

Modeling and Verification of Probabilistic Systems

Lecture 7: Probabilistic Bisimulation

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Overview

1 Strong Bisimulation

2 Probabilistic Bisimulation

- Quotient Markov Chain
- Examples

3 Logical Preservation

- The Logics PCTL, PCTL* and PCTL⁻
- Preservation Theorem

4 Summary

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Labeled transition system

Transition system

A *(labeled) transition system* TS is a quadruple $(S, Act, \rightarrow, I_0, AP, L)$ where

- ▶ S is a (possibly infinitely countable) set of states.
- ▶ Act is a (possibly infinitely countable) set of actions.
- ▶ $\rightarrow \subseteq S \times Act \times S$ is a transition relation.
- ▶ $I_0 \subseteq S$ the set of initial states.
- ▶ AP is a set of atomic propositions.
- ▶ $L : S \rightarrow 2^{AP}$ is the labeling function.

Notation

We write $s \xrightarrow{\alpha} s'$ instead of $(s, \alpha, s') \in \rightarrow$.

Strong bisimulation

Strong bisimulation relation

[Milner, 1980 & Park, 1981]

Let $TS = (S, Act, \longrightarrow, I_0, AP, L)$ be a transition system and $R \subseteq S \times S$.

Then R is a **strong bisimulation** on TS whenever for all $(s, t) \in R$:

1. $L(s) = L(t)$
2. if $s \xrightarrow{\alpha} s'$ then there exists $t' \in S$ such that $t \xrightarrow{\alpha} t'$ and $(s', t') \in R$
3. if $t \xrightarrow{\alpha} t'$ then there exists $s' \in S$ such that $s \xrightarrow{\alpha} s'$ and $(s', t') \in R$

Strong bisimilarity

Let $TS = (S, Act, \longrightarrow, I_0, AP, L)$ be a transition system and $s, t \in S$.

Then: s is **strongly bisimilar** to t , notation $s \sim t$, if there **exists** a strong bisimulation R such that $(s, t) \in R$.

Remarks

Not every bisimulation relation is transitive. But: \sim is an equivalence.

Strongly bisimilar transition systems

Bisimilar transition systems

Let TS_1, TS_2 be transition systems over the same set of atomic propositions with initial states $I_{0,1}$ and $I_{0,2}$, respectively.

Consider the transition system $TS = TS_1 \uplus TS_2$ that results from the **disjoint union** of TS_1 and TS_2 .

Then: TS_1 and TS_2 are called **strongly bisimilar** if there exists a strong bisimulation R on $S_1 \uplus S_2$ such that:

1. $\forall s \in I_{0,1} \exists t \in I_{0,2} (s, t) \in R$, and
2. $\forall t \in I_{0,2} \exists s \in I_{0,1} (s, t) \in R$.

Strong bisimulation

Pictorial representation

$$s \xrightarrow{\alpha} s'$$

 R t

$$s \xrightarrow{\alpha} s'$$

can be completed to

$$R$$

$$t \xrightarrow{\alpha} t'$$

and

 s R

$$t \xrightarrow{\alpha} t'$$

$$s \xrightarrow{\alpha} s'$$

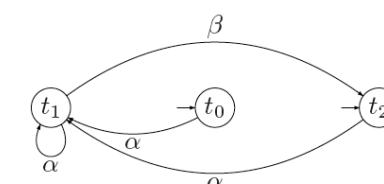
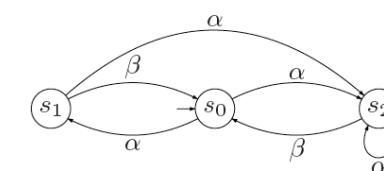
can be completed to

$$R$$

$$t \xrightarrow{\alpha} t'$$

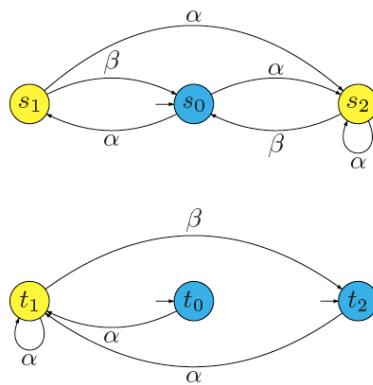
Example (1)

Are these transition systems strongly bisimilar? (No propositions.)



Example (2)

Yes, they are!



Quotient LTS under \sim

Quotient transition system

For $TS = (S, \text{Act}, \longrightarrow, I_0, AP, L)$ and strong bisimilarity $\sim \subseteq S \times S$ let

$TS/\sim = (S', \text{Act}, \longrightarrow', I'_0, AP, L')$, the *quotient* of TS under \sim

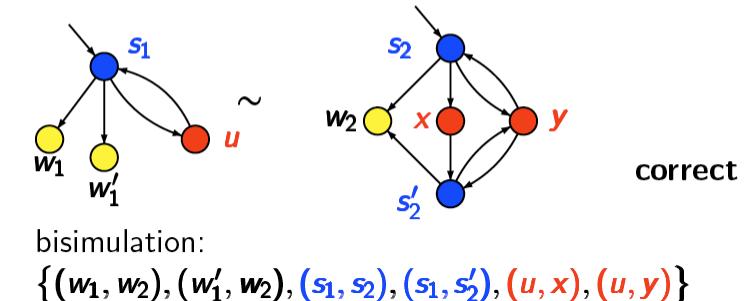
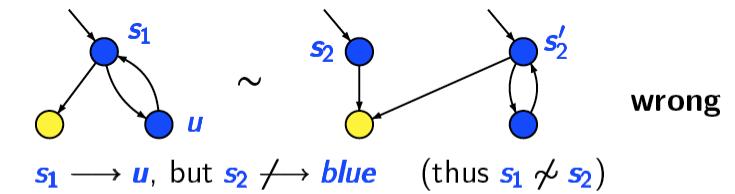
where

- ▶ $S' = S/\sim = \{[s]_\sim \mid s \in S\}$ with $[s]_\sim = \{s' \in S \mid s \sim s'\}$
- ▶ \longrightarrow' is defined by:
$$\frac{s \xrightarrow{\alpha} s'}{[s]_\sim \xrightarrow{\alpha} [s']_\sim}$$
- ▶ $I'_0 = \{[s_0]_\sim \mid s_0 \in I_0\}$, the equivalence class of the initial states in TS
- ▶ $L'([s]_\sim) = L(s)$.

Remarks

L' is well-defined as all states in $[s]_\sim$ are equally labeled. Note that if $s \xrightarrow{\alpha} s'$, then for all $t \sim s$ we have $s \xrightarrow{\alpha} t'$ with $s' \sim t'$.

Correct or wrong?



Quotient transition system

For any transition system TS it holds: $TS \sim TS/\sim$.

Proof:

The binary relation:

$$R = \{(s, [s]_\sim) \mid s \in S\}$$

is a strong bisimulation on the pair $(TS, TS/\sim)$.

Strong bisimulation revisited

Auxiliary predicate

Let $P : S \times Act \times 2^S \rightarrow \{0, 1\}$ be a predicate such that for $S' \subseteq S$:

$$P(s, \alpha, S') = \begin{cases} 1 & \text{if } \exists s' \in S'. s \xrightarrow{\alpha} s' \\ 0 & \text{otherwise.} \end{cases}$$

Alternative definition of strong bisimulation

Let $TS = (S, Act, \longrightarrow, I_0, AP, L)$ and R an *equivalence relation* on S .

Then: R is a *strong bisimulation* on S if for $(s, t) \in R$:

1. $L(s) = L(t)$, and
2. $P(s, \alpha, C) = P(t, \alpha, C)$ for all C in S/R and $\alpha \in Act$.

This definition is equivalent to the previous one. Proof is left as an exercise.

Probabilistic bisimulation: intuition

Intuition

- ▶ Strong bisimulation is used to *compare* labeled transition systems.
- ▶ Strongly bisimilar states exhibit the same step-wise behaviour.
- ▶ Our aim: adapt bisimulation to discrete-time Markov chains.
- ▶ This yields a probabilistic variant of strong bisimulation.

- ▶ When do two DTMC states exhibit the same step-wise behaviour?
- ▶ Key: if their transition probability for each equivalence class coincides.

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Probabilistic bisimulation

Probabilistic bisimulation

[Larsen & Skou, 1989]

Let $\mathcal{D} = (S, P, \iota_{\text{init}}, AP, L)$ be a DTMC and $R \subseteq S \times S$ an *equivalence*.

Then: R is a *probabilistic bisimulation* on S if for any $(s, t) \in R$:

1. $L(s) = L(t)$, and
2. $\mathbf{P}(s, C) = \mathbf{P}(t, C)$ for all equivalence classes $C \in S/R$

where $\mathbf{P}(s, C) = \sum_{s' \in C} \mathbf{P}(s, s')$.

For states in R , the probability of moving by a single transition to some equivalence class is equal.

Probabilistic bisimilarity

Let \mathcal{D} be a DTMC and s, t states in \mathcal{D} . Then: s is *probabilistically bisimilar* to t , denoted $s \sim_p t$, if there *exists* a probabilistic bisimulation R with $(s, t) \in R$.

Probabilistic bisimulation

Probabilistic bisimulation

Let $\mathcal{D} = (S, \mathbf{P}, \iota_{\text{init}}, AP, L)$ be a DTMC and $R \subseteq S \times S$ an equivalence.

Then: R is a probabilistic bisimulation on S if for any $(s, t) \in R$:

1. $L(s) = L(t)$, and
2. $\mathbf{P}(s, C) = \mathbf{P}(t, C)$ for all equivalence classes $C \in S/R$.

Remarks

As opposed to bisimulation on states in transition systems, any probabilistic bisimulation is an equivalence.

Bisimilar DTMCs

Let $\mathcal{D}_1, \mathcal{D}_2$ be DTMCs over the same set of atomic propositions with initial distributions ι_{init}^1 and ι_{init}^2 , respectively.

Consider the DTMC $\mathcal{D} = \mathcal{D}_1 \uplus \mathcal{D}_2$ that results from the disjoint union of \mathcal{D}_1 and \mathcal{D}_2 .

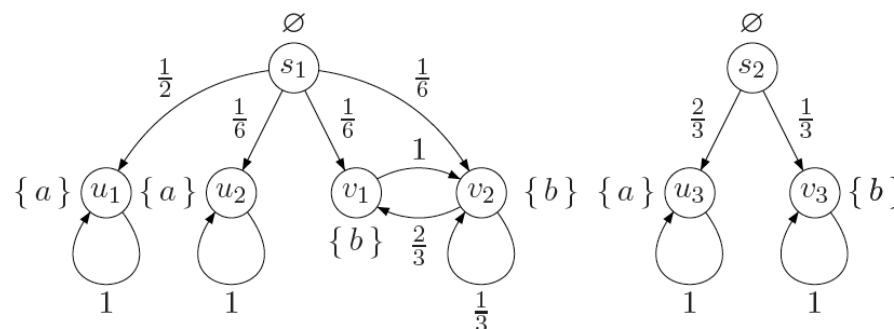
Then \mathcal{D}_1 and \mathcal{D}_2 are bisimilar if

$$\iota_{\text{init}}^1(C) = \iota_{\text{init}}^2(C)$$

for each bisimulation equivalence class C of $\mathcal{D} = \mathcal{D}_1 \uplus \mathcal{D}_2$.

Here, $\iota_{\text{init}}(C)$ denotes $\sum_{s \in C} \iota_{\text{init}}(s)$.

Example



Quotient under \sim_p

Quotient DTMC under \sim_p

For $\mathcal{D} = (S, \mathbf{P}, \iota_{\text{init}}, AP, L)$ and probabilistic bisimulation $\sim_p \subseteq S \times S$ let

$$\mathcal{D}/\sim_p = (S', \mathbf{P}', \iota'_{\text{init}}, AP, L'), \quad \text{the quotient of } \mathcal{D} \text{ under } \sim_p$$

where

- $S' = S/\sim_p = \{ [s]_{\sim_p} \mid s \in S \}$ with $[s]_{\sim_p} = \{ s' \in S \mid s \sim_p s' \}$
- $\mathbf{P}'([s]_{\sim_p}, [s']_{\sim_p}) = \mathbf{P}(s, [s']_{\sim_p})$
- $\iota'_{\text{init}}([s]_{\sim_p}) = \sum_{s' \in [s]_{\sim_p}} \iota_{\text{init}}(s)$
- $L'([s]_{\sim_p}) = L(s)$.

Remarks

The transition probability from $[s]_{\sim_p}$ to $[t]_{\sim_p}$ equals $\mathbf{P}(s, [t]_{\sim_p})$. This is well-defined as $\mathbf{P}(s, C) = \mathbf{P}(s', C)$ for all $s \sim_p s'$ and all bisimulation equivalence classes C .

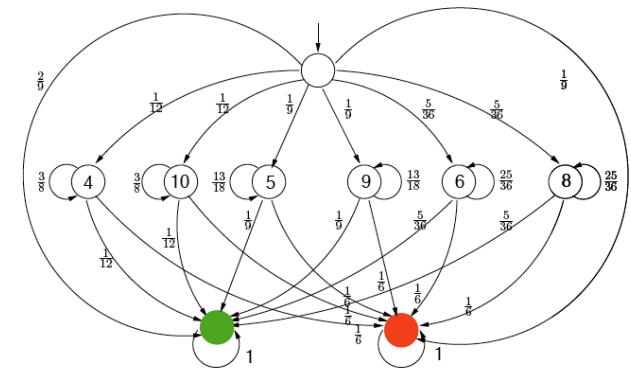
Craps

- ▶ Roll two dice and bet
- ▶ Come-out roll (“pass line” wager):
 - ▶ outcome 7 or 11: win
 - ▶ outcome 2, 3, or 12: lose (“craps”)
 - ▶ any other outcome: roll again (outcome is “point”)
- ▶ Repeat until 7 or the “point” is thrown:
 - ▶ outcome 7: lose (“seven-out”)
 - ▶ outcome the **point**: win
 - ▶ any other outcome: roll again

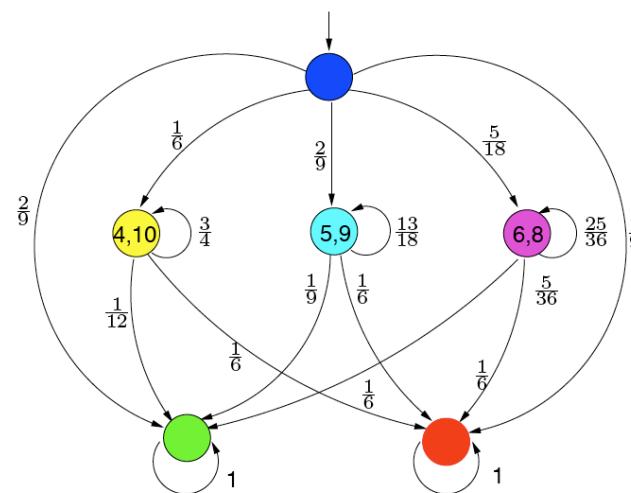


A DTMC model of Craps

- ▶ Come-out roll:
 - ▶ 7 or 11: win
 - ▶ 2, 3, or 12: lose
 - ▶ else: roll again
- ▶ Next roll(s):
 - ▶ 7: lose
 - ▶ point: win
 - ▶ else: roll again



Quotient DTMC of Craps under \sim_p



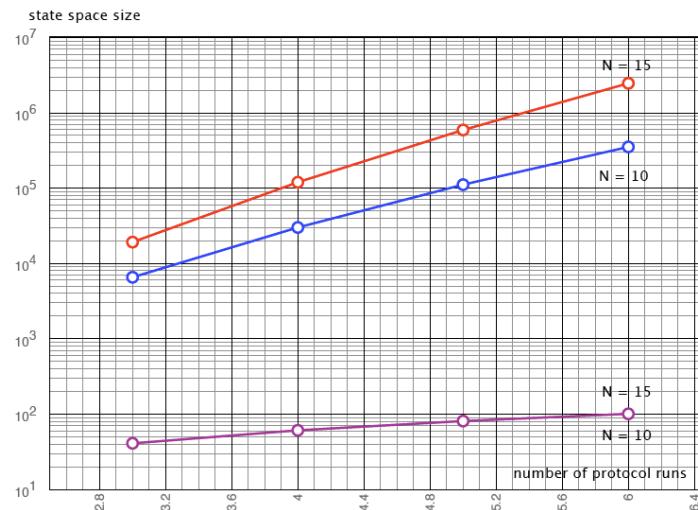
Example: Crowds protocol

Security: Crowds protocol

[Reiter & Rubin, 1998]

- ▶ A protocol for **anonymous web browsing** (variants: mCrowds, BT-Crowds)
- ▶ Hide user's communication by **random routing** within a crowd
 - ▶ sender selects a crowd member randomly using a uniform distribution
 - ▶ selected router flips a biased coin:
 - ▶ with probability $1 - p$: direct delivery to final destination
 - ▶ otherwise: select a next router randomly (uniformly)
 - ▶ once a routing path has been established, use it until crowd changes
- ▶ Rebuild routing paths on crowd changes
- ▶ Property: Crowds protocol ensures “probable innocence”:
 - ▶ probability real sender is discovered $< \frac{1}{2}$ if $N \geq \frac{p}{p-1} \cdot (c+1)$
 - ▶ where N is crowd's size and c is number of corrupt crowd members

State space reduction under \sim_p



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PCTL syntax

Probabilistic Computation Tree Logic: Syntax

PCTL consists of state- and path-formulas.

- PCTL *state formulas* over the set AP obey the grammar:

$$\Phi ::= \text{true} \mid a \mid \Phi_1 \wedge \Phi_2 \mid \neg \Phi \mid \mathbb{P}_J(\varphi)$$

where $a \in AP$, φ is a path formula and $J \subseteq [0, 1]$, $J \neq \emptyset$ is a non-empty interval.

- PCTL *path formulae* are formed according to the following grammar:

$$\varphi ::= \bigcirc \Phi \mid \Phi_1 \cup \Phi_2 \mid \Phi_1 \mathbb{U}^{\leq n} \Phi_2$$

where Φ , Φ_1 , and Φ_2 are state formulae and $n \in \mathbb{N}$.

Preservation of PCTL-formulas

Bisimulation preserves PCTL

Let \mathcal{D} be a DTMC and s, t states in \mathcal{D} . Then:

$$s \sim_p t \text{ if and only if } s \text{ and } t \text{ are PCTL-equivalent.}$$

Remarks

$s \sim_p t$ implies that

1. transient probabilities, reachability probabilities,
2. repeated reachability, persistence probabilities
3. all qualitative PCTL formulas

for s and t are equal.

If for PCTL-formula Φ we have $s \models \Phi$ but $t \not\models \Phi$, then it follows $s \not\sim_p t$. A single PCTL-formula suffices!

PCTL* syntax

Probabilistic Computation Tree Logic: Syntax

PCTL* consists of state- and path-formulas.

- PCTL* *state formulas* over the set AP obey the grammar:

$$\Phi ::= \text{true} \mid a \mid \Phi_1 \wedge \Phi_2 \mid \neg\Phi \mid \mathbb{P}_J(\varphi)$$

where $a \in AP$, φ is a path formula and $J \subseteq [0, 1]$, $J \neq \emptyset$ is a non-empty interval.

- PCTL* *path formulae* are formed according to the following grammar:

$$\varphi ::= \Phi \mid \neg\varphi \mid \varphi_1 \wedge \varphi_2 \mid \bigcirc \varphi \mid \varphi_1 \mathbb{U} \varphi_2$$

where Φ is a state formula and φ , φ_1 , and φ_2 are path formulae.

PCTL* semantics (2)

Satisfaction relation for path formulas

Let $\pi = s_0 s_1 s_2 \dots$ be an infinite path in (possibly infinite) DTMC \mathcal{D} . Let $\pi^i = s_i s_{i+1} s_{i+2} \dots$ denotes the i -th suffix of π .

The satisfaction relation \models is defined for state formulas by:

$$\begin{aligned} \pi \models \Phi &\quad \text{iff } \pi[0] \models \Phi \\ \pi \models \neg\varphi &\quad \text{iff not } \pi \models \varphi \\ \pi \models \varphi_1 \wedge \varphi_2 &\quad \text{iff } \pi \models \varphi_1 \text{ and } \pi \models \varphi_2 \\ \pi \models \bigcirc \varphi &\quad \text{iff } \pi^1 \models \varphi \\ \pi \models \varphi_1 \mathbb{U} \varphi_2 &\quad \text{iff } \exists k \geq 0. (\pi^k \models \varphi_2 \wedge \forall 0 \leq i < k. \pi^i \models \varphi_1) \end{aligned}$$

PCTL* semantics (1)

Notation

$\mathcal{D}, s \models \Phi$ if and only if state-formula Φ holds in state s of (possibly infinite) DTMC \mathcal{D} . As \mathcal{D} is known from the context we simply write $s \models \Phi$.

Satisfaction relation for state formulas

The satisfaction relation \models is defined for PCTL* state formulas by:

$$\begin{aligned} s \models a &\quad \text{iff } a \in L(s) \\ s \models \neg\Phi &\quad \text{iff not } (s \models \Phi) \\ s \models \Phi \wedge \Psi &\quad \text{iff } (s \models \Phi) \text{ and } (s \models \Psi) \\ s \models \mathbb{P}_J(\varphi) &\quad \text{iff } \Pr(s \models \varphi) \in J \end{aligned}$$

where $\Pr(s \models \varphi) = \Pr_s\{\pi \in \text{Paths}(s) \mid \pi \models \varphi\}$

Measurability

PCTL* measurability

For any PCTL* path formula φ and state s of DTMC \mathcal{D} , the set $\{\pi \in \text{Paths}(s) \mid \pi \models \varphi\}$ is measurable.

Proof:

Left as an exercise, using the result for PCTL measurability.

Bounded until in PCTL*

Bounded until

Bounded until can be defined using the other operators:

$$\varphi_1 U^{\leq n} \varphi_2 = \bigvee_{0 \leq i \leq n} \psi_i \quad \text{where } \psi_0 = \varphi_2 \text{ and } \psi_{i+1} = \varphi_1 \wedge \bigcirc \psi_i \text{ for } i \geq 0.$$

Examples in PCTL* but not in PCTL

$\mathbb{P}_{>\frac{1}{4}}(\bigcirc a U \bigcirc b)$ and $\mathbb{P}_{=1}(\mathbb{P}_{>\frac{1}{2}}(\square \lozenge a) \vee \mathbb{P}_{\leq \frac{1}{3}}(\lozenge \square b))$.

PCTL⁻ syntax

Simple Probabilistic Computation Tree Logic: Syntax

PCTL⁻ only consists of state-formulas. These formulas over the set AP obey the grammar:

$$\Phi ::= a \mid \Phi_1 \wedge \Phi_2 \mid \mathbb{P}_{\leq p}(\bigcirc \Phi)$$

where $a \in AP$ and p is a probability in $[0, 1]$.

Remarks

This is a truly simple logic. It does not contain the until-operator. Negation is not present and cannot be expressed. Only upper bounds on probabilities.

The next theorem shows that PCTL-, PCTL*- and PCTL⁻-equivalence coincide.

Preservation of PCTL*-formulas

Bisimulation preserves PCTL*

Let \mathcal{D} be a DTMC and s, t states in \mathcal{D} . Then:

$$s \sim_p t \quad \text{if and only if} \quad s \text{ and } t \text{ are PCTL*}-\text{equivalent}.$$

Remarks

1. Bisimulation thus preserves not only all PCTL but also all PCTL* formulas.
2. By the last two results it follows that PCTL- and PCTL*-equivalence coincide. Thus any two states that satisfy the same PCTL formulas, satisfy the same PCTL* formulas.

Preservation of PCTL

PCTL/PCTL* and Bisimulation Equivalence

Let \mathcal{D} be a DTMC and s_1, s_2 states in \mathcal{D} . Then, the following statements are equivalent:

- (a) $s_1 \sim_p s_2$.
- (b) s_1 and s_2 are PCTL*-equivalent, i.e., fulfill the same PCTL* formulas
- (c) s_1 and s_2 are PCTL-equivalent, i.e., fulfill the same PCTL formulas
- (d) s_1 and s_2 are PCTL⁻-equivalent, i.e., fulfill the same PCTL⁻ formulas

Proof:

1. (a) \Rightarrow (b): by structural induction on PCTL* formulas.
2. (b) \Rightarrow (c): trivial as PCTL is a sublogic of PCTL*.
3. (c) \Rightarrow (d): trivial as PCTL⁻ is a sublogic of PCTL.
4. (d) \Rightarrow (a): involved. First finite DTMCs, then for arbitrary DTMCs.

Proof

IEEE 802.11 group communication protocol

OD	original DTMC			quotient DTMC		red. factor	
	states	transitions	ver. time	blocks	total time	states	time
4	1125	5369	122	71	13	15.9	9.00
12	37349	236313	7180	1821	642	20.5	11.2
20	231525	1590329	50133	10627	5431	21.8	9.2
28	804837	5750873	195086	35961	24716	22.4	7.9
36	2076773	15187833	5103900	91391	77694	22.7	6.6
40	3101445	22871849	7725041	135752	127489	22.9	6.1

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Summary

- ▶ Bisimilar states have equal transition probabilities to all equivalence classes.
- ▶ \sim_p is the coarsest probabilistic bisimulation.
- ▶ In a quotient DTMC all states are equivalence classes under \sim_p .
- ▶ Bisimulation, i.e., \sim_p , and PCTL-equivalence coincide.
- ▶ PCTL, PCTL* and PCTL⁻-equivalence coincide.
- ▶ To show $s \not\sim_p t$, show $s \models \Phi$ and $t \not\models \Phi$ for $\Phi \in \text{PCTL}^-$.
- ▶ Bisimulation may yield up to exponential savings in state space.

Take-home message

Probabilistic bisimulation coincides with a notion from the sixties, named (ordinary) lumpability.