The Verification of Probabilistic Lossy Channel Systems

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Outline of the Talk

Channel Systems With Unreliable Channels

Probabilistic Lossy Channel Systems

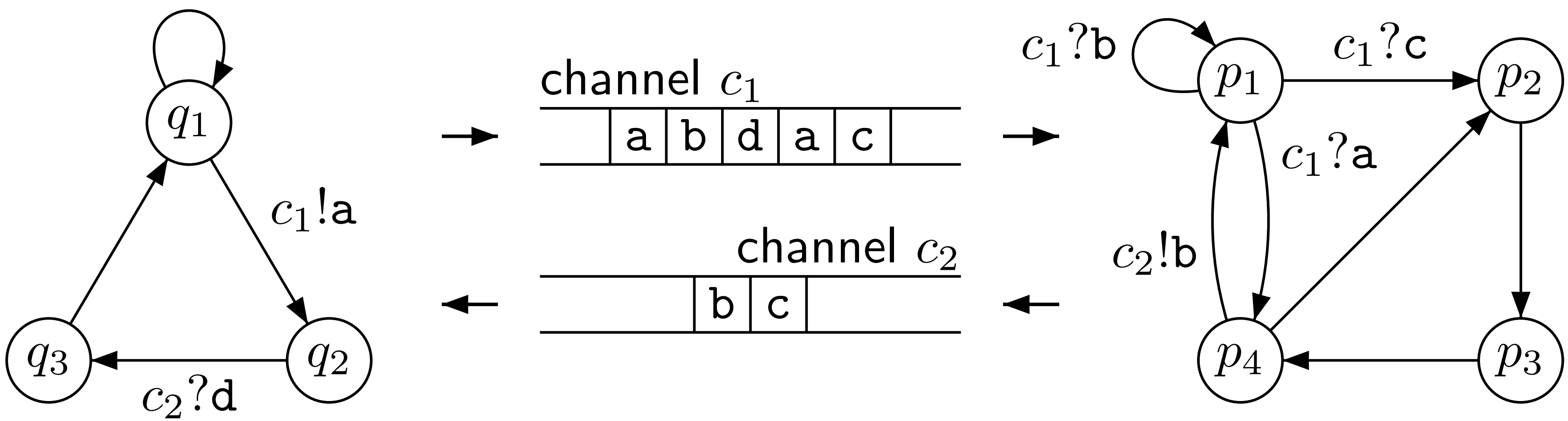
Qualitative Verification

Quantitative Verification

Adversarial Verification

Channel Systems

A.k.a. "communicating finite-state machines"



Natural model for asynchronous communication protocols: SDL, Estelle

[von Bochmann 1978; Brand & Zafiropulo 1983]

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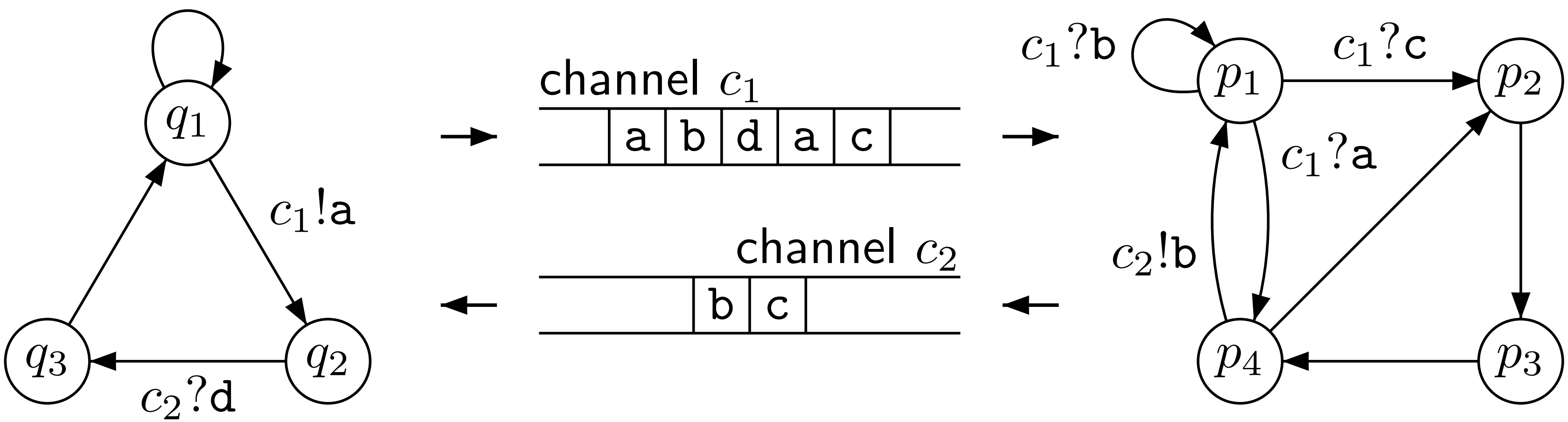

Natural model for asynchronous communication protocols: SDL, Estelle

[von Bochmann 1978; Brand & Zafiropulo 1983]

Turing powerful!

Hence fully automated verification, aka model checking, is impossible on principle grounds.

The Paradox of Lossy Channel Systems

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These lossy channel systems are well-suited to the analysis of asynchronous protocols that are designed to cope with message losses.

Channel Systems: Perfect

W.l.o.g., we only consider systems made of one component and several channels.

$S = \langle Q, \Sigma, C, \Delta \rangle$ with
- $Q = \{q, \ldots\}$, the *control states*
- $\Sigma = \{a, b, \ldots\}$, the *messages*
- $C = \{c_1, c_2, \ldots, c_n\}$, the *channels*
- $\Delta \subseteq Q \times C \times \{?, !\} \times \Sigma \times Q$, the *rules*

Rules in Δ written e.g. as "$(q, c!a, q')$"

A *configuration* of S: $\sigma = \langle q, u_1, \ldots, u_n \rangle$

Perfect steps: $\langle q, u_1, \ldots, u_n \rangle \rightarrow \langle r, v_1, \ldots, v_n \rangle$ if
— $(q, c_i?a, r)$ is a rule, $u_i = a.v_i$ and $v_j = u_j$ for $j \neq i$, or
— $(q, c_i!a, r)$ is a rule, $v_i = u_i.a$ and $v_j = u_j$ for $j \neq i$.
NB: no test for emptiness

Channel Systems: Lossy

Subword ordering: $abba \sqsubseteq abracadabra$

Subword relation for configurations: $\sigma \sqsubseteq \sigma'$

Lossy steps: $\sigma \rightarrow_{\text{lossy}} \sigma' \overset{\text{def}}{\Leftrightarrow} \sigma \sqsupseteq \delta \rightarrow_{\text{perf}} \delta' \sqsupseteq \sigma'$

Corollary: If $\sigma_1 \rightarrow \sigma_2$ then $\sigma_1' \rightarrow \sigma_2'$ for any $\sigma_1' \sqsupseteq \sigma_1$ and $\sigma_2' \sqsubseteq \sigma_2$.

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Lemma [Higman 1952]: the subword ordering is a well-quasi-order (wqo), i.e. any infinite sequence $u_0, u_1, u_2, \ldots$ of words has an infinite increasing subsequence $u_{i_0} \sqsubseteq u_{i_1} \sqsubseteq u_{i_2} \sqsubseteq \cdots$

$\Rightarrow$ Applies equivalently to configurations of S ordered by $\sqsubseteq$.

Corollary. Any set of configurations has a finite number of minimal elements.

Lossy Channel Systems Are Not Trivial

Recurrent reachability is undecidable [Abdulla & Jonsson 1996a].

(Hence model checking of temporal properties is undecidable too.)

Boundedness is undecidable [Mayr 2003] (see also [DJS 1999]).

All behavioral equivalences are undecidable [S. 2001].

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In practice, the main limitation for verification is the undecidability of model checking properties involving liveness and/or fairness.

Probabilistic Lossy Channel Systems

Basic idea is to assume that *message losses follow probabilistic rules*, e.g. there is a known “failure rate” [PN 1997].

More realist than just non-deterministic losses (protocols are designed with the idea that losses are not that likely).

Randomization helps in general.
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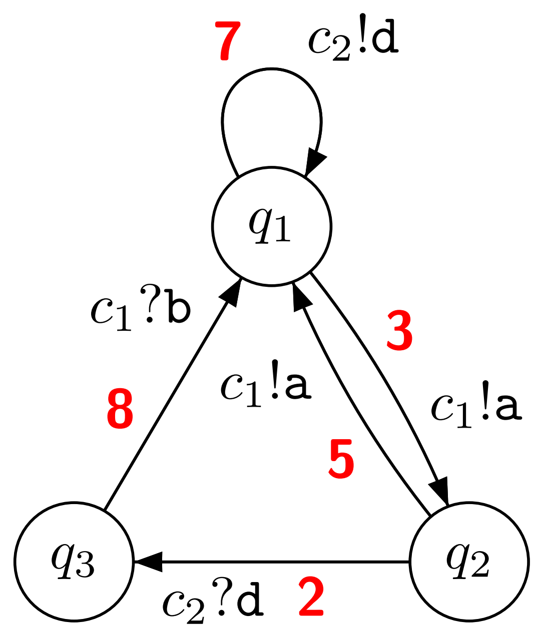

Markovian Semantics

Semantics in form of a countable Markov chain.

Two interpretations of p_{loss}:
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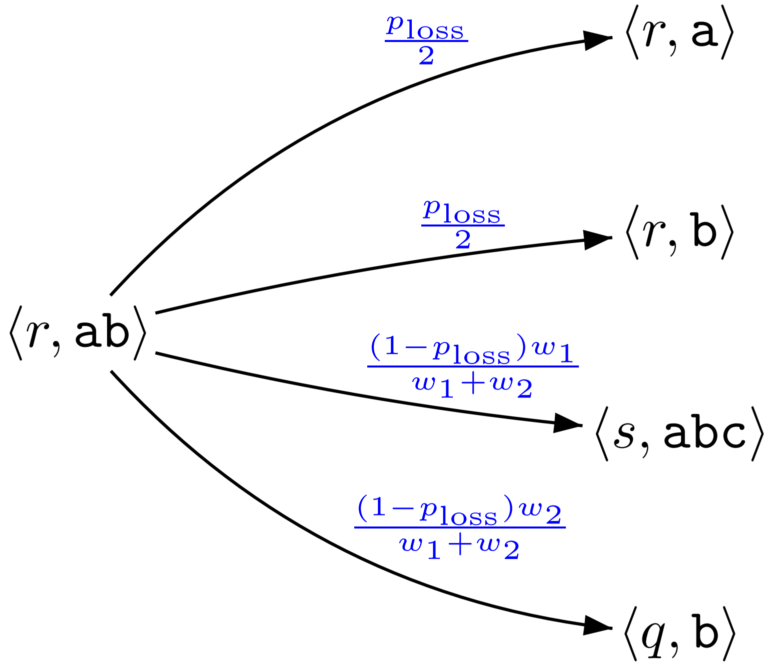

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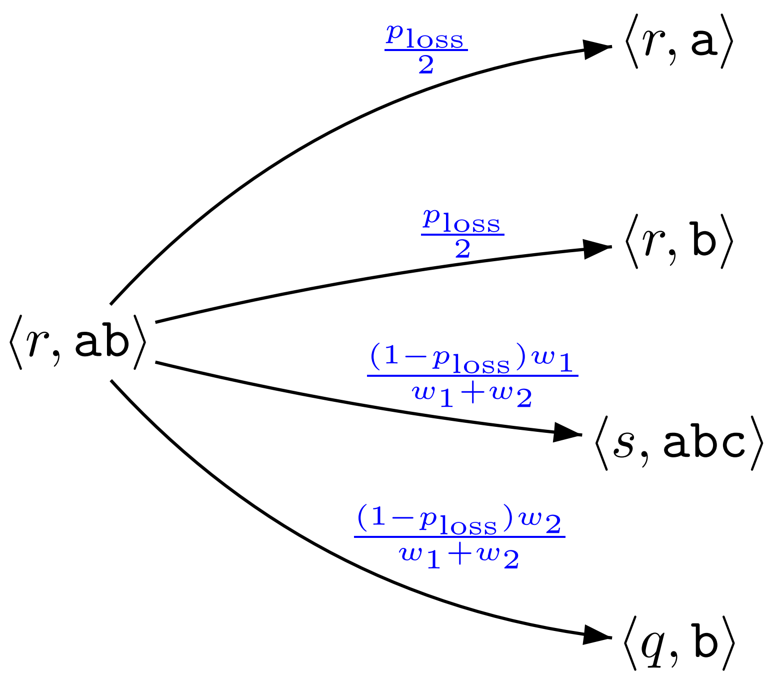

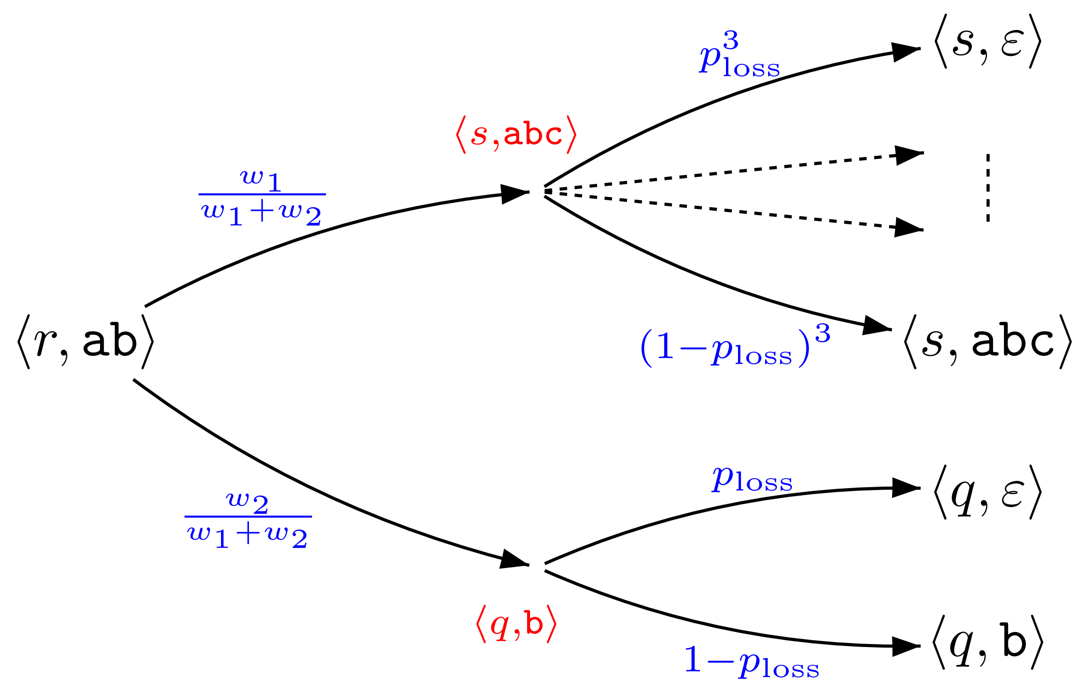

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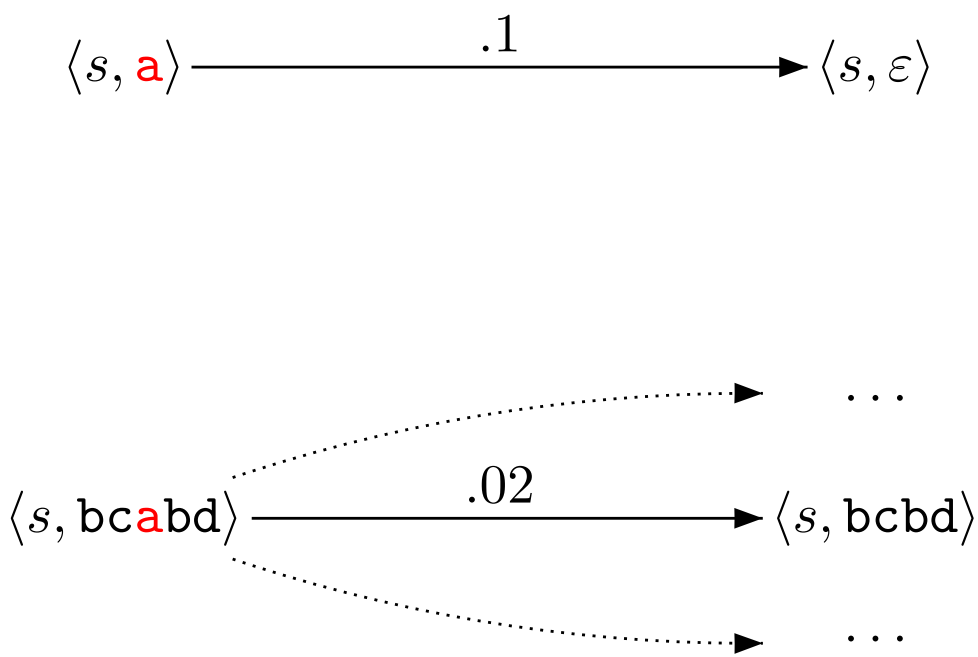

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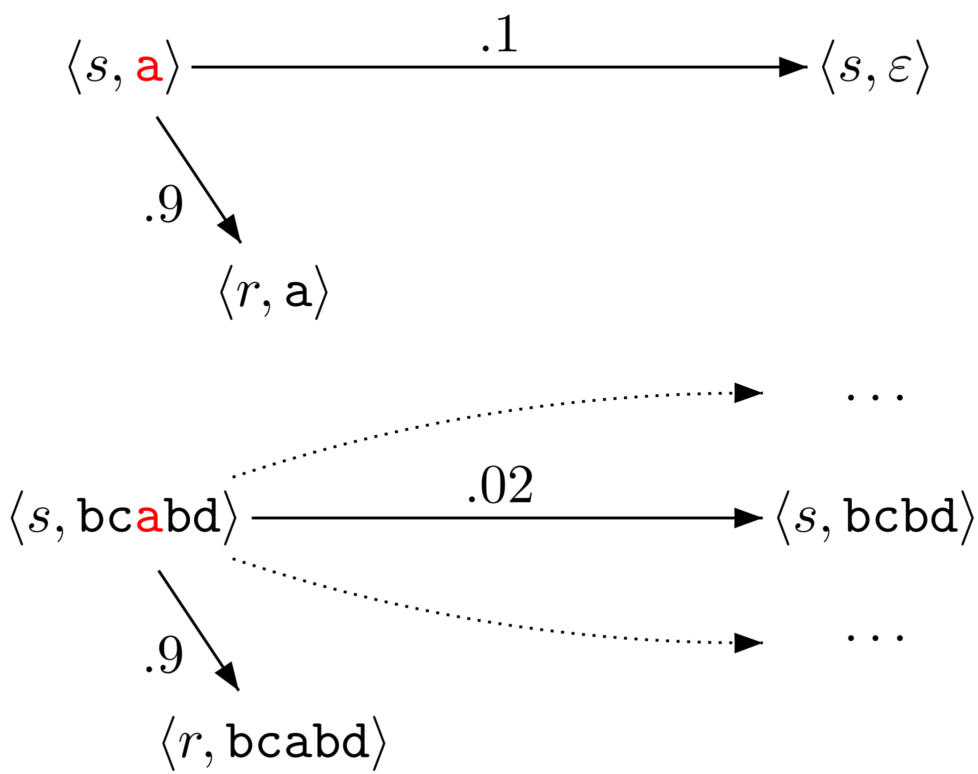

Message losses are not independent events!

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Furthermore, whether $\mathbb{P}(S \models \varphi) = 1$ does not depend on p_{loss}, on the weights, on the choice of a model.

Finite attractors play an essential rôle...

Finite attractors

An *attractor* is a set $W_0 \subseteq W$ of configurations s.t.
for all $\sigma \in W$, $\mathbb{P}(\sigma \models \Diamond W_0) = 1$.

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We show how finite attractors provide finitary conditions for properties of countable Markov chains.

Algorithmic Ideas

A method for checking $\mathbb{P}(S \models \varphi) = 1$:

1. Reduce $\mathbb{P}(S \models \varphi)$ to $\mathbb{P}(S' \models \bigwedge_i \Box\Diamond Q_i \Rightarrow \Box\Diamond Q'_i)$ for $S' = S \otimes \mathcal{A}_\varphi$.

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2. Build the *finite* graph $G_{S'}$ of all configurations from W_0 with an edge $\langle s, \varepsilon \rangle \longrightarrow \langle r, \varepsilon \rangle$ if $\langle r, \varepsilon \rangle$ is reachable from $\langle s, \varepsilon \rangle$.

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5. All this only needs reachability analysis of S'. Hence decidability.

An Assessment Of Qualitative Verification

+ Circumvents the undecidability of model checking lossy channel systems.

+ That precise values for weights etc. do not change the result is a bonus point: this means we only assumed some kind of fairness property.

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– We'll see later that the fairness assumption is sometimes not realistic.

– What about properties that do not hold almost surely but, say, 99% of the time?

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Theorem [Rab03]: There is a way to compute, for any *tolerance* $\tau > 0$, a probability p s.t. $p - \tau \leq \mathbb{P}(S \models \varphi) \leq p + \tau$.

NB: Earlier solution by [PN97] is flawed.

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This approximability result holds for the local-fault model (and the global-fault model when $p_{\text{loss}} \geq .5$).

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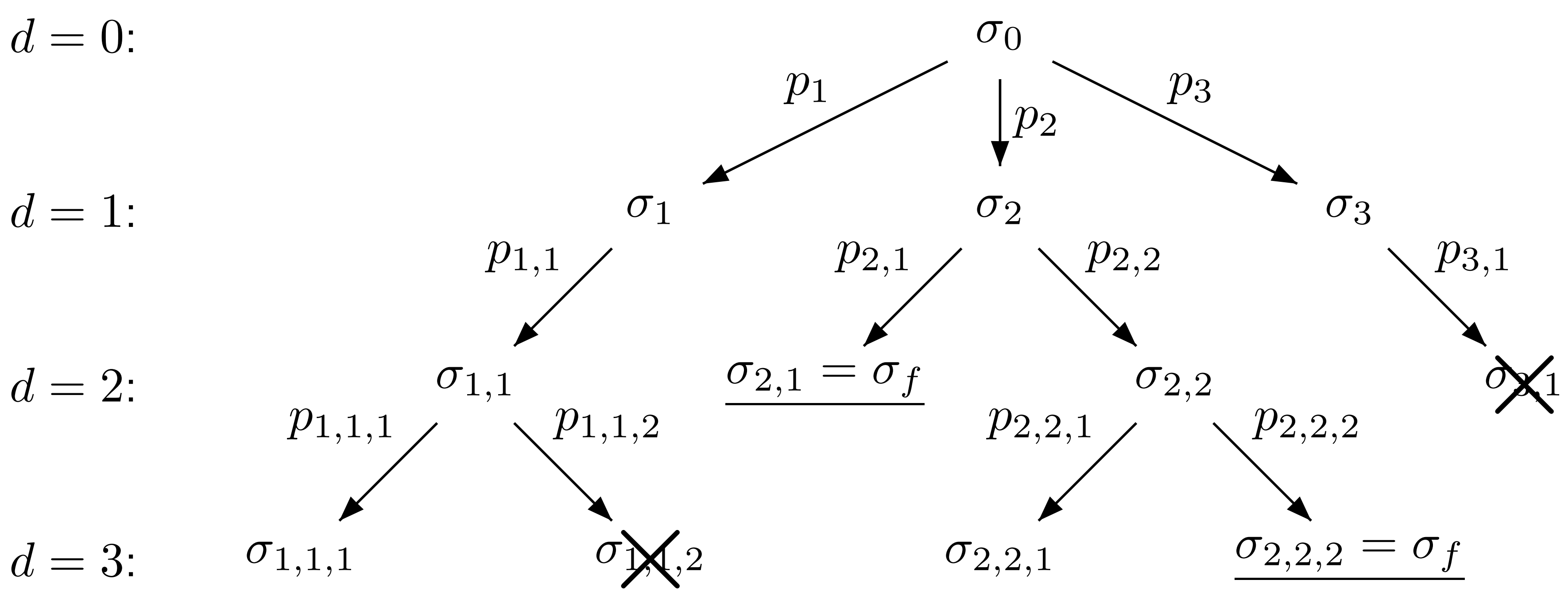

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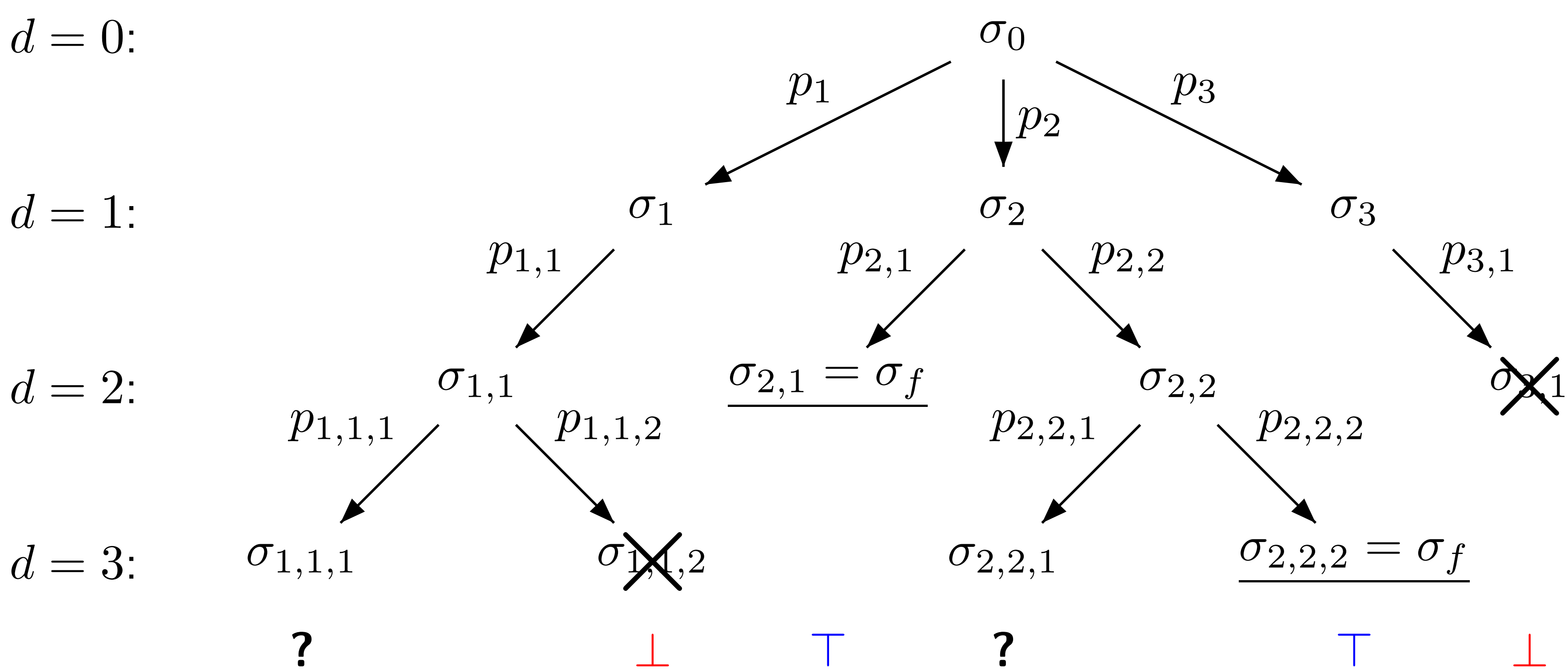

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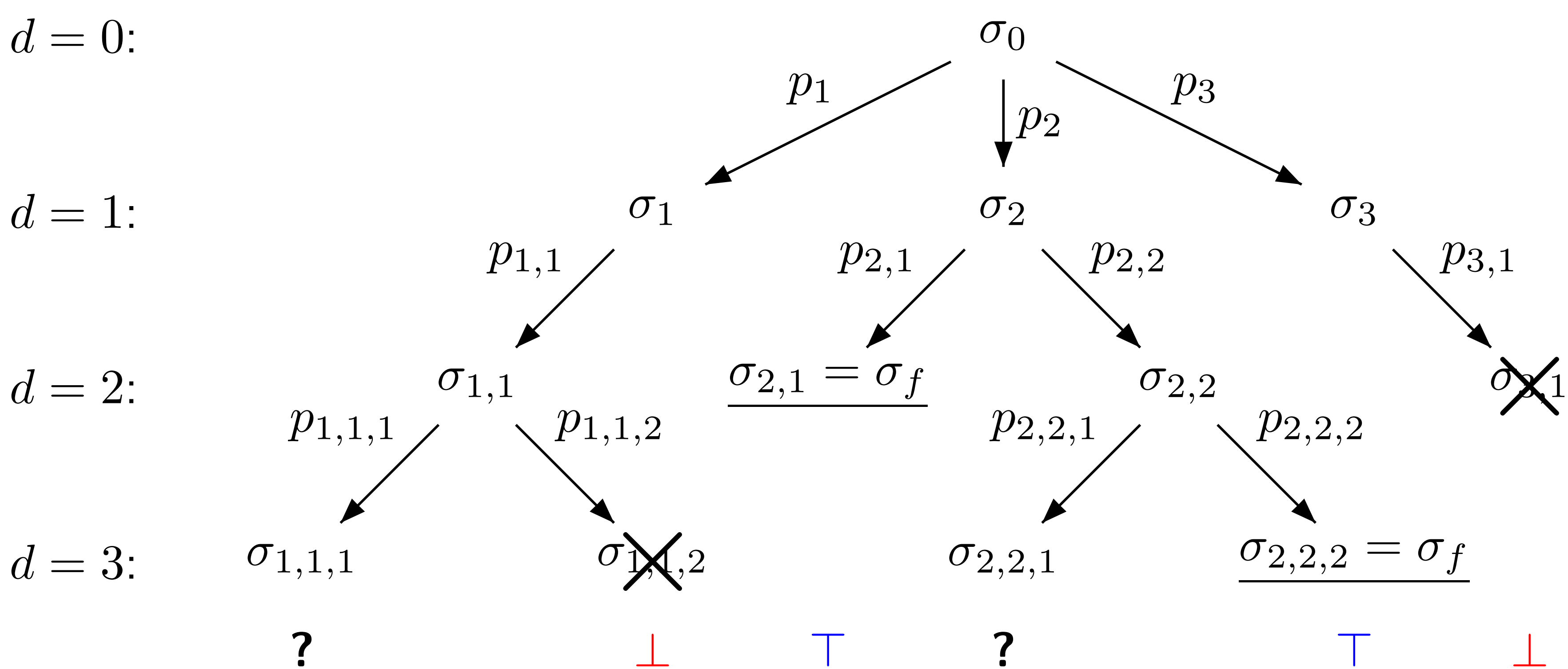

$$\mathbb{P}^d_{\top} \leq \mathbb{P}(\sigma_0 \models \Diamond\sigma_f) \leq \mathbb{P}^d_{\top} + \mathbb{P}^d_{?}.$$

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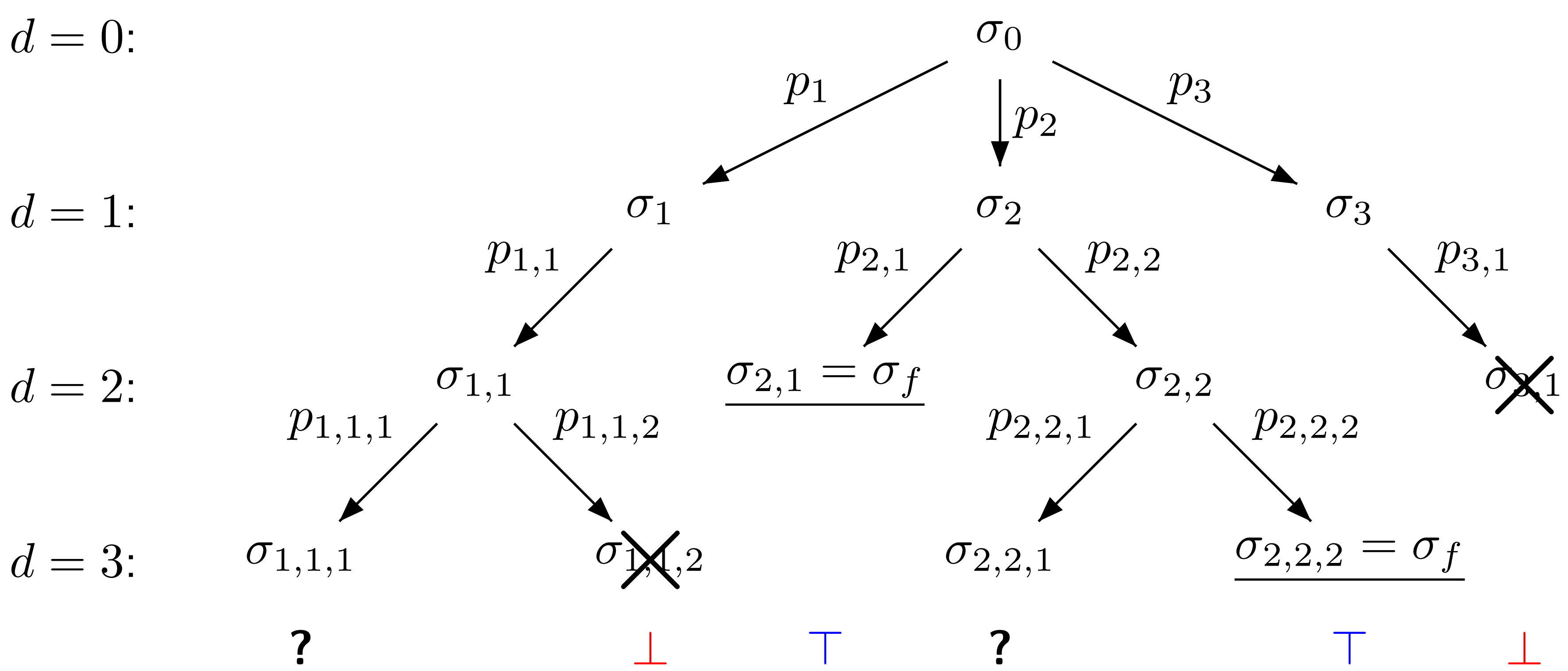

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$\lim_{d \to \infty} \mathbb{P}^d_? = 0$ for systems with a finite attractor!

An Assessment Of Quantitative Verification

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– Requires that rules be given weights: where do these come from?

Beyond Markov Chains

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Then we can ask questions such as "*does* $\mathbb{P}(\varphi) = 1$ *under all scheduling policies?*" (This is the adversarial qualitative viewpoint).

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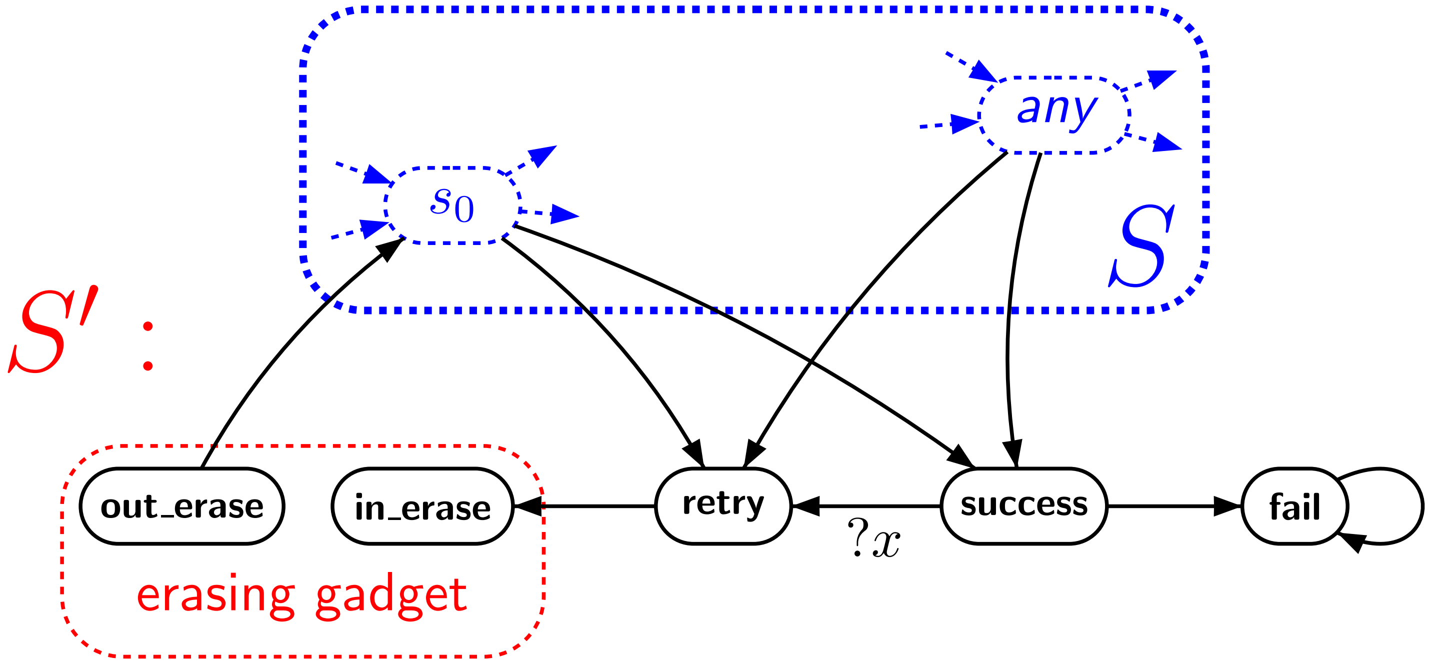

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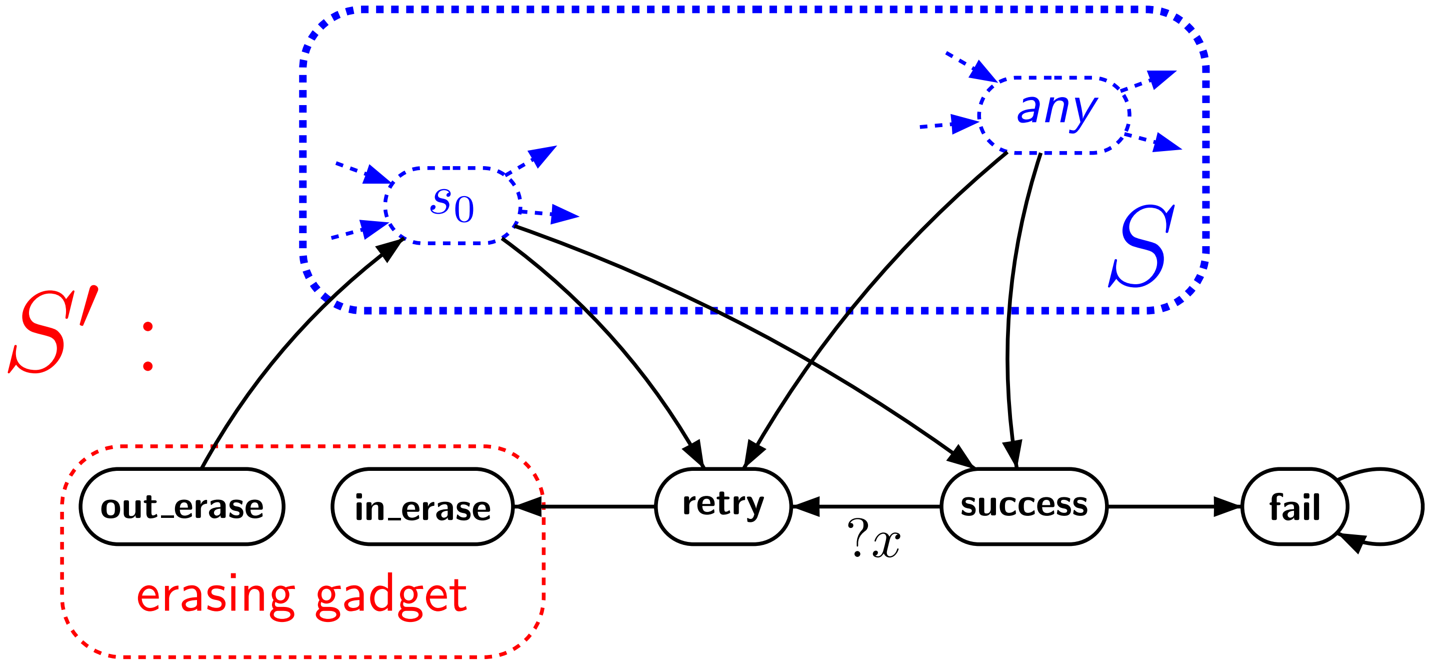

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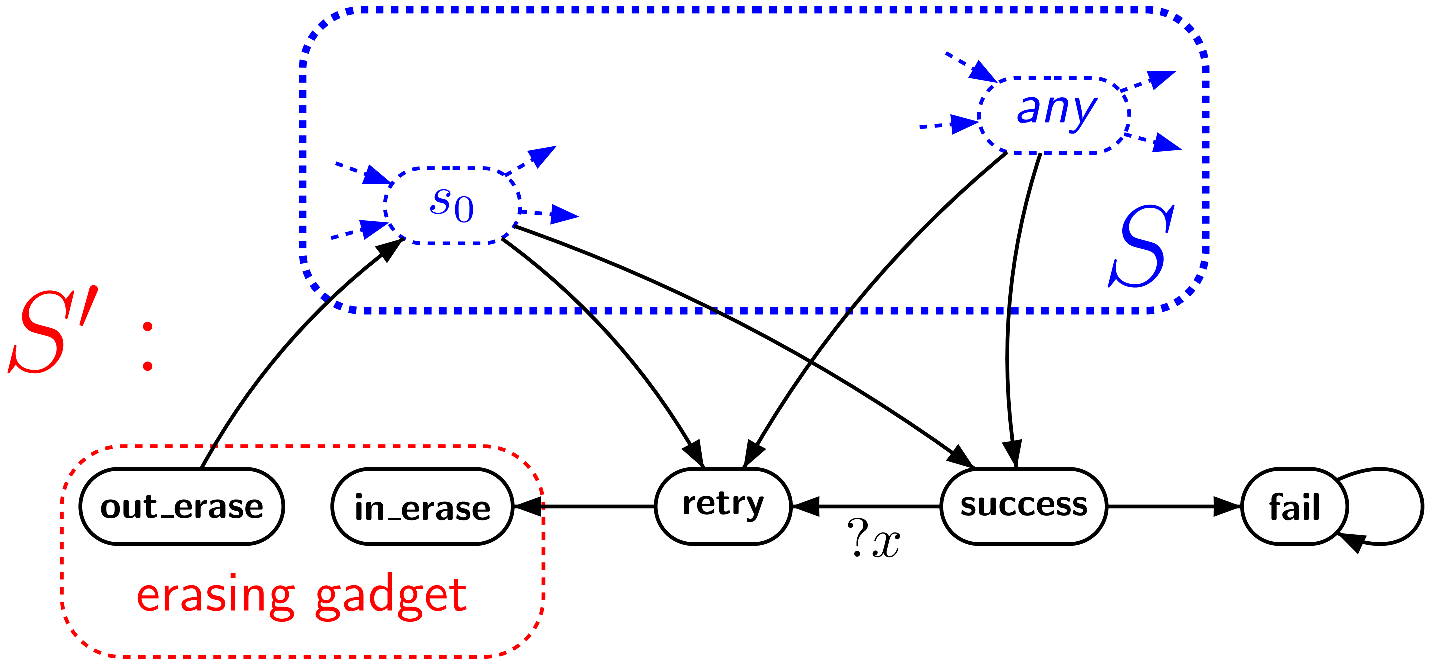

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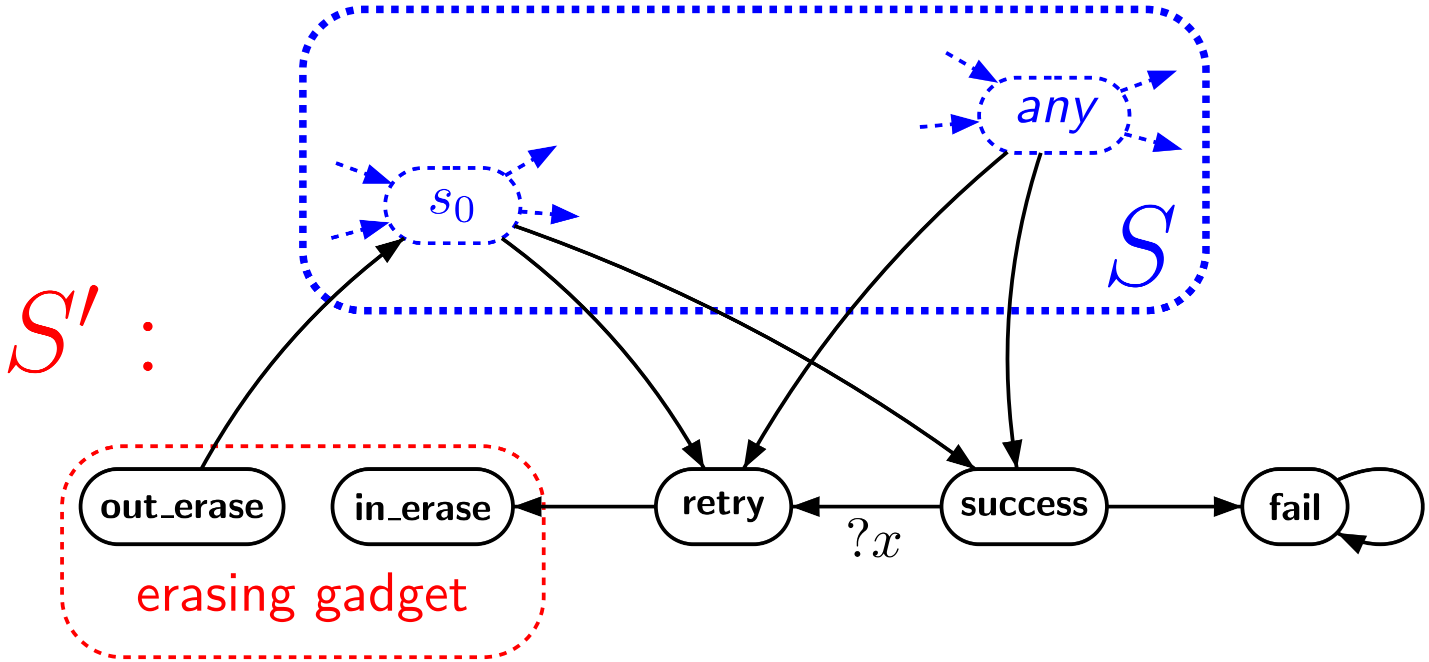

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Corollary: model checking qualitative properties under all scheduling policies is undecidable.

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Some remaining open problems:

– What about cooperative qualitative model checking?

– What about computing minimal and maximal probabilities?

Concluding remarks

It is possible to analyze systems combining two hard features: probabilities and infinite state space.

Quantitative analysis is possible.

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Qualitative analysis of Markovian decision processes is a good substitute for traditional linear-time model checking (minus the undecidability!).

Randomization helps.

All this is still new and many open questions remain.

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