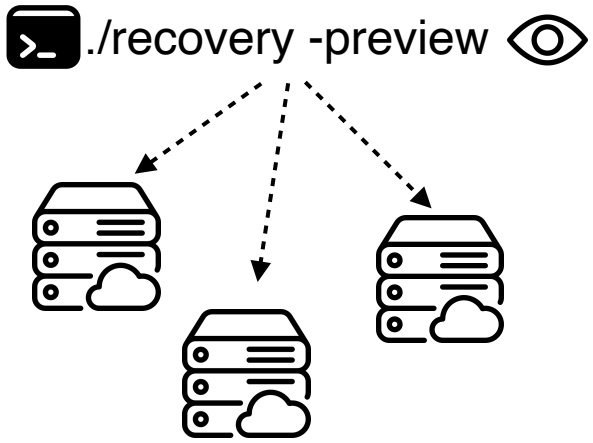
Evaluation: detection

JIRA Id.	Id.	Sys.Feature	Symptom
Solr-17515	SL1	Follower Recovery	State Inconsistency
Solr-10914	SL2	Follower Recovery	Partial Failure
Solr-6056	SL3	Core Recovery	Zombie(whole-cluster)
HDFS-16689	HF1	Namenode Failover	Service Unavailability
HDFS-9908	HF2	Error Handler	Cluster Initialization Failure
HDFS-14459	HF3	Error Handler	Incorrect Results
HDFS-10320	HF4	Datanode Recovery	Service Unavailability
HDFS-4937	HF5	Datanode Recovery	Partial Failure
Cassandra-13938	CA1	Node Recovery	Crash(Cascading)
Cassandra-14096	CA2	Node Recovery	Out-of-Memory
Cassandra-7560	CA3	Inconsistency	Partial Failure
Cassandra-6415	CA4	Inconsistency	Partial Failure
HBase-19980	HB1	Snapshot Recovery	State Inconsistency
HBase-13567	HB2	RegionServer Failover	State Inconsistency
HBase-25898	HB3	RegionServer Failover	Crash(Cascading)
YARN-7562	YN1	ResourceManager Failover	Service Unavailability
YARN-4347	YN2	ResourceManager Failover	Service Unavailability
YARN-6403	YN3	NodeManager Recovery	Crash
YARN-2816	YN4	NodeManager Recovery	Crash

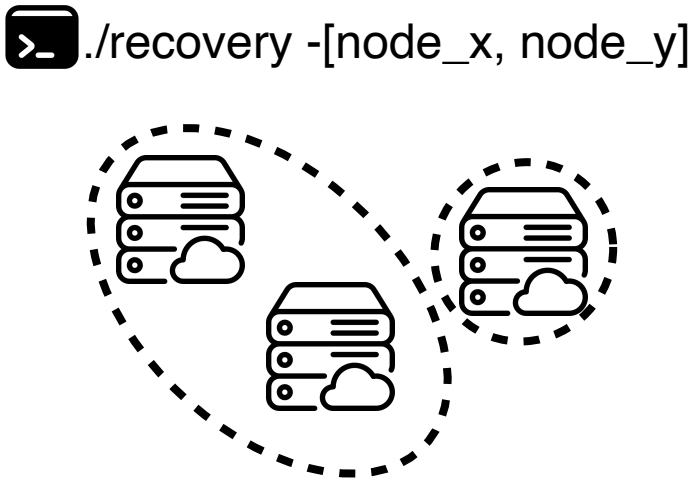
20 real-world recovery failures reproduced for evaluation

Evaluation: detection

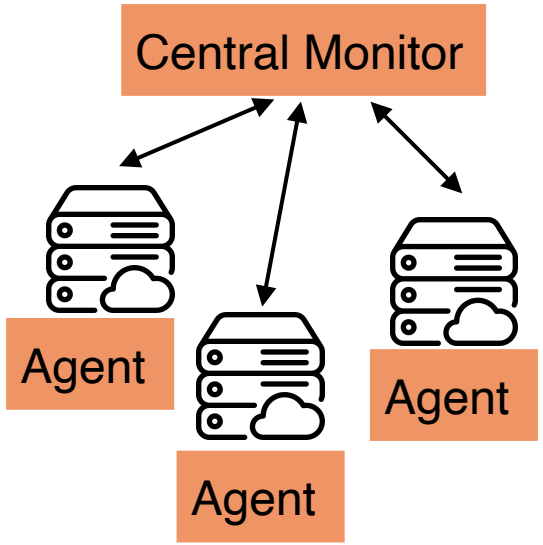
- We compare our approach with four baselines



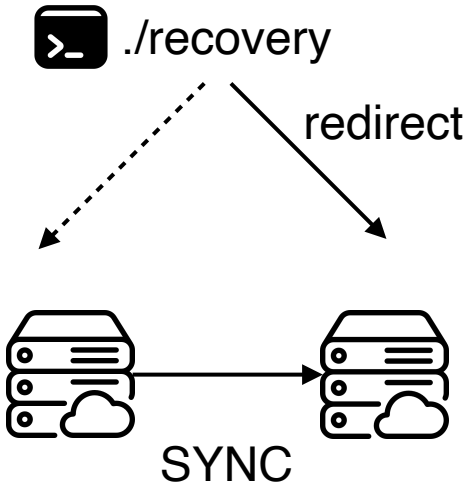
Built-in preview



A/B testing

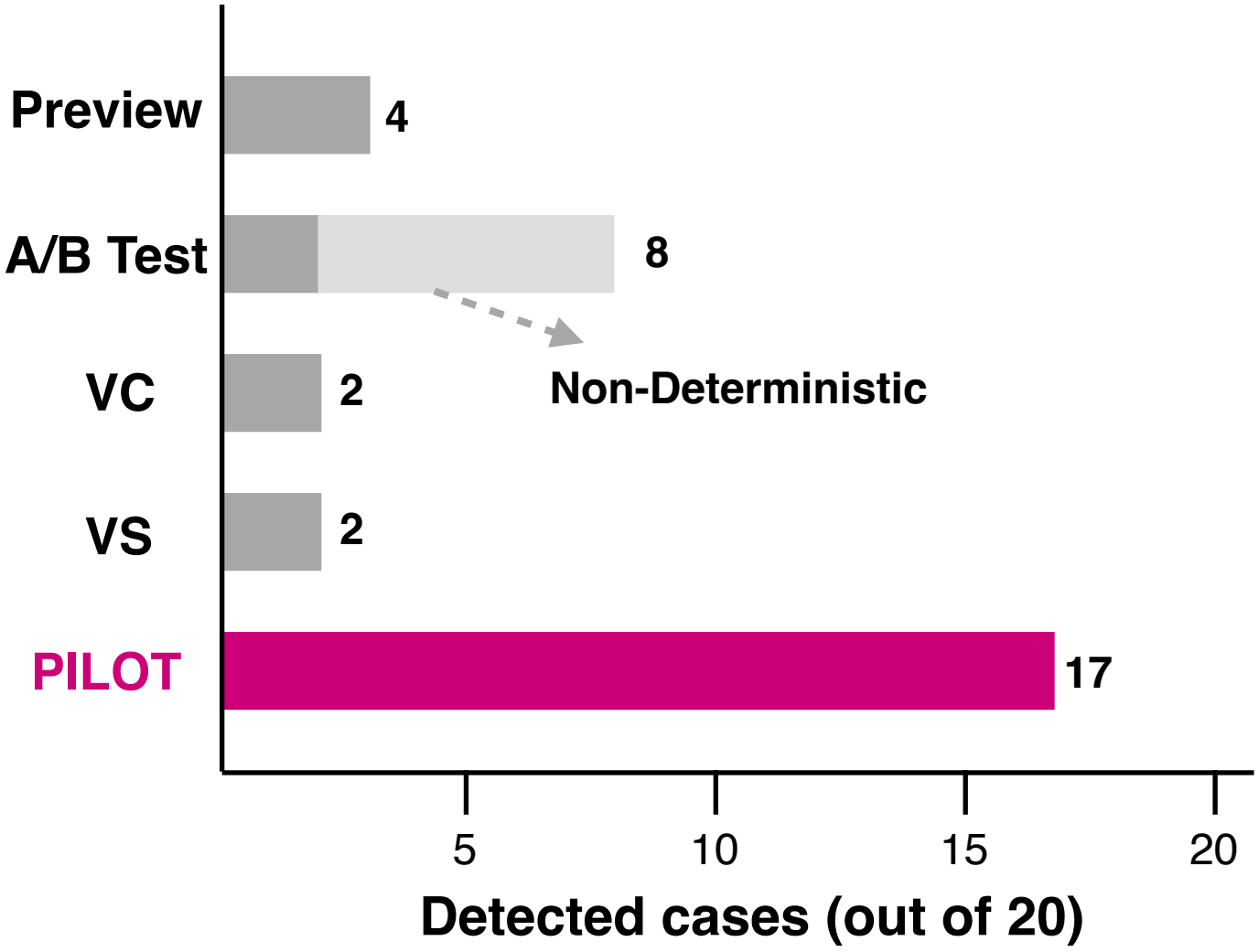


Correlate runtime logs
Vicious Cycle [ASE'23]

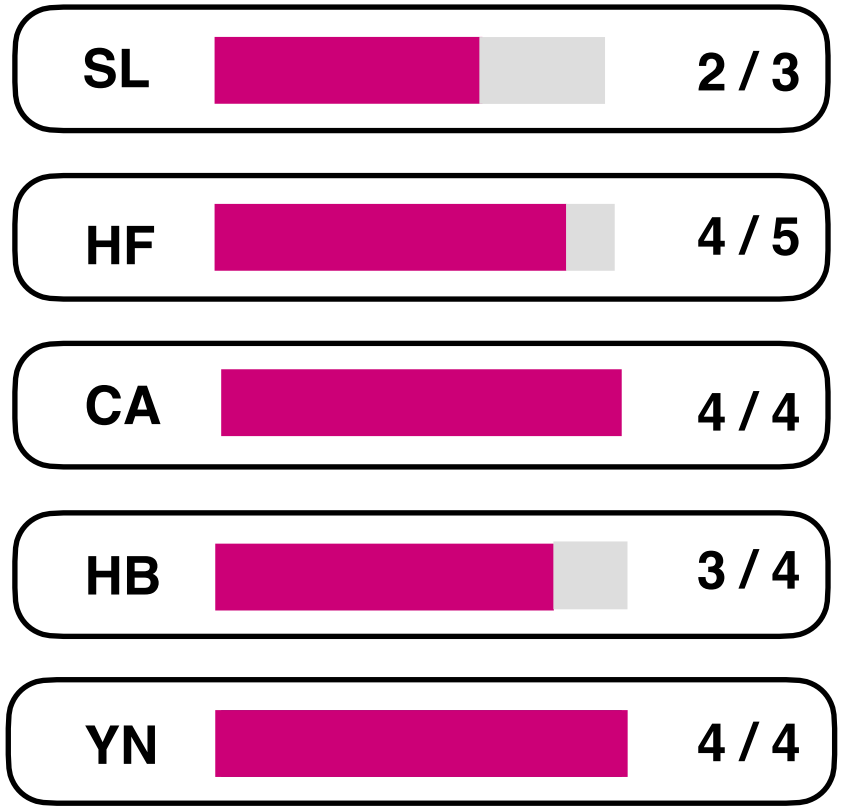


Replay traffic to masked components
Validation Slice [OSDI'04]

Evaluation: detection



17/20
cases detected by PILOT

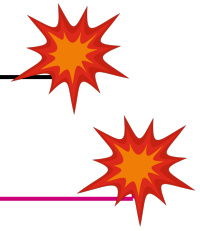


Evaluation: recovery time

Avg. Detection time of recovery failure

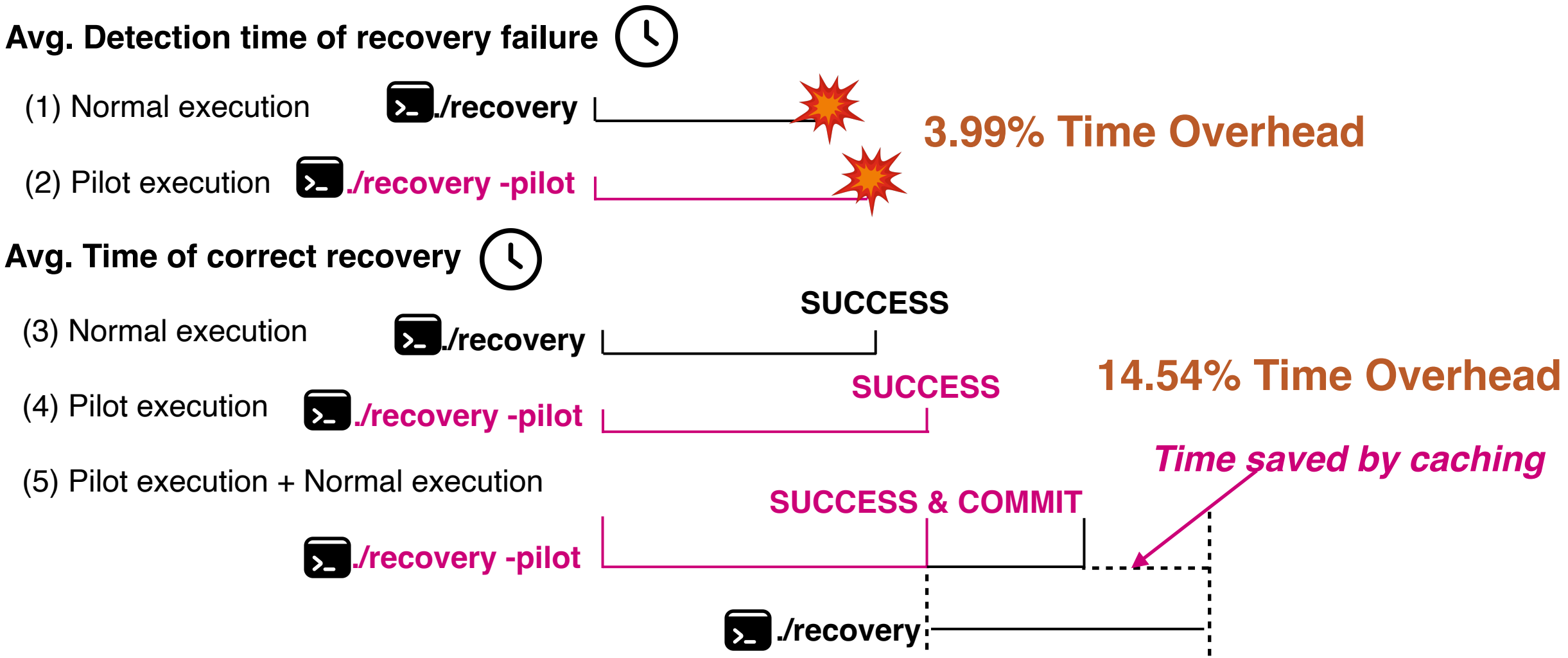
(1) Normal execution **./recovery**

(2) Pilot execution **./recovery -pilot**



3.99% Time Overhead

Evaluation: recovery time



PILOT Exposed a Critical HBase Recovery Bug

HBase / HBASE-28589

Server side DoNotRetryException not propagated to client

Edit | Add comment | Agile Board | More | Reopen Issue

Details

Type:	Bug	Status:	RESOLVED
Priority:	Critical	Resolution:	Fixed
Affects Version/s:	2.0.0, 2.4.0, 2.5.0, 2.6.0, 3.0.0	Fix Version/s:	2.7.0, 3.0.0-beta-2, 2.6.4, 2.5.13
Component/s:	IPC/RPC		
Labels:	pull-request-available		
Tags:	Retry, RPC, cascading failure, region server		
External issue URL:	https://github.com/apache/hbase/pull/7156		

Description

When an IOException occurs during response creation in ServerCall.setResponse(), the method only catches the IOException and logs a warning and sets the response to null. This causes the client to receive no response or experience connection issues without knowing what went wrong on the server side.

Conclusion

- Recovery in production distributed systems can be risky.
- Pilot execution turns recovery into a previewable "dry-run" action.
- In-situ dry-runs are feasible with phantom threads and context propagation.
- PILOT is a first step toward validatable cloud management.

Key results

- Studied **75** real-world recovery failures
- PILOT detects **17/20** real-world recovery failures
- PILOT adds modest **overhead** to original recovery

github.com/LiftLab-UVA/PilotExecution

vnr3ne@virginia.edu