Belief Increasing in SKL Model Frames

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Abstract. Three-Valued Strong Kleene Logic [16], provides an adequate framework to deal with belief increasing. In this paper, undefined truth-value is used to denote opinionless information. Through an informative refinement, such information could become to be true or false in a step by step way. Our approach is based upon model frames [9], that are sets of informatively ordered three-valued interpretations. A relation of compatibility among frames, being a partial informative order, is defined. Belief increasing is accomplished by using the compatibility relation that is based on concatenation operation over model frames. A correspondence between model frames and analytic tableaux is outlined. It provides to deal with model frames by using that powerful proof method [11].

1 Introduction

Classical approaches to belief change are the Alchourron-Gärdenfors-Makinson (AGM) [1] and the Update Theory of Katsuno and Mendelzon (KM) [15]. In order to change the logically closed belief base $\psi$ with a sentence $\mu$, AGM proposal provides with expansion, contraction and revision operations. Expansion is applied whenever $\mu$ is consistent with $\psi$, obtaining logical closure from $\psi \cup \{\mu\}$; contraction to get out from $\psi$ the sentence $\mu$ together with some deductively-related formulas; and revision being a $\neg\mu$-contraction followed by a $\mu$ expansion. Alchourron et al. proposed the so called rationality postulates to be satisfied by any revision operator. On the other hand, KM approach provides eight postulates to update with $\mu$ any arbitrary sets of sentences $\psi$ (not only logically closed ones as AGM does). In case of inconsistency between $\psi$ and $\mu$, semantically, AGM results in the closest model to $\psi$ satisfying $\mu$, while KM release, for each model of $\psi$, the models of $\mu$ closest to it [15].

The main drawback of those fruitful approaches to belief change consists, essentially, in the lack of flexibility to deal with no-considered revision or updating cases, or the contraintuitive results that they provide dealing with ambiguous information. Brewka and Hertzberg [6] as well as Del Val and Shoham [7] propose to use Action Theory through axioms of action encoding the circumstances of specific updating or revision. We coincide to consider that the point is the capability to handle particular information based on a general framework.
Thus, the paramount of this paper is twofold:

- Provide a intuitive framework for representation and change of belief using model frames defined by Doherty [9]
- Outline an equivalence between model frames and Analytic Tableaux such that this flexible proof method [11] is used to deal with belief in a computational perspective intuitions preserving.

In section 2, three-valued $SKL$ is introduced together with Belnap’s informative partial order over model frames. From $SKL$ and the informative order we outline our epistemic definitions in section 3, developing a (constructive-like) logic of belief. In section 4 correspondence between epistemic model frames and analytic tableaux is mentioned showing that tableaux proof method is well applied in our intend. In the last section a brief comparison between AGM paradigm and Update Theory with respect to our approach is developed.

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2.1 Strong Kleene Logic

For Strong Kleene Logic, propositional language $L$ is defined from a finite set of sentences $\Sigma$ and the primitive connectives negation $\neg$ and disjunction $\lor$. From those connectives the conjunction $\land$ and implication $\rightarrow$ are defined in the classical way. Let $F$ be the set of $L(\Sigma)$-formulas. Semantical definitions for disjunction and negation in the Strong Kleene Logic are given in Table 1. Let true, false and undefined be truth-values denoted with $t$, $f$ and $u$.

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**Definition 1.** A three-valued interpretation $I$, is a valuation function from $F$ to $\{t, f, u\}$ in accordance with logical connectives definition. $I$ is equivalent to $I^t \cup I^f \cup I^u$ in such a way that $I^t$ is the set of true formulas, $I^f$ the set of false formulas and $I^u$ the set of undefined formulas. When $I^u$ is the empty set we say that $I$ is complete with respect to true and false truth-values. Let $I(F)$ be the set of three-valued interpretations of formulas in $F$.

2.2 Informative Order

In this section we concern with the approach that use an informative order to deal with knowledge and belief (see e.g [2, 4, 9]), in order not reduce them to
truth-semantic-logical aspect. Herein an informative order over interpretations of sets of beliefs is given. Underline objective is to deal with belief change in a step by step way. The intuitive point is that seems natural to consider the following:

- Having true, false and undefined statements, true or false ones provide more information than undefined statements.

We propose that when undefined information turns up defined, as true or false, beliefs could increase.

We observe that increasing of belief can be considered a belief expansion-like operation of Alchourron, Gärdenfors and Makinson Paradigm [1, 14]. It is well known, however, that in the seminal AGM approach, change of belief includes also elimination and revision of current beliefs by using contraction and revision operations. On the other hand, Updating Theory [15] is the classical approach to belief updating. As mentioned in the introduction, this approach has subtle differences with the AGM one and constitutes the other significant view of belief change. In section 5 we outline the way in which our proposal can deal with contraction, revision and updating operations. Now, the informative partial order defined for Doherty over \{t, f, u\} set [9] is introduced.

**Definition 2.** The Degree of information among \(t, f\) and \(u\) truth-values, is defined as follows: \(u \preceq_i t, u \preceq_i f\) and \(t, f\) are not comparable.

Let \(\mathcal{T}\) be a subset of \(\mathcal{I}(\mathcal{F})\). The informative partial order \(\preceq_i\) is introduced over \(\mathcal{T}\) in the following way: given an \(I, I' \in \mathcal{T}\), \(I \preceq_i I'\) is satisfied if and only if \(I' \subseteq I''\), \(I' \subseteq I'\) and \(I'' \supseteq I''\). The order \(\preceq_i\) is a partial one on \(\mathcal{T}\).

Intuition of that order is that given two interpretations of a set \(\mathcal{P}\) of formulas, interpretation with more undefined formulas is less informed than the one having more true or false formulas. Then, for \(\mathcal{P} \subset \mathcal{F}\) such that \(I(P) \preceq_i I'(P)\) for every \(P \in \mathcal{P}\), \(I'\) is more informed than \(I\) with respect to \(\mathcal{P}\), denoted \(I \preceq_{\mathcal{P}} I'\). In this case it is said that \(I'\) is an informative refinement of \(I\) with respect to \(\mathcal{P}\).

**Example:** Let \(\mathcal{P} = \{P\}\) be the only sentence of language \(\mathcal{L}\); \(I_0 = (u), I_1 = (t), I_2 = (f)\) be the interpretations of \(\mathcal{F}\). Then \(I_1, I_2\) are informative refinements of \(I_0\) and thus more informed than it.

The following formal structure providing a suitable framework for our epistemic approach is an extension of model frame defined by Doherty [10]. The underling objective is to capture the dynamic manner in which beliefs change. We consider that it ddepends of worlds being explored. Gradual exploration is allowed by using the informative order \(\preceq_i\) among model frames.

**Definition 3.** A model frame is an ordered 3-tuple \(\mathcal{M} = (\mathcal{T}, I_0, \preceq_i)\), where \(\mathcal{T} \subseteq \mathcal{I}(\mathcal{F})\) is a set of interpretations and \(I_0 \in \mathcal{T}\) is called the current (actual or present) interpretation. For any \(I' \in \mathcal{T}\), we assume that \(I_0 \preceq_i I'\). Thus, any interpretation in \(\mathcal{M}\) is at least as informed as \(I_0\).
Notice that as interpretation $I_0$ remains fixed, it constitutes an invariant and characterizes the model frame. Following definition will be used in the following comments and in belief definition.

**Definition 4.** An interpretation $J$ is maximal in $\mathcal{M}$ if and only if there is no $J'$ in $\mathcal{M}$ such that $J \preceq J'$.

A model frame can be seen as a set of possible worlds that provides a description of the state of the things together with its possible extensions (see fig 1). Whenever worlds corresponding with the (informatively) maximal interpretation in the model frame contain undefined statements, extension of belief could be performed as it should show below (see 4).

On the other hand, informative order $\preceq_i$ can be considered an accessibility relation among interpretations in $\mathcal{T}$ as follows: $I'$ is accessible (compatible) for $I$ whenever $I'$ is an informative refinement of $I$. Moreover, if for every $I \in \mathcal{T}$, in a model frame $\mathcal{M}$, $I(\alpha) \in \{t, f\}$, then this last one is a structure of Kripke$^3$.

### 3 Belief

In this section a belief definition is proposed. Propositional language $\mathcal{L}$ is extended by adding a modal operator of belief, $B$. The language extended with these modal operators is denoted $\mathcal{BL}$ by belief language. The following satisfaction definition is relative to model frame.

**Definition 5.** A sentence $\alpha \in \mathcal{F}$ is satisfied by the interpretation $I \in \mathcal{T}$ of the model frame $\mathcal{M}$, denoted $I \models_{\mathcal{M}} \alpha$, if and only if $I(\alpha) = T$. It is said that the frame satisfies $\alpha$, $\mathcal{M} \models \alpha$, if every $I \in \mathcal{T}$ satisfies $\alpha$. For a set $\Gamma$ such that any sentence of $\Gamma$ is satisfied by $\mathcal{M}$, is said that the frame $\mathcal{M}$ satisfies $\Gamma$, $\mathcal{M} \models \Gamma$.

Notice that this satisfaction definition is for no modal formulas only; for belief modal ones is given below. Relativity of model frame satisfaction is welcome in our aim to encourage the point of view considering belief relative to actual information and context. This semantical flexibility can be syntactically well treated using a method based on Analytic Tableaux. Now we give belief definition.

**Definition 6.** A formula $\alpha$ is believed in the interpretation $I$ of the model frame $\mathcal{M}$, denoted $I \models_{\mathcal{M}} B(\alpha)$, if and only if, for every maximal $J$ of $\mathcal{M}$ with $I \preceq_i J$, $J \models \alpha$ (see fig 2). Whenever for every $I$ of $\mathcal{M}$, $I \models_{\mathcal{M}} B(\alpha)$, it is said that $\models_{\mathcal{M}} B(\alpha)$.

$^3$ A structure of Kripke is a 3-tuple $< W, R, \nu >$ such that $W$ is a nonempty set of worlds, $R$ a possibility relation and $\nu$ a valuation function [18].
Then, a statement is belief in $\mathcal{M}$ if it is true in the interpretation $I_0$ or if being undefined in $I_0$, it becomes true in every maximal interpretation of the frame.

![Figure 2: Belief](image)

### 3.1 Consistency over Belief Increasing

Our formalism provides the possibility to reason from initial, possibly not consistent beliefs set, in a not trivial way. Each one of the contradictory sentences, if any, are considered in different parts of the total frame. In fact, increasing (expansion) of beliefs happens in different directions, being consistent each one of them. Now we define compatibility relation among model frames; based upon it, in addition to concatenation and unification operations over frames, change of the initial beliefs, as increasing or modification, is considered. (A comparison with Logic of Explicit and Implicit Belief in [10].)

### 3.2 Compatible frames

We are interested in model frames that change in order to model the dynamic character of a cognitive process. A model frame defined by Doherty in [9] is static; is beforehand given and does not change at all. However, solution to our requirements can be done by introducing an operation, namely of concatenation, among Doherty's model frames. The intuitive idea of concatenation is the following:

- To add information to a maximally informed world in the frame, if possible, in such a way that it allows to increase beliefs.

Let $\mathcal{M}_1 = \langle T_1, I_0^1, \leq_1^1 \rangle$, $\mathcal{M}_2 = \langle T_2, I_0^2, \leq_2^2 \rangle$ be two model frames.

**Definition 7.** Model frame $\mathcal{M} = \langle T, \leq, I_0^3 \rangle$ is the concatenation of $\mathcal{M}_2$ with $\mathcal{M}_1$, denoted $\mathcal{M} = \mathcal{M}_1 \odot \mathcal{M}_2$, if and only if

1) $I_0^3$ is a maximal interpretation of $\mathcal{M}_1$.

2) $T = T_1 \cup T_2$.

By definition, $I_0^3 \preceq I'$ for every $I' \in T_1 \cup T_2$. Notice that concatenation is defined over maximal interpretations only. Thus, further information is added to maximally informed worlds in the frame. It could be of interest to define
concatenation for every interpretation in the model frame but this is behind the scope of this work.

Notice that frame concatenation is based upon the informative orders of model frames. Then, the possibility to concatenate $M_2$ to $M_1$ depends on the fact that interpretations in $M_2$ could be informative refinements of a maximal interpretation in $M_1$ (see fig 3 and the next example). Concatenation is applied to increase belief from undefined statements by changing them to true or false, providing a constructive way to obtain beliefs from opinionless information.

Now we define an accessibility relation among model frames. Jaako Hintikka's intuitions about use accessibility relation of Kripke's semantics of possible worlds [18] to model knowledge and belief [14], are very suited, being the formalisation weakness that does not capture adequately such intuitions. Using concatenation, a relation of possibility, called of compatibility, is defined. That relation captures the constructive and dynamic manner in which we think epistemic and doxastic alternatives (worlds) are conceived by a limited rational agent. The intuitive idea of compatibility is the following:

- Given a current frame describing a situation, any frame being coherently more informed than it, is compatible with it. (It is worth to think in the particular case when frames are defined by a single world.)

Definition 8. A model frame $M_2$ is compatible with model frame $M_1$ if and only if, there is a succession of model frames $N_1, \ldots, N_n$ such that $N_1 = M_1$, $N_n = M_2$, and $N_{i+1}$ is concatenated to $N_i$ for $i = 1, \ldots, n - 1$.

Then, compatible model frames with $M_1$ correspond to informative refinements that can be obtained from a maximal world in $M_1$ (see example 2). Thus, $M_2$ is compatible for $M_1$ if it is more informed than $M_1$ in some of the directions with undefined information that $M_1$ has. By definition, any concatenated frame to $M_1$ is compatible with it.

\footnote{In [19] a wide analysis about this point is developed.}
Let $N_1, \ldots, N_l$ model frames with interpretation set $T_1, \ldots, T_l$, respectively. The following is a remarkable fact.

**Proposition 9.** If each set of interpretations $T_i$ for $i = 1, \ldots, l$ is a singleton, then each model frame is a world. In that case, accessibility relation is over possible worlds.

Thus, compatibility relation is a step by step possibility relation among sets of possible worlds in Kleene's three-valued logic.

**Proposition 10.** Partial order over $T$ set of a model frame $M$ corresponds to an accessibility relation inside $M$.

**Example:** Let the following set of statements, with initial interpretation $I_0$ such that $I_0(P) = u$ for every $P \in \mathcal{P}$.

\[
\mathcal{P} = \{ \text{Misery} \rightarrow \text{Rebellion}, \text{Rebellion} \rightarrow \text{Negotiation} \lor \text{Repression}, \text{Rebellion} \land \text{Negotiation} \rightarrow \text{Solution}, \text{Rebellion} \land \text{Repression} \rightarrow \text{War}, \text{Solution} \rightarrow \lnot \text{Misery}, \text{War} \rightarrow \text{MoreMisery} \}
\]

Informative order is indicated in the following model frame (fig 4). In the figure we use the initial letter of each predicate to deal with it, except to denote Rebellion with $Rb$ and Repression with $Rp$. Formulas without indicated truth-value are considered undefined. It is assumed that true and false formulas in upper interpretations are present in the following ones.

In the example we can draw the possible scenarios that could be allowed from a (unhappy) situation. It depends on the way in which opinionless statements describing the initial situation become true. At the final steps of current frame, there are two compatible (possible) evolving frames—not resolved yet in the example—of current frame. One with a good (desired) evolution corresponds with that eventually statement (3) is true; the other, with unhappy evolve, corresponds with having as true statement (4). (It depends on the beliefs of the active (implicit) agents.) In each case a compatible model frame can be concatenated to the current one.

### 4 Analytic Tableaux as Frames of Beliefs

We will use as proof system the analytic tableaux method [11] because its flexibility is adequate to introduce doxastic conditions over sets of formulas [2, 9, 17]. There are already characterization of Gentzen type provers for three-valued logics [3]. In fact, Avron distinguishes between the ones that are based upon a logic in which the undefined truth-value denotes incomplet or unknown information, from those that use undefined denoting inconsistent information. The
most known of the first ones corresponds with Kleene’s and Lukasiewicz’ logics\textsuperscript{5}. Moreover, there are multivalued-logic theorem provers [5, 20].

\textbf{Fig. 4 Analytic Tableaux as Frame of Belief}

Our proposed approach uses undefined as incomplete or unknown. We can add doxastic conditions through tableaux like rules, or as belief statements in open branches of tableaux containing current interesting information. It is easy to show from the last example the natural manner in which a frame of beliefs can be represented through an analytic tableaux (see fig 4). The correspondence can be established under the following considerations:

- Current model frame is contained in the set of paths of the associated tableaux.
- The informative order over interpretations in the model frame allows the order in which classical tableaux rules are applied over the set of formulas.
- Whenever a formula becomes true in the frame, the closure that such change of value conveys is performed by application of classical tableaux rules.
- Classical $\alpha, \beta, \pi, \nu$-rules of tableaux [11] when applied over true formulas evolve in tableaux paths such that its model frames counterparts are the virtual concatenations of current model frame.
- Virtual extensions (by concatenation) of the model frame correspond with tableaux extensions through open branches.

Incorporation of above considerations can be done appending to classical tableaux rules, the following one denoted UD:

- Whenever an undefined formula becomes true or false, then a tableaux is opened and all its logical consequences are deduced.

\textsuperscript{5} An example of the inconsistent view is the Paraconsistent Logics of Newton d’Acosta (see [3]).
According to UD rule, whenever an undefined formula becomes true or false, a tableaux is opened and classical rules are applied. In the associated tableaux of the example, β-rule was applied over implication and disjunctive formulas as soon as they turned up true, and its logical consequences obtained. It is assumed that every tableaux satisfies all the formulas in upper tableaux. Closed tableaux are marked with X and corresponds with incompatible (impossible) situations for model frame.

5 Related Works and Discussion

In the introduction was mentioned that classical approaches to belief change are those of AGM paradigm [1, 14] and Update Theory (UT) [15]. The first one defines operations of expansion, contraction and revision over logically closed sets (called belief sets,) while the second deals with belief updating for arbitrary sets. In the proposed approach, using concatenation operation, it follows increasing (expansion) of belief. Now we can outline the way in which it is possible to deal with contraction, revision and update of beliefs in a nonless natural way.

Intuitive idea of revision of a beliefs set ψ with new information μ is to modify as little as possible ψ in such a way that it entails μ, preserving consistency. In our approach it conveys the modification of the frame M such that μ becomes true in all maximal interpretation of M.

If μ is true or undefined in every interpretation of M then is an μ-belief expansion on M, while if μ is false in some interpretation, it arises a contradiction in M.

In this case is proceeded in the following manner:

- It should be erased interpretations of the frame, by turning undefined formulas that being true conveys contradictions with formula μ.

As much as needed to preserve consistency in the frame are the erased interpretations. Syntactical operativity is performed using the analytic tableaux associated with the model frame. Contradiction in analytic tableaux appears whenever an open branch of the tableaux becomes close. The erasure of contradictory interpretation in the frame corresponds with the erasure of the closed branches in the tableaux that were generated by making μ true. Unconsistency over tableaux branch is backward translated until it disappears. Thereafter contradiction is eliminated, is possible that μ becomes to be true in all maximal interpretation of the revised frame M′.

We observe that erasure can be done in several ways. It is necessary to consider additional criteria in order to obtain certain erasure(s) among the possible ones. Adopted criteria can be translated over Analytic Tableaux as rules, constraints or strategies over deduction process [19].

Now we make some observations:

1.) In the case of expansion, there are open branches in the associated tableaux to the frame, over which the operation is done.

2.) The erasure of frame interpretations could be considered the contraction operation over the frame.
3.) In AGM approach, revision operation of $\psi$ by $\mu$ is equivalent to contraction for $\neg A$ and expansion by $\mu$. This is the manner in which revision of a model frame is performed.

Thus, expansion, contraction and revision operation can be performed over model frames.

With respect with belief updating a similar thing should be done. Intuitive idea of UT is that the world has changed and is necessary to update beliefs. Whenever the updating formula $\mu$ do not conveys contradiction with the old beliefs in $\psi$, revision and updating are equivalent. The case in which contradictions arise, seems that UT generalizes the AGM approach [7]. There are situations in which UT allows different alternatives to belief updating that AGM does not.

However, UT axiomatization, given certain information, results in unintuitive updations. This is the case when $\mu$ is a disjunction that is not in $\psi$ but is entailed by it (remember that UT deals with arbitrary sets.) This situation corresponds with update $\psi$ with so-called ambiguous information [6]. Minimal change criterion of UT expressed by axiom U2 (see [15]), conveys unintuitive results in spite of being information describing so simple situations; e.g. flipping a coin, the result provided by UT due axiom U2, is the last visible-side-coin, that is a biased one.

The same is applicable to deal with the undefined of a person that having a job, receives a new (might be better) job proposal. UT chooses always the old job.

Model frames approach provides to deal with different alternatives for updating with ambiguous information. We have reasons to be optimistics to deal with problematic questions of belief change using the proposed approach. Alternative scenarios can be coherently included in a model frame without any kind of implicit bias. While an alternative is not justified enough, it cannot be a belief in the frame, but nor is excluded. In this step it is a local belief satisfied under more specific circumstances. Further information is needed in order to become a global belief. In this case, the other alternative statements, if any, is neither globally rejected. It could remain as local information as well. Further details constitute the material of our current research.

Concluding Remarks

This paper proposes to deal with belief increasing (expansion) using model frames that are sets of informatively ordered possible worlds in three-valued Strong Kleene Logic. The undefined truth-value is used to indicate current but opinionless information. True and false information is considered more informed than the undefined one, and it constitutes an informative order. From that order, a compatibility relation over model frames is defined, such that in addition to concatenation frames operation, belief change is allowed. The proposed formalism provides to deal, locally, with contradictory or incoherent beliefs. Using the informative order in a step by step manner ideal reasoning and logical omniscience are avoided. The epistemical framework has a suited syntactical proof method using analytic tableaux.

Part of our forthcoming work is the introduction as far as possible, of strategies for tableaux calculi in modal logic that has been recently developed in [8].
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