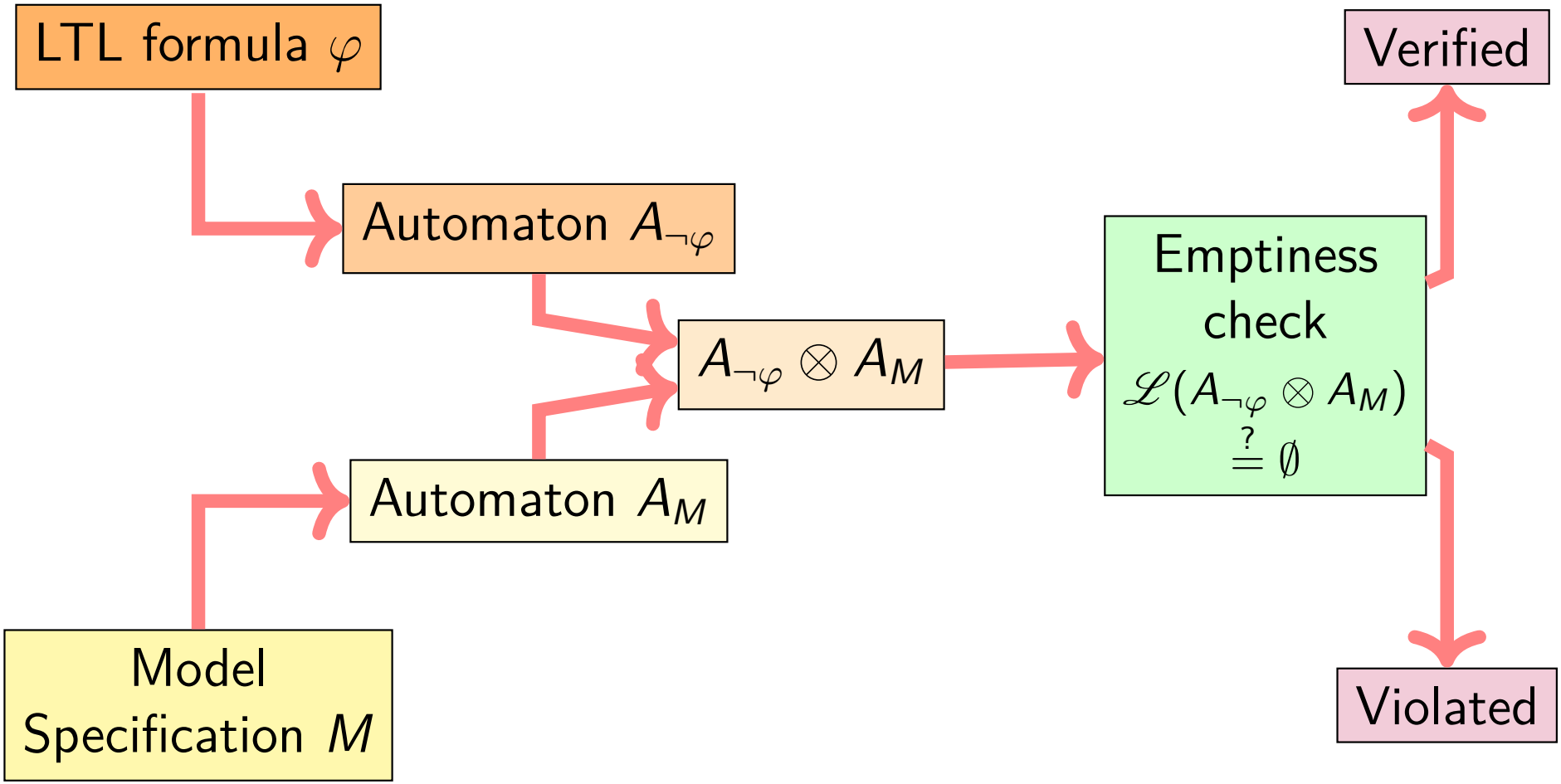
Combining Parallel Emptiness Checks with Partial Order Reductions

D. Poitrenaud, E. Renault

Friday November 8th

Automata-Theoretic Approach to Model Checking



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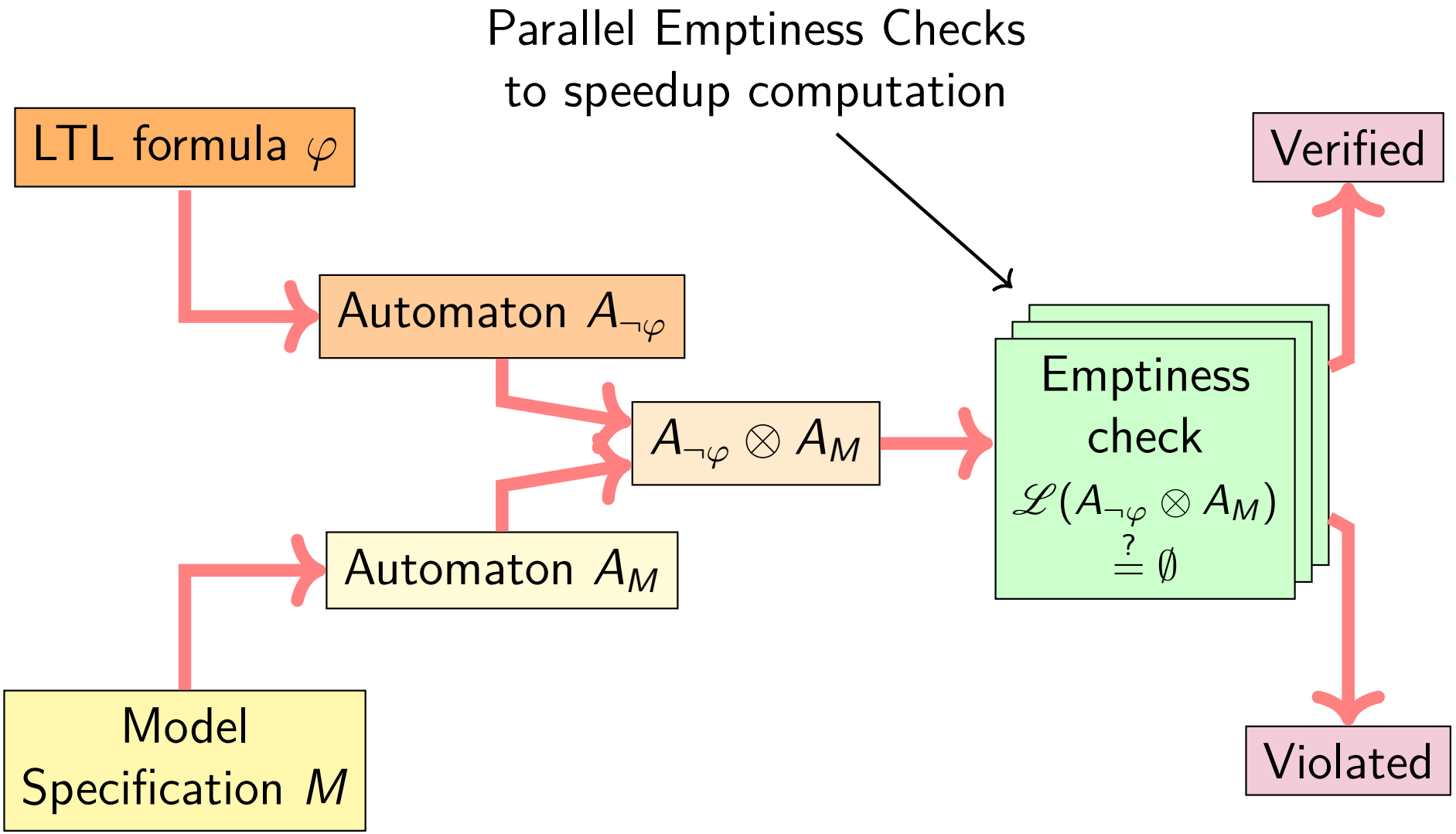

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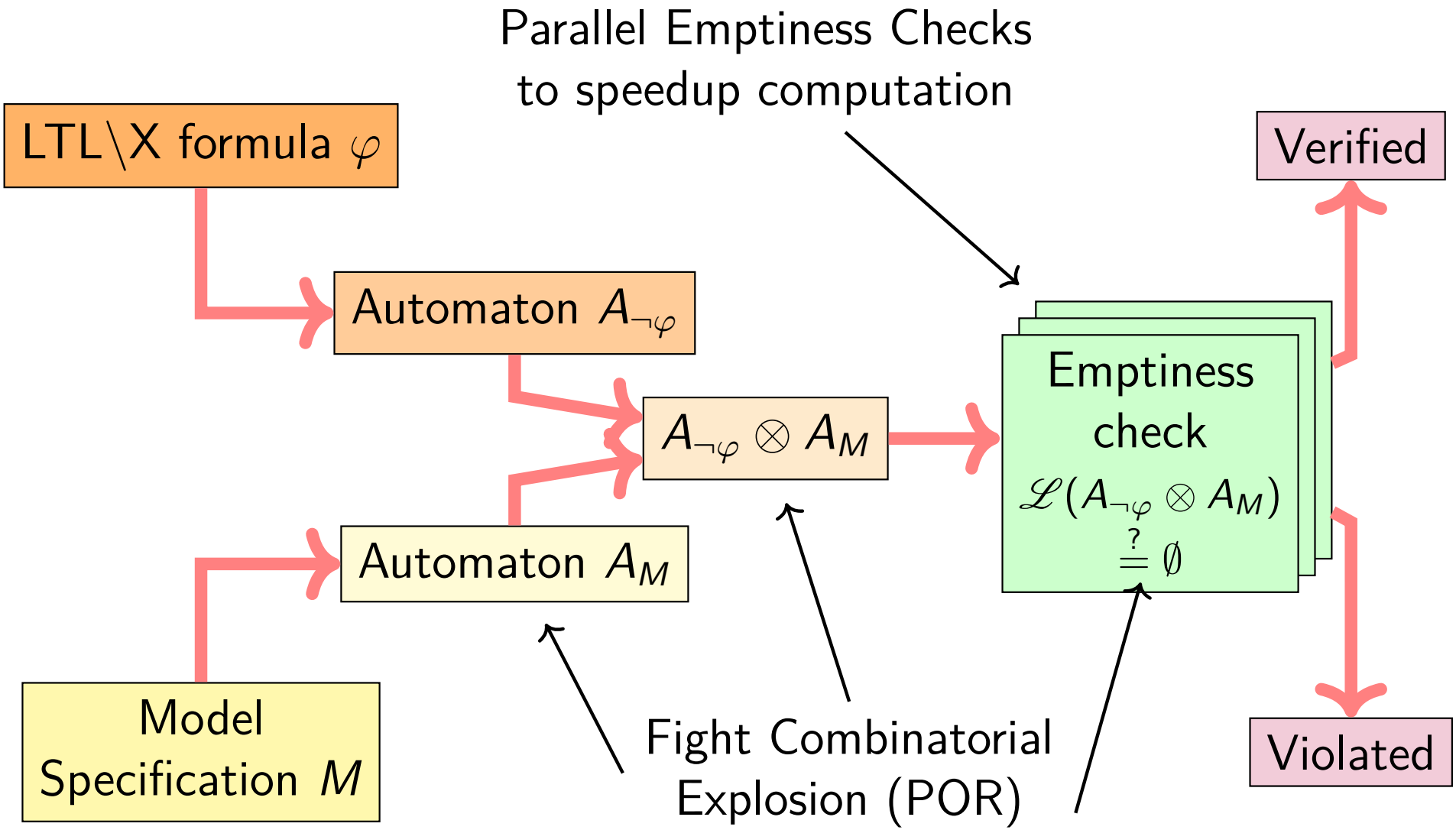
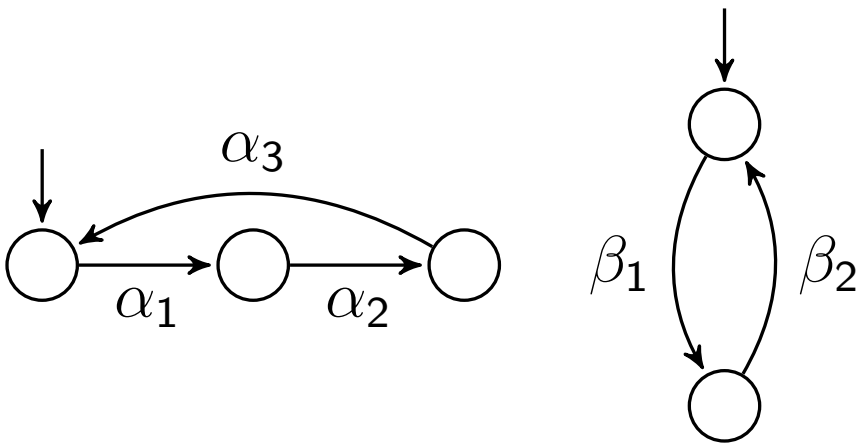


State Space Explosion

- Two concurrent processes
- β_1, β_2 independent of α_1, α_2, and α_3

Process 1 | Process 2



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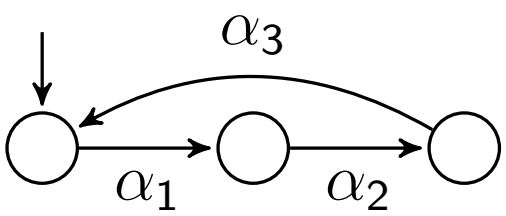
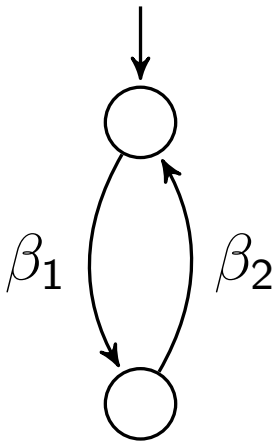
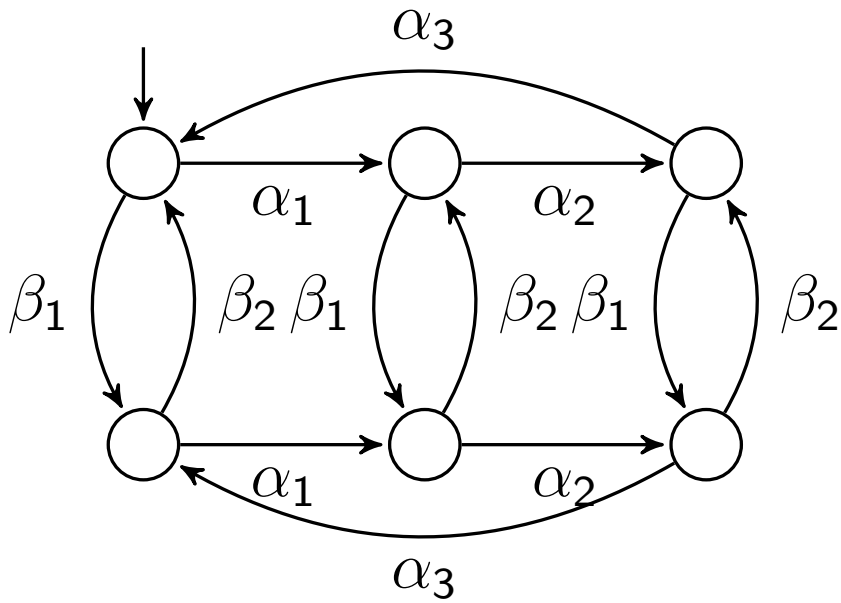


Process 2



State Space

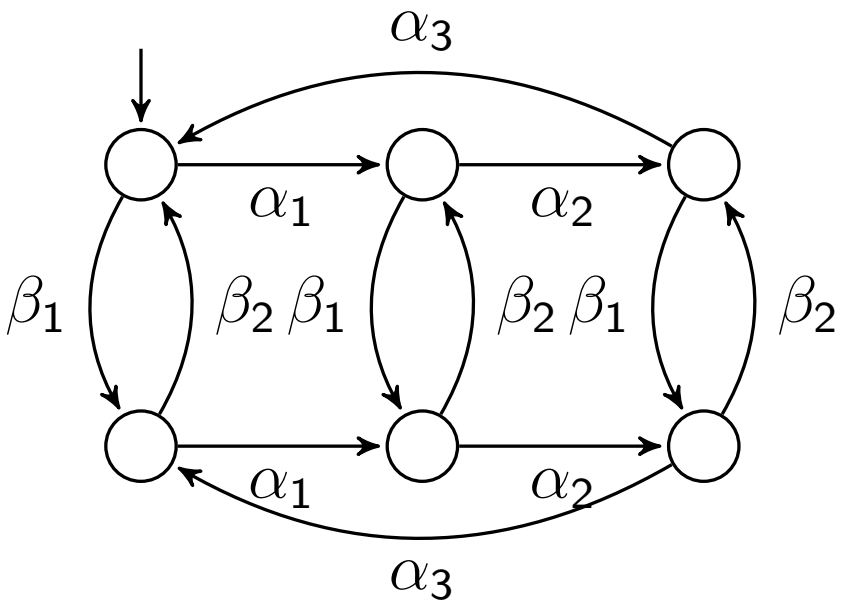


Process interleavings are one of the main sources of state-space explosion for explicit model checkers

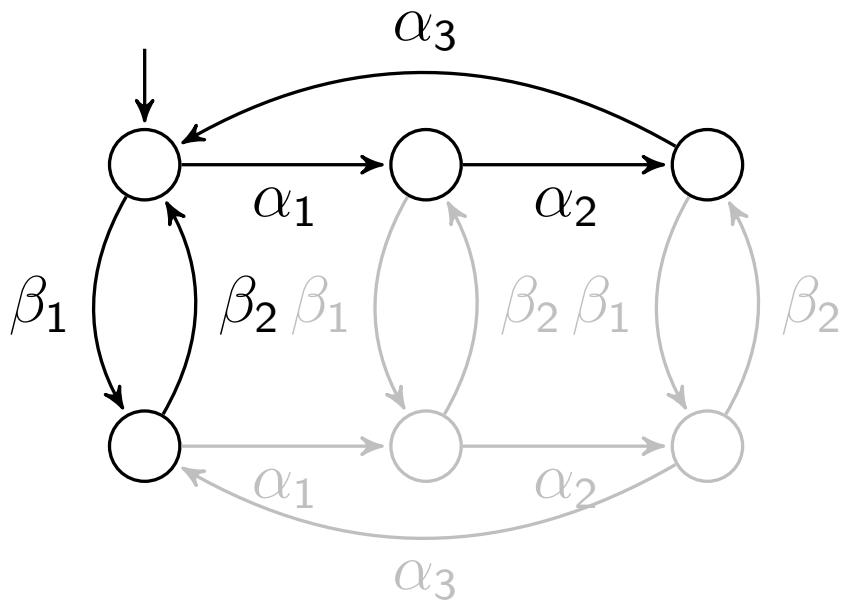
Partial Order Reductions (POR)

- Build a reduced state space
- For each state only consider a **reduced** subset of actions

State Space



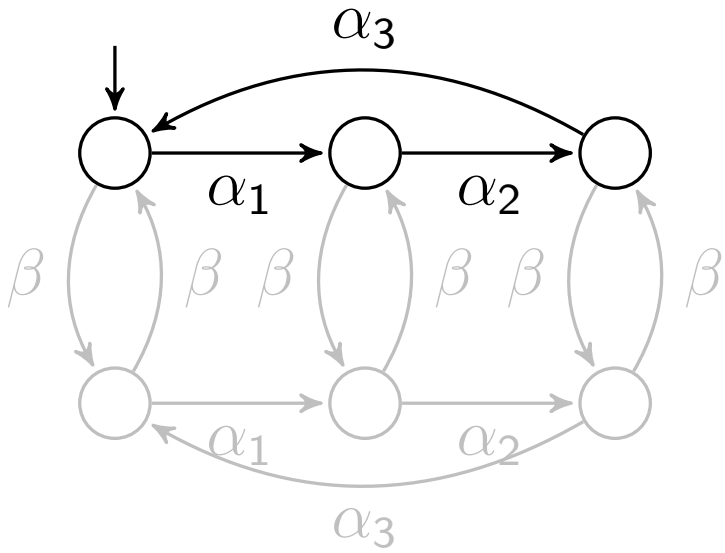
Possible Reduced State Space



POR work if and only if the property to check is stuttering invariant

The Ignoring Problem for Liveness Properties

- If the same actions are consistently ignored along a cycle, they may never be executed (below β is never executed)



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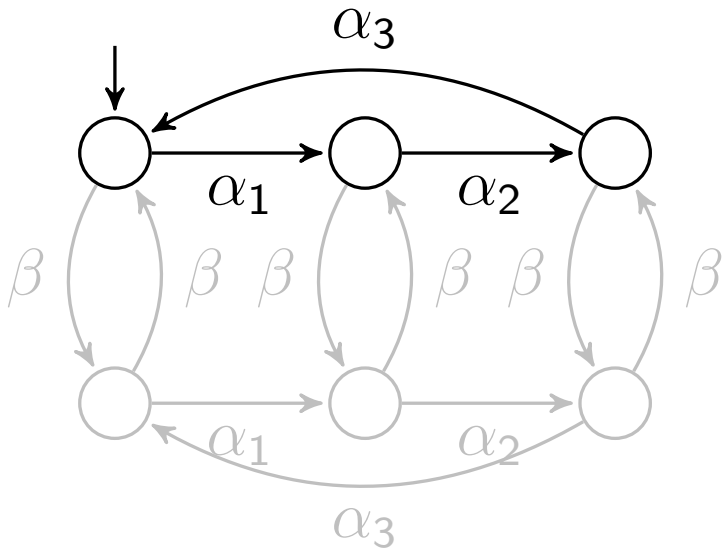
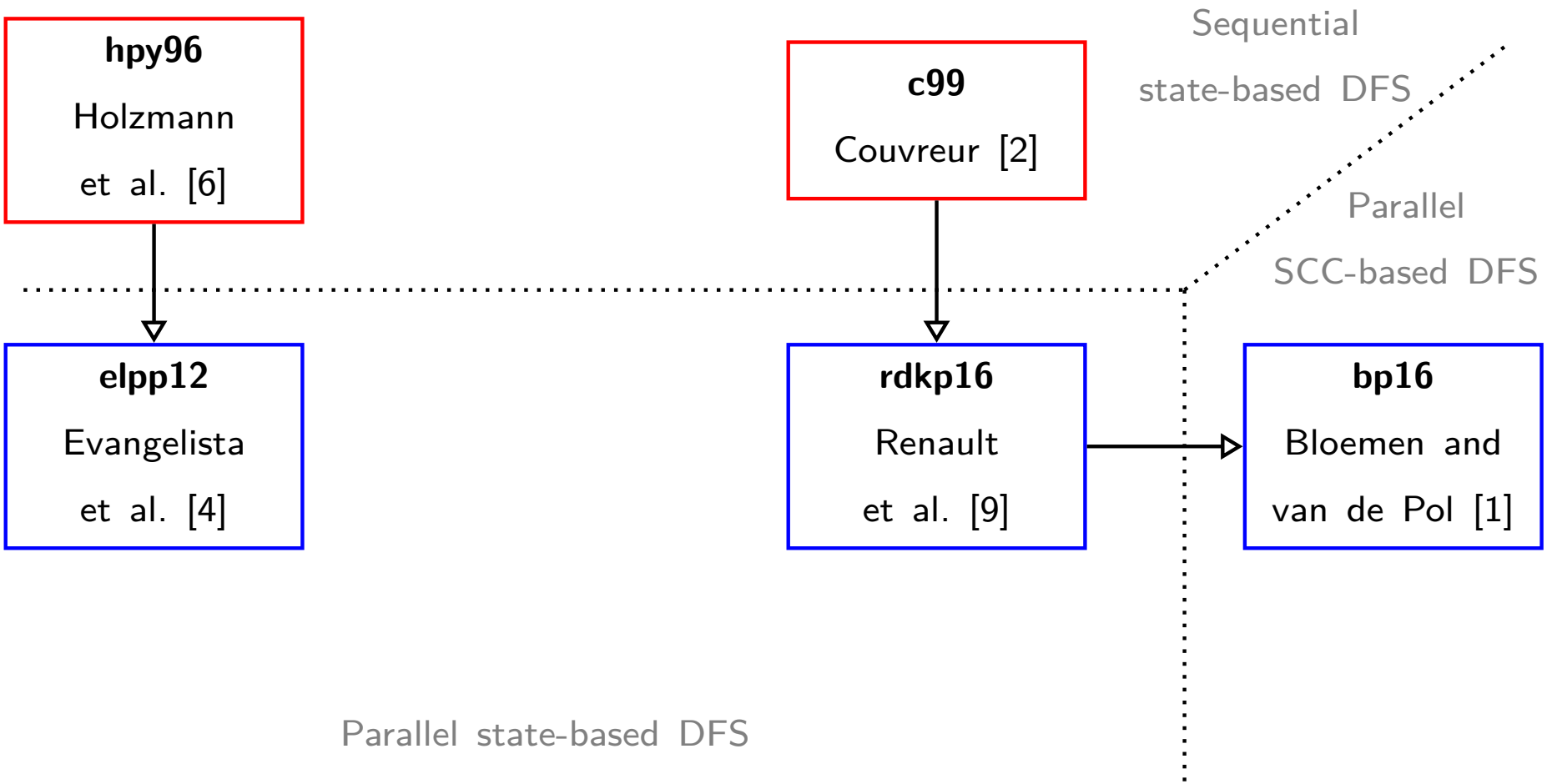


Requires an extra condition: the proviso

A proviso[a] ensures that every cycle in the reduced graph contains at least one **expanded state**, i.e, a state where all actions are considered.

[a] More simpler provisos can be applied for safety properties Evangelista and Pajault [5]

State-Of-The-Art: Emptiness Cheks & POR



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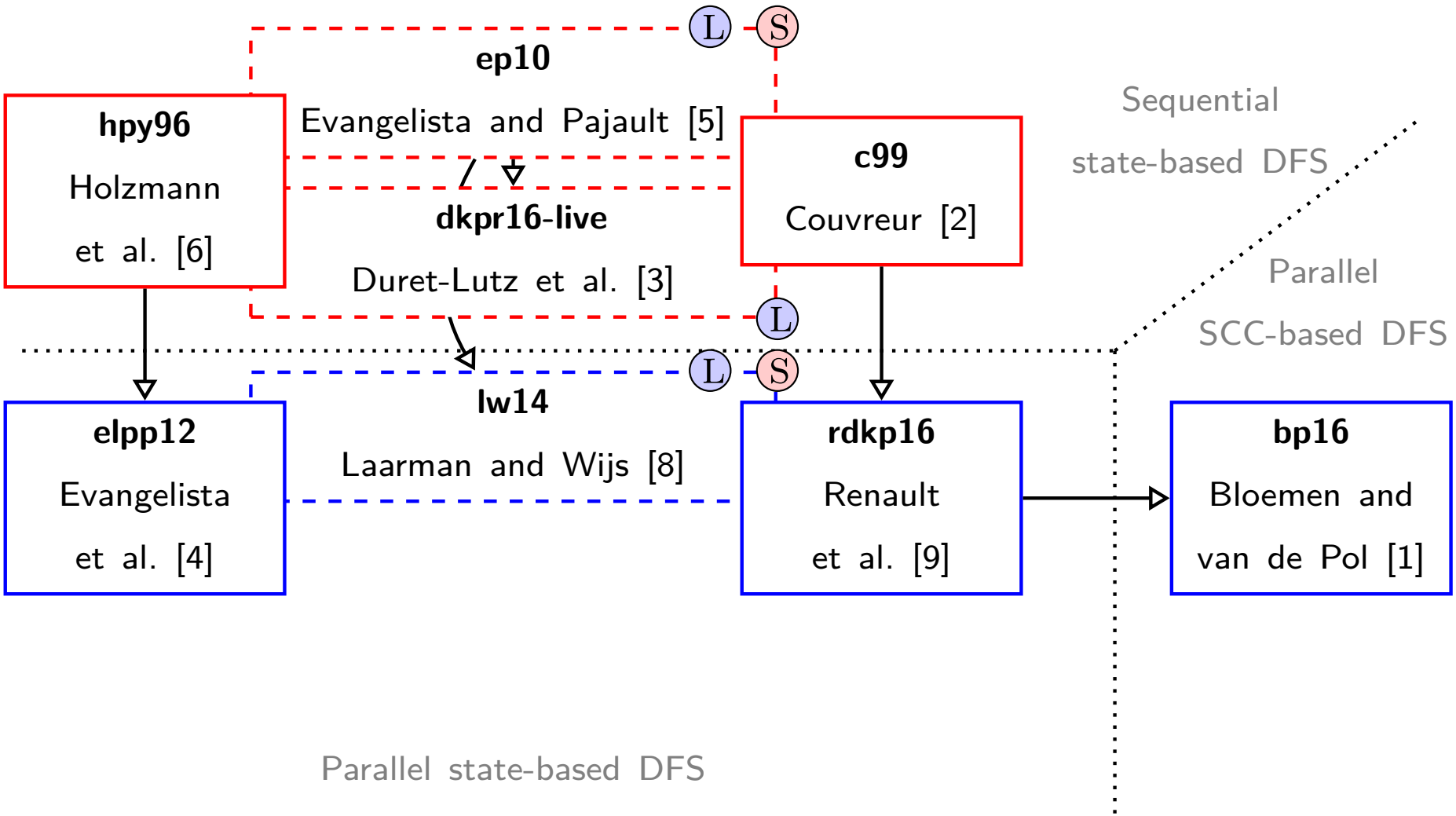

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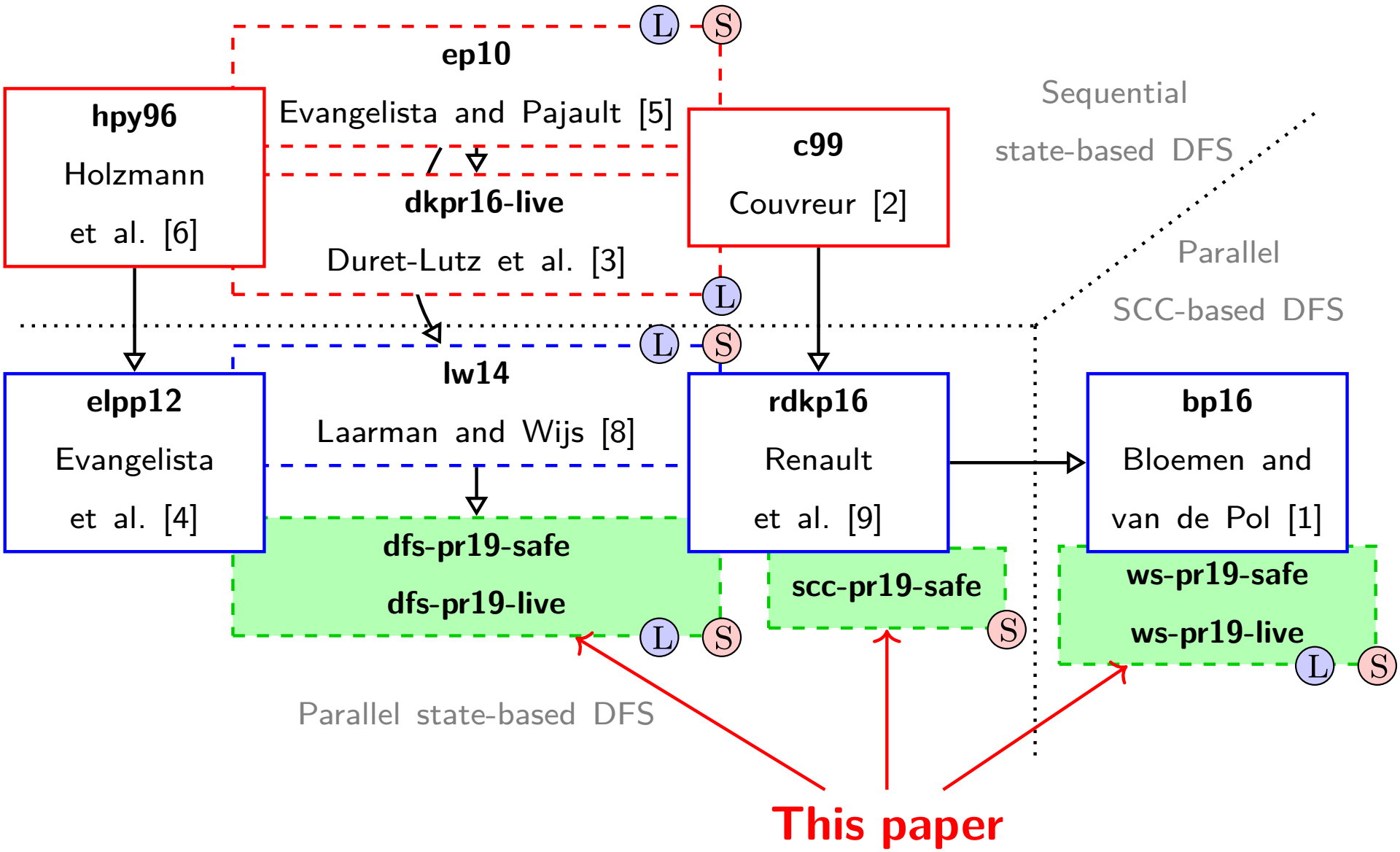

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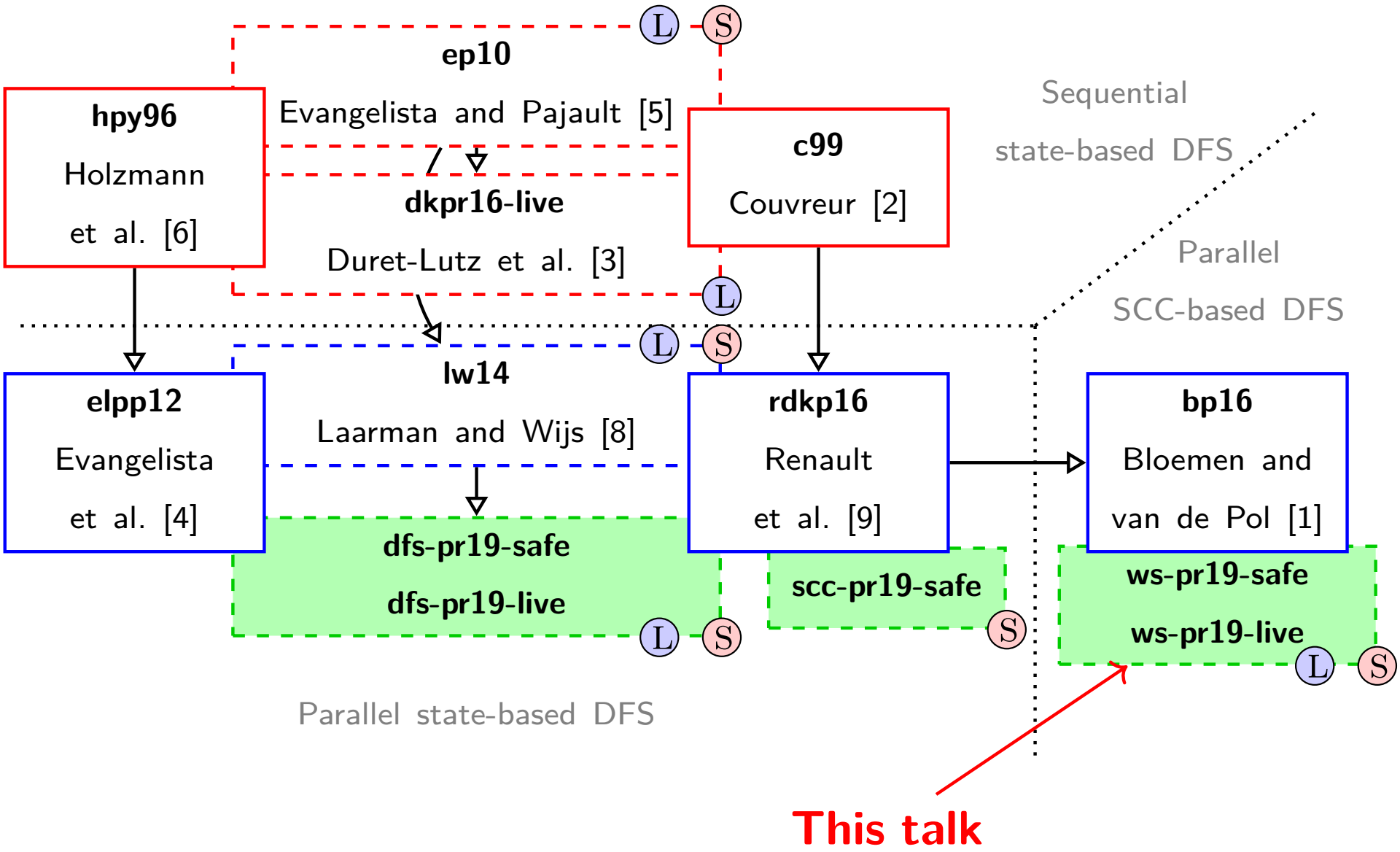
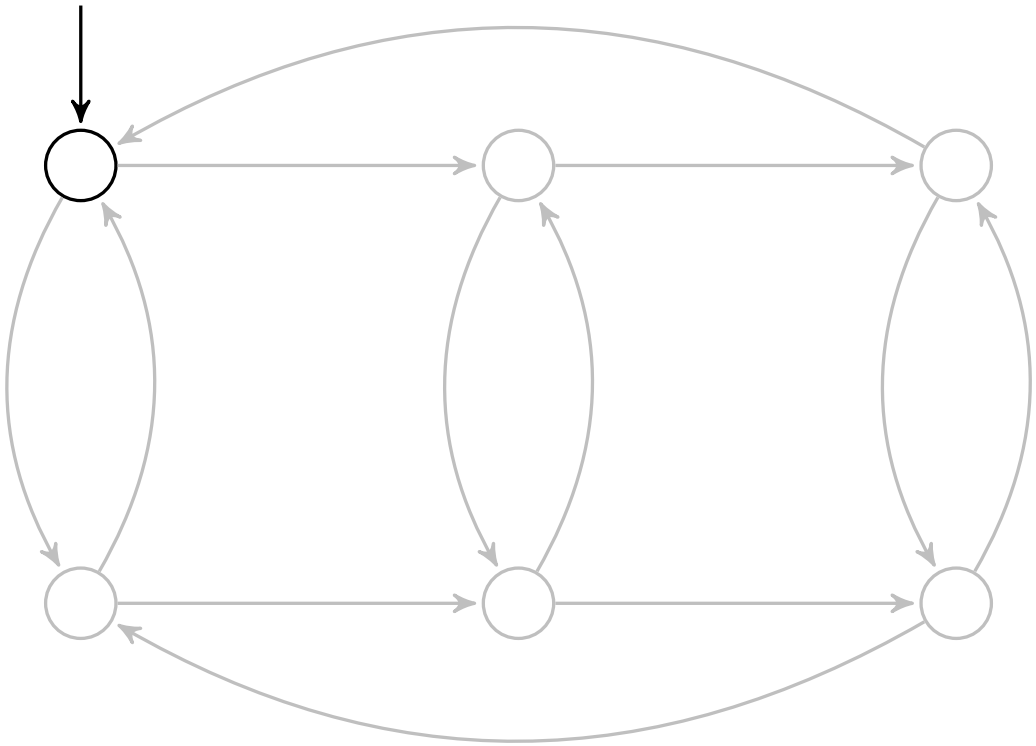


Bloemen's Emptiness Check explained



Start by the initial state (on-the-fly compatibility)

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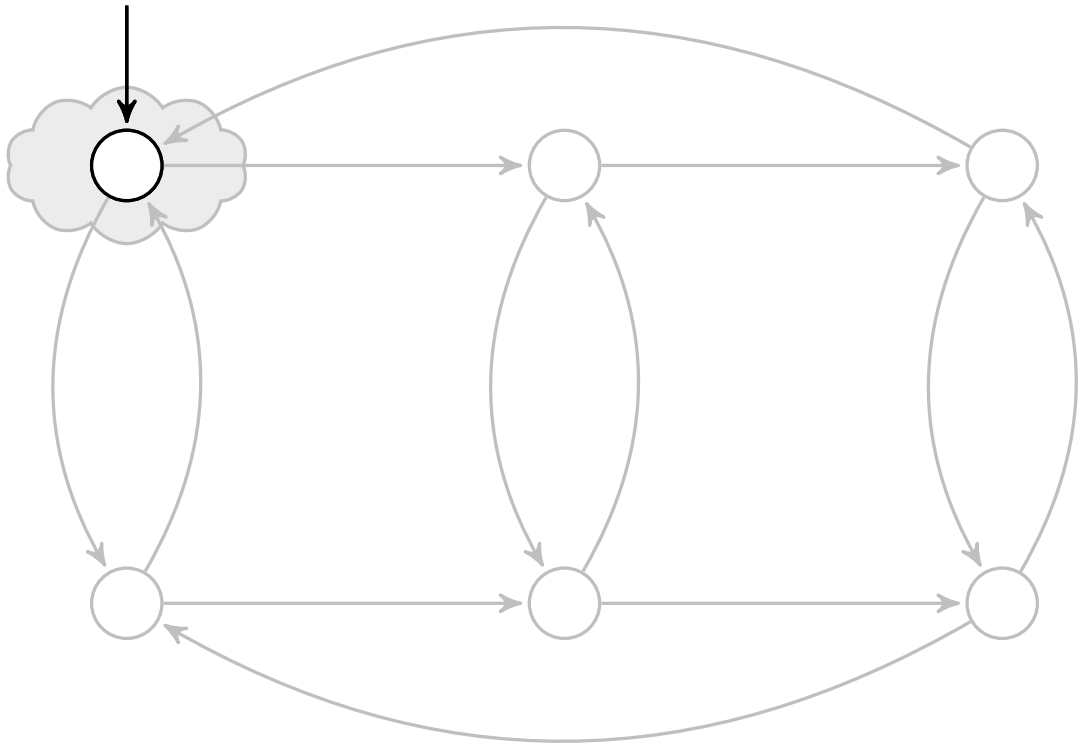
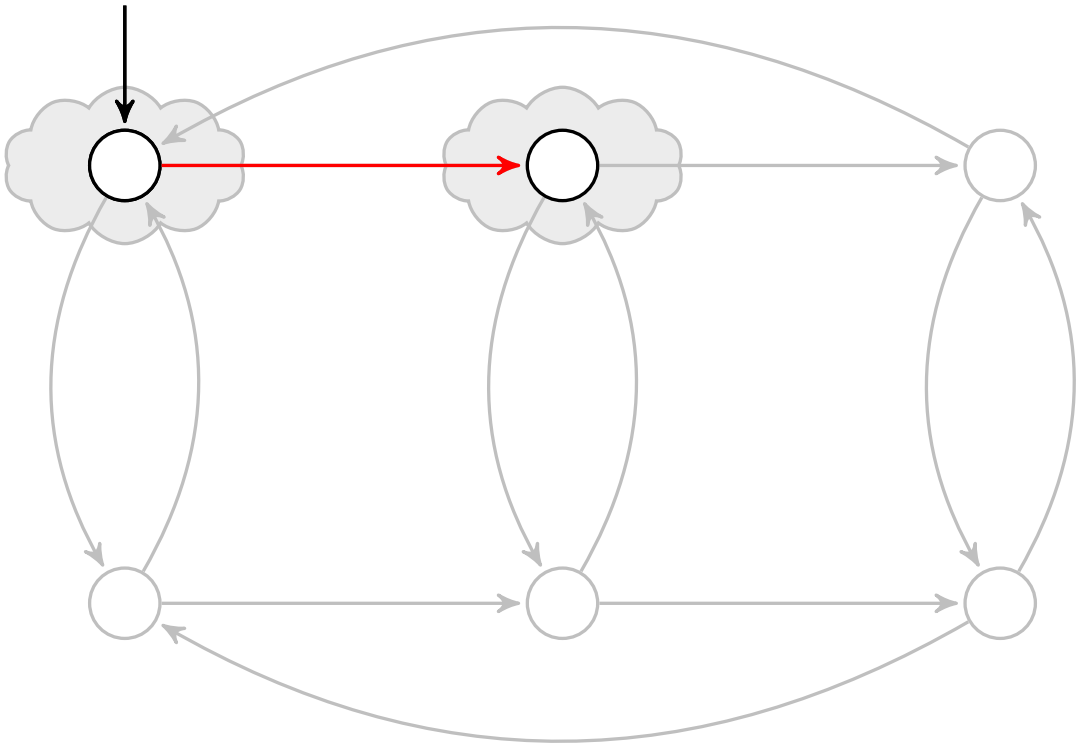


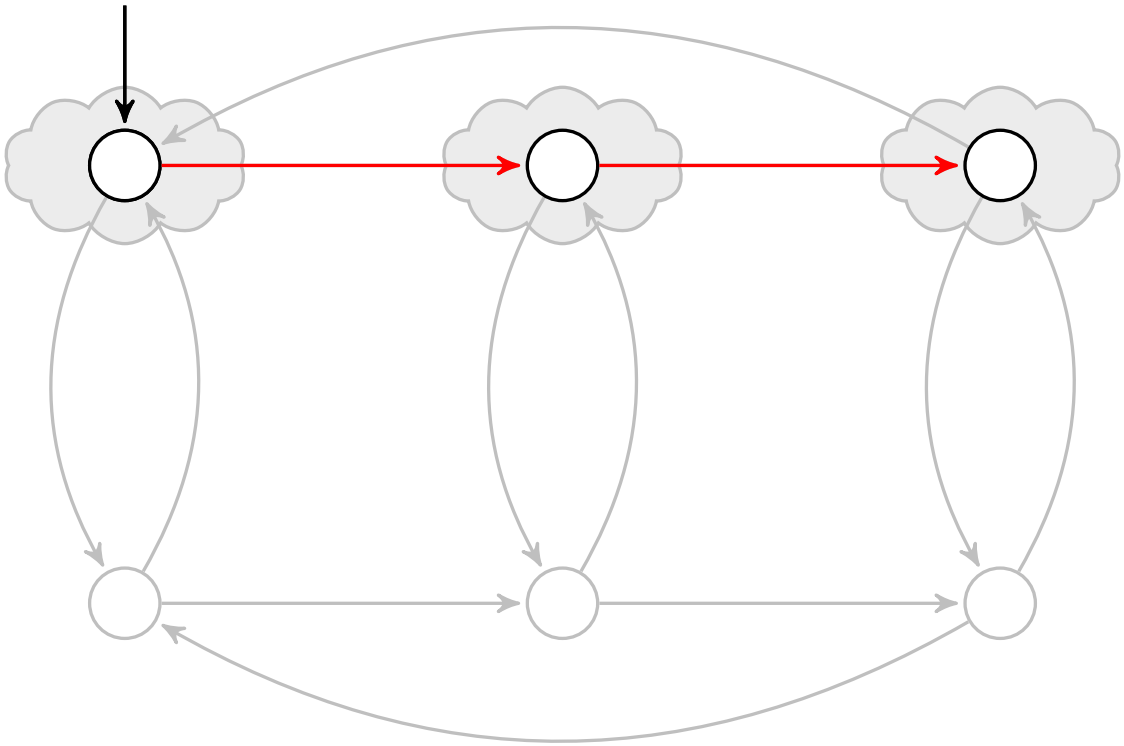
Clouds represent the actual knwoledge of SCCs

Bloemen's Emptiness Check explained



Red edges represent the DFS stack

Bloemen's Emptiness Check explained



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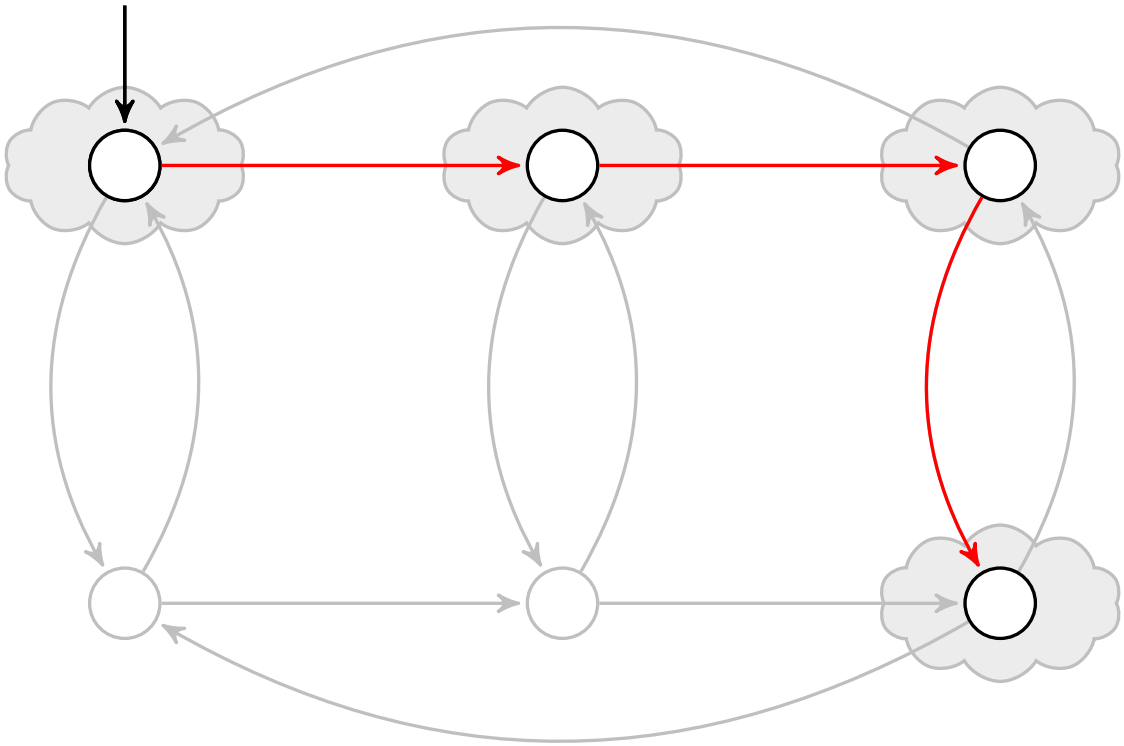

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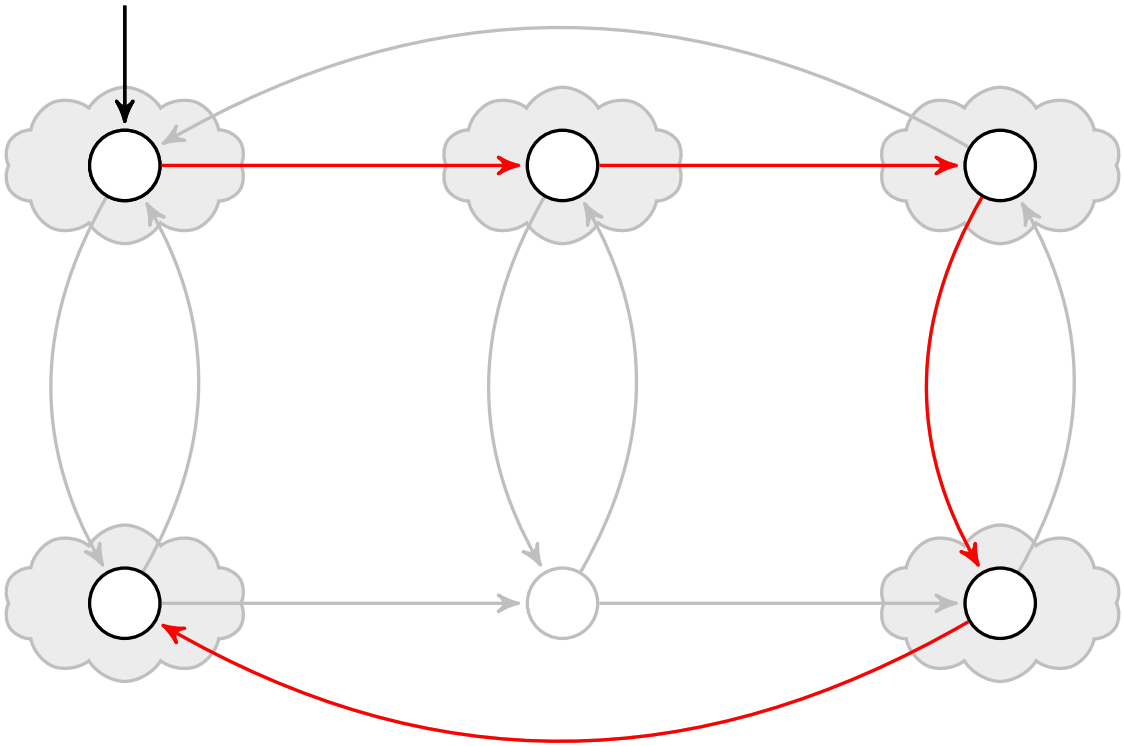

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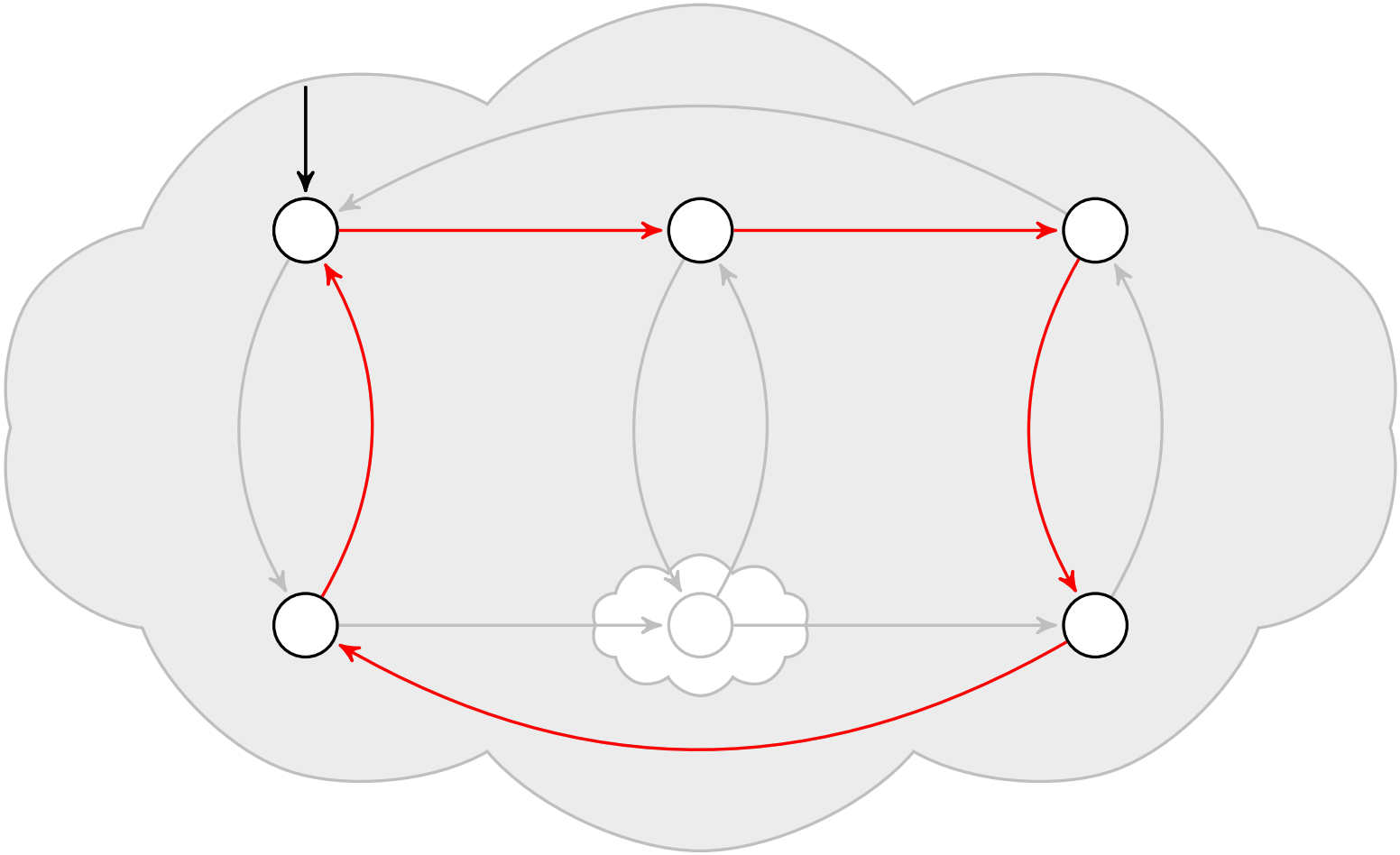
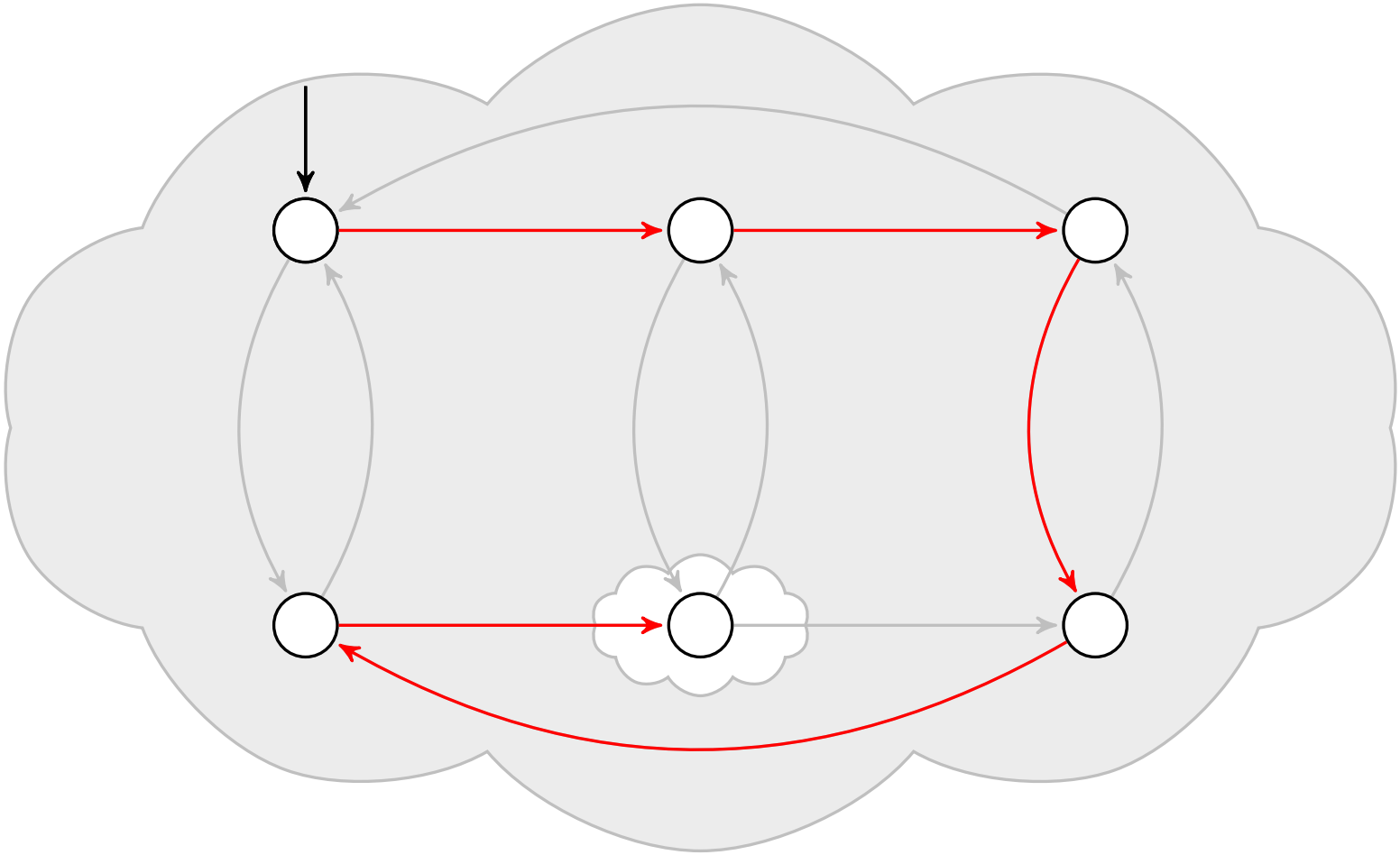


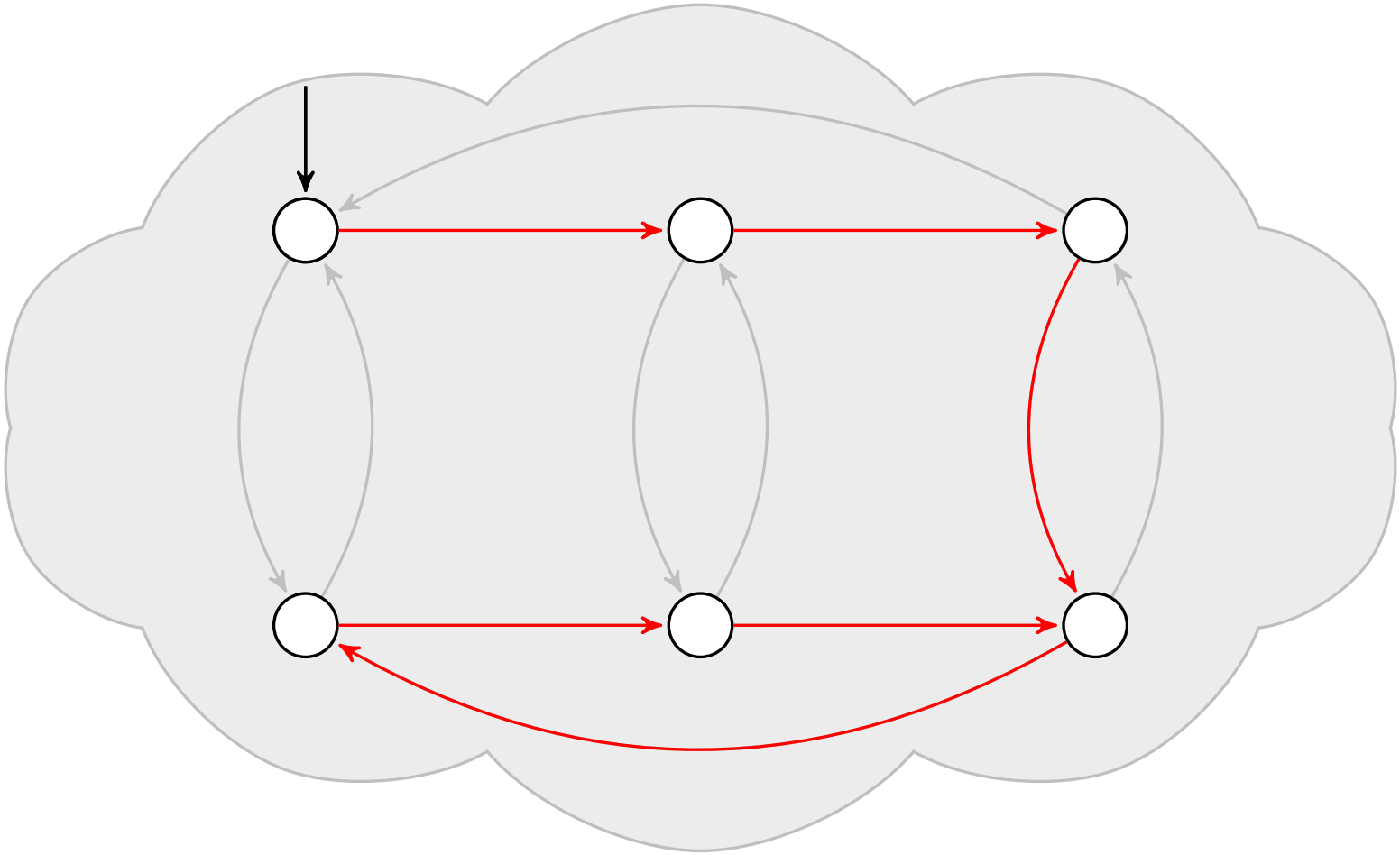
All (except one) states are discovered to belong to the same SCC

Bloemen's Emptiness Check explained



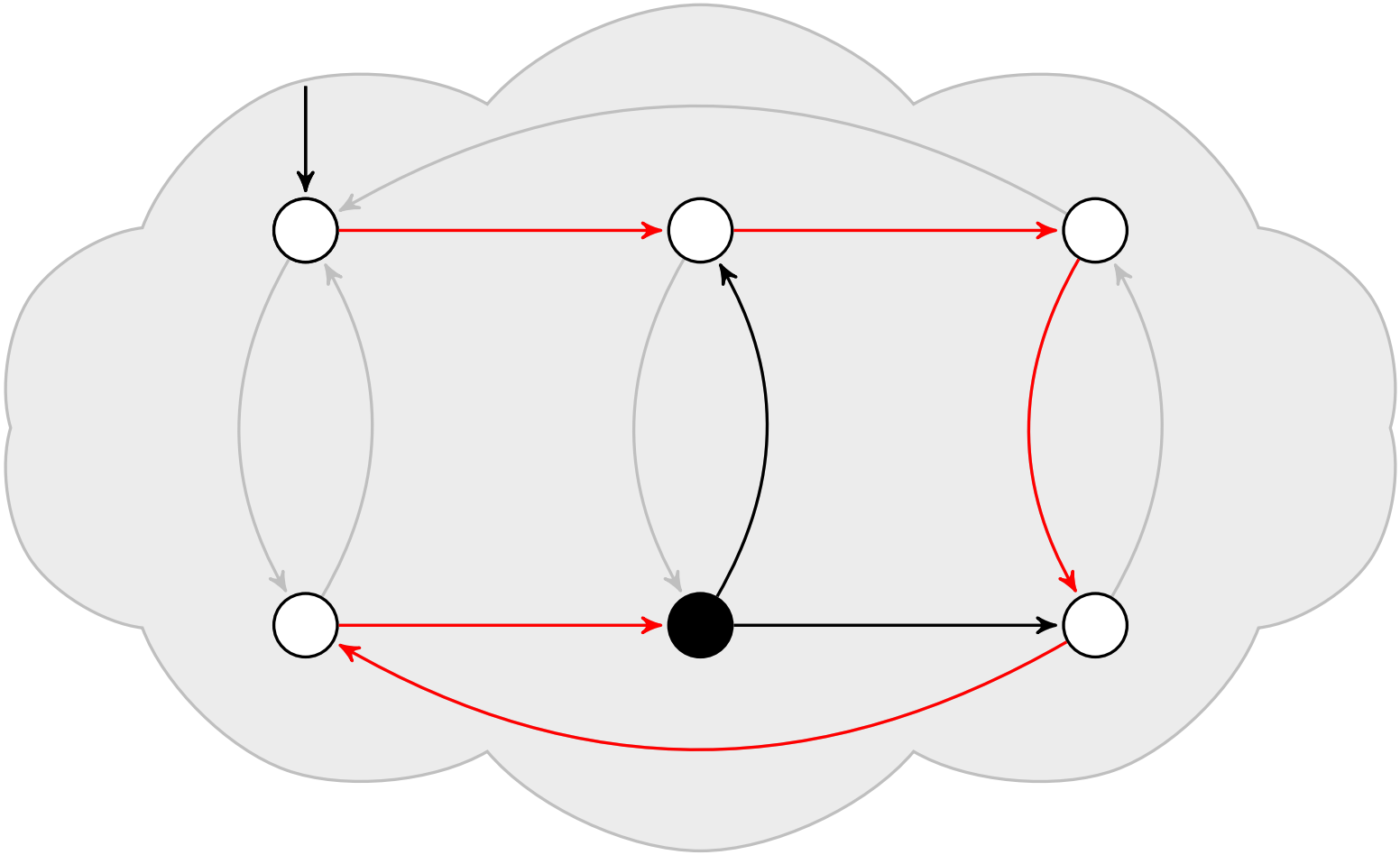
Continue DFS towards new successors

Bloemen's Emptiness Check explained



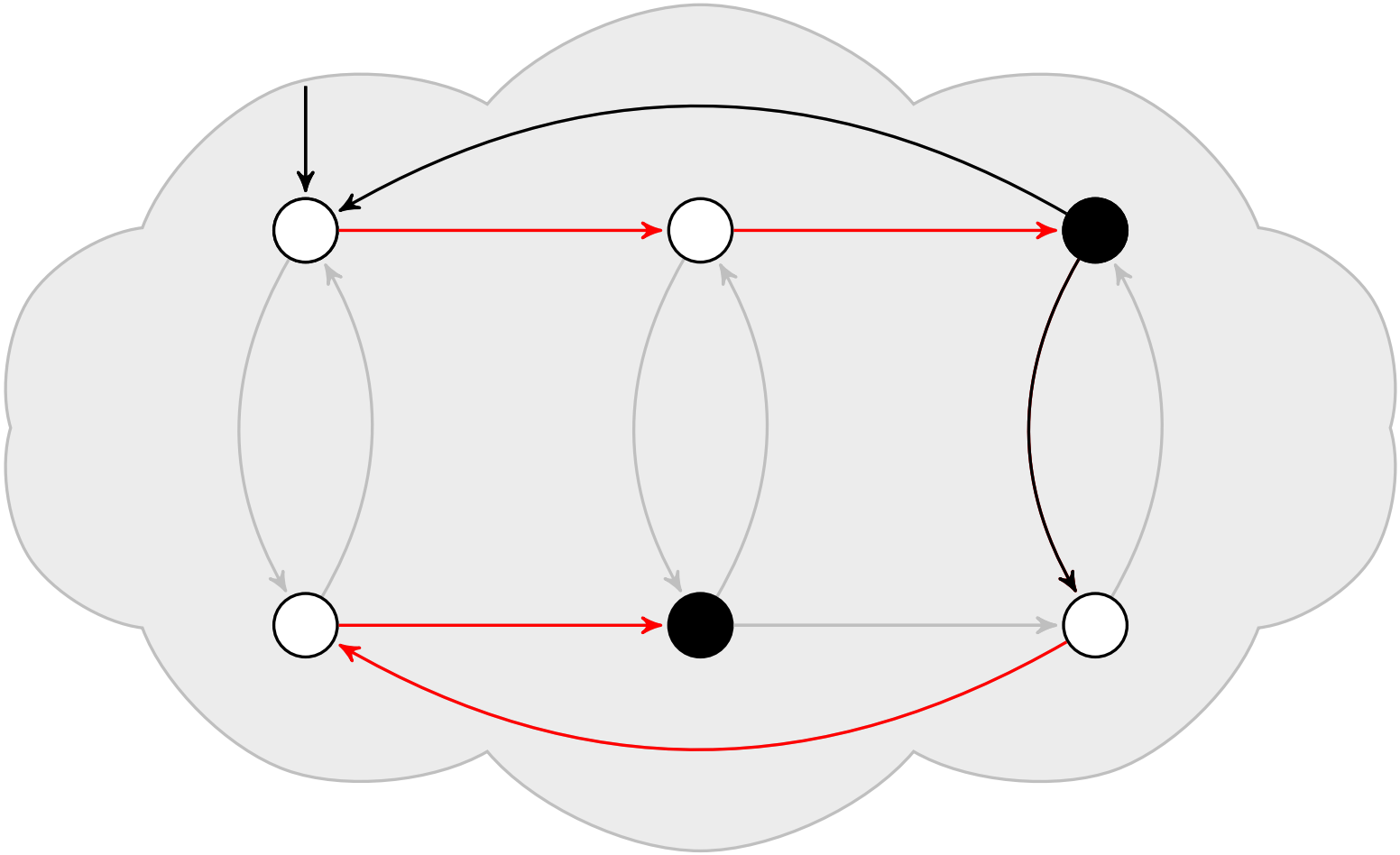
The state is detected to belong to the (only) SCC

Bloemen's Emptiness Check explained



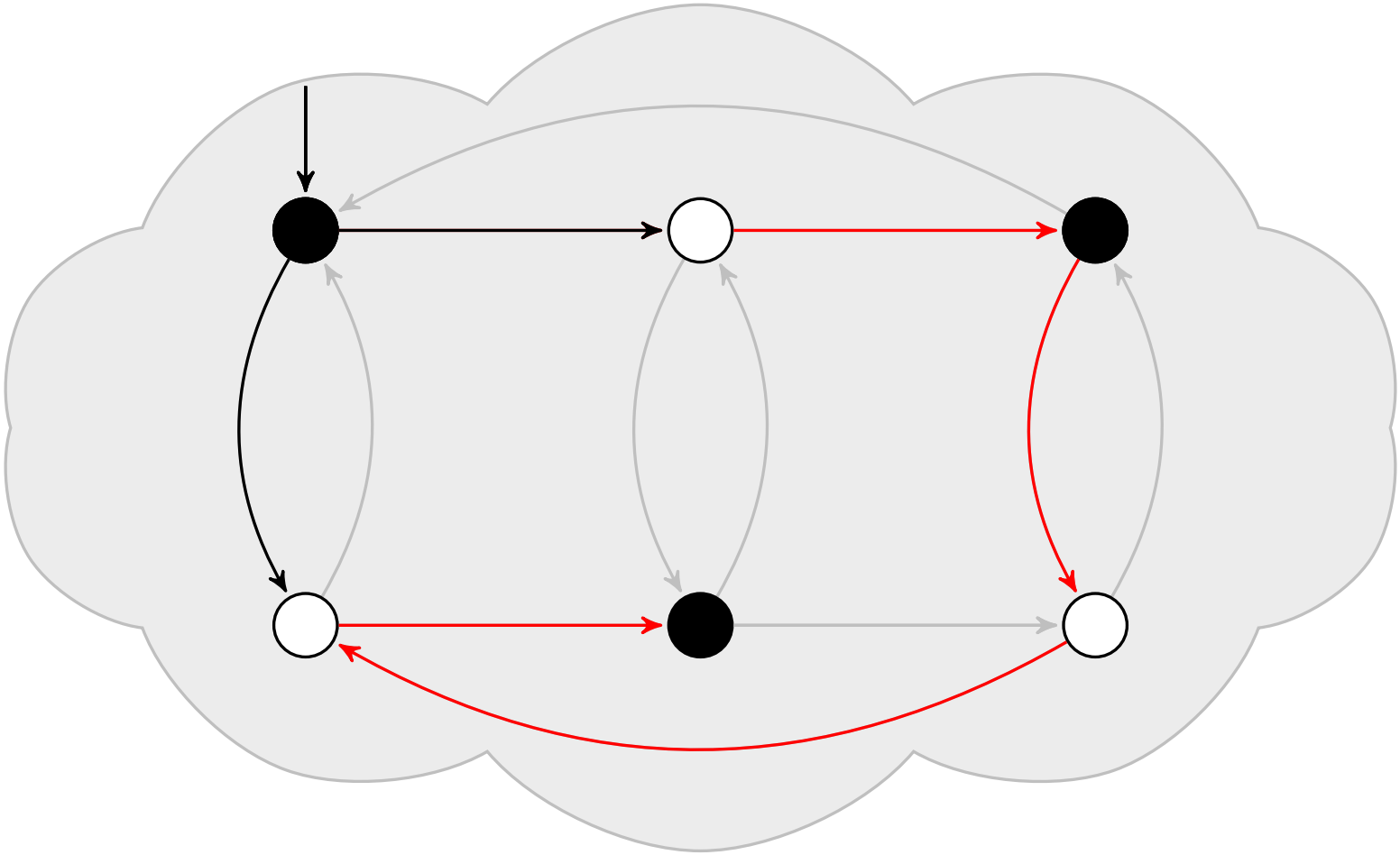
Its successors already belong to this SCC, the state is tagged DONE

Bloemen's Emptiness Check explained



Pick states randomly and tag them DONE

Bloemen's Emptiness Check explained



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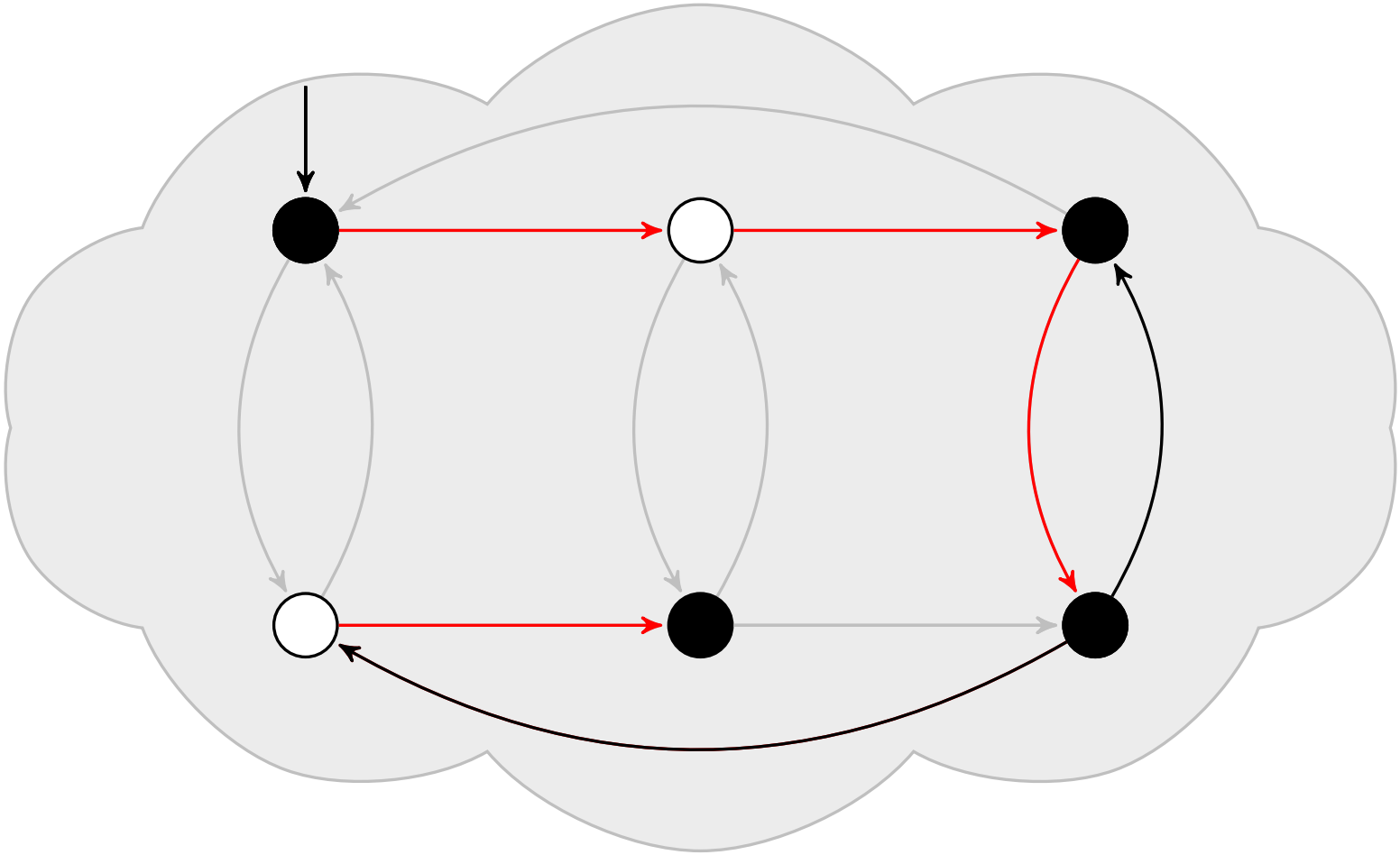

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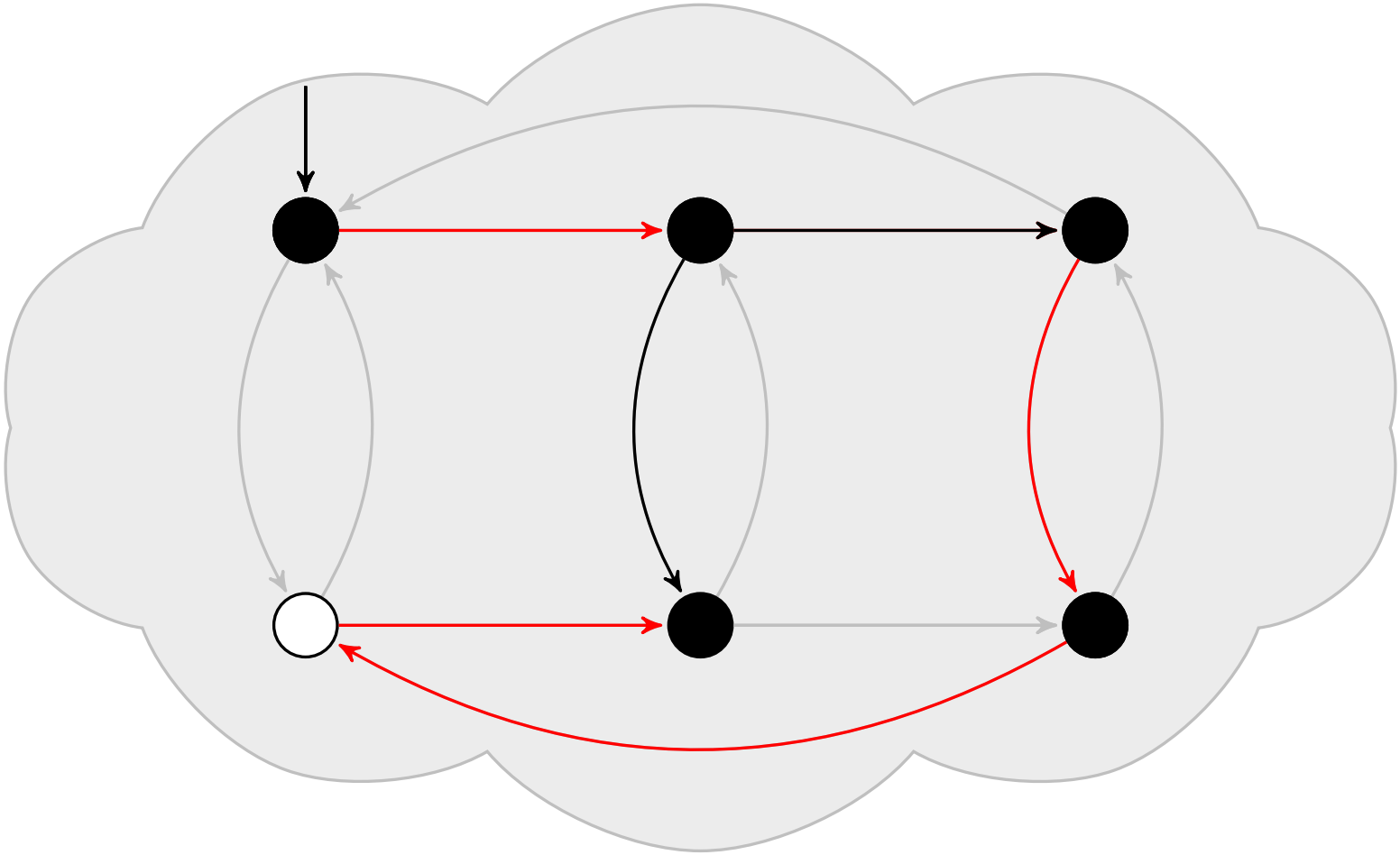

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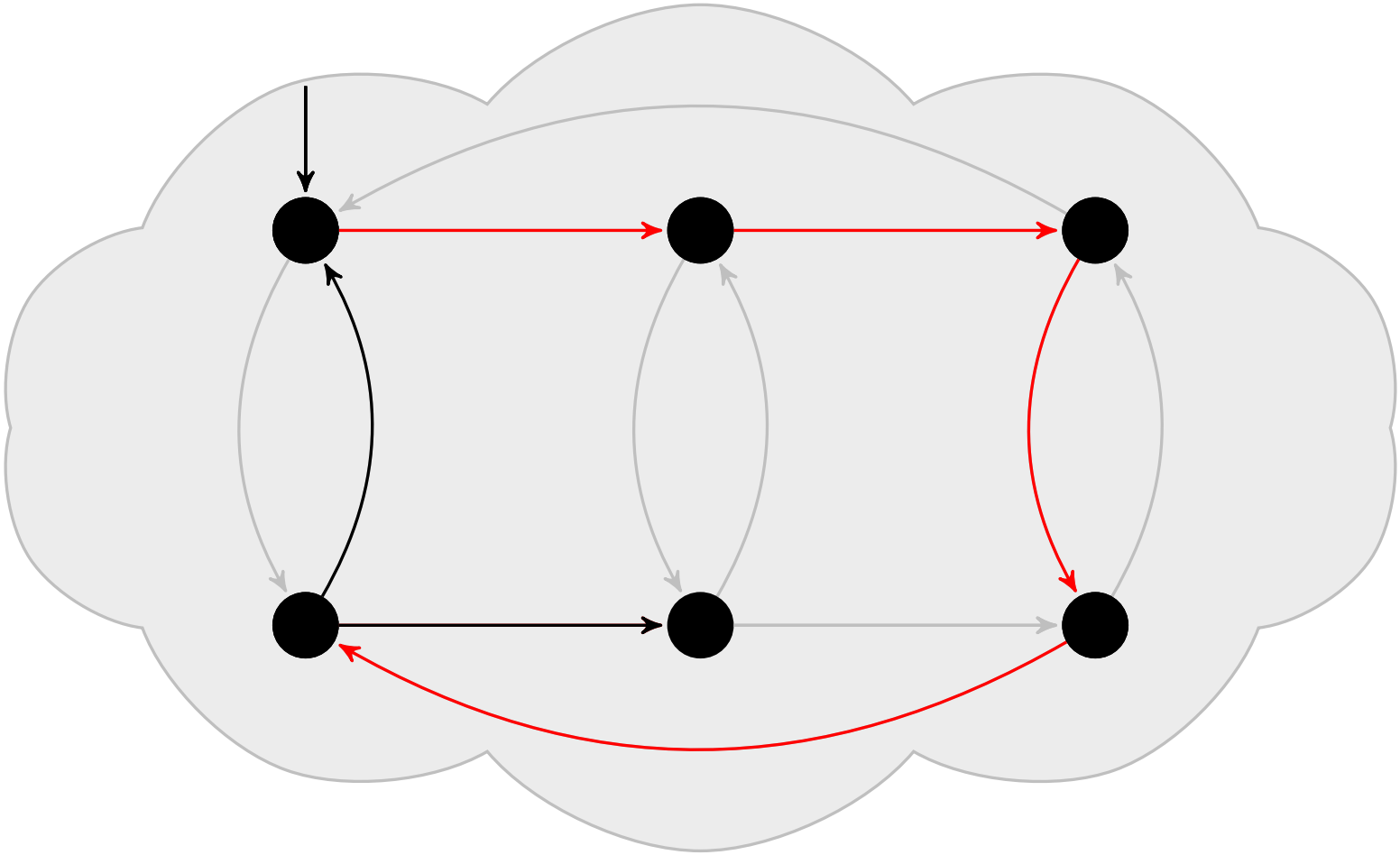

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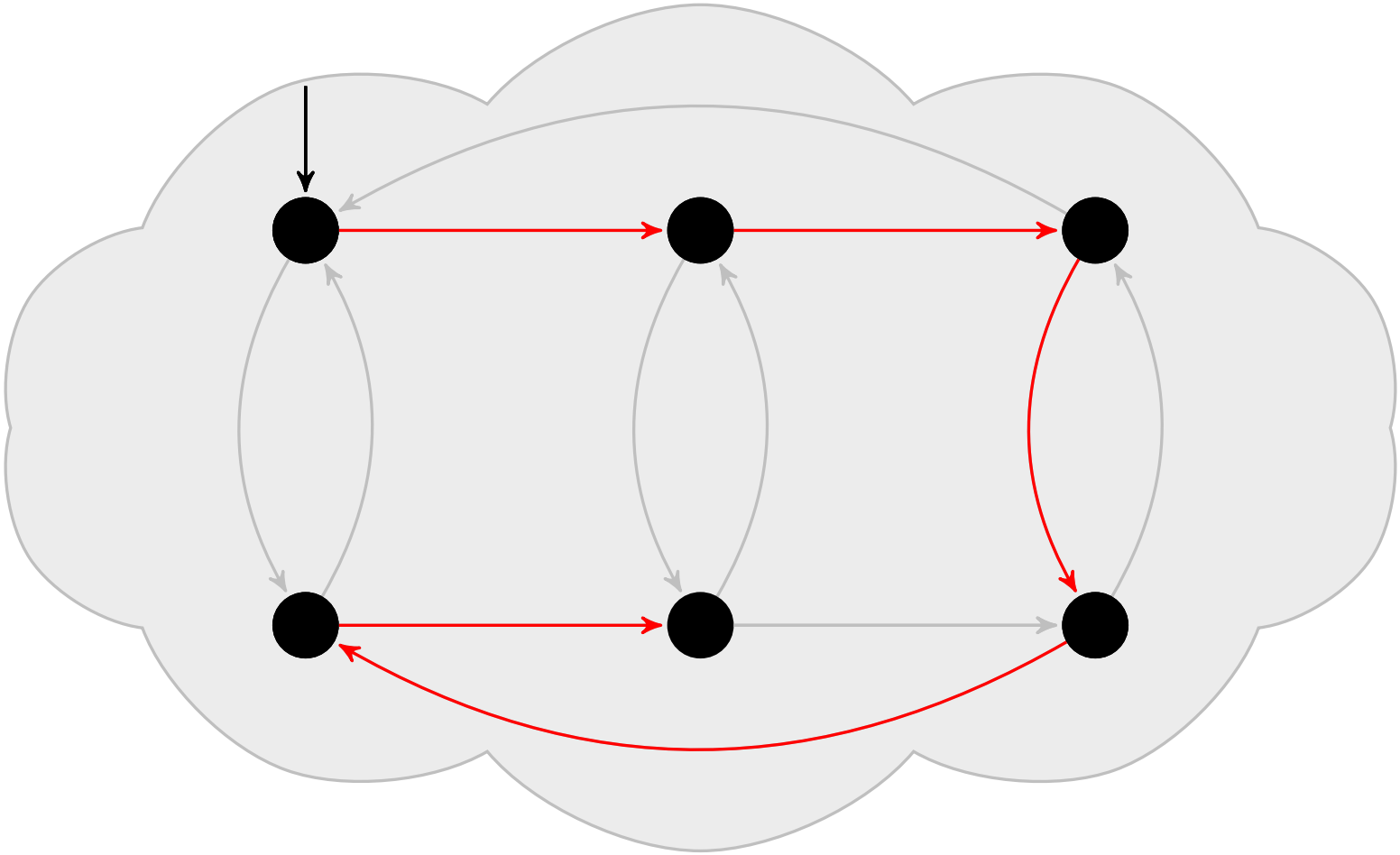


The SCC has been explored, backtrack!

Problematic

Problem's description

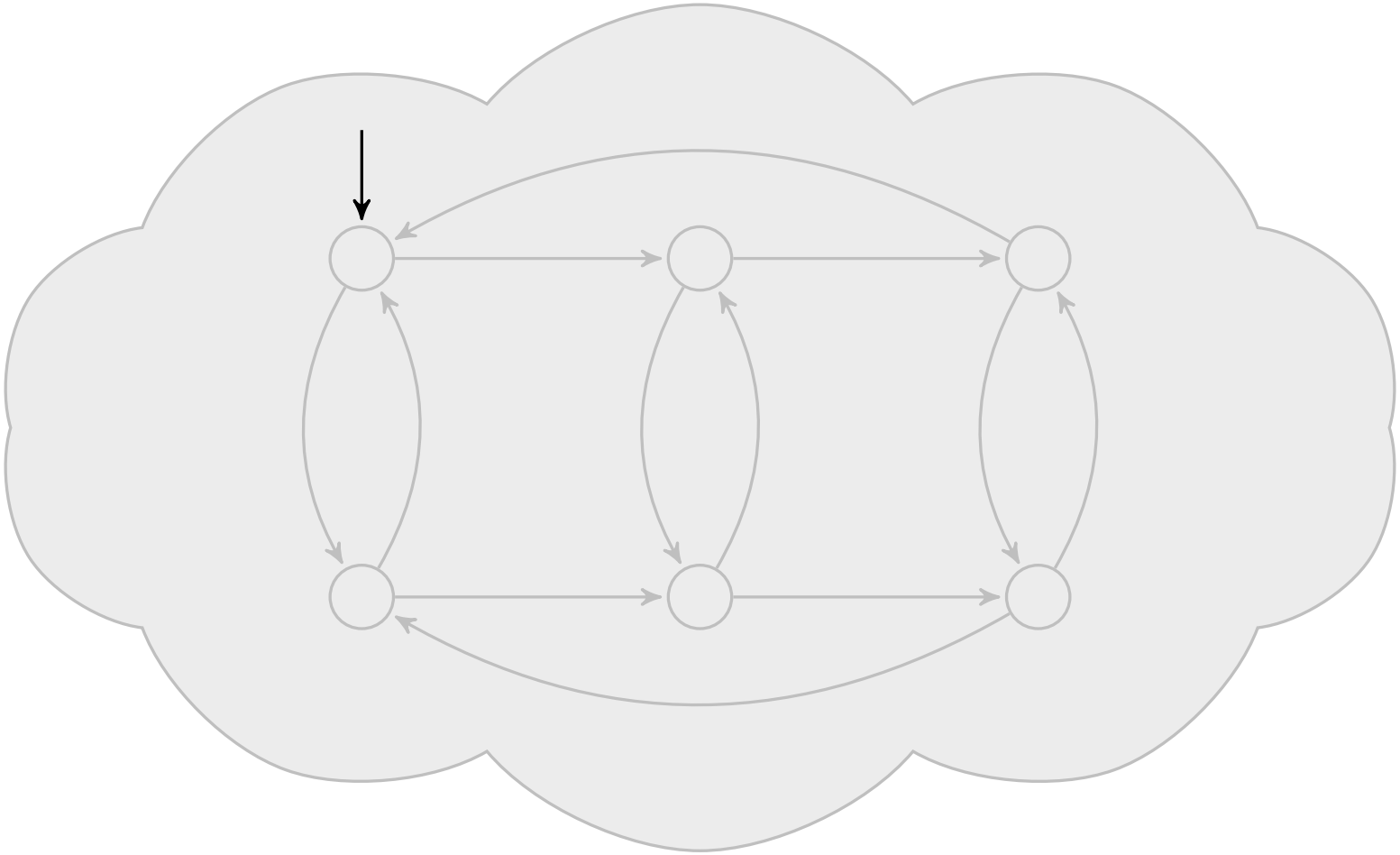
How to ensure that each cycle contains
(at least) one expanded cycle?

Rewording

Given a set of states (that belong to the same SCC), how can you decide wether an expansion is required only by considering the DONE status of its successors?

Sequential Solution: A Pessimistic Approach

Idea: expand states with one successor DONE



Pick randomly one state and mark it DONE

Sequential Solution: A Pessimistic Approach

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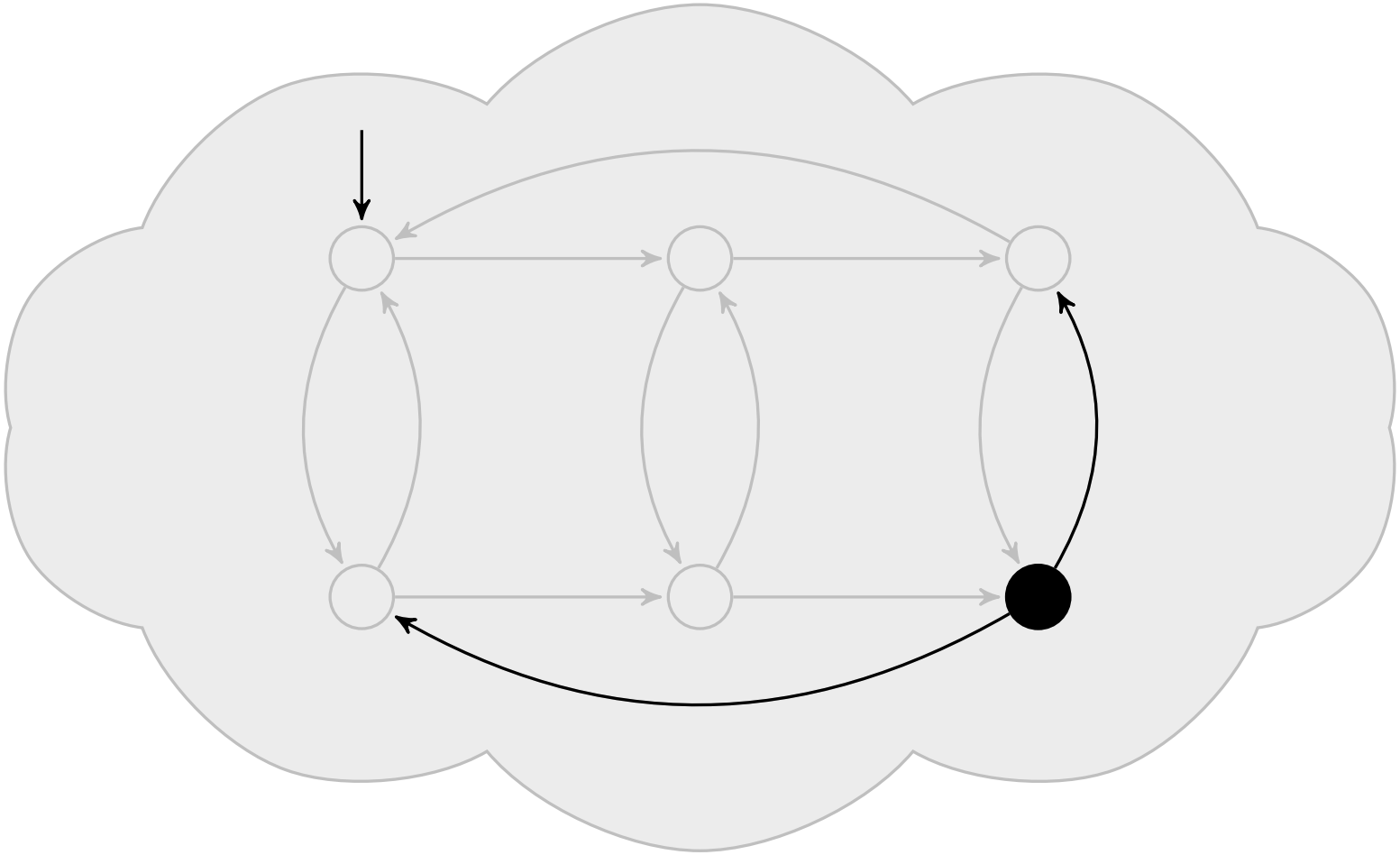

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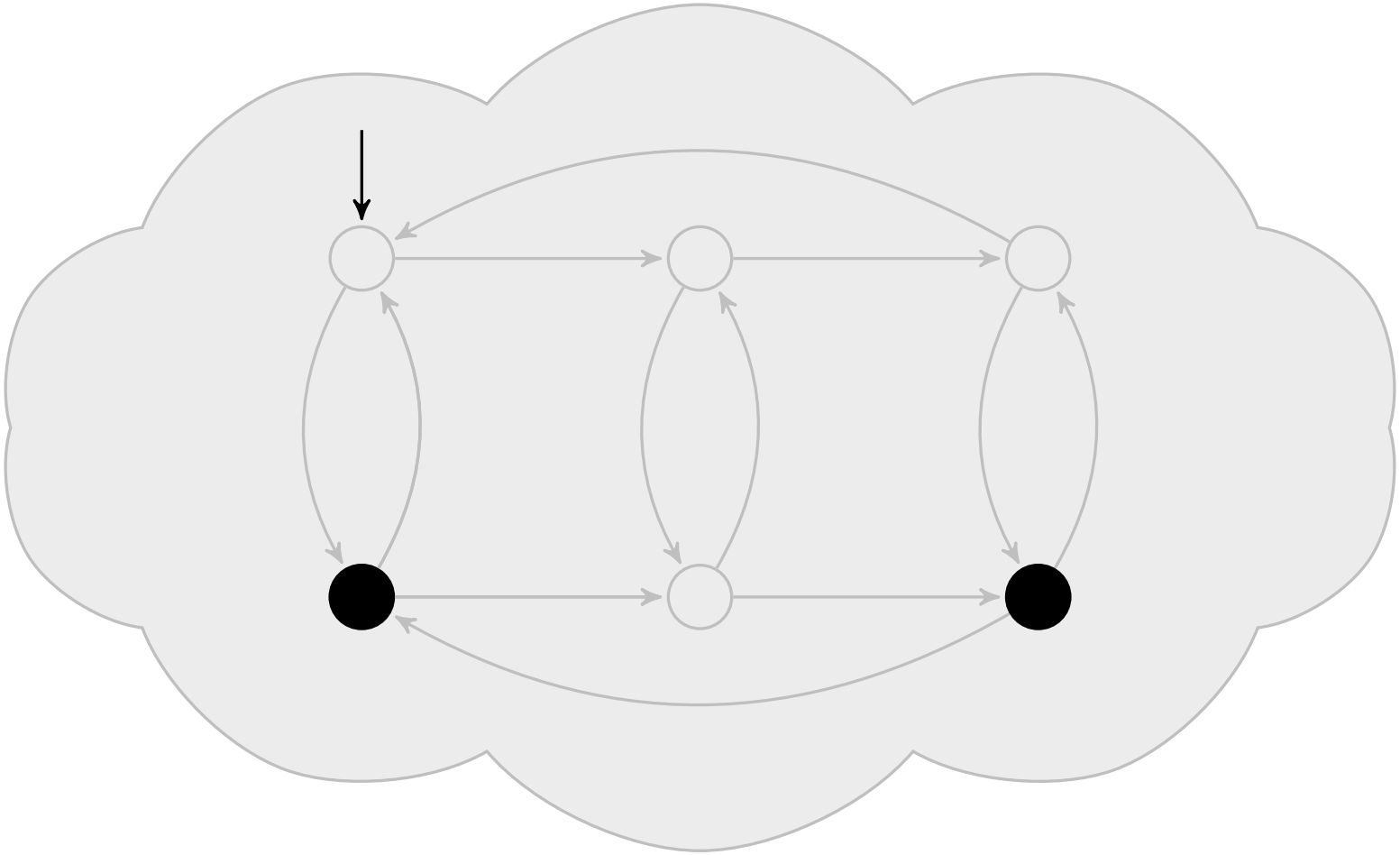

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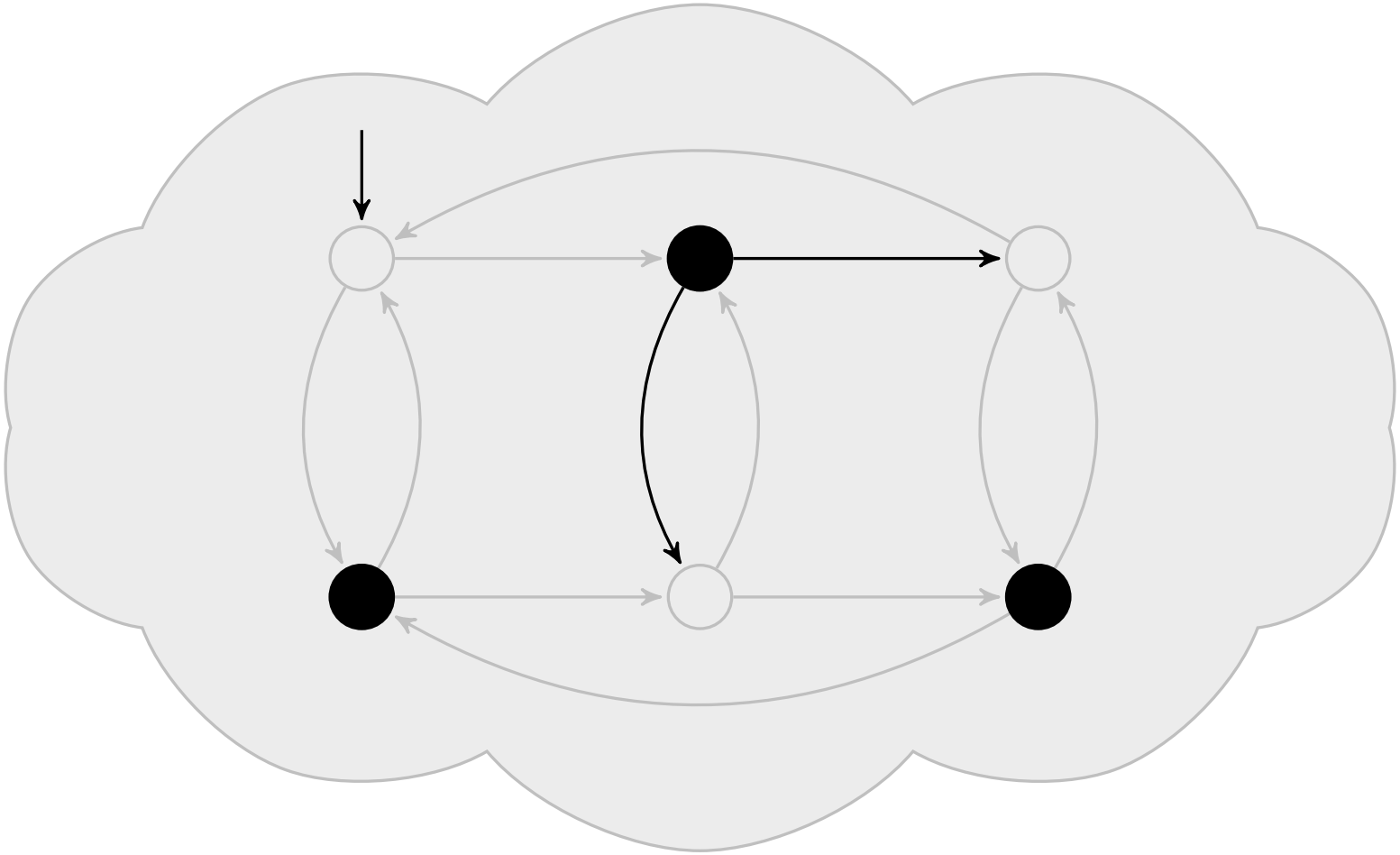

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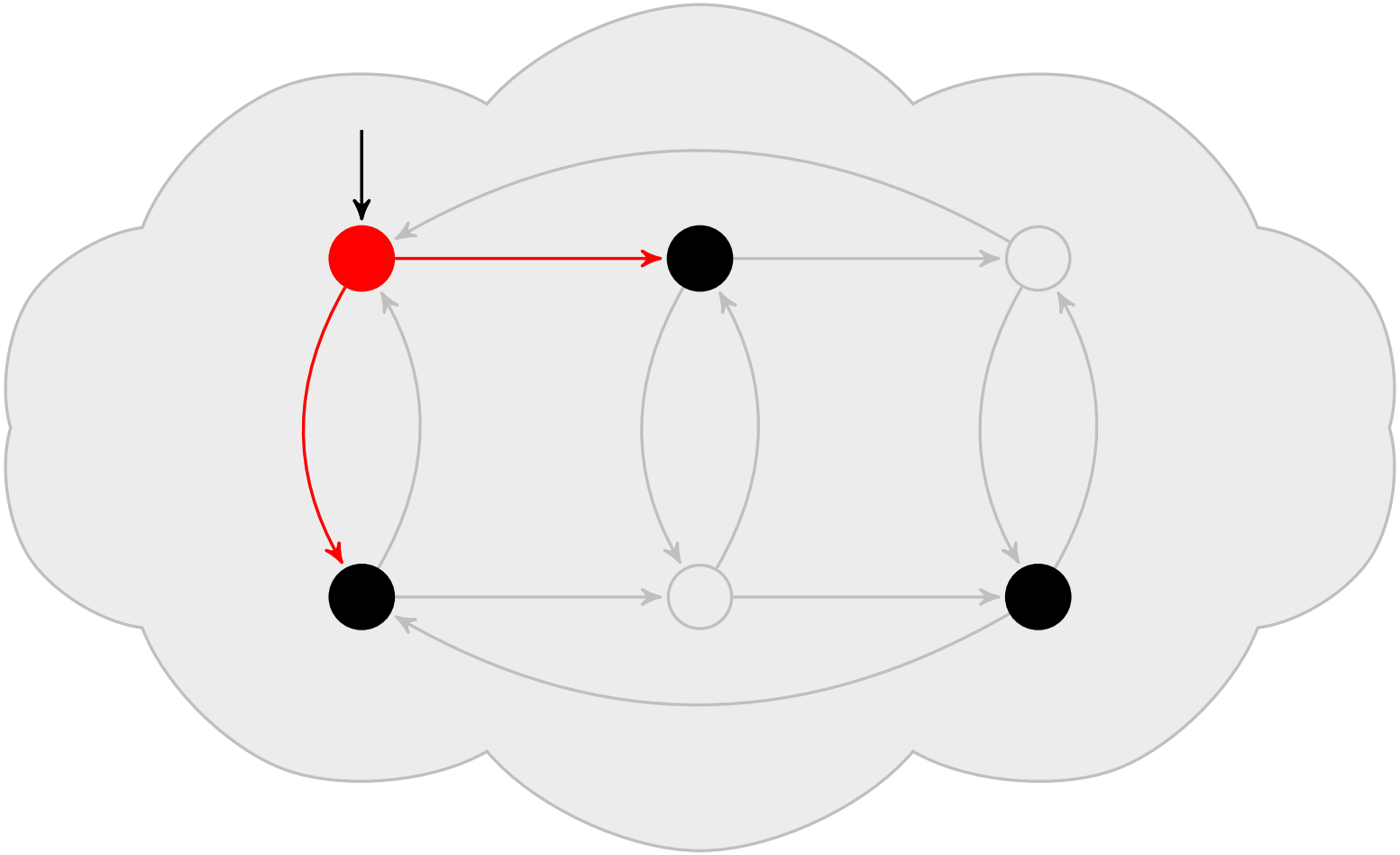

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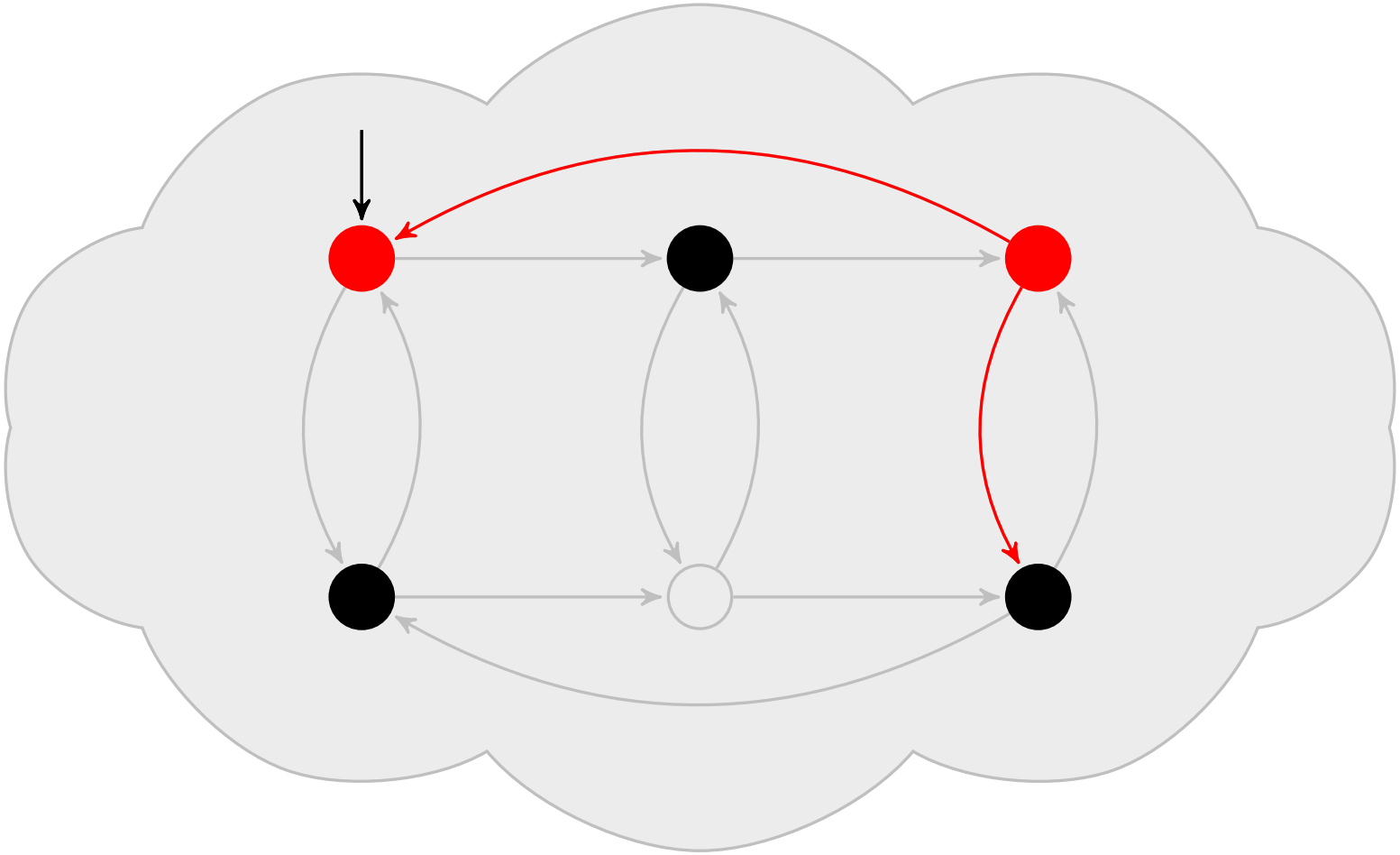
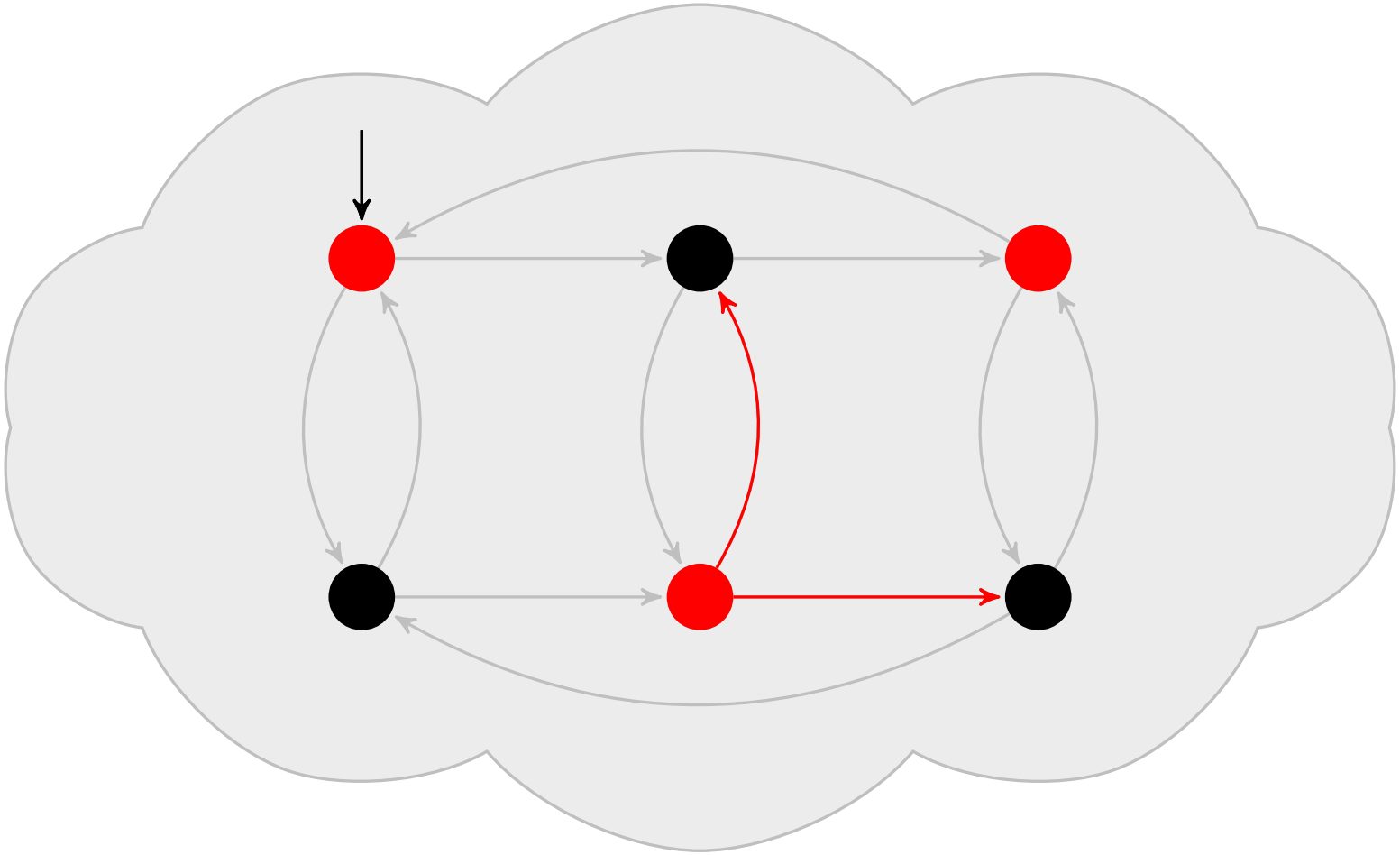


State has one DONE successor: expand it!

Sequential Solution: A Pessimistic Approach

Idea: expand states with one successor DONE



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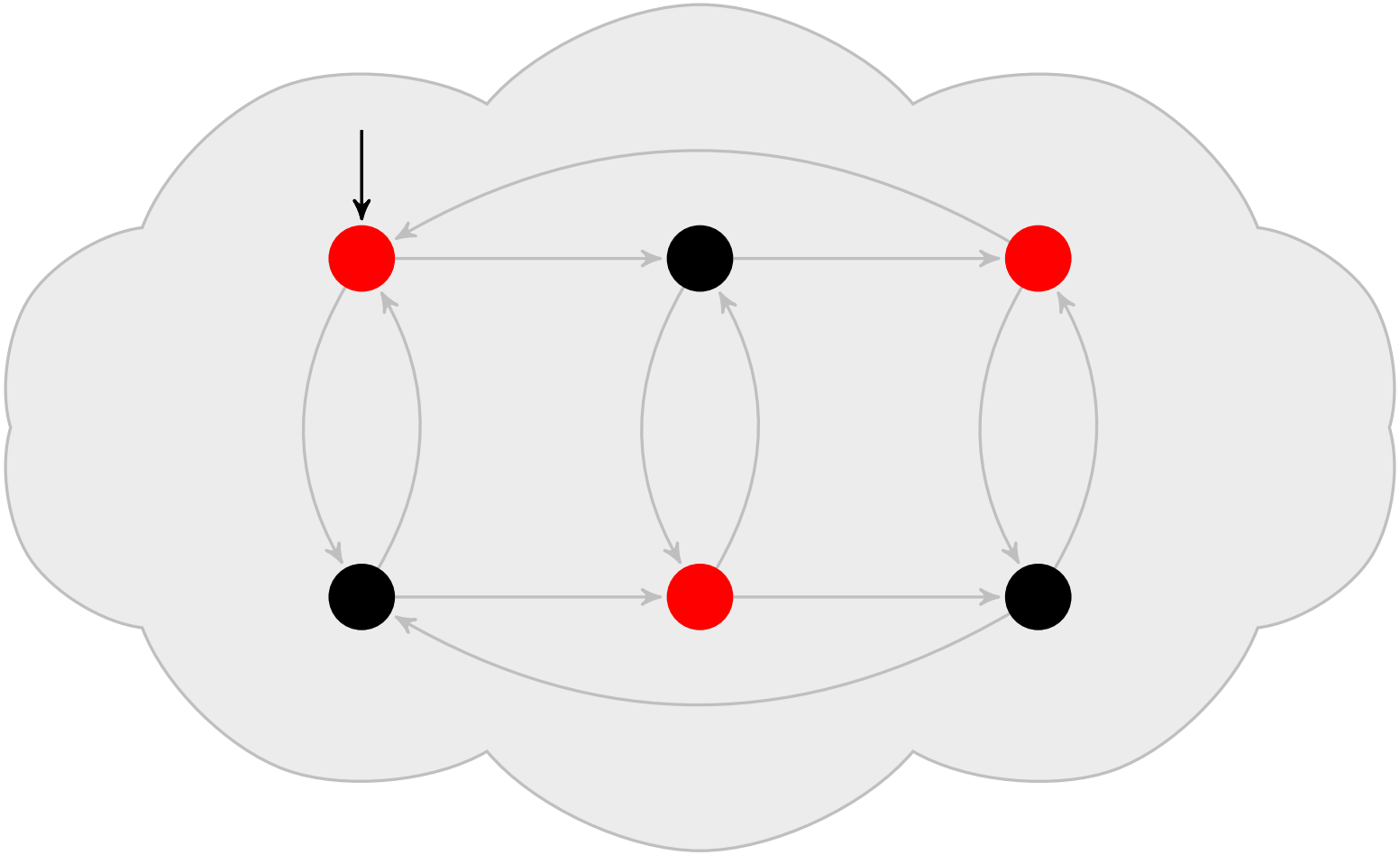
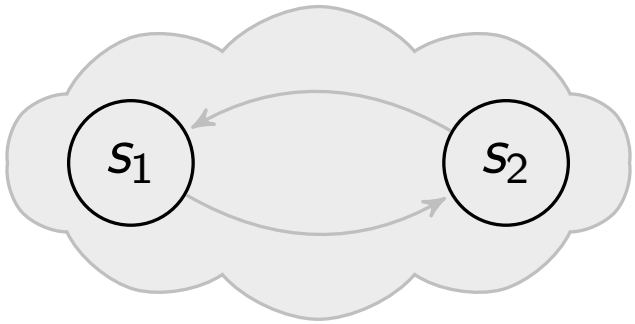


State has one DONE successor: expand it!

Parallelisation: Problem Statement

This idea does not work in parallel

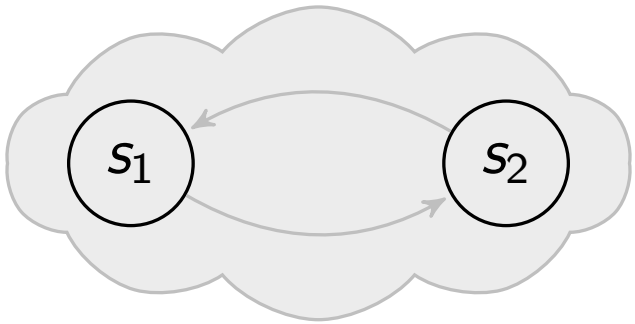
- s_1 and s_2 are known to be in the same SCC
- Thread 1 process s_1
- Thread 2 process s_2
- Thread 1 checks s_2: not expanded
- Thread 2 checks s_1: not expanded
- Both s_1 and s_2 are tagged DONE



Parallelisation: Pessimistic Solution

A state currently processed is tagged WIP. If a state s has a successor tagged WIP, s is expanded.

- s_1 is tagged WIP
- s_2 is tagged WIP
- Thread 1 check successors: s_2 is WIP, state will be expanded
- Thread 2 check successors: s_1 is WIP, state will be expanded



Others Results and Remarks

The WS-PR19-LIVE presented above is a pessimistic approach:

- Sequential: $N/2$ expansions in average, for an SCC of size N
- Parallel: ?

The paper also suggests:

- An adaptation of Bloemen's algorithm for safety WS-PR19-SAFE
- An adaptation of other parallel emptiness check with provisos for safety and liveness: DFS-PR19-SAFE, DFS-PR19-LIVE, and SCC-PR19-SAFE

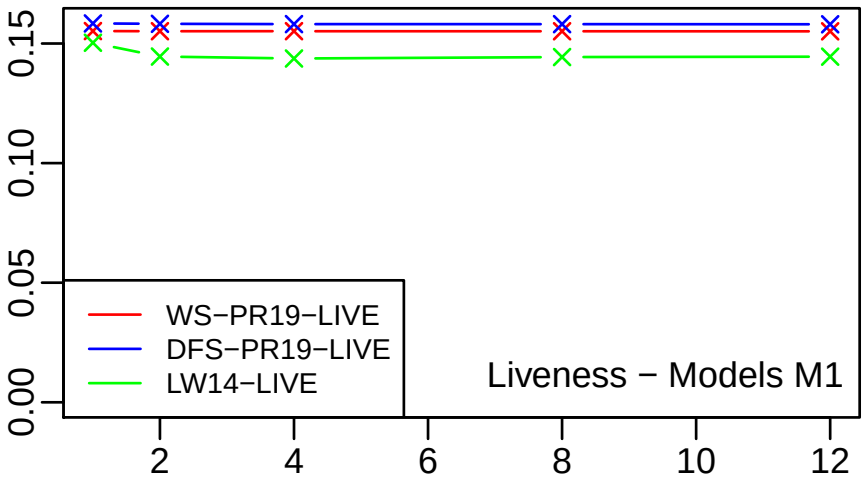
All the approaches presented in this paper are:

- Compatible with *Persistent sets*, *Stubborn set* and *Ample set*
- **Compatible with on-the-fly exploration technique**

Evaluation

- 21 models from the BEEM benchmark divided into two categories:
  - $\mathcal{M}_1$: models with short cycles and many small SCCs
  - $\mathcal{M}_2$: models with long cycles and a small number of large SCCs
- Reductions are implemented by the way of the stubborn-set method from Valmari
- Maximum running time 40 minutes (in sequential)
- Up to 12 threads (the maximum we can test)
- Compare the 5 algorithms we propose against state of the art algorithm (**lw14**)

Reduction


0.00
0.05
0.10
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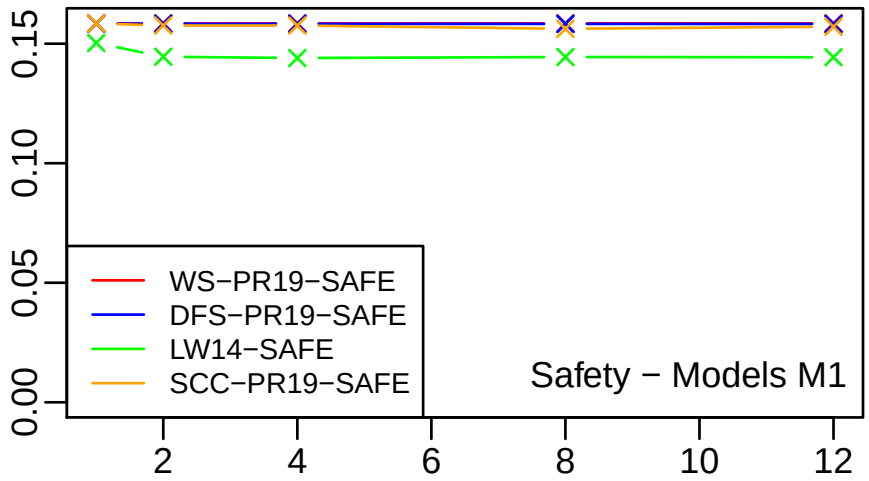
2
4
6
8
10
12
WS−PR19−LIVE
DFS−PR19−LIVE
LW14−LIVE
Liveness − Models M1


0.00
0.05
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0.15
2
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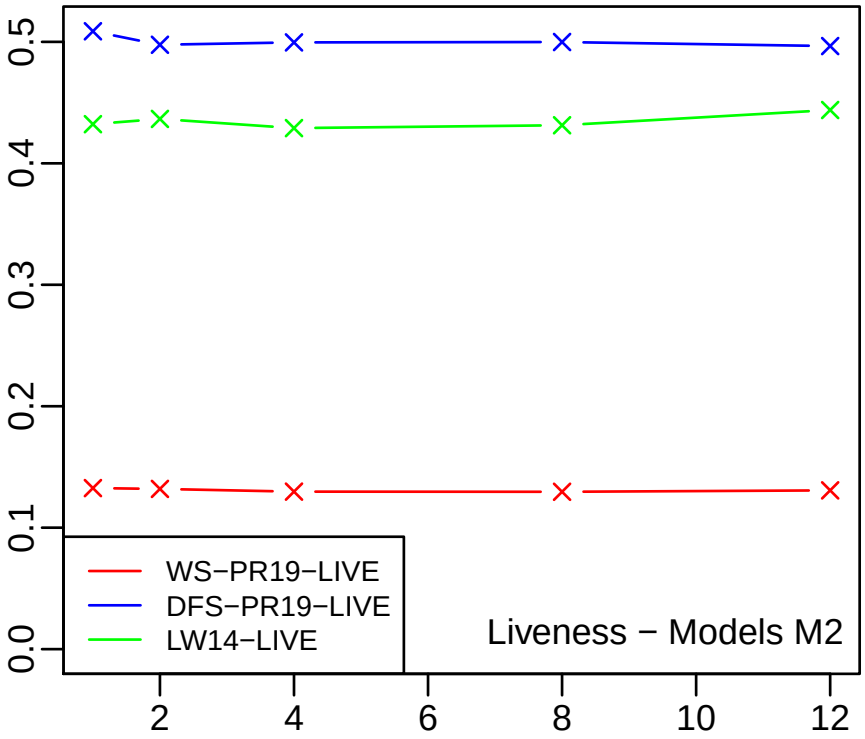
WS−PR19−SAFE
DFS−PR19−SAFE
LW14−SAFE
SCC−PR19−SAFE
Safety − Models M1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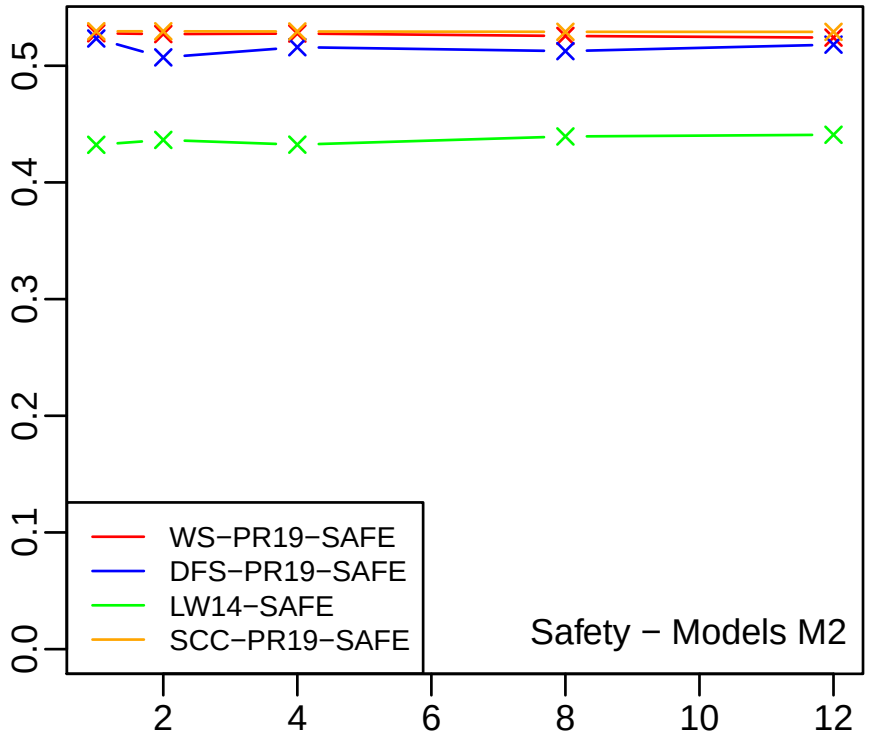
12
WS−PR19−LIVE
DFS−PR19−LIVE
LW14−LIVE
Liveness − Models M2


0.0
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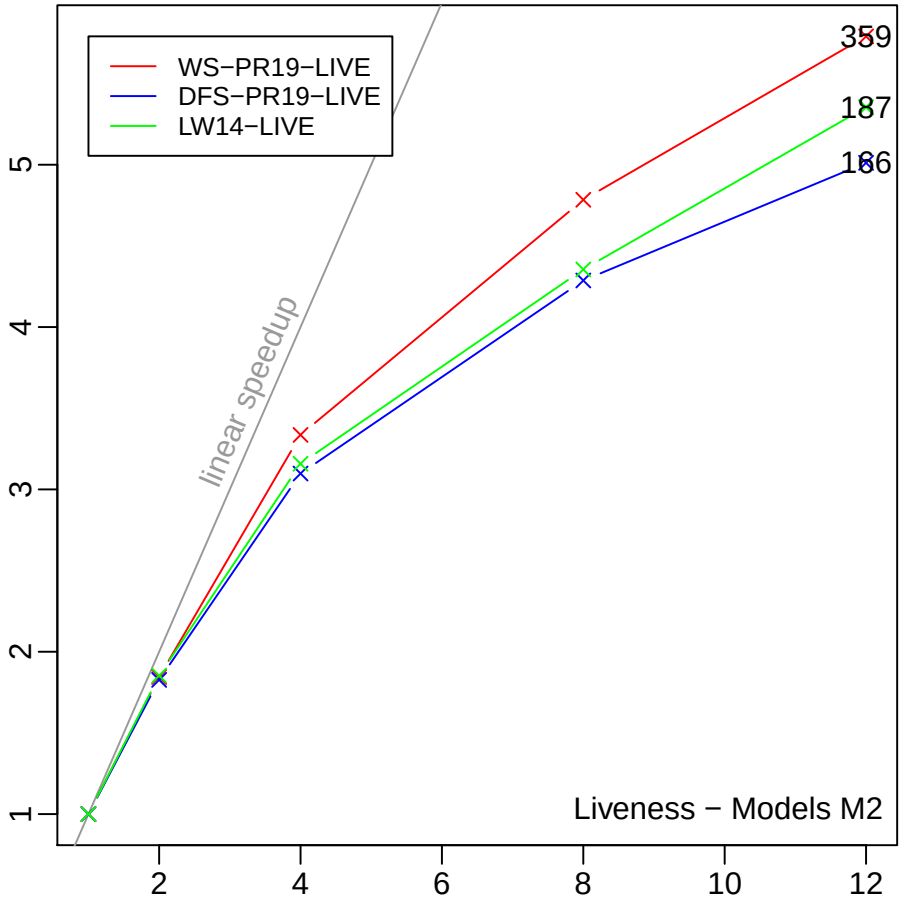
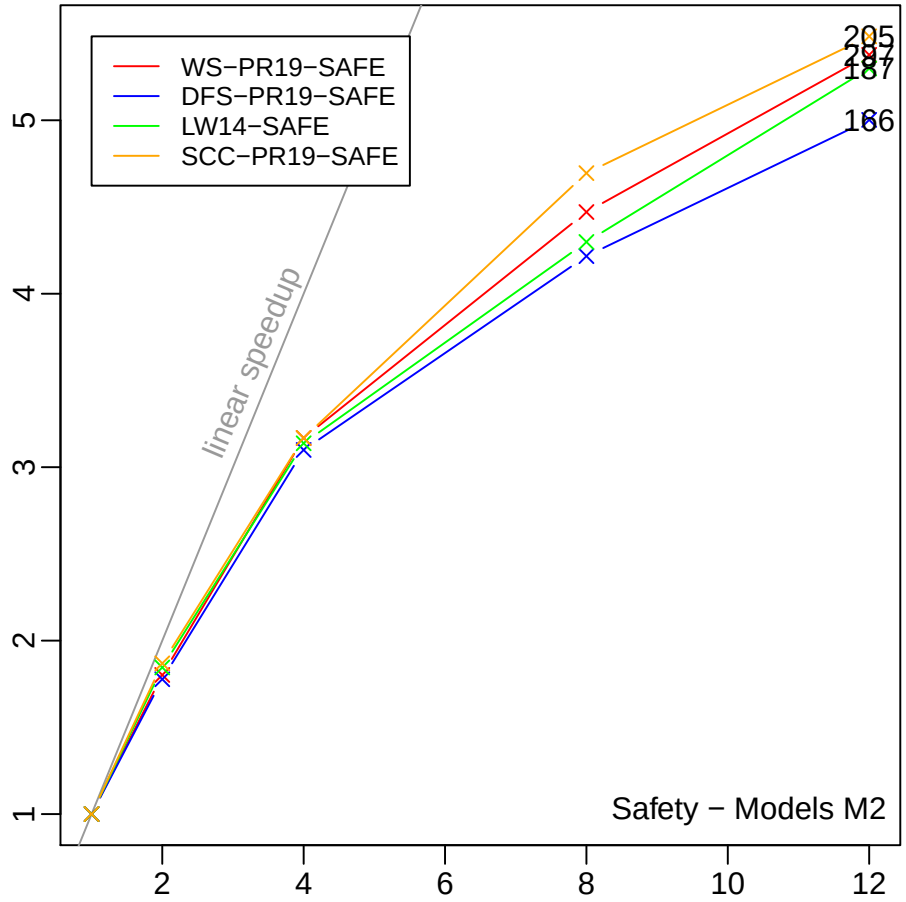
WS−PR19−SAFE
DFS−PR19−SAFE
LW14−SAFE
SCC−PR19−SAFE
Safety − Models M2

Speedup


WS−PR19−LIVE
DFS−PR19−LIVE
LW14−LIVE
linear speedup
359
187
166
Liveness − Models M2
1
2
3
4
5
2
4
6
8
10
12


WS−PR19−SAFE
DFS−PR19−SAFE
LW14−SAFE
SCC−PR19−SAFE
linear speedup
205
187
166
Safety − Models M2
1
2
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Conclusion & Perspective

- Combine POR with SOTAs emptiness check for both liveness and safety properites
- Intensive evaluation
- Independant of the reduction technique: ample set, sttuborn set, etc. (see Laarman et al. [7] for survey)

Perspectives

Can we build an non-pessimistic algorithm for the combination between Bloemen's emptiness check and POR?

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