Negotiating over Ontological Correspondences with Asymmetric and Incomplete Knowledge

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ABSTRACT

Effective communication is dependent on agents correctly interpreting the messages exchanged, based on the entities (or vocabulary) within the messages, and their ontological definitions. As agents are not guaranteed to share the same vocabulary, correspondences (i.e. mappings between corresponding entities in different ontologies) should be selected that provide a (logically) coherent alignment between the agents' ontologies. In this paper, we show how two agents, each possessing incomplete sets of private, heterogeneous (and typically ambiguous) correspondences, can each disclose a subset of these to facilitate agreement on the construction of an unambiguous alignment. We formally present an inquiry dialogue and illustrate how agents negotiate by exchanging their beliefs of the utilities of each correspondence. We empirically demonstrate how our distributed approach can still identify solutions that are typically 95% of the optimal solution (found centrally with complete information). Compared to *reference* alignments, our approach increases the precision of the resulting alignment by up to 40% whilst only slightly affecting recall, with each agent disclosing on average only 16.76% of its individual correspondences.

Categories and Subject Descriptors

I.2.11 [**Distributed Artificial Intelligence**]: Multiagent systems

Keywords

Ontology alignment; dialogues; negotiation

1. INTRODUCTION

Within open, distributed computing environments, effective communication is dependent on the ability of agents to reach a mutual understanding of the entities found in the exchanged messages. These entities, which are typically defined within some logical theory, or *ontology*, may be private to the owner (an agent, institution, commercial organisation, etc), and thus not fully exposed or shared. This may be due to the knowledge encoded within the ontologies being confidential or commercially sensitive. Furthermore, disclosed ontological axioms could be exploited by other self-interested agents (and thus have intrinsic value to the owner whilst undisclosed), where agents may compete over multiple transactions. Thus, the lack of explicitly shared semantics can impede comprehension of the exchanged messages. Knowledge integration has traditionally depended on the creation of *alignments* between pairs of ontologies (consisting of sets of *mappings* between the corresponding entities). However, most systems that align ontologies rely on the respective ontologies to be fully shared [7], and no single approach can provide a panacea for all ontology pairs. Although such systems can support limited knowledge integration within closed or controlled scenarios, they cannot readily facilitate autonomous integration within open, dynamic and opportunistic environments (such as in commerce, linked open-data systems or mobile systems). However, once constructed, the alignments can be exchanged and shared by other agents (given the right context), and thus provide some support within such open environments.

Two divergent approaches have emerged whereby agents align their respective ontologies. Agents can *exchange* messages that consist of conceptual definitions (including their axioms and related concepts), so that each agent can evolve its ontology to include the exchanged concepts [2, 11]. Alternatively, various negotiation and argumentation techniques have been exploited to discover mutually acceptable alignments [10, 8]; typically using a course-grained decision metric based on the *type* of correspondence, rather than whether each correspondence is *acceptable* to each agent or whether the resulting alignment is unambiguous or coherent. However, these approaches assume that alignments are all publicly available, and shared amongst each of the agents.

We propose a novel inquiry dialogue that allows agents to assert, counter, accept and reject correspondences shared by different agents. It assumes that agents have acquired correspondences from past encounters, or from publicly available alignment systems, that they keep private, and that each agent associates some utility, or *degree of belief* to each known correspondence. However, this knowledge is typically *asymmetric* and *incomplete* (i.e. not all agents may be aware of some correspondences, and their associated utility can vary greatly). Therefore, agents need to engage in an inquiry dialogue where they select which correspondences to disclose in order to ascertain the joint viability and acceptability of each correspondence. Furthermore, as different correspondences may map a single entity in one ontology to different entities in other ontologies (and vice versa), this ambiguity (in the form of one-to-many mappings) needs to be resolved for the ontologies to be effectively used.

In this paper, we formally present the *Correspondence Inclusion Dialogue* (*CID*), whereby agents negotiate by exchanging beliefs of the utilities of each correspondence. We empirically demonstrate how our distributed approach identifies solutions that are typically 95% of the optimal solution. Compared to *reference* alignments, our approach increases the precision of the resulting alignment by up to 40% whilst only slightly affecting recall, with each agent disclosing on average only 16.76% of its individual correspondences.

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The remainder of this paper is organised as follows: the *Correspondence Inclusion Dialogue* is presented in Section 2, and illustrated through an example in Section 3. It is then empirically evaluated with respect to the alignments produced in Section 4. Related work is presented in Section 5, before concluding in Section 6.

2. THE CORRESPONDENCE INCLUSION DIALOGUE

Agents have traditionally communicated by exchanging symbols which have an intended meaning. Whilst this meaning, or *semantics*, may be implicit within closed systems, they should be explicitly defined within open systems through the creation of ontologies. However, as agents can differ in the ontologies they assume, the resulting semantic heterogeneity can impede meaningful communication. One solution is to *align* the ontologies; i.e. find *correspondences* between the ontological entities to resolve this semantic heterogeneity. However, this raises the question: *how can agents align ontologies that they do not want to disclose?*

One approach is to utilise individual alignments[1] that the agents possess, and have them collaborate to find a set of correspondences to align their ontologies. However, certain correspondences may be found frequently by different alignment approaches, whereas others could be spurious or erroneous, and only appear rarely, resulting in different degrees of confidence or belief. Also, agents will typically only be aware of a subset of correspondences, and thus the knowledge of one agent can be very different to that of another.

A simplistic approach to aligning ontologies could be for the agents to share all of their correspondences. However, this can lead to *ambiguity* (i.e. when an entity in one ontology is mapped to several other entities in another ontology), resulting in undesirable behaviour, such as incoherence and inconsistency within the ontologies. Thus, agents need to agree on what correspondences they believe to be the most relevant to resolve ambiguous combinations, whilst attempting to reduce the number of messages communicated, and minimise the number of beliefs disclosed.

The *Correspondence Inclusion Dialogue* enables two agents to exchange knowledge about ontological correspondences through a dialogical game that satisfies the following: 1) each agent is aware of a set of correspondences, each with an associated *degree of belief*; 2) there should be no *ambiguity* with respect to either the source entities in the resulting alignment, or the target entities; 3) if alternative choices of correspondences exist, the selection is based on the combined, or *joint degree of belief* of both agents; 4) no correspondences should be selected where their joint degree of belief is less than some defined *admissibility threshold*; and 5) the alignment should be generated by disclosing as few beliefs as possible.

2.1 Representing Beliefs

The *Correspondence Inclusion Dialogue* consists of: a number of communicative acts, or *moves*; a set of rules, or *pre-conditions* which state which moves an agent can legally make; and a set of actions, or *post-conditions* that occur if a given move is made. We assume that there are always exactly two agents within our environment, $Alice$ and Bob (similar to [3]), which participate in the dialogue. $\mathcal{P}$ denotes the dialogue participants, such that $\mathcal{P} = \varnothing$ prior to the start of the dialogue, and $\mathcal{P} = \{Alice, Bob\}$ once both agents have joined the dialogue. Each agent plays a role in each dialogue move, i.e. the agent is either a *sender* x or *recipient* $\hat{x}$.

The dialogue assumes that each agent commits to an *ontology* $\mathcal{O}$, which is an explicit and formally defined vocabulary representing the agent's knowledge about the environment, and its background knowledge (domain knowledge, beliefs, tasks, etc.). $\mathcal{O}$ is modelled as a set of axioms describing classes and the relations existing between them[2] and $\widetilde{\mathcal{O}}$ is the *ontology signature*; i.e. the set of class and property names used in $\mathcal{O}$. To avoid confusion, the sender's ontology is denoted $\mathcal{O}^x$, whereas the recipient's ontology is $\mathcal{O}^{\hat{x}}$.

During any given encounter, the sender and the recipient use only part of their ontology (i.e. their "working" ontology $\mathcal{W}^x$ and $\mathcal{W}^{\hat{x}}$) to communicate. Both $\mathcal{W}^x$ and $\mathcal{W}^{\hat{x}}$ are fragments[3] of the sender and recipient ontologies (respectively) that denote each agent's private subset of the ontology used to model the corresponding entities used in the transaction. We also assume that agents do not disclose their "working" ontologies, and hence the participants involved in the encounter have no knowledge whether these ontologies overlap completely, partially, or in the worst case not at all (which would imply that no interaction would be possible [5]).

For agents to interoperate, they need to determine an *alignment* $AL^{<\mathcal{W}^x, \mathcal{W}^{\hat{x}}>}$ between the two vocabulary fragments $\mathcal{W}^x$ and $\mathcal{W}^{\hat{x}}$ for that encounter. An alignment [7] consists of a set of *correspondences* that establish a logical relationship between the entities (classes, properties or roles, and instances) belonging to each of the two ontologies, and a set of logical relations. Hence, a correspondence is a mapping between an entity in a source ontology ($\mathcal{O}_S$), and a corresponding entity in a target ontology ($\mathcal{O}_T$). The universe of all possible correspondences is denoted $\mathcal{C}$.

Definition 1: *A* **correspondence** *is a triple denoted* $c = \langle e, e', r \rangle$ *such that* $e \in \widetilde{\mathcal{O}_S}$, $e' \in \widetilde{\mathcal{O}_T}$, $r \in \{=\}$.

In this study, we only consider *logical equivalence* (as opposed to *subsumption* ($\sqsubseteq$) and *disjointness* ($\perp$)), and thus symmetric correspondences, i.e. $\langle e, e', = \rangle$ and $\langle e', e, = \rangle$ are equivalent[4].

The aim of the dialogue is to select an *unambiguous* set of correspondences, $AL \subseteq \mathcal{C}$, which maps between the entities in $\mathcal{W}^x$ and those in $\mathcal{W}^{\hat{x}}$. The function $\mathsf{ent}(c)$ returns the set of entities e, e' for a corespondence c.

Each agent associates an individual *degree of belief* κ_c, $0 \leq \kappa_c \leq 1$, to a correspondence c, which represents the likelihood of c being included in some alignment. Although no assumptions are made regarding how this value is determined, it could for example reflect the probability of the validity of the correspondence. However, these values should not change (i.e. an agent *commits* to the beliefs) once an agent joins the dialogue. In the reminder of the paper we use κ_c^x and $\kappa_c^{\hat{x}}$ to distinguish a degree of belief held by the sender on a correspondence c from an analogous one held by the recipient. Thus, the pair $\langle c, \kappa_c \rangle$ is a **belief** an agent holds on c. We refer to beliefs sent by x as $\phi \in \Phi$, the beliefs sent by $\hat{x}$ (to x) are referred to as $\psi \in \Psi$, and the set of all beliefs is denoted $\mathcal{B}$, where $\Phi, \Psi \subseteq \mathcal{B}$. The function $\mathsf{corr} : \mathcal{B} \mapsto \mathcal{C}$ returns the correspondence c for some belief ϕ or ψ, and the function $\mathsf{degree} : \mathcal{B} \mapsto [0, 1]$ returns the agent's degree of belief κ in some belief ϕ or ψ, such that we can say $\phi = \langle \mathsf{corr}(\phi), \mathsf{degree}(\phi) \rangle$. A belief ϕ is grounded within some ontology fragment $\mathcal{W}$ (denoted $\mathsf{grounded}(\phi, \mathcal{W})$) if $\exists e \in \mathsf{ent}(\mathsf{corr}(\phi))$, s.t. $e \in \widetilde{\mathcal{W}}$, where $\widetilde{\mathcal{W}}$ is the signature of $\mathcal{W}$.

Each agent manages a private knowledge base, known as the *Alignment Store* (Δ), which stores the beliefs an agent has over its correspondences, and a public knowledge base, or *Joint Belief*

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[1] In this paper, we do not address where the correspondences come from, but as in other studies [8, 10], we assume that these could be obtained from various other sources prior to the current encounter.

[2] Here we restrict the ontology definition to classes and roles only.

[3] We do not prescribe the logical properties exhibited by the fragment, but refer to the work on ontology modularisation, e.g. [4].

[4] As this implies that $AL^{\langle \mathcal{W}^x, \mathcal{W}^{\hat{x}} \rangle} = AL^{\langle \mathcal{W}^{\hat{x}}, \mathcal{W}^x \rangle}$, we omit the superscript for AL throughout the rest of the paper.

Store (JB), which holds correspondences that have been shared. We distinguish between the sender's stores (Δ^x and JB^x) and the recipient's stores ($\Delta^{\hat{x}}$ and $JB^{\hat{x}}$) respectively. The sender's Joint Belief Store JB^x (conversely $JB^{\hat{x}}$) contains beliefs that are exchanged as part of the dialogue and hence contains beliefs sent and received by x ($\hat{x}$). Throughout the dialogue, both agents will be aware of all of the beliefs shared; i.e. $JB^x = JB^{\hat{x}}$.

2.2 Disclosing Beliefs

Within the dialogue, the agents try to ascertain the *unambiguous* correspondences (i.e. where no entity appears more than once in the alignment) to include in the final alignment AL, such that the joint degrees of belief of the correspondences in AL are maximised, and not less than the *admissibility threshold*, ϵ. This is used to filter out correspondences with a low κ, whilst minimising the number of beliefs disclosed with $\hat{x}$. To facilitate this, the sender x needs to determine the joint degree of belief for each correspondence c.

Definition 2: *The function* joint : $\mathcal{C} \mapsto [0,1]$ *returns the* joint degree of belief *for some $c \in \mathcal{C}$, where $c = \mathsf{corr}(\phi) = \mathsf{corr}(\psi)$:*

$$\mathsf{joint}(c) = \begin{cases} \text{avg}(\kappa_c^x, \kappa_c^{\hat{x}}) & \psi \in JB^x; \phi \in \Delta^x \\ \frac{1}{2}(\kappa_c^{\hat{x}}) & \psi \in JB^x; \phi \notin \Delta^x \wedge \phi \notin JB^x \\ \text{avg}(\kappa_c^x, \kappa_{upper}^x) & \phi \in \Delta^x; \phi, \psi \notin JB^x \end{cases}$$

When the sender x receives a belief ψ from $\hat{x}$ ($\psi \in JB^x$) on a correspondence c, it can assess the joint degree of belief for c as the average between its own degree of belief and the one by $\hat{x}$, assuming that x holds a belief on c, i.e. $\phi \in \Delta^x$ (**Case 1**). If, however, x has no prior knowledge of c (i.e. $\phi \notin \Delta^x$), then $\kappa_c^x = 0$, and the joint degree of belief depends only on $\kappa_c^{\hat{x}}$ (**Case 2**). Finally, if x holds a belief on c that has not yet been disclosed to $\hat{x}$ ($\phi \in \Delta^x; \phi \notin JB^x$) and if ψ has not been disclosed by $\hat{x}$ ($\psi \notin JB^x$), then $\kappa_c^{\hat{x}}$ can only be estimated (**Case 3**).

Each agent takes it in turn to propose a belief regarding some correspondence c, and the other participant confirms whether or not the actual joint degree of belief is $\geq \epsilon$, the *admissibility threshold*. If c is ambiguous (i.e. an alternative correspondence exists, which could be considered), then the agents can attack c by counter-proposing alternate correspondences using the *object* move (Definition 8 in Section 2.3). As agents exchange beliefs, they determine the joint degree of belief $\mathsf{joint}(c)$ for each correspondence c.

Proposals are made by identifying an undisclosed correspondence with the highest degree of belief κ_c^x. As the dialogue proceeds, each subsequent correspondence asserted will have an equivalent or lower degree of belief than the one previously asserted by the same agent. Thus, when x receives an assertion regarding a belief ψ that is not in JB^x, it can exploit this property to determine an *upper bound* $0 \leq \kappa_{upper}^x \leq 1$ of the joint degree of belief of subsequent correspondences, given its own knowledge and the previous assertion. For example, if the recipient $\hat{x}$ had previously asserted a belief $\psi = \langle c, \kappa_c^{\hat{x}} \rangle$, the sender x knows that $\hat{x}$ has no other beliefs which will be $\geq \kappa_c^{\hat{x}}$. When x makes a subsequent move, it can *estimate* the joint degree of belief for some other correspondence c' to be $\mathsf{joint}_{est}(c') \leq avg(\kappa_c^x, \kappa_{upper}^x)$, where $\kappa_{upper}^x = \kappa_c^{\hat{x}}$ asserted by $\hat{x}$. If the estimated $\mathsf{joint}_{est}(c') < \epsilon$, then the actual joint degree of belief will also fall below the admissibility threshold, and therefore will be rejected. This allows an agent to determine if it is rational to propose any further beliefs w.r.t. the admissibility threshold, given this *upper bound* for another agent.

Ambiguities can occur within alignments when more than one correspondence maps several entities in the source ontology to a single entity in the target ontology (or vice versa). Thus, objections can be made to shared beliefs when the possibility of an ambiguity occurs, given an initial asserted belief. To resolve these, an attack graph $\langle Ag, \rhd \rangle$ is constructed (based on Dung's Argumentation Framework [6]) from the dialogue moves, where $Ag \subseteq JB^x$ (or $JB^{\hat{x}}$, as $JB^x = JB^{\hat{x}}$) is a set of beliefs, $\rhd$ represents the set of attacks between beliefs in Ag, and $\langle \phi, \phi' \rangle \in \rhd$ denotes ϕ attacks ϕ'. The best combination of unambiguous correspondences can hence be determined, once all possible beliefs relating to an ambiguity have been shared. An ambiguity can be determined if there is some entity that exists in the correspondences of two beliefs.

Definition 3: *An* **ambiguity** *occurs between beliefs ϕ, ϕ', $\phi \neq \phi'$ (denoted* $\mathsf{ambiguous}(\phi, \phi')$*) iff* $\mathsf{ent}(\mathsf{corr}(\phi)) \cap \mathsf{ent}(\mathsf{corr}(\phi')) \neq \varnothing$.

A belief ϕ *attacks* another belief ϕ' if the two beliefs cause an *ambiguity*, and the joint degree of belief for ϕ is greater than or equal to that of ϕ'. For example, an ambiguity exists between beliefs $\phi = \langle \langle a, x, = \rangle, 0.8 \rangle$ and $\phi' = \langle \langle b, x, = \rangle, 0.5 \rangle$, as they both share the entity x. If $\mathsf{joint}(\mathsf{corr}(\phi)) = 0.7$, and $\mathsf{joint}(\mathsf{corr}(\phi')) = 0.65$ (see Table 1), then assuming $\epsilon < 0.65$, we say ϕ *attacks* ϕ'.

Definition 4: *Given two beliefs $\phi, \phi', \phi \neq \phi'$,* $\mathsf{attacks}(\phi, \phi')$ *is true iff* $\mathsf{ambiguous}(\phi, \phi') \wedge \mathsf{joint}(\mathsf{corr}(\phi)) \geq \mathsf{joint}(\mathsf{corr}(\phi')) \geq \epsilon$.

2.3 The Formal Dialogue Model

The *Correspondence Inclusion Dialogue* represents a sequence of moves denoted $\mathcal{M}$ between the participating agents [3], where a move is a message exchanged between two agents, and is of the form $m_s = \langle x, \tau, \phi, \phi^{att} \rangle$. We denote τ as the move type s.t. $\tau \in \mathcal{T}$, where $\mathcal{T} = \{$*join, assert, object, reject, accept, endassert, close*$\}$. The content of the move is represented by two beliefs: ϕ represents a belief that agent x has for some correspondence, and includes the degree of belief that it has for that correspondence; and ϕ^{att} represents a belief x has for some correspondence that the agent is attacking. For some moves, it may not be necessary to specify a belief; in which case it will be empty or unspecified (represented as *nil*). The sender is given by the function sender : $\mathcal{M} \mapsto \mathcal{P}$, whereas the move type is given by movetype : $\mathcal{M} \mapsto \mathcal{T}$.

Definition 5: *A* **dialogue***, denoted $\mathcal{M}$, is a sequence of moves $\langle m_r, \ldots, m_t \rangle$, where $r, t \in \mathbb{N}, r < t$ are time points, involving 2 participants $x, \hat{x} \in \mathcal{P}$ where the roles of the participants are sender x and recipient $\hat{x}$, such that:*

1. $m_r = \langle x, join, nil, nil \rangle$
2. $m_t = \langle x, close, nil, nil \rangle$
3. $\mathsf{sender}(m_s) = x \in \mathcal{P}, \mathsf{movetype}(m_s) \neq join$ *where* $(r < s \leq t)$

As the dialogue progresses over time, each move is denoted m_s, $r < s \leq t$, where r is the time point of the first move of the dialogue, t is the time point of the last move, and s is the time point of the current move. The first move of a dialogue must always be a *join* move (condition 1); conversely, the last move should be a *close* move (condition 2). Finally, only participants of the dialogue can make moves (condition 3), other than the *join* move itself. The dialogue can only proceed once all of the participants have joined it; i.e., when they have all uttered a *join* move. The state diagram for the dialogue is given in Figure 1. Note that the move *matched-close* is given to illustrate how the dialogue terminates; this is explained below (see Definition 12 for the *close* move).

To ensure that agents take turns to utter *assert* moves, each agent monitors the identity of the last sender, denoted ρ. The agent that can utter a move to transition from state 3AB (Figure 1) is determined by ρ. A sender x can also follow a move m_{s-1} with another m_s if the move m_{s-1} was an *accept* or *reject* move (ie. $\mathsf{movetype}(m_{s-1}) \in \{accept, reject\}$); see states labelled 4A for *Alice* and 4B for *Bob* in Figure 1. This enables an agent to respond in some way (in this case, to accept or reject a correspondence) be-

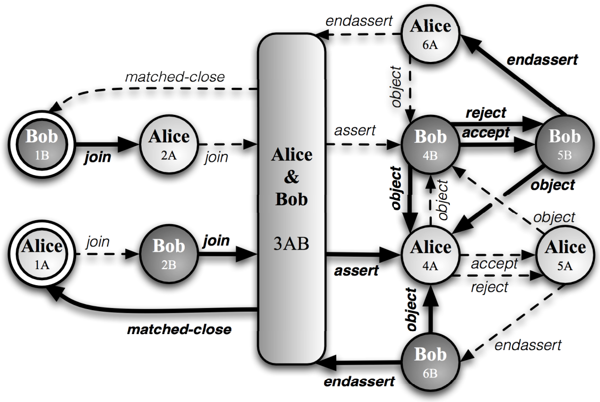

Figure 1: The dialogue as a state diagram. Nodes indicate the agent whose turn it is to utter a move. Moves uttered by Alice are labelled with a light font and solid line, whereas those uttered by Bob are labelled with a heavy font and dashed line.

fore making some other proposition (such as raising a *object* move), or signalling its intention to end the negotiation round (through an *endassert* move). This is illustrated by moves 5 and 6 in Figure 2.

Definition 6: *The move* m_s = **join** *for sender* x *has the syntax* $\langle x, join, nil, nil\rangle$*, where the following conditions hold:*

- *Pre-conditions*
    1. $x \notin \mathcal{P}$*, where* $\mathcal{P}$ *is the set of dialogue participants.*
- *Post-conditions*
    1. $\mathcal{P}' = \mathcal{P} \cup \{x\}$
    2. $JB^x = \varnothing$
    3. $\rho = x$

Prior to the dialogue, we assume that there are no *participants* of the dialogue; i.e. $\mathcal{P} = \varnothing$. An agent x can **join** the dialogue if it is not yet a participant (pre-condition 1). Once x has joined the dialogue, it is added to the list of participants (post-condition 1), and an empty joint belief store is created (post-condition 2). Finally, each agent tracks the most recent joining participant (post-condition 3), to ensure that it does not utter the first *assert* move.

After all of the agents have joined the dialogue, the value of the upper bound estimate $\kappa^x_{upper} \in [0, 1]$ managed by each agent for the other participant is set to the upper value, 1.0. The dialogue then proceeds in *negotiation rounds*, whereby the agents take turns to initiate a round by uttering an *assert* move for some correspondence c. Correspondences are asserted, accepted, rejected or countered based on the agents degree of belief in the correspondence (Figure 2). When the sender x asserts the belief $\phi = \langle c, \kappa^x_c\rangle$, it discloses its personal degree of belief κ^x_c in the correspondence c to the receiver $\hat{x}$, which can then either agree or object to the viability of this correspondence by exposing its own belief $\psi = \langle c, \kappa^{\hat{x}}_c\rangle$. The negotiation round terminates when both agents have no further counter proposals to make with respect to the currently considered beliefs (i.e. the previous *assert* and any subsequent objections), and both utter a sequence of contiguous *endassert* moves.

Definition 7: *The move* m_s = **assert** *for sender* x *has the syntax* $\langle x, assert, \phi, nil\rangle$*, where the following conditions hold:*

- *Pre-conditions*
    1. $x \neq \rho$
    2. $\mathsf{movetype}(m_{s-1}) \in \{join, endassert, close\}$
    3. $\exists\phi \in \Delta^x$*, s.t.*
        - *(a)* $\phi \notin JB^x$
        - *(b)* $\forall\phi' \in \Delta^x$*, if* $\phi' \notin JB^x, \mathsf{degree}(\phi') \leq \mathsf{degree}(\phi)$
        - *(c)* $\mathsf{grounded}(\phi, \mathcal{W}^x)$
        - *(d)* $\mathsf{joint}_{est}(\mathsf{corr}(\phi)) \geq \epsilon$
- *Post-conditions*
    1. $JB^{x'} = \{\phi\} \cup JB^x$; $JB^{\hat{x}'} = \{\phi\} \cup JB^{\hat{x}}$
    2. $\kappa^{\hat{x}}_{upper} = \mathsf{degree}(\phi)$
    3. $Ag' = Ag \cup \{\langle \mathsf{corr}(\phi), \mathsf{joint}_{est}(\phi)\rangle\}$
    4. $\rho = x$

To ensure that the agents take turns in asserting beliefs, the agent x should not have uttered the previous *assert* move (pre-condition 1), and there should not be an ongoing negotiation round (pre-condition 2). A belief ϕ from the joint belief store (pre-condition 3) will be asserted if it: a) has not yet been disclosed to another agent; b) has the highest degree of belief of any beliefs that also satisfy the pre-conditions; c) represents a correspondence in the working ontology; and d) the estimated joint degree of belief is not below the threshold ϵ. Once the assert has been uttered, the disclosed belief will be added to the joint belief stores of both agents (post-condition 1), and the upper bound estimate for the sending agent will be updated by the recipient $\hat{x}$ (post-condition 2). Finally we add the assertion as an argument to each agent's attack-graph Ag, with the estimated degree of belief (post-condition 3); this argument will then be updated with the actual degree of belief if the belief is accepted (Definition 9) or objected to (Definition 8), or removed if the belief is rejected (Definition 10).

There are three scenarios where x responds with *object*:

1. when a new correspondence has appeared in a previous *assert* or *object* move. In this case, the sender needs to respond with its own belief of the correspondence, but may also want to raise its own objection (see move 4 in Figure 2).
2. when there is an undisclosed correspondence that could be used to attack a previously disclosed correspondence. This is where agents can identify other attacks on ambiguous correspondences (see move 6 in Figure 2).
3. when a disclosed correspondence could attack another disclosed correspondence, but the attack does not appear in the attack graph Ag. This ensures that all possible attacks have been identified within Ag (see move 10 in Figure 2).

In each case, the attack is added to the attack graph.

Definition 8: *The move* m_s = **object** *for sender* x *has the syntax* $\langle x, object, \phi, \phi^{att}\rangle$*, where these conditions hold:*

- *Pre-conditions*
    1. $\mathsf{movetype}(m_{s-1}) \notin \{join, close\}$
    2. $\exists\psi^{att} \in JB^x$*, s.t. one of the following hold:*
        - *(a)* $\phi^{att} \in \Delta^x, \mathsf{corr}(\phi^{att}) = \mathsf{corr}(\psi^{att})$
        - *or*
        - *(b)* $\phi^{att} \notin \Delta^x, \exists\phi^{att} \in \mathcal{B}$ *s.t.* $\phi^{att} = \langle \mathsf{corr}(\psi^{att}), 0\rangle$
    3. $\exists\phi : \phi \in \Delta^x \vee \phi \in JB^x$*, where* $\mathsf{attacks}(\phi, \phi^{att})$
    4. $\langle \phi, \phi^{att}\rangle \notin \rhd$
    5. $\mathsf{grounded}(\phi^{att}, \mathcal{W}^x)$, $\mathsf{grounded}(\phi, \mathcal{W}^x)$
- *Post-conditions*
    1. $b = \langle \mathsf{corr}(\phi), \mathsf{joint}(\phi)\rangle \in \mathcal{B}$;
       $b^{att} = \langle \mathsf{corr}(\phi^{att}), \mathsf{joint}(\phi^{att})\rangle \in \mathcal{B}$
    2. $Ag' = (Ag \setminus b^{est}) \cup \{b, b^{att}\}$*, where*
       $\mathsf{corr}(b^{est}) = \mathsf{corr}(\phi^{att})$
    3. $\rhd' = \rhd \cup \{\langle b, b^{att}\rangle\}$
    4. $JB^{x'} = \{\phi, \phi^{att}\} \cup JB^x$; $JB^{\hat{x}'} = \{\phi, \phi^{att}\} \cup JB^{\hat{x}}$

An agent can raise an objection (i.e. can *attack*) given a new belief ϕ to a previously disclosed belief ϕ^{att} in any negotiation round in response to any move except *join* and *close* (pre-condition 1). There exists some other attacked belief ψ^{att} that shares the same correspondence as ϕ^{att} that (a) either exists in the alignment store, or (b) that is unknown and we have to construct it with $\kappa^x_c = 0$ (pre-condition 2). There is another belief ϕ in the alignment store or joint belief store which attacks ϕ^{att} (pre-condition 3). The attack relation is not in the attack graph (pre-condition 4), and both beliefs ϕ and ϕ^{att} are grounded within the working dialogue (pre-condition 5). Given these conditions, the sender can utter the *object* move, disclosing its own belief ϕ^{att} for the disclosed belief ψ^{att}, but also disclosing another belief ϕ that attacks the correspondence that appears in both ϕ^{att} and ψ^{att}. Two new beliefs b and b^{att} are created for beliefs ϕ and ϕ^{att} respectively (post-condition 1). However, in each case, they represent the correspondence, and the joint degree of belief for that correspondence. This avoids having to manage multiple beliefs per correspondence for each agent in the attack graph. The two new beliefs are added the the argumentation framework (post-condition 2), and any belief b^{est} which represented an estimated joint degree of belief for ϕ^{att} is replaced with b^{att}. The attack between b and b^{att} is also added to the attack graph (post-condition 3) and the disclosed beliefs ϕ^{att} and ϕ are added to the joint belief stores of all the agents (post-condition 3)[5].

Once an objection has been raised, if the new belief in the objection was previously undisclosed (scenarios 1 & 2), then it should be either accepted or rejected, given the following definitions:

Definition 9: *The move* $m_s =$ **accept** *for sender* x *has the syntax* $\langle x, accept, \phi, nil\rangle$*, where the following conditions hold:*

- *Pre-conditions*
  1. $\mathsf{movetype}(m_{s-1}) \in \{assert, object\}$
  2. $\exists \psi \in JB^x, \nexists \phi \in JB^x$*, s.t. one of the following hold:*
     (a) $\phi \in \Delta^x, \mathsf{corr}(\phi) = \mathsf{corr}(\psi)$
     or
     (b) $\phi \notin \Delta^x, \exists \phi \in \mathcal{B}$ *s.t.* $\phi = \langle \mathsf{corr}(\psi), 0\rangle$
  3. $\mathsf{grounded}(\phi, \mathcal{W}^x)$
  4. $\mathsf{joint}(\mathsf{corr}(\phi)) \geq \epsilon$
- *Post-conditions*
  1. $JB^{x'} = \{\phi\} \cup JB^x$; $JB^{\hat{x}'} = \{\phi\} \cup JB^{\hat{x}}$
  2. $Ag' = (Ag \setminus b^{est}) \cup \{b\}$*, where* $\mathsf{corr}(b^{est}) = \mathsf{corr}(\phi)$*,* $b = \langle \mathsf{corr}(\phi), \mathsf{joint}(\phi)\rangle \in \mathcal{B}$

The *accept* move is used to "accept" the viability of some belief that appeared in the preceding *assert* or *object* move (pre-condition 1). There exists some new belief, ψ within the joint belief store, for which there is no corresponding ϕ in the joint belief store (pre-condition 2), the belief ϕ also appears in the working ontology (pre-condition 3), and the joint degree of belief for ϕ is not below threshold. If these conditions hold, then the belief ψ is accepted by disclosing the corresponding ϕ, which is then added to the joint belief store of both agents (post-condition 1). As the preceding *assert* or *object* moves had inserted b^{est} (with $\mathsf{joint}_{est}(c)$) in the attack graph, this estimate needs to be updated (post-condition 2).

Note that when an objection is made between two existing beliefs that have already been disclosed and accepted (scenario 3), the beliefs involved will already exist within the joint belief store (thus violating pre-condition 2 above). In this case, the objection should simply be followed by an accept move, but with no post-conditions.

Definition 10: *The move* $m_s =$ **reject** *for sender* x *has the syntax* $\langle x, reject, \psi, nil\rangle$*, where the following conditions hold:*

- *Pre-conditions*
  1. $\mathsf{movetype}(m_{s-1}) \in \{assert, object\}$
  2. $\exists \psi \in JB^x$*, s.t.* $\nexists \phi \in JB^x, \mathsf{corr}(\psi) = \mathsf{corr}(\phi)$
  3. $\neg\mathsf{grounded}(\psi, \mathcal{W}^x) \vee \mathsf{joint}(\mathsf{corr}(\psi)) < \epsilon$
- *Post-conditions*
  1. $\exists b^{est} \in Ag$*, s.t.* $b^{est} = \langle \mathsf{corr}(\psi), \mathsf{joint}(\psi)\rangle$
  2. $Ag' = (Ag \setminus b^{est})$
  3. $\rhd' = \rhd \setminus \{\langle \phi', b^{est}\rangle\}$*, s.t.* $\phi' \in Ag$

In contrast to the *accept* move, the *reject* move "rejects" the viability of some belief ψ that appeared in the preceding *assert* or *object* move (pre-condition 1). Given this new belief, ψ within the joint belief store, for which there is no corresponding ϕ in the joint belief store (pre-condition 2), ψ will be rejected iff it is not in the working ontology or if the joint degree of belief is below threshold (pre-condition 3). If these conditions hold, then by definition, there should be some associated belief b^{est} in the attack graph (post-condition 1) which should be removed (post-condition 2), and all corresponding attacks should also be removed (post-condition 3). Unlike other moves, *reject* includes ψ's belief rather than its own one for the same correspondence, and does not disclose its own belief for the rejected belief.

Definition 11: *The move* $m_s =$ **endassert** *for* x *has the syntax* $\langle x, endassert, nil, nil\rangle$*, where the following pre-conditions hold:*

1. $\mathsf{movetype}(m_{s-1}) \in \{$*accept, reject, endassert*$\}$
2. $\forall \psi \in JB^x, \exists \phi \in JB^x$*, s.t.* $\phi = \langle \mathsf{corr}(\psi), \kappa\rangle$
3. $\forall \phi, \psi \in JB^x$*, no other argument* $\phi' \notin Ag$ *attacks* ϕ *and* ψ

An agent can **endassert** the dialogue after a belief has been accepted or rejected, or the other agent has no more objections to make (pre-condition 1), if it has no more objections to make to any of the beliefs raised in the negotiation dialogue (pre-condition 2), and there are no further viable attacks that have not already been included in the attack graph (pre-condition 3).

A dialogue will not terminate until all agents utter a contiguous sequence of *close* moves (called a *matched-close* [3]).

Definition 12: *The move* $m_s =$ **close** *for sender* x *has the syntax* $\langle x, close, nil, nil\rangle$*, where the following conditions hold:*

- *Pre-conditions*
  1. $\mathsf{movetype}(m_{s-1}) \in \{join, endassert, close\}$
  2. $\nexists \phi \in \Delta^x, \phi \notin JB^x$, $\mathsf{joint}(\mathsf{corr}(\phi)) \geq \epsilon$
- *Post-conditions*
  1. *if matched-close, then* $\mathcal{P} = \varnothing$

An agent can only **close** the dialogue immediately after a *join*, *endassert* or *close* (pre-condition 1), and if no further candidate correspondences exist with a joint degree of belief not below threshold ϵ (pre-condition 2). If m_s resulted in a *matched-close*, then all agents are removed from the set of participants (post-condition 1).

2.4 Resolving the attack graphs

Once the dialogue has closed (i.e. after a *matched-close*), the agents resolve the attack graph $\langle Ag, \rhd\rangle$ to determine which of the correspondences disclosed should be included in the final alignment. We introduce here a heuristic approach for resolving the graph, based on Dung's argumentation framework [6].

Recall that, as $JB^x = JB^{\hat{x}}$, both agents will form identical attack graphs. Each graph (see the example in Figure 3) includes only those correspondences which appeared in an *assert* or *object* move, and then were subsequently accepted, or themselves objected to (i.e. attacked). The objections are represented as edges between the vertices, such that vertices with a higher joint degree of belief will *attack* vertices with lower values. The attack graph is traversed, starting with the highest value vertex; if the highest value vertex *attacks* another vertex, that other vertex is then removed from the graph. This continues until all of the remaining vertices have been traversed. For example, in Figure 3, $\langle a, x, =\rangle$ attacks $\langle b, x, =\rangle$, which can no longer attack either $\langle b, w, =\rangle$ or $\langle b, z, =\rangle$. $\langle b, w, =\rangle$ attacks $\langle b, z, =\rangle$, which is then removed from the graph. The correspondences found in the remaining vertices (once all attacks have been resolved) are included within the final alignment AL.

3. INQUIRY DIALOGUE EXAMPLE

We illustrate how two agents utilise the proposed inquiry dialogue to find an alignment by means of an example. Two agents,

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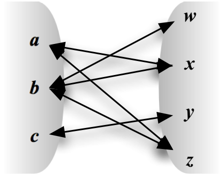
[5] Note that *object* moves do not affect the estimated upper bounds, as they do not reflect a belief with the highest κ for the sender.

Alice and *Bob*, each possess a private ontological fragment that provides the conceptualisation for the entities that they use to communicate. Each agent has acquired a subset of correspondences, and has associated a weight, or *degree of belief* κ_c to each correspondence (Table 1) in the range $[0, 1]$. Not every correspondence is known to every agent; for example, *Alice* only knows about the correspondences $\langle b, z, =\rangle$ and $\langle a, z, =\rangle$, whereas she knows nothing about $\langle c, y, =\rangle$. The degree of belief κ_c associated to each correspondence c known is also private to each agent. In Table 1 we summarise κ_c and $\mathsf{joint}(c)$ for each c for the two agents, and illustrate the correspondences between the entities in the two ontologies. We also assume that both agents utilise an *admissibility threshold* $\epsilon = 0.45$ to filter out correspondences with a low $\mathsf{joint}(c)$.

Table 1: The individual and joint *degrees of belief* for the correspondences, and how they map between ontological entities.

c	κ_c^{Alice}	κ_c^{Bob}	$\mathsf{joint}(c)$
$\langle a, x, =\rangle$	0.8	0.6	**0.7**
$\langle b, x, =\rangle$	0.5	0.8	**0.65**
$\langle b, w, =\rangle$	0.6	0.4	**0.5**
$\langle b, z, =\rangle$	0.9	—	**0.45**
$\langle c, y, =\rangle$	—	0.2	**0.1**
$\langle a, z, =\rangle$	0.1	—	**0.05**



The example dialogue between *Alice* and *Bob* is presented in Figure 2. The turn order is non-deterministic; in this example, *Alice* makes the first *assert*[6]. The two agents initiate the dialogue by both uttering the *join* move (omitted from Figure 2). Each exchange is shown, with its move identifier. As each belief disclosed states the agent's individual degree of belief, values will differ depending on the sender. For example, *Bob* discloses $\kappa^{Bob}_{\langle b,x,=\rangle} = 0.8$ in move 3, whereas in *Alice's* response in move 4, she discloses $\kappa^{Alice}_{\langle b,x,=\rangle} = 0.5$. Each agent maintains an estimate of the other agents *upper bound*, which reflects the maximum degree of belief an agent has in its undisclosed correspondences.

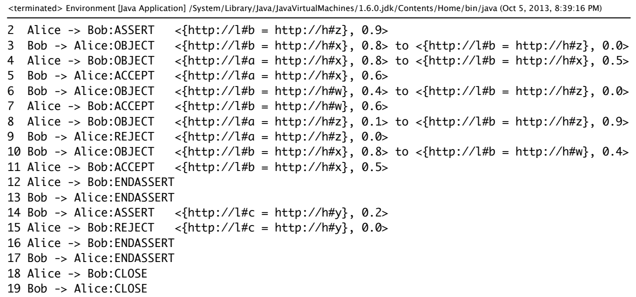
Move 2: *Alice* selects one of her undisclosed correspondences with the highest κ_c; in this case, $\langle b, z, =\rangle$. Initially, *Alice* assumes *Bob's* upper bound is 1, and estimates the upper bound estimate for correspondence c (denoted $\mathsf{joint}_{est}(c)$) to be $\frac{1}{2}(0.9 + 1.0) = 0.95$. As this is above ϵ, she asserts the tuple $\langle\langle b, z, =\rangle, 0.9\rangle$.

Move 3: As *Bob* was previously unaware of this correspondence, he calculates the actual $\mathsf{joint}(\langle b, z, =\rangle)$ as $\frac{1}{2}(0.9 + 0.0) = 0.45$. Furthermore, *Bob* knows of an alternative correspondence $\langle b, x, =\rangle$ that shares the entity b with *Alice's* asserted correspondence. He knows, from *Alice's* previous assertion, that she will possess no correspondences with κ_c greater than 0.9 (as she would have asserted a belief with the highest κ_c), and therefore estimates an upper bound on $\mathsf{joint}_{est}(\langle b, x, =\rangle)$ to be $\frac{1}{2}(0.9 + 0.8) = 0.85$. As this is greater than the actual value for $\mathsf{joint}(\langle b, z, =\rangle) = 0.45$, he utters an *object* move, disclosing the alternative correspondence to *Alice's* correspondence, with his κ_c values for both.

Moves 4-5: *Alice* has a lower $\kappa_{\langle b,x,=\rangle} = 0.5$, and thus calculates $\mathsf{joint}(\langle b, x, =\rangle) = \frac{1}{2}(0.5 + 0.8) = 0.65$. As $\langle a, x, =\rangle$ shares the entity x but has a higher $\mathsf{joint}_{est}(\langle a, x, =\rangle) = \frac{1}{2}(0.8 + 1.0) = 0.9$, *Alice* utters her own objection. *Bob* computes the actual value ($\mathsf{joint}(\langle a, x, =\rangle) = \frac{1}{2}(0.8 + 0.6) = 0.7$); as he has no other correspondences that could object to *Alice's* objection, he accepts it.

To ensure that each agent takes turns in the negotiation, they *follow* an *accept* or *reject* move with another utterance.

Moves 6-9: *Bob* could now follow the acceptance by closing the negotiation or raising an alternative objection to one of the earlier proposed correspondences (including those he disclosed). One such alternative is the correspondence $\langle b, w, =\rangle$, which again has the entity b in common with *Alice's* original assertion. *Alice* accepts the proposal of this correspondence, and then raises her own objection to her initially asserted correspondence, with $\langle a, z, =\rangle$ in move 8, with the rationale that the estimated joint degree of belief is $\mathsf{joint}_{est}(\langle a, z, =\rangle) = \frac{1}{2}(0.1 + 1.0) = 0.5$, which is now greater than $\mathsf{joint}(\langle b, z, =\rangle) = 0.45$. However, as *Bob* has no degree of belief for this correspondence, he calculates the actual joint value to be $\mathsf{joint}(\langle a, z, =\rangle) = \frac{1}{2}(0.1 + 0.0) = 0.05$, and rejects it.



```
<terminated> Environment [Java Application] /System/Library/Java/JavaVirtualMachines/1.6.0.jdk/Contents/Home/bin/java (Oct 5, 2013, 8:39:16 PM)
2  Alice -> Bob:ASSERT   <{http://l#b = http://h#z}, 0.9>
3  Bob -> Alice:OBJECT   <{http://l#b = http://h#x}, 0.8> to <{http://l#b = http://h#z}, 0.0>
4  Alice -> Bob:OBJECT   <{http://l#a = http://h#x}, 0.8> to <{http://l#b = http://h#x}, 0.5>
5  Bob -> Alice:ACCEPT   <{http://l#a = http://h#x}, 0.6>
6  Bob -> Alice:OBJECT   <{http://l#b = http://h#w}, 0.4> to <{http://l#b = http://h#z}, 0.0>
7  Alice -> Bob:ACCEPT   <{http://l#b = http://h#w}, 0.6>
8  Alice -> Bob:OBJECT   <{http://l#a = http://h#z}, 0.1> to <{http://l#b = http://h#z}, 0.9>
9  Bob -> Alice:REJECT   <{http://l#a = http://h#z}, 0.0>
10 Bob -> Alice:OBJECT   <{http://l#b = http://h#x}, 0.8> to <{http://l#b = http://h#w}, 0.4>
11 Alice -> Bob:ACCEPT   <{http://l#b = http://h#x}, 0.5>
12 Alice -> Bob:ENDASSERT
13 Bob -> Alice:ENDASSERT
14 Bob -> Alice:ASSERT   <{http://l#c = http://h#y}, 0.2>
15 Alice -> Bob:REJECT   <{http://l#c = http://h#y}, 0.0>
16 Alice -> Bob:ENDASSERT
17 Bob -> Alice:ENDASSERT
18 Alice -> Bob:CLOSE
19 Bob -> Alice:CLOSE
```

Figure 2: The messages exchanged between *Alice* and *Bob* in the example dialogue with two negotiation rounds.

Moves 10-11: At this point, *Bob* has no further correspondences that he wants to disclose. However, whilst checking for possible objections, he discovers that $\mathsf{joint}(\langle b, x, =\rangle) \geq \mathsf{joint}(\langle b, w, =\rangle)$, yet neither he or *Alice* had raised this objection. Despite the fact that both agents know the actual joint degrees of belief for both correspondences, he utters the objection to *Alice's* move. As this includes correspondences that have already been disclosed, *Alice* simply responds by accepting this objection (move 11).

Moves 12-13: *Alice* utters an *endassert*, signalling that she has no further objections to the correspondences exchanged so far. *Bob* also has no further objections, so by also uttering a subsequent *endassert*, the negotiation round ends.

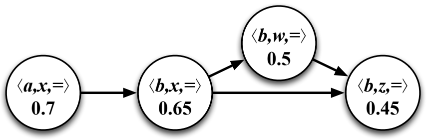


Figure 3: The Final Attack Graph $\langle Ag, \rhd\rangle$.

Moves 14-19: A new negotiation round can now commence. As *Alice* uttered the previous *assert* in move 2, it is now *Bob's* turn to utter an *assert*, resulting in a new negotiation round, which then continues, until both agents utter the *endassert*. At this point, as neither agent has any other correspondences to assert, they both issue a *close* utterance, and the dialogue ends.

Each agent can now review the objections that were raised during the negotiation rounds, and from these, resolve their attack graphs (Figure 3). As attacks are resolved by finding the vertex with the highest value, the attack from $\langle a, x, =\rangle$ is resolved first. It attacks $\langle b, x, =\rangle$, which can no longer attack either $\langle b, w, =\rangle$ or $\langle b, z, =\rangle$. The next highest vertex is then considered (in this case $\langle b, w, =\rangle$), which attacks $\langle b, z, =\rangle$. Thus the only vertices remaining in the graph are $\langle a, x, =\rangle$ and $\langle b, w, =\rangle$, which are added to the final alignment.

4. EMPIRICAL EVALUATION

We empirically evaluate how effective the proposed dialogue is in finding alignments between two agents, given their ontologies, by investigating the alignment solutions found, and the cost (in terms of messages exchanged). We also explore how the use of

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[6] Although the turn order can affect the number of messages exchanged (for example, if *Bob* makes the first *assert* move, then fewer moves will be made), the resulting outcome is not affected.

the admissibility threshold ϵ can affect the resulting alignments, by eliminating possibly spurious or erroneous correspondences (i.e. those will little evidence to support their validity). The following three hypotheses have been tested using OAEI[7] data sets:

1. Selecting and combining correspondences taken from a number of different alignment methods can yield comparable performance to existing alignment methods, when measured using the *precision*, *recall* and *f-measure* metrics;
2. Eliminating low utility correspondences improves dialogue performance with respect to the resulting alignment, and the number of correspondences disclosed;
3. Solutions found by agents with asynchronous and incomplete knowledge are similar to those found using a centralised approach with complete knowledge.

The OEAI 2012 Conference Track comprises various ontologies describing the same conceptual domain (conference organisation) and alignments between pairs of ontologies, generated by 17 different ontology alignment approaches. Seven ontologies were selected as these were accompanied by *reference alignments* (defined by a domain expert), resulting in 17 different alignments for each pair of ontologies, and $\frac{7!}{(7-2)!2!} = 21$ ontology combination pairs.

The empirical evaluations were conducted over each of the 21 ontology pairs (i.e. for each experiment, an agent would be assigned an ontology, but would have no knowledge of the ontology of the other agent), with a random selection of 16 alignments divided between the two agents (such that each agent knows of 8 alignments). The allocation was random, and ensured that no alignment belonged to both agents. We exploited the fact that, as the alignments were generated independently, a number of correspondences would be found in more than one alignment. Thus, each agent calculated κ_c for each c by determining the probability of finding it in the alignments each agent possessed. Experiments were also repeated for different admissibility thresholds; as 16 alignments were divided between the two agents, the threshold was varied in sixteenths; e.g. $\epsilon = \frac{2}{16}$ required there to be at least two instances of a correspondence c to be found (i.e. $\mathsf{joint}(c) \geq \frac{2}{16}$) before c was considered. Each experiment was repeated 500 times.

The resulting alignments were evaluated using the *precision*, *recall* and *f-measure* metrics, where: **precision** (p) is the proportion of correspondences found by the dialogue that are correct (i.e. in the *reference alignment*); **recall** (r) is the proportion of correct correspondences with respect to the number of correspondences in the *reference alignment*; and the **f-measure** (f) represents the harmonic mean of p and r.

A baseline was generated by assuming that a naive approach for finding an alignment would consist of an agent randomly picking and using one of the pre-defined alignments. Thus, we compute the average performance of the 17 alignment methods for each ontology pair, and report the precision ($\overline{p_{\mathcal{A}}}$) and recall ($\overline{r_{\mathcal{A}}}$) results in columns 2 and 3 (in bold) in Table 2. To evaluate the alignments generated by the dialogue, we calculate the precision ($\overline{p_{\mathcal{D}}}$) and recall ($\overline{r_{\mathcal{D}}}$) for each ontology pair (columns 4-9 in Table 2), for three different admissibility thresholds: $\epsilon = \frac{1}{16}$ to evaluate the performance when no filtering occurs (i.e. the existence of one correspondence is sufficient for consideration by the dialogue); $\epsilon_l = \frac{3}{16}$ and $\epsilon_u = \frac{14}{16}$ represent the lower and upper ranges where the average f-measure for the dialogue's alignment is significantly higher (using a one-sided paired t-test where $\alpha = 0.05$) than $\overline{f_{\mathcal{A}}}$. Figure 4 demonstrates how, in most cases, the f-measure performance of the dialogue is significantly higher than that achieved from selecting an alignment at random, when $\epsilon_l \leq \epsilon < \epsilon_u$. The graph plots the difference in f-measure (denoted $\delta f_{\mathcal{D}}$) between that achieved using the average alignments ($\overline{f_{\mathcal{A}}}$), and that achieved by the dialogue for all 21 ontology pairs (i.e. values above zero indicate a better f-measure, whereas those below are worse). The lower (ϵ_l) and upper (ϵ_u) bounds are indicated by the two vertical limits on the graph Thus, the dialogue produces alignments that are more precise than selecting an original alignment at random in this range, although r is worse when $\epsilon < \frac{5}{16}$. At $\epsilon = \frac{5}{16}$, p ranges from -5.5% to a 40.3% increase for different ontology pairs, whereas r ranges from -12% to 19% increase. The maximum p occurs at $\epsilon = \frac{6}{16}$ for *cmt-ekaw* (47.37%), whereas r falls in general to between 0% and -12.19%.

Table 2: Precision and Recall for the Ontology Pairs

Ontology Pair	Alignment Average		Admissibility Thresholds (ϵ) 1/16		3/16		14/16	
	$\overline{p_{\mathcal{A}}}$	$\overline{r_{\mathcal{A}}}$	$\overline{p_{\mathcal{D}}}$	$\overline{r_{\mathcal{D}}}$	$\overline{p_{\mathcal{D}}}$	$\overline{r_{\mathcal{D}}}$	$\overline{p_{\mathcal{D}}}$	$\overline{r_{\mathcal{D}}}$
cmt-conference	**0.50**	**0.41**	0.16	0.79	0.52	0.66	0.67	0.27
cmt-confOf	**0.63**	**0.32**	0.15	0.52	0.68	0.41	0.99	0.14
cmt-edas	**0.65**	**0.66**	0.14	0.79	0.63	0.75	1.00	0.62
cmt-ekaw	**0.57**	**0.48**	0.10	0.55	0.47	0.55	1.00	0.45
cmt-iasted	**0.61**	**1.00**	0.07	1.00	0.61	1.00	0.80	1.00
cmt-sigkdd	**0.70**	**0.72**	0.21	0.92	0.75	0.91	0.99	0.59
conference-confof	**0.64**	**0.62**	0.17	0.76	0.55	0.72	0.88	0.47
conference-edas	**0.57**	**0.55**	0.14	0.78	0.50	0.68	0.88	0.41
conference-ekaw	**0.56**	**0.45**	0.24	0.81	0.63	0.66	0.67	0.32
conference-iasted	**0.52**	**0.33**	0.09	0.55	0.47	0.35	0.80	0.29
conference-sigkdd	**0.67**	**0.60**	0.19	0.85	0.73	0.71	0.96	0.53
confof-edas	**0.60**	**0.50**	0.19	0.65	0.51	0.58	0.87	0.38
confof-ekaw	**0.76**	**0.52**	0.27	0.86	0.76	0.78	0.97	0.40
confof-iasted	**0.67**	**0.54**	0.11	0.78	0.44	0.74	1.00	0.44
confof-sigkdd	**0.74**	**0.62**	0.13	1.00	0.85	0.81	1.00	0.57
edas-ekaw	**0.58**	**0.47**	0.18	0.73	0.65	0.63	0.80	0.39
edas-iasted	**0.63**	**0.43**	0.10	0.64	0.72	0.55	0.88	0.37
edas-sigkdd	**0.74**	**0.49**	0.16	0.67	0.62	0.47	1.00	0.47
ekaw-iasted	**0.65**	**0.63**	0.09	0.79	0.40	0.70	1.00	0.60
ekaw-sigkdd	**0.75**	**0.66**	0.13	0.77	0.77	0.70	1.00	0.57
iasted-sigkdd	**0.60**	**0.80**	0.20	1.00	0.63	1.00	0.91	0.73
Overall Average	**0.64**	**0.56**	0.15	0.77	0.61	0.68	0.91	0.48

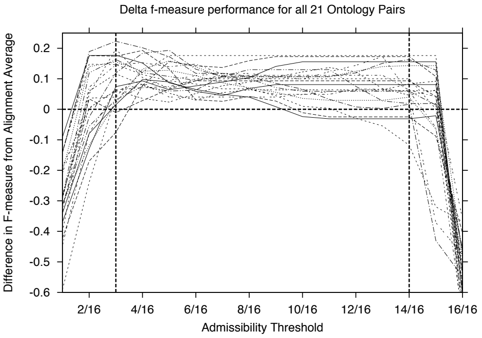

Figure 4: Delta f-measures ($\delta f_{\mathcal{D}}$) for all 21 ontology pairs.

The dialogue performance degrades for low and high thresholds. When $\epsilon = \frac{1}{16}$ (i.e. no filtering), a large number of correspondences appear in the alignment, yielding a high r but very low p, suggesting that although the correct correspondences were found, a high number of incorrect ones were also included. Whilst this could be a property of the dataset used (several alignments include a number of rare, but erroneous correspondences), it demonstrates the value of eliminating low utility correspondences (e.g. in this case, those that were found in the source alignments with low frequency). When $\epsilon > \frac{14}{16}$, a high number of correspondences are eliminated (an average of 2.8% of each agent's correspondences appear in the final alignment when $\epsilon = \frac{16}{16}$), resulting in a sharp drop in $\delta f_{\mathcal{D}}$. This support hypotheses 1&2 when the evidence threshold is used.

The number of correspondences disclosed, and those selected for the final alignment were measured, and presented as a percentage of the number of original, distinct correspondences (i.e. those found in all 16 alignments used for each experiment, ignoring duplicates). With no filtering (i.e. $\epsilon = \frac{1}{16}$), 89.2% of the correspondences were

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[7] `http://oaei.ontologymatching.org`

disclosed (averaged across all 21 ontology pairs), with 56.3% appearing in the final alignment. These values fell exponentially as ϵ increased, and when $\epsilon = \frac{3}{16}$, only 22.3% of the correspondences were disclosed (with 12.5% in the final alignment), suggesting that a large number of disclosed correspondences were either objected to, or rejected, supporting hypothesis 2. However, by $\epsilon = \frac{7}{16}$, these percentages converged, suggesting that at higher thresholds, there were few objections to the 8.9% of correspondences asserted.

To verify hypothesis 3, a recursive-descent algorithm was implemented to exhaustively search for all possible ambiguity-free alignments. Each dialogue was accompanied by an exhaustive search, using the same data[8]. The alignments were scored, based on the average degree of belief for the constituent correspondences, and this was compared with the score for that resulting from the dialogue. In all but 3 of the ontology pairs (when $\epsilon = \frac{2}{16}$), the alignment generated scored within 94.9% of the optimal exhaustive solution.

4.1 Logical Coherence

Relying on asynchronous and incomplete knowledge does not allow agents to verify that the resulting alignments preserve logical coherence in their original ontologies. These alignments should not introduce, or cause the derivation of any new semantic relations between the entities in these ontologies; i.e. $\mathcal{O}_S \cup AL \cup \mathcal{O}_T$ should be coherent (i.e. should only contain satisfiable concepts). However, our assumption of incomplete and asynchronous knowledge implies that x only knows $\mathcal{O}_S$ and AL, and hence can only compute that all the classes in ontology $\mathcal{O}_S \cup AL$ are satisfiable. Analogously, $\hat{x}$ can only check the coherence of $\mathcal{O}_T \cup AL$. In both cases, verifying that all of the entities in the new merged ontologies are satisfiable does not guarantee that the merged ontology is coherent. Whilst this might not be a problem under current assumptions, we will address the coherence of the joint model in future work.

5. RELATED WORK

A number of different approaches have addressed the reconciliation of heterogeneous ontologies by using some form of rational reasoning. Argumentation has been used as a rational means for agents to select ontology correspondences based on the notion of partial-order preferences over their different properties (e.g. *structural* vs *terminological*) [8]. A variant was also proposed [10] which represented ontology mappings as disjunctive queries in Description Logics. Typically, these approaches have used a course-grained decision metric based on the *type* of correspondence, rather than whether or not each correspondence was *acceptable* to each agent (given other mutually accepted correspondences), and do not consider the notion of private, or asymmetric knowledge (the correspondences are assumed to be publicly accessible). [9] used a Max-Sum algorithm for synthesising ontology alignment methods whilst maximising social welfare in a group of interacting agents. Although similar to the aims of our study, [9] assumes that all agents have knowledge of the ontologies to align, and each agent is associated with an alignment method with its own preferences on the assessed relation, and quantified by a degree of confidence.

6. CONCLUSIONS

We have formally presented and empirically evaluated an inquiry dialogue that facilitates negotiation over asymmetric and incomplete knowledge of ontological correspondences. Our dialogue enables two agents to selectively disclose private beliefs regarding the quality, or *degree of belief* of ontological correspondences. Ambiguities are resolved through the use of an attack-graph, that identifies solutions based on the combined beliefs. The dialogue was implemented and empirically evaluated using correspondences found in alignments sourced from 17 different approaches over 21 ontology pairs, and using a set of reference alignments. The results supported the hypotheses that, by filtering low probability correspondences, alignments generated by our dialogue performed as well as selecting an existing alignment approach at random, whilst significantly reducing the number of correspondences disclosed.

In future work, we will instantiate a preference-based argumentation framework [1] to resolve the attack graph, by modelling the inclusion of correspondences within the final alignment propositionally, and resolving attacks through the definition of a preference relation based on the joint degree of belief of the disclosed correspondences. The formal properties of the dialogue and the instantiated argumentation framework will be explored.

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[8] No tests were performed at the lowest threshold (i.e. $\epsilon = \frac{1}{16}$, where no filtering occurred), due to the combinatorial explosion in the number of solutions generated.