Signaling Games with Partially Observable Actions as a Model of Conversational Grounding

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Abstract

We present a game-theoretic model that formalizes core ideas of conversational grounding theory. This game-theoretic model is based on the concept of signaling games, originally proposed as a model of linguistic convention. We extend signaling games with an observation model, which allows for the possibility that the actions a dialog participant takes may only be partially observable to others. We then apply this model to the domain of referential communication tasks, a type of task commonly used in psycholinguistic experiments.

1 Introduction

The conversational grounding theory of Herbert Clark and colleagues (Clark and Wilkes-Gibbs 1986), (Clark and Schaefer 1987), (Clark and Schaefer 1989), (Clark and Brennan 1991), (Clark 1996) proposes that language use in dialog is a form of rational joint action, executed by dialog participants in order to systematically and collaboratively add to their common ground of shared knowledge and beliefs. In this paper we address the issue of constructing a formal model of conversational grounding. In particular, we propose that game theory (Myerson 1991), (Osborne and Rubinstein 1994) is well-suited to the task. Game theory, to date the dominant formal approach to analyzing multiagent interaction (Shoham and Leyton-Brown 2009), provides the necessary analytical tools to formalize the core ideas and intuitions of grounding theory.

In this paper, we focus on a class of task-oriented dialogs frequently used in psycholinguistic experiments, known as referential communication tasks (Krauss and Weinheimer 1966), (Clark and Wilkes-Gibbs 1986), (Horton and Keysar 1996), (Gergle, Kraut, and Fussell 2004). Successful completion of such tasks requires participants to engage in information exchange that crucially relies on resolving referential descriptions about task objects. The game-theoretic model we propose for such tasks is based on a class of games known as signaling games (Lewis 1969), (Spence 1973), (Crawford and Sobel 1982), (Stalnaker 2005). A signaling game is a Bayesian extensive game with observable actions, in which an informed player must communicate with an uninformed player in order for the two to coordinate on an action. The informed player knows the true state of the world, and can send a signal to the uninformed player. The uninformed player must then select an action that determines the payoffs for both players. A standard signaling game provides a reasonable first approximation of typical referential communication tasks.

However, standard signaling games cannot directly account for grounding behaviors, because they don’t allow for the possibility that a player may have only partial information about which message was sent by the other player. In order to model this type of uncertainty in communication, we propose a new type of signaling game, which we call signaling games with partially observable actions. This type of game extends signaling games with an observation model, allowing for the possibility that messages from the informed player are only partially observable to the uninformed player. The addition of an observation model turns a standard signaling game into an extensive game of imperfect information. The uninformed player receives observations of messages, which provide probabilistic information about the messages that generate them.

This rest of this paper is structured as follows. Section 2 reviews four core claims of grounding theory. Section 3 reviews standard signaling games and explains why they are inadequate to account for all four claims. This section then introduces an extension to such games to allow for imperfect information with respect to an agent’s actions. Section 4 shows how this new class of games provides formal analogs to the four core claims of grounding theory. Section 5 discusses related work on formalizing conversational grounding theory, and Section 6 concludes and provides suggestions for future work.

2 Grounding theory

Grounding theory takes the Gricean idea that language use is a type of rational action, and applies it to the mechanisms and processes by which dialog participants coordinate sequences of dialog actions. According to grounding theory, successful language use in dialog requires participants to coordinate their knowledge, beliefs, and behaviors on a variety of levels, from their attentional focus up through the ultimate goal of the activity to which the dialog is directed. Grounding theory further claims that participants act in a way that maximizes the likelihood of achieving their goals, while simultaneously minimizing the amount of effort that they must
expend in order to do so.

(Clarke and Wilkes-Gibbs 1986) provide evidence for this view of language use by looking at patterns of linguistic behaviors in a referential communication task. Example (1) is from an experiment in which participants work together to arrange a set of tangram figures. One of the participants (called “A”) knows how the figures are to be arranged, while the other (called “B”) must do the arranging. Notice how in this example a single referential description is split across multiple “installments”, interleaved with an acknowledgement from B that provides feedback to A about the incremental description.

(1)  

A: And the next one is the one with the triangle to the right...  
B: Okay.  
A: With the square connected to it.

This is one among many such examples where the participants collaborated on fashioning referential descriptions to identify a figure. Clark and Wilkes-Gibbs attributed these types of collaborative referring descriptions to the dialog participants making trade-offs in cost and uncertainty: while chunking up the referential description into multiple installments increases cost (in terms of time and effort), it also increases confidence that the referential description has been successfully understood by the addressee, by allowing for early detection and repair of potential miscommunication. In situations where a high degree of confidence in mutual understanding is important, dialog participants may deem the extra costs to be worthwhile.

Formalizing conversational grounding theory is not of just academic interest. Grounding phenomena are pervasive in dialog. For example, (Traum 1994) calculated that approximately 50% of the utterances in the TRAINS task-oriented dialog corpus (Allen et al. 2000) are directed towards coordinating understanding. Clearly, any successful computational conversational agent is going to have to be able to deal with such utterances. A formal theory of conversational grounding is a precondition for a principled computational implementation of such agents.

Various formulations of grounding theory have been presented in the works of Clark and colleagues, but the following four claims are core to all of them:

1. Communicative acts are joint actions: Conversation is a joint activity composed of a sequence of communicative acts, each of which is a joint action. Joint actions are composed of participatory individual actions that share a joint goal, and are executed in coordination with each other.

2. Coordination of joint actions is achieved through the common ground: In order to succeed, communicative acts require participants to coordinate on both content and process. Coordination is achieved by relying on the common ground of knowledge and beliefs shared by the participants. Furthermore, a successfully executed communicative joint action advances the goals of the agents by incrementally adding to this common ground.

3. The grounding criterion: The participants in a joint action try to establish the mutual belief that the contributor has succeeded in adding to the common ground to a criterion sufficient for current purposes. Grounding is the collective process by which this mutual belief is achieved.

4. The principle of least collaborative effort: speakers and addressees try to minimize collaborative effort, the work both speakers and addressees do from the initiation of each contribution to its mutual acceptance.

The next section introduces a game-theoretic model of communication that formalizes these four claims within the context of referential communication tasks.

3 Game-theoretic model

Before introducing our game-theoretic model, we first present a simple example of a cooperative referential communication task, which we call the lock task. In this task, two agents collaborate to open a combination lock. One agent, the helper, knows the combination, while the other agent, the worker, does not. On the other hand, the worker has the physical ability to rotate the disks on the lock, while the helper does not. For the basic version of the lock task, we assume that the goals of the helper and the worker are perfectly aligned. Imagine that opening the lock provides access to some treasure, the value of which is to be equally divided between them. This gives the helper and the worker every incentive to cooperate on opening the lock in order to gain the reward. The basic version of the lock task therefore serves as an abstract model of a typical referential communication task.

Signaling games

Following (Shoham and Leyton-Brown 2009), a signaling game is defined as a two-player Bayesian extensive game with observable actions, in which:

- An initial move of chance selects a game to be played according to a commonly known distribution;
- Player 1 is informed of that choice and chooses an action;
- Player 2 then chooses an action without knowing chance’s choice, but knowing player 1’s choice.

Signaling games were first proposed in (Lewis 1969) in order to model linguistic convention. They have subsequently been used in economics, theoretical biology, and formal approaches to pragmatics (see(Benz, Jaeger, and van Rooij 2005)). In this type of game, every player observes with full certainty the actions of every other player, and the only uncertainty in the game is about an initial move of chance that distributes private payoff relevant information among the players (Osborne and Rubinstein 1994). In the literature on game theory, this private information is called the player’s type (Harsanyi 1967).

Figure 1 shows the lock task as a signaling game. It depicts a game with three players: h, w, and c. These represent the helper, the worker, and chance, respectively. The first move belongs to chance, selecting the solution to the combination lock. In this scenario, the lock has only one rotating disk, and the disk has only two possible values, either d_{1} or d_{2}. After chance selects the solution to the lock
moves are fully observable to the other players. Given this, the worker can
observe messages from the helper, and can send messages to the worker about
vital, payoff relevant information. The helper knows the solution to the lock,
and hence provides an abstract model of alternative ways to
communication he received, and the probability distributions of the
same information, in which:

Partial observability can be passive or active.

Passive partial observability

- An initial move of chance selects a game to be played according to a commonly known distribution.
- Player 1 is informed of that choice and chooses an action.
- Chance then chooses an observation for player 2 according to a commonly known distribution.
- Player 2 then chooses an action only knowing the observation he received, and the probability distributions of the chance moves.

Figure 2 shows the lock task as a signaling game with partially observable actions. Once again the initial move is made by chance, who selects lock solution $d_1$ or $d_2$ with probability $\frac{1}{2}$. The next move belongs to the helper. The helper uses the information available to him to communicate the same information, namely “the lock solution is 1”. Likewise, $m_2$ and $m_2'$ are to be interpreted as alternative ways to communicate “the lock solution is 2”. This game tree therefore provides an abstract model of alternative ways to communicate the same information.

Looking forward, we can see that choosing $m_1$ or $m_2$ leads to payoffs $(M - C)$ or $-(L + C)$, while choosing $m_1'$ or $m_2'$ leads to payoffs $(M - C')$ or $-(L + C')$. The value $M$ represents the payoff for both players when the worker chooses the “correct” action (i.e., setting the lock to 1 when the solution is 1, and to 2 when the solution is 2). Conversely, the value $L$ represents the penalty for both players when the worker chooses the incorrect action, such as setting the lock to 2 when the solution is 1. The values $C$ and $C'$ are the costs associated with particular messages, where $C$ is the cost of $m_1$ and $m_2$, and $C'$ is the cost of $m_1'$ and $m_2'$. 

**Partially observable actions**

We now define an extension to signaling games, which we call **signaling games with partially observable actions**. These are two-player extensive game with imperfect information, in which:

- An initial move of chance selects a game to be played according to a commonly known distribution;
- Player 1 is informed of that choice and chooses an action;
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Figure 2 shows the lock task as a signaling game with partially observable actions. Once again the initial move is made by chance, who selects lock solution $d_1$ or $d_2$ with probability $\frac{1}{2}$. The next move belongs to the helper. Her information sets at this point distinguish between the two histories $(d_1)$ and $(d_2)$, hence she knows the solution to the lock. If history $(d_1)$ occurs, then the helper has two action choices, $m_1$ or $m_1'$. If history $(d_2)$ occurs, then the helper has two other action choices, $m_2$ or $m_2'$. Both $m_1$ and $m_1'$ are to be interpreted as alternative ways of communicating the same information, namely “the lock solution is 1”. Likewise, $m_2$ and $m_2'$ are to be interpreted as alternative ways to communicate “the lock solution is 2”. This game tree therefore provides an abstract model of alternative ways to communicate the same information.

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- An initial move of chance selects a game to be played according to a commonly known distribution;
- Player 1 is informed of that choice and chooses an action;
- Chance then chooses an observation for player 2 according to a commonly known distribution;
- Player 2 then chooses an action only knowing the observation he received, and the probability distributions of the chance moves.
After the helper makes her choice, the next move is again made by chance. Chance selects an observation of the message action selected by the helper.1 Chance selects either observation \( o_1 \) or \( o_2 \) after \( m_1 \) and \( m_2 \) respectively, and observation \( o'_1 \) or \( o'_2 \) after \( m'_1 \) and \( m'_2 \). If the helper sends message \( m_1 \), chance selects \( o_1 \) with probability \( (1 - \epsilon) \), and \( o_2 \) with probability \( \epsilon \). If the helper sends message \( m_2 \), chance selects \( o_2 \) with probability \( (1 - \epsilon) \), and \( o_1 \) with probability \( \epsilon \). After messages \( m'_1 \) and \( m'_2 \), the observation probabilities are \( (1 - \epsilon') \) for \( o'_1 \) and \( o'_2 \), respectively. Chance’s probability distributions over these observations provides the worker with exogenously determined probabilistic information about which message the helper sent.

Both \( \epsilon \) and \( \epsilon' \) are to be interpreted as the likelihood of communicative error, given a helper message. That is, it represents the possibility that the message that the helper sends is not understood properly for some reason, whether due to a noisy channel, listener distraction, or lexical ambiguity. It is the level of uncertainty that both helper and worker have about the success of a communicative act. For this game, and for reasons to be made clear shortly, we require that \( 0 \leq \epsilon \leq \epsilon' \leq \frac{1}{2} \). The boundary cases for these values are \( \epsilon = \epsilon' = 0 \), and \( \epsilon = \epsilon' = \frac{1}{2} \). In the first case, where both \( \epsilon = \epsilon' = 0 \), the game reduces to a garden variety signaling game, such as the one shown in Figure 1. With no possibility for error, the helper’s messages become completely observable to the worker, and the only remaining uncertainty is the worker’s uncertainty about the move of chance that begins the game. In the second case, where both \( \epsilon = \epsilon' = \frac{1}{2} \), the helper’s messages bear no useful information for the worker, since they are completely ambiguous. Useful communication can therefore occur only between these two extremes.

After receiving a message observation from chance, the worker then takes his action, selecting either \( s_1 \) or \( s_2 \). The payoffs to the players are then determined by which terminal history was followed in the game tree. Unlike the signaling game shown in Figure 1, the payoffs in this game take into account the cost of a message, which is deducted from the payoff received at the end of the game. The specific amount depends on the message that is sent: \( m_1 \) and \( m_2 \) each cost an amount \( C \), while \( m'_1 \) and \( m'_2 \) each cost an amount \( C' \). For this game, we stipulate that \( C \leq C' \). With the above restriction that \( \epsilon \leq \epsilon' \), this leads to the following interpretation of the game in Figure 2: sending \( m'_1 \) (respectively \( m'_2 \)) results in a higher degree of confidence that the message will be correctly recovered by the worker than does sending message \( m_1 \) (respectively \( m_2 \)), but this extra confidence comes at a potential price, since \( C' \) is at least as big as \( C \).

A standard solution concept for an extensive game of imperfect information is the sequential equilibrium (Osborne and Rubinstein 1994). A sequential equilibrium provides a strategy for each player that is a best response to the strategies of the other players, given beliefs about the game in the form of probability distributions over information sets. In this case, a strategy for player \( i \) is an action selection (or a probability distribution over actions) at each point in the game tree where it is the turn of player \( i \) to choose. Player \( i \) will choose a strategy that maximizes the expected payoff to player \( i \), given beliefs about the current state, and expectations about what the other players will do.

Here we focus on the helper’s equilibrium strategy, i.e., which message she should choose to send to the worker.2 At each of her choice points in the game tree, the helper must decide between messages \( m_1 \) and \( m'_1 \), and messages \( m_2 \) and \( m'_2 \). We can show that the helper’s best choice in each case depends on a simple relationship among the \( C, C', \epsilon \), and \( \epsilon' \). Denote \( C' - C \) as \( \Delta(C) \) and \( \epsilon - \epsilon' \) as \( \Delta(\epsilon) \). If \( \Delta(C)/(M + L) < \Delta(\epsilon) \), then the helper should choose the higher cost (and more reliable) “primed” messages \( (m'_1, m'_2) \). If \( \Delta(C)/(M + L) > \Delta(\epsilon) \), then the helper should choose the lower cost (and less reliable) non-primed messages \( (m_1, m_2) \). In other words, we simply take the difference in the costs of the two messages (normalized with respect to \( M + L \)), and compare it to the gain in confidence that results.

4 Connecting the model to grounding theory
We now review how signaling games with partially observable actions allow us to formally model the four core concepts of grounding theory described in Section 2.

Joint actions
According to grounding theory, a joint action is one that is carried out by an ensemble of people that are acting in coordination with one another. In a game of pure coordination, such as the example in Figure 2, the players share the same

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1The double dashed lines at this point indicate that the remainder of the game tree has been elided, in order to reduce the visual complexity of the diagram. The worker’s choices after each of these elisions is either \( s_1 \) or \( s_2 \), and the payoffs are identical to their sister (unelided) nodes in the tree.

2See (Thompson 2009) for a full derivation of the sequential equilibrium for this game.
payoffs in every outcome, therefore their interests are perfectly aligned. In such a game, players must execute coordinated individual actions in order to achieve the best possible outcome. The game-theoretic model therefore provides us with a formalization of the concept of joint action.

Common ground

If communicative acts are joint actions, then how do participants coordinate on their execution? The answer, according to Clark, lies in their common ground, which is “the sum of their mutual, common, or joint knowledge, beliefs, and suppositions” (Clark 1996) (p. 93). A proposition \( P \) is said to be part of the common ground among a group of agents if it is common knowledge or common belief among the agents that \( P \) is true (Lewis 1969), (Aumann 1976). One way of characterizing common knowledge of a proposition \( P \) among a group of agents is as an infinite hierarchy of statements: everyone knows \( P \), everyone knows that everyone knows \( P \), and so on. Common belief is defined in a similar fashion, with belief replacing knowledge as the epistemic operator.

However, it is a general result that any possibility for communicative error makes common knowledge of the communicated content impossible (Halpern and Moses 1990). This result is particularly relevant for theories of communication in dialog, because human language is inherently ambiguous, susceptible to noisy channel problems, and errors in both production and comprehension. Fortunately however, it turns out that full common knowledge is not an absolute requirement to achieve a high degree of coordination among agents. Approximate common knowledge, in the form of probabilistic common beliefs, is sufficient in many cases of practical interest (Monderer and Samet 1989), (Morris and Shin 1997). This fact is particularly fortunate for the case of signaling games with partially observable actions, because in general this type of game does not allow for full common knowledge of communicated content. On the other hand, this type of game does allow for probabilistic common belief.

We show this formally using the set-theoretic approach to (common) knowledge established by (Aumann 1976). Given our previous assumption that \( 0 \leq \epsilon \leq \epsilon' \leq \frac{1}{2} \), it is easy to show that the helper and the worker in Figure 2 will never achieve full common knowledge of communicated content. In this case \( \Omega \) consists of the set of eight possible histories at the stage before the worker takes his action:

\[
\Omega = \{(d_1, m_1, o_1), (d_1, m_1, o_2), (d_2, m_2, o_1), \\
(d_2, m_2, o_2), (d_1, m'_1, o'_1), (d_1, m'_1, o'_2), \\
(d_2, m'_2, o'_1), (d_2, m'_2, o'_2)\}
\]

Given the structure of the game in Figure 2, the information partition induced by the information function \( \Pi_h \) of the helper is represented as follows:

\[
\Pi_h = \{(d_1, m_1, o_1), (d_1, m_1, o_2), \\
(d_1, m'_1, o'_1), (d_1, m'_1, o'_2), \\
(d_2, m_2, o_1), (d_2, m_2, o_2), \\
(d_2, m'_2, o'_1), (d_2, m'_2, o'_2)\}
\]

This partition represents the fact that the helper knows the action of chance at the beginning of the game, and the helper knows what message she sent to the worker. However, the helper does not know which observation the worker received. Conversely, the information partition induced by the information function \( \Pi_w \) of the worker represents the fact that he does know what observation he received, but is uncertain about the initial action of chance and the message that the helper sent:

\[
\Pi_w = \{(d_1, m_1, o_1), (d_2, m_2, o_1), \\
(d_1, m'_1, o'_1), (d_2, m'_2, o'_1), \\
(d_1, m_1, o_2), (d_2, m_2, o_2), \\
(d_1, m'_1, o'_2), (d_2, m'_2, o'_2)\}
\]

Now as an example, consider the case where \( \omega = (d_1, m_1, o_1) \) is the actual state of the world. That is, the solution to the lock is \( d_1 \), the helper has sent message \( m_1 \), and the worker has received observation \( o_1 \). At this state, we have \( \Pi_h(\omega) = \{(d_1, m_1, o_1), (d_1, m_1, o_2)\} \) and \( \Pi_w(\omega) = \{(d_1, m_1, o_1), (d_2, m_2, o_1)\} \). Therefore, it fails to be the case that either player has individual knowledge that the event \( E = \{\omega\} \) has occurred, since neither \( \Pi_h(\omega) \) nor \( \Pi_w(\omega) \) is a subset of \( E \). So common knowledge of \( E \) is clearly impossible in this situation. This situation is the case no matter which history in \( \Omega \) is the true state.

We therefore adopt a weaker notion of common ground to explain how communication and coordination occurs during the game shown in Figure 2. This weaker notion is provided by (Monderer and Samet 1989), who extend the set-theoretic definitions of (common) knowledge to the case of probabilistic (common) belief. An agent \( i \) is said to believe event \( E \) with probability at least \( p \) at state \( \omega \) (“\( i \) believes \( E \) at state \( \omega \)” if at \( \omega \) he assigns probability \( p \) or higher to the set of states contained in \( E \). Formally, we have \( B^p_i(E) = \{\omega : Pr(E|h_i(\omega)) \geq p\} \). Given this definition, common p-belief is defined in a straightforward way as a generalization of the set-theoretic definition of common knowledge.

To see how to apply the notion of common p-belief to the game in Figure 2, consider the belief state possibilities of the game summarized in Table 1. The leftmost column shows four of the possible states of the game at the point before the worker selects his action. The next column shows the prior probabilities for these states. The third and fourth columns show updated probabilities for the helper after chance selects either \( d_1 \) or \( d_2 \) (respectively) as the lock solution at the beginning of the game. The fifth and sixth columns show the updated probabilities for the worker after chance selects either observation \( o'_1 \) or \( o'_2 \) (respectively).

Now consider the state \( (d_1, m'_1, o'_1) \), where chance selects \( d_1 \) as the solution to the lock at the beginning of the game,
the helper selects action $m'_1$, and chance then provides the worker with observation $o'_1$. In this case, the helper and the worker each assign the true state a probability of $1 - \epsilon'$; therefore, the players have achieved mutual p-belief in state $(d_1, m'_1, o'_1)$ at the p-level of $1 - \epsilon'$. In fact, we can say something stronger. Letting $E = \{(d_1, m'_1, o'_1)\}$, we have:

$$B_h^{(1-\epsilon')}(E) = \{(d_1, m'_1, o'_1), (d_1, m'_1, o'_2)\}$$

$$B_w^{(1-\epsilon')}(E) = \{(d_1, m'_1, o'_1), (d_2, m'_2, o'_1)\}$$

Therefore, since $E \subseteq B_h^{(1-\epsilon')}(E)$ and $E \subseteq B_w^{(1-\epsilon')}(E)$, it is also the case that the helper and the worker have achieved common p-belief in event $E = \{(d_1, m'_1, o'_1)\}$ at the p-level of $1 - \epsilon'$. As $\epsilon'$ approaches 0, this common p-belief can get arbitrarily close to full common knowledge.

This scenario describes a “good” case, where the message and observation “coincide” and proper coordination occurs. However, consider another possible state in Table 1: $(d_1, m'_1, o'_2)$. In this state, the helper still assigns probability $1 - \epsilon'$ to the state $(d_1, m'_1, o'_1)$, because the helper only knows that $d_1$ is true and that she has sent message $m'_1$. She only assigns a probability $\epsilon'$ to the state that actually occurs, namely $(d_1, m'_1, o'_2)$. On the other hand, the worker assigns probability 0 to state $(d_1, m'_1, o'_1)$ because this is inconsistent with the observation $o'_2$ that he has received. Given this observation, the worker assigns probability $\epsilon'$ to the true state, and probability $1 - \epsilon'$ to state $(d_2, m'_2, o'_2)$. Therefore, the worker will take action $s_2$, given his equilibrium strategy. Common p-belief for the true state of the game exists only at the p-level $\epsilon'$, and coordination therefore fails, even though both players have played their part of the equilibrium strategy profile. It is presumably to reduce the possibility of failures such as these that dialog participants engage in grounding behaviors, such as shown in Example (1).

The grounding criterion

The grounding criterion states that participants in a joint action try to establish the mutual belief that the contributor has succeeded in adding to the common ground to a criterion sufficient for current purposes. In the game in Figure 2, “mutual belief” is formalized as common p-belief. Given this, we can frame the question of what it means for a given level of common p-belief to be “sufficient for current purposes” in a signaling game with partially observable actions. The answer to this question is that it depends on the payoffs associated with outcomes, and the uncertainties associated with individual actions. We select the action that maximizes the expected payoff (the action dictated by the equilibrium strategy), and the level of common p-belief established is a result of selecting this action, and the following observation generated by chance. This is the level that is “sufficient for current purposes”, because it is in fact the level that is optimally obtainable for current purposes, taking into consideration costs and payoffs. The force of the grounding criterion therefore follows naturally from the game-theoretic approach, and does not need to be independently stipulated.

Least collaborative effort

The principle of least collaborative effort states that speakers and addressees try to minimize collaborative effort, the work both speakers and addressees do from the initiation of each contribution to its mutual acceptance. In the game in Figure 2, “effort” is formalized in terms of the cost parameter associated with the individual outcomes. Since this is a game of pure coordination, this cost is always shared by both players. It can therefore be regarded as “collaborative effort”. If dialog participants were to choose a strategy with higher costs than the equilibrium strategy, this would result in a lower expected payoff to both players, since the extra cost is not justified by the corresponding increase in certainty. The force of the principle of least collaborative effort therefore follows naturally from the game-theoretic approach, in the context of a game of pure coordination, and does not need to be independently stipulated.

5 Related work

There have been several attempts to formalize Clark’s theory of conversational grounding. One of the first of these attempts was the contribution model of (Clark and Schaefer 1987), (Clark and Schaefer 1989). The contribution model is essentially a syntactic approach to grounding in dialog, organizing multiple dialog utterances into a single contribution graph. A contribution graph is composed of contributions, which in turn are composed of presentations and acceptances. Each presentation and acceptance is either an utterance (the basic unit from which larger scale units are composed), or another contribution that is embedded underneath it.

As a model of conversational grounding, contribution graphs have several drawbacks, some of which are described by (Traum 1999). The primary drawbacks with respect to the goals of this paper relate to the fact that contribution graphs have no means to represent degree of uncertainty in the common ground, nor do they have means for representing costs and payoffs. Contribution graphs can therefore say nothing about trading off cost and uncertainty to explain grounding behaviors like the multiple installments in Example (1).
In seminal work, (Traum 1994) presents a computational model of grounding referred to as the grounding acts model. This was one of the first explicit models of grounding to be used in a fully functional spoken dialog system (Allen et al. 2000). The grounding acts model is situated within a larger theory of conversation acts (Traum 1994), a generalization of classic speech act theory (Searle 1969) that takes into account Clark’s view of utterances in dialog as constitutive parts of larger joint actions.

Although the grounding acts model constitutes a major step forward as a computational model of grounding, (Traum 1999) highlights a number of issues, two of which are relevant to this paper. Like the contribution model, the grounding acts model assumes that grounding is binary in nature – each discourse unit is either grounded or not grounded. Also like the contribution model, there are no means to represent the cost of a conversation act. Therefore, the model does not allow us to explain grounding behavior in terms of a trade-off of cost and uncertainty.

In response to these two deficiencies, (Traum and Dillenbourg 1998) and (Traum 1999) proposed the use of decision theory. Such a decision-theoretic approach to grounding was developed further in the work of Eric Horvitz and Tim Paek (Paek and Horvitz 1999), (Paek and Horvitz 2000a), (Paek and Horvitz 2000b). Horvitz and Paek viewed the problem of conversational grounding as an application of general principles of decision making under uncertainty. To illustrate the decision-theoretic approach, (Paek and Horvitz 2000a) adopted the perspective of a listener who must make a one-shot decision on whether or not to make a repair to a speaker’s utterance.

The decision-theoretic approach of Horvitz and Paek shares much with the game-theoretic approach to grounding taken in this paper. However, there are at least two differences. First and foremost, game theory explicitly adopts a multiagent perspective. This is a key point, because the core concepts of grounding theory are intrinsically multiagent in character. A second difference is that the game-theoretic model in this paper takes a sequential approach to decision making, rather than modeling dialog as a one-shot decision process. This difference becomes more significant were we to generalize the signaling game approach to more than a single dialog turn.

Finally, (de Jaegher 2005) also studies grounding in the context of game theory. However, he does so by looking at extensions to the electronic mail game of (Rubinstein 1989), rather than looking at signaling games. de Jaegher shows that evolutionarily stable Nash equilibria in the (extended) electronic mail game contain message sequences that can be tied back to sequences of grounding acts in Traum’s grounding acts model. At a superficial level, our work is primarily differentiated from his by our decision to use signaling games as the basis for analysis, and by using the sequential equilibrium as the solution concept. More substantively, we differ also in that we examine errors of message discrimination rather than errors of message detection, and we provide a model of an agent’s private information at the start of the game, a key point in the context of referential communication tasks.

6 Conclusions and future work

In this paper we have presented a game-theoretic model of conversational grounding for referential communication tasks. The starting point for our model was the theory of signaling games. However, standard signaling games are insufficient to model grounding, because they have no means for representing imperfect information about another player’s actions. Therefore, we augmented signaling games with an observation model, generating a class of games we call signaling games with partially observable actions. The addition of an observation model allows for the possibility of exogenously determined uncertainty with respect to communicative actions.

In future work, we plan to examine games other than games of pure coordination. There are many situations where the interests of agents only partially overlap, or do not overlap at all, such as the games described in (de Jaegher 2005). These situations are modeled in game theory by assigning to players non-identical preference relations over outcomes. (Morris and Shin 1997) describe results from game theory that show how the strategic concerns of players interact with their belief states, in terms of the degree of coordination that results. For example, it turns out that whether or not common p-belief (at a certain level of p) is necessary for coordination partially depends on whether or not the interests of the players are aligned. It would be interesting to examine the implications of these results into the model of grounding described in this paper.

One of the ultimate goals of this work is to make the core ideas and intuitions of grounding theory precise enough to be used in a computational implementation of a conversational agent. Our intentions here are to leverage work on existing implementations of conversational agents, especially those that take theoretically motivated approaches to conversational grounding (Traum 1994), (Paek and Horvitz 2000b), (DeVault and Stone 2006). In particular, we intend to take advantage of the empirically motivated ontology of conversational acts developed by (Traum 1994). There is nothing to prevent the game-theoretic model from using the grounding act model’s ontology of conversation act types, by including them in the game players’ action sets.

We also intend to explore connections with another strand of recent research in dialog systems, which has taken the approach of modeling dialog as a partially observable Markov decision process (POMDP) (Thomson and Young 2010). There are clear connections between the game-theoretic approach to grounding described in this thesis, and the POMDP approach to dialog. The most important difference, however, is that the game-theoretic approach models a multiagent interaction, whereas POMDPs model single agents and their environment. However, there has been recent work generalizing POMDPs to the multiagent case, in the form of decentralized POMDPs (Dec-POMDPs) (Bernstein et al. 2002), (Seuken and Zilberstein 2008). It would be of interest to attempt a translation of the game-theoretic model described in this paper into the Dec-POMDP formalism. Such a translation would make it possible to take advantage of existing computational work on solving Dec-POMDPs.
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