Model checking modal transition systems using Kripke structures

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Relevant papers: see www.doc.ic.ac.uk/˜mrh/research.html
This talk: see www.doc.ic.ac.uk/˜mrh/vmcai2002.ps

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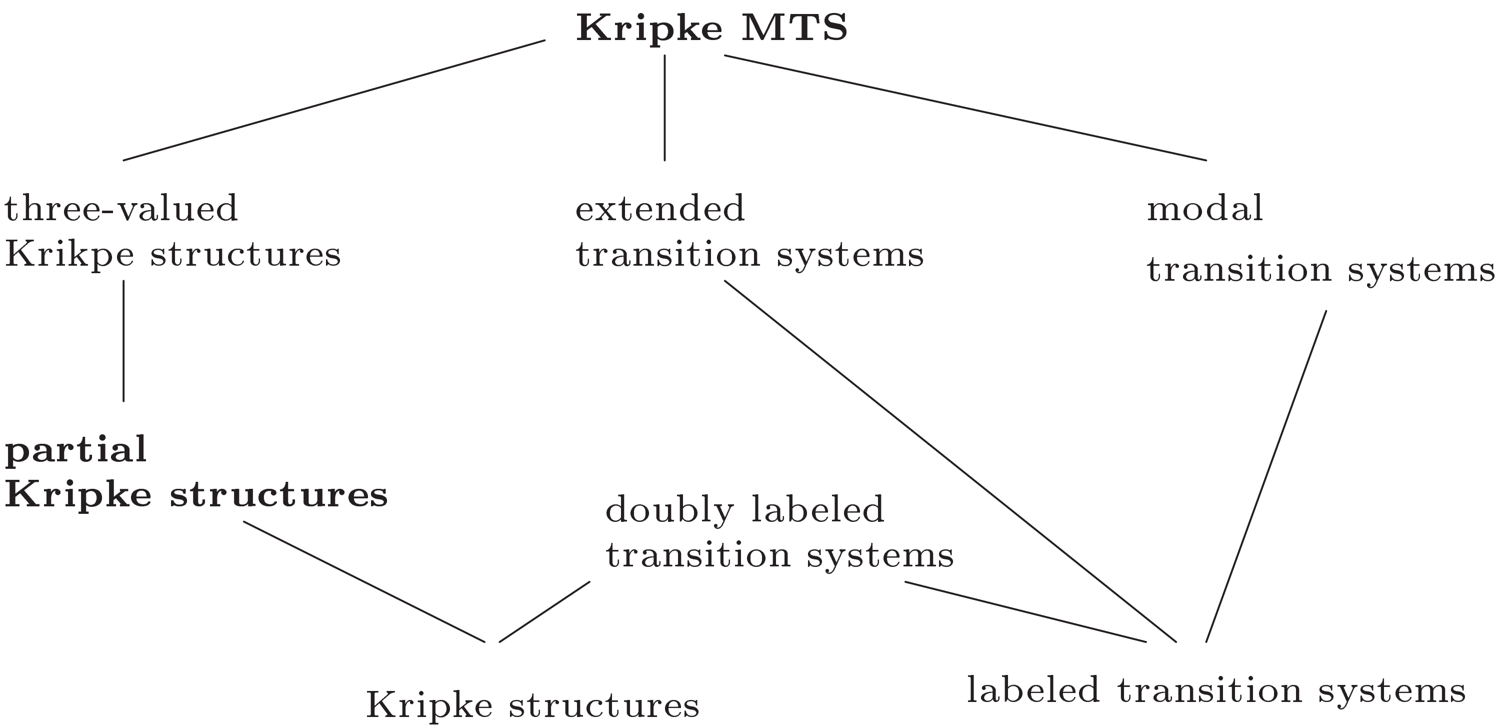
- For models that are three-valued on states **and** behavior, such a reduction serves as a **blueprint for tool interfaces**.
- Does such a reduction support techniques important in practice (e.g. **fairness constraints**)?

A hierarchy of two/three-valued models



A Hasse diagram of classes of two-valued (doubly labeled transition systems, Kripke structures, and labeled transition systems) and three-valued (all other classes) models, where the order represents class inclusion up to isomorphism.

Kripke modal transition systems

- A **Kripke MTS** $\mathcal{M}$ (HJS'01) with signature $(\mathtt{Act}, \mathtt{AP})$ is a pair $(\mathcal{M}^{\mathrm{a}}, \mathcal{M}^{\mathrm{c}})$, with $\mathcal{M}^{\mathrm{m}} = (\Sigma, R^{\mathrm{m}}, L^{\mathrm{m}})$ such that

$$R^{\mathrm{m}} \subseteq \Sigma \times \mathtt{Act} \times \Sigma$$

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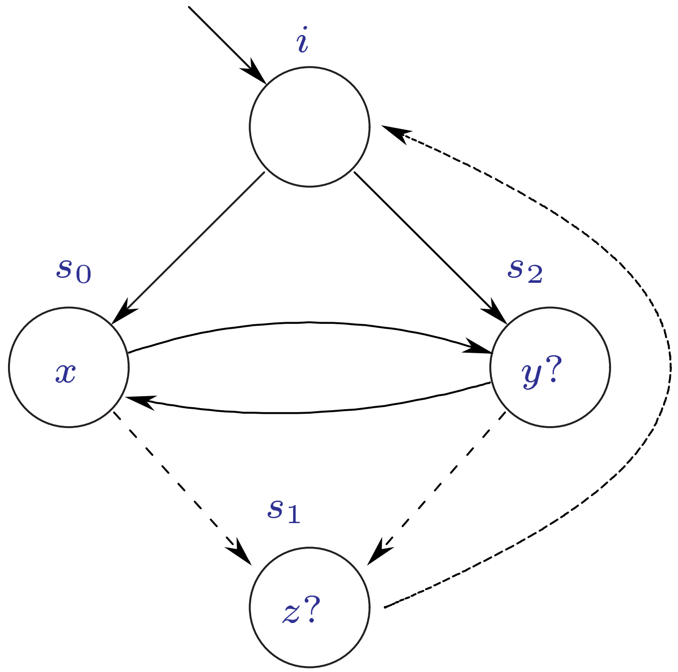
- $\mathcal{M}^{\mathrm{a}}$ specifies **guaranteed** state and behavior, $\mathcal{M}^{\mathrm{c}}$ specifies **possible** state and behavior.

- Models with $\mathcal{M}^{\mathrm{a}} = \mathcal{M}^{\mathrm{c}}$ correspond to doubly labeled transition systems.

Modeling laptop modes



A Kripke MTS modeling laptop modes, where x, y, and z denote "AC powered", "battery powered", and "in suspend mode" (respectively).

Sound property semantics

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[\![\, p \,]\!]^{\mathrm{m}}_{\rho} &\stackrel{\mathrm{def}}{=} \{s \in \Sigma \mid p \in L^{\mathrm{m}}(s)\} \\
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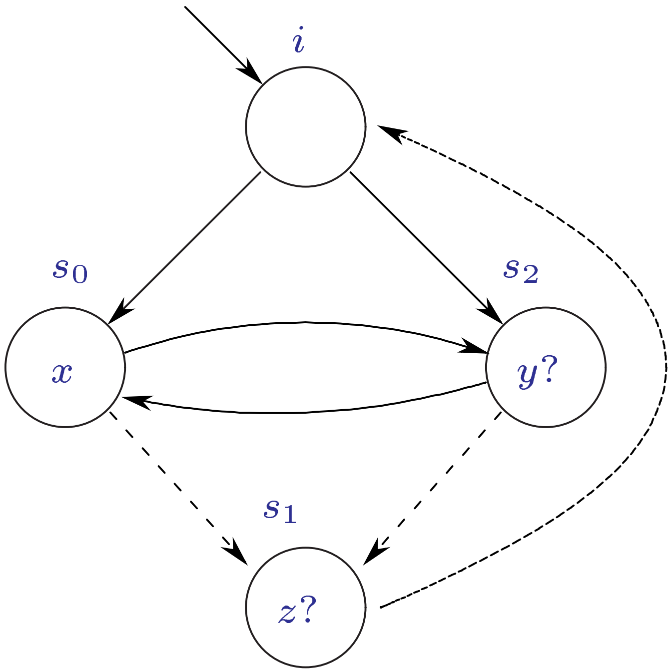
Except for treatment of negation, the property semantics over Kripke MTSs is as for doubly labeled transition systems. We have **soundness** for all ϕ: if $s \prec t$, then (i) $s \in \llbracket\, \phi \,\rrbracket_\rho^{\mathrm{c}}$ implies $t \in \llbracket\, \phi \,\rrbracket_\rho^{\mathrm{c}}$ and (ii) $t \in \llbracket\, \phi \,\rrbracket_\rho^{\mathrm{a}}$ implies $s \in \llbracket\, \phi \,\rrbracket_\rho^{\mathrm{a}}$.

An example check



The evaluation of $(\mathcal{M}, i) \models^{\mathrm{a}} \mathrm{AG}\,\mathrm{EF}\, z$ effectively checks whether all R^{c}-reachable states contain a R^{a}-path to a state s, where $z \in L^{\mathrm{a}}(s)$.

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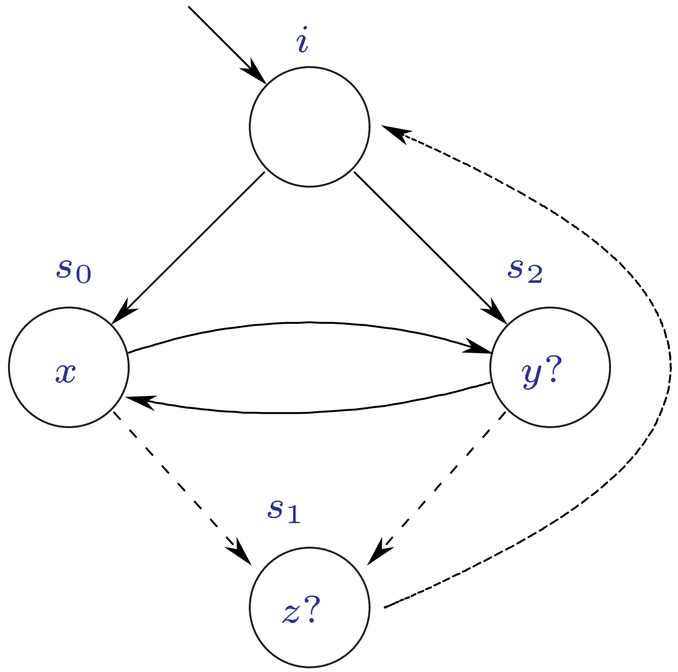

The evaluation of $(\mathcal{M}, i) \models^{\mathrm{a}} \mathrm{AG}\,\mathrm{EF}\, z$ effectively checks whether all R^{c}-reachable states contain a R^{a}-path to a state s, where $z \in L^{\mathrm{a}}(s)$. The evaluation of $(\mathcal{M}, i) \models^{\mathrm{c}} \mathrm{AG}\,\mathrm{EF}\, z$ conducts the same analysis, except that the modalities of paths are swapped.

Stage #1 of reduction [GHJ'01]

Reduce the model-checking problem for Kripke MTSs $\mathcal{M}$ with signature $(\mathtt{Act}, \mathtt{AP})$ to two model-checking problems for doubly labeled transition systems $\mathcal{M}^{\mathrm{p}} = (\Sigma, R^{\mathrm{p}}, L^{\mathrm{a}})$ and $\mathcal{M}^{\mathrm{o}} = (\Sigma, R^{\mathrm{o}}, L^{\mathrm{c}})$ with signature $(\overline{\mathtt{Act}}, \mathtt{AP})$, where

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Correctness: For any state $s \in \Sigma$, we then have

$$(\mathcal{M}, s) \models^{\mathrm{a}}_{\rho} \phi \qquad \text{iff} \qquad (\mathcal{M}^{\mathrm{p}}, s) \models_{\rho} T(\phi^+)$$

$$(\mathcal{M}, s) \models^{\mathrm{c}}_{\rho} \phi \qquad \text{iff} \qquad (\mathcal{M}^{\mathrm{o}}, s) \models_{\rho} T(\phi^+).$$

Stage #2 of reduction: formulas

First, we translate any DLTS formula with signature $(\overline{\mathtt{Act}}, \mathtt{AP})$ into Kripke structure formulas with signature $\overline{\mathtt{Act}} + \mathtt{AP}$:

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K(\neg\phi) &\stackrel{\text{def}}{=} \neg K(\phi) \\
K(\phi_1 \wedge \phi_2) &\stackrel{\text{def}}{=} K(\phi_1) \wedge K(\phi_2) & K(\phi_1 \vee \phi_2) &\stackrel{\text{def}}{=} K(\phi_1) \vee K(\phi_2) \\
K((\exists\alpha)\phi) &\stackrel{\text{def}}{=} \mathrm{EX}\,(K(\phi) \wedge \alpha) & K((\forall\alpha)\phi) &\stackrel{\text{def}}{=} \mathrm{AX}\,(\neg\alpha \vee K(\phi)) \\
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This translation preserves the fixed-point structure of formulas (alternation-depth fragments).

Stage #2 of reduction: models

Second, given a DLTS $\mathcal{L} = (\Sigma, R, L)$ with signature $(\mathtt{Act}, \mathtt{AP})$, we define a Kripke structure $\mathrm{K}[\mathcal{L}] = (\Sigma \times \mathtt{Act}, \bar{R}, \bar{L})$ with signature $\mathtt{Act} + \mathtt{AP}$ where

$$\bar{R} \stackrel{\text{def}}{=} \{((s, \alpha), (s', \beta)) \mid \alpha \in \mathtt{Act},\ (s, \beta, s') \in R\}$$

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Correctness: For any ϕ with signature $(\mathtt{Act}, \mathtt{AP})$ and any $s \in \Sigma$, and any ρ as above, we have

$$[\![\, \phi \,]\!]_\rho \times \mathtt{Act} = [\![\, K(\phi) \,]\!]_{\rho_{\mathcal{K}}}.$$

where $\rho_{\mathcal{K}}(Z) \stackrel{\text{def}}{=} \rho(Z) \times \mathtt{Act}$.

Assessment of this reduction

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4. can hardwire (simple) fairness in the logic (potentially expensive),
5. but cannot separate fairness algorithmically as the first reduction mixes elements of R^{a} and R^{c}.

Conclusions

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- . . . mixed message and a case for three-valued tools?

Related work

(Bruns & Godefroid'00): pioneered such reductions for **partial Kripke structures** $\mathcal{K} = (\Sigma, R, L)$, where $L\colon \Sigma \times \mathtt{AP} \to \{\text{false}, \text{true}, \perp\}$.

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(Dams, Gerth & Grumberg'00): study fair CTL* over mixed transition systems, transitions and propositions come in two flavors: free and constrained ones; convert ϕ into positive normal form and annotate ϕ on path quantifiers and atomic propositions; annotations guide the satisfaction relation in its choice of free or constrained fair paths; soundness of that approach for fair CTL* over mixed transition systems is proved.