DELPHIC: PRACTICAL DEL PLANNING VIA POSSIBILITIES

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Epistemic Planning

Epistemic planning is an enrichment of automated (multi-agent) planning where the concept of **knowledge**/**belief** is taken into account:

- Agents might do something depending on **what they know**
- Cooperative setting: agents want to reach a common goal
- Centralized setting: a single omniscient entity (the planner) is responsible for finding a solution

A Simple Running Example

Example (Coin in the Box)

Initial situation. Anne, Bob and Carl are in the same room. A coin placed inside a closed box. Everybody knows that the box is closed (c), but no one knows the position of the coin.

There are two possible situations:

- The coin lies heads up (h), and
- The coin lies tails up ($\neg h$).

Goals can include **epistemic conditions**:

- Anne knows/believes that h,
- Bob knows/believes that Anne knows/believes whether h or not,
- Carl knows/believes that Anne does not know/believe whether h,
- Both Bob and Carl do not know/believe whether h.

DYNAMIC EPISTEMIC LOGIC

The Language

Let $\mathcal{P}$ be a finite set of propositional atoms and $\mathcal{AG} = \{1, \ldots, n\}$ a finite set of agents.

Definition (Language $\mathcal{L}_{\mathcal{P},\mathcal{AG}}$)

$$\varphi ::= p \mid \neg\varphi \mid \varphi \wedge \varphi \mid \Box_i \varphi,$$

Example (Coin in the Box)

Let $\mathcal{P} = \{c, h\}$ and $\mathcal{AG} = \{Anne, Bob, Carl\}$. We can state the conditions of our example as follows:

Initial conditions:

- $\bigwedge_{i \in \mathcal{AG}} (\neg\Box_i h \wedge \neg\Box_i \neg h)$
- $\bigwedge_{i \in \mathcal{AG}} \Box_i c$

Goal conditions:

- $\Box_{Anne} h$
- $\Box_{Bob}(\Box_{Anne} h \vee \Box_{Anne} \neg h)$
- $\Box_{Carl}(\neg\Box_{Anne} h \wedge \neg\Box_{Anne} \neg h)$
- $\bigwedge_{i \in \{Bob, Carl\}} (\neg\Box_i h \wedge \neg\Box_i \neg h)$

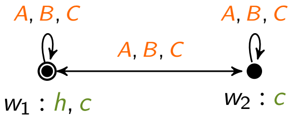
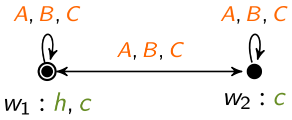


Figure: Initial state.

Epistemic states (pointed Kripke models):

- Worlds: possible situations
- Relations: what agents consider to be possible
- Valuation: what is considered to be true in each world
- Designated worlds: actual situations

The Semantics



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Definition (Truth)

$$
\begin{array}{lll}
(M, w) \models p & \text{iff} & w \in V(p) \\
(M, w) \models \neg\varphi & \text{iff} & (M, w) \not\models \varphi \\
(M, w) \models \varphi \wedge \psi & \text{iff} & (M, w) \models \varphi \text{ and } (M, w) \models \psi \\
(M, w) \models \Box_i \varphi & \text{iff} & \forall v \text{ if } wR_i v \text{ then } (M, v) \models \varphi
\end{array}
$$

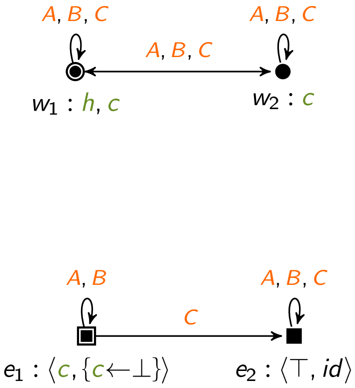

Figure: Anne opens the box while only Bob is looking (Carl is distracted).

Actions (pointed event models):

- Events: what **might happen** relatively to some agents' perspective
- Relations: akin to those of epistemic models
- Preconditions: what is needed for an event to occur
- Postconditions: how an event changes a world
- Designated events: what actually happens

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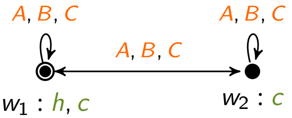

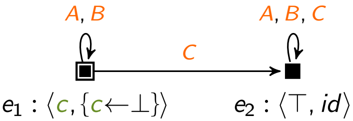

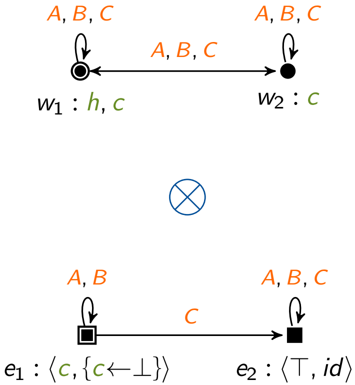

Product update:

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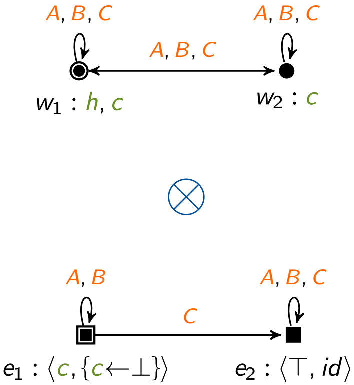

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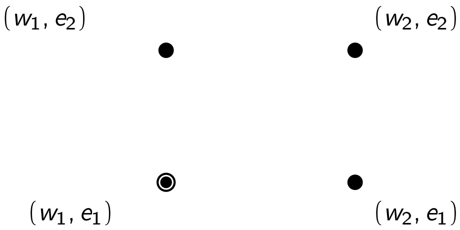

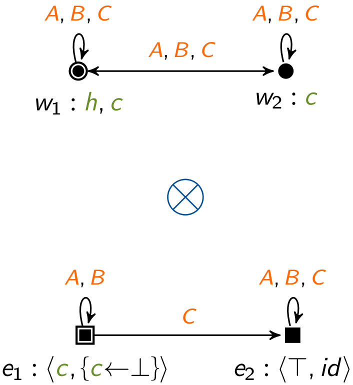

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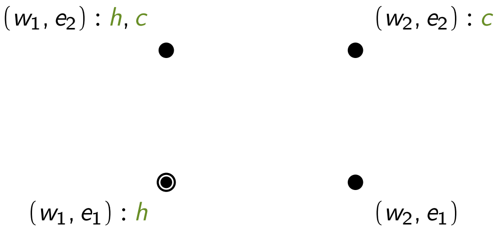

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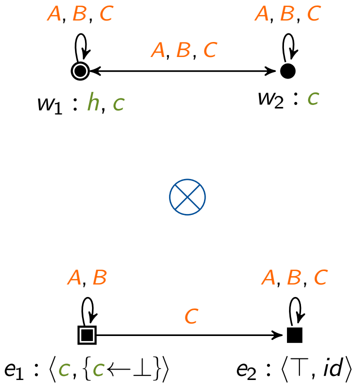

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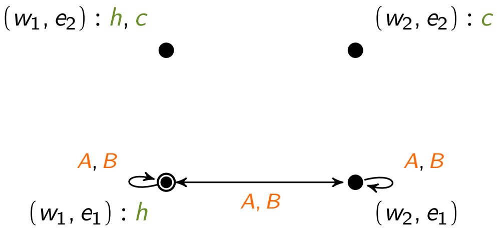

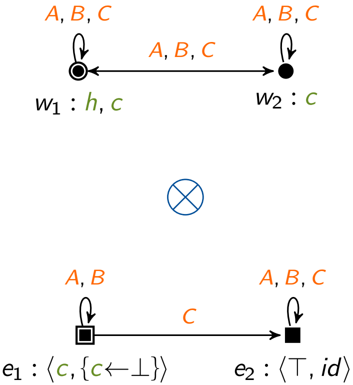

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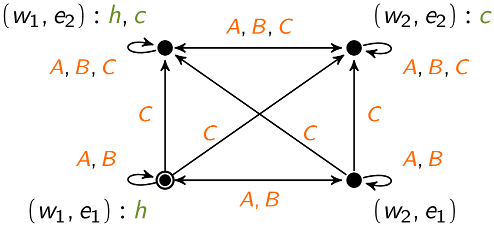

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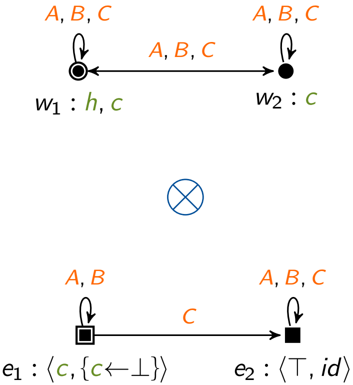

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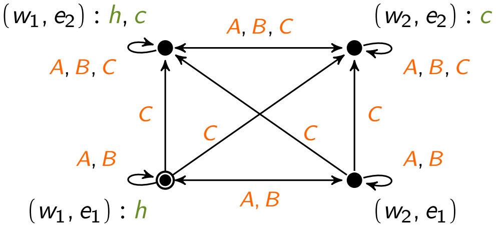

Notice that w_1 (resp., w_2) and (w_1, e_2) (resp., (w_2, e_2)) encode the **same information**, but they are **distinct objects**!

DELPHIC

DEL-planning with a **P**ossibility-based **H**omogeneous **I**nformation **C**haracterisation:

- Epistemic models represented by **possibilities**
- Event models represented by **eventualities**
- New semantics for actions: **union update**

Possibilities

Definition (Possibility [GG97])

A **possibility** u is a function that assigns to each atom $p \in \mathcal{P}$ a truth value $\mathsf{u}(p) \in \{0, 1\}$ and to each agent $i \in \mathcal{AG}$ a *set of possibilities* $\mathsf{u}(i)$.

Definition (Possibility spectrum)

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Intuitively:

- $\mathsf{u}(p)$ specifies the truth value of the atom p (plays the role of the valuation function)
- $\mathsf{u}(i)$ is the set of all the worlds that agent i considers possible in u (plays the role of the accessibility relations)
- A possibility spectrum plays the role of the designated worlds

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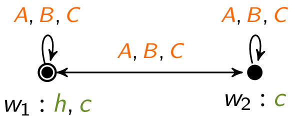

$U = \{w_1\}$, where:

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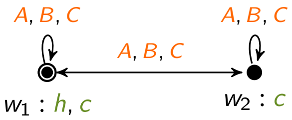

$\mathsf{U} = \{\mathsf{w}_1\}$, where:

- $\mathsf{w}_1(h) = \mathsf{w}_1(c) = 1$
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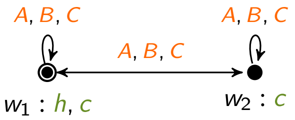

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$$\begin{array}{lll} \mathsf{u} \models p & \text{iff} & \mathsf{u}(p) = 1 \\ \mathsf{u} \models \neg\varphi & \text{iff} & \mathsf{u} \not\models \varphi \\ \mathsf{u} \models \varphi \wedge \psi & \text{iff} & \mathsf{u} \models \varphi \text{ and } \mathsf{u} \models \psi \\ \mathsf{u} \models \Box_i \varphi & \text{iff} & \forall \mathsf{v} \text{ if } \mathsf{v} \in \mathsf{u}(i) \text{ then } \mathsf{v} \models \varphi \end{array}$$

Finally, $\mathsf{U} \models \varphi$ iff $\mathsf{v} \models \varphi$, for all $\mathsf{v} \in \mathsf{U}$.

Eventualities

Let $pre \notin \mathcal{P}$ be a fresh atom and let $\mathcal{P}' = \mathcal{P} \cup \{pre\}$.

Definition (Eventuality)

An **eventuality** e is a function that assigns to each atom $p' \in \mathcal{P}'$ a formula $\mathsf{e}(p') \in \mathcal{L}_{\mathcal{P},\mathcal{AG}}$ and to each agent $i \in \mathcal{AG}$ a *set of eventualities* $\mathsf{e}(i)$.

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- $\mathsf{e}(p)$ specifies postcondition of p in e
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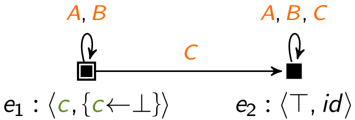

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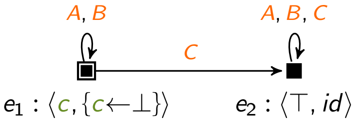

$\mathsf{E} = \{\mathsf{e}_1\}$, where:

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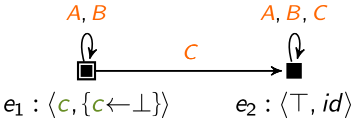

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Union Update

An eventuality e is **applicable** in a possibility u iff $\mathsf{u} \models \mathsf{e}(pre)$.

Definition (Union Update)

The **union update** of a possibility u with an applicable eventuality e is the possibility $\mathsf{u}' = \mathsf{u} \uplus \mathsf{e}$, such that:

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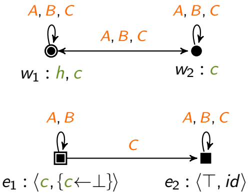

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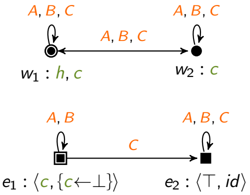

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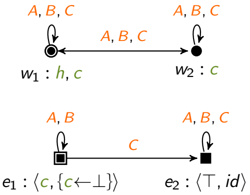

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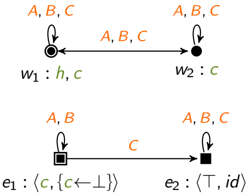
Example



$\mathsf{U} \uplus \mathsf{E} = \{\mathsf{w}_1 \uplus \mathsf{e}_1\} = \{\mathsf{w}_1^1\}$, where:

- $\mathsf{w}_1^1(c) = 0$ and $\mathsf{w}_1^1(h) = 1$
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Union Update

An eventuality e is **applicable** in a possibility u iff $\mathsf{u} \models \mathsf{e}(pre)$.

Definition (Union Update)

The **union update** of a possibility u with an applicable eventuality e is the possibility $\mathsf{u}' = \mathsf{u} \uplus \mathsf{e}$, such that:

- $\mathsf{u}'(p) = 1$ iff $\mathsf{u} \models \mathsf{e}(p)$
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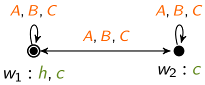

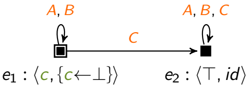

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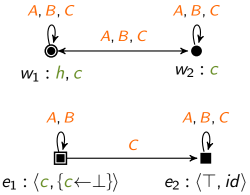

$U \uplus E = \{w_1 \uplus e_1\} = \{w_1^1\}$, where:

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- $w_1^2 = w_1$ and $w_2^2 = w_2$ (we can **reuse old information**!)

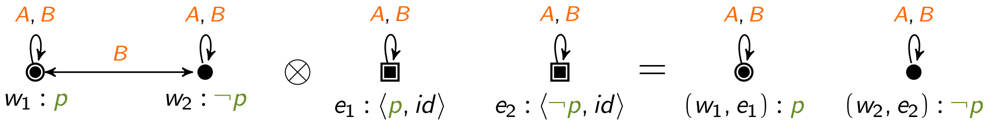
DISCUSSION

Why DELPHIC? – A Tecnical Standpoint

DELPHIC overcomes some shortcomings of DEL:

- Does not reuse old information (as shown before)
- *Blind* cross-product: may result into unreachable information
  - → World (w_2, e_2) is redundant: it is **not reachable** from a designated world

Example



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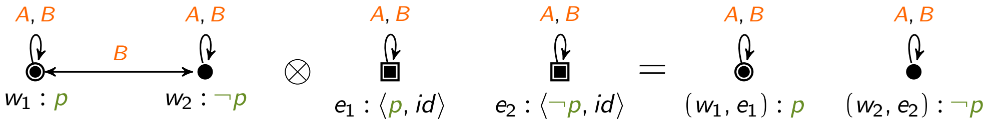

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- $e_1(pre)= \ p$, $e_1(p)=p$ and $e_1(A)=e_1(B)=\{e_1\}$
- $e_2(pre)=\neg p$, $e_2(p)=p$ and $e_2(A)=e_2(B)=\{e_2\}$

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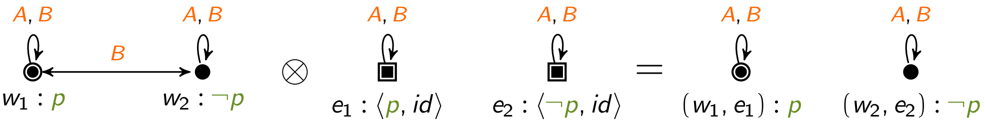

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- $\mathrm{e}_1(pre)= p$, $\mathrm{e}_1(p)=p$ and $\mathrm{e}_1(A)=\mathrm{e}_1(B)=\{\mathrm{e}_1\}$
- $\mathrm{e}_2(pre)=\neg p$, $\mathrm{e}_2(p)=p$ and $\mathrm{e}_2(A)=\mathrm{e}_2(B)=\{\mathrm{e}_2\}$

In DELPHIC every possibility is **reachable**: $\mathrm{U} \uplus \mathrm{E} = \{\mathrm{w}_1 \uplus \mathrm{e}_1\} = \{\mathrm{w}_1\}$.

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- Thus, possibilities are minimal objects (w.r.t. bisimulation)
  - $\rightarrow$ Possibilities allow for a **more compact representation**

We can exploit this property in **implementations of tools**:

- Possibilities have already been proved to provide more efficient implementations
- Epistemic planner **EFP 2.0** [Fab+20]: relies on a framework called $m\mathcal{A}^*$ [Bar+15], which is a fragment of DEL

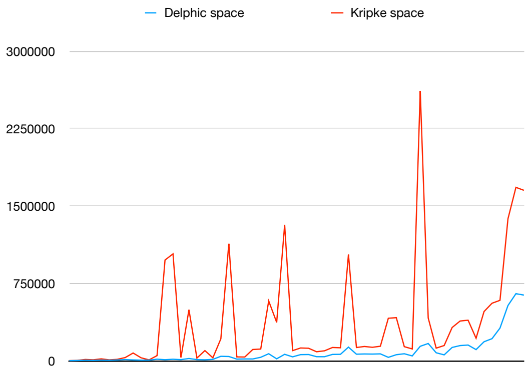
EXPERIMENTAL EVALUATION

Experimental Setup

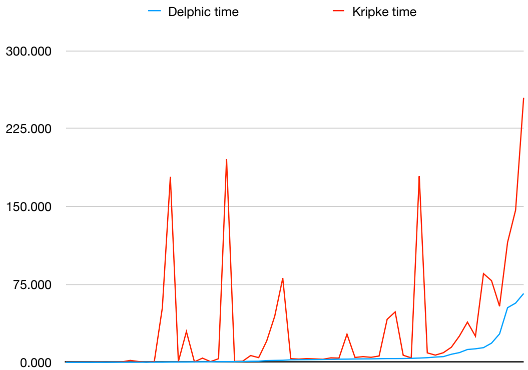
- We implemented DELPHIC and the traditional Kripke-based DEL semantics.
- We used the well-known declarative language **ASP** (*Answer Set Programming*).
  - → Fair and transparent comparison.
- We compared the two ASP models both in terms of space and time.
  - → We used benchmarks found in the literature.

You can find our implementation here: `github.com/a-burigana/delphic_asp`.

Experimental Evaluation

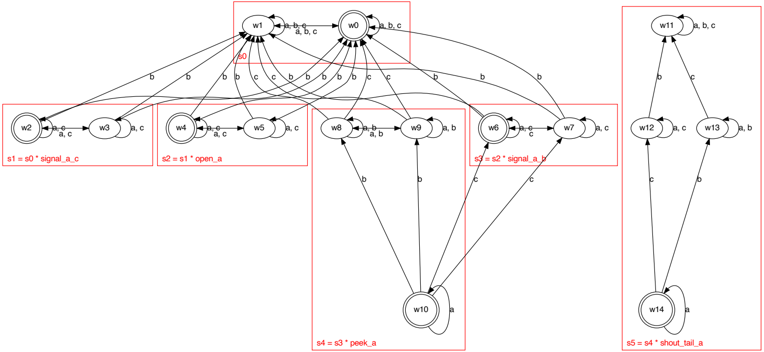


(a) Space results



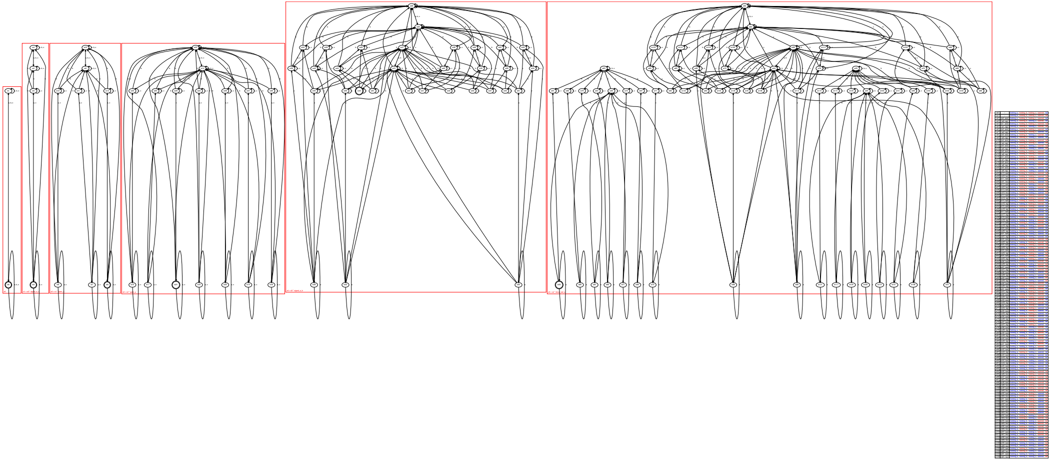
(b) Time results

DELPHIC vs. Kripke



w0	-	looking_a, -looking_b, -looking_c, -opened, tail
w1	-	looking_a, -looking_b, -looking_c, -opened, -tail
w2	(w0, sig)	looking_a, -looking_b, looking_c, -opened, tail
w3	(w1, sig)	looking_a, -looking_b, looking_c, -opened, -tail
w4	(w2, sig)	looking_a, -looking_b, looking_c, opened, tail
w5	(w3, sig)	looking_a, -looking_b, looking_c, opened, -tail
w6	(w4, sig)	looking_a, -looking_b, looking_c, opened, tail
w7	(w5, tau)	looking_a, -looking_b, looking_c, opened, -tail
w8	(w0, sig)	looking_a, looking_b, -looking_c, -opened, tail
w9	(w1, sig)	looking_a, looking_b, -looking_c, -opened, -tail
w10	(w6, sig)	looking_a, looking_b, looking_c, opened, tail
w11	(w0, sig)	looking_a, -looking_b, -looking_c, -opened, tail
w12	(w6, sig)	looking_a, -looking_b, looking_c, opened, tail
w13	(w8, sig)	looking_a, looking_b, -looking_c, -opened, tail
w14	(w10, sig)	looking_a, looking_b, looking_c, opened, tail

DELPHIC vs. Kripke



CONCLUSIONS

Conclusions and Future Works

- We introduced DELPHIC, an alternative semantics for Dynamic Epistemic Logic.
- The DELPHIC framework is **equivalent** to the Kripke-based one.
- We empirically showed that DELPHIC outperforms the traditional Kripke-based semantics both in space and time.

Future works:

- Implement DELPHIC in more competitive solvers (*e.g.*, *EFP* [Fab+20]).

THANK YOU

Questions?