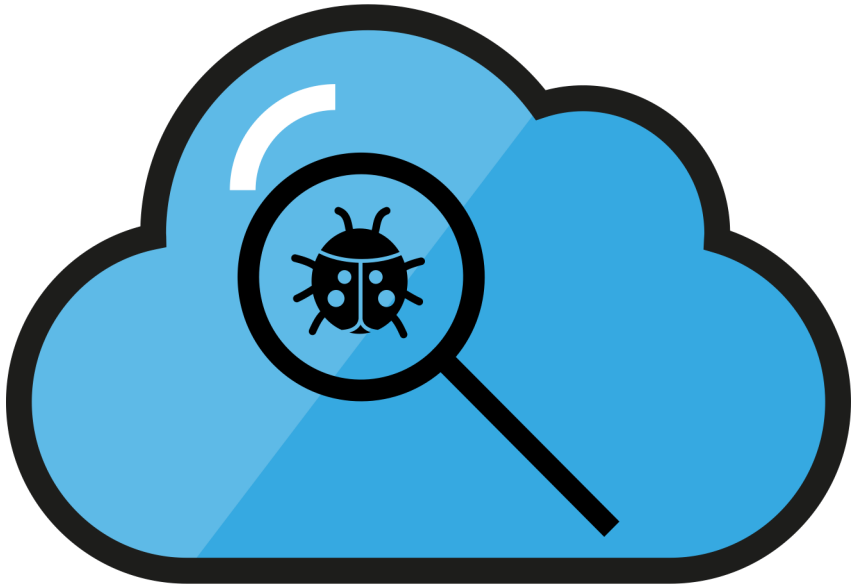
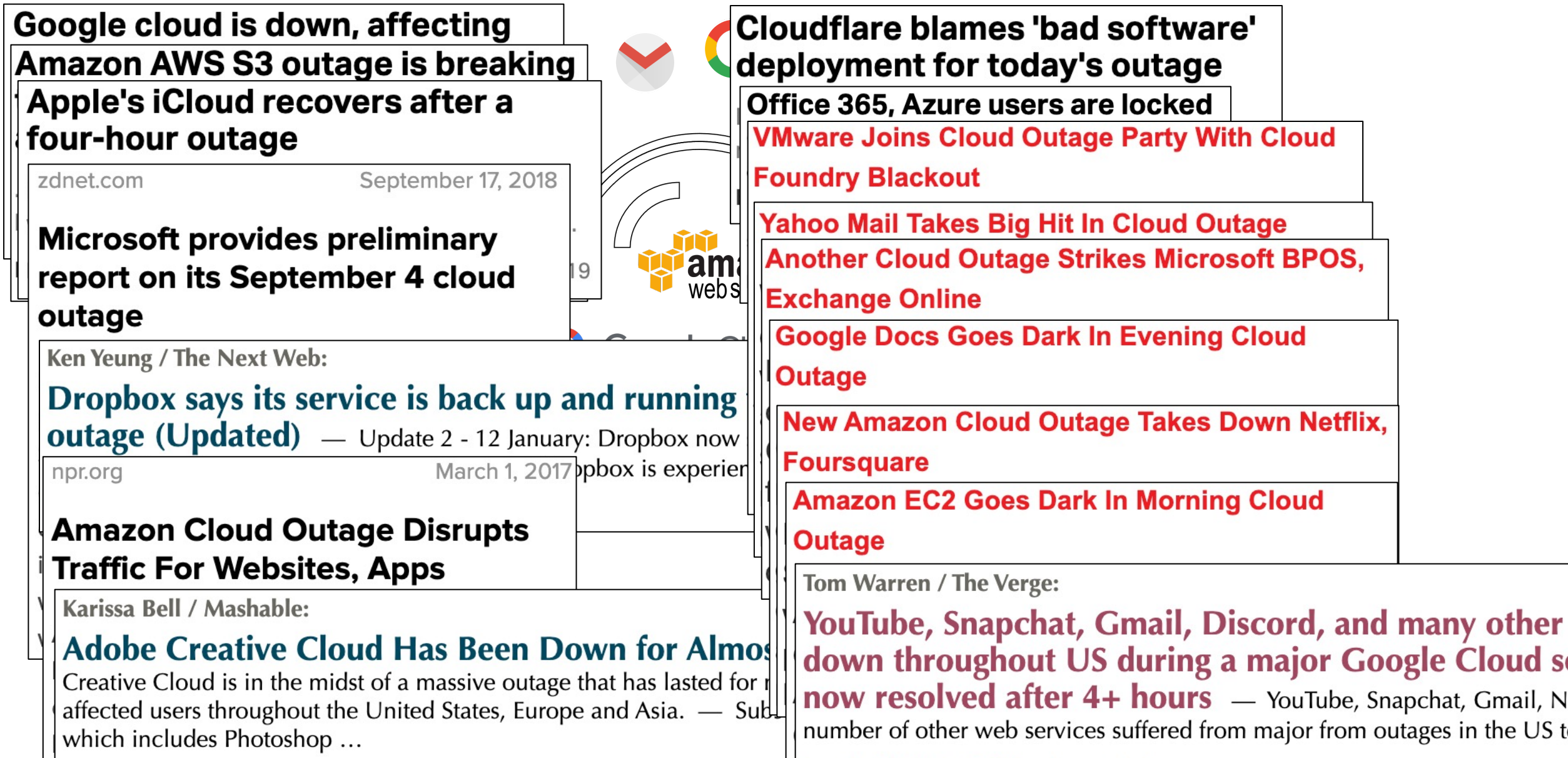
Automating Failure Diagnosis for Distributed Systems



Yongle Zhang

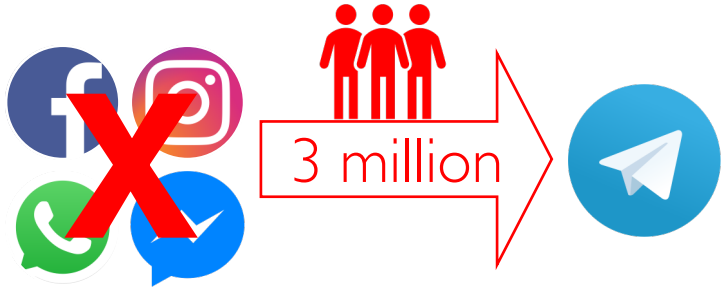
Purdue University

Most Internet services live on the cloud



Cloud failures have severe consequences

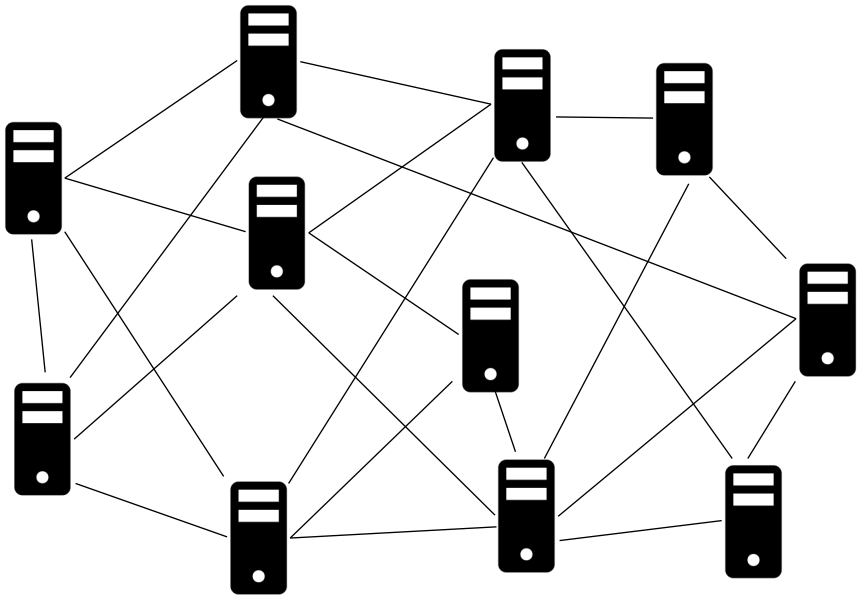
- Significant cost
  - E.g., 2018 Amazon Primeday [1]
- Frustrates & loses users
  - E.g., 03/13/2019 Facebook [2]
- Disrupts all services on the cloud
  - E.g., 02/2017 AWS [3]



[1]: https://www.cbronline.com/news/amazon-outage-lost-sales
[2]: https://techcrunch.com/2019/03/14/telegram-gets-3m-new-signups-during-facebook-apps-outage/
[3]: https://venturebeat.com/2017/02/28/aws-is-investigating-s3-issues-affecting-quora-slack-trello/

Failure diagnosis is important

Failure diagnosis for cloud systems is hard

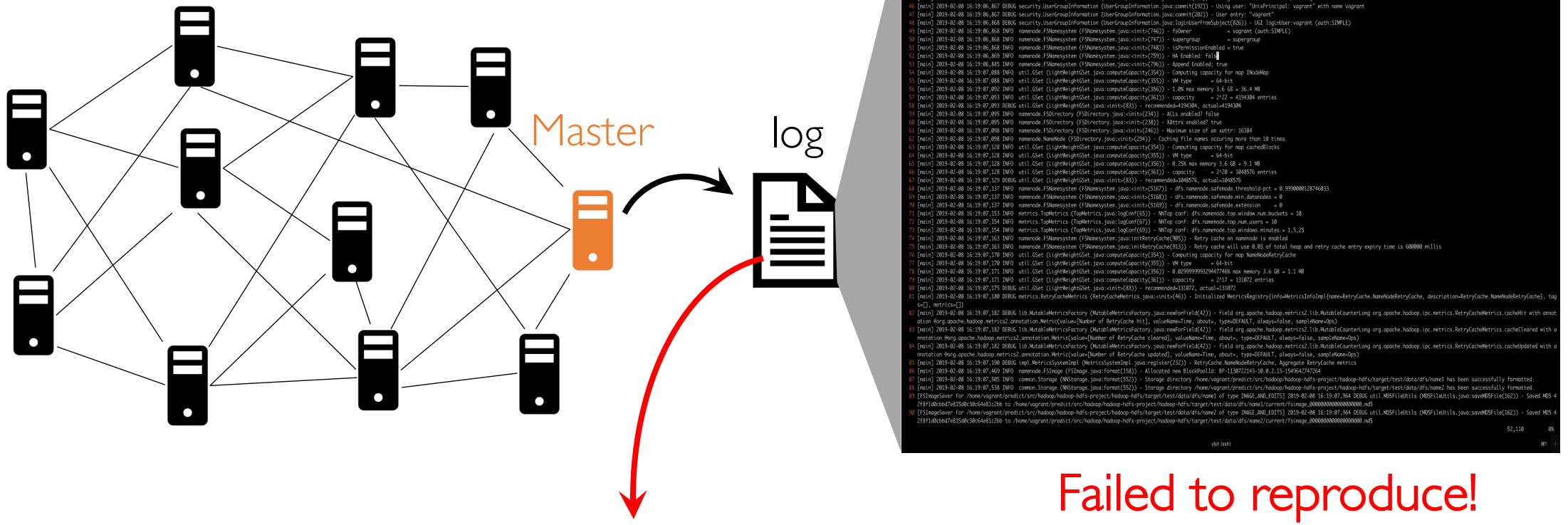


distributed system

Diagnosing HDFS-10453 took a month

- Step 1: reproduce the failure
- Challenge: large cluster, numerous operations
- Tried: 1) diff. cluster configurations, 2) diff. user operations, 3) diff. workloads

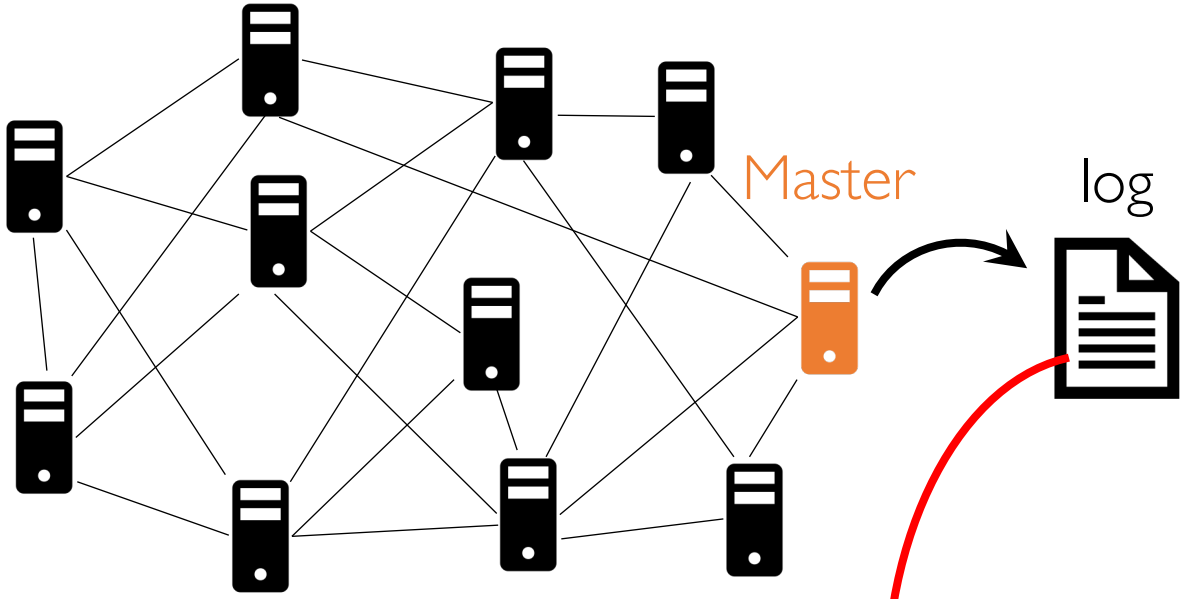
Hadoop distributed file system



Diagnosing HDFS-10453 took a month

- Step 2: locate the root cause
- Challenge: complex failure execution
- Tried numerous rounds of printf-debugging → took 1 month

Hadoop distributed file system




```
void replicateBlock(Block blk) {
                                                    ca;
  if (numNeeded > 0)
    Log.error("Failed to replicate.");
}
```

```
2019-02-08 16:19:17,126 ERROR Failed to replicate.
```

HDFS-10453 root cause

ReplicationMonitor thread

```
1.  void replicateBlock(Block blk) {
2.    int numNeeded = 3 - blk.nReplica;
3.    while(numNeeded > 0) {
4.      node = chooseNextRandomNode(..);
5.      if (blk.size <= node.capacity){
6.        ... // replicate b to this node
7.        numNeeded--;
8.      }
9.    }
10.   if (numNeeded > 0)
11.     Log.error("Failed to replicate.");
12. }
```

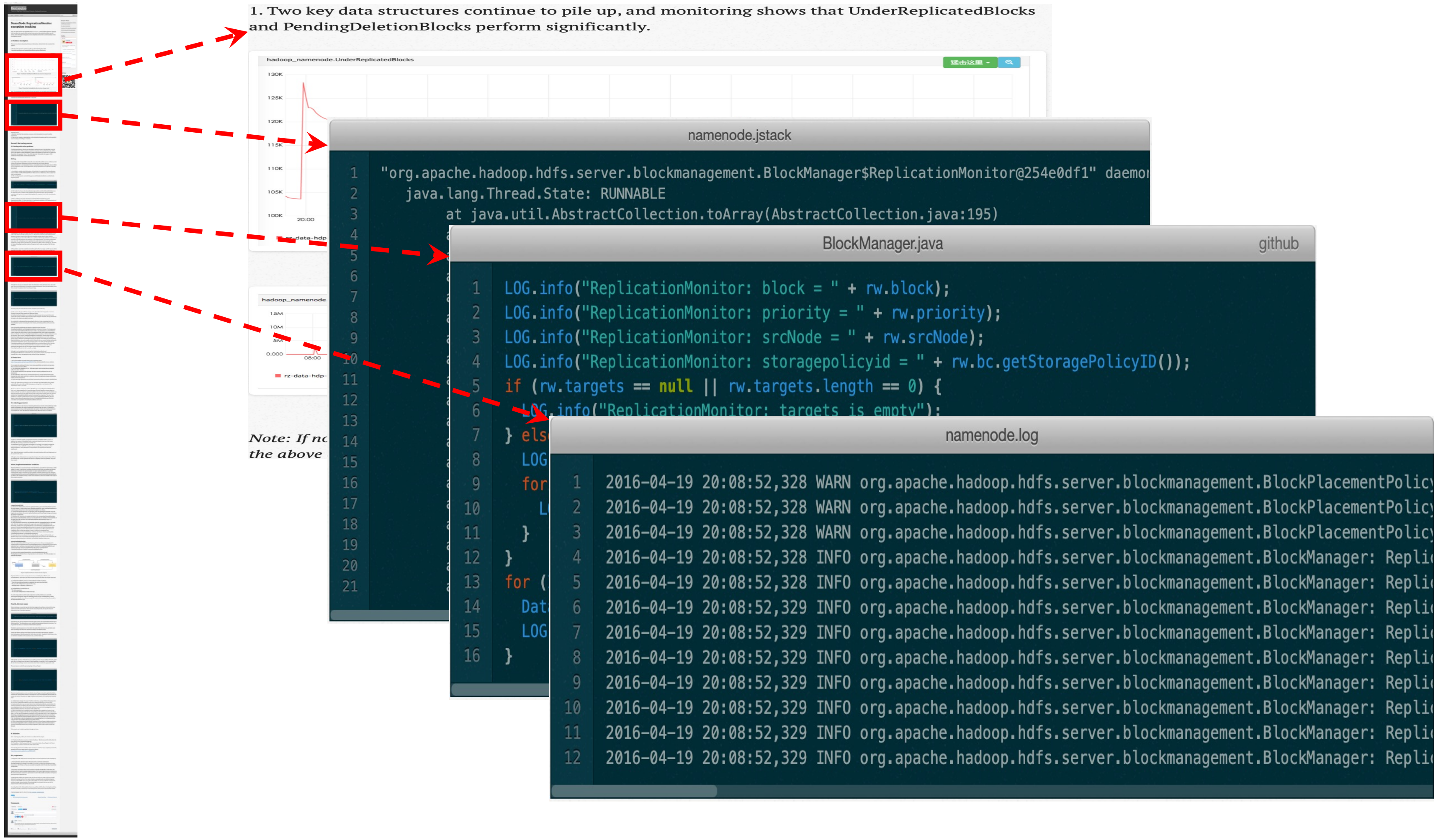
DeleteBlock thread

```
13. void deleteBlock(Block blk) {
14.   blk.size = Long.MAX_VALUE;
15.   FileSystem.remove(blk);
16. }
```

- A data race

Diagnosing HDFS-10453 took a month

- Developers got frustrated & wrote a blog[1]



[1]: NameNode RepicationMonitor anomaly diagnosis, https://hexiaoqiao.github.io/blog/2016/09/13/namenode-repicationmonitor-exception-trace/

Automating diagnosis

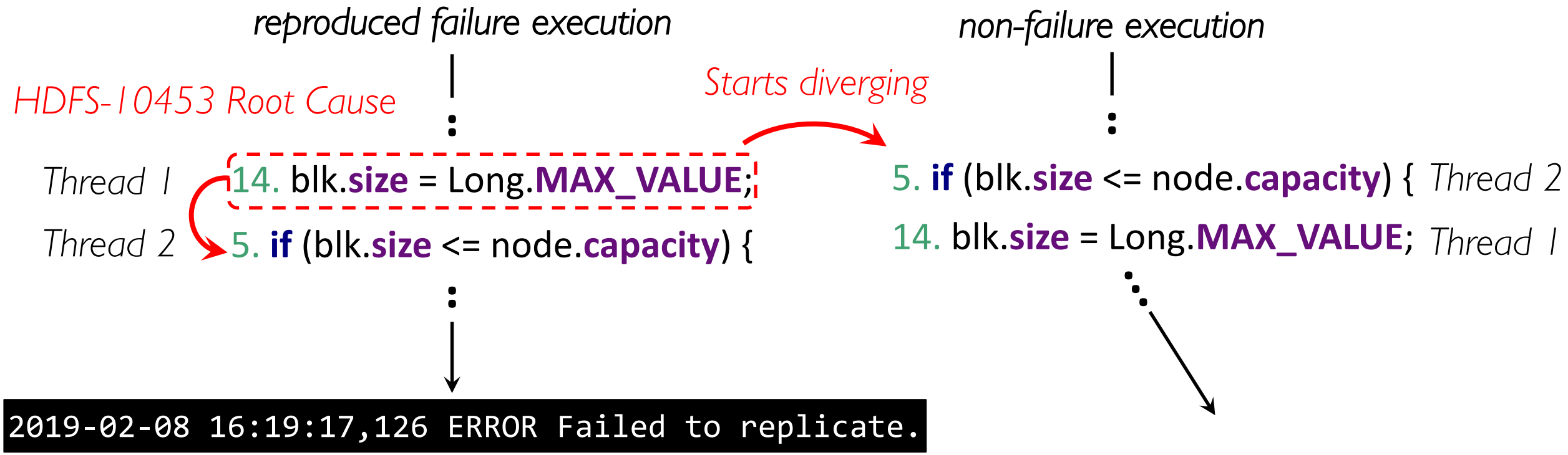
- Pensieve [SOSP'17]: automates failure reproduction
  - Input: logs + bytecode + symptom
  - Output: minimum steps to reproduce failures

```
initCluster(4);
create("a.txt",3);
stopDataNode(1);
delete("a.txt");
```

HDFS-10453 reproduction

Automating diagnosis

- Kairux [SOSP'19]: automates root cause localization
  - reproduced execution + symptom → root cause + non-failure execution



"software bugs - the most common cause of cloud incidents" *[Liu et al., HotOS'2019]*

Approach & impact

Approach › **Replicate how developers diagnose failures**

- Exploits human intuitions and principles
- Scales diagnosis techniques to distributed systems

Outline

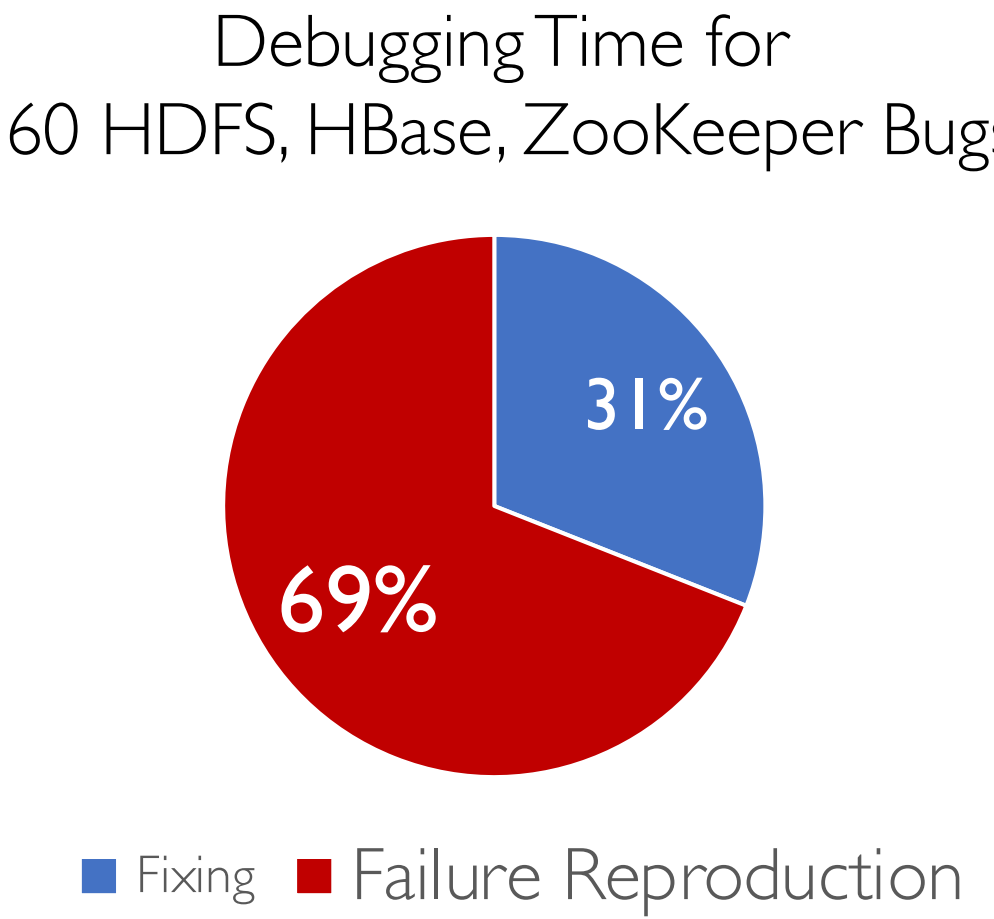
- Introduction

- Pensieve [SOSP'17]: automates failure reproduction
  - logs + bytecode + symptom → minimum steps to reproduce failures

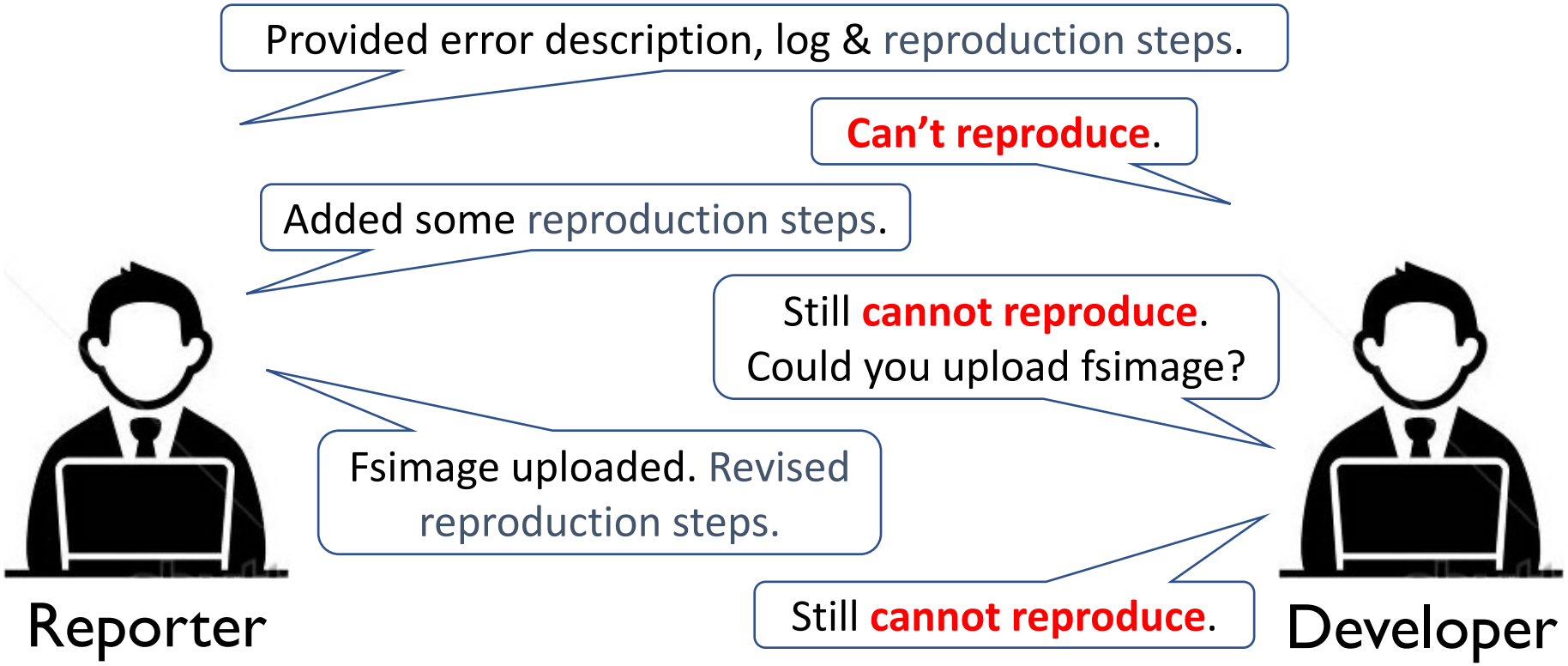
- Kairux [SOSP'19]: automates root cause localization

- Bigger picture

Failure reproduction is time-consuming

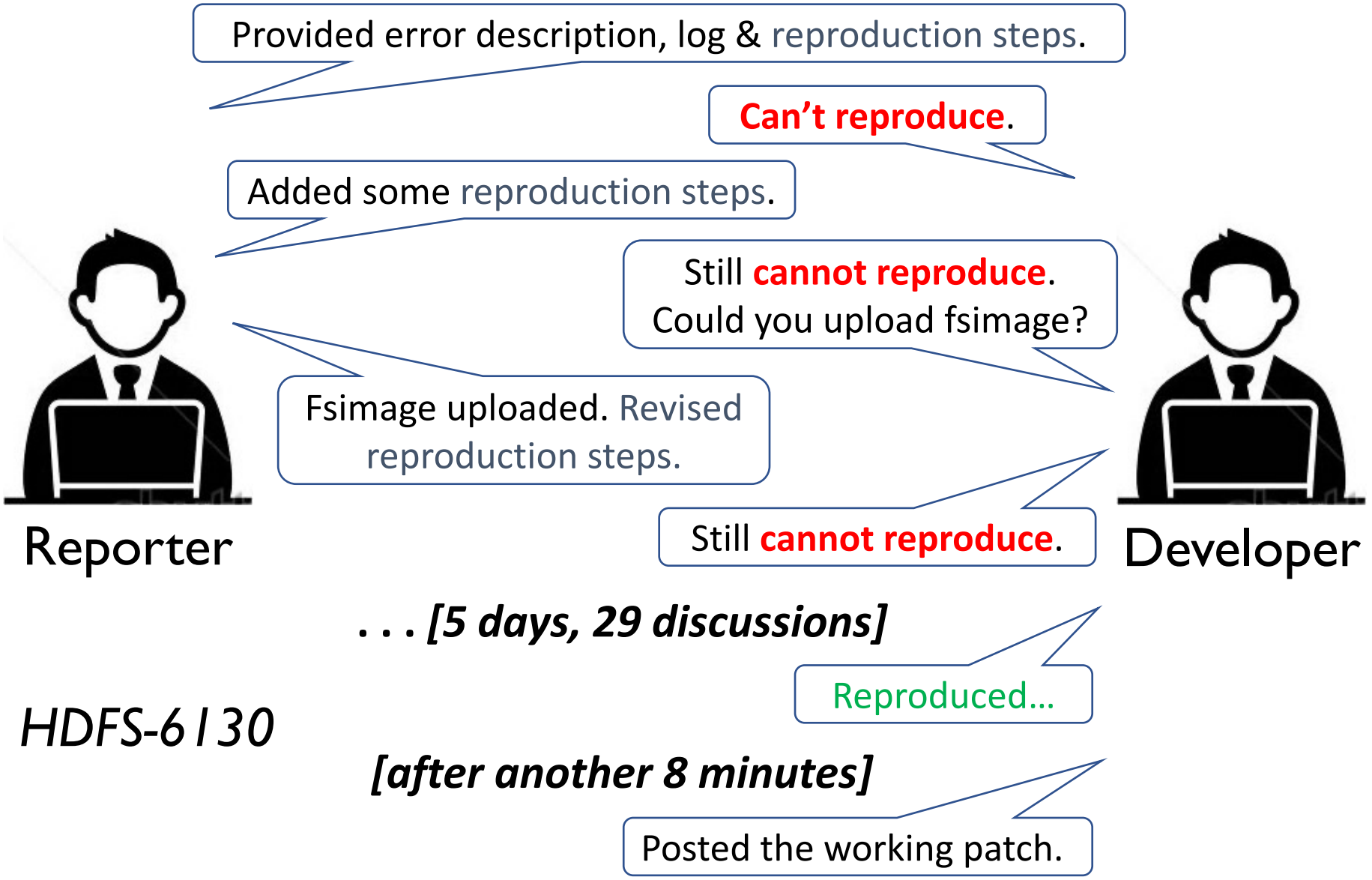


A Real-World Debugging Procedure



HDFS-6130

A Real-World Debugging Procedure



Existing Solutions Are Limited

- Record-and-replay (deterministic replay)
  - Intrusive: modifies existing software stack
  - Incurs performance overhead

- Symbolic Execution
  - E.g., ESD [Zamfir EuroSys'10], SherLog [Yuan ASPLOS'10].
  - Pros: precise & non-intrusive
  - Cons: hard to scale to large systems

Scalability of Symbolic Execution

```
1.for(int i=0;i<blocks.length;i++){
2.  if(blocks[i].genStamp!=VALID_GS)
3.    log("invalid block. . .");
4.}
```

Simplified code snippet for HDFS-4022

Scalability of Symbolic Execution

```
1.for(int i=0;i<blocks.length;i++){
2.  if(blocks[i].genStamp!=VALID_GS)
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Simplified code snippet for HDFS-4022

- Enumerates every possible execution path

Scalability of Symbolic Execution

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- Enumerates every possible execution path

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blocks[i].genStamp!=VALID_GS
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Simplified code snippet for HDFS-4022

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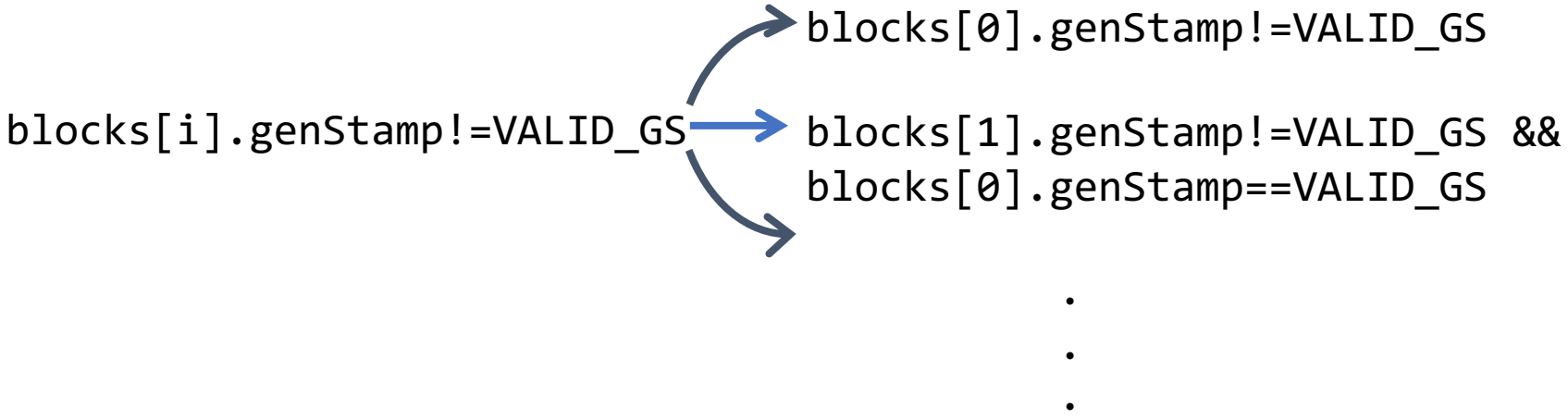

Scalability of Symbolic Execution

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3.    log("invalid block. . .");
4.}
```

Simplified code snippet for HDFS-4022

- Enumerates every possible execution path

```
                                  blocks[0].genStamp!=VALID_GS
                                            OR
blocks[i].genStamp!=VALID_GS  →   blocks[1].genStamp!=VALID_GS &&
                                  blocks[0].genStamp==VALID_GS
                                            OR
                                              .
                                              .
                                              .
```

Scalability of Symbolic Execution

```
1.for(int i=0;i<blocks.length;i++){
2.  if(blocks[i].genStamp!=VALID_GS)
3.    log("invalid block. . .");
4.}
```

Simplified code snippet for HDFS-4022

- Enumerates every possible execution path

Failure	*Total Branch Instructions*	*S.E. Stopped At (Instructions)*	*Condition Size*	*Pensieve instruction*
HDFS-4022	72,943,652	693	109,018,324	166

Core Idea – Partial Trace Observation

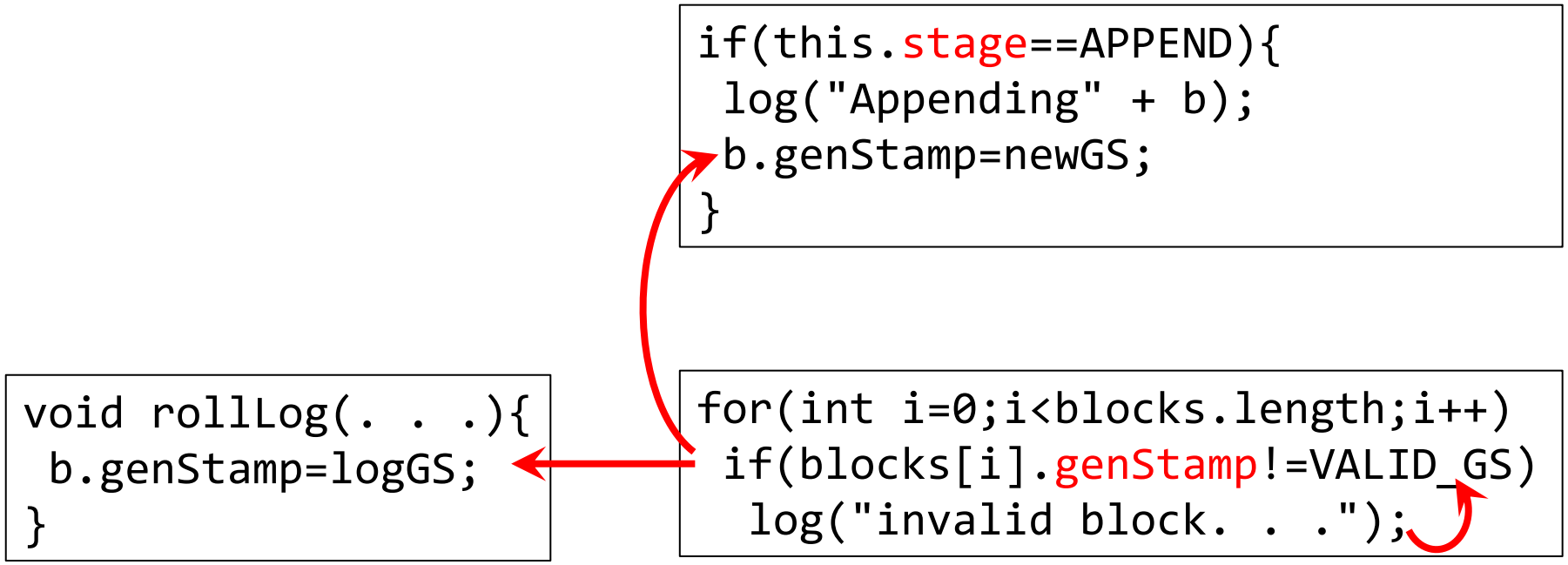
Developers almost never debug a failure by reconstructing its complete execution path.

Instead, they construct a simplified trace which only contains events that are likely to be causally relevant to the failure.

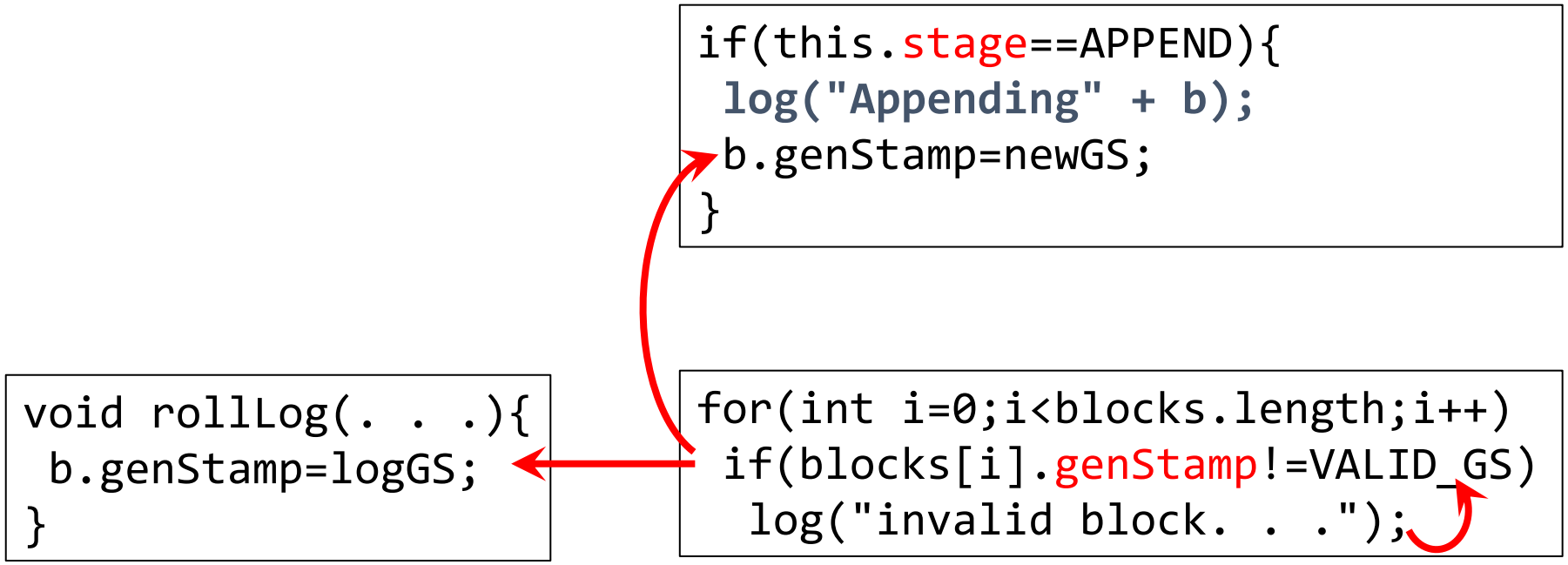
How do developers debug HDFS-4022?

```
for(int i=0;i<blocks.length;i++)
 if(blocks[i].genStamp!=VALID_GS)
  log("invalid block. . .");
```

How do developers debug HDFS-4022?



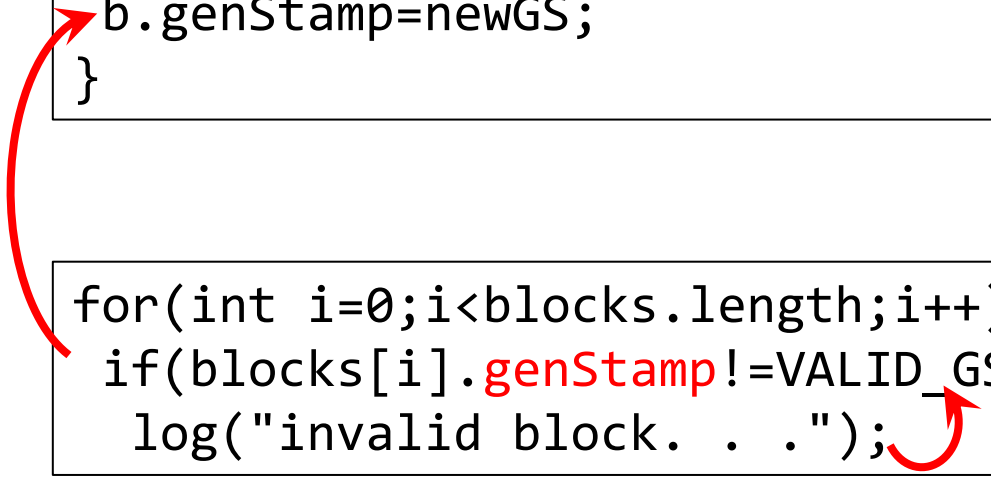
How do developers debug HDFS-4022?



How do developers debug HDFS-4022?

```
if(this.stage==APPEND){
 log("Appending" + b);
b.genStamp=newGS;
}
```

```
for(int i=0;i<blocks.length;i++)
 if(blocks[i].genStamp!=VALID_GS)
  log("invalid block. . .");
```



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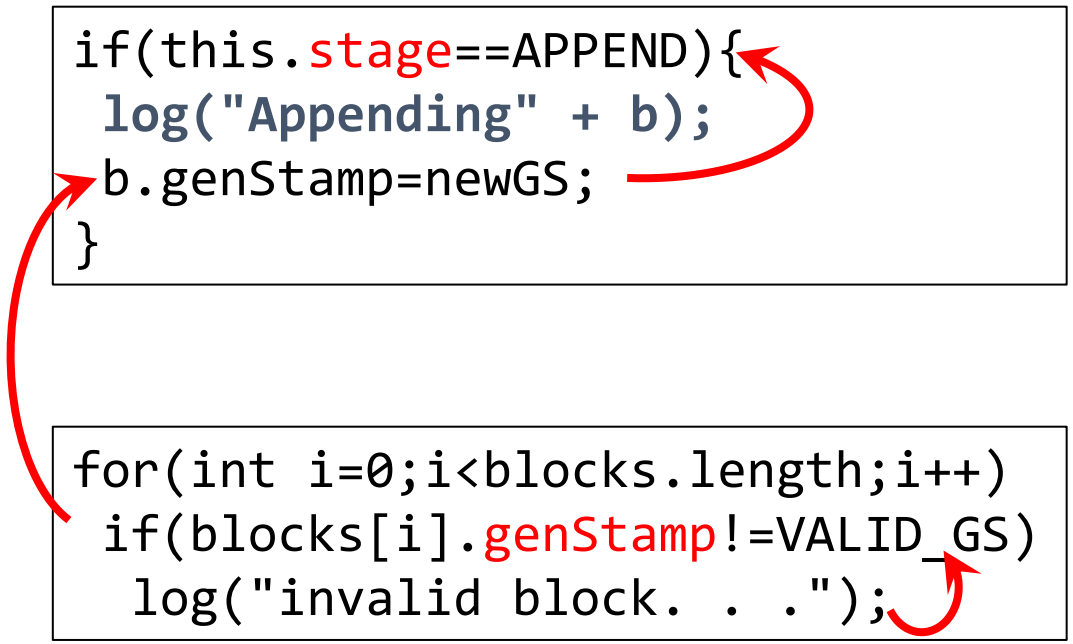

How do developers debug HDFS-4022?

Client.java

```
void append(. . .){
 stage=APPEND;
 . . .
}
```

```
if(this.stage==APPEND){
 log("Appending" + b);
b.genStamp=newGS;
}
```

```
for(int i=0;i<blocks.length;i++)
 if(blocks[i].genStamp!=VALID_GS)
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```
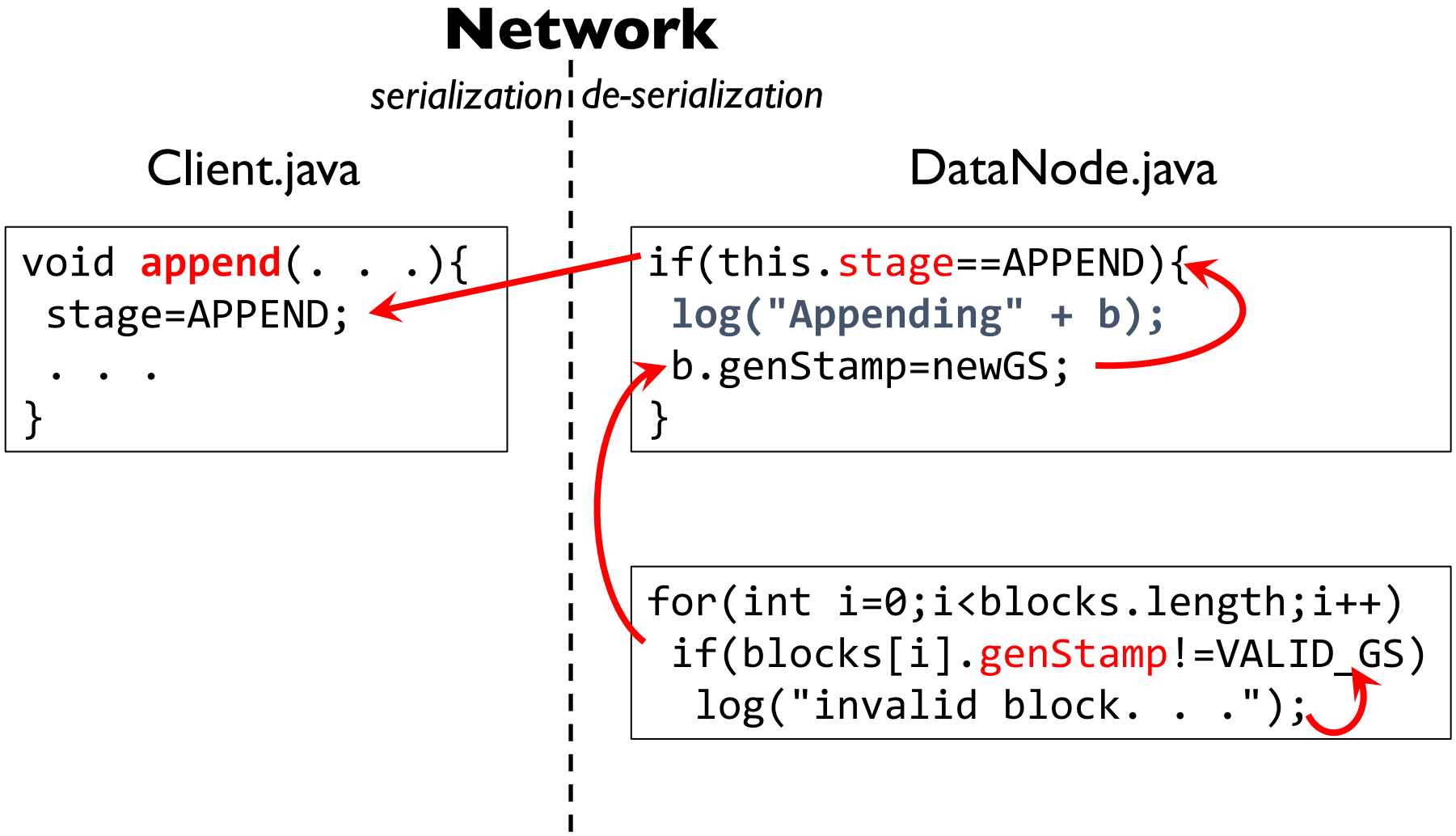

How do developers debug HDFS-4022?



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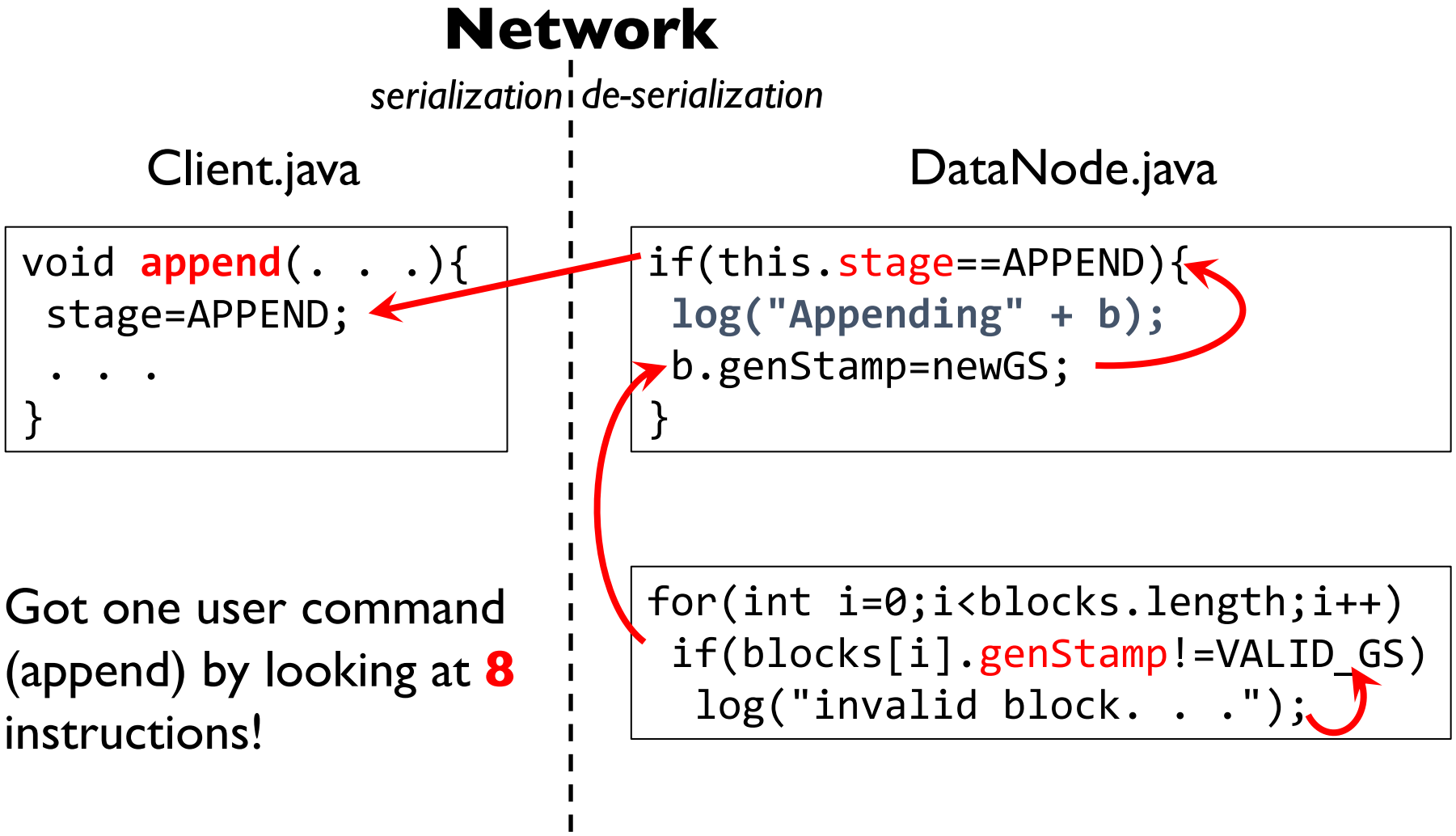


Pensieve: automated failure reproduction

Command Line Input (HDFS-4022)

```
./pensieve
-jar ./hadoop-hdfs-2.0.0-alpha.jar // Java bytecode
-log ./HDFS-logs/                  // failure logs
-error ./HDFS-logs/dn2.log#800     // symptoms
```

dn2.log

```
800: 2019-02-08 16:19:17,126 ERROR invalid block
```

Output: reproduction

```
initCluster(1);                // start 1-machine cluster
create(“a.txt”,2);             // create 2-replica file
append(“a.txt”,“X”);           // append to file
addDataNode();                 // add a datanode on the fly
```

Evaluation of Pensieve

- Evaluated on 18 cases from JVM distributed systems
  - HDFS, HBase, ZooKeeper, Cassandra
  - with noisy logs generated from manual reproduction

- Overall Result
  - Successfully reproduces 72%

Case study: HDFS-4022

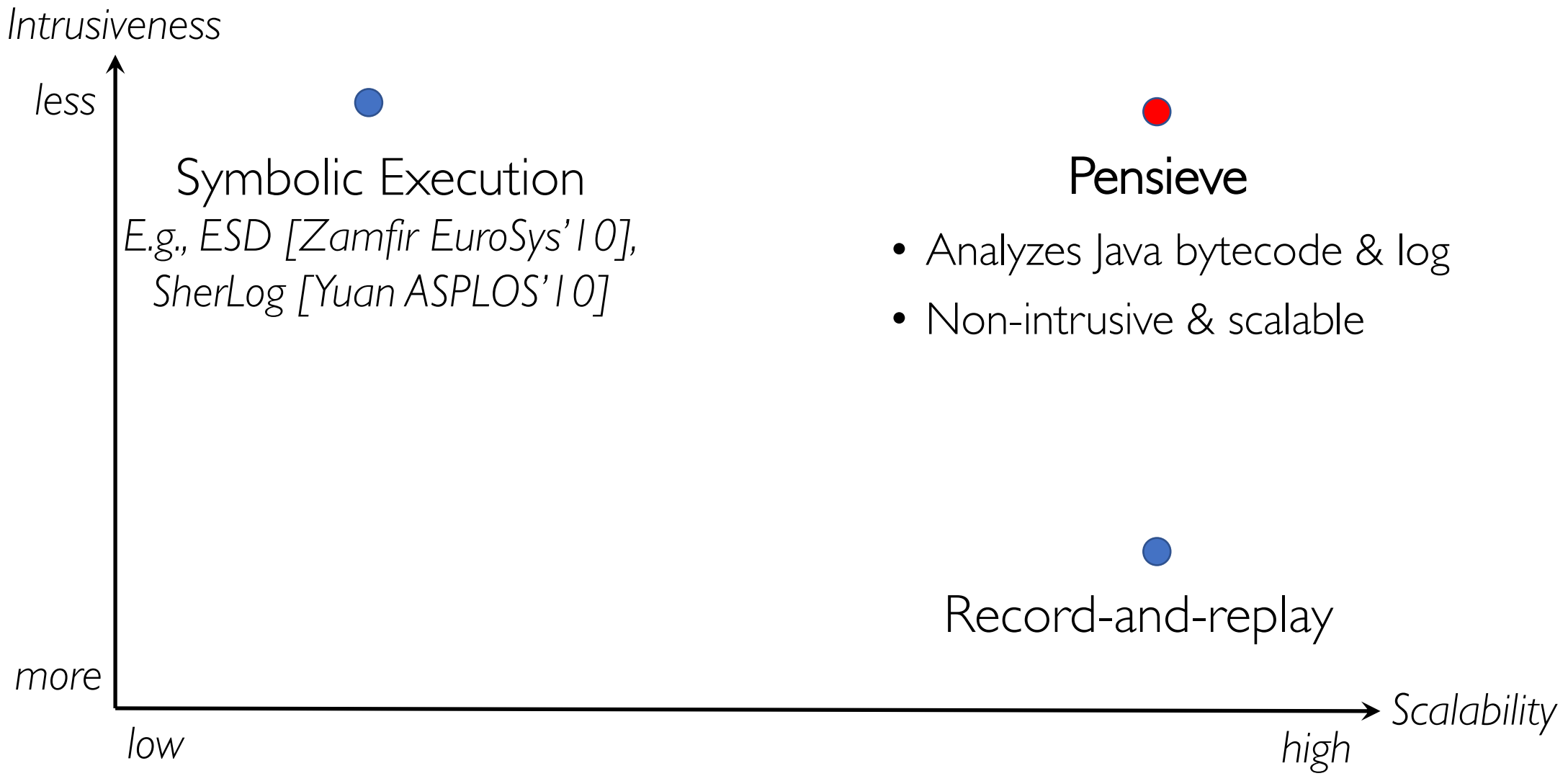
```
initCluster(4);
create("a.txt",3);
stopDataNode(1);
append("a.txt","data");
```

Developers' reproduction

```
initCluster(3);
setConfig("policy", "ALWAYS");
create("a.txt",2);
stopDataNode(1);
append("a.txt","data");
```

Pensieve's reproduction – ***fewer nodes!***

Related work: failure reproduction



Pensieve

- Partial Trace Observation: the natural way human beings reproduce failures

Developers construct a simplified trace which only contains events that are likely to be causally relevant to the failure.

- Pensieve: automated failure reproduction
  - Scales to real-world distributed systems
  - Non-intrusive & relies on logs

Outline

- Introduction

- Pensieve [SOSP'17]: automates failure reproduction

- Kairux [SOSP'19]: automates root cause localization
  - Assumption: failure is reproduced
  - Answers "what is a root cause?"

- Bigger picture

Kairux: root cause localization

- Input
  - reproduced failure execution e_f
- Output
  - the location of one single root cause in e_f
  - a non-failure execution that avoids the root cause

Existing works are neither precise nor scalable

Understandability (execution context that explains the root cause)

Probabilistic approach

E.g., spectrum-based *[Jones et al., ICSE'02]*, statistical debugging *[Liblit et al., PLDI'05]*

Execution searching

E.g., Image *[Tucek et al., SOSP'07]*, BugEx *[Kobler et al., ISSTA'12]*, Holmes *[Johnson et al., ICSE'20]*

```
void func(...) {
 if (a1 > 0) {...}
 ...
 if (an > 0)
   Log.error("ERROR");
}
```

search space 2^n (T/F, …, T/F)

Delta debugging

```
10. if (numNeeded > 0)
11.   Log.error("Failed to replicate...");
```

Predicate-switching *[Zhang et al., ICSE'06]*

Kairux

- *Instruments program to record predicates*
- *Instruments program to record failure*
- *Based on a precise, scalable definition of root cause*
- *Selects single failure execution with minimal differences*
  - *Reduces search space, scales to distributed systems*
  - *Finds single root cause location*
- *Root cause candidates: strong statistical correlation*
  - *Explains the root cause*

Scalability

What is a root cause?

What is the fundamental property of a root cause that allows us to build a tool to automatically search for it?

What is a root cause?

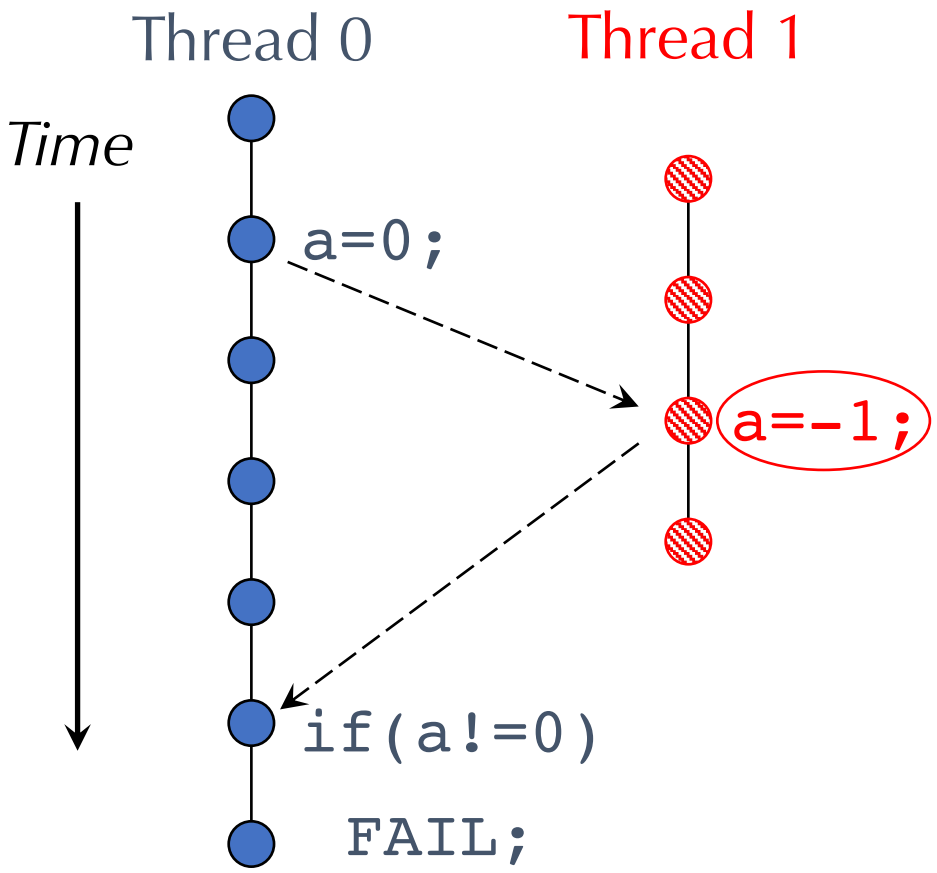
The most basic reason for a failure which, if corrected, would have prevented the failure from occurring.

– Wilson et al. ASQ Quality Press 1993

What is a root cause?

1. The root cause is an instruction in the failure execution which, if changed, would have resulted in a correct execution.

HDFS-10453 simplified



2. The root cause is the most basic cause of the failure.

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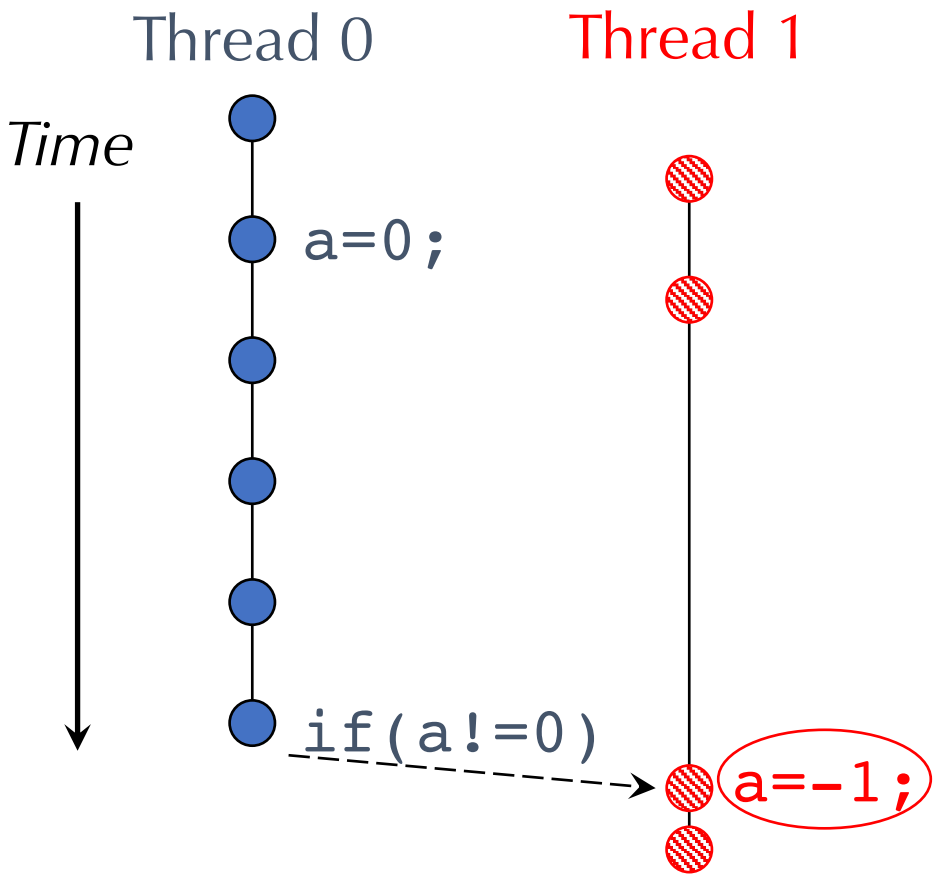

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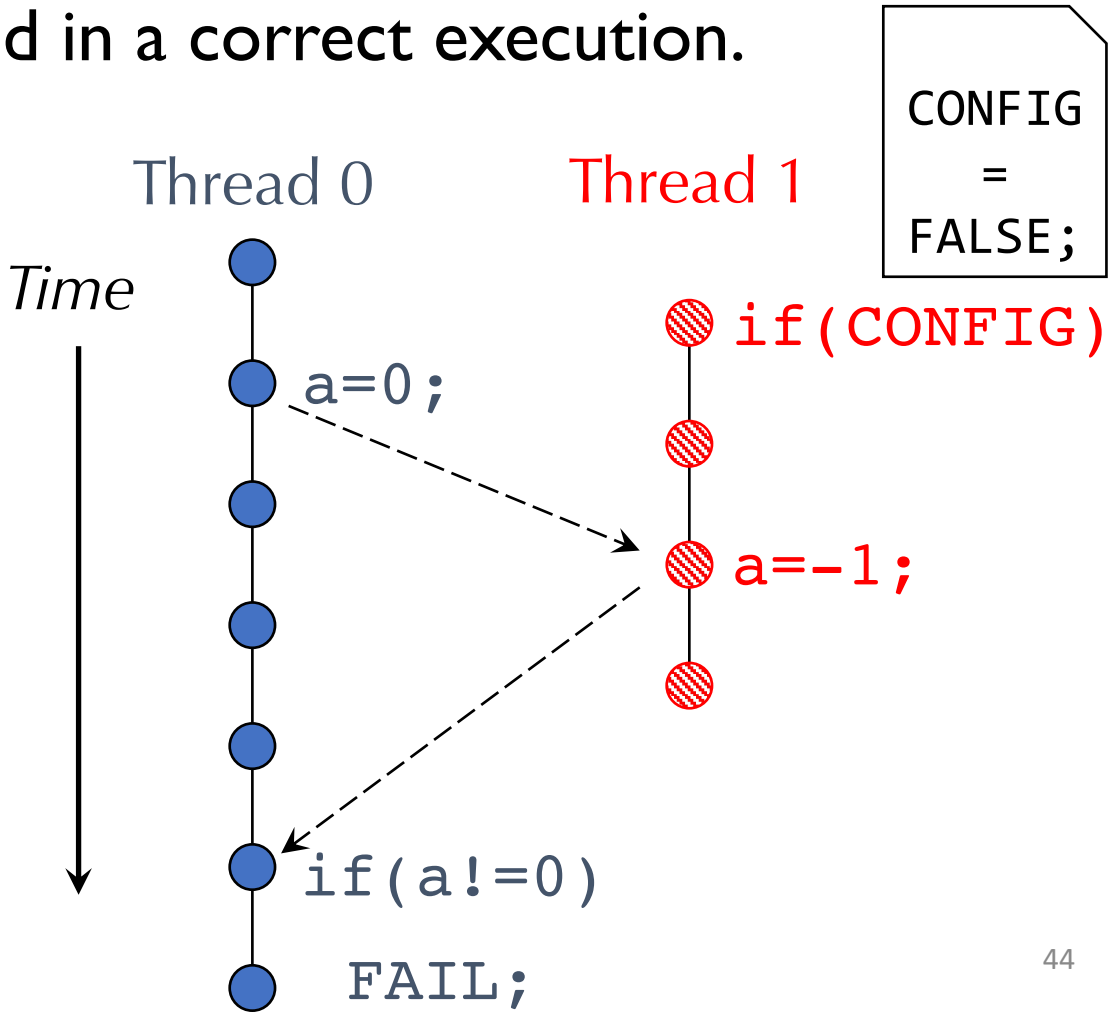

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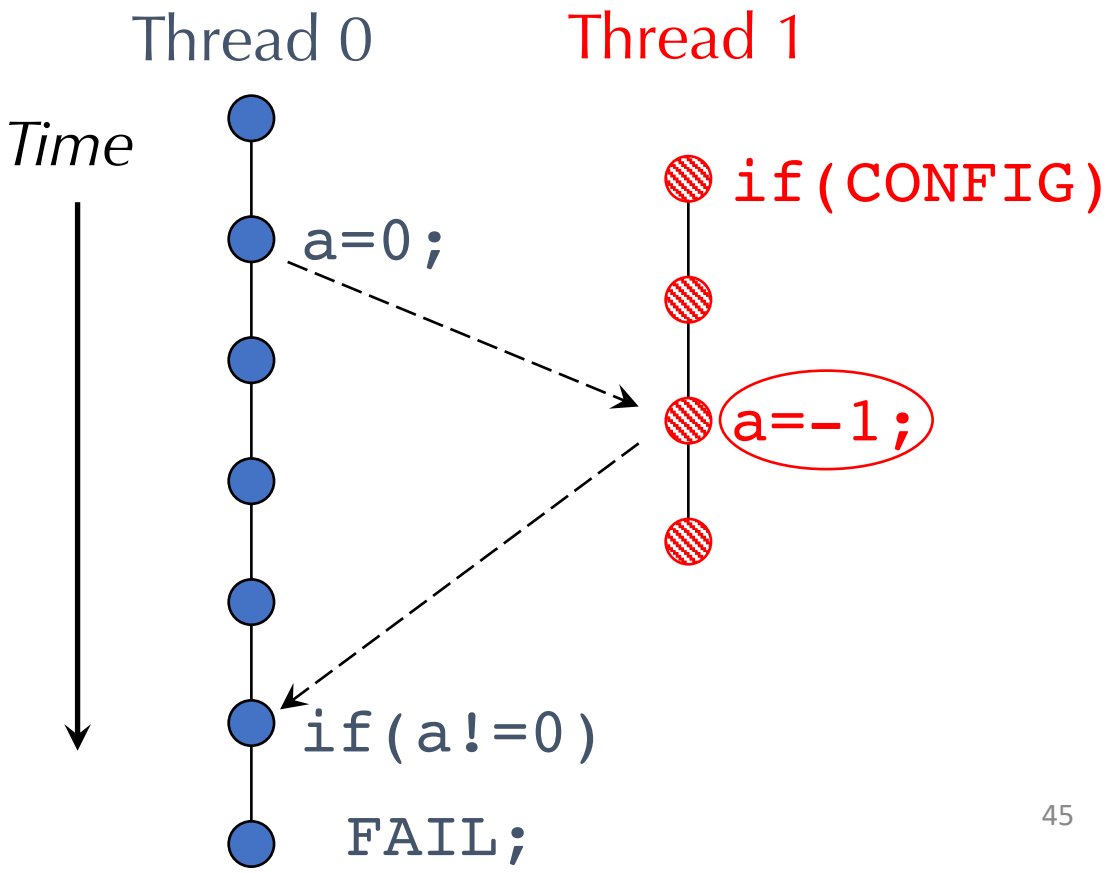
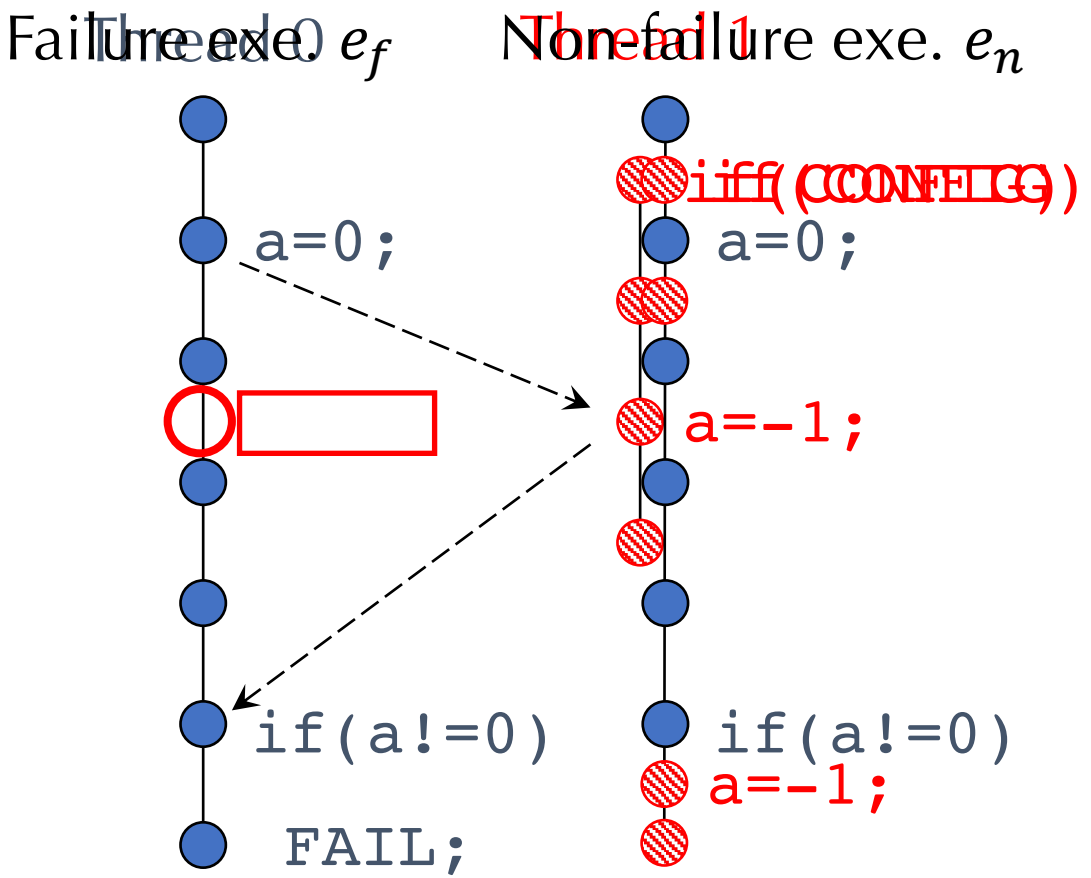


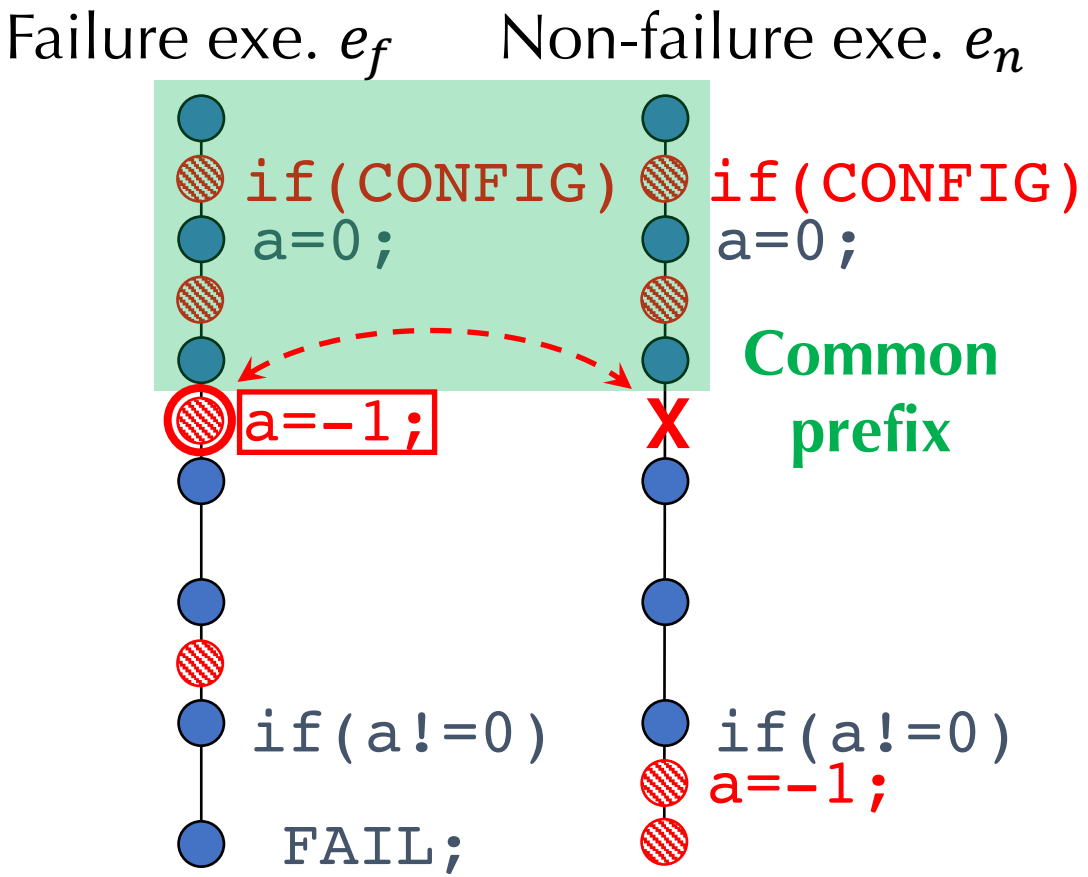
2. The root cause is the most basic cause of the failure.

Refined Definition of Root Cause

The root cause is the **first** instruction in the failure execution e_f that once executed would **inevitably** result in the failure

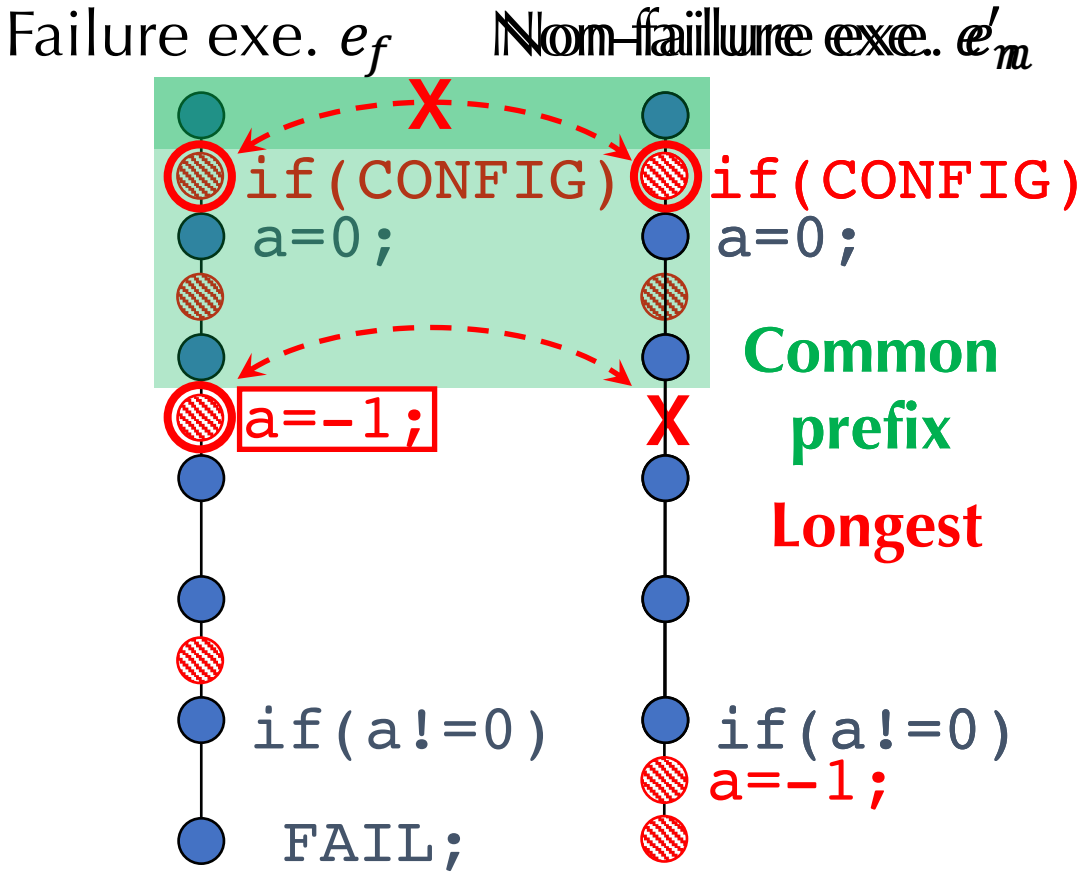


Inflection Point



Their inflection point is the first instruction in e_f that differs from the instruction at the same point in e_n.

Inflection Point Hypothesis



Their inflection point is the first instruction in e_f that differs from the instruction at the same point in e_n.

$\sum_n$: the set of all valid non-failure executions.

The root cause is located at the inflection point between e_f and $e_n \in \sum_n$ that has the longest common prefix with e_f.

Inflection Point Hypothesis – highly scalable

- A non-failure execution with minimal execution trace differences
  - Search space: 2^n
- A non-failure execution with the longest common prefix
  - Search space: n

```
void func(...) {
 if (a1 > 0) {...}   T/F
 ...                  ...
 if (an > 0)         T/F
   Log.error("ERROR");
}
```

search space 2^n

Failure exe. e_f	Non-failure exe. e_n	Skipped exe.s
T	T	F
F	...	...
...	...	...
T	...	...

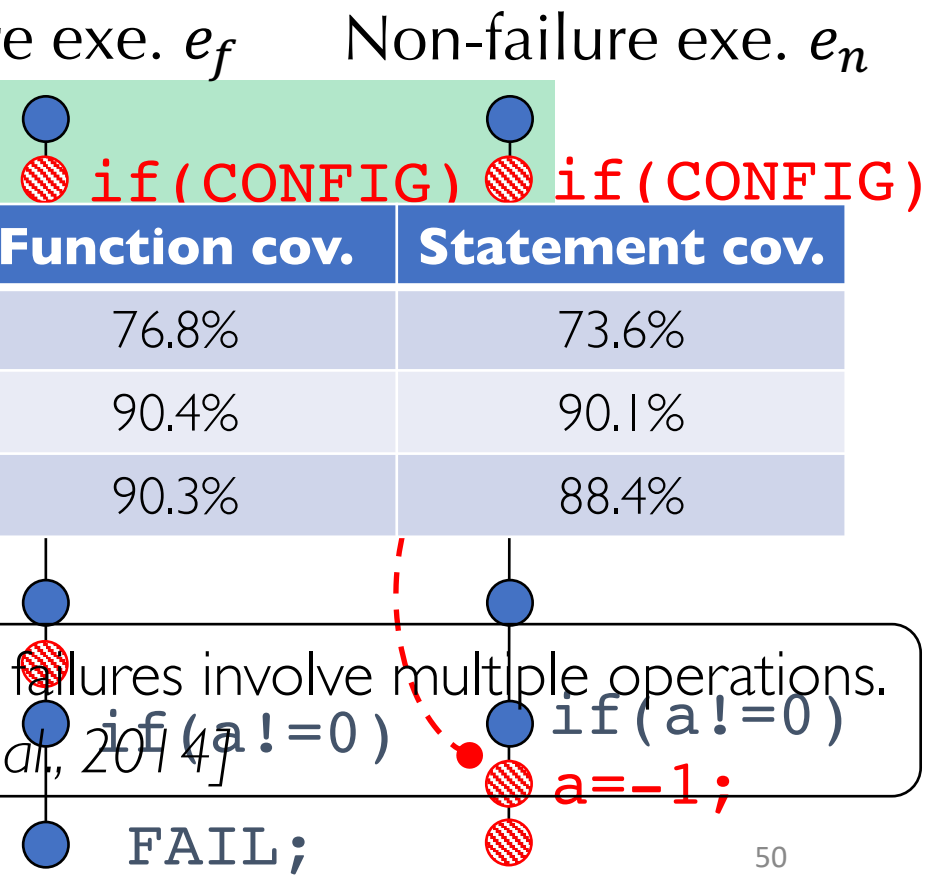
Kairux – Automated root cause localization

Construct the non-failure execution e_n that has the longest common prefix.

- Key ideas
  - Adaptive dynamic slicing to obtain partial order
  - Use test cases
  - Stitch test cases to c
  - Modify existing test c

System	Class cov.	Function cov.	Statement cov.
Cassandra 3.11.4	88.2%	76.8%	73.6%
HDFS 3.1.2	87.7%	90.4%	90.1%
ZooKeeper 3.4.11	90.6%	90.3%	88.4%

77% real-world distributed system failures involve multiple operations.
[Yuan et al., 2014]



Evaluation of Kairux

- Evaluated Kairux on 10 cases from JVM distributed systems
  - HDFS, HBase, ZooKeeper
  - One case with noisy operations generated from manual reproduction

- Successfully finds inflection points for 7
  - 3 unsuccessful cases:
    - root cause locates in an operation not covered by test cases

- Reduces the # of instructions to diagnose

	# instr. in dynamic slice	# instr. in longest prefix	# tests combined
Avg.	309	165	1.43

Kairux

- Inflection Point Hypothesis: precise, scalable definition of root cause

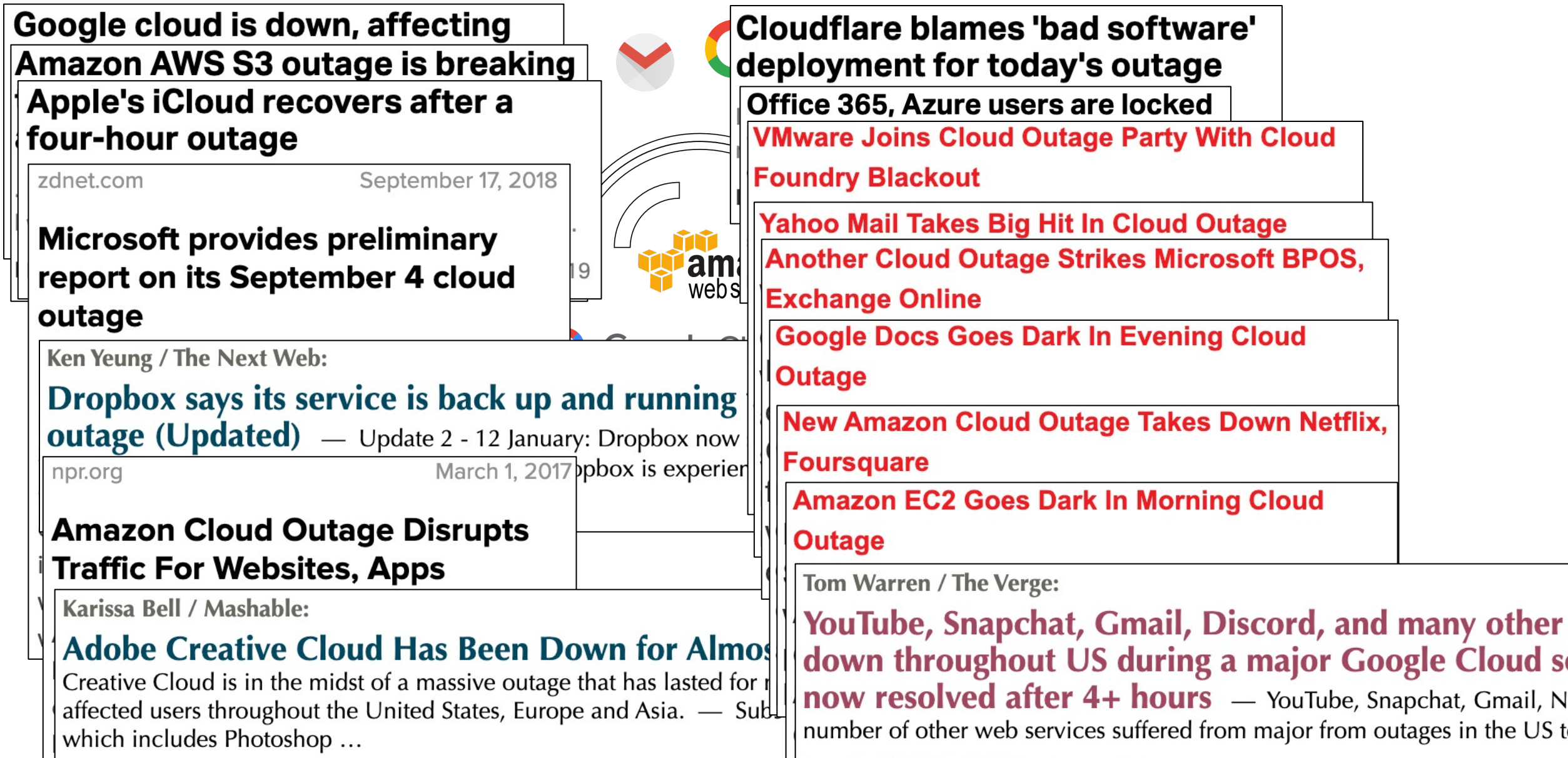
The root cause is located at the inflection point between e_f and $e_n \in \sum_n$ that has the longest common prefix with e_f.

- Kairux
  - transforms the inflection point hypothesis to a practical tool
  - effective in locating root cause in real distributed system failures

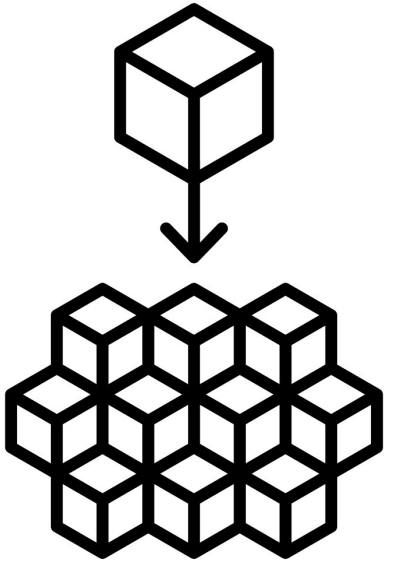
Outline

- Introduction
- Kairux [SOSP'19]: automates root cause localization
- Pensieve [SOSP'17]: automates failure reproduction
- Bigger picture

Most Internet services live on the cloud



Automated diagnosis on microservices

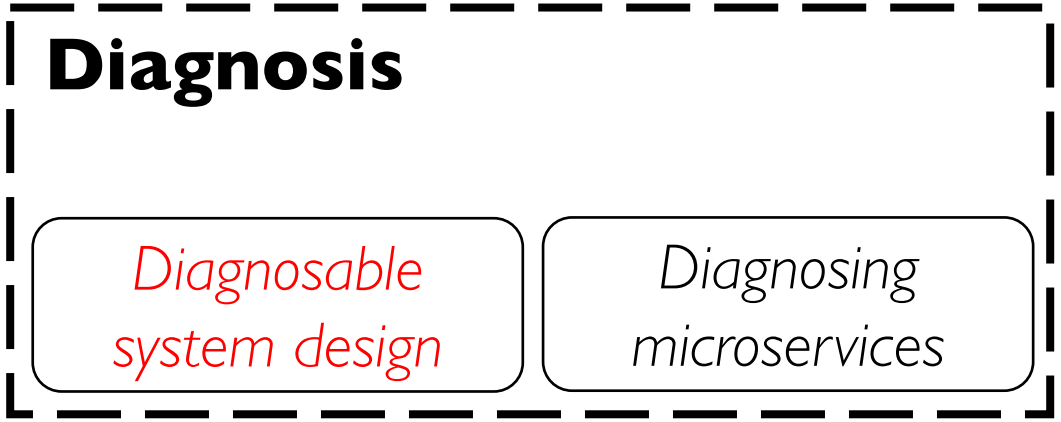


- My previous work
  - exploits human intuitions and principles
  - scales diagnosis techniques to distributed systems

- Challenges in diagnosing microservices – increasing complexity
  - More layers, more interactions between layers & components
  - Dynamically created & destroyed instances
  - Heterogeneous language, hardware

- No existing tools work!

Diagnosable system design



- Challenge: increasing complexity of software systems
  - Hard to understand & diagnose
- Towards diagnosable system design
  - What is the critical information needed for diagnosis?

Backup slides