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Testing Multithreaded Programs with DPOR

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Introduction

- Testing programs is hard due to state space explosion.
- Some solutions:
  - Single threaded with inputs: dynamic symbolic execution (DSE)
  - Multithreaded with no inputs: partial order reduction.
  - Multithreaded with inputs: combination of both.

Topics of this Slideset

1. Introduction to testing multithreaded programs and partial order reduction

2. Our contributions in the ACSD 2012 paper:
   Saarikivi, O., Kähkönen, K., and Heljanko, K.: Improving Dynamic Partial Order Reductions for Concolic Testing:

   - Our improvement to dynamic partial order reduction (DPOR)
   - How to combine DPOR with dynamic symbolic execution
   - Our implementation and experiments

Testing multithreaded programs

- Behavior is affected by schedule $\rightarrow$ we must be able to control scheduling.
- Scheduling can be done on the level of *visible operations*, which are operations that can affect other threads.
- In our approach an execution tree formed of the scheduling decisions is explored.
- Explore the execution tree by repeatedly exploring alternate interleavings.

Example: Exploring execution trees

- Globals:

```
int a = 1;
```

- Thread 1:

```
int m = a;
a = 2;
```

- Thread 2:

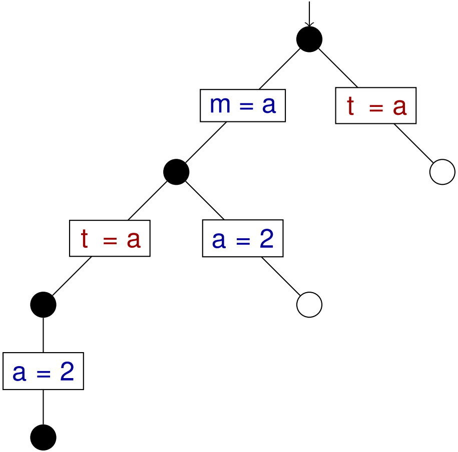
```
int t = a;
```

- Final state:

m==1

t==1

a==2



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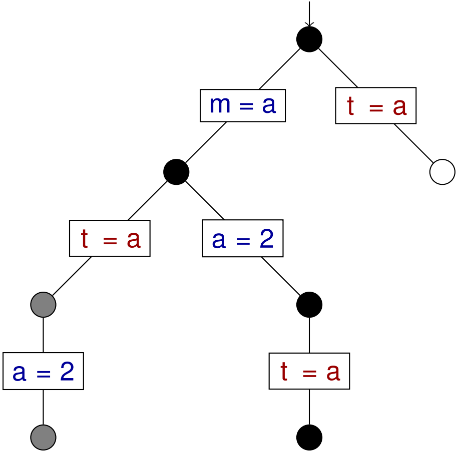

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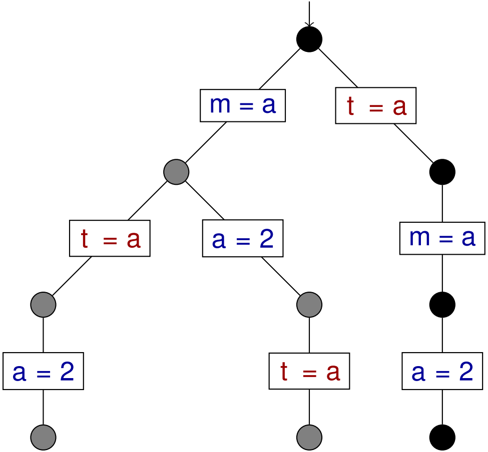


Partial order reduction

- In this work we consider the case of finding deadlocks and assertion errors.
- For some visible operations the order of execution doesn't matter.
- Partial order reduction methods exploit these independencies to reduce the amount of interleavings explored.

DPOR

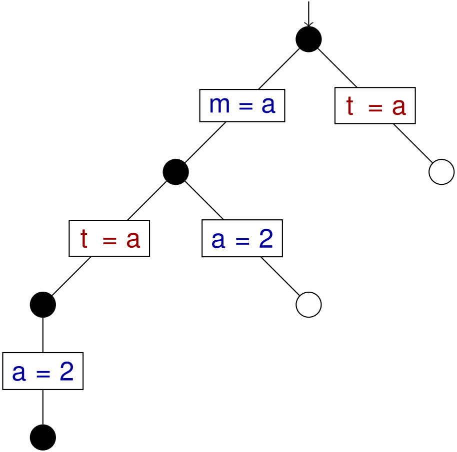
- The dynamic partial order reduction (DPOR) algorithm by Flanagan and Godefroid (2005) calculates what additional interleavings need to be explored from the history of the current execution.
- Once DPOR has fully explored the subtree from a state it will have explored a *persistent set* of operations from that state.
- When a race condition is identified during execution, a *backtracking point* is added to explore the alternate schedule later.
- Backtracking points are explored until no unexplored ones remain.

Identifying backtracking points

- DPOR tracks the causal relationships of visible operations for identifying backtracking points.
- Our implementation uses vector clocks for tracking the causality.
- Also last accesses to communication objects (COs) are tracked.
- A backtracking point is added if:
  1. A thread's next operation uses a previously accessed CO, and
  2. the two visible operations are concurrent.

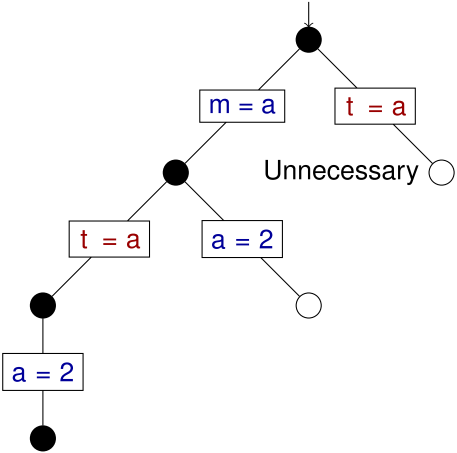
DPOR and concurrent reads

- DPOR uses vector clocks to detect independence of operations
- Original DPOR does not exploit the independence of multiple reads on the same shared variable.
- In the previous example the original DPOR would not have achieved any reduction.



Our modification to DPOR

- Extends DPOR to track the causal structure of reads and writes.
- We have refined the vector clock operations to implement the tracking.
- When identifying backtracking points:
  - For reads we only consider the previous write operation.
  - For writes all reads up to the previous write are examined.



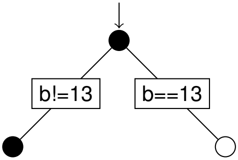
Dynamic Symbolic Execution

- Globals:

```
int a = 1;
int b = input;
```

- Code:

```
int m = a;
if (b == 13) {
    a = 2;
}
```



- First random execution with b = 109 on the right.
- Constraint from first execution:

  $\neg(b = 13)$

- Solve new inputs with an SMT solver.

Combining the DPOR and DSE

- Globals:

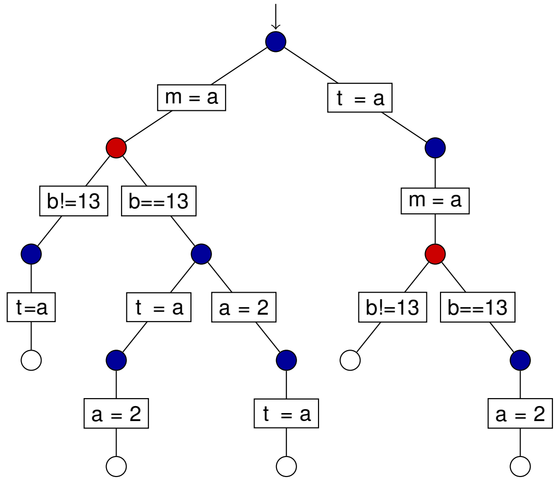
```
int a = 1;
int b = input;
```

- Thread 1:

```
int m = a;
if (b == 13) {
    a = 2;
}
```

- Thread 2:

```
int t = a;
```



About our tool

- The LIME Concolic Tester (LCT) is a tool that uses a client-server model to distribute work to multiple computers over a network.
- Open source and available for download at: `http://www.tcs.hut.fi/Software/lime/`
- We have also implemented *sleep sets* in our tool.
- Further details on how DPOR and sleep sets were implemented in the client-server model with multiple concurrent clients are available in our paper.

Experiments

- We have evaluated our modified DPOR against unmodified DPOR and the “race detection and flipping algorithm” of jCUTE by Koushik Sen and Gul Agha.
- The reduction achieved by DPOR depends on the first random schedules explored. We report the average of several independent measurements.
- For our modified DPOR the effect of using sleep sets was also evaluated.

Experiments cont.

Program	Number of test executions to achieve path coverage			
	DPOR	DPOR-CR	DPOR-CR, sleep sets	jCUTE
Indexer (12)	8614.6	154	27	**8**
Indexer (13)	> 10000	> 10000	722.4	**343**
File System (14)	6.8	3.2	2.6	**2**
File System (16)	568.4	26.8	**19.5**	31
File System (18)	> 10000	250.2	**145.8**	2026
Parallel Pi (3)	> 10000	3217.8	19.2	**6**
Parallel Pi (5)	> 10000	> 10000	1220.6	**120**
Bounded Buffer	64.4	67.2	16	**8**
Sync Queue	> 10000	> 10000	**9**	N/A

Numbers for DPOR columns are averages of 5 separate measurements.

Conclusion

- We have modified the DPOR algorithm to exploit the commutativity of read operations.
- We have implemented the modified DPOR algorithm with sleep sets in our testing tool LCT, an open source DSE tool designed for distributed use.
- Our modifications to DPOR allow it to achieve competitive amounts of reduction.