DELPHIC: TOWARDS AN EFFICIENT POSSIBILITY-BASED EPISTEMIC PLANNING FRAMEWORK

Alessandro Burigana
Free University of Bozen-Bolzano, Italy

Paolo Felli
University of Bologna, Italy

Marco Montali
Free University of Bozen-Bolzano, Italy

OVERLAY 2022
November 28
Udine, Italy

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 $\mathcal{L}^{C}_{\mathcal{P},\mathcal{AG}}$)

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

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:

- $\bigwedge_{i \in \mathcal{AG}} (\neg\Box_i h \wedge \neg\Box_i \neg h)$
- $C_{\{Anne, Bob, Carl\}} c$

Goal conditions:

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

The Semantics

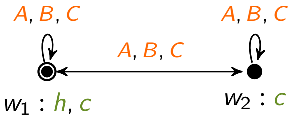


Figure: Initial state.

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

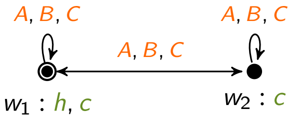


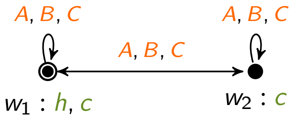
Figure: Initial state.

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

Definition (Truth)

$(M, w) \models p$	iff	$w \in V(p)$
$(M, w) \models \neg\varphi$	iff	$(M, w) \not\models \varphi$
$(M, w) \models \varphi \wedge \psi$	iff	$(M, w) \models \varphi$ and $(M, w) \models \psi$
$(M, w) \models \Box_i \varphi$	iff	$\forall v$ if $wR_i v$ then $(M, v) \models \varphi$
$(M, w) \models C_G \varphi$	iff	$\forall v$ if $wR_G^* v$ then $(M, v) \models \varphi$



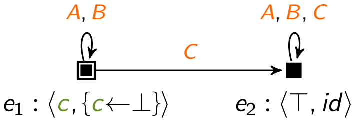
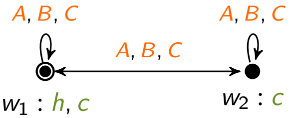


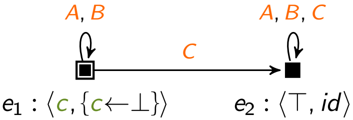
Figure: Anne opens the box while only Bob is looking (Carl is distracted).

Actions (pointed event models):

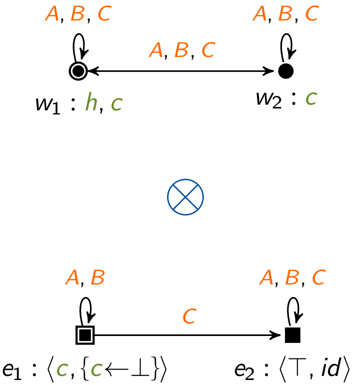
- Events: what **might happen** relatively to some agents' perspective
- Relations: akin to those of epistemic models
- Preconditions: what is needed for an event to occur
- Postconditions: how an event changes a world
- Designated events: what actually happens

The Semantics



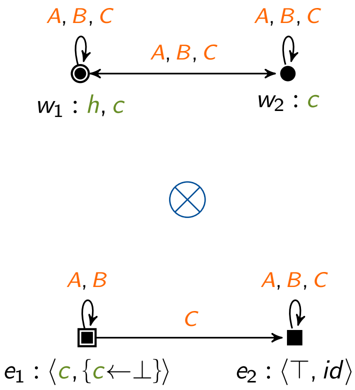


The Semantics

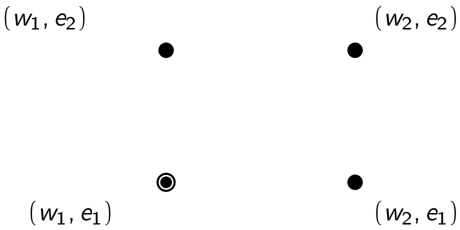


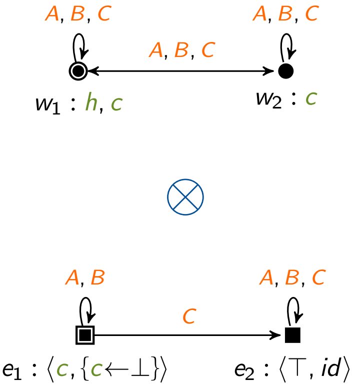
Product update:

The Semantics

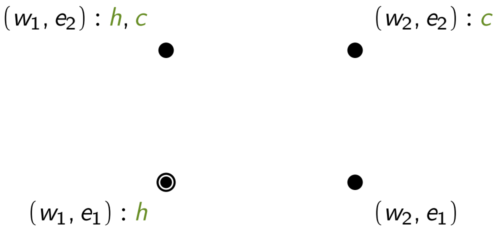


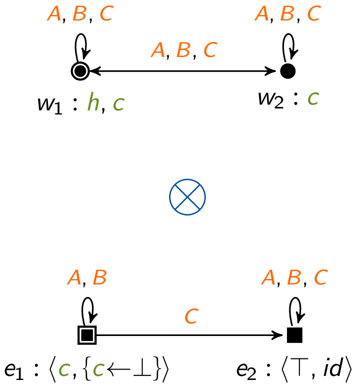
Product update:



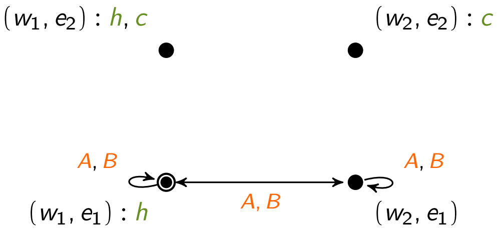


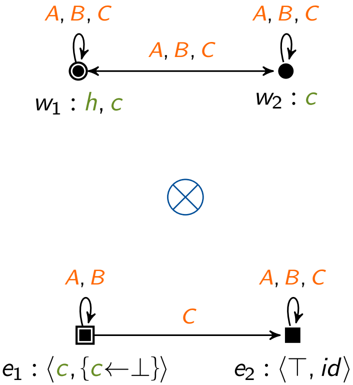
Product update:



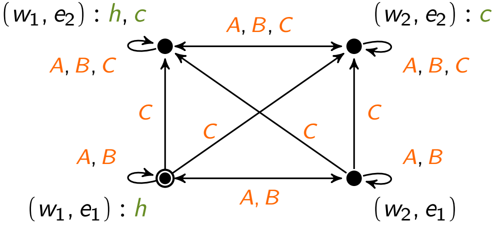


Product update:

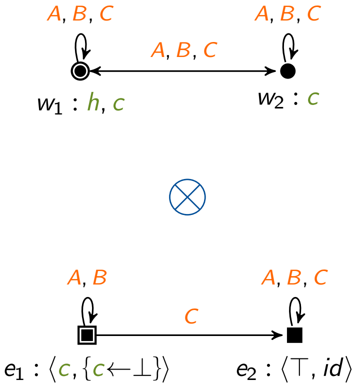




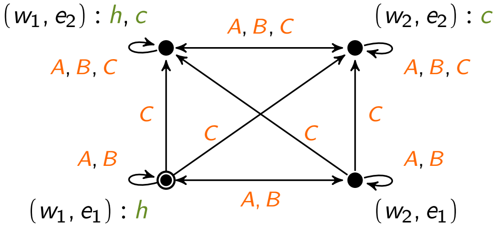
Product update:



The Semantics



Product update:



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

DELPHIC: A Novel Framework for Epistemic Planning

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 [journals/jolli/Gerbrandy1997])

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)

A **possibility spectrum** is a non-empty set $\mathsf{U} = \{\mathsf{u}_1, \ldots, \mathsf{u}_k\}$ of designated possibilities.

Possibilities

Definition (Possibility [journals/jolli/Gerbrandy1997])

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)

A **possibility spectrum** is a non-empty set $\mathsf{U} = \{\mathsf{u}_1, \dots, \mathsf{u}_k\}$ of designated possibilities.

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

Possibilities

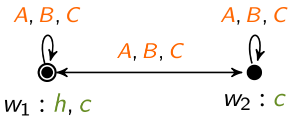
Definition (Possibility [journals/jolli/Gerbrandy1997])

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

Definition (Possibility spectrum)

A **possibility spectrum** is a non-empty set $U = \{u_1, \ldots, u_k\}$ of designated possibilities.

Example



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

Possibilities

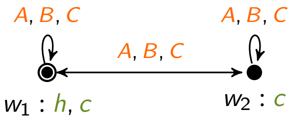
Definition (Possibility [journals/jolli/Gerbrandy1997])

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)

A **possibility spectrum** is a non-empty set $\mathsf{U} = \{\mathsf{u}_1, \ldots, \mathsf{u}_k\}$ of designated possibilities.

Example



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

- $\mathsf{w}_1(h) = \mathsf{w}_1(c) = 1$
- $\mathsf{w}_1(A) = \mathsf{w}_1(B) = \mathsf{w}_1(C) = \{\mathsf{w}_1, \mathsf{w}_2\}$

Possibilities

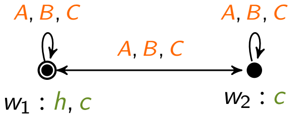
Definition (Possibility [journals/jolli/Gerbrandy1997])

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

Definition (Possibility spectrum)

A **possibility spectrum** is a non-empty set $U = \{u_1, \ldots, u_k\}$ of designated possibilities.

Example



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

- $w_1(h) = w_1(c) = 1$
- $w_1(A) = w_1(B) = w_1(C) = \{w_1, w_2\}$
- $w_2(h) = 0$ and $w_2(c) = 1$
- $w_2(A) = w_2(B) = w_2(C) = \{w_1, w_2\}$

Possibilities

Definition (Possibility [journals/jolli/Gerbrandy1997])

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

Definition (Possibility spectrum)

A **possibility spectrum** is a non-empty set $U = \{u_1, \ldots, u_k\}$ of designated possibilities.

Definition (Truth)

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

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

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 $\mathsf{e}(p') \in \mathcal{L}^{C}_{\mathcal{P},\mathcal{AG}}$ and to each agent $i \in \mathcal{AG}$ a *set of eventualities* $\mathsf{e}(i)$.

Definition (Eventuality spectrum)

An **eventuality spectrum** is a finite set $\mathsf{E} = \{\mathsf{e}_1, \ldots \mathsf{e}_k\}$ of designated eventualities.

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 $\mathsf{e}(p') \in \mathcal{L}^{C}_{\mathcal{P},\mathcal{AG}}$ and to each agent $i \in \mathcal{AG}$ a *set of eventualities* $\mathsf{e}(i)$.

Definition (Eventuality spectrum)

An **eventuality spectrum** is a finite set $\mathsf{E} = \{\mathsf{e}_1, \ldots \mathsf{e}_k\}$ of designated eventualities.

Intuitively:

- $\mathsf{e}(pre)$ specifies precondition of e
- $\mathsf{e}(p)$ specifies postcondition of p in e
- $\mathsf{e}(i)$ is the set of all the eventualities that agent i considers possible in e (plays the role of the accessibility relations)
- An eventuality spectrum plays the role of the designated worlds

Eventualities

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

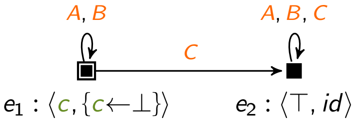
Definition (Eventuality)

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

Definition (Eventuality spectrum)

An **eventuality spectrum** is a finite set $\mathsf{E} = \{\mathsf{e}_1, \ldots \mathsf{e}_k\}$ of designated eventualities.

Example



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

Eventualities

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

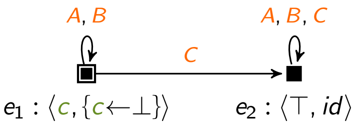
Definition (Eventuality)

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

Definition (Eventuality spectrum)

An **eventuality spectrum** is a finite set $\mathsf{E} = \{\mathsf{e}_1, \dots \mathsf{e}_k\}$ of designated eventualities.

Example



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

- $\mathsf{e}_1(pre) = c$, $\mathsf{e}_1(h) = h$ and $\mathsf{e}_1(c) = \bot$
- $\mathsf{e}_1(A) = \mathsf{e}_1(B) = \{\mathsf{e}_1\}$ and $\mathsf{e}_1(C) = \{\mathsf{e}_2\}$

Eventualities

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

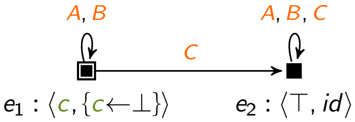
Definition (Eventuality)

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

Definition (Eventuality spectrum)

An **eventuality spectrum** is a finite set $\mathsf{E} = \{\mathsf{e}_1, \ldots \mathsf{e}_k\}$ of designated eventualities.

Example



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

- $\mathsf{e}_1(pre) = c$, $\mathsf{e}_1(h) = h$ and $\mathsf{e}_1(c) = \bot$
- $\mathsf{e}_1(A) = \mathsf{e}_1(B) = \{\mathsf{e}_1\}$ and $\mathsf{e}_1(C) = \{\mathsf{e}_2\}$
- $\mathsf{e}_2(pre) = \top$, $\mathsf{e}_2(h) = h$ and $\mathsf{e}_2(c) = c$
- $\mathsf{e}_2(A) = \mathsf{e}_2(B) = \mathsf{e}_2(C) = \{\mathsf{e}_2\}$

Union Update

Definition (Union Update)

The **union update** of a possibility u with an eventuality e is the possibility $u' = u \uplus e$, such that if $u \not\models e(pre)$, then $u' = \varnothing$; otherwise:

- $u'(p) = 1$ iff $u \models e(p)$
- $u'(i) = \{v \uplus f \mid v \in u(i), f \in e(i)$ and $v \models f(pre)\}$

The **union update** of a possibility spectrum U with an eventuality spectrum E is the possibility spectrum $U \uplus E = \{u \uplus e \mid u \in U, e \in E$ and $u \models e(pre)\}$.

Union Update

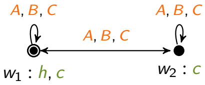
Definition (Union Update)

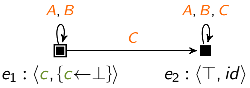
The **union update** of a possibility u with an eventuality e is the possibility $u' = u \uplus e$, such that if $u \not\models e(pre)$, then $u' = \varnothing$; otherwise:

- $u'(p) = 1$ iff $u \models e(p)$
- $u'(i) = \{v \uplus f \mid v \in u(i), f \in e(i)$ and $v \models f(pre)\}$

The **union update** of a possibility spectrum U with an eventuality spectrum E is the possibility spectrum $U \uplus E = \{u \uplus e \mid u \in U, e \in E$ and $u \models e(pre)\}$.

Example





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

Union Update

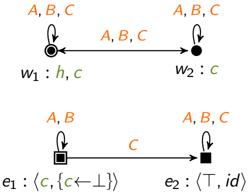
Definition (Union Update)

The **union update** of a possibility u with an eventuality e is the possibility $\mathsf{u}' = \mathsf{u} \uplus \mathsf{e}$, such that if $\mathsf{u} \not\models \mathsf{e}(pre)$, then $\mathsf{u}' = \varnothing$; otherwise:

- $\mathsf{u}'(p) = 1$ iff $\mathsf{u} \models \mathsf{e}(p)$
- $\mathsf{u}'(i) = \{\mathsf{v} \uplus \mathsf{f} \mid \mathsf{v} \in \mathsf{u}(i), \mathsf{f} \in \mathsf{e}(i)$ and $\mathsf{v} \models \mathsf{f}(pre)\}$

The **union update** of a possibility spectrum U with an eventuality spectrum E is the possibility spectrum $\mathsf{U} \uplus \mathsf{E} = \{\mathsf{u} \uplus \mathsf{e} \mid \mathsf{u} \in \mathsf{U}, \mathsf{e} \in \mathsf{E}$ and $\mathsf{u} \models \mathsf{e}(pre)\}$.

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 $\mathsf{w}_1^1(h) = 1$
- $\mathsf{w}_1^1(A) = \mathsf{w}_1^1(B) = \{\mathsf{w}_1 \uplus \mathsf{e}_1, \mathsf{w}_2 \uplus \mathsf{e}_1\}$ and $\mathsf{w}_1^1(C) = \{\mathsf{w}_1 \uplus \mathsf{e}_2, \mathsf{w}_2 \uplus \mathsf{e}_2\}$

Union Update

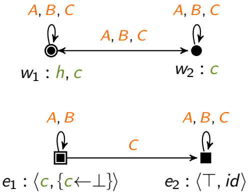
Definition (Union Update)

The **union update** of a possibility u with an eventuality e is the possibility $\mathsf{u}' = \mathsf{u} \boxtimes \mathsf{e}$, such that if $\mathsf{u} \not\models \mathsf{e}(pre)$, then $\mathsf{u}' = \varnothing$; otherwise:

- $\mathsf{u}'(p) = 1$ iff $\mathsf{u} \models \mathsf{e}(p)$
- $\mathsf{u}'(i) = \{\mathsf{v} \boxtimes \mathsf{f} \mid \mathsf{v} \in \mathsf{u}(i), \mathsf{f} \in \mathsf{e}(i)$ and $\mathsf{v} \models \mathsf{f}(pre)\}$

The **union update** of a possibility spectrum U with an eventuality spectrum E is the possibility spectrum $\mathsf{U} \boxtimes \mathsf{E} = \{\mathsf{u} \boxtimes \mathsf{e} \mid \mathsf{u} \in \mathsf{U}, \mathsf{e} \in \mathsf{E}$ and $\mathsf{u} \models \mathsf{e}(pre)\}$.

Example



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

- $\mathsf{w}_1^1(c) = 0$ and $\mathsf{w}_1^1(h) = 1$
- $\mathsf{w}_1^1(A) = \mathsf{w}_1^1(B) = \{\mathsf{w}_1^1, \mathsf{w}_2^1\}$ and $\mathsf{w}_1^1(C) = \{\mathsf{w}_1^2, \mathsf{w}_2^2\}$

Union Update

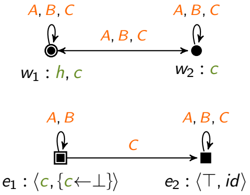
Definition (Union Update)

The **union update** of a possibility u with an eventuality e is the possibility $\mathsf{u}' = \mathsf{u} \uplus \mathsf{e}$, such that if $\mathsf{u} \not\models \mathsf{e}(pre)$, then $\mathsf{u}' = \varnothing$; otherwise:

- $\mathsf{u}'(p) = 1$ iff $\mathsf{u} \models \mathsf{e}(p)$
- $\mathsf{u}'(i) = \{\mathsf{v} \uplus \mathsf{f} \mid \mathsf{v} \in \mathsf{u}(i), \mathsf{f} \in \mathsf{e}(i)$ and $\mathsf{v} \models \mathsf{f}(pre)\}$

The **union update** of a possibility spectrum U with an eventuality spectrum E is the possibility spectrum $\mathsf{U} \uplus \mathsf{E} = \{\mathsf{u} \uplus \mathsf{e} \mid \mathsf{u} \in \mathsf{U}, \mathsf{e} \in \mathsf{E}$ and $\mathsf{u} \models \mathsf{e}(pre)\}$.

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 $\mathsf{w}_1^1(h) = 1$
- $\mathsf{w}_1^1(A) = \mathsf{w}_1^1(B) = \{\mathsf{w}_1^1, \mathsf{w}_2^1\}$ and $\mathsf{w}_1^1(C) = \{\mathsf{w}_1^2, \mathsf{w}_2^2\}$
- $\mathsf{w}_2^1(c) = 0$ and $\mathsf{w}_2^1(h) = 0$
- $\mathsf{w}_2^1(A) = \mathsf{w}_2^1(B) = \{\mathsf{w}_1 \uplus \mathsf{e}_1, \mathsf{w}_2 \uplus \mathsf{e}_1\}$ and $\mathsf{w}_2^1(C) = \{\mathsf{w}_1 \uplus \mathsf{e}_2, \mathsf{w}_2 \uplus \mathsf{e}_2\}$

Union Update

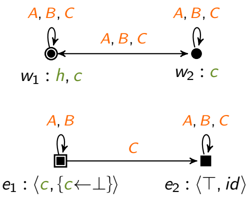
Definition (Union Update)

The **union update** of a possibility u with an eventuality e is the possibility $\mathsf{u}' = \mathsf{u} \uplus \mathsf{e}$, such that if $\mathsf{u} \not\models \mathsf{e}(\mathit{pre})$, then $\mathsf{u}' = \varnothing$; otherwise:

- $\mathsf{u}'(p) = 1$ iff $\mathsf{u} \models \mathsf{e}(p)$
- $\mathsf{u}'(i) = \{\mathsf{v} \uplus \mathsf{f} \mid \mathsf{v} \in \mathsf{u}(i), \mathsf{f} \in \mathsf{e}(i)$ and $\mathsf{v} \models \mathsf{f}(\mathit{pre})\}$

The **union update** of a possibility spectrum U with an eventuality spectrum E is the possibility spectrum $\mathsf{U} \uplus \mathsf{E} = \{\mathsf{u} \uplus \mathsf{e} \mid \mathsf{u} \in \mathsf{U}, \mathsf{e} \in \mathsf{E}$ and $\mathsf{u} \models \mathsf{e}(\mathit{pre})\}$.

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 $\mathsf{w}_1^1(h) = 1$
- $\mathsf{w}_1^1(A) = \mathsf{w}_1^1(B) = \{\mathsf{w}_1^1, \mathsf{w}_2^1\}$ and $\mathsf{w}_1^1(C) = \{\mathsf{w}_1^2, \mathsf{w}_2^2\}$
- $\mathsf{w}_2^1(c) = 0$ and $\mathsf{w}_2^1(h) = 0$
- $\mathsf{w}_2^1(A) = \mathsf{w}_2^1(B) = \{\mathsf{w}_1^1, \mathsf{w}_2^1\}$ and $\mathsf{w}_2^1(C) = \{\mathsf{w}_1^2, \mathsf{w}_2^2\}$

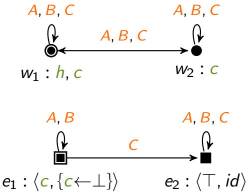
Definition (Union Update)

The **union update** of a possibility u with an eventuality e is the possibility $\mathsf{u}' = \mathsf{u} \uplus \mathsf{e}$, such that if $\mathsf{u} \not\models \mathsf{e}(pre)$, then $\mathsf{u}' = \varnothing$; otherwise:

- $\mathsf{u}'(p) = 1$ iff $\mathsf{u} \models \mathsf{e}(p)$
- $\mathsf{u}'(i) = \{\mathsf{v} \uplus \mathsf{f} \mid \mathsf{v} \in \mathsf{u}(i), \mathsf{f} \in \mathsf{e}(i)$ and $\mathsf{v} \models \mathsf{f}(pre)\}$

The **union update** of a possibility spectrum U with an eventuality spectrum E is the possibility spectrum $\mathsf{U} \uplus \mathsf{E} = \{\mathsf{u} \uplus \mathsf{e} \mid \mathsf{u} \in \mathsf{U}, \mathsf{e} \in \mathsf{E}$ and $\mathsf{u} \models \mathsf{e}(pre)\}$.

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 $\mathsf{w}_1^1(h) = 1$
- $\mathsf{w}_1^1(A) = \mathsf{w}_1^1(B) = \{\mathsf{w}_1^1, \mathsf{w}_2^1\}$ and $\mathsf{w}_1^1(C) = \{\mathsf{w}_1^2, \mathsf{w}_2^2\}$
- $\mathsf{w}_2^1(c) = 0$ and $\mathsf{w}_2^1(h) = 0$
- $\mathsf{w}_2^1(A) = \mathsf{w}_2^1(B) = \{\mathsf{w}_1^1, \mathsf{w}_2^1\}$ and $\mathsf{w}_2^1(C) = \{\mathsf{w}_1^2, \mathsf{w}_2^2\}$
- $\mathsf{w}_1^2 = \mathsf{w}_1$ and $\mathsf{w}_2^2 = \mathsf{w}_2$ (we can **reuse old information**!)

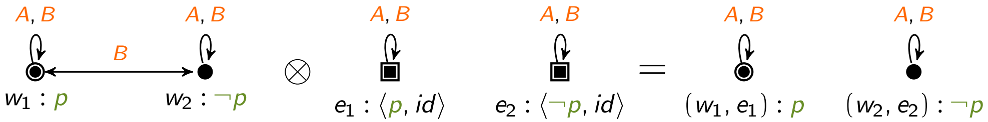
DISCUSSION

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

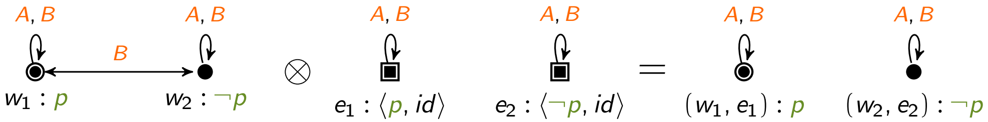
Example



DELPHIC overcomes some Shortcomings of DEL:

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

Example



Let $\mathrm{U} = \{\mathrm{w}_1\}$ and $\mathrm{E} = \{\mathrm{e}_1, \mathrm{e}_2\}$, where:

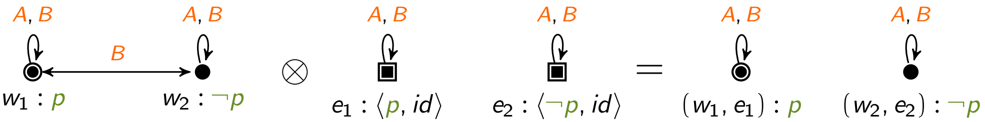
- $\mathrm{w}_1(p)=1$ and $\mathrm{w}_1(A)=\mathrm{w}_1(B)=\{\mathrm{w}_1, \mathrm{w}_2\}$
- $\mathrm{w}_2(p)=0$ and $\mathrm{w}_2(A)=\mathrm{w}_2(B)=\{\mathrm{w}_1, \mathrm{w}_2\}$
- $\mathrm{e}_1(pre)= \ p$, $\mathrm{e}_1(p)=p$ and $\mathrm{e}_1(A)=\mathrm{e}_1(B)=\{\mathrm{e}_1\}$
- $\mathrm{e}_2(pre)=\neg p$, $\mathrm{e}_2(p)=p$ and $\mathrm{e}_2(A)=\mathrm{e}_2(B)=\{\mathrm{e}_2\}$

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



Let $\mathsf{U} = \{\mathsf{w}_1\}$ and $\mathsf{E} = \{\mathsf{e}_1, \mathsf{e}_2\}$, where:

- $\mathsf{w}_1(p)$=1 and $\mathsf{w}_1(A)$=$\mathsf{w}_1(B)$=$\{\mathsf{w}_1, \mathsf{w}_2\}$
- $\mathsf{w}_2(p)$=0 and $\mathsf{w}_2(A)$=$\mathsf{w}_2(B)$=$\{\mathsf{w}_1, \mathsf{w}_2\}$
- $\mathsf{e}_1(pre)$= p, $\mathsf{e}_1(p)$=p and $\mathsf{e}_1(A)$=$\mathsf{e}_1(B)$=$\{\mathsf{e}_1\}$
- $\mathsf{e}_2(pre)$=$\neg p$, $\mathsf{e}_2(p)$=p and $\mathsf{e}_2(A)$=$\mathsf{e}_2(B)$=$\{\mathsf{e}_2\}$

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

Why DELPHIC? – A Theoretical Standpoint

As shown by Gerbrandy [journals/jolli/Gerbrandy1997], possibilities and Kripke models are tightly related. In particular:

- To each Kripke model, we can associate a correspondent **equivalent** possibility (and vice versa)
  - → We have already seen this intuitively
- We can study properties about possibilities by exploiting the extended literature on Kripke models

Why DELPHIC? – An Implementation Standpoint

Moreover, the relation between possibilities and Kripke models have interesting implications in terms of implementations:

- To each Kripke model, we can associate a correspondent **equivalent** possibility (and vice versa)
- If two Kripke models are bisimilar, they share the same correspondent possibility
- Thus, possibilities are minimal objects (w.r.t. bisimulation)

  $\rightarrow$ Possibilities allow for a **more compact representation**

Why DELPHIC? – An Implementation Standpoint

Moreover, the relation between possibilities and Kripke models have interesting implications in terms of implementations:

- To each Kripke model, we can associate a correspondent **equivalent** possibility (and vice versa)
- If two Kripke models are bisimilar, they share the same correspondent possibility
- 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** [conf/icaps/Fabiano2020]: relies on a framework called $m\mathcal{A}^*$ [journals/corr/Baral2015], which is a fragment of DEL

Why DELPHIC? – A Conceptual Standpoint

In DEL, a Kripke models represents information by means of different *heterogeneous* components: worlds, accessibility relations, valuation function.

In DELPHIC, a possibility represents a whole **possible situation**: what is true in that particular situation *and* what agents consider possible.

Why DELPHIC? – A Conceptual Standpoint

In DEL, a Kripke models represents information by means of different *heterogeneous* components: worlds, accessibility relations, valuation function.

In DELPHIC, a possibility represents a whole **possible situation**: what is true in that particular situation *and* what agents consider possible.

→ In short, a possibility represents a *possibility*.

→ Closer to how humans reason about situations

FUTURE WORKS

Future Works

In the immediate future (X):

- Implement both DELPHIC and DEL to obtain empirical evidence
- Declarative encoding (ASP, Prolog, SMT, ...): transparent comparison

More in the future (F):

- Implement DELPHIC in the solver *EFP* [conf/icaps/Fabiano2020]

THANK YOU

Questions?