A Hybrid Approach to Cloud System Performance Bug Detection, Diagnosis and Fix

Ting Dai

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NC State University

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About Me

- **Background:**
  - Master and Bachelor degree from Nanjing University of Posts and Telecommunications, China
  - Summer intern in InsightFinder and IBM T.J. Watson Research

- **Select papers:**
  - FabZK: Supporting Privacy-Preserving, Auditable Smart Contracts in Hyperledger Fabric [DSN'19]
  - DScope: Detecting Real-World Data Corruption Hang Bugs in Cloud Server Systems [SoCC'18]
  - Hytrace: A Hybrid Approach to Performance Bug Diagnosis in Production Cloud Infrastructures [TPDS'18, SoCC'17]
  - Understanding Real-World Timeout Problems in Cloud Server Systems [IC2E'18]

Real-World Performance Problems

- Nov. 2014, Microsoft Azure storage service outage caused by an infinite loop [link]

- Feb. 2016, Redis cloud outage caused by a resource-intensive infinite loop [link]

- Jan. 2018, Intel Meltdown patch will slow down your AWS EC2 server [link]

State-of-the-Art

Static analysis

Facebook Infer, Findbugs, PMD, Camarel[ICSE'15], Jin et al.[PLDI'12], etc

- **Advantage**:
  - No runtime overhead
  - Program semantics
- **Disadvantage**:
  - High FP by generic approaches
  - High FN by specific approaches

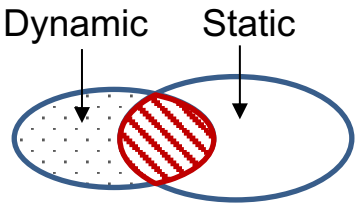
Dynamic analysis

PerfScope[SoCC'14], PerfCompass[TPDS'15], X-ray[OSDI'12], PBI[ASPLOS'13], etc

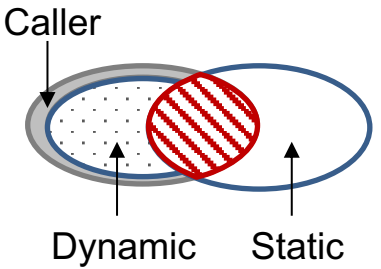
- **Advantage:**
  - More accurate due to runtime behavior
- **Disadvantage:**
  - Limited coverage (FN)

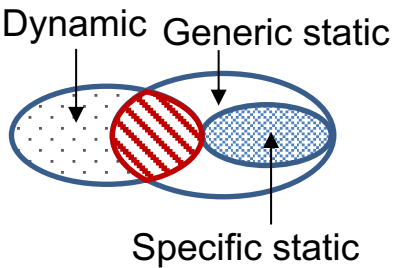
Hybrid Analysis

- **Rationale:**
  - Functions with buggy characteristics which are also experiencing a runtime problem are **most** likely related to a bug.



- **Design choice:**
  - A suspicious caller function can cause its callee functions behave abnormally runtime.
  - Generic static approach.





My Contributions

Hytrace	A hybrid approach for diagnosing generic performance bugs.
DScope	Advanced detection for specific performance bugs --- data corruption hang bugs.
HangFix	Auto-fix for software hang bugs caused by data processing and inter-process communication failures.

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Oral preliminary

- Hytrace — A hybrid approach for diagnosing generic performance bugs.
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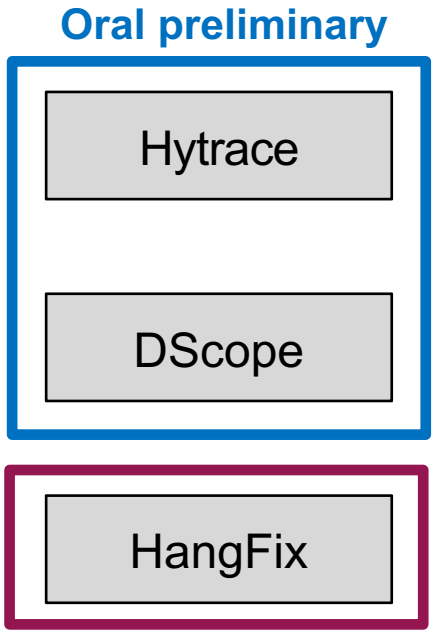


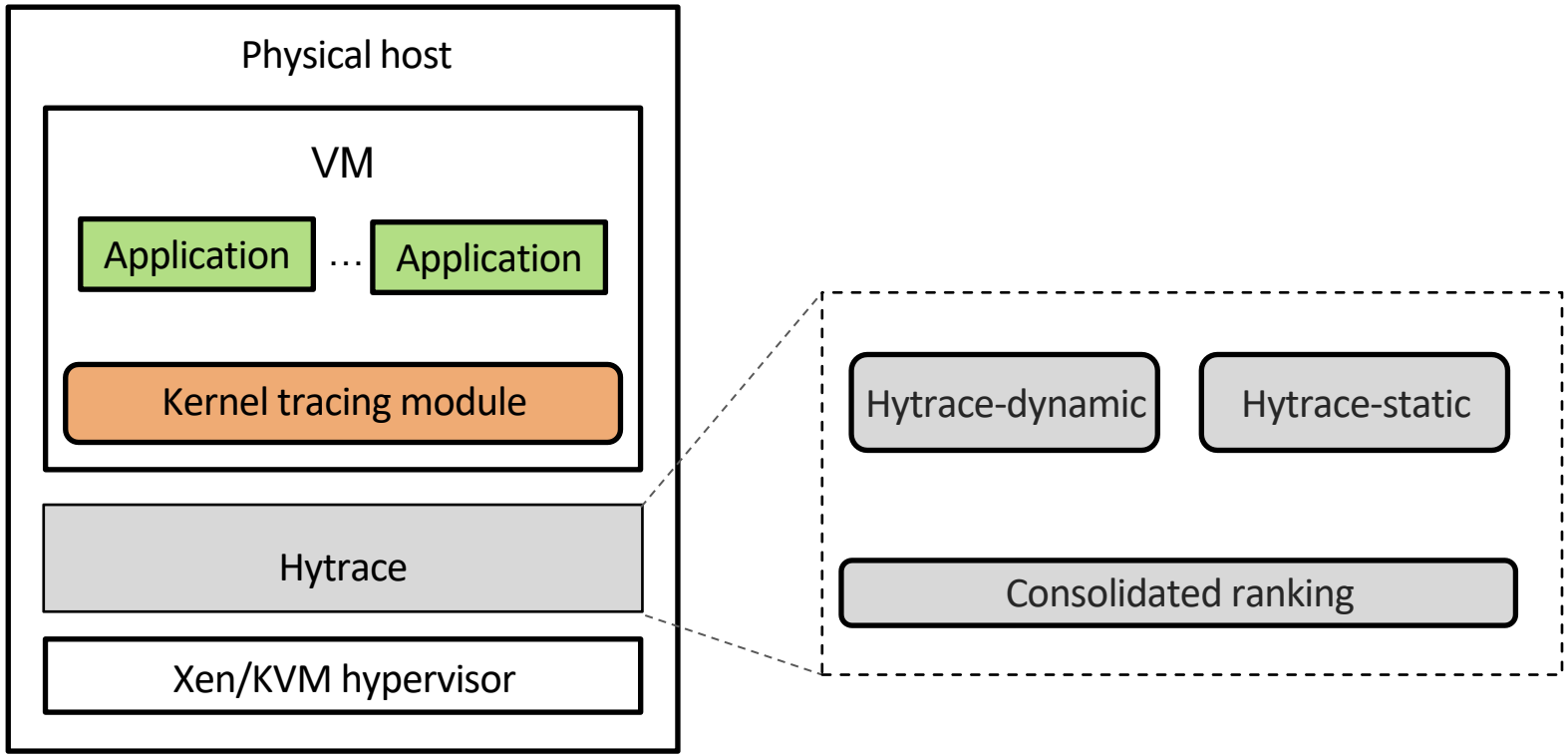
A hybrid approach for diagnosing generic performance bugs.

Advanced detection for specific performance bugs --- data corruption hang bugs.

Auto-fix for software hang bugs caused by data processing and inter-process communication failures.

Hytrace: A Hybrid Approach to Performance Bug Diagnosis in Production Cloud Infrastructures

Overview of Hytrace



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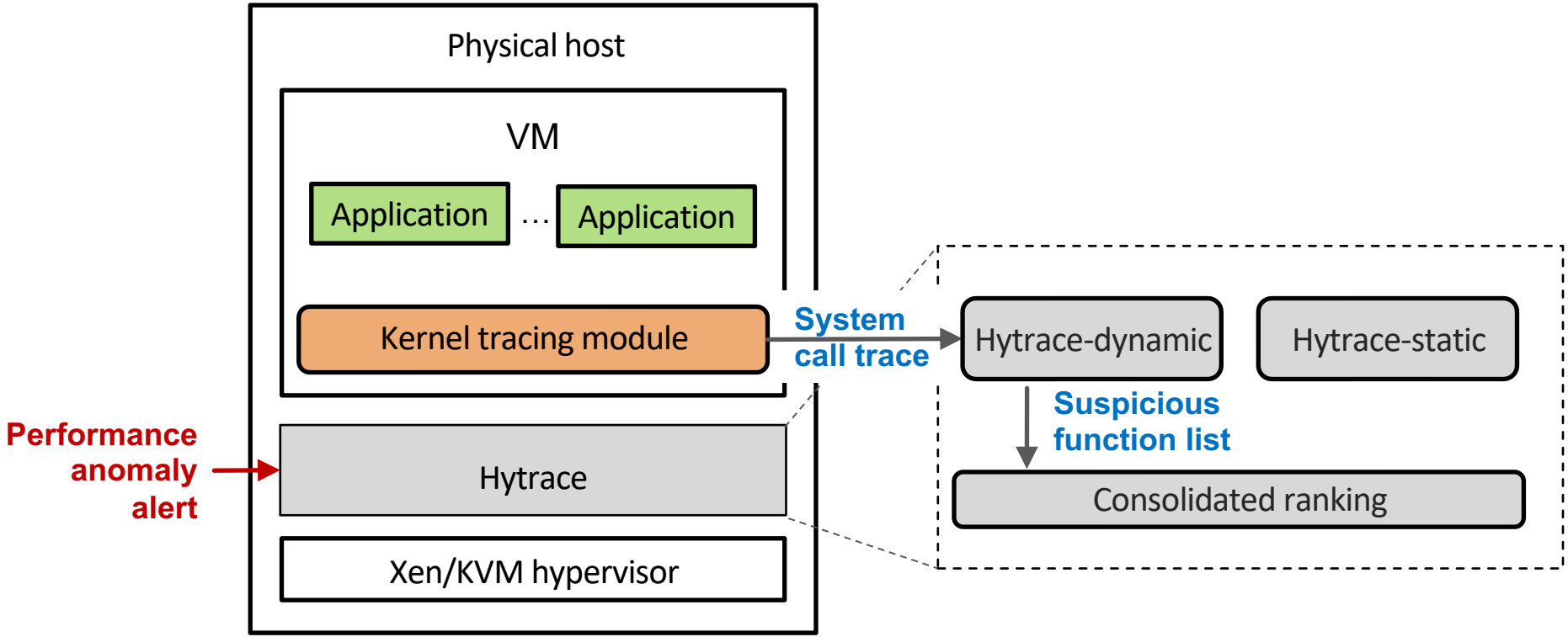

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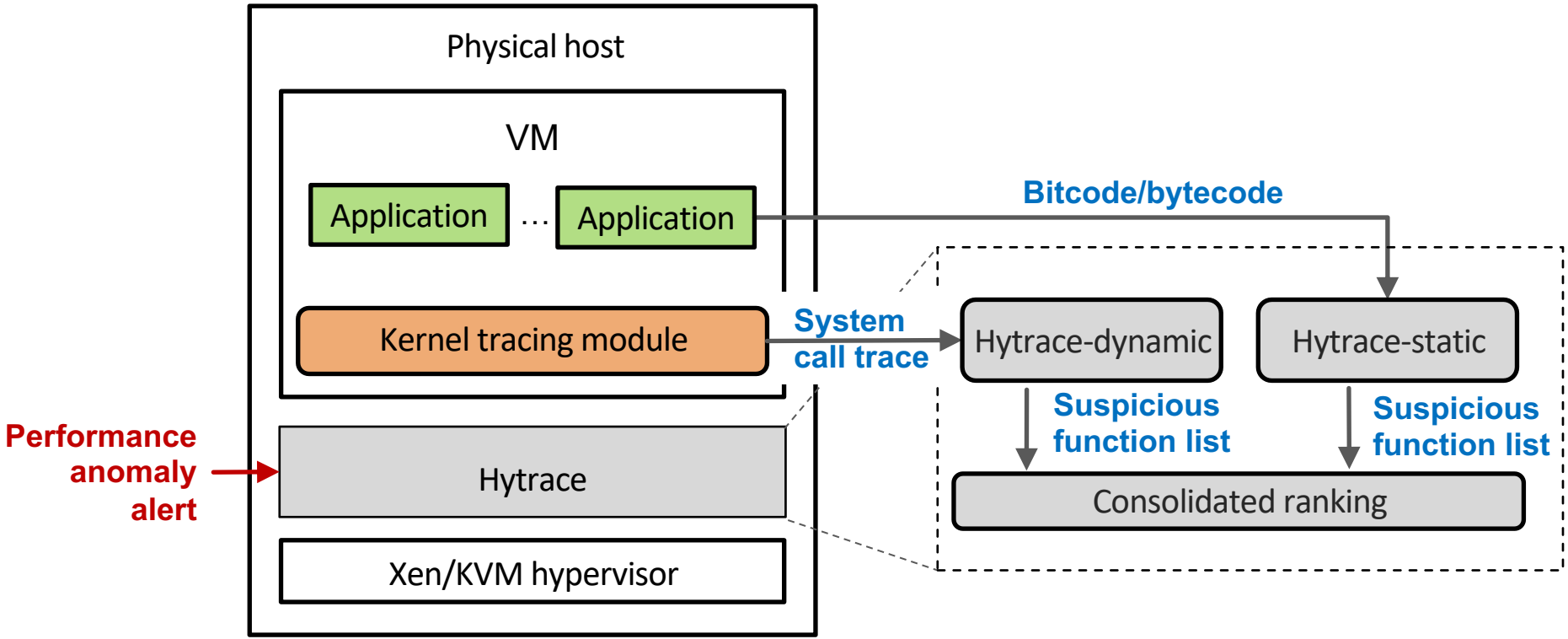

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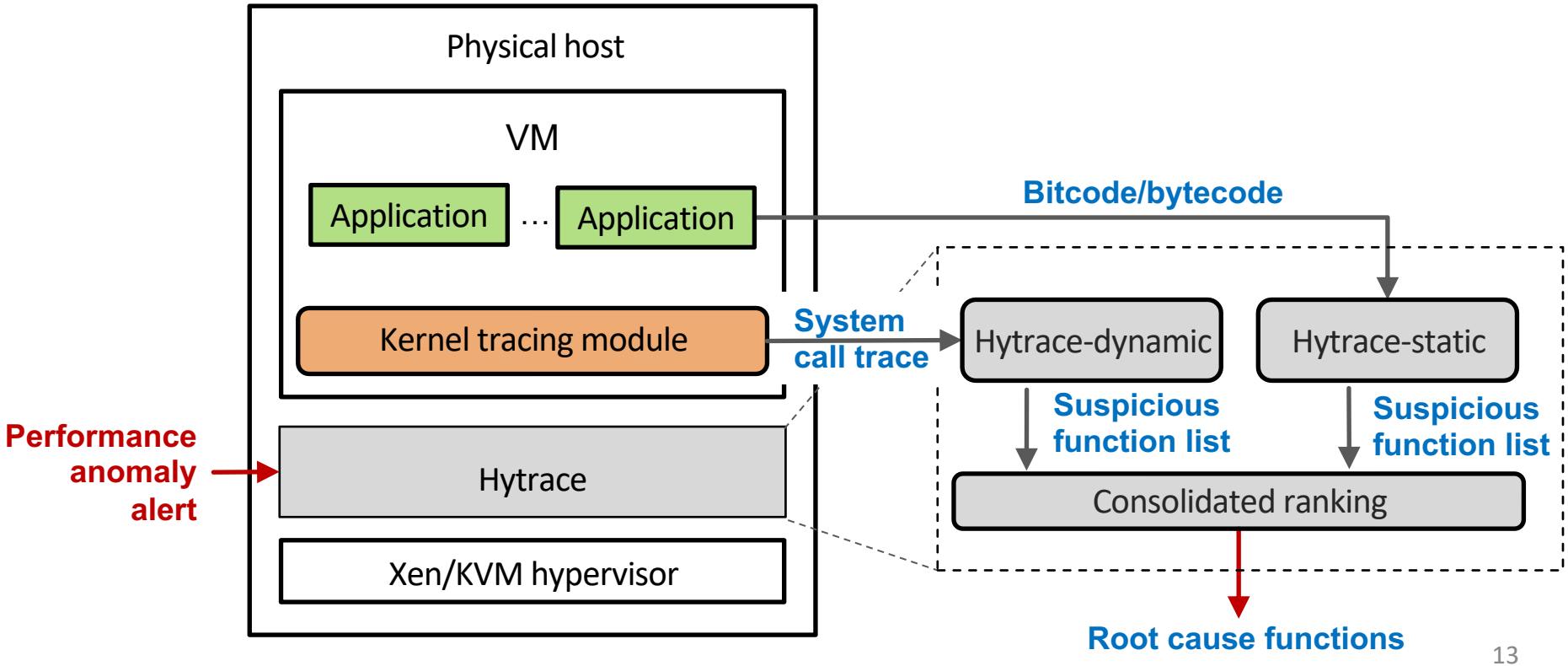

Result Summary

- Hytrace is a hybrid performance diagnosis approach.
  - Combines offline static analysis and online dynamic bug inference.
  - Evaluated over **133** performance bugs on 9 cloud server systems.
  - Reduces FP functions & improve the rank of bug related functions.
  - Imposes less than **3%** CPU overhead to production cloud environments.

DScope: Detecting Real-World Data Corruption Hang Bugs in Cloud Server Systems

A Data Corruption Hang Bug Example

Overview of DScope

Hadoop-8614

```
183  public static void skipFully(
             InputStream in, long len) … {
184    while (len > 0) {
185      long ret = in.skip(len);
           …
           …
189      len -= ret;
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Corrupted InputStream

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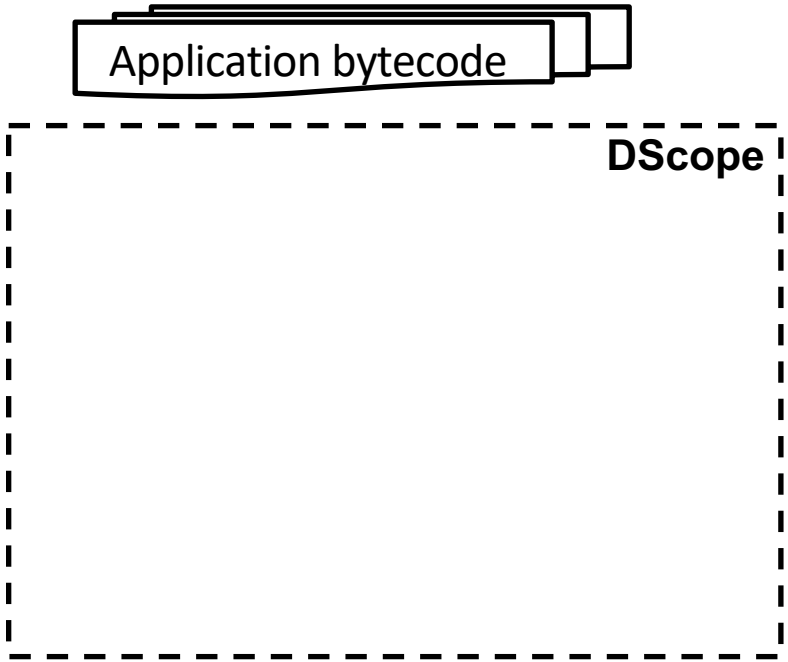

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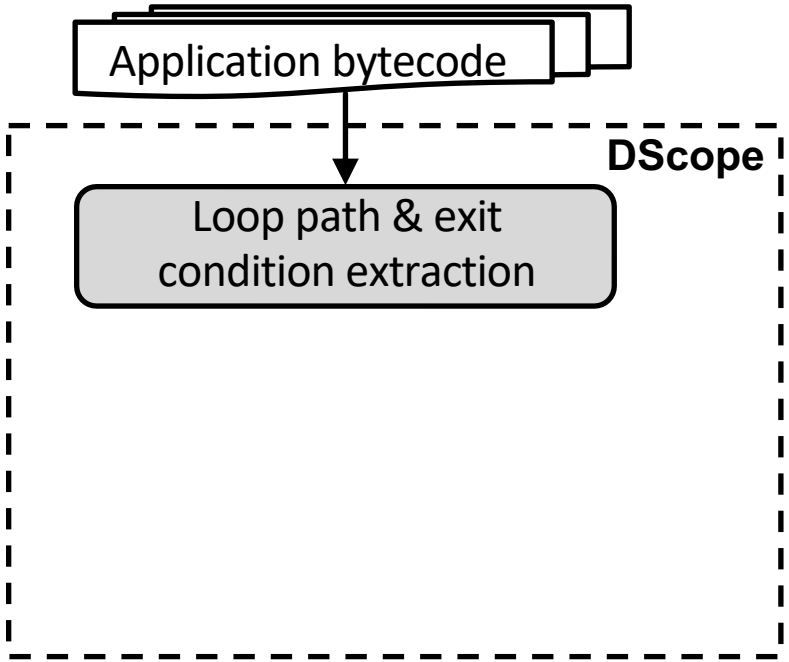

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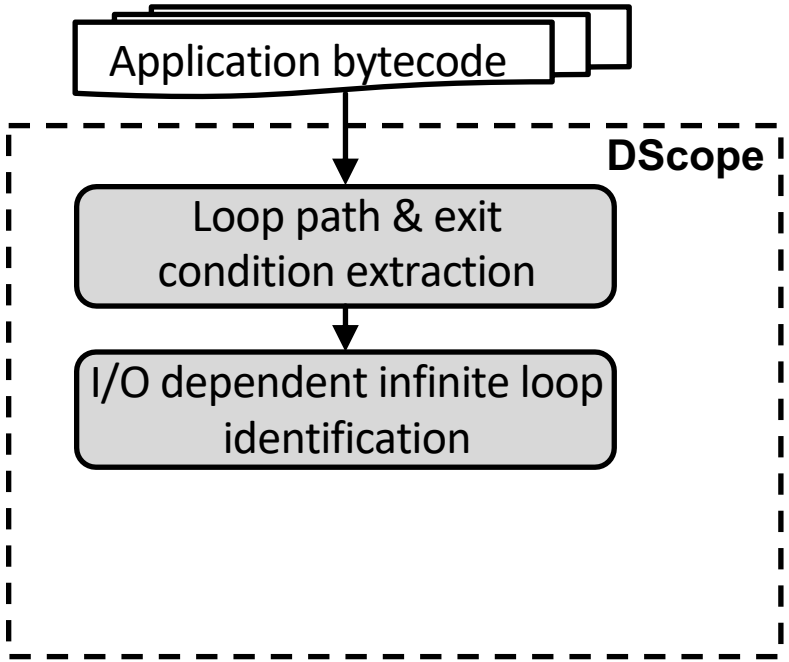

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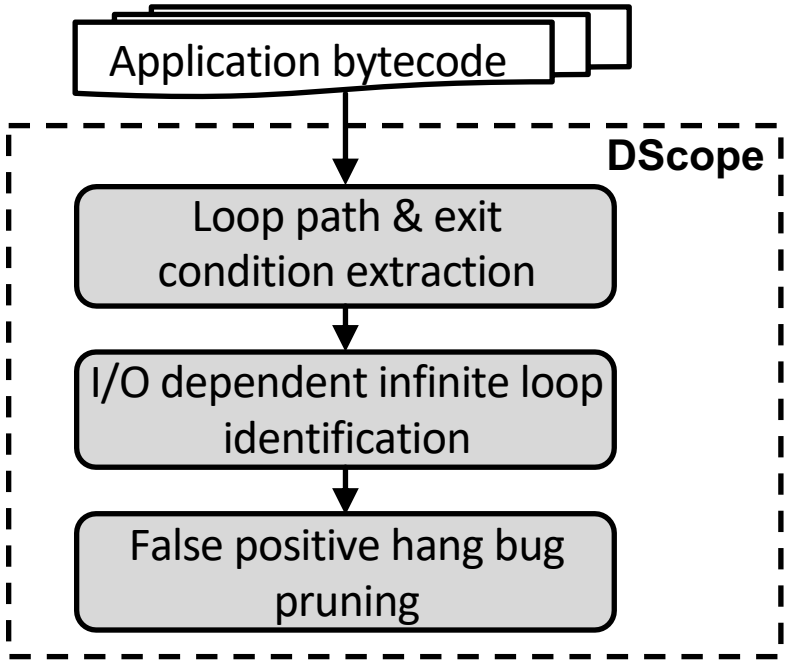

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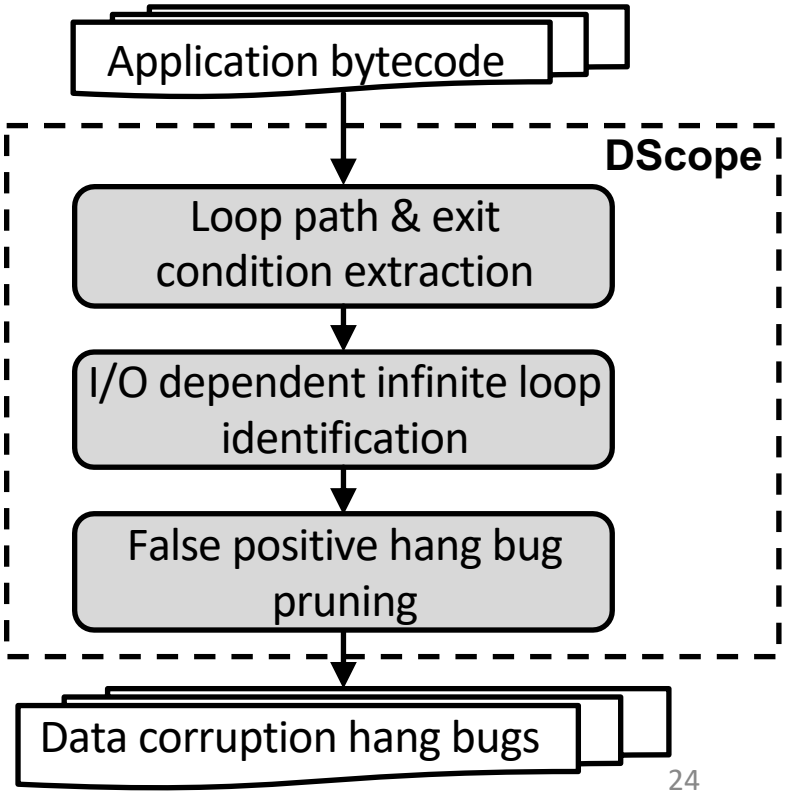

Bug Detection Results

System		DScope		Findbugs	Infer
		TP	FP	TP	TP
Cassandra	v2.0.8	2	1	0	1
Compress	v1.0	2	2	0	-
Hadoop Common	v0.23.0	4	6	0	0
	v2.5.0	6	6	0	0
Mapreduce	v0.23.0	3	0	0	0
	v2.5.0	2	0	0	0
HDFS	v0.23.0	1	1	0	0
	v2.5.0	3	5	1	-
Yarn	v0.23.0	2	2	1	0
	v2.5.0	2	5	0	0
Hive	v1.0.0	7	6	0	-
	v2.3.2	5	1	0	0
Kafka	v0.10.0.0	1	1	0	0
Lucene	V2.1.0	2	1	0	0
Total		42	37	2	1

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Total		42	37	2	1

Result Summary

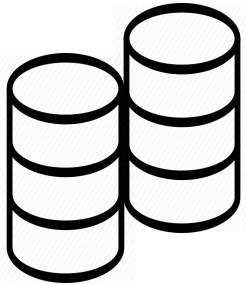
- DScope is a new data corruption hang bug detection tool for cloud server systems.
  - Combines candidate bug discovery and false positive filtering.
  - Evaluated over 9 cloud server systems and detects **42** true data corruption hang bugs including **29** new bugs.

HangFix: Automatically Fixing Software Hang Bugs in Cloud Systems

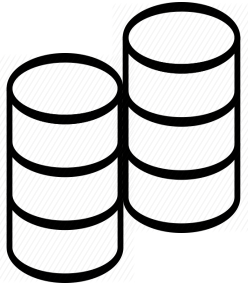
Real-World Hang Problem Caused by Data Corruption

BRITISH AIRWAYS

British Airway service was down for hours with financial penalty of £ 100 million.



Primary data center



Backup data center

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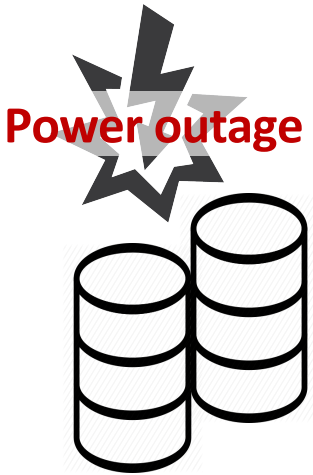

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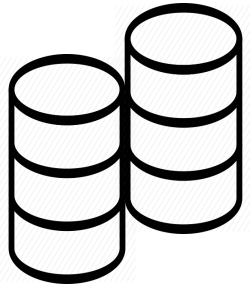

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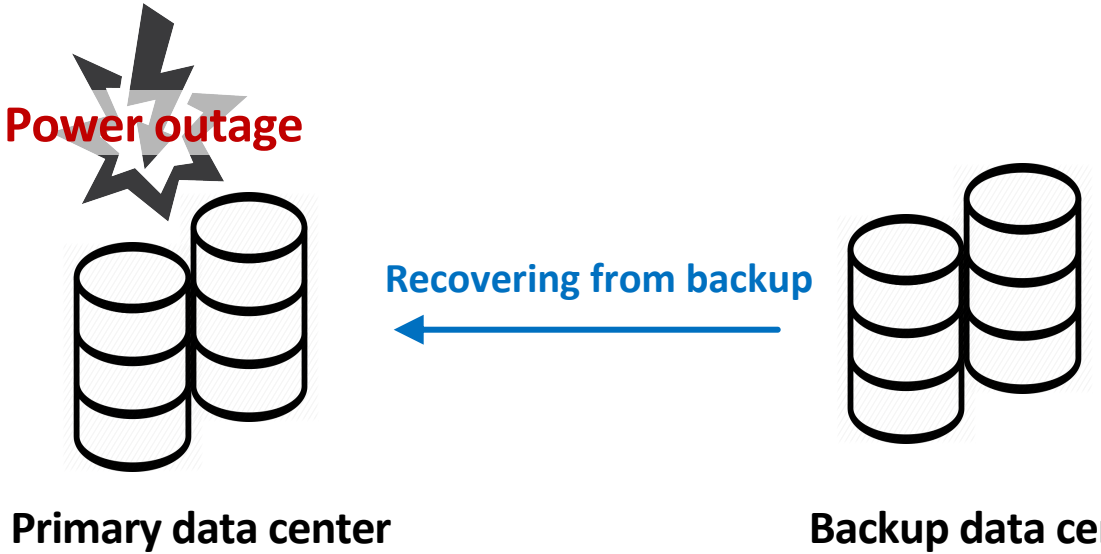

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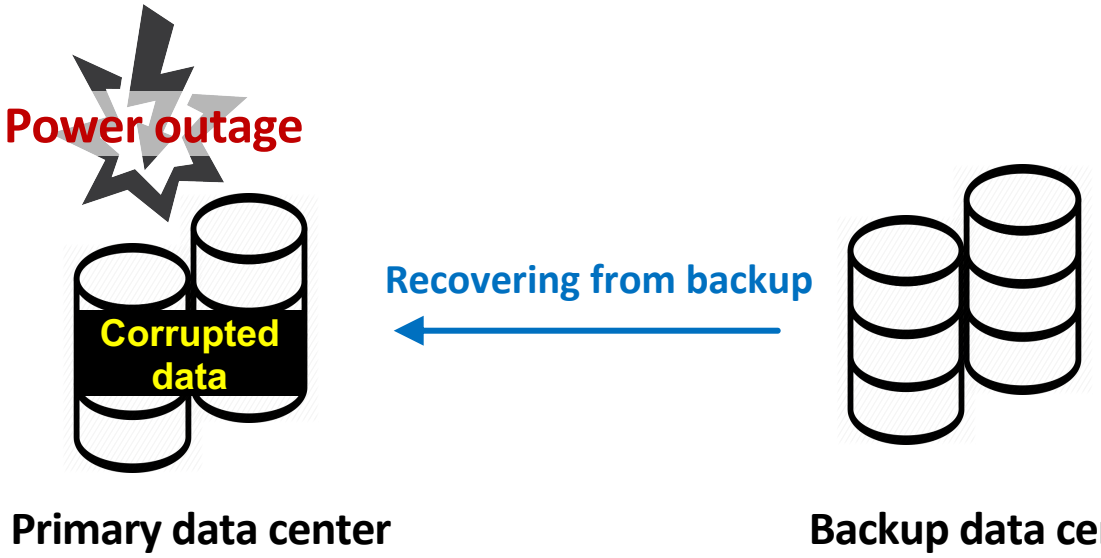

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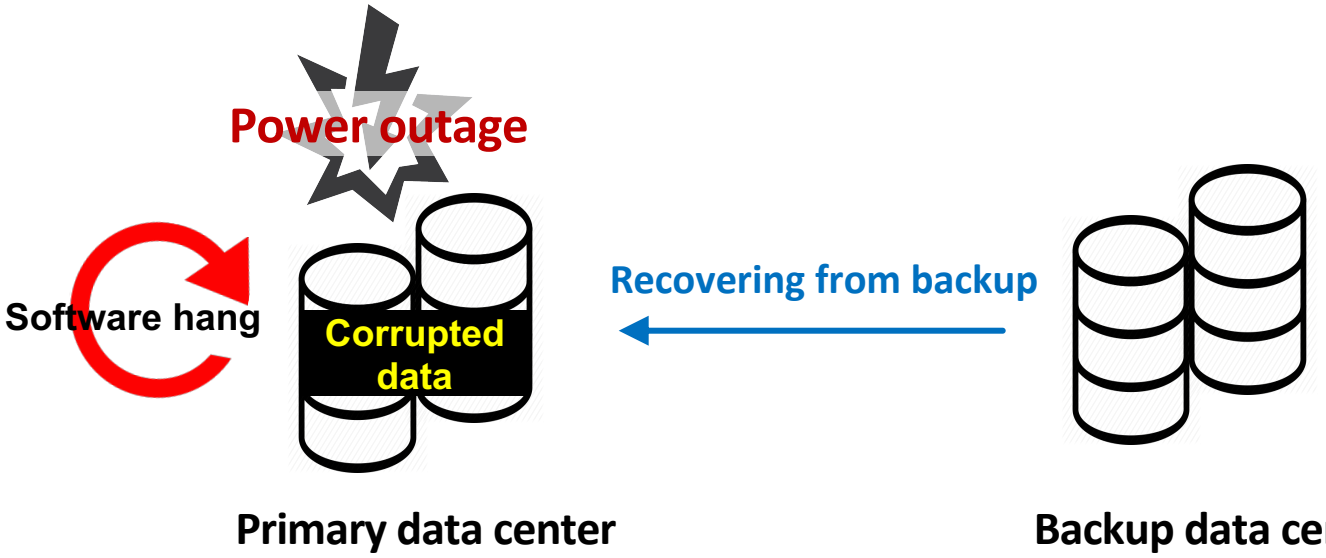

Real-World Hang Problem Caused by Inter-process communication failure

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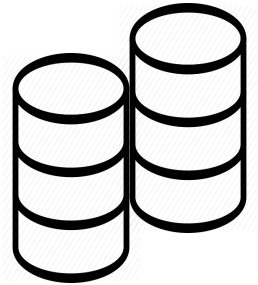

Storage servers

Metadata server

NETFLIX

airbnb

IMDb

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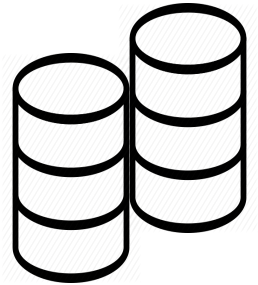

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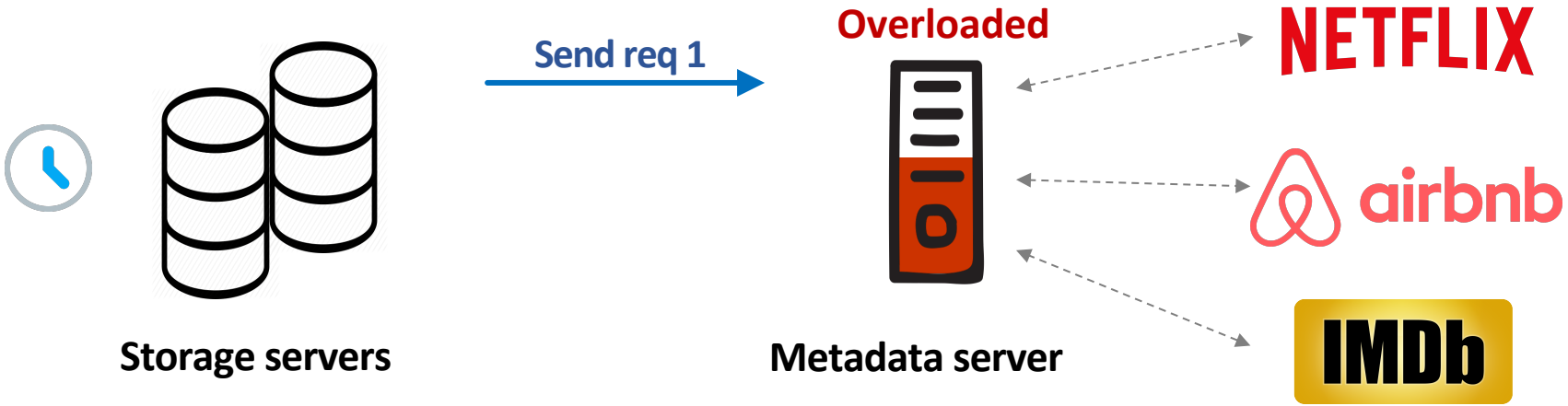

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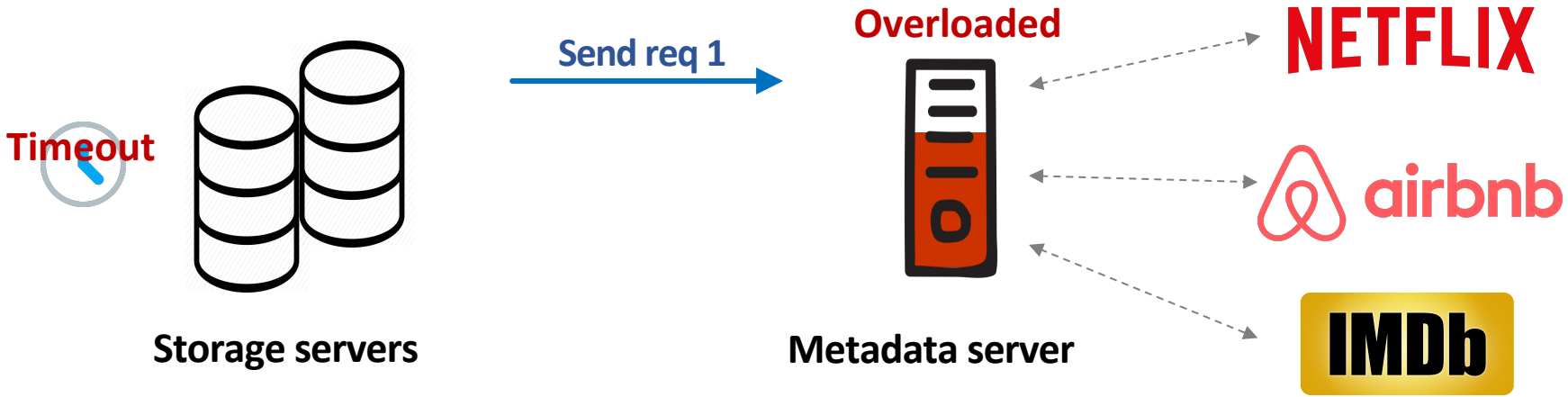

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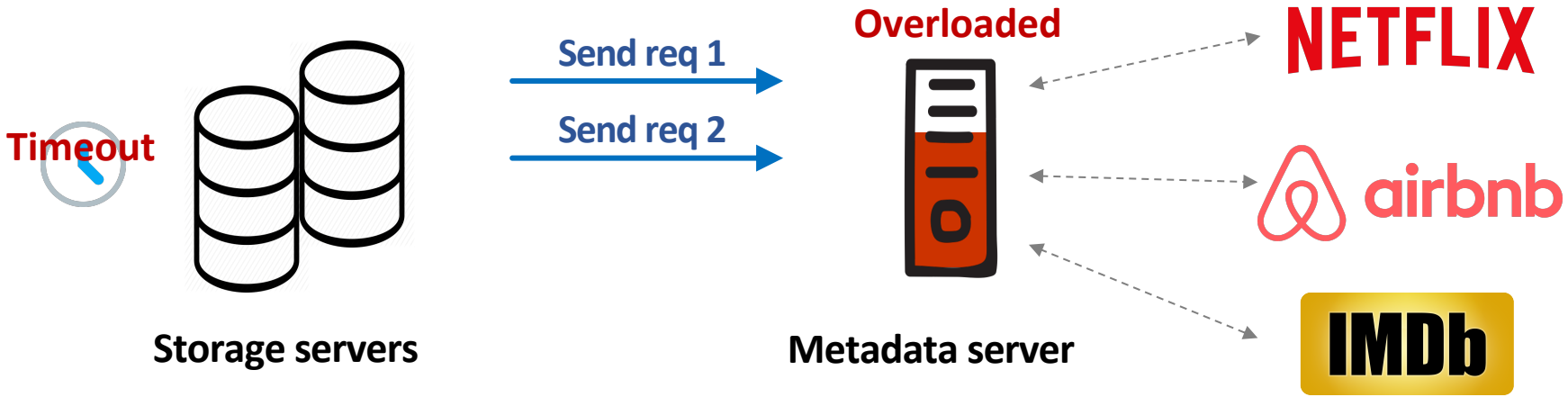

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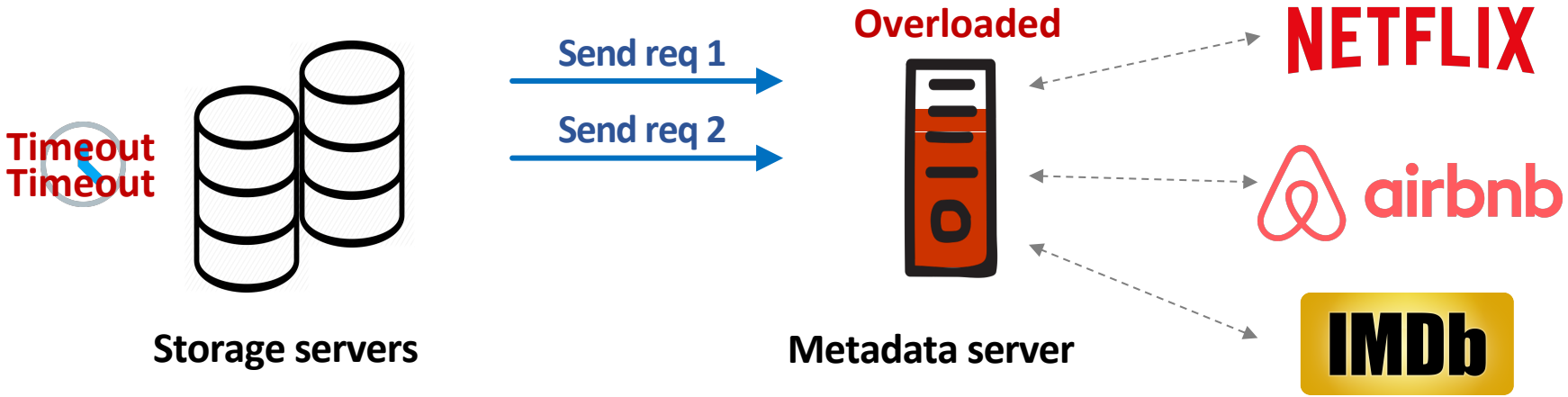

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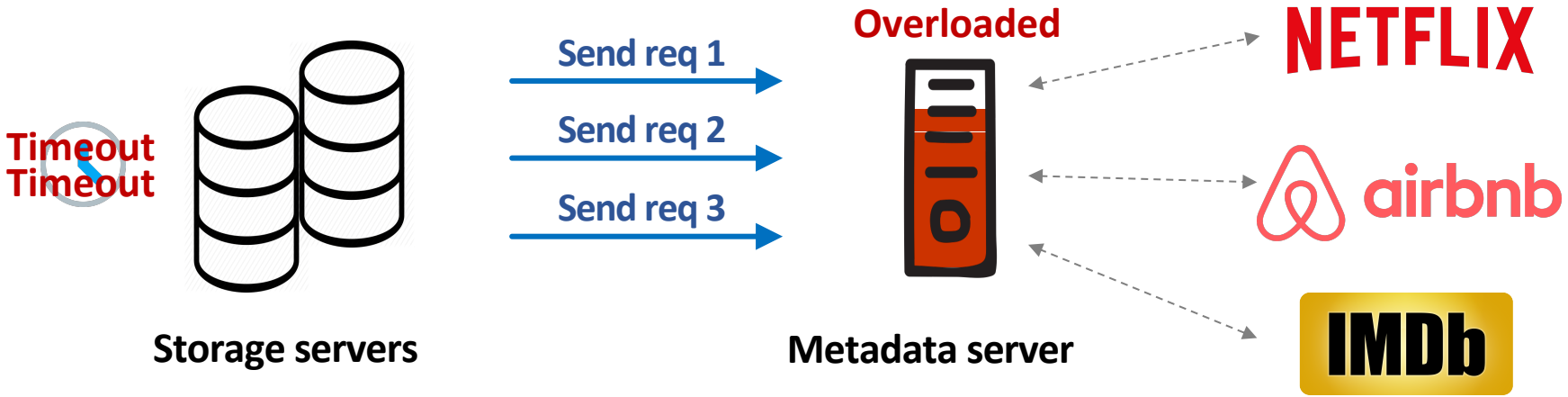

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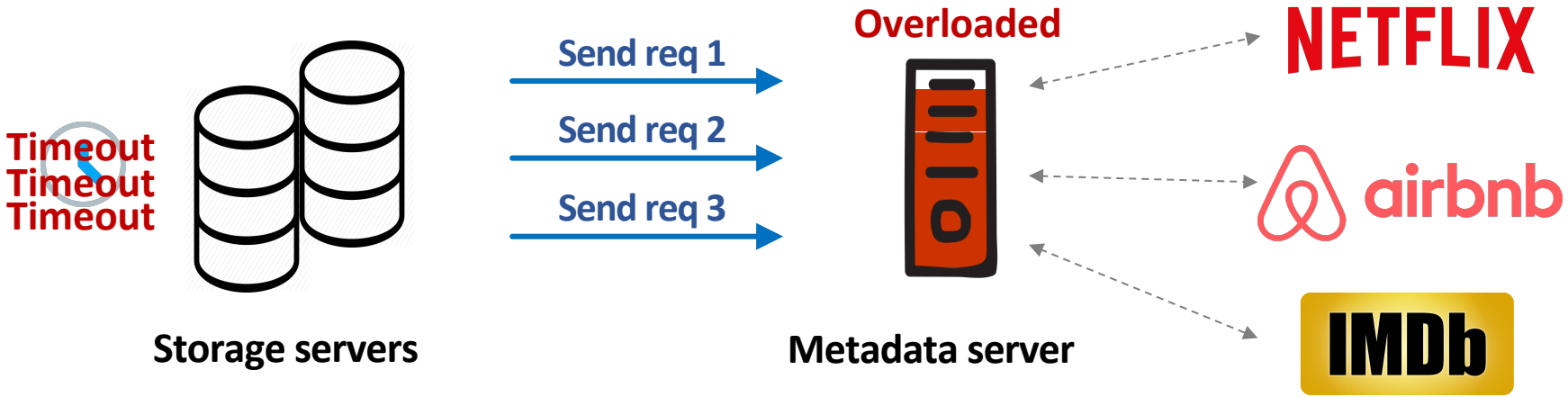

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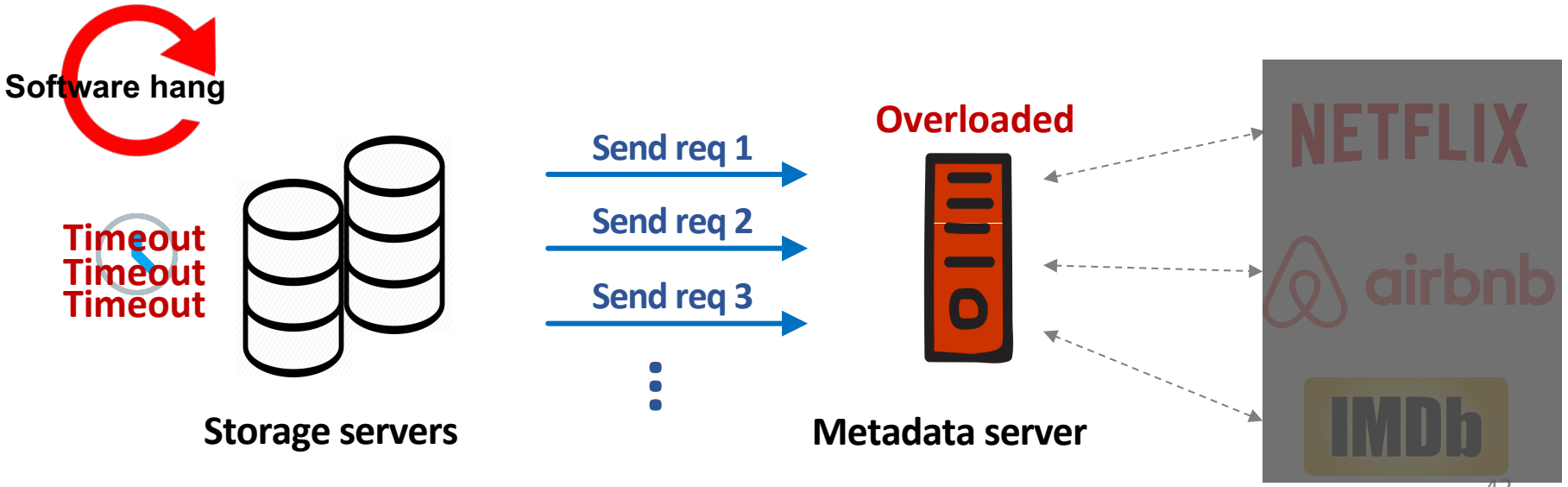
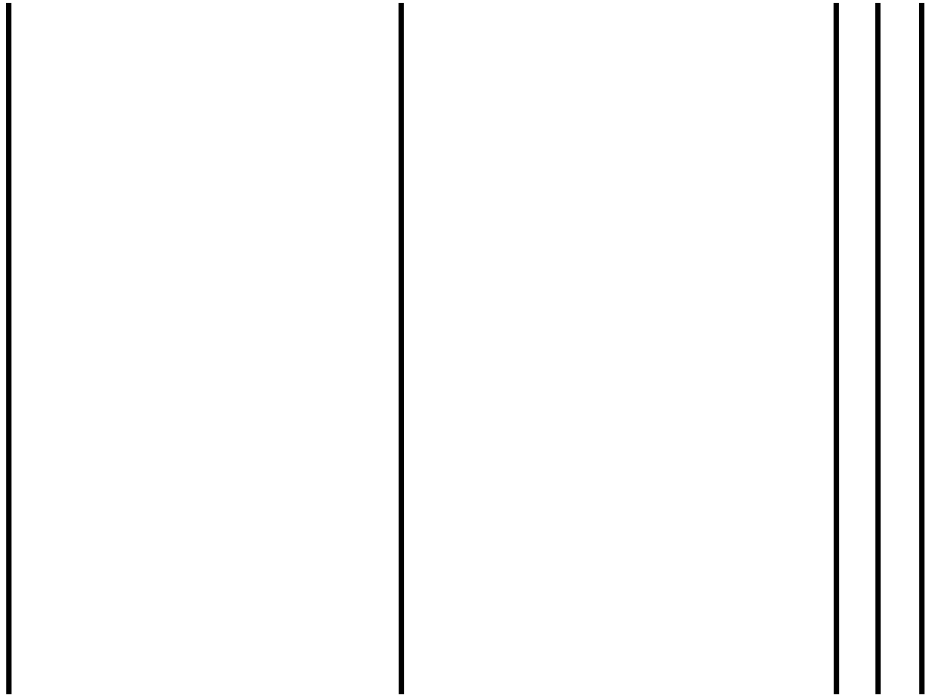


A Hang Bug Example

HBase-8389



HBase HDFS NameNode HDFS DataNodes

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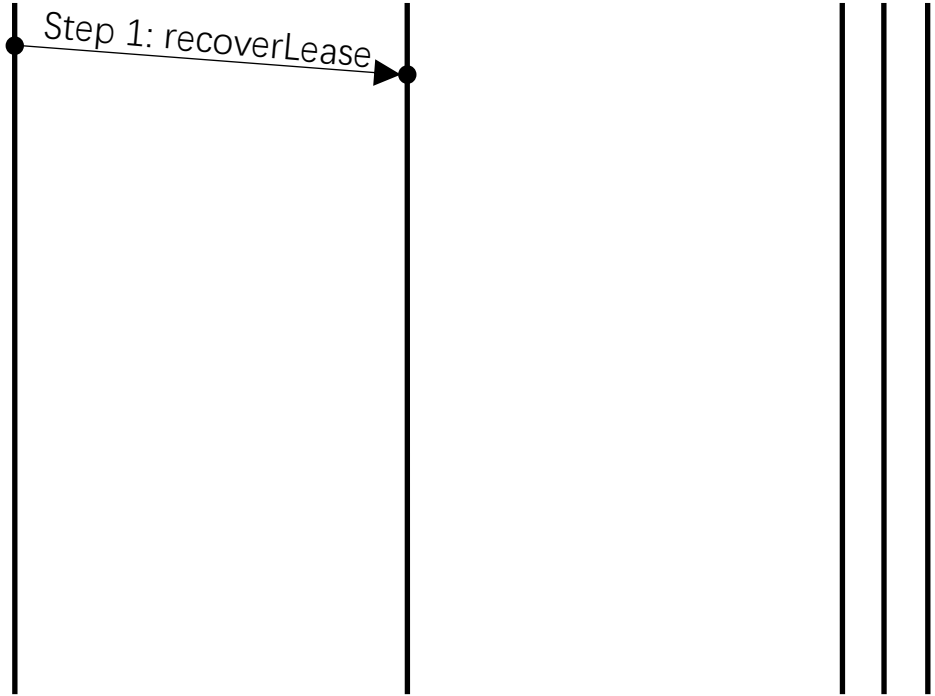

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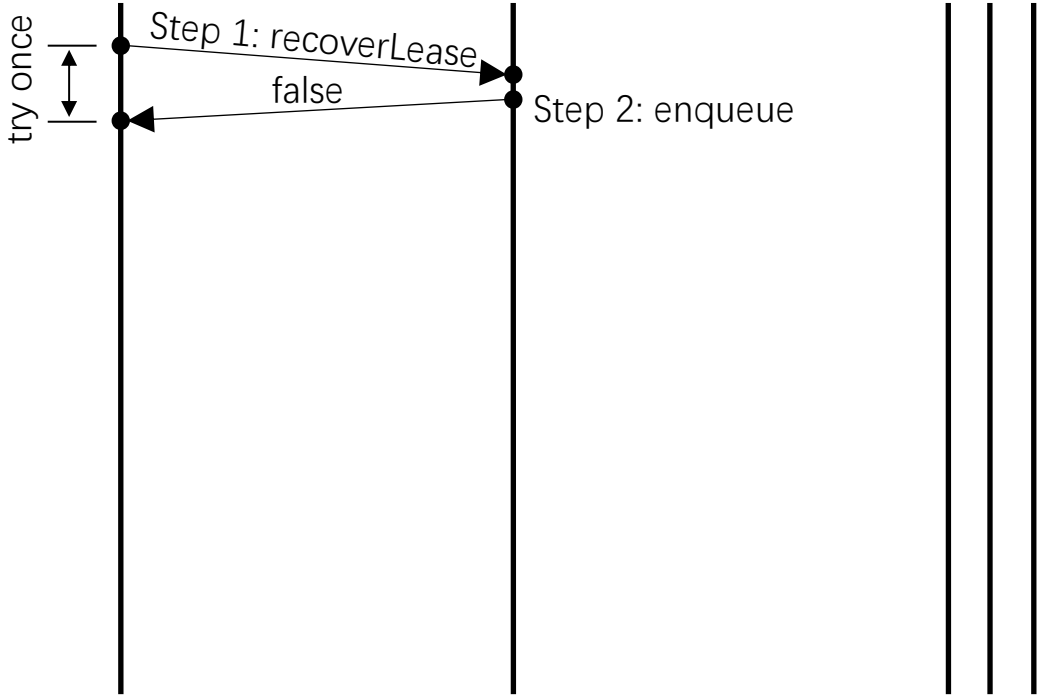

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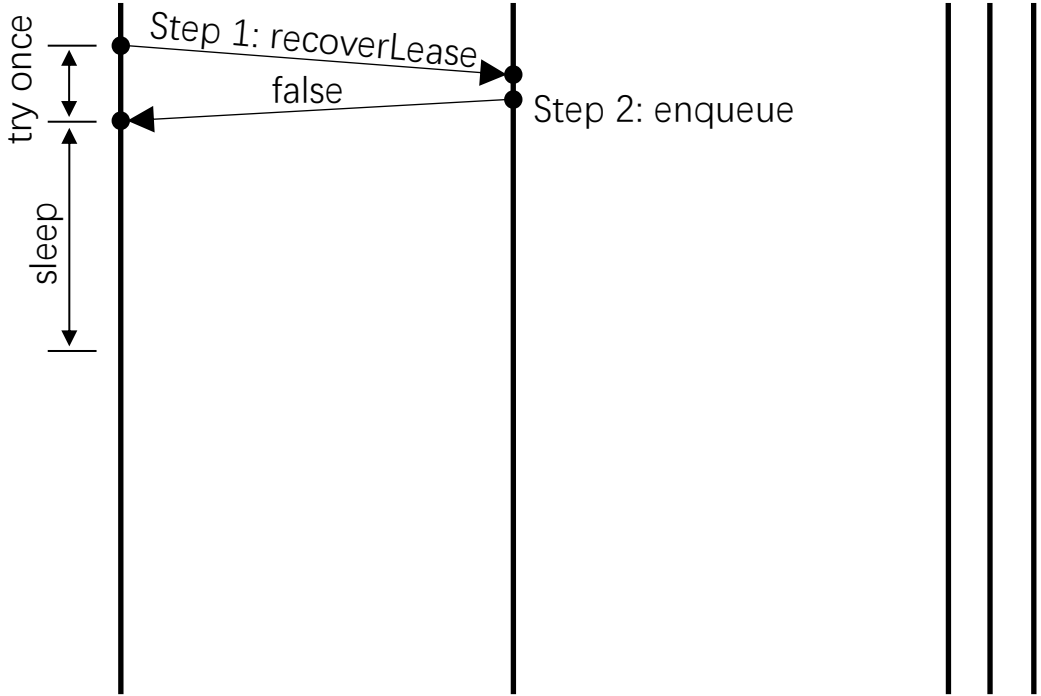

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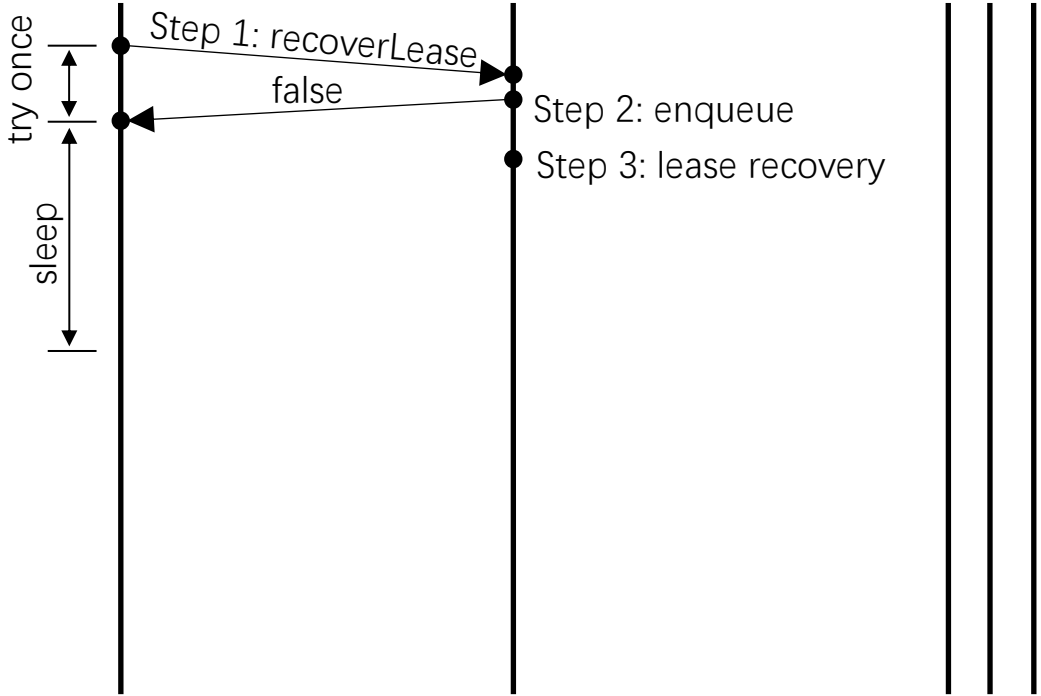

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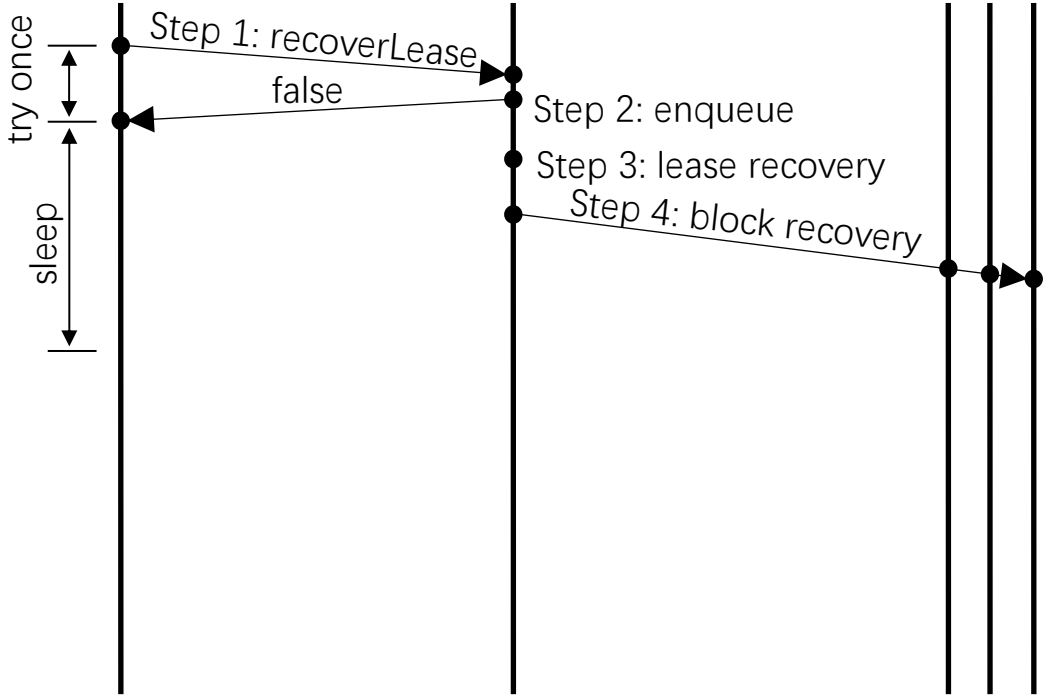

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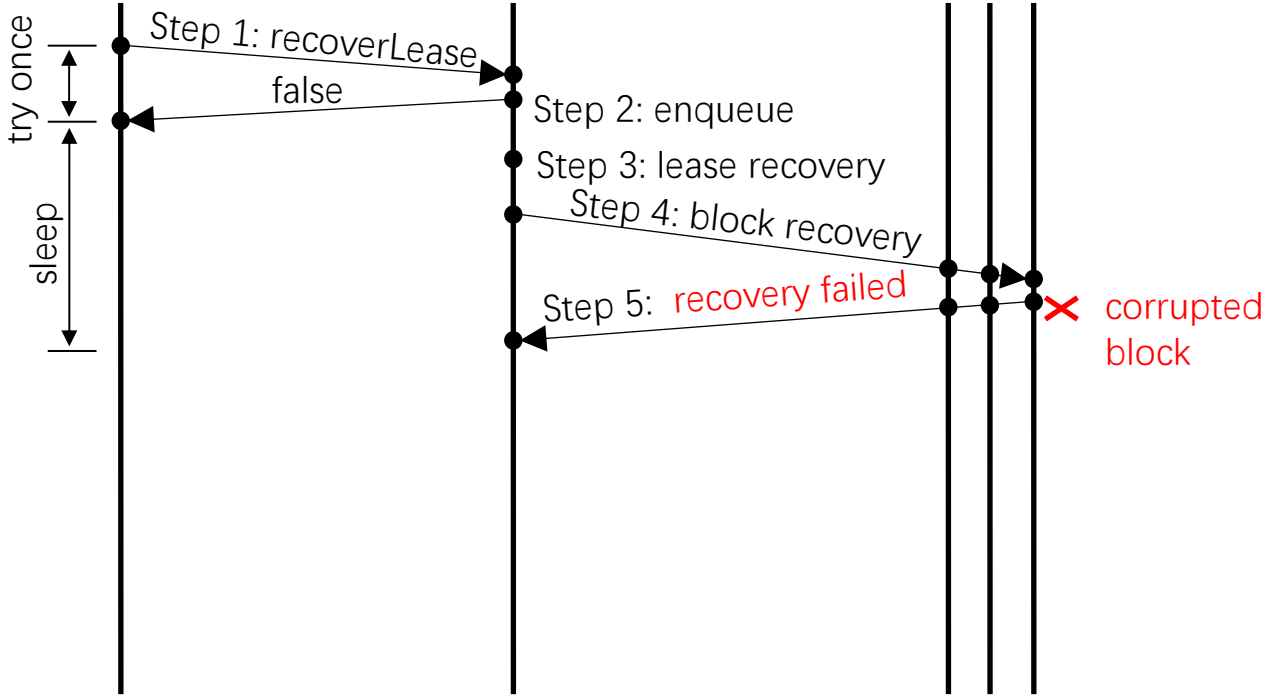

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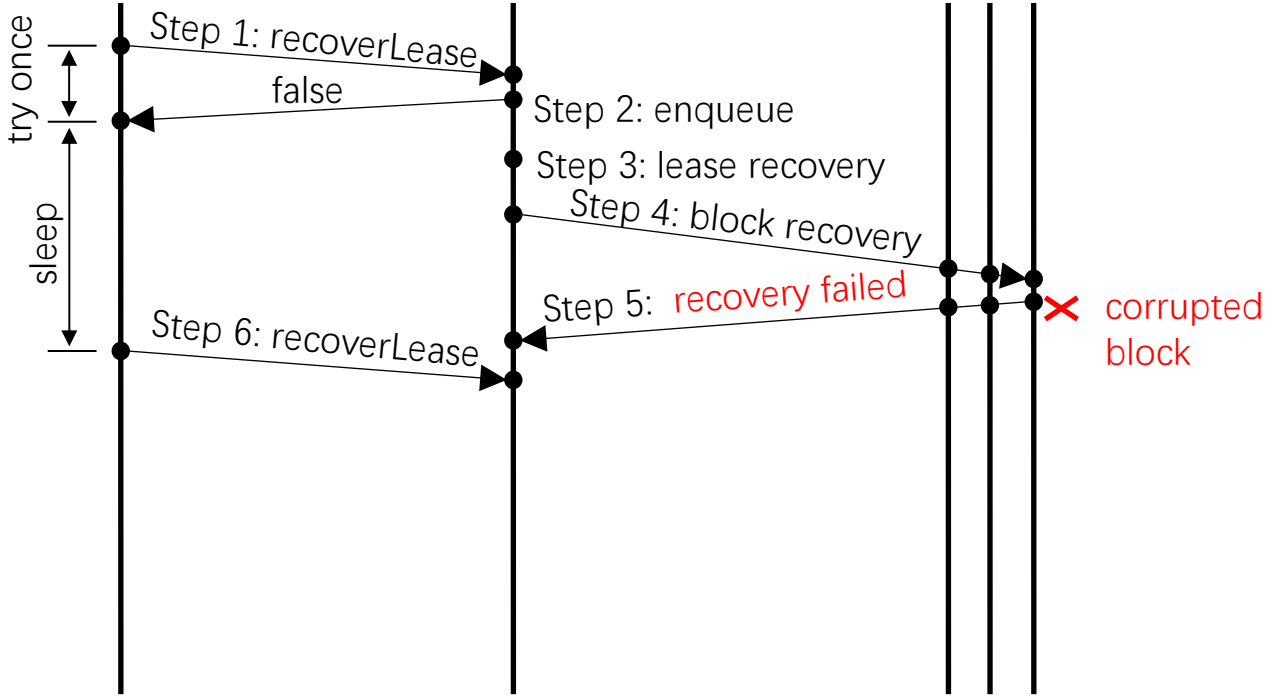

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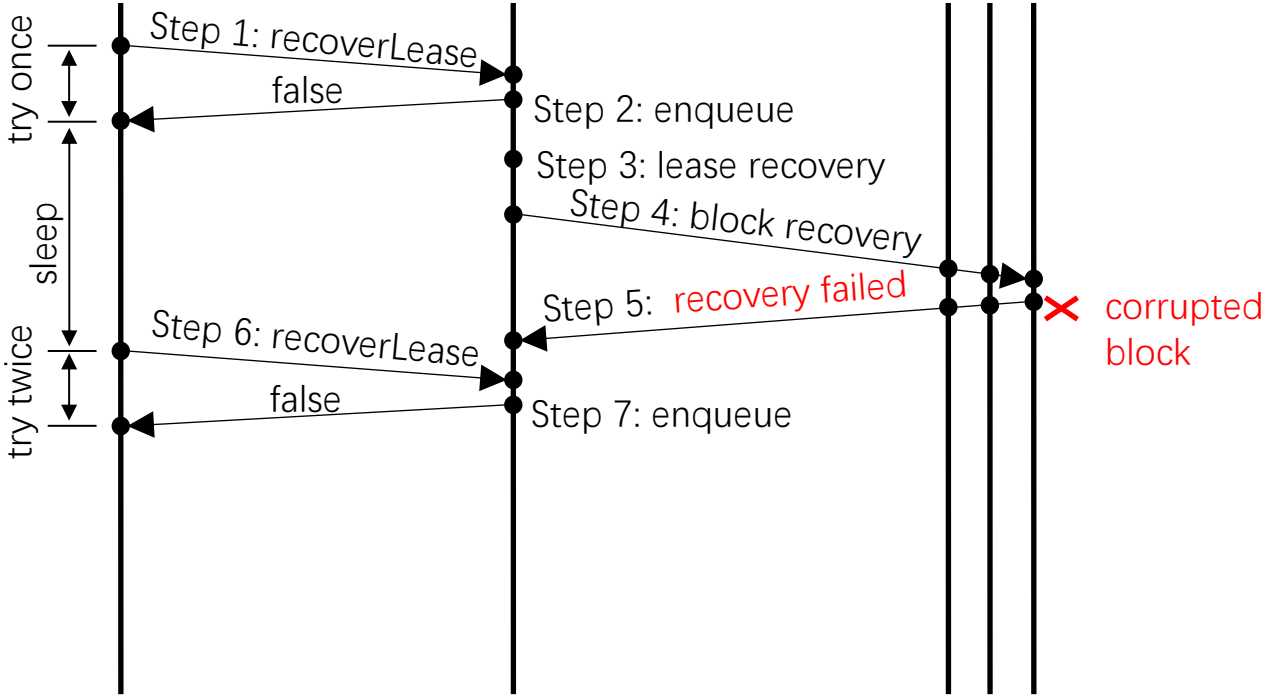
HBase-8389



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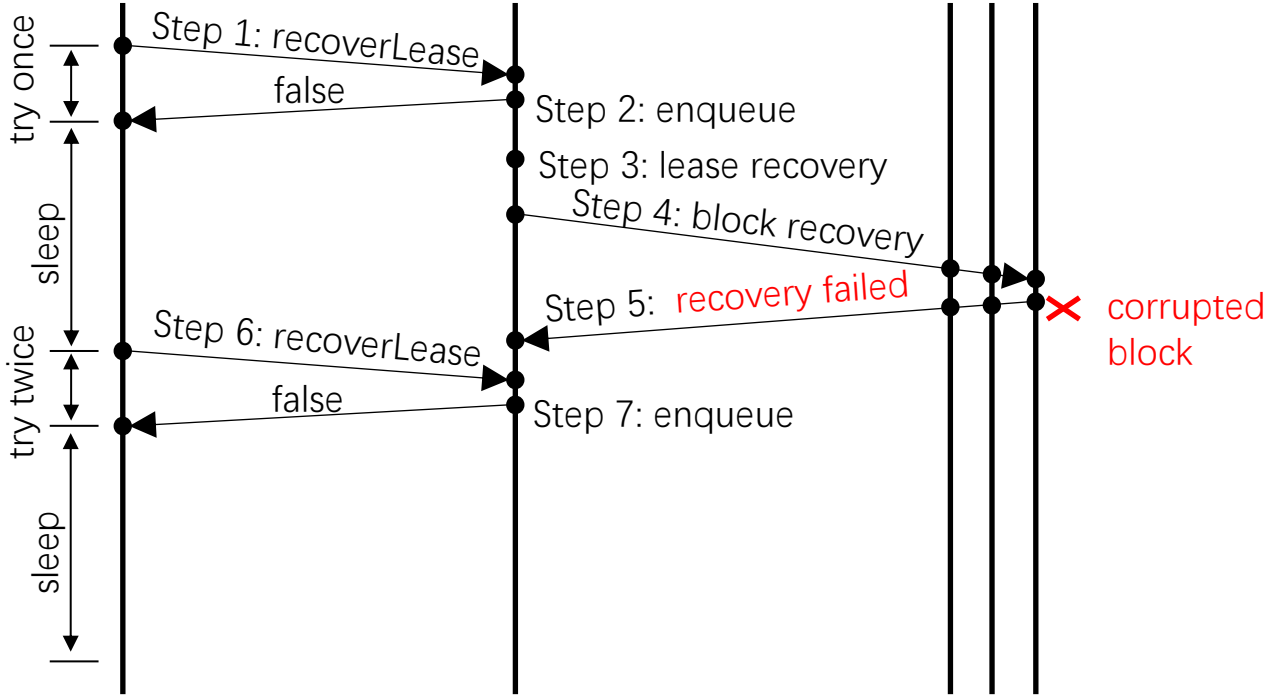

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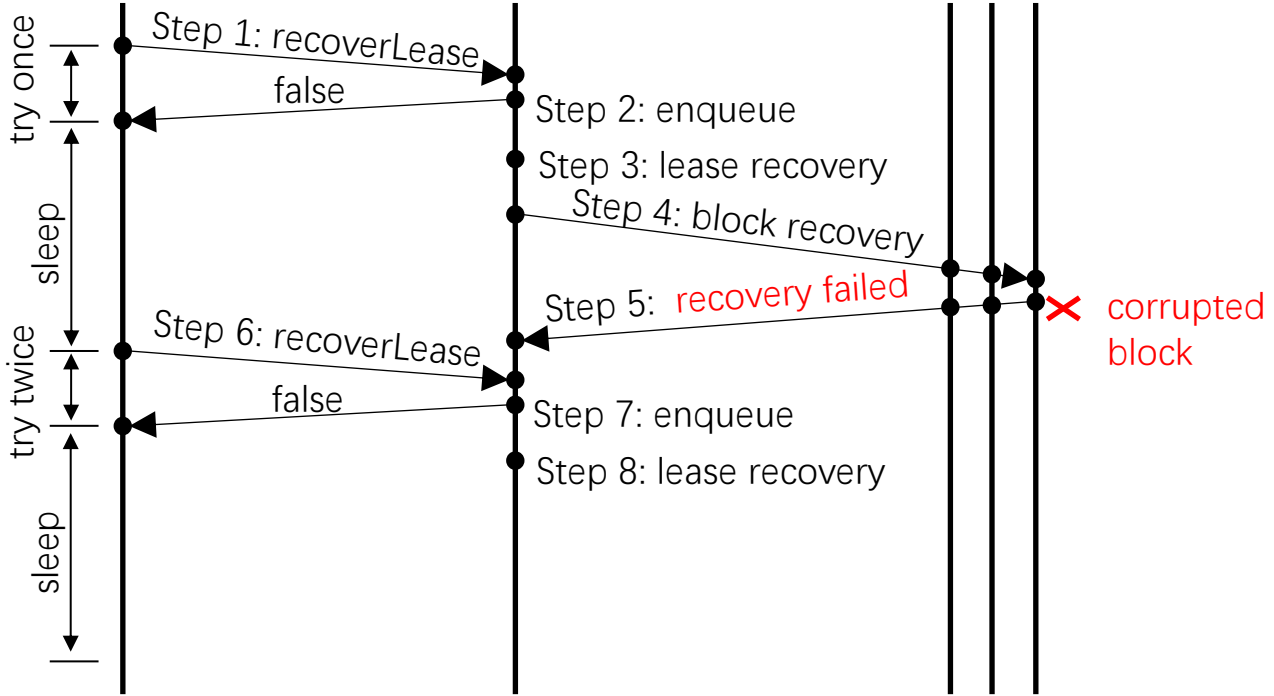

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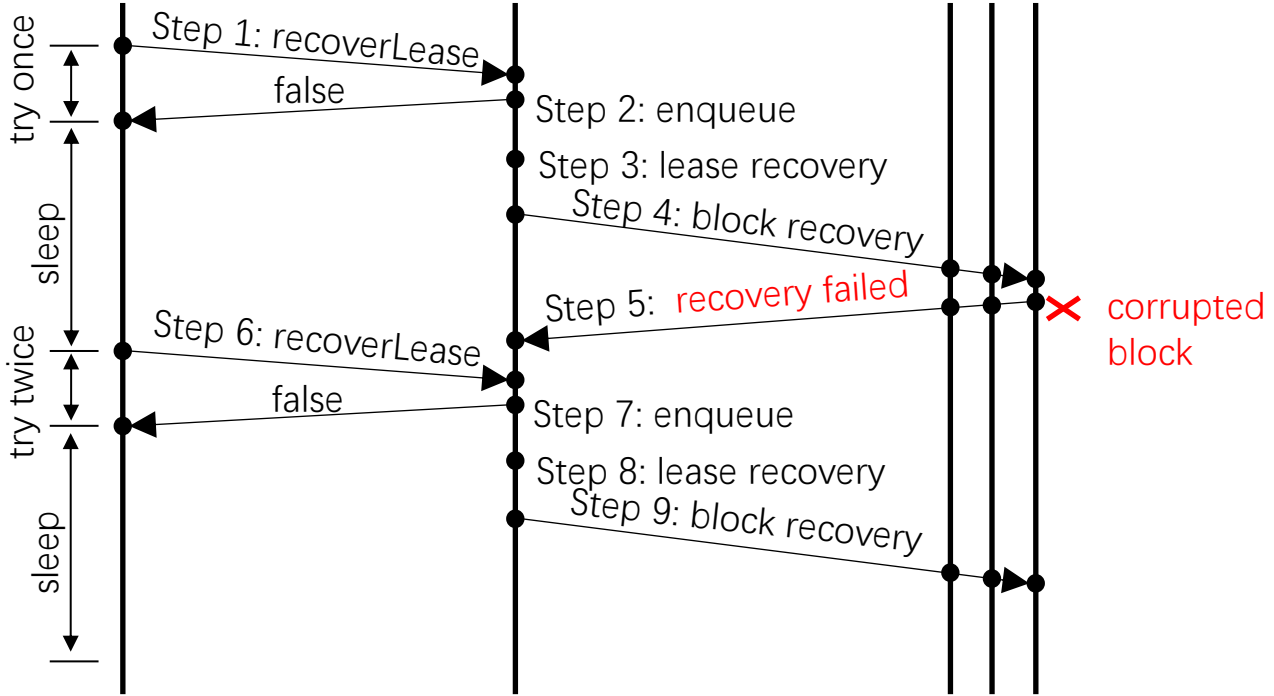

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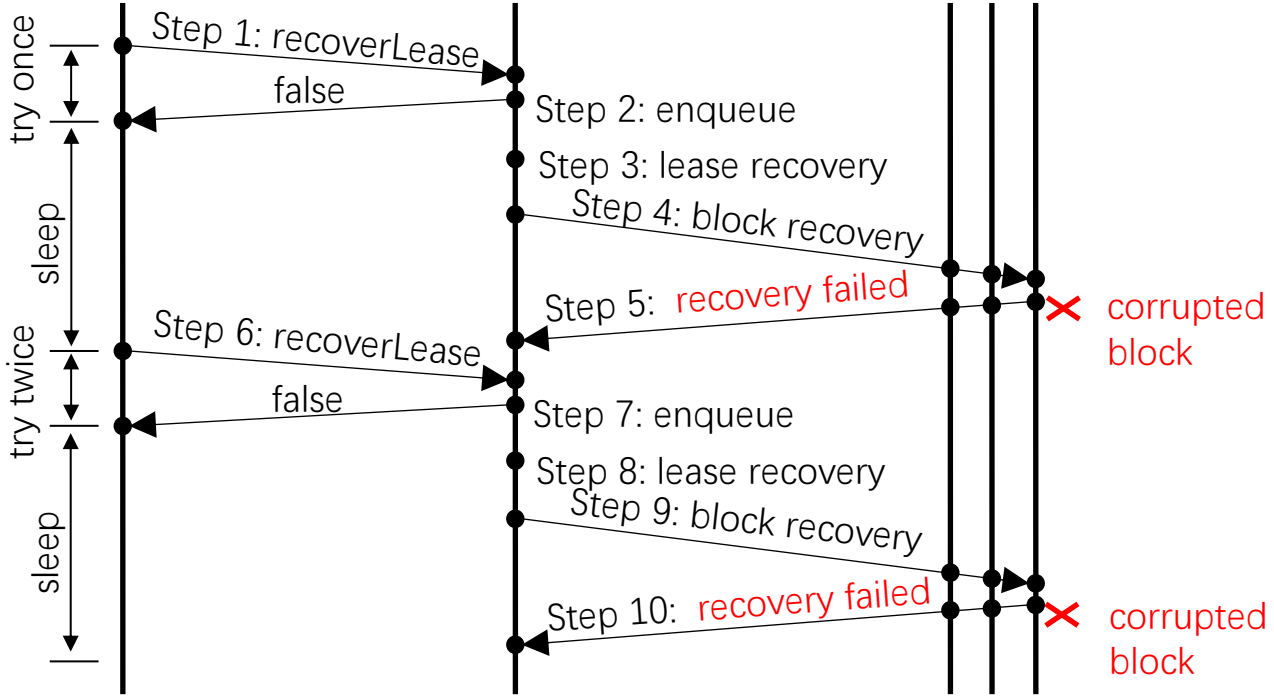

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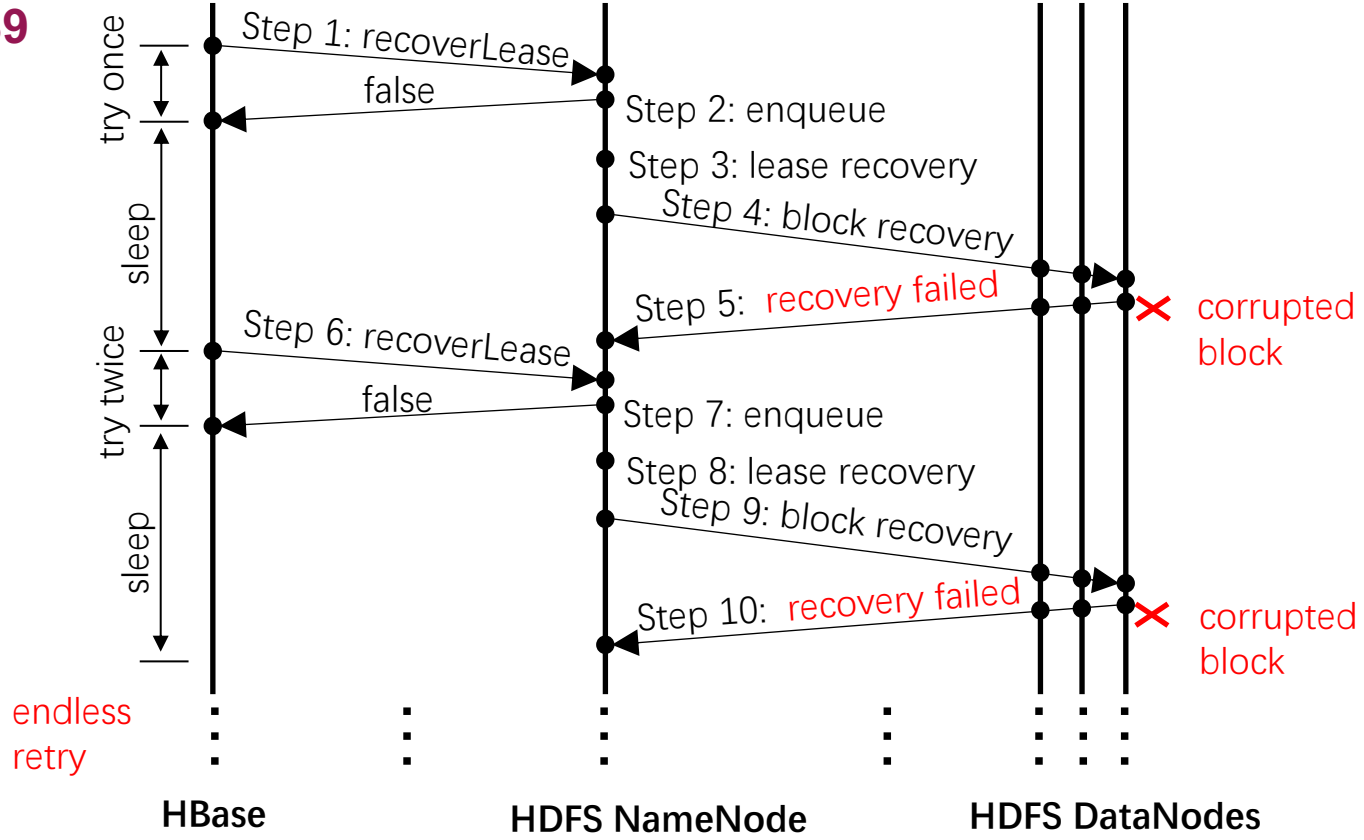

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Overview of HangFix

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HBase-8389

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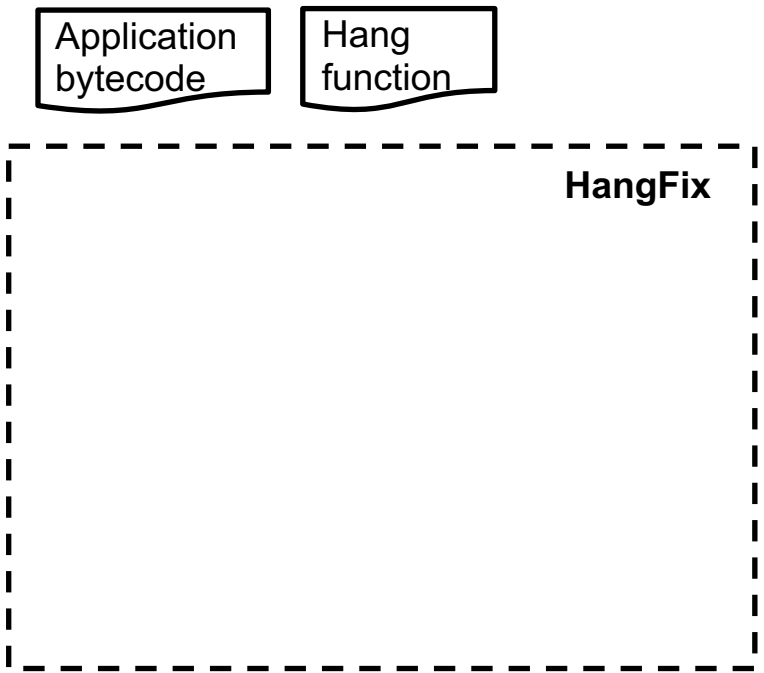

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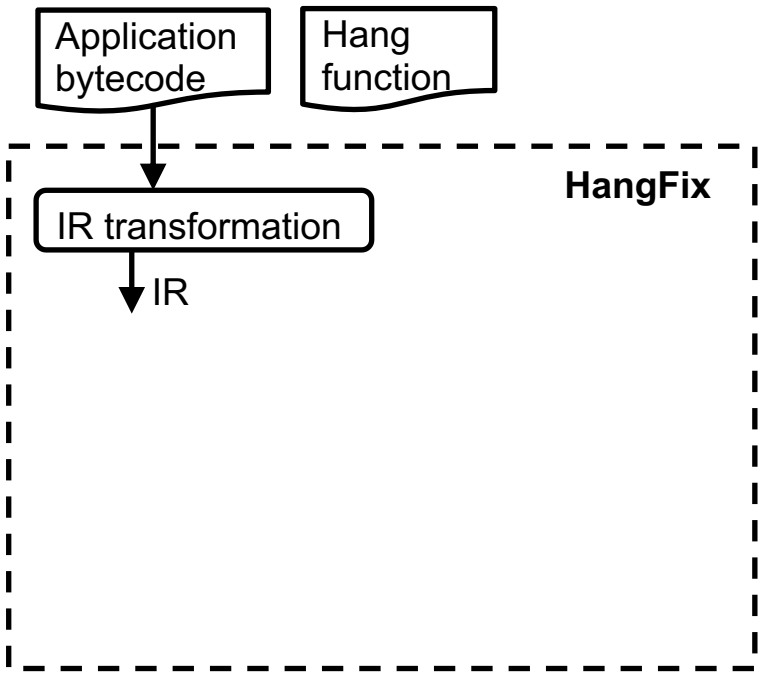

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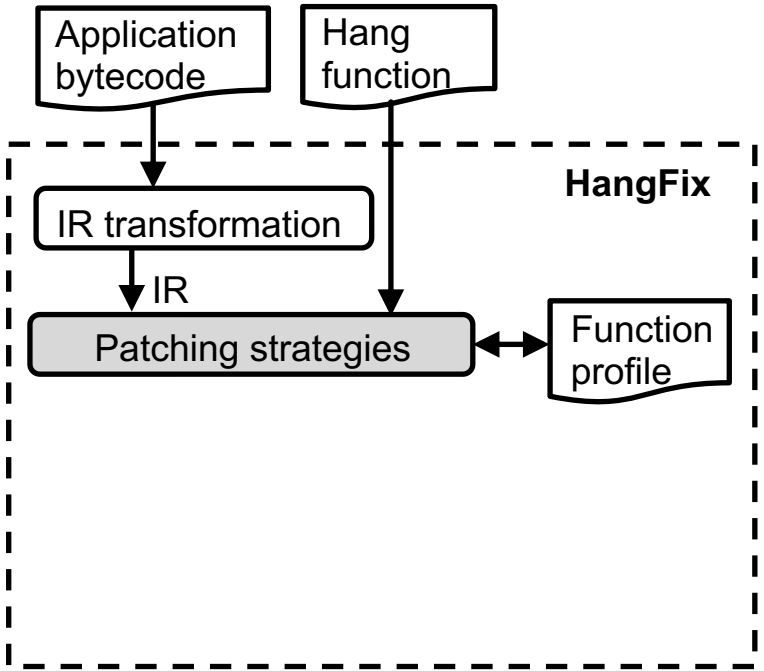

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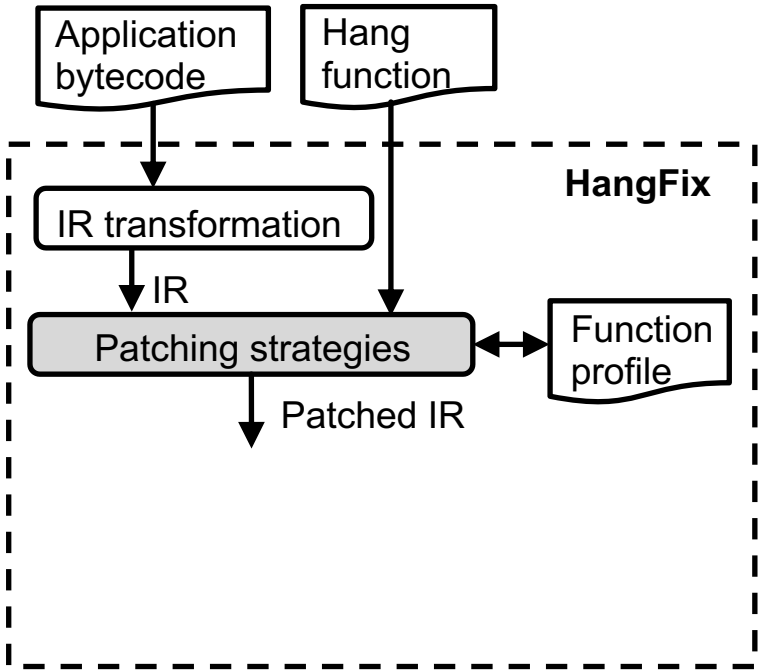

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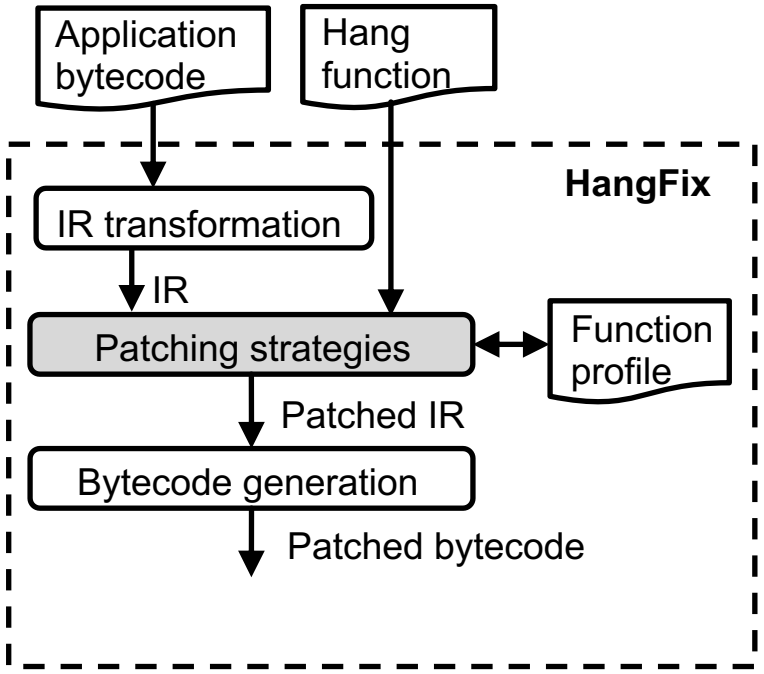

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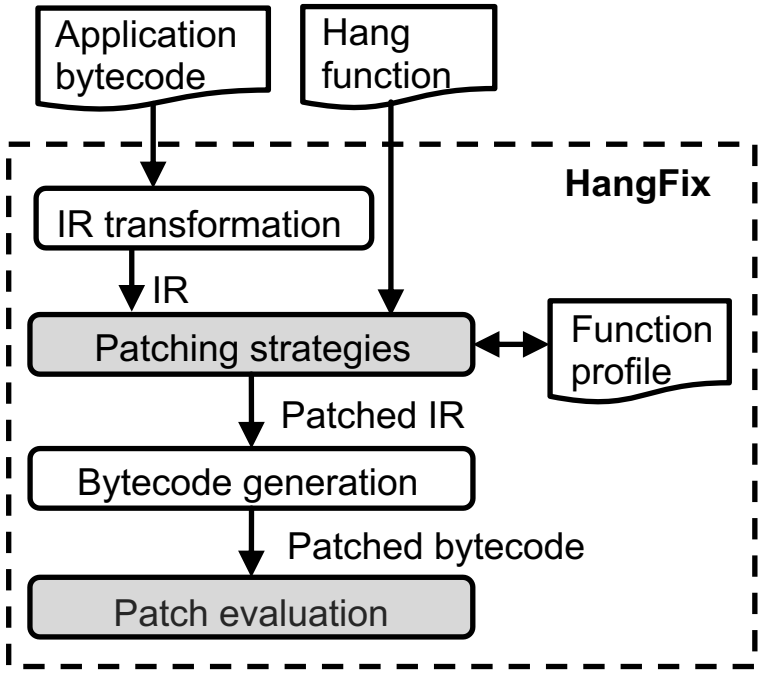

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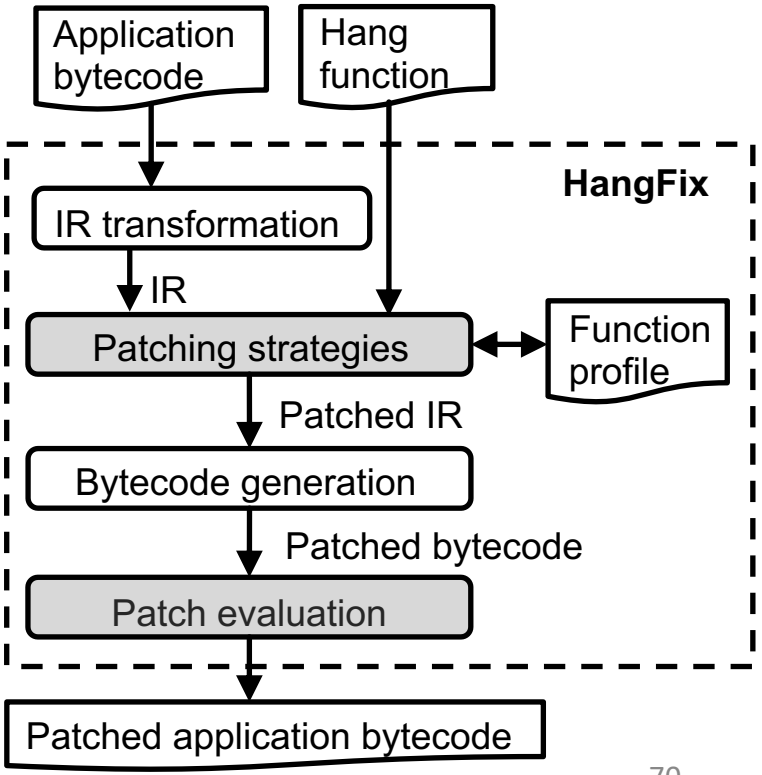

Methodology

- Search all the hang bugs in JIRA using key words: *hang*, *corruption*, *communicate, connect, read, write*;
- Popular cloud systems: Hadoop, Cassandra, etc;
- Extensively studied all the hang bugs to my best knowledge.

Commonly Seen Hang Bug Patterns

- Pattern #1: Unexpected return value causes the loop stride to be incorrectly updated
- Pattern #2: Misconfigured variables cause the loop stride or index incorrectly updated
- Pattern #3: Improper exception or error handling skips loop index updating operations
- Pattern #4: Blocking-prone operations

Patching Strategies

- Strategy #1: Checking error-prone return values to terminate an infinite loop
- Strategy #2: Checking misconfigured variable to restore default value or break the loop if the default value does not exist
- Strategy #3: Tracing the execution of index update operations and re-executing them or breaking the loop
- Strategy #4: Adding missing timeout over blocking-prone operations

Pattern #1: Unexpected return value causes the loop stride to be incorrectly updated

- The loop stride depends on an operation's returning value;
- The operation **returns** an **unexpected error code** due to some underlying faults such as **data corruption**.

Pattern #1: Unexpected return value causes the loop stride to be incorrectly updated

Cassandra-7330

```
114 protected void drain(InputStream dis,
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Loop stride

Be the same or get increased

0 or -1 (unexpected return)

- The loop stride depends on an operation's returning value;
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Fixing Pattern #1 Hang Bug

Patching Strategy:

- Identify error-prone return values which are used to update the loop stride and terminate the loop by throwing an exception with a known type.

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Patching Steps:

- Traverses the CFG of the hang function **f**;
- Extracts all the invocation statements from f along the loop path;
- Checks whether every error-prone return value of every invocation $\mathbf{f_i}$ is checked.

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0 and -1 are not checked.

Function profile

Class: DataInputStream
Method: long skip(long)
Error-prone return: 0, -1

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Patching Steps:

- An if branch with the condition of $r_i == r_{err}$;
- If more than one error-prone return values, a combined condition in the form of $r_i >= r_{err\_min}$ or $r_i <= r_{err\_max}$;
- A known exception with the same type of the exception declared by function **f**.

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Pattern #2: Misconfigured variables cause the loop stride or index incorrectly updated

- An **operation's parameter** or a **class field variable** is misconfigured.
- They reset the **loop index** to **the same value** in each iteration;
- They set the **loop stride** to be **non-positive**/**non-negative** infinitely when the loop has a fixed **upper**/**lower** bound.

Pattern #2: Misconfigured variables cause the loop stride or index incorrectly updated

Hadoop-15415

```
96 public static void copyBytes(…) {
97  int buffSize = conf.getInt("buffer.size",4096);
98  copyBytes(in, buffSize, true);
99 }
```

```
74 public static void copyBytes(…) {
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loop index

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Pattern #2: Misconfigured variables cause the loop stride or index incorrectly updated

Hadoop-15415

```
96 public static void copyBytes(…) {
97  int buffSize = conf.getInt("buffer.size",4096);
98  copyBytes(in, buffSize, true);
99 }
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```
74 public static void copyBytes(…) {
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84   bytesRead = in.read(buf);
85 }}
```

Misconfigued to be 0

zero-size array

loop index

- An **operation's parameter** or a **class field variable** is misconfigured.
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always be 0

- An **operation's parameter** or a **class field variable** is misconfigured.
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Fixing Pattern #2 Hang Bug

Patching Strategy:

- Identifies the misconfigured variables and 1) automatically restores the default configuration values or 2) breaks the loop if the variable's default value does not exist.

Fixing Pattern #2 Hang Bug

Hadoop-15415

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Patching Steps:

Fixing Pattern #2 Hang Bug

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```

Patching Steps:

- Traverses the CFG of the hang function **f**;
- Extracts all the invocation statements from **f** along the loop path;
- Checks whether every error-prone parameter of every invocation $\mathbf{f_i}$ is checked;

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buf.size is not checked.

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Function profile

Class: InputStream
Method: int skip(byte[])
Error-prone para: byte[0]

Fixing Pattern #2 Hang Bug

Hadoop-15415

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Fixing Pattern #2 Hang Bug

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```

Patching Steps:

- Conducts inter-procedural analysis on the whole program to retrieve the call graph to function **f**;
- Performs data-dependency analysis backwards along the call path to identify the configuration statement;

Fixing Pattern #2 Hang Bug

Hadoop-15415

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96 public static void copyBytes(…) {
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Patching Steps:

Fixing Pattern #2 Hang Bug

Hadoop-15415

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Patching Steps:

- Add a checker after the configuration statement;
- An if branch with the condition of $r_i == r_{err}$ (Combined condition, optional);
- Restore default value;

Fixing Pattern #2 Hang Bug

Hadoop-15415

```
96 public static void copyBytes(…) {
97  int buffSize = conf.getInt("buffer.size",4096);
   + if(buffSize == 0)   buffSize = 4096; //default
98  copyBytes(in, buffSize, true);
99 }
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```
74 public static void copyBytes(…) {
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77  byte[] buf = new byte[buffSize];
78  int bytesRead = in.read(buf);
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78  int bytesRead = in.read(buf);
79  while (bytesRead >= 0) {
84    bytesRead = in.read(buf);
  +  if(buffSize == 0)  break;    //loop tail
85 }}
```

Patching Steps:

- Add a checker after the configuration statement;
- An if branch with the condition of $r_i == r_{err}$ (Combined condition, optional);
- Restore default value;
- Add a checker if undefined configuration statement or public hang function;
- Break statement;

Pattern #3: Improper exception or error handling skips loop index updating operations

- **Exception** happens or **error code** is returned;
- An **improper exception/error handling** changes the control flow;
- Causes the **loop index updating operations** to be **skipped**.

Pattern #3: Improper exception or error handling skips loop index updating operations

Cassandra-9881

```
103  public void scrub() {
120   while (!dataFile.isEOF()){
129    try{
130     key = sstable.partitioner.decorateKey(
                ByteBufferUtil.readWithShortLength(
                                                dataFile));
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corrupted

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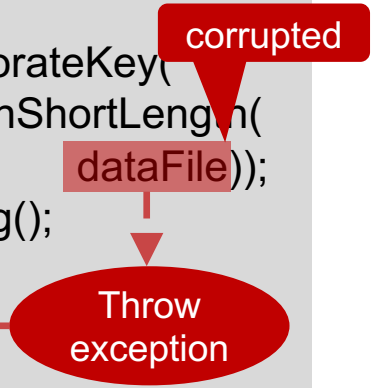

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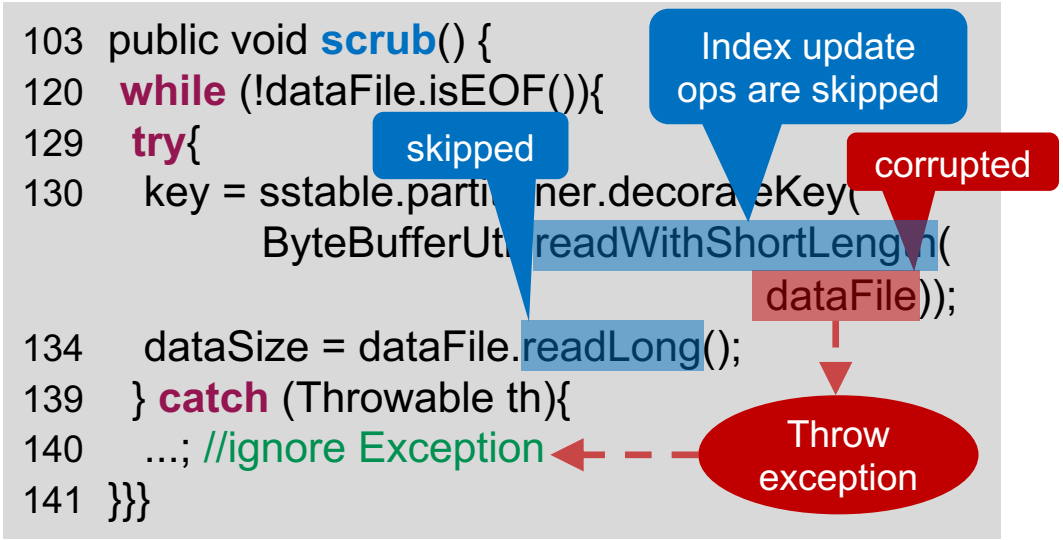

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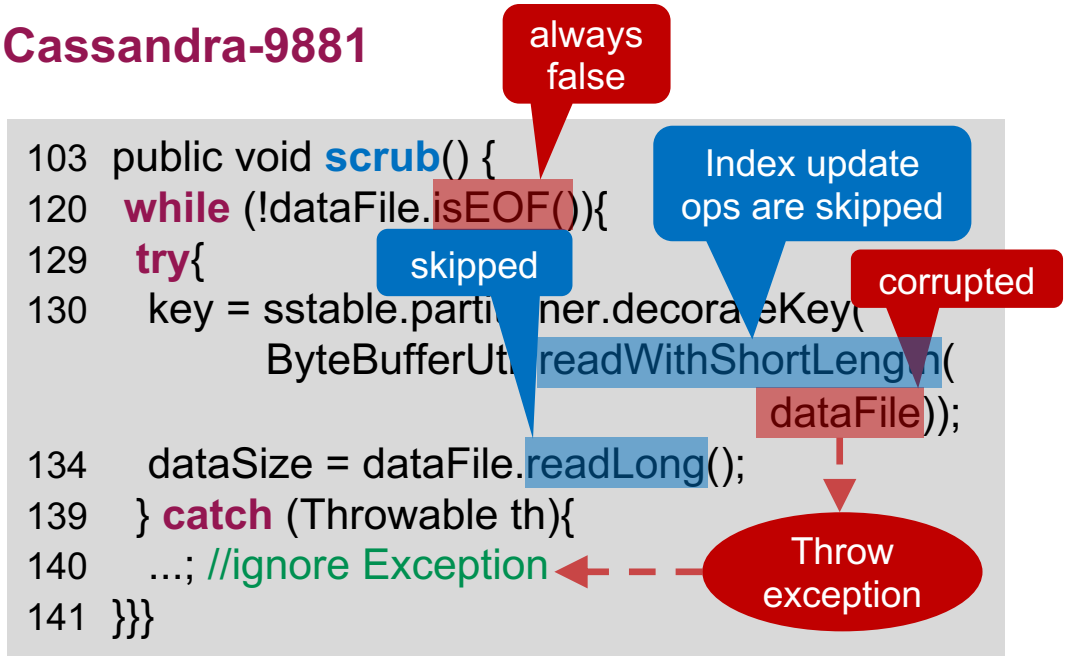

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Fixing Pattern #3 Hang Bug

Patching Strategy:

- Identifies the unexecuted loop index updating operations and 1) re-executes those operations or 2) terminates the loop by throwing a checkable and acceptable exception.

Fixing Pattern #3 Hang Bug

Cassandra-9881

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120   while (!dataFile.isEOF()){
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Patching Steps:

Fixing Pattern #3 Hang Bug

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141  }}}
```

Patching Steps:

- Introduces a counter variable to record the execution of index updating operations;
- Increases or decreases the counter value by one after each index-forwarding or index-reversing operation;
- Checks the counter value and terminate the loop or re-execute index updating operations if the loop index is not updated;

Fixing Pattern #3 Hang Bug

Cassandra-9881

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```

Re-execution can fail

Patching Steps:

- Introduces a counter variable to record the execution of index updating operations;
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Cassandra-9881

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        …
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Patching Steps:

Fixing Pattern #3 Hang Bug

Cassandra-9881

```
436  private void scrubOne() throws IOException {
444   scrubber.scrub();
459  }
```

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```

Patching Steps:

- Checks the **call stack** of **f** backwards until it identifies the *n*-hop caller function of **f** who **declares a checkable exception** in its function signature;
- **Inserts** the same checkable exception in the signatures of function **f** and its *i*-hop callers, $i = 1, 2, ..., n - 1$;
- If there are more than one checkable exceptions, chooses the first and most specific one.

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Pattern #4: Blocking-prone operations

- **Component A blocks** itself waiting to be awakened or **keeps polling** from **Component B** until an operation finishes.
- **A** is where the hang function resides while **B** can be another thread, another node, in JNI code or even OS code.

Pattern #4: Blocking-prone operations

Hive-5235

```
81 public void decompress(ByteBuffer in,
              ByteBuffer out) throws IOException {
93  try {
94   int cnt = inflater.inflate(
95               out.array(), out.arrayOffset() +
96               out.position(), out.remaining());
97  } catch (DataFormatException e) {
98   throw new IOException("Corrupted data");
99 }}
```

JNI

- **Component A blocks** itself waiting to be awakened or **keeps polling** from **Component B** until an operation finishes.
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JNI

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Fixing Pattern #4 Hang Bug

Patching Strategy:

Fixing Pattern #4 Hang Bug

Patching Strategy:

- Identifies the blocking-prone operations and inserts timeout settings on those blocking-prone operations.
  - Checks the elapsed time in each loop iteration and terminates the loop when it has used up the preset time -– infinite polling;
  - Invokes timeout setting APIs;
  - Quarantines the blocking-prone operation in a thread with timeout.

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```

Patching Steps:

- Inquires the *function profile* and detects that the blocking-prone operation;
- Quarantines the blocking-prone operation in a callable or runnable thread with **timeout** settings.

Fixing Pattern #4 Hang Bug

Hive-5235

```
81 public void decompress(ByteBuffe
             ByteBuffer out) throws IOEx
93  try {
94-  int cnt = inflater.inflate(
  +  int cnt = inflateWithTO(inflater,
95              out.array(), out.arrayOffset() +
96              out.position(), out.remaining());
97  } catch (DataFormatException e) {
98   throw new IOException("Corrupted data");
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```

Has timeout setting

Patching Steps:

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Fixing Pattern #4 Hang Bug

Hive-5235

```
public int inflateWithTO(final Inflater inflater,
                    final byte[] b, final int off, final int len)
                              throws DataFormatException {
 ExecutorService executor =
                  Executors.newSingleThreadExecutor();
 Callable<Integer> callable = new Callable<Integer>() {
  @Override
  public Integer call() throws DataFormatException {
   return inflater.inflate(b, off, len);  }};
 Future<Integer> future = executor.submit(callable);
 int cnt = 0;
 try { cnt = future.get(timeout, TimeUnit.MILLISECONDS);
 } catch (Exception e) {         future.cancel(true);
  throw new DataFormatException("Blocking");
 } finally { executor.shutdown(); }
 return cnt; }
```

Patching Steps:

Fixing Pattern #4 Hang Bug

Hive-5235

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 Callable<Integer> callable = new Callable<Integer>() {
  @Override
  public Integer call() throws DataFormatException {
   return inflater.inflate(b, off, len);  }};
 Future<Integer> future = executor.submit(callable);
 int cnt = 0;
 try { cnt = future.get(timeout, TimeUnit.MILLISECONDS);
 } catch (Exception e) {        future.cancel(true);
  throw new DataFormatException("Blocking");
 } finally { executor.shutdown(); }
 return cnt; }
```

target operation

Patching Steps:

- Uses the Executor-Callable-Future format to quarantine the target op inside a callable thread;

Fixing Pattern #4 Hang Bug

Hive-5235

```
public int inflateWithTO(final Inflater inflater,
                  final byte[] b, final int off, final int len)
                        throws DataFormatException {
 ExecutorService executor =
               Executors.newSingleThreadExecutor();
 Callable<Integer> callable = new Callable<Integer>() {
  @Override
  public Integer call() throws DataFormatException {
   return inflater.inflate(b, off, len);  }};
 Future<Integer> future = executor.submit(callable);
 int cnt = 0;
 try { cnt = future.get(timeout, TimeUnit.MILLISECONDS);
 } catch (Exception e) {        future.cancel(true);
  throw new DataFormatException("Blocking");
 } finally { executor.shutdown(); }
 return cnt; }
```

Patching Steps:

Fixing Pattern #4 Hang Bug

Hive-5235

```
public int inflateWithTO(final Inflater inflater,
                         final byte[] b, final int off, final int len)
                                 throws DataFormatException {
ExecutorService executor =
+ private Configuration conf = new Configuration();
+ private String KEY = "inflate.timeout";
+ private long DEFAULT= 5000;
+ private long timeout =conf.getLong(KEY, DEFAULT);
int cnt = 0;
try { cnt = future.get(timeout, TimeUnit.MILLISECONDS);
} catch (Exception e) {        future.cancel(true);
 throw new DataFormatException("Blocking");
} finally { executor.shutdown(); }
return cnt; }
```

Patching Steps:

- The timeout setting is in the future.get() function with a configurable timeout variable.
- Introduces a configurable timeout variable $\mathbf{var}_{\mathbf{new}}$ with the default value of **v**.
- Extracts the default value by searching the system's configuration files using keywords, such as "timeout", "interval", "block", "poll".

Fixing Pattern #4 Hang Bug

Hive-5235

```
public int inflateWithTO(final Inflater inflater,
                         final byte[] b, final int off, final int len)
                                 throws DataFormatException {
ExecutorService executor =
+ private Configuration conf = new Configuration();
+ private String KEY = "inflate.timeout";
+ private long DEFAULT= 5000;
+ private long timeout =conf.getLong(KEY, DEFAULT);
int cnt = 0;
try { cnt = future.get(timeout, TimeUnit.MILLISECONDS);
} catch (Exception e) {        future.cancel(true);
 throw new DataFormatException("Blocking");
} finally { executor.shutdown(); }
return cnt; }
```

Patching Steps:

- The timeout setting is in the future.get() function with a configurable timeout variable.
- Introduces a configurable timeout variable $\mathbf{var}_{\mathbf{new}}$ with the default value of **v**.
- Extracts the default value by searching the system's configuration files using keywords, such as "timeout", "interval", "block", "poll".

Fixing Pattern #4 Hang Bug

Hive-5235

```
81 public void decompress(…) throws IOException {
93  try {
 +  int cnt = inflateWithTO(inflater, …);
97  } catch (DataFormatException e) {
98   throw new IOException("Corrupted data");
99 }}
```

```
public int inflateWithTO(final Inflater inflater, …)
                         throws                    {
 …
 try { cnt = future.get(timeout, TimeUnit.MILLISECONDS);
 } catch (Exception e) {
  throw new
 }
…}
```

Patching Steps:

- **Exception transformation** into existing exception handling mechanism.

Fixing Pattern #4 Hang Bug

Hive-5235

```
81 public void decompress(…) throws IOException {
93  try {
 +  int cnt = inflateWithTO(inflater, …);
97  } catch (DataFormatException e) {
98   throw new IOException("Corrupted data");
99 }}
```

```
public int inflateWithTO(final Inflater inflater, …)
                         throws DataFormatException {
 …
 try { cnt = future.get(timeout, TimeUnit.MILLISECONDS);
 } catch (Exception e) {
  throw new DataFormatException("Blocking…");
 }
…}
```

Patching Steps:

- **Exception transformation** into existing exception handling mechanism.

Evaluation Methodology

#	Bug name	#	Bug name	#	Bug name
1	Cassandra-7330	15	HDFS-13513	29	HBase-8389
2	Cassandra-9881	16	HDFS-13514	30	Hive-5235
3	Compress-87	17	HDFS-14481	31	Hive-13397
4	Compress-451	18	HDFS-14501	32	Hive-18142
5	Hadoop-8614	19	HDFS-14540	33	Hive-18216
6	Hadoop-15088	20	Mapreduce-2185	34	Hive-18217
7	Hadoop-15415	21	Mapreduce-5066	35	Hive-18219
8	Hadoop-15417	22	Mapreduce-6990	36	Hive-19391
9	Hadoop-15424	23	Mapreduce-6991	37	Hive-19392
10	Hadoop-15425	24	Mapreduce-7088	38	Hive-19395
11	Hadoop-15429	25	Mapreduce-7089	39	Hive-19406
12	HDFS-4882	26	Yarn-163	40	Kafka-6271
13	HDFS-5438	27	Yarn-1630	41	Lucene-772
14	HDFS-10223	28	Yarn-2905	42	Lucene-8294

- Implemented a prototype of HangFix using Soot;
- Benchmarks: 42 real-world hang bugs from 10 cloud server systems.

Patch Evaluation

- We manually studied each bug and wrote testcases to reproduce all 42 hang bugs.
- We evaluate whether HangFix can fix a bug by checking whether the patched application bytecode can successfully pass the testcases.
- We compare HangFix with manual patches presented in bug reports in JIRA to further validate the effectiveness of HangFix.

Patch Correctness

Bug name	Manual	HangFix
Cassandra-7330	✓	✓
Compress-87	✓	✓
Hadoop-8614	✓	✓
Hadoop-15088	×	✓
Hadoop-15424	×	✓
Hadoop-15425	×	✓
Mapreduce-6990	×	✓
Yarn-163	×	✓
Yarn-2905	✓	✓
Hive-13397	✓	✓
Hive-18142	×	✓
Hive-18219	×	✓
Kafka-6271	×	✓
Pattern #1	**5**	**13**

Bug name	Manual	HangFix
Compress-45	✓	✓
Hadoop-15415	×	✓
Hadoop-15417	×	✓
Hadoop-15429	×	✓
HDFS-13513	×	✓
HDFS-13514	×	✓
HDFS-14481	×	✓
HDFS-14501	×	✓
Mapreduce-7088	×	✓
Mapreduce-7089	×	✓
Hive-19392	×	✓
Hive-19395	×	✓
Lucene-8294	✓	✓
Pattern #2	**2**	**13**

Bug name	Manual	HangFix
Cassandra-9881	×	✓
HDFS-4882	✓	×
Mapreduce-2185	✓	✓
Mapreduce-6991	×	✓
Hive-18216	×	✓
Hive-18217	×	✓
Pattern #3	**2**	**5**

Bug name	Manual	HangFix
HDFS-10223	✓	✓
HDFS-5438	✓	×
HDFS-14540	×	✓
Mapreduce-5066	✓	✓
Yarn-1630	✓	✓
HBase-8389	✓	✓
Hive-5235	×	✓
Hive-19391	×	✓
Hive-19406	×	✓
Lucene-772	×	✓
Pattern #4	**5**	**9**

Patch Correctness

Bug name	Manual	HangFix
Cassandra-7330	✓	✓
Compress-87	✓	✓
Hadoop-8614	✓	✓
Hadoop-15088	×	✓
Hadoop-15424	×	✓
Hadoop-15425	×	✓
Mapreduce-6990	×	✓
Yarn-163	×	✓
Yarn-2905	✓	✓
Hive-13397	✓	✓
Hive-18142	×	✓
Hive-18219	×	✓
Kafka-6271	×	✓
Pattern #1	**5**	**13**

Bug name	Manual	HangFix
Compress-45	✓	✓
Hadoop-15415	×	✓
Hadoop-15417	×	✓
Hadoop-15429	×	✓
HDFS-13513	×	✓
HDFS-13514	×	✓
HDFS-14481	×	✓
HDFS-14501	×	✓
Mapreduce-7088	×	✓
Mapreduce-7089	×	✓
Hive-19392	×	✓
Hive-19395	×	✓
Lucene-8294	✓	✓
Pattern #2	**2**	**13**

Bug name	Manual	HangFix
Cassandra-9881	×	✓
HDFS-4882	✓	×
Mapreduce-2185	✓	✓
Mapreduce-6991	×	✓
Hive-18216	×	✓
Hive-18217	×	✓
Pattern #3	**2**	**5**

Bug name	Manual	HangFix
HDFS-10223	✓	✓
HDFS-5438	✓	×
HDFS-14540	×	✓
Mapreduce-5066	✓	✓
Yarn-1630	✓	✓
HBase-8389	✓	✓
Hive-5235	×	✓
Hive-19391	×	✓
Hive-19406	×	✓
Lucene-772	×	✓
Pattern #4	**5**	**9**

- **HangFix successfully fixes 40 out of 42 hang bugs;**

Patch Correctness

Bug name	Manual	HangFix
Cassandra-7330	✓	✓
Compress-87	✓	✓
Hadoop-8614	✓	✓
Hadoop-15088	×	✓
Hadoop-15424	×	✓
Hadoop-15425	×	✓
Mapreduce-6990	×	✓
Yarn-163	×	✓
Yarn-2905	✓	✓
Hive-13397	✓	✓
Hive-18142	×	✓
Hive-18219	×	✓
Kafka-6271	×	✓
Pattern #1	**5**	**13**

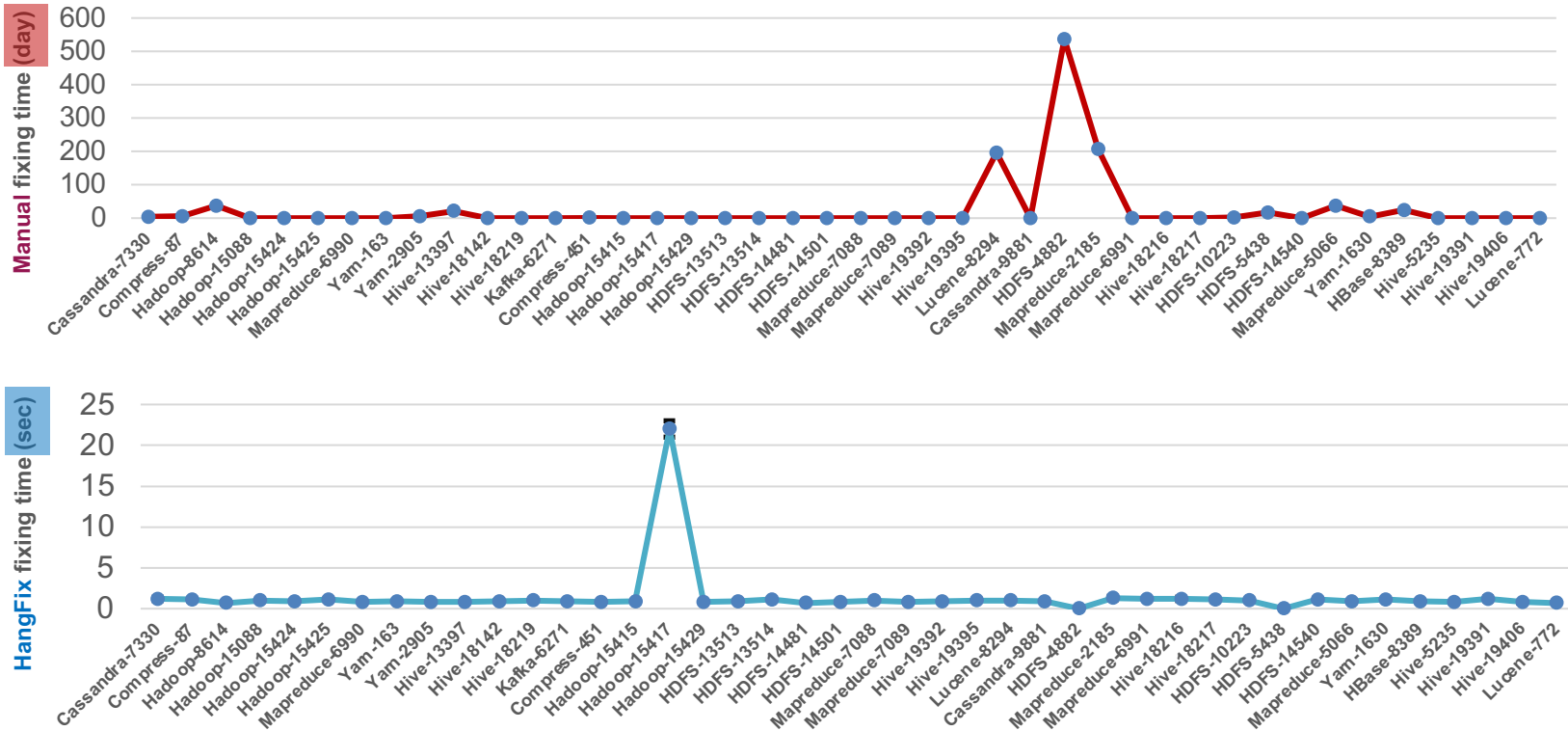
Bug name	Manual	HangFix
Compress-45	✓	✓
Hadoop-15415	×	✓
Hadoop-15417	×	✓
Hadoop-15429	×	✓
HDFS-13513	×	✓
HDFS-13514	×	✓
HDFS-14481	×	✓
HDFS-14501	×	✓
Mapreduce-7088	×	✓
Mapreduce-7089	×	✓
Hive-19392	×	✓
Hive-19395	×	✓
Lucene-8294	✓	✓
Pattern #2	**2**	**13**

Bug name	Manual	HangFix
Cassandra-9881	×	✓
HDFS-4882	✓	×
Mapreduce-2185	✓	✓
Mapreduce-6991	×	✓
Hive-18216	×	✓
Hive-18217	×	✓
Pattern #3	**2**	**5**

Bug name	Manual	HangFix
HDFS-10223	✓	✓
HDFS-5438	✓	×
HDFS-14540	×	✓
Mapreduce-5066	✓	✓
Yarn-1630	✓	✓
HBase-8389	✓	✓
Hive-5235	×	✓
Hive-19391	×	✓
Hive-19406	×	✓
Lucene-772	×	✓
Pattern #4	**5**	**9**

- **Manual patch can only fix 14 bugs.**
- **HangFix successfully fixes 40 out of 42 hang bugs;**

Fixing Time


Manual fixing time (day)
600
500
400
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Cassandra-7330
Compress-87
Hadoop-8614
Hadoop-15088
Hadoop-15424
Hadoop-15425
Mapreduce-6990
Yam-163
Yam-2905
Hive-13397
Hive-18142
Hive-18219
Kafka-6271
Compress-451
Hadoop-15415
Hadoop-15417
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Mapreduce-7088
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HDFS-14540
Mapreduce-5066
Yam-1630
HBase-8389
Hive-5235
Hive-19391
Hive-19406
Lucene-772
HangFix fixing time (sec)
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Cassandra-7330
Compress-87
Hadoop-8614
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Hadoop-15424
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Mapreduce-6990
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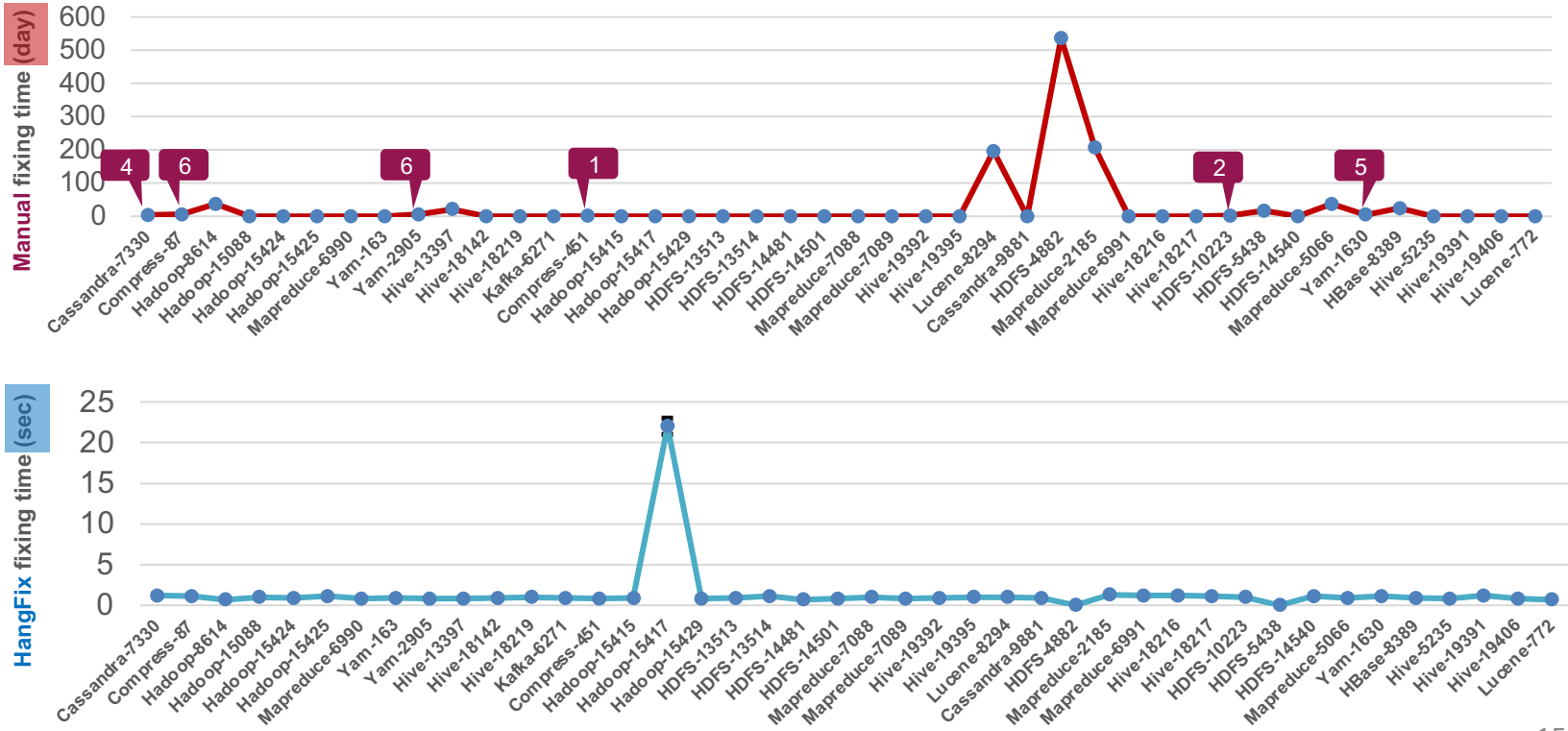
HBase-8389
Hive-5235
Hive-19391
Hive-19406
Lucene-772

Fixing Time


Manual fixing time (day)
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Cassandra-7330
Compress-87
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Mapreduce-6990
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HangFix fixing time (sec)
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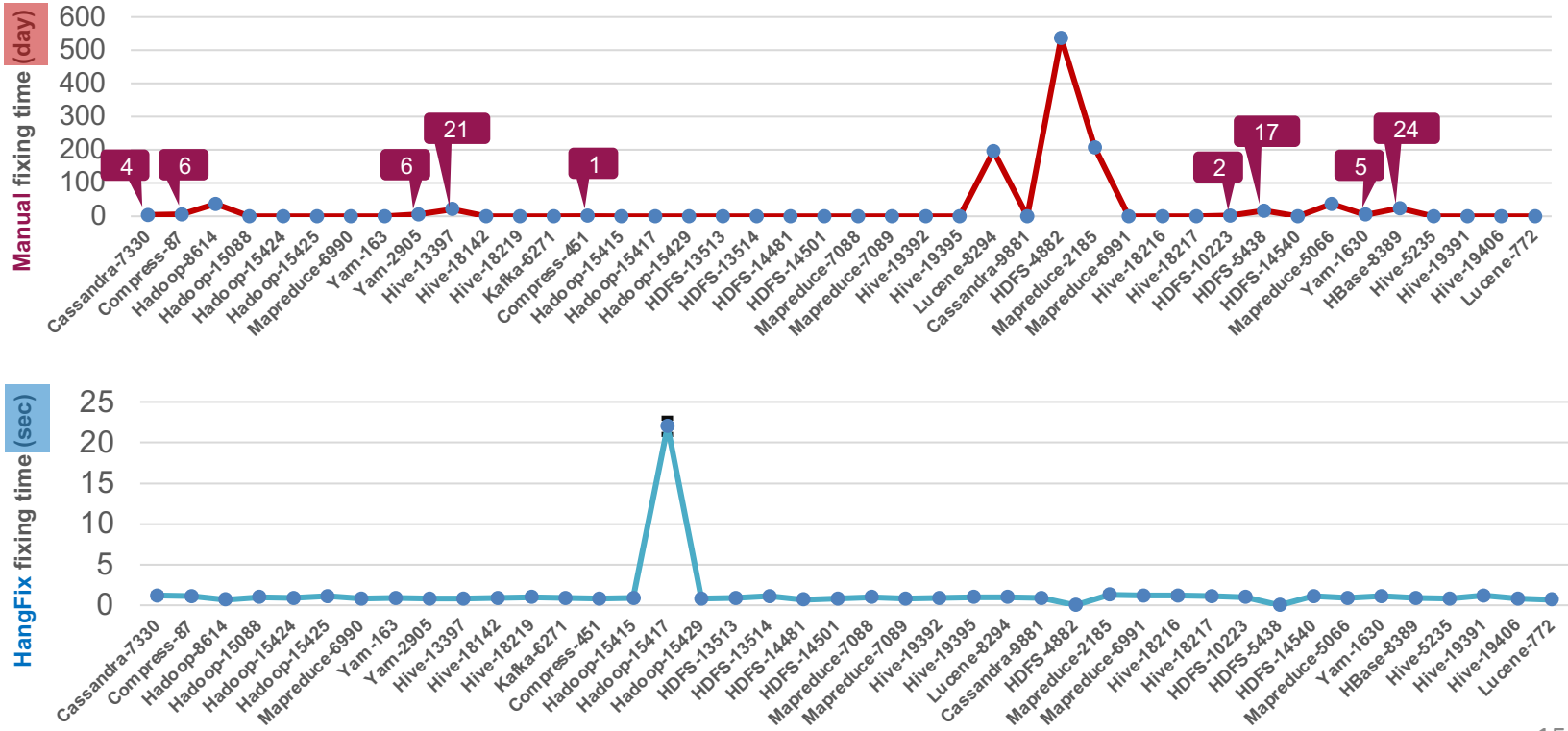
Hive-19406
Lucene-772

Fixing Time


Manual fixing time (day)
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HangFix fixing time (sec)
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Mapreduce-5066
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Hive-19406
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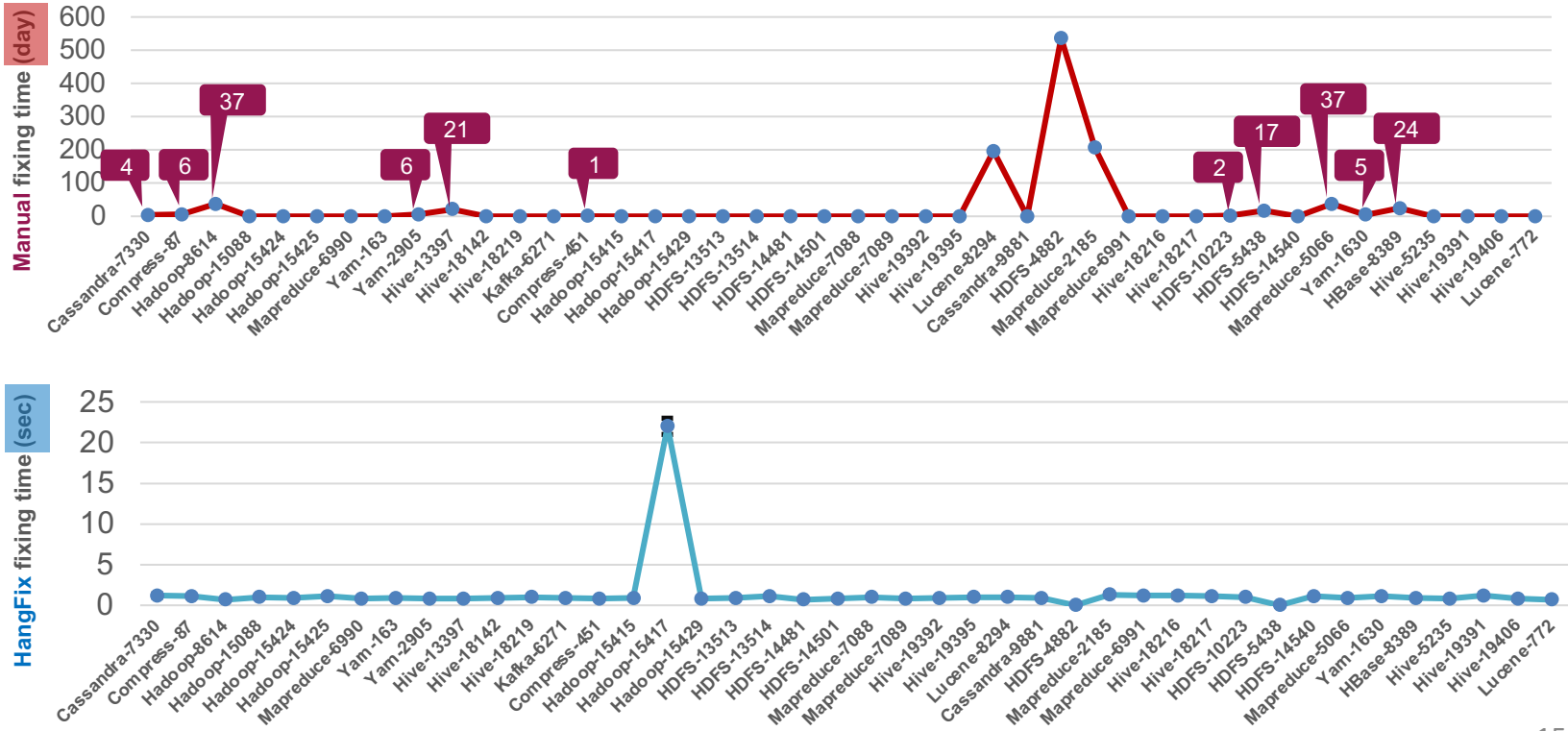
Fixing Time


Manual fixing time (day)
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Mapreduce-5066
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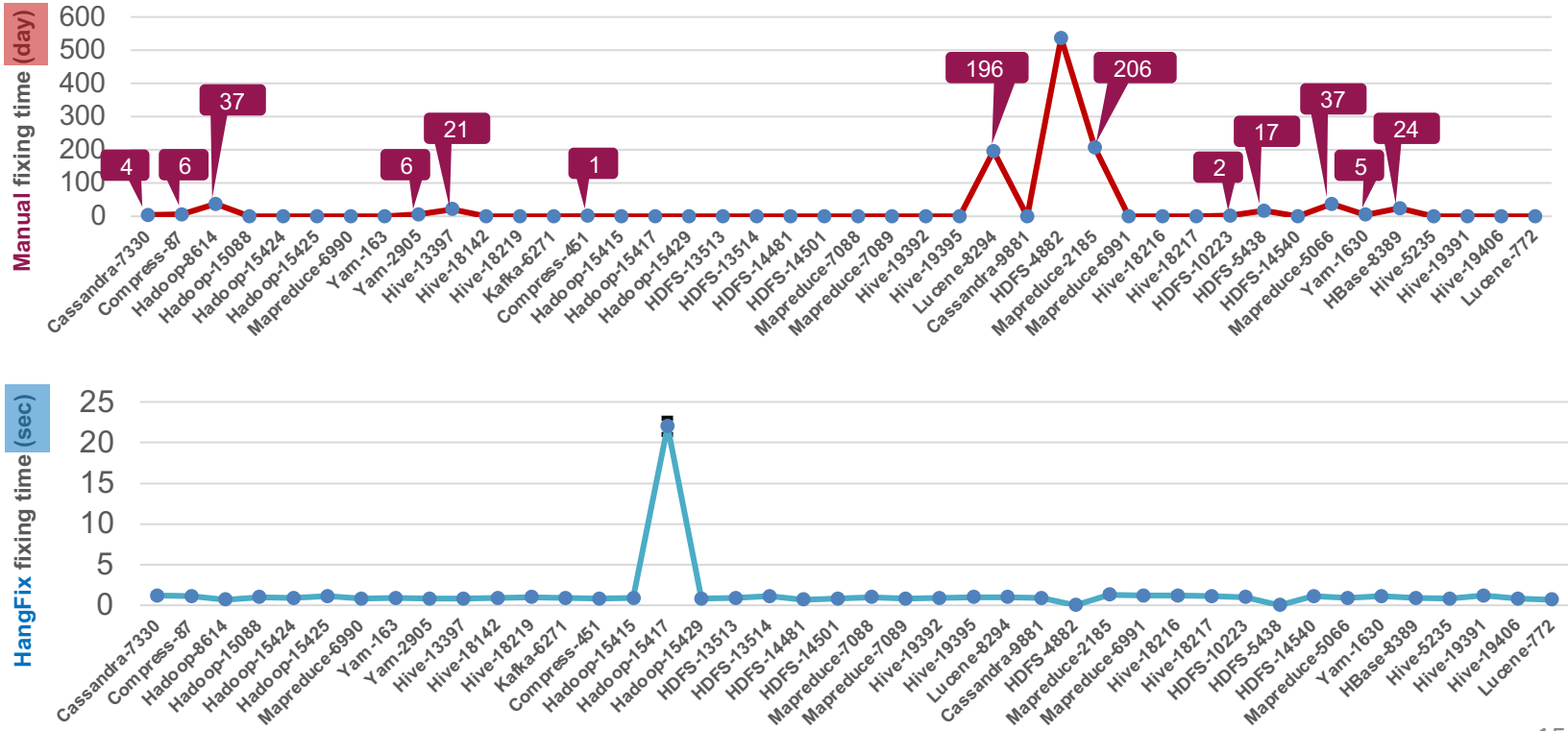
Hive-19391
Hive-19406
Lucene-772

Fixing Time


Manual fixing time (day)
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Cassandra-7330
Compress-87
Hadoop-8614
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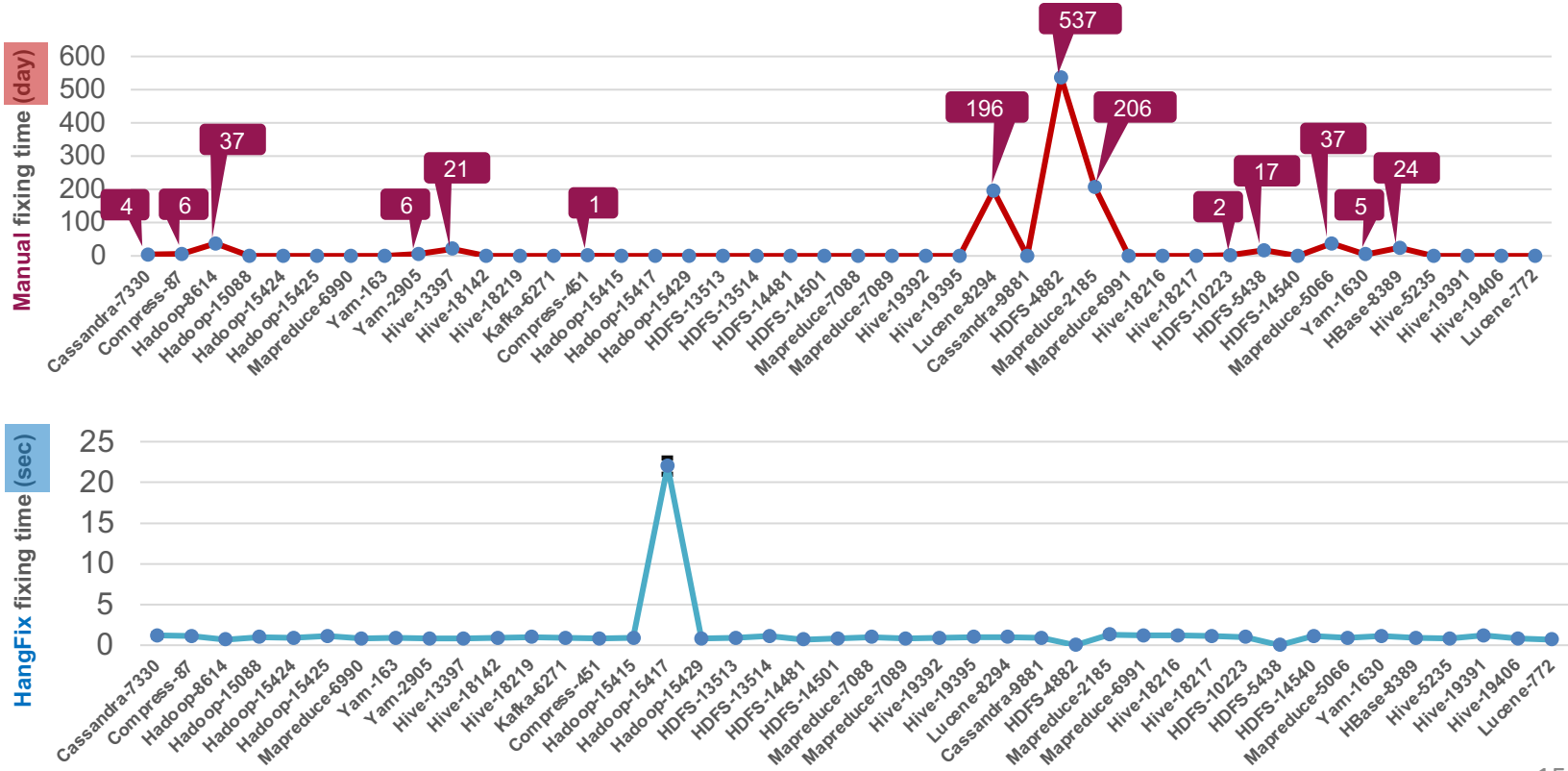
Mapreduce-5066
Yam-1630
HBase-8389
Hive-5235
Hive-19391
Hive-19406
Lucene-772

Fixing Time


Manual fixing time (day)
600
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Cassandra-7330
Compress-87
Hadoop-8614
Hadoop-15088
Hadoop-15424
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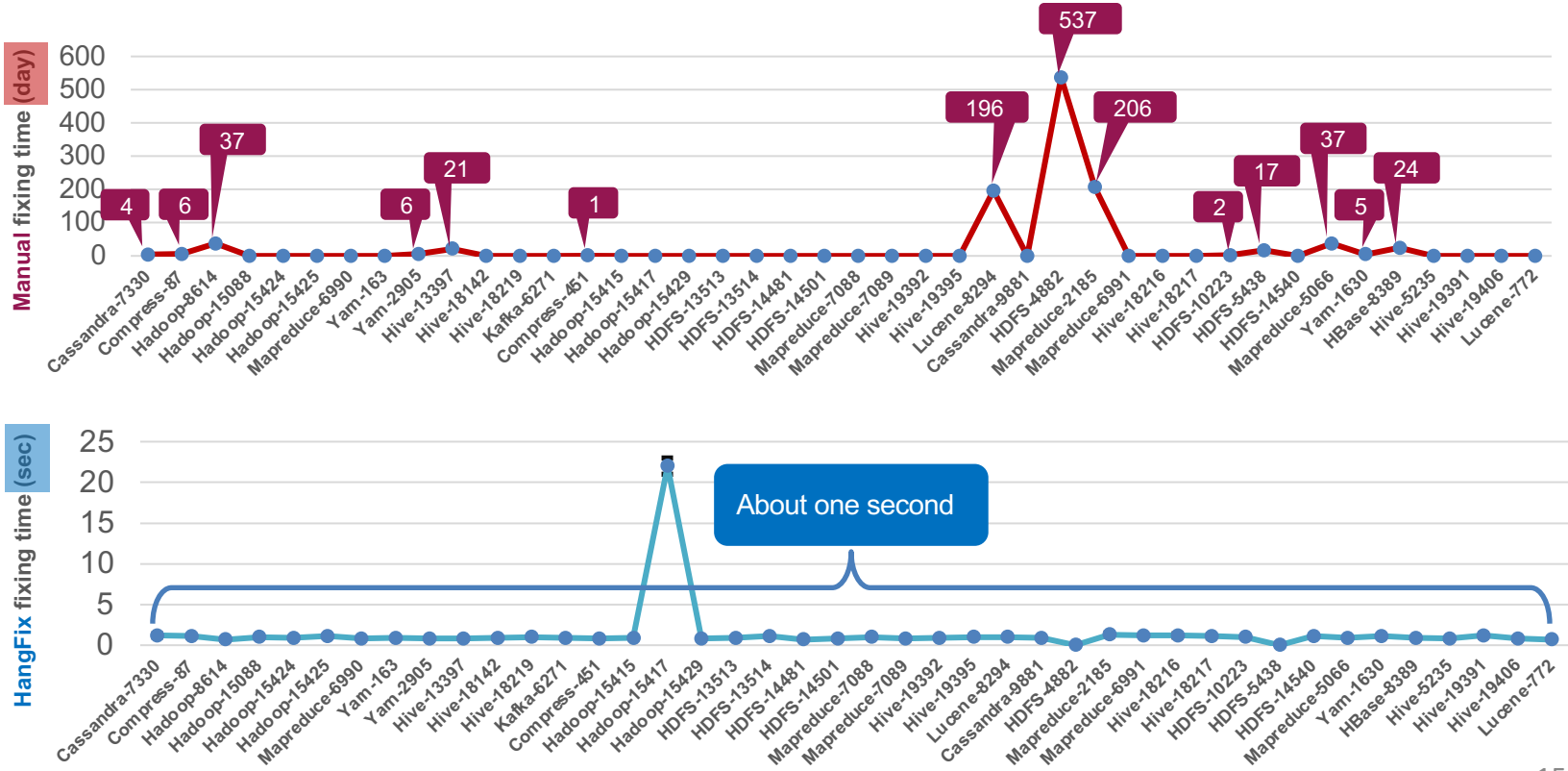
Hive-19406
Lucene-772
HangFix fixing time (sec)
25
20
15
10
5
0
Cassandra-7330
Compress-87
Hadoop-8614
Hadoop-15088
Hadoop-15424
Hadoop-15425
Mapreduce-6990
Yam-163
Yam-2905
Hive-13397
Hive-18142
Hive-18219
Kafka-6271
Compress-451
Hadoop-15415
Hadoop-15417
Hadoop-15429
HDFS-13513
HDFS-13514
HDFS-14481
HDFS-14501
Mapreduce-7088
Mapreduce-7089
Hive-19392
Hive-19395
Lucene-8294
Cassandra-9881
HDFS-4882
Mapreduce-2185
Mapreduce-6991
Hive-18216
Hive-18217
HDFS-10223
HDFS-5438
HDFS-14540
Mapreduce-5066
Yam-1630
HBase-8389
Hive-5235
Hive-19391
Hive-19406
Lucene-772

Fixing Time


Manual fixing time (day)
600
500
400
300
200
100
0
4
6
37
6
21
1
196
537
206
2
17
37
5
24
Cassandra-7330
Compress-87
Hadoop-8614
Hadoop-15088
Hadoop-15424
Hadoop-15425
Mapreduce-6990
Yam-163
Yam-2905
Hive-13397
Hive-18142
Hive-18219
Kafka-6271
Compress-451
Hadoop-15415
Hadoop-15417
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HDFS-13513
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Mapreduce-7088
Mapreduce-7089
Hive-19392
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HDFS-4882
Mapreduce-2185
Mapreduce-6991
Hive-18216
Hive-18217
HDFS-10223
HDFS-5438
HDFS-14540
Mapreduce-5066
Yam-1630
HBase-8389
Hive-5235
Hive-19391
Hive-19406
Lucene-772
HangFix fixing time (sec)
25
20
15
10
5
0
About one second
Cassandra-7330
Compress-87
Hadoop-8614
Hadoop-15088
Hadoop-15424
Hadoop-15425
Mapreduce-6990
Yam-163
Yam-2905
Hive-13397
Hive-18142
Hive-18219
Kafka-6271
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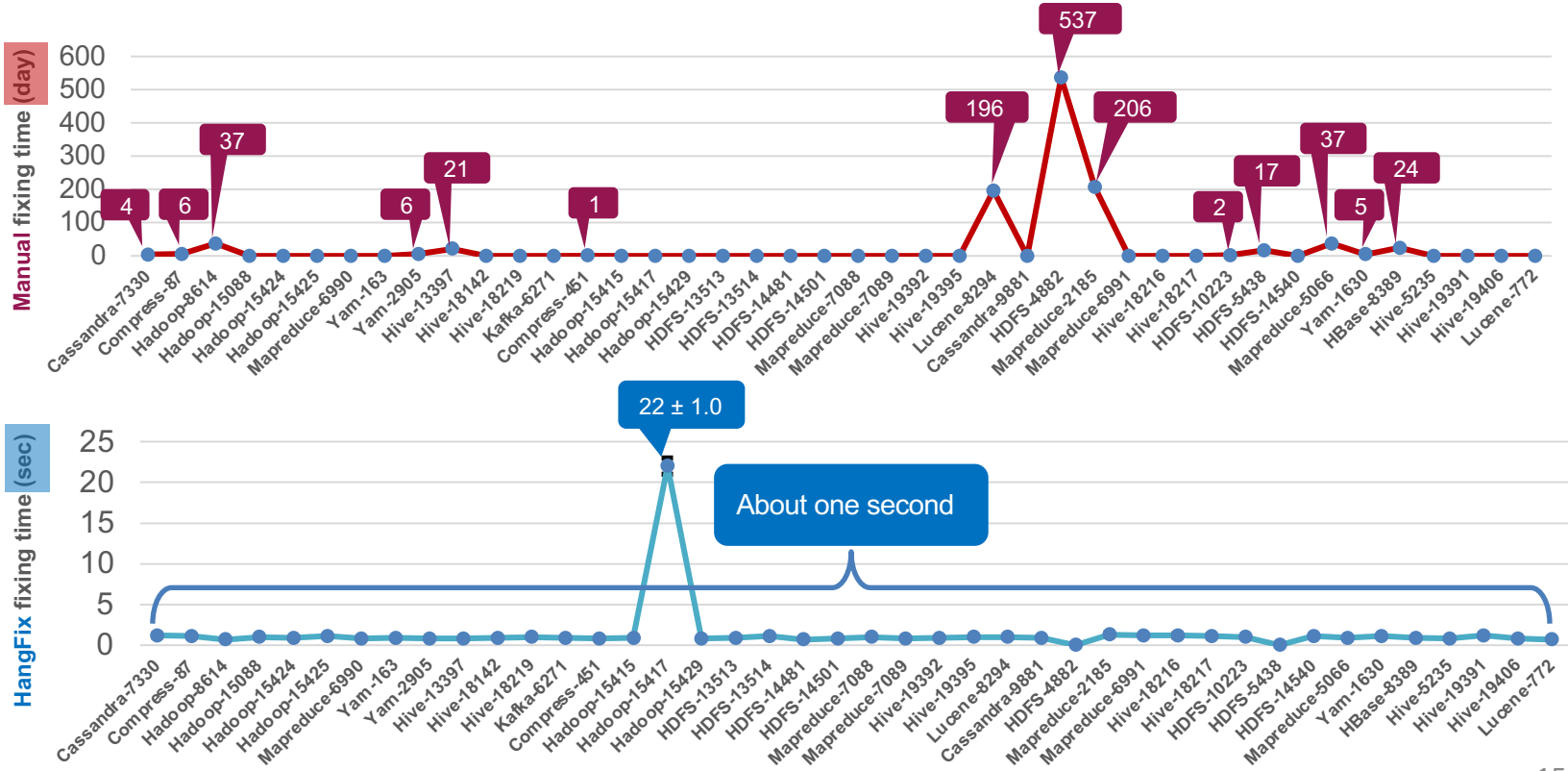
HDFS-5438
HDFS-14540
Mapreduce-5066
Yam-1630
HBase-8389
Hive-5235
Hive-19391
Hive-19406
Lucene-772

Fixing Time


Manual fixing time (day)
600
500
400
300
200
100
0
4
6
37
6
21
1
196
537
206
2
17
37
5
24
Cassandra-7330
Compress-87
Hadoop-8614
Hadoop-15088
Hadoop-15424
Hadoop-15425
Mapreduce-6990
Yam-163
Yam-2905
Hive-13397
Hive-18142
Hive-18219
Kafka-6271
Compress-451
Hadoop-15415
Hadoop-15417
Hadoop-15429
HDFS-13513
HDFS-13514
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HDFS-5438
HDFS-14540
Mapreduce-5066
Yam-1630
HBase-8389
Hive-5235
Hive-19391
Hive-19406
Lucene-772
HangFix fixing time (sec)
25
20
15
10
5
0
22 ± 1.0
About one second
Cassandra-7330
Compress-87
Hadoop-8614
Hadoop-15088
Hadoop-15424
Hadoop-15425
Mapreduce-6990
Yam-163
Yam-2905
Hive-13397
Hive-18142
Hive-18219
Kafka-6271
Compress-451
Hadoop-15415
Hadoop-15417
Hadoop-15429
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HDFS-13514
HDFS-14481
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Mapreduce-7088
Mapreduce-7089
Hive-19392
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HDFS-5438
HDFS-14540
Mapreduce-5066
Yam-1630
HBase-8389
Hive-5235
Hive-19391
Hive-19406
Lucene-772

Negative Case Example

HDFS-4882

```
393 private synchronized void checkLeases() {
      ...
395  for(; sortedLeases.size() > 0; ) {
396    final Lease oldest = sortedLeases.first();
       ...

412    if(fsnamesystem.internalReleaseLease(p, ...)) {
413      LOG.info("...");
414      removing.add(p); //remove p from sortedLeases

416    } else {
417      LOG.info("...");
418    }

       ...
429 }}
```

Negative Case Example

HDFS-4882

```
393 private synchronized void checkLeases() {
      ...
395  for(; sortedLeases.size() > 0; ) {
396    final Lease oldest = sortedLeases.first();
       ...

412    if(fsnamesystem.internalReleaseLease(p, ...)) {
413      LOG.info("...");
414      removing.add(p); //remove p from sortedLeases

416    } else {
417      LOG.info("...");
418    }

       ...
429 }}
```

A file associated with the lease path p is corrupted

Negative Case Example

HDFS-4882

```
393 private synchronized void checkLeases() {
      ...
395  for(; sortedLeases.size() > 0; ) {
396    final Lease oldest = sortedLeases.first();
       ...

412    if(fsnamesystem.internalReleaseLease(p, ...)) {
413      LOG.info("...");
414      removing.add(p); //remove p from sortedLeases

416    } else {
417      LOG.info("...");
418    }

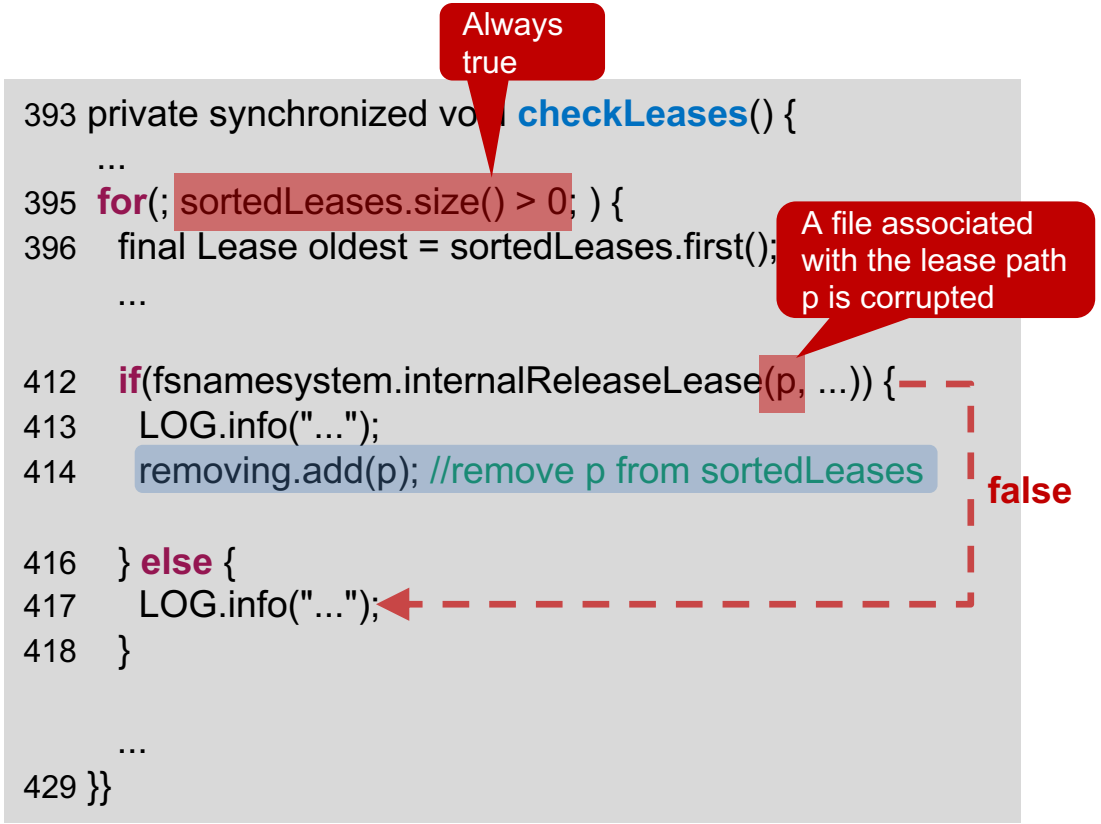
       ...
429 }}
```

A file associated with the lease path p is corrupted

false

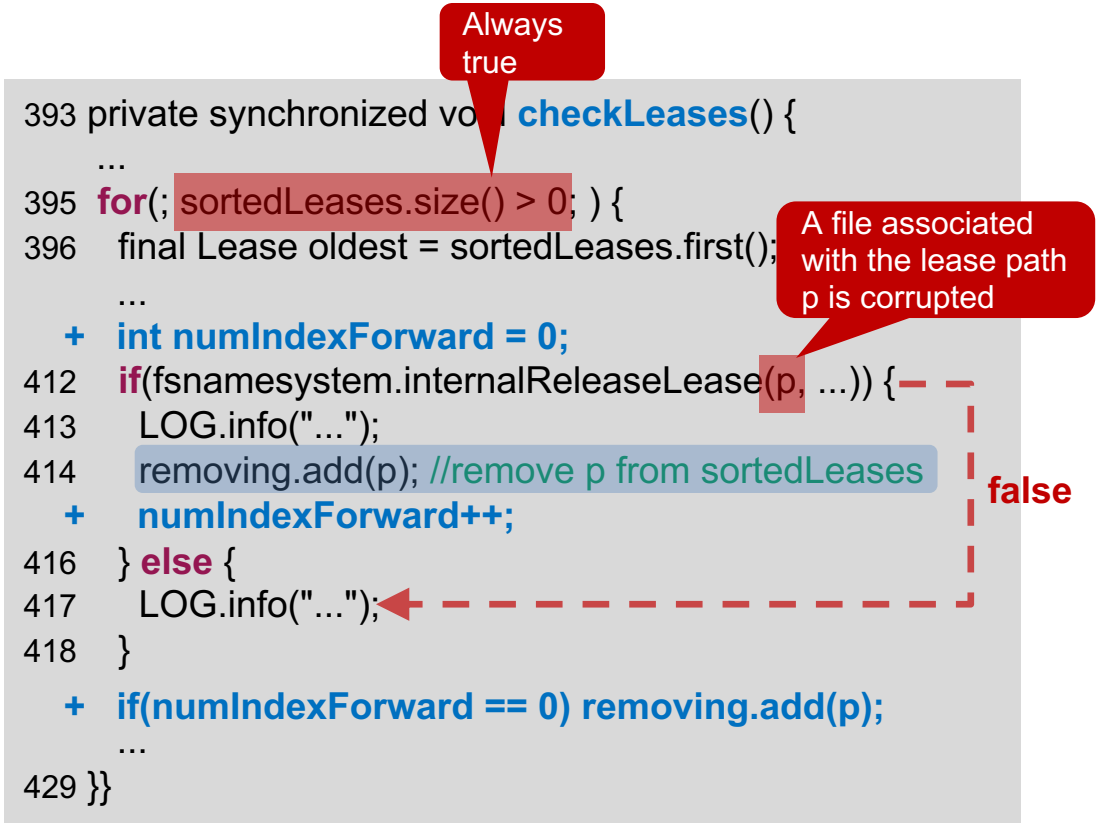
Negative Case Example

HDFS-4882



Negative Case Example

HDFS-4882



Negative Case Example

HDFS-4882

```
393 private synchronized void checkLeases() {
      ...
395  for(; sortedLeases.size() > 0; ) {
396    final Lease oldest = sortedLeases.first();
       ...
   +   int numIndexForward = 0;
412    if(fsnamesystem.internalReleaseLease(p, ...)) {
413      LOG.info("...");
414      removing.add(p); //remove p from sortedLeases
   +     numIndexForward++;
416    } else {
417      LOG.info("...");
418    }
   +   if(numIndexForward == 0) removing.add(p);
       ...
429 }}
```

Negative Case Example

Keep processing the same corrupted block

HDFS-4882

```
369  public void run() {
370   for(; fsnamesystem.isRunning(); ) {
        ...
374     checkLeases();
        ...
388  }}
```

```
393 private synchronized void checkLeases() {
      ...
395  for(; sortedLeases.size() > 0; ) {
396    final Lease oldest = sortedLeases.first();
       ...
   +   int numIndexForward = 0;
412    if(fsnamesystem.internalReleaseLease(p, ...)) {
413      LOG.info("...");
414      removing.add(p); //remove p from sortedLeases
   +     numIndexForward++;
416    } else {
417      LOG.info("...");
418    }
   +   if(numIndexForward == 0) removing.add(p);
       ...
429 }}
```

Negative Case Example

HDFS-4882

```
369  public void run() {
370   for(; fsnamesystem.isRunning(); ) {
        ...
374    checkLeases();
     +  fsnamesystem.getEditLog().logSync();
        ...
388  }}
```

Restore the corrupted block

```
393 private synchronized void checkLeases() {
      ...
395  for(; sortedLeases.size() > 0; ) {
396    final Lease oldest = sortedLeases.first();
       ...
     +  int numIndexForward = 0;
412    if(fsnamesystem.internalReleaseLease(p, ...)) {
413      LOG.info("...");
414      removing.add(p); //remove p from sortedLeases
     +    numIndexForward++;
416    } else {
417      LOG.info("...");
418    }
     +  if(numIndexForward == 0) removing.add(p);
       ...
429 }}
```

Keep processing the same corrupted block

Result Summary

- HangFix is an application-agnostic hang bug fixing tool.
  - Identifies hang bug patterns and produces software patches based on automatically generated patching strategies.
  - Evaluated on **42** real-world software hang bugs in 10 commonly used cloud server systems. HangFix successfully fixes **40** out of 42 hang bugs within **seconds**.

Conclusion

- **Hytrace**: a hybrid approach to generic performance bug diagnosis.
  - Combines offline static analysis and online dynamic bug inference.
  - Evaluated over **133** performance bugs on 9 cloud server systems.
  - Reduces FP functions & improve the rank of root-cause functions.

- **DScope**: an advanced data corruption hang bug detection tool.
  - Combines candidate bug discovery and false positive filtering.
  - Evaluated over 9 cloud server systems and detects **42** true data corruption hang bugs including **29** new bugs.

- **HangFix**: an application-agnostic hang bug fixing tool.
  - Identifies hang bug patterns and produces software patches based on automatically generated patching strategies.
  - Evaluated on **42** real-world software hang bugs in 10 commonly used cloud server systems. HangFix successfully fixes **40** out of 42 hang bugs within **seconds**.

Limitation & Future Work

- Supporting hybrid diagnosis on distributed performance bugs.
- Integrating inter-procedural analysis on DScope.
- Strengthening the fixing strategies on HangFix.

Thank you