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Semantic Atomicity for Multithreaded Programs

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Parallel Correctness is Hard

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- Difficult to write correct parallel software.
  - **Key:** Interference between parallel threads.
  - **Atomicity** – freedom from harmful interference; a fundamental parallel correctness property.
- **Today**: **Semantic atomicity**.
  - Specifying atomicity with respect to user-defined, semantic equivalence.
  - Efficiently testing such specifications.
  - **Overall Goal:** Lightweight, useful specs to help programmers find and fix parallelism bugs.

Outline

- Overview + Motivation
- **Background: Atomicity**
- Specifying Semantic Atomicity
- Testing Semantic Atomicity
- Experimental Evaluation
- Conclusion

Background: Atomicity

- Atomicity a **non-interference property**.
  - Block of code is **atomic** if it behaves **as if** executed all-at-once and without interruption.
  - Interference from other threads is **benign** – cannot change overall program behavior.

Background: Atomicity

- Atomicity a **non-interference property**.
  - Block of code is **atomic** if it behaves **as if** executed all-at-once and without interruption.

```
int bal = 0;

deposit(int a) {
  @atomic {
    int t = bal;
    bal = t + a;
  }
}
```

Atomic **specification**.

Programmer **intends** that this code is atomic.

Want to **check** specification.

Is the code actually atomic?

Background: Atomicity

- Atomicity a **non-interference property**.
  - Block of code is **atomic** if it behaves **as if** executed all-at-once and without interruption.

```
int bal = 0;

deposit(int a) {
  @atomic {
    int t = bal;
    bal = t + a;
  }
}
```

Thread 1:

deposit(10)

t = 0

bal = 10

Thread 2:

deposit(5)

t = 0

bal = 5

Atomicity specification does **not** hold.

Background: Atomicity

- Atomicity a **non-interference property**.
  - Block of code is **atomic** if it behaves **as if** executed all-at-once and without interruption.

```
int bal = 0;

deposit(int a) {
  @atomic {
    int t = bal;
    while (!CAS(&bal, t, t+a))
      t = bal;
  }
}
```

With CAS, updates to balance are atomic.

Atomicity specification **does** hold.

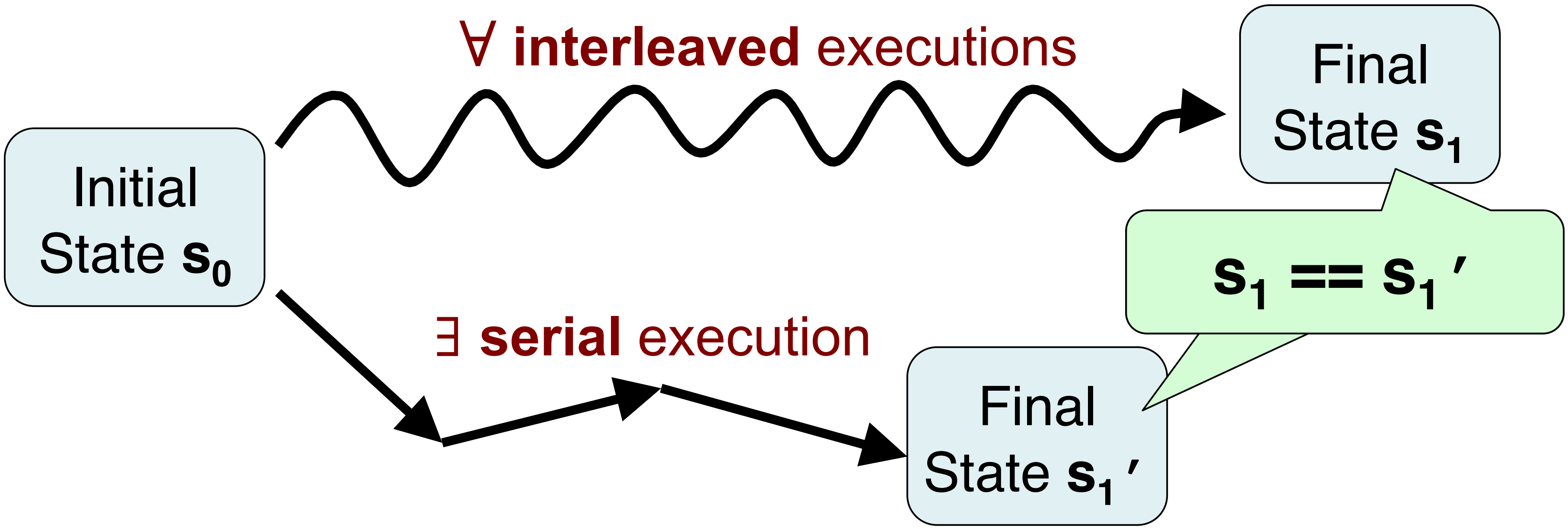
Background: Atomicity

- **Formally:** Two semantics for a program P with specified atomic blocks.
  - **Interleaved:** Threads interleave normally.

  - **Serial:** When one thread opens an atomic block, no other thread runs until it closes.

Background: Atomicity

- Formally, program P is **atomic** iff:
  - **For all interleaved** executions E yielding s_1, there **exists** a **serial** E′ yielding an identical final state.



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Motivating Example

```
    ConcurrentLinkedQueue q;
    q.add(1);  q.add(1);

Thread 1:                    Thread 2:
 @atomic {                    @atomic {
   q.remove(1);                 q.remove(1);
 }                            }
```

- Michael & Scott non-blocking queue, in the Java standard library
- Internally, a linked list with lazy deletion.

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Motivating Example

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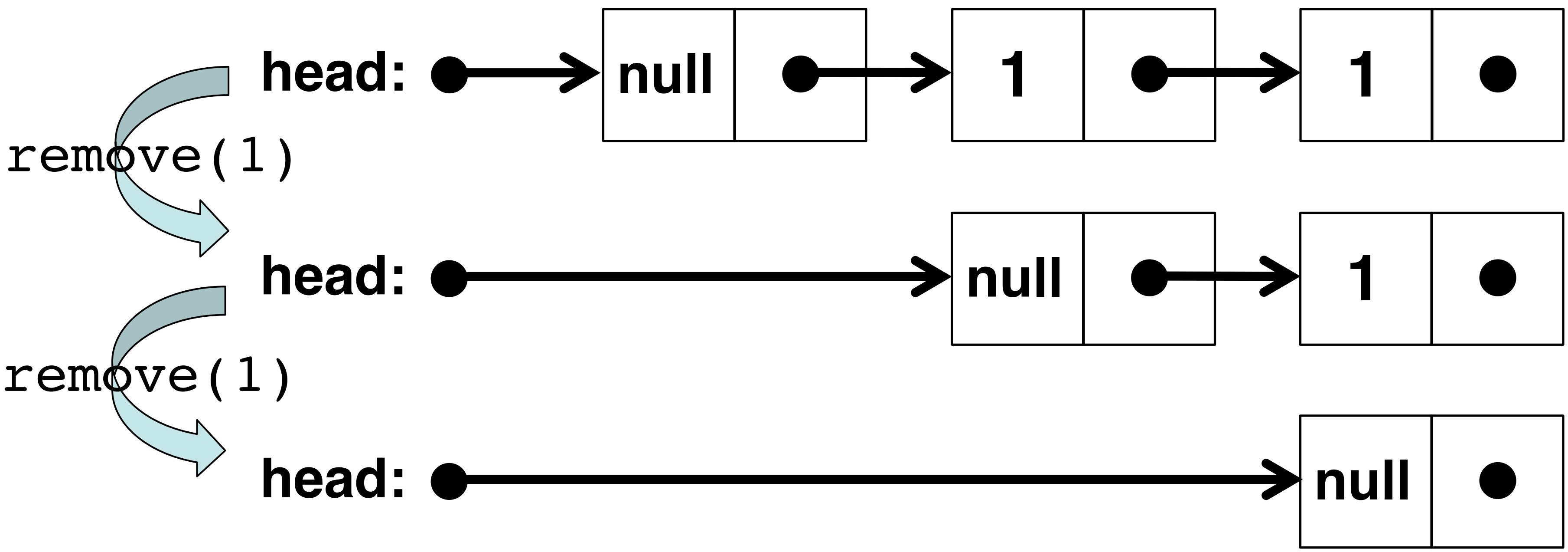
```
Thread 1:
 @atomic {
   q.remove(1);
 }
```

```
Thread 2:
 @atomic {
   q.remove(1);
 }
```

- In any **serial** execution:

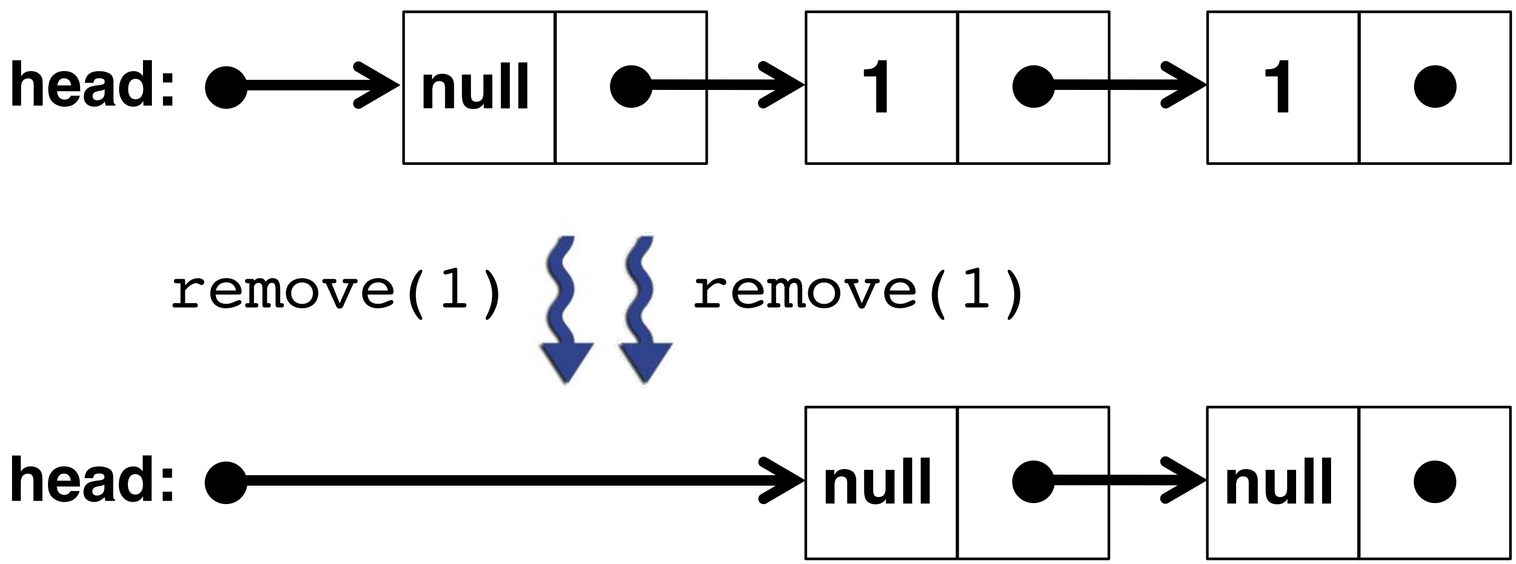


Motivating Example

```
Thread 1:
 @atomic {
   q.remove(1);
 }

Thread 2:
 @atomic {
   q.remove(1);
 }
```

- But in an **interleaved** execution:

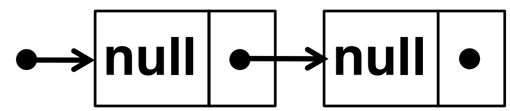


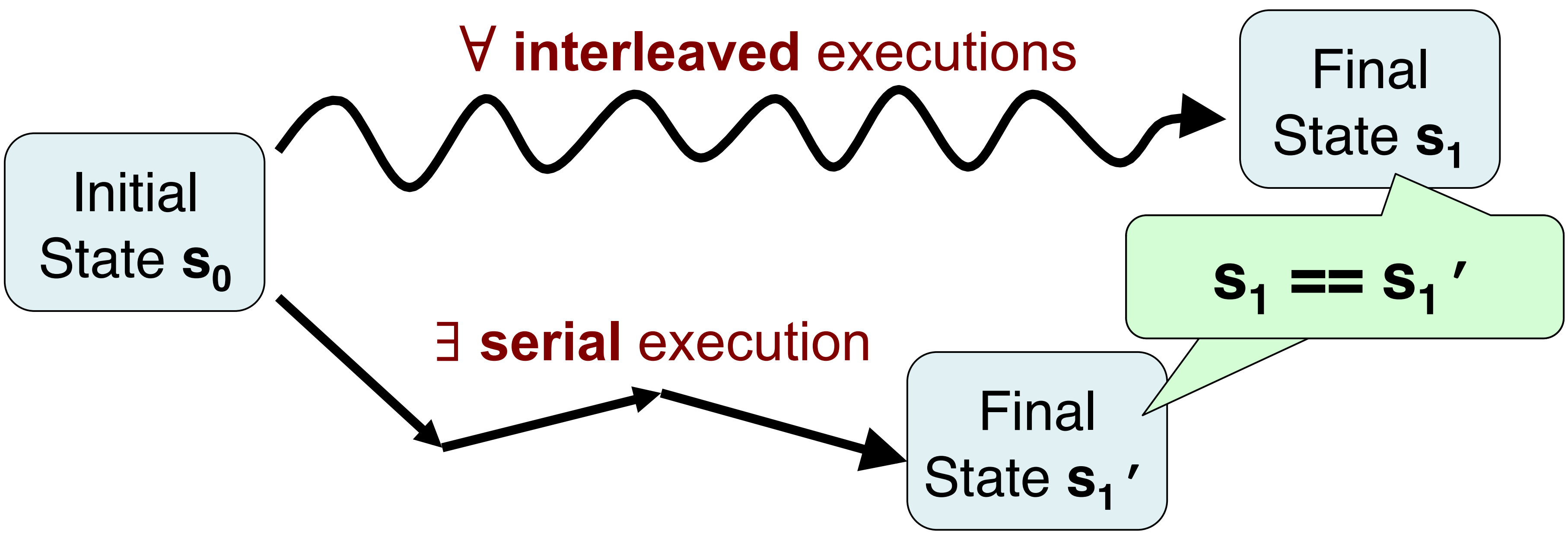
Motivating Example

```
Thread 1:
  @atomic {
    q.remove(1);
  }

Thread 2:
  @atomic {
    q.remove(1);
  }
```

- Traditional atomicity requires:

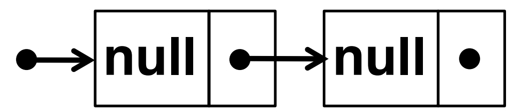


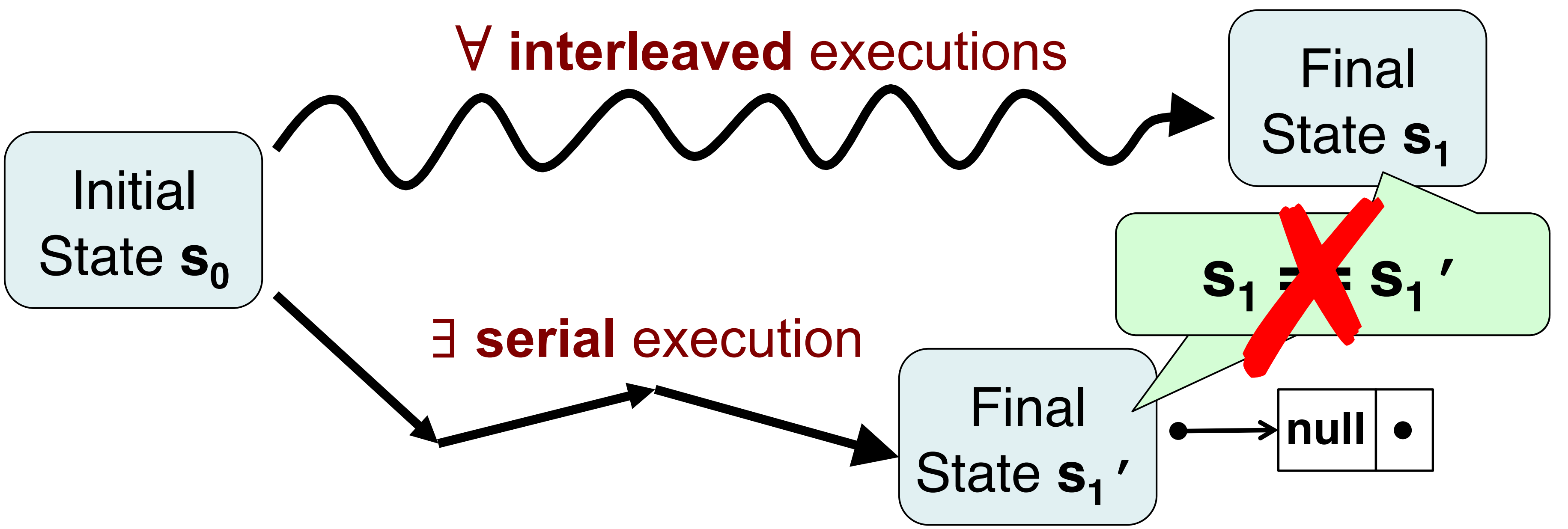


Motivating Example

```
Thread 1:                    Thread 2:
 @atomic {                    @atomic {
   q.remove(1);                 q.remove(1);
 }                            }
```

- Traditional atomicity requires:



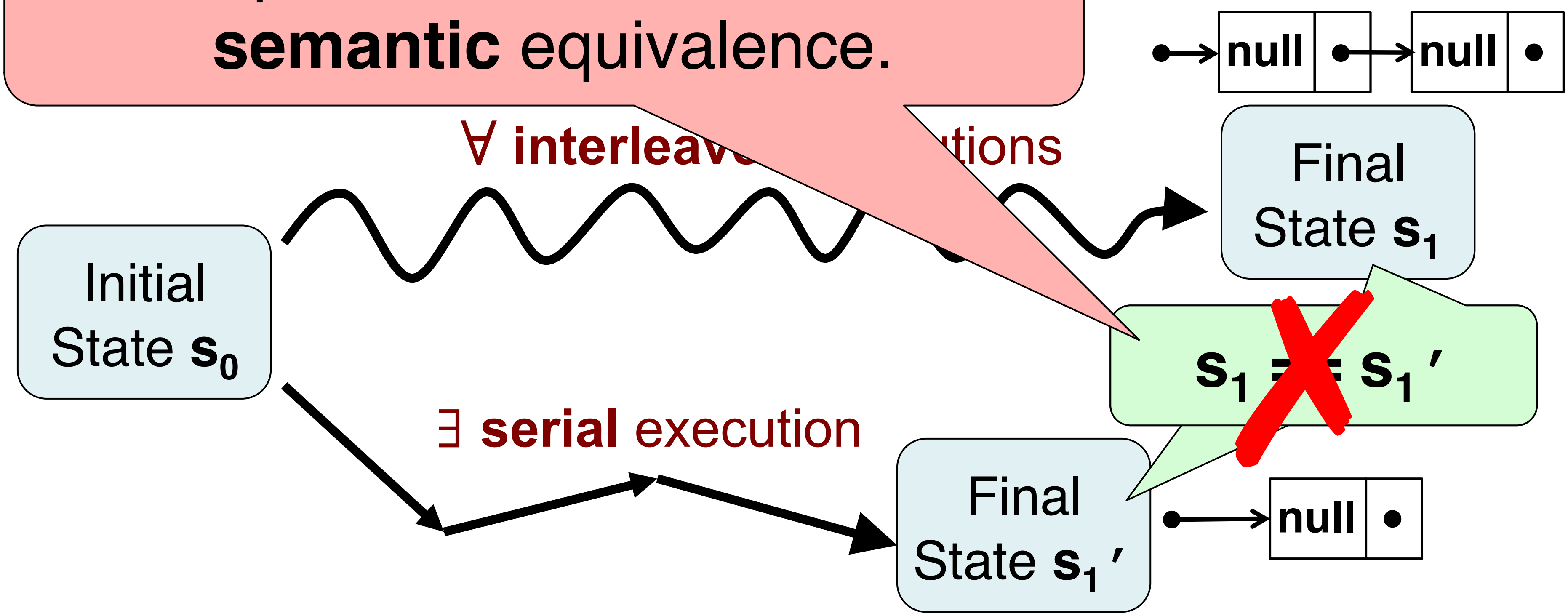


Motivating Example

```
Thread 1:
 @atomic {
   q.remove(1);
 }

Thread 2:
 @atomic {
   q.remove(1);
 }
```

Replace with user-defined **semantic** equivalence.



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Semantic Atomicity

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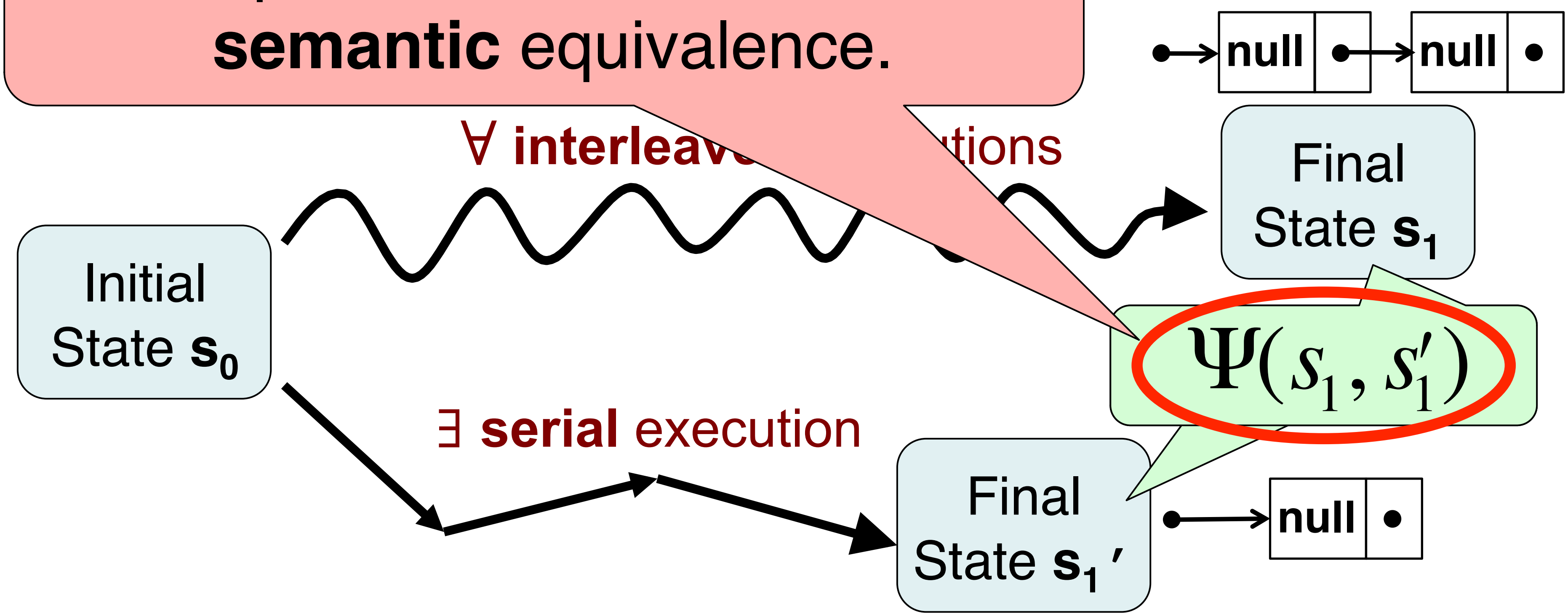
```
Thread 1:
  @atomic {
    q.remove(1);
  }

Thread 2:
  @atomic {
    q.remove(1);
  }
```

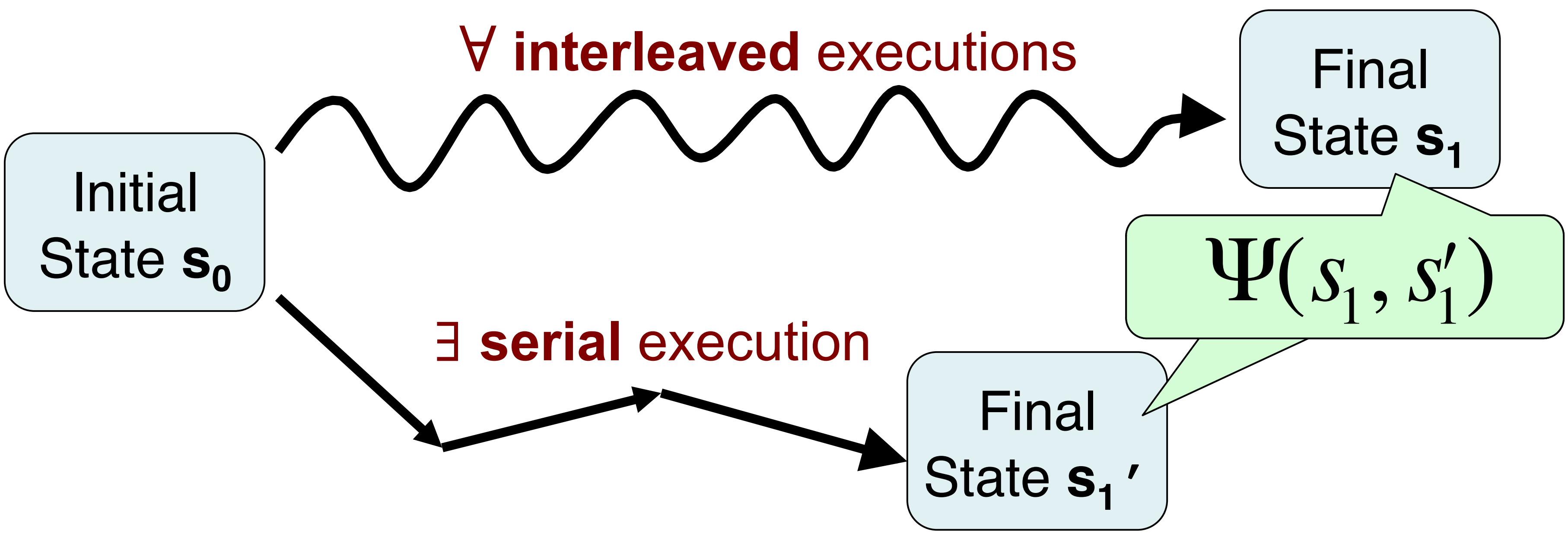
Replace with user-defined **semantic** equivalence.



Semantic Atomicity Example

```
Thread 1:                     Thread 2:
 @atomic {                     @atomic {
   q.remove(1);                  q.remove(1);
 }                             }

   Atomicity predicate: q.equals(q')
```



Bridge Predicates

Thread 1:

```
@atomic {
  q.remove(1);
}
```

Thread 2:

```
@atomic {
  q.remove(1);
}
```

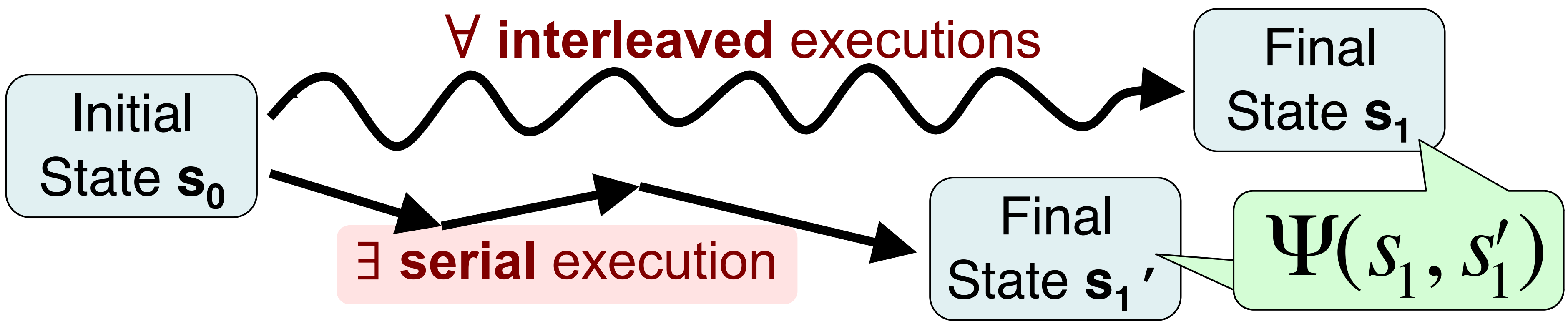
Atomicity predicate: **q.equals(q')**

Bridge predicate.

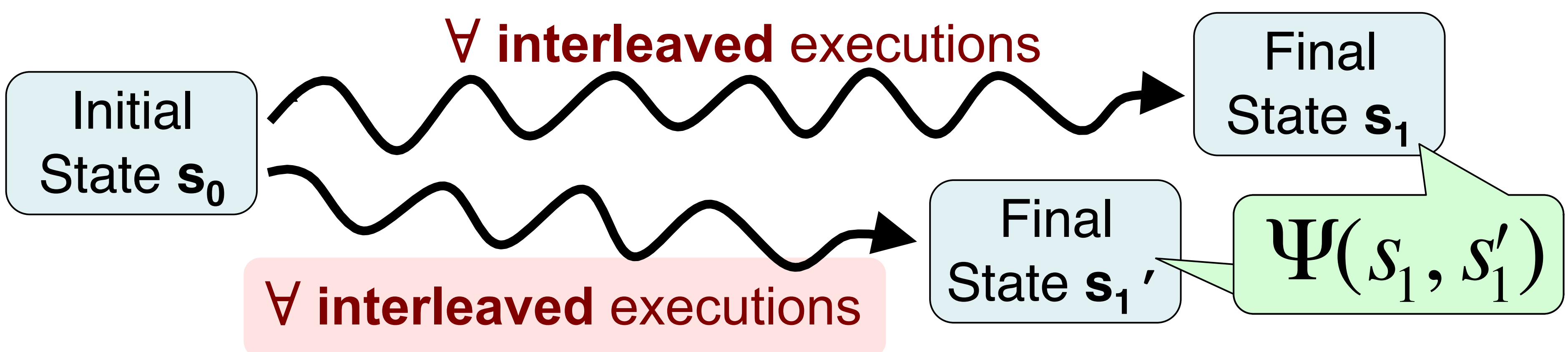
- Burnim, Sen, "Asserting and Checking Determinism for Multithreaded Programs", FSE 2009, CACM 2010.

Atomicity vs. Determinism

- Semantic **Atomicity**:



- Semantic **Determinism**:



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Semantic Atomicity Example

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```
int bal = 0;
int conflicts = 0;

deposit(int a) {
  @atomic {
    int t = bal;
    while (!CAS(&bal, t, t+a)) {
      t = bal;
      conflicts += 1;
    }
  }
}
```

With CAS, updates to balance are atomic.

"Performance counter" of # of CAS failures.

Atomicity predicate: bal == bal'

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Semantic Atomicity Example

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```
        ConcurrentList list;

Thread 1:                     Thread 2:
 @atomic {                     @atomic {
    ...                           ...
    list.add(1);                  list.add(3);
    ...                           ...
    list.add(2);                  list.add(4);
 }                             }

Atomicity predicate: eqSets(list,list')
```

- If `list` is [1,3,2,4], an atomicity violation?
  - User must specify **intended** atomicity.

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Testing Semantic Atomicity

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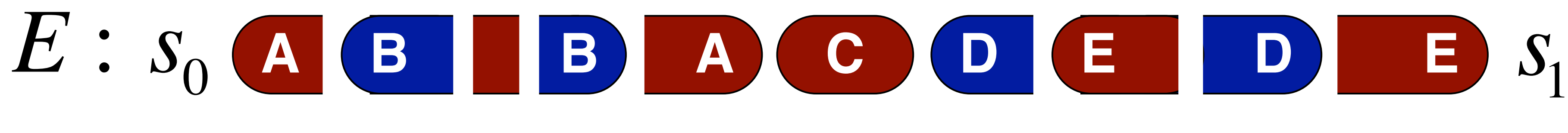
- **Interleaved** run E is **semantically atomic** w.r.t. Ψ iff there exists a **serial** run E' s.t.:
  - The final states of E, E' satisfy $\Psi(s_1, s_1')$.



Is E semantically atomic w/ respect to Ψ?

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Testing Semantic Atomicity

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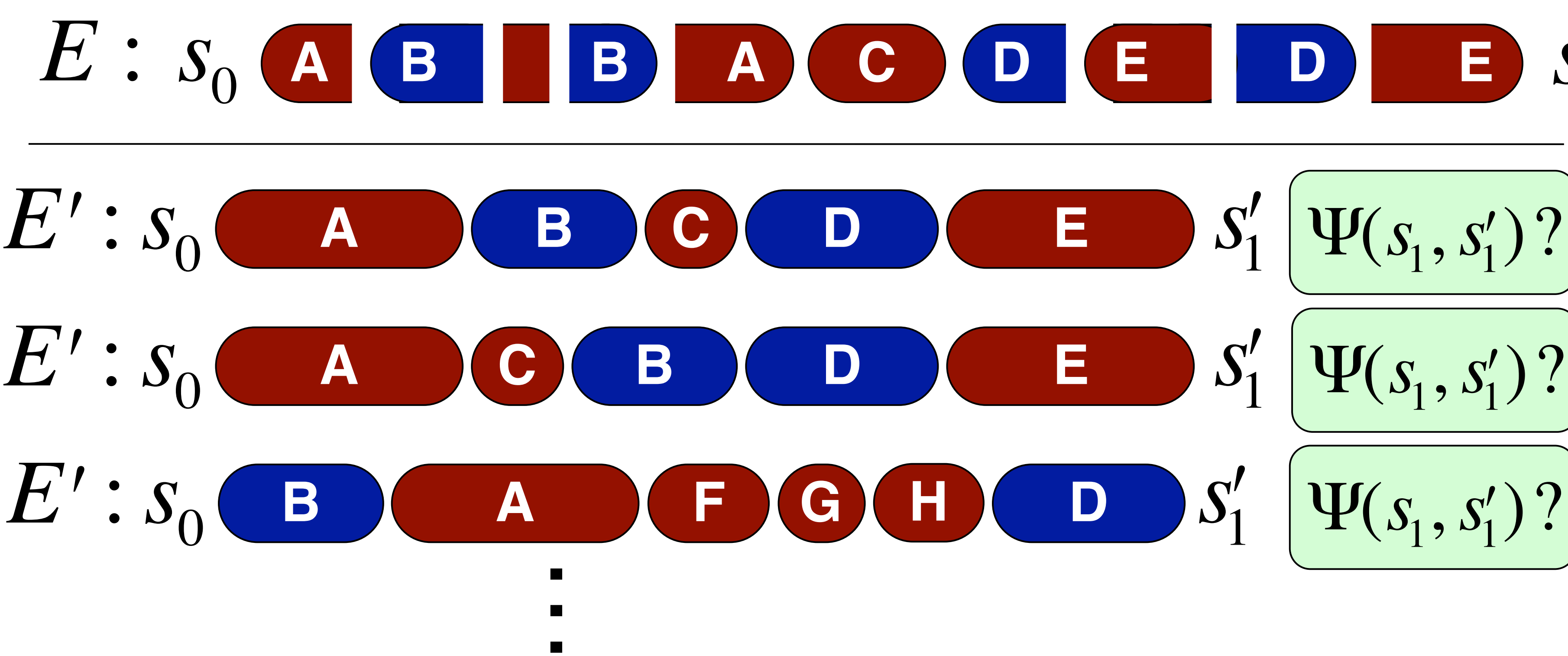
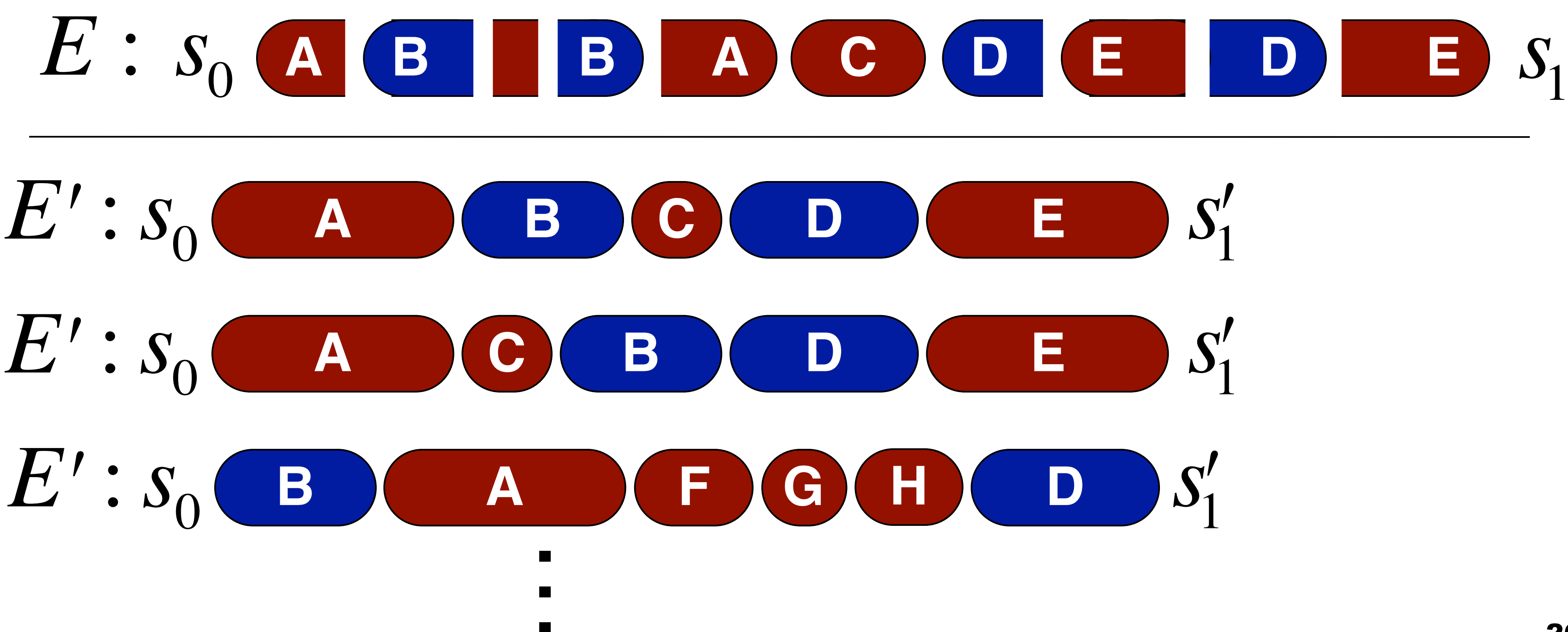
- **Interleaved** run E is **semantically atomic** w.r.t. Ψ iff there exists a **serial** run E' s.t.:
  - The final states of E, E' satisfy $\Psi(s_1, s_1')$.



Testing Semantic Atomicity

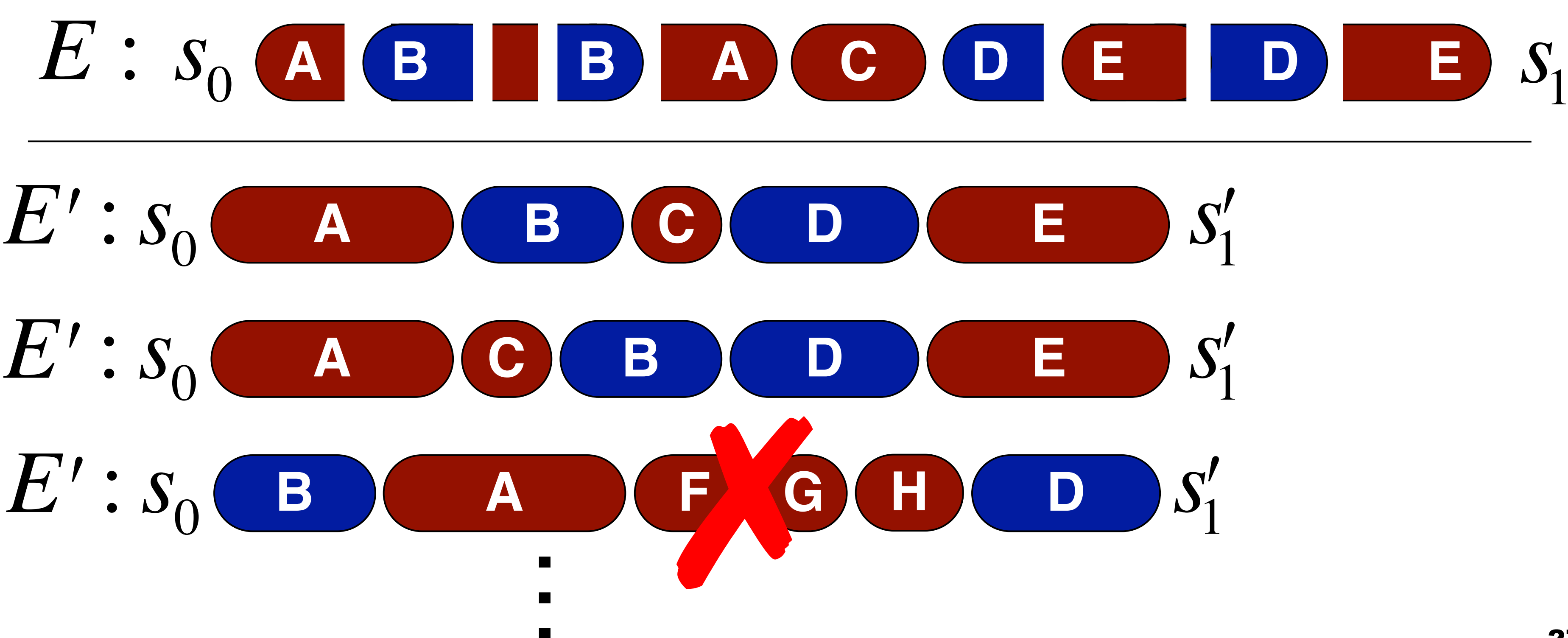
Infeasible to try all serial executions.

Can we **restrict** this search?



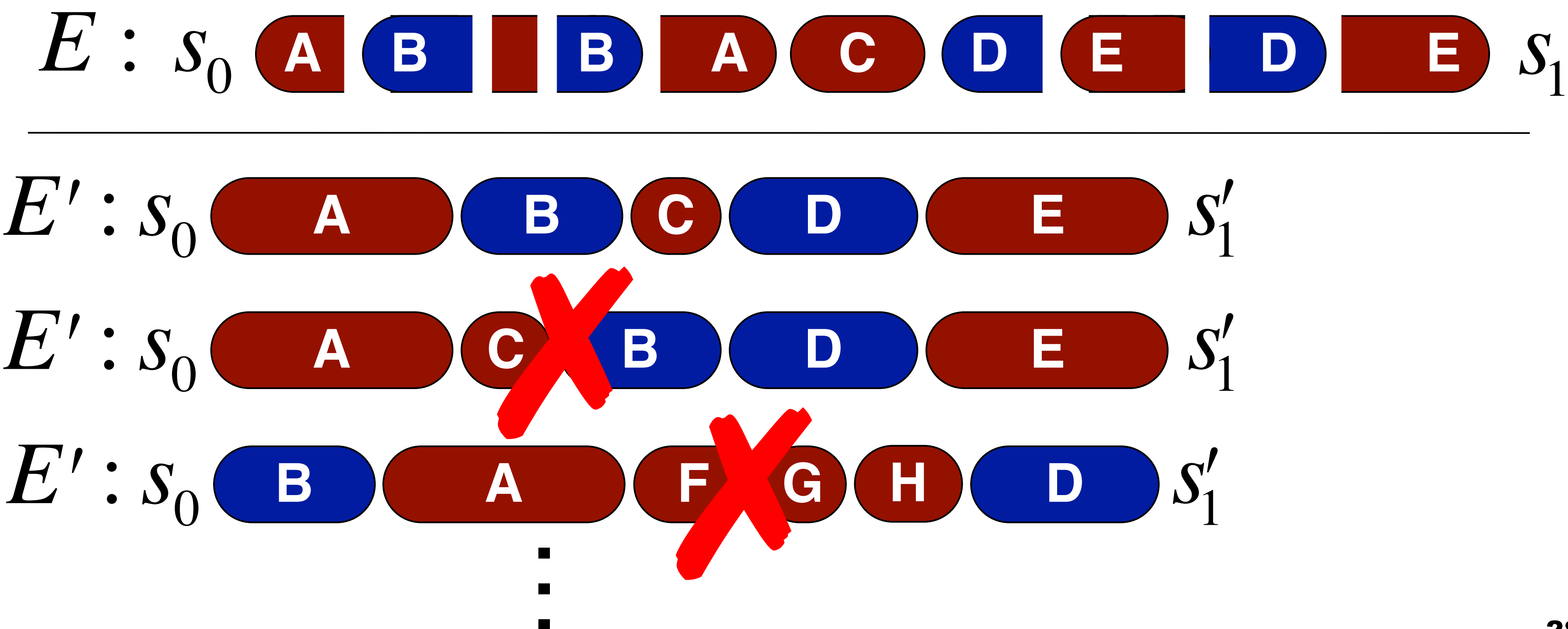
Testing Semantic Atomicity

1. The final states of E, E' satisfy $\Psi(s_1, s_1')$.
2. E and E' execute the same atomic blocks.



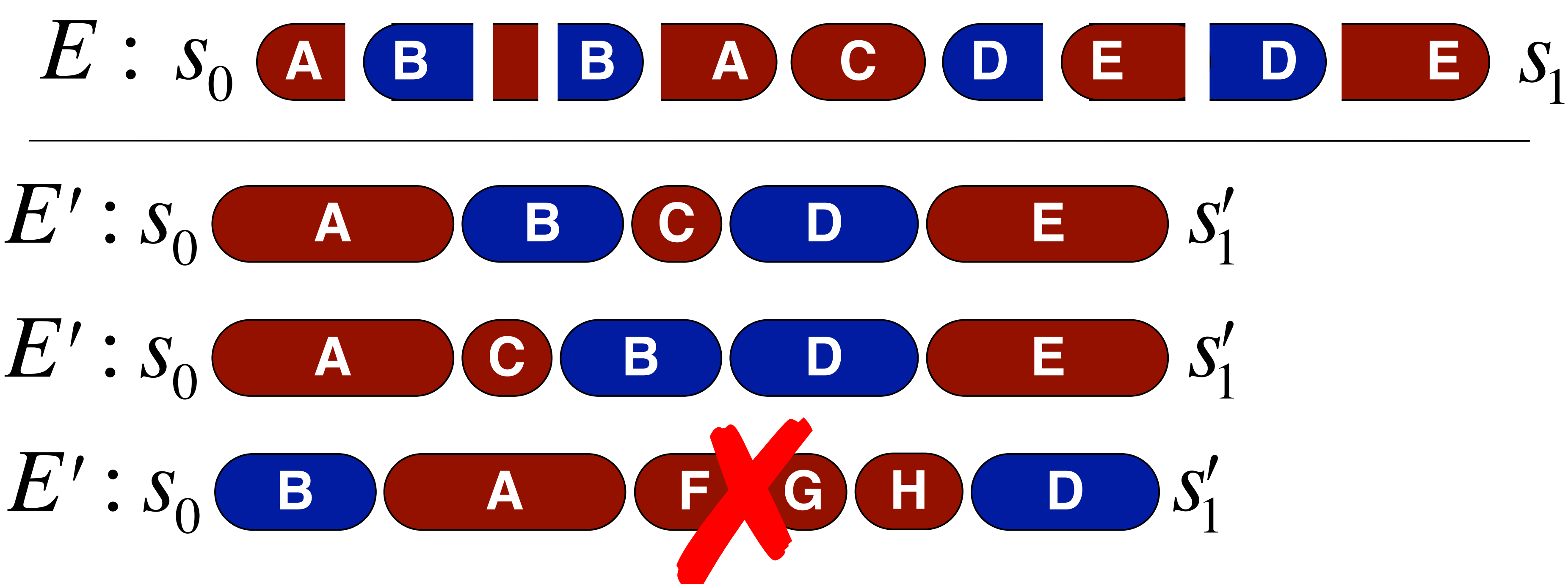
Testing Semantic Atomicity

1. The final states of E, E' satisfy $\Psi(s_1, s_1')$.
2. E and E' execute the same atomic blocks.
3. Non-overlapping atomic blocks appear in the same order in E and E' .



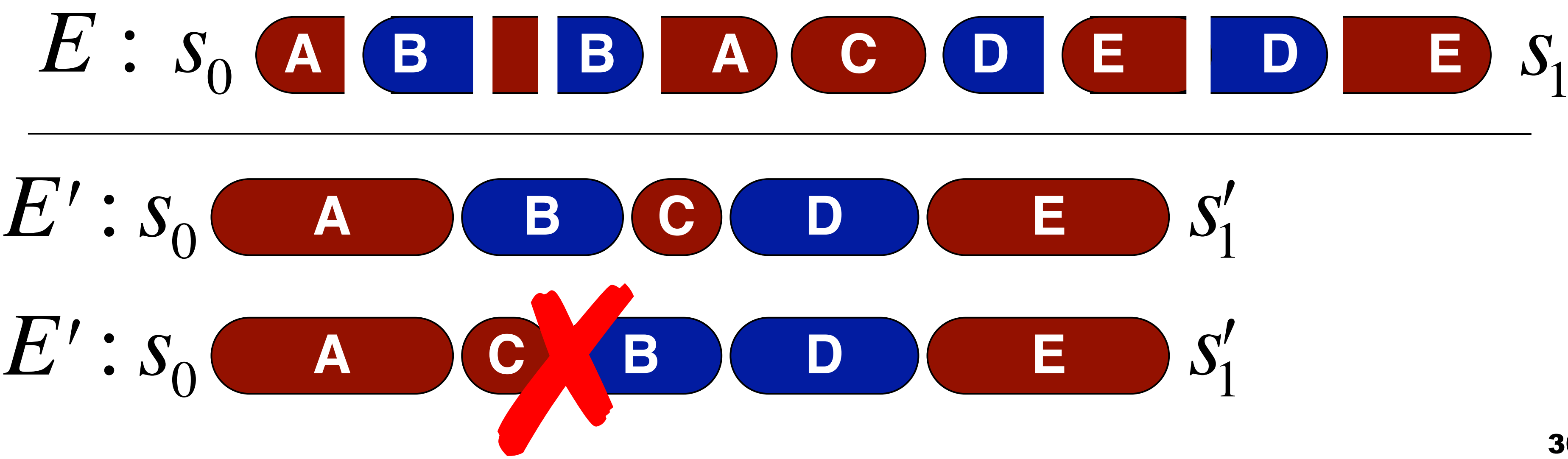
Semantic Serializability

- **Def:** Interleaved run E is **semantically serializable** iff exists a serial run E' s.t.:
  1. The final states of E, E' satisfy $\Psi(s_1, s_1')$.
  2. E and E' execute the same atomic blocks.



Semantic Strict Serializability

- **Def:** Interleaved E is **semantically strictly serializable** iff exists a serial run E' s.t.:
  1. The final states of E, E' satisfy $\Psi(s_1, s_1')$.
  2. E and E' execute the same atomic blocks.
  3. Non-overlapping atomic blocks appear in the same order in E and E' .



Semantic Strict Serializability

- **Def:** Interleaved E is **semantically strictly serializable** iff exists a serial run E' s.t.:
  1. The final states of E, E' satisfy $\Psi(s_1, s_1')$.
  2. E and E' execute the same atomic blocks.
  3. Non-overlapping atomic blocks appear in the same order in E and E'.

E has **N** blocks, with **≤ *K* overlapping**.

==>

Can check semantic strict serializability by examining **≤ *K!*** serial runs.

Testing Semantic Atomicity

- To test atomicity of program P:
  - Systematically/randomly generate executions E with **≤ *K* overlapping atomic blocks**.
  - For each E, report a violation if not **semantically strictly serializable**.
- **Small Scope Hypothesis:** Can find bugs with small # of overlapping atomic blocks.

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Experimental Evaluation

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- Wrote semantic atomicity specs for several Java benchmarks.
  - Concurrent data structures and parallel apps.
- **Setup:** For each benchmark:
  - Generate 200-900 random interleaved runs, with one atomic block interrupted by ≤4 others.
  - Check semantic strict serializability of each.
  - To compare, also check conflict-serializability.

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Experimental Results I

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Benchmark	LoC	Test Runs	Semantic Atomicity Violations		Strict Atomicity Violations	
			Runs	Static Blocks	Runs	Static Blocks
JDK LinkedQueue	200	241	7	**2**	**≫7**	**4**
JDK SkipListMap	1400	487	6	**2**	**≫7**	**4**
JDK CwArrayList	600	222	0	0	0	0
lock-free list	100	319	57	**1**	**≫57**	**2**
lazy list-based set	100	231	0	0	**≫0**	**2**

Experimental Results II

Benchmark	LoC	Test Runs	Semantic Atomicity Violations		Strict Atomicity Violations	
			Runs	Static Blocks	Runs	Static Blocks
PJ pi	150	20	5	**1**	5	1
PJ keysearch	200	904	0	0	0	0
PJ fractal	250	73	0	0	0	0
PJ phylogenetic	4400	603	27	**1**	**≫27**	**2**

Application benchmarks from Parallel Java Library (Kaminsky 2007), use ~15000 LoC from PJ library.

JDK Atomicity Bug

```
ConcurrentLinkedQueue q;
q.add(1);  q.add(2);

Thread 1:                  Thread 2:
 @atomic {
   q.remove(1);             @atomic {
 }                            sz = q.size();
 @atomic {                  }
   q.add(3);
 }
       Atomic with respect to:
         q.equals(q') ∧ (sz == sz')
```

- **Not atomic:** `q.size()` can return `sz=3`.

Semantic Atomicity Bug II

```
parallel-for (t in trees) {
   @atomic {
      cost = compute_cost(t);
      synchronized (min_cost) {
         min_cost = min(min_cost, cost);
      }
      if (cost == min_cost) {
         min_tree = t;
      }
   }
}       Atomic with respect to:
           min_tree.equals(min_tree')
             ∧ (min_cost == min_cost')
```

Updates to `min_tree` not synchronized.

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Conclusion

- **Semantic atomicity**.
  - Generalization for capturing high-level non-interference properties of real, complex code.
  - Testing via strict serializability.
  - Found several unknown atomicity errors.
- **Overall Goal:** Lightweight specifications for parallel correctness.
  - Easy for programmers to write.
  - With testing, effective in finding real bugs.
  - Determinism [CACM'10,ICSE'10], NDSeq [PLDI '11]

Questions?