Reachability testing for concurrent programs

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Overview

- Introduction
- Some existing tools
- Reachability testing
  - Concepts
  - Algorithm
  - Implementation
  - Optimizations
  - Results
- Conclusion

Concurrent programs

- Multiple non-independent executions
  - Multithreaded programs
  - Distributed programs
- Very difficult to test
  - Non deterministic interleavings/irreproducible

```
Thread1          Thread2          Thread3
t.send(1)        t.send(2)        x = t.recv()
                                  y = t.recv()
                                  print x - y
```

  - Difficult to breakdown because problems come from interactions

Approaches to testing

- Deterministic testing
  - Run all possible interleavings (how?)
  - Select a subset of interleavings and force execution to follow
- Non-deterministic testing
  - Run repeatedly for <u>some</u> time
  - Easy but inefficient, problems may appear at only extreme conditions at customers' computers
- Prefix-based testing
  - Run test deterministically at the beginning
  - Follow by nondeterminstic runs

Model checking/SPIN

- Use a modeling language PROMELA
- Explore all possible states of a program
- Support full LTL logic
- Suffer state explosion problem
  - Partial order reduction to relieve the problem
  - Use for very critical portion of software
  - Verify network protocols

Java PathFinder

- Formal verification tool developed by NASA Ames Research center
- A more easier to use SPIN
- Explore ALL possible execution paths of a java program without recompling
  - Also visit all possible states of the program
  - Check every state for violations of assertions/ /properties/exceptions/deadlocks/livelock
  - Has a lot of heuristics and optimization to work with big programs.
- VeriSoft for C/C++

Concutest-junit

- A concurrency-aware version of junit developed at Rice University
- Improvements:
  - Catch errors in auxiliary threads
  - Have new invariants to check threading related problems
  - Can insert delays at critical places
  - Can record and playback specific interleavings

ConTest

- A tool to test concurrent java programs developed by IBM Haifa Research Lab
- Works without recompiling/new test
  - Instruments existing bytecode
  - Inserts heuristic sleep() and yield() instructions to expose problems
  - Run multiple times

Reachability testing (prefix-based testing)

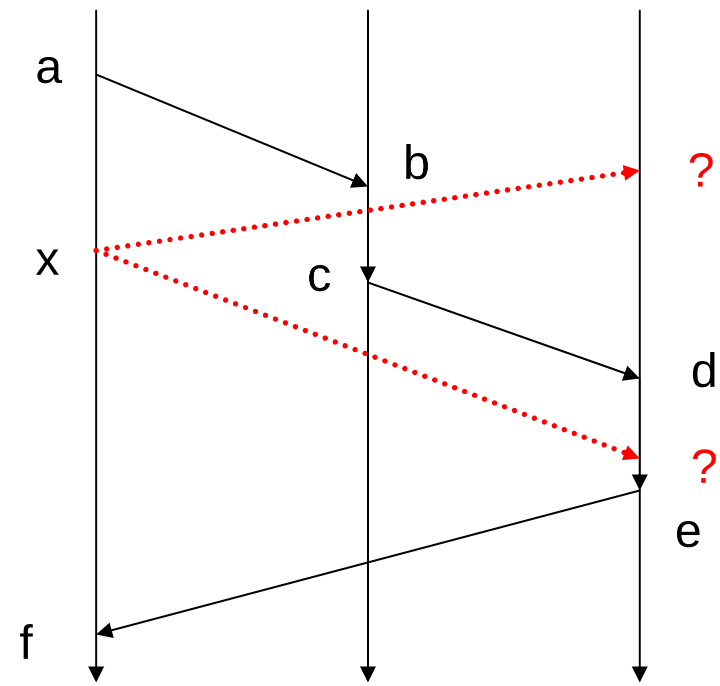
- Concepts
- Algorithm
- Implementations
- Optimizations
- Results

SYN-sequence

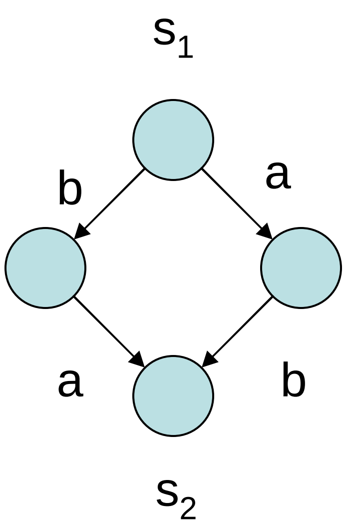
- We only care about the order of operations whose interleavings has effect on execution
  - Sending/receiving data with another thread
  - Semaphore/Monitors
- General execution model: send/receive
- SYN-sequence: sequence of synchronization <u>events</u>
- Aim: execute all possible SYN-sequences

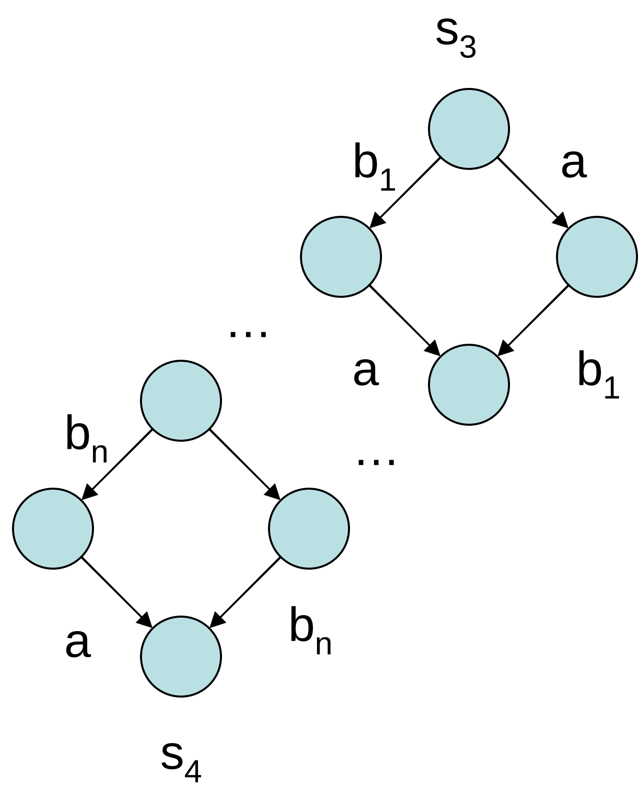
Happen-before relation

- Gives us the order of events, usually <u>partial</u>.
- We can extract these relations by watching an execution
- The unordered events are subjected to testing
- Why vector clock but not single global clock?



Partial order reduction





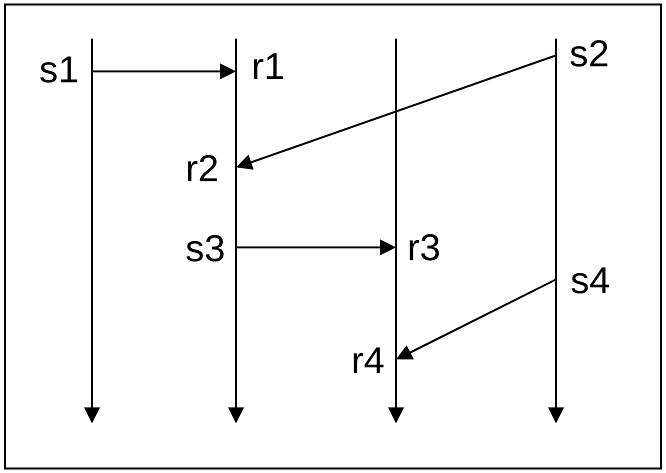
Algorithm (RichTest)

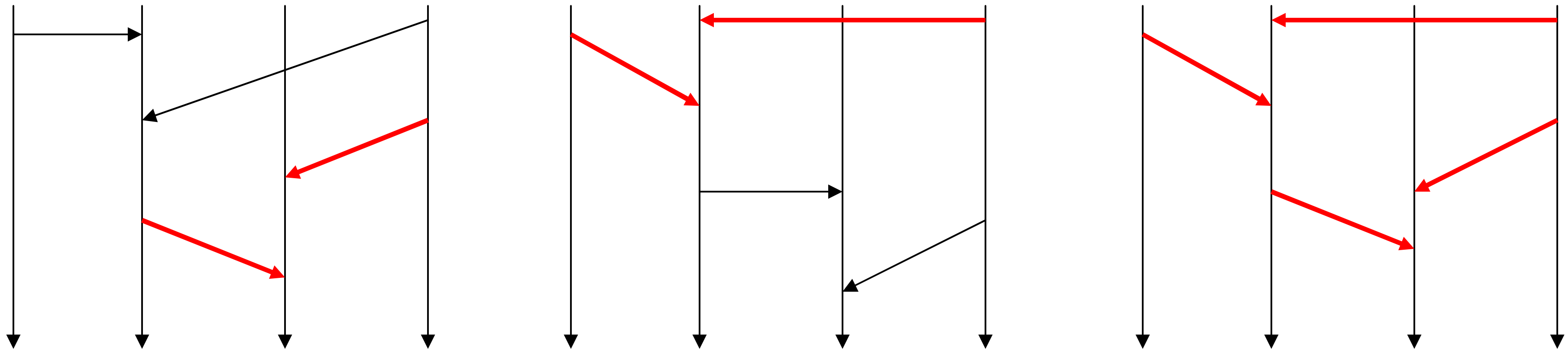
- Run and collect a SYN-sequence s*
- *S* ← {*s**}
- Repeat
  - Get a sequence *s* ← S
  - Runs each ***variant*** of s to collect sequences $s_1, s_2, \ldots s_m$
  - S ← $\{s_1, s_2, \ldots, s_m\}$

  Until S = empty

Example

Thread 1	Thread 2	Thread 3	Thread 4
`P2.send(a)`	`x=p2.recv();`	`u=p3.recv()`	`p2.send(b)`
	`y=p2.recv();`	`v=p3.recv()`	`p3.send(d);`
	`p3.send(c);`		





More concepts

- Race condition: A receive() operation may match with different send()’s
- Race_set(r): all send events that can possibly be matched with the receive operation r

Race table

Contains one column for each receive event r that has a nonempty race_set(r). The numbers in each row represent

- -1: remove r
- 0: no change
- 1..|race_set(r)|: match r to the i^{th} send in race_set(r)

Example

```
Thread 1
P2.send(a)
```

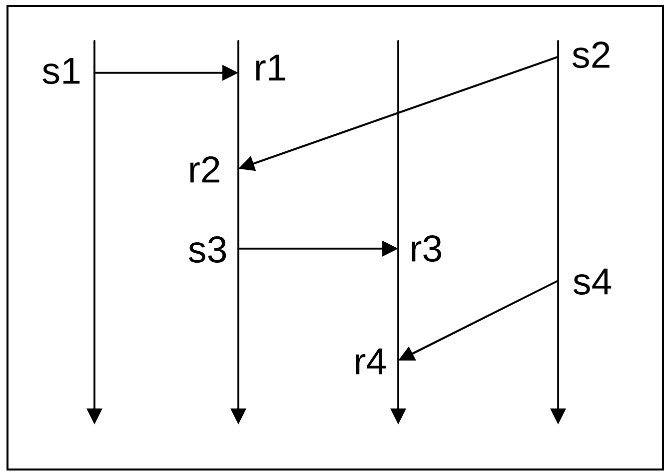
```
Thread 2
x=p2.recv();
y=p2.recv();
p3.send(c);
```

```
Thread 3
u=p3.recv()
v=p3.recv()
```

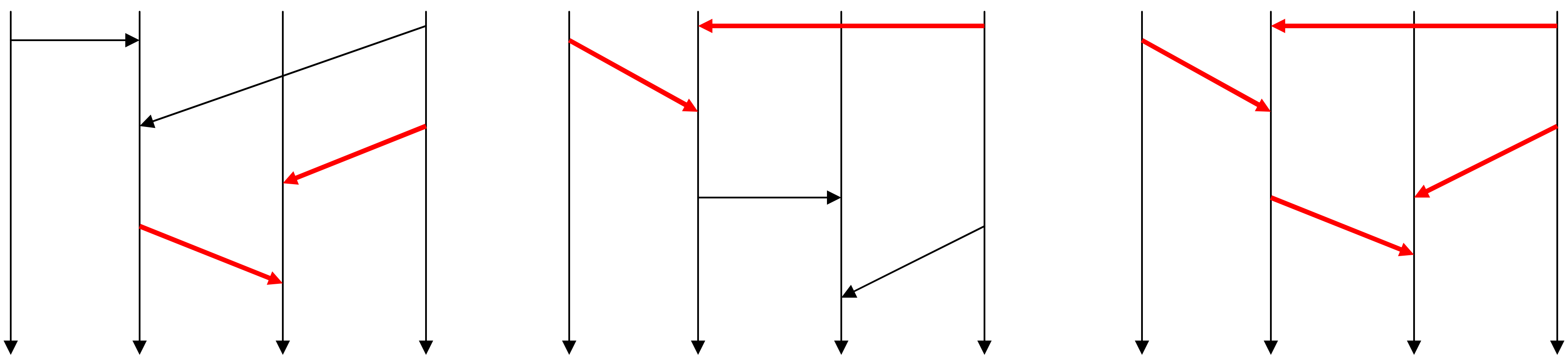
```
Thread 4
p2.send(b)
p3.send(d);
```

race_set(r1) = {s1,s2}

race_set(r3) = {s3,s4}



r_1	r_3
0	1
1	0
1	1



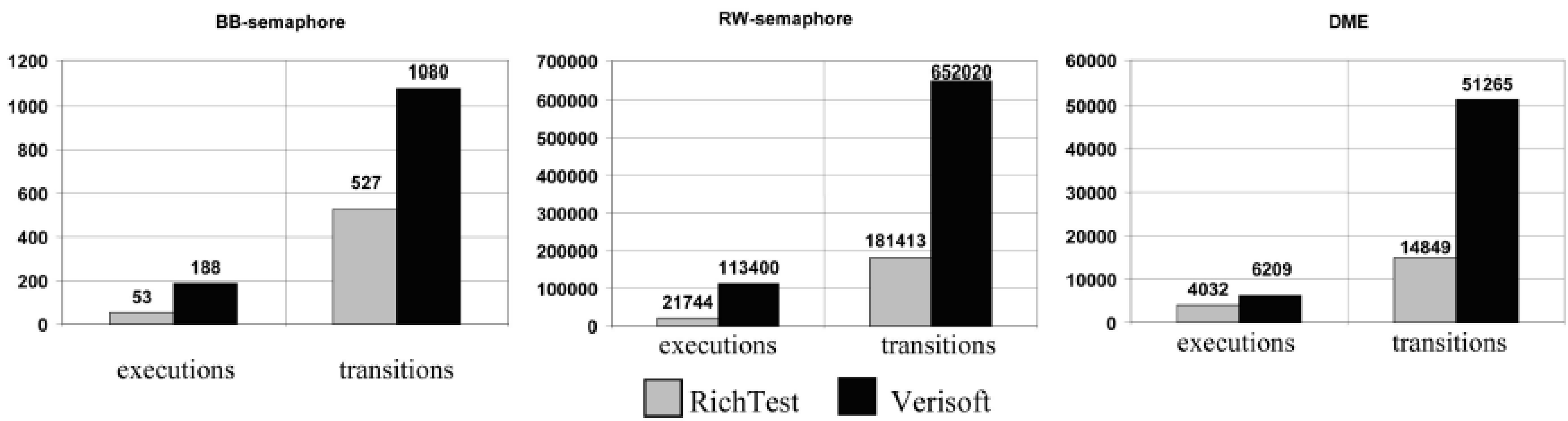
Implementation

- Library of synchronization objects: semaphores, monitors, send, receive
- Control/record the execution using the library
- No modification to thread scheduler
  - Portable to other operating systems and languages

Optimization

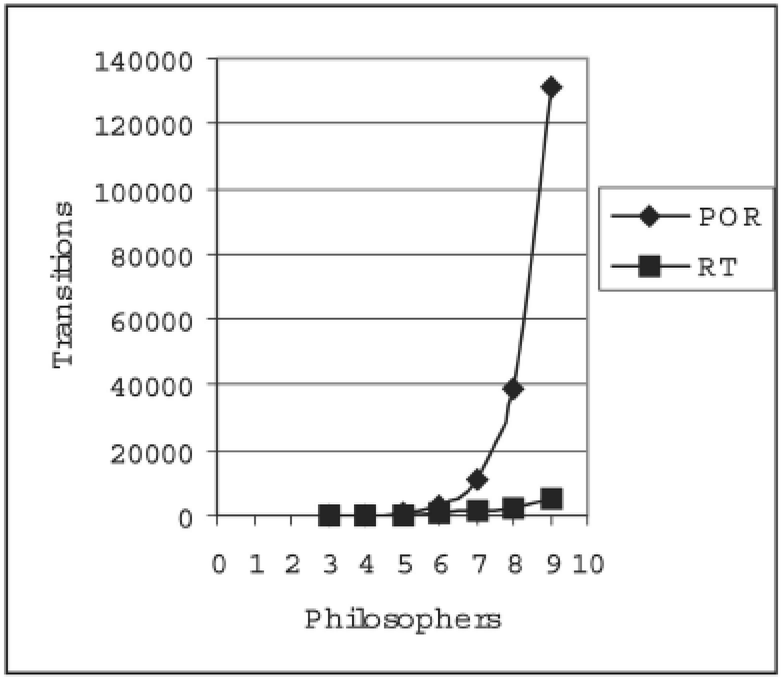
- Aim: Do not visit a SYN-sequence twice
- Keeping a list of visited SYN-sequence is expensive
- Trick: only include variants that obeys a specific set of rules. Proven that
  - We can still visit all SYN-sequences
  - Can start from any SYN-sequence
  - Computationally inexpensive to check

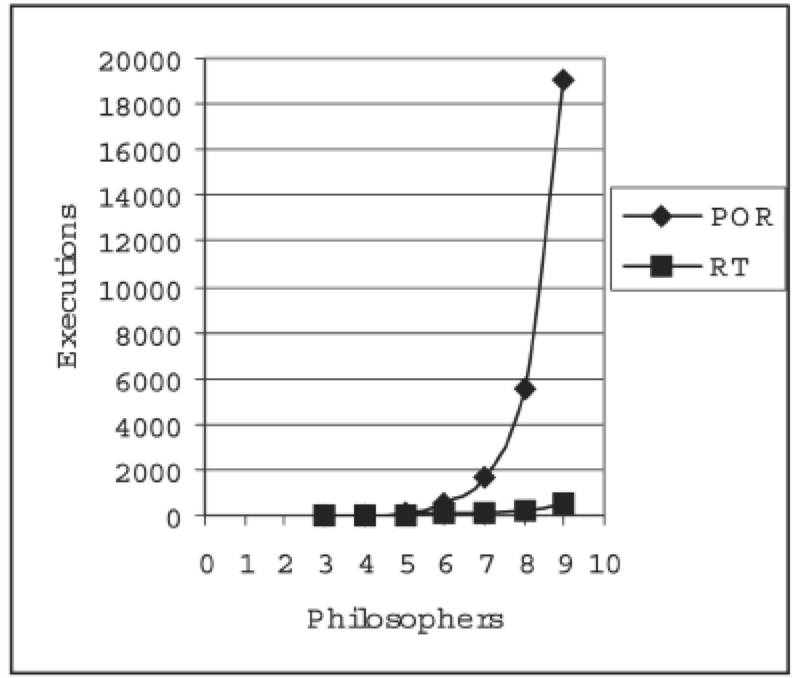
Results



BB-semaphore
1200
1000
800
600
400
200
0
53
188
527
1080
executions
transitions
RW-semaphore
700000
600000
500000
400000
300000
200000
100000
0
21744
113400
181413
652020
executions
transitions
DME
60000
50000
40000
30000
20000
10000
0
4032
6209
14849
51265
executions
transitions
RichTest
Verisoft

Results


Transitions
140000
120000
100000
80000
60000
40000
20000
0
0 1 2 3 4 5 6 7 8 9 10
Philosophers
POR
RT


Executions
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 3 4 5 6 7 8 9 10
Philosophers
POR
RT

Conclusion

- The new method for reachability testing
  - Guarantees the execution of every SYN-seqence exactly once
  - Does not require keeping a list of all visited SYN-sequences
  - Outperforms existing partial order reduction based techniques
  - Is platform independent