Splitting Techniques for Conditional Belief Bases for Nonmonotonic Reasoning

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Abstract

In nonmonotonic reasoning with belief bases, we often ask the question wether a formula A entails a formula B in the context of a belief base Δ. We want to investigate how to answer such a query in the most efficient way, that is which elements in the belief base are actually relevant to answering the query and which are not. The research question we want to investigate is therefore "Given a belief base Δ and two formulas A and B, find a sufficiently small subbase $\Delta' \subseteq \Delta$, such that A entails B in the context of Δ' if and only if A entails B in the context of Δ".

1. Motivation

One of the central questions of KRR is that of non-monotonic reasoning, i.e., given two formulas A and B and a belief base Δ, does A entail B in the context of Δ? Many formalisms for this sort of inductive inference have been proposed, such as System P [1], System Z [1], lexicographic entailment [2], skeptical c-inference [3, 4], System W [5, 6] and many more. These inference systems are often quite complicated and hard to manually compute even for belief bases of middling size as they often involve possible world semantics which scale exponentially in the size of the underlying signature. This quite straightforwardly leads to our research question: "Given a belief base Δ and two formulas A and B, find a sufficiently small subbase $\Delta' \subseteq \Delta$, such that A entails B in the context of Δ' if and only if A entails B in the context of Δ". This amounts to isolating the conditionals of a given belief base relevant for a certain query. If the relevant elements involved are already known it is far easier to answer a query by leaving aside those which are not relevant for it. This is also in line with a cognitive view of reasoning, where humans usually focus only on the relevant parts of a problem, leaving aside knowledge irrelevant for the question at hand. This type of localization is also important for implementations of inference systems where it can be vital to focus only on relevant aspects of a given problem to make a computation feasible.

2. Formal Basics

We consider a finitely generated propositional language $\mathcal{L}$ over a signature Σ with atoms $a, b, c, \ldots$ and with formulas $A, B, C, \ldots$ As models of formulas we will use the set Ω of *possible worlds* over $\mathcal{L}$. We will use ω both for the model and the corresponding conjunction of all positive or negated atoms. For subsets Σ_i of Σ, let $\mathcal{L}(\Sigma_i)$ denote the propositional language defined by Σ_i, with associated set of interpretations $\Omega(\Sigma_i)$. With ω^i we denote the reduct of ω to Σ_i [7]. Conditionals $(B|A)$ are meant to express plausible, yet defeasible rules "If A then plausibly B". $(B|A)$ is *verified* by ω if $\omega \models AB$ and *falsified* by ω if $\omega \models A\overline{B}$. A conditional $(B|A)$ is called *self-fulfilling*, or *trivial*, if $A \models B$, i.e., there is no world that falsifies it. A belief base Δ is a finite set of conditionals, and we focus on (strongly) consistent belief bases in the sense of [8, 1]. A semantic framework for interpreting conditionals are *ordinal conditional functions (OCFs)* $\kappa : \Omega \to \mathbb{N} \cup \{\infty\}$ with $\kappa^{-1}(0) \neq \emptyset$, also called *ranking functions*

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[9]. Intuitively, less plausible worlds are assigned higher numbers. Formulas are assigned the rank of their most plausible models, i.e. $\kappa(A) := \min\{\kappa(\omega) \mid \omega \models A\}$. A conditional $(B|A)$ is *accepted* by κ, written as $\kappa \models (B|A)$, iff $\kappa(AB) < \kappa(A\overline{B})$. A belief base Δ is accepted by κ, written $\kappa \models \Delta$, iff κ accepts all its conditionals. The nonmonotonic inference relation $\mid\!\sim_\kappa$ induced by κ is

$$A \mid\!\sim_\kappa B \quad \text{iff} \quad A \equiv \bot \text{ or } \kappa(AB) < \kappa(A\overline{B}). \tag{1}$$

To formalize inductive inference from belief bases the notion of an *inductive inference operator* was introduced [10] which is a mapping $\mathbf{C}$ that assigns to each belief base $\Delta \subseteq (\mathcal{L} \mid \mathcal{L})$ an inference relation $\mid\!\sim_\Delta$ on $\mathcal{L}$, i.e., $\mathbf{C} : \Delta \mapsto \mid\!\sim_\Delta$, such that Direct Inference (DI): If $(B|A) \in \Delta$ then $A \mid\!\sim_\Delta B$, and Trivial Vacuity (TV): $A \mid\!\sim_\emptyset B$ implies $A \models B$ are satisfied.

3. State of the Art and Related Work

Localized reasoning has been investigated in a variety of works. The mechanism of *focused inference* was introduced in [11]. The idea behind this approach is to gradually increase the amount of conditionals considered when answering a query by first taking only those closest to the query into account. Then the set of conditionals is gradually increased by a measure of syntactic distance until the query can be answered. Obtaining correct answers, however, crucially relies on the semi-monotonicity of the relevant inference operator, which, from those mentioned in this paper, only System P satisfies. This approach was generalized using an activation function [12] with the intent to model more closely human reasoning and their understanding of relevant knowledge.

A recent work on localized reasoning is due to [13] where a context-based refinement of the belief base was introduced utilizing a refiner function and a context. Utilizing the query as a context this approach is related to the research question posed here.

A substantial amount of work has been done on *syntax splitting* [14] which means that the signature splits into disjoint subsignatures. This approach has since been picked up in a variety of works (e.g. [15, 16, 17]). A related idea of minimum irrelevance was investigated in [18]. For inductive inference from belief bases, syntax splitting has been characterized as "syntax splitting = relevance + independence" [10]; this approach considers splittings over a belief bases Δ into disjoint subbases Δ_1 and Δ_2 induced by a syntax splitting over the underlying signature. As a disjoint split of the signature is rare in real applications and thus poses a severe restriction, this notion was generalized to conditional syntax splitting [17], allowing the signatures to overlap on some elements.

Definition 1 ([17]). *A belief base* Δ splits into subbases Δ_1,Δ_2 conditional on Σ_3*, if there are* $\Sigma_1, \Sigma_2 \subseteq \Sigma$ *such that* $\Delta_i = \Delta \cap (\mathcal{L}(\Sigma_i \cup \Sigma_3) \mid \mathcal{L}(\Sigma_i \cup \Sigma_3))$ *for* $i = 1, 2$*, and* $\{\Sigma_1, \Sigma_2, \Sigma_3\}$ *is a partition of* Σ*. This is denoted as*

$$\Delta = \Delta_1 \bigcup_{\Sigma_1,\Sigma_2} \Delta_2 \mid \Sigma_3. \tag{2}$$

We denote the intersection of the subbases Δ_1 and Δ_2 by $\Delta_3 = \Delta_1 \cap \Delta_2$, containing all conditionals over the language of Σ_3. As it turns out however, a purely syntactic separation is not sufficient to ensure independence between the subbases in general. Thus safe conditional syntax splittings were introduced.

Definition 2 ([17]). *A belief base* $\Delta = \Delta_1 \bigcup_{\Sigma_1,\Sigma_2} \Delta_2 \mid \Sigma_3$ *can be* safely split into subbases Δ_1, Δ_2 conditional on a subsignature Σ_3*, writing*

$$\Delta = \Delta_1 \overset{\mathsf{s}}{\bigcup_{\Sigma_1,\Sigma_2}} \Delta_2 \mid \Sigma_3 \tag{3}$$

if the following safety property *holds for* $i, i' \in \{1, 2\}, i \neq i'$*:*

$$\text{for every } \omega^i\omega^3 \in \Omega_{\Sigma_i \cup \Sigma_3}, \text{ there is } \omega^{i'} \in \Omega_{\Sigma^{i'}} \text{ s.t. } \omega^i\omega^3\omega^{i'} \not\models \bigvee_{(F|E) \in \Delta_{i'}} E \wedge \neg F. \tag{4}$$

Safety, in essence, demands that no valuation of the signature elements of Σ_3 may force the falsification of a conditional in Δ. The notion of conditional syntax splitting was then formalized analogously to postulates for syntax splitting [10] as a property for inductive inference operators via the following postulates.

Definition 3 ([17]). *For any $\Delta = \Delta_1 \bigcup^{\mathsf{s}}_{\Sigma_1,\Sigma_2} \Delta_2 \mid \Sigma_3$, for $i \in \{1,2\}$, and any $A, B \in \mathcal{L}(\Sigma_i), D \in \mathcal{L}(\Sigma_j)$ and a complete conjunction $E \in \mathcal{L}(\Sigma_3)$, such that $DE \not\mathrel{|\!\sim}_\Delta \bot$, an inductive inference operator $\mathbf{C}$ satisfies*

(CRel) *if $AE \mathrel{|\!\sim}_\Delta B$ iff $AE \mathrel{|\!\sim}_{\Delta_i} B$.*

(CInd) *if $AE \mathrel{|\!\sim}_\Delta B$ iff $AED \mathrel{|\!\sim}_\Delta B$.*

(CSynSplit) *if it satisfies (CRel) and (CInd).*

4. Current Results

Two major works have been published as part of this research [19, 20]. The paper [19] showed that two different kinds of reasoning with c-representations satisfy conditional syntax splitting.

A c-representation is a special kind of ranking function, that assigns penalty points to worlds based on the conditionals they falsify [21, 22]. c-Inference [3, 4] is the inductive inference $\mathrel{|\!\sim}^{\textit{c-sk}}_\Delta$ obtained by taking all c-representations into account, i.e. $A \mathrel{|\!\sim}^{\textit{c-sk}}_\Delta B$ iff $A \mathrel{|\!\sim}_\kappa B$ for all c-representations κ of Δ.

Proposition 4 ([19]). *c-Inference satisfies (CRel) and (CInd) and thus (CSynSplit).*

A selection strategy σ assigns to each belief base a unique c-representation [23], thus yielding an inductive inference operator via $\mathbf{C}^{\textit{c-rep}}_\sigma : \Delta \mapsto \kappa_{\sigma(\Delta)}$ where $\mathrel{|\!\sim}_{\kappa_{\sigma(\Delta)}}$ is obtained via Equation (1). In general $\mathbf{C}^{\textit{c-rep}}_\sigma$ does not satisfy (CSynSplit). But in [19] the postulate (IP-CSP) for selection strategies was introduced, demanding that, for any $\Delta = \Delta_1 \bigcup^{\mathsf{s}}_{\Sigma_1,\Sigma_2} \Delta_2 \mid \Sigma_3$, the selection strategy σ assigns the same impact to the conditionals of Δ_i in Δ as in Δ_i.

(IP-CSP) [19] A selection strategy σ is *impact preserving w.r.t. safe conditional belief base splitting* if, for every safe conditional belief base splitting $\Delta = \Delta_1 \bigcup^{\mathsf{s}}_{\Sigma_1,\Sigma_2} \Delta_2 \mid \Sigma_3$, for $i \in \{1,2\}$, we have $\sigma(\Delta_i) = \sigma(\Delta)|_{\Delta_i}$.

With this the following proposition was shown.

Proposition 5 ([19]). *Let σ be a selection strategy that satisfies (IP-CSP). Then $\mathbf{C}^{\textit{c-rep}}_\sigma$ satisfies (CRel) and (CInd) and thus (CSynSplit).*

Additionally in [19] the following result was also shown.

Lemma 6 ([19]). *Let $\Delta = \Delta_1 \bigcup^{\mathsf{s}}_{\Sigma_1,\Sigma_2} \Delta_2 \mid \Sigma_3$, then $\Delta_3 = \Delta_1 \cap \Delta_2$ contains only self-fulfilling conditionals.*

Thus the safety condition as defined in [17] is quite restrictive; the intersection of the two belief bases of a safe splitting cannot contain any "meaningful" conditionals.

In the work [20] the safety condition was therefore generalized, allowing more meaningful conditionals in the intersection and thus broadening the applicability of conditional syntax splitting postulates to more splittings and more belief bases.

Definition 7 ([20]). *A belief base $\Delta = \Delta_1 \bigcup_{\Sigma_1,\Sigma_2} \Delta_2 \mid \Sigma_3$ can be* generalized safely split into subbases Δ_1, Δ_2 conditional on a subsignature Σ_3, *writing*

$$\Delta = \Delta_1 \bigcup^{\mathsf{gs}}_{\Sigma_1,\Sigma_2} \Delta_2 \mid \Sigma_3 \tag{5}$$

if the following generalized safety property *holds for $i, i' \in \{1,2\}, i \neq i'$:*

$$\text{for every } \omega^i\omega^3 \in \Omega_{\Sigma_i \cup \Sigma_3}, \text{ there is } \omega^{i'} \in \Omega_{\Sigma_{i'}} \text{ s.t. } \omega^i\omega^3\omega^{i'} \not\models \bigvee_{(F|E)\in\Delta_{i'}\setminus\Delta_3} E \wedge \neg F. \tag{6}$$

The deciding difference in (6) compared to (4) is that only conditionals in $\Delta_{i'} \setminus \Delta_3$ are considered for the generalized safety property as opposed to all conditionals in $\Delta_{i'}$ for the safety property. Following this generalization of the safety property, the postulates (CRel), (CInd) and (CSynSplit) were generalized accordingly.

Definition 8 ([20]). *For any $\Delta = \Delta_1 \bigcup^{\mathbf{gs}}_{\Sigma_1,\Sigma_2} \Delta_2 \mid \Sigma_3$, for $i \in \{1,2\}$, and any $A, B \in \mathcal{L}(\Sigma_i)$, $D \in \mathcal{L}(\Sigma_j)$ and a complete conjunction $E \in \mathcal{L}(\Sigma_3)$, such that $DE \not\mid\!\sim_\Delta \bot$, an inductive inference operator $\mathbf{C}$ satisfies*

(CRel$^{\mathbf{g}}$) *if $AE \mid\!\sim_\Delta B$ iff $AE \mid\!\sim_{\Delta_i} B$.*

(CInd$^{\mathbf{g}}$) *if $AE \mid\!\sim_\Delta B$ iff $AED \mid\!\sim_\Delta B$.*

(CSynSplit$^{\mathbf{g}}$) *if it satisfies (CRel^{g}) and (CInd^{g}).*

The postulate (CSynSplit^{g}) properly generalizes (CSynSplit) as stated in the following proposition.

Proposition 9 ([20]). *(CSynSplit^{g}) implies (CSynSplit) but not vice versa.*

In [20] it was then shown that skeptical c-inference also satisfies this generalized version of conditional syntax splitting.

Proposition 10 ([20]). *c-Inference satisfies (CRel^{g}) and (CInd^{g}) and thus (CSynSplit^{g}).*

With regard to reasoning with single c-representations the postulate (IP-CSP) for selection strategies was also adapted for generalized safe splittings into the postulate (IP-CSP^{g}).

(IP-CSP$^{\mathbf{g}}$) [20] A selection strategy σ is *impact preserving w.r.t. generalized safe conditional belief base splitting* if, for every generalized safe conditional belief base splitting $\Delta = \Delta_1 \bigcup^{\mathbf{gs}}_{\Sigma_1,\Sigma_2} \Delta_2 \mid \Sigma_3$, for $i \in \{1,2\}$, we have $\sigma(\Delta_i) = \sigma(\Delta)|_{\Delta_i}$.

Accordingly, inference with c-representations based on a selection strategy satisfying this postulate have been shown to satisfy (CSynSplit^{g}).

Proposition 11 ([20]). *Let σ be a selection strategy that satisfies (IP-CSP^{g}). Then $\mathbf{C}^{\text{c-rep}}_{\sigma}$ satisfies (CRel^{g}) and (CInd^{g}) and thus (CSynSplit^{g}).*

Additionally, in [20] another subclass of conditional syntax splittings, called *genuine* splittings was identified.

Definition 12 ([20]). *Let Δ be a belief base over a signature Σ. A conditional syntax splitting $\Delta = \Delta_1 \bigcup_{\Sigma_1,\Sigma_2} \Delta_2 \mid \Sigma_3$ of Δ is called* genuine, *if $\Delta_1 \not\subseteq \Delta_2$ and $\Delta_2 \not\subseteq \Delta_1$.*

Intuitively, we call a splitting genuine if each subbase contains information that can not be found in the other subbase. This means that non-genuine splittings cannot be exploited for inductive inference, and the postulates (CRel^{g}) and (CInd^{g}) describe only trivial cases. We illustrate the importance of identifying genuine splittings and our generalization of the safety property with an example.

Example 13 (Δ^{rain}, [20]). *We consider the belief base $\Delta^{rain} = \{(\overline{s}|r), (\overline{r}|s), (b|sr), (o|s\overline{r}), (\overline{o}|r), (u|or)\}$. One of the possible conditionals syntax splittings of Δ^{rain} is*

$$\Delta^{rain} = \{(\overline{s}|r), (\overline{r}|s), (b|sr)\} \bigcup^{\mathbf{gs}}_{\{b\},\{o,u\}} \{(\overline{s}|r), (\overline{r}|s), (o|s\overline{r}), (\overline{o}|r), (u|or)\} \mid \{s, r\} \tag{7}$$

which, however, is not safe. Δ^{rain} has a total of 37 conditional syntax splittings, out of which 32 are generalized safe splittings, but only 16 are safe splittings. Only 5 of the 37 splittings are genuine. The splitting (7) is both generalized safe and genuine. For the belief base Δ^{rain} all genuine splittings are generalized safe, while no safe splitting is genuine.

5. Future Work

The next step in this line of research is to investigate how a fitting conditional syntax splitting for a given query and belief base might be found. That is, given a belief base Δ and two formulas A and B, find a conditional syntax splitting $\Delta = \Delta_1 \bigcup^{\mathsf{gs}}_{\Sigma_1,\Sigma_2} \Delta_2 \mid \Sigma_3$, such that A entails B in the context of Δ if and only if A entails B in the context of Δ_1 and such that Δ is minimal with this property. An obvious problem is that this computation might be even more expensive than simply working out the query directly, thus it seems reasonable to develop heuristics such that Δ_1 might not be minimal but "sufficiently small" instead. For this we plan to develop algorithms and implement them to evaluate their benefits for implementations of inductive inference operators. Another possible direction is the integration of conditional syntax splitting with focused inference [11] as an approximation from "both directions": While conditional syntax splitting chiefly concerns itself with which conditionals are not relevant, focused inference instead governs which conditionals are necessarily relevant for a query. Integrating these frameworks could therefore lead to the construction of a sort of upper and lower bound of conditionals relevant for a given query. Additionally, we plan to investigate the case where both a conditional syntax splitting and a query are given. Not all queries can benefit from a given conditional syntax splitting as the requirement is that a full conjunction over Σ_3 is part of the antecedent of the query. Therefore, we plan to investigate how queries might be transformed or optimized to take advantage of a given syntax splitting. Furthermore, the concept of *case splittings* [24] has been investigated where the antecedents of the conditionals are required to split into exclusive and exhaustive sets partitioning the belief base. We intend to investigate expanding this approach to also consider splittings into non-exclusive cases that may share some atoms in an analogous way to conditional syntax splitting. Of all these avenues, we intend to prioritize the development of an algorithm for finding appropriate conditional syntax splittings and then further refine this by investigating the other mentioned research directions.

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Declaration on Generative AI

The author has not employed any Generative AI tools.

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