Partial Order Reductions for Temporal, Epistemic, and Strategy Logics

Everything you always wanted to know about POR ....
but were afraid to ask for

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Outline

- Methods of state space reductions
- Some history of Partial Order Reductions (POR)
- POR for temporal logics: LTL-X, CTL*-X
- POR for epistemic logics: LTLK-X, CTL*K-X
- POR for strategy logics: $sATL^*_{ir}$ and $sATL^*_{iR}$

Model checking for modal logics

Model checking problem

$$M, s \overset{?}{\models} \varphi$$

a Kripke model — a modal formula

Complexity

From P-Time to undecidable.
But, $|M|$ is typically exponential in the size of a system !!!

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Possible solutions

- Symbolic model checking - BDD-based (Lomuscio, Raimondi), SAT-based Unbounded Model Checking for ATL (Kacprzak, Lomuscio, Penczek)
- Abstractions - multi-valued model checking over abstract models for variants of ATL(K) (Belardinelli, Lomuscio, Michaliszyn)
- Bisimulation-based reductions - for ATL_{ir} (Belardinelli, Condurache, Dima, ...)
- Symmetry reductions - model checking over smaller models for CTLK (see Cohen, Dams, Lomuscio, Qu)
- Upper and lower approximations - for ATL_{ir} (Jamroga, Knapik, Kurpiewski)
- **Partial order reductions** - model checking over smaller models for LTLK-X, CTLK-X, sATL* (Lomuscio, Penczek, Qu, Jamroga, ...)
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Partial Order Reductions

Idea

- This is a method of generating reduced state spaces of distributed systems which preserve properties of our interest.
- The reduction exploits the idea that when a property does not distinguish between the interleavings of the same (Mazurkiewicz) trace, then it is sufficient to generate a reduced state space which contains only one interleaving for each trace.
- In practice one generates more than one interleaving per trace, but as few as possible.

History of Partial Order Reductions

Three Big Names

- Antti Valmari, ICATPN 1989 - stubborn sets
- Patrice Godefroid, CAV 1990, CAV 1991 - sleep sets
- Doron Peled, CONCUR 1992 - ample sets

Syntax

I assume that you are familiar with LTL, CTL*, and epistemic logics ...

Syntax of ATL*:

$$\phi ::= \mathsf{p} \mid \neg\phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid \langle\langle A \rangle\rangle\gamma,$$

$$\gamma ::= \phi \mid \gamma \wedge \gamma \mid \gamma \vee \gamma \mid \mathsf{X}\,\gamma \mid \gamma\,\mathsf{U}\,\gamma \mid \gamma R \gamma,$$

where $p \in \mathcal{AP}$ and A - a set o agents.

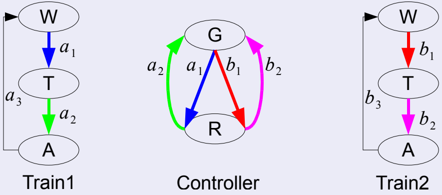


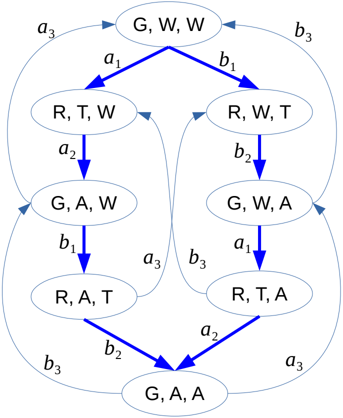
Figure: TC composed of two trains and the controler

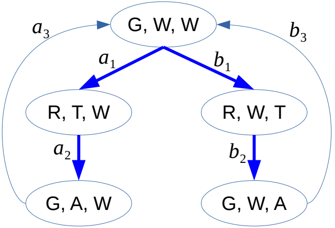
Interleaved Interpreted Systems

A Model is tuple
$\mathcal{A} = (Agents, Act, \mathcal{Q}, \mathcal{AP}, \mathcal{V}, prot, trans, \{\sim_i | \ i \in Agents\})$, s.t.:

- $Agents$ is a finite set of all the agents,
- $Act = A_1 \cup \ldots \cup A_n$ is a finite set of actions,
- $\mathcal{Q} = L_1 \times \ldots \times L_n$ is a finite set of global locations (states),
- $\mathcal{V}\colon \mathcal{Q} \to 2^{\mathcal{AP}}$ is a valuation function,
- $prot_i\colon L_i \to 2^{A_i}$ - a protocol function of agent i,
- $t_i : L_i \times A_i \to L_i$ - an i-local evolution partial function,
- $trans : \mathcal{Q} \times Act \to \mathcal{Q}$ - an interleaved evolution partial function: $trans((g_1, \ldots, g_n), \mathrm{act}) = (g'_1, \ldots, g'_n)$ iff $t_i(g_i, \mathrm{act}) = g'_i$ if $\mathrm{act} \in A_i$ and $g_i = g'_i$ if $\mathrm{act} \notin A_i$,
- $g \sim_i g'$ iff $g_i = g'_i$ for each $i \in Agents$ - the indistinguishabilty relations.

the full model	a reduced model





Semantics of ATL*: ($Y \in \{IR, iR, Ir, ir\}$).

$M, g \models_Y \langle\langle A \rangle\rangle \gamma$ iff
there is a joint Y-strategy σ_A for agents A such that,
for each path $\pi \in out_M(g, \sigma_A)$, we have $M, \pi \models_Y \gamma$, where

- I - complete information, i - incomplete information,
- R - perfect recall, r - imperfect recall.

Properties of TGC in ATL*:

- $\langle\langle c \rangle\rangle G(\neg \text{in\_tunnel}_1)$ - the controller can keep Train 1 out,
- $\langle\langle c \rangle\rangle F(\text{in\_tunnel}_1 \wedge F \neg \text{in\_tunnel}_1)$ - the controller can let Train 1 through,

Explaining the idea behind POR

POR aims at generating reduced models, preserving some temporal formula ψ.

- Independency of actions
  $Ind = \{(a, b) \mid Agents(a) \cap Agents(b) = \emptyset\}$, restricted such that either a or b is invisible, i.e., does not change the valuations of the atomic propositions used in ψ,
- Two infinite sequences of global locations and actions: $g_0 a_0 g_1 a_1 \ldots$ and $g_0 a'_0 g'_1 a'_1 \ldots$ that differ in the ordering of independent actions only are called trace equivalent,
- ψ does not distinguish between trace-equivalent sequences.

Algorithm DFS-POR

DFS-POR is used to compute paths of the reduced model M'.
A stack represents the path $\pi = g_0 a_0 g_1 a_1 \cdots g_n$ currently being visited.
For g_n, the following three operations are computed in a loop:

1. The set $en(g_n) \subseteq Act$ of enabled actions is identified and a subset $E(g_n) \subseteq en(g_n)$ of necessary actions is heuristically selected.
2. For any action $a \in E(g_n)$ compute the successor state g' of g_n such that $g_n \stackrel{a}{\to} g'$, and add g' to the stack.
   Recursively proceed to explore the submodel originating at g'.
3. Remove g_n from the stack.

Catch

The problem of computing a minimal $E(g)$ is NP-complete.

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Conditions for selection of $E(g)$

Basic Conditions

C1 Along each path π in M that starts at g, each action $a \in Act \setminus E(g)$ that is dependent on an action in $E(g)$ cannot be executed in π without an action in $E(g)$ is executed first.

C2 If $E(g) \neq en(g)$, then each action in $E(g)$ is invisible,

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Equivalence on states and paths

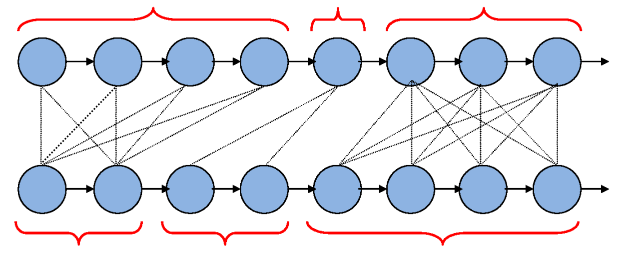

Figure: Two stuttering equivalent paths π and π'

A dotted line between two states g and g' means that $V(g) = V(g')$.

POR for LTL-X

[Peled 1992]

- Logic: LTL-X
- Equivalence induced on models: stuttering trace equivalence,
- $M' \subseteq M$ - the reduced model generated by DFS-POR
- If $E(g)$ satisfies **C1, C2, C3**, then $M, g^0 \models \varphi$ iff $M', g^0 \models \varphi$, for any LTL-X formula φ,
- If $E(g)$ satisfies **C1,C3**, then $M, g^0 \models_{CF} \varphi$ iff $M', g^0 \models_{CF} \varphi$, for any LTL-X formula φ.

CF Concurrency Fairness - no action can be eventually always enabled in a path and be independent of the executed actions.

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POR for CTL*-X

[Gerth, Kuiper, Peled, Penczek 1995]

- Logic: CTL*-X
- Equivalence induced on models: stuttering bisimulation,
- $M' \subseteq M$ - the reduced model generated by DFS-POR
- If $E(g)$ satisfies **C1, C2, C3, C4**, then
  $M, g^0 \models \varphi$ iff $M', g^0 \models \varphi$, for any CTL*-X formula φ,
- If $E(g)$ satisfies **C1, C3, C4**, then
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C4 If $E(g) \neq en(g)$, then $E(g)$ is a singleton.

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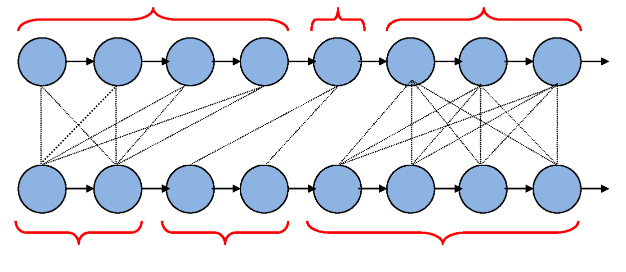

Figure: Two J-stuttering equivalent paths π and π'

$J \subseteq Agents$. A dotted line between two states g and g' means that $V(g) = V(g')$ and $g \sim_J g'$.

$$M, g \models K_i\gamma \text{ iff for all } g' \in Q \text{ if } g \sim_i g' \text{ we have } M, g' \models \gamma.$$

POR for LTLK^J-X (only K_i with $i \in J$)

[Lomuscio, Penczek, Qu, AAMAS 2010]

- Logic: LTLK^J-X
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POR for CTL*K^J-X (only K_i with $i \in J$)

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sATL* over interleaved models

Restrictions of ATL*

- sATL* (simple ATL*) - ATL* without the next state operator and without nested strategic operators,
- sATL_{ir}, sATL^{*}_{ir}
- Model checking $sATL_{ir}$ and sATL^{*}_{ir} is PSPACE-complete in the size of the model representation and the length of a formula.
- sATL_{iR}, sATL^{*}_{iR}
- Model checking $sATL_{iR}$ and sATL^{*}_{iR} is undecidable.

POR for sATL$^*_{ir}$

[Dembiński, Jamroga, Mazurkiewicz, Penczek, AAMAS 2018, Best Paper Award Nomination]

- Logic: sATL$^*_{ir}$
- Equivalence induced on models: ?!?
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- If $E(g)$ satisfies **C1,C3**, then $M, g^0 \models_{CF} \varphi$ iff $M', g^0 \models_{CF} \varphi$, for any sATL$^*_{ir}$ formula φ.

Remark: the above theorem does not hold for sATL$^*_{Ir}$.

POR for $sATL^*_{ir}$

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[Jamroga, Penczek, Sidoruk, 2019]

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Remark: the above theorem does not hold for $sATL^*_{IR}$.

Experimental Results - Trains and Controller (TC)

Modified partial order reduction algorithms for LTL-X can be used for $sATL^*_{ir}$ and $sATL^*_{iR}$.

Property: Controller has a strategy to keep Train 1 out of the tunnel:

$$\langle\langle c \rangle\rangle G(\neg \text{in\_tunnel}_1)$$

Models for n trains

$F(n) \geq 2^{n+1}$ - the size of the full model.
$R(n) = 2n + 1$ - the size of the reduced model.
The reduced model is *exponentially smaller* than the full one.

More benchmarks

We have experimental results for Faulty TGC, Simple Voting Protocol, and Bridge Endplays with n cards, amounting to $40\% - 90\%$ reductions of the state spaces.

Experimental Results - Trains and Controller (TC)

Modified partial order reduction algorithms for LTL-X can be used for $sATL^*_{ir}$ and $sATL^*_{iR}$.

Property: Controller has a strategy to keep Train 1 out of the tunnel:

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Future work

- Combining POR with model checking methods for sATL*$_{ir}$
- Symbolic on-the-fly model checking for sATL*$_{ir}$
- Application to e-voting protocols

Thank You !