A Generative Inquiry Dialogue System

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ABSTRACT

The majority of existing work on agent dialogues considers negotiation, persuasion or deliberation dialogues. We focus on inquiry dialogues that allow two agents to share knowledge in order to construct an argument for a specific claim. Inquiry dialogues are particularly useful in cooperative domains such as healthcare, and can be embedded within other dialogue types. Existing inquiry dialogue systems only model dialogues, meaning they provide a protocol which dictates what the possible legal next moves are but not which of these moves to make. Our system not only includes a general dialogue-game style inquiry protocol but also a strategy, for an agent to use with this protocol, that selects exactly one of the legal moves to make. We propose a benchmark against which we compare our dialogues, being the arguments that can be constructed from the union of the agents' beliefs, and use this to define soundness and completeness properties for inquiry dialogues. We show that these properties hold for all well-formed inquiry dialogues in our system.

Keywords

Argumentation, negotiation, and conflict handling. Communication: languages, semantics, pragmatics, protocols, and conversations. Cooperative distributed problem solving: coordination, cooperation, and teamwork.

1. INTRODUCTION

Dialogue games are now a common approach to defining communicative agent behaviour, especially when this behaviour is argumentation-based (e.g. [9, 11]). Dialogue games are normally made up of a set of communicative acts called moves, a set of rules that state which moves it is legal to make at any point in a dialogue (the *protocol*), a set of rules that define the effect of making a move, and a set of rules that determine when a dialogue terminates. Most of the work so far has looked only at modelling different types of dialogue from the Walton and Krabbe typology [14], here we provide a generative system.

In this paper we focus on inquiry dialogues. Walton and Krabbe define an inquiry dialogue as arising from an initial situation of "general ignorance" and as having the main goal to achieve the "growth of knowledge and agreement". Each individual participating in an inquiry dialogue has the goal to "find a 'proof' or destroy one" [14, page 66]. No formal definition of inquiry dialogues is given, leaving this classification somewhat open to interpretation. To address this, we have defined two different types of inquiry dialogue, each of which we believe fits this general definition: *warrant inquiry* and *argument inquiry*. In a warrant inquiry dialogue, the 'proof' takes the form of a dialectical tree (essentially a tree with an argument at each node, whose arcs represent the counter-argument relation and that has at its root an argument whose claim is the topic of the dialogue). In an argument inquiry dialogue, the 'proof' takes the form of an argument for the topic of the dialogue. Argument inquiry dialogues are commonly embedded in warrant inquiry dialogues. In this paper, we will focus only on argument inquiry dialogues.

As far as we are aware, there are only two groups that have proposed inquiry protocols. The Liverpool-Toulouse group proposed a protocol for general inquiry dialogues (e.g. [2, 9]), however this protocol can lead to unsuccessful dialogues in which no argument for the topic is found even when such an argument does exist in the union of the two agents beliefs. In [8], McBurney and Parsons present a specialised inquiry protocol for use in scientific domains, such as in assessments of carcinogenic risk of new chemicals, however this protocol is too complicated for general use, containing over thirty specialised moves. Neither of these groups have proposed a strategy for use with their inquiry protocol, i.e. their systems model inquiry dialogues but are not sufficient to generate them.

A key contribution of this work is that we not only provide a protocol for modelling inquiry dialogues but we also provide a specific strategy to be followed, making this system sufficient to also *generate* inquiry dialogues. Other works have also considered the automation of dialogues. For example, [12] gives an account of the different factors which must be considered when designing a dialogue strategy. The Liverpool-Toulouse group [9] explore the effect of different agent attitudes, which reduce the set of legal moves from which an agent must choose a move but do not select exactly one of the legal moves to make. Pasquier *et al.*'s cog-

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nitive coherence theory [10] addresses the pragmatic issue of dialogue generation, but it is not clear what behaviour this would produce. Both [1] and [7] propose a formalism for representing the private strategy of an agent to which argumentation is then applied to determine the move to be made at a point in a dialogue, however neither give a specific strategy for inquiry dialogues.

The lack of specific dialogue strategies proposed in the literature makes it hard to analyse the general behaviour of dialogues. A specific strategy that has been proposed for persuasion dialogues is in [3], but this is not formally stated and no analysis of the dialogue behaviour is given. As far as we are aware, ours is the only example of a system that incorporates a strategy capable of generating inquiry dialogues, and this allows us to consider soundness and completeness properties for our system.

2. MOTIVATION

Our work has been motivated by the medical domain. Argumentation allows us to deal with the incomplete, inconsistent and uncertain knowledge that is characteristic of medical knowledge. There are often many different healthcare professionals involved in the care of a patient, each of whom has a particular type of specialised knowledge and who must cooperate in order to provide the best possible care for the patient. For example, in hospitals in the UK it is usually the case that there is a multi-disciplinary meeting each week to discuss patients with breast cancer. There may be around twenty different healthcare professionals at such a meeting including, for example, nurses, radiographers, oncologists, surgeons and even statisticians. The diagnosis and prognosis of each of the current breast cancer patients are discussed at such meetings and different treatment plans are considered. However, healthcare professionals do not always make the correct decision given the available knowledge. According to various studies, a patient with breast cancer may be up to seven times more likely to receive a cure at one of the best specialist centres than at a general medical facility [5]. We wish to standardise the level of care provided to patients by providing agent-based support.

Inquiry dialogues are a type of dialogue that would be of particular use in the healthcare domain, where it is often the case that people have distinct types of knowledge and so need to interact with others in order to have all the information necessary to make a decision. Consider the situation in which a consultant must diagnose a patient who has suspected cancer. The consultant will have lots of knowledge about cancer and the different forms suggested by different sets of symptoms however, having only a short amount of time to spend with each of her patients, she will probably not have as much knowledge about the patient's specific symptoms as the patient's general practitioner (GP). The consultant may enter into an inquiry dialogue with the GP in order to share relevant bits of information to jointly construct a justification for a particular diagnosis.

As we are dealing with the safety-critical medical domain, it is essential that the dialogues our system produces arrive at the appropriate outcome, i.e. we wish the outcome of our dialogues to be predetermined. As discussed in [9], this can be be viewed as a positive or negative feature of a dialogue system depending on the application. In a more competitive environment it may well be the case that we wish it to be possible for agents to behave in an intelligent manner in order to influence the outcome of a dialogue. However, we want our dialogues to always lead to the 'ideal' outcome. That is to say, we want the dialogues generated by our system to be sound and complete, in relation to some standard benchmark. We compare the outcome of our dialogues with the outcome that would be arrived at by a single agent that has as its beliefs the union of both the agents participating in the dialogues beliefs. This is, in some sense, the ideal situation, where there are no constraints on the sharing of beliefs.

3. KNOWLEDGE REPRESENTATION AND ARGUMENTS

We adapt García and Simari's Defeasible Logic Programming (DeLP) [6] for representing each agent's beliefs. DeLP is a formalism that combines logic programming with defeasible argumentation. It allows an agent to reason with inconsistent and incomplete knowledge that may change dynamically over time. DeLP also provides a dialectical reasoning mechanism for deciding whether an argument is warranted, however this is not necessary for the presentation here. We assume that we are dealing with a restricted set of propositional logic and that a literal is either an atom α or a negated atom $\neg\alpha$.

The presentation in this section differs slightly from that in [6] as García and Simari assume a set of strict rules, which we assume to be empty, and they assume facts to be non-defeasible. We assume that all knowledge is defeasible due to the nature of medical knowledge, which is constantly expanding. They also use a restricted set of first-order logic in which all literals are either ground atoms or negated ground atoms but we use propositional logic here for ease of presentation.

DEFINITION 3.1. *A* **defeasible rule** *is denoted $\alpha_1 \wedge \ldots \wedge \alpha_n \rightarrow \alpha_0$ where α_i is a literal for $0 \leq i \leq n$. A* **defeasible fact** *is denoted α where α is a literal. A* **belief** *is either a defeasible rule or a defeasible fact. $\mathcal{B}$ denotes the set of all beliefs.*

Note that the symbols $\wedge$ and $\rightarrow$ are not being used here to represent classical conjunction or implication, but rather represent meta-relations between sets of literals. In particular, there is no contraposition.

Each agent is identified by a unique id x taken from a set $\mathcal{I}$. Each agent has a, possibly inconsistent, belief base.

DEFINITION 3.2. *A* **belief base** *associated with an agent x is a finite set, denoted Σ^x, such that $\Sigma^x \subseteq \mathcal{B}$ and $x \in \mathcal{I}$.*

We now define what constitutes a defeasible derivation. This has been adapted slightly from [6] in order to deal with our assumption that the set of strict rules is empty.

DEFINITION 3.3. *Let Ψ be a set of beliefs and α a literal. A* **defeasible derivation** *of α from Ψ, denoted $\Psi \mathrel{|\!\sim} \alpha$, is a finite sequence $\alpha_1, \alpha_2, \ldots, \alpha_n$ of literals such that α_n is α and each literal α_m ($1 \leq m \leq n$) is in the sequence because:*

- *α_m is a defeasible fact in Ψ, or*
- *there exists a defeasible rule $\beta_1 \wedge \ldots \wedge \beta_j \rightarrow \alpha_m$ in Ψ such that every literal β_i ($1 \leq i \leq j$) is an element α_k preceding α_m in the sequence ($k < m$).*

We now define an argument as being a minimally consistent set from which the claim can be defeasibly derived.

Definition 3.4. *An* **argument** *constructed from a set of, possibly inconsistent, beliefs* Ψ ($\Psi \subseteq \mathcal{B}$) *is a tuple* $\langle \Phi, \phi \rangle$ *where* ϕ *is a defeasible fact and* Φ *is a set of beliefs such that:*

1. $\Phi \subseteq \Psi$,
2. $\Phi \mid\sim \phi$,
3. $\forall \phi, \phi'$ *s.t.* $\Phi \mid\sim \phi$ *and* $\Phi \mid\sim \phi'$, *it is not the case that* $\phi \cup \phi' \vdash \perp$ *(where* $\vdash$ *represents classical implicaion),*
4. *there is no subset of* Φ *that satisfies (1-3).*

Φ *is called the* **support** *of the argument and* ϕ *is called the* **claim**. *The set of all arguments that can be constructed from a set of beliefs* Ψ *is denoted* $\mathcal{A}(\Psi)$.

In the following section we define our dialogue system for argument inquiry dialogues. This allows two agents to share beliefs in order to jointly construct arguments for a specific claim.

4. DIALOGUE SYSTEM

The communicative acts in a dialogue are called *moves*. We assume that there are always exactly two agents (*participants*) taking part in a dialogue, each with its own identifier taken from the set $\mathcal{I}$. Each participant takes it in turn to make a move to the other participant. For a dialogue involving participants $x_1, x_2 \in \mathcal{I}$, we also refer to participants using the meta-variables P and $\overline{P}$ such that if P is x_1 then $\overline{P}$ is x_2 and if P is x_2 then $\overline{P}$ is x_1.

A move in our system is of the form $\langle Agent, Act, Content \rangle$. *Agent* is the identifier of the agent to which the move is addressed (the *receiver* of the move), *Act* is the type of move, and the *Content* gives the details of the move. The format for moves used in argument inquiry dialogues is shown in Table 1, and the set of all argument inquiry moves meeting the format defined in Table 1 is denoted $\mathcal{M}$. Note that the system allows for other types of dialogues to be generated and these might require the addition of extra moves. Also, $\mathsf{Receiver} : \mathcal{M} \mapsto \mathcal{I}$ is a function such that $\mathsf{Receiver}(\langle Agent, Act, Content \rangle) = Agent$.

As a dialogue progresses over time, we denote each timepoint by a natural number. A dialogue is simply a sequence of moves, each of which is made from one participant to the other. Each move is indexed by the timepoint when the move was made. Exactly one move is made at each timepoint. The dialogue itself is indexed with two timepoints, indexing the first and last moves of the dialogue.

Definition 4.1. *A* **dialogue**, *denoted* D_r^t, *is a sequence of moves of the form* $[m_r, \ldots, m_t]$ *involving two participants* x_1 *and* x_2 *such that* $x_1, x_2 \in \mathcal{I}$, $x_1 \neq x_2$, $r, t \in \mathbb{N}$ *and the following conditions hold:*

1. m_r *is a move of the form* $\langle P, open, \gamma \rangle$
2. $\mathsf{Receiver}(m_s) \in \{x_1, x_2\}$ $(r \leq s \leq t)$
3. $\mathsf{Receiver}(m_s) \neq \mathsf{Receiver}(m_{s+1})$ $(r \leq s < t)$

The **topic** *of the dialogue* D_r^t *is returned by* $\mathsf{Topic}(D_r^t)$ *such that* $\mathsf{Topic}(D_r^t) = \gamma$. *The set of all dialogues is denoted* $\mathcal{D}$.

Move	Format
open	$\langle x, open, \gamma \rangle$
assert	$\langle x, assert, \langle \Phi, \phi \rangle \rangle$
close	$\langle x, close, \gamma \rangle$

Table 1: The format for moves used in argument inquiry dialogues, where γ is a belief, $\langle \Phi, \phi \rangle$ is an argument and x is an agent ($x \in \mathcal{I}$).

The first move of a dialogue D_r^t must always be an open move (condition 1 of the previous definition), every move of the dialogue must be made to a participant of the dialogue (condition 2), and the agents take it in turns to receive moves (condition 3).

We now define some terminology that allows us to talk about the relationship between two dialogues.

Definition 4.2. *Let* D_r^t *and* $D_{r_1}^{t_1}$ *be two dialogues.* $D_{r_1}^{t_1}$ *is a* **sub-dialogue** *of* D_r^t *iff* $D_{r_1}^{t_1}$ *is a sub-sequence of* D_r^t $(r < r_1 \leq t_1 \leq t)$. D_r^t *is a* **top-level** *dialogue iff* $r = 1$. D_1^t *is a* **top-dialogue of** D_r^t *iff either the sequence* D_1^t *is the same as the sequence* D_r^t *or* D_r^t *is a sub-dialogue of* D_1^t. *If* D_r^t *is a sequence of* n *moves,* $D_r^{t_2}$ **extends** D_r^t *iff the first* n *moves of* $D_r^{t_2}$ *are the sequence* D_r^t.

In order to terminate a dialogue, two close moves must appear next to each other in the sequence (called a *matched-close*).

Definition 4.3. *Let* D_r^t *be a dialogue with participants* x_1 *and* x_2 *such that* $\mathsf{Topic}(D_r^t) = \gamma$. *We say that* m_s $(r < s \leq t)$, *is a* **matched-close for** D_r^t *iff* $m_{s-1} = \langle P, close, \gamma \rangle$ *and* $m_s = \langle \overline{P}, close, \gamma \rangle$.

So a matched-close will terminate a dialogue D_r^t but only if D_r^t has not already terminated and any sub-dialogues that are embedded within D_r^t have already terminated.

Definition 4.4. *Let* D_r^t *be a dialogue.* D_r^t **terminates at** t *iff the following conditions hold:*

1. m_t *is a matched-close for* D_r^t,
2. $\neg \exists D_r^{t_1}$ *s.t.* $D_r^{t_1}$ *terminates at* t_1 *and* D_r^t *extends* $D_r^{t_1}$,
3. $\forall D_{r_1}^{t_1}$ *if* $D_{r_1}^{t_1}$ *is a sub-dialogue of* D_r^t,
   then $\exists D_{r_1}^{t_2}$ *s.t.* $D_{r_1}^{t_2}$ *terminates at* t_2
   and either $D_{r_1}^{t_2}$ *extends* $D_{r_1}^{t_1}$ *or* $D_{r_1}^{t_1}$ *extends* $D_{r_1}^{t_2}$,
   and $D_{r_1}^{t_2}$ *is a sub-dialogue of* D_r^t.

As we are often dealing with multiple nested dialogues it is sometimes useful to refer to the current dialogue, which is the innermost dialogue that has not yet terminated.

Definition 4.5. *Let* D_r^t *be a dialogue. The* **current dialogue** *is returned by* $\mathsf{Current}(D_r^t)$ *such that* $\mathsf{Current}(D_r^t) = D_{r_1}^t$ $(1 \leq r \leq r_1 \leq t)$ *where the following conditions hold:*

1. $m_{r_1} = \langle x, open, \gamma \rangle$ *for some* $x \in \mathcal{I}$ *and some* $\gamma \in \mathcal{B}$,
2. $\forall D_{r_2}^{t_1}$ *if* $D_{r_2}^{t_1}$ *is a sub-dialogue of* $D_{r_1}^t$,
   then $\exists D_{r_2}^{t_2}$ *s.t. either* $D_{r_2}^{t_2}$ *extends* $D_{r_2}^{t_1}$ *or*
   $D_{r_2}^{t_1}$ *extends* $D_{r_2}^{t_2}$,
   and $D_{r_2}^{t_2}$ *is a sub-dialogue of* $D_{r_1}^t$
   and $D_{r_2}^{t_2}$ *terminates at* t_2,

3. $\neg\exists D_{r_1}^{t_3}$ *s.t.* $D_{r_1}^{t}$ *extends* $D_{r_1}^{t_3}$ *and* $D_{r_1}^{t_3}$ *terminates at* t_3.

The **topic of the current dialogue** *is returned by the function* $\mathsf{cTopic}(D_r^t)$ *such that* $\mathsf{cTopic}(D_r^t) = \mathsf{Topic}(\mathsf{Current}(D_r^t))$.

A schematic example of nested argument inquiry dialogues is now given. The top-level dialogue is D_1^t, such that:

$$D_1^t = [m_1, \dots, m_i, \dots, m_j, \dots, m_{k-1}, m_k, \dots, m_{t-1}, m_t]$$

where

$$\begin{array}{c} m_1 = \langle P_1, open, \gamma_1 \rangle \quad m_i = \langle P_i, open, \gamma_i \rangle \\ m_j = \langle P_j, open, \gamma_j \rangle \quad m_{k-1} = \langle P_{k-1}, close, \gamma_j \rangle \\ m_k = \langle P_k, close, \gamma_j \rangle \quad m_{t-1} = \langle P_{t-1}, close, \gamma_i \rangle \\ m_t = \langle P_t, close, \gamma_i \rangle \end{array}$$

D_1^t has not yet terminated and is the current dialogue. There are two sub-dialogues of D_1^t, the first is D_i^t and this terminates at t.

$$D_i^t = [m_i, \dots, m_j, \dots, m_{k-1}, m_k, \dots, m_{t-1}, m_t]$$

The second is $D_j^k = [m_j, \dots, m_{k-1}, m_k]$, which terminates at k.

We adopt the standard approach of associating a *commitment store* with each agent participating in a dialogue. A commitment store is a set of beliefs that the agent has asserted so far in the course of the dialogue. As a commitment store consists of things that the agent has already publicly declared, its contents are visible to the other agent participating in the dialogue. For this reason, when constructing an argument, an agent may make use of not only its own beliefs but also those from the other agent's commitment store.

Definition 4.6. *A* **commitment store** *associated with an agent* x *at a timepoint* t*, denoted* CS_x^t*, where* $x \in \mathcal{I}$ *and* $t \in \mathbb{N}$*, is a set of beliefs (i.e.* $CS_x^t \subseteq \mathcal{B}$*).*

An agent's commitment store grows monotonically over time. If an agent makes a move asserting an argument, every element of the support is added to the agent's commitment store. This is the only time the commitment store is updated.

Definition 4.7. **Commitment store update.** *Let the current dialogue be* D_r^t *with participants* x_1 *and* x_2.

$$CS_P^t = \begin{cases} \emptyset & \textit{iff } t = 0, \\ CS_P^{t-1} \cup \Phi & \textit{iff } m_t = \langle \overline{P}, assert, \langle \Phi, \phi \rangle \rangle, \\ CS_P^{t-1} & \textit{otherwise.} \end{cases}$$

The goal of an argument inquiry dialogue is for a pair of agents to jointly construct an argument for a particular claim, ϕ. So the first move of a top-level argument inquiry dialogue is an open move with the defeasible fact ϕ as its content. Now, if one agent knows of a defeasible rule $\alpha_1 \wedge \dots \wedge \alpha_n \rightarrow \phi$, then it can make a move to open a nested argument inquiry dialogue with $\alpha_1 \wedge \dots \wedge \alpha_n \rightarrow \phi$ as its topic. If the two participants could jointly provide an argument for each literal α_i ($1 \leq i \leq n$) in the antecedent of the topic, then it would be possible to construct an argument for ϕ. We keep track of this set of literals in a *question store*: so when an argument inquiry dialogue with topic $\alpha_1 \wedge \dots \wedge \alpha_n \rightarrow \phi$ is opened, a question store associated with that dialogue is created whose contents are $\{\alpha_1, \dots, \alpha_n\}$. Throughout the dialogue the participating agents will both try to provide arguments for the literals in the question store. This may lead them to open further nested argument inquiry dialogues that have as a topic a rule whose consequent is a literal in the current question store.

Definition 4.8. *Let* γ *be a defeasible fact. Let* δ *be a defeasible rule of the form* $\alpha_1 \wedge \dots \wedge \alpha_n \rightarrow \beta$*. For a dialogue* D_r^t *with participants* x_1 *and* x_2*, a* **question store***, denoted* QS_r*, is a finite set of literals such that:*

$$QS_r = \begin{cases} \{\gamma\} & \textit{iff } m_r = \langle P, open, \gamma \rangle, \\ \{\alpha_1, \dots, \alpha_n\} & \textit{iff } m_r = \langle P, open, \delta \rangle, \\ \emptyset & \textit{otherwise.} \end{cases}$$

The **question store of the current dialogue** *is returned by* cQS *such that* $\mathsf{cQS}(D_r^t) = QS_{r_1}$ *iff* $\mathsf{Current}(D_r^t) = D_{r_1}^t$.

A protocol is a function that returns the set of moves that are legal for an agent to make at a particular point in a particular type of dialogue. Here we give the specific protocol for argument inquiry dialogues. It takes the top-level dialogue that the agents are participating in and the identifier of the agent whose turn it is to move, and returns the set of legal moves that the agent may make.

Definition 4.9. *The* **argument inquiry protocol** *is a function* $\Pi : \mathcal{D} \times \mathcal{I} \mapsto \wp(\mathcal{M})$*. If* D_1^t *is a well-formed, top-level dialogue with participants* x_1 *and* x_2 *such that* $\mathsf{Receiver}(m_t) = P$*,* $1 \leq t$ *and* $\mathsf{cTopic}(D_1^t) = \gamma$*, then* $\Pi(D_1^t, P)$ *is*

$$\Pi_{assert}(D_1^t, P) \cup \Pi_{open}(D_1^t, P) \cup \{\langle P, close, \gamma \rangle\}$$

where

$$\begin{array}{l} \Pi_{assert}(D_1^t, P) = \{\langle \overline{P}, assert, \langle \Phi, \phi \rangle \rangle | \\ \quad \textit{(1)}\ \phi \in cQS(D_1^t), \\ \quad (2) \neg\exists t' \textit{ s.t. } 1 < t' \leq t \\ \qquad \textit{and } m_{t'} = \langle X, assert, \langle \Phi, \phi \rangle \rangle \\ \qquad \textit{and } X \in \{x_1, x_2\}\} \end{array}$$

$$\begin{array}{l} \Pi_{open}(D_1^t, P) = \{\langle \overline{P}, open, \beta_1 \wedge \dots \wedge \beta_n \rightarrow \alpha \rangle | \\ \quad \textit{(1)}\ \alpha \in cQS(D_1^t), \\ \quad \textit{(2)} \neg\exists t' \textit{ s.t. } 1 < t' \leq t \\ \qquad \textit{and } m_{t'} = \langle X, open, \beta_1 \wedge \dots \wedge \beta_n \rightarrow \alpha \rangle \\ \qquad \textit{and } X \in \{x_1, x_2\}\} \end{array}$$

Note that it is straightforward to check conformance with the protocol as the protocol only refers to public elements of the dialogue.

We will shortly give a specific strategy function that allows an agent to select exactly one legal move to make at each timepoint in an argument inquiry dialogue. A strategy is personal to an agent and the move that it returns depends on the agent's private beliefs. The argument inquiry strategy states that if there are any legal moves that assert an argument that can be constructed by the agent then a single one of these moves is selected (according to a selection function that we define shortly denoted $\mathsf{Pick_a}$), else if there are any legal open moves with a defeasible rule as their content that is in the agent's beliefs then a single one of these moves is selected (according to a selection function that we define shortly denoted $\mathsf{Pick_o}$). If there are no such moves then a close move is made.

$$\Omega(D_1^t, P) = \begin{cases} \mathsf{Pick_a}(\mathsf{Asserts}(D_1^t, P)) & \text{iff } \mathsf{Asserts}(D_1^t, P) \neq \emptyset \\ \mathsf{Pick_o}(\mathsf{Opens}(D_1^t, P)) & \text{iff } \mathsf{Asserts}(D_1^t, P) = \emptyset \text{ and } \mathsf{Opens}(D_1^t, P) \neq \emptyset \\ \langle P, close, \mathsf{cTopic}(D_1^t) \rangle & \text{iff } \mathsf{Asserts}(D_1^t, P) = \emptyset \text{ and } \mathsf{Opens}(D_1^t, P) = \emptyset \end{cases}$$

$$\text{where } \mathsf{Asserts}(D_1^t, P) = \{\langle \overline{P}, assert, \langle \Phi, \phi \rangle \rangle \in \Pi_{assert}(D_1^t, P) \mid \langle \Phi, \phi \rangle \in \mathcal{A}(\Sigma^P \cup CS^t_{\overline{P}})\}$$

$$\mathsf{Opens}(D_1^t, P) = \{\langle \overline{P}, open, \theta \rangle \in \Pi_{open}(D_1^t, P) \mid \theta \in \Sigma^P\}$$

Figure 1: The argument inquiry strategy function.

In order to select a single one of the legal assert or open moves, we assign a unique number to the move content and carry out a comparison of these numbers. Let us assume that $\mathcal{B}$ is composed of a finite number Z of atoms. Let us also assume that there is a registration function μ over these atoms. So, for a literal L, $\mu(L)$ returns a unique single digit number base Z (this number is only like an id number and can be arbitrarily assigned). For a rule $L_1 \wedge \ldots \wedge L_n \rightarrow L_{n+1}$, $\mu(L_1 \wedge \ldots \wedge L_n \rightarrow L_{n+1})$ is an $n+1$ digit number of the form $\mu(L_1) \ldots \mu(L_n)\mu(L_{n+1})$. This gives a unique base Z number for each formula in $\mathcal{B}$ and allows us to choose a unique open move.

Definition 4.10. *Consider the set of open moves $\Psi = \{\langle P, open, \phi_1 \rangle, \ldots, \langle P, open, \phi_k \rangle\}$. The function* $\mathsf{Pick_o}$ *returns the* **chosen open move**. $\mathsf{Pick_o}(\Psi) = \langle P, open, \phi_i \rangle$ *$(1 \leq i \leq k)$ such that for all j $(1 \leq j \leq k)$ if $i \neq j$, then $\mu(\phi_i) < \mu(\phi_j)$.*

We can similarly assign a number to each argument in $\mathcal{A}(\mathcal{B})$ using a registration function λ together with μ. For an argument $\langle \{\phi_1, \ldots, \phi_n\}, \phi_{n+1} \rangle$,

$$\lambda(\langle \{\phi_1, \ldots, \phi_n\}, \phi_{n+1} \rangle) = \langle d_1, \ldots d_n, d_{n+1} \rangle$$

where $d_1 < \ldots < d_n < d_{n+1}$ and $\langle d_1, \ldots, d_n, d_{n+1} \rangle$ is a permutation of $\langle \mu(\phi_1), \ldots, \mu(\phi_n), \mu(\phi_{n+1}) \rangle$ (where μ is the registration function for $\mathcal{B}$). The function λ returns a unique tuple of base Z numbers for each argument. We use a standard lexicographical comparison, denoted $\prec_{lex}$, of these tuples of numbers to chose a unique assert move.

Definition 4.11. *Consider the set of assert moves $\Psi = \{\langle P, assert, \langle \Phi_1, \phi_1 \rangle \rangle, \ldots, \langle P, assert, \langle \Phi_k, \phi_k \rangle \rangle\}$. The function* $\mathsf{Pick_a}$ *returns the* **chosen assert move**. $\mathsf{Pick_a}(\Psi) = \langle P, assert, \langle \Phi_i, \phi_i \rangle \rangle$ *$(1 \leq i \leq k)$ such that for all j $(1 \leq j \leq k)$ if $i \neq j$, then $\lambda(\langle \Phi_i, \phi_i \rangle) \prec_{lex} \lambda(\langle \Phi_j, \phi_j \rangle)$.*

We now use these functions to define the argument inquiry strategy. It takes the top-level dialogue that the agents are participating in and the identifier of the agent whose turn it is to move, and returns exactly one of the legal moves.

Definition 4.12. *The* **argument inquiry strategy** *is a function $\Omega : \mathcal{D} \times \mathcal{I} \mapsto \mathcal{M}$ as given in Figure 1.*

Note that a top-level argument inquiry dialogue will always have a defeasible fact as its topic, but each of its sub-dialogues will always have a defeasible rule as its topic. The argument inquiry strategy constrains an agent to only opening nested sub-dialogues that have as their topic a defeasible rule that is present in the agent's belief base. This prevents an agent from opening a nested sub-dialogue unless it at least knows of a rule that might help construct a desired argument.

We are now able to define a well-formed argument inquiry dialogue. This is a dialogue that does not continue after it has terminated and that is generated by the argument inquiry strategy.

Definition 4.13. *Let D_r^t be a dialogue with participants x_1 and x_2. D_r^t is a* **well-formed argument inquiry dialogue** *iff the following conditions hold:*

1. *$\neg\exists t'$ $(r < t' < t)$ s.t. D_r^t extends $D_r^{t'}$ and $D_r^{t'}$ terminates at t',*
2. *$\forall s$ $(r \leq s < t)$ s.t. D_r^t extends D_r^s,*
   if D_1^t is a top-dialogue of D_r^t and
   D_1^s is a top-dialogue of D_r^s and
   D_1^t extends D_1^s and
   $\mathsf{Receiver}(m_s) = P$ *(where $P \in \{x_1, x_2\}$),*
   then $\Omega(D_1^s, P) = m_{s+1}$

An example of a well-formed argument inquiry dialogue with participants x_1 and x_2 is shown in Table 2. The first column of the table gives the value of t, the second column gives the commitment store of agent x_1, the third column gives the move m_t, the fourth column gives the commitment store of the agent x_2 and the fifth column gives the contents of any question stores that are not equal to the empty set. The agents' belief bases are shown at the top of the table. We have highlighted nested sub-dialogues by drawing a box around them. Note that we assume some higher-level planning component that guides the agent when deciding whether to enter into a dialogue, who this dialogue should be with and on what topic, i.e. that makes the decision to make the move m_1.

In our simple example, it seems that it would be more straightforward to pool both agents beliefs and apply a reasoning procedure to this set of beliefs. However, given a real-world scenario this would not necessarily be the case. When dealing with the medical domain we have to consider privacy issues that would restrict agents from simply pooling all beliefs. It is also sometimes the case that agents have vast belief bases and the communication cost involved in sharing all beliefs would be prohibitive.

5. SOUNDNESS AND COMPLETENESS

We believe that it is important to consider soundness and completeness properties if we are to understand the behaviour of our dialogues. This is particularly the case when

$\Sigma^{x_1} = \{d, b \to c\}$ $\qquad$ $\Sigma^{x_2} = \{e, d \wedge e \to b, a \to b\}$

t	$CS^t_{x_1}$	m_t	$CS^t_{x_2}$	QS_t
1		$\langle x_1, open, c\rangle$		$QS_1 = \{c\}$
2		$\langle x_2, open, b \to c\rangle$		$QS_2 = \{b\}$
3		$\langle x_1, open, a \to b\rangle$		$QS_3 = \{a\}$
4		$\langle x_2, close, a \to b\rangle$		
5		$\langle x_1, close, a \to b\rangle$		
6		$\langle x_2, close, b \to c\rangle$		
7		$\langle x_1, open, d \wedge e \to b\rangle$		$QS_7 = \{d, e\}$
8	d	$\langle x_2, assert, \langle\{d\}, d\rangle\rangle$		
9		$\langle x_1, assert, \langle\{e\}, e\rangle\rangle$	e	
10		$\langle x_2, close, d \wedge e \to b\rangle$		
11		$\langle x_1, close, d \wedge e \to b\rangle$		
12		$\langle x_2, close, b \to c\rangle$		
13		$\langle x_1, assert, \langle\{d, e, d \wedge e \to b\}, b\rangle\rangle$	$d, d \wedge e \to b$	
14		$\langle x_2, close, b \to c\rangle$		
15		$\langle x_1, close, b \to c\rangle$		
16	$e, d \wedge e \to b, b \to c$	$\langle x_2, assert, \langle\{d, e, d \wedge e \to b, b \to c\}, c\rangle\rangle$		
17		$\langle x_1, close, c\rangle$		
18		$\langle x_2, close, c\rangle$		

Table 2: Nested argument inquiry dialogue example. Recall, commitment stores grow monotonically with t, e.g. $CS^1_{x_1} = \emptyset$, $CS^8_{x_1} = \{d\}$, $CS^{16}_{x_1} = \{d, e, d \wedge e \to b, b \to c\}$. The agents' belief bases are shown at the top of the table. Note agent x_2 makes the first move to agent x_1. Let $\mu(a) = 1$, $\mu(b) = 2$, $\mu(c) = 3$, $\mu(d) = 4$ & $\mu(e) = 5$. The goal of the dialogue, which is successfully achieved, is to find an argument for c, $\mathsf{Outcome}(d^{18}_1) = \{\langle d, e, d \wedge e \to b, b \to c\}, c\rangle\}$. Three nested sub-dialogues appear in D^{18}_1: D^{15}_2, D^5_3 & D^{11}_7. D^5_3 & D^{11}_7 are also sub-dialogues of D^{15}_2. $\mathsf{Outcome}(D^{15}_2) = \{\langle\{d, e, d \wedge e \to b\}, b\rangle\}$. $\mathsf{Outcome}(D^5_3) = \emptyset$. $\mathsf{Outcome}(D^{11}_7) = \{\langle\{d\}, d\rangle, \langle\{e\}, e\rangle\}$.

dealing with a domain such as the medical domain, where we wish a certain outcome to be guaranteed given a particular situation. In order to consider such properties we must first define what the outcome of an argument inquiry dialogue is and then propose a benchmark to compare our dialogues to. We define the outcome of an argument inquiry dialogue as the set of all arguments that can be constructed from the union of the commitment stores and whose claims are in the question store.

Definition 5.1. *The* **argument inquiry outcome** *of a dialogue is a function* $\mathsf{Outcome} : \mathcal{D} \mapsto \wp(\mathcal{A}(\mathcal{B}))$. *If D^t_r is a well-formed argument inquiry dialogue with participants x_1 and x_2, then*
$\mathsf{Outcome}(D^t_r) = \{\langle\Phi, \phi\rangle \in \mathcal{A}(CS^t_{x_1} \cup CS^t_{x_2}) \mid \phi \in QS_r\}$

The goal of an argument inquiry dialogue is for the two agents to share appropriate parts of their knowledge in order to try to construct an argument for a specific claim or claims. The benchmark that we compare the outcome of the dialogue with is the set of arguments that can be constructed from the union of the two agents' beliefs. So this benchmark is, in a sense, the 'ideal situation' where there are clearly no constraints on the sharing of beliefs.

As far as we are aware, the only other similar work that considers soundness and completeness properties is [13]. In [13] Sadri *et al.* define different agent programs for negotiation. If such an agent program is both exhaustive and deterministic then exactly one move is suggested by the program at a timepoint, making such a program generative and allowing consideration of soundness and completeness properties. Since other inquiry dialogue systems do not provide a specific strategy, they miss the chance to better understand the dialogue behaviour by considering such properties.

We say that an argument inquiry dialogue is sound if and only if, when the outcome of the dialogue includes an argument, then that same argument can be constructed from the union of the two participating agents' beliefs.

Definition 5.2. *Let D^t_r be a well-formed argument inquiry dialogue with participants x_1 and x_2. We say that D^t_r is* **sound** *iff, if $\langle\Phi, \phi\rangle \in \mathsf{Outcome}(D^t_r)$, then $\langle\Phi, \phi\rangle \in \mathcal{A}(\Sigma^{x_1} \cup \Sigma^{x_2})$.*

In order to show that all argument inquiry dialogues are sound we need to introduce a few lemmas. Please note that we have omitted the more obvious proofs from this presentation but for a thourough discussion of all results please refer to the first author's thesis [4].

The first states that if an agent asserts an argument, then it must be able to construct the argument from its beliefs and the other agent's commitment store. This is clear from the definition of the argument inquiry strategy.

Lemma 5.1. *Let D^t_r be a well-formed argument inquiry dialogue with participants x_1 and x_2. If D^t_1 is a top-dialogue of D^t_r and $\Omega(D^t_1, P) = \langle\overline{P}, assert, \langle\Phi, \phi\rangle\rangle$, then $\langle\Phi, \phi\rangle \in \mathcal{A}(\Sigma^P \cup CS^t_{\overline{P}})$.*

From Lemma 5.1 and the fact that the commitment stores are only updated when an assert move is made, we get the lemma that a commitment store is always a subset of the union of the two agents' beliefs.

Lemma 5.2. *If D_r^t is a well-formed argument inquiry dialogue with participants x_1 and x_2, then $CS_{x_1}^t \cup CS_{x_2}^t \subseteq \Sigma^{x_1} \cup \Sigma^{x_2}$.*

The next lemma states that if we have a set Φ that is a subset of a set of beliefs Ψ, then the set of arguments that can be constructed from Φ is a subset of the set of arguments that can be constructed from Ψ.

Lemma 5.3. *Let $\Phi \subseteq \mathcal{B}$ and $\Psi \subseteq \mathcal{B}$ be two sets. If $\Phi \subseteq \Psi$, then $\mathcal{A}(\Phi) \subseteq \mathcal{A}(\Psi)$.*

We now show that argument inquiry dialogues are sound.

Theorem 5.1. *If D_r^t is a well-formed argument inquiry dialogue with participants x_1 and x_2, then D_r^t is sound.*
Proof: *Assume $\langle\Phi, \phi\rangle \in \mathsf{Outcome}(D_r^t)$. From Def. 5.1, $\langle\Phi, \phi\rangle \in \mathcal{A}(CS_{x_1}^t \cup CS_{x_2}^t)$. From Lem. 5.2 $CS_{x_1}^t \cup CS_{x_2}^t \subseteq \Sigma^{x_1} \cup \Sigma^{x_2}$. Hence, from Lem. 5.3, $\langle\Phi, \phi\rangle \in \mathcal{A}(\Sigma^{x_1} \cup \Sigma^{x_2})$. Hence, D_r^t is sound.* □

Similarly, an argument inquiry dialogue is complete if and only if, if the dialogue terminates at t and it is possible to construct an argument for a literal in the question store from the union of the two participating agents' beliefs, then that argument will be in the outcome of the dialogue at t.

Definition 5.3. *Let D_r^t be a well-formed argument inquiry dialogue with participants x_1 and x_2. We say that D_r^t is* **complete** *iff, if D_r^t terminates at t, $\phi \in QS_r$ and there exists Φ such that $\langle\Phi, \phi\rangle \in \mathcal{A}(\Sigma^{x_1} \cup \Sigma^{x_2})$, then $\langle\Phi, \phi\rangle \in \mathsf{Outcome}(D_r^t)$.*

In order to show that all argument inquiry dialogues are complete we need to give some further lemmas. The first states that if an argument inquiry dialogue terminates at t, then the set of legal moves from which an agent must choose the move m_t does not include any open or assert moves. This is clear from the definition of the argument inquiry strategy.

Lemma 5.4. *If D_r^t is a well-formed argument inquiry dialogue that terminates at t with participants x_1 and x_2 such that $\mathsf{Receiver}(m_{t-1}) = P$ and D_r^t extends D_r^{t-1} and D_1^{t-1} is a top-dialogue of D_r^{t-1}, then $\mathsf{Asserts}(D_1^{t-1}, P) = \emptyset$ and $\mathsf{Opens}(D_1^{t-1}, P) = \emptyset$.*

From Lemma 5.4 and the definitions of the argument inquiry strategy and the argument inquiry protocol we get the following lemma that if two agents are in an argument inquiry dialogue that terminates at t and there exists some r $(1 \le r < t)$ such that $\phi \in QS_r$ and there is an argument for ϕ of the form $\langle\{\phi\}, \phi\rangle$ that can be constructed from the union of the two agents' beliefs, then ϕ will be in the union of the commitment stores at timepoint t.

Lemma 5.5. *For all r $(1 \le r < t)$, if D_r^t is a well-formed argument inquiry dialogue that terminates at t with participants x_1 and x_2 such that $\phi \in QS_r$ and there exists $\langle\Phi, \phi\rangle \in \mathcal{A}(\Sigma^{x_1} \cup \Sigma^{x_2})$, then $\phi \in CS_{x_1}^t \cup CS_{x_2}^t$.*

From Lemma 5.4 and the definitions of the argument inquiry strategy and the argument inquiry protocol we also get the following lemma that if there is a defeasible rule whose consequent is present in the question store, then there will be a timepoint at which a question store will be created that contains all the literals of the antecedent of the defeasible rule.

Lemma 5.6. *For all r $(1 \le r < t)$, if D_r^t is a well-formed argument inquiry dialogue that terminates at t with participants x_1 and x_2 such that $\phi \in QS_r$ and there exists a defeasible rule $\alpha_1 \wedge \ldots \wedge \alpha_n \rightarrow \phi \in \Sigma^{x_1} \cup \Sigma^{x_2}$, then there exists t_1 $(1 < t_1 < t)$ such that $QS_{t_1} = \{\alpha_1, \ldots, \alpha_n\}$ and D_r^t extends $D_r^{t_1}$.*

We now show that argument inquiry dialogues are complete.

Theorem 5.2. *If D_r^t is a well-formed argument inquiry dialogue with participants x_1 and x_2, then D_r^t is complete.*
Proof: *If D_r^t does not terminate at t then D_r^t is complete. So assume D_r^t terminates at t, $\phi \in QS_r$, and $\langle\Phi, \phi\rangle \in \mathcal{A}(\Sigma^{x_1} \cup \Sigma^{x_2})$. By Def. 3.4, $\Phi \subseteq \Sigma^{x_1} \cup \Sigma^{x_2}$. There are two cases. (Case 1) $\Phi = \{\phi\}$. Hence by Lem. 5.5, $\phi \in CS_{x_1}^t \cup CS_{x_2}^t$. From Def. 5.1, $\langle\Phi, \phi\rangle \in \mathsf{Outcome}(D_r^t)$. (Case 2) $\exists \alpha_1 \wedge \ldots \wedge \alpha_n \rightarrow \phi \in \Phi$. By Def. 3.4, $\forall \alpha_i \exists \Phi_i$ such that $\langle\Phi_i, \alpha_i\rangle \in \mathcal{A}(\Sigma^{x_1} \cup \Sigma^{x_2})$. From Lem. 5.6, $\exists t_1$, $(1 < t_1 \le t)$, such that $QS_{t_1} = \{\alpha_1, \ldots, \alpha_n\}$. Each Φ_i is either an example of case 1 or case 2, so, by recursion, $\exists r_2, t_2$, $(r < r_2 < t_2 \le t)$, such that $\langle\Phi_i, \alpha_i\rangle \in \mathsf{Outcome}(D_{r_2}^{t_2})$. Hence, from Def. 3.4, $\langle\Phi, \phi\rangle \in \mathsf{Outcome}(D_r^t)$.* □

The previous result is particularly interesting if we know that an argument inquiry dialogue terminates. Fortunately, we can show that all argument inquiry dialogues terminate (as agents' belief bases are finite, hence there are only a finite number of assert and open moves that can be generated and agents cannot repeat these moves).

Theorem 5.3. *For any well-formed argument inquiry dialogue D_r^t, there exists a t_1 $(r < t \le t_1)$ such that $D_r^{t_1}$ terminates at t_1 and $D_r^{t_1}$ extends D_r^t.*

From Theorems 5.2 and 5.3, we get the desired result that if an argument can be constructed from the union of the two participating agents' beliefs whose claim is a literal from the current question store, then there will come a timepoint at which that argument is in the outcome of the dialogue.

Theorem 5.4. *Let D_r^t be a well-formed argument inquiry dialogue with participants x_1 and x_2. If $\phi \in QS_r$ and there exists Φ such that $\langle\Phi, \phi\rangle \in \mathcal{A}(\Sigma^{x_1} \cup \Sigma^{x_2})$, then there exists t_1 $(1 < t_1)$ such that $D_r^{t_1}$ extends D_r^t and $\langle\Phi, \phi\rangle \in \mathsf{Outcome}(D_r^{t_1})$.*

To summarise our results, we have shown that all argument inquiry dialogues terminate and that when an argument inquiry dialogue does terminate the set of arguments which makes up its outcome will be exactly the same as the set of all arguments that can be constructed from the union of the participating agents' beliefs and that have as their claim a literal that is in the question store.

6. FUTURE WORK

In future work we would like to look at relaxing some of the assumptions we have made. As this is the first piece of work examining soundness and completeness properties of inquiry dialogues, it is only a stepping stone on the way to being able to provide agents in the medical domain with the capability to fully support interactions such as the multi-disciplinary meeting discussed in Section 2. We would like to allow more than two agents to take part in an argument inquiry dialogue. There are often more than two individuals involved in making a decision in the medical domain and we would like our system to be able to deal with this.

We currently assume that an agent's belief base does not change during a dialogue, and would like to consider the implications of dropping this assumption. It is likely that an agent may be carrying our several tasks at once and may even be involved in several different dialogues at once, and as a result it may be regularly updating its beliefs. This raises several questions. For example, if an agent's belief base kept growing during a dialogue, would it be possible to generate infinite dialogues? And what should an agent do if it has cause to remove a belief from its belief base that it asserted earlier in the dialogue?

We would also like to further explore the benchmark which we compare our dialogue outcomes to. We currently compare the outcome that two agents participating in a dialogue arrive at with that which would be arrived at by a single agent that had as its beliefs the union of the participating agents' beliefs. This seems like an ideal situation as there are no constraints on the sharing of beliefs. However, it is only ideal if we accept that the agents each have the same level of expertise regarding the beliefs. Consider the situation in which a medical student is discussing a diagnosis with a consultant. In this situation, the ideal benchmark might be the outcome that the consultant would reach without taking into account any of the student's beliefs. Or there may be a situation in which we wish our argument inquiry dialogues not to produce every argument for a certain claim but only those which are considered to be the 'best' in some sense.

We have not presented our warrant inquiry dialogue here but we have found that argument inquiry dialogues are frequently embedded within warrant inquiry dialogues. We believe that, as one of the more simple dialogue types, it is particularly useful to embed argument inquiry dialogues within other dialogues, particularly when the agents are cooperating to some degree. We would like to further investigate the utility of argument inquiry dialogues when embedded in dialogues of different types.

7. CONCLUSIONS

We have presented a dialogue system and given details of a specific protocol and strategy for generating inquiry dialogues between two agents. This system is intended for use in a cooperative domain where we wish the results of a dialogue to be predetermined, such as the medical domain. Other groups have presented protocols capable of modelling inquiry dialogues (e.g. [9, 8]), however none have provided the means to select exactly one legal move at each timepoint. We have addressed this problem by providing a strategy function that selects exactly one move from the set of legal moves returned by the protocol. We have proposed a benchmark against which to compare the outcome of our dialogues, being a single agent reasoning with the union of the participating agents' beliefs, and have shown that dialogues generated by our system are always sound and complete in relation to this benchmark. No other group has considered such properties of inquiry dialogues. We have only given details relating to argument inquiry dialogues but our system is capable of dealing with dialogues of different types (e.g. warrant inquiry dialogues) with the definition of alternative moves, protocols, strategies and outcome functions.

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