Formal Representation of Common Ground in Dialogue

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1. Introduction

Common ground, a set of shared beliefs between interlocutors in a discourse, is an essential component of everyday conversation. It has also been a topic across many disciplines, such as linguistics and cognitive science (Kiparsky and Kiparsky, 1968; Karttunen, 1971b,a; Clark, 1996; Horton and Gerrig, 2016), computer science, artificial intelligence, and natural language processing (Grosz and Sidner, 1990; Cohen and Levesque, 1990; Traum, 1994; Del Tredici et al., 2022), and philosophy (Lewis, 1969; Stalnaker, 2002). When people talk, they convey not only the propositional content of their utterances but also their beliefs about that content, e.g., when John says: *Perhaps Mary's baby wakes her up*, he signals the tentativeness of his belief about whether Mary's baby wakes up Mary or not. Let us call this proposition p. Let us further assume that Joseph, John's interlocutor, says he agrees. Given this interaction, John and Joseph's common ground is updated with the information that both speakers have the belief that p is possible, and that both speakers believe the other has this belief, and so on.

Detecting people's beliefs and their common ground is interesting from cognitive and computational perspectives. First, common ground gives us insight to people's cognitive states, which in turn has implication on their choice of language usage. Secondly, building an interpretable model of common ground which reflects our cognitive assumptions can be used to improve today's natural language processing technology.

Using the CALLHOME corpus (Canavan et al., 1997), which consists of unscripted phone conversation between two speakers, we develop an annotation procedure that reflects how people recognize others' beliefs and update common ground. Furthermore we build a formal axiomatic logic model to represent this procedure. For the initial stage of this project, we focus solely on representing questions, as they provide non-trivial cases of common ground updates.

2. Data

The CALLHOME corpus is a collection of dialogues between family and close friends. Since to the best of our knowledge, there is no corpus annotated for common ground, it is reasonable to begin with conversations between two people. Those conversations are unscripted, meaning that the speakers were free to converse about any topic. Since the speakers are familiar with each other, we can safely assume that their common ground set is non empty at the beginning of the conversation. The CALLHOME corpus gives access to audio and manual transcripts, allowing for a more accurate extraction of discussed propositions.

3. Annotation Procedure

Common ground is defined in terms of belief. Multiple annotations of belief procedures have been proposed (Saurí and Pustejovsky, 2009; Diab et al., 2009; Ross and Pavlick, 2019; Marie-Catherine de Marneffe, 2019). We adopt and simplify the FactBank corpus annotations. We use CT+ to express that a speaker has a certain belief that

p, CT- to express that a speaker is certain that *not* p, PS to indicate that speaker believes that p is possible, and NB to mark that a speaker does not have any belief towards p.

What makes our work different from other work in terms of belief annotation is that we annotate beliefs from the perspective of two speakers simultaneously. Based on confidence values towards propositions of both speakers, we can deduce whether or not a proposition was just added to common ground (JA), has already been part of the common ground (IN), or was rejected (RT). This setup allows us to keep track of potential updates of the common ground in a conversation.

4. Questions and Annotation Examples

We identified three types of questions in CALLHOME. This categorization reflects three distinct types of beliefs a speaker may express towards propositions under questions.

Type I represents questions expressing no belief (NB) towards the embedded proposition. Yes/no questions are the representative of this set. The speaker does not express any belief towards the entertained proposition. For example, when Mary asks Joseph: *Does the baby wake you up?*, she does not commit to any belief towards the proposition *The baby wakes Joseph up.* Her belief is updated once Jospeh provides an answer.

Type II are questions expressing possible belief (PS) towards the proposition. Interestingly, most kinds of questions we identified in the corpus so far belong to that group. Let us consider the familiar example from above and negate the auxiliary (*Doesn't the baby wake you up?*). By using this question, Mary signals that she does believe that the baby possibly wakes Joseph up. She seems to be searching for reassurance.

Type III are questions containing a proposition that is already part of the common ground (IN) between speakers. Sometimes what is considered a question from a syntactic or prosodic perspective may actually not be a request for information at all. An obvious example is a rhetorical question, e.g. *Doesn't every baby want to be loved?* Here Mary is communicating two things. First that she believes the proposition that every baby is loved. Second, that she believes that Jospeh believes that proposition as well. In other words, Mary is reaffirming that the proposition is believed by and is in the common ground from the perspective of Mary and Joseph. Another example where a speaker refers to information which has already been in the common ground are wh-questions, which presuppose the non-queried portion of the question. For instance, by asking *When did the baby wake you up*, Mary is signalling that the proposition that the baby woke Joseph up is believed by both participants, and is not likely to be questioned.

5. Proposed Logic

We present a propositional logic of beliefs to model updates to the common ground as seen in the annotations developed for our corpus. This approach takes inspiration from Cohen and Levesque (1990). The logical language $\mathcal{L}$ allows each annotation to be translated into a corresponding formula from the set of formulas $\mathcal{F}$ in our language $\mathcal{L}$. In this regard the beliefs expressed in every conversation can be thought of as a sequence of formulas and our corpus, from a logical perspective, is a collection of these sequences.

Let $\textsc{Var}$ be a countably infinite set of propositional variables, denoted by lowercase letters. Conversations take place between two agents in $\textsc{Agent}$. Since we wish to model how the common ground is being updated through conversation, we introduce a finite set of times in $\textsc{Time}$. The premise of our work is not to assign truth to propositions extracted from the dialogues but to assign beliefs of agents towards those propositions. To reflect that we introduce two propositional connectives,

$$\mathbf{CB}^t_a\varphi \coloneqq \text{“At time } t\text{, agent } a \text{ believes that certainly } \varphi\text{”}$$

$$\mathbf{PB}^t_a\varphi \coloneqq \text{“At time } t\text{, agent } a \text{ believes that possibly } \varphi\text{”}$$

Both of these require that an agent assigns some confidence to the corresponding formula, $\varphi \in \mathcal{F}$. To represent the case where an agent is entertaining φ (and may or may not have assigned a belief strength), we introduce an additional connective,

$$\mathbf{E}^t_a\varphi \coloneqq \text{“At time } t\text{, agent } a \text{ entertains } \varphi\text{”}$$

Together with negation and conjunction, we arrive at a set of connectives $\textsc{Con}$ for $\mathcal{L}$.

$$\textsc{Con} = \{\neg, \wedge, \mathbf{E}^t_a, \mathbf{PB}^t_a, \mathbf{CB}^t_a\} \text{ where } a \in \textsc{Agent},\ t \in \textsc{Time}$$

The set of formulas $\mathcal{F}$ is constructed recursively from our alphabet $\mathcal{A}$, that is to say the sets $\textsc{Var}$, $\textsc{Agent}$, $\textsc{Time}$, and $\textsc{Con}$.

Definition. *The set $\mathcal{F}$, consisting of all syntactically valid formulas in $\mathcal{L}$, is the smallest set such that,*

1. $\textsc{Var} \subseteq \mathcal{F}$
2. *If $\varphi \in \mathcal{F}$ and $\circ \in \textsc{Con} - \{\wedge\}$, then $\circ\varphi \in \mathcal{F}$*
3. *If $\varphi_1, \varphi_2 \in \mathcal{F}$, then $(\varphi_1 \wedge \varphi_2) \in \mathcal{F}$*

This constitutes the full set of well-formed formulas for our language $\mathcal{L}$.

Aspects of the annotation introduced in §3 can now be represented in our logical language $\mathcal{L}$. To do so, we introduce additional connectives defined in terms of our set $\textsc{Con}$.

$$\textbf{\textsc{Ct+}}^t_a\varphi \coloneqq \mathbf{CB}^t_a\varphi \qquad \textbf{\textsc{Ct-}}^t_a\varphi \coloneqq \mathbf{CB}^t_a\neg\varphi$$
$$\textbf{\textsc{Ps}}^t_a\varphi \coloneqq \mathbf{PB}^t_a\varphi \qquad \textbf{\textsc{Nb}}^t_a\varphi \coloneqq \mathbf{E}^t_a\varphi \wedge \neg\textbf{\textsc{Ct+}}^t_a\varphi \wedge \neg\textbf{\textsc{Ct-}}^t_a\varphi \wedge \neg\textbf{\textsc{Ps}}^t_a\varphi$$

Additionally, we can define what it means for a proposition to be in the common ground using $\mathcal{L}$. For brevity, let $\Delta \in \{\textbf{\textsc{Ps}}, \textbf{\textsc{Ct+}}, \textbf{\textsc{Ct-}}\}$[1],

$$\Delta^t_{a,b}\varphi \coloneqq \Delta^t_a\varphi \wedge \mathbf{CB}^t_a\Delta^t_b\varphi \wedge \mathbf{CB}^t_a\mathbf{CB}^t_b\Delta^t_a\varphi \wedge \cdots$$
$$\textbf{\textsc{Cg}}^t_{a,b}\varphi \coloneqq \textbf{\textsc{Ps}}^t_{a,b}\varphi \vee \textbf{\textsc{Ct+}}^t_{a,b}\varphi \vee \textbf{\textsc{Ct-}}^t_{a,b}\varphi$$

Critically, $\textbf{\textsc{Cg}}^t_{a,b}\varphi \neq \textbf{\textsc{Cg}}^t_{b,a}\varphi$.[2] This is because each agent has their own conception of the common ground and they do necessarily have to match. A misunderstanding between speakers can be understood as divergence of their common grounds. Similarly, we define logical representations for annotations of $\textbf{\textsc{Ja}}$, $\textbf{\textsc{In}}$, and $\textbf{\textsc{Rt}}$.

$$\textbf{\textsc{Ja}}^{t_i}_{a,b}\varphi \coloneqq (\neg\textbf{\textsc{Cg}}^{t_{i-1}}_{a,b}\varphi \wedge \textbf{\textsc{Cg}}^{t_i}_{a,b}\varphi) \quad \textbf{\textsc{In}}^{t_i}_{a,b}\varphi \coloneqq (\textbf{\textsc{Cg}}^{t_{i-1}}_{a,b}\varphi \wedge \textbf{\textsc{Cg}}^{t_i}_{a,b}\varphi) \quad \textbf{\textsc{Rt}}^{t_i}_{a,b}\varphi \coloneqq \neg\textbf{\textsc{Cg}}^{t_i}_{a,b}\varphi$$

With these, we can represent annotations of the corpus with corresponding formulae in our logical language $\mathcal{L}$.

6. Semantics and Application

A formula $\varphi \in \mathcal{F}$ is assigned truth based on the corresponding annotated dialogue. Let us consider an example from §4 with the following propositions p_1 = "A asks B if the baby wakes B up" and p_2 = "The baby wakes B up".

Time	Utterance	Prop.	Bel:A	Bel:B	CG:A	CG:B
t_1	*A: Does the baby wake you up?*	p_1	**Ct+**	**Ct+**	**Ja**	**Ja**
		p_2	**Nb**	**Ct+**	-	-
t_2	*B: Yeah.*	p_2	**Ct+**	**Ct+**	**Ja**	**Ja**

We translate the explicit content into the following.

$$\varphi_1 \coloneqq (\textbf{\textsc{Ct+}}^{t_1}_a p_1 \wedge \textbf{\textsc{Ct+}}^{t_1}_b p_1) \wedge (\textbf{\textsc{Nb}}^{t_1}_a p_2 \wedge \textbf{\textsc{Ct+}}^{t_1}_b p_2) \wedge (\textbf{\textsc{Ja}}^{t_1}_{a,b} p_1 \wedge \textbf{\textsc{Ja}}^{t_1}_{b,a} p_1)$$
$$\varphi_2 \coloneqq (\textbf{\textsc{Ct+}}^{t_2}_a p_2 \wedge \textbf{\textsc{Ct+}}^{t_2}_b p_2) \wedge (\textbf{\textsc{Ja}}^{t_2}_{a,b} p_2 \wedge \textbf{\textsc{Ja}}^{t_2}_{b,a} p_2)$$

The challenge we are faced with is identifying how one is supposed to infer common ground from the surface level beliefs presented. It is observed empirically and intuitively that,

$$(\textbf{\textsc{Ct+}}^{t_1}_a p_1 \wedge \textbf{\textsc{Ct+}}^{t_1}_b p_1) \nvdash (\textbf{\textsc{Ja}}^{t_1}_{a,b} p_1 \wedge \textbf{\textsc{Ja}}^{t_1}_{b,a} p_1)$$
$$(\textbf{\textsc{Nb}}^{t_1}_a p_2 \wedge \textbf{\textsc{Ct+}}^{t_1}_b p_2) \wedge (\textbf{\textsc{Ct+}}^{t_2}_a p_2 \wedge \textbf{\textsc{Ct+}}^{t_2}_b p_2) \nvdash (\textbf{\textsc{Ja}}^{t_2}_{a,b} p_2 \wedge \textbf{\textsc{Ja}}^{t_2}_{b,a} p_2)$$

1. Note the deliberate exclusion of $\textbf{\textsc{Nb}}$.
2. Note that $\Delta^t_{a,b}\varphi \implies \textbf{\textsc{Cg}}^t_{a,b}\varphi$. This is because Δ indicates that it is in the common ground with some level of confidence while $\textbf{\textsc{Cg}}$ indicates that it is in the common ground with an unspecified confidence.

Therefore we must identify the process which allows participants to get from the single-agent beliefs on the left, to the multi-agent beliefs on the right. Space does not permit a full discussion of this issue. In this abstract we outline a model and methodology for extracting common ground from a dialogue between two speakers. In the written paper we develop a methodology for building a set of rules of inference and semantics derived from empirical observations of natural language in which these rules are sound. Future work will extend this to include more complex social interactions.

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