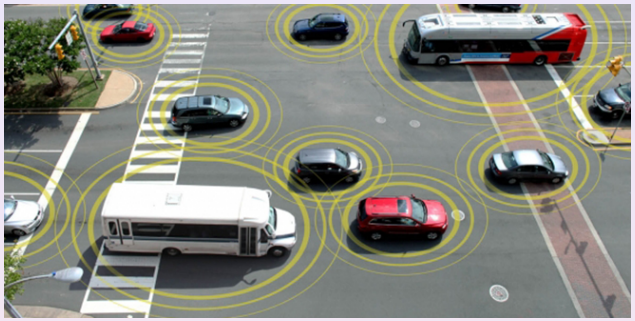
Epistemic reasoning in AI

François Schwarzentruber

École Normale Supérieure Rennes

Habilitation à diriger des recherches – 3 May 2019

Automation of complex tasks



Autonomous cars

Intelligent farming

Nuclear decommissioning

cars, robots, humans

Several *agents* that interact with the environment and with each others.

Imperfect information

- Agents have local view of the environment
- Agents communicate
- Agents act

Decisions are taken with respect to *knowledge*.

Interaction relies on knowledge

if I know it is safe **then**
`I go`

if I know you are at the market place **then**
`I join you`

if (I know it is safe) and (I know you do not know it is safe) **then**
`I tell you it is safe`

if I know you know it is safe **then**
`I do not tell you it is safe`

if I know you know I know it is safe or not **then**
`I do not wait for a message from you`

Need to build understandable multi-agent systems

Motivation

- Robots interacting with humans
- Legal issues in case of failure



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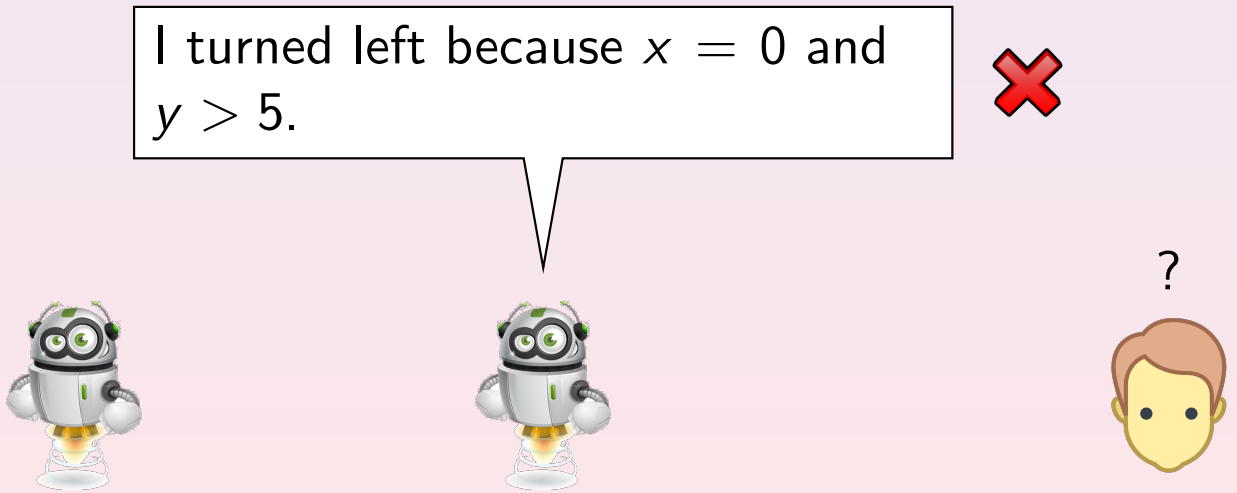

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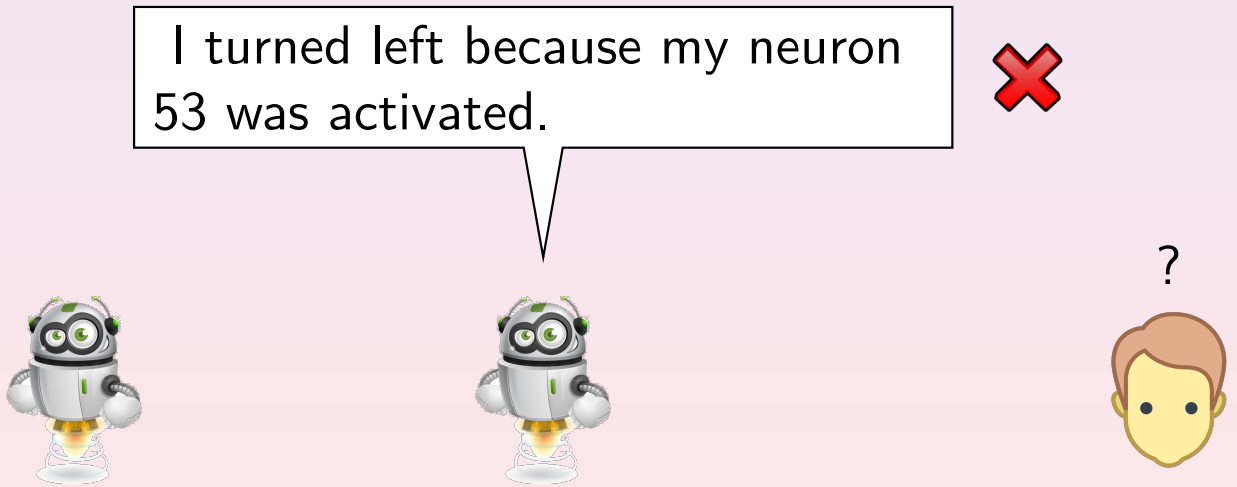

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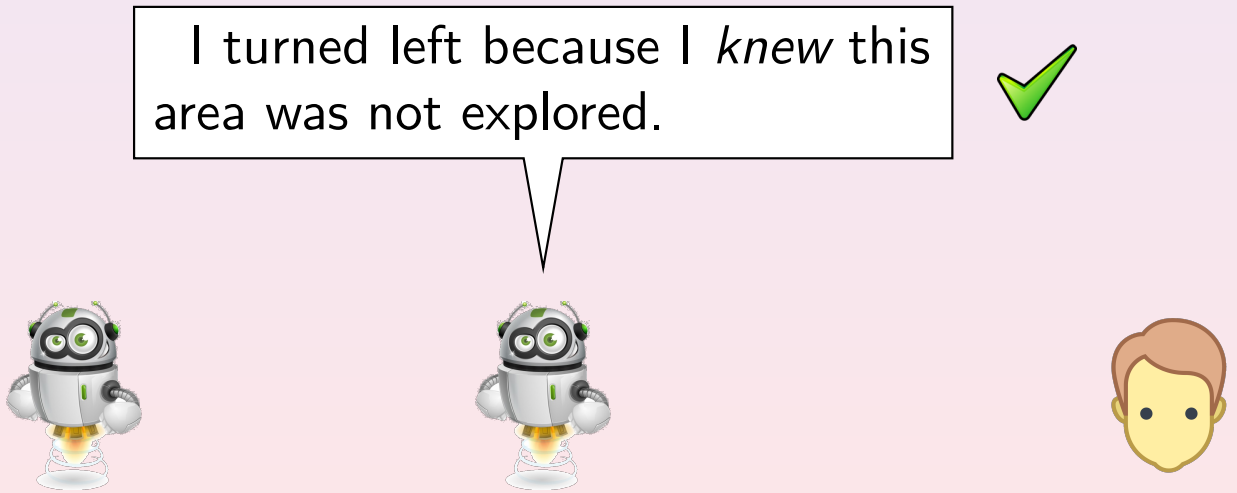

Solution: reasoning about knowledge

Given:

- what agents sense;
- the actions and communications that occurred

What does each agent know?

My contribution in 2011-2019 in a nutshell:

Mathematical and computational properties of dynamic epistemic logic.

Outline

1. The Hintikka's World project
2. Modeling knowledge and actions
3. Reasoning tasks in dynamic epistemic logic
4. Epistemic planning in dynamic epistemic logic
5. Conclusion

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   - Motivation 1: face the difficulties to explain possible worlds
   - Motivation 2: disseminating in many communities
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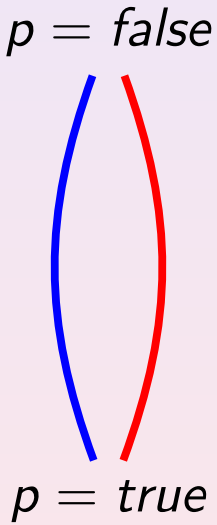
Once upon a time... In 2011-2012...

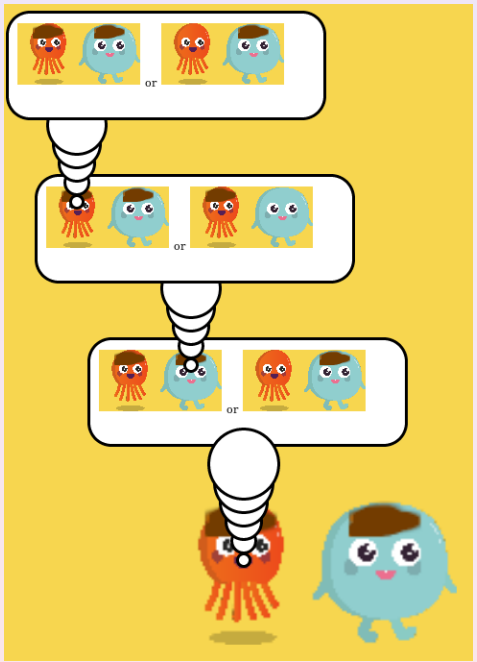
I explained epistemic logic to other researchers in logic/AI/verification...



... but nobody understood me...

Possible worlds

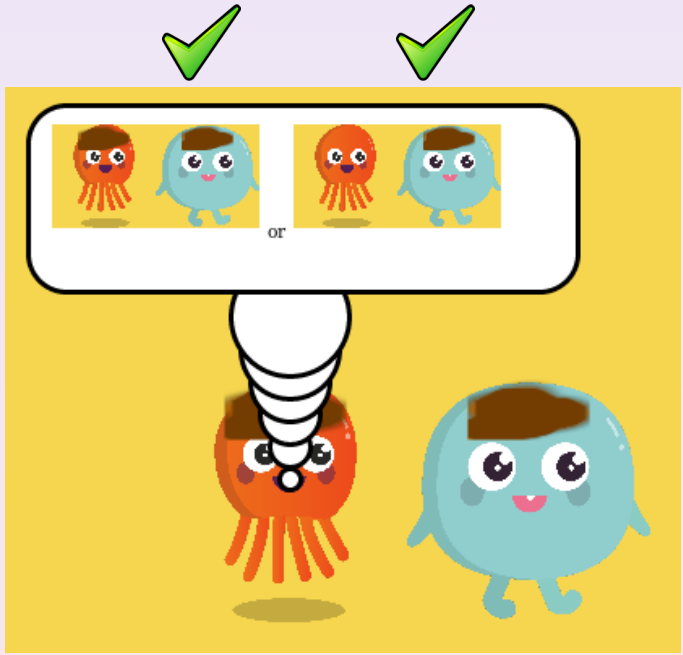
... but, since 2017, everybody understood me with comics...



`http://hintikkasworld.irisa.fr/`

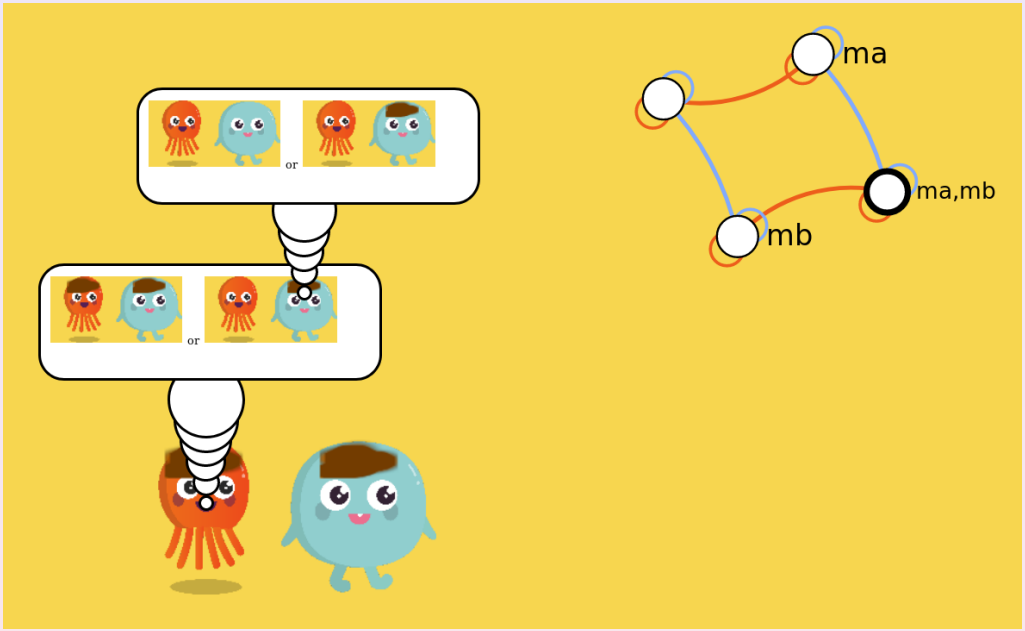
[demo IJCAI-ECAI 2018]

Semantics of knowing something



Agent a knows that b is dirty.

Epistemic states = pointed Kripke structures



Comics = unraveling of a pointed Kripke structure.

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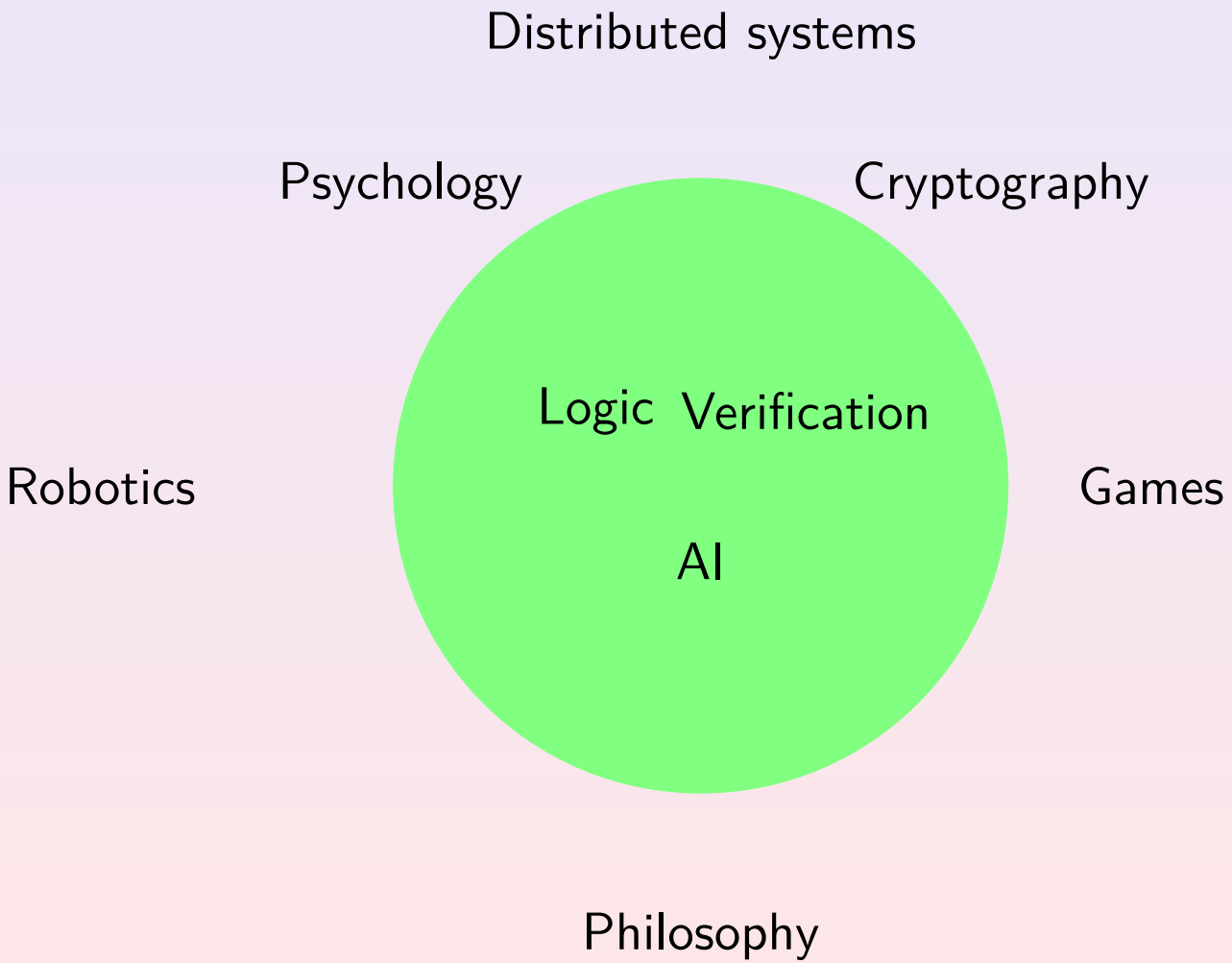
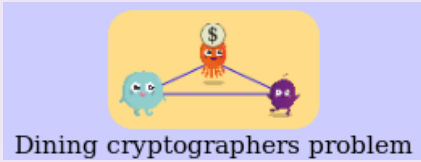
Explaining these models in many communities



Explaining these models in many communities

Distributed systems



Psychology

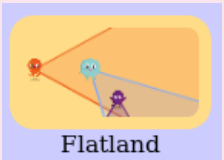
Cryptography

Logic Verification

AI

Robotics

Games



Philosophy

Dissemination

Tutorials on epistemic reasoning

- at EASSS 2017 with Sophie Pinchinat
- at ECAI-IJCAI 2018
- at AAMAS 2019, IJCAI 2019 with Tristan Charrier

Talks for presenting Hintikka's World in 2017

- to logicians/philosophers in Bochum
- to psychologists at IME (Institut médico-éducatif) near Rennes.

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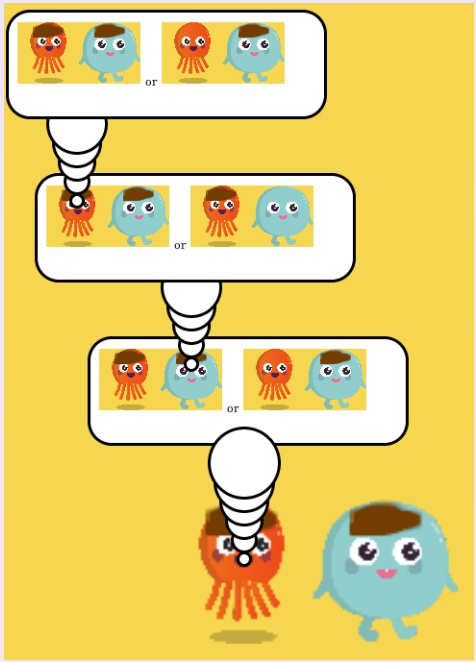
Open-source project



http://hintikkasworld.irisa.fr/

https://gitlab.inria.fr/fschwarz/hintikkasworld

[demo IJCAI-ECAI 2018]

- Web app
- Modular source code in Typescript
- Easy to add new examples
- Several contributors

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   - In the verification/model checking community
   - In philosophy / AI
   - Syntactic specifications
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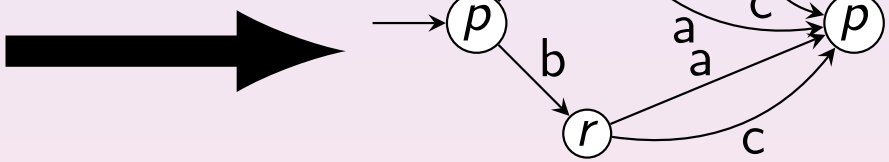
In the verification/model checking community

```
// HelloWin.cpp : Defines the entry point for the application.
//

#include "stdafx.h"
#include "resource.h"

#define MAX_LOADSTRING 100

// Global Variables:
HINSTANCE hInst;                                // current instance
TCHAR szTitle[MAX_LOADSTRING];                  // The title b
TCHAR szWindowClass[MAX_LOADSTRING];                        // The

// Foward declarations of functions included in this code module:
ATOM                MyRegisterClass(HINSTANCE hInstance);
BOOL                InitInstance(HINSTANCE, int);
LRESULT CALLBACK    WndProc(HWND, UINT, WPARAM, LPARAM);
LRESULT CALLBACK    About(HWND, UINT, WPARAM, LPARAM);

int APIENTRY WinMain(HINSTANCE hInstance,
                     HINSTANCE hPrevInstance,
                     LPSTR     lpCmdLine,
                     int       nCmdShow)
{
    // TODO: Place code here.
    MSG msg;
    HACCEL hAccelTable;

    // Initialize global strings
    LoadString(hInstance, IDS_APP_TITLE, szTitle, MAX_LOADSTRING);
    LoadString(hInstance, IDC_HELLOWIN, szWindowClass, MAX_LOADSTRING);
    MyRegisterClass(hInstance);

    // Perform application initialization:
    if (!InitInstance (hInstance, nCmdShow))
    {
```

Program



Transition system

Action = an edge $\longrightarrow$

In the verification/model checking community

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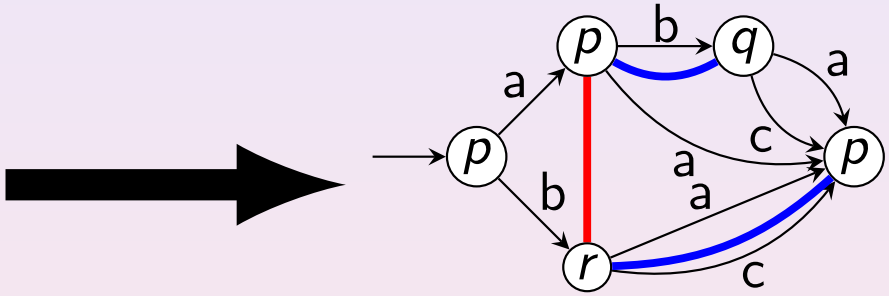

Transition system

Action = an edge $\longrightarrow$
Epistemic = edges

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In philosophy / AI

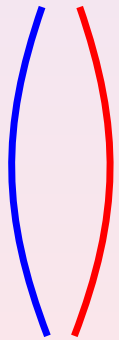
The mechanism of actions is important.

Public/private announcement	Announce 'She knows you hold $5\Diamond$'
Public action	play card $5\Diamond$
Private action	secretly remove card $5\Diamond$
Belief revision	learn p although believing $\neg p$

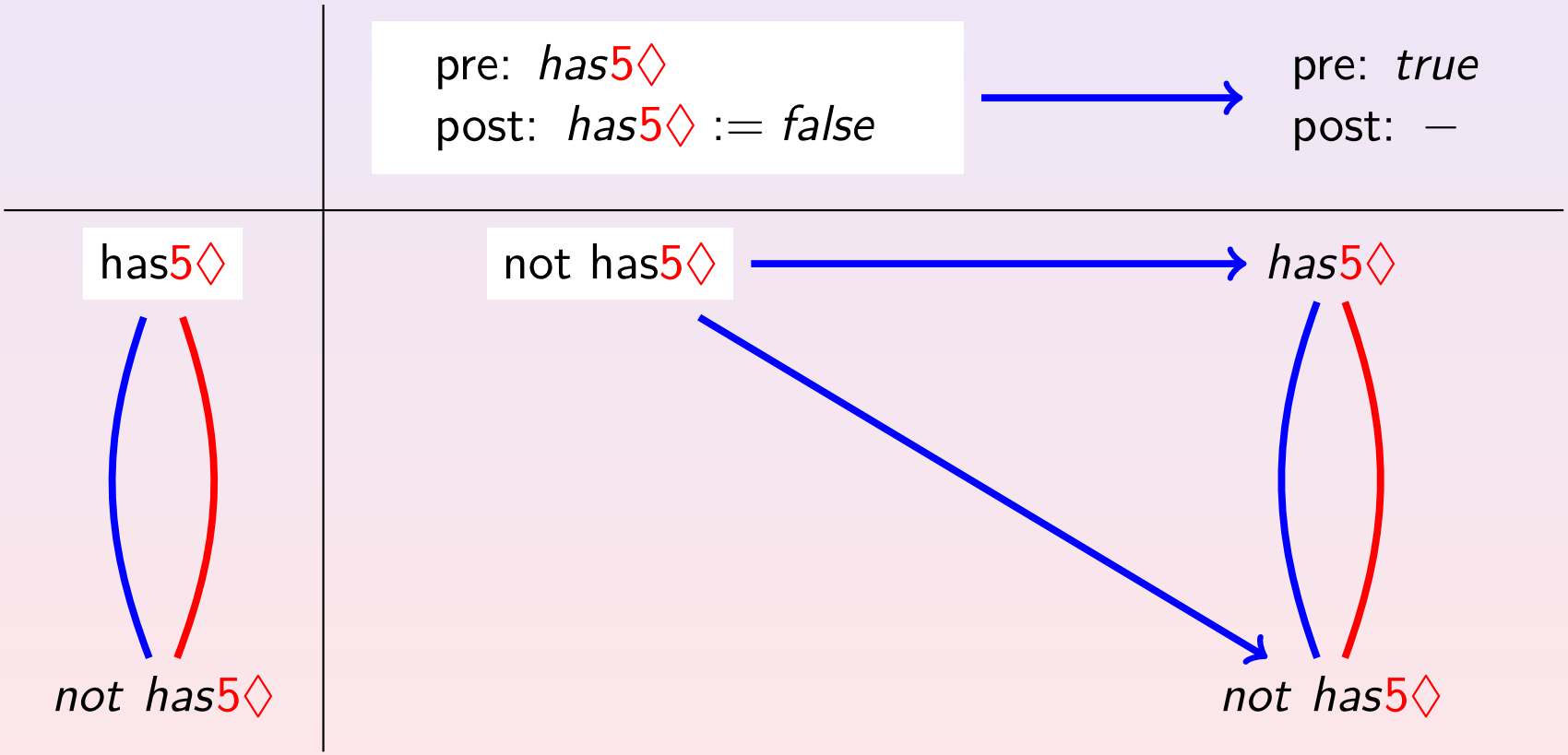
Solution: Dynamic epistemic logic

	State	Action
Classical planning	has5◊	pre: *has5◊* post: *has5◊* := *false*

Solution: Dynamic epistemic logic

	State	Action
Classical planning	has5◊	pre: *has5◊* post: *has5◊* := *false*
DEL [Baltag et al. TARK 1998] [van Ditmarsch et al. 2007] = Kripkean models of classical planning	has5◊  *not has5◊*	pre: *has5◊* post: *has5◊* := *false*  pre: *true* post: –

Computing the next state: product update



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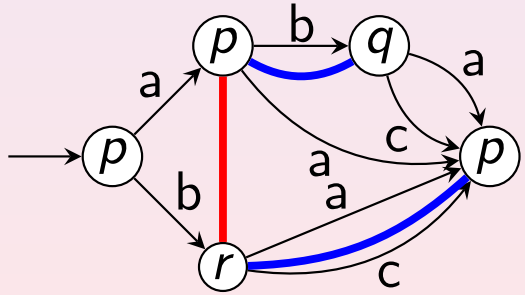
Syntactic specifications

Game description language [Love et al. 2008] [Thielscher, IJCAI 2017]	agent a sees the game position
Flatland  [Balbiani et al., IGPL 2014] [Gasquet, Goranko, _, AAMAS 2014] [Gasquet, Goranko, _, JAAMAS 2016]	agent a sees agent b
Visibility atoms  [Charrier et al. KR 2016]	a sees the truth value of p
Paying attention to public announcements  [Bolander et al. JoLLI 2016]	$B_a payAtt(b) \rightarrow [p!]B_a B_b p$
Asynchronous announcements  [Knight et al. MS in CS 2019]	$[p!][read_a]K_a p$
Epistemic gossip  [van Ditmarsch et al., JAL 2017]	$[call_{ab}]K_a secret_b$

From DEL to epistemic temporal logics

Syntactic specification

Models of
dynamic epistemic logic



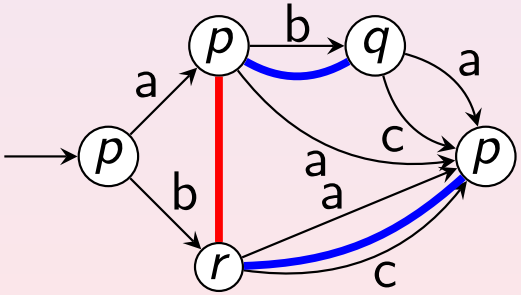
Epistemic temporal model

From DEL to epistemic temporal logics

Syntactic specification

- ✓ Easy to specify
- ✓ Succinct
- ✗ Ad-hoc languages
- ✗ Hand-crafted semantics

Models of
dynamic epistemic logic



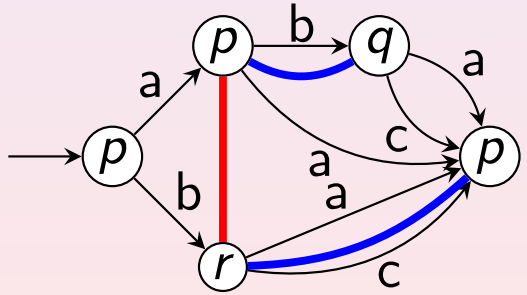
Epistemic temporal model

From DEL to epistemic temporal logics

Syntactic specification

Models of
dynamic epistemic logic

- ✓ Elegant Kripkean extension of classical planning
- ✓ Succinct
- ✓ Classification in terms of action types
- ✓ Has probabilistic extension
- ✓ Has extensions that encompass belief revision
- ✗ Perfect-recall only
- ✗ Synchronous only



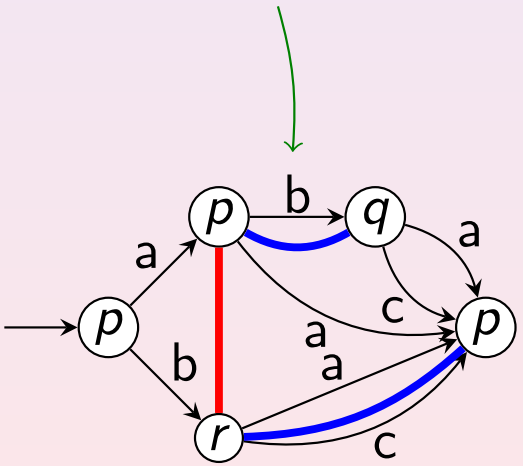
Epistemic temporal model

From DEL to epistemic temporal logics

Syntactic specification

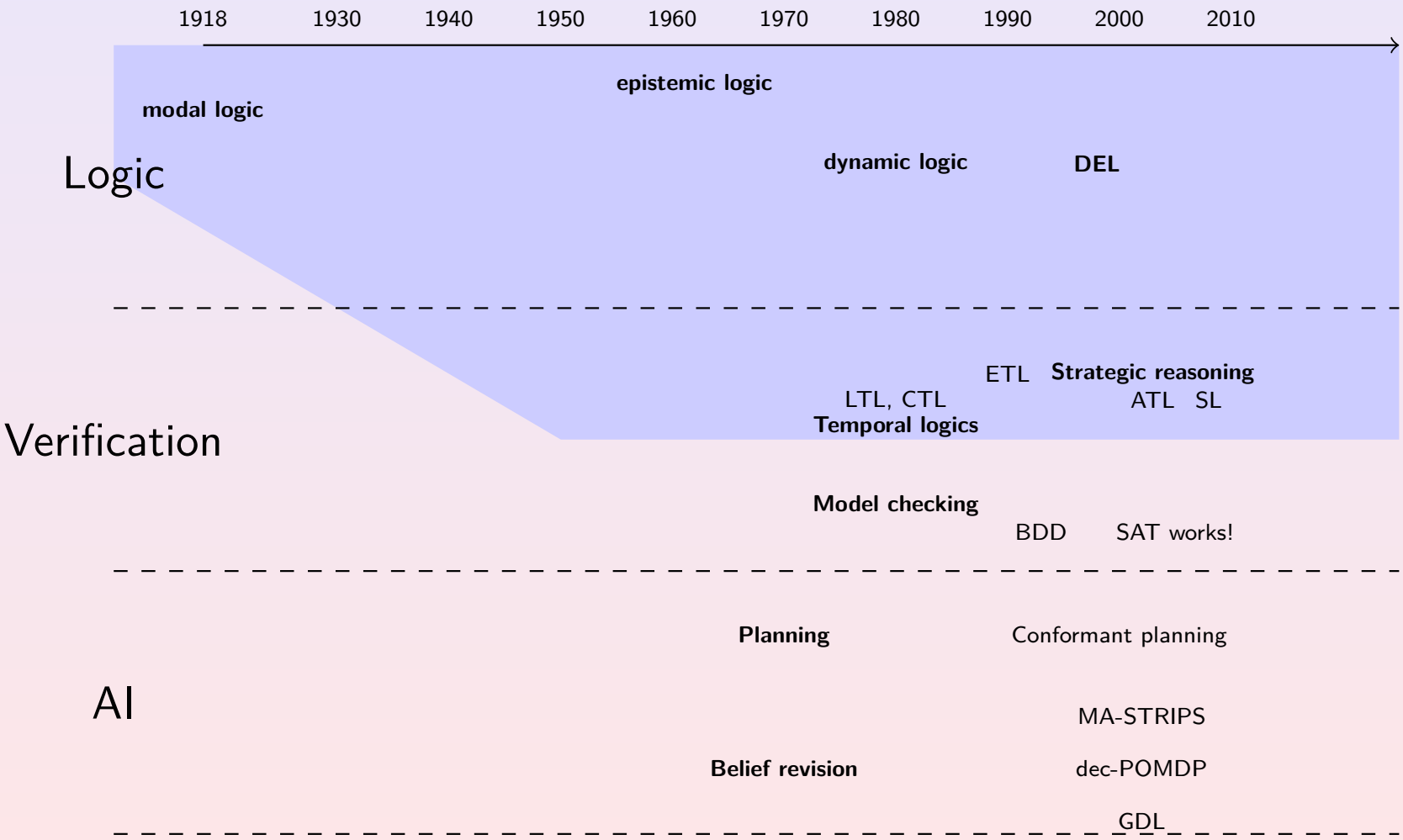
Models of
dynamic epistemic logic

- ✓ Elegant
- ✓ Allows for async/no perfect-recall semantics
- ✗ Type of actions lost
- ✗ Not Succinct (usually infinite)

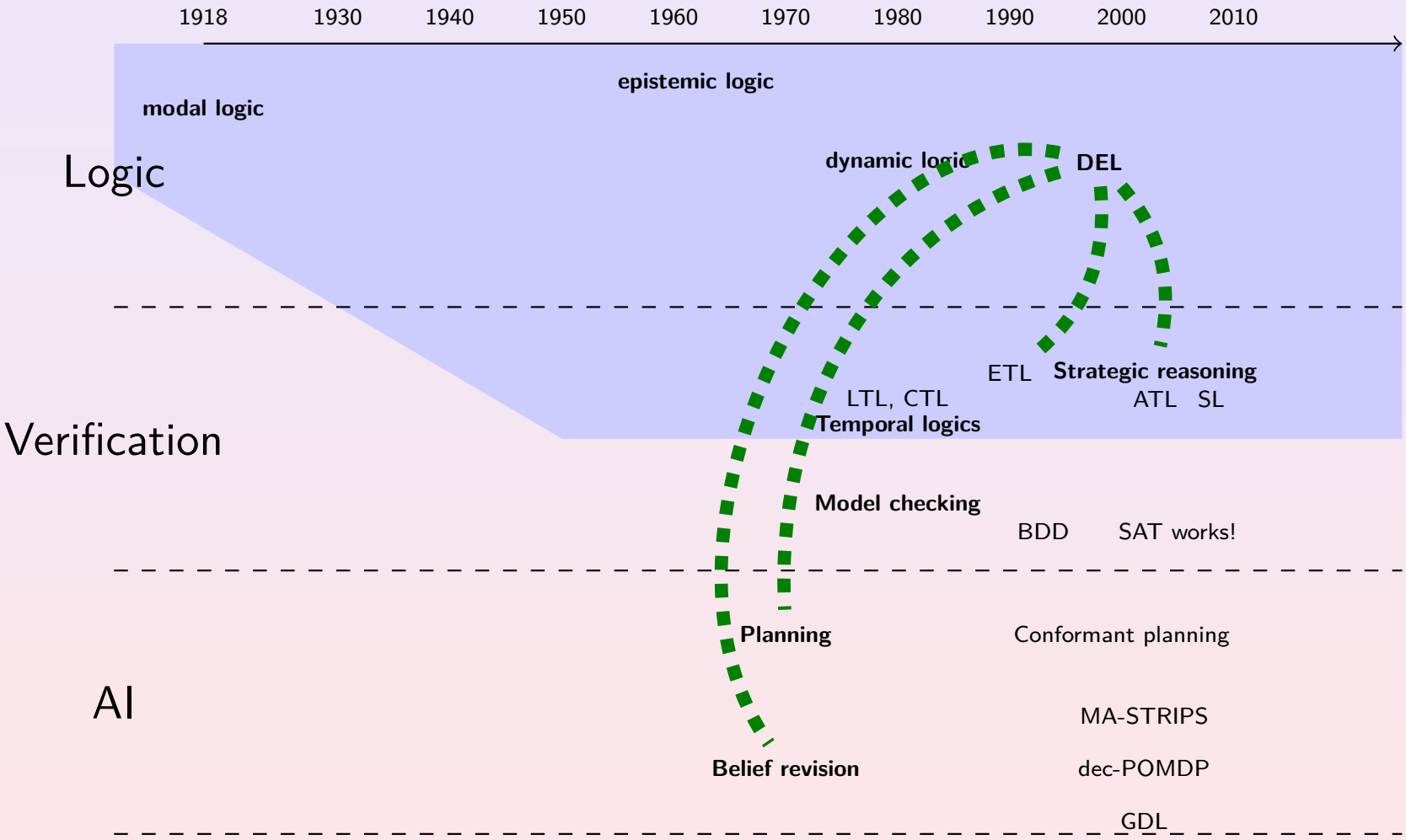


Epistemic temporal model

Timeline


1918
1930
1940
1950
1960
1970
1980
1990
2000
2010
epistemic logic
modal logic
Logic
dynamic logic
DEL
ETL
Strategic reasoning
LTL, CTL
ATL
SL
Temporal logics
Verification
Model checking
BDD
SAT works!
Planning
Conformant planning
AI
MA-STRIPS
Belief revision
dec-POMDP
GDL

Timeline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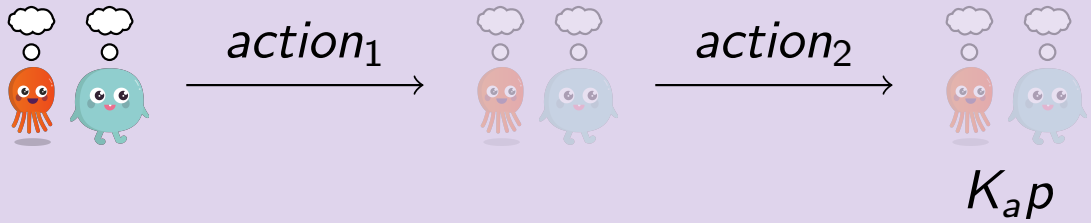
Model checking problem

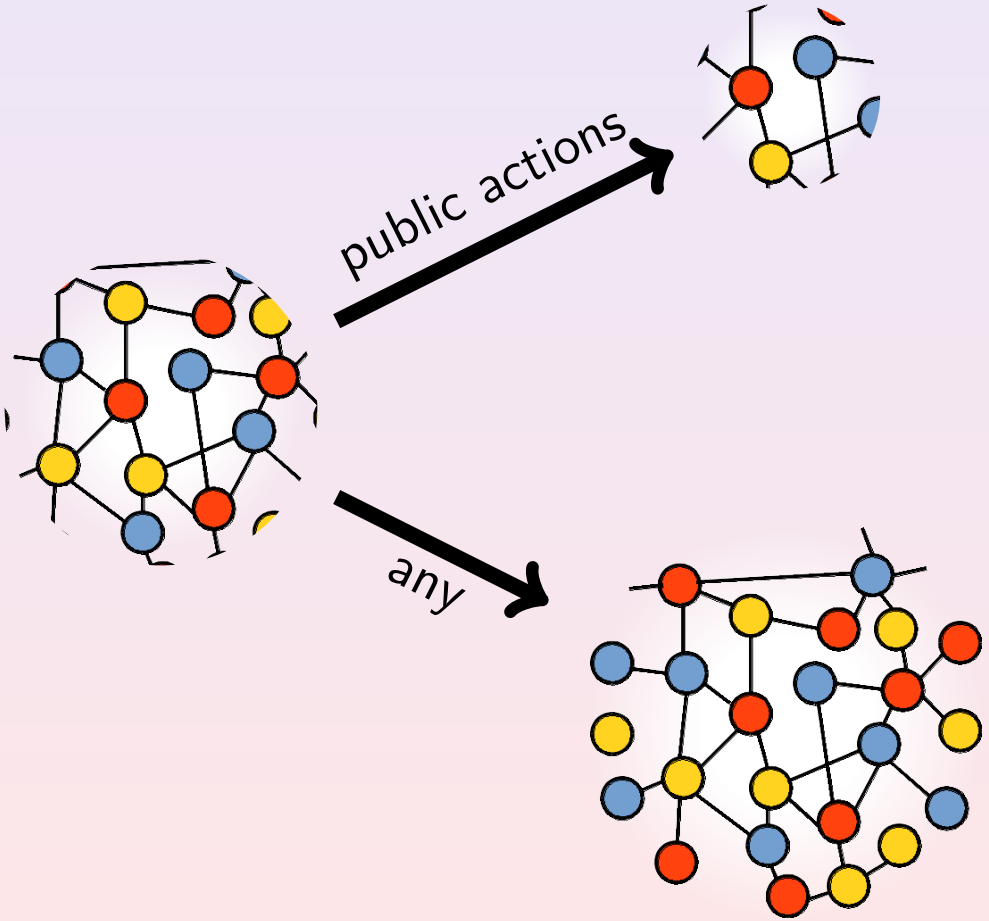
Definition (model checking problem)

- Input:
  - An epistemic state 
  - A formula, e.g. $\langle action_1; action_2 \rangle K_a p$;
- Output: yes if



no otherwise.

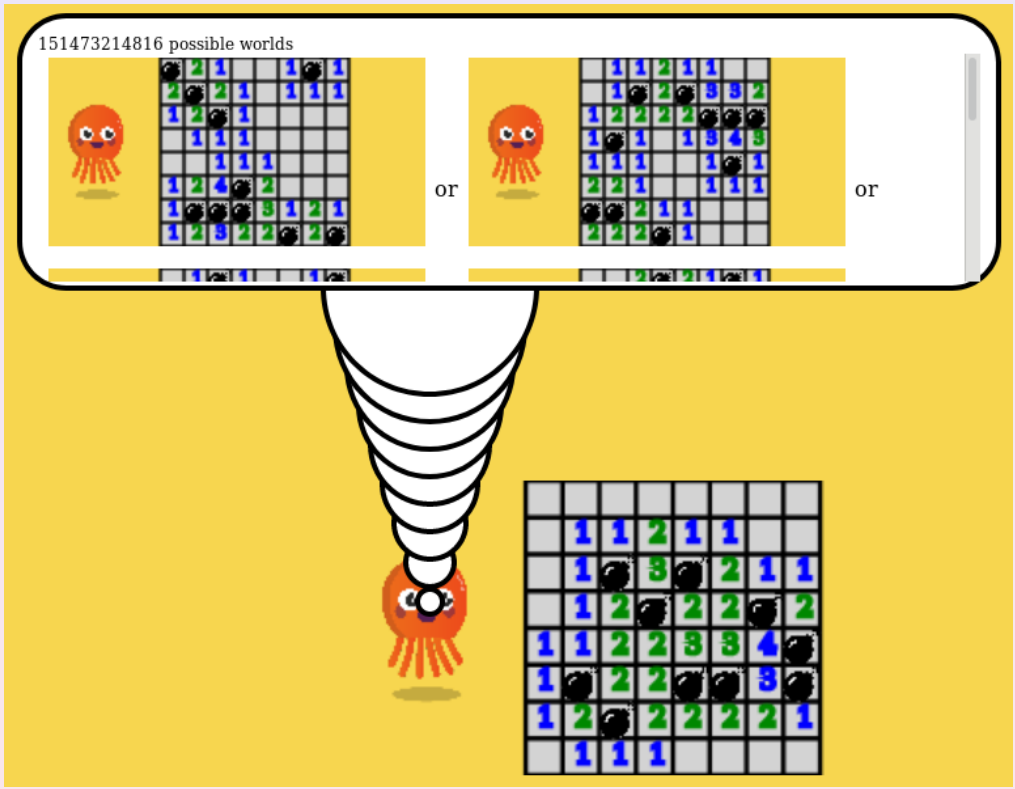
Model checking complexity



P-complete
[van Benthem, 2011]

PSPACE-complete
[Aucher, _, TARK 2013]
[Pol et al. 2016]

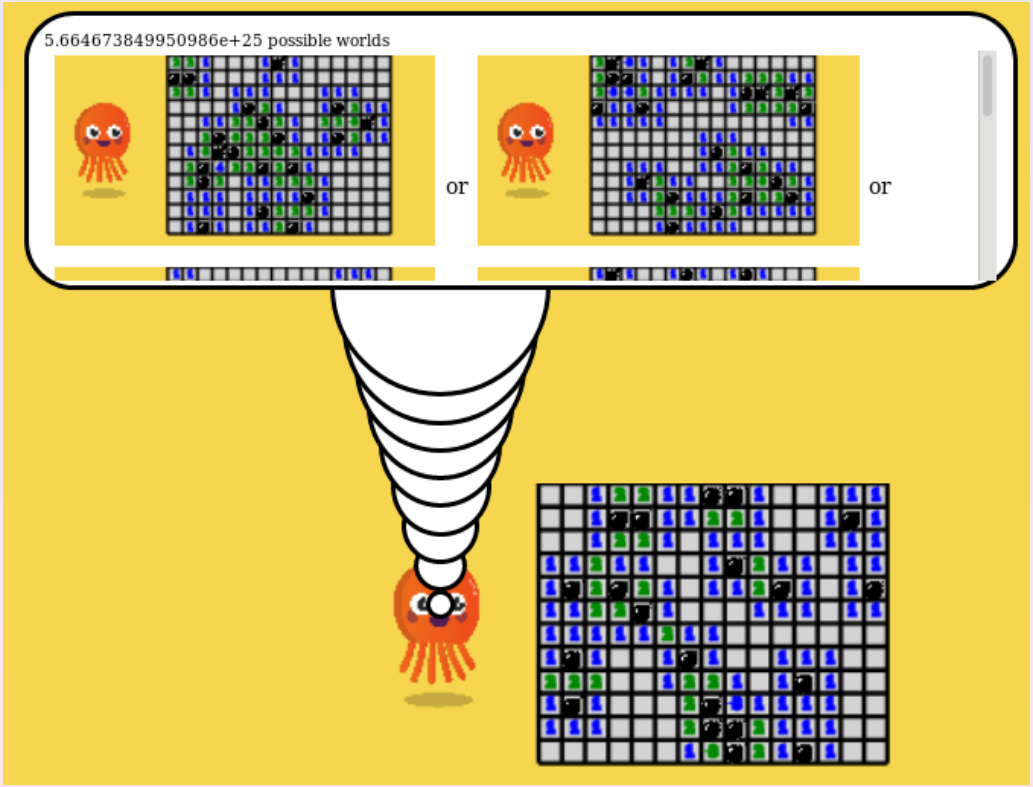
State explosion problem



Example

Minesweeper easy 8×8 with 10 bombs: $> 10^{12}$ possible worlds.

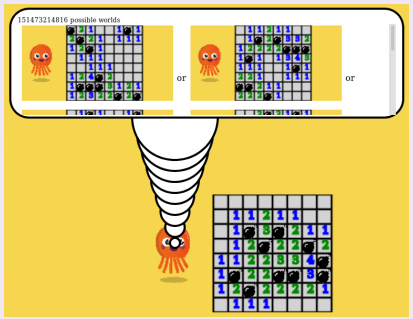
State explosion problem



Example

Minesweeper 10×12 with 20 bombs: $> 10^{25}$ possible worlds.

Solution to the state explosion problem

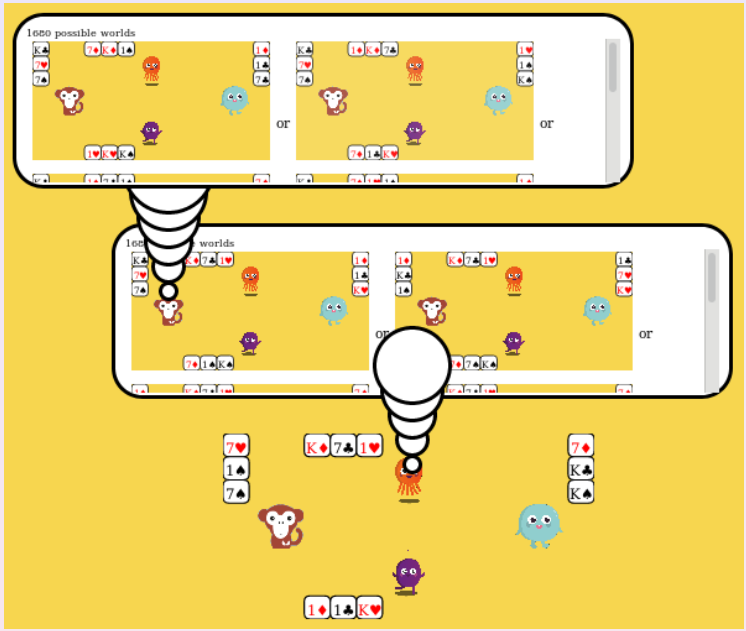


[Benthem et al. 2015], [Benthem et al. 2018]

[Charrier _ AAMAS 2017], [Charrier _ AiML 2018]

- Succinct representations of epistemic states **and** actions;
- Easy to specify by means of accessibility programs;
- Succinct model checking still in PSPACE.

Impact



Theoretical

Existence of a (uniform) strategy in **bounded** imperfect info games is in PSPACE.

(cf. Abdallah's talk)

Implementation: PSPACE techniques

Symbolic Model checking implemented in Hintikka's World:

- by Sébastien Gamblin and Alexandre Niveau (univ. Caen)
- using BDDs (C wrapper of CUDD compiled in `wasm`).

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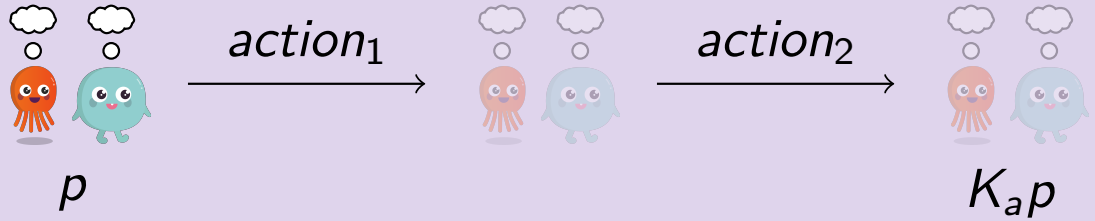
Theorem proving

Motivation: parametrized verification

for all epistemic states in which p holds:

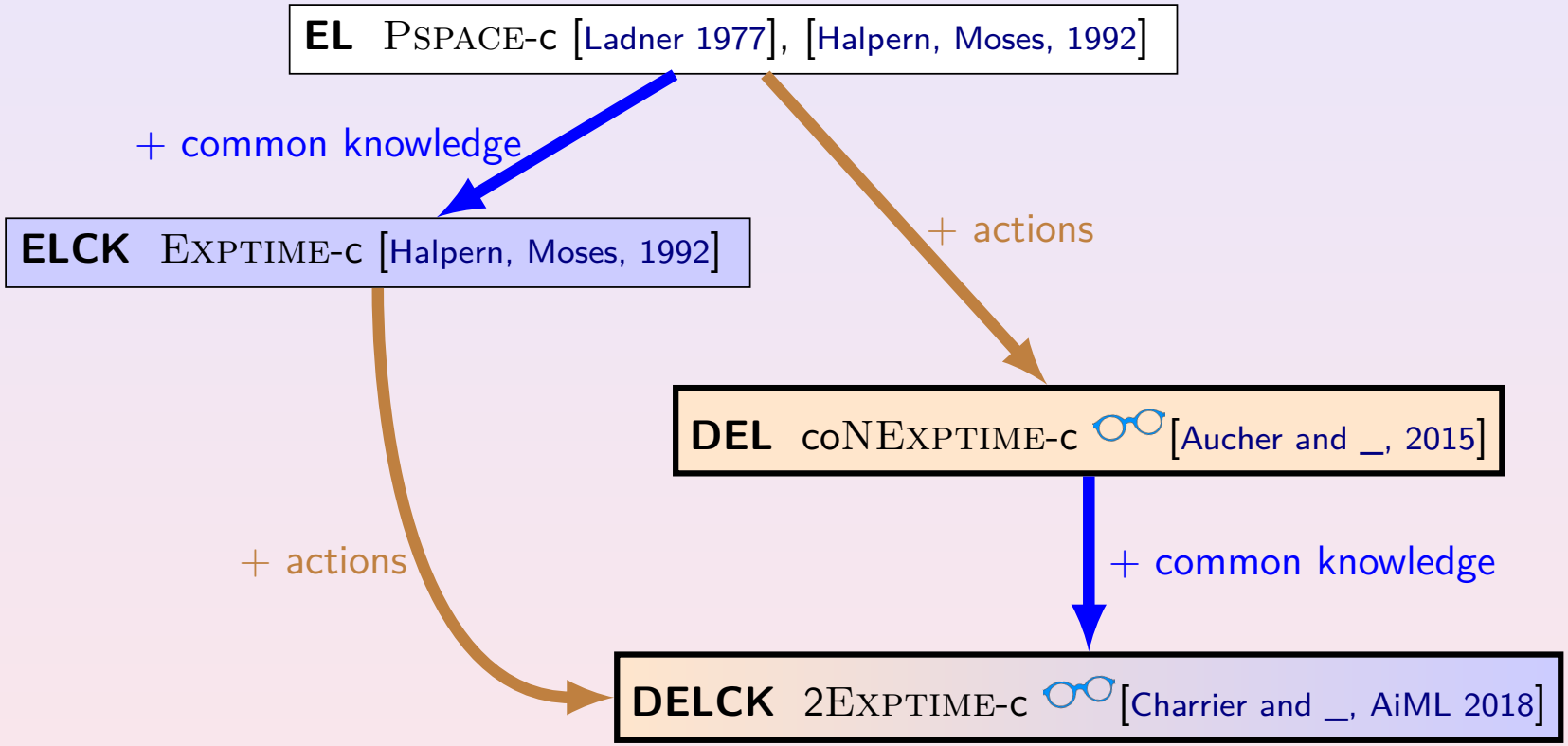


$p \to \langle action_1; action_2 \rangle K_a p$ is a *theorem*, i.e. true in all epistemic states.

Definition

- Input: a formula φ;
- Output: yes if φ is a theorem, no otherwise.

Theorem proving is highly intractable



- Semi-product modal logics have high complexities;
- Model checking more practical than theorem proving [Halper, Vardi, KR 1991].

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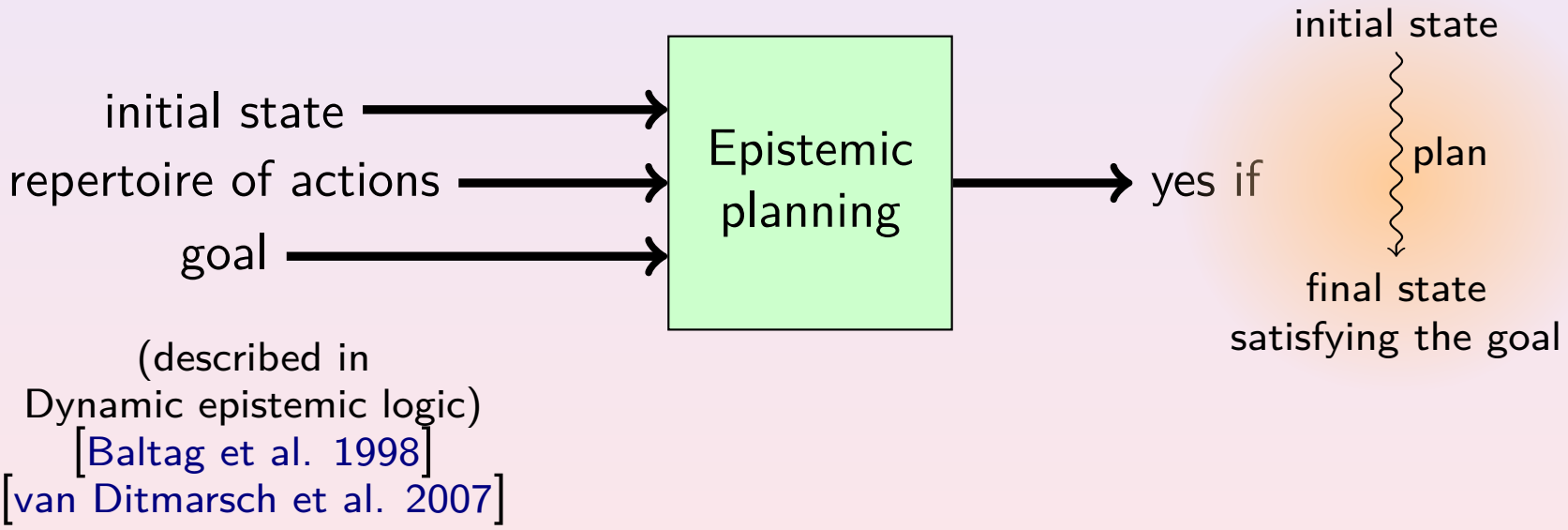
   - Undecidability of epistemic planning
   - Decidability when pre/post are Boolean
   - Complexity results
5. Conclusion

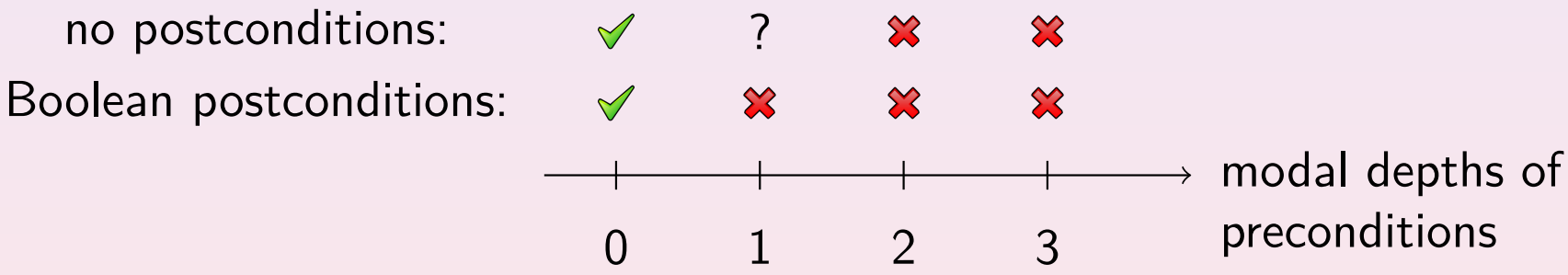
Epistemic planning

[Andersen, Bolander, 2011]

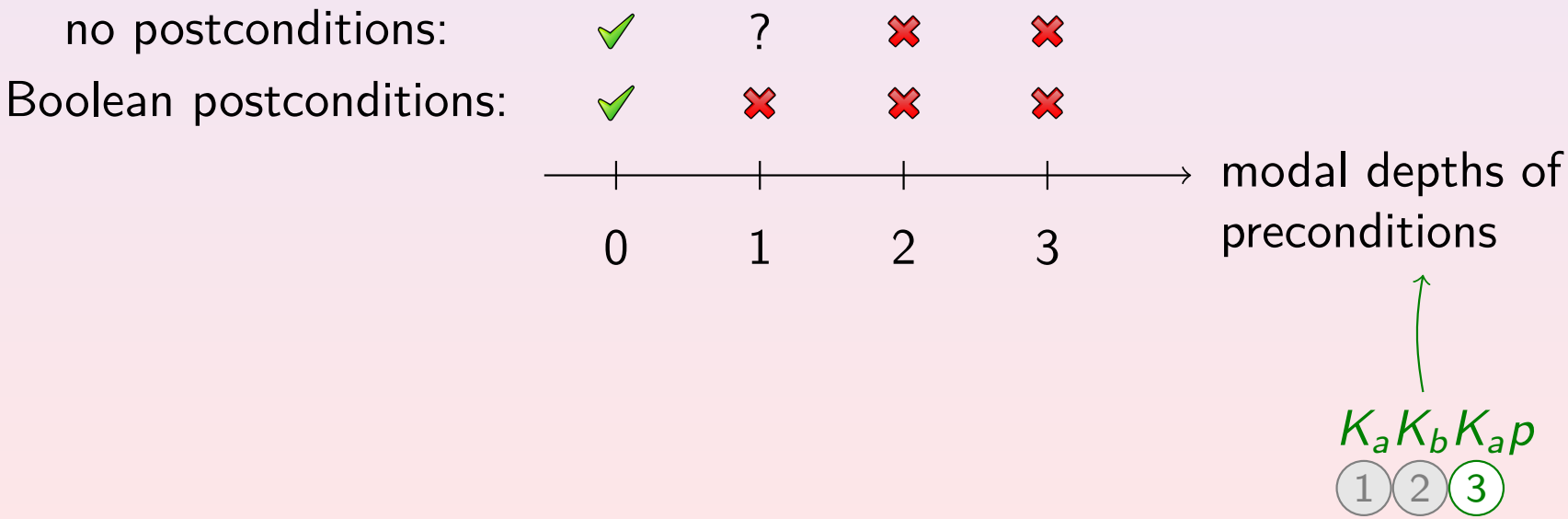


(described in Dynamic epistemic logic)
[Baltag et al. 1998]
[van Ditmarsch et al. 2007]

Decidability and undecidability of epistemic planning



Decidability and undecidability of epistemic planning



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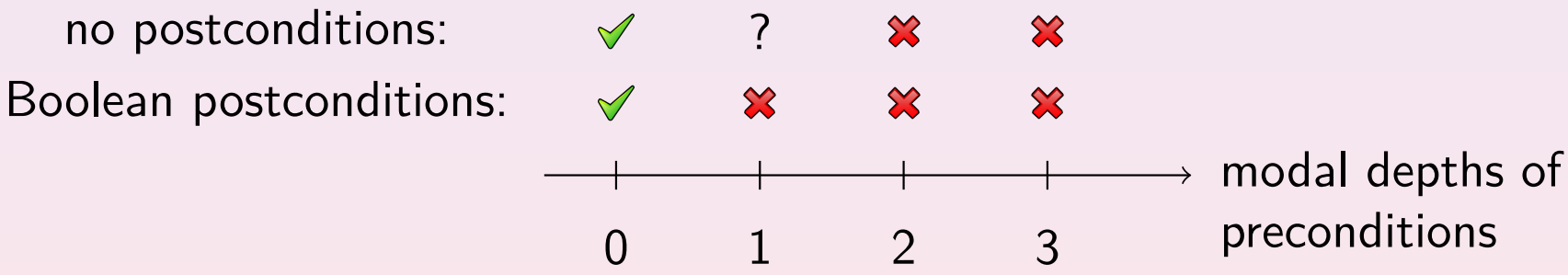
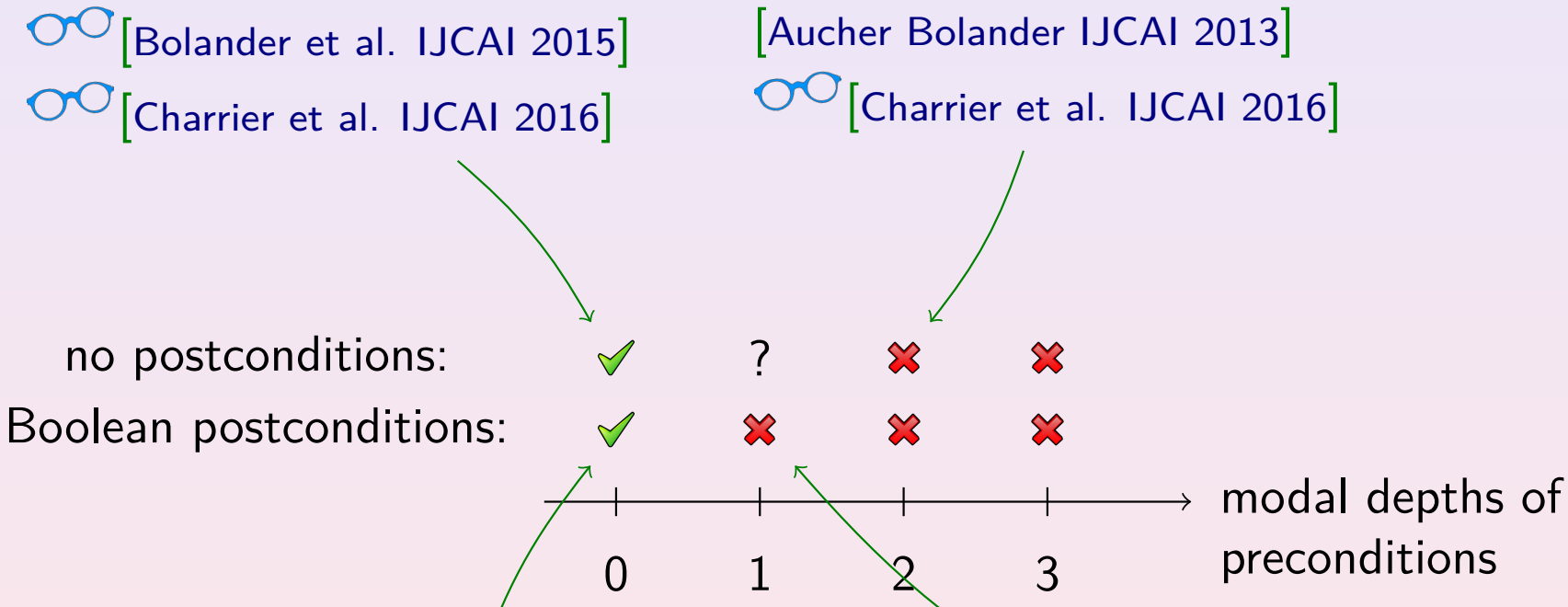


Decidability and undecidability of epistemic planning

[Bolander et al. IJCAI 2015]
[Charrier et al. IJCAI 2016]

[Aucher Bolander IJCAI 2013]
[Charrier et al. IJCAI 2016]



[Yu, Wen and Liu, IJCAI 2013]
[Aucher et al., SR2014]
[Douéneau-Tabot et al., AiML 2018]

[Andersen, Bolander, 2011]
[Lê Cong et al., IJCAI 2018]

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Epistemic planning is undecidable

Theorem

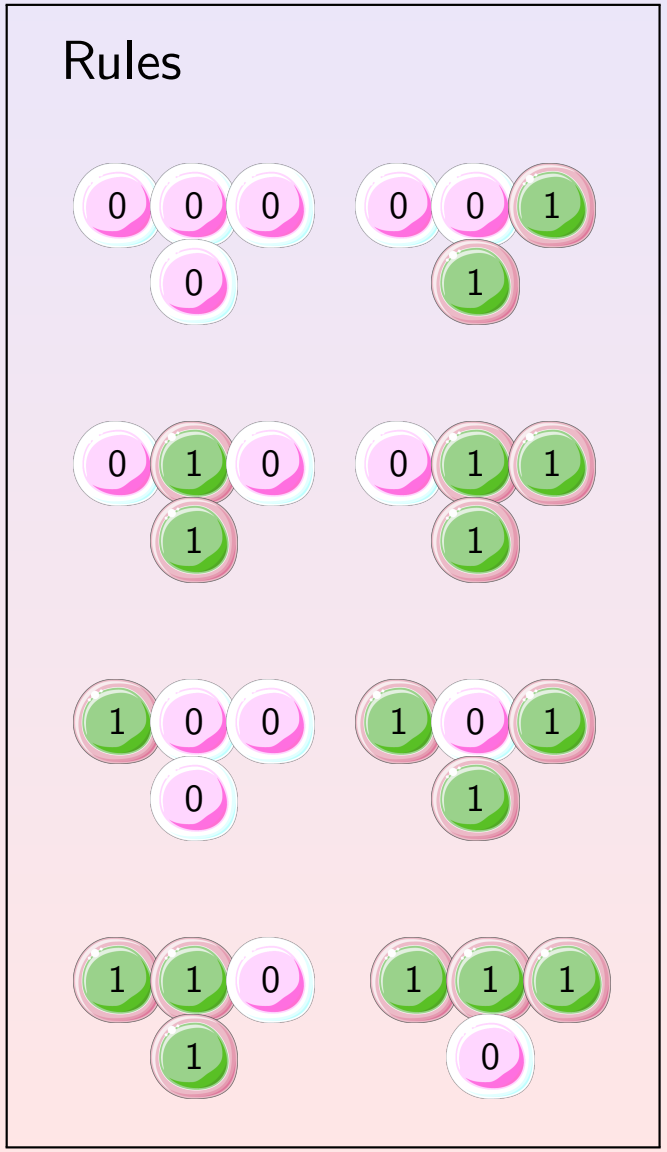
Epistemic planning is undecidable for:

$$\overbrace{\underbrace{\text{two agents} + \text{Boolean post} + \text{md(pre)} \leq 1}_{\text{[Andersen, Bolander, JANCL 2011]}} + \text{fixed repertoire of one action} + \text{6 atomic propositions}}^{\text{[Lê Cong, Pinchinat, \_, IJCAI-ECAI 2018]}}$$

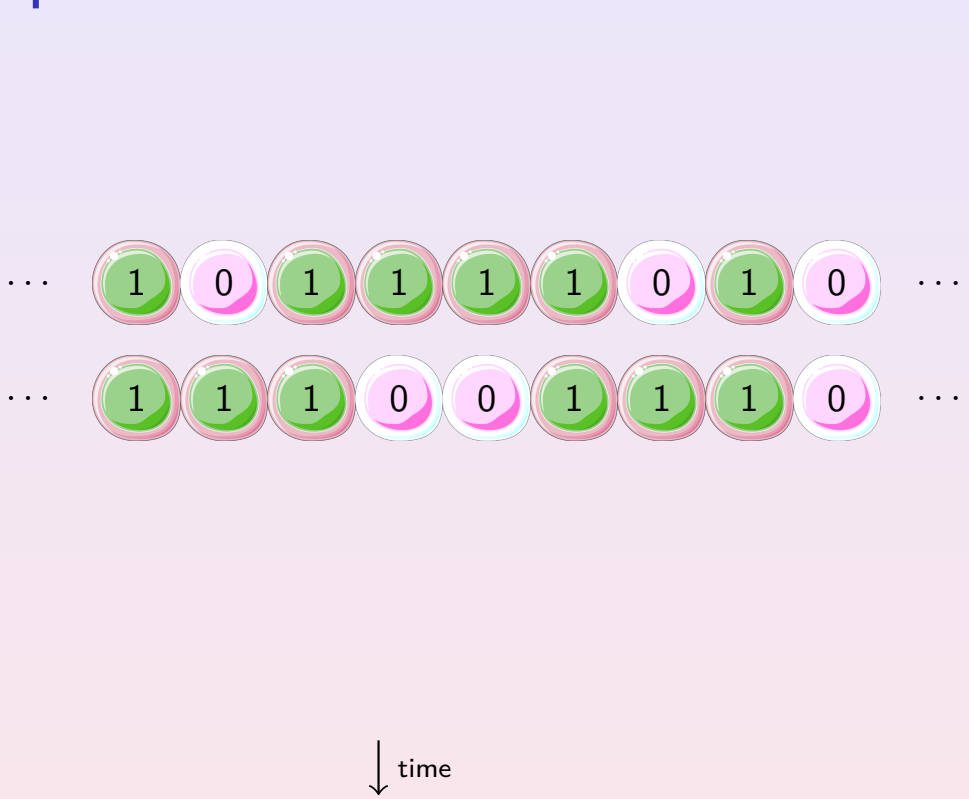
Proof: reduction from halting problem of a small universal cellular automaton.

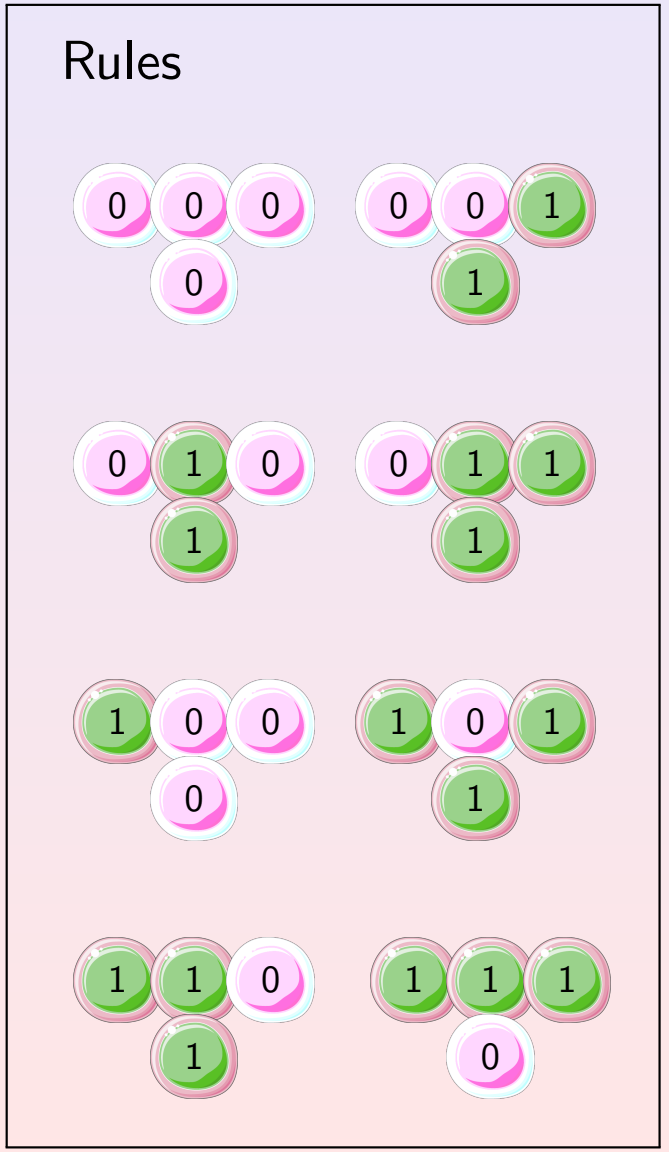
Example: the 110 Rule cellular automaton

time



Example: the 110 Rule cellular automaton





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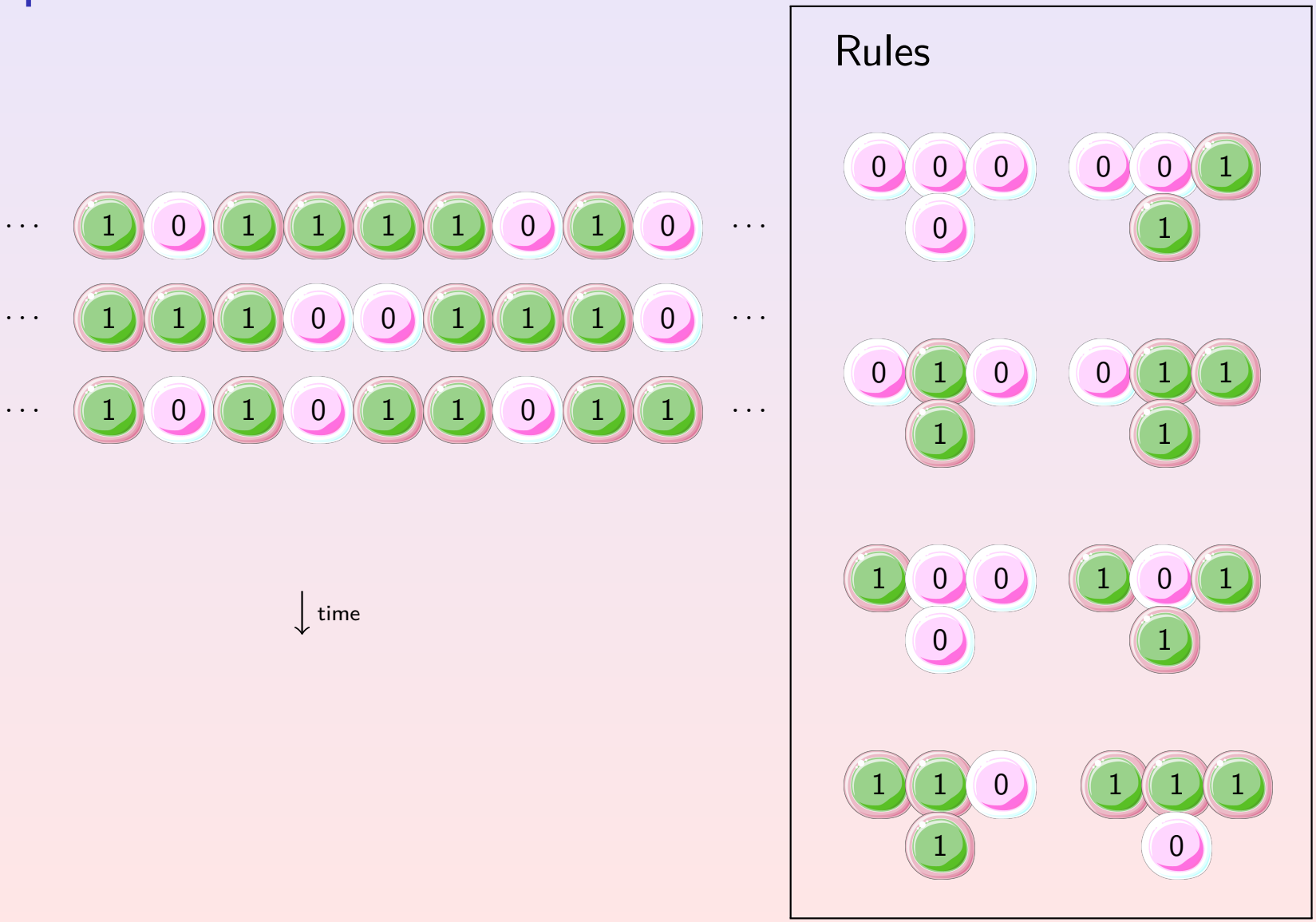

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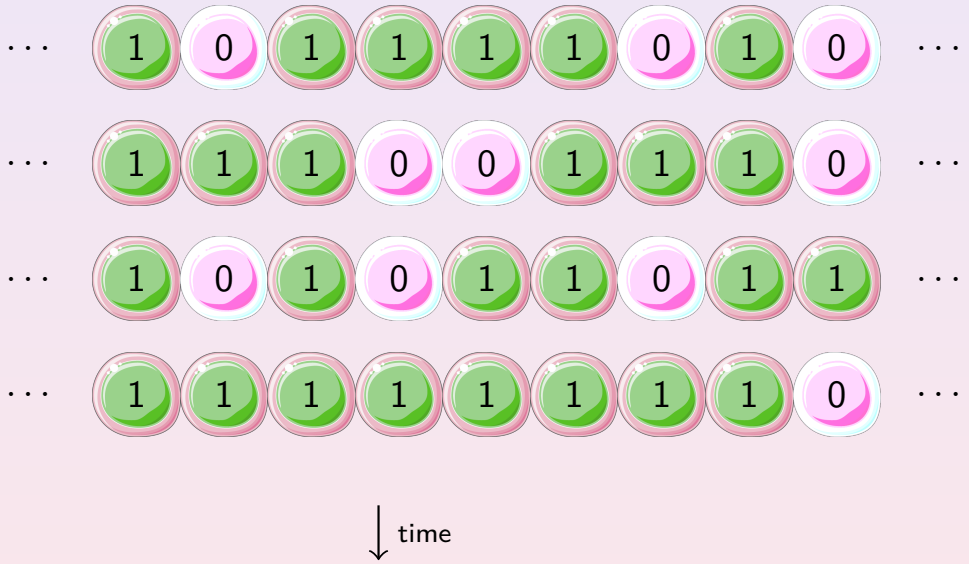

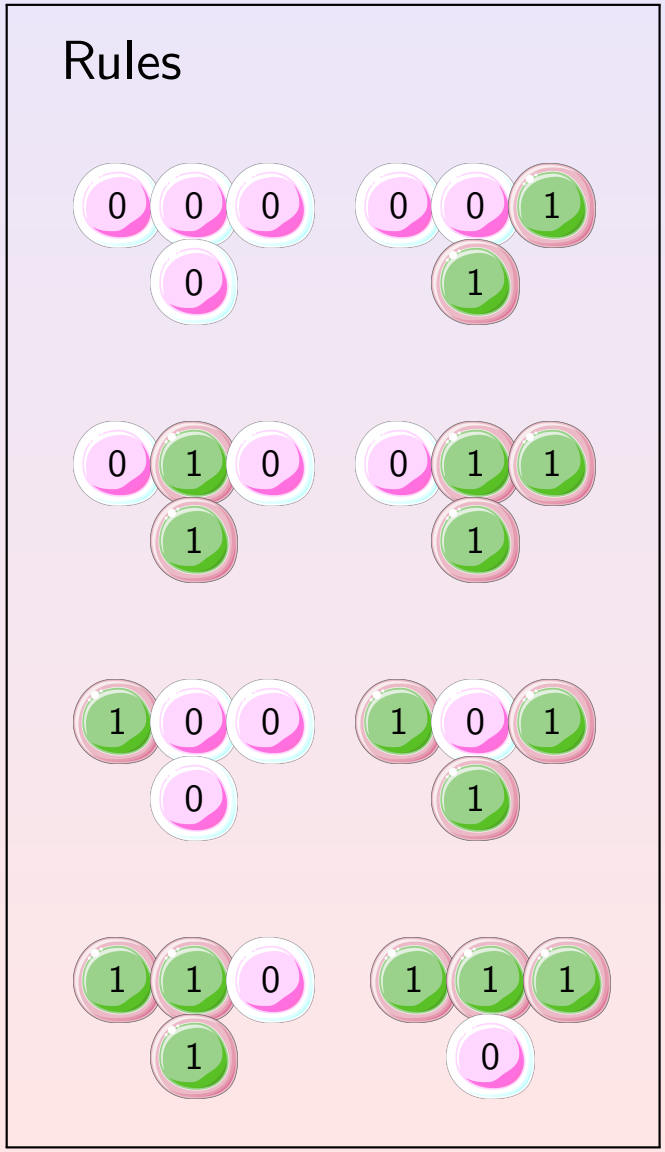

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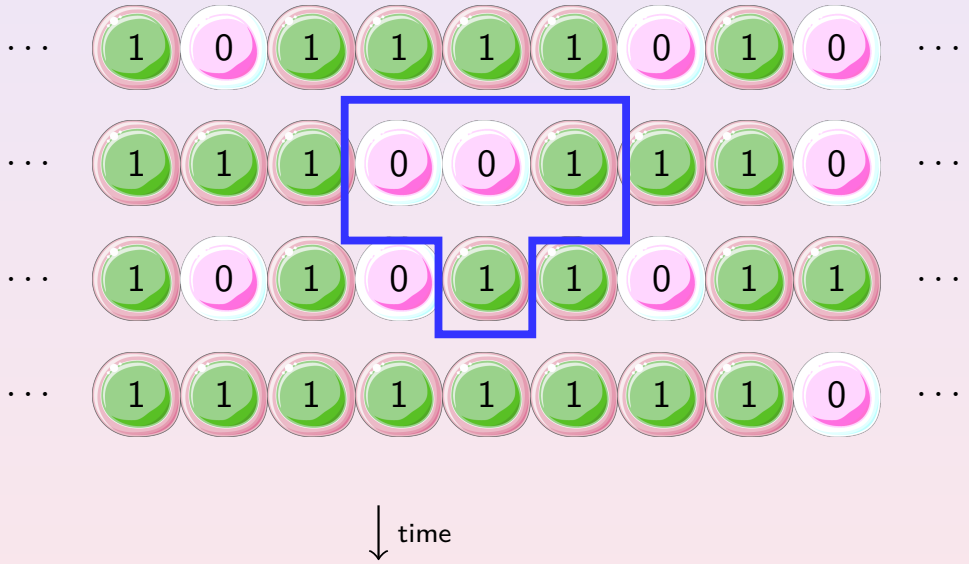
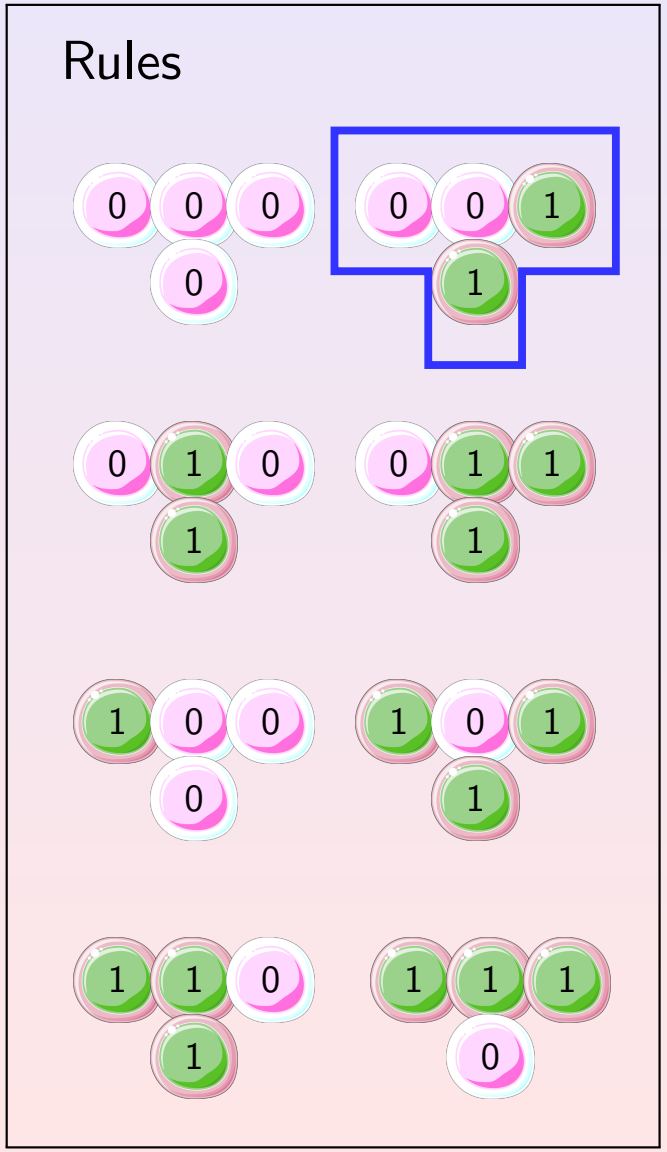
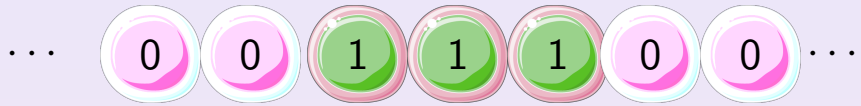
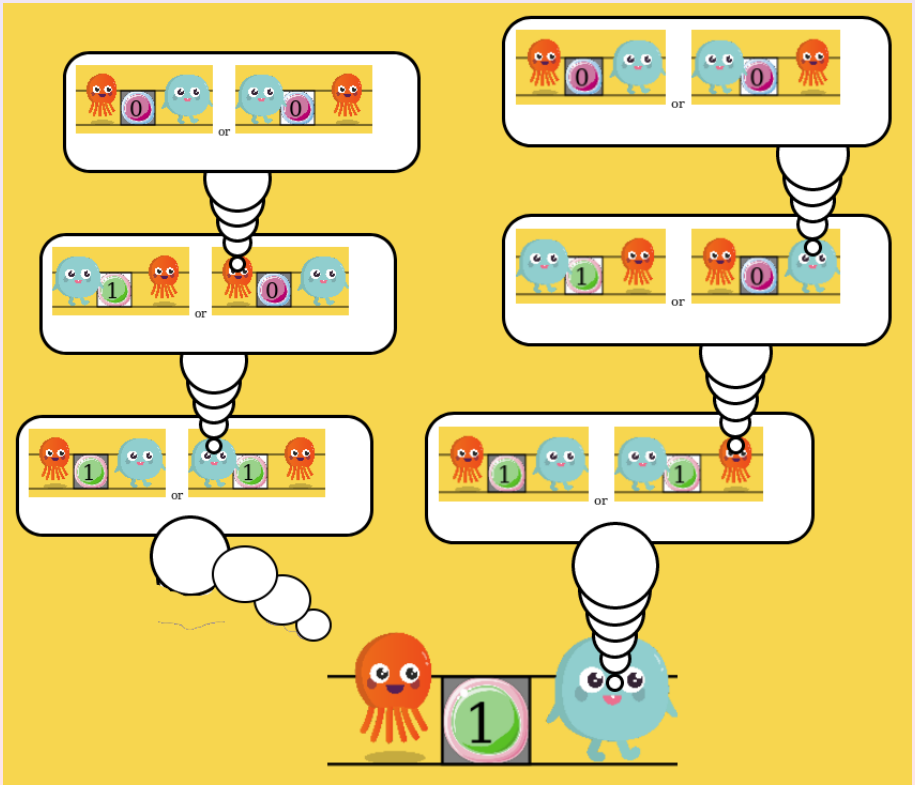




Encoding an automaton configuration in a state





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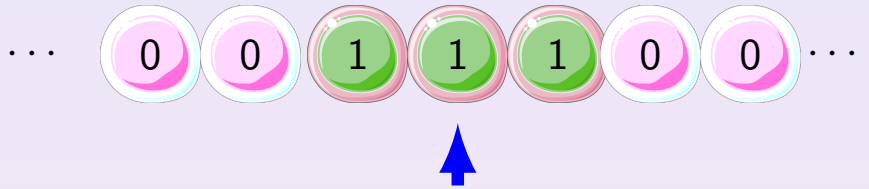

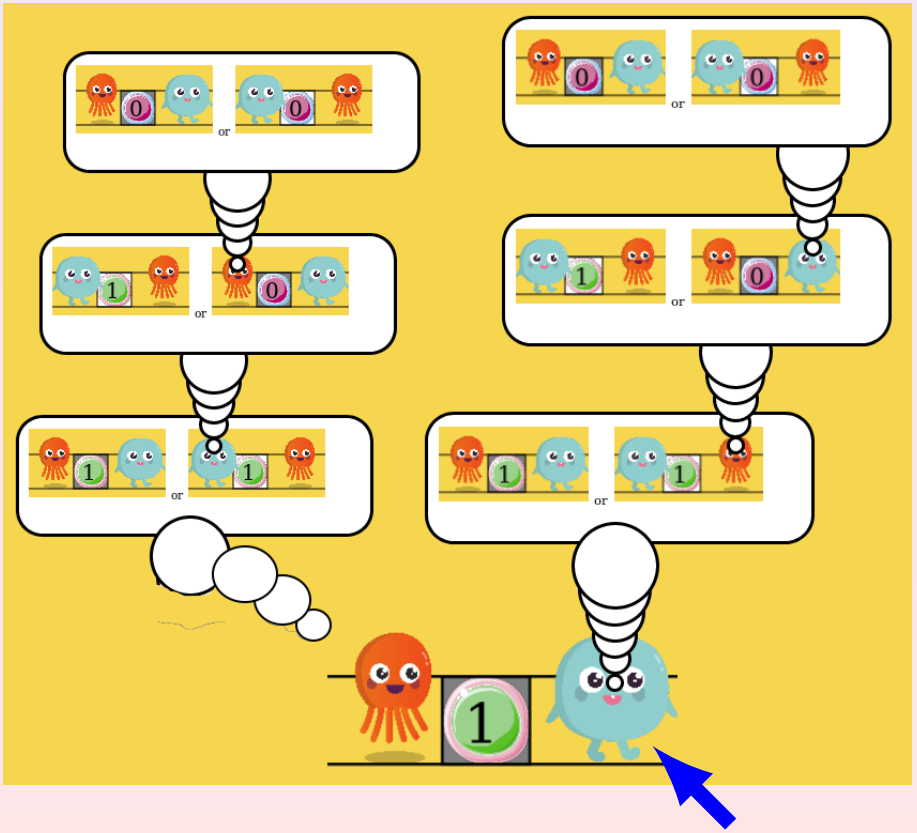

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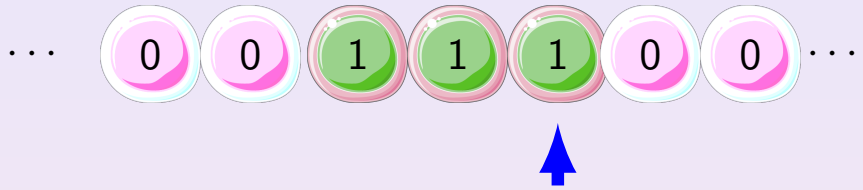

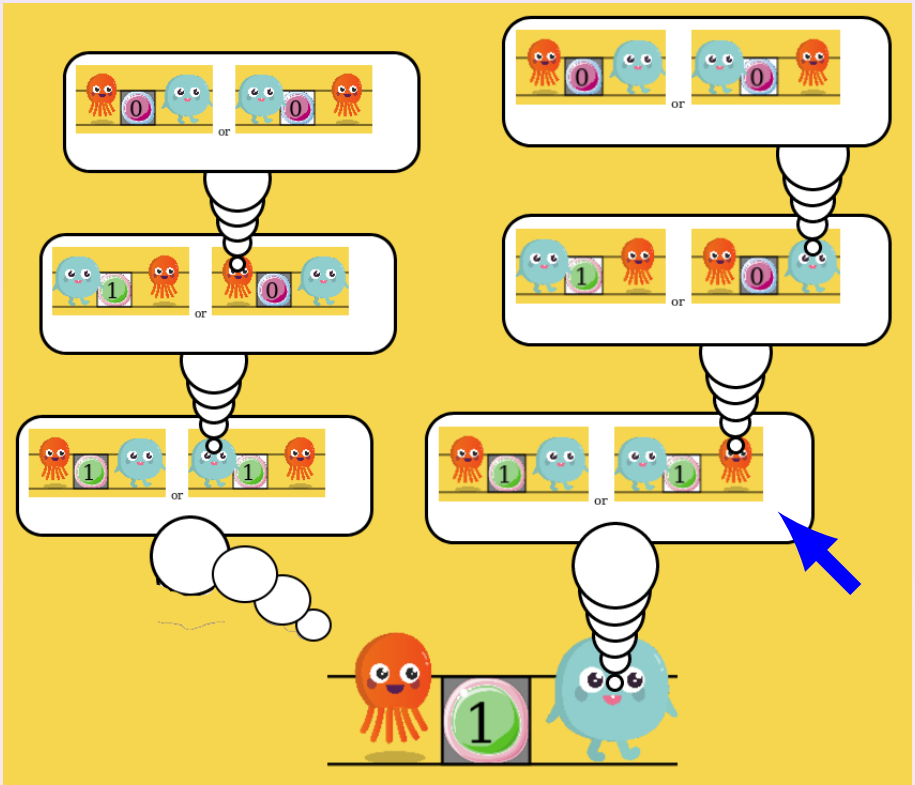

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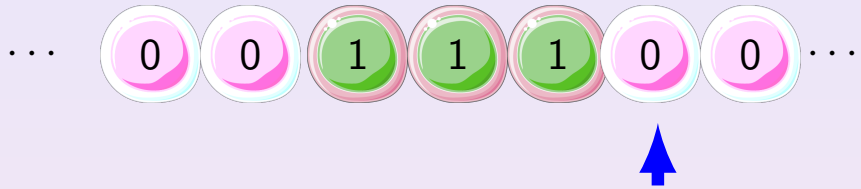

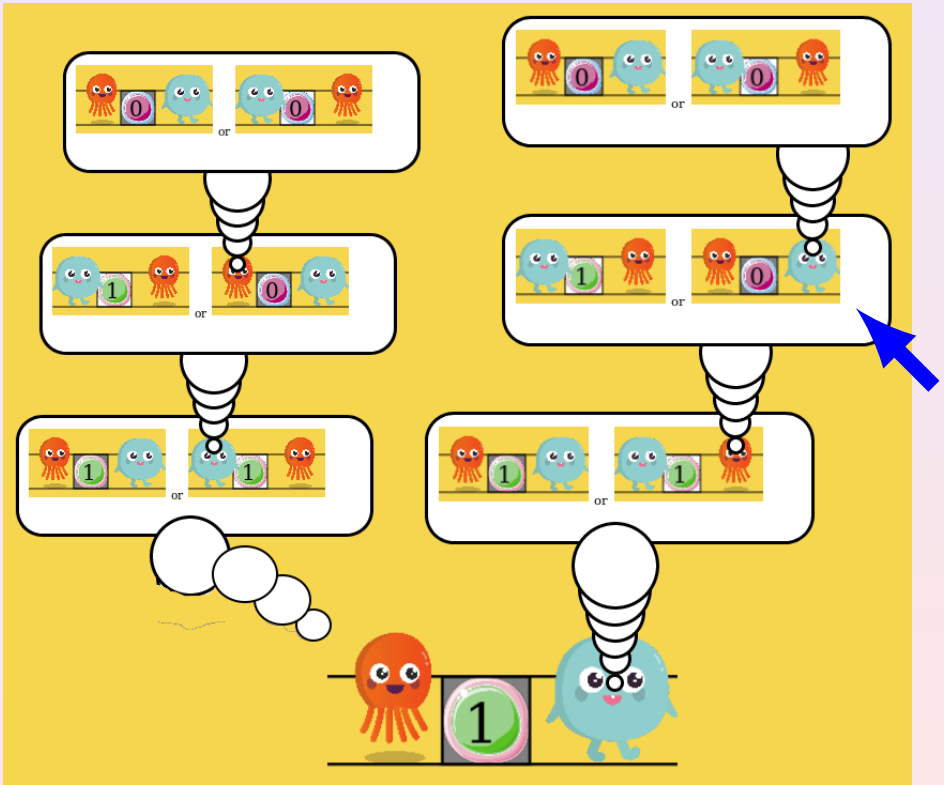

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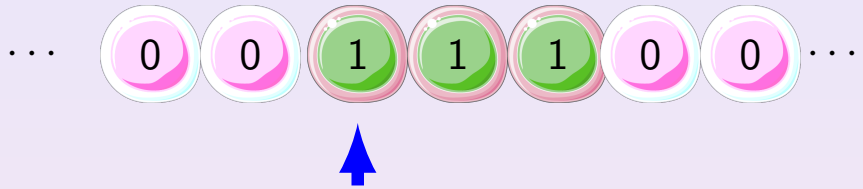

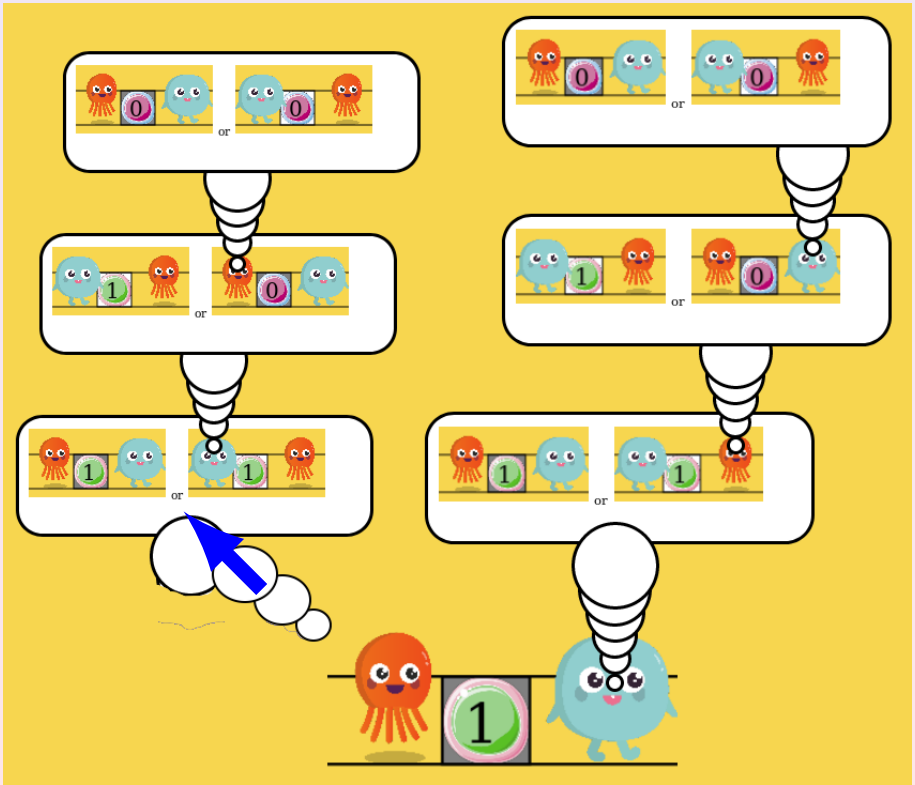

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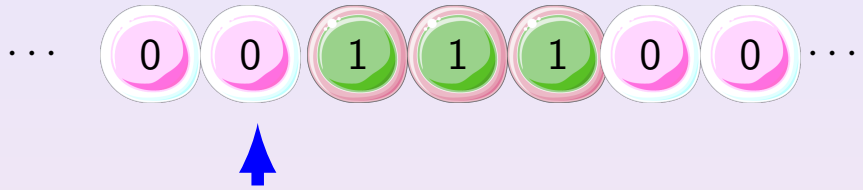

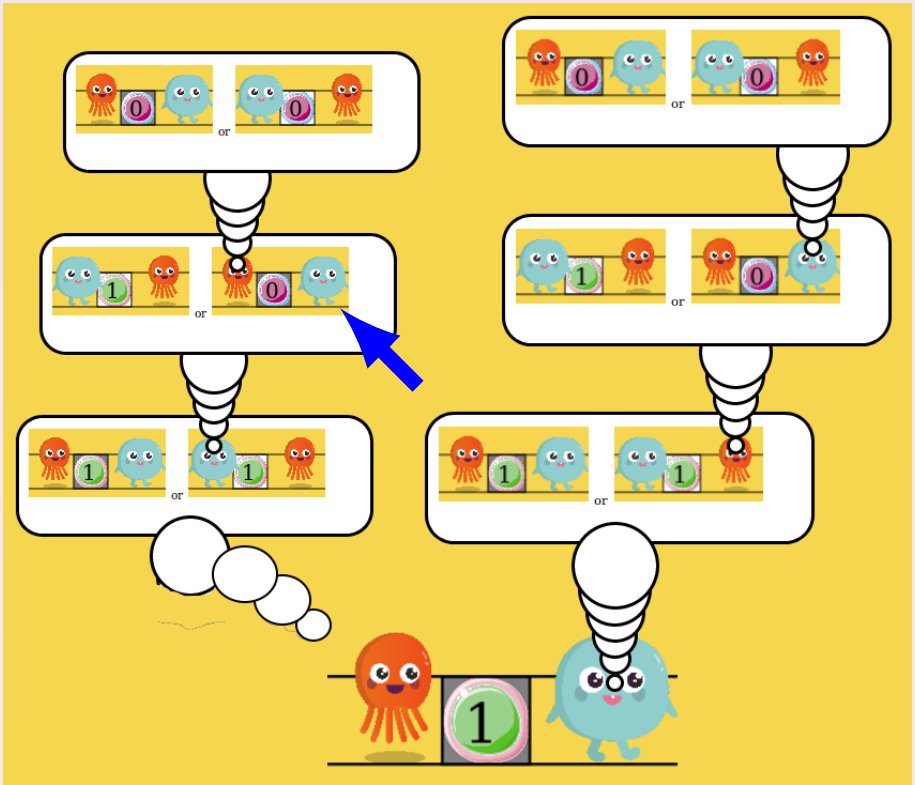

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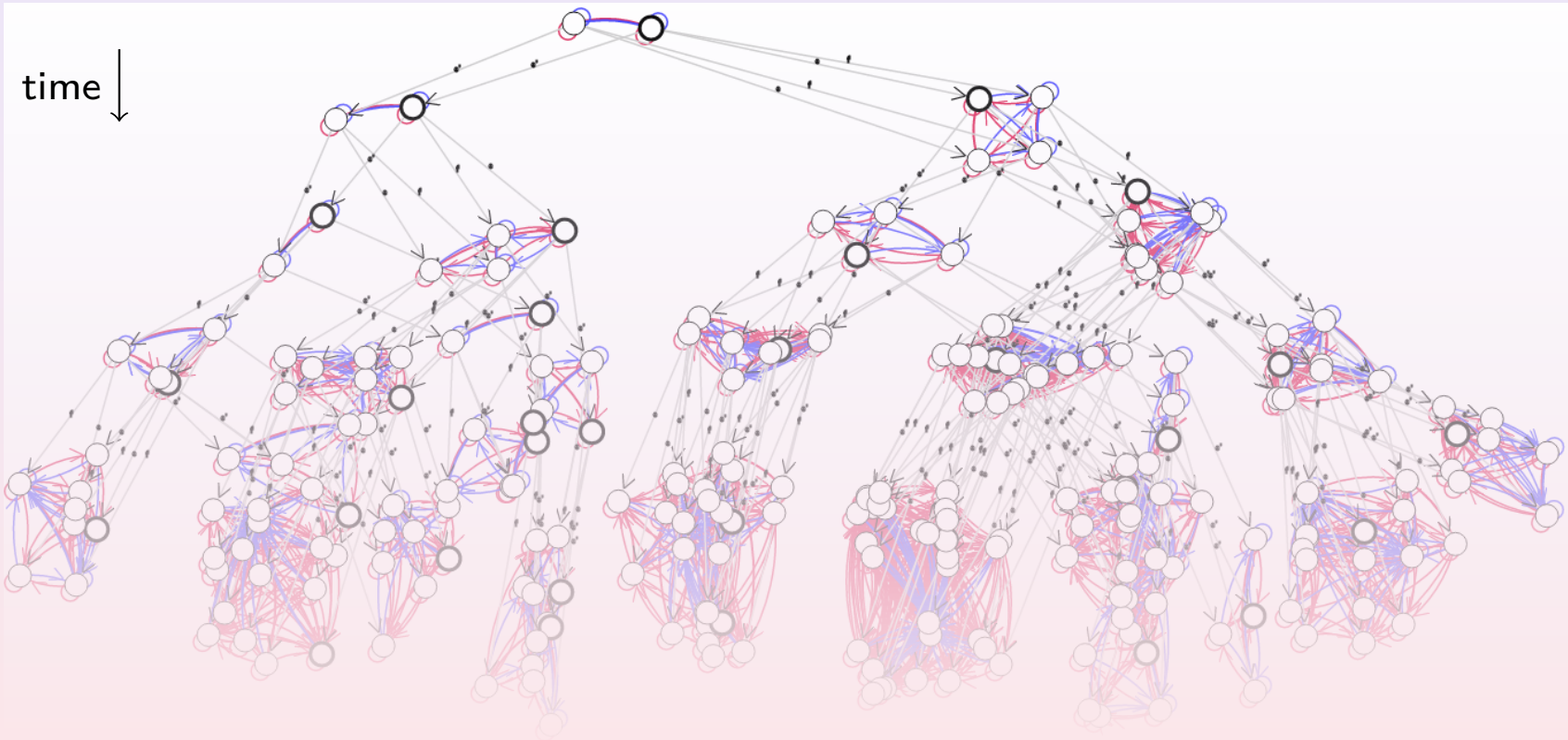
(Infinite) epistemic temporal structures



Epistemic planning: first-order query $\exists x, goal(x)$

Decidability when pre/post are Boolean

Theorem ([Yu, Wen, and Liu 2013], [Aucher, Maubert, and Pinchinat 2014])

When pre/post are Boolean, epistemic planning is decidable.

Epistemic planning is a first-order-query

|

first-order-query on automatic structures is decidable.

|

Epistemic temporal structures are automatic

Theorem (👓 [Douéneau-Tabot, Pinchinat and _, 2018])

Even decidable for goals in epistemic linear μ-calculus.

(cf. Sophie's talk)

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Complexity results on epistemic planning

	one centralized planner [Bolander et al. IJCAI 2015]	many players [in submission]
public announcements	NP-c	PSPACE-c
public actions	PSPACE-c	EXPTIME-c
Boolean pre/post	decidable	undecidable [Reif, Peterson, 1979]
all	undecidable	

Uninformed semantics (cf. Bastien's talk).

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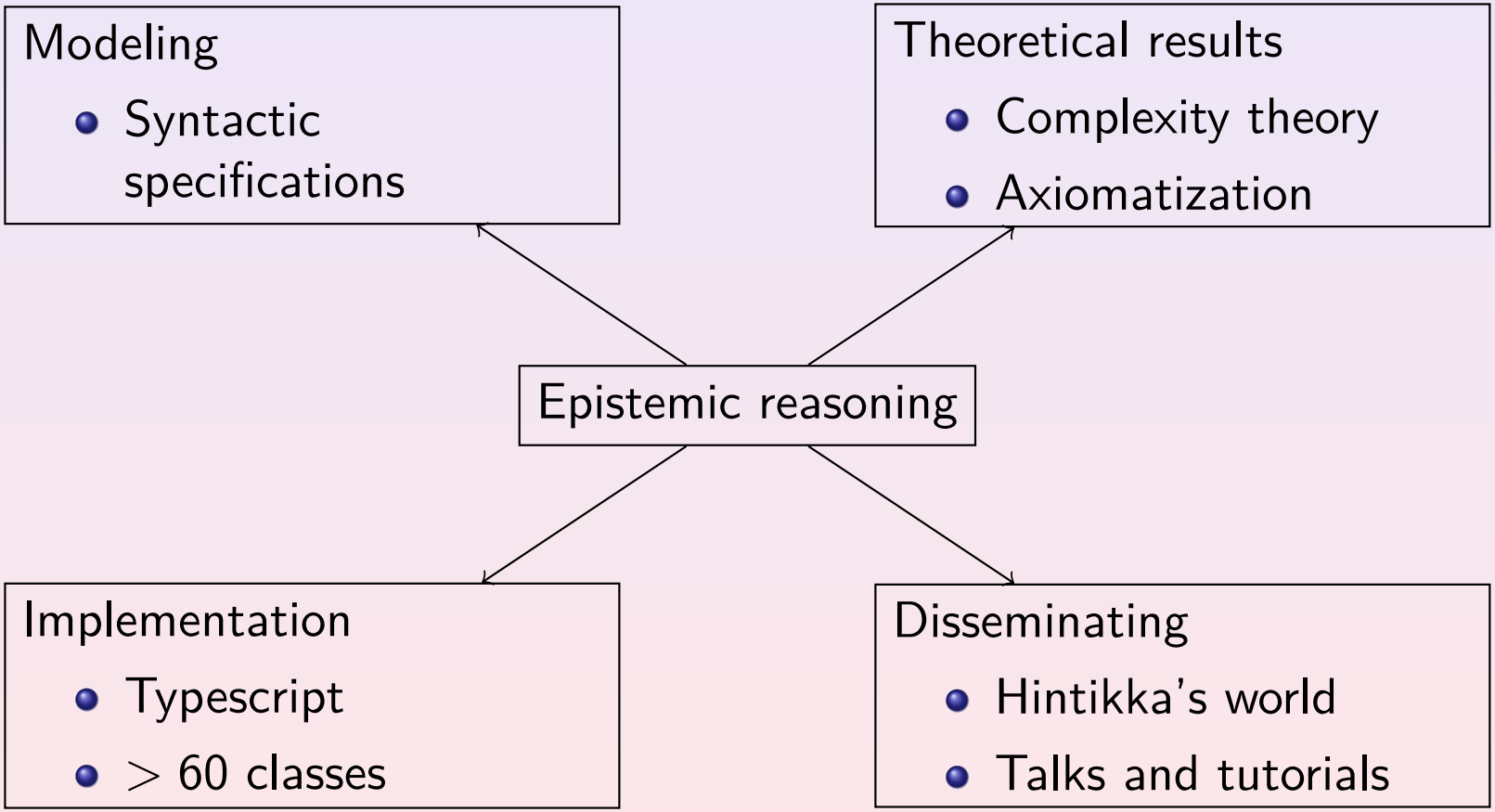
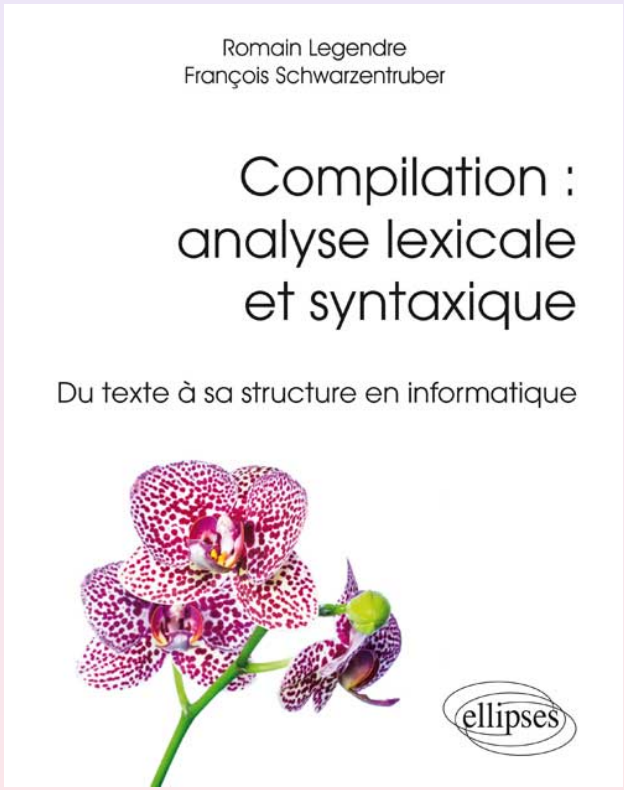
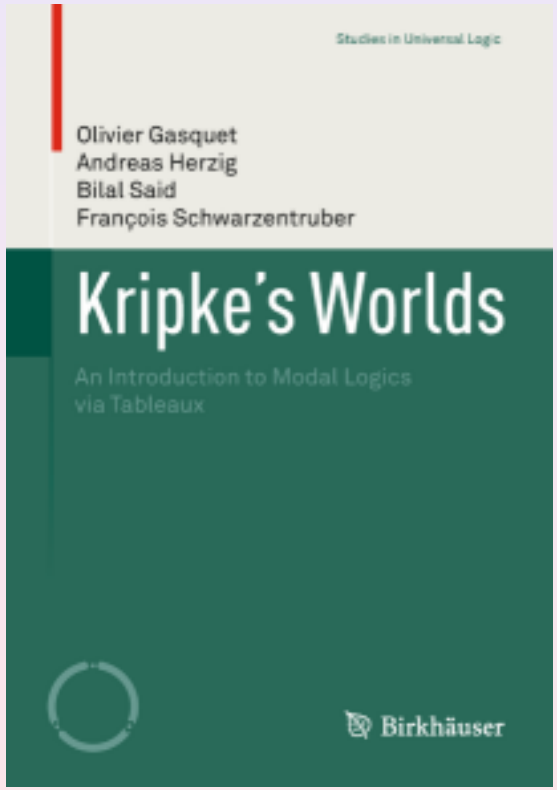
Summary of my contribution



Books


Romain Legendre
François Schwarzentruber
Compilation : analyse lexicale et syntaxique
Du texte à sa structure en informatique
ellipses


Studies in Universal Logic
Olivier Gasquet
Andreas Herzig
Bilal Said
François Schwarzentruber
Kripke's Worlds
An Introduction to Modal Logics via Tableaux
Birkhäuser

Research activities

Program committees

IJCAI 201x, AAMAS 201x, AAAI 2019, **demo track of IJCAI 2019**

Organization

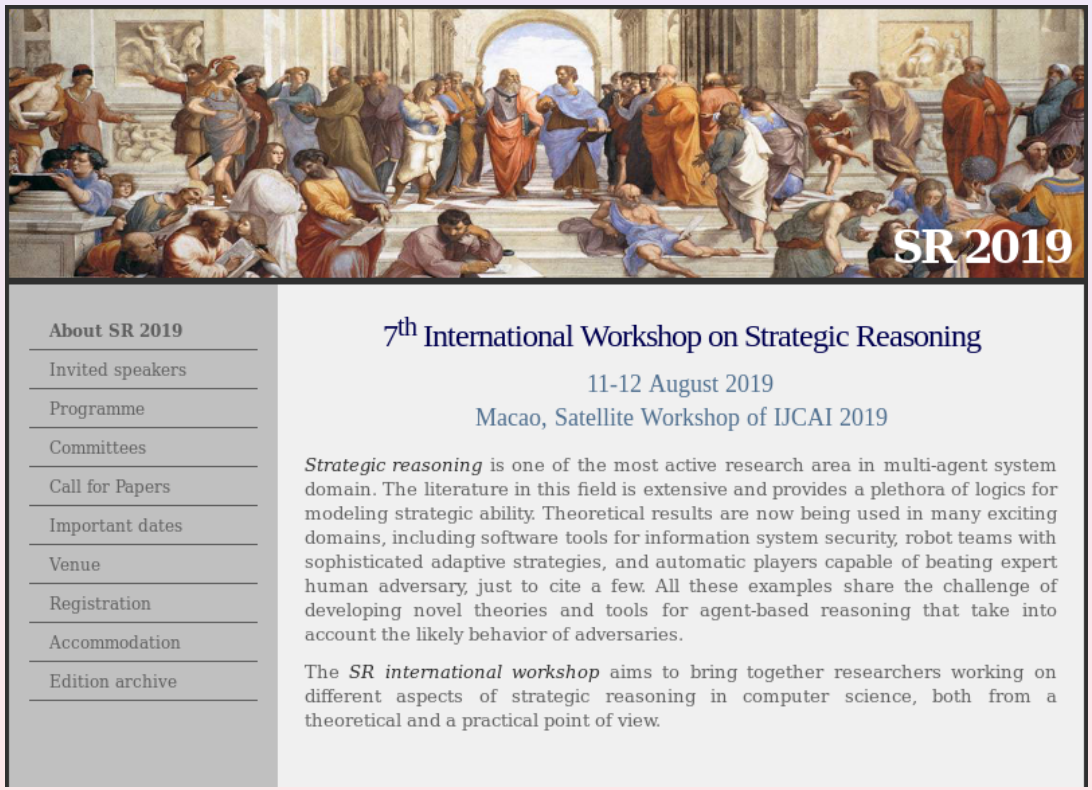
- LOFT 2010
- Tools for teaching logic in 2015
- Robolog 2017
- French conference for young researchers in 2018
- FMAI 2019
- Strategic reasoning 2019 @ IJCAI 2019

Tutorials

IJCAI-ECAI 2018, AAMAS 2019, IJCAI 2019

Advertising: Strategic reasoning 2019 @ IJCAI 2019

Deadline: 12 May 2019



Top-down VS bottom-up research

Epistemic reasoning

↓

Research

Tristan Charrier
(PhD 2015-2018)
co-supervised with
Sophie Pinchinat

Research

↑

Attack tree synthesis

Sébastien Lê Cong
(PhD 2018-2020)
co-supervised with
Sophie Pinchinat

Research

↑

UAVs for firemen

Arthur Queffelec
(PhD 2018-2020)
co-supervised with
Ocan Sankur
UAV-Retina Project
hed by
François Bodin

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DEL and formal language theory

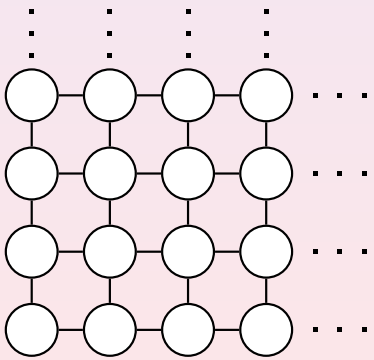
Question

Is epistemic planning (pre md 1, ~~post~~) decidable?

First-order query is decidable

First-order query is undecidable

Automatic structures



Pushdown automata?
Caucal hierarchy?

Turing-complete structures

Knowledge-based programs as plans

KBP for agent a

if a knows it is sunny
  say hello
  goto park
else
  stay silent
  goto café

KBP for agent b

wait for a message
if b knows a knows it is sunny
  goto park
else
  goto café

[Saffidine, Zanuttini, _, AAAI 2018]

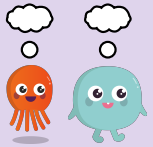
- Operational semantics;
- Informed semantics (cf. Bastien's talk):
  common knowledge of the KBPs synchronous execution;
- Complexity of the verification of distributed KBPs.

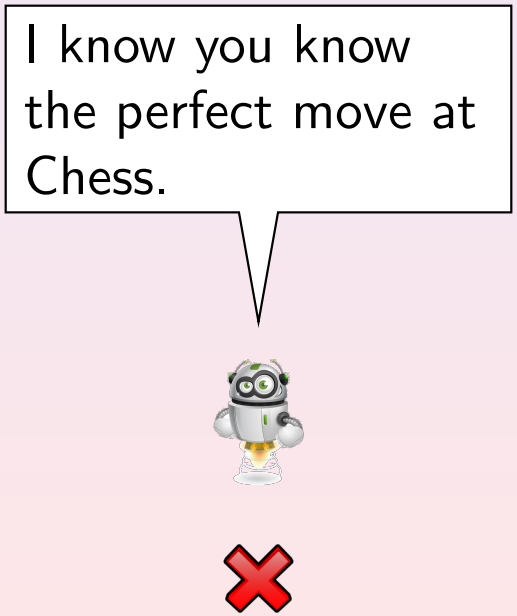
Question

How to synthesize KBPs?

Limited belief

Issue when interacting with humans: logical omniscience

Because knowledge computation not modeled in the semantics  .

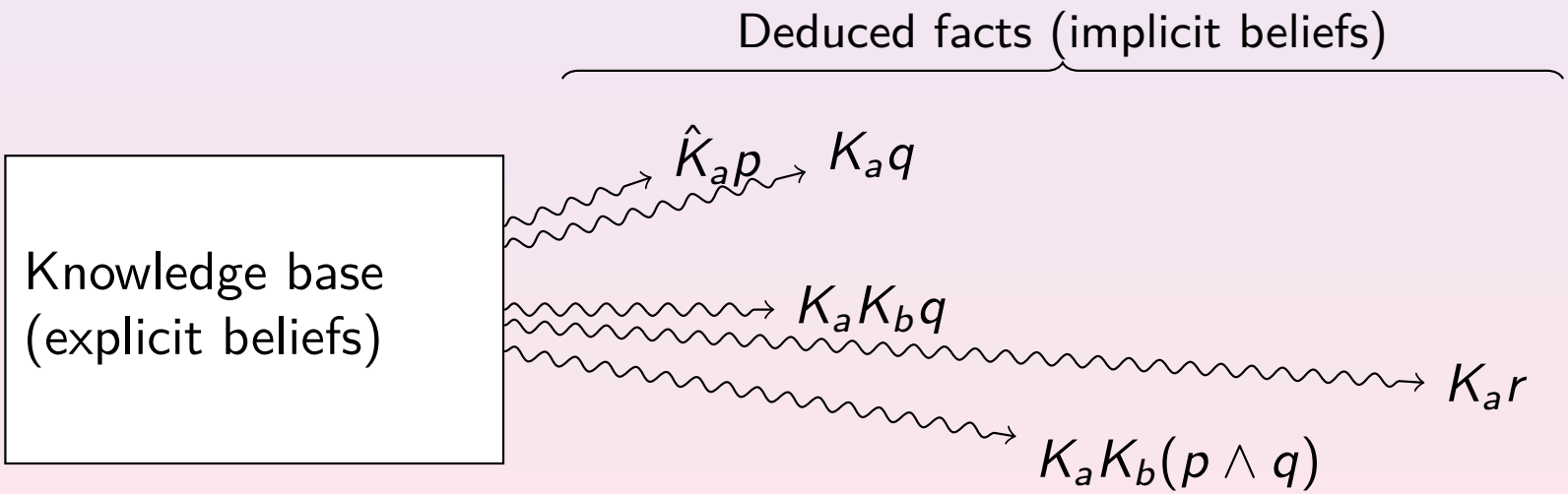


Limited belief

Limited belief

Solution

Model the knowledge computation via *proof systems*!
[Levesque, 1984], [Lakemeyer, 1994], [Kaplan and Schubert, 2000]



[Liu et al., 2004], [Schwering, 2017], [Chen, Saffidine, Schwering, 2018]

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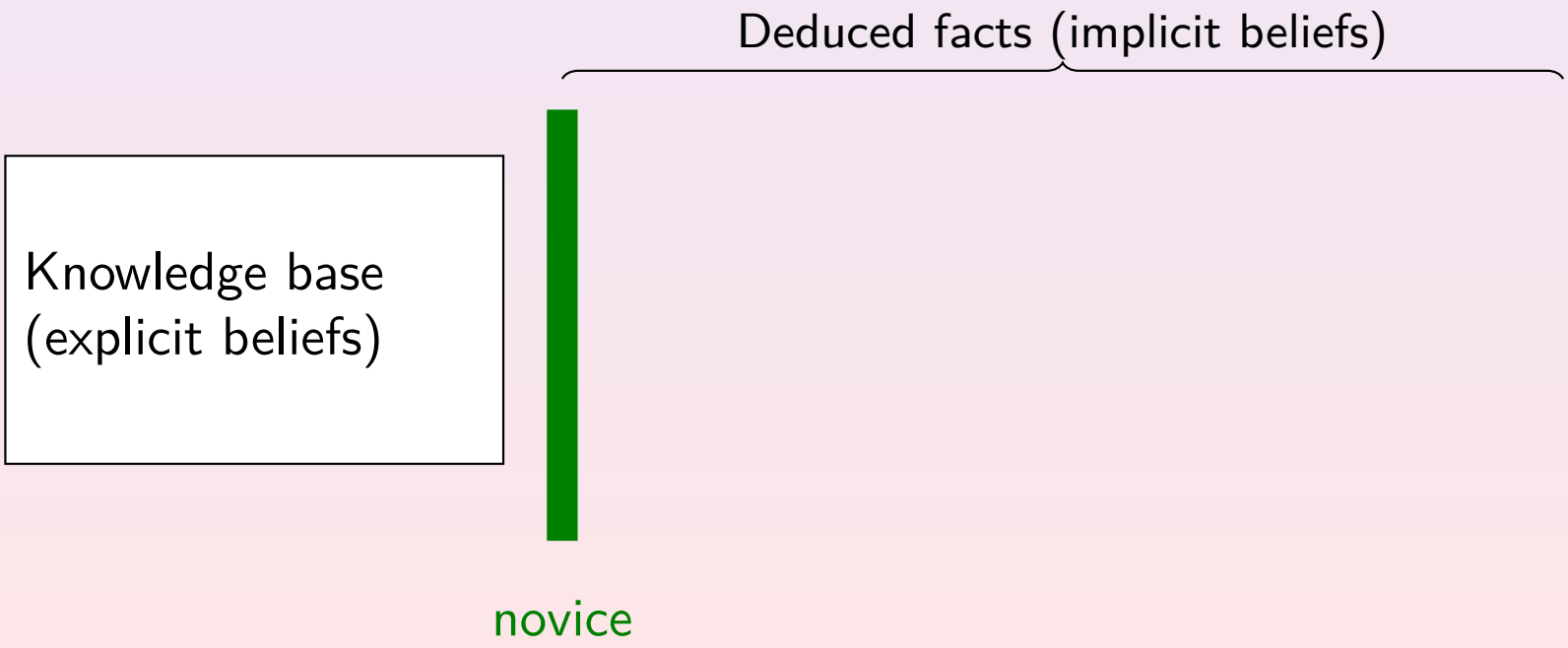

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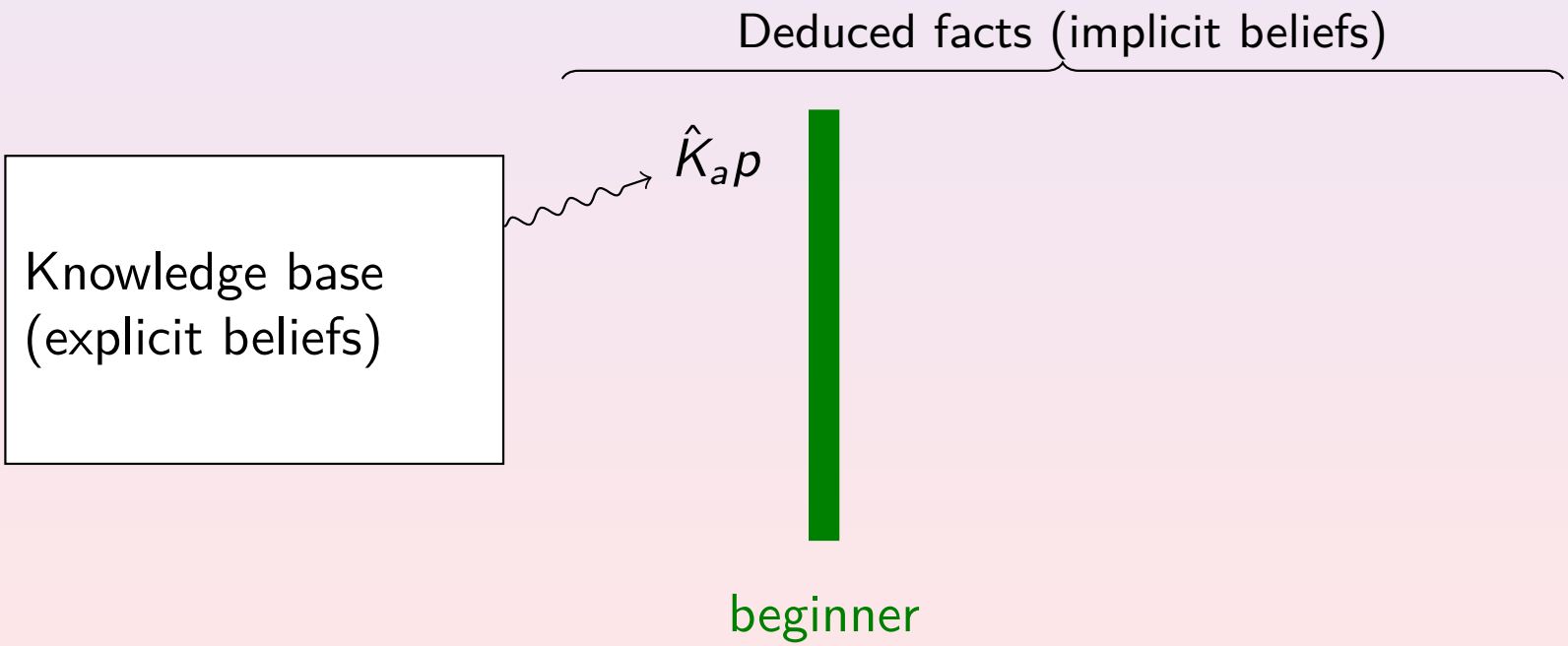

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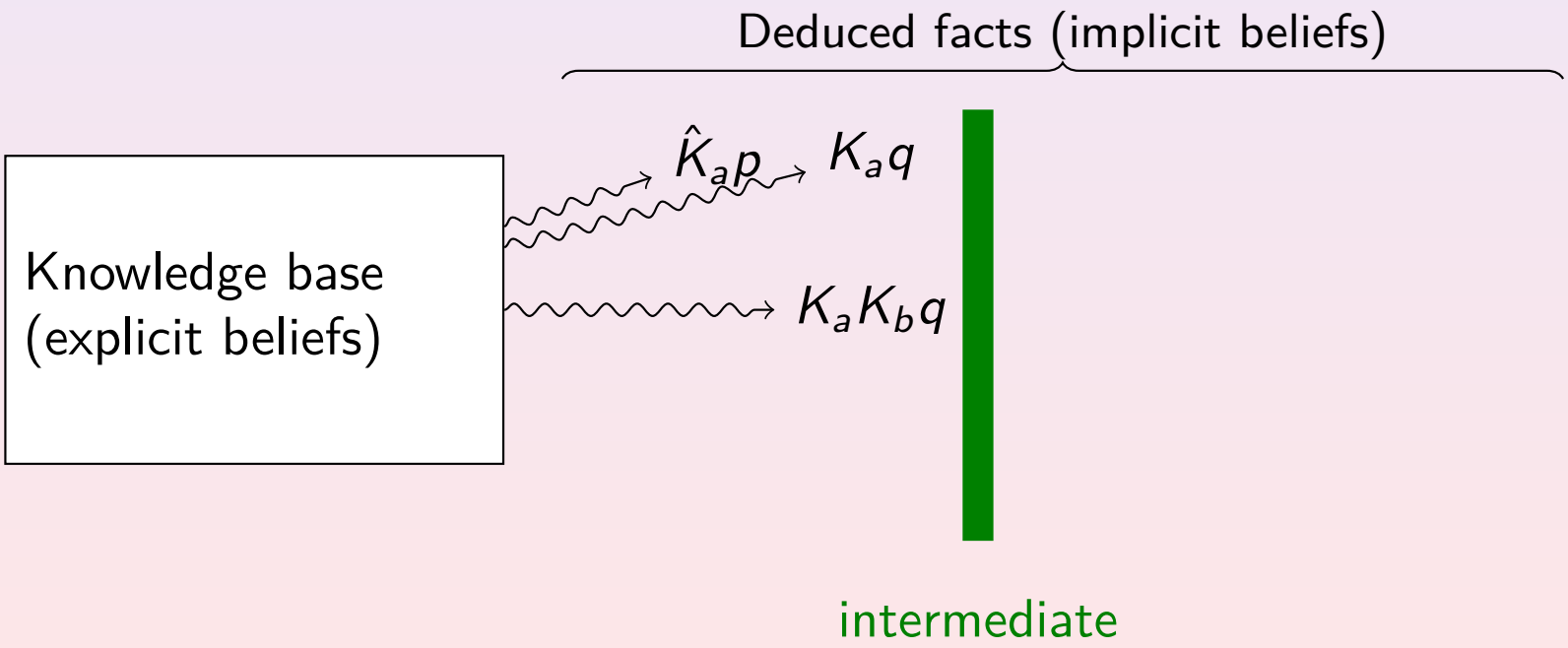

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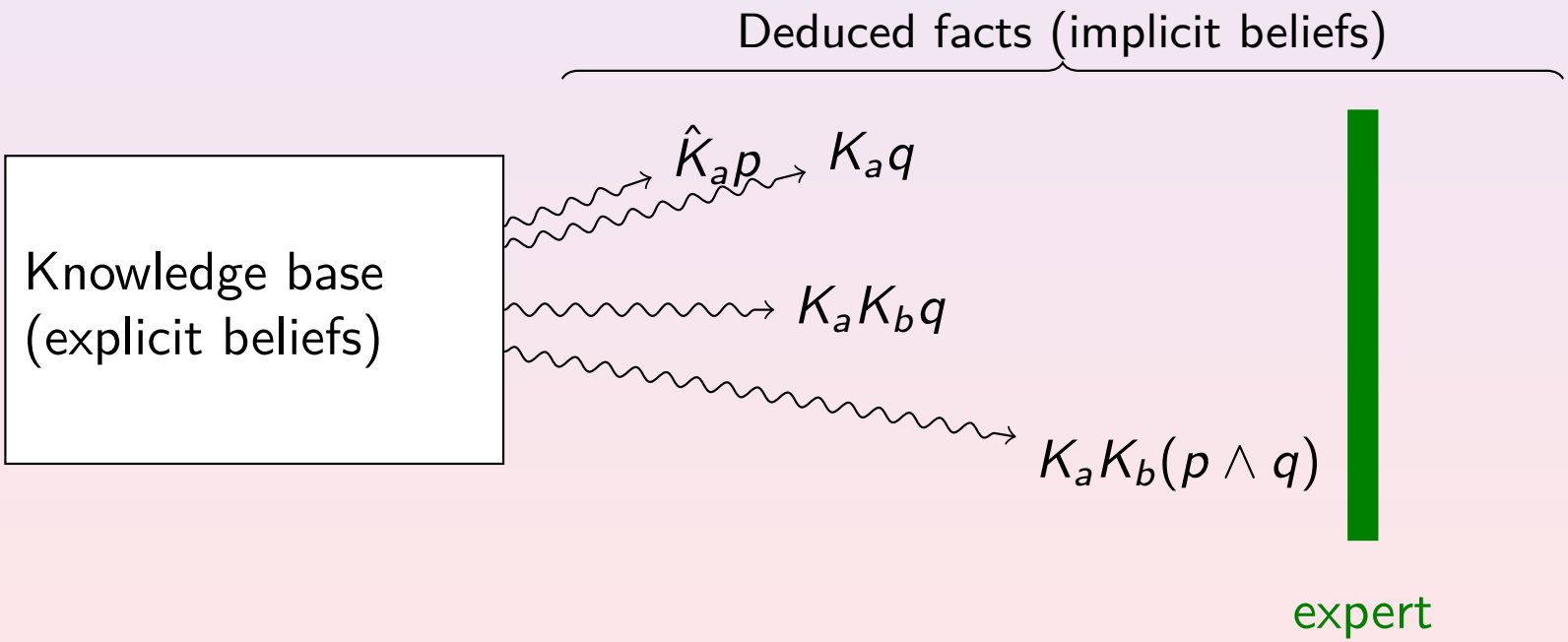

[Liu et al., 2004], [Schwering, 2017], [Chen, Saffidine, Schwering, 2018]

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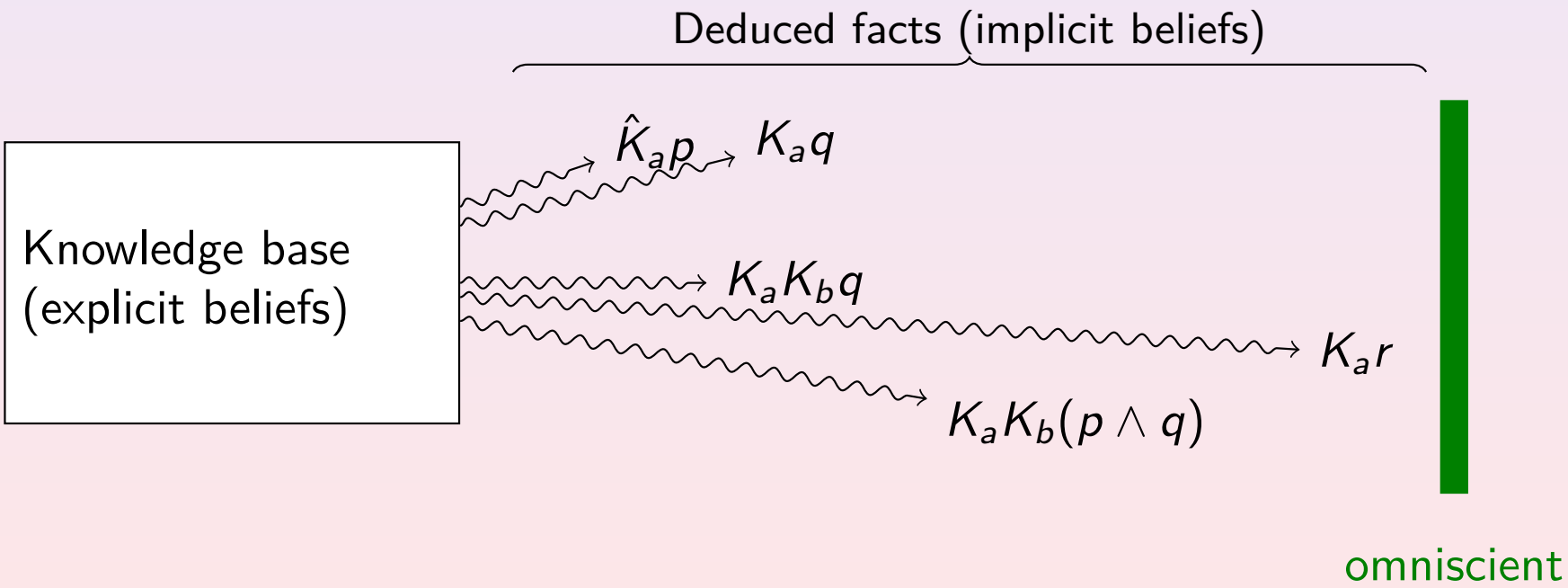


[Liu et al., 2004], [Schwering, 2017], [Chen, Saffidine, Schwering, 2018]

Limited belief

Theorem

With one agent, theorem proving is:

- *NP-complete,*
- *but PSPACE-complete when the belief level is part of the input*

[Chen, Saffidine, Schwering, 2018]

Question

- *Extension to the multi-agent case?*
- *Extension to DEL actions?*
- *Provide approximate solutions?*

Hintikka's World

Implement many different models

- belief revision, plausibility models
- probabilistic models
- interpreted systems
- explicit VS implicit beliefs
- verification/synthesize of knowledge-based programs

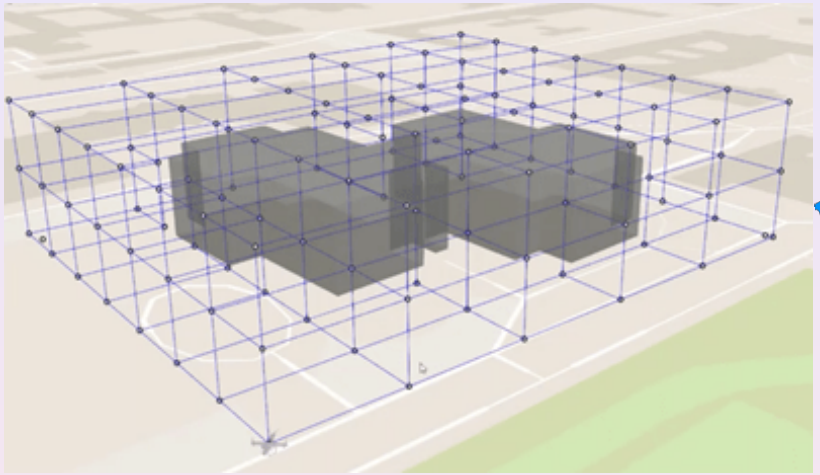
Add other examples

From distributed systems, imperfect info of the dining philosophers, etc. (cf. Yoram's talk), (cf. Valentin's talk), (cf. Hans and Vaishnavi's talk)

A tool for advertising AI techniques

Planning SAT Sampling (cf. Kuldeep's talk)

Planning of a fleet of connected UAVs



[Bodin et al. demo IJCAI-ECAI 2018]

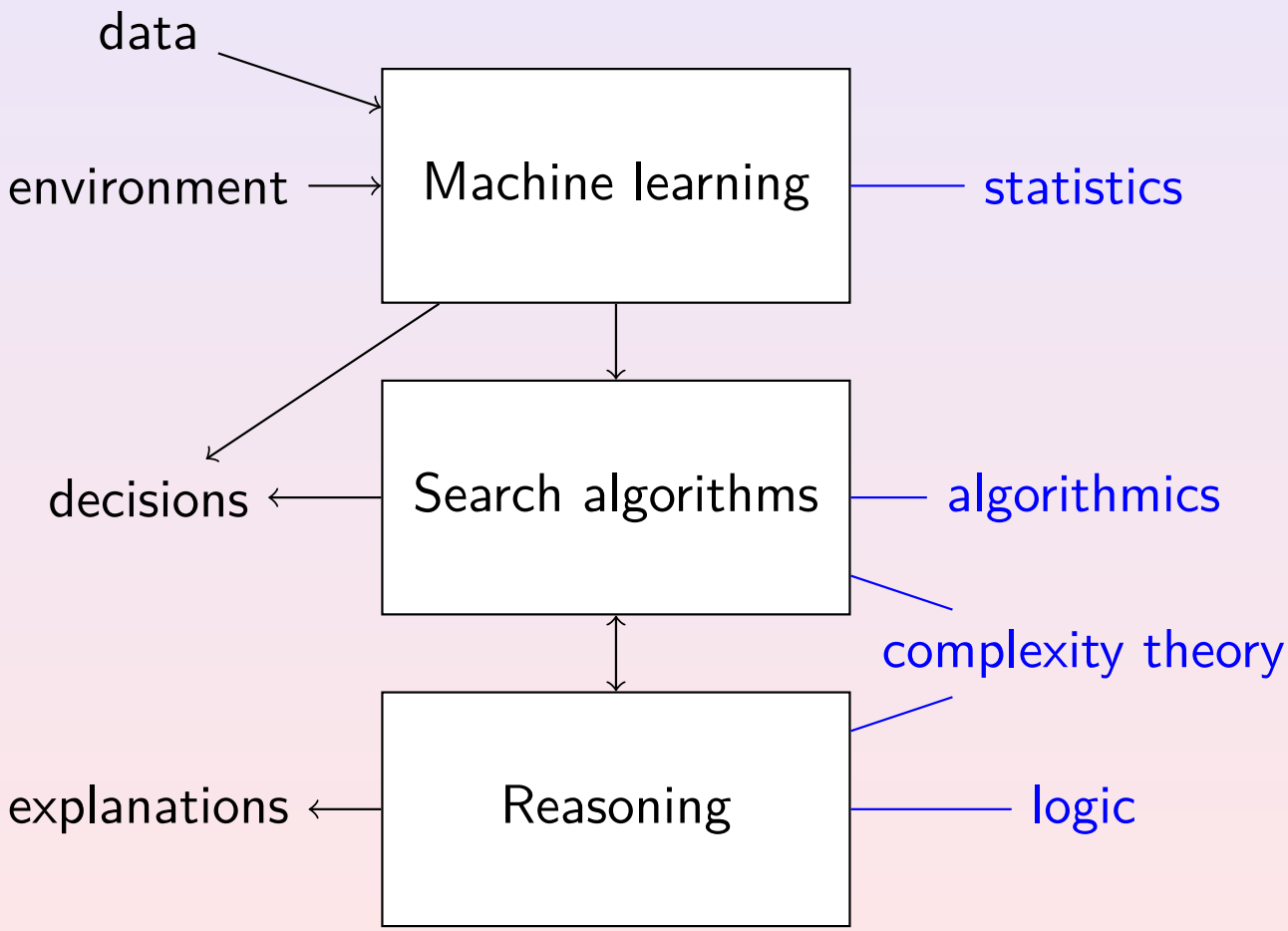
Perfect information case

- Complexity results [Charrier, Queffelec et al. AAMAS 2019];
- Implement A^* variants.

Imperfect information case

- Find adequate fragments of decPOMDP;
- KBPs to explain behaviors of UAVs.

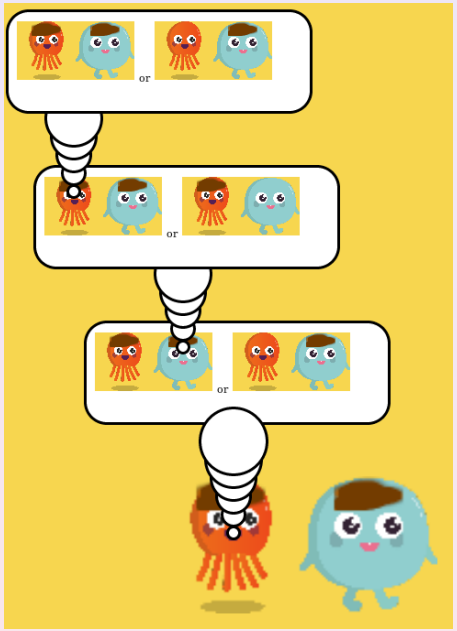
Overview of Artificial Intelligence



Acknowledgment

- Sophie Pinchinat: for her collaboration, huge support
- Tristan Charrier, PhD Student, many complexity results in succinct models, model checking, SAT
- Gaëtan Douenot-Tabot, a bachelor student for his work on automata structures
- Guillaume Aucher for his collaboration
- Hans van Ditmarsch for a long-stay in Nancy
- Valentin Goranko for a one-week stay in Stockholm
- Andreas Herzig, Emiliano Lorini for stays in Toulouse
- Thomas Bolander for a one-week in Copenhagen
- Abdallah Saffidine, Bruno Zanuttini for a recent collaboration on knowledge-based programs
- The School of Art LISAA, Rennes, for the design of Hintikka's World
- Anass Lakhar, Eva Soulier: master 1 students contributing to Hintikka's World
- Sébastien Gamblin, Alexandre Niveau, contributing to symbolic models into Hintikka's World. Stays in Caen
- Arthur Queffelec for advising rewritting Hintikka's World in Typescript

Thank for your attention



http://hintikkasworld.irisa.fr/

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