Weak-Consistency Specification via Visibility Relaxation

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Motivation

Concurrent Objects

High-level abstractions

e.g. numeric & collection ADTs

Low-level performance

e.g. lock-free shared-memory access

Available on modern platforms

e.g. dozens in JDK

```
/**
 * a concurrent collection is thread-
 * safe, but not governed by a single
 * exclusion lock.
 */
package java.util.concurrent;

// we've considered these objects
class ConcurrentHashMap { … }
class ConcurrentSkipListMap { … }
class ConcurrentSkipListSet { … }
class ConcurrentLinkedQueue { … }
class LinkedTransferQueue { … }
class LinkedBlockingQueue { … }
class ConcurrentLinkedDeque { … }

// and there are several more
```

Weak Consistency

Performance optimization

avoid synchronization bottlenecks

weaken guarantees

Out in the wild

e.g. collections in JDK

Undermines reasoning

“Weakly consistent” is imprecise

```
package java.util.concurrent;
class ConcurrentSkipListSet { … }

/**
 * Iterators and spliterators are
 * weakly consistent...
 *
 * They are guaranteed to traverse
 * elements as they existed upon
 * construction exactly once and may
 * (but are not guaranteed to) reflect
 * any modification subsequent to
 * construction.
 */
```

E.g. The Size Method

```
/**
 * ... the size method is not a
 * constant-time operation...
 * determining the current number of
 * elements requires a traversal of
 * the elements ... may report
 * inaccurate results if ... modified
 * during traversal.
 */
class ConcurrentSkipListMap { … }
```

Requirements?

allow n = 0

forbid n = -1, 42, 100, …

Generic methodologies?

not tied to sets nor sizes

reuse existing functional spec

```
new Thread(() -> {

    s.add(1);
    s.remove(2);

}).start();

new Thread(() -> {

    s.add(2);
    var n = s.size();

}).start();
```

ADT-admitted linearizations

```
add(1); remove(2); add(2); size() => 2
add(1); add(2); remove(2); size() => 1
add(1); add(2); size() => 2; remove(2)
add(2); add(1); remove(2); size() => 1
add(2); size() => 1; add(1); remove(2)
```

Visibility Relaxation

Axiomatic framework

Linearization + visibilities

Burckhardt et al.

Which criterion?

causal consistency
doesn't allow n = 0

eventual consistency
doesn't constrain n at all

How to mix?

add & remove remain atomic

Linearization

`add(1); add(2); remove(2);` **`size() => n`**

visibility of size			
`add(1)`	`add(2)`	`remove(2)`	**`n`**
			0
		√	**0**
	√		1
√			1
	√	√	**0**
√		√	1
√	√		2
√	√	√	1

Contributions

Visibility Relaxation

an annotation language

Sequential happens-before consistency (SHBC)

effective consistency validation

Empirical study

derive JDK specifications

```
interface WeakSizeSet<E> {

    // complete visibility
    public boolean add(E elem);

    // complete visibility
    public boolean remove(E elem);

    // monotonic visibility
    public monotonic int size();

}
```

Visibility Relaxation

Programs & Behaviors

Program Order (PO)

per-thread invocation order

Happens-Before (HB)

PO with synchronization

Outcome

invocations’ return values

Behavior

HB with outcome

Implementation

maps programs to behaviors

Program

```
{ add(1); remove(2) } || { add(2); size() }
```

Implementation

`ConcurrentSkipListSet`

Behaviors/Outcomes

```
[ false, true, false, 0 ]
[ false, true, false, 1 ]
...
```

Linearizations

Linearization Order

total order over invocations

includes happens-before

Visibility Relation

subsequence of linearized-before

ADT Consistency

subsequence admits return value

Program

```
{ add(1); remove(2) } || { add(2); size() }
```

Happens-Before

```
add(1) -> remove(2)
add(2) -> size()
```

Linearization

```
add(2); add(1); remove(2); size()
```

visible to size

ADT sequence

```
add(2); remove(2); size() => 0
```

Predicates & Specifications

Visibility Predicates

lower bounds on visibility

Visibility Specification

one predicate per method

Consistency

only consider linearizations satisfying per-method predicates

weak

no constraints

basic

must see happened-before

monotonic

also must see those seen by happens-before

peer

also must see those which happened before seen

causal

also visibility is transitive

complete

must see all linearized before

E.g. The Size Method

Consistent w/ monotonic

size sees add(2)

and all seen by add(2)
i.e. none

Inconsistent w/ peer

size sees remove(2)

not HB-predecessor add(1)

Program

```
{ add(1); remove(2) } || { add(2); size() }
```

↓

Happens-Before

```
add(1) -> remove(2)
add(2) -> size()
```

↓

Linearization

```
add(2); add(1); remove(2); size()
```

visible to size

↓

ADT sequence

```
add(2); remove(2); size() => 0
```

Assertion-Based Validation

Compute expected behaviors

for a given test program

Record observed behavior

return values & happens-before

Assert the inclusion

e.g. via hashing

```
function expected({ po, hbs }, Impl, Spec) {
  for (let hb of hbs) {
    for (let { lin, vis } of hb.lins()) {
      if (!Spec.isSatisfied(lin, vis, hb))
        continue;
      let ret = {};
      for (let i of lin) {
        let seq = vis(i);
        let res = Impl.execute(seq);
        ret[i] = res[res.length - 1];
      }
      yield { hb, ret };
} } }
```

Sequential Happens-Before Consistency

vs. Linearizability

Real-Time (RT) Order

return action precedes call

platform agnostic

Happens-Before (HB) Order

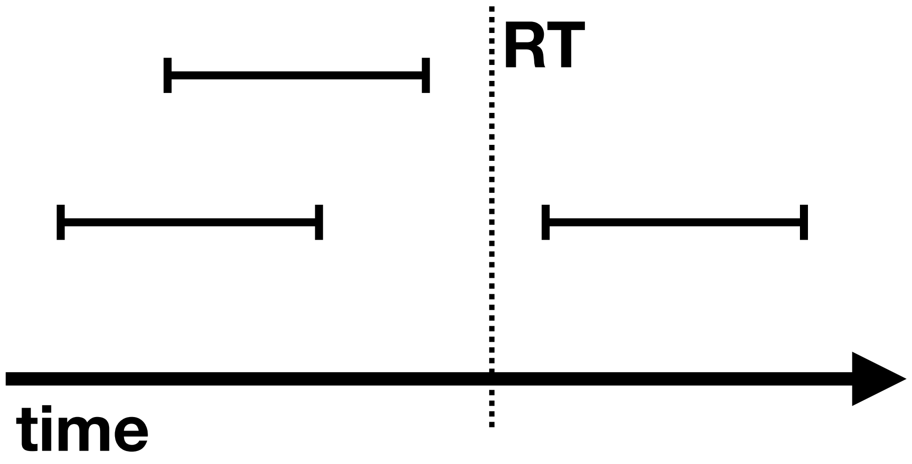
platform dependent

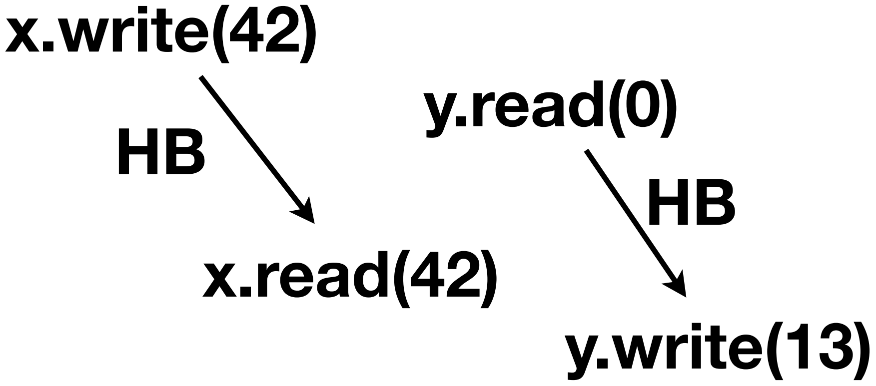
e.g. Java volatile variables, locks

Sequential HB Consistency

linearizations of HB, not RT

extends SC from PO to HB





Real-Time

Runtime monitoring?

platform specs eschew guarantees

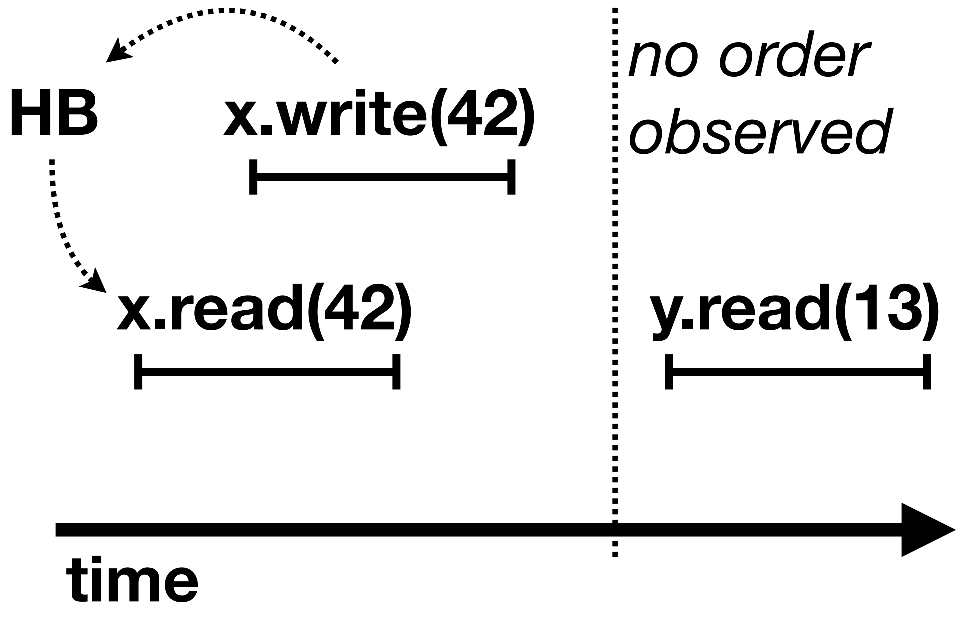
recording mechanisms interfere

Sound linearizability?

impossible w/o platform guarantees!

Leverage happens-before?

LIN becomes SHBC



Platform Properties

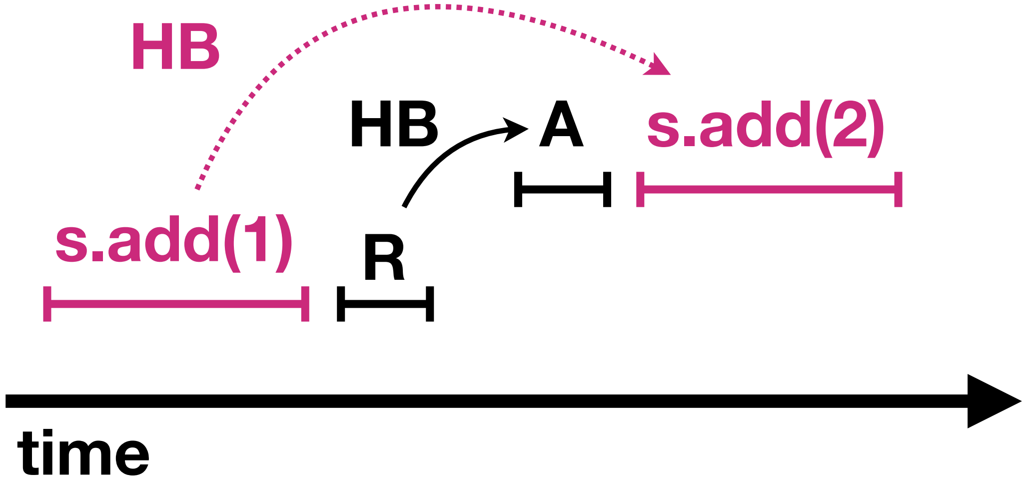
Real-Time Soundness (RTS)

happens-before implies real-time

Real-Time Consistency (RTC)

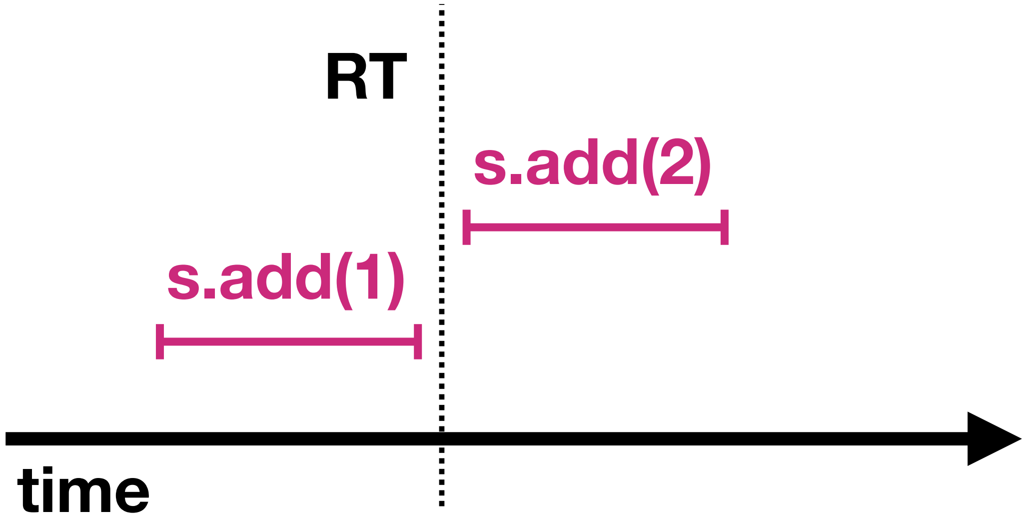
real-time implies happens-before*

(without interference)



Real-Time Limit Consistency

every admitted real-time order is captured* by a happens-before order



*given sufficient instrumentation

Real-Time Instrumentation

Memory-Based

requires instruction barriers

requires atomic read-call & ret-write

requires location independence (PSO)

Clock-Based

requires high-precision

requires negligible latency

requires atomic read-call & ret-read

```
// invocation 1
boolean[] before1 = {
    done[I3],
    done[I4]
};
s.add(1);
done[I1] = true;

// invocation 2
boolean[] before2 = {
    done[I3],
    done[I4]
};
s.add(2);
done[I2] = true;

// reconstruct order
boolean[][] before = {
    before1,
    before2
};
```

Equivalences

LIN implies SHBC

for RTS platforms

SHBC implies LIN

per execution, on RTC platforms

SHBC implies LIN

per object, on RTCL platforms

Empirical Study

Hypotheses

Atomicity

JDK methods not generally atomic

Specification

with visibility annotations

Validation

SHBC uncovers violations

Empirical Setup

7 JDK collections

Maps, Sets, Queues, Deques

Random Test Generation

2 threads, 3–6 invocations, 1–2 values

100K programs per object

Stress Testing

1 second per test program

Simplification

without synchronization

ConcurrentHashMap: size

`{ put(1,0); put(1,1); size() } || { remove(1) }`

outcome	atomic?	frequency
`null, 0, 0, 1`	✓	949
`null, 0, 1, 1`	✓	746,263
`null, 0, 1, null`	✓	2,614,780
`null, null, 1, 0`	✓	14,833
null, null, **2**, 0	×	35

JDK Atomicity

50+ non-atomic methods

roughly 40% of those tested

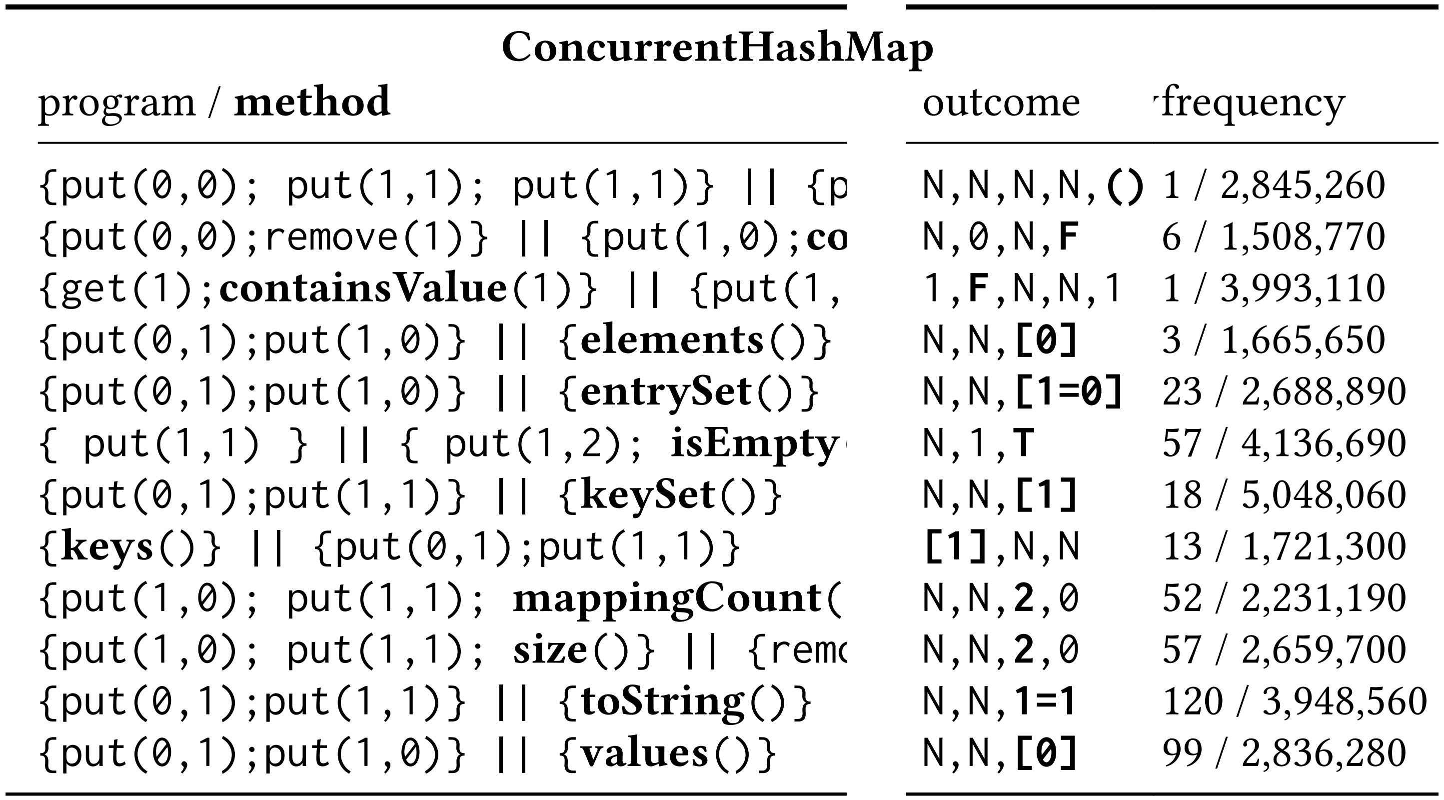
Some predictable

docs mention weak consistency
e.g. size, iterator, elements, …

Others unexpected

breaks internal invariants
e.g. clear

weak-memory behaviors
e.g. final keyword missing from peekLast, …



<table>
<tr><th colspan="3">ConcurrentHashMap</th></tr>
<tr><th>program / method</th><th>outcome</th><th>frequency</th></tr>
<tr><td>{put(0,0); put(1,1); put(1,1)} || {p</td><td>N,N,N,N,()</td><td>1 / 2,845,260</td></tr>
<tr><td>{put(0,0);remove(1)} || {put(1,0);co</td><td>N,0,N,F</td><td>6 / 1,508,770</td></tr>
<tr><td>{get(1);containsValue(1)} || {put(1,</td><td>1,F,N,N,1</td><td>1 / 3,993,110</td></tr>
<tr><td>{put(0,1);put(1,0)} || {elements()}</td><td>N,N,[0]</td><td>3 / 1,665,650</td></tr>
<tr><td>{put(0,1);put(1,0)} || {entrySet()}</td><td>N,N,[1=0]</td><td>23 / 2,688,890</td></tr>
<tr><td>{ put(1,1) } || { put(1,2); isEmpty</td><td>N,1,T</td><td>57 / 4,136,690</td></tr>
<tr><td>{put(0,1);put(1,1)} || {keySet()}</td><td>N,N,[1]</td><td>18 / 5,048,060</td></tr>
<tr><td>{keys()} || {put(0,1);put(1,1)}</td><td>[1],N,N</td><td>13 / 1,721,300</td></tr>
<tr><td>{put(1,0); put(1,1); mappingCount(</td><td>N,N,2,0</td><td>52 / 2,231,190</td></tr>
<tr><td>{put(1,0); put(1,1); size()} || {rem</td><td>N,N,2,0</td><td>57 / 2,659,700</td></tr>
<tr><td>{put(0,1);put(1,1)} || {toString()}</td><td>N,N,1=1</td><td>120 / 3,948,560</td></tr>
<tr><td>{put(0,1);put(1,0)} || {values()}</td><td>N,N,[0]</td><td>99 / 2,836,280</td></tr>
</table>

JDK Specification

84 complete

mostly single-element operations

29 monotonic

meaning of “weakly consistent?”

3 weak

isEmpty, toArray, toString

18 inconsistent

most indicate bugs

few are intended

e.g. ConcurrentHashMap

complete

put, get, remove, containsKey, replace, putIfAbsent

monotonic

contains, containsValue, keys, values, elements, entrySet, keySet, toString

weak

isEmpty

inconsistent

clear, size, mappingCount

JDK Validation

SHBC is effective

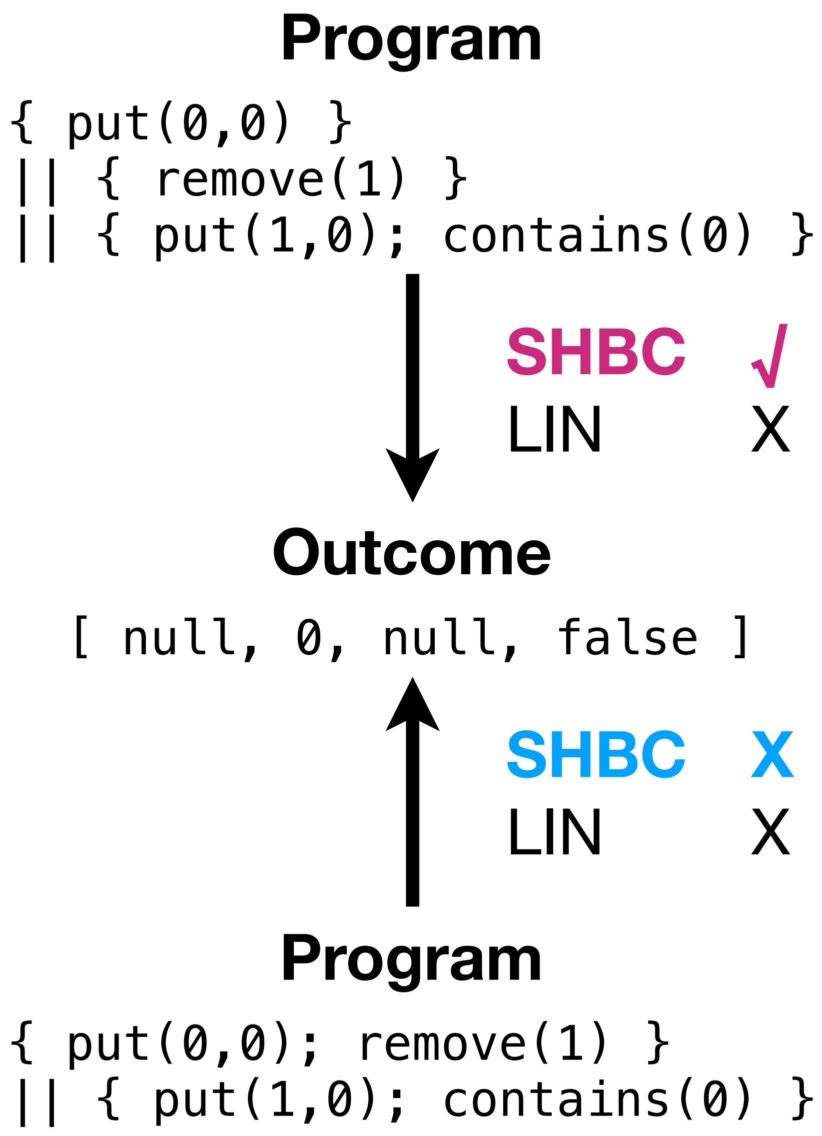
identifies violations w/o real-time

SHBC is efficient

millions of executions per second

Randomness useful

e.g. unexpected argument combos



Program

```
{ put(0,0) }
|| { remove(1) }
|| { put(1,0); contains(0) }
```

SHBC √
LIN X

Outcome

```
[ null, 0, null, false ]
```

SHBC **X**
LIN X

Program

```
{ put(0,0); remove(1) }
|| { put(1,0); contains(0) }
```

Conclusion

Visibility relaxation

generic yet precise semantics

Sequential happens-before consistency

efficient validation

integration with modern platforms

Empirical study

effective specification and validation