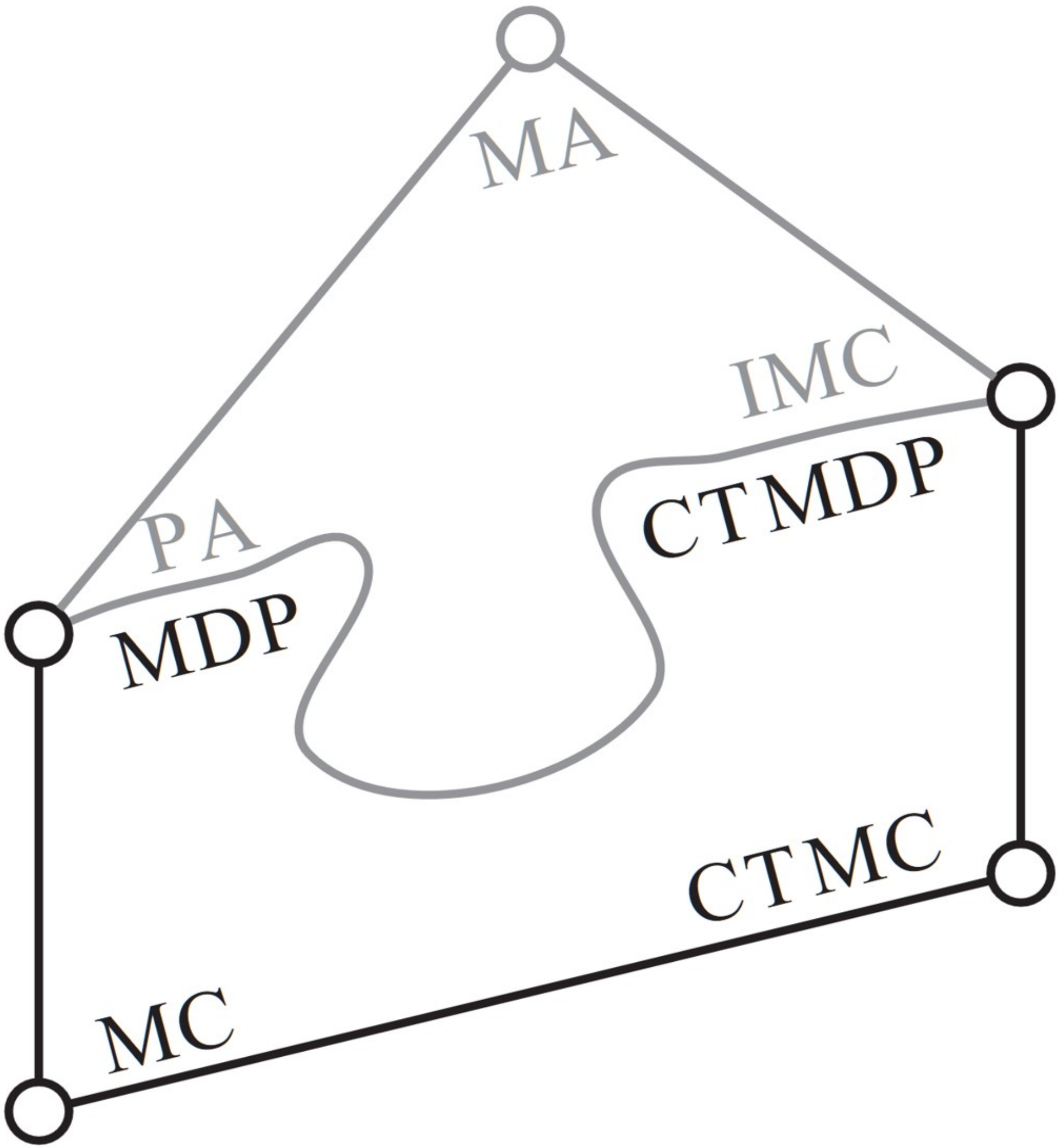
Markov Automata

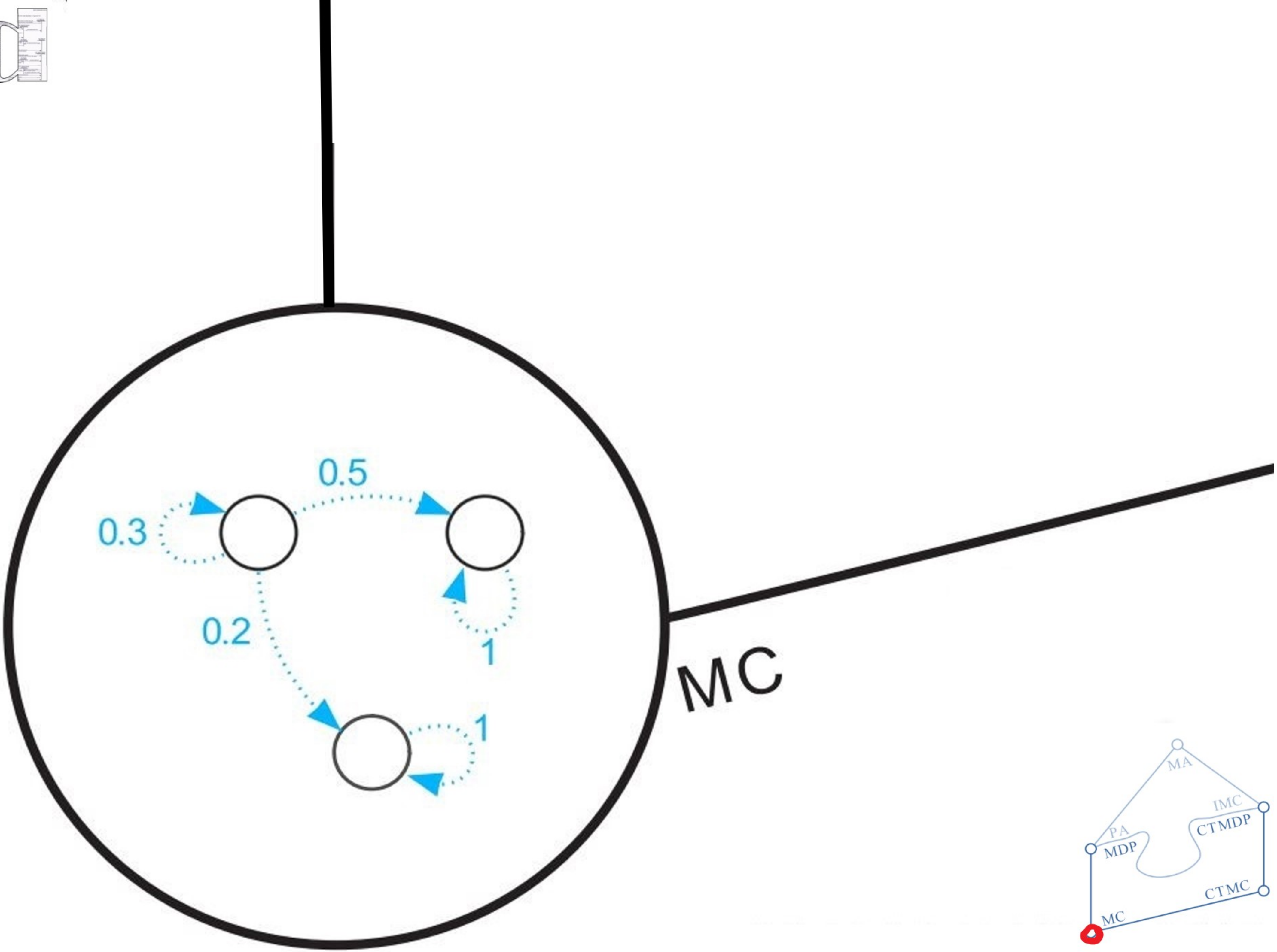
The state of affairs

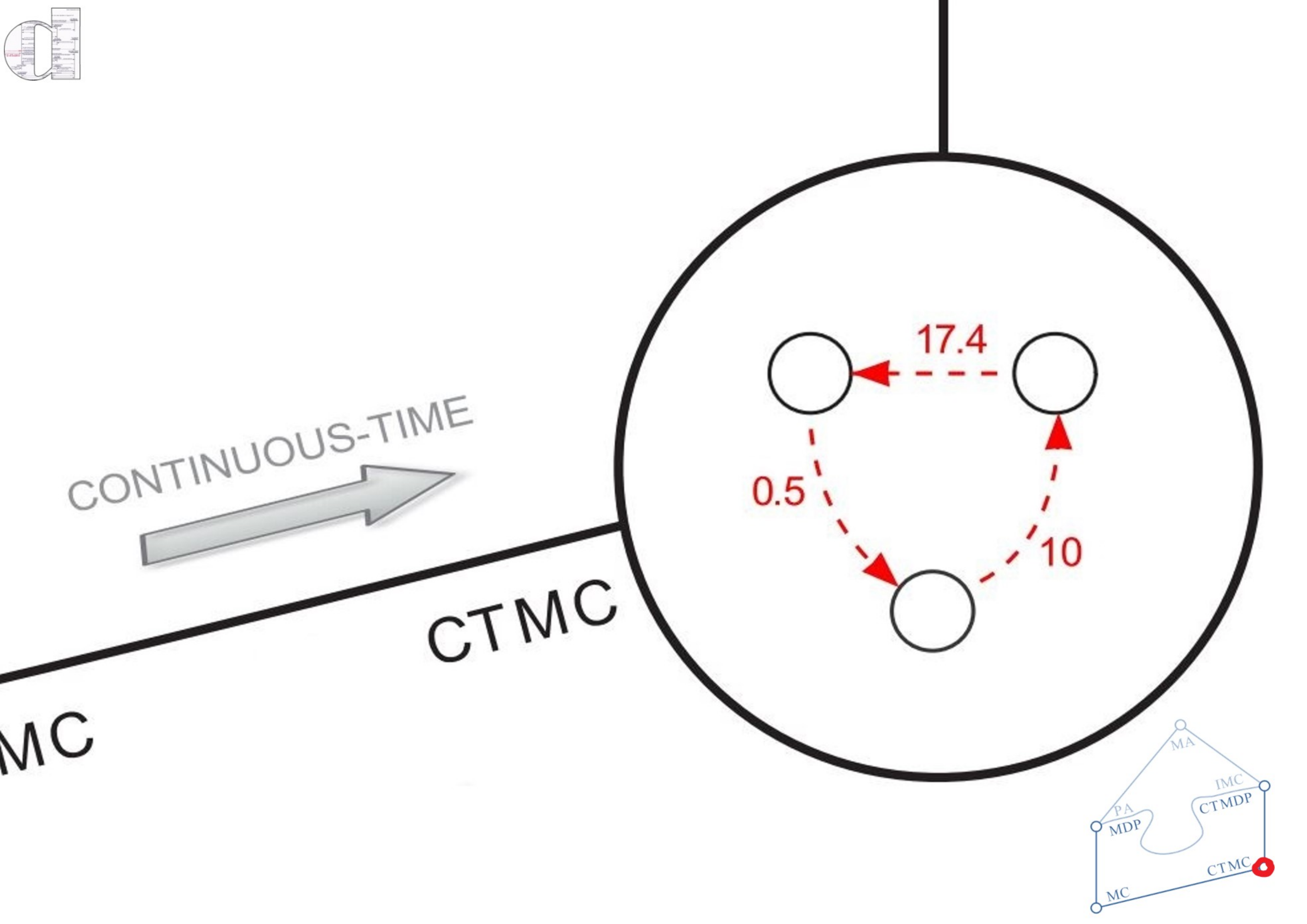
Holger Hermanns
Saarland University

Markov Automata?

- What?
- Why?
- How?
  - Construction
  - Compression
  - Verification
  - Extension
- Open Challenges




0.5
0.3
0.2
1
1
MC
MA
IMC
CTMDP
PA
MDP
CTMC
MC

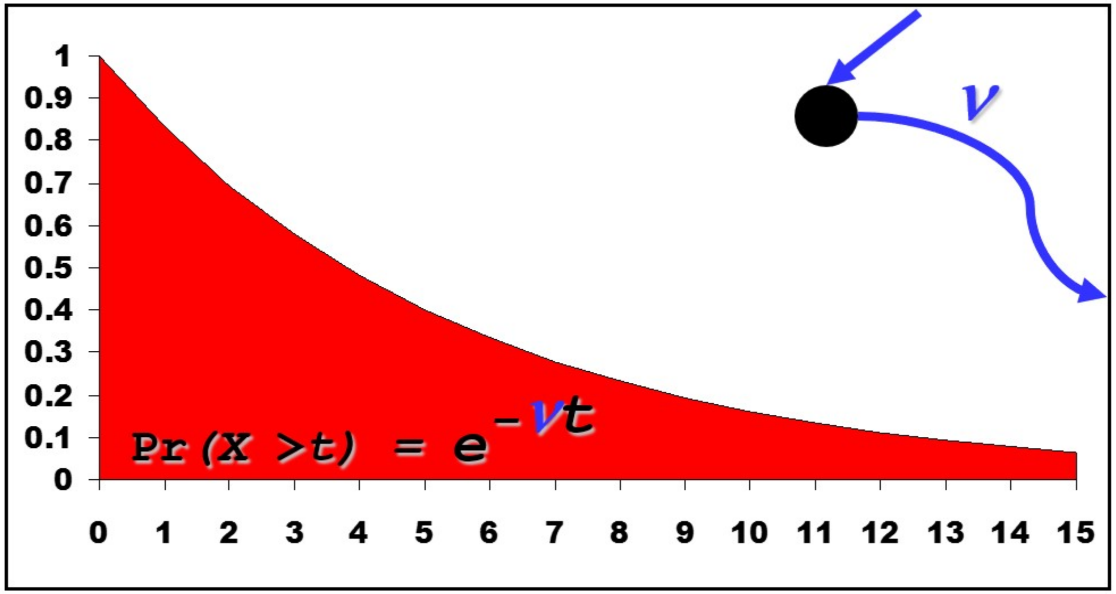


CONTINUOUS-TIME
17.4
0.5
10
CTMC
MC
MA
IMC
CTMDP
PA
MDP
CTMC
MC

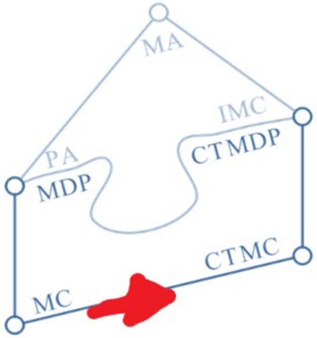
Continuous Time?

"CTMC"

- basically transition-weighted automata.
- all times are *exponentially distributed;*



- sojourn time in states are *memory-less;*



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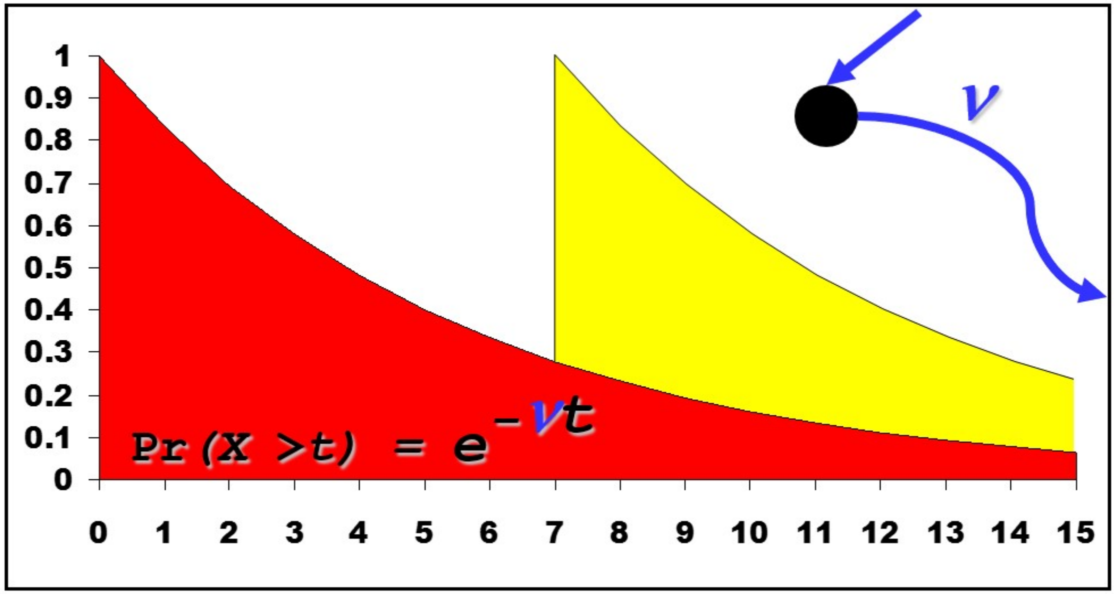
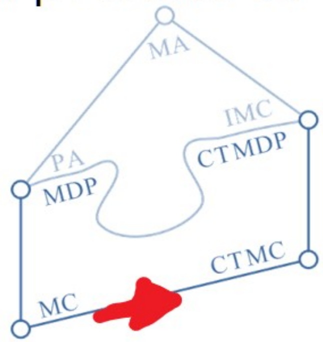
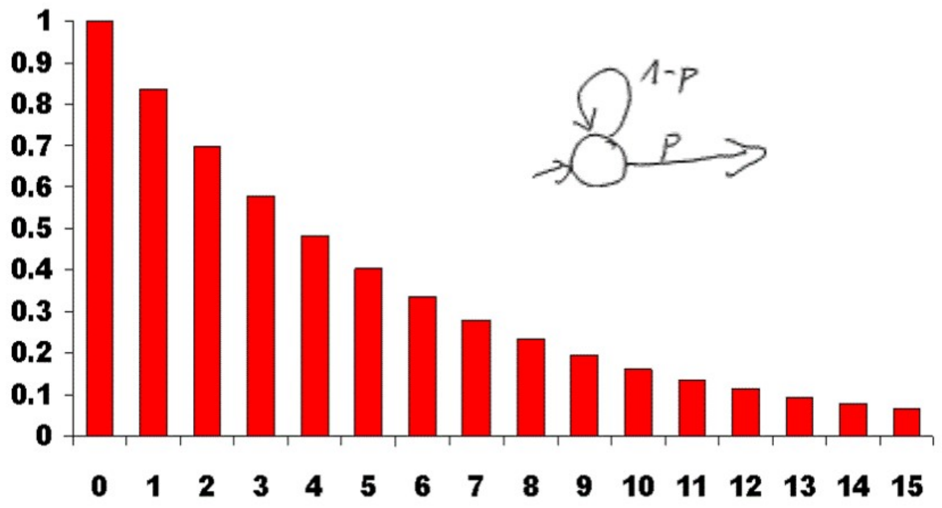


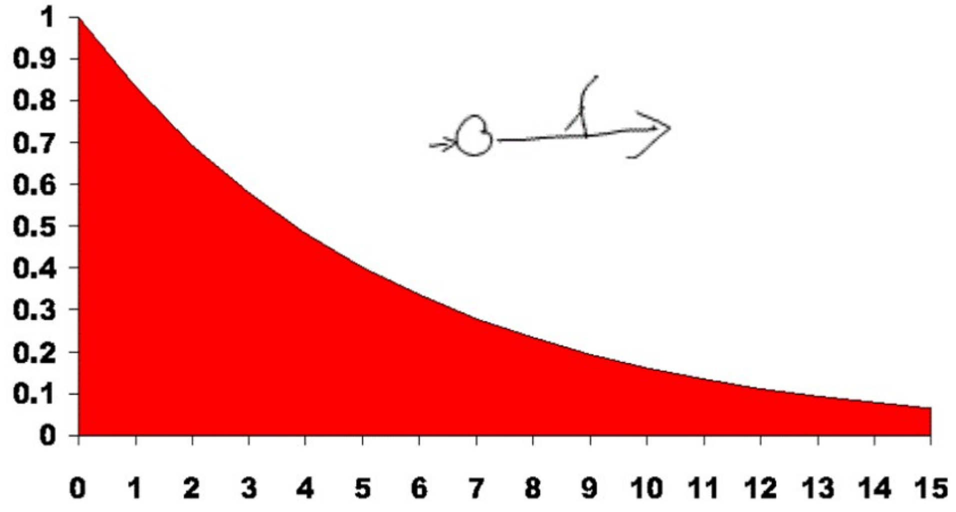
- sojourn time in states are *memory-less*;

- very well investigated class of stochastic processes,
- *efficient* and numerically *stable* analysis algorithms available;
- best guess, if only mean values are known;
- very widely used in practice.



Discrete vs. Continuous Time?

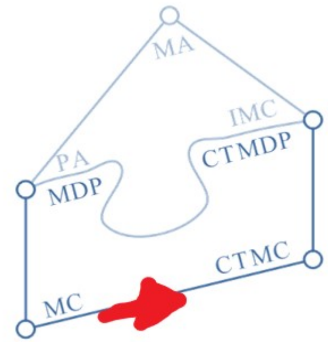




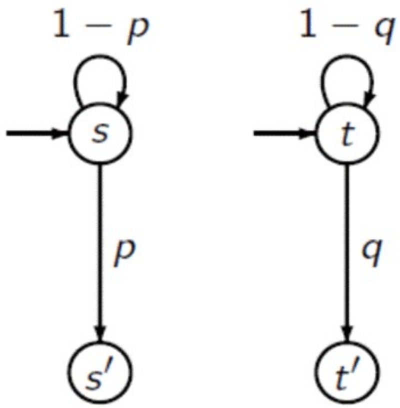
- For a given time step Δ a discretised exponential distribution is a geometric distribution.
- In the limit $\Delta \to 0$ a geometric distribution is an exponential distribution.
- This can be lifted to MCs:

  For each CTMC $\mathcal{M}$ and time step Δ,

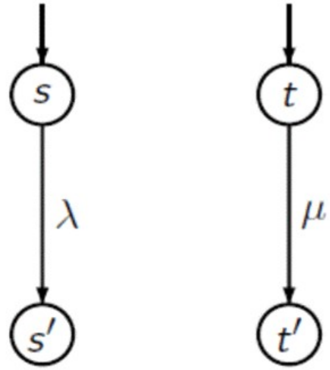
  there is discretised DTMC $\mathcal{D}_\Delta$.



Discrete vs. Continuous Time?

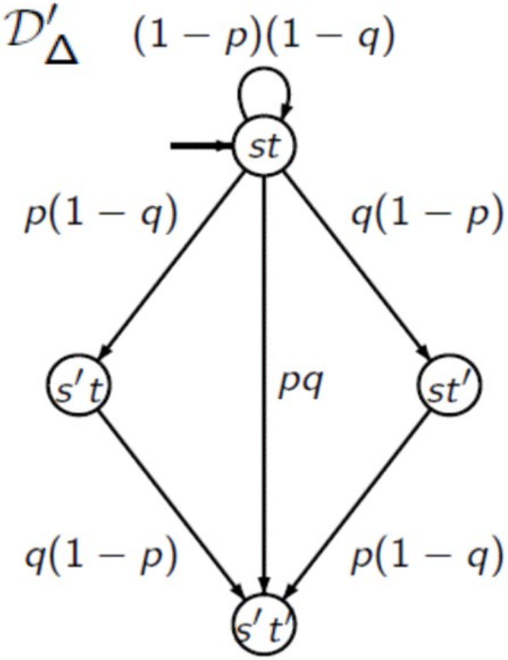


$$\mathbf{Q}^{|||} = \lim_{\Delta \to 0} (\mathbf{P}_{\Delta}^{\otimes} - \mathbf{I})/\Delta$$



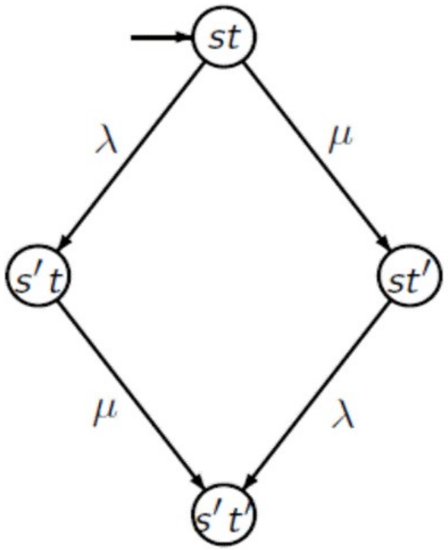
Synchronous Composition for MC

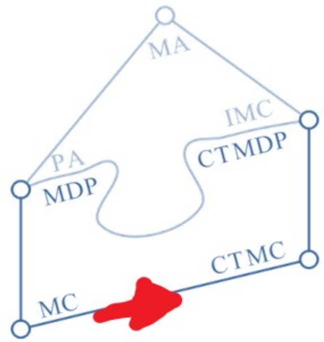
$\mathcal{D}_{\Delta} \otimes \mathcal{D}'_{\Delta}$

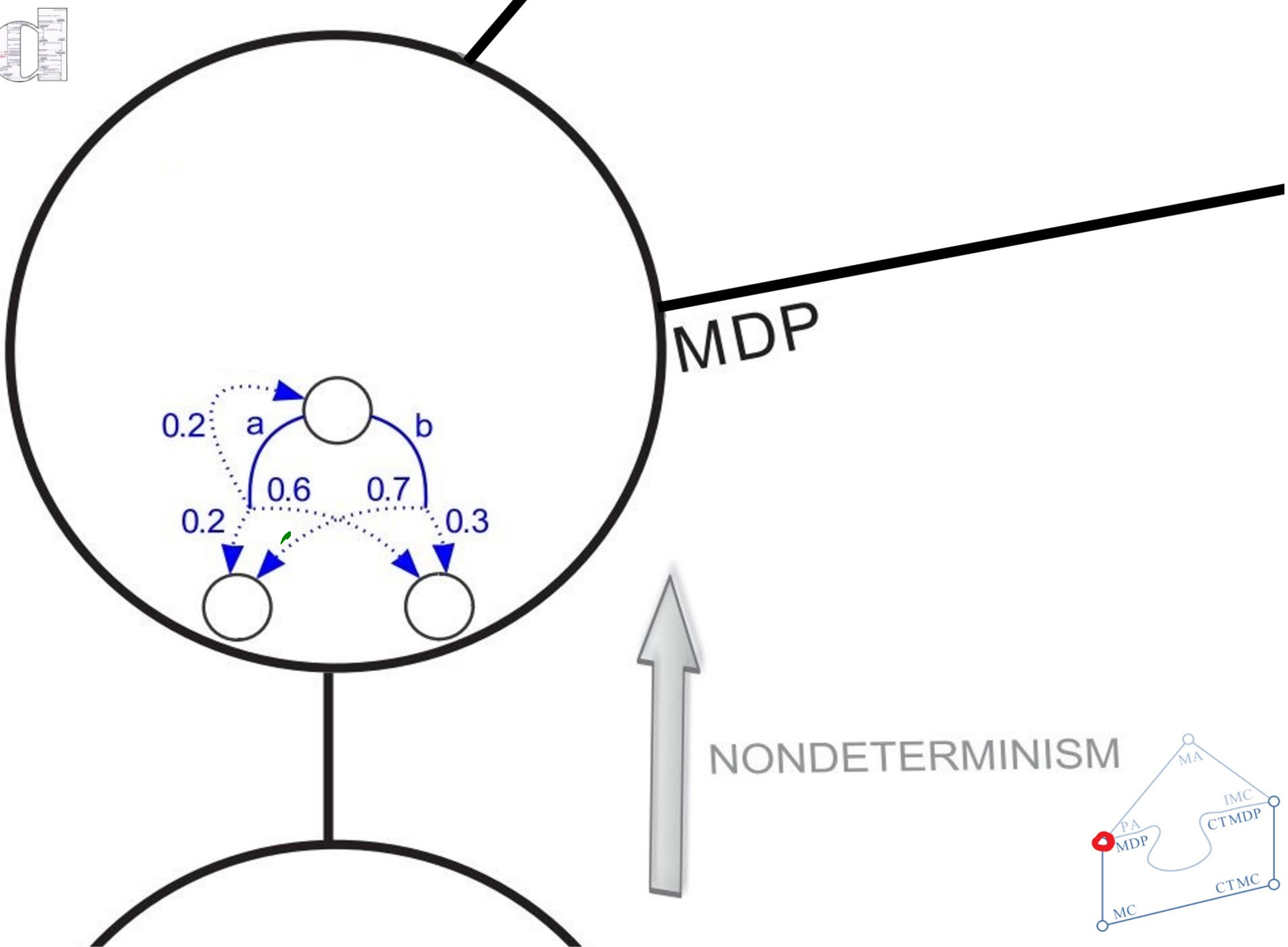


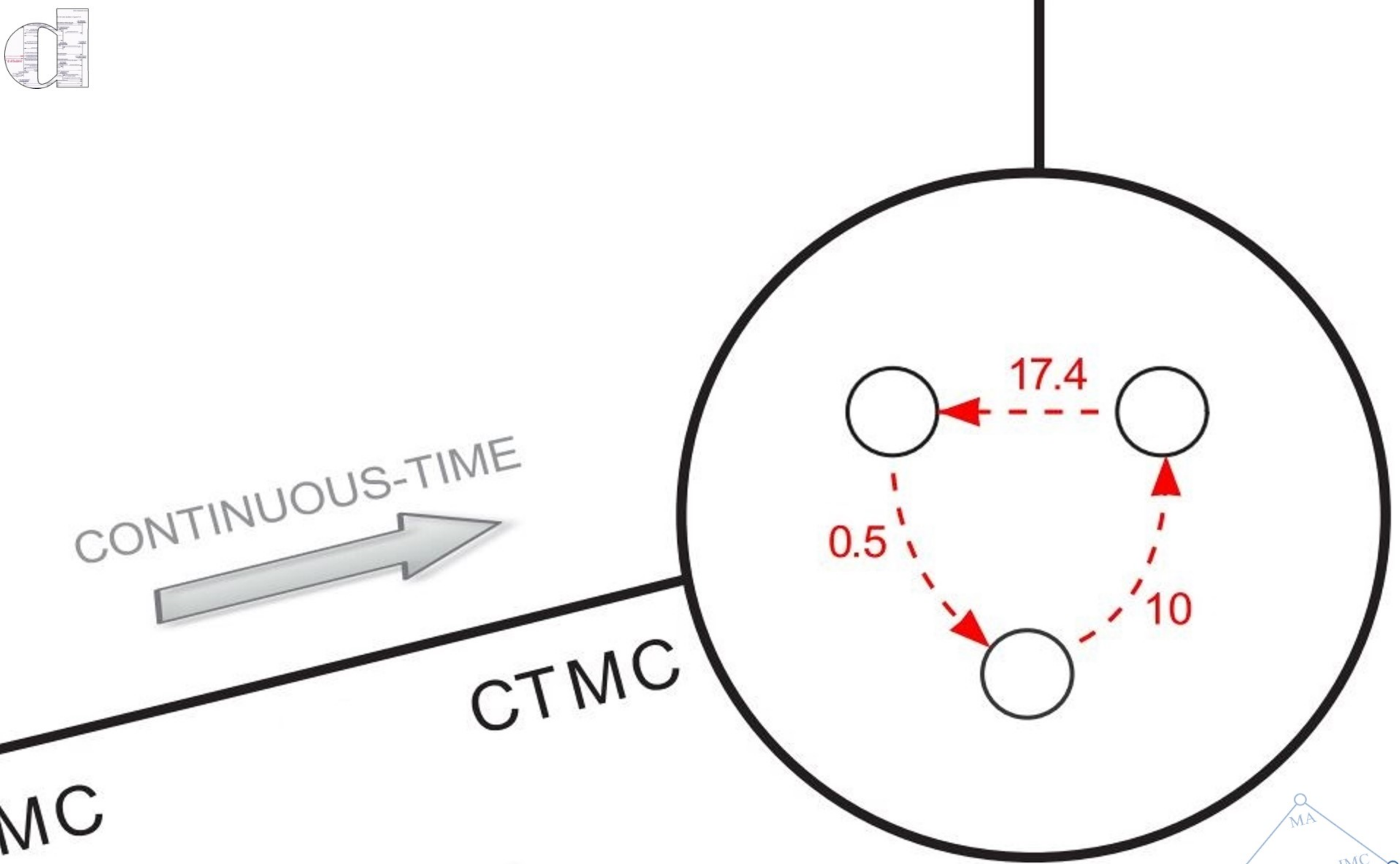
Interleaving for CTMC

$\mathcal{M} \,|||\, \mathcal{M}'$

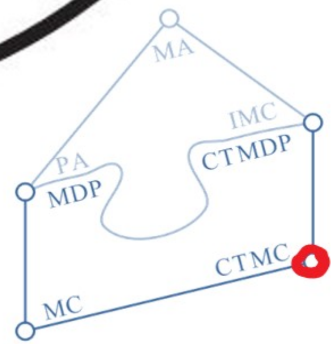




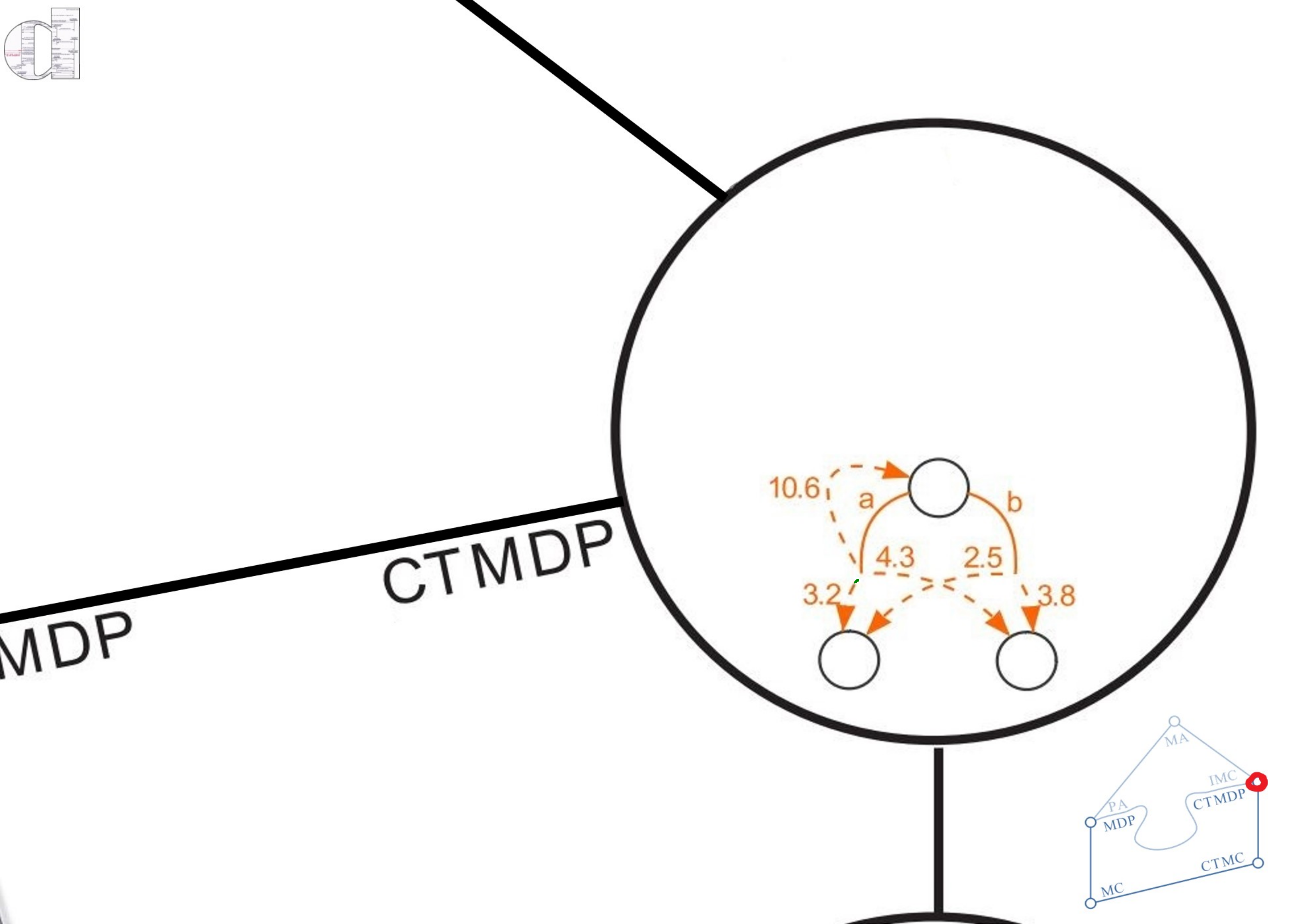

MDP
0.2
a
b
0.6
0.7
0.2
0.3
NONDETERMINISM
MA
IMC
PA
CTMDP
MDP
CTMC
MC



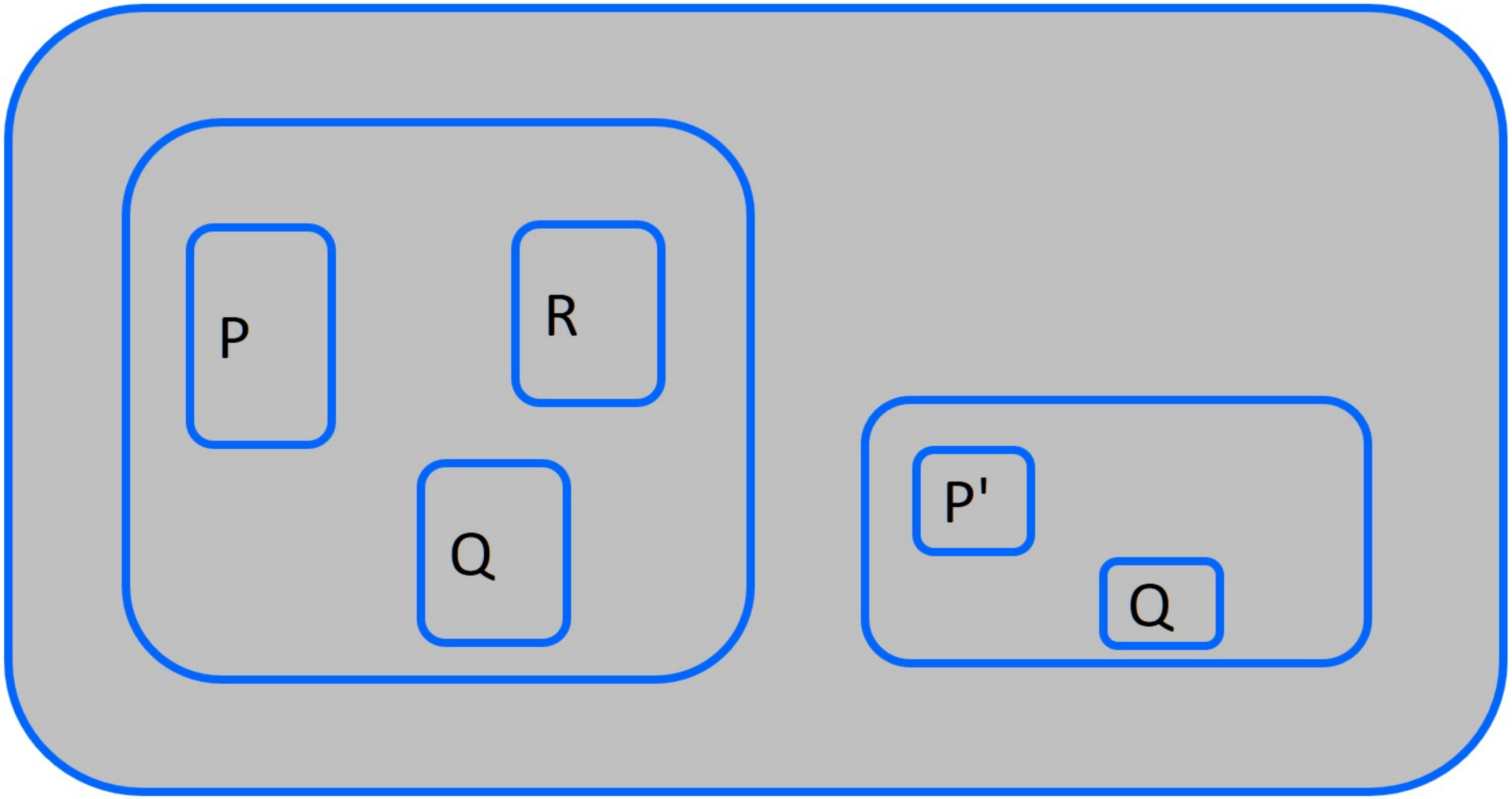
CONTINUOUS-TIME
CTMC
MC
17.4
0.5
10



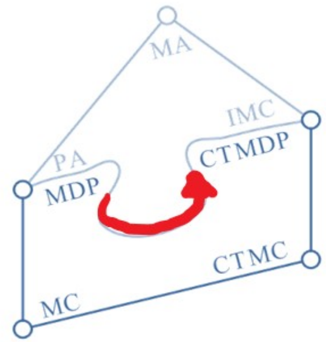
MA
IMC
CTMDP
PA
MDP
CTMC
MC


MDP
CTMDP
10.6
a
b
4.3
2.5
3.2
3.8
MA
IMC
PA
CTMDP
MDP
CTMC
MC

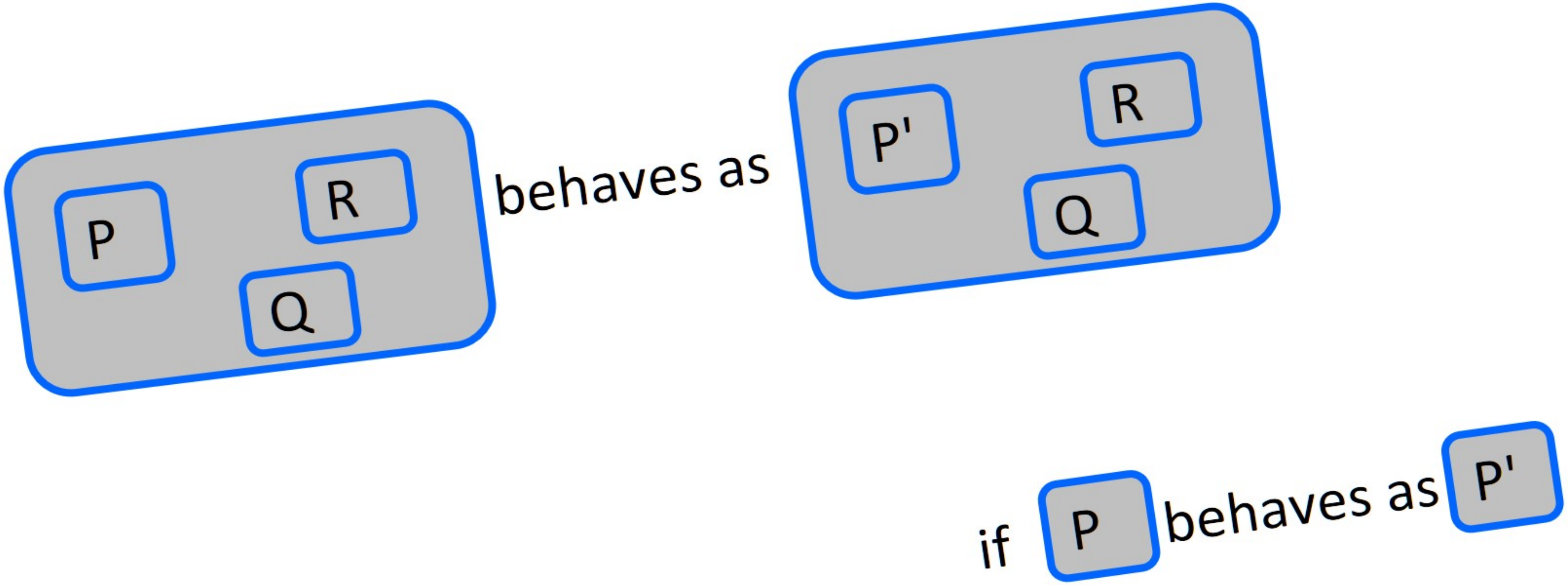
Compositionality?



Process Algebraic Composition Operators.

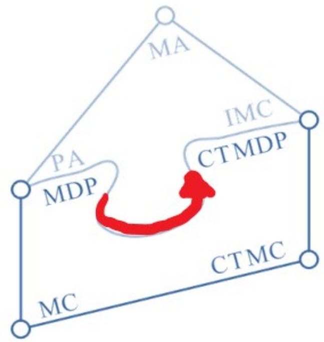


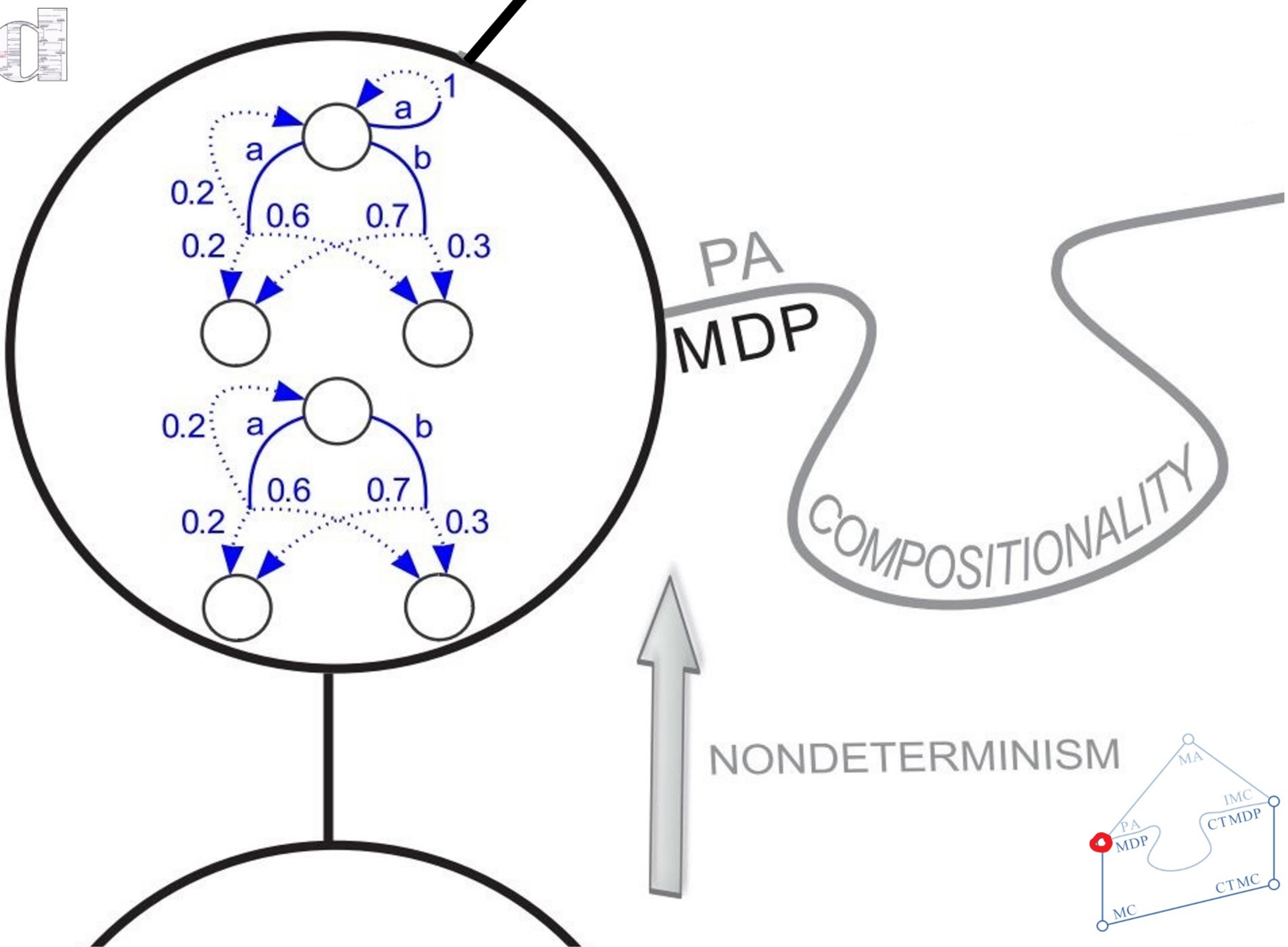
Compositionality?



Process Algebraic Composition Operators.

Natural Notions of Bisimulation, are Congruences.





a
1
a
b
0.2
0.6
0.7
0.2
0.3
0.2
a
b
0.6
0.7
0.2
0.3
PA
MDP
COMPOSITIONALITY
NONDETERMINISM
MA
IMC
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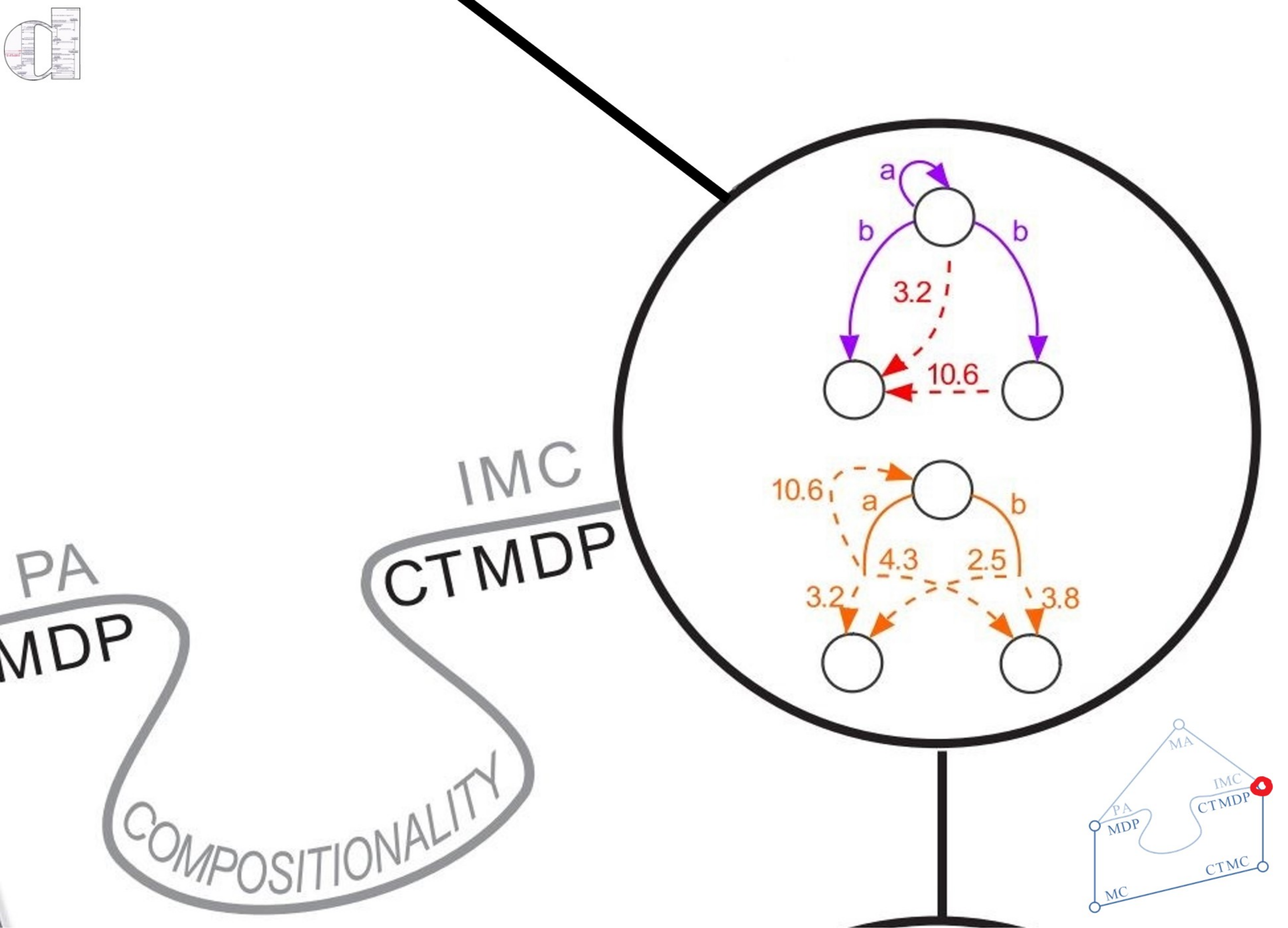
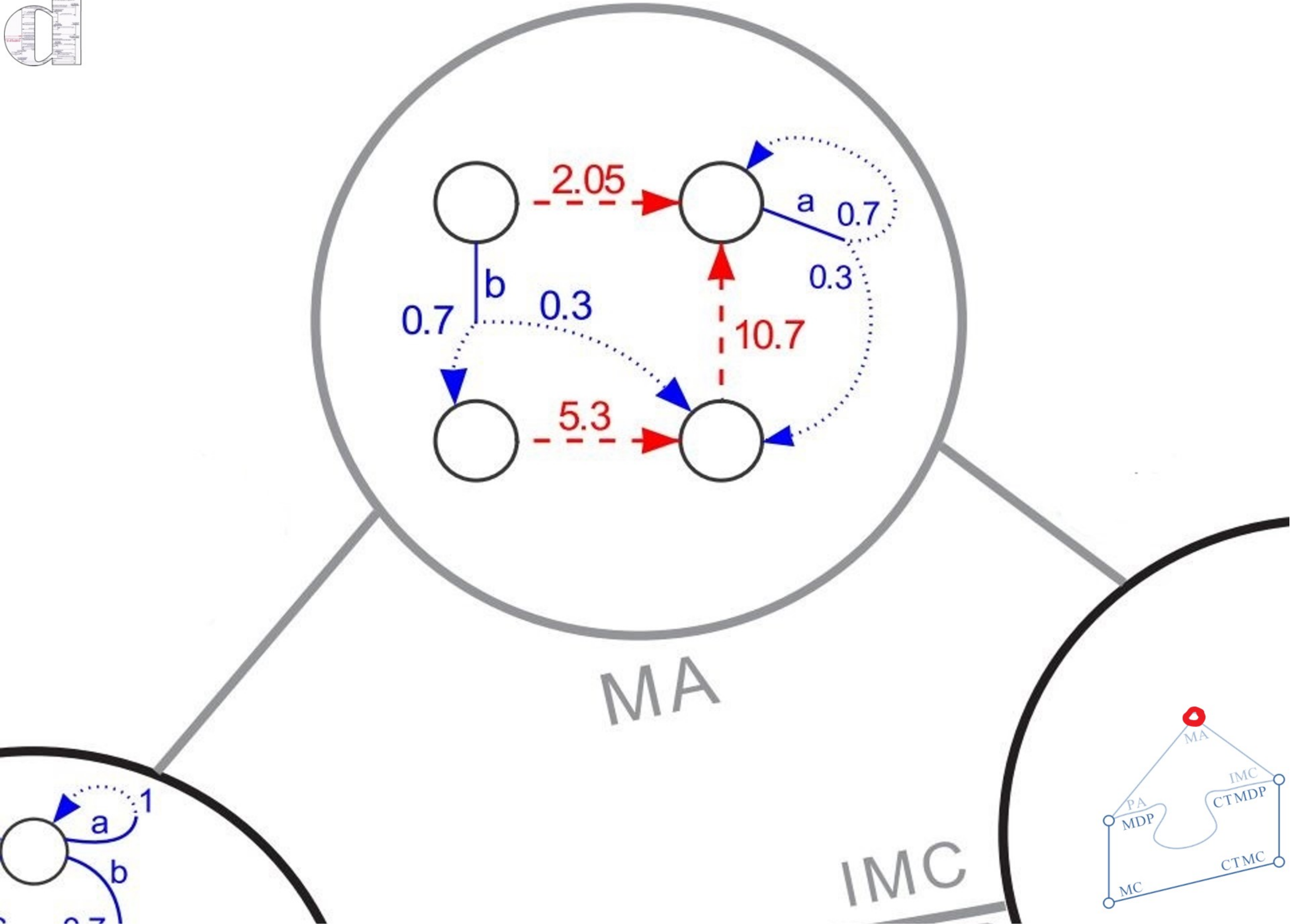
PA
MDP
CTMC
MC


IMC
CTMDP
PA
MDP
COMPOSITIONALITY
a
b
b
3.2
10.6
10.6
a
b
4.3
2.5
3.2
3.8
MA
IMC
CTMDP
PA
MDP
MC
CTMC



2.05
a
0.7
0.3
b
0.7
0.3
10.7
5.3
MA
1
a
b
IMC
MA
IMC
CTMDP
PA
MDP
CTMC
MC

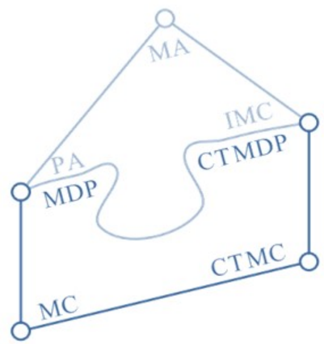
Christian Eisentraut, Holger Hermanns, Lijun Zhang:
On Probabilistic Automata in Continuous Time. LICS 2010: 342-351

Christian Eisentraut, Holger Hermanns, Lijun Zhang:
Concurrency and Composition in a Stochastic World. CONCUR 2010: 21-39

Markov Automata Semantics

Yuxin Deng, Matthew Hennessy:
On the semantics of Markov automata. Inf. Comput. 222: 139-168 (2013)

Christian Eisentraut, Holger Hermanns, Joost-Pieter Katoen, Lijun Zhang:
A Semantics for Every GSPN. Petri Nets 2013: 90-109



Markov Automata

Definition 1. *A Markov automaton MA is a quintuple* $(S, Act, \longrightarrow, \twoheadrightarrow, s_o)$, *where*
- S *is a nonempty finite set of states,*
- Act *is a set of actions containing the internal action* τ,
- $\longrightarrow \subset S \times Act \times Dist(S)$ *is a set of probabilistic transitions, and*
- $\twoheadrightarrow \subset S \times \mathbb{R}_{\geq 0} \times S$ *is a set of Markov timed transitions, and*
- $s_o \in S$ *is the initial state.*

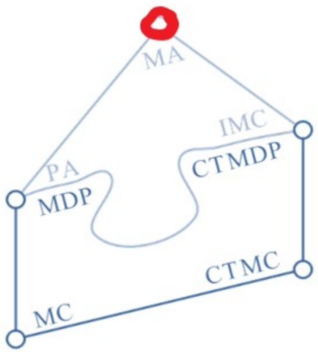
Labelled Transition Systems: If $\twoheadrightarrow = \emptyset$ and $\longrightarrow$ is Dirac.

Discrete-time Markov chains: If $\twoheadrightarrow = \emptyset$ and $|Act| = 1$ and $\longrightarrow$ is deterministic.

Continuous-time Markov chains: If $\longrightarrow = \emptyset$.

Probabilistic Automata: If $\twoheadrightarrow = \emptyset$.

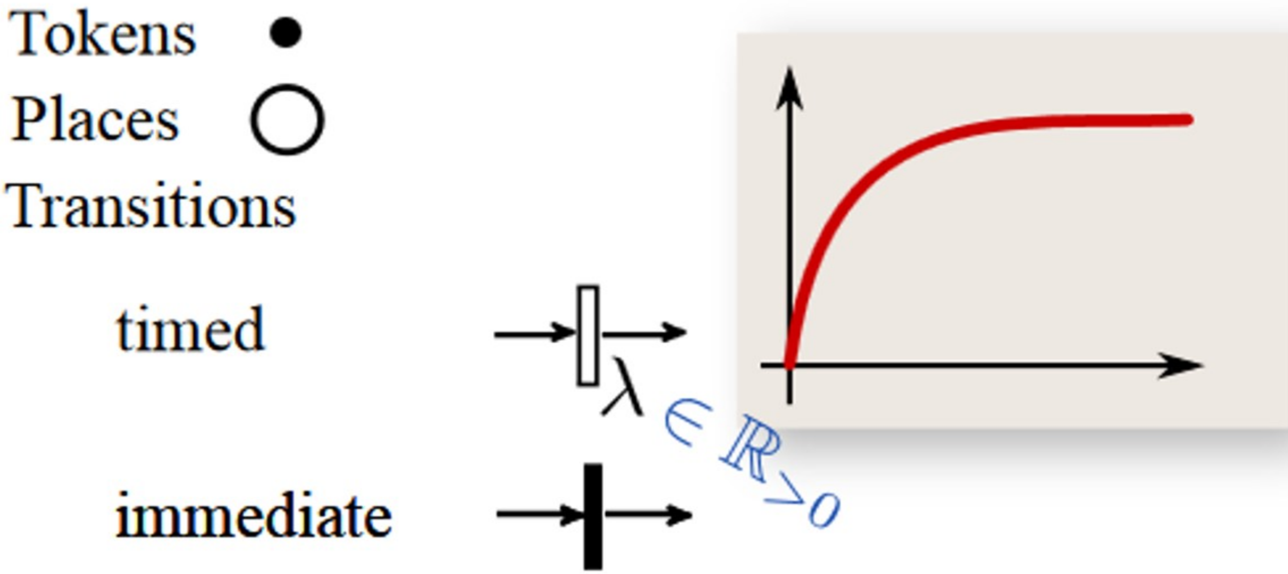
Interactive Markov chains: If $\longrightarrow$ is Dirac.



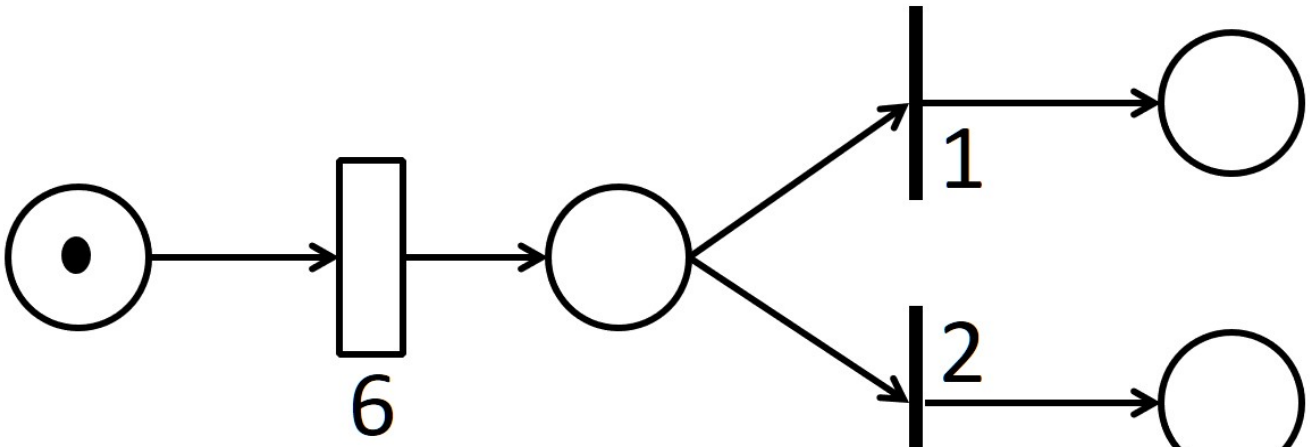
Generalized Stochastic Petri Net

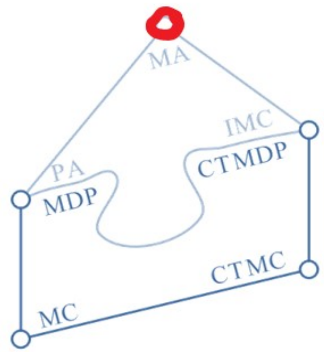
Very popular.

target formalism
for xyzML



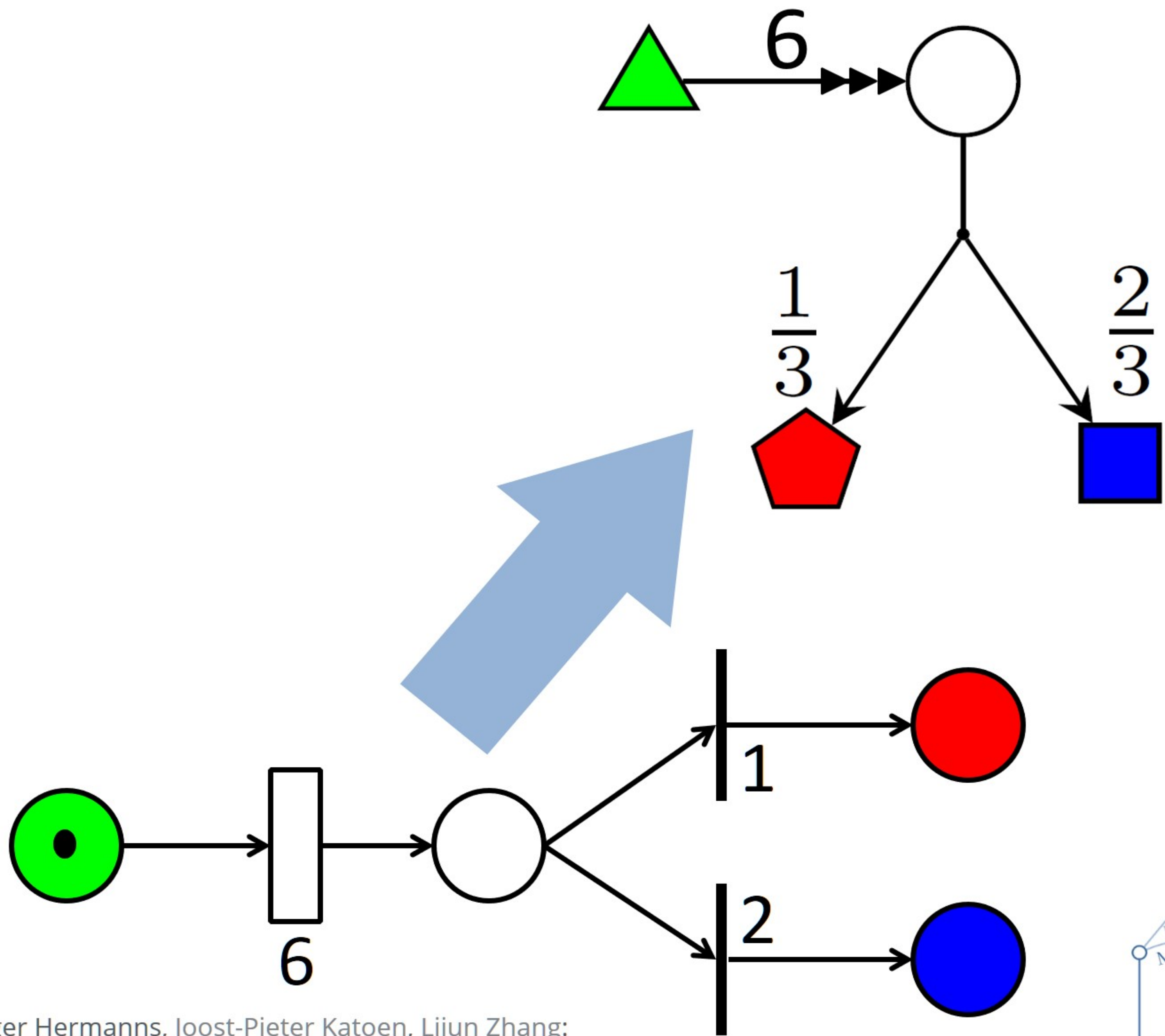
Incomplete semantics for more than 25 years.

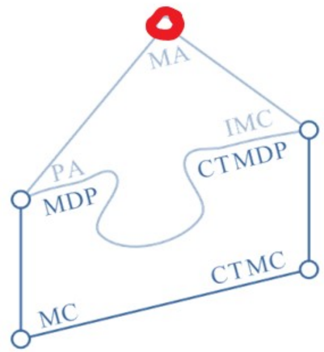




Meant to map on CTMC.

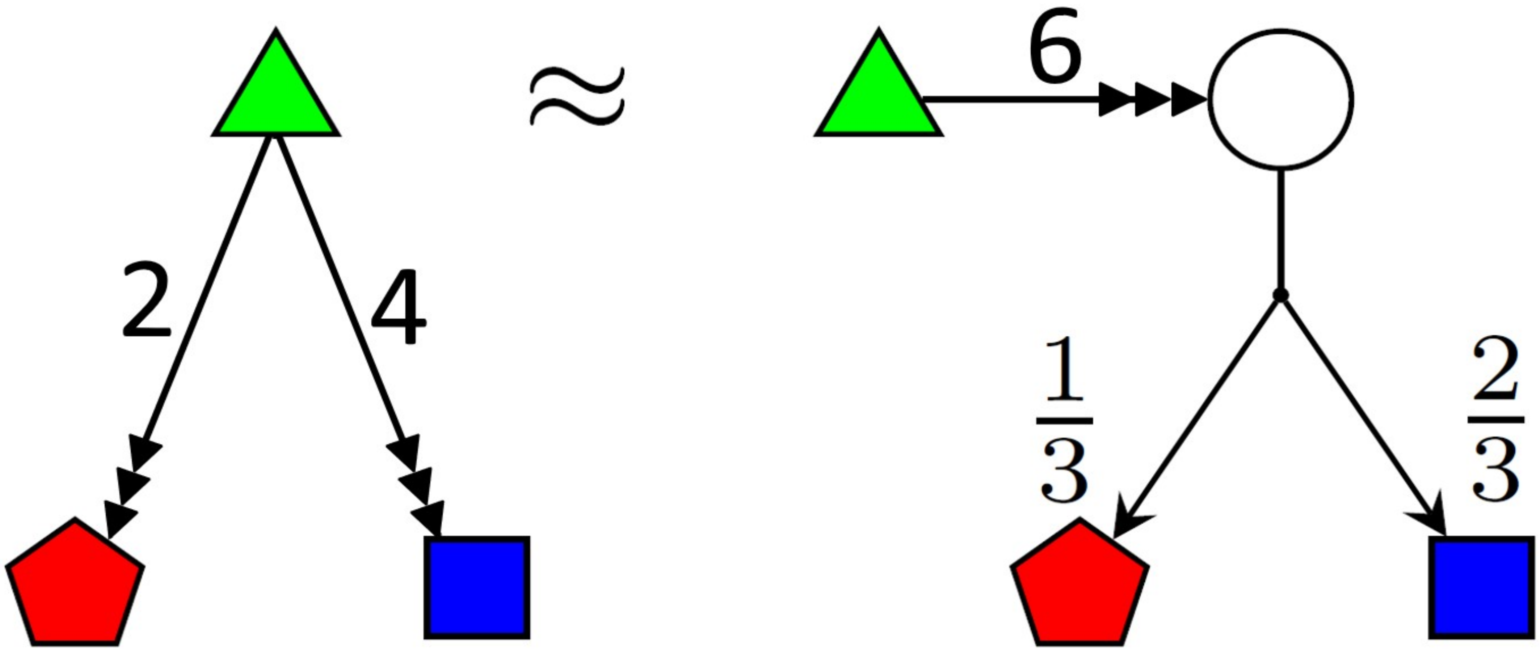
GSPN Semantics: Markov Automata

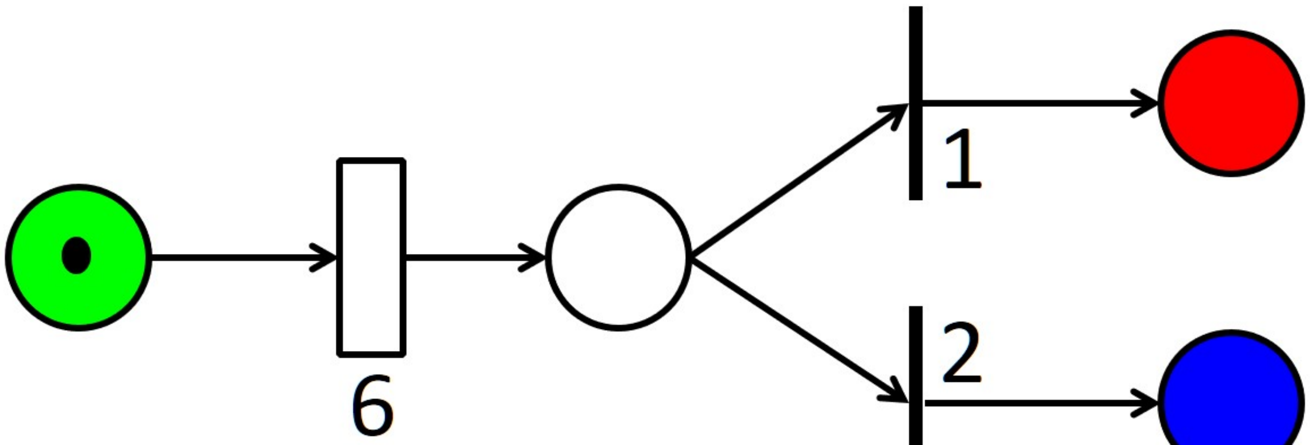


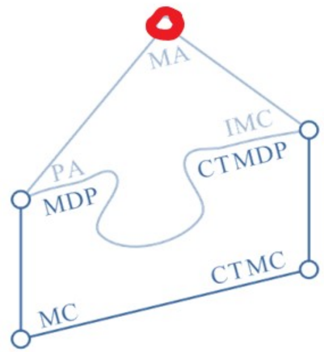


Christian Eisentraut, Holger Hermanns, Joost-Pieter Katoen, Lijun Zhang:
A Semantics for Every GSPN. Petri Nets 2013: 90-109

MA Weak Bisimulation







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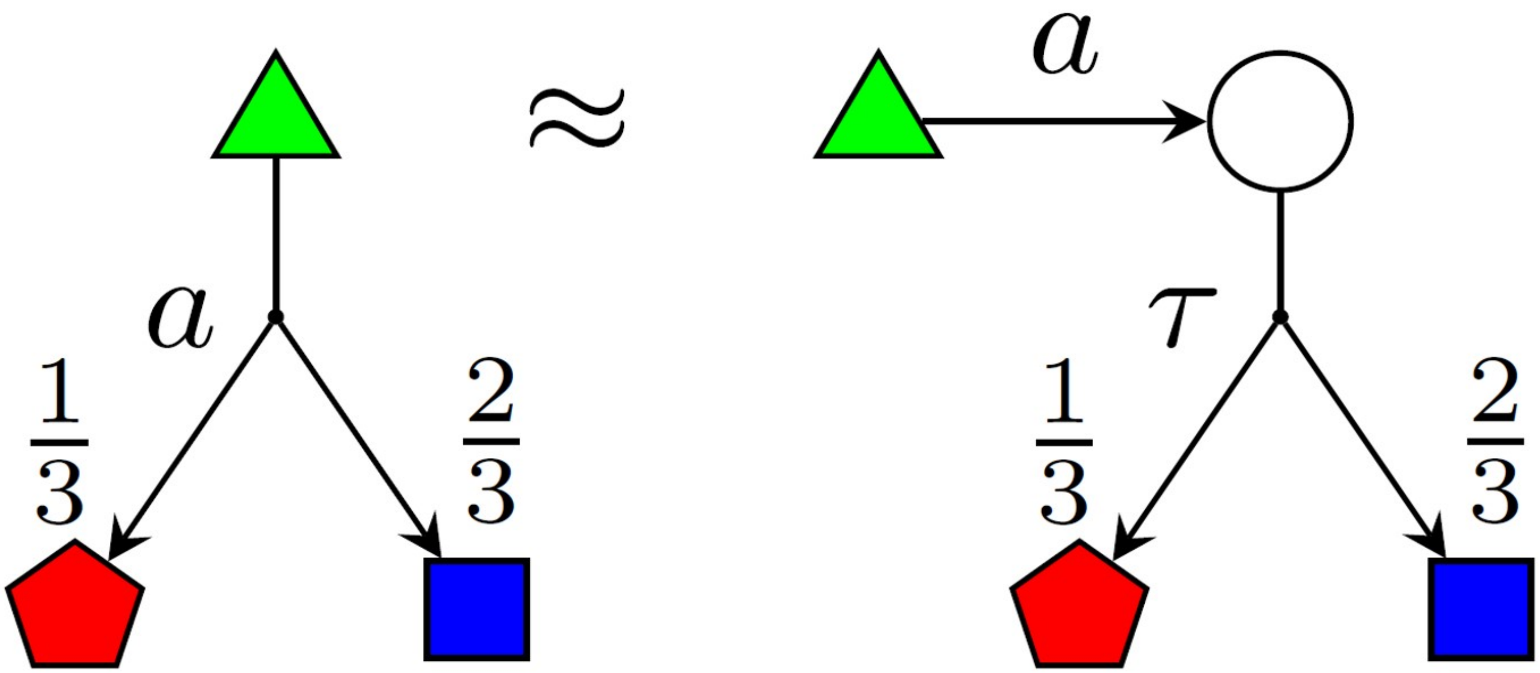


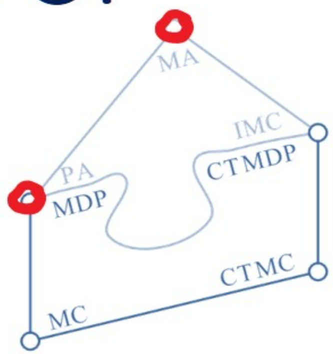
- explained on PA -

How can this work?

There is no state on the left that matches state ○.

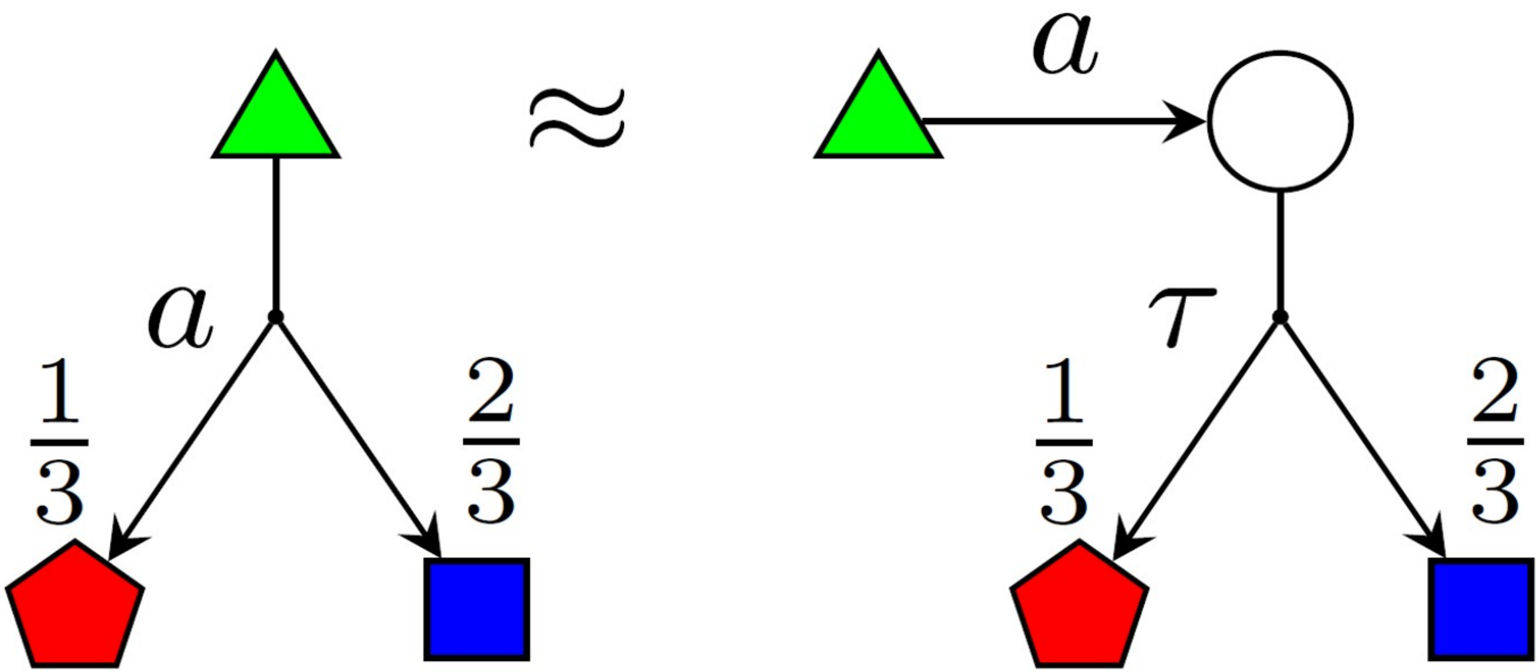
Well, there is a matching distribution.

Bisimulations on distributions!



Christian Eisentraut, Holger Hermanns, Lijun Zhang:
On Probabilistic Automata in Continuous Time. LICS 2010: 342-351

Weak Distribution Bisimulation



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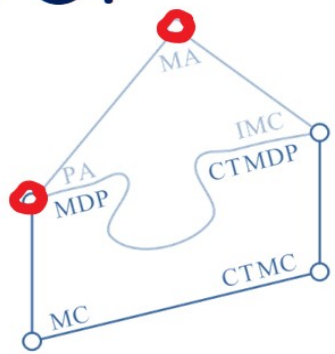

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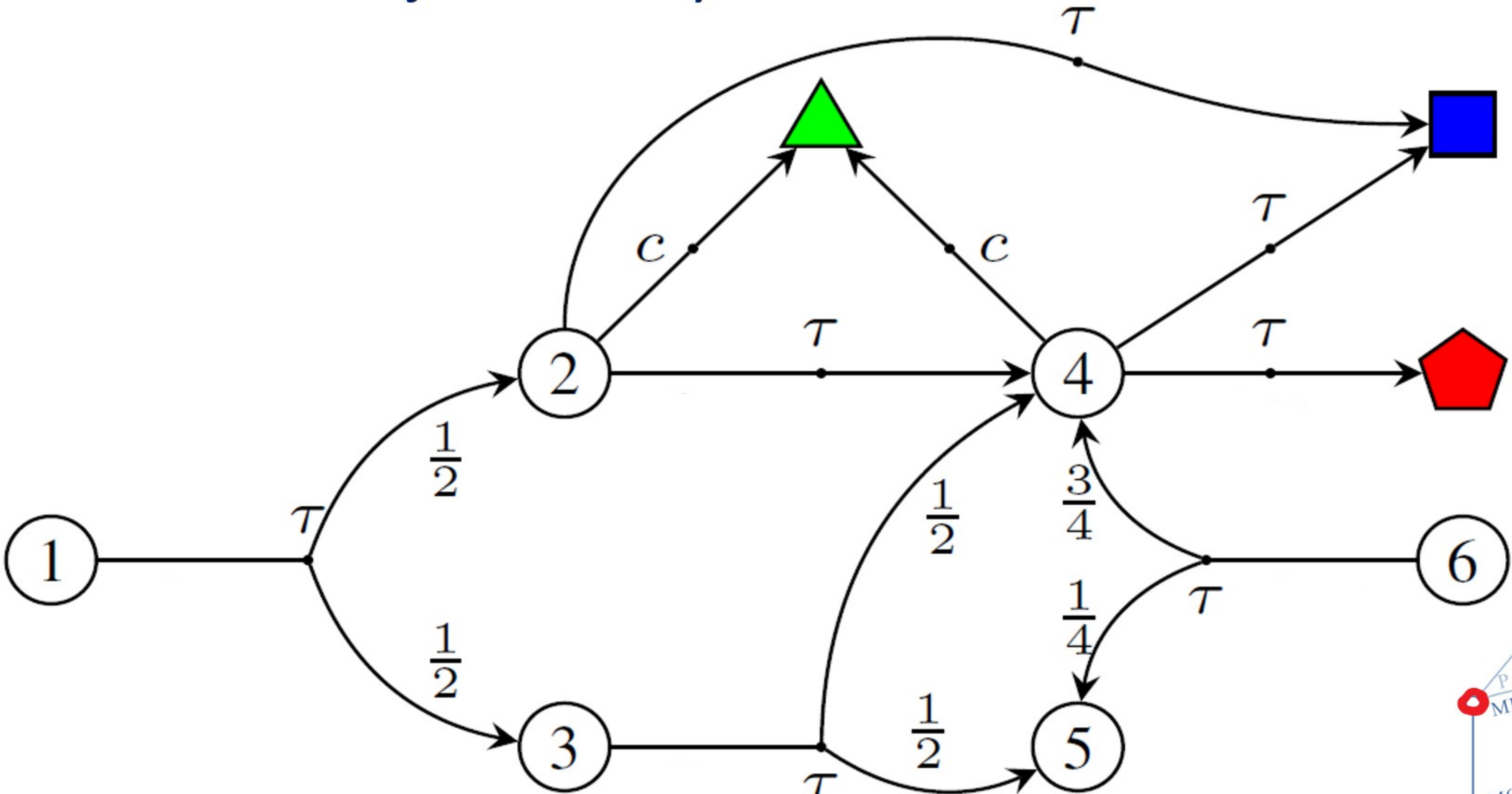
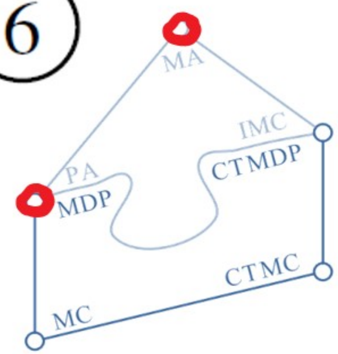
Weak Distribution Bisimulation in Action

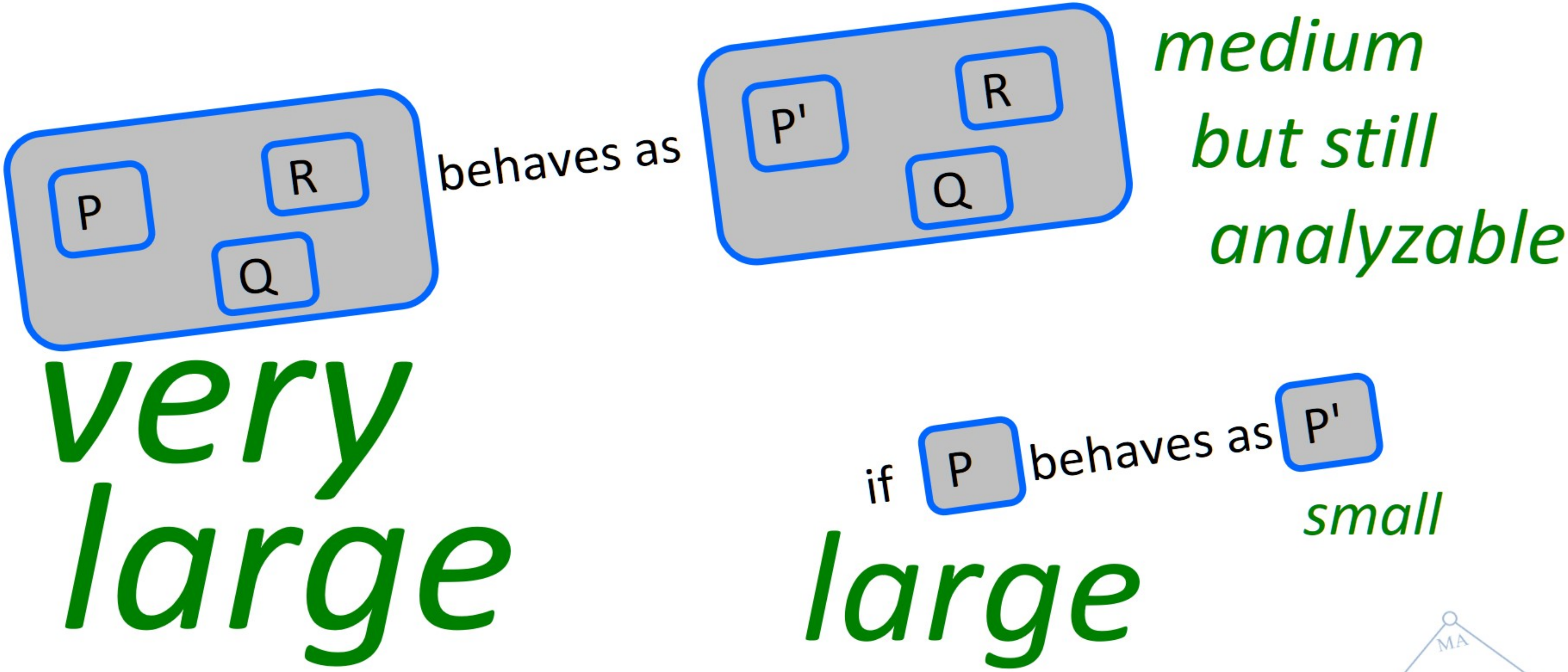
State ① exhibits the same observable behaviour as ⑥.

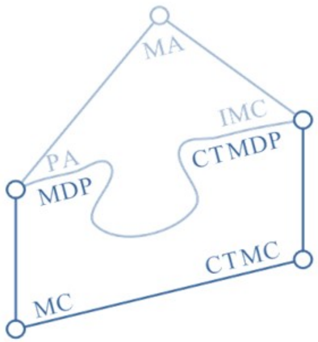
justified by weak distribution bisimulation.





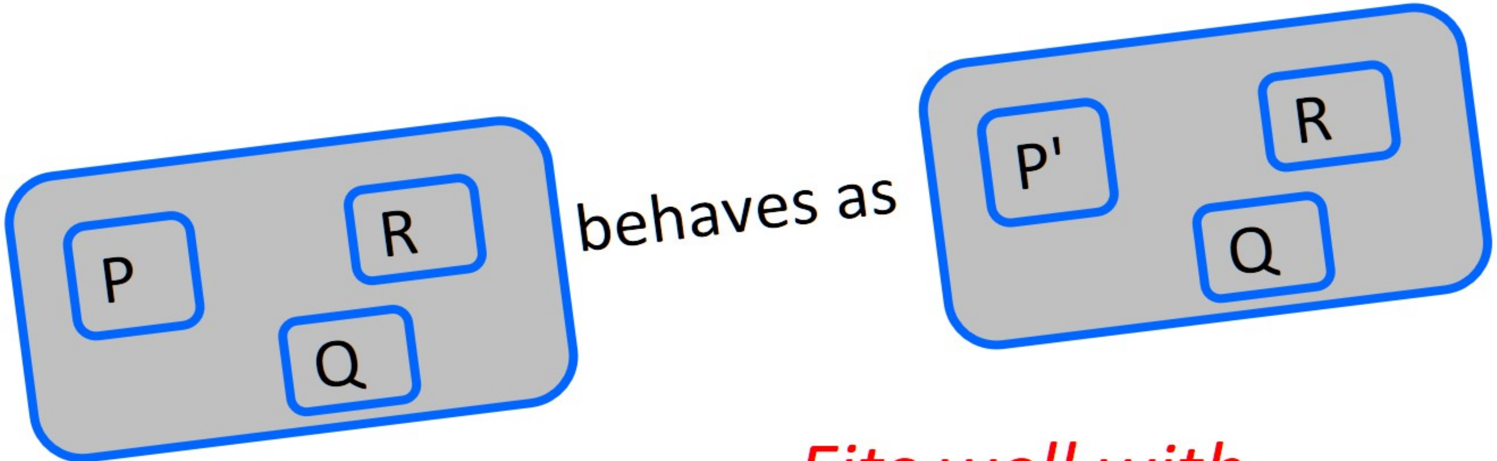
Compositional Equivalences





"Applied" Process Algebra

Compositional Equivalences

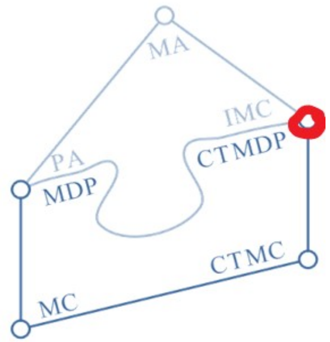


medium but still analyzable

very large

Fits well with ***dependability evaluation***

$> 10^{200}$ reduced to 10^{6}



Eckard Böde, Marc Herbstritt, Holger Hermanns, Sven Johr, Thomas Peikenkamp, Reza Pulungan, Jan-Hendrik Rakow
Compositional Dependability Evaluation for STATEMATE. IEEE Trans. Software Eng. 35(2): 274-292 (2009)

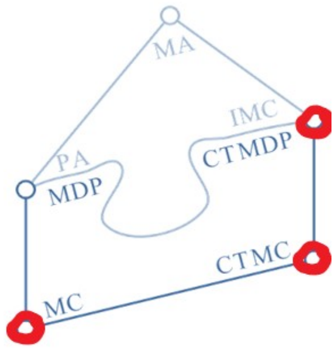
Compositional Minimization

- Based on (strong, or better) weak bisimulations;

- Congruence property wrt
  parallel composition and hiding operators;

- Requires an efficient decision algorithm
  which can be turned into a minimization algorithm;

- Cubic algorithms for the base models.

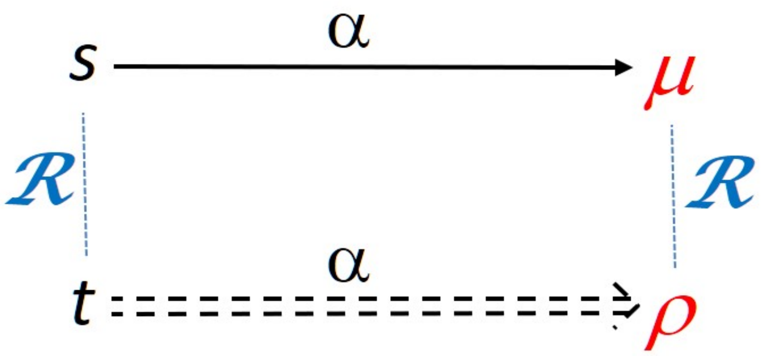


PA Weak Bisimulation Decision Algorithm

Core Problem:

matching a challenger transition

$$\forall\, s, t, \alpha, \mu \;\exists\; \rho$$



with a weak defender transition

can be coded as an LP-problem

and be embedded in

partition refinement strategy

max Σf_i

under constraints

$0 \le f_i \le c_i\ (< \infty)$

$f_0 + f_8 = f_1 + f_4$

$f_1 = f_2 + f_3$

$f_2 = f_9$

$f_3 = f_{10}$

$f_4 = f_5 + f_6 + f_7$

$f_5 = f_8 + f_{11}$

$f_6 = f_{12}$

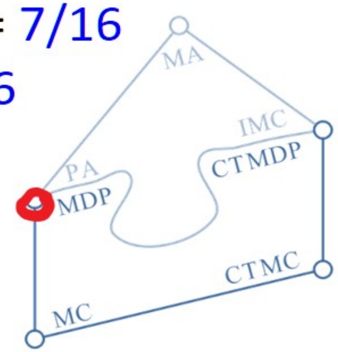
$f_7 = f_{13}$

$f_0 = 1$

$f_9 + f_{12} = 5/16$

$f_{10} + f_{11} = 7/16$

$f_{13} = 4/16$



Andrea Turrini, Holger Hermanns:
Polynomial time decision algorithms for probabilistic automata. Inf. Comput. 244: 134-171 (2015)

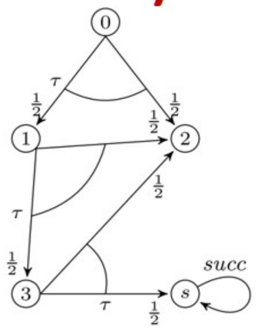
Weak Bisimulation in Action

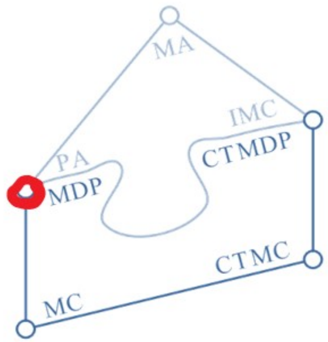
Sweep over the PRISM PA collection

Problem	$\|S\|$	$\|D\|$	$\|S_{\bowtie}\|$	$\|D_{\bowtie}\|$	$T_{\mathcal{A}_{\bowtie}}$	$\|[S]_{\approx}\|$	$\|[D]_{\approx}\|$	$T_{[\mathcal{A}_{\bowtie}]_{\approx}}$
csma2	1038	1054	835	849	1s	449	459	1s
csma2-sa	1038	1054	621	630	7s	233	237	< 1s
csma2-sa-nt	1038	1054	91	98	< 1s	87	90	< 1s
dining4	2165	4540	161	300	< 1s	1	1	< 1s
firewire3	611	694	425	469	5s	425	469	5s
firewire3-nt	611	694	29	62	< 1s	4	4	< 1s
wlan_dl0dl6	97	148	63	94	< 1s	59	86	1s
wlan0col0	2954	3972	1097	1591	14s	798	1092	120s
zeroconf	670	827	341	433	< 1s	334	420	14s
zeroconf-nt	670	827	52	75	< 1s	41	52	< 1s

Components	$\|S_{\circlearrowleft}\|$	$\|D_{\circlearrowleft}\|$	$\|[S]_{\approx}\|$	$\|[D]_{\approx}\|$	$T_{\approx}$
$i_1 = d_1 \parallel d_2$	41	92	20	41	4s
$i_2 = [i_1]_{\approx} \parallel d_3$	105	247	33	75	33s
$i_3 = [i_2]_{\approx} \parallel d_4$	180	482	45	107	330s
$i_4 = [i_3]_{\approx} \parallel d_5$	248	706	57	139	20m
$[i_4]_{\approx} \parallel d_6$	178	372	7	6	22m
$d_1 \parallel d_2 \parallel d_3 \parallel d_4$	2242	4708	5	4	39s
$d_1 \parallel d_2 \parallel \ldots \parallel d_5$	12042	31184	6	5	335s
$d_1 \parallel d_2 \parallel \ldots \parallel d_6$	63511	196642	7	6	22m
$d_1 \parallel d_2 \parallel \ldots \parallel d_7$	329784	1189626	8	7	59m
$d_1 \parallel d_2 \parallel \ldots \parallel d_8$	1689417	6961480	9	8	161m

Compositional minimization applied to dining cryptographer anonymity

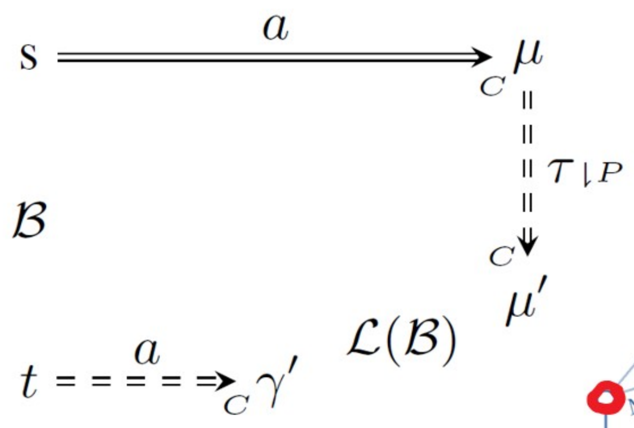


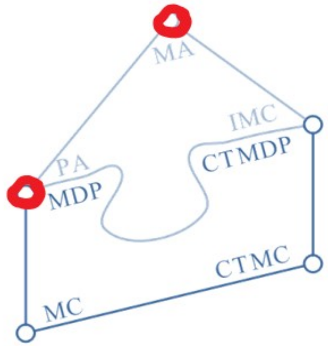


Luis María Ferrer Fioriti, Vahid Hashemi, Holger Hermanns, Andrea Turrini:
Probabilistic Automata Weak Bisimulation: Theory and Practice. Formal Asp. Comput. To appear

Weak Distribution Bisimulation Decision Algorithm

- Exploits a state-based characterisation.
- Preprocessing: Eliminate maximal τ-end components.
- Brute force guess of "preserving transition" set *P*.
- Overall strategy: standard partition refinement approach.
- Step conditions are encoded as LP-problems.
- Challenger transitions range over weak transitions induced by Dirac determinate schedulers.





Christian Eisentraut, Holger Hermanns, Julia Krämer, Andrea Turrini, Lijun Zhang: **Deciding Bisimilarities on Distributions.** QEST 2013: 72-88

Complexity

Polynomial-time decision algorithms

except for Markov automata.

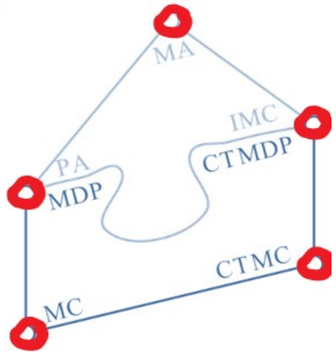
There: Two sources of exponentiality.

- **Weak transitions appear as challengers.**

  We do not know if strong challengers suffice.

- **Set of preserving transitions is guessed.**

  Possibility to intertwine with computation of $\mathscr{B}$?



Johann Schuster, Markus Siegle:
Markov Automata: Deciding weak bisimulation by means of non-naïvely vanishing states. Inf. Comput. 237: 151-173 (2014)

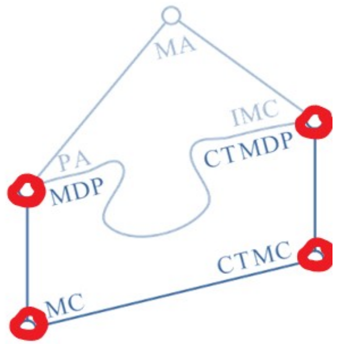
Christian Eisentraut, Holger Hermanns, Julia Krämer, Andrea Turrini, Lijun Zhang:
Deciding Bisimilarities on Distributions. QEST 2013: 72-88

Minimality

Quotient Construction:

- Take one representative per equivalence class.
- Then: Number of states is minimal.
- Then: Number of transitions can be made minimal.
- Then: Sum of transition fanout can be made minimal.

- This works for weak bisimulation (on PA etc).
- But not for weak distribution bisimulation.



Christian Eisentraut, Holger Hermanns, Johann Schuster, Andrea Turrini, Lijun Zhang:
The Quest for Minimal Quotients for Probabilistic Automata. TACAS 2013: 16-31

Joost-Pieter Katoen:
Concurrency Meets Probability: Theory and Practice - (Abstract). CONCUR 2013: 44-45

Mark Timmer, Jaco van de Pol, Mariëlle Stoelinga:
Confluence Reduction for Markov Automata. FORMATS 2013: 243-257

Mark Timmer, Joost-Pieter Katoen, Jaco van de Pol, Mariëlle Stoelinga:
Efficient Modelling and Generation of Markov Automata. CONCUR 2012: 364-379

Markov Automata

Construction & Compression

Marco Bozzano, Alessandro Cimatti, Joost-Pieter Katoen, Viet Yen Nguyen, Thomas Noll, Marco Roveri:
Safety, Dependability and Performance Analysis of Extended AADL Models. Comput. J. 54(5): 754-775 (2011)

Hichem Boudali, Pepijn Crouzen, Mariëlle Stoelinga:
A Rigorous, Compositional, and Extensible Framework for Dynamic Fault Tree Analysis.
128-143 (2010)

Johann Schuster, Markus Siegle:
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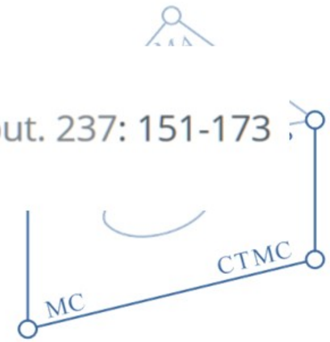
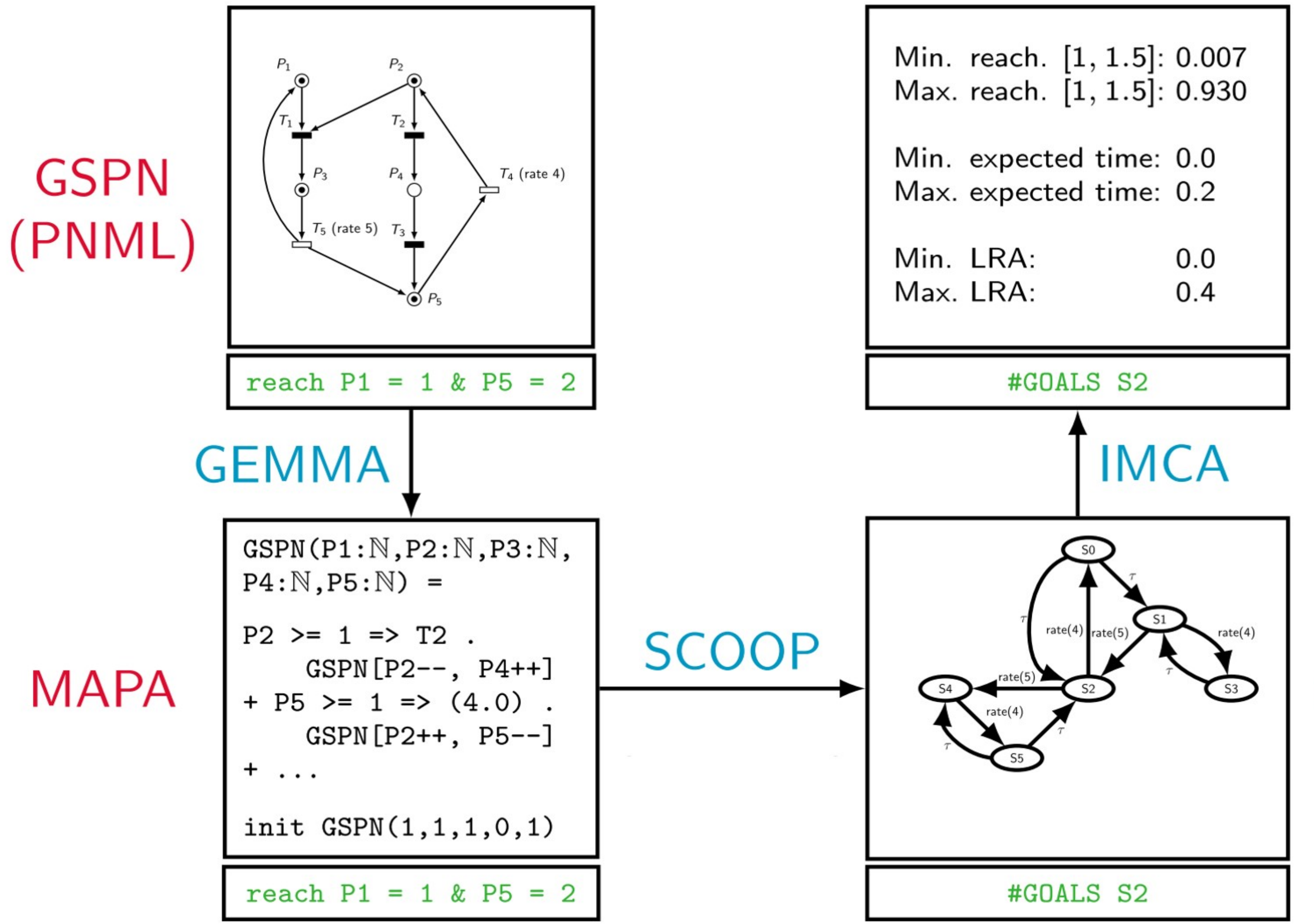
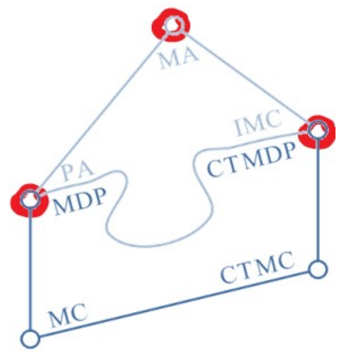
Christian Eisentraut, Holger Hermanns, Julia Krämer, Andrea Turrini, Lijun Zhang:
Deciding Bisimilarities on Distributions. QEST 2013: 72-88



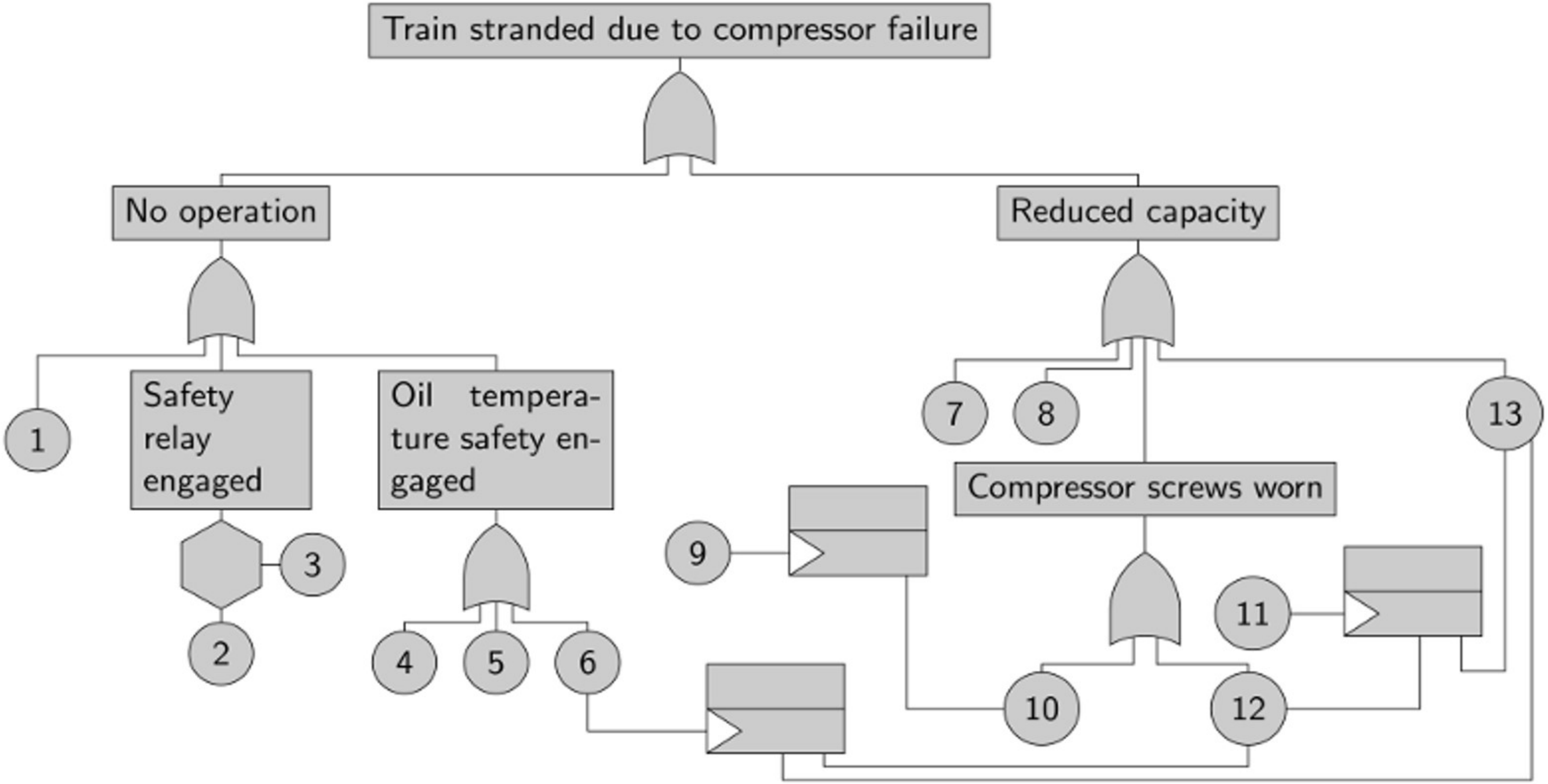
MAMA Tool Chain





Mark Timmer, Joost-Pieter Katoen, Jaco van de Pol, Mariëlle Stoelinga:
Efficient Modelling and Generation of Markov Automata. CONCUR 2012: 364-379

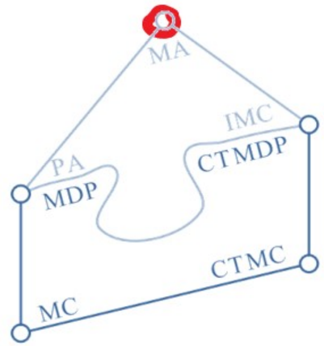
More of this: Failure-Prone Systems



Can all be coded up into MA components.

Marco Bozzano, Alessandro Cimatti, Joost-Pieter Katoen, Viet Yen Nguyen, Thomas Noll, Marco Roveri:
Safety, Dependability and Performance Analysis of Extended AADL Models. Comput. J. 54(5): 754-775 (2011)

Hichem Boudali, Pepijn Crouzen, Mariëlle Stoelinga:
A Rigorous, Compositional, and Extensible Framework for Dynamic Fault Tree Analysis.
IEEE Trans. Dependable Sec. Comput. 7(2): 128-143 (2010)

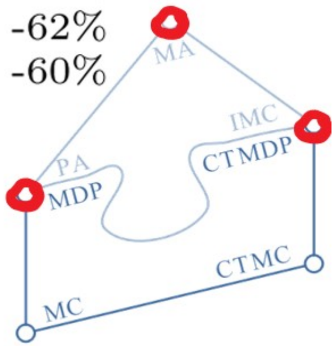


More of this: Confluence Reduction

Rewrites the state space representation

so as to eliminate τ-confluent transition.

	Original state space				Reduced state space				Impact	
Specification	States	Trans.	SCOOP	IMCA	States	Trans.	SCOOP	IMCA	States	Time
leader-3-7	25,505	34,257	4.7	102.5	5,564	6,819	5.1	9.3	-78%	-87%
leader-3-9	52,465	71,034	9.7	212.0	11,058	13,661	10.4	17.8	-79%	-87%
leader-3-11	93,801	127,683	18.0	429.3	19,344	24,043	19.2	31.9	-79%	-89%
leader-4-2	8,467	11,600	2.1	74.0	2,204	2,859	2.5	6.8	-74%	-88%
leader-4-3	35,468	50,612	9.0	363.8	7,876	10,352	8.7	33.3	-78%	-89%
leader-4-4	101,261	148,024	25.8	1,309.8	20,857	28,023	24.3	94.4	-79%	-91%
polling-2-2-4	4,811	8,578	0.7	3.7	3,047	6,814	0.7	2.3	-37%	-32%
polling-2-2-6	27,651	51,098	12.7	91.0	16,557	40,004	5.4	49.0	-40%	-48%
polling-2-4-2	6,667	11,290	0.9	39.9	4,745	9,368	0.9	26.6	-29%	-33%
polling-2-5-2	27,659	47,130	4.0	1,571.7	19,721	39,192	4.0	1,054.6	-29%	-33%
polling-3-2-2	2,600	4,909	0.4	7.1	1,914	4,223	0.5	4.8	-26%	-29%
polling-4-6-1	15,439	29,506	3.1	330.4	4,802	18,869	3.0	109.4	-69%	-66%
polling-5-4-1	21,880	43,760	5.1	815.9	6,250	28,130	5.1	318.3	-71%	-61%
processor-2	2,508	4,608	0.7	2.8	1,514	3,043	0.8	1.2	-44%	-43%
processor-3	10,852	20,872	3.1	66.3	6,509	13,738	3.3	23.0	-45%	-62%
processor-4	31,832	62,356	10.8	924.5	19,025	41,018	10.3	365.6	-45%	-60%



Mark Timmer, Jaco van de Pol, Mariëlle Stoelinga:
Confluence Reduction for Markov Automata. FORMATS 2013: 243-257

Hassan Hatefi, Holger Hermanns:
Model Checking Algorithms for Markov Automata. ECEASST 53 (2012)

Dennis Guck, Hassan Hatefi, Holger Hermanns, Joost-Pieter Katoen, Mark Timmer:
Analysis of Timed and Long-Run Objectives for Markov Automata. Logical Methods in Computer Science 10(3) (2014)

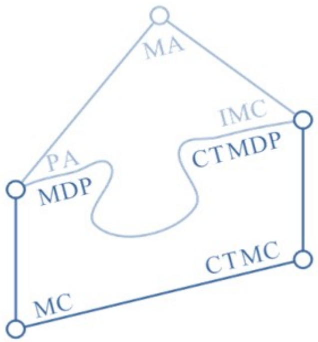
Bettina Braitling, Luis María Ferrer Fioriti, Hassan Hatefi, Ralf Wimmer, Bernd Becker, Holger Hermanns:
MeGARA: Menu-based Game Abstraction and Abstraction Refinement of Markov Automata. QAPL 2014: 48-63

Markov Automata Model Checking

Dennis Guck, Mark Timmer, Hassan Hatefi, Enno Ruijters, Mariëlle Stoelinga:
Modelling and Analysis of Markov Reward Automata. ATVA 2014: 168-184

Bettina Braitling, Luis María Ferrer Fioriti, Hassan Hatefi, Ralf Wimmer, Bernd Becker, Holger Hermanns:
Abstraction-Based Computation of Reward Measures for Markov Automata. VMCAI 2015: 172-189

Hassan Hatefi, Bettina Braitling, Ralf Wimmer, Luis María Ferrer Fioriti, Holger Hermanns, Bernd Becker:
Cost vs. Time in Stochastic Games and Markov Automata. SETTA 2015: 19-34

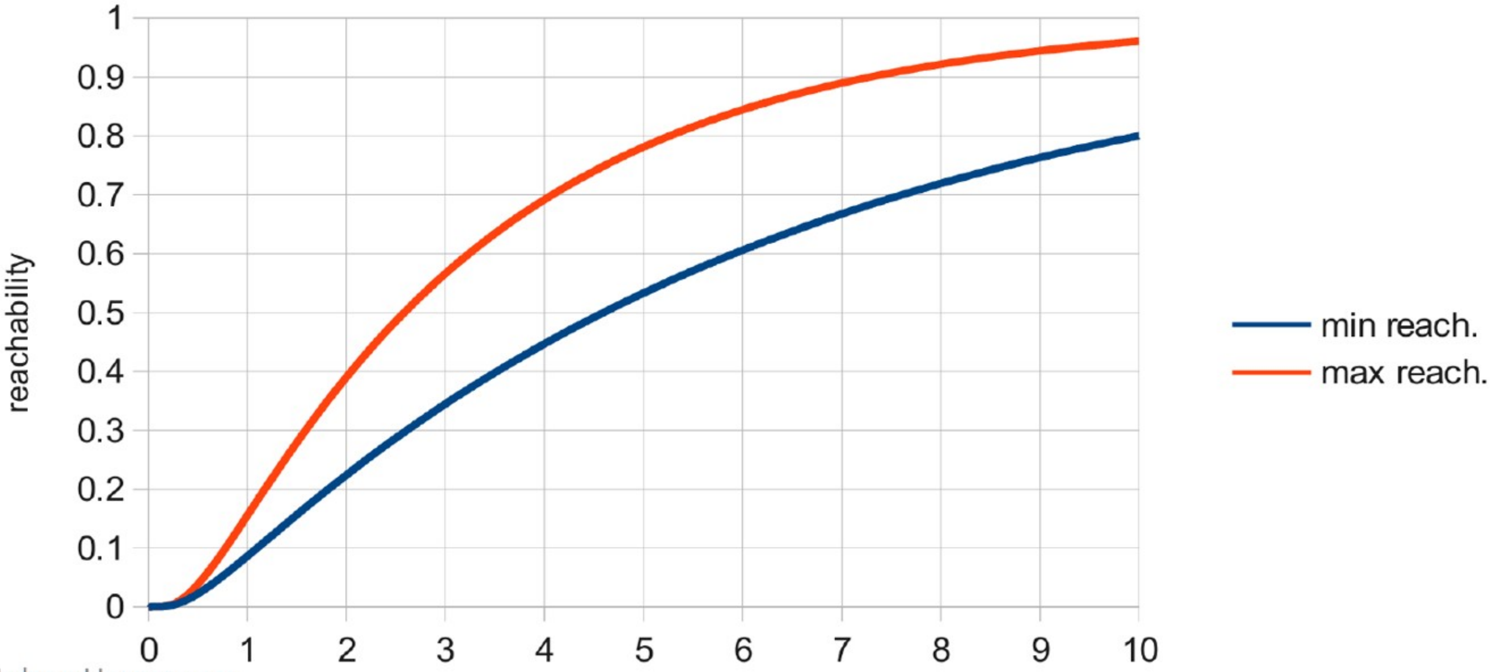


Model Checking CSL/PCTL

$$\Phi ::= a \quad | \quad \neg\Phi \quad | \quad \Phi \wedge \Phi \quad | \quad \mathcal{P}_{\trianglelefteq p}(\phi)$$

$$\phi ::= \mathcal{X}^I\Phi \quad | \quad \Phi\,\mathcal{U}\,\Phi \quad | \quad \Phi\,\mathcal{U}^I\,\Phi$$

- Mostly reduces to MDP setting.
- Main Challenge: Time bounded reachability.



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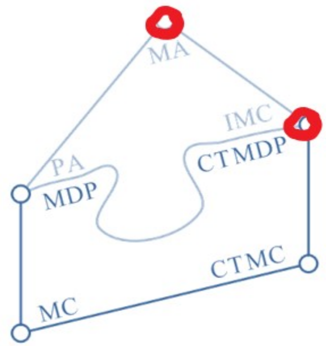
Model Checking Algorithms for Markov Automata. ECEASST 53 (2012)

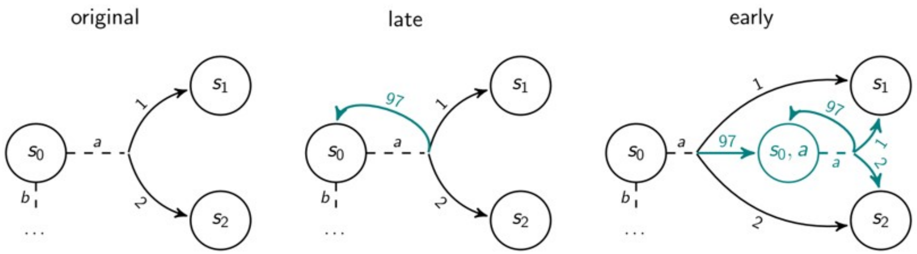


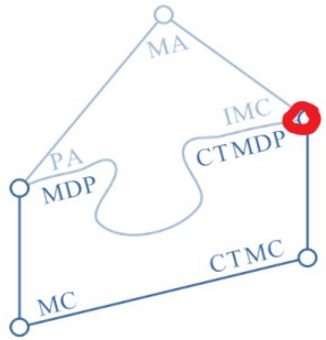
CTMDP Time Bounded Reachability

- Various algorithm have been proposed, in different setting.
- None of them achieve the efficiency known from CTMC.
- Exception:
  - Greedy Algorithm for Uniform Models.
  - Assumes time-abstract policies only.

Christel Baier, Holger Hermanns, Joost-Pieter Katoen, Boudewijn R. Haverkort: **Efficient computation of time-bounded reachability probabilities in uniform continuous-time Markov decision processes.** Theor. Comput. Sci. 345(1): 2-26 (2005)

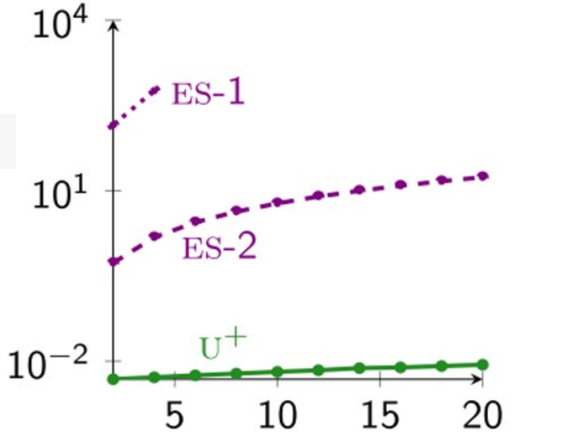
- U^+ lifts both restrictions at once, and is very simple.
- It uniformises the model,
  doubling the uniformisation rate until sufficient.



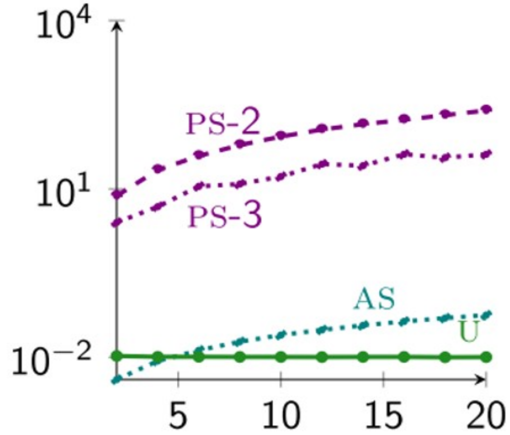


Yuliya Butkova, Hassan Hatefi, Holger Hermanns, Jan Krcál: **Optimal Continuous Time Markov Decisions.** ATVA 2015: 166-182

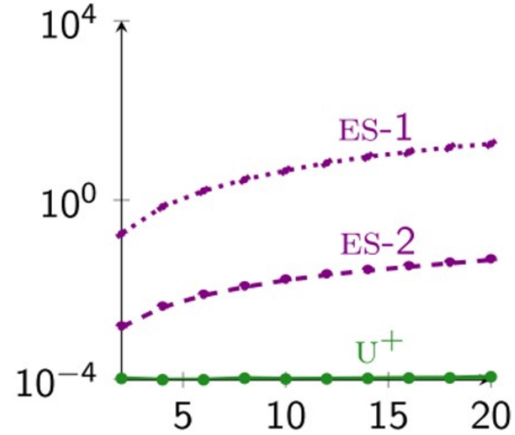
CTMDP Time Bounded Reachability



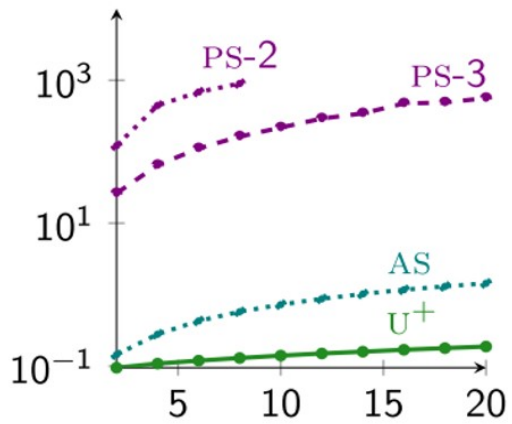
ES-1000-10, early, ⅄ = 2, $|S| = 1004$, $\lambda = 10$, $\epsilon = 10^{-4}$



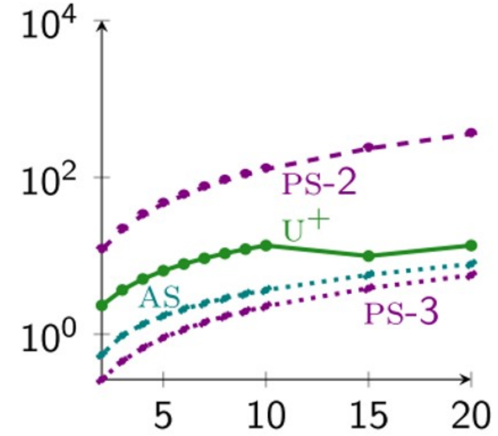
ES-1000-10, late, ⅄ = 2, $|S| = 1004$, $\lambda = 10$, $\epsilon = 10^{-6}$



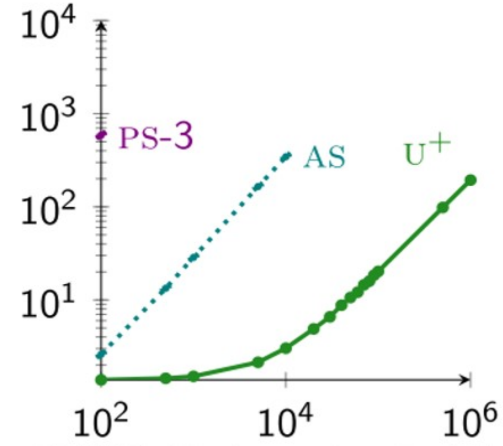
PS-1-1, early, ⅄ = 2, $|S| = 17$, $\lambda = 2.8$, $\epsilon = 10^{-4}$



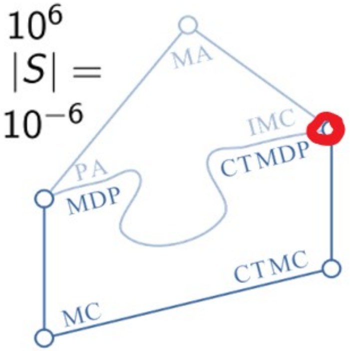
PS-4-2, late, ⅄ = 4, $|S| = 10\,593$, $\lambda = 5.6$, $\epsilon = 10^{-6}$



QS-2-2, late, ⅄ = 8, $|S| = 796$, $\lambda = 11.3$, $\epsilon = 10^{-6}$



FTWC-16, late, ⅄ = 5, $|S| = 10\,130$, $\lambda = 2.06$, $\epsilon = 10^{-6}$



Yuliya Butkova, Hassan Hatefi, Holger Hermanns, Jan Krcál:
Optimal Continuous Time Markov Decisions. ATVA 2015: 166-182

Long-Run Averages & Expectations

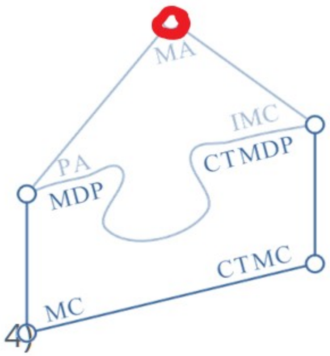
Given a set *G* of states of interest, one aims for

- Minimal and maximal expected time to reach *G*

  can be solved via stochastic shortest path computations

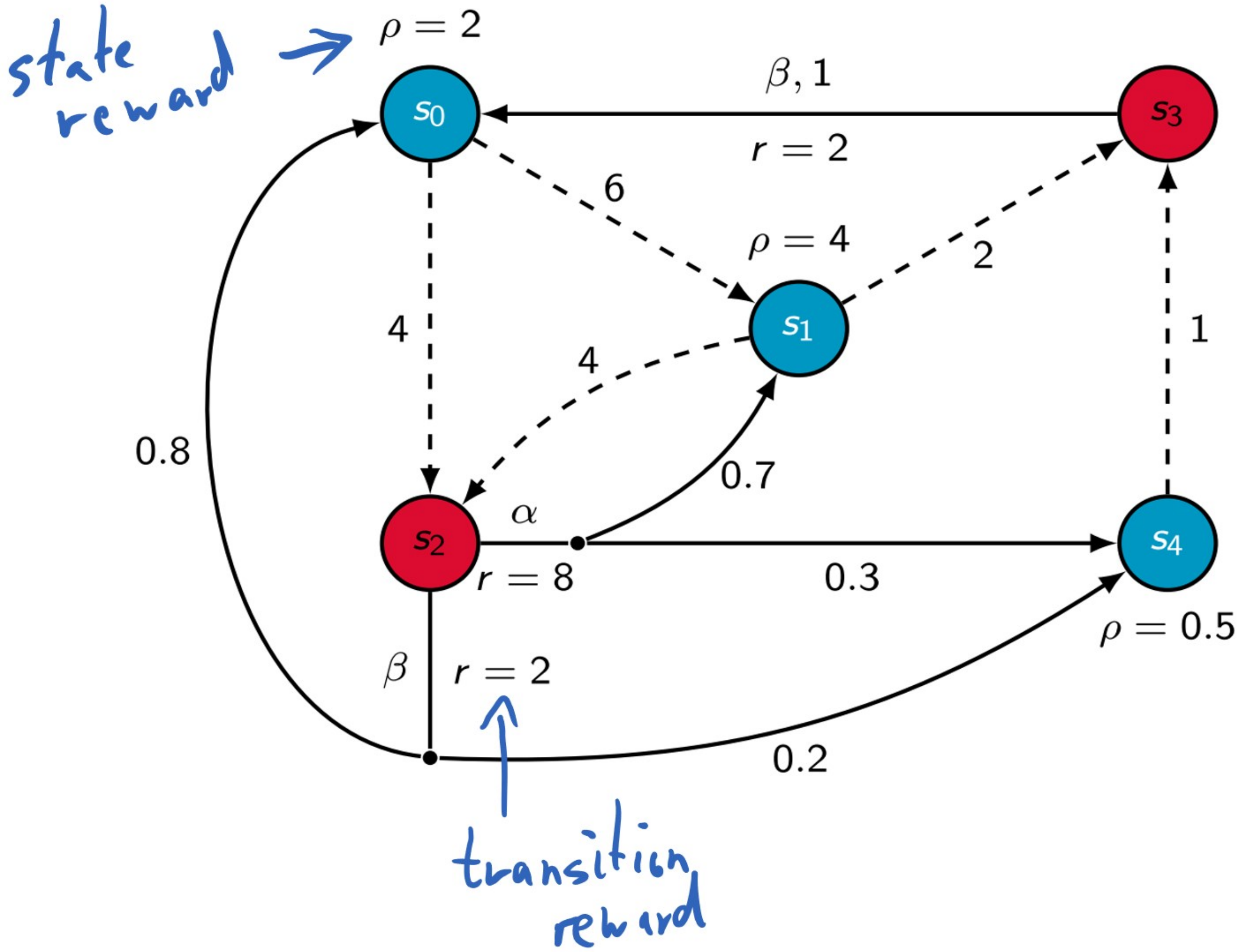
- Minimal and maximal long run fraction of time spent in *G*

  reduces to MDP setting with residence times as costs



Dennis Guck, Hassan Hatefi, Holger Hermanns, Joost-Pieter Katoen, Mark Timmer:
Analysis of Timed and Long-Run Objectives for Markov Automata. Logical Methods in Computer Science 10(3) (2014)

Adding Costs: Markov Reward Automata

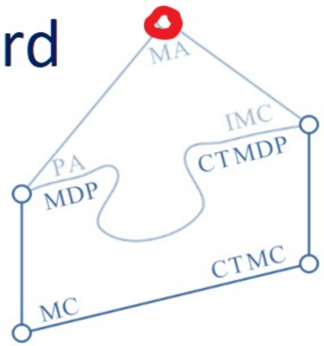


Algorithms extend smoothly

- Expected reward prior to goal
- Long-run reward rate

[de Alfaro] helps

- Time bounded reward

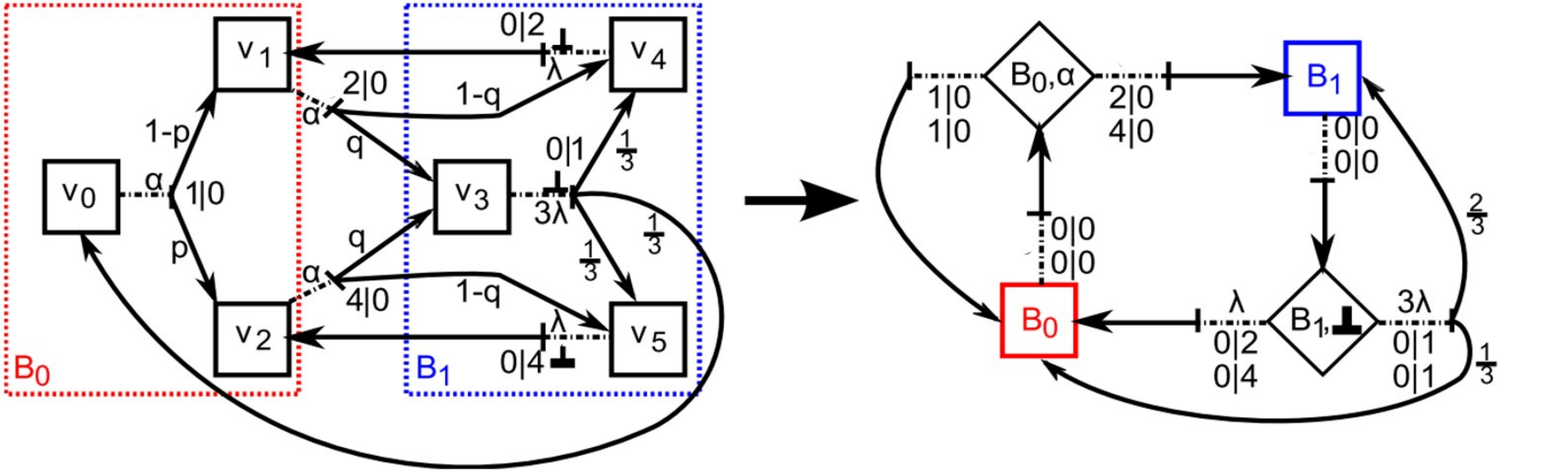


Dennis Guck, Mark Timmer, Hassan Hatefi, Enno Ruijters, Mariëlle Stoelinga: **Modelling and Analysis of Markov Reward Automata.** ATVA 2014: 168-184

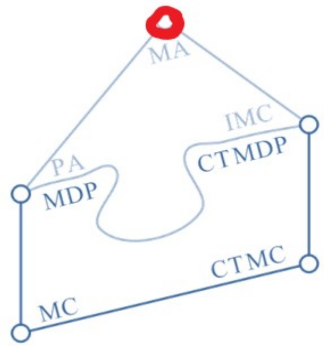
Attacking Size

- Abstraction refinement applied to

  Markov Reward Automata.



Game-based abstractions



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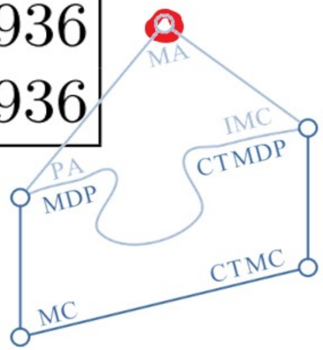
Modelling and Analysis of Markov Reward Automata. ATVA 2014: 168-184

Attacking Size

- Abstraction refinement applied to
  Markov Reward Automata.

name	#states	budget = 10 min	budget = 10 max	budget = 20 min	budget = 20 max	budget = 50 min	budget = 50 max
DPMS-2-5	508	0.759	0.859	1.557	1.924	3.910	5.150
DPMS-2-10	1,588	0.759	0.859	1.557	1.924	3.910	5.150
DPMS-2-20	5,548	0.759	0.859	1.557	1.924	3.910	5.150
DPMS-3-5	5,190	0.785	0.883	1.617	1.930	4.129	5.088
DPMS-3-10	29,530	0.785	0.883	1.617	1.930	4.129	5.088
DPMS-3-20	195,810	0.785	0.883	1.617	1.930	4.129	5.088
DPMS-4-5	47,528	0.784	0.877	1.617	1.889	4.143	4.936
DPMS-4-10	492,478	0.784	0.877	1.617	1.889	4.143	4.936

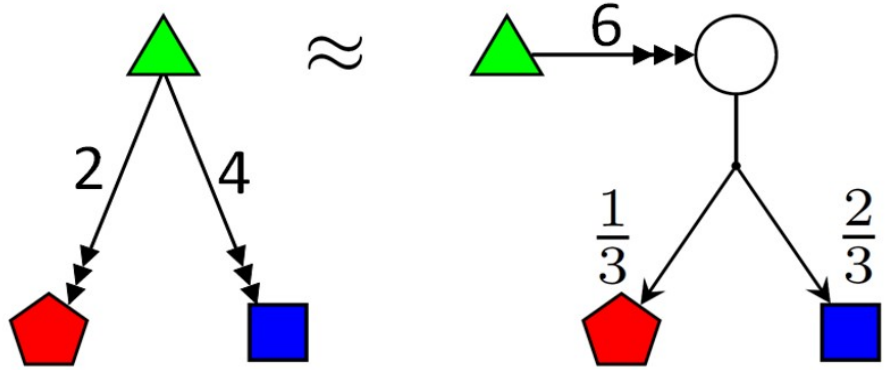


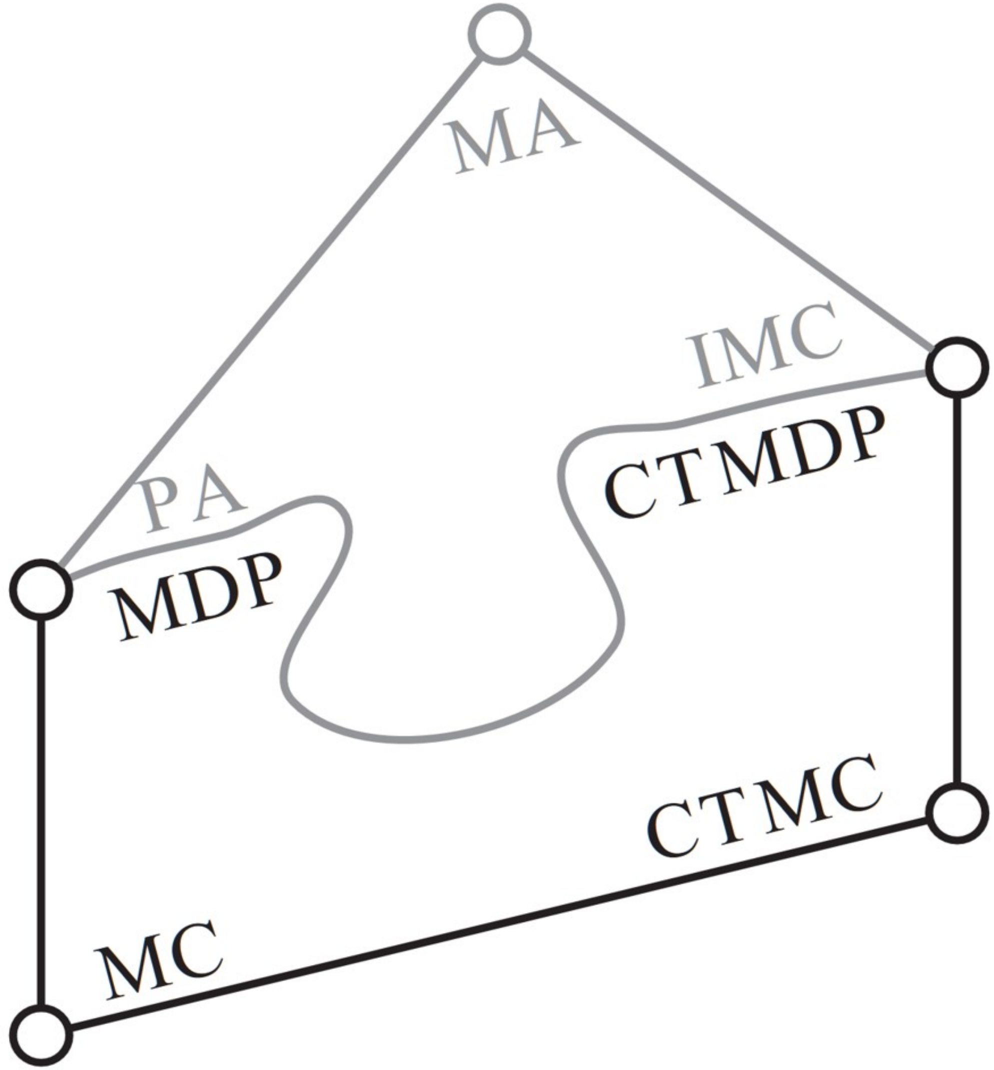
Hassan Hatefi, Bettina Braitling, Ralf Wimmer, Luis María Ferrer Fioriti, Holger Hermanns, Bernd Becker:
Cost vs. Time in Stochastic Games and Markov Automata. SETTA 2015: 19-34

Summary

- What?
- Why?
- How?
  - Construction
  - Compression
  - Verification
  - Extension

- Open Challenges





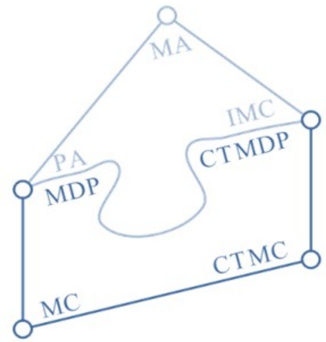
Outlook

Solve the open challenges

- Polynomial-time algorithm
  for weak distribution bisimulation?

- Lifting U^+ to Markov Reward Automata.

- …



Not Covered

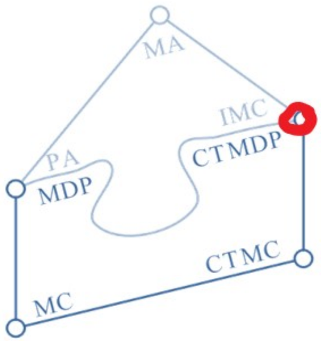
Open Interpretation of CT Models

Tomás Brázdil, Holger Hermanns, Jan Krcál, Jan Kretínský, Vojtech Rehák:
Verification of Open Interactive Markov Chains. FSTTCS 2012: 474-485

Holger Hermanns, Jan Krcál, Jan Kretínský:
Compositional Verification and Optimization of Interactive Markov Chains. CONCUR 2013: 364-379

Distributed Synthesis in Continuous Time

justifies absence of interleaving scheduler
provided distributions have
continuous support.



Holger Hermanns, Jan Krcál, Steen Veester:
Distributed Synthesis in Continuous Time. FOSSACS 2016. To appear