Testing and Verifying Atomicity of Composed Concurrent Operations

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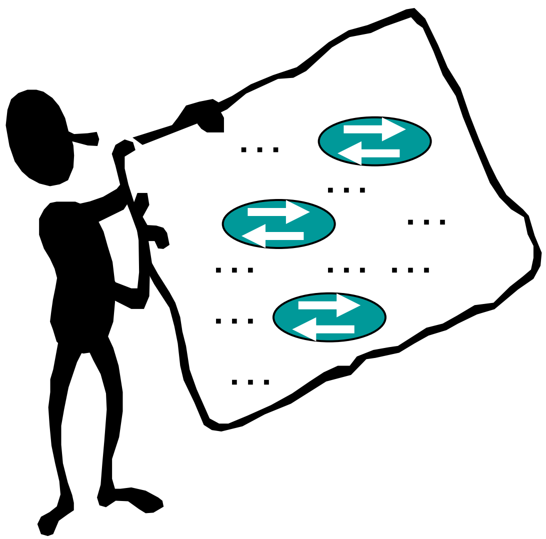
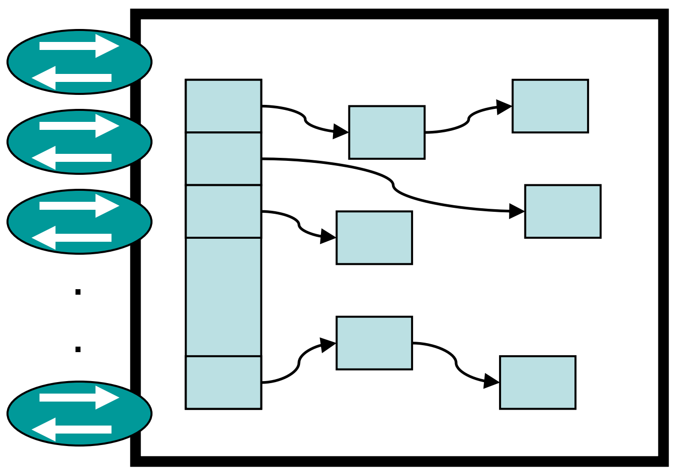
Specifying and Verifying Software Composition

- Efficient libraries are widely available
- Composing software in a way which guarantee correctness:
  - Specification
  - Verification
  - Synthesis
  - Performance

Concurrent Data Structures

- Writing highly concurrent data structures is complicated
- Modern programming languages provide efficient concurrent collections with atomic operations





TOMCAT Motivating Example

TOMCAT 5.* / 6.*

```
attr = new HashMap();
attr = new ConcurrentHashMap();
...
Attribute removeAttribute(String name){
  Attribute val = null;
   synchronized(attr) {
   /* synchronized(attr) { */
     found = attr.containsKey(name) ;
     if (found) {
       val = attr.get(name);
       attr.remove(name);
     }
   }
   /* } */
   return val;
}
```

Invariant: removeAttribute(name) returns the removed value or null if it does not exist

```
removeAttribute(“A”)  {
  Attribute val = null;
```

attr.put(“A”, o);

```
found = attr.containsKey(“A”) ;
    if (found) {
  val = attr.get(“A”);
```

attr.remove(“A”);

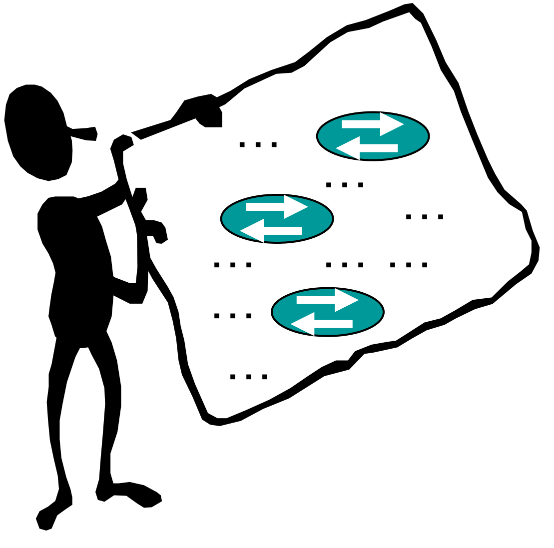
```
  attr.remove(“A”);
    }
  return val;
```

o

☒ *Invariant: removeAttribute(name) returns the removed value or null if it does not exist*

Challenge

Testing and Verifying the atomicity of composed operations



Challenges in Testing

- Specifying software correctness
- Bugs occur in rarely executed traces
  - Especially true in concurrent systems
- Scalability of dynamic checking
  - large traces
- Hard to find programs to test

Challenges in Verification

- Specifying software correctness
- Many sources of unboundedness
  - Data
    - Integers
    - Stack
    - Heap
    - …
  - Interleavings
- Scalability of static checking
  - Large programs
- Hard to find programs to verify

Testing atomicity of composed operations

OOPSLA’11

Challenge 1: Long traces

- Assume that composed operations are written inside encapsulated methods
- Modular testing
  - Unit testing in all contexts
  - Composed operations need to be correct in all contexts
- May lead to false warnings

False Warning

```
if (m.contains(k))
    return m.get(k);
else
    return k;
```

```
m.remove(k);
```

- False warning in clients without remove
- Sometimes indicate “future bugs”

Challenge 2: Specification

- Check that composed operations are Linearizable [Herlihy & Wing, TOPLAS'90]
  - Returns the same result as some sequential run

Linearizability

```
removeAttribute("A")  {
   Attribute val = null;
```

```
attr.put("A", o);        null
```

```
found = attr.containsKey("A") ;
   if (found) {
   val = attr.get("A");
```

```
attr.remove("A");        o
```

```
   attr.remove("A");
   }
   return val;           o
```

```
attr.put("A", o);        null
attr.remove("A");        o
removeAttribute("A")  {
   Attribute val = null;
found = attr.containsKey("A") ;
   if (found) {
   return val;           null
```

```
removeAttribute("A")  {
   Attribute val = null;
found = attr.containsKey("A") ;
   if (found) {
   return val;           null
attr.put("A", o);        null
attr.remove("A");        o
```

```
attr.put("A", o);        null
removeAttribute("A")  {
   Attribute val = null;
found = attr.containsKey("A") ;
   if (found) {
   val = attr.get("A");
   attr.remove("A");
   }
   return val;           o
attr.remove("A");        null
```

But Linearizability errors only occur in rarely executed paths

```
removeAttribute(“A”)  {
  Attribute val = null;
```

attr.put(“A”, o);

```
found = attr.containsKey(“A”) ;
        if (found) {
    val = attr.get(“A”);
```

attr.remove(“A”);

```
    attr.remove(“A”);
        }
      return val;
```

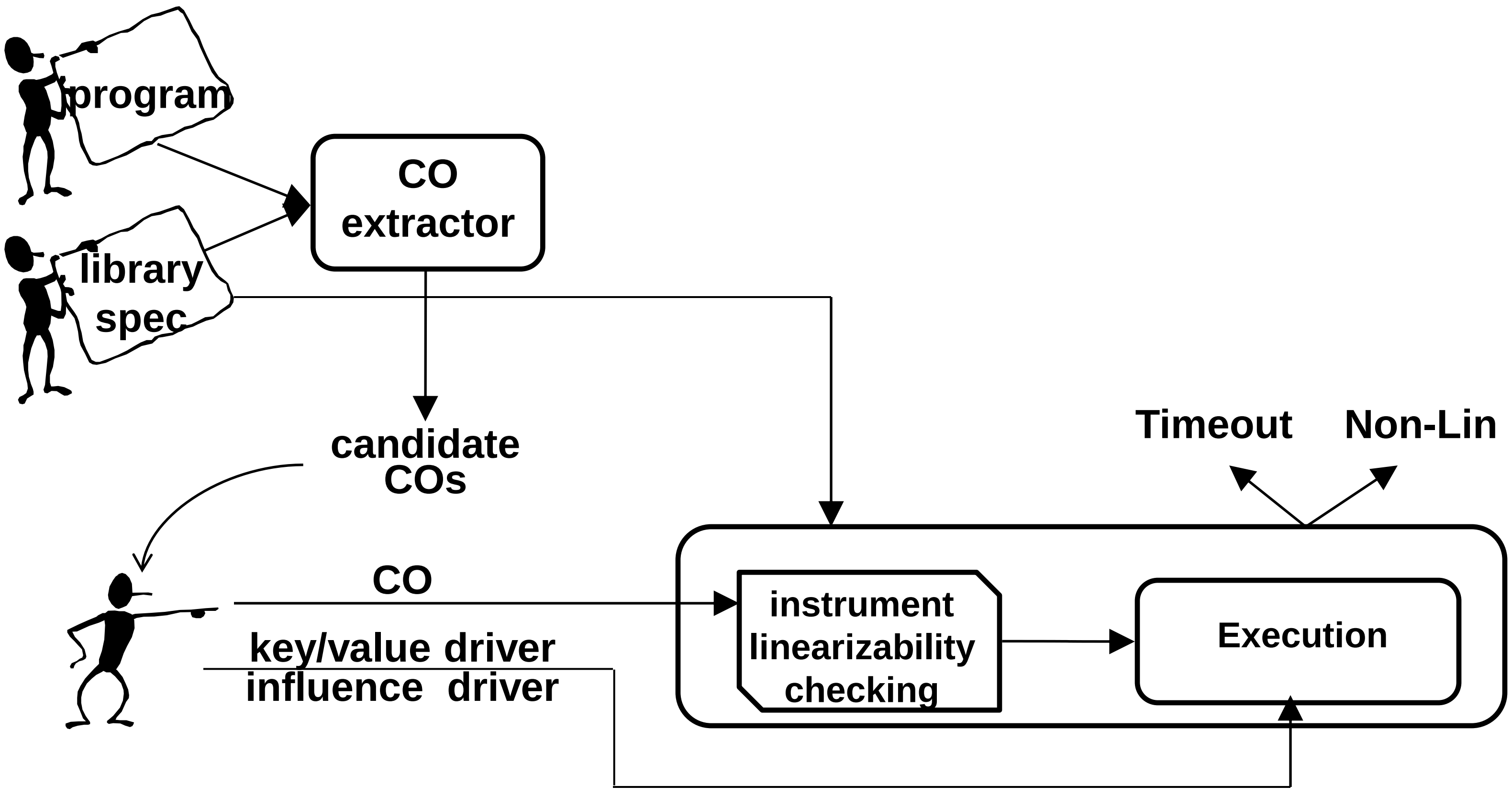
Linearizability errors only occur in rarely executed paths

- Only consider "atomic" executions of base collection operations [TACAS'10, Ball et. al.]
- Employ commutativity/influence of base collection operations
  - Operations on different key commute
  - Partial order reduction using the collection interface

Influence table

Operation	**Condition**	**Potential Action**
get(k)	get(k) == null	put(k,*)
get(k)	get(k) != null	remove(k)
containsKey(k)	get(k) == null	put(k,*)
containsKey(k)	get(k) != null	remove(k)
remove(k)	get(k) == null	put(k,*)
remove(k)	get(k) != null	remove(k)

COLT Tester


program
library
spec
CO
extractor
candidate
COs
CO
key/value driver
influence driver
Timeout
Non-Lin
instrument
linearizability
checking
Execution

```
Attribute removeAttribute(String name){
   Attribute val = null;
   found = attr.containsKey(name) ;
   if (found) {
      val = attr.get(name);
      attr.remove(name);
   }
   return val;
}
```

---

removeAttribute(“A”) {
Attribute val = null;

attr.put(“A”, o); null

found = attr.containsKey(“A”) ;
if (found) {
val = attr.get(“A”);

attr.remove(“A”); o

attr.remove(“A”);
}
return val; o

```
removeAttribute("A")  {
  Attribute val = null;
```

```
attr.put("A", o);        null
```

```
found = attr.containsKey("A") ;
  if (found) {
    val = attr.get("A");
```

```
attr.remove("A");        o
```

```
    attr.remove("A");
  }
  return val;        o
```

```
attr.put("A", o);        null
attr.remove("A");        o
removeAttribute("A")  {
  Attribute val = null;
found = attr.containsKey("A") ;
  if (found) {
  return val;        null
```

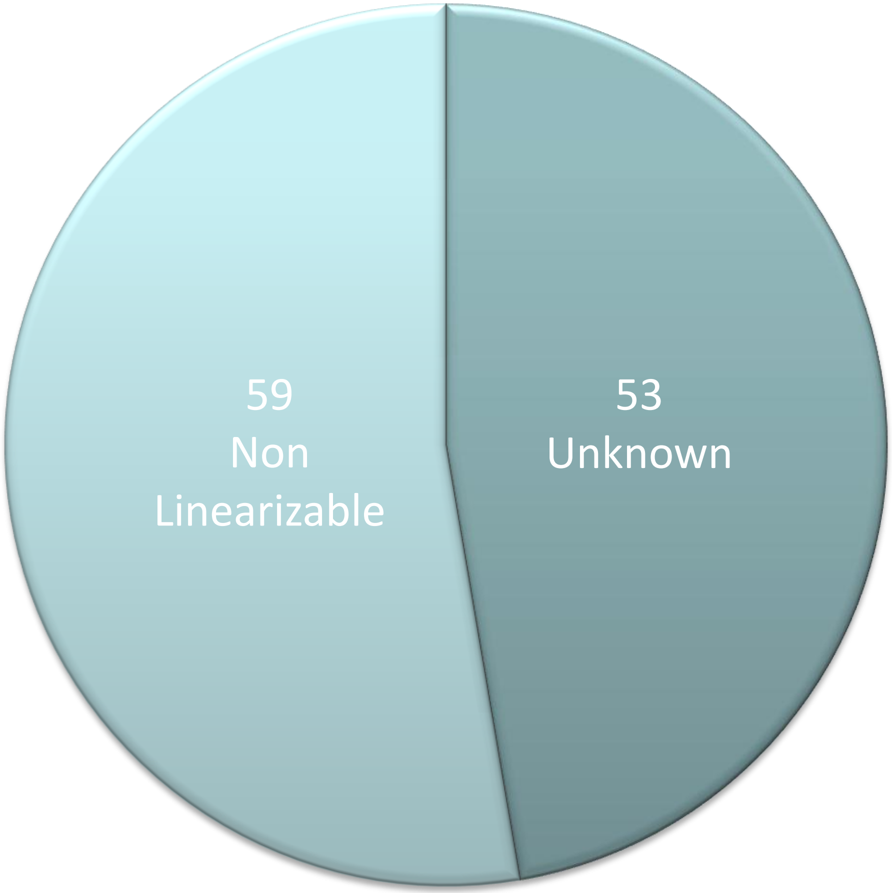
```
removeAttribute("A")  {
  Attribute val = null;
found = attr.containsKey("A") ;
  if (found) {
  return val;        null
attr.put("A", o);        null
attr.remove("A");        o
```

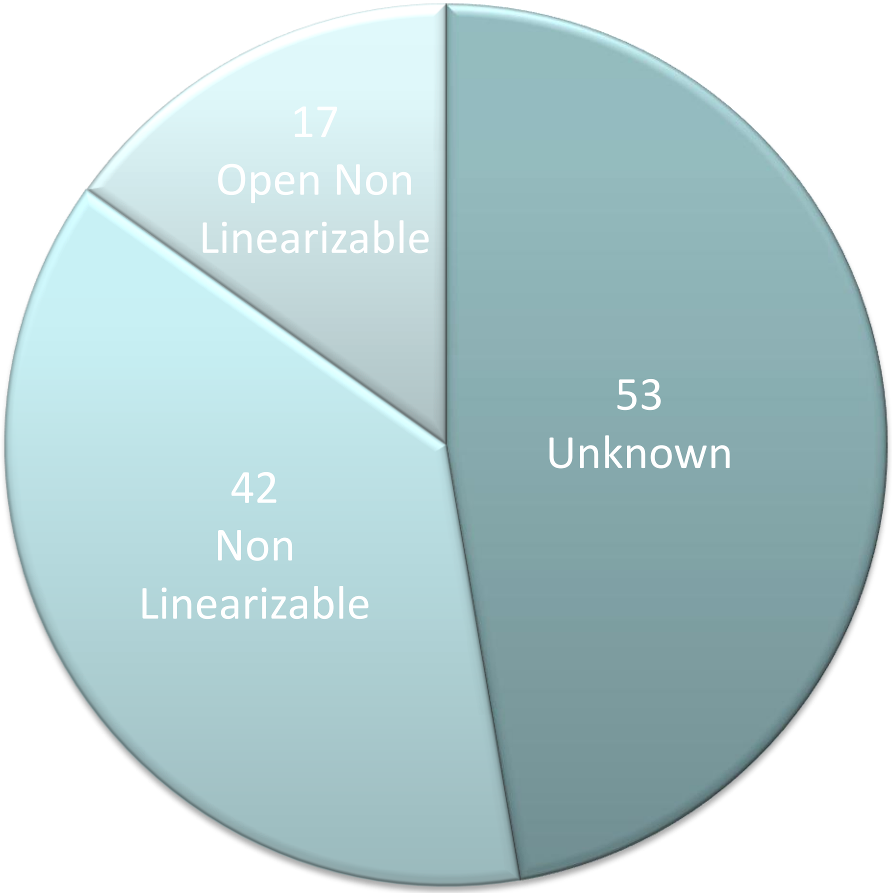
```
attr.put("A", o);        null
removeAttribute("A")  {
  Attribute val = null;
found = attr.containsKey("A") ;
  if (found) {
  val = attr.get("A");
  attr.remove("A");
  }
  return val;        o
attr.remove("A");        null
```

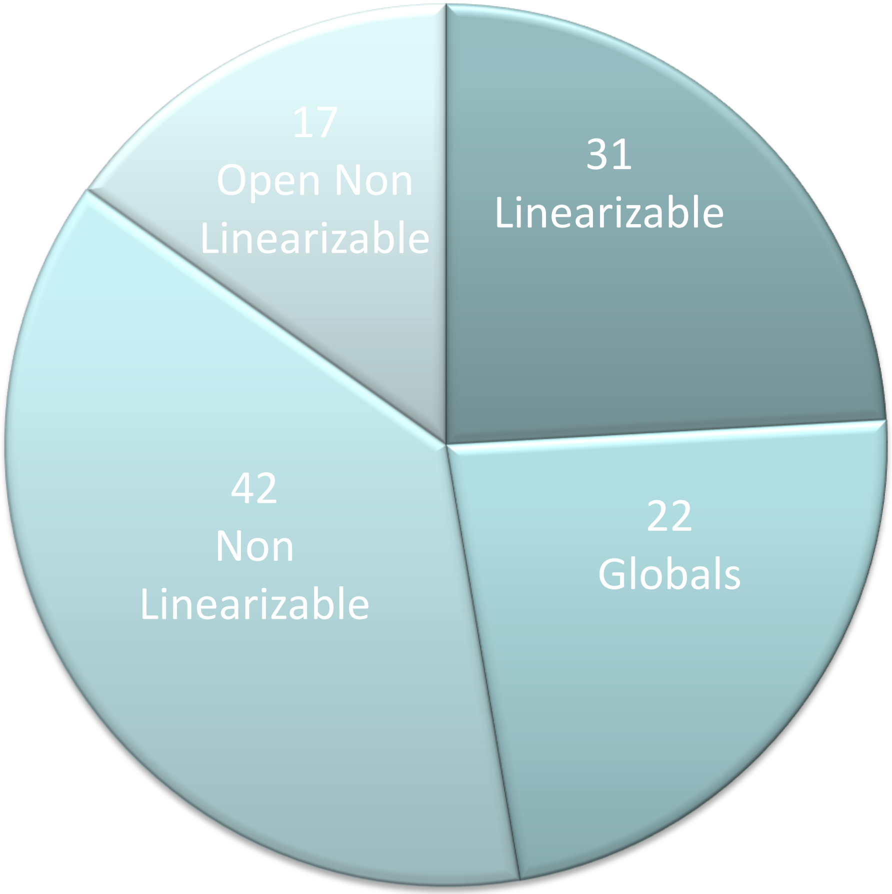
Evaluation

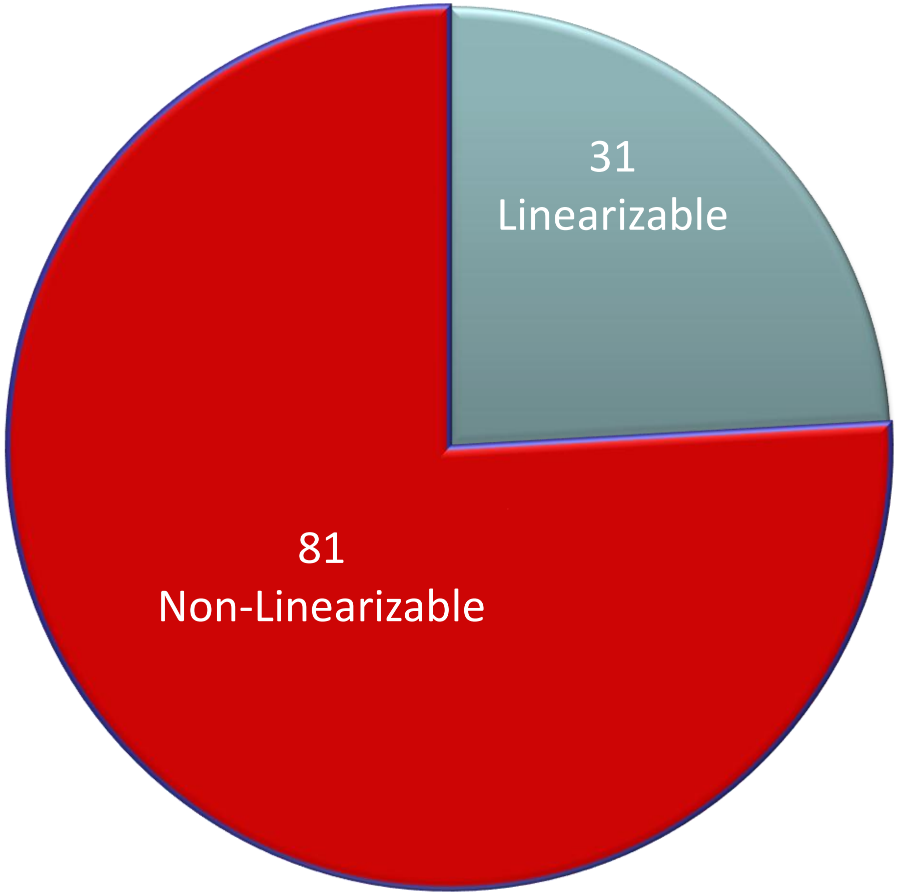
- Use Google code search and Koders to search for collection operations methods with at least two operations
- Used simple static analysis to extract composed operations
  - 29% needed manual modification
- Check Linearizability of **all** public domain composed operations
- Extracted **112** composed operations from **55** applications
  - Apache Tomcat, Cassandra, MyFaces – Trinidad, …
- Each run took less than a second
- Without influence timeout always occur


112
Unknown


59
Non
Linearizable
53
Unknown


17
Open Non
Linearizable
53
Unknown
42
Non
Linearizable


31
Linearizable
22
Globals
42
Non
Linearizable
17
Open Non
Linearizable


31
Linearizable
81
Non-Linearizable

Results

- Reported the bugs with fixes
- Even bugs in open environment
- As a result of the paper the Java library is being changed

"A preliminary version is in the pre-java8 "jsr166e" package as ConcurrentHashMapV8. We can't release the actual version yet because it relies on Java8 lambda (closure) syntax support. See links from http://gee.cs.oswego.edu/dl/concurrency-interest/index.html including: http://gee.cs.oswego.edu/dl/jsr166/dist/jsr166edocs/jsr166e/ConcurrentHashMapV8.html

Good luck continuing to find errors and misuses that can help us create better concurrency components!"

Verifying atomicity of composed operations

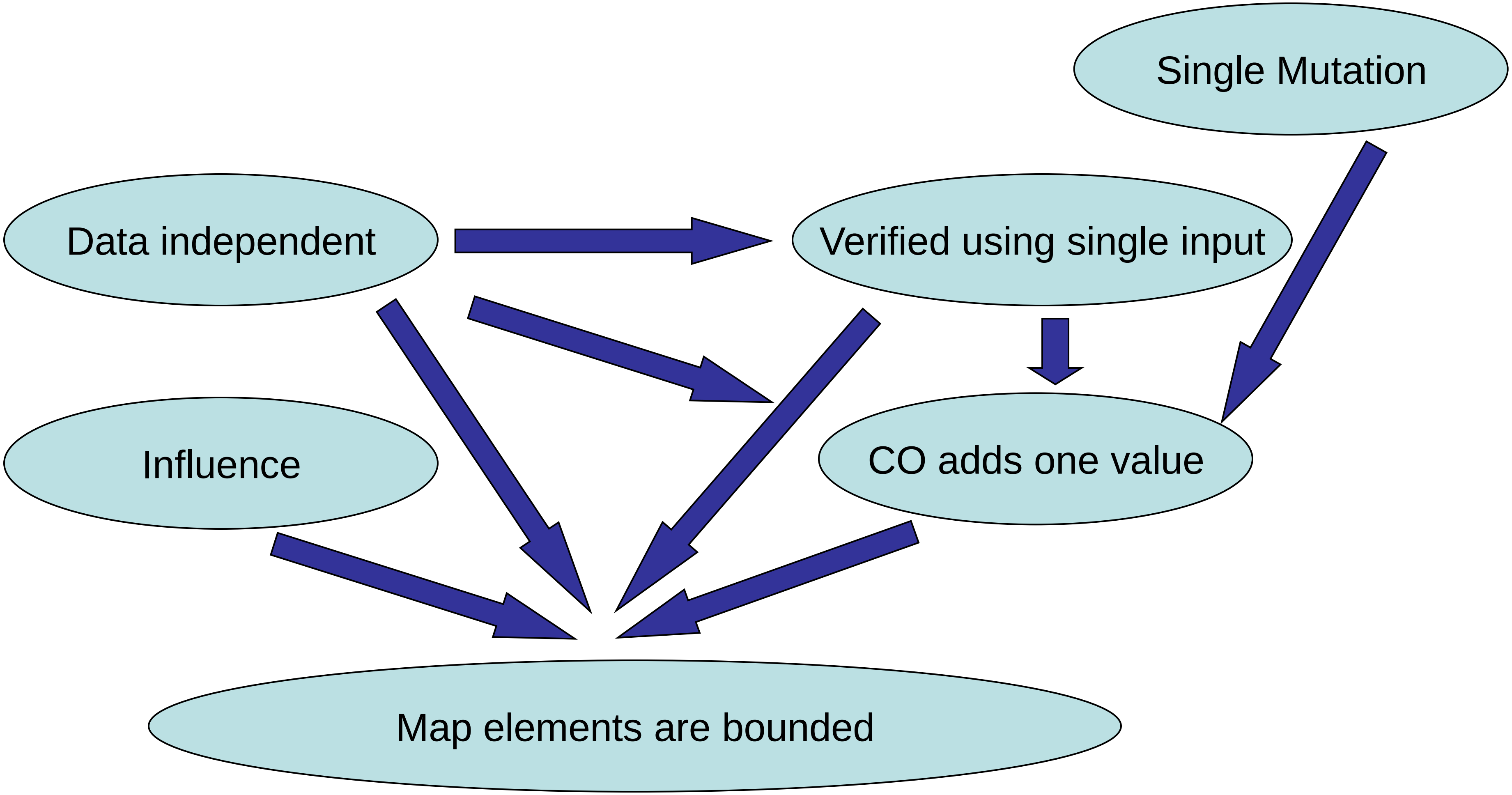
Motivation

- Unbounded number of potential composed operations
  - There exists no “thick” interface
- Automatically prove Linearizability for composed operations beyond the ones provided
  - Already supports the existing interface
  - No higher order functions
- Zero false alarms
  - beyond modularity

Data independent [Wolper, POPL'86]

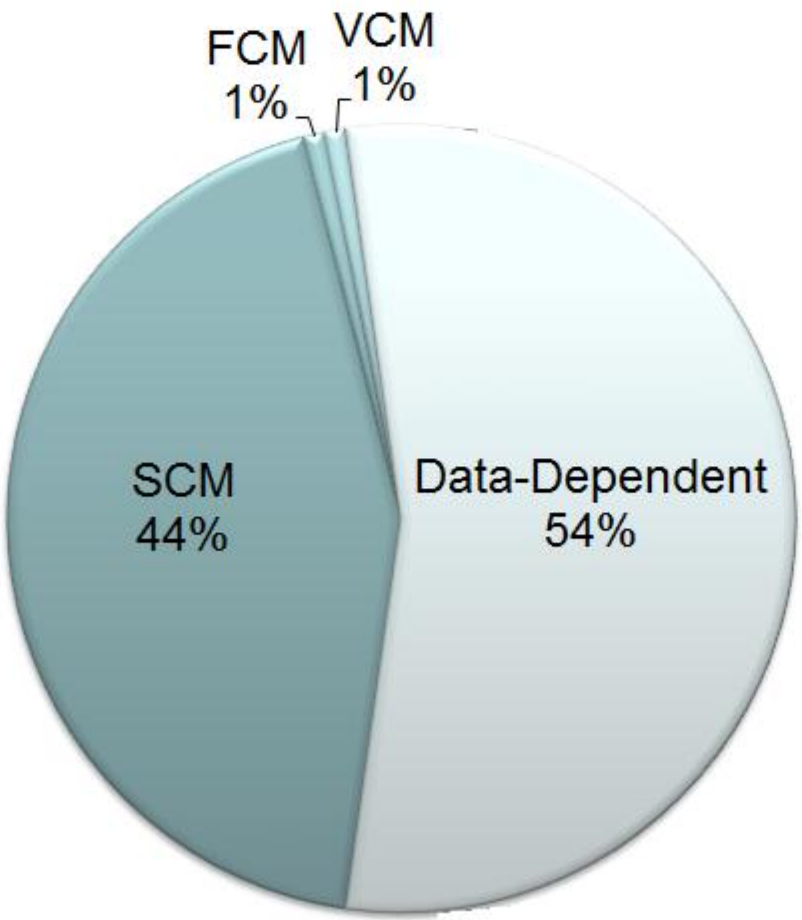
```
Attribute removeAttribute(String name){
   Attribute val = null;
   found = attr.containsKey(name) ;
   if (found) {
     val = attr.get(name);
     attr.remove(name);
   }
   return val;
}
```

Verifying data independent operations using Linearization points in the code

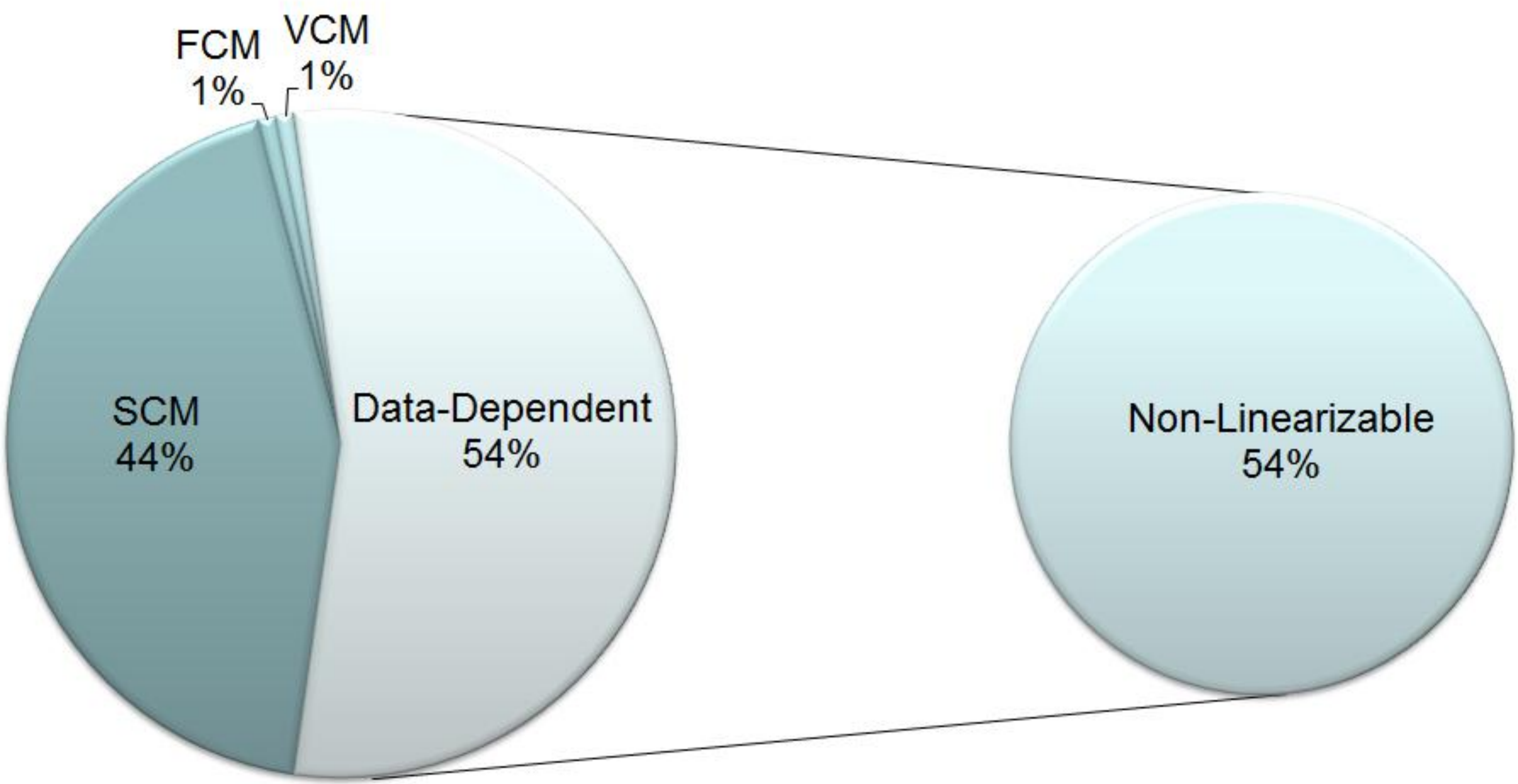


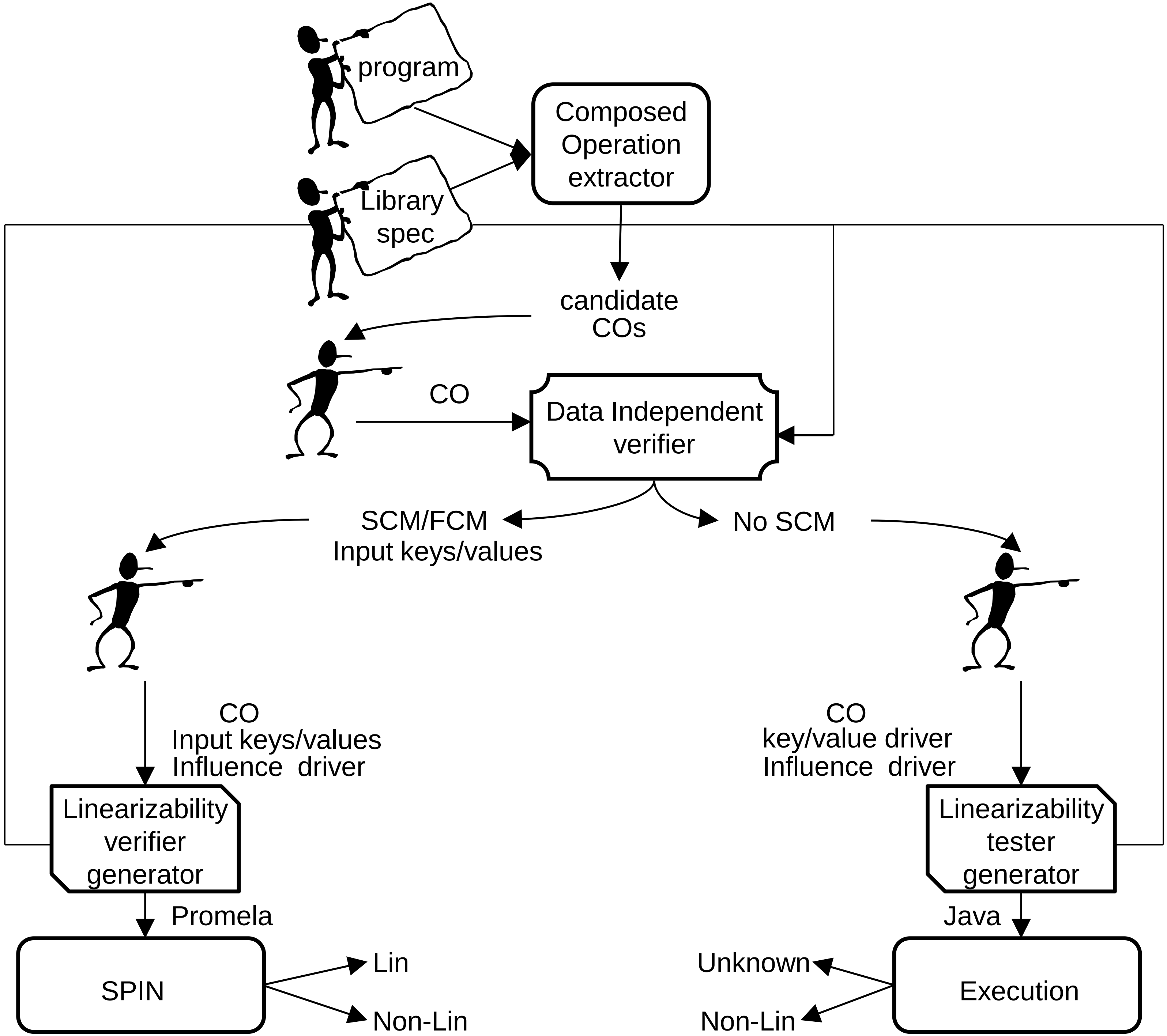
Verifying data independent operations

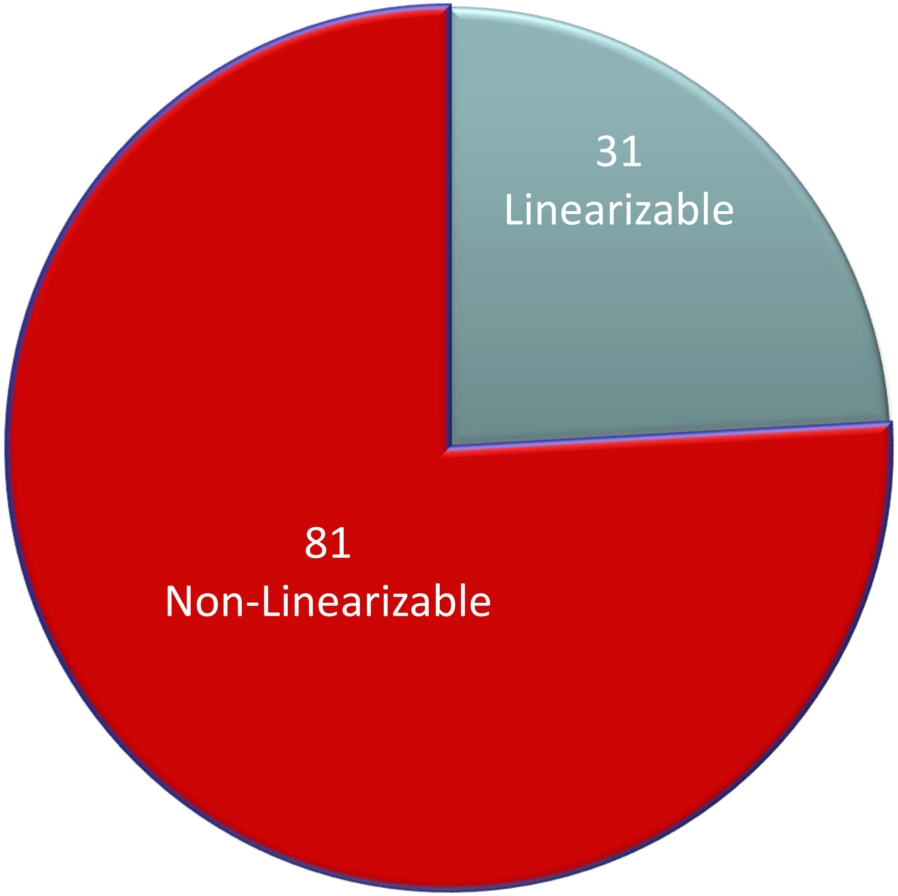
- Small model reduction
- Decidable when the local state is bounded
- Explore all possible executions using:
  - One input key and finite number of values
  - Influenced based environment uses single value
- Employ SPIN



FCM
1%
VCM
1%
SCM
44%
Data-Dependent
54%


FCM
1%
VCM
1%
SCM
44%
Data-Dependent
54%
Non-Linearizable
54%


program
Library spec
Composed Operation extractor
candidate COs
CO
Data Independent verifier
SCM/FCM
Input keys/values
No SCM
CO
Input keys/values
Influence driver
CO
key/value driver
Influence driver
Linearizability verifier generator
Linearizability tester generator
Promela
Java
SPIN
Lin
Non-Lin
Unknown
Non-Lin
Execution



31
Linearizable
81
Non-Linearizable

Summary

- Writing concurrent data structures is hard
- Employing atomic library operations is error prone
- Modular linearizability checking
- Leverage influence
- Leverage data independence

- Sweet spot
  - Identify important bugs together with a traces showing and explaining the violations
  - Hard to find
  - Prove the linearizability of several composed operations
  - Simple and efficient technique