Negotiation as Mutual Belief Revision

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Abstract

This paper presents an axiomatic approach to negotiation protocol analysis. We consider a negotiation procedure as multiple stages of mutual belief revision. A set of postulates in AGM-style of belief revision are proposed to specify rational behavior of negotiation. An explicit construction of negotiation function is given in which negotiation process is viewed as the interaction of two iterated revision operations. As a result the proposed axiomatic system is proved to be consistent. Finally, we examine our approach with an instantiation of Rosenschein and Zlotkin's Monotonic Concession Protocol of Negotiation.

1 Introduction

Negotiation has been investigated from many perspectives, including economics, applied mathematics, psychology, sociology and computer science [19][3] [21][12][5] [5][18]. Significant advances have been made in both quantitative and qualitative analysis of negotiating processes. Quantitative approaches, especially those which are inspired by game-theory, dominate much of the existing work. Sometimes, numeric utility functions can be used as analytic bases for decision making because they may provide accurate evaluations of situations. However, such numeric evaluations are often unreliable, or even simply unavailable. In real life negotiation, logical reasoning often dominates the process, with numeric analysis playing an auxiliary role in the decision making. Despite this, there has not been much work on logic-based approaches to negotiation[22] [12][18]. This paper attempts to alleviate this deficiency by introducing a logical framework to capture notions of rational behavior of negotiation. We give an axiomatic analysis of negotiating process based on belief revision theory.

Negotiation is a process of consensus-seeking among two or more parties. The parties in negotiation first verbalize contradictory demands or offers. These demands or offers change with the progress of the negotiation through mutual persuasion or argumentation till an mutual acceptable agreement has been reached. If we consider the demands(or offers) of parties as their beliefs on the matter in question, the change of the demands of each party reflects the change of its beliefs during the progress of negotiation. The parties who are convinced to accept part of the other parties' demands would perform a belief revision. New belief states of participants represent their revised demands which are normally closer to each other and apt to reach an agreement. We term such kind of belief revision *mutual belief revision.*

Different from the AGM belief revision in which an agent is principally concerned with minimizing loss of its beliefs[1], each agent in mutual belief revision not only tries to keep as many of its own beliefs as possible but also intends to learn from the other agents as much as possible. Negotiation behaves in a similar manner. A negotiator normally tries her best to keep all her demands and is also ready to accept selectively some demands from his opponents in order to reduce conflicts, avoid failure and maximize gains from negotiation. The logical framework we introduce attempts to model this *combination of cooperation and competition*. As a starting point of the investigation, we restrict ourselves to the case of two agents. We propose a set of postulates to capture rational behavior of mutual belief revision and negotiation. These postulates are mostly inspired by the AGM framework of belief revision and part of Darwiche and Pearl's iterated belief revision.

2 Postulates for mutual belief revision and negotiation

We assume an agent to have a deductively closed set of beliefs taken from some underlying propositional language $\mathcal{L}$ The language is that of classical propositional logic with an associated consequence operation Cn. Thus a set K of sentences is a *belief set* when $K = Cn(K)$. If F, G are two sets of sentences, $F + G$ denotes $Cn(F \cup G)$.

In this section we propose a set of axioms to specify properties of mutual belief revision and negotiation between two agents. The idea is the following. Suppose that K_1 and K_2 are the current belief states of two agents. During the mutual belief revision, each agent accepts part of beliefs from the other agent and revises her belief states to preserve consistency. As a result, both agents' belief states will be revised and the resulting belief states, denoted by $N_1(K_1, K_2)$ and $N_2(K_1, K_2)$, normally get closer each other. The following picture depicts the changes of belief states in mutual belief revision.

In negotiation setting, revision of belief states of an agent reflects change of its demands or offers in each negotiation round. Therefore if X and Y are the initial demands/offers of two agents, respectively, $N_1(X,Y)$ and $N_2(X,Y)$ are their revised demands/offers after the round of negotiation. And a possible agreement reached in the negotiation should be just $N_1(X,Y) \cap N_2(X,Y)$ or a subset of it.

Formally, a mutual revision or negotiation function is a two-input and two-output function $N(X,Y) = (N_1(X,Y), N_2(X,Y))$, where X and Y represent the initial belief sets or demands of each agent and $N_1(X,Y)$ and $N_2(X,Y)$ the revised belief sets or demands of each agent respectively. Note that X and Y here are not required to be logically closed.

Definition 1 A function $N : 2^{\mathcal{L}} \times 2^{\mathcal{L}} \to 2^{\mathcal{L}} \times 2^{\mathcal{L}}$ is a *mutual belief revision* or *negotiation function* if it satisfies the following postulates:

(N1) $N_1(X,Y) = Cn(N_1(X,Y))$; $N_2(X,Y) = Cn(N_2(X,Y))$.

(N2) $N_1(X,Y) \subseteq X + Y$; $N_2(X,Y) \subseteq X + Y$.

(N3) $N_1(X,Y)$ is inconsistent iff X or Y is inconsistent;
$N_2(X,Y)$ is inconsistent iff X or Y is inconsistent.

(N4) If $X \cup Y$ is consistent, $X + Y \subseteq N_1(X,Y)$ and $X + Y \subseteq N_2(X,Y)$.

(N5) If $Cn(X) = Cn(Y)$, then $N(X,Z) = N(Y,Z)$ and $N(Z,X) = N(Z,Y)$.

(N6) $Cn(Y) \cap N_1(X,Y) \subseteq N_2(X,Y)$; $Cn(X) \cap N_2(X,Y) \subseteq N_1(X,Y)$.

(N7) If $F \subseteq Cn(Y) \cap N_1(X,Y)$, then $N(N_1(X,F),Y) = N(X,Y)$.
If $F \subseteq Cn(X) \cap N_2(X,Y)$, then $N(X, N_2(F,Y)) = N(X,Y)$.

Intuitively, (N1) says that the resulting belief state of each agent is logically closed as assume in the AGM theory. (N2) states that no third party's information is introduced if there is no conflict between two agents. (N3) says that mutual belief revision can only happen between rational agents. (N4) says that each agent will accept all the beliefs of the other agent if no conflict arises. This is the cooperative aspect of mutual belief revision that an agent is happy to accommodate the other party whenever possible. (N5) assumes that mutual belief revision is syntax-independent, i.e. logically equivalent descriptions of belief states should lead to the same results.

Similar interpretation of these postulates can also be given in terms of negotiation. If we localize the belief state of an agent on the matters of a negotiation, its belief set represents its demands in the negotiation, which is called the *demand set* of the agent. (N1) then states that each negotiator should be aware of that she is responsible to undertake all the items and their consequences of her demands once they are included in an agreement. (N2) assumes that if no conflicts between the demands of two agents, amendments of demands may only be done within both sides' initial demand sets[1]. (N3) means that no negotiation can proceed from inconsistent demands. (N4) and (N5) are similar.

It is easy to see that postulates (N1)-(N5) are counterparts of AGM postulates for belief revision. Notice that we have not a counterpart of *success postulate*. It is unreasonable to assume that one side of negotiation would accept all the demands of the other side. In fact, we can view a mutual revision function as two non-prioritized belief revision operators[7].

Postulates (N6) and (N7) deviate slightly in style from AGM. We call (N6) the *principle of no recantation*. It states that once the demands of an agent are accepted by the other agent, it will not allowed for the agent to withdraw them (Note that $Cn(X) \cap N_2(X, Y)$ represents the demands of agent 1 which have been accepted by agent 2 after negotiation.) We consider this as a rational restriction in negotiation protocol. In belief change setting this reflects the principle of information economy. Once an agent knows that her beliefs are accepted by other agents, she will more value them. We remark that (N6) does not imply the following condition:

$$K_1 \cap K_2 \subseteq N_1(K_1, K_2) \cap N_2(K_1, K_2)$$

which says that common items of initial demands must be included in the last agreement of negotiation. This condition is not generally acceptable because sometimes if both sides decide to give up a common item (in order to keep some more beneficial demands), it would not be in the last agreement. The following is an example.

Example 1 *Let $K_1 = Cn(\{p, q \to \neg r, r\})$ and $K_2 = Cn(\{q, p \to \neg r, r\})$. If both agents value r much less than the other items, then r may be given up by both sides.*

(N7) deals with multiple stages of negotiation or iterated mutual belief revision. It is a typical strategy in negotiation that a negotiator poses its demands in stages. At each stage, the negotiator may reveal only part of her demands, hiding something tough or alternatives, and tries to persuade the other side to change her mind. (N7) says that if one can expect that some of her demands will be definitely accepted by the other side, it is unnecessary to pose them in stages. Therefore it would be useless to put weak demands first.

[1] Note that if there are conflicts between the demands of two agents, the amended demand sets could be anything since $X + Y$ will be inconsistent.

3 Iterated belief revision

It has been shown in the last section that there exists close relationship between AGM belief revision and mutual belief revision. We will show that the AGM revision function is a special case of mutual belief revision. Moreover, mutual belief revision implies an iterated revision mechanism. One of the postulates for iterated belief revision proposed by Darwiche and Pearl is required by mutual belief revision.

To show these, we first recall some basic facts of iterated belief revision in single agent environments.

To best suit the context of mutual belief revision, instead of using the original AGM framework, we shall exploit the multiple version of the AGM theory[17] [23], which allows us to revise a belief set by another belief set. Formally, for any belief set K and a set F of sentences, $K \otimes F$ stands for the new belief set that results when K is revised by the new information F. The operation is required to satisfy the following postulates:

($\otimes$1) $K \otimes F = Cn(K \otimes F)$.

($\otimes$2) $F \subseteq K \otimes F$.

($\otimes$3) $K \otimes F \subseteq K + F$.

($\otimes$4) If $F \cup K$ is consistent, $K + F \subseteq K \otimes F$.

($\otimes$5) $K \otimes F$ is inconsistent if F is inconsistent.

($\otimes$6) If $Cn(F_1) = Cn(F_2)$, $K \otimes F_1 = K \otimes F_2$.

($\otimes$7) $K \otimes (F_1 \cup F_2) \subseteq (K \otimes F_1) + F_2$.

($\otimes$8) If $F_2 \cup (K \otimes F_1)$ is consistent, $(K \otimes F_1) + F_2 \subseteq K \otimes (F_1 \cup F_2)$.

The associated contraction function $\ominus$ can be defined by the following identity:

($\ominus Def$) $K \ominus F = (K \otimes F) \cap K$

A negotiation process normally consists of several stages of mutual belief revision. To simulate such a process, an iterated mechanism of belief revision is required[2]. The following assumption has been accepted by several different iterated belief revision formalisms:

($\otimes$IBR) $(K \otimes F_1) \otimes (F_1 \cup F_2) = K \otimes (F_1 \cup F_2)$

It is easy to see that ($\otimes$IBR) is the multiple version of the postulate ($C1$) in [4]. The consistency of the postulate with other postulates for multiple belief revision has been proved in [25].

[2] This is similar to some other settings, say belief fusion [15].

Theorem 1 [25] ($\otimes$*1*)-($\otimes$*6*) *are consistent with* ($\otimes$IBR).

¿From now on, we will call a revision function an *iterated belief revision* if it satisfy the postulates ($\otimes$1)-($\otimes$8) and ($\otimes$IBR). Note that such an iterated revision function is different from Darwiche and Pearl's one since we use the exact AGM postulates. This should be fine because ($\otimes$IBR) goes well with AGM postulates. However, how to adjust our formulism by using Darwiche and Pearl's formalism should be a promising research topic for the future.

4 Construction of negotiation operator

In this section we provide a construction of negotiation function by using two independent iterated revision operators to simulate the process of belief change by two autonomous agents.

4.1 Negotiation set

Let X and Y be two sets of sentences, representing the initial demands or offers of two agents, respectively. We will call the pair (X, Y) a *negotiation encounter*. The naive way to define a negotiation function is to define it as two revision operations that each agent revises its demands by the other agent's demands:

$N(X, Y) \stackrel{def}{=} (Cn(X) \otimes_1 Y,\ Cn(Y) \otimes_2 X)$

Unfortunately, this definition is obviously inappropriate because it implies that one agent accepts the whole demand set of the other without care about her own demands. Typically, one agent accepts only part of demands from her opponent during a stage of negotiation. To model such a synthesis of cooperation and competition in negotiation, we introduce the following concepts.

Definition 2 Given two iterated revision functions $\otimes_1$ and $\otimes_2$. A *deal* over an encounter (X, Y) is a pair (Ψ_1, Ψ_2) such that $\Psi_1 \subseteq Cn(X), \Psi_2 \subseteq Cn(Y)$ and satisfies the fix-point condition:

$$Cn(\Psi_1 \cup \Psi_2) = (Cn(X) \otimes_1 \Psi_2) \cap (Cn(Y) \otimes_2 \Psi_1) \quad (1)$$

Intuitively, a deal is an agreement between two agents in which agent 1 accepts part of demands, Ψ_2, from agent 2 whereas agent 2 accepts part of demands, Φ_1, from agent 1.

A deal δ=(Ψ_1, Ψ_2) *dominates* a deal δ'=(Ψ_1', Ψ_2') if they satisfies the following two conditions:

1. either $\Psi_1' \subset \Psi_1$ and $\Psi_2' \subseteq \Psi_2$ or $\Psi_1' \subseteq \Psi_1$ and $\Psi_2' \subset \Psi_2$, and
2. $Cn(X) \otimes_1 \Psi_2' = Cn(X) \otimes_1 \Psi_2$ and $Cn(Y) \otimes_2 \Psi_1' = Cn(Y) \otimes_2 \Psi_1$.

In the other words, δ dominates δ' if at least one agent agrees to accept more demands from the other without sacrificing any agent's profits.

A deal δ is called *pareto optimal* if there does not exist a deal which dominates δ.

A deal δ=(Ψ_1, Ψ_2) over (X, Y) is called *rational* if it satisfies the following conditions:

$Cn(X) \cap (Cn(Y) \otimes_2 \Psi_1) \subseteq Cn(X) \otimes_1 \Psi_2$

$Cn(Y) \cap (Cn(X) \otimes_1 \Psi_2) \subseteq Cn(Y) \otimes_2 \Psi_1$

which means that if the demands of one agent have been accepted by the other, they will be kept in her amended demand set.

Definition 3 A deal is a *negotiable alternative* over (X, Y) if it is pareto optimal and rational. The set of all the negotiable alternatives is called the *negotiation set* of (X, Y), denoted by $\mathcal{NS}(X, Y)$.

The following lemma lists some properties of negotiation sets.

Lemma 1 *Let (X, Y) be any encounter.*

1. *For any $(\Psi_1, \Psi_2) \in \mathcal{NS}(X, Y)$, Ψ_1 and Ψ_2 are logically closed.*
2. *If $X \cup Y$ is consistent, $\mathcal{NS}(X, Y) = \{(Cn(X), Cn(Y))\}$.*
3. *If $X \cup Y$ is inconsistent, $(Cn(X) \cap Cn(Y), Cn(X) \cap Cn(Y)) \in \mathcal{NS}(X, Y)$.*
4. *For any $(\Psi_1, \Psi_2) \in \mathcal{NS}(X, Y)$,*
   $\Psi_1 = Cn(X) \cap (Cn(Y) \otimes_2 \Psi_1)$ *and* $\Psi_2 = Cn(Y) \cap (Cn(X) \otimes_1 \Psi_2)$.

The lemma shows that if $X \cup Y$ is consistent then $(Cn(X), Cn(Y))$ is the unique deal in the negotiation set of the encounter (X, Y). If it is inconsistent, the negotiation set could have more than one elements but it always includes a deal $(Cn(X) \cap Cn(Y), Cn(X) \cap Cn(Y))$, which we call it the *conflict deal* of the encounter.

Example 2 Consider an encounter (X, Y) where $X = \{p, q\}$ and $Y = \{\neg p, \neg q\}$. Let $\otimes_1$ and $\otimes_2$ are any iterated revision functions. Then the conflict deal will be $(Cn(\{p \leftrightarrow q\}), Cn(\{p \leftrightarrow q\}))$, which is in the negotiation set. Two other extreme cases, $(Cn(X), Cn(\{p \leftrightarrow q\}))$ and $(Cn(\{p \leftrightarrow q\}), Cn(Y))$, are also negotiable alternatives. If each agent is going to take some offers from the other, then more "balanced" negotiation could happen. However the result will heavily depend on the evaluation on their demands and counter-demands. Suppose that for agent 1, p is more entrenched than q and for agent 2 $\neg q$ is more entrenched than $\neg p$. Then $(Cn(\{p\}), Cn(\{\neg q\}))$ will be a negotiable alternative whereas $(Cn(\{q\}), Cn(\{\neg p\}))$ is not. $\Box$

4.2 Selection function

Negotiation protocol is applied to regulate negotiations. It rules out irrational negotiation behavior but makes no decisions for negotiation participants. The outcomes of a negotiation mainly depend on the strategies of negotiators and their evaluation on negotiation alternatives. Therefore, a concrete negotiation is a decision-making procedure with which each agent chooses a deal from negotiation set. If both agents choose the same deal, then an agreement is reached; otherwise, the conflict deal will be the result of the negotiation. Anyhow, a negotiation process is nothing but a selection mechanism which chooses a deal from negotiation set. Let γ be a selection function which selects an element from a nonempty set. We will abbreviate $\gamma(\mathcal{NS}(X,Y))$ to $\gamma(X,Y)$. As usual, $\gamma_i(X,Y)$ means the i^{th} component of $\gamma(X,Y)$. Now we define negotiation function as follows:

Definition 4 *Let $\otimes_1$ and $\otimes_2$ be two iterated revision functions and γ a selection function. Define a negotiation function N as follows: for any encounter (X,Y),*

1. *if both X and Y are consistent, $N(X,Y) = (Cn(X) \otimes_1 \Phi_2, Cn(Y) \otimes_2 \Phi_1)$ where $(\Phi_1, \Phi_2) = \gamma(X,Y)$; otherwise,*
2. *$N(X,Y) = (\mathcal{L}, \mathcal{L})$.*

It is easy to see that given an encounter (X,Y), if the selection function γ selects the conflict deal to the encounter, then $N(X,Y) = (X,Y)$.

It is easy to verify that any negotiation function N satisfies (N1)-(N6). However (N7) does not necessarily hold. In fact, (N7) requires kinds of uniformity in the selection mechanism over different negotiation situation. Arbitrary selection functions can not embody the rationality of negotiation behavior.

Definition 5 A selection function γ is *downwards compatible* if for any $F_1 \subseteq \gamma_1(X,Y)$ and $F_2 \subseteq \gamma_2(X,Y)$,

$\gamma(Cn(X) \otimes_1 F_2, Cn(Y) \otimes_2 F_1) = (\gamma_1(X,Y) + F_2, \gamma_2(X,Y) + F_1)$.

Example 3 Let γ be a selection function such that $\gamma(X,Y) = (Cn(X) \cap Cn(Y), Cn(X) \cap Cn(Y))$. Then γ is downwards compatible. In other wards, always standing still is a kind of uniform negotiation behavior.

Now we come to the main result of the paper.

Theorem 2 *If γ is a downwards compatible selection function, the negotiation function defined by Definition 4 satisfies (N1)-(N7).*

Since a downwards compatible selection function always exists, this theorem shows again the consistency of the negotiation postulates.

5 Monotonic Concession Protocol

Unlike most game-theory based approaches to negotiation, the purpose of this research is not to design particular negotiation strategies for individual agents. We aim to provide a formal language and an analysis tool to describe and evaluate negotiation protocols. In this section, we will show an example of such an analysis by using Rosenschein and Zlotkin's *Monotonic Concession Protocol* [21].

Monotonic Concession Protocol deals with negotiations between two agents. The agents start by simultaneously proposing one deal from the space of possible deals. An agreement is reached if both agents chose the same deal or one agent offered a deal that exceeded what the other one asked for. If no agreement has been reached, the protocol continues to another round. Each agent has two choices: to stand still or to concede. An agent is not allowed to offer the other agent less than her did in the previous round. If neither agent concedes at some step, then the negotiation ends with the conflict deal. Otherwise the negotiation continues (see [21] page 40).

The feature of the protocol is that agents cannot backtrack, nor can they both simultaneously stand still in the negotiation more than once. As a result, the negotiation process is monotonic and ensures convergence to a deal.

To make the protocol more specific, let's assume that the initial demands of the agents are X and Y, respectively. At the first round, each agent chooses a deal from the negotiation set $\mathcal{NS}(X,Y)$, say $\delta' = (\Psi'_1, \Psi'_2)$ and $\delta'' = (\Psi''_1, \Psi''_2)$. If $\delta' = \delta''$, then an agreement is reached. Otherwise, each agent makes a decision whether she is going to stand still or to concede. If an agent chose to concede, say agent 1, she should amend her demand set so that the new demand set includes Ψ'_2 as well as Ψ''_1, and then chooses another deal from the new negotiation set that extends Ψ'_2.

To such a protocol, if both agents apply iterated belief revision when revise their demands set and they make the same decision on whether to stand-still or to concede for any given pair of demand sets, then we have the following

Theorem 3 *Any negotiation under the protocol satisfies postulates (N1)-(N6).*

Unfortunately, (N7) does not automatically hold. To satisfy (N7), we need more specification on the belief revision and decision-making behavior. We leave this for a longer version of the paper.

6 Related work

There have been several streams of research which related to this work. One of them is the work on arbitration, belief merging and knowledge fusion [10][11]. All these researches deal with conflicts between agents. In fact, for any given negotiation function N, we can define an "arbitration" operator $\triangle$ as: for any belief set K_1 and K_2,

$$K_1 \triangle K_2 = N_1(K_1, K_2) \cap N_2(K_1, K_2)$$

Then we can easily verify that $\triangle$ satisfies most of Revesz's postulates and Liberatore and Schaerf's postulates for arbitration operation[20][10]. However the differences between negotiation and arbitration are obvious. For instance, the following postulate does not necessarily hold in negotiation setting:

If K_1 is consistent, so is $K_1 \cup (K_1 \triangle K_2)$.

In fact, negotiation addresses difference issues from belief arbitration as well as belief merging and knowledge fusion. It is normally required that the outcome of arbitration is fair for all agents. However it is not required for negotiation outcomes. "The more *powerful* one is, the closer the negotiated outcome is to one's most desired agreement". Fair negotiation means a fair negotiation protocol rather than a fair outcome. On the other hand, fairness of outcomes can be easily introduced into negotiating processes by applying game-theoretic techniques. Therefore a formal framework for negotiation may be used to formalize arbitration, merging, or fusion of knowledge and beliefs.

Another stream of work is that of non-prioritized belief revision[7][2]. Particularly, Booth in [2] showed a way to model non-prioritized belief revision via negotiation process. However, his work aimed to provide a formalism for non-prioritized revision rather than a formal framework for negotiation.

There have been several attempts to consider belief revision in the setting of multi-agent systems[11][14][16]. In [16] mutual belief revision is referred to the process of belief revision by which an agent in synchronous multi-agent systems revises its beliefs about other agents' beliefs. Instead of axiomatic analysis, a Kripkean semantical theory was presented for modelling such kind of mutual belief revision.

In terms of logical approach to negotiation, there are numbers of researches on argumentation-based negotiation[22][12][18]. Although the goal is similar, the formalisms and emphases of the work are distinct from ours.

7 Conclusion

This paper presented a formal framework for negotiation protocol analysis. A set of AGM-style postulates was presented to model rational negotiation behavior. Its consistency was proved through an explicit construction of negotiation function in which negotiation process was modelled by two related iterated belief revision operations. This model also captured the characteristic of negotiation that negotiation is an organic synthesis of cooperation and competition between agents.

Many problems remain to explore. A representation theorem for the postulates is to be given. To this end, a necessary and sufficient condition for postulate (N7) is needed. We emphasize that the overall purpose of this research is not to present a logical analysis for a particular negotiation protocol but to provide a formal language for describing rational negotiation behavior. The postulates presented in this paper are less than complete. We believe that more characteristics of negotiation process can be investigated in this framework. For instance, the following property of negotiation can be described in our language, which states sort of terminability of negotiation process:

$$N(N_1(X,Y), N_2(X,Y)) = N(X,Y)$$

It can be proved that it is consistent but independent with the existing postulates.

Negotiation is not a process reserved only for the skilled diplomat, top salesperson, or ardent advocate for organized labor; it is something that everyone does, almost daily [9]. We believe that a logic-based investigation on negotiation is helpful for us to get a better understanding of such a way of reasoning of human being.

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