

# Towards a Dynamic Theory of Belief-Sharing in Cooperative Dialogues

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## 1 Introduction

In this paper, we propose a dynamic theory of belief-sharing which deals with certain processes of forming and revising shared beliefs during cooperative dialogues.

Since Clark & Marshall(1981) the problem of determination of the referents of referring expressions has been discussed in relation to mutual knowledge. In natural language processing, there have also been several studies treating this problem of referent-determination in terms of mutual knowledge (Perrault & Cohen, 1981; Joshi, 1982; Nadathur & Joshi, 1983; Appelt, 1985). In this paper, we conceive referent-determination as a process of belief-sharing in dialogues, and propose a formal theory of dialogue in which referent-determination can be characterized as part of belief-sharing processes. We use Discourse Representation Theory (DRT) to model the characteristics of referents in discourse (Kamp, 1981, 1990; Asher, 1993), and propose a model of dynamic maintenance of the mutual beliefs of the participants in dialogues based on Clause Maintenance System (CMS) (Doyle, 1979; Levesque, 1989; Poole, 1988; Reggia, 1983; de Kleer, 1986; Reiter & de Kleer, 1987). By this model, we characterize the relationships between a dialogue process and its successfulness, which is mainly illustrated by examples of referent-determination but can be applied to any type of belief-sharing.

## 2 Dynamic Maintenance of Shared Beliefs

### 2.1 DRS

However cooperative, real-world dialogues are fraught with hedges, understatements, or even white lies, which would necessitate introducing a distinction between what is literally conveyed by an utterance, and its real intent on the part of both speaker and hearer. In this study, however, we restrict ourselves to those cases without such complications, and assume that an utterance reflects the speaker's intent in a straight manner, and is taken as such by the hearer. The con-

tent of an utterance is represented in the following style:

(1)  $K$ :

$a, b, x, y, z, \dots$
$Bel(a, K)$
$Bel(b, K)$
$A(x), B(y), C(z), \dots$

We call  $K$  discourse representation structure (**DRS**),  $\{a, b, x, y, z, \dots\}$   $K$ 's domain ( $\mathbf{U}_K$ ), the elements of  $\mathbf{U}_K$  discourse referents, the boxed area below the unbroken line  $K$ 's condition part ( $\mathbf{C}_K$ ), and  $\mathbf{C}_K$ 's elements conditions.  $K$  is represented as  $\langle \mathbf{U}_K, \mathbf{C}_K \rangle$ . The broken line divides  $\mathbf{C}_K$  into the self-referential part **SRP** (above the line), and the dialogue database **DB**( $K$ ) (below the line). A condition is the result of an  $n$  ( $\geq 0$ ) times application of  $Bel(\alpha, \cdot)$  to a first-order formula  $p$ .  $Bel(\alpha, \cdot)$  is called a belief operator, where  $\alpha$  designates the utterer. Given  $\phi$  as a condition,  $Bel(\alpha, \phi)$  reads "the participant  $\alpha$  believes  $\phi$ ."  $n$  is called the rank of  $\phi$  with regard to its embedding within belief operators. Conditions of rank 0 are called bare formulas, while those with a rank greater than 0 belief formulas.  $K$  represents the shared beliefs formed through a dialogue between the two participants  $a$  and  $b$ . The conditions in **SRP** indicate a recursive embedding of self-referential belief structure with regard to common knowledge, and are assumed throughout the dialogue. By contrast, **DB**( $K$ ) is empty when a dialogue starts off. Thus, at the outset of a dialogue, the **DRS**  $K_0 = \langle \{a, b\}, \{Bel(a, K_0), Bel(b, K_0)\} \rangle$ . As an utterance is made, new discourse entities may be introduced, making it necessary to add new conditions to **DB**( $K$ ) and sometimes to retract or negate part of the conditions in **DB**( $K$ ). With the progress of the dialogue, the **DRS** changes from  $K_0 \Rightarrow K_1 \Rightarrow \dots \Rightarrow K_n \Rightarrow \dots$

Since only cooperative dialogues are considered, the goal is to arrive at a **DRS** in which no contradictory beliefs are held by the participants. But this goal is not always achieved. We also assume that at certain points of a dialogue, the participants can hold contradictory beliefs, and that the same participant

can hold contradictory beliefs at different points of a dialogue, whereas the same participant cannot hold contradictory beliefs at any particular point.

In what follows, we just indicate  $\mathbf{DB}(K)$  unless otherwise noted.

## 2.2 How shared beliefs are registered

An utterance made by a participant in a dialogue is transformed into a condition(s) and registered in  $\mathbf{DB}(K)$ , following the constraints stated below.

First, discourse referents are taken to be epistemological entities without counterparts in surface sentences, but introduced into the  $\mathbf{DRS}$  by the participants of a dialogue, and of which properties corresponding to surface linguistic expressions are predicated. Thus, an utterance

(2) *a*: Sato is a student

is not analyzed as

(3) *student*(Sato)

but as

(4) *Sato*(*x*), *student*(*x*)

with the discourse referent *x* introduced into  $\mathbf{U}_K$  by *a*, and the predicates corresponding to expressions in the utterance.

Second, an utterance is registered not in the form of a bare formula, but in the form of a belief formula indicating the belief agent. (4), for example, is registered as

(5) *Bel*(*a*, *Sato*(*x*)), *Bel*(*a*, *student*(*x*))

because at (2), *b* has not agreed with or opposed *a*'s utterance. Note that (5) is nevertheless a shared belief at this point. Suppose (6) is uttered following upon (2):

(6) *b*: Yes, he is.

This utterance is interpreted as

(7) *Bel*(*b*, *Sato*(*x*)), *Bel*(*b*, *student*(*x*))

and so registered in  $\mathbf{DB}(K)$ . At this point, both (5) and (7) are shared beliefs, which means (4) is a belief shared by *a* and *b*. This transition is formulated as the axiom of shared belief:

(8) The axiom of shared belief  
When  $\mathbf{DB}(K)$  contains *Bel*(*a*, *p*), and *Bel*(*b*, *p*),  $\mathbf{DB}(K')$  obtained from  $\mathbf{DB}(K)$  by the substitution of *p* for them is equivalent to  $\mathbf{DB}(K)$ .

$\mathbf{DB}(K)$  can be derived from  $\mathbf{DB}(K')$  without using this axiom, since *K* has the self-referential part  $\mathbf{SRP}$ . But the converse does not hold. The axiom of shared belief allows the rank of shared beliefs to be zero, while the conditions in general are initially registered with a rank higher than zero.

Third, there is involved a step of identification in the transition from *b*'s utterance of (6) to the condition (7). Just as the discourse referent *x* was introduced by *a*'s utterance of (2), *b* introduces a distinct discourse referent *y*, in terms of which

(9) *Bel*(*b*, *Sato*(*y*)), *Bel*(*b*, *student*(*y*))

is registered in  $\mathbf{DB}(K)$ . We assume that *a* and *b* agree to the identity of *x* and *y* at this point.

To sum up, in dialogue (2), (6),  $\mathbf{DB}(K)$  is composed of (5) alone when (2) is uttered, but is extended by the utterance of (6) as follows:

(10) *Bel*(*a*, *x* = *y*), *Bel*(*b*, *x* = *y*),  
*Bel*(*a*, *Sato*(*x*)), *Bel*(*a*, *Sato*(*y*)),  
*Bel*(*b*, *Sato*(*x*)), *Bel*(*b*, *Sato*(*y*)),  
*Bel*(*a*, *student*(*x*)), *Bel*(*a*, *student*(*y*)),  
*Bel*(*b*, *student*(*x*)), *Bel*(*b*, *student*(*y*)).

By applying the axiom of shared belief, and *x* = *y*, we obtain

(11) *Sato*(*x*), *student*(*x*)

By contrast,

(12) 1.*a*: Sato is a student.  
2.*b*: No, he is an office clerk now.

can only have its  $\mathbf{DB}(K)$  reduced to

(13) *Sato*(*x*),  
*Bel*(*a*, *student*(*x*)), *Bel*(*b*, *office\_clerk*(*x*)).

## 3 Diachronic analysis of dialogue

In this section, we consider the changes  $\mathbf{DRS}$ 's undergo in the course of a dialogue. In (2), (6) in the previous section, we saw a case where a  $\mathbf{DRS}$  with nothing but shared beliefs is successfully obtained in one inning, so to speak, without incurring any conflict. We will look at the other three kinds of cases in which conflicts are treated in particular ways which admit of formalization in terms of CMS.

### 3.1 Direct solution of conflicts

Consider the following dialogue.

(14) 1. *a*: Sato is a good guy.  
2. *b*: By no means, he is a liar.  
3. *a*: No kidding.

Just after (14.2) is uttered,  $\mathbf{DB}(K)$  looks as follows:

(15) *Bel*(*a*, *x* = *y*), *Bel*(*b*, *x* = *y*),  
*Bel*(*a*, *Sato*(*x*)), *Bel*(*a*, *Sato*(*y*)),  
*Bel*(*b*, *Sato*(*x*)), *Bel*(*b*, *Sato*(*y*)),  
*Bel*(*a*, *good*(*x*)),  
*Bel*(*b*, *liar*(*y*)).

The utterance of (14.3) is considered as the consequence of an inference such as this:

- (16) 1.  $x = y$   
 2.  $Sato(x)$   
 3.  $Bel(a, good(x))$   
 4.  $Bel(b, liar(x))$

is derived from (15). (16.3-4) do not bring about an inconsistency since they are belief formulas with different propositions inside. But obviously,  $a$  has drawn an inconsistency by taking off the belief operators, and carrying out the following inference.

- (17) 1.  $x = y$   
 2.  $liar(y)$   
 3.  $liar(x)$  1, 2  
 4.  $\forall x(liar(x) \rightarrow \neg good(x))$   
 5.  $\neg good(x)$  3, 4  
 6.  $good(x)$   
 7.  $\square$  5, 6

Suppose (14) is continued as follows:

- (18)  $a$ : I mean the Sato in the linguistics department.  
 $b$ : Oh, I thought you were talking about the Sato in the AI department. The one you mean is indeed a good guy.

- (19)  $a$ : He does sometimes. But you can't dislike him.  
 $b$ : I guess not.

In this case, in order to avoid the conflict, one traces its causes, and retracts the weakest one (16.1) for (18), and (17.4) for (19), or replaces it by its negation. As a result, (18), for example, is associated with

- (20)  $Bel(a, \neg x = y)$ ,  
 $Bel(a, Sato(x))$ ,  
 $Bel(a, Sato(y))$ ,  
 $Bel(b, \neg x = y)$ ,  
 $Bel(b, Sato(x))$ ,  
 $Bel(b, Sato(y))$ ,  
 $Bel(a, LiD(x))$ ,  $Bel(a, AiD(y))$ ,  
 $Bel(a, \forall x(liar(x) \rightarrow \neg good(x)))$ ,  
 $Bel(b, LiD(x))$ ,  $Bel(b, AiD(y))$ ,  
 $Bel(b, \forall x(liar(x) \rightarrow \neg good(x)))$ ,  
 $Bel(a, good(x))$ ,  $Bel(a, liar(y))$ ,  
 $Bel(b, good(x))$ ,  $Bel(b, liar(y))$ .

All  $Bel$ 's can be taken off in (20), resulting in

- (21)  $\neg x = y, Sato(x), Sato(y)$ ,  
 $LiD(x), AiD(y), \forall x(liar(x) \rightarrow \neg good(x))$ ,  
 $good(x), liar(y)$ ,

which is shared by  $a$  and  $b$ .

### 3.2 Indirect solution of conflicts

Consider the following dialogue.

- (22) 1.a: Today's meeting is held at 203, isn't it?  
 2.b: No, I heard it is at the small conference room.  
 3.b: Who told you that?  
 4.a: Sato told me yesterday.  
 5.b: That's strange. I'll call the office.  
 6.b: They say it was changed from 203 to the small conference room today.  
 7.a: I sec.

The inference of (22) is formalized as follows:

- (23) 1.  $Sato$   
 2.  $Sato \rightarrow 203$   
 3. 203 1, 2  
 4.  $office$   
 5.  $office \rightarrow s.c.r$   
 6.  $s.c.r$  4, 5  
 7.  $s.c.r \rightarrow \neg 203$   
 8.  $\neg 203$  6, 7  
 9.  $\square$  3, 8

In this case, the conflict between (22.1) and (22.2) cannot be solved between themselves. (22.3) to (22.6) reflects the process of deciding which is to be preferred by tracing the source of each condition. That is, when one cannot choose between two conflicting conditions  $p_1$  and  $p_2$  on their own account, one replaces  $p_1$  and  $p_2$  by  $q_1$ ,  $q_1 \rightarrow p_1$  and  $q_2$ ,  $q_2 \rightarrow p_2$ , respectively, and decide which of  $q_1, q_2$  is to be preferred so that one can avoid the conflict by retracting the weaker condition in favor of the stronger.

### 3.3 Conflicts ending in a draw

Consider the following case.

- (24) 1.a: That's Muranishi over there.  
 2.b: No, it's Hokuto.  
 3.a: Really?

This case is formalized as follows:

- (25) 1.  $x = y$   
 2.  $Hokuto(y)$   
 3.  $Hokuto(x)$  1, 2  
 4.  $Muranishi(x)$   
 5.  $\forall x(Muranishi(x) \rightarrow \neg Hokuto(x))$   
 6.  $\neg Hokuto(x)$  4, 5  
 7.  $\square$  3, 6

As (24.3) indicates, there is no retractable belief in  $DB(K)$ , which caused the dialog to end in a breakdown.

### 3.4 Formalization of diachronic analysis

The processes of belief revision illustrated in 3.1 through 3.3 can be formalized as in (27). First, we define some terms:

- (26) i) Let  $\alpha$  be one of the participants  $a$  and  $b$  in a dialogue, and  $\beta$  the other.  
 ii) Given  $p$  in  $\mathbf{DB}(K)$ , substitute  $Bel(\alpha, p)$  and  $Bel(\beta, p)$  for it. When  $Bel(\alpha, p)$  is replaced by  $Bel(\alpha, \neg p)$ , it is called  $p$ 's self-denial by  $\alpha$ . When  $Bel(\alpha, p)$  is simply retracted, it is called  $p$ 's self-withdrawal by  $\alpha$ .  
 iii) When  $Bel(\alpha, p)$ ,  $Bel(\beta, p)$ , and  $p$  are substituted for by  $\neg p$ , it is called  $p$ 's strong-denial. When they are simply retracted, it is called  $p$ 's strong-withdrawal.  
 iv) Let  $\Sigma$  be a set of Horn-clauses,  $PI(\Sigma)$  the set of its prime implicants. When  $\neg p \in \{\neg p_1, \dots, \neg p_n\}$  for any  $q \vee \neg p_1 \vee \dots \vee \neg p_n \in PI(\Sigma)$ ,  $q$  is subordinate to  $p$ .
- (27) Whenever a new condition is added to  $\mathbf{DB}(K)$  in response to a dialogue move, the participant  $\alpha$  starts her CMS, calculates a way of resolving any conflict, and revises  $\mathbf{DB}(K)$  dynamically:  
 1) a) When a condition is explicitly registered in  $\mathbf{DB}(K)$ , strip off its belief operator (if any), add it to CMS as an atomic formula.  
 b) Add implicitly assumed conditionals such as  $\forall x(Muranishi(x) \rightarrow \neg Hokuto(x))$  to CMS as an atomic formula.  
 c) Add the implicit inference rules in the dialogue to CMS as a conditional formula. (E.g., the inference rule  $a, b/c$  corresponds to the conditional formula  $c \leftarrow a, b$ .)  
 2) Let  $\Sigma$  be the set of CMS-clauses obtained in 1). Change  $\Sigma$  into  $PI(\Sigma)$  (the set of its prime implicants).  
 a) If  $PI(\Sigma) \not\vdash \square$ , then the dialogue succeeds. Either terminate it, or go on to another.  
 b) If  $PI(\Sigma) \vdash \square$ , unless there is a retractable or deniable assumption  $p$  in  $\Sigma$ , go to c). If there is, try to make either  $p$ 's strong-denial or strong-withdrawal. If it fails, go to c). If successful, for all  $q$  such that  $q$  is subordinate to  $p$ , make  $q$ 's self-withdrawal, and call the result  $\Sigma'$ .  
 A) If  $PI(\Sigma') \not\vdash \square$ , then the dialogue succeeds. Either terminate it, or go on to another.  
 B) If  $PI(\Sigma') \vdash \square$ , then  $\Sigma := \Sigma'$  and go to b).  
 c) If every assumption  $p$  in  $\Sigma$  is well justified, the dialogue fails. If any  $p$  has negotiable justifications  $q_1, \dots, q_n$ , replace  $p$  by  $p \leftarrow q_1, \dots, q_n; q_1, \dots, q_n$  and call the result  $\Sigma'$ . Set  $\Sigma := \Sigma'$ , and go to b).

## 4 Synchronic analysis of dialogue

Next, according to Ogata(1993), we consider a classification which characterizes the degree of belief-sharing for the participants at a particular point of the conversation, and the correctness of the shared beliefs.

- (28) 1) The beliefs are all shared by the participants: see (2), (6) above.  $\mathbf{DB}(K)$  contains no conditions prefixed with  $Bel$ . Since the set of beliefs of either participant is considered to be consistent,  $PI(\Sigma) \not\vdash \square$  for the CMS corresponding to the **DRS**.  
 2) There remain some conditions prefixed with  $Bel$  in  $\mathbf{DB}(K)$ , but  $PI(\Sigma) \not\vdash \square$  for the CMS corresponding to the **DRS**. A typical case is when  $\beta$ 's assertions properly include  $\alpha$ 's beliefs and about the rest of  $\beta$ 's assertions  $\alpha$  has not been able to decide in one way or another.  
 3) There remain some conditions prefixed with  $Bel$  in  $\mathbf{DB}(K)$ , and  $PI(\Sigma) \vdash \square$ . This is a case of breakdown as seen in (25).  
 We call these three cases, respectively, 1) observationally successful, 2) observationally consistent, and 3) observationally unsuccessful.

Take the case of (2), (6) again. The dialogue was successfully terminated because the Sato  $a$  had in mind and the Sato  $b$  had in mind were both students. But suppose  $a$ 's Sato was a student in the linguistics department, and  $b$ 's Sato in the AI department, that is, they were different persons. Or suppose  $a$  and  $b$  had the same Sato in mind, but that he was no longer a student at the time. These two cases are observationally successful, but the participants end up with the wrong beliefs. In order to meet this gap, we introduce a standard of correctness that might be embodied by God's viewpoint, the reality, or the conventions of the language community to which the participants belong. We call this standard the facts. The categories in (28) are further broken down relative to the facts as in (29):

Define  $K'$  as the result of adding the facts to the  $\mathbf{DB}(K)$  of a **DRS**  $K$ , and extending  $\mathbf{U}_K$  accordingly. Let  $PI(\Sigma')$  be the set of prime implicants for the CMS corresponding to  $\mathbf{DB}(K')$ . The facts are a set of bare formulas. Then (28) is subclassified as follows:

- (29) 1) observationally successful  
 a)  $PI(\Sigma') \not\vdash \square$ ,  
 b)  $PI(\Sigma') \vdash \square$ .  
 2) observationally consistent  
 a)  $PI(\Sigma') \not\vdash \square$ ,  
 b)  $PI(\Sigma') \vdash \square$ .  
 3) observationally unsuccessful  
 $PI(\Sigma') \vdash \square$ .

We call 1a) strongly successful, 2a) strongly consistent, and the rest (the cases where  $PI(\Sigma') \vdash \square$ ) strongly unsuccessful. A comparison of (28) and (29) suggests the following implications whose converses do not hold:

- (30) a) strongly successful  $\rightarrow$  observationally successful  
 b) observationally unsuccessful  $\rightarrow$  strongly unsuccessful  
 c) strongly consistent  $\rightarrow$  observationally consistent

#### 4.1 Characterization of expressions referring to individuals

We consider the problem of how the concepts of success introduced in the previous section might be applied to the dialogues identifying the denotation of individual terms, especially proper nouns.

- (31) *a*: That's Sato over there.  
*b*: Yes, it is.

**DB**(*K*) for (31) is

- (32) a)  $x = y$ ,  
 b)  $Sato(x), Sato(y)$ .

If *a* and *b* believe there is only one Sato in this situation, (32b) becomes

- (33)  $Bel(a, \iota x.Bel(a, Sato(x)) = x)$ ,  
 $Bel(b, \iota x.Bel(a, Sato(x)) = x)$ ,  
 $Bel(a, \iota x.Bel(b, Sato(x)) = y)$ ,  
 $Bel(b, \iota x.Bel(b, Sato(x)) = y)$ ,

which gives rise to

- (34)  $\iota x.Bel(a, Sato(x)) = x$ ,  
 $\iota x.Bel(b, Sato(x)) = y$ .

From this, we obtain by (32a)

- (35)  $\iota x.Bel(a, Sato(x)) = \iota x.Bel(b, Sato(x))$ .

If (31) is a case of strong success in which "Sato" correctly refers to the unique Sato, **DB**(*K'*) contains

- (36)  $x = z, \iota x.Sato(x) = z$ .

From (32a), (34), and (36), we can derive

- (37)  $\iota x.Sato(x) =$   
 $\iota x.Bel(a, Sato(x)) = \iota x.Bel(b, Sato(x))$ .

In general, of an atomic formula  $T(x)$ , we call  $\iota x.Bel(a, T(x))$  *a*'s intended referent,  $\iota x.Bel(b, T(x))$  *b*'s intended referent, and  $\iota x.T(x)$  the semantic referent. Thus, a strongly successful dialogue with regard to an identification of an individual referent is a case where *a*'s intended referent, *b*'s intended referent, and the semantic referent all coincide.

However, if in (31) the individual referred to is Kinoshita rather than Sato, **DB**(*K'*) will contain

- (38)  $\neg(z = x), \iota x.Sato(x) = z$ .

If *a* and *b* have different Sato's in mind, **DB**(*K'*) will contain

- (39)  $\iota x.Sato(x) = \dagger, \neg(\dagger = x)$ .

In either case, the result is strongly unsuccessful:

- (40)  $\neg(\iota x.Sato(x) = \iota x.Bel(a, Sato(x)))$ ,  
 $\neg(\iota x.Sato(x) = \iota x.Bel(b, Sato(x)))$ .

A case of being observationally unsuccessful such as (24) will be

- (41)  $\neg(\iota x.Bel(a, Sato(x)) = \iota x.Bel(b, Sato(x)))$ .

By indicating *a*'s intended referent, *b*'s intended referent, and the semantic referent by **Ta**, **Tb**, and **Tcom**, respectively, we can summarize what has been discussed above as follows:

- (42) strongly successful: **Tcom** = **Ta** = **Tb**,  
 observationally successful: **Ta** = **Tb**,  
 strongly unsuccessful: **Tcom** ≠ **Ta**,  
**Tcom** ≠ **Tb**,  
 observationally unsuccessful: **Ta** ≠ **Tb**.

## 5 Conclusion

In this paper, we proposed a system which combines DRS with CMS, and an algorithm for the dynamic revision of shared beliefs in cooperative dialogues. Further, the degree of success in dialogues was formalized.

Still, the following problems remain to be solved:

- 1) The treatment of background knowledge must be made precise. E.g., ' $Sato \rightarrow 203$ ' in (23), or ' $\forall x(Muranishi(x) \rightarrow \neg Hokuto(x))$ ' in (25) is implicitly introduced into the inference without explanation of its origin.
- 2) The translation procedure of an utterance into the condition of DRS must be formalized.
- 3) It's necessary to give a semantic foundation to our system.
- 4) Implementation of a system which simulates our dialogue mechanism.

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