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# Improved Testing of Multithreaded Programs with Dynamic Symbolic Execution

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# Validation Methods for Concurrent Systems

There are many system validation approaches:

- Model based approaches:
  - Model-based Testing: Automatically generating tests for an implementation from a model of a concurrent system
  - Model Checking: Exhaustively exploring the behavior of a model of a concurrent system
  - Theorem proving, Abstraction, …
- Source code analysis based approaches:
  - Automated test generation tools
  - Static analysis tools
  - Software model checking, Theorem Proving for source code, …

# Model Based vs. Source Code Based Approaches

- Model based approaches require building the verification model
  - In hardware design the model is your design
  - Usually not so for software:
    - Often a significant time effort is needed for building the system model
    - Making the cost-benefit argument is not easy for non-safety-critical software
- Source code analysis tools make model building cheap: The tools build the model from source code as they go

# The Automated Testing Problem

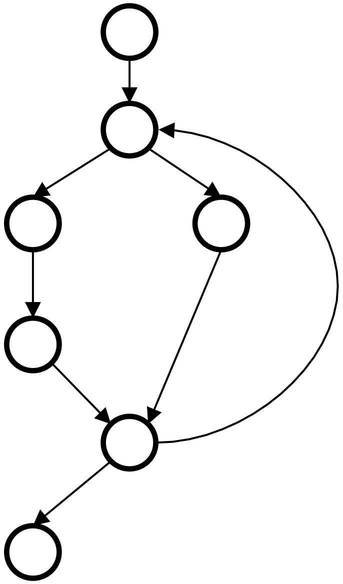
- How to automatically test the local state reachability in multithreaded programs that read input values
  - E.g., find assertion violations, uncaught exceptions, etc.
- Our tools use a subset of Java as its input language
- The main challenge: path explosion and numerous interleavings of threads
- One popular testing approach: dynamic symbolic execution (DSE) + partial order reduction
- New approach: DSE + unfoldings

# Dynamic Symbolic Execution

- DSE aims to systematically explore different execution paths of the program under test

```
x = input
x = x + 5

if (x > 10) {
 ...
}
...
```



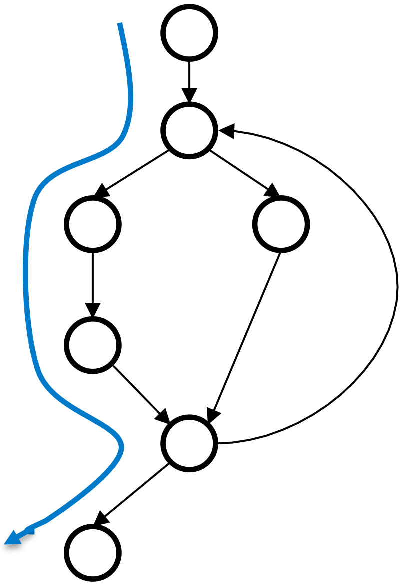
Control flow graph

# Dynamic Symbolic Execution

- DSE typically starts with a random execution
- The program is executed concretely and symbolically

```
x = input
x = x + 5

if (x > 10) {
 ...
}
...
```



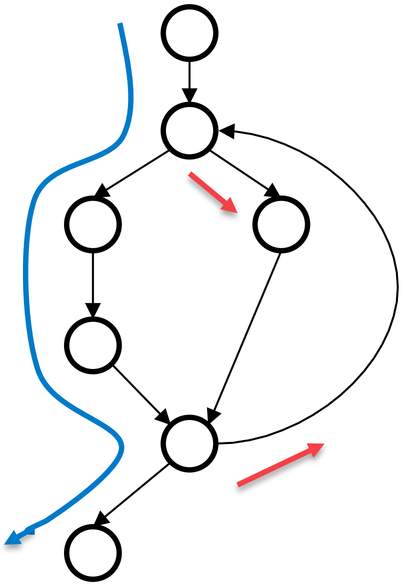
Control flow graph

# Dynamic Symbolic Execution

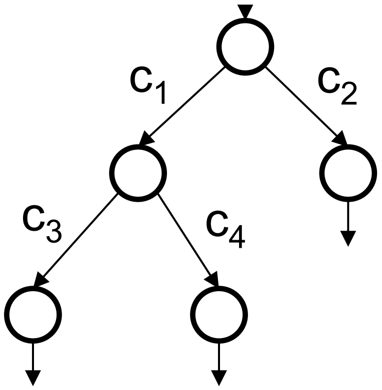
- Symbolic execution generates constraints at branch points that define input values leading to true and false branches

```
x = input
x = x + 5

if (x > 10) {
 ...
}
...
```



Control flow graph

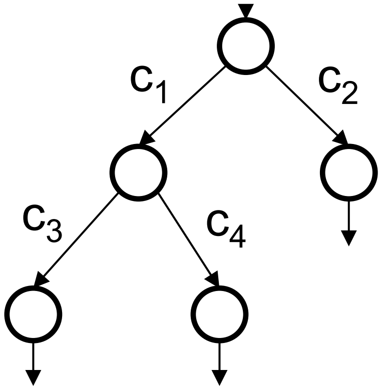


$c_1 = input_1 + 5 > 10$

$c_2 = input_1 + 5 \leq 10$

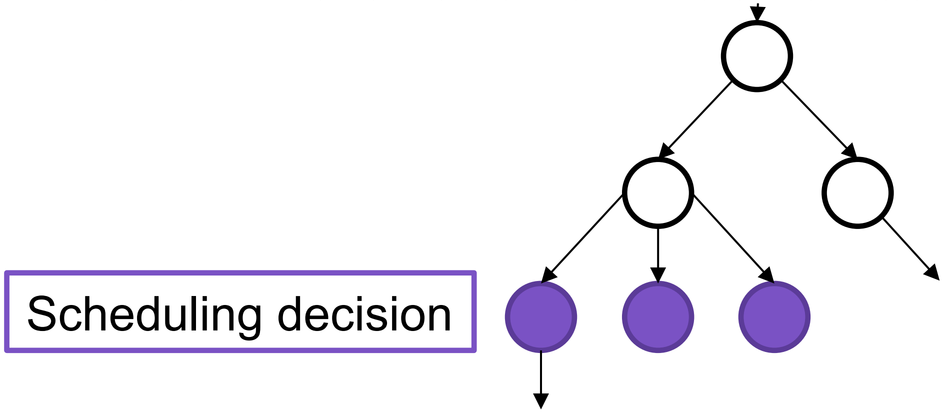
# Dynamic Symbolic Execution

- A conjunction of symbolic constraints along an execution path is called a path constraint
  - Solved using SAT modulo theories (SMT)-solvers to obtain concrete test inputs for unexplored execution paths
  - E.g., $\mathrm{pc}\colon\ \mathrm{input}_1 + 5 > 10 \wedge \mathrm{input}_2 * \mathrm{input}_1 = 50$
  - Solution: $\mathrm{input}_1 = 10 \text{ and } \mathrm{input}_2 = 5$



# What about Multithreaded Programs?

- We need to be able to reconstruct scheduling scenarios
- Take full control of the scheduler
- Execute threads one by one until a global operation (e.g., access of shared variable or lock) is reached
- Branch the execution tree for each enabled operation



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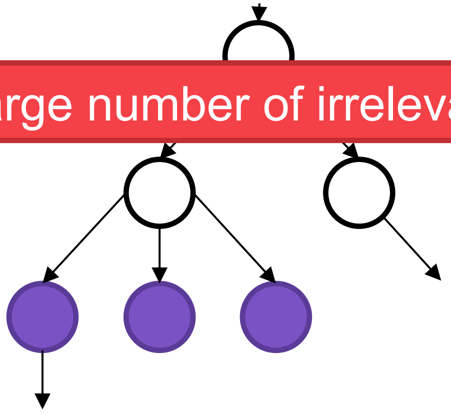
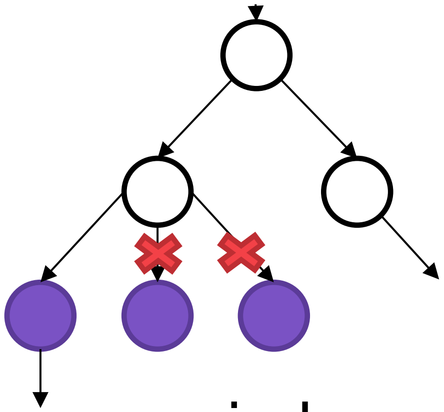


Problem: a large number of irrelevant interleavings

# One Solution: Partial-Order Reduction

- Ignore provably irrelevant parts of the symbolic execution tree



- Existing algorithms use independence of state transitions:
  - dynamic partial-order reduction (DPOR) [FlaGod05]
  - race detection and flipping [SenAgh06]

# Independence of State Transitions

- There are several notions of independence that can be statically derived from the program source code:
  - Two operations in different processes on local data are independent
  - Two reads in different processes to the same global variable are independent with each other
  - Two writes in different processes to two different global variables are independent
  - Etc.

# Independence of State Transitions

- Independence induces diamond structures in the state space as follows

- A pair **t** and **u** independent state transitions satisfy the following two properties for all sequences of state transitions **w**, **w′** of the system:
  1. If **w t u w′** is an execution of the system,

     then so is **w u t w′** ; and
  2. If **w t** and **w u** are executions of the system, then so are **w t u** and **w u t**

# Mazurkiewics Traces

- If we have an execution **w″** = **w t u w′** such that **t** and **u** are independent, then the execution **w u t w′** will lead to the same final state
- If we take the union of all execution sequences that can be obtained from **w″** by the transitive closure of repeatedly permuting any two adjacent independent state transitions we obtain the equivalence class called *Mazurkiewicz trace* [**w″**]
- All executions in the Mazurkiewicz trace are executable and will lead to the same final state – testing one of them suffices!
- If a partial order reduction method preserves one test from each Mazurkiewicz trace, it will also preserve all deadlocks

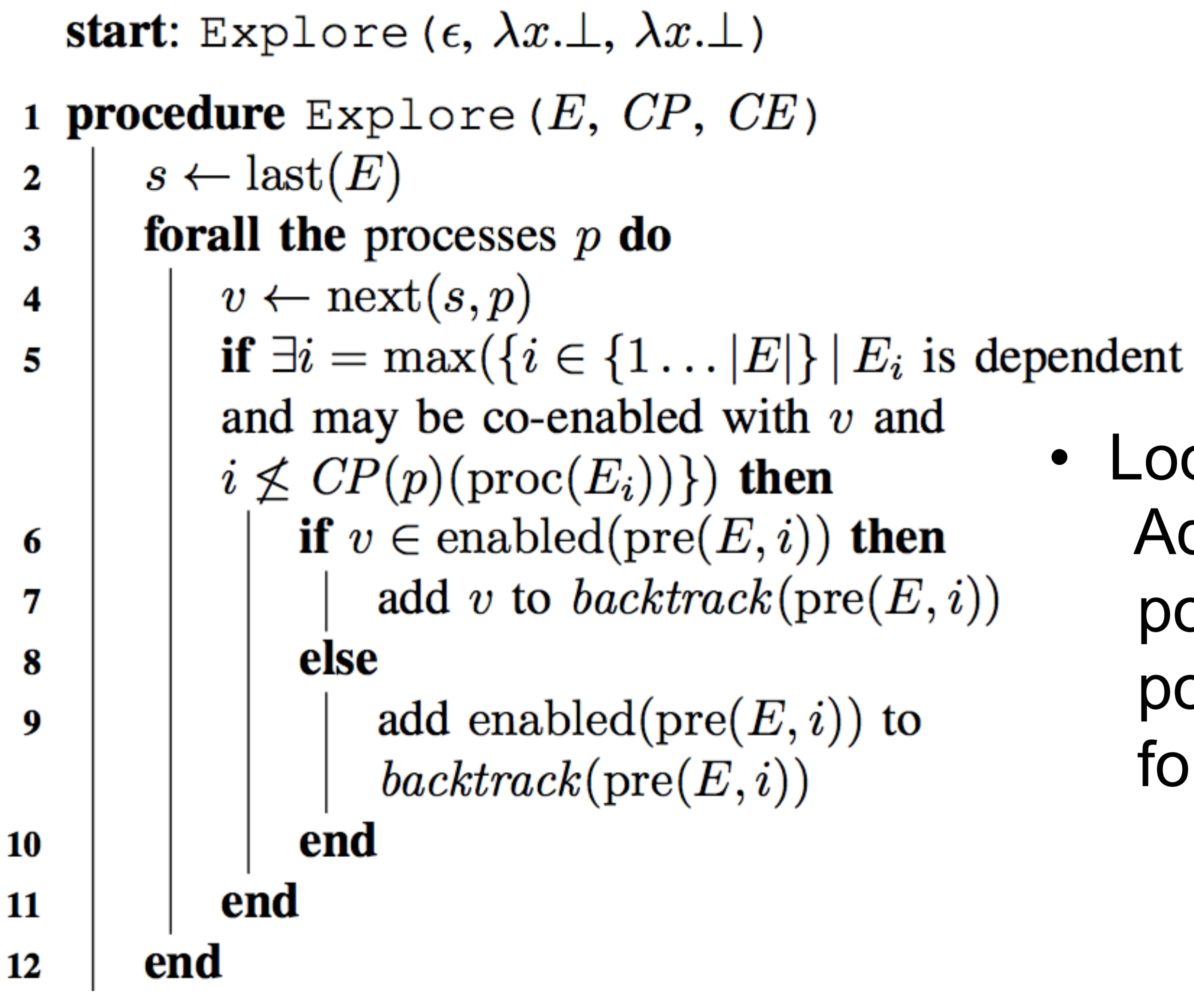
# Dynamic Partial-Order Reduction (DPOR)

- DPOR algorithm by Flanagan and Godefroid (2005) calculates what additional interleavings need to be explored based on 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
  - Will find all deadlocks and assertions on local states
- As any persistent set approach preserves one interleaving from each Mazurkiewicz trace

# DPOR – Algorithm Intuition

- The DPOR algorithm does a depth-first traversal of the execution tree
- It tries to detect races between state transitions, e.g., a case when in a test run a global variable X is first written by process 1, that could be also concurrently read by process 2
- When race conditions are detected a backtracking point is added to try both outcomes of the race
- In the example, a backtracking point would be added just before write by process 1 to also explore the other interleaving where the read by process 2 happens first

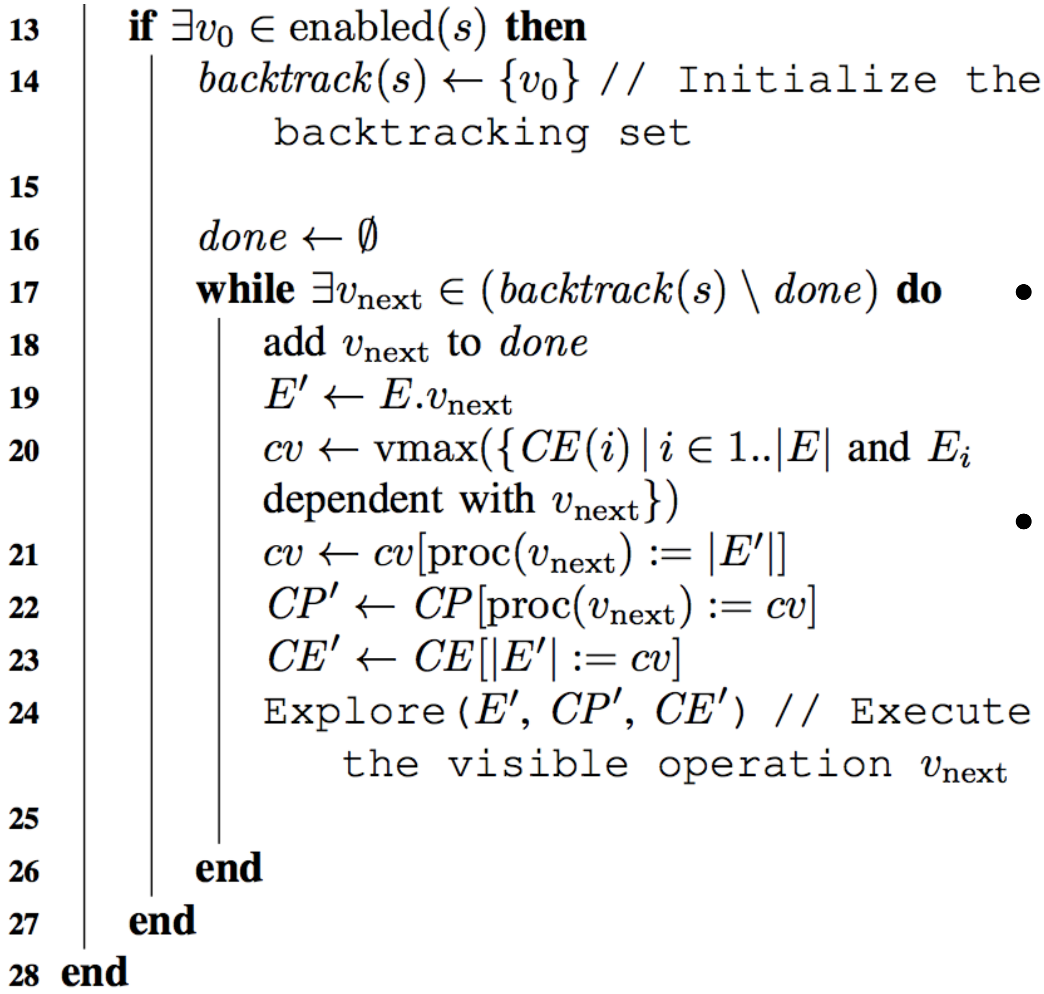
# Basic DPOR Pseudocode – Part 1



```
start: Explore($\epsilon$, $\lambda x.\bot$, $\lambda x.\bot$)

procedure Explore($E$, $CP$, $CE$)
    $s \leftarrow \mathrm{last}(E)$
    forall the processes $p$ do
        $v \leftarrow \mathrm{next}(s, p)$
        if $\exists i = \max(\{i \in \{1 \ldots |E|\} \mid E_i$ is dependent
        and may be co-enabled with $v$ and
        $i \not\leq CP(p)(\mathrm{proc}(E_i))\})$ then
            if $v \in \mathrm{enabled}(\mathrm{pre}(E, i))$ then
                add $v$ to $\mathit{backtrack}(\mathrm{pre}(E, i))$
            else
                add $\mathrm{enabled}(\mathrm{pre}(E, i))$ to
                $\mathit{backtrack}(\mathrm{pre}(E, i))$
            end
        end
    end
```

- Looks for races: Adds backtrack points for any potential races found

# Basic DPOR Pseudocode – Part 2



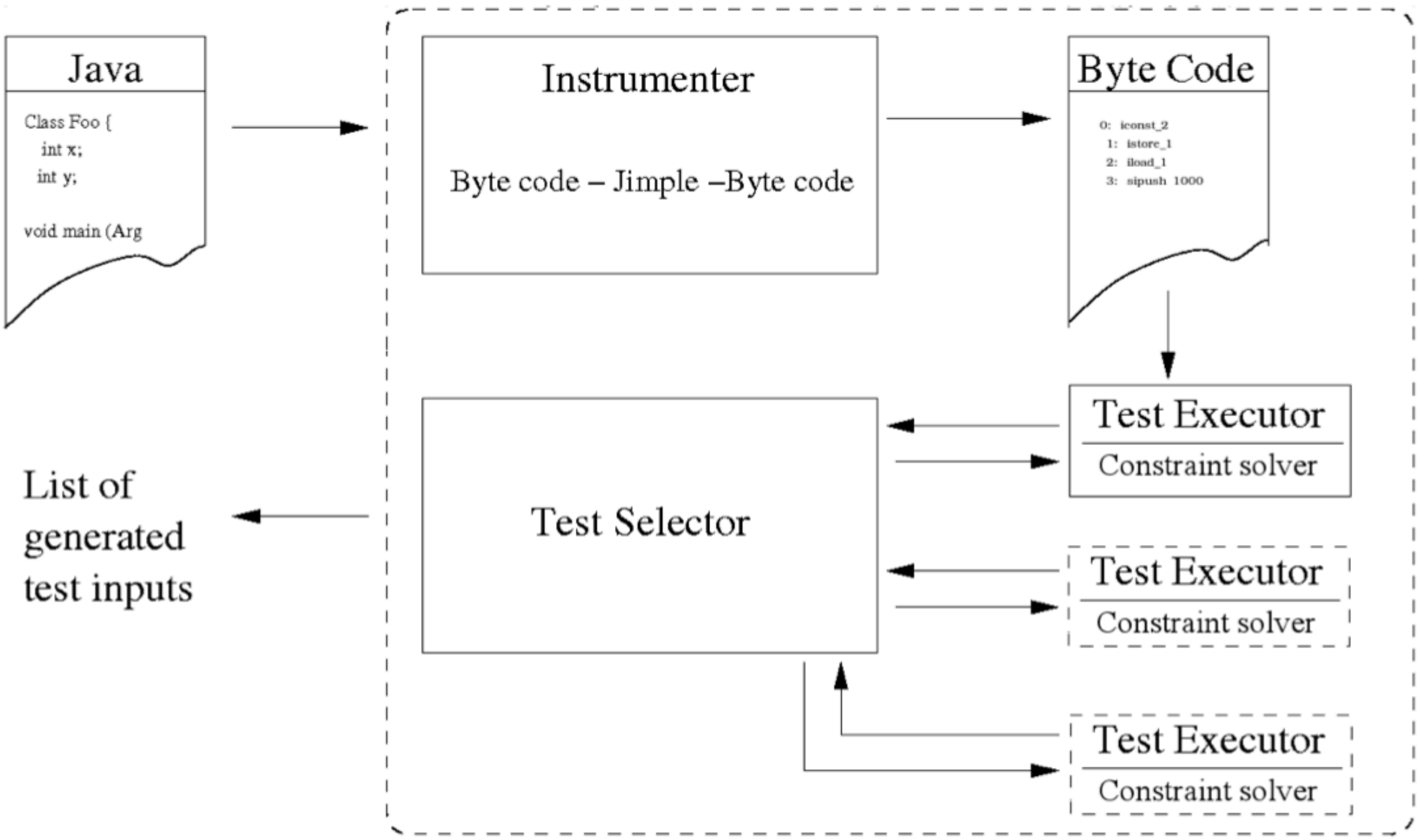
```
    if $\exists v_0 \in \mathrm{enabled}(s)$ then
        $backtrack(s) \leftarrow \{v_0\}$ // Initialize the backtracking set

        $done \leftarrow \emptyset$
        while $\exists v_{\mathrm{next}} \in (backtrack(s) \setminus done)$ do
            add $v_{\mathrm{next}}$ to $done$
            $E' \leftarrow E.v_{\mathrm{next}}$
            $cv \leftarrow \mathrm{vmax}(\{CE(i) \mid i \in 1..|E| \text{ and } E_i \text{ dependent with } v_{\mathrm{next}}\})$
            $cv \leftarrow cv[\mathrm{proc}(v_{\mathrm{next}}) := |E'|]$
            $CP' \leftarrow CP[\mathrm{proc}(v_{\mathrm{next}}) := cv]$
            $CE' \leftarrow CE[|E'| := cv]$
            Explore($E'$, $CP'$, $CE'$) // Execute the visible operation $v_{\mathrm{next}}$

        end
    end
end
```

- Execute forward using backtrack sets
- Update vector clocks for race detection

# Identifying Backtracking Points in DPOR

- To detect races, DPOR tracks the causal relationships of global operations in order to identify backtracking points
- In typical implementations the causal relationships are tracked by using vector clocks
- An optimized DPOR approach pseudocode can be found from:
  - Saarikivi, O., Kähkönen, K., and Heljanko, K.: Improving Dynamic Partial Order Reductions for Concolic Testing. ACSD 2012.
- Slideset: Testing Multithreaded programs with DPOR

# Parallelizing DSE: LCT Architecture

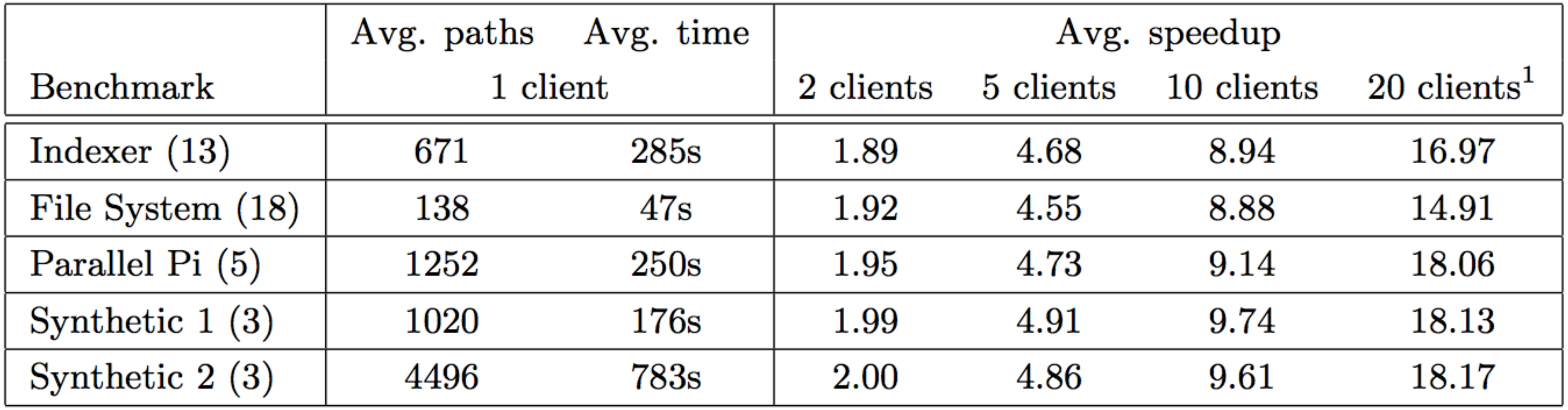


```
Class Foo {
  int x;
  int y;

void main (Arg
```

```
0:  iconst_2
 1:  istore_1
 2:  iload_1
 3:  sipush  1000
```

# Parallelization of LCT (PDMC’12)

- DSE+DPOR parallelizes excellently, LCT speedups from: Kähkönen, K., Saarikivi, O., and Heljanko, K.: LCT: A Parallel Distributed Testing Tool for Multithreaded Java Programs, PDMC’12
- The experiments below have both DPOR and Sleep Sets enabled but LCT still achieves good speedups



| Benchmark | Avg. paths<br>1 client | Avg. time<br>1 client | Avg. speedup<br>2 clients | 5 clients | 10 clients | 20 clients$^1$ |
|---|---|---|---|---|---|---|
| Indexer (13) | 671 | 285s | 1.89 | 4.68 | 8.94 | 16.97 |
| File System (18) | 138 | 47s | 1.92 | 4.55 | 8.88 | 14.91 |
| Parallel Pi (5) | 1252 | 250s | 1.95 | 4.73 | 9.14 | 18.06 |
| Synthetic 1 (3) | 1020 | 176s | 1.99 | 4.91 | 9.74 | 18.13 |
| Synthetic 2 (3) | 4496 | 783s | 2.00 | 4.86 | 9.61 | 18.17 |

# Sleep Sets

- *Sleep sets* were invented by Patrice Godefroid in:
  - P. Godefroid. Using Partial Orders to Improve Automatic Verification Methods. In Proc. 2nd Workshop on Computer Aided Verification, LNCS 531, p. 176-185, 1990
- The algorithm maintains Sleep sets, which allow for a sound truncation of some of the execution tree branches
- Sleep sets provide nice additional reduction on top of DPOR and thus are an easy extra addition to it
- For details, see: Patrice Godefroid: Partial-Order Methods for the Verification of Concurrent Systems - An Approach to the State-Explosion Problem. LNCS 1032, 1996

# Sleep Set Pseudocode (P. Godefroid'96)

```
Initialize: $Stack$ is empty; $H$ is empty;
            $s_0.Sleep = \emptyset$;
            push ($s_0$) onto $Stack$;
Loop: while $Stack \neq \emptyset$ do {
            pop ($s$) from $Stack$;
            if $s$ is NOT already in $H$ then {
               enter $s$ in $H$;
               $T$ = Persistent_Set($s$) $\setminus s.Sleep$
               }
            else {
               $T = \{t \mid t \in H(s).Sleep \wedge t \notin s.Sleep\}$;
               $s.Sleep = s.Sleep \cap H(s).Sleep$;
               $H(s).Sleep = s.Sleep$
               }
            for all $t$ in $T$ do {
                 $s'$ = succ($s$) after $t$; /* $t$ is executed */
                 $s'.Sleep = \{t' \in s.Sleep \mid (t, t')$ are independent in $s$ };
                 push ($s'$) onto $Stack$;
                 $s.Sleep = s.Sleep \cup \{t\}$
                 }
            }
```

- Can be combined with persistent sets (e.g., DPOR)
- Ignore: Only for stateful search
- Fire transitions and update sleep sets

# Example of Sleep Set POR Reduction

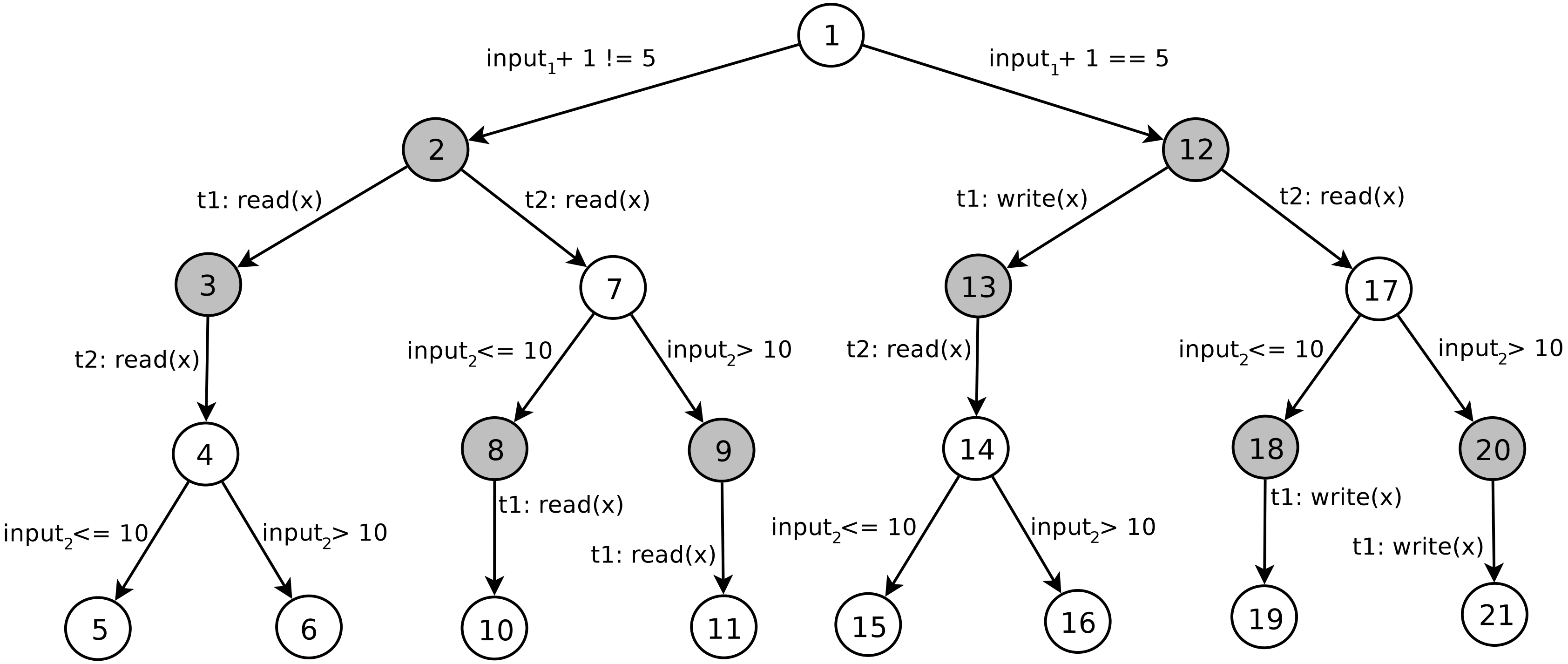
```
Global vars:

X = 0;
```

```
Thread 1:

1: i1 = input();
2: i1 = i1 + 1;
3: if (i1 == 5)
4:      X = 5;
5: else
6:      a = X;
```

```
Thread 2:

7: i2 = input();
8: b = X;
9: if (i2 > 10)
10:     b = 0;
```

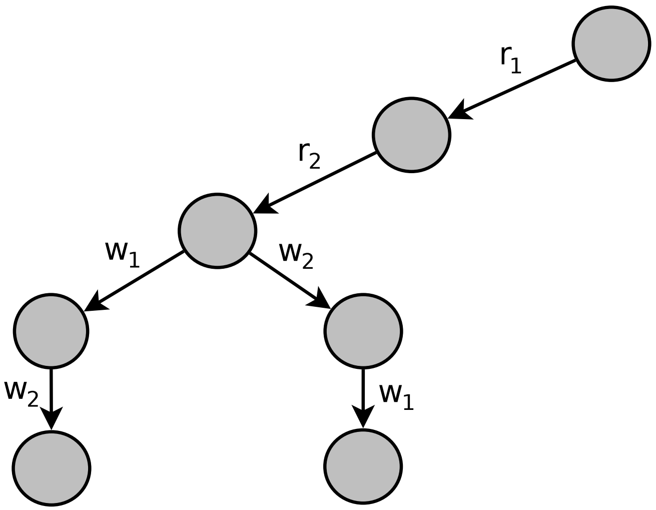
# Sleep Set Reduction Example

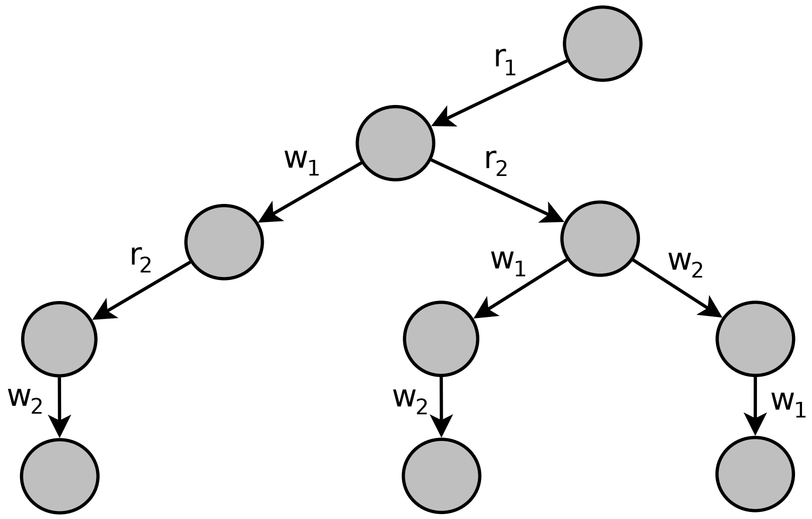
- At node 2 only one of the two independent read interleavings is needed
- The sleep set method is able to prune the subtrees rooted under node 7



# DPOR is Search Order Dependent

```
Global variables:   Thread 1:       Thread 2:
X = 0;              1: a = X;       3: b = X;
Y = 0;              2: Y = 1;       4: Y = 2;
```



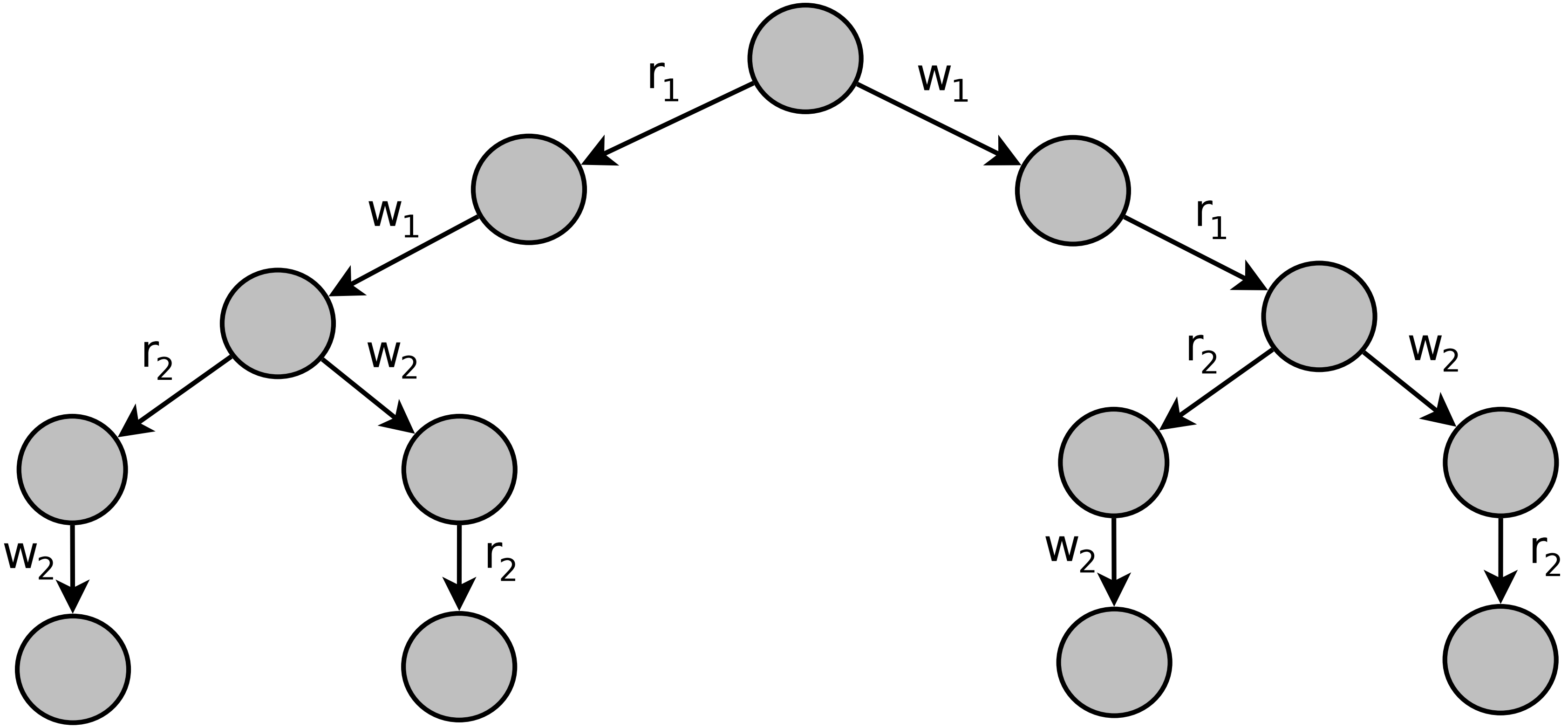


# Family of Programs with Exponential DPOR Reduced Execution Trees

- Example: Add N variables and 2N threads: There will be $2^N$ test runs as there are $2^N$ deadlocks (Mazurkiewicz traces), and DPOR preserves one test run for each deadlock (Mazurkiewicz trace)

```
Global variables:    Thread 1:          Thread 2:

X = 0;               1: a = X;          2: X = 1;

Y = 0;

                     Thread 3:          Thread 4:

                     3: b = Y;          4: Y = 2;
```

# Exponentially Growing DPOR Example, N=2 with $2^N = 4$ test runs

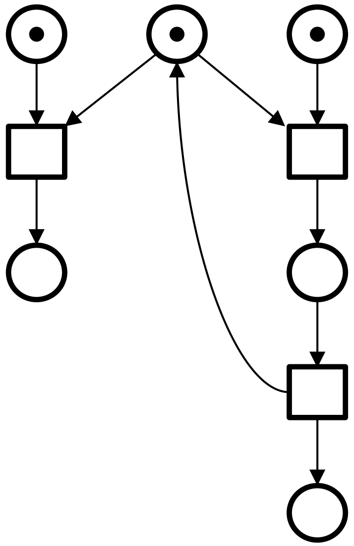


# Another Solution?

- Can we create a symbolic representation of the executions that contain all the interleavings but in more compact form than with execution trees?
- **Yes**, with Unfoldings
- Originally created by Ken McMillan
- Book: Esparza, J. and Heljanko, K.: Unfoldings - A Partial-Order Approach to Model Checking. EATCS Monographs in Theoretical Computer Science, Springer, ISBN 978-3-540-77425-9, 172 p., 2008.
- http://users.ics.aalto.fi/kepa/publications/Unfoldings-Esparza-Heljanko.pdf

# What Are Unfoldings?

- Unwinding of a control flow graph is an execution tree
- Unwinding of a Petri net (Java code) is an unfolding
- Can be exponentially more compact than exec. trees



Petri net

Initial unfolding

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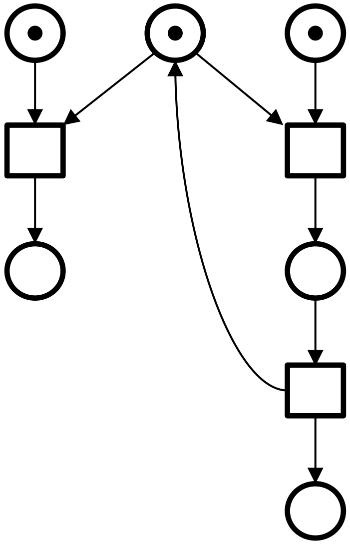
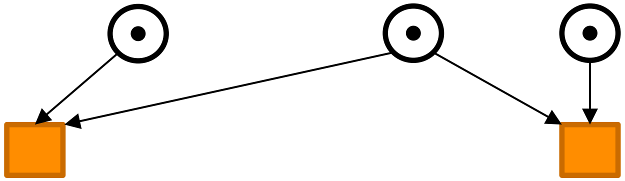


Petri net



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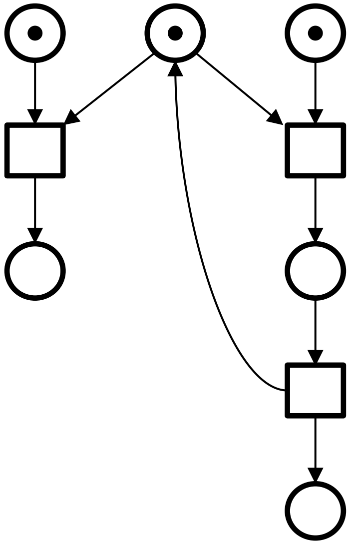
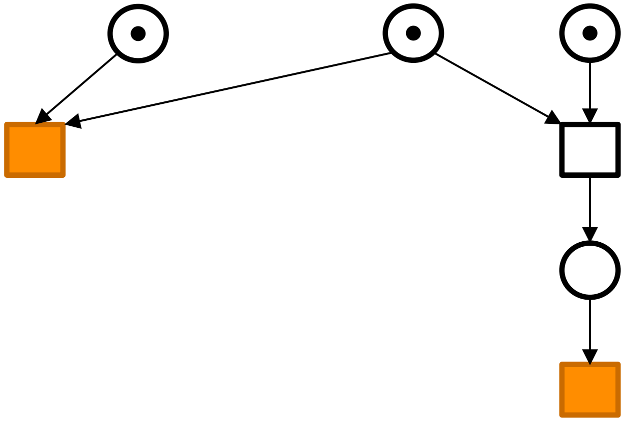


Petri net



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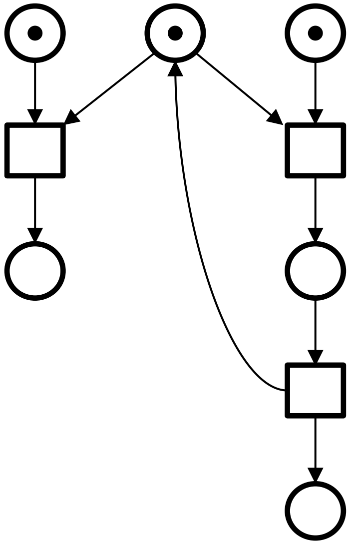
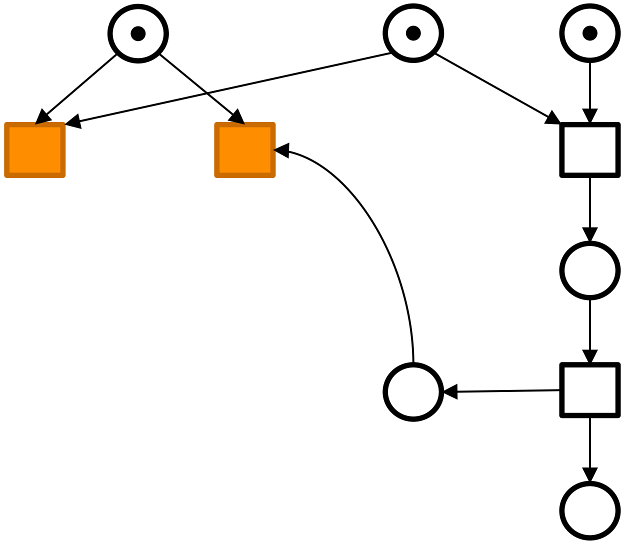


Petri net



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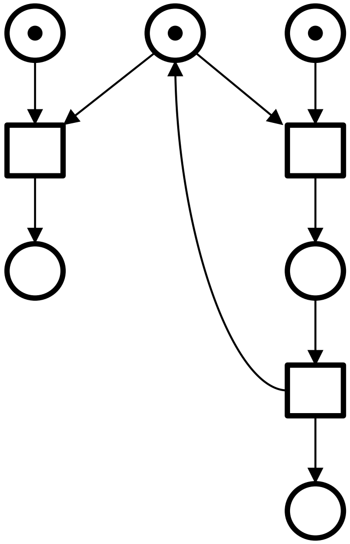
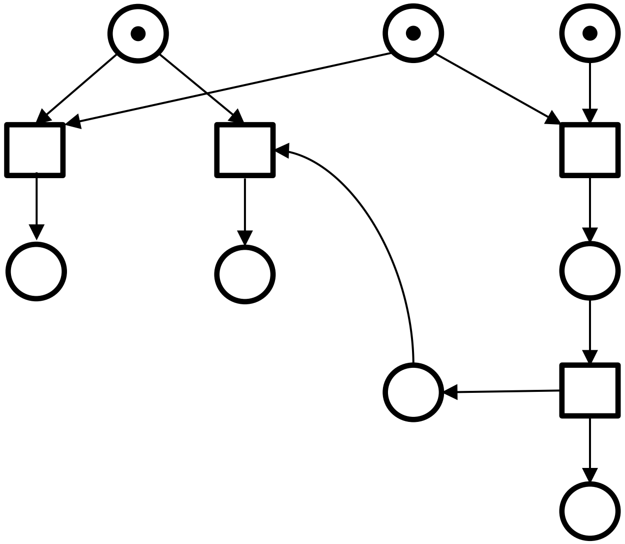
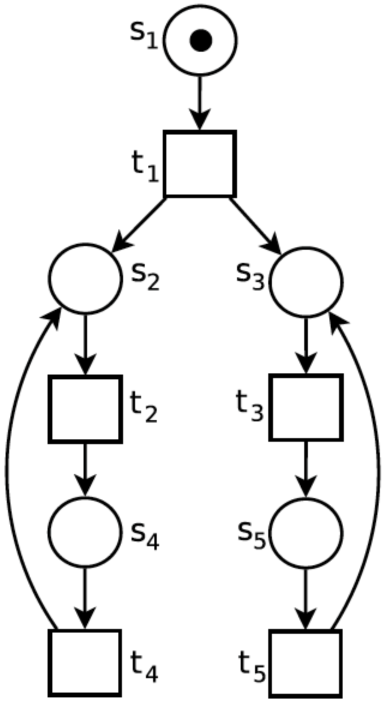


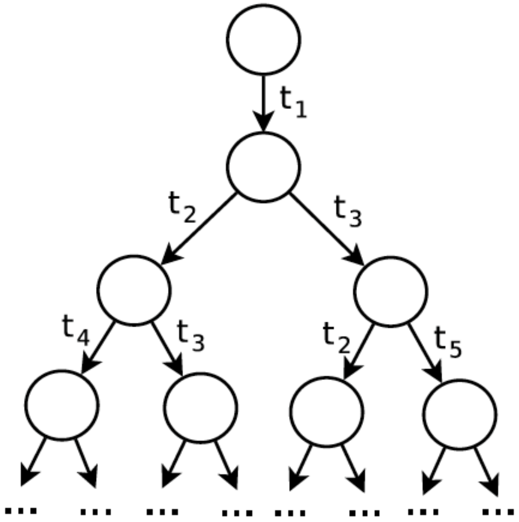
Petri net

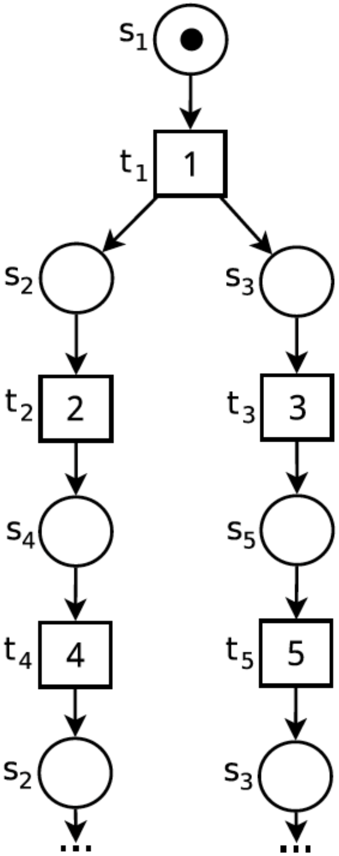


Unfolding

# Example: Petri net, Execution Tree, Unfolding



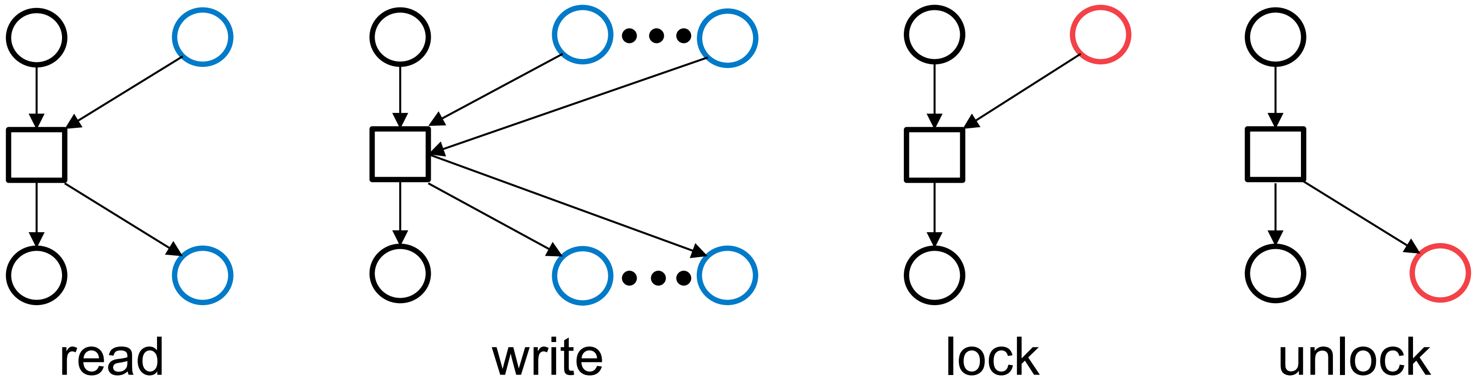




- Note: Execution tree grows exponentially in the levels, unfolding grows only linearly

# Using Unfoldings with DSE

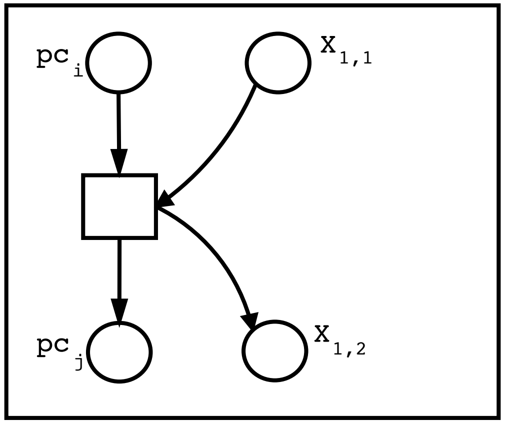
- When a test execution encounters a global operation, extend the unfolding with one of the following events:



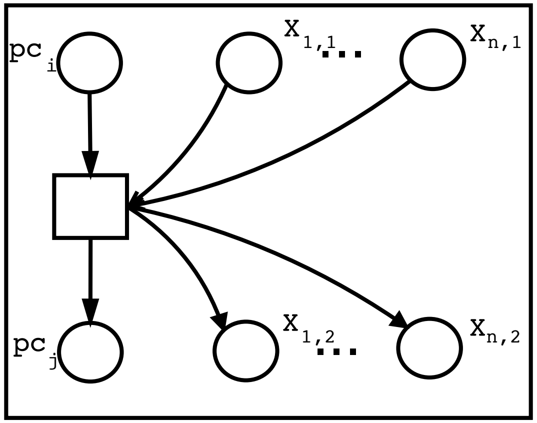
- Trick: Place Replication of global variables into N variables, one per each process – makes all reads independent of other reads

# Shared Variables have Local Copies

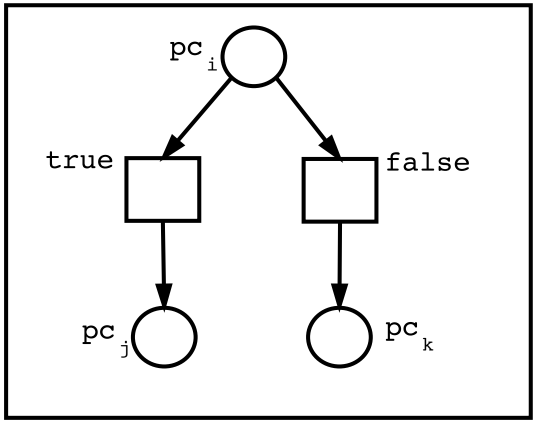
read global variable

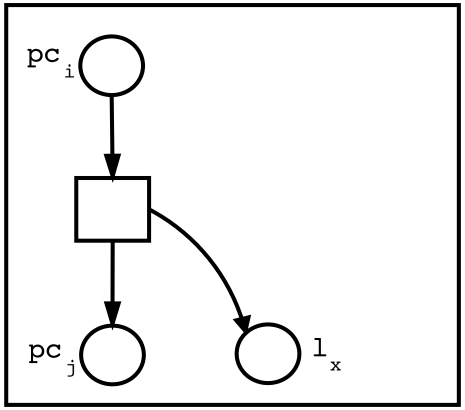


write global variable

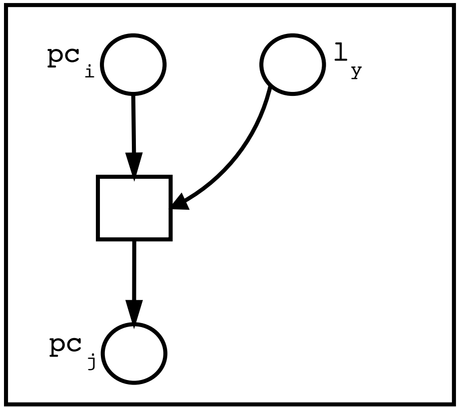


symbolic branching





release lock l



acquire lock l

Write modifies all copies of the variable X

# From Java Source Code to Unfoldings

- The unfolding shows the control and data flows possible in all different ways to solve races in the Java code
- The underlying Petri net is never explicitly built in the tool, we compute possible extensions on the Java code level
- Our unfolding has no data in it – The unfolding is an over-approximation of the possible concurrent executions of the Java code
- Once a potential extension has been selected to extend the unfolding, the SMT solver is used to find data values that lead to that branch being executed, if possible
- Branches that are non-feasible (due to data) are pruned

# Example – Unfolding Shows Data Flows

Global variables:

```
int x = 0;
```

Thread 1:

```
local int a = x;
if (a > 0)
  error();
```

Thread 2:

```
local int b = x;
if (b == 0)
  x = input();
```

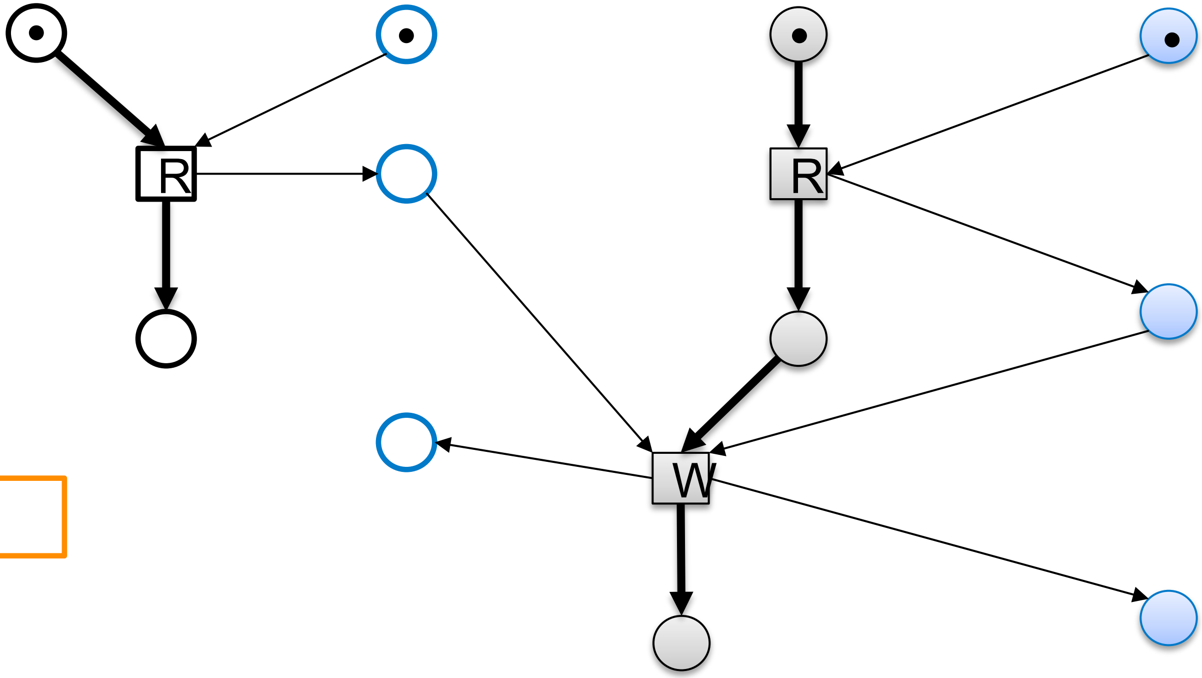
Initial unfolding

# Example – Unfolding Shows Data Flows

Global variables:
int x = 0;

Thread 1:
local int a = x;
if (a > 0)
  error();

Thread 2:
local int b = x;
if (b == 0)
  x = input();



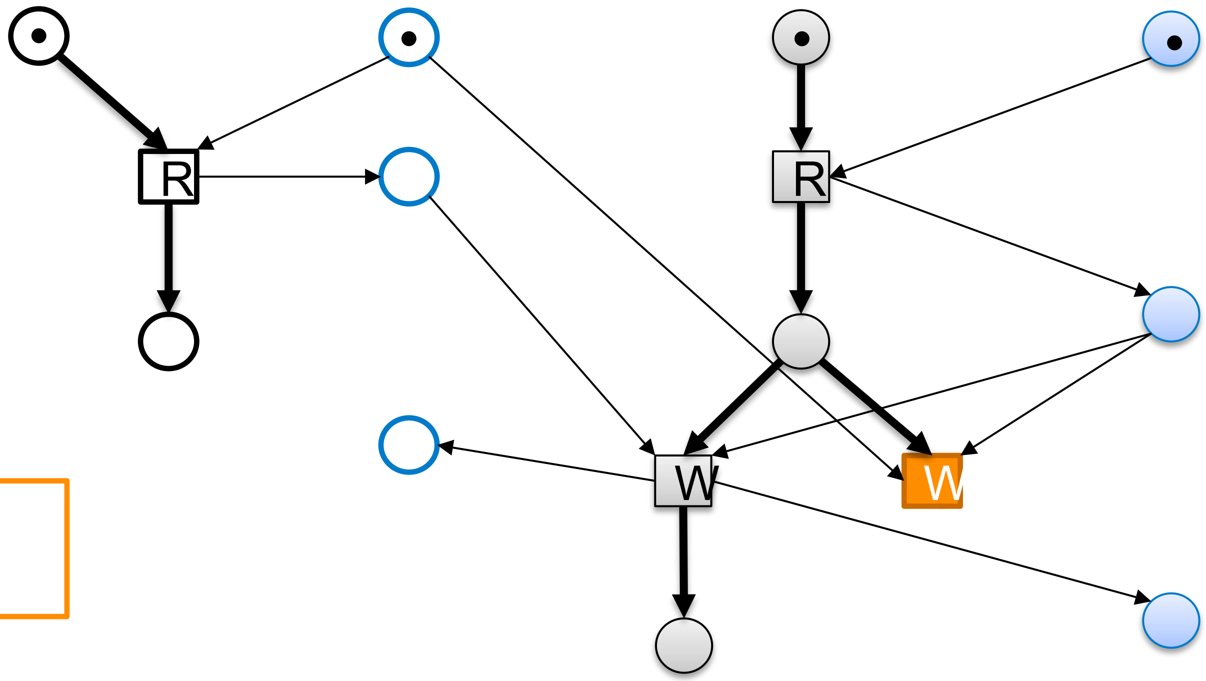
First test run

# Example – Unfolding Shows Data Flows

Global variables:
int x = 0;

Thread 1:
local int a = x;
if (a > 0)
  error();

Thread 2:
local int b = x;
if (b == 0)
  x = input();



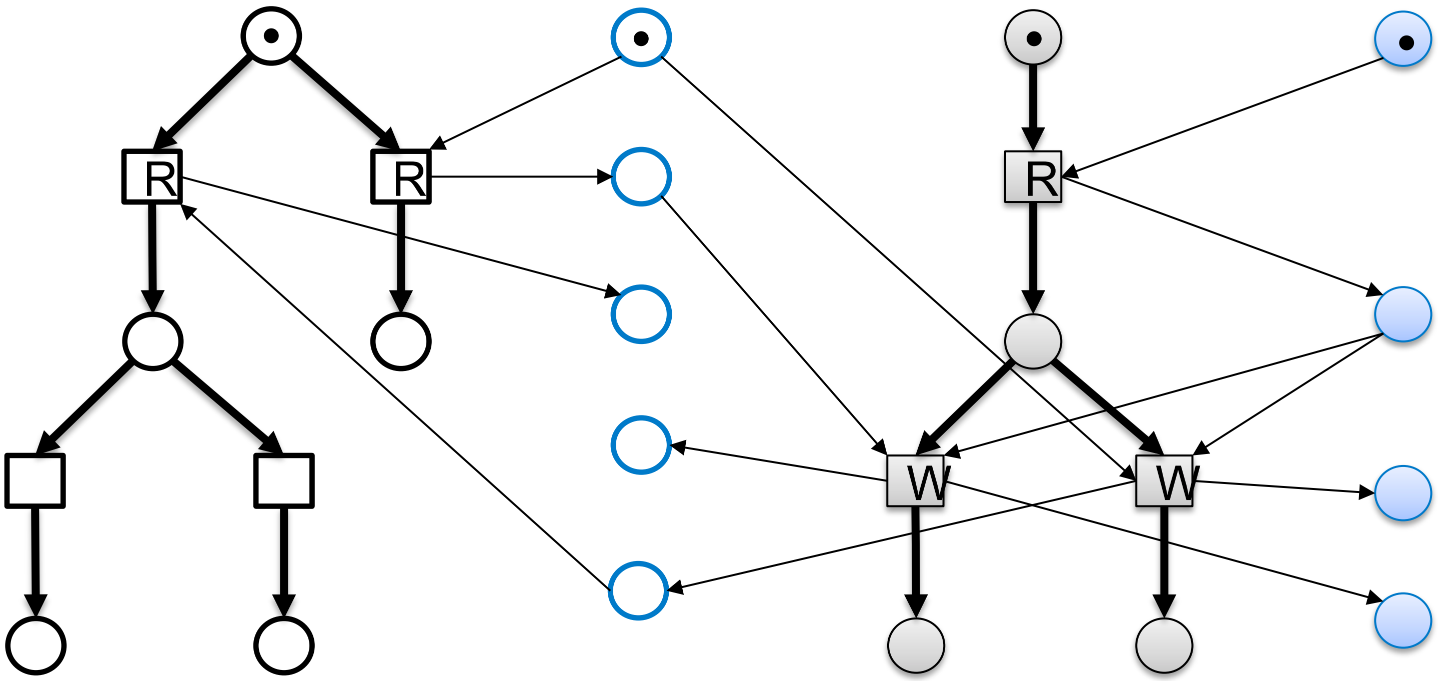
Find possible extensions

# Example– Unfolding Shows Data Flows

Global variables:
int x = 0;

Thread 1:
local int a = x;
if (a > 0)
  error();

Thread 2:
local int b = x;
if (b == 0)
  x = input();



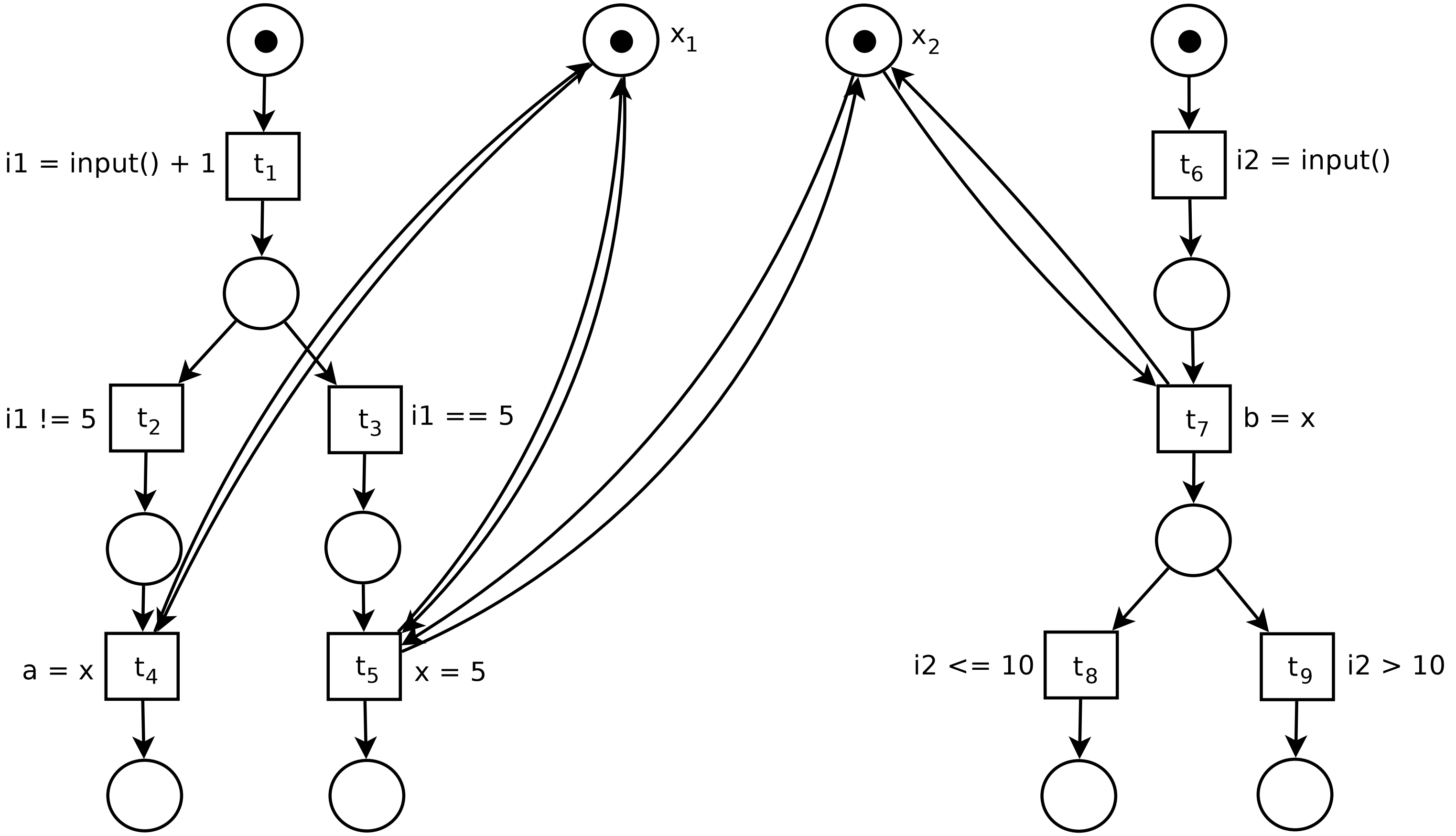
# Another Example Program

```
Global vars:

X = 0;
```

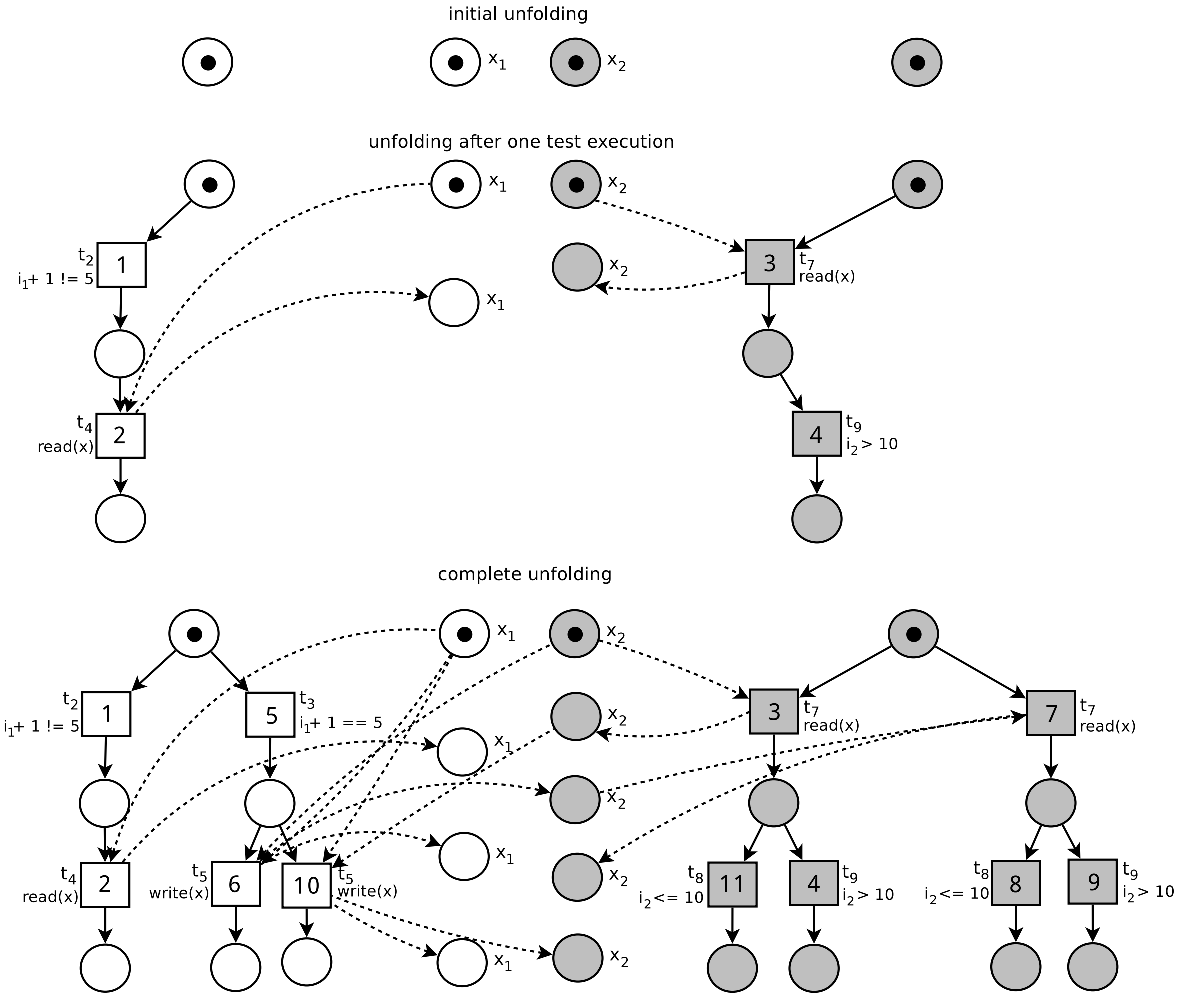
```
Thread 1:

1: i1 = input();

2: i1 = i1 + 1;

3: if (i1 == 5)

4:     X = 5;

5: else

6:     a = X;
```

```
Thread 2:

7: i2 = input();

8: b = X;

9: if (i2 > 10)

10:     b = 0;
```

# Program Representation as Petri Net



# Unfolding of the Program Representation



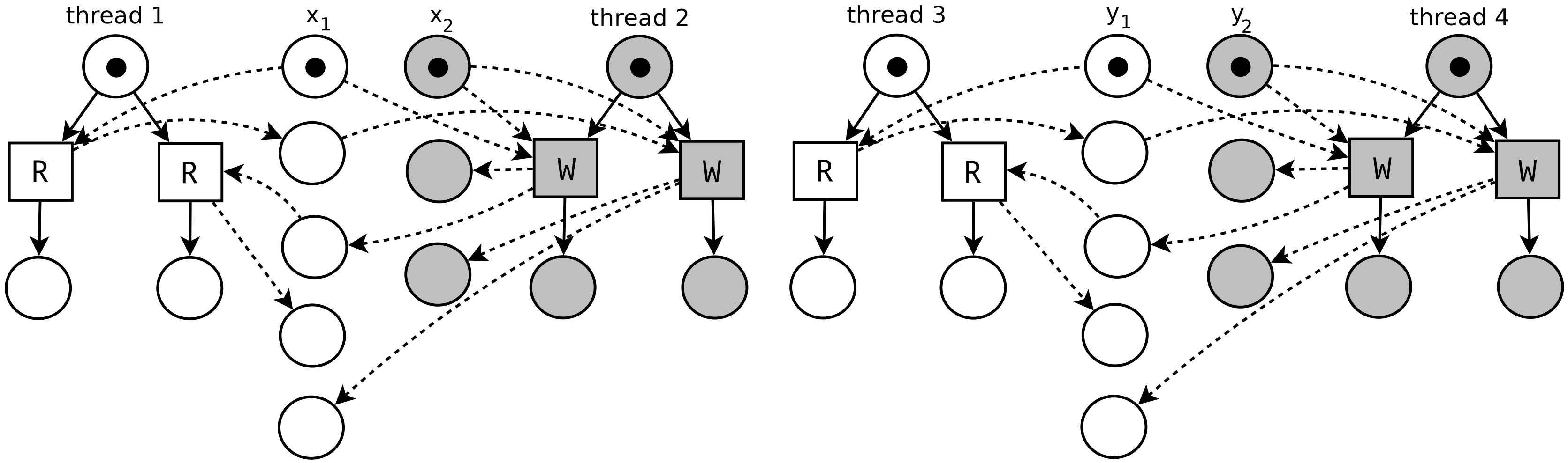
# Recap: Family of Programs with Exponential DPOR Reduced Execution Trees

- Example: Add N variables and 2N threads: There will be $2^N$ test for any partial order reduction method preserving all Mazurkiewicz traces, e.g., DPOR, persistent, ample, stubborn, and sleep sets

```
Global variables:    Thread 1:          Thread 2:

X = 0;               1: a = X;          2: X = 1;

Y = 0;

                     Thread 3:          Thread 4:

                     3: b = Y;          4: Y = 2;
```

# Example Unfolding Grows Linear in N

- Unfolding of the example is O(N), see below, while the DPOR reduced execution tree is $O(2^N)$



- Unfoldings will be exponentially more compact than any deadlock (Mazurkiewicz trace) preserving POR method!

# What is Preserved by Unfoldings

- The unfolding of the previous example can be covered by two test runs
- The unfolding preserves the reachability of local states and executability of statements
- Thus asserts on local state can be checked
- Reachability of global states e.g., deadlocks, is symbolic in the unfolding – allows unfoldings to be smaller
- Reachability of a global state is present in the unfolding – it is a symbolic representation of the system behavior
- Checking any global state reachability question can be done in NP in the unfolding size using an SAT solver

# Unfolding based Testing Algorithm

```
Input: A program $P$
unf := initial unfolding
extensions := events enabled in the initial state
while $extensions \neq \emptyset$ do
    choose $target \in extensions$
    if $target \notin unf$ then
        statement_sequence := EXECUTE($P$, target, $k$)
        $M$ = initial marking
        for all $stmt \in statement\_sequence$ do
            $e$ = CORRESPONDINGEVENT(stmt, $M$)
            if $e \notin unf$ then
                add $e$ and its output conditions to unf
                $extensions := extensions \setminus \{e\}$
                pe := POSSIBLEEXTENSIONS($e$, unf)
                $extensions := extensions \cup pe$
            $M$ = FIREEVENT($e$, $M$)
```

# Computing Possible Extensions

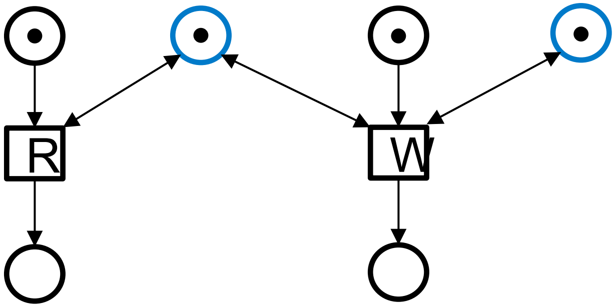
- Finding *possible extensions* is the most computationally expensive part of unfolding (NP-complete [Heljanko'99])
- It is possible to use existing backtracking search based potential extension algorithms with DSE
  - Designed for arbitrary Petri nets
  - Can be very expensive in practice
- Key observation: It is possible to limit the search space of potential extensions due to restricted form of unfoldings generated by the algorithm
  - Same worst case behavior, but in practice very efficient, see ASE'2012 paper for details

# Specialized Algorithm for Possible Extensions

- In a Petri net representation of a program under test (not constructed explicitly in our algorithm) the places for shared variables are always marked
- This results in a tree like connection of the unfolded shared variable places and allows very efficient potential extension search, see [ASE'12]

Thread 1:
local int a = x; (read)

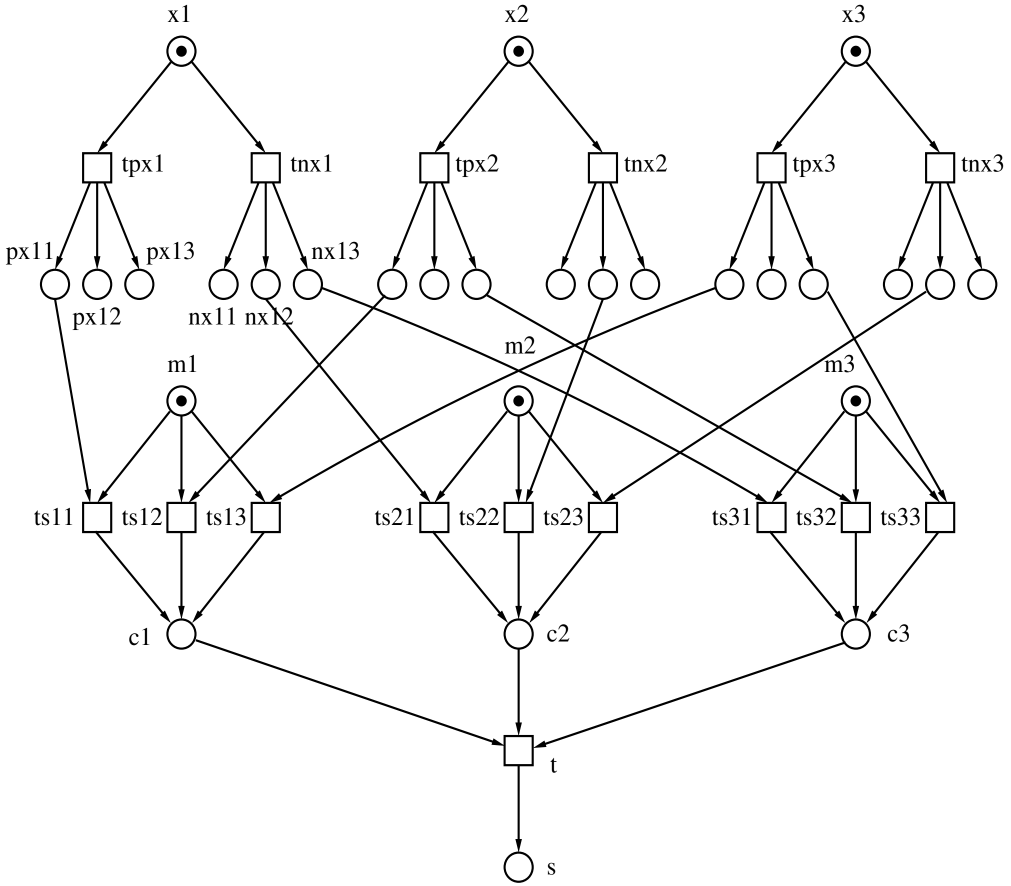
Thread 2:
x = 5; (write)



# NP-Hardness of Possible Extensions

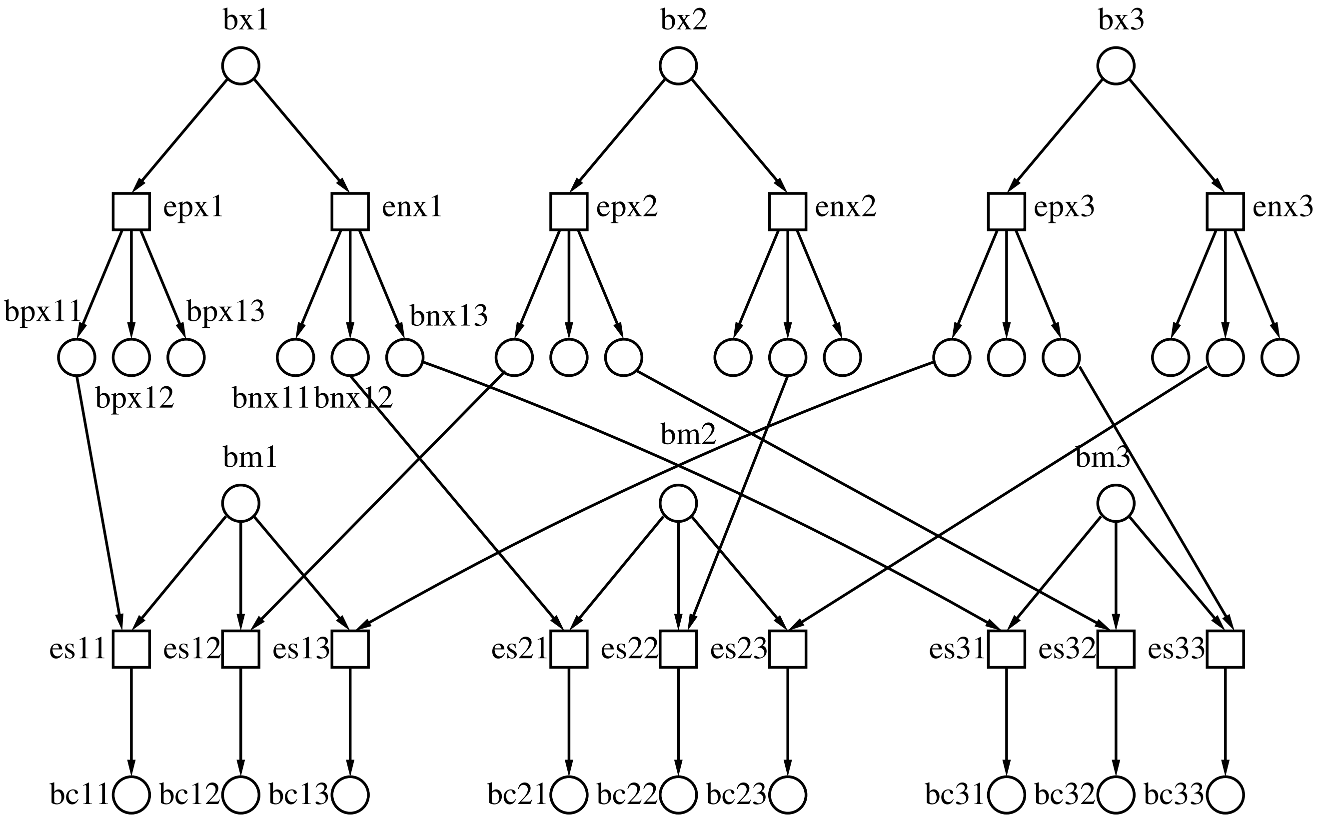
Consider the 3-SAT Formula below turned into a Petri net:

(x1 ⋁ x2 ⋁ v3) ⋀ (!x1 ⋁ !x2 ⋁ !x3) ⋀ (!x1 ⋁ x2 ⋁ x3)



# NP-Hardness of Possible Extensions

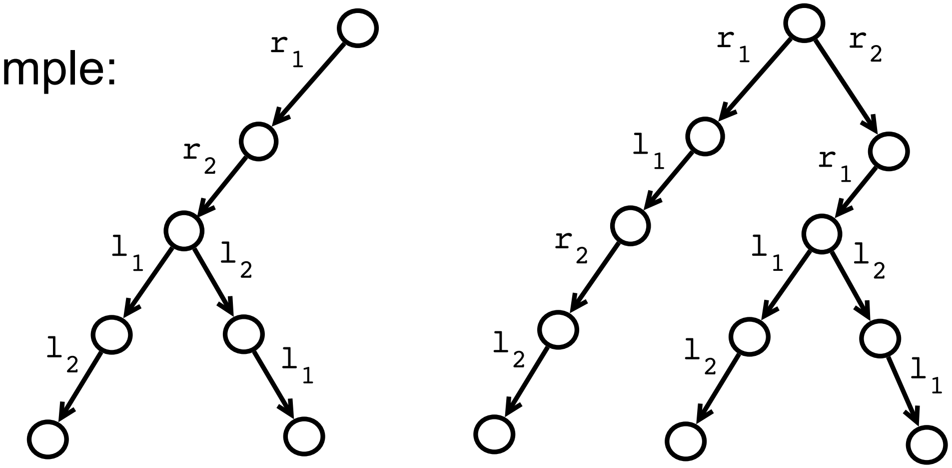
- The formula is satisfiable iff transition t is a possible extension of the following prefix of the unfolding:



# Comparison with DPOR and Race Detection and Flipping

- The amount of reduction obtained by dynamic partial-order approaches depend on the order events are added to the symbolic execution tree
  - Unfolding approach always generates canonical representation regardless of the execution order

DPOR example:



# Comparison with DPOR and Race Detection and Flipping

- Unfolding approach is computationally more expensive per test run than DPOR but requires less test runs
  - The reduction to the number of test runs can be exponential
  - Recall the system with 2N threads and N shared variables, which consist of a thread reading and writing a variable $X_i$.
  - It has an exponential number of Mazurkiewics traces but a linear size unfolding

# Additional Observations

- The unfolding approach is especially useful for programs whose control depends heavily on input values
  - DPOR might have to explore large subtrees generated by DSE multiple times if it does not manage to ignore all irrelevant interleavings of threads
- One limitation of ASE’12 algorithm is that it does not cleanly support dynamic thread creation
  - Fixed in our ACSD’14 paper by using contextual nets

# Using Contextual Unfoldings (ACSD’14)

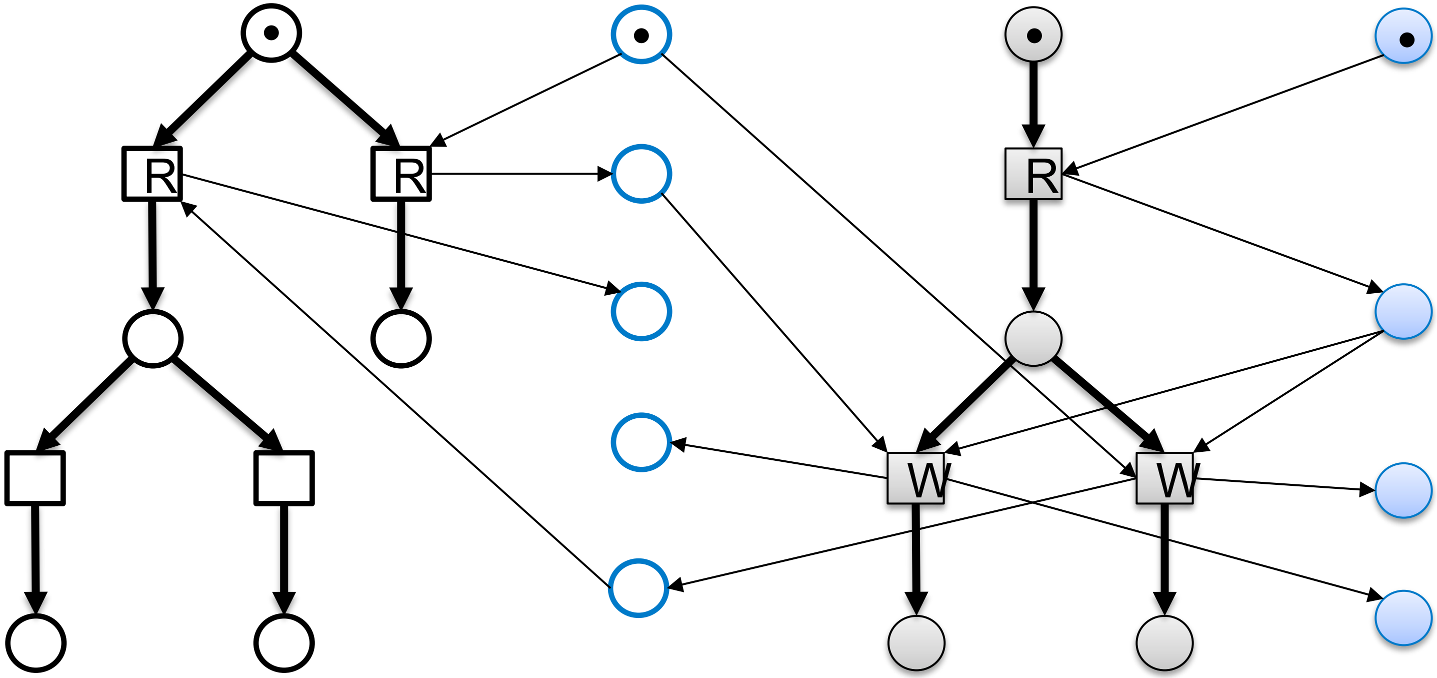
- *Contextual nets* (Petri nets with read arcs) allow an even more compact representation of the control and data flow
- *Read arcs* are denoted with lines instead of arrows
- A read arc requires a token to be present for transition to be enabled but firing it does not consume the token
- A more compact representation using read arcs can potentially be covered with less test executions
- However, computing potential extensions becomes computationally more demanding in practice (not in theory)

# Recap: Example as Ordinary Petri net

Global variables:
int x = 0;

Thread 1:
local int a = x;
if (a > 0)
  error();

Thread 2:
local int b = x;
if (b == 0)
  x = input();

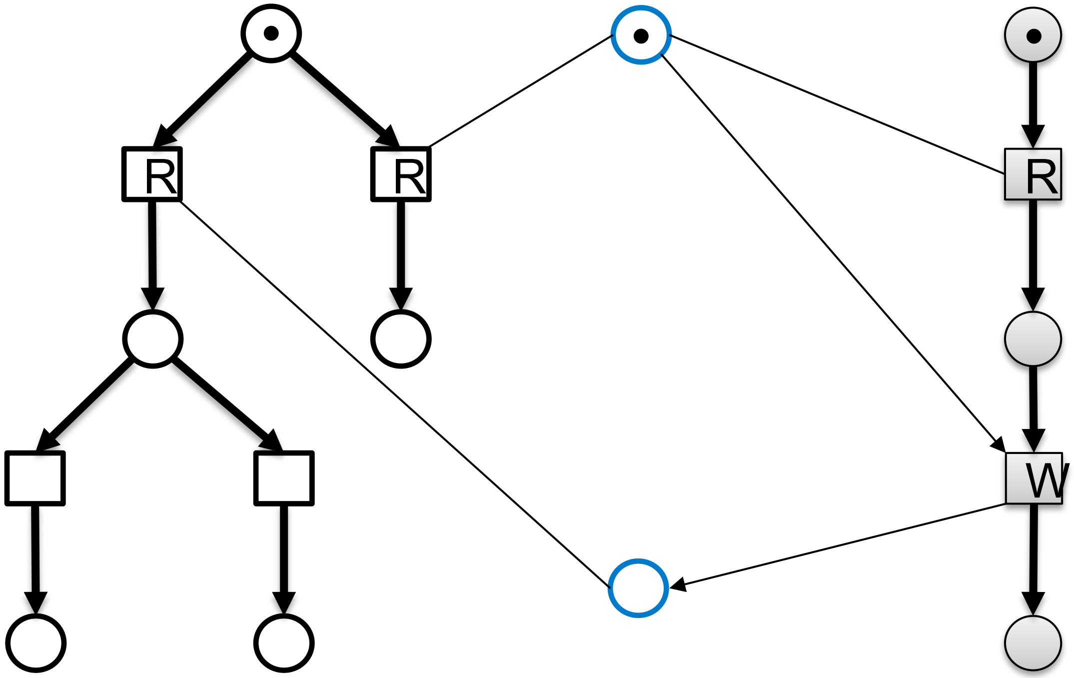


# Example with Read Arcs

Global variables:
int x = 0;

Thread 1:
local int a = x;
if (a > 0)
  error();

Thread 2:
local int b = x;
if (b == 0)
  x = input();



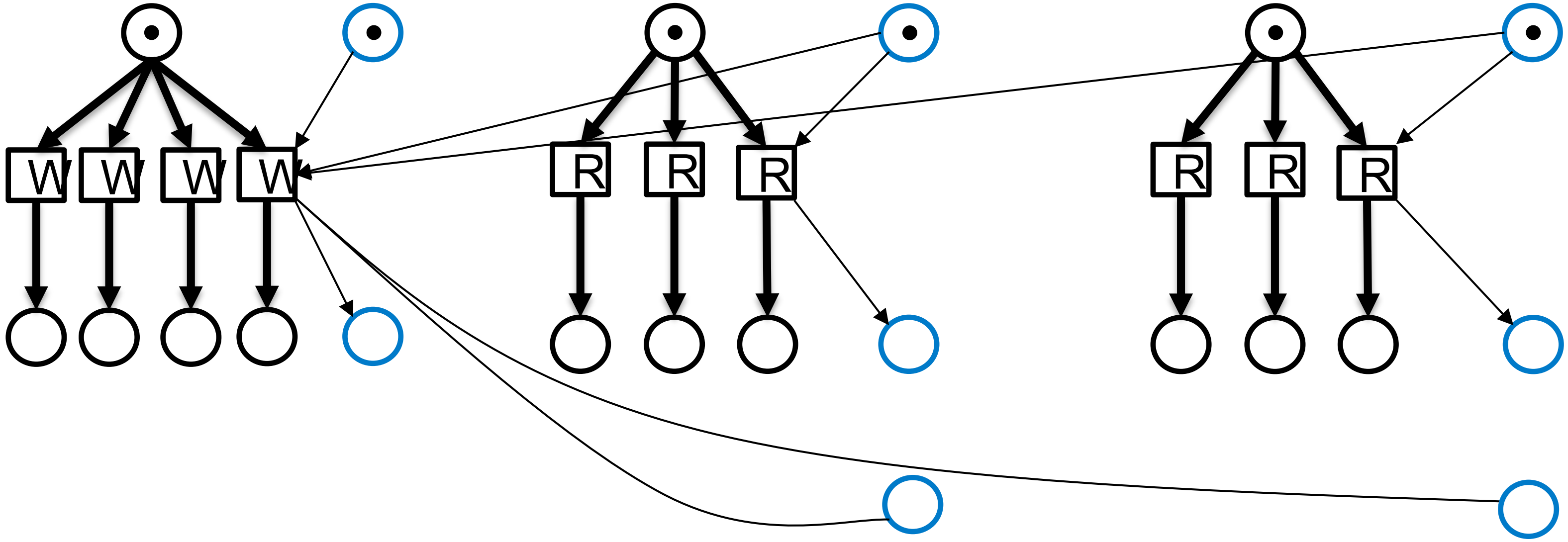
# Another Example (Place Replication)

Global variables:
int x = 0;

Thread 1:
x = 5;

Thread 2:
local int a = x;

Thread 3:
local int b = x;



- Requires 4 test executions to explore all subsets of two reads before write

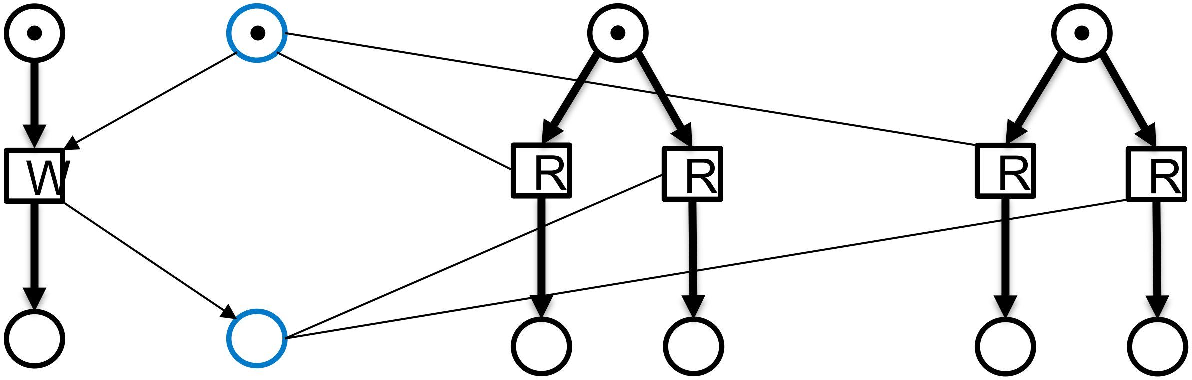
# Another Example (Read Arcs)

Global variables:
int x = 0;

Thread 1:
x = 5;

Thread 2:
local int a = x;

Thread 3:
local int b = x;



- Contextual unfoldings can be exponentially more compact (just add more reads)!
- Only requires two test to be covered

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# Almost the Same Example Program

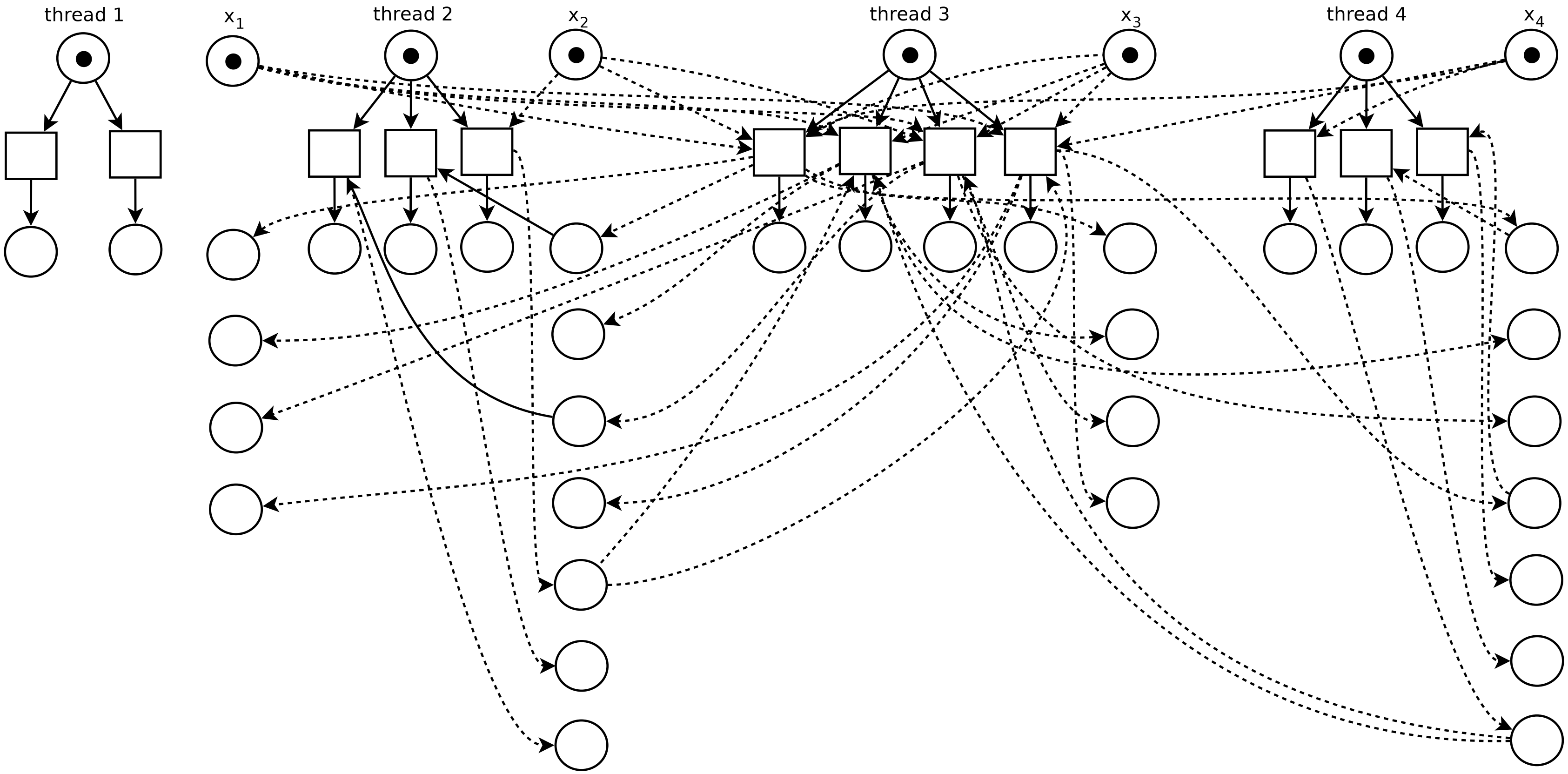
```
Thread 1:
a = input();
if (a == 10)
  a = 0;
```

```
Thread 2:
b = X;
```

```
Thread 3:
X = 5;
```

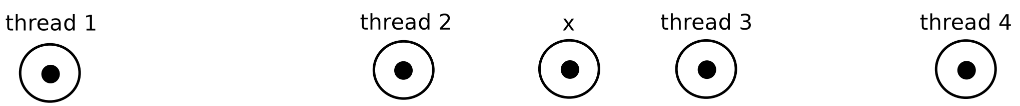
```
Thread 4:
c = x;
```

# Unfolding Using Petri Net – All arcs!

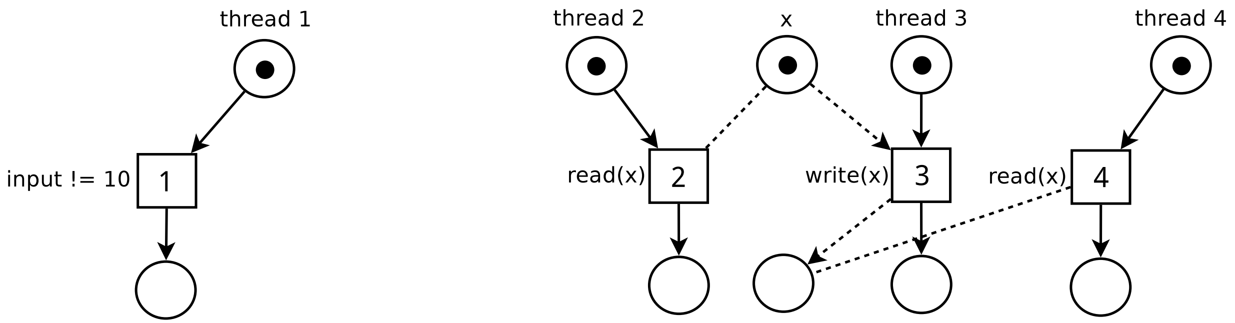


# Unfolding with Contextual Nets – Natural

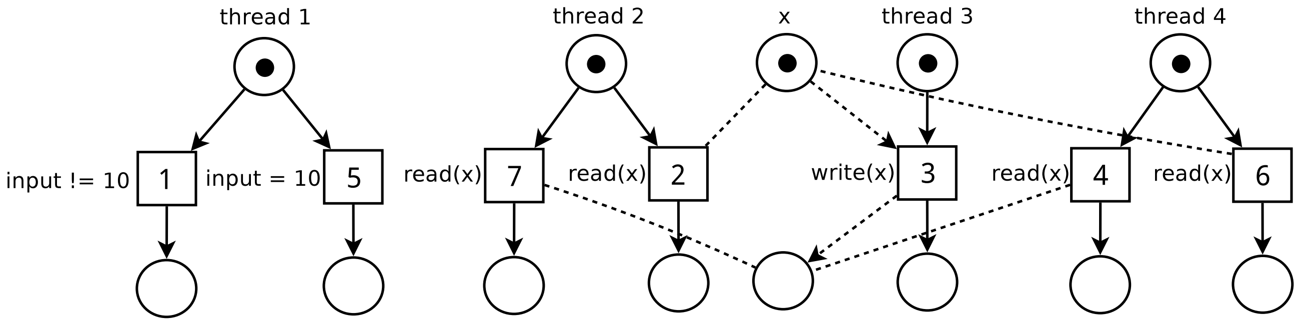
initial unfolding



unfolding after one test execution

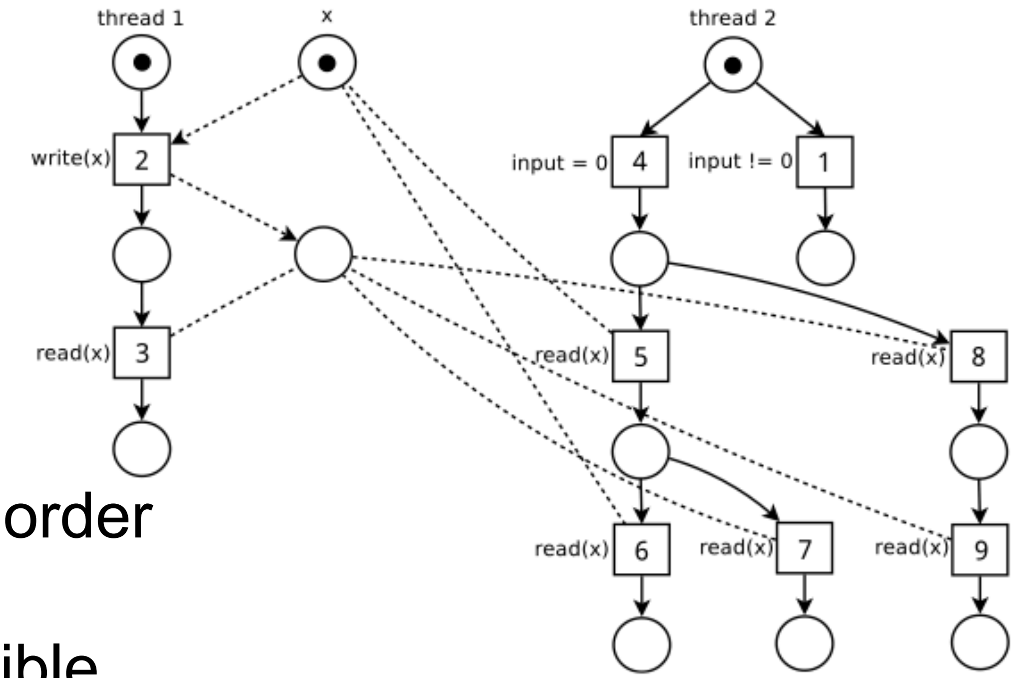


complete unfolding



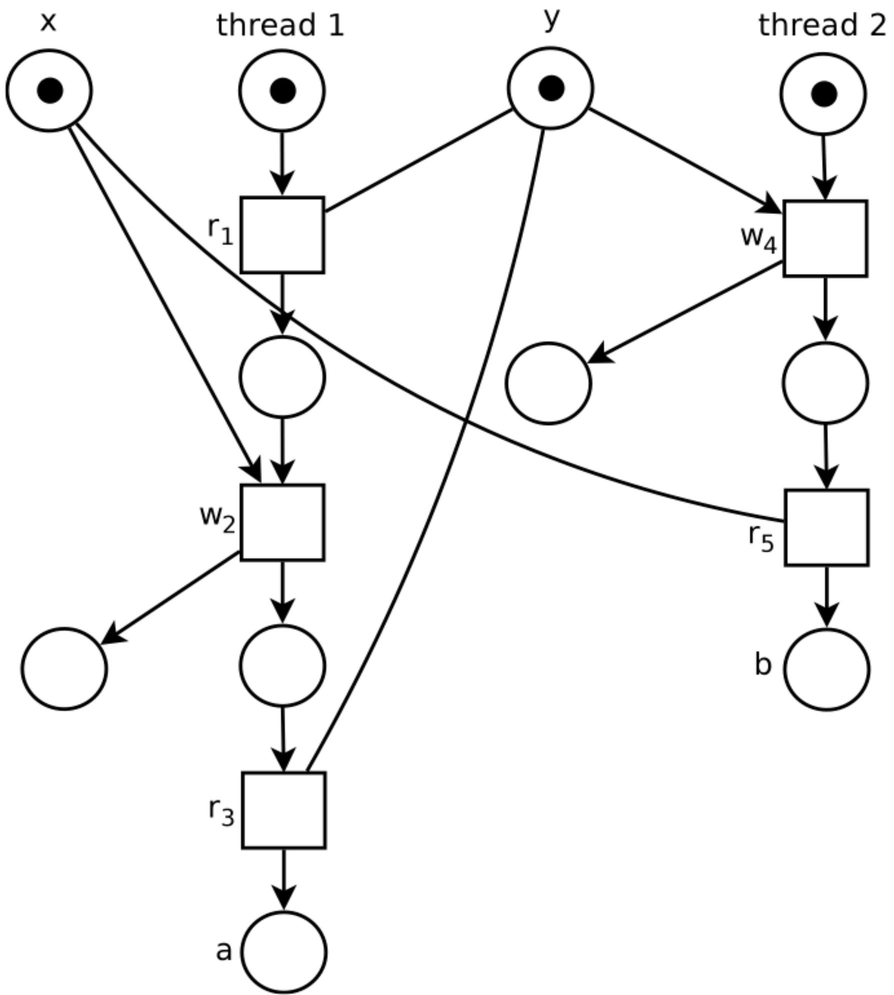
# Additional Example

```
Global variables:    Thread 1:        Thread 2:
X = 0;               1: X = 5;        3: b = input();
                     2: a = X;        4: if (b == 0)
                                      5:     c = X;
                                      6:     d = X;
```



- Execution order
  2,4,5
  is impossible

# Read Arcs Induce Cycles of Causality



- No way to fire both $r_3$ and $r_5$ !

- $w_2$ before $r_3$
- $r_3$ before $w_4$
- $w_4$ before $r_5$
- $r_5$ before $w_2$

- No ordering of $\{w_2, r_3, w_4, r_5\}$ possible!

# Petri nets vs Contextual nets

- Contextual nets are sometimes much more (exponentially) compact (but not for all systems!)
- Contextual nets often have also less test runs to explore for the same system
- Contextual nets have a more complex theory
- Algorithms for contextual nets are more complex (need to check for acyclicity of ordering relation), and thus sometimes slower per generated test case
- Dynamic thread creation is easy with contextual nets

# Experiments – Unfoldings vs DPOR

| | Unfolding | | DPOR | |
|---|---|---|---|---|
| **program** | **paths** | **time** | **paths** | **time** |
| Szymanski | **65138** | 2m 3s | **65138** | **0m 30s** |
| Filesystem 1 | **3** | **0m 0s** | 142 | 0m 4s |
| Filesystem 2 | **3** | **0m 0s** | 2227 | 0m 46s |
| Fib 1 | **19605** | **0m 17s** | 21102 | 0m 21s |
| Fib 2 | **218243** | 4m 18s | 232531 | **4m 2s** |
| Updater 1 | **33269** | 2m 22s | 33463 | **2m 6s** |
| Updater 2 | **33497** | 2m 24s | 34031 | **2m 13s** |
| Locking | **2520** | 0m 8s | **2520** | **0m 6s** |
| Synthetic 1 | **926** | **0m 3s** | 1661 | 0m 4s |
| Synthetic 2 | **8205** | **0m 41s** | 22462 | 1m 20s |

# Experiments – Petri vs Contextual nets

| | Unfolding | | Contextual unfolding | |
|---|---|---|---|---|
| **program** | **paths** | **time** | **paths** | **time** |
| Szymanski | **65138** | **2m 3s** | **65138** | 2m 37s |
| Fib 1 | 19605 | 0m 17s | **4959** | **0m 6s** |
| Fib 2 | 218243 | 4m 18s | **46918** | **0m 54s** |
| Updater 1 | **33269** | **2m 22s** | **33269** | 3m 24s |
| Synthetic 1 | 926 | **0m 3s** | **773** | **0m 3s** |
| Synthetic 2 | 8205 | 0m 41s | **3221** | **0m 18s** |
| Locking 2 | **22680** | **0m 55s** | **22680** | 1m 3s |

# Summary for Unfoldings in Testing

- A new approach to test multithreaded programs
- The restricted form of the unfoldings allows efficient implementation of the algorithm, crucial for performance!
- Unfoldings are competitive with existing approaches and can be substantially faster in some cases
- Can be exponentially smaller than any persistent set algorithm – Only preserves local state reachability
- Global state reachability is more complex:
  - Encode the unfolding as SMT formula in order to check global properties of the program under test

# Lightweight State Capturing for Automated Testing of Multithreaded Programs (TAP’14)

- DSE testing tools usually do not store the reached states explicitly
- It can be very expensive to test whether a set of states reached by one branch is a subset of a set of states reached by another branch
- Usually such a subsumption check involves SMT solver proving inclusion between two symbolic path constraints, which can be expensive
- What can be done without using SMT solver based inclusion checks?
- Our Solution: Use a Petri net abstraction to capture some paths with identical sets of reachable states – cut-off testing when such states are found

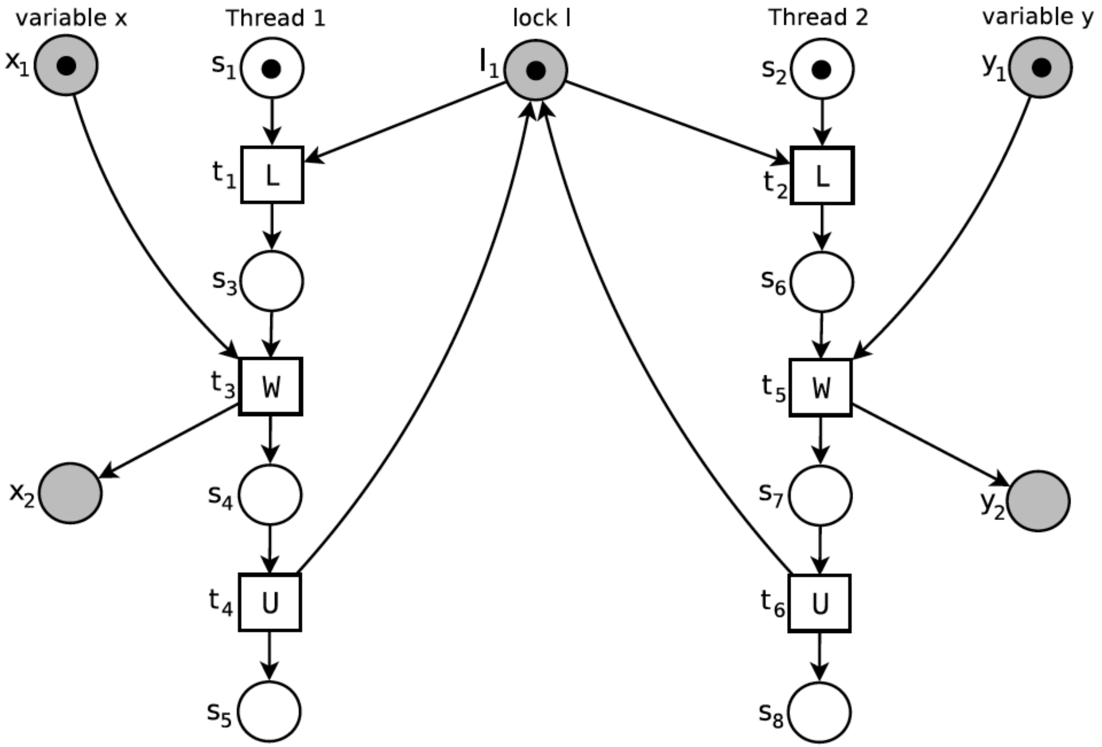
# Motivating Example

- The two interleavings will result in the same final state:

```
Global variables:
int x = 0;
int y = 0;

Thread 1:
1: acquire(lock);
2: x = 1;
3: release(lock);

Thread 2:
4: acquire(lock);
5: y = 1;
6: release(lock);
```



# Solution – Lightweight State Matching

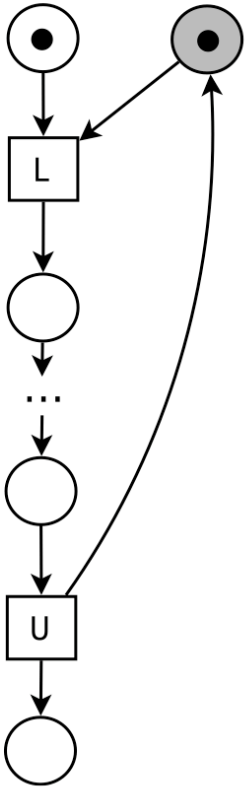
- Generate from the tested system a state matching abstraction such that:
  - If the abstraction reaches a state M in two different test executions, then the symbolically represented sets of states reached by the two executions will be identical
  - Note: The converse is not true: If two different test executions reach the same symbolically represented sets of states, the abstraction might be in two different states M and M’

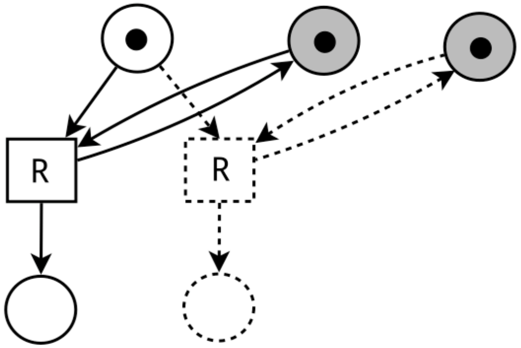
# Solution – Lightweight State Matching

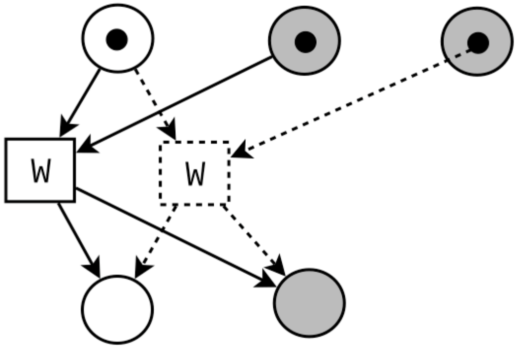
- We will use a Petri net based abstraction:
  - Locks have no internal state, lock+unlock combination will return the system into the same internal state
  - Reads will not modify the global variables read, just the local state of the process
  - Writes will modify both the local state of the process and the global variable

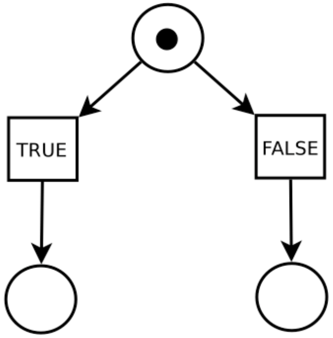
# Abstraction Modeling Constructs

- Lock&unlock will always use the same lock place, read modifies only local state, write modifies local state&var:

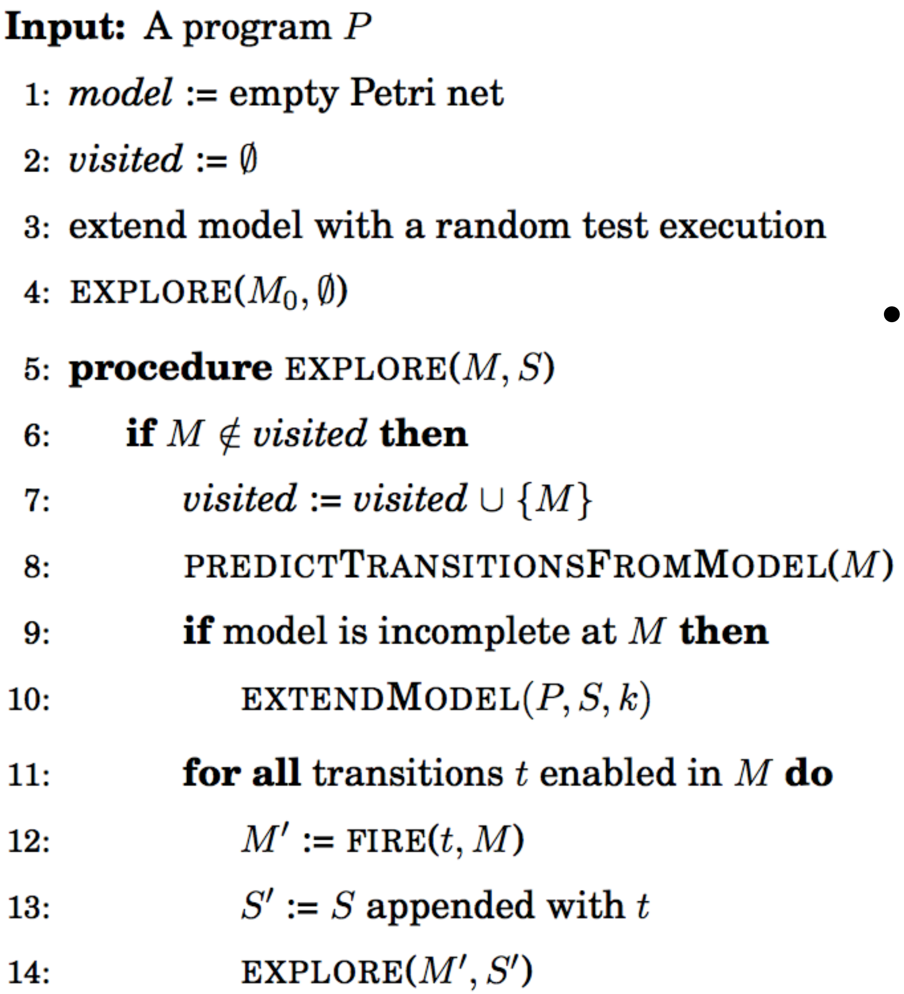

Locking and unlocking


Reading a shared variable


Writing to a shared variable


Symbolic branching

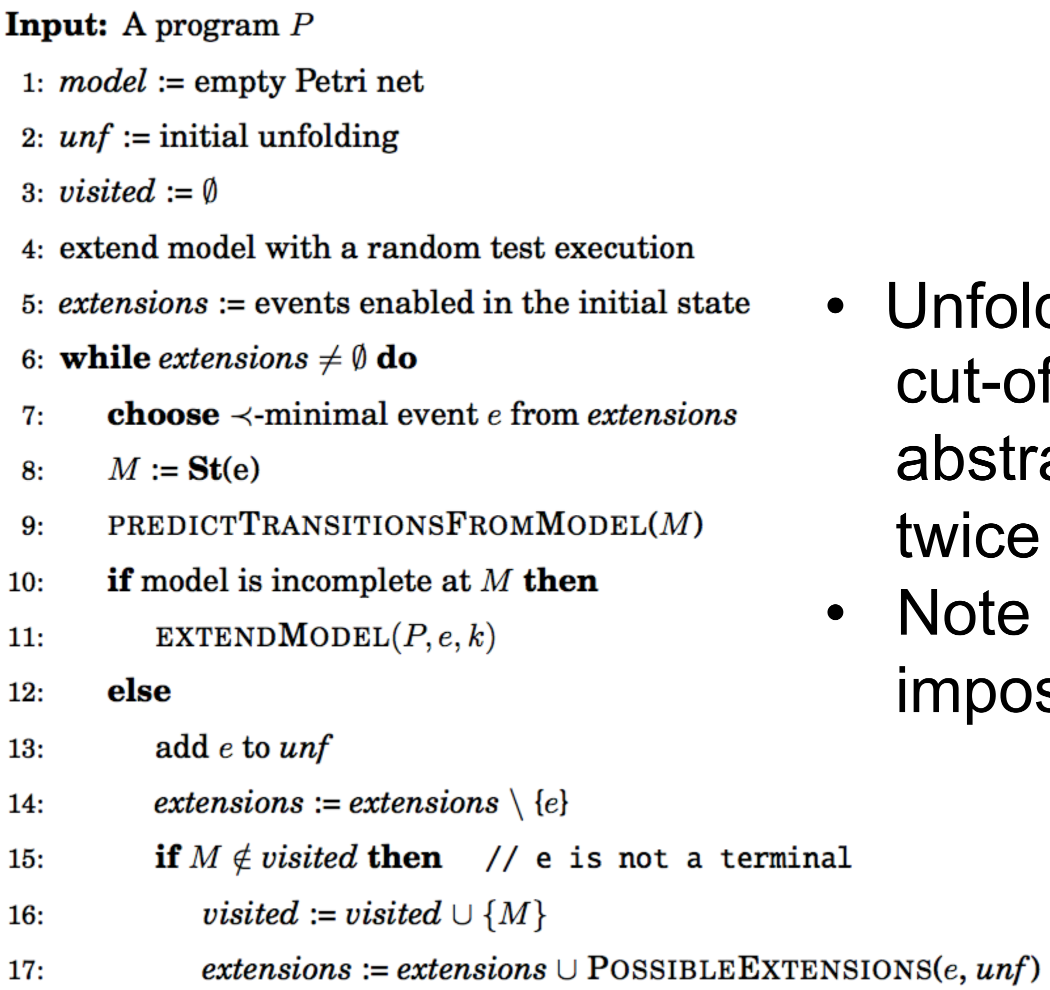
# Naïve Lightweight State Matching



```
Input: A program $P$
model := empty Petri net
visited := $\emptyset$
extend model with a random test execution
EXPLORE($M_0$, $\emptyset$)
procedure EXPLORE($M$, $S$)
    if $M \notin$ visited then
        visited := visited $\cup \{M\}$
        PREDICTTRANSITIONSFROMMODEL($M$)
        if model is incomplete at $M$ then
            EXTENDMODEL($P$, $S$, $k$)
        for all transitions $t$ enabled in $M$ do
            $M'$ := FIRE($t$, $M$)
            $S'$ := $S$ appended with $t$
            EXPLORE($M'$, $S'$)
```

- Just basic DFS with cut-off if the same abstract state M is seen twice

# Unfolding based Lightweight State Matching



```
Input: A program $P$
 1: $model$ := empty Petri net
 2: $unf$ := initial unfolding
 3: $visited := \emptyset$
 4: extend model with a random test execution
 5: $extensions$ := events enabled in the initial state
 6: while $extensions \neq \emptyset$ do
 7:     choose $\prec$-minimal event $e$ from $extensions$
 8:     $M$ := St(e)
 9:     PREDICTTRANSITIONSFROMMODEL($M$)
10:     if model is incomplete at $M$ then
11:         EXTENDMODEL($P, e, k$)
12:     else
13:         add $e$ to $unf$
14:         $extensions := extensions \setminus \{e\}$
15:         if $M \notin visited$ then    // e is not a terminal
16:             $visited := visited \cup \{M\}$
17:             $extensions := extensions \cup$ POSSIBLEEXTENSIONS($e$, $unf$)
```

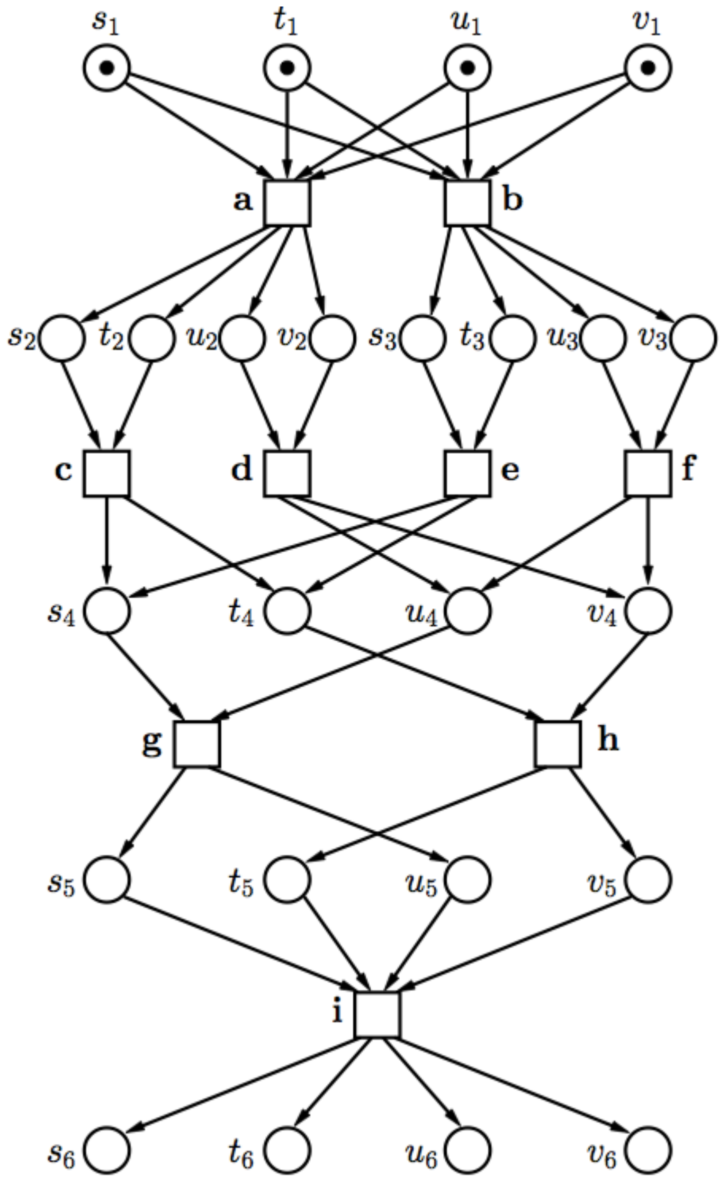
- Unfolding with cut-off if the same abstract state M is seen twice
- Note search order imposed on line 7!

# Why use Order $<$ on Line 7 when Extending Unfolding?

- Note that on line 7 a minimal event according to an Adequate Order $<$ on events to be added to the unfolding is selected
- Such an order was first presented by Esparza, J., Römer, S., Vogler, W.: An improvement of McMillan's unfolding algorithm. Formal Methods in System Design 20(3), 285–310 (2002)
- If an arbitrary order would be used on line 7, the algorithm would become unsound!
- For more information, see Chapter 4.4 of: Esparza, J. and Heljanko, K.: Unfoldings - A Partial-Order Approach to Model Checking.

# Unsoundeness:

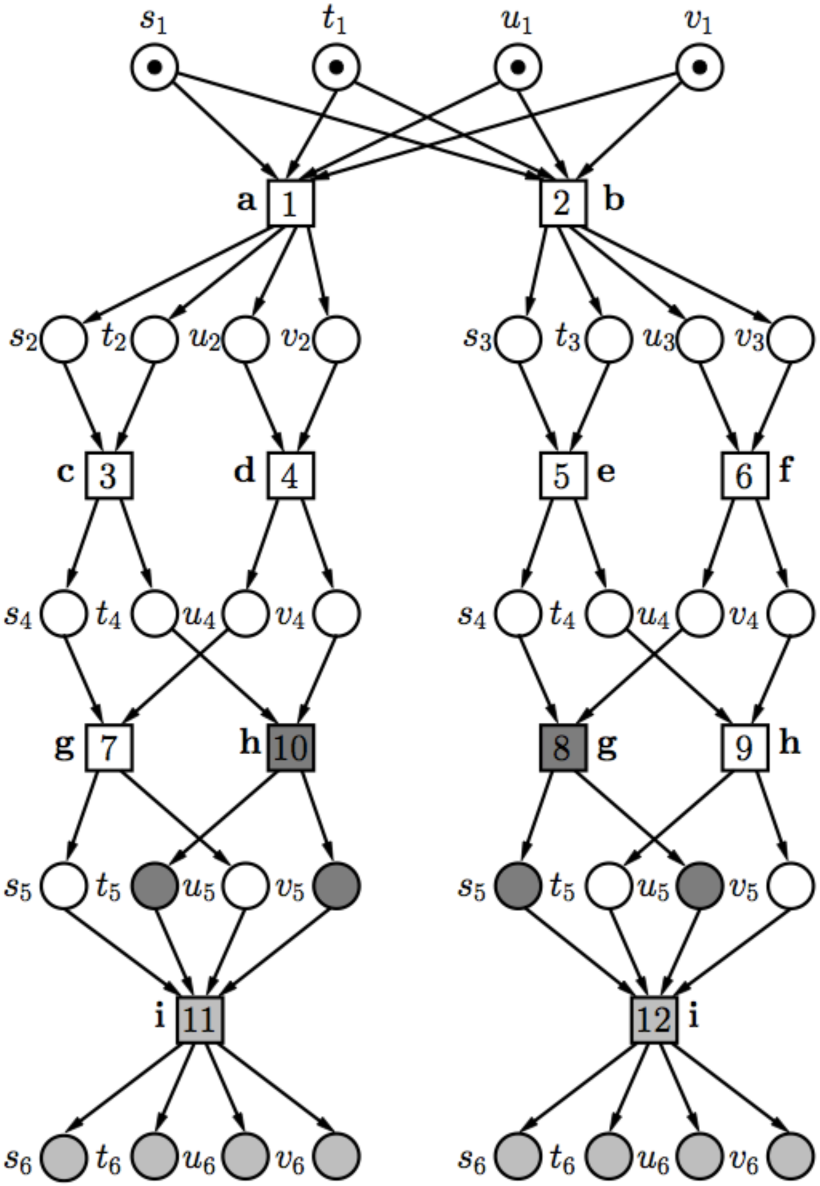
- Smallest known example where unsoundeness occurs



# Unsound Cuts:

- Using the order given by numbers will cut both 8 and 9, leaving both 11 and 12 undiscovered!

- This can be fixed!



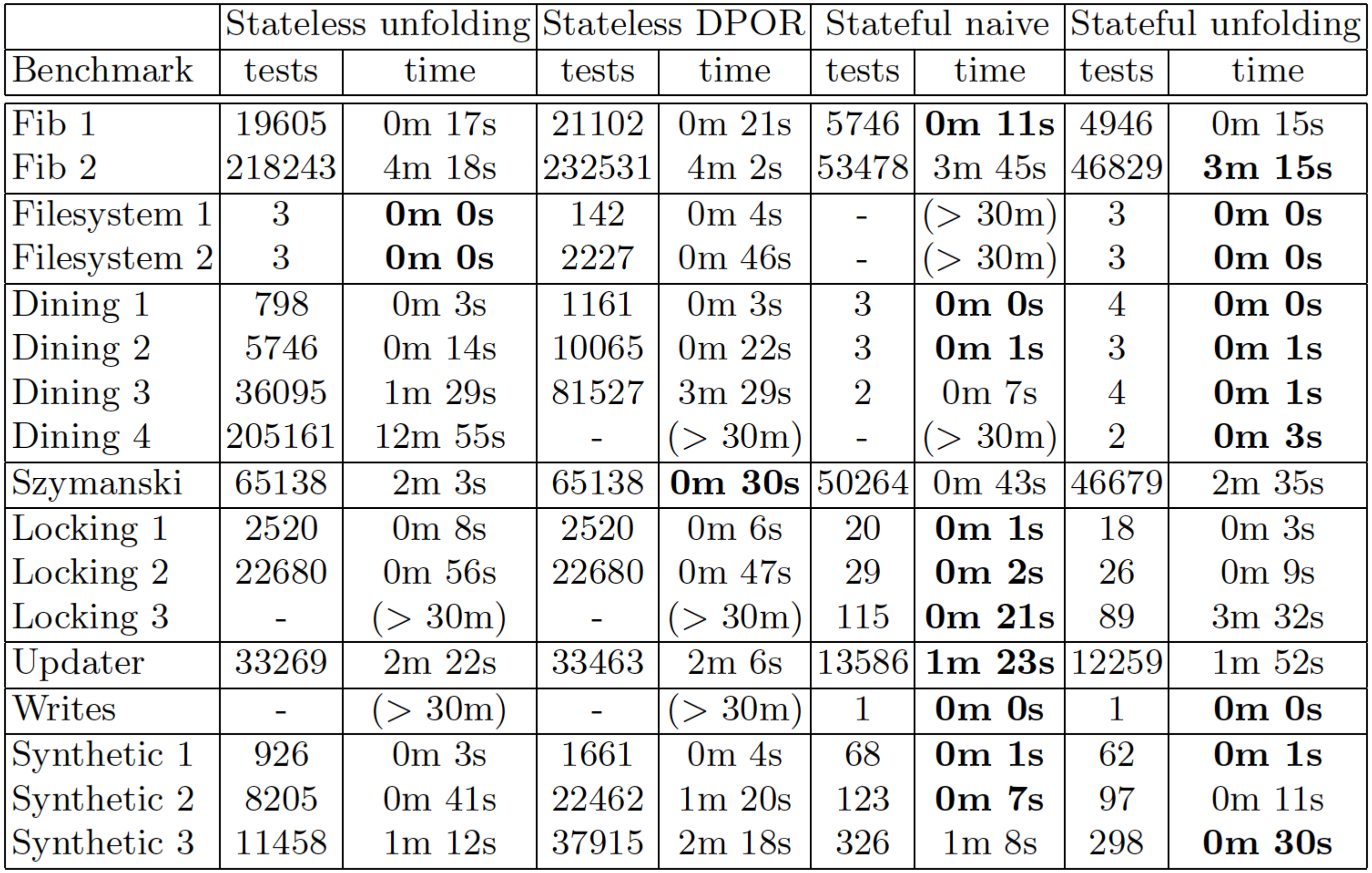
# Adequate Orders

- The adequate order $\prec$ on traces needs to satisfy the following:
  1. $\prec$ is well-founded (contains no infinite descending chain); and
  2. If $[\mathbf{w}] \prec [\mathbf{w'}]$ then $[\mathbf{w}\ \mathbf{w''}] \prec [\mathbf{w'}\ \mathbf{w''}]$.

- Surprisingly Chatain and Khomenko were able to prove that (1) above implies (2), and thus a sufficient condition on an adequate order $\prec$ is that it is well founded

- Using property (2) repeatedly it is possible to show all reachable local states have a representative in the unfolding also when cut-offs are used to cut branches away
- Thus our algorithm is sound when $\prec$ is an adequate order!

# Experimental Results



| | Stateless unfolding | | Stateless DPOR | | Stateful naive | | Stateful unfolding | |
|---|---|---|---|---|---|---|---|---|
| Benchmark | tests | time | tests | time | tests | time | tests | time |
| Fib 1 | 19605 | 0m 17s | 21102 | 0m 21s | 5746 | **0m 11s** | 4946 | 0m 15s |
| Fib 2 | 218243 | 4m 18s | 232531 | 4m 2s | 53478 | 3m 45s | 46829 | **3m 15s** |
| Filesystem 1 | 3 | **0m 0s** | 142 | 0m 4s | - | (> 30m) | 3 | **0m 0s** |
| Filesystem 2 | 3 | **0m 0s** | 2227 | 0m 46s | - | (> 30m) | 3 | **0m 0s** |
| Dining 1 | 798 | 0m 3s | 1161 | 0m 3s | 3 | **0m 0s** | 4 | **0m 0s** |
| Dining 2 | 5746 | 0m 14s | 10065 | 0m 22s | 3 | **0m 1s** | 3 | **0m 1s** |
| Dining 3 | 36095 | 1m 29s | 81527 | 3m 29s | 2 | 0m 7s | 4 | **0m 1s** |
| Dining 4 | 205161 | 12m 55s | - | (> 30m) | - | (> 30m) | 2 | **0m 3s** |
| Szymanski | 65138 | 2m 3s | 65138 | **0m 30s** | 50264 | 0m 43s | 46679 | 2m 35s |
| Locking 1 | 2520 | 0m 8s | 2520 | 0m 6s | 20 | **0m 1s** | 18 | 0m 3s |
| Locking 2 | 22680 | 0m 56s | 22680 | 0m 47s | 29 | **0m 2s** | 26 | 0m 9s |
| Locking 3 | - | (> 30m) | - | (> 30m) | 115 | **0m 21s** | 89 | 3m 32s |
| Updater | 33269 | 2m 22s | 33463 | 2m 6s | 13586 | **1m 23s** | 12259 | 1m 52s |
| Writes | - | (> 30m) | - | (> 30m) | 1 | **0m 0s** | 1 | **0m 0s** |
| Synthetic 1 | 926 | 0m 3s | 1661 | 0m 4s | 68 | **0m 1s** | 62 | **0m 1s** |
| Synthetic 2 | 8205 | 0m 41s | 22462 | 1m 20s | 123 | **0m 7s** | 97 | 0m 11s |
| Synthetic 3 | 11458 | 1m 12s | 37915 | 2m 18s | 326 | 1m 8s | 298 | **0m 30s** |

# Summary – Lightweight State Matching

- Lightweight state matching can yield dramatic reductions in the number of explored test runs
- This holds despite that no SMT solver is being used for state matching
- The naïve state matching testing algorithm can sometimes beat advanced DPOR and unfolding approaches
- Adding lightweight state matching to DPOR is straightforward future work
- Adding state matching to unfoldings requires the use of adequate orders from unfolding theory to remain sound

# Conclusions

- When testing multithreaded programs partial order reductions should be used
- Partial order reduction combines nicely with dynamic symbolic execution (DSE)
- DPOR together with sleep sets can be implemented in a fairly straightforward fashion based e.g., on our ACSD’12 paper for pseudocode and PDMC’12 for its parallelization
- Unfoldings can be exponentially more compact than DPOR
    - More complex theory and algorithms needed
- State matching is essential to improve performance
- TODO: Explore border between Testing and Model Checking

# References for this talk

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