Vicious Cycles in Distributed Software Systems

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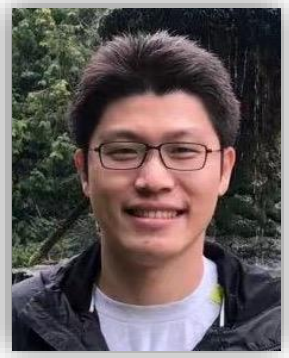

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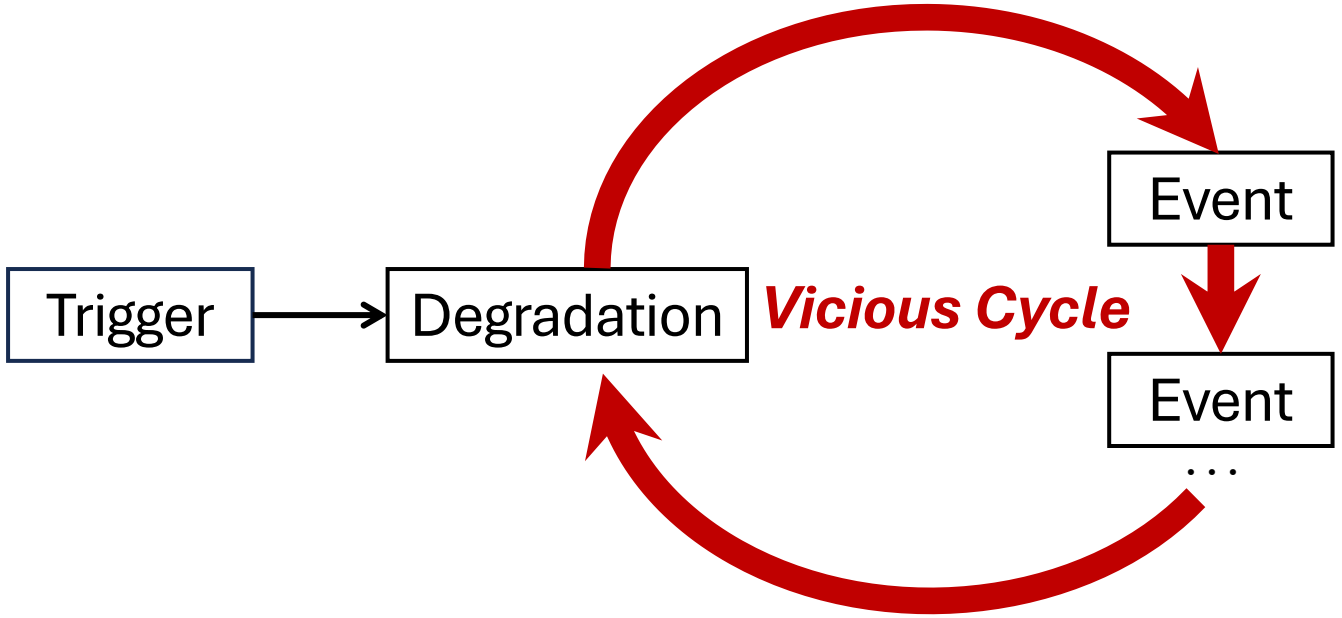
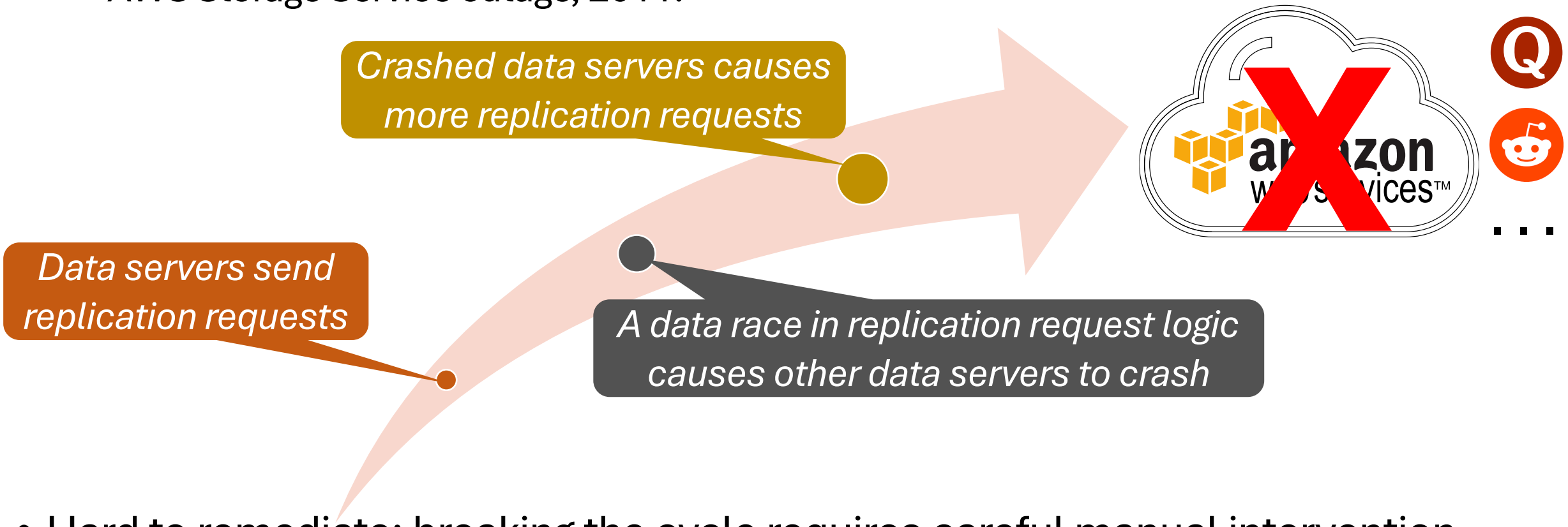
Vicious Cycle: Self-Reinforcing Failures in Distributed Systems

- Vicious Cycle: A **self-reinforcing** cycle between events and system degradation during a distributed system's execution.
  - Degradation: e.g., node crash, missing data blocks
  - Event: Any other normal execution in the system



Vicious Cycles are Catastrophic!

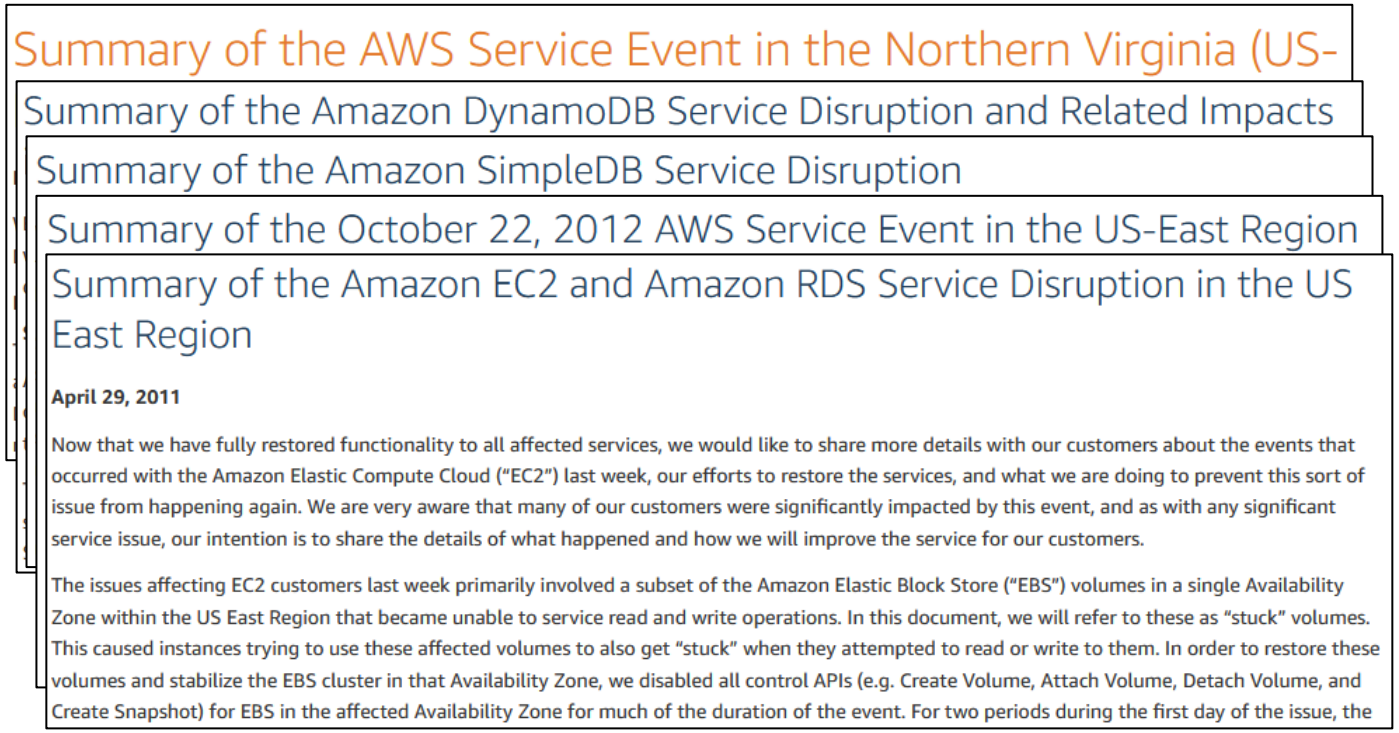
- Large-scale impact: the cycle propagates across nodes.
  - AWS Storage Service outage, 2011.



- Hard to remediate: breaking the cycle requires careful manual intervention.
  - AWS outage took 3 days to recover: fine-grained throttling, adding physical servers.

Vicious Cycles are a Major Reason for Cloud Outage

- One third of the **most catastrophic** AWS outages involve vicious cycles.
  - Most recent one in 2021.



"Once a system reaches a certain level of reliability, most major incidents involve a self-reinforcing cycle." [1]

[1] https://surfingcomplexity.blog/2017/06/24/a-conjecture-on-why-reliable-systems-fail/

Vicious Cycles are Under-Investigated

- Existing studies are limited
  - Guo et al. [1] investigated four vicious cycles
  - Huang et al. [2] focuses on contention-induced vicious cycles
  - Both performed on proprietary cloud systems

[1] Guo, Zhenyu, et al. "Failure recovery: When the cure is worse than the disease." 14th Workshop on Hot Topics in Operating Systems (HotOS XIV). 2013.
[2] Huang, Lexiang, et al. "Metastable failures in the wild." 16th USENIX Symposium on Operating Systems Design and Implementation (OSDI 22). 2022.

First Empirical Study on Vicious Cycles in Open-Source D.S.

- 33 Vicious Cycles, on 13 open-source distributed software systems
  - Studied systems: HDFS, Hadoop, HBase, Cassandra, Kafka, etc.
  - Case collection: Keyword-based searching with manual filtering
  - Source-code-level study with 8 bugs reproduced for better understanding
    - Each one takes one week on average

Contribution

- 16 findings revealing unique characteristics of vicious cycles
  - Symptom
    - Majority (55%) of vicious cycles' degradation grows exponentially, while almost half grows linearly.
  - Root cause
    - Key insight: Vicious cycles are formed due to **missing** or **insufficiently informed** error handlers.
  - Triggering conditions
  - Fixing strategies

- Feasibility study: Automatically detecting & preventing vicious cycles
  - Feeding error handlers with required causal information

- The bug dataset, detailed analysis, and code are publicly available[1].

[1] https://github.com/lin-tan/vcstudy

Root Cause: How are Vicious Cycles Formed?

Insufficiently Informed Error Handlers

Vicious Cycle Type	Subtype	Interference
Unexpected Cycle (60%)	Incorrect Degradation Recovery (36%)	Performance (21%)
		Functional (15%)
	Unconstrained Retry (24%)	Performance (24%)
Unexpected Error (40%)	Undetected Error (18%)	N/A
	Unhandled Error (22%)	N/A

Missing Error Handlers

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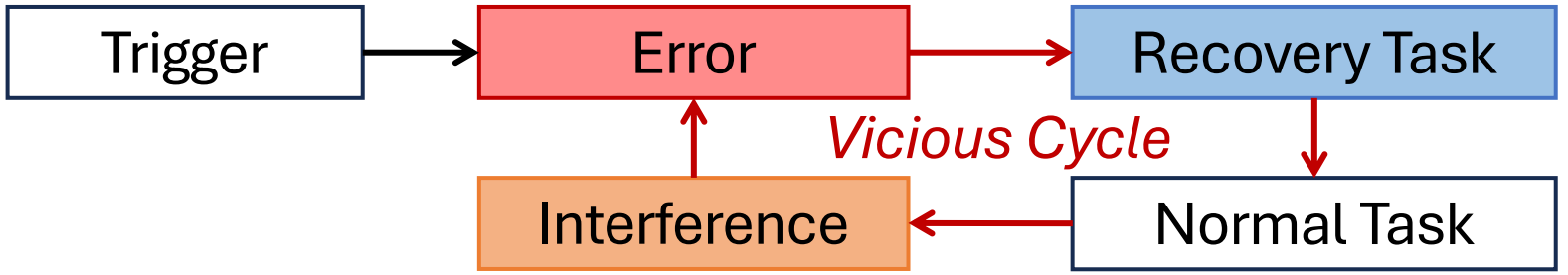
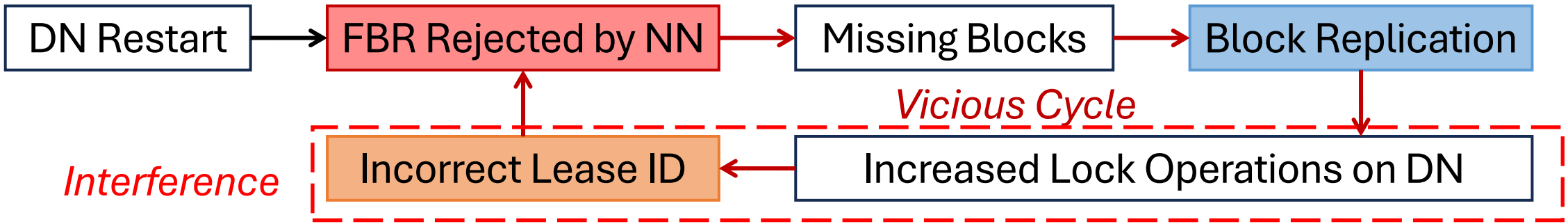
Unexpected Cycle: Insufficiently Informed Error Handler



- An external trigger causes an **error**.
- The **recovery task** performed by the error handler unexpectedly **interferes** with the request handling and causes other requests to fail.
  - Functional interference: IO error, deadlock, data race, etc.
  - Performance interference: CPU, memory, and network contention

Incorrect Degradation Recovery w/ Functional Interference

- HDFS-12914: HDFS loses a large number of DataNodes after restart.



- *DN: DataNode*
- *FBR: Full Block Report (part of DN registration after restart)*
- *NN: NameNode*

Unexpected Cycle Example 2: Performance Interference

<table>
<tr><td rowspan="3">Unexpected Cycle (60%)</td><td rowspan="2">Incorrect Degradation Recovery (36%)</td><td>Performance (21%)</td></tr>
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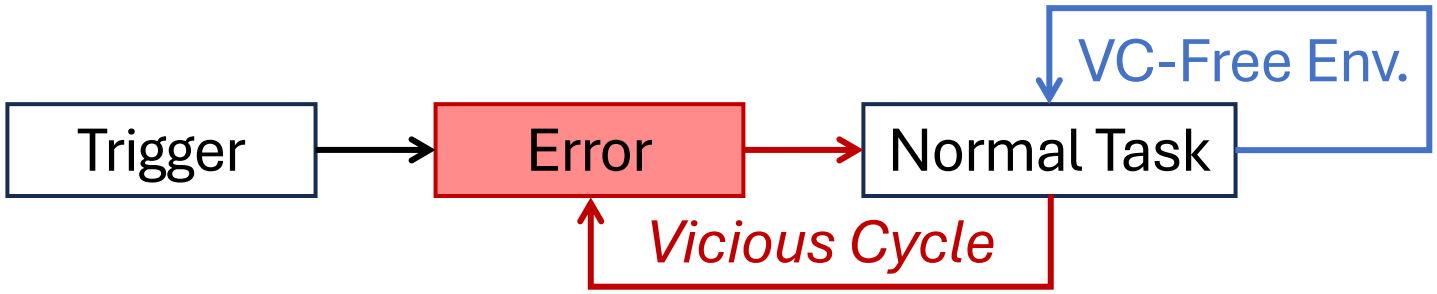
- Feasibility study 1: Applying exponential backoff

More details in the paper!

Unexpected Error's Propagation Along a Global Cycle



- An error that hinders the task completion is propagated along a global cycle.
  - Unhandled Error: The error in the cycle is observed, but not properly handled.
  - Undetected Error: The error in the cycle is silent, thus, no error handler is implemented.

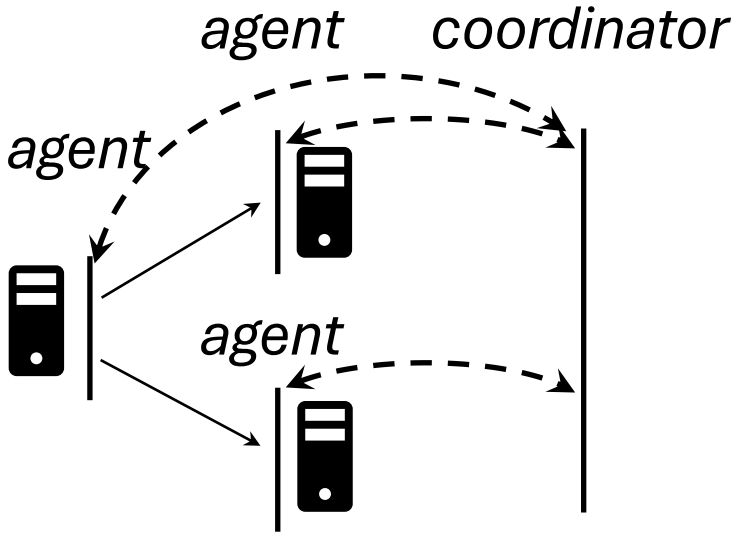
UE Subtype 1: Deadly Retry of Unhandled Errors

- Retry error-inducing requests on multiple nodes, causing them to fail.

- Root cause: missing causal information
  - Unable to infer the causality between the error and the error-inducing retried request

UE Subtype 1: Deadly Retry of Unhandled Errors

- Feasibility study 2: Preventing deadly retries
  - Infer causality between error and request
  - Local agent: Records RPC requests and fatal errors.
  - Central coordinator
    - Monitors repeated fatal errors from different nodes
    - Compares recent RPCs from failed nodes to identify the error-inducing retried request, and blocks the request
  - Result: Successfully prevents two vicious cycles



UE Subtype 2: Undetected Error Causing Vicious Cycles

- Vicious cycle: Undetected error spread by a normal loop execution.
  - Reason: Error detector fails to distinguish an error from a normal execution.
  - Majority (83%) are caused by logic errors: hard to detect automatically.

Potential Solutions

- Detect & break the cycle: Informed recovery decision
  - Infer the causal relationship between requests and errors

- Test for the cycle: Trigger the interference
  - Targeted fault injection to trigger the interference between error handler & request handler

We need better error handlers with rich feedback information!

More findings and lessons in the paper!