On-The-Fly Partial Order Reduction

Lecture #11 of Advanced Model Checking

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Outline of partial-order reduction

- During state space generation obtain $\widehat{TS}$
  - a *reduced version* of transition system TS such that $\widehat{TS} \triangleq TS$
  - $\Rightarrow$ this preserves all stutter sensitive LT properties, such as $\text{LTL}_{\setminus\bigcirc}$
  - at state s select a (small) subset of enabled actions in s
  - different approaches on how to select such set: consider Peled's *ample sets*
- *Static* partial-order reduction
  - obtain a high-level description of $\widehat{TS}$ (without generating TS)
  - $\Rightarrow$ POR is preprocessing phase of model checking
- *Dynamic (or: on-the-fly)* partial-order reduction
  - construct $\widehat{TS}$ during $\text{LTL}_{\setminus\bigcirc}$ model checking
  - if accept cycle is found, there is no need to generate entire $\widehat{TS}$

Ample-set conditions for LTL

(A1) **Nonemptiness condition**

$\varnothing \neq$ *ample*$(s) \subseteq$ *Act*(s)

(A2) **Dependency condition**

Let $s \xrightarrow{\beta_1} \ldots \xrightarrow{\beta_n} s_n \xrightarrow{\alpha} t$ be a finite execution fragment in *TS* such that α depends on *ample*(s). Then: $\beta_i \in$ *ample*(s) for some $0 < i \leqslant n$.

(A3) **Stutter condition**

If *ample*$(s) \neq$ *Act*(s) then any $\alpha \in$ *ample*(s) is a stutter action.

(A4) **Cycle condition**

For any cycle $s_0\, s_1 \, \ldots \, s_n$ in $\widehat{TS}$ and $\alpha \in$ *Act*(s_i), for any $0 < i \leqslant n$, there exists $j \in \{ 1, \ldots, n \}$ such that $\alpha \in$ *ample*(s_j).

Correctness theorem

For action-deterministic, finite *TS* without terminal states:

if conditions (A1) through (A4) are satisfied, then $\widehat{TS} \triangleq TS$.

Strong cycle condition

(A4') Strong cycle condition

On any cycle $s_0\, s_1\, \ldots\, s_n$ in $\widehat{\mathit{TS}}$,

there exists $j \in \{1, \ldots, n\}$ such that *ample*$(s_j) =$ *Act*(s_j).

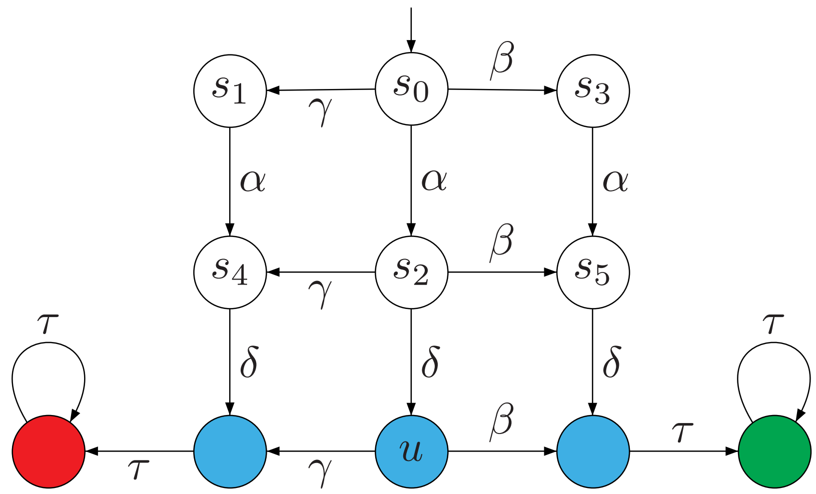
- If (A1) through (A3) hold: (A4') implies the cycle condition (A4)
- (A4') can be checked easily in DFS when backward edge is found

The branching-time ample approach

- Linear-time ample approach:
  - during state space generation obtain $\widehat{TS}$ such that $\widehat{TS} \triangleq TS$
  - $\Rightarrow$ this preserves all stutter sensitive LT properties, such as $\mathrm{LTL}_{\setminus\bigcirc}$
  - static partial order reduction: generate $\widehat{TS}$ prior to verification
  - on-the-fly partial order reduction: generate $\widehat{TS}$ during the verification
  - generation of $\widehat{TS}$ by means of static analysis of program graphs
- Branching-time ample approach
  - during state space generation obtain $\widehat{TS}$ such that $\widehat{TS} \approx^{div} TS$
  - $\Rightarrow$ this preserves all $\mathrm{CTL}_{\setminus\bigcirc}$ and $\mathrm{CTL}^*_{\setminus\bigcirc}$ formulas
  - static partial order reduction only

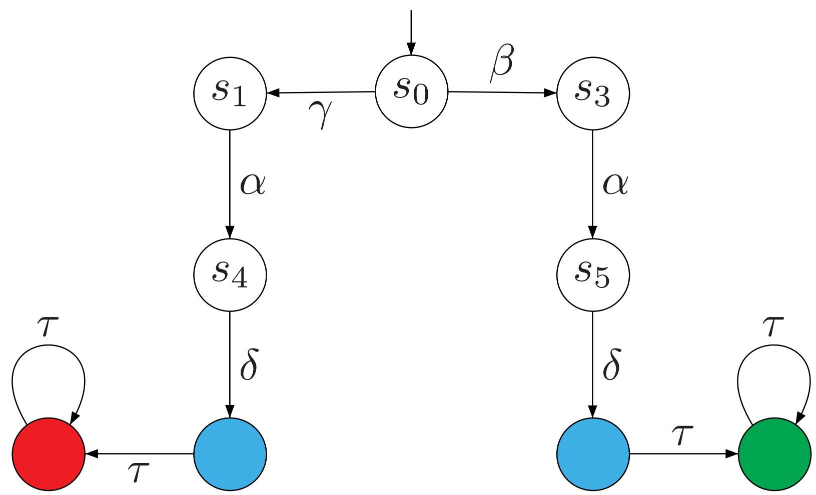
as $\approx^{div}$ is strictly finer than $\triangleq$, try (A1) through (A4)

Example



transition system *TS*

Conditions (A1)-(A4) are insufficient



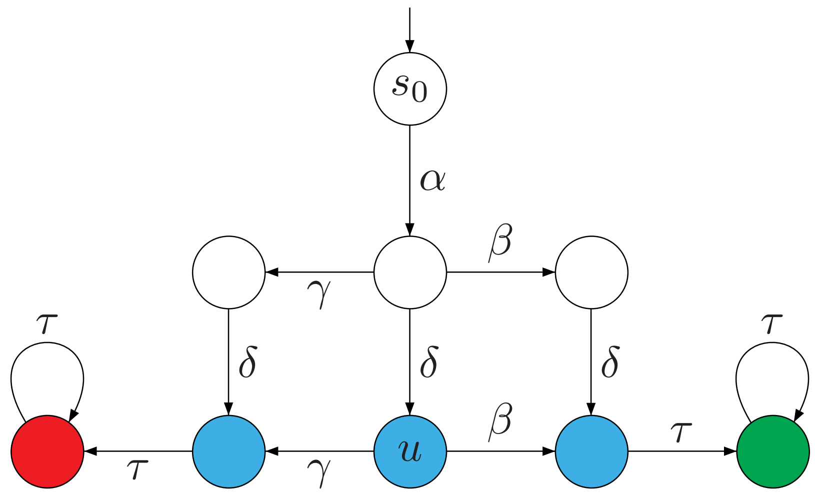
$\widehat{TS} \models \forall\Box\Big(a \;\rightarrow\; (\forall\Diamond b \vee \forall\Diamond c)\Big)$ but *TS* does not and thus $\widehat{TS} \not\approx^{div} TS$

Branching condition

(A5)

If $\mathit{ample}(s) \neq \mathit{Act}(s)$ then $|\mathit{ample}(s)| = 1$

A sound reduction for CTL$^*_{\setminus\bigcirc}$



$\widehat{TS} \not\models \forall\Box\Big(a \;\rightarrow\; (\forall\Diamond b \vee \forall\Diamond c)\Big)$ and *TS* does not ;in fact $\widehat{TS} \approx^{div} TS$

Correctness theorem

For action-deterministic, finite *TS* without terminal states:

if conditions (A1) through (A5) are satisfied, then $\widehat{TS} \approx^{div} TS$.

recall that this implies that $\widehat{TS}$ and TS are $\mathrm{CTL}^*_{\setminus \bigcirc}$-equivalent

Ample-set conditions for CTL*

(A1) **Nonemptiness condition**

$\varnothing \neq$ *ample*$(s) \subseteq$ *Act*(s)

(A2) **Dependency condition**

Let $s \xrightarrow{\beta_1} \ldots \xrightarrow{\beta_n} s_n \xrightarrow{\alpha} t$ be a finite execution fragment in *TS* such that α depends on *ample*(s). Then: $\beta_i \in$ *ample*(s) for some $0 < i \leqslant n$.

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For any cycle $s_0\, s_1\, \ldots\, s_n$ in $\widehat{TS}$ and $\alpha \in$ *Act*(s_i), for some $0 < i \leqslant n$, there exists $j \in \{\, 1, \ldots, n \,\}$ such that $\alpha \in$ *ample*(s_j).

(A5) **Branching condition**

If *ample*$(s) \neq$ *Act*(s) then $|$*ample*$(s)| \; = \; 1$