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

Ting Dai[1], Jingzhu He[1], Xiaohui (Helen) Gu[1], Shan Lu[2], Peipei Wang[1]

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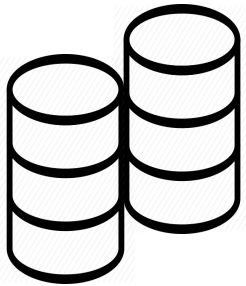
SOCC ACM Symposium on Cloud Computing

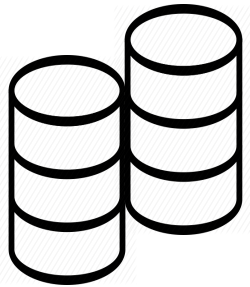
Real-World Data Corruption Problem

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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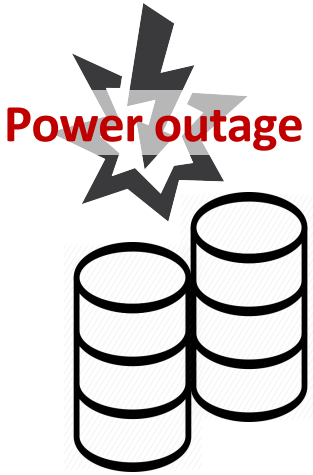

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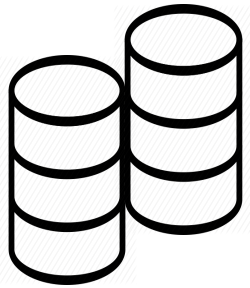

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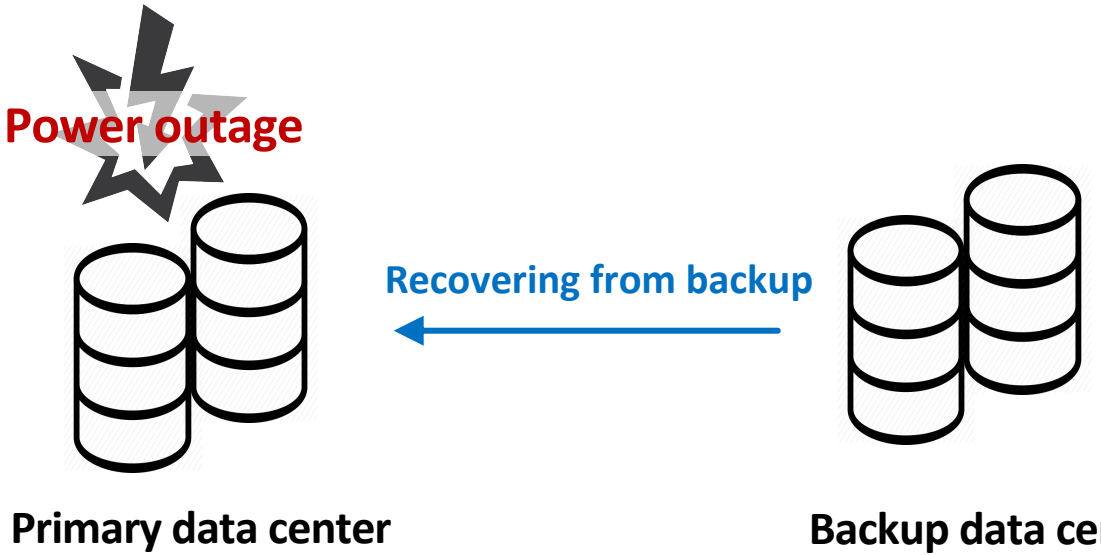

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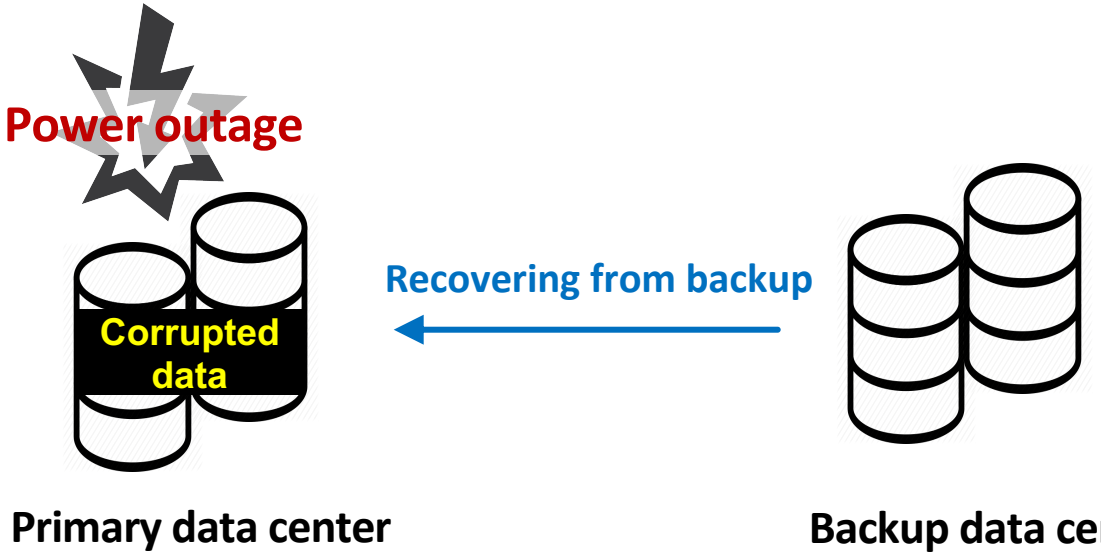

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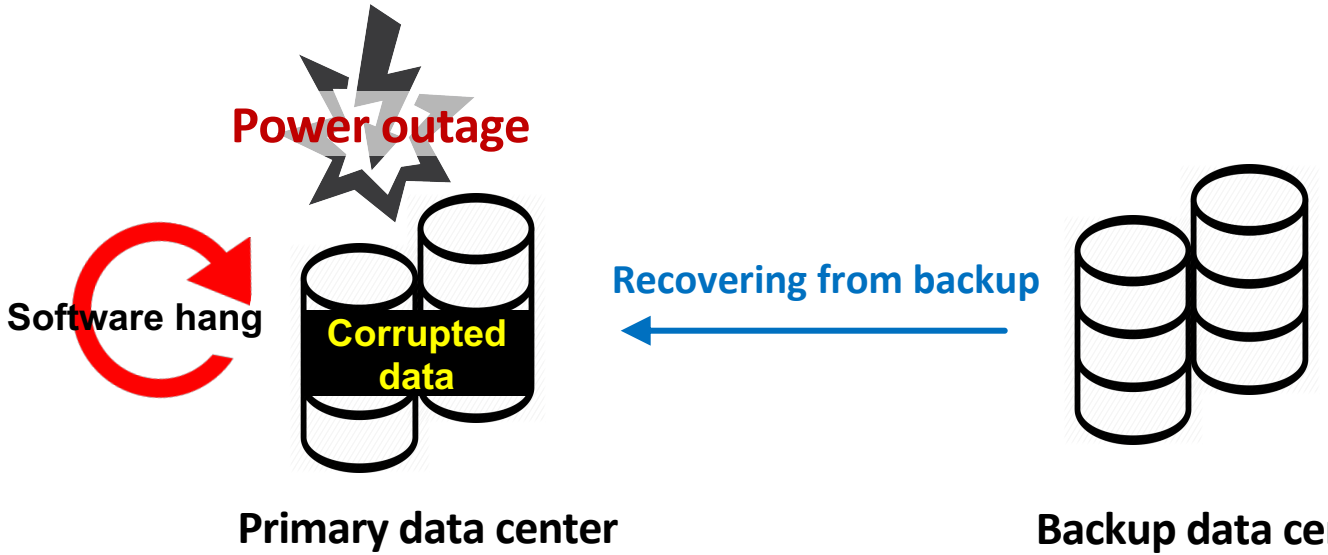

A Data Corruption Hang Bug Example

Hadoop-8614

```
183  public static void skipFully(
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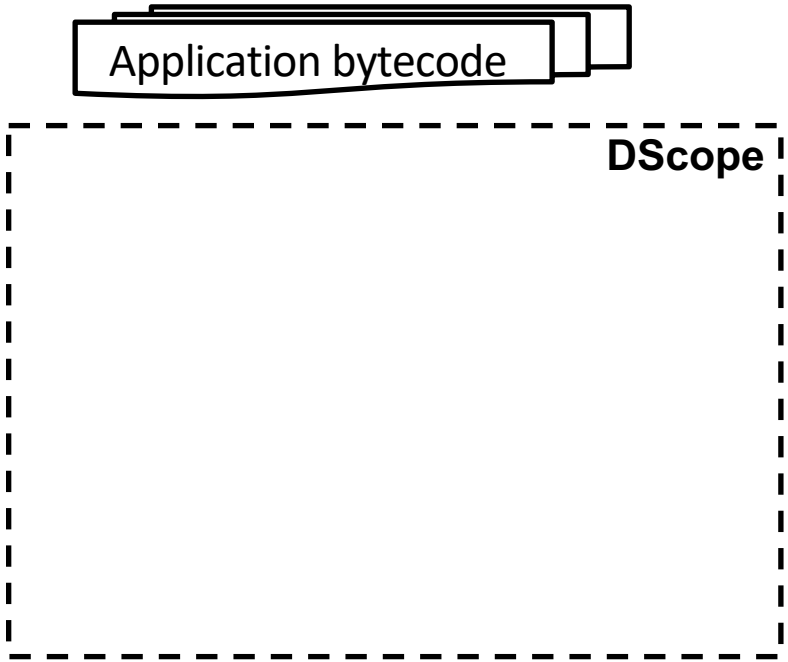

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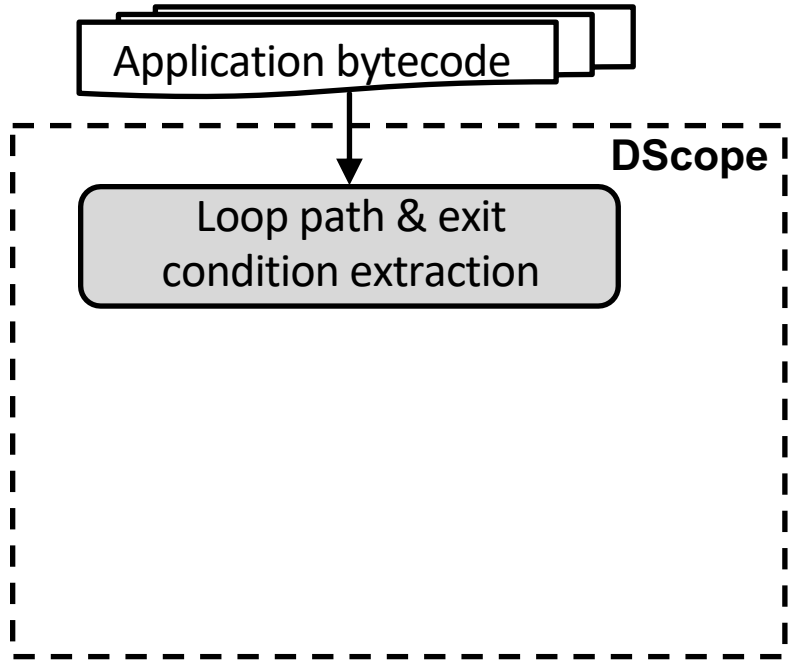

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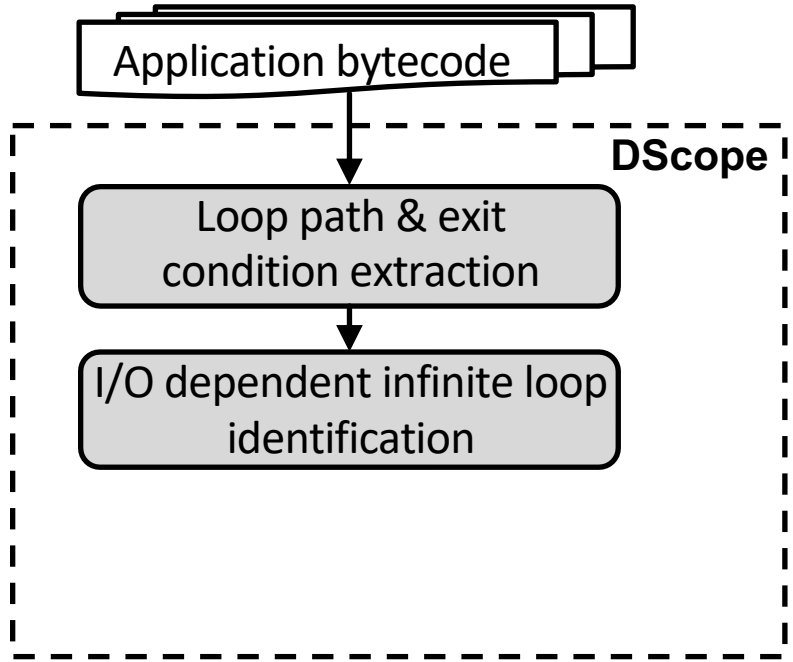

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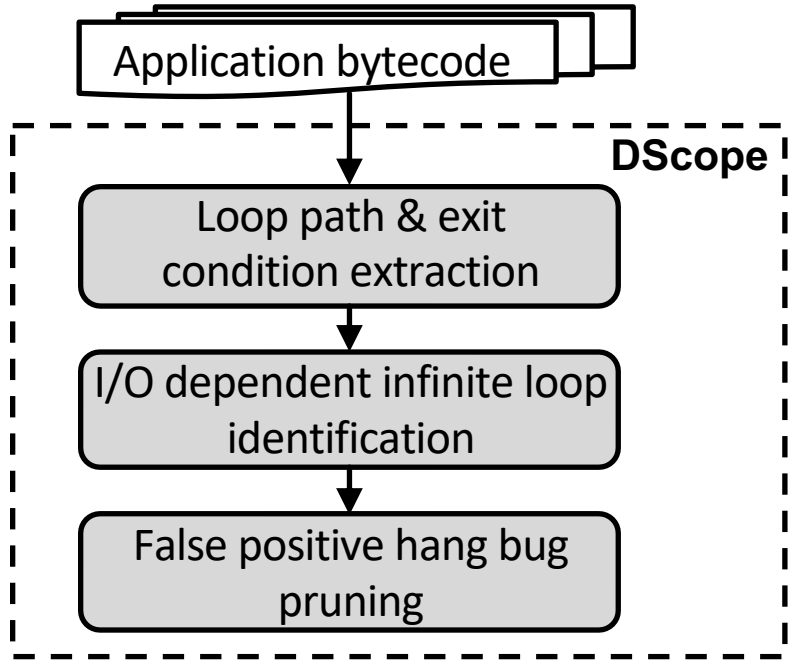

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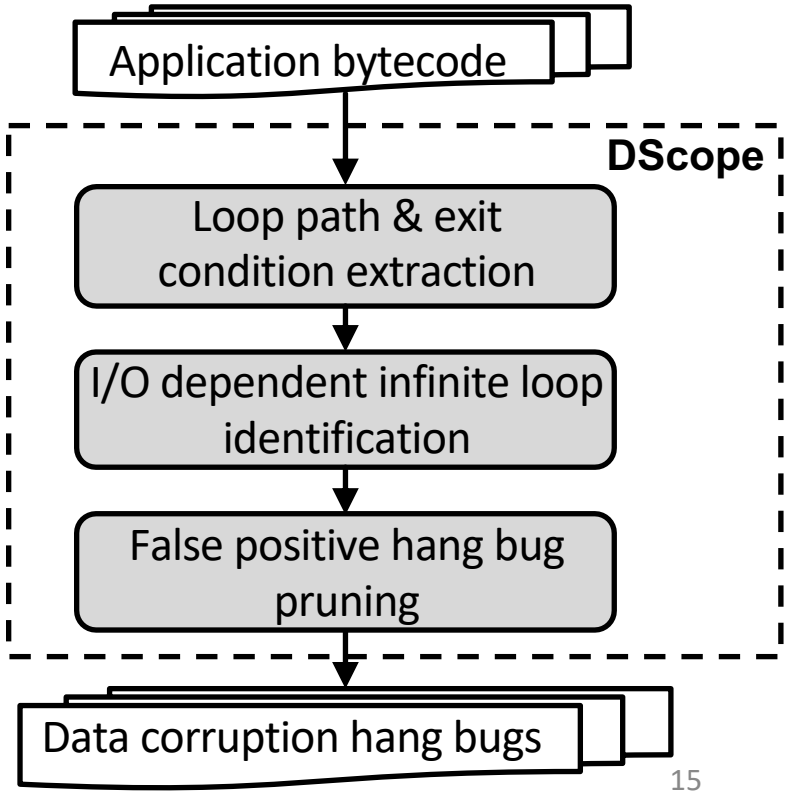

Loop Path & Exit Condition Extraction

- **Simple Loops**

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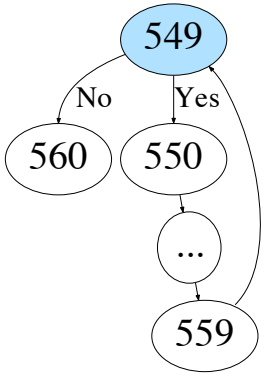
```
549   for ( int j = 0; j < length; j++)  {
550     String rack = racks[j] ;
        . . .
559   }
560
```



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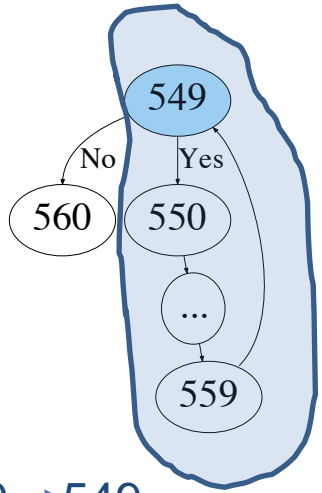

Loop path: 549→550→ … →559 →560 →549

Exit condition: j >= length

Loop Path & Exit Condition Extraction

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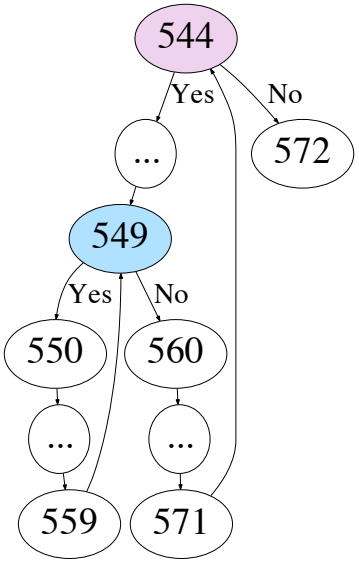

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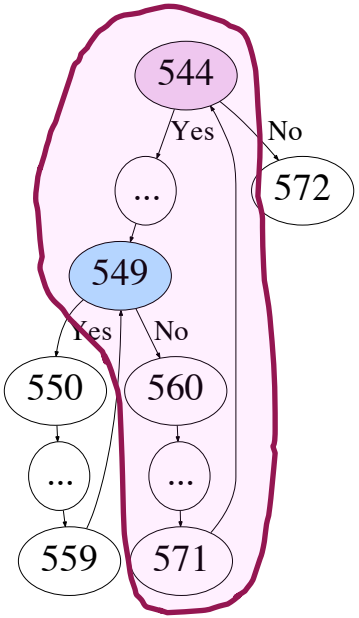

Loop paths:

Outer: 544 → … → 549 → 560 → … → 571 → 544

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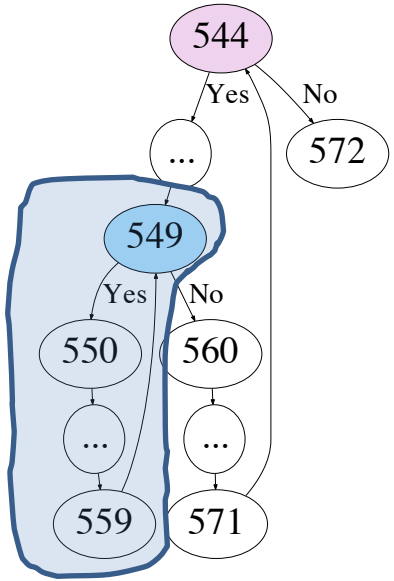

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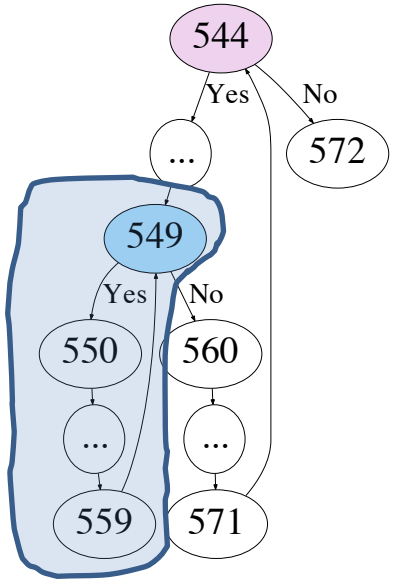

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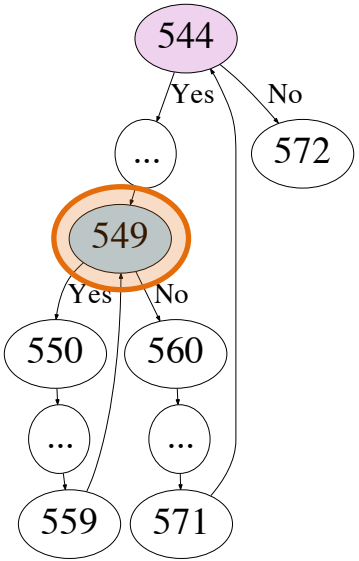

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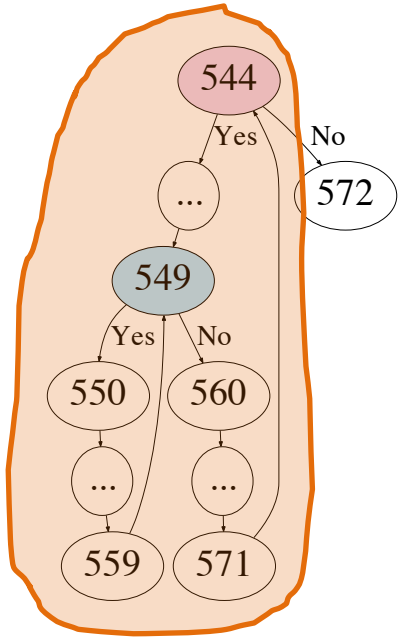

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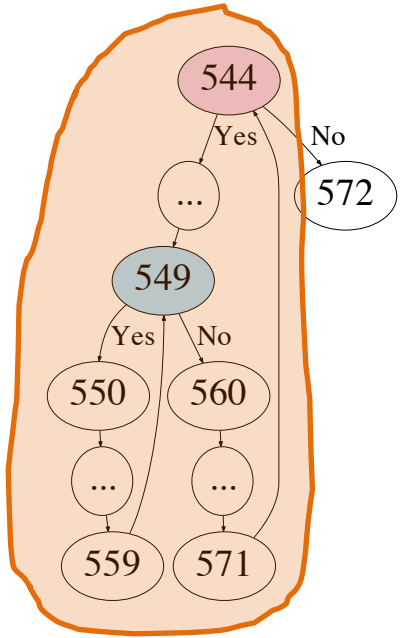

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DScope then extracts the exit conditions for each loop path.

Loop Path & Exit Condition Extraction

- **Loops with exception handling**

```
120  while (!dataFile.isEOF()) {
       …
129    try {
130      key = decorateKey(…dataFile);
         …
139    } catch (Throwable th) {
140      //ignore exception
141    }
       …
185    try {
186      if (key == null)
187        throw new IOError(…);
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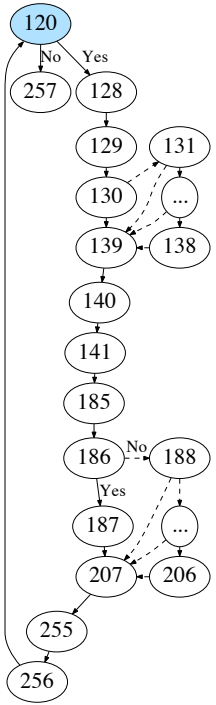

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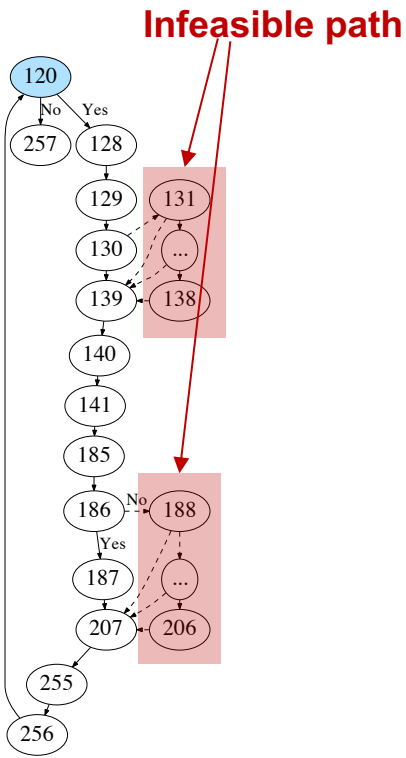

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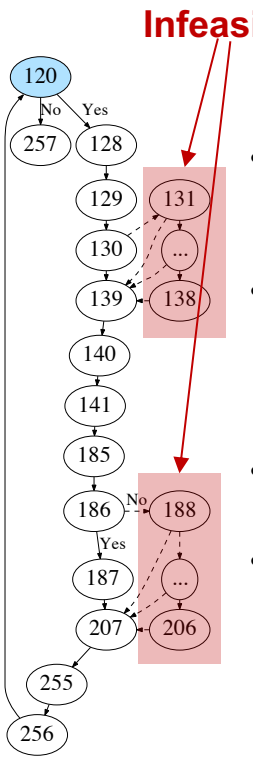

- Group invocation statements based on arguments.
- All the statements in the same group throw exceptions when their arguments get corrupted.
- Remove infeasible loop paths.
- Extract exit conditions of the feasible loop paths.

I/O Dependent Infinite Loop Identification

- **Exit conditions directly depend on I/O operations**

```
//Soot IR
198  $i1 = r0.<InputStream: read()>(r2) //$i1 is an I/O related variable
199   if $i1 == -1 goto line #203          //``$i1 == -1" is the exit condition
        ...
202   goto line #198
```

I/O Dependent Infinite Loop Identification

- **Exit conditions indirectly depend on I/O operations**

```
//Soot IR
 3  if l8 >= l0 goto line #12 //``l8 >= l0'' is the exit condition
    ...
 5  $l2 = l0 - l8
 6  $l4 = $r2.<InputStream: skip>($l2) //$l4 is an I/O related variable
 7  $b5 = $l4 cmp 0L
 8  if $b5 == 0 goto line #12 //``$b5 == 0'' is the exit condition
 9  $l7 = $l8 + $l4
10  i8 = $l7
11  goto line #3
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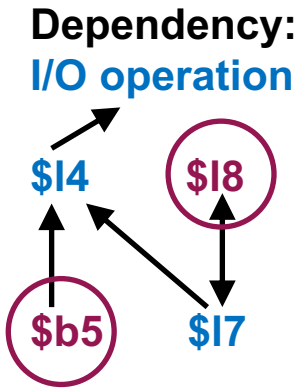

I/O Dependent Infinite Loop Identification

- **Exit conditions depend on complex I/O related variables**
  - DScope performs an integrated analysis by linking variable information from IR code, Java source code, and Java bytecode.
  - User annotated I/O variables.

False Positive Filtering

Hadoop v2.5.0 WritableUtils.java

```
307  public static long readVLong(DataInput stream)…{
308      byte firstByte = stream.readByte();
309      int len = decodeVIntSize(firstByte);
          …
314      for (int idx = 0; idx < len-1; idx++) {
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     }  }
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It's a FP because the loop stride is always 1 and the upper bound (len-1) is fixed.

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It's a FP because the loop stride is always 1 and the upper bound (len-1) is fixed.

len is I/O dependent

- **False positive condition**:
  - The loop stride is always **positive** when the loop index has a fixed **upper** bound;
  - The loop stride is always **negative** when the loop index has a fixed **lower** bound.

Loop Stride and Bound Inference

Loop Stride and Bound Inference

- **Stride and bounds are denoted by**
  - **Numeric primitives**

```
for (int idx = 0; idx < len-1; idx++) {
    …
 }
```

Bound (len-1)

Stride (1)

Loop Stride and Bound Inference

- **Stride and bounds are denoted by**
  - **APIs in 60 commonly used Java classes**
    Forward index Reverse index Check bounds
    Reset index Update bounds

Loop Stride and Bound Inference

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```
RandomAccessReader dataFile;

while (!dataFile.isEOF()) {
    …
    dataSize = dataFile.readLong();
}
```

Bound checking

Stride forwarding

Evaluation

System	Description	# of bugs
Cassandra	Distributed database management system	2
Compress	Libraries for I/O ops on compressed file	2
Hadoop Common	Hadoop utilities and libraries	10
Mapreduce	Hadoop big data processing framework	5
HDFS	Hadoop distributed file system	4
Yarn	Hadoop resource management platform	4
Hive	Data warehouse	12
Kafka	Distributed streaming platform	1
Lucene	Indexing and search server	2

- **Implemented a prototype of DScope using Soot;**
- **State-of-the-art static bug detectors**:
  - **Findbugs**
  - **Infer**

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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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	-
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Data Corruption Hang Bug Types

- Type 1: Error codes returned by I/O operations directly affect loop strides.
- Type 2: Corrupted data content indirectly affects loop strides.
- Type 3: Improper exception handling directly affects loop strides.
- Type 4: Improper exception handling indirectly affects loop strides.

Data Corruption Hang Bug Types

- **Type 1: Error codes returned by I/O operations directly affect loop strides.**

Hadoop-8614

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

0

The loop stride (ret) is always 0 when in is corrupted.

Data Corruption Hang Bug Types

- **Type 2: Corrupted data content indirectly affects loop strides.**

HDFS-13514

```
194 BUFFER_SIZE = conf.getInt();
```

```
78   private void readLocalFile(Path path, ...) … {
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84     byte[] data = new byte[BUFFER_SIZE];
85     long size = 0;
86     while (size >= 0) {
87       size = in.read(data);
     } }
```

Data Corruption Hang Bug Types

- **Type 2: Corrupted data content indirectly affects loop strides.**

HDFS-13514

```
194 BUFFER_SIZE = conf.getInt(); Corrupted configuration file
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        } }
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0

empty array

The loop stride (size) is always 0 when conducting read op on an empty array.

False Negative Example

The loop index, stride or bounds are **only** related to specific application I/O functions.

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HDFS-5438

```
1668   while (!fileComplete) {
1669       fileComplete = dfsClient.namenode.complete(src,
                                dfsClient.clientName, last);
           ...
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Corrupted block

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HDFS-5438

Application function

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Corrupted block

False Positive Example

Hadoop v2.5 BlockReaderLocal.java

```
472  private int readWithBounceBuffer(
                          ByteBuffer buf…) …{
481     do {
          …
502       bb = drainDataBuf(buf);
512     } while (buf.remaining() > 0);
          …
514  }
```

Check bounds

```
277 private int drainDataBuf(
                  ByteBuffer buf) {
          …
286     buf.put(dataBuf);
          …
291 }
```

Forward index

False Positive Example

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Forward index

- **The forwarding-index Java APIs and the checking-bounds Java APIs are located in different application function.**

Conclusion

- 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.

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Thank you