(Dis)Belief Change based on Messages Processing

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Abstract. This paper focuses on the features of belief change when agents have to consider information received from other agents. We focus on belief change operators when agents have to process messages about a static world. We propose to consider agents' belief state as a set of pairs ⟨belief, origin of the belief⟩ combined with a preference relation over the agents embedded in the multi-agent system. The belief revision procedure for handling received messages is a safe base revision procedure where messages are considered in their syntactic form. According to the reliability of the sources of the conflicting belief, agents remove the less reliable belief in order to handle the received message. Notice that the less reliable source can be the sender of the message itself. In order not to loose precious information conflicting belief are not removed but considered as *potential* belief. As the agent changes its belief, potential belief is reconsidered and may be reinstated as current belief. In a similar way, messages can concern statements that should not be believed, called *disbelief*. As belief, disbelief can become potential. These different kinds of belief enables us to propose a new semantics for a modal based language for describing (dis)belief. Agents may handle sequences of messages since the proposed belief change operators handle iterated belief change.

1 Introduction

It is quite common to characterize intelligent agents in cognitive terms such as the well known belief, desire, intention mental attitudes [13]. In that context, belief change is a key problem for agents. In a multi-agent system, agents communicate with each other in order to solve a problem such as building a plan or establishing a diagnosis.

In this paper we focus on how an agent should change its beliefs when it receives new information from the other agents, i.e. how its beliefs should look like after interpreting the received message [11]. We focus here on multi agent systems that exchange messages about a world that do not change. In that context, belief change has to be considered as belief revision. In our proposal agents handle iterated belief revision [2] which is a key feature when we consider autonomous agents able to take into account sequences of messages. In addition, agents do not always adopt the received messages so that the proposed operators belong to the family of non-prioritized operators [7]. Agents consider the reliability of the senders to select inconsistent beliefs that should be dropped when a change raises inconsistencies in their beliefs.

Instead of dropping inconsistent belief, agents move them into a *potential belief* set. As new messages come, some potential beliefs become consistent with the new beliefs set. Agents move them to this new set. This approach enables agents to consider as much as possible of the received messages. At the same time, agents maintain a set of statements that should not be believed: these statements, called *disbeliefs*, are justified by messages describing what should not be believed. We show that our belief change operators in that context respect most of the AGM postulates.
This work extends a previous one [10] (i) by removing a strong constraint that was requiring a linear order over the (dis)beliefs for revising them and (ii) by proposing a modal-language for describing epistemic attitudes. The semantics of this language is based on the interpretation of the messages and the notions of belief, disbelief and potential belief. This language allows to describe the opinion of an agent. After it received a message with content ϕ: the agent has an opinion about ϕ and it believes or disbelieves ϕ.

The paper is organized as follows: section 2 presents an intuitive example for justifying our framework. Section 3 presents the formal definitions for describing an agent's belief state, messages and reliability levels of beliefs. Section 4 presents a semantics for describing epistemic attitudes based on the agent's (dis)belief state. In section 5, we present constructive definitions for the change functions. In section 6 we revisit the intuitive example in a formal way. Section 7 concludes the paper by discussing related works and some open issues.

2 An intuitive example

Let us consider three agents: Paul, Peter and the police department. Paul tells to Peter that *John is a murderer*. Peter adopts this statement and believes it. Paul also says to Peter that *if John is a murderer, John will go to jail*. Thus, Peter believes that John has killed somebody and consequently that John will go to jail. Next, the police department tells to Peter that *if John is a murderer then there is evidence* against him. In addition, they say that they do not believe that there is evidence against John. Because Peter considers the police department has a more reliable source of information than Paul, Peter does not believe, i.e. disbelieves, that John has killed somebody and thus he also disbelieves that John will go to jail. This last statement may be considered as a "potential belief" since Peter may adopt it later if the police department tells in a future message that it has been proved that John is a murderer. Suppose that next the police department tells to Peter it has found evidence that John has actually killed

someone. Thus, Peter both believes that there is evidence and potential belief "John is a murderer" is consistent again with Peter's beliefs. Thus Peter believes again that John is a murderer and that John will go to jail.
As we can see, every message received by an agent triggers a change in its beliefs. Some messages do not concern belief but rather disbelief. A new disbelief may entail inconsistency with the already adopted beliefs. Consequently, the agent have to reconsider some beliefs as potential beliefs. At the same time, the agent may reinstate potential beliefs when it changes its set of beliefs and disbeliefs.

3 Agent beliefs

We assume that beliefs are expressed in a propositional language $\mathcal{L}_0$. Changes in a belief set are caused by communication. We assume throughout the paper that the external world is *static*; handling changes caused by "physical" actions would require the integration of belief update to our formalism, which we leave for further work. Thus, we are considering cases such as diagnosis. We assume that messages are sent point-to-point. In order to identify the sender of messages we introduce a set of agent id: let $A = \{a, b, c \cdots\}$ be this set. We usually denote by s the sender agent and by r the receiver.

3.1 Describing messages

In our context, an agent may send two kinds of messages to other agents: agent a informs agent b that ϕ holds or not. These messages may occur after a request sent by b to a and asking if ϕ holds or not. In more formal terms, we get:

Definition 1 (Message). *A message M is defined as a tuple of receiver r, sender s, content ϕ, status st. The receiver and the sender are agent ids, the content is an $\mathcal{L}_0$-formula and the status is one of the two possible status:* {`Hold`, `NotHold`}. *Inconsistent statements are not allowed ($\phi \nvdash \bot$). Let $\mathcal{M}$ be the set of all possible messages.*

When the agent r receives a message about ϕ with a status equals to `Hold`, it will try to insert ϕ in its belief base. Similarly, if the status of ϕ is equal to `NotHold`, agent r will consider ϕ as a disbelief, i.e. it should not believe ϕ. Thus `NotHold`ϕ is not equivalent to `Hold`$\neg\phi$. At each moment one agent sent one message and the receiver changes its beliefs and disbeliefs accordingly.

Definition 2 (Sequence of messages). *A sequence of messages σ is a function which associates integers and messages: $\sigma : \mathbb{N} \rightarrow \mathcal{M}$*

3.2 Describing agent beliefs

The key idea is to represent the "belief state" of an agent as three sets:

- a set of labeled statements representing *current beliefs*. The set of current belief changes with respect to the flow of messages about statements which have a status equal to `Hold`;

- a set of *disbeliefs* representing statements that should not be believed by the agent. The set of disbeliefs changes with respect to the flow of messages including statements that do not hold;
- a set of *potential beliefs*: messages received by the agent which could not be handled since they are in conflict with its current beliefs (respectively disbeliefs). As the current beliefs (disbeliefs) change with respect to the received messages, some potential beliefs may become consistent with the new current beliefs (disbeliefs) and thus will be considered as current beliefs (disbeliefs) in future states.

To represent beliefs of an agent, we define a signed belief as a pair ⟨statement, origin of the statement⟩ (the associated message):

Definition 3 (Signed belief). *Let σ be a sequence of messages. A signed belief is a pair $\langle \phi, i \rangle$ where ϕ is a $\mathcal{L}_0$-formula and $i \in \mathbb{N}$ s.t. $(\exists r, s, st)(\sigma(i) = \langle r, s, \phi, st \rangle)$. Let $\mathcal{S}$ be the set of signed beliefs and let $\mathcal{SB} = 2^{\mathcal{S}}$ be the set of all sets of signed beliefs.*

Example 1. Let a and b be two agents and a message $\sigma(1) = \langle a, b, \neg\phi, \texttt{Hold} \rangle$. The pair $\langle \neg\phi, 1 \rangle$ is the associated signed belief.

Based on the set of signed beliefs, we define which statements are inferred by an agent:

Definition 4 (Belief set). *Let Bel be a function which maps a signed beliefs set S to a set of $\mathcal{L}_0$-formulas: $Bel(S) = \{\psi | \bigwedge_{\langle \phi, i \rangle \in S} \phi \vdash \psi\}$. $Bel(S)$ represents the* belief set *associated to S.*

Example 2. Suppose two messages $\sigma(1) = \langle a, b, \neg\phi, \texttt{Hold} \rangle$ and $\sigma(2) = \langle a, b, \neg\phi \rightarrow \phi', \texttt{Hold} \rangle$. The belief set associated to $S = \{\langle \neg\phi, 1 \rangle, \langle \neg\phi \rightarrow \phi', 2 \rangle\}$ contains all the consequences of $\neg\phi, \neg\phi \rightarrow \phi'$, i.e. $\phi' \subseteq Bel(S)$.

From a set of signed beliefs, we consider the minimal subsets entailing a specific conclusion. Let ϕ be a formula and S a set of signed beliefs. Let *support* be a function returning the set of minimal subsets of S entailing ϕ.

$$support(S, \phi) = \{s' | s' \subseteq S, Bel(s') \vdash \phi \text{ and } \forall s'' \subset s' (Bel(s'') \nvdash \phi)\}$$

In order to describe what is believed by an agent, we introduce the notion of epistemic state. An epistemic state describes what is "currently" believed by the agent, what should not be believed and what could be potentially believed or disbelieved. Let us stress that our definition of epistemic states should not be confused with the epistemic states defined by [2] since we do not consider preferences at this stage.

Definition 5 (Epistemic state). *Let σ be a sequence of messages. The* epistemic state *of agent r is a structure: $\langle CB, DB, PB \rangle$ where $CB \in \mathcal{SB}$, $DB \in \mathcal{SB}$ and $PB \in \mathcal{SB}$. CB represents the current beliefs, DB represents disbeliefs and PB represents the potential beliefs such that:*

1. $(\forall \langle \phi, i \rangle \in CB)(\exists s)$ *s.t.* $(\sigma(i) = \langle r, s, \phi, \texttt{Hold} \rangle)$ *and* $Bel(CB) \nvdash \bot$;
2. $(\forall \langle \phi, i \rangle \in DB)$ $(\exists s)$ *s.t.* $\sigma(i) = \langle r, s, \phi, \texttt{NotHold} \rangle)$ *and* $(Bel(CB) \nvdash \phi)$;
3. $(\forall \langle \phi, i \rangle \in PB$ *s.t.* $(\exists s)\sigma(i) = \langle r, s, \phi, \texttt{Hold} \rangle)(Bel(CB) \wedge \phi \vdash \bot$ *or* $(\exists \langle \phi', i' \rangle \in DB)(Bel(CB) \wedge \phi \vdash \phi'))$;
4. $(\forall \langle \phi, i \rangle \in PB$ *s.t.* $(\exists s)\sigma(i) = \langle r, s, \phi, \texttt{NotHold} \rangle)$ $(Bel(CB) \vdash \phi)$;

Let $\mathcal{ES}$ *be the set of all epistemic states.*

According to definition 5, condition (1) states that statements in CB are consistent and have their status equals to `Hold`; condition (2) states a similar constraint for disbeliefs; condition (3) and (4) states that potential beliefs are signed beliefs in conflict with current beliefs or disbeliefs.

Example 3. Suppose the following messages $\sigma(1) = \langle a, b, \neg\phi, \texttt{Hold} \rangle$, $\sigma(2) = \langle a, b, \neg\phi \rightarrow \phi', \texttt{Hold} \rangle$, $\sigma(3) = \langle a, c, \neg\phi', \texttt{Hold} \rangle$, $\sigma(4) = \langle a, c, \phi'', \texttt{NotHold} \rangle$ and $\sigma(5) = \langle a, d, \phi' \rightarrow \phi'', \texttt{Hold} \rangle$. Assume agent a has adopted messages 1 and 2 as current beliefs and message 4 as a disbelief: let $E = \langle \{\langle \neg\phi, 1 \rangle, \langle \neg\phi \rightarrow \phi', 2 \rangle\}, \{\langle \phi'', 4 \rangle\}, \{\langle \neg\phi', 3 \rangle, \langle \phi' \rightarrow \phi'', 5 \rangle\} \rangle$ be its epistemic state. The signed belief $\langle \neg\phi', 3 \rangle$ belongs to PB since $\neg\phi'$ contradicts $Bel(CB)$. The signed belief $\langle \phi' \rightarrow \phi'', 5 \rangle$ also belongs to PB because if it were a member of CB then the disbelief $\langle \phi'', 4 \rangle$ would have been violated.

According to example 5, agent a could have reached another epistemic state by selecting other messages for its current beliefs and disbeliefs. Actually, agents use a procedure for changing their epistemic states. This procedure considers the reliability of the senders in order to state what are current beliefs, disbeliefs and potential beliefs. This procedure will be discussed section 5 after giving a semantics for interpreting messages.

4 A semantics for describing belief and disbelief

The aim of this section is to propose a modal based language for reasoning about the epistemic states of agents. By considering current beliefs, disbeliefs and potential beliefs we describe the following epistemic attitudes:

- an agent has an opinion about ϕ: the agent believes or disbelieves ϕ;
- an agent believes ϕ: ϕ belongs to its current beliefs set;
- an agent does not believe ϕ: ϕ belongs to its set of disbeliefs;
- an agent could believe, respectively disbelieve, ϕ: ϕ belongs to its set of potential beliefs. Thus it has no opinion about ϕ.

Notice that we do not define non-beliefs by considering beliefs. The classical approach such as the BDI-based representations, supposes that an agent does not believe a statement if this statement does not belong to its set of beliefs. We propose to re-consider this approach by considering two cases: (i) an agent has an opinion on ϕ (i.e. it previously received a message about ϕ) and it does not believe ϕ; (ii) an agent has no opinion about ϕ since it does not received any message about this statement. This distinction is useful when we consider the context of an investigation: the detectives may explicitly ignore some testimonies.

The proposed logic extends the propositional logic by considering modal-like operators. Let $\mathcal{L}$ be this language. We limit the agent's belief to propositional sentences. In order to define $\mathcal{L}$, we introduce the following notations: $\mathsf{B}_a\phi$ means agent a believes ϕ; $\mathsf{DB}_a\phi$ means agent a disbelieves ϕ; $\mathsf{O}_a\phi$ means agent a has an opinion about ϕ, $\mathsf{PB}_a\phi$ means that ϕ is a potential belief for a; $\mathsf{PDB}_a\phi$ means that ϕ is a potential disbelief for a. $\mathsf{P}\phi$ means that the $\mathcal{L}$-statement ϕ has hold in the past.

Definition 6 (Syntax). *A $\mathcal{L}$-formula is defined as follows. Let $\mathcal{PROP}$ be a set of propositional symbols. If $\phi \in \mathcal{L}_0$ and $a \in A$ then $\mathsf{B}_a\phi \in \mathcal{L}$, $\mathsf{DB}_a\phi \in \mathcal{L}$, $\mathsf{O}_a\phi \in \mathcal{L}$, $\mathsf{PB}_a\phi \in \mathcal{L}$, $\mathsf{PDB}_a\phi \in \mathcal{L}$; if $\phi, \psi \in \mathcal{L}$ then $\phi \vee \psi$, $\phi \wedge \psi$, $\phi \rightarrow \psi$, $\neg\phi$, $\mathsf{P}\phi$ belong to $\mathcal{L}$.*

Let us consider a function M which associates moment n, agent ids and epistemic states: $M : \mathbb{N} \times A \rightarrow \mathcal{ES}$. With respect to a sequence of messages and an interpretation M we define agent's epistemic attitudes:

Definition 7 ($\models$). *Let σ be a sequence, M an interpretation, a an agent id and $n \in \mathbb{N}$. Let $E_a^n = \langle CB_a^n, DB_a^n, PB_a^n \rangle = M(n, a)$. A model M and a sequence σ satisfy a formula ϕ at n according to the following rules:*

- $M, \sigma, n \models \mathsf{B}_a\phi$ *iff* $\phi \in Bel(CB_a^n)$.
- $M, \sigma, n \models \mathsf{DB}_a\phi$ *iff* $\exists\langle\phi, k\rangle \in DB_a^n$.
- $M, \sigma, n \models \mathsf{PB}_a\phi$ *iff* $M, \sigma, n \not\models \mathsf{B}_a\phi$ *and* $support(CB_a^n \cup \{\langle\psi, k\rangle \in PB_a^n | \exists s \text{ s.t. } \sigma(k) = \langle a, s, \psi, \texttt{Hold}\rangle\},\ \phi) \neq \emptyset$.
- $M, \sigma, n \models \mathsf{PDB}_a\phi$ *iff* $\exists\langle\phi, k\rangle \in PB_a^n$ *s.t.* $\exists s\sigma(k) = \langle a, s, \phi, \texttt{NotHold}\rangle$.
- $M, \sigma, n \models \mathsf{O}_a\phi$ *iff* $M, \sigma, n \models \mathsf{B}_a\phi$ *or* $M, \sigma, n \models \mathsf{DB}_a\phi$.
- $M, \sigma, n \models \mathsf{P}\phi$ *iff* $\exists n' < n$ *s.t.* $M, \sigma, n' \models \phi$.
- $M, \sigma, n \models \neg\phi$ *iff* $M, \sigma, n \not\models \phi$.
- $M, \sigma, n \models \phi \vee \psi$ *iff* $M, \sigma, n \models \phi$ *or* $M, \sigma, n \models \psi$.
- $M, \sigma, n \models \phi \wedge \psi$ *iff* $M, \sigma, n \models \phi$ *and* $M, \sigma, n \models \psi$.
- $M, \sigma, n \models \phi \rightarrow \psi$ *iff if* $M, \sigma, n \models \phi$ *then* $M, \sigma, n \models \psi$.

We write $\models \phi$ iff for all σ, M and n, we have $M, \sigma, n \models \phi$

The following formulas characterizing some epistemic attitudes are valid in our framework:

(1) $\mathsf{B}_a(\phi \rightarrow \psi) \rightarrow (\mathsf{B}_a\phi \rightarrow \mathsf{B}_a\psi)$ (2) $\mathsf{P}(\phi \rightarrow \psi) \rightarrow (\mathsf{P}\phi \rightarrow \mathsf{P}\psi)$

(3) $\mathsf{B}_a\phi \rightarrow \neg\mathsf{B}_a\neg\phi$ (4) $\mathsf{DB}_a\phi \rightarrow \neg\mathsf{B}_a\phi$

Formulas (1) and (2) correspond to the K axiom schema. Formula (3) corresponds to the D axiom schema (consistency of current beliefs). Last formula enforces the consistency of current beliefs by linking them to current beliefs (i.e. none disbelief is believed) Let us mention that the K-like formula, $\mathsf{O}_a(\phi \rightarrow \psi) \rightarrow (\mathsf{O}_a\phi \rightarrow \mathsf{O}_a\psi)$, is not valid. Notice also that the opposite of formula (4): $\neg\mathsf{B}_a\phi \rightarrow \mathsf{DB}_a\phi$, is not valid. This is due to our distinction between belief, disbelief and ignorance.

Example 4. Let us reconsider example 3. According to the sequence of messages σ and the interpretation $M(6,a) = \langle \{\langle \neg\phi, 1\rangle, \langle \neg\phi \rightarrow \phi', 2\rangle\}, \{\langle \phi'', 4\rangle\}, \{\langle \neg\phi', 3\rangle, \langle \phi' \rightarrow \phi'', 5\rangle\}\rangle$, we get the following epistemic attitudes:

$$M, \sigma, 6 \models \mathsf{O}_a\phi' \wedge \mathsf{B}_a\phi' \wedge \mathsf{O}_a\phi'' \wedge \mathsf{DB}_a\phi'' \wedge \mathsf{PB}_a\phi'$$

Here, we have considered belief, disbelief and potential belief in a descriptive way. In the next section, we focus on the constructive aspect: how agents change their epistemic state with respect to a new message.

5 Epistemic state change

In order to handle messages, agents need change operators. The proposed operators belong to the family of non-prioritized operators [5, 7] because the main criterion for adopting a message is the reliability of the sender and not the novelty of the message. In our context, the operators have to handle belief, disbelief and potential belief.
The reliability of agents introduces a preference order noted $\leqslant$: each agent considers its own most reliable sources. Agents that could not be distinguished are considered in an equal way which entails a total preorder. This preorder entails a preorder over signed beliefs (since every signed belief is associated to a message through σ and thus to a sender). This latter preorder over signed beliefs will be used (i) to check if a change operation has to occur and (ii) to select (dis)beliefs to be retained in the change operation.

Definition 8 (Agent preferences). *Let $\mathcal{P}$ be a function associating each agent a with a total preorder $\leqslant_a$, $\mathcal{P} : A \rightarrow 2^{A \times A}$. $\mathcal{P}$ describes the* agent preferences.

Writing $a <_r b$ means that b is a strictly better source than a for agent r: $a \leqslant_r b$ but $b \nleqslant_r a$. The preorder over agents entails a preorder over signed beliefs also noted $\leqslant_r$.

Definition 9 (Preferences over signed beliefs). *Let us consider two signed beliefs $\langle \phi, i\rangle$ and $\langle \psi, j\rangle$ s.t. $\sigma(i) = \langle r, s, \phi, st\rangle$ and $\sigma(j) = \langle r, s', \phi, st'\rangle$. Let $\leqslant_r$ be the preferences of agent r. Preferences over signed beliefs are determined as follows: $\langle \phi, i\rangle \leqslant_r \langle \psi, j\rangle$ iff $s \leqslant_r s'$.*

Let S be a set of signed beliefs; since $\mathcal{P}(r)$ is total, $min(S)$ is always defined.
According to their current belief base and their preferences, agents change their epistemic state as they interact with other agents. We describe the two main kinds of belief change: contraction and revision. Let us consider a set of agents A where their initial epistemic states is empty: $(\forall a \in A) E_a^0 = \langle \emptyset, \emptyset, \emptyset\rangle$, some preferences $\mathcal{P}$ and a sequence of messages σ. Messages received by agents entail a revision or a contraction action. Let $n \in \mathbb{N}$ and $\sigma(n) = \langle r, s, \phi, status\rangle$ be a message. Suppose $E_a^n = \langle CB, DB, PB\rangle$ be the epistemic state of agent a at n. The epistemic state of a is recursively defined accordingly to $\mathcal{P}(a)$ for any message received by a at $n' < n$. Since only one message is sent at n, only one agent changes its epistemic state.

Definition 10. *Let A be a set of agents, E_a^n be the epistemic state of each agent a at n and $\sigma(n) = \langle r, s, \phi, status\rangle$ be a message.*

$$E_a^{n+1} = \begin{cases} (E_a^n) & \text{if } a \neq r \\ (E_a^n)^*_{\langle \phi, n\rangle} & \text{if } status = \texttt{Hold} \text{ and } a = r \\ (E_a^n)^-_{\langle \phi, n\rangle} & \text{if } status = \texttt{NotHold} \text{ and } a = r \end{cases}$$

Agents are autonomous, thus, the change action should not be specific to a belief state but must be appropriate for handling sequences of belief change. Our framework enables agent to handle iterated belief change [2] since preferences are not specific to an epistemic state. When agents determine which beliefs should be dropped they consider beliefs in their syntactic form, i.e. the messages, and thus change will be based on this approach [4, 9].

Agent r *revises* its epistemic state if the status of the received statement is `Hold`: it inserts in a consistent way the new piece of information and moves some of its current beliefs or disbeliefs into its potential beliefs set. Agent r *contracts* its epistemic state if the status of the received statement is `NotHold`: it moves some current beliefs into its set of potential beliefs and expands its set of disbeliefs. In both cases, agent r reconsiders its potential beliefs in order to reinstate some of them if they are consistent with the new epistemic state.

5.1 Contraction

In this section, we describe the contraction operator $-$. Let $\sigma(n) = \langle r, s, \phi, \texttt{NotHold}\rangle$ be a message, $E^n = \langle CB, DB, PB\rangle$ be the epistemic state of agent r at n and $E^{n+1} = (E^n)^-_{\langle \phi, n\rangle}$ be the resulting epistemic state of the contraction of E^n by the signed belief $\langle \phi, n\rangle$. When we contract the epistemic state of agent r, we check the degree of ϕ according to preferences (see def 11): if s is lower than the highest degree of a conflicting belief of r then ϕ simply goes to the potential belief set; otherwise agent s has to be trusted and we actually performed the contraction.

In order to check the degree of ϕ, we consider the set Γ of minimal subsets of $\mathcal{L}_0$-statements issued from CB entailing ϕ: $\Gamma = support(CB, \phi)$. Then, we employ a complete preorder with maximal elements on the entire set Γ [9] based on $\leqslant_r$: we say that a set γ_1 is preferred to a set γ_2, noted $\gamma_2 \ll_r \gamma_1$, if the maximal element of γ_1 is strictly preferred to the maximal element of γ_2; γ_1 is equally preferred to γ_2, $\gamma_2 =_r \gamma_1$, if the maximal element of γ_1 is equal to the maximal element of γ_2. Note that such maximal elements of γ always exist.

Definition 11 uses the following notions that will be further discussed in the following of the paper: function *esc* gives the new current belief set and it is a safe contraction function [1] based on $\ll_r$. Current beliefs which have been removed by contraction function *esc* are added to the potential beliefs. If the received message do not entail a contraction then it is considered as a "potential disbelief". The set Π represents the most preferred potential beliefs which are consistent with the contracted current beliefs set. it has to be added to $esc(CB, \langle \phi, n \rangle)$. Similarly, the set Δ represents the potential disbeliefs that have to be reinstated (since current beliefs have been changed) (definition of Π and Δ are presented definition 13).

Definition 11 (-). *Let $\sigma(n) = \langle r, s, \phi, \texttt{NotHold} \rangle$ be a message and $E^{-}_{\langle \phi, n \rangle}$ be the epistemic state of agent r at the moment $n+1$ s.t.:*

- *if $Bel(CB) \vdash \phi$ and $\exists \gamma \in support(CB, \phi)$ s.t. $\{\langle \phi, n \rangle\} \ll_r \gamma$ then*

$$E^{-}_{\langle \phi, n \rangle} = \langle CB, DB, PB \cup \{\langle \phi, n \rangle\} \rangle$$

- *else*

$$E^{-}_{\langle \phi, n \rangle} = \langle esc(CB, \langle \phi, n \rangle) \cup \Pi, DB \cup \Delta \cup \{\langle \phi, n \rangle\}, \\ PB - \Pi - \Delta \cup (CB - esc(CB, \langle \phi, n \rangle)) \rangle$$

The contraction operator is a two stage operator: firstly the current beliefs are contracted if the sender of the message is sufficiently reliable and secondly, the potential beliefs that are consistent with the resulted current beliefs are added to them.

First stage, contracting CB: Here, we use the degree of each conflicting belief. We remove minimal elements in every set $\gamma \in support(CB, \phi)$, one by one, in an iterative way, w.r.t. $\ll_r$. Let $\mathsf{min}(\Gamma)$ be the set of minimal subsets of Γ with respect to $\ll_r$. The contraction function, esc removes from CB the less reliable signed beliefs belonging to $\mathsf{min}(\Gamma)$, i.e. $min(\mathsf{min}(\Gamma))$.

Definition 12 (esc). *The contraction of the current signed beliefs of an epistemic state E by a signed belief $sb = \langle \phi, n \rangle$ is defined as $esc(CB, sb) = CB^{|\Gamma|}$ where $CB^{|\Gamma|}$ is defined as follows:*

- *$CB^0 = CB$, $\Gamma^0 = support(CB^0, \phi)$;*
- *$CB^{i+1} = CB^i - min(\cup_{\gamma \in \mathsf{min}(\Gamma^i)} \gamma)$;*
- *$\Gamma^{i+1} = support(CB^{i+1}, \phi)$.*

Before stating the behavior of esc we reformulate the AGM postulates [6] w.r.t. our definitions:

(C1) $esc(CB, \langle \phi, n \rangle)$ is a set of signed beliefs.
(C2) $esc(CB, \langle \phi, n \rangle) \subseteq CB$.
(C3) If $\phi \notin Bel(CB)$ then $esc(CB, \langle \phi, n \rangle) = CB$.
(C4) If $\nvdash \phi$ then $\phi \notin Bel(esc(CB, \langle \phi, n \rangle))$.
(C5) If $\phi \in Bel(CB)$, then $CB \subseteq esc(CB, \langle \phi, n \rangle) \cup \{\langle \phi, n+1 \rangle\}$.
(C6) If $\vdash \phi \leftrightarrow \psi$, then $esc(CB, \langle \phi, n \rangle) = esc(CB, \langle \psi, n \rangle)$.
(C7) $esc(CB, \langle \phi, n \rangle) \cap esc(CB, \langle \psi, n \rangle) \subseteq esc(CB, \langle \phi \rightarrow \psi, n \rangle)$.
(C8) If $\phi \notin Bel(esc(CB, \langle \phi \wedge \psi, n \rangle))$, then $esc(CB, \langle \phi \wedge \psi, n \rangle) \subseteq esc(CB, \langle \phi, n \rangle)$.

We get the following theorem for the contraction function *esc*:

Theorem 1 ([9]). *Let r be an agent, $\leqslant_r$ be its preferences, $E^n = \langle CB, DB, PB\rangle$ its epistemic state and a message $\sigma(n) = \langle r, s, \phi, \texttt{NotHold}\rangle$. The contraction function esc determined by E^n, $\leqslant_r$ and $\langle \phi, n\rangle$ satisfies AGM postulates for contraction (C1) through (C5), (C7) and (C8).*

AGM postulate (C6) which states the syntax irrelevance principle is not satisfied since we consider a syntax-based technique.

Second stage, adding/removing potential beliefs and disbeliefs: After contracting its current belief set, agent r has to consider all potential beliefs. Indeed, some potential beliefs may be consistent with new set $esc(CB, sb)$. A potential belief may be reinstated if it does not entail (i) an inconsistency with the current beliefs, (ii) nor with the disbeliefs and (iii) no potential disbelief is more reliable. In order to define which potential beliefs may be reinstated, we introduce two functions, *CBeligible* and *DBeligible*, which state if a potential belief may be reintroduced in the set of current beliefs or disbeliefs.

Sets Π and Δ represent the sets of potential beliefs that have to be reinstated as current belief and disbelief. For this, we consider the most preferred potential beliefs with the contracted current beliefs set and we build Π, a set of potential beliefs that should be added to $esc(CB, \langle \phi, n\rangle)$, i.e. to the new set of current beliefs. We proceed in a similar way for the set Δ.

Definition 13 (Π and Δ). *The set Π of potential beliefs to add to the new current beliefs set and the set Δ of potential beliefs that have to be considered as disbeliefs are defined as follows:*

- $PB^0 = PB$, $\Pi^0 = \emptyset$, $\Delta^0 = \emptyset$;
- *Let* $\langle \psi, k\rangle \in PB^i$. *If*
  1. $CBeligible(\langle esc(CB, \langle \phi, n\rangle) \cup \Pi^i, DB \cup \Delta^i, PB^i\rangle, \{\langle \psi, k\rangle\}) = \mathsf{true}$ *and;*
  2. $(\forall \langle \psi', k'\rangle \in PB^i) CBeligible(\langle esc(CB, \langle \phi, n\rangle) \cup \Pi^i, DB \cup \Delta^i, PB^i\rangle, \{\langle \psi', k'\rangle\}) = \mathsf{true} \Rightarrow \langle \psi, k\rangle <_r \langle \psi', k'\rangle$.

  then
  $$\Pi^{i+1} = \Pi^i \cup \{\langle \psi, k\rangle\} \text{ and } \Delta^{i+1} = \Delta^i$$
- *Let* $\langle \psi, k\rangle \in PB^i$. *If* $DBeligible(\langle esc(CB, \langle \phi, n\rangle) \cup \Pi^i, DB \cup \Delta^i, PB^i\rangle, \{\langle \psi, k\rangle\}) = \mathsf{true}$ *then*
  $$\Delta^{i+1} = \Delta^i \cup \{\langle \psi, k\rangle\} \text{ and } \Pi^{i+1} = \Pi^i$$
- $PB^{i+1} = PB^i - \{\langle \psi, k\rangle\}$.

The sets Π, Δ are equal to $\Pi^{|PB|}$ and $\Delta^{|PB|}$.

The sets Π and Δ have to be removed from the potential beliefs. Now, we give the definitions of the functions *CDeligible* and *DBeligible* which states if a potential belief can be reinstated.

Definition 14 (CBeligible). *Let $CBeligible$ be a function stating if a signed belief can be added to a set of current beliefs. Let $E_r = \langle CB, DB, PB \rangle$ be the epistemic state of agent r, $\langle \psi, k \rangle$ be a signed belief, $\leqslant_r$ be the preferences of r and σ be a sequence of messages.*

- $CBeligible(E_r, \langle \psi, k \rangle) = \mathsf{true}$ *iff:*
  1. $(\exists s')(\sigma(k) = \langle r, s', \psi, \mathtt{Hold} \rangle)$;
  2. $Bel(CB \cup \{\langle \psi, k \rangle\}) \nvdash \bot$ *and*
  3. $(\forall \langle \psi', k' \rangle \in DB)$ $((\forall \gamma \in support(CB \cup \{\langle \psi, k \rangle\}, \psi'))(\langle \psi, k \rangle \in \gamma \Rightarrow \{\langle \psi', k' \rangle\} \ll_r \gamma))$.
  4. $(\forall \langle \psi', k' \rangle \in PB)$ $(\exists s'')(\sigma(k') = \langle r, s'', \psi', \mathtt{NotHold} \rangle) \Rightarrow \langle \psi', k' \rangle \leqslant_r \langle \psi, k \rangle$
- $CBeligible(E_r, \langle \psi, k \rangle) = \mathsf{false}$ *otherwise.*

In other words, a signed belief may be chosen for becoming a current belief (w.r.t. to an epistemic state) iff (1) the status of the signed belief is `Hold` (i.e. the agent has to consider that the statement has to be believed); (2) the statement is consistent with the current beliefs; (3) the statement do not entail the violation of a disbelief or if it entails a violation of a disbelief then the statement is more reliable than the violated disbeliefs; (4) there is no potential disbelief that is more "important" (w.r.t. to the preferences) than this signed belief. In a similar way, $DBeligible$ is a function stating if a potential disbelief has to be considered as a disbelief.

Definition 15 (DBeligible). *Let $DBeligible$ be a function stating if a signed belief can be added to a set of disbeliefs. Let $E_r = \langle CB, DB, PB \rangle$ be the epistemic state of agent r, $\langle \psi, k \rangle$ be a signed belief, $\leqslant$ be the preferences of r and σ be a sequence of messages.*

- $DBeligible(E_r, \langle \psi, k \rangle) = \mathsf{true}$ *iff:*
  1. $(\exists s')(\sigma(k) = \langle r, s', \psi, \mathtt{NotHold} \rangle)$;
  2. $Bel(CB) \nvdash \psi$ *or* $(\forall \gamma \in support(CB, \psi))(\{\langle \psi, k \rangle\} \not\ll_r \gamma)$
  3. $(\forall \langle \psi', k' \rangle \in PB)$ $(\exists s'')(\sigma(k') = \langle r, s'', \psi', \mathtt{Hold} \rangle) \Rightarrow \langle \psi', k' \rangle \leqslant_r \langle \psi, k \rangle$
- $DBeligible(E_r, \langle \psi, k \rangle) = \mathsf{false}$ *otherwise.*

A signed belief may be inserted in a set of disbeliefs iff: (1) if the status of the signed belief is equal to `NotHold`; (2) the current beliefs do not entail the statement associated to the signed belief or, if the statement is entailed by the current beliefs, then the statement is more reliable than every minimal subsets issued from the current beliefs entailing it; there is no possible belief that is more reliable than this possible disbelief.

A consequence of the definition of $-$ is that every state has a successor state.

Observation 1 *Let E be an epistemic state and sb a signed belief. E^-_{sb} is an epistemic state.*

Notice that according to the definitions of $CBeligible$ and $DBeligible$ a contracted epistemic state may admit several successor states.

Observation 2 *Let E be an epistemic state and sb a signed belief. There exists at least one epistemic state characterizing E^-_{sb}.*

5.2 Revision

Our revision operation is based on the safe contraction operation previously defined and the Levi identity. In order to contract the epistemic state, we introduce the notion of the negation of a signed belief:

Definition 16 ($\overline{\langle\phi, i\rangle}$)**.** *Let σ be a sequence of messages and $m = \langle r, s, \phi, \texttt{Hold}\rangle$ be a message s.t. $\sigma(i) = m$. Let $\overline{\langle\phi, i\rangle}$ be a signed belief, called the mirror of $\langle\phi, i\rangle$ s.t. the associated message to $\overline{\langle\phi, i\rangle}$ is equal to $\langle r, s, \neg\phi, \texttt{NotHold}\rangle$.*

Let $\sigma(n) = \langle r, s, \phi, \texttt{Hold}\rangle$ be a message, E^n be the epistemic state of agent r at n and $E^{n+1} = (E^n)^*_{\langle\phi,n\rangle}$ be the resulting epistemic state of the revision of E^n by the signed belief $\langle\phi, n\rangle$. Set of current beliefs CB is "contracted" by the mirror of $\langle\phi, n\rangle\rangle$:

Definition 17 (esr)**.** *Let $E = \langle CB, DB, PB\rangle$ be an epistemic state. The revision of the set CB by a signed belief $\langle\phi, n\rangle$, s.t. $\sigma(n) = \langle r, s, \phi, \texttt{Hold}\rangle$ is defined as:*

$$esr(CB, \langle\phi, n\rangle) = esc(CB, \overline{\langle\phi, n\rangle}) \cup \{\langle\phi, n\rangle\}$$

As for the contraction function esc all the postulates describing revision actions [6] are satisfied except the syntax-independence postulate.

The second stage where we consider potential beliefs that may be reinstated slightly differs from the one previously described. The main difference concerns the disbeliefs since some of them should no longer hold. The disbeliefs that should no longer considered have to be removed from DB and transferred into PB. Definitions of Π is unchanged. Let $\overline{\Delta}$ be this set of this disbeliefs:

$$\begin{aligned}\overline{\Delta} = \{\langle\psi, k\rangle | \sigma(k) = \langle r, s', \psi, \texttt{NotHold}\rangle \text{ and } \\ Bel(esr(CB, \langle\phi, n\rangle) \cup \Pi) \vdash \psi \text{ and } \\ (\exists\gamma \in support(esr(CB, \langle\phi, n\rangle, \psi)))(\{\langle\psi, k\rangle\} \ll_r \gamma)\}\end{aligned}$$

Definition 18 ($*$)**.** *Let $E^*_{\langle\phi,n\rangle}$ be the epistemic state of agent r at moment $n+1$:*

- *if $((\exists\langle\psi, k\rangle \in DB)$ s.t. $(\forall\gamma \in support(esr(CB, \langle\phi, n\rangle), \psi))(\gamma \ll_r \{\langle\psi, k\rangle\}))$ or $((\exists\gamma \in support(CB, \neg\phi)(\{\langle\phi, n\rangle\} \ll_r \gamma))$ then*

$$E^*_{\langle\phi,n\rangle} = \langle CB, DB, PB \cup \{\langle\phi, n\rangle\}\rangle$$

- *else*

$$E^*_{\langle\phi,n\rangle} = \langle esr(CB, \langle\phi, n\rangle) \cup \Pi, DB \cup \Delta - \overline{\Delta}, PB - \Pi - \Delta \cup \overline{\Delta}\rangle$$

As for the contraction function, we can make a similar observation about the successor states.

Observation 3 *Let E be an epistemic state and sb a signed belief. There exists at least one epistemic state characterizing E^*_{sb}.*

Now, we describe the behavior of the function $*$, i.e. how this function respects AGM postulates. We propose here to rephrase the AGM postulates for revision in a way similar to those exhibit by A. Darwiche and J. Pearl in [2] for their epistemic states. Before introducing the modified postulates which are a KM formulation of the AGM postulates [2, 8], let us briefly describe the expansion of an epistemic state. Let sb be a signed belief and E an epistemic state:

$$E^+_{sb} = \langle CB \cup \{sb\}, DB, PB\rangle$$

To simplify notation in the postulates, we use $Bel(E)$ instead of $Bel(CB)$ ($E = \langle CB, DB, PB\rangle$). The modified AGM postulates are:

($R * 1$) $Bel(E^*_{\langle\phi,n\rangle}) \vdash \phi$.
($R * 2$) If $Bel(E) \nvdash \neg\phi$ then $E^*_{\langle\phi,n\rangle} = E^+_{\langle\phi,n\rangle}$.
($R * 3$) If $\nvdash \neg\phi$ then $Bel(E^*_{\langle\phi,n\rangle}) \nvdash \bot$.
($R * 4$) If $E = F$ and $\phi \leftrightarrow \psi$ then $Bel(E^*_{\langle\phi,n\rangle}) \leftrightarrow Bel(F^*_{\langle\psi,n\rangle})$.
($R * 5$) $Bel((E^*_{\langle\phi,n\rangle})^+_{\langle\psi,n+1\rangle}) \vdash Bel(E^*_{\langle\phi\wedge\psi,n\rangle})$.
($R * 6$) If $Bel((E^*_{\langle\phi,n\rangle})^+_{\langle\psi,n+1\rangle}) \nvdash \bot$ then $Bel(E^*_{\langle\phi\wedge\psi,n\rangle}) \vdash Bel((E^*_{\langle\phi,n\rangle})^+_{\langle\psi,n+1\rangle})$.

We have the following theorem:

Theorem 2. *Let r be an agent, $\leqslant_r$ be its preferences, $E^n = \langle CB, DB, PB\rangle$ its epistemic state and a message $\sigma(n) = \langle r, s, \phi, \mathtt{Hold}\rangle$. The revision function $*$ determined by E^n, $\leqslant_r$ and $\langle\phi, n\rangle$ satisfies modified AGM postulates for revision* ($R * 2$) *and* ($R * 3$).

AGM postulate ($R * 1$) which states the success principle is not satisfied since cases may occur where input is not inserted in the current beliefs. ($R * 4$) states syntax irrelevance principle and as previously it is not satisfied since we consider a syntax-based technique (regardless the definition of the equality of two epistemic states). Postulates ($R * 5$) and ($R * 6$) are not satisfied since input may be considered in the resulting epistemic state as current or potential belief.

Because function $*$ is non-prioritized, postulates introduced by A. Darwiche and J. Pearl in [2] characterizing iterated revision do not hold.

5.3 Linking change action and models for epistemic attitudes

Since we have shown how a sequence of actions is handled for constructing epistemic states, we refine interpretation function M described section 4. Let σ be a sequence of messages, $\mathcal{P}$ be agent preferences. Let $M : \mathbb{N} \times A \rightarrow \mathcal{ES}$ be the interpretation function defined as follows:

- for all $a \in A$, $M(0, a) = \langle\emptyset, \emptyset, \emptyset\rangle$
- for all $a \in A$ and $n > 0$ s.t. $\sigma(n-1) = \langle r, s, \phi, status\rangle$:

$$M(n, a) = \begin{cases} M(n-1, a) & \text{if } a \neq r \\ M(n-1, a)^*_{\langle\phi,n\rangle} & \text{if } status = \mathtt{Hold} \text{ and } a = r \\ M(n-1, a)^-_{\langle\phi,n\rangle} & \text{if } status = \mathtt{NotHold} \text{ and } a = r \end{cases}$$

Actually, the procedure for handling changes, and thus the sequence of messages, justifies the epistemic attitudes section 4.

6 Revisiting the Example

In this section, we revisit the example described at the beginning of the paper. Let us consider three agents $pa(ul)$, $pe(ter)$, $po(lice)$. The preferences of *peter* are: $\mathcal{P}(pe) = \langle\{(pa < pe, pe < po)\}\rangle$ and the initial state is $E^0_{pe} = \langle\emptyset, \emptyset, \emptyset\rangle$. *murd*, *evid* and *jail* stand for *murderer*, *evidence* and *jail*. Let us consider what *paul* tells to *peter* about John: we get the following messages $\sigma(0)$ and $\sigma(1)$:

$$\sigma(0) = \langle pe, pa, murd, \texttt{Hold}\rangle$$
$$\sigma(1) = \langle pe, pa, murd \rightarrow jail, \texttt{Hold}\rangle$$

After processing these two messages as revision actions, *peter* believes all the consequences of $Bel(CB^1_pe) = \{\alpha | murd \wedge (murd \rightarrow jail) \vdash \alpha\}$. The resulting epistemic states are:

$$E^1 = \langle\{\langle murd, 0\rangle\}, \emptyset, \emptyset\rangle$$
$$E^2 = \langle\{\langle murd, 0\rangle, \langle murd \rightarrow jail, 1\rangle\}, \emptyset, \emptyset\rangle$$

Next *peter* processes the messages sent by the police (john is a murderer iff there is evidence against him; and the police do not believe there is evidence):

$$\sigma(2) = \langle pe, po, murd \rightarrow evid, \texttt{Hold}\rangle$$
$$\sigma(3) = \langle pe, po, evid, \texttt{NotHold}\rangle$$

According to the preferences and the change operators, we get the following epistemic states for *peter*:

$$E^3 = \langle\{\langle murd, 0\rangle, \langle murd \rightarrow jail, 1\rangle, \langle murd \rightarrow evid, 2\rangle\}, \emptyset, \emptyset\rangle$$
$$E^4 = \langle\{\langle murd \rightarrow jail, 1\rangle, \langle murd \rightarrow evid, 2\rangle\}, \{\langle evid, 3\rangle\}, \{\langle murd, 0\rangle\}\}\rangle$$

At this moment, *peter* does no longer believe that John is a murderer and he will go to jail. Indeed $Bel(CB^3_{pe}) \vdash evidence$ and *evidence* is inserted in DB^4_{pe} (because of the reliability of the police) and thus *murderer* is moved into PB^4_{pe}. Finally, the *police* informs *peter* about proofs against John:

$$\sigma(4) = \langle pe, po, evid, \texttt{Hold}\rangle$$

We get the following epistemic state for *peter*:

$$E^5 = \langle\{\langle murd, 0\rangle, \langle murd \rightarrow jail, 1\rangle, \langle murd \rightarrow evid, 2\rangle, \langle evid, 4\rangle\}, \emptyset, \{\langle evid, 3\rangle\}\}\rangle$$

Messages 0, 1, 2 and 4 entail a revision operation while message 3 entails a contraction operation. Notice that statement "John is a murderer" has been reinstated as a current belief since it is consistent with the new epistemic state.

Let us also notice that the last message (*police* informs *peter* that *evidence* holds) entails that *jail* is believed by *peter*. This is due to the fact that agent *police* is more reliable that *paul*. Suppose now, that instead of agent *police*, agent *paul* informs *peter* about evidence against John. We have:

$$\sigma(4b) = \langle pe, pa, evid, \texttt{Hold}\rangle$$

Finally, we get the following epistemic state for *peter*:

$$E^{5b} = \langle\{\langle murd \rightarrow jail, 1\rangle, \langle murd \rightarrow evid, 2\rangle\}, \{\langle evid, 3\rangle\}, \{\langle murd, 0\rangle, \langle evid, 4\rangle\}\}\rangle$$

In other words, disbelief *evid*(*ence*) which is stronger (since it has been send by *po* and *po* is better than *pa*) prevents agent *peter* to adopt the statement *murd*(*erer*). However, *peter* considers that there is potentially evidence against John.

Let M be an interpretation function reflecting the changes, i.e. $M(5, pe) = E^5$. According to the sequence of messages and M, we get the following epistemic attitudes about the content of the messages:

$$M, \sigma, 5 \models \mathsf{B}_{pe} jail \qquad M, \sigma, 5b \models \mathsf{DB}_{pe} evidence$$
$$M, \sigma, 5 \models \mathsf{O}_{pe} murderer \qquad M, \sigma, 5b \models \mathsf{P}(\mathsf{B}_{pe} murderer)$$
$$M, \sigma, 5 \models \mathsf{PDB}_{pe} evid \wedge murd \qquad M, \sigma, 5b \models \mathsf{PB}_{pe} jail$$

Next, let us assume a statement γ s.t. γ has nothing in common with ϕ and ψ; a_1 has no opinion about γ and thus does not believe or disbelieve γ:

$$M, \sigma, 5 \models \neg\mathsf{O}_{a_1}\gamma \wedge \neg\mathsf{B}_{a_1}\gamma \wedge \neg\mathsf{DB}_{a_1}\gamma$$

7 Discussion

Our work focus on belief change when agents exchange information about a static world. The first characteristic of our operators is to enable agents to handle any sequence of messages. The second characteristic of our framework is to keep all the received messages and to reconsider them whenever a change action occurs so that received information is handled as much as possible. The third characteristic of our proposal is a semantics for describing beliefs, disbeliefs, potential beliefs which is explicitly based on messages. Moreover, the proposed semantics enables to represent opinions.

A. Dragoni and P. Giorgini present a similar framework [3]. They propose to apply non-prioritized belief revision in a multi-agent system by considering the origin of information. Based on the reliability of the incoming statements, agents can reject new information. Agents can also reconsider all the previous messages and more specifically discarded beliefs can be reinstated. J.W. Roorda et al. [12] present also a similar work based on modal logics. They propose a function returning the history of messages and a second one to select a subset of messages in a consistent way. Thus, changes are handled only by expansions. The main difference with our work is that they do not consider disbeliefs in an explicit way and thus they do not take into account contraction operations. A second difference is that we consider more fine-grain epistemic attitudes: for instance, we can describe potential belief and thus what could be believed by agents. Our approach does have some limitations. In a short term, we would like to generalize our framework in order to handle the limitation about the static world, i.e. handling belief update. In a more longer term, our aim is to enable agents to reason about their different kinds of beliefs so that they can initiate messages for acquiring new information and adopting new epistemic attitudes (knowledge, goals, desires, commitments...). We are currently investigating all these topics.

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