TD 8: Partial-Order Reduction

Exercise 1. Consider the following transition system with state set $S = \{s_0, \ldots, s_7\}$ and transition alphabet $\Delta = \{a, b, c, d\}$:

1. Compute the independance set I and the set of invisible actions U.
2. Propose an assignment $red : S \to 2^{\Delta}$ of ample sets satisfying conditions C_0–C_3 of the lecture notes.

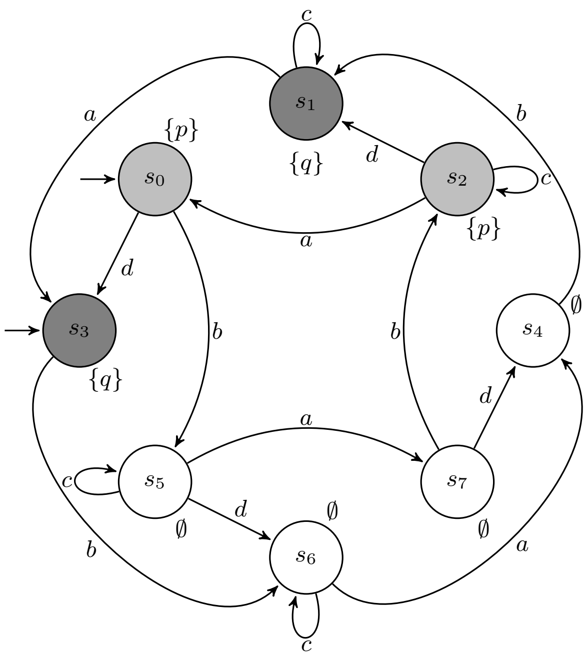
   Reminder:

   (C0) $red(s) = \emptyset$ iff $en(s) = \emptyset$.

   (C1) For every path $s \xrightarrow{a_1} s_1 \xrightarrow{a_2} \cdots \xrightarrow{a_n} s_n \xrightarrow{a} t$ in $\mathcal{K}$ (for any $n \geq 0$), if $a \notin red(s)$ and a depends on some action in $red(s)$ (i.e. there exists $b \in red(s)$ such that $(a, b) \notin I$), then there exists $1 \leq i \leq n$ such that $a_i \in red(s)$.

   (C2) If $red(s) \neq en(s)$, then all actions in $red(s)$ are invisible.

   (C3) For all cycles in the reduced system $\mathcal{K}'$, the following holds: if $a \in en(s)$ for some state s in the cycle, then $a \in red(s')$ for some (possibly other) state s' in the cycle.



Exercise 2.

1. Consider the condition (C_1''): for any s with $red(s) \neq en(s)$, any a in $red(s)$ is independent from every b in $en(s)\backslash red(s)$. Show that (C_1) implies (C_1''), but $(C_0), (C_1''), (C_2), (C_3)$ is not sufficient to ensure that the reduced system $\mathcal{K}'$ is stuttering equivalent to $\mathcal{K}$.

2. Show that (C_0)–(C_2) does not ensure stuttering equivalence.

Exercise 3. Let φ be an LTL formula. We define the X-depth $d_{\mathsf{X}}(\varphi)$ and the U-depth $d_{\mathsf{U}}(\varphi)$ of φ as the maximal nesting of X- or U-operators in φ:

$$
\begin{aligned}
d_{\mathsf{X}}(p) &= 0 & d_{\mathsf{U}}(p) &= 0\\
d_{\mathsf{X}}(\neg\varphi) &= d_{\mathsf{X}}(\varphi) & d_{\mathsf{U}}(\neg\varphi) &= d_{\mathsf{U}}(\varphi)\\
d_{\mathsf{X}}(\varphi\wedge\psi) &= \max(d_{\mathsf{X}}(\varphi), d_{\mathsf{X}}(\psi)) & d_{\mathsf{U}}(\varphi\wedge\psi) &= \max(d_{\mathsf{U}}(\varphi), d_{\mathsf{U}}(\psi))\\
d_{\mathsf{X}}(\mathsf{X}\,\varphi) &= 1 + d_{\mathsf{X}}(\varphi) & d_{\mathsf{U}}(\mathsf{X}\,\varphi) &= d_{\mathsf{U}}(\varphi)\\
d_{\mathsf{X}}(\varphi\,\mathsf{U}\,\psi) &= \max(d_{\mathsf{X}}(\varphi), d_{\mathsf{X}}(\psi)) & d_{\mathsf{U}}(\varphi\,\mathsf{U}\,\psi) &= 1 + \max(d_{\mathsf{U}}(\varphi), d_{\mathsf{U}}(\psi))
\end{aligned}
$$

We denote by LTL($\mathsf{U}^m, \mathsf{X}^n$) the set of LTL formulas φ with $d_{\mathsf{X}}(\varphi) \leq n$ and $d_{\mathsf{U}}(\varphi) \leq m$, where $n = \infty$ or $m = \infty$ indicates no restriction of the operator in question.

1. We say that two words $w, w' \in \Sigma^\omega$ are *n-stutter-equivalent* if there exists letters $a_0, a_1, \ldots \in \Sigma$ and $f, g : \mathbb{N} \to \mathbb{N}^*$ such that $w = a_0^{f(0)} a_1^{f(1)} \ldots$, $w' = a_0^{g(0)} a_1^{g(1)} \ldots$, and for all $i \geq 0$, $a_i = a_{i+1}$ implies $a_i = a_j$ for all $j > i$, and $f(i) \leq n+1$ or $g(i) \leq n+1$ implies $f(i) = g(i)$.

   Show that for all $n \geq 0$ and $\varphi \in$ LTL($\mathsf{U}^\infty, \mathsf{X}^n$), $L(\varphi)$ is closed under n-stutter-equivalence.

2. A similar principle can be formulated when the U-depth is restricted, by considering stuttering of factors instead of letters. Show that for all $m \geq 1$ and $\varphi \in$ LTL($\mathsf{U}^m, \mathsf{X}^0$), for all $u, v \in \Sigma^*$ and $w \in \Sigma^\omega$, we have $uv^m w \in L(\varphi)$ iff $uv^{m+1} w \in L(\varphi)$.

Exercise 4. Let $\mathcal{K} = (S, A, \to, r, \mathrm{AP}, \nu)$ be a deterministic labelled Kripke structure, I an independance set, U a set of invisible action, and for all s, $red(s) \subseteq en(s)$. We let $V = A \setminus U$ be the set of visible actions. Assume that red satisfies the following conditions:

(C1) For every path $s \xrightarrow{a_1} s_1 \xrightarrow{a_2} \cdots \xrightarrow{a_n} s_n \xrightarrow{a} t$ in $\mathcal{K}$ (for any $n \geq 0$), if $a \notin red(s)$ and a depends on some action in $red(s)$ (i.e. there exists $b \in red(s)$ such that $(a, b) \notin I$), then there exists $1 \leq i \leq n$ such that $a_i \in red(s)$.

(C4) $(V \times V) \cap I = \varnothing$.

(C5) If $red(s) \neq en(s)$, then $red(s)$ contains at least one visible action.

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1. Show that for all $s \in S$, $en(s) \setminus red(s) \subseteq U$.
2. Show that for all $s \in S$, if there is an infinite invisible path in $\mathcal{K}$ starting at s, then there is also an infinite invisible path in the reduced system $\mathcal{K}'$ starting at s.
3. Show that $\mathcal{K}$ and $\mathcal{K}'$ are stuttering equivalent.