Intensional Model for Data Integration System in Open Environment

Islam Ali and Kenneth McIsaac
Department of Electrical and Computer Engineering, Western University, Richmond Street, London, Ontario, Canada

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Abstract: Open environment allows agents to associate and/or dissociate with the environment without affecting the overall functionality of the system. There are several challenges to modeling data integration systems (DIS) in open environment. This is because of the distributed, dynamic, heterogeneous, and loosely coupled nature of open environment. It is also important to note that information systems are intensional in nature. This is because the belief of an agent and the knowledge of an information system are intensional contexts. Open environments are also intensional in nature. This is because, the dynamic nature of open environment imposes no constrains on the set of participating agents or the number information systems plugged into the system. We propose the use of Mediated P2P architecture for the architecture of data integration systems in open environment. The DIS is formulated using Intensional Epistemic Logic (IEL). We also present an interface and query answering semantics that are based on the IEL. The proposed model accounts for the intensional, distributed, dynamic, and loosely-coupled characteristics of open environment.

1 INTRODUCTION

Ontology is being used, to address the issue of heterogeneity between various data sources, in several fields. (Gusenkov, Bukharaev, and Birialtsev 2019) applied the use of ontology to corporate data integration. (Chen et al. 2017) used a goal driven learning process to construct an ontology that evolves through a learning process. Ontology has also been applied in toxicology (Boyles et al. 2019), air traffic management (Egami et al. 2020) and many other fields. This is because ontologies have explicit semantics. These semantics are maintainable and, if maintained, are up to date. Ontology has also been used to bridge the heterogeneity gap in open environment (Wang 2009), (Xue 2010), and (Ali and Ghenniwa 2014).

In open environment, however, there are several other challenges. The dynamic nature is one of the most challenging aspects for modeling in open environment (Ali and Ghenniwa 2012) and (Ali and Ghenniwa 2014). In open environment, there are no constraints on the set of data sources or the number of information systems plugged into the system. The system needs to account for data sources entering and leaving the environment at any time (Ali and Ghenniwa 2012) and (Ali and Ghenniwa 2014).

Open environments are also distributed in nature. Moreover, the agents that associate with the environment can posses certain degree of autonomy. This means, the knowledge of each agent about the beliefs of another agent can be different. This is because these relative beliefs will depend on what each agent decide to share with other agents. It will also depend on any accessibility rules and constraints each agent sets while dealing with other agents. This emphasises the loosely-coupled nature of open environment (Ali and Ghenniwa 2014).

(Wang 2009) proposed a framework to address the heterogeneous, autonomous, and distributed characteristics of open environment. The proposed model followed an extensional reduction formalization (Guarino and Giaretta 1995), (Guarino 1998), and (Guarino, Oberle, and Staab 2009). The extensional reduction model is based on the possible world approach (Anderson 1984). There are several formal and intuitive concerns about the use of possible world approach to describe intensional matters (Jubien 1988), (Bealer 1982), (Bealer 1998), and (Bealer 1979). As shown in (Ali and Ghenniwa 2012) and (Ali and Ghenniwa 2014), this is particularly challenging when modeling information systems in open environment. This is also quite evident in (Wang 2009) when the author uses a

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definition for equivalence that is extensional in nature.

(Xue 2010) presented another framework to address the data integration in open environment. The author attempted to address three main issues, namely; the heterogeneity, the architecture, and the modeling and representation of ontologies. The author in (Xue 2010) proposed the use of ontology and semantic matching to bridge the heterogeneity gap between various information systems. In (Xue 2010), however, database schemas were used to extract semantics and to generate ontologies. This yields a set of data-driven-ontologies (DDO). The use of DDO is a good idea when an ontology is missing. However, relying on the schema as a source of semantics is inadequate. This is because the semantics embedded in the database schemas are lost, tossed, outdated, and/or not maintainable.

Moreover, the author in (Xue 2010) employed a frame-based language (Xue, Ghenniwa, and Shen 2010). It is known that Frame-based languages are limited in their expressiveness and reasoning. The semantics of Frame-based languages are also not precisely defined (Selman and Levesque 1993). The author in (Xue 2010) also used an extensional reduction model. It has been shown in (Ali and Ghenniwa 2012) and (Ali and Ghenniwa 2014) that the extension reduction model does not address the needs of an open environment.

And finally, a mediated architecture was adopted by (Xue 2010). Similar architectures are also utilized in (Ali and Ghenniwa 2014), (Calvanese et al. 2018) and (De Giacomo et al. 2018). The mediated architecture relaxes the requirement that each information system behaves as a DIS on its own. This is a constraint that P2P systems (Majkić 2009) naturally require. On the other hand, the mediated architecture is centralized and, as such, is not adequate for open environment.

In this work, a framework for data integration system is presented. The proposed framework addresses the issues mentioned above. We will start by shedding some light on the IEL as the IEL is important to modeling DIS in open environment.

2 PROPOSITIONAL EPISTEMIC LOGIC

Epistemic logic is the logic of knowledge and belief. Even though, epistemic logic and doxastic logic formalize the knowledge and belief, respectively, the term epistemic logic is also commonly used to refer to both the logic of knowledge and the logic of belief. The main focus of epistemic logic is the propositional knowledge. That said, an agent bears the propositional attitude "knowing" or "believing" towards a proposition. As such, when we say: "Joe knows that Tom loves Merry" we are asserting that Joe is an agent who bears the propositional attitude "knows" towards the proposition expressed by "Tom loves Merry".

The syntax of the propositional epistemic logic is simply the result of augmenting the language of propositional logic with the unary knowledge or belief operators K_a or B_a; where a is an agent, and the operators K and B are the epistemic operators for knowledge and belief respectively. In that sense, if P is an arbitrary proposition, following is how these operators are read:

K_aP reads "Agent a knows that P"

And for the belief operator of doxastic logic:

B_aP reads "Agent a believes that P"

3 INTENSIONAL EPISTEMIC LOGIC

As discussed in (Fitting 2006) and (Bealer 1979) knowledge and beliefs are intensional matters. The same interpretation is adopted by (Ali and Ghenniwa 2012) in the context of knowledge engineering. IEL (Jiang 1993) offers a way to properly handle relative intensions in nested believes. The most distinguished feature of the intensional epistemic logic is the use of intensional index on the terms. The basic idea is that, given a formula like $B_a\, p(b)$, b does not have to have to be rigid. That means, b does not have to have the same meaning everywhere in the formula or same denotation in all possible worlds. And so, we need some mean to distinguish the case when b is evaluated inside the intensional scope of agent a, and the case when b is evaluated outside the intensional scope of agent a. to achieve this, a superscripted index is attached to each term to denote the number of the believe operator that contains the intended meaning of the term. If a term is not attached with an intensional index, then the intended meaning of the term is rigid. For example; the formula $B_a(Q \wedge B_bQ)$, where Q's intended meaning is in the scope of B_a, can be represented in IEL as $B_a(Q^1 \wedge B_bQ^1)$. If the second Q in the original formula is intended to be local to B_b, then the formula should be represented, in IEL, as: $B_a(Q^1 \wedge B_b Q^2)$.

As such, the language for IEL (Jiang 1993) is a first order logic language with equality, augmented with the believe operator *B* for each agent, with superscripted terms.

4 INTENSONAL MODEL FOR ONTOLOGY-BASED DIS

There are two major architectures for virtual data integration; the mediated architecture, and the Peer-to-Peer P2P architecture. While a P2P DIS allows the flexibility of querying against any peer, the mediator-based approach does not require every single information system to act as a DIS on its own. The P2P architecture, however, requires that every information system behaves as a DIS. This is too high of an expectation in open environment. At the same time, the mediated architecture adopted in, (Xue 2010) and (Ali and Ghenniwa 2014), is centralized. This makes it inadequate for an open environment which is distributed in nature.

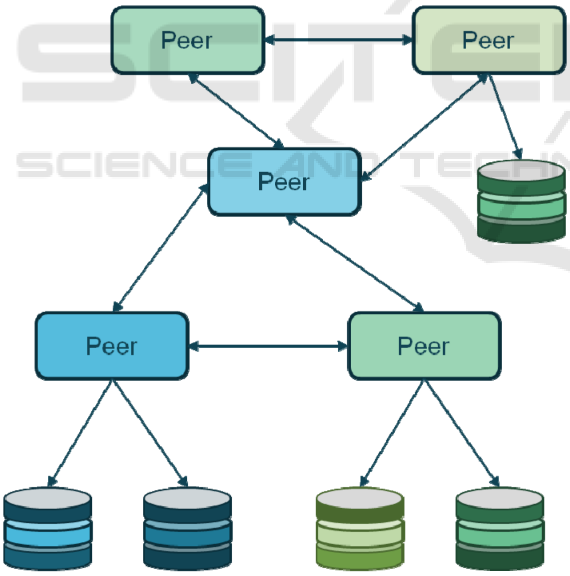

Figure 1: Mediated Peer-to-Peer Architecture.

We argue that the Mediated P2P architecture, first proposed in (Halevy et al. 2003) and (Lumineau, Doucet, and Gançarski 2006) is a good compromise between the mediated and the P2P architectures. The Mediated P2P architecture, shown in Figure 1, is distributed but yet, it does not expect every single information system to work as a DIS on its own. This is the balance that can address the needs for modeling in open environment.

The IEL is utilized for the formulation and semantics of the Mediated P2P DIS in open environment. Using IEL, given the formula $B_a q(x)$, the query $q(x)$ does not have to have the same interpretation in all possible worlds. Attaching a superscripted index to the term or the query will indicate the number of the belief operator that will include the intended meaning or the intended interpretation of the term or the query. Another main feature of the proposed model is that, the answer to a query does not have to depend on the satisfaction of the query in a universal model of the whole P2P system. Instead, every mediator network will be treated as a separate entity and the answer to the query will be the union of all the answers coming separately from each mediated network

In this formulation, a Mediated P2P DIS will be modeled as a two level logic system. Each level will be modeled as a set of IEL theories. The first level is the P2P level which will model the interaction between various mediators for the purpose of answering a user query. The second level will be a mediated level that will model the interaction inside the local network of each peer.

The main reason why the model is divided into two levels is to distinguish between the theory of one peer, a mediator, and the theory of the P2P system. This will abstract out the structure of one mediated network and the interaction that will happen within the mediator's network. More importantly, as has been discussed earlier, the open environment is dynamic in nature. And as such, it is important to separate the interaction between peers from the interactions within each peer's local network. This way, the addition or withdrawal of a data source are abstracted out so they do not affect the logic theory or the interaction at the P2P level or at the level of other peers' local networks.

Also, from a practical point of view, a peer only interacts with the other peers that have direct connections to it. As such, with the exception of its immediate neighbours, a peer cannot distinguish the status of another peer. That said, reasoning will take place in stages and each stage will be represented by a separate IEL theory.

Definition: An ontology based Mediated P2P DIS of *N* peers in open environment is defined as:

$$MP2P = \{MP_i | 1 \leq i \leq N\} \quad (1)$$

where MP_i is a mediated peer network defined as:

$$MP_i = (OP_i, OG_i, S_i, R_i, G_i, L_i) \quad (2)$$

where:

OP_i: is the private ontology that is local to the peer MP_i and is not accessible to other mediated peers.

OG_i: is a global ontology for the mediated network MP_i that is shared with the immediate P2P neighbours of the mediated peer MP_i.
The following relationship holds between the private ontology and the global ontology of peer MP_i:

$$OG_i \subseteq_O OP_i \tag{3}$$

The operator $\subseteq_O$ in equation (3) is understood as; any query that can be answered by ontology OG_i can also be answered by OP_i.

S_i: is a set of data sources for the mediated peer MP_i.

R_i: is a set of accessibility relations between the peer MP_i and other peers in the P2P network.

G_i: is a set of P2P interfaces G_{ij}, each of which consists of a set of mappings between the elements of the private ontology OP_i of the peer MP_i and the global ontology OG_j of its immediate P2P neighbouring peer MP_j. A concept of one ontology is defined as a query over another ontology.

$$q_i(x) \rightsquigarrow q_j(x) \tag{4}$$

The mapping above maps an ontological view over the local ontology OP_i to another ontological view over the global ontology OG_j. The ontological view is defined as:
Definition: *Ontological View*: an ontological view over an ontology is a stored query over that ontology.

L_i: is a set of sets of local mappings L_{ik}. Each L_{ik} is a set of local mappings between the concepts of the private ontology OP_i of the peer MP_i and the local ontologies of the data source $S_{ik} \in S_i$, where S_i is the set of local data sources for the mediator peer MP_i.

Traditionally, the entire DIS is represented as a single theory. When dealing with a distributed system, if a query is posed to the private ontology OP_i of a peer MP_i, the answers to the intensionally equivalent query that is executed against another peers will be considered as part of the global answer to the original user query. However, these answers are based on the relative believes of each peer about the knowledge of its own neighbours. As such, the peer MP_i can only make claims about what it beliefs the knowledge of its own neighbour is. As such the global answer will be expressed in terms of the nested believes and will be calculated in stages until the last peer is reached. This shows that the whole network in the IEL setting may not be formulized as a single theory. Instead, every mediated peer and its immediate neighbours are represented by a separate theory. At the same time, the mediated network of each peer has its own IEL theory as well.
Definition: The ontology based Mediated P2P DIS in open environment is formalized as a set T_{GP} of N distinguished global IEL theories, one for each mediated network MP_i, and a set T_{LP} of N distinguished local IEL theories, one for each mediated network. This can be expressed as follows:

$$T_{MP2P} = < T_{GP}, T_{LP} > \tag{5}$$

where:

$$T_{GP} = \{T_{GPi} | 1 \leq i \leq N\} \tag{6}$$

and,

$$T_{LP} = \{T_{LPi} | 1 \leq i \leq N\} \tag{7}$$

Each global, P2P, IEL theory T_{GPi} is defined by:

- A set of agents $AGTS$:

$$AGTS = \{P_i\} \cup \{P_j | MP_j \in R_i(MP_i)\} \tag{8}$$

- The alphabet $A_{TGPi:}$ A_{TGPi} for the IEL theory T_{GPi} is the disjoint union of the alphabets of the private ontology OPi and the alphabets of the global ontologies OG_j of its immediate P2P neighbours.

$$\mathcal{A}_{TGPi} = \mathcal{A}_{OPi} \sqcup \{\mathcal{A}_{OGj} | MP_j \in R_i(MP_i)\} \tag{9}$$

- All the formulas of the private ontology OP_i, and the global ontologies OG_j of the immediate neighbours of MP_i are going to be axioms in the theory T_{GPi}
- For every global mapping assertion in the set G_{ij} of the form:

$$q_1(x) \rightsquigarrow q_2(x) \tag{10}$$

there is an axiom in T_{GPi} in the form:

$$\forall x (B_{Pi} B_{Pj} q_1(x)^2 \leftarrow B_{Pj} q_2(x)^1) \tag{11}$$

The assertion in equation (11) is interpreted as; if mediated peer MP_j believes something about the query $q_2(x)$, then the neighbouring P2P mediated peer MP_i believes that peer MP_j believes the same thing about the query $q_1(x)$ evaluated at mediated peer MP_j. Here query $q_1(x)$ evaluated at peer MP_j is understood to be the result of applying the appropriate P2P mappings to $q_1(x)$ to yield a query $q_2(x)$ over the global ontology of mediated peer MP_j and executing the query $q_2(x)$ to get the answer in an actual interpretation at mediated peer MP_j.

On the other hand, each local, Mediated, IEL theory T_{LPi} is defined by:

- A set of agents $AGTS$:

$$AGTS = \{P_i\} \cup S_i \tag{12}$$

- The alphabet A_{TLPi} for the IEL theory T_{LPi} is the disjoint union of the alphabets of the private ontology OP_i and the alphabets of the set S_i of its local data sources.

$$\mathcal{A}_{TLPi} = \mathcal{A}_{OPi} \sqcup \{\mathcal{A}_{Sik} | S_{ik} \in S_i\} \tag{13}$$

- All the formulas of the private ontology OP_i and the ontologies of all data sources of its local mediated network are going to be axioms in the theory T_{LPi}.
- For every local mapping assertion in the set L_{ik} of the form:

$$q_1(x) \rightsquigarrow q_2(x) \tag{14}$$

there is an axiom in T_{LPi} in the form:

$$\forall x(B_{Pi}q_1(x)^1 \leftarrow q_2(x)) \tag{15}$$

The assertion in equation (15) is understood as; if there is an assignment that makes query $q_2(x)$ true in the intended interpretation of data source S_k of mediated network MPi, then MP_i believes the same thing about the intensionally equivalent global query $q_1(x)$. Here query $q_2(x)$ is the result of applying the appropriate local mappings L_{ik} to $q_1(x)$.

In this setting, the system can be seen as a set of collaborating data integration systems. Each data integration system consists of a peer, the set of its neighbouring peers, and the set of its local data sources.

5 INTERFACE AND QUERY SEMANTICS

The interface between one peer and the data sources within its mediated network will be modelled as Global-As-View GAV mapping (Lenzerini 2002). This is because queries will always come from the mediator to a data source. On the other hand, since the query can be asked to any peer, we model the mapping between peers in the P2P network as GLAV model (Friedman, Levy, and Millstein 1999). In the GLAV model, queries of one ontology are mapped to equivalent queries over other ontologies. This mapping requires the two queries to be equivalent. The intensional equivalence between two queries is expressed as follows:

$$q_1(x) \equiv_{in} q_2(x) \tag{16}$$

Another important point is that, the answer to a query posed to a peer is expressed in terms of its local beliefs plus the nested relative believes of the peers that are accessible from this peer. These neighbours are found using the accessibility function R defined above. Using the IEL, the intensional index will indicate the belief operator, and in turns the domain, in which the query will be evaluated.

The intensional semantics for the Mediated P2P data integration system in open environment is described below.

We consider a model $\mathcal{M}$ for the intensional epistemic logic ontology driven Mediated P2P data integration network of N peers, i.e. N mediated networks, as a structure:

$$\mathcal{M} = <W, \pi, D, \mathcal{K}> \tag{17}$$

where,

- W: is the set of the different states or interpretations for the Mediated P2P network. Here we limit the set of possible interpretations to the actual interpretations, intended interpretation, at each peer's network.
- π: is a set of reflexive relations on the form (w_{ik}, w_{ik}) where w_{ik} is a possible states for the mediator peer MP_i and ($w_{ik} \in W$). As such, it is enough for the query to be satisfied in the actual world in order for the extensionalization of the query to be an answer.
- $D = \{D_1, D_2, \ldots D_N\}$ is the disjoint union of the domains of all the mediator in the network.
- $\mathcal{K}$: is a set of extensionalization functions for the mediators. It follows that, for a query $q(x)$ posed to a mediator peer MP_i, the local answer to the query is $\mathcal{k}_i(q_i(x)) \in D_i$. The global answer includes all the answers for the equivalent queries $\mathcal{k}_j(G_{ij}(qi(x))) \in D_j$ for each mediated network MP_j accessible to mediated network MP_i and so on.

1. A query $q(x)$ is satisfied in a state w_{ik} of a peer MP_i by the tuple of constants c, $\mathcal{M}, w_{ik} \vDash_c q(x)$ if $\mathcal{k}_j(q(x)) = c \in D_i$ and

$q(c)$ is true in interpretation w_{ik}, where $k_j(q(x))$ is the extensionalization of query $q(x)$ in the world w_{ik} of a peer MP_i.

2. An atom of the form $B_{Pi}(q(x)^1)$ is satisfied in the world w_{ik} of mediator peer MP_i by the tuple $c, \mathcal{M}, w_{ik} \vDash_c B_{Pi}\, q(x)^1$, if $q(c)$ is true in state w_i of mediator peer MP_i and $k_i(q(x)) = c \in D_i$. This is equivalent to saying that $q(c)$ is true in all worlds w_j where $(w_i, w_j) \in \pi$. However, π is only a reflexive relation. This means that, the set of possible worlds for peer MP_i is a set of only one member which is the actual world w_{ik} for mediator peer MP_i.
3. An atom of the form $B_{Pi}\ B_{Pj}(q(x)^2)$ is satisfied in the peer MP_i by the tuple of constants $c, \mathcal{M}, P_i \vDash_c B_{Pi}\, B_{Pj}\, q(x)^2$ if peer MP_j is accessible from MP_i and $G_{ij}(q(c))$ is true in a world w_{jl} of MP_j and the extensionalization of query $G_{ij}(q(x))$ in the world w_{jl} of MP_j is $k_j(G_{ij}(q(x))) = c \in D_j$.
4. An atom of the form $B_{Pi}\ B_{Pj}\ \dots\ B_{Pm}(q(x))$ with n nested modal belief operators is satisfied in the actual world of peer MP_i by the tuple of constants c if $B_{Pj}\ \dots\ B_{Pm}(G_{ij}(q(x)^{DEC}))$ is satisfied in a possible world of mediator peer MP_j by the tuple of constants $c \in D_j$. Here $q(x)^{DEC}$ is the result of decreasing all the intensional indexes in the formula $q(x)$ by 1.

6 QUERY ANSWERING

Answering queries in a mediated P2P network in open environment can be challenging. There are several formal and practical challenges. In this work, we will attempt to describe the query answering semantics in light of the proposed intensional epistemic logic model. (Yang and Garcia-Molina 2002) presented three different approaches for finding an answer to a query in a P2P network. The methods described in (Yang and Garcia-Molina 2002) depend on some metrics. These metrics depend on, for example, whether satisfying the query is more important or optimizing the execution time is of more value. In order to describe the query answering semantics for the proposed Mediated P2P model, we will use the satisfiability of the query as our metric. As such, all possible routes for an answer will be pursued.

Consider the Mediated P2P network in Figure 2. For simplicity, the mediated network is abstracted

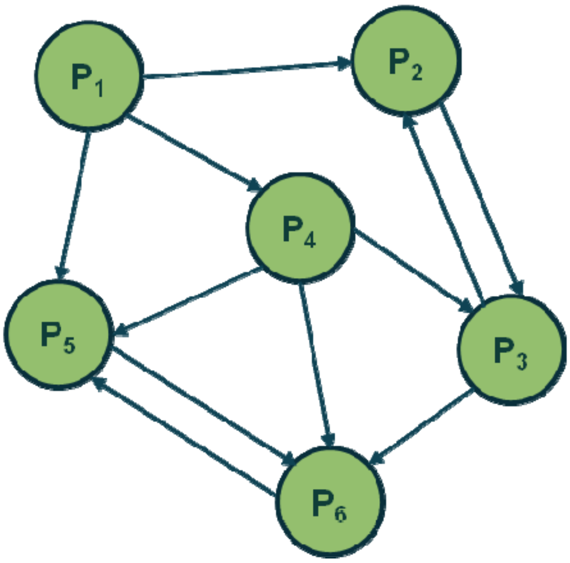

Figure 2: P2P network with 6 peers.

out. Since the graph in Figure 2 is cyclic, the tree in Figure 3 is formed. In Figure 3, the nodes, in the level past the second level, are prefixed in order to indicate the route to that node. Calculating all the possible answers to a query posed to the peer P_1 in Figure 2 is equivalent to calculating the answers at all nodes of the tree in Figure 3. This assumes some mappings exist from the root to the node at which the query answer is calculated. The global answer to query $q(x)$ is expressed in term of the set of all possible answers. If we refer to the global answer as Ans_g and the possible answers as Ans_p, the global answer for $q(x)$ at P_i is expressed as follows:

$$Ans_g\,(q(x), MP_i) = B_{Pi}\, q(x)^1 \cup Ans_p\,(q(x), P_i, P_i) \tag{18}$$

where,

$$B_{Pi}\, q(x)^1 = \bigcup_{k \in Si} k_{ik}(q(x)) \tag{19}$$

and,

$$Ans_p\,(q(x), P_i, P_i) = \bigcup_{j \in Children(Pi)} Ans_P\,(q(x), P_i, P_j) \tag{20}$$

and,

$$Ans_p\,(q(x), P_i, P_j) = B_{Pi}B_{Pj}\, q(x)^2 \cup Ans_p\,(G_{ij}(q(x)), P_j, P_j) \tag{21}$$

The global answer to the query is the set of all possible answers in the query tree in a nested manner. In that sense, the beliefs of a nodes about a query affects the beliefs of all its ancestors about the equivalent queries but not the other way around. In order to describe the local answer to a query $q_j(x)$ at

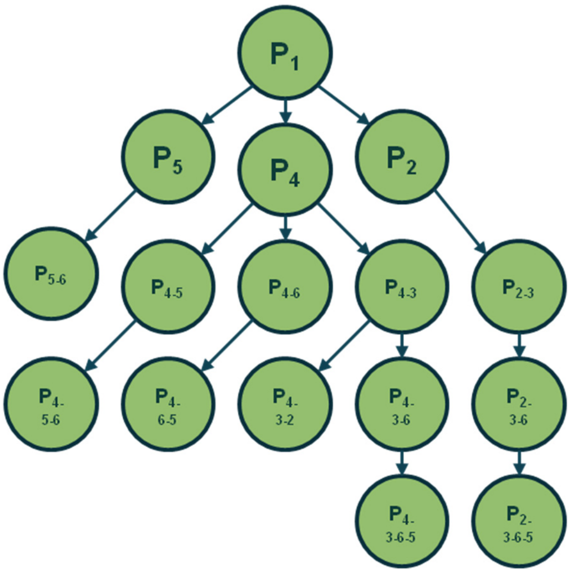

Figure 3: Acyclic query answering tree.

a peer MP_j we will consider a data source S_{jk} in the mediated network of MP_j. We will also consider that the query $q_j(x)$ is expressed over the global ontology of peer MP_j. The semantics of the local answer to the query $q_j(x)$ is described as follows:

$$Ans_l(q_j(x), P_j, S_{jk}) = B_{Pj}B_{Sjk}\, q_j(x)^1 = ƙ_{jk}(q_j(x)) \qquad (22)$$

Where $ƙ_{jk}(q_j(x)$ is the extensionalization of the intensionally equivalent query to $q_j(x)$ after applying the proper local mapping L_{jk}.

As has been demonstrated, the use of intensional epistemic logic enables us to present a model that, not only accounts for the intensional nature of information systems and open environment, but also is able to describe the relative beliefs between various agents. This allows us to address the loosely-coupled nature of open environment. It also facilitates the development of clear intensional semantics for query answering in open environment.

7 CONCLUSION

An intensional model for data integration system in open environment is proposed. The architecture used is Mediated P2P architecture. This architecture is distributed in nature. But it also does not require every single information source to act as a DIS on its own. This addresses the distributed nature of open environment while eliminating the requirement that every information system acts as a DIS on its own. The DIS is formulated as a two level logic system. Each level consists of N intensional epistemic logic theories. This relaxes the constraint that all data information systems share the same domain. It also allows information systems to associate or dissociate with the system without affecting the overall functionality. Since information systems are intensional in nature, using intensional logic is a nature choice. Also, employing the intensional epistemic logic enabled us to describe the relative beliefs between different peers. This is particularly useful to address the loosely-coupled nature of open environment. This, also, is a key to specifying clear semantics for query answering in open environment.

REFERENCES

Ali, Islam, and Hamada Ghenniwa. 2012. "Conceptualization-A Novel Intensional-Based Model." In *KEOD*, 2:257–264. SCITEPRESS.

Ali, Islam, and Hamada Ghenniwa. 2014. "Ontology-Driven Mediated Data Integration in Open Environment." In *KEOD*, 230–239.

Anderson, C. Anthony. 1984. "General Intensional Logic." In *Handbook of Philosophical Logic: Volume II: Extensions of Classical Logic*, edited by D. Gabbay and F. Guenthner, 355–85. Synthese Library. Dordrecht: Springer Netherlands.

Bealer, George. 1979. "Theories of Properties, Relations, and Propositions." *The Journal of Philosophy* 76 (11): 634–48.

Bealer, George. 1982. *Quality and Concept*. Oxford University Press. https://philarchive.org.

Bealer, George. 1998. "Intensional Entities." In *Routledge Encyclopaedia of Philosophy*, 803–7. London: Routledge.

Boyles, R. R., A. E. Thessen, A. Waldrop, and M. A. Haendel. 2019. "Ontology-Based Data Integration for Advancing Toxicological Knowledge." *Current Opinion in Toxicology*, Systems Toxicology, 16 (August): 67–74.

Calvanese, Diego, Giuseppe De Giacomo, Domenico Lembo, Maurizio Lenzerini, and Riccardo Rosati. 2018. "Ontology-Based Data Access and Integration." In *Encyclopedia of Database Systems*, edited by Ling Liu and M. Tamer Özsu, 2590–96. New York, NY: Springer.

Chen, Jingliang, Dmytro Dosyn, Vasyl Lytvyn, and Anatoliy Sachenko. 2017. "Smart Data Integration by Goal Driven Ontology Learning." In *Advances in Big Data*, edited by Plamen Angelov, Yannis Manolopoulos, Lazaros Iliadis, Asim Roy, and Marley Vellasco, 283–92. Advances in Intelligent Systems and Computing. Cham: Springer International Publishing.

De Giacomo, Giuseppe, Domenico Lembo, Maurizio Lenzerini, Antonella Poggi, and Riccardo Rosati.

2018. “Using Ontologies for Semantic Data Integration.” In *A Comprehensive Guide Through the Italian Database Research Over the Last 25 Years*, edited by Sergio Flesca, Sergio Greco, Elio Masciari, and Domenico Saccà, 187–202. Studies in Big Data. Cham: Springer International Publishing.

Egami, Shusaku, Xiaodong Lu, Tadashi Koga, and Yasuto Sumiya. 2020. “Ontology-Based Data Integration for Semantic Interoperability in Air Traffic Management.” In *2020 IEEE 14th International Conference on Semantic Computing (ICSC)*, 295–302.

Fitting, Melvin. 2006. “Intensional Logic.” In *The Stanford Encyclopedia of Philosophy*, edited by Edward N. Zalta, Spring 2020. Metaphysics Research Lab, Stanford University.

Friedman, Marc, Alon Levy, and Todd Millstein. 1999. “Navigational Plans for Data Integration.” In *Proceedings of the 1999 International Conference on Intelligent Information Integration - Volume 23*, 72–78. III’99. Stockholm, Sweden: CEUR-WS.org.

Guarino, Nicola. 1998. *Formal Ontology in Information Systems: Proceedings of the First International Conference (FOIS’98), June 6-8, Trento, Italy*. Vol. 46. IOS press.

Guarino, Nicola, and Pierdaniele Giaretta. 1995. “Ontologies and Knowledge Bases.” *Towards Very Large Knowledge Bases*, 1–2.

Guarino, Nicola, Daniel Oberle, and Steffen Staab. 2009. “What Is an Ontology?” In *Handbook on Ontologies*, 1–17. Springer.

Gusenkov, A., N. Bukharaev, and E. Birialtsev. 2019. “On Ontology Based Data Integration: Problems and Solutions.” *Journal of Physics: Conference Series* 1203 (April): 012059.

Halevy, A.Y., Z.G. Ives, D. Suciu, and I. Tatarinov. 2003. “Schema Mediation in Peer Data Management Systems.” In *Proceedings 19th International Conference on Data Engineering (Cat. No.03CH37405)*, 505–16.

Jiang, Yue J. 1993. “An Intensional Epistemic Logic.” *Studia Logica: An International Journal for Symbolic Logic* 52 (2): 259–80.

Jubien, Michael. 1988. “Problems with Possible Worlds.” In *Philosophical Analysis: A Defense by Example*, edited by David F. Austin, 299–322. Philosophical Studies Series. Dordrecht: Springer Netherlands.

Lenzerini, Maurizio. 2002. “Data Integration: A Theoretical Perspective.” In *Proceedings of the Twenty-First ACM SIGMOD-SIGACT-SIGART Symposium on Principles of Database Systems*, 233–246. PODS ’02. Madison, Wisconsin: Association for Computing Machinery.

Lumineau, Nicolas, Anne Doucet, and Stéphane Gançarski. 2006. “Thematic Schema Building for Mediation-Based Peer-to-Peer Architecture.” *Electronic Notes in Theoretical Computer Science*, Proceedings of the International Workshop on Database Interoperability (InterDB 2005), 150 (2): 21–36.

Majkić, Zoran. 2009. “Intensional First-Order Logic for P2P Database Systems.” Edited by Stefano Spaccapietra. *Journal on Data Semantics XII*, Lecture Notes in Computer Science, , 131–52.

Selman, Bart, and Hector J. Levesque. 1993. “The Complexity of Path-Based Defeasible Inheritance.” *Artificial Intelligence* 62 (2): 303–39.

Wang, Ying Daisy. 2009. “Ontology-Driven Semantic Transformation for Cooperative Information Systems.” University of Western Ontario.

Xue, Yunjiao. 2010. “Ontological View-Driven Semantic Integration in Open Environments.”

Xue, Yunjiao, Hamada H. Ghenniwa, and Weiming Shen. 2010. “A Frame-Based Ontological View Specification Language.” In *The 2010 14th International Conference on Computer Supported Cooperative Work in Design*, 228–33.

Yang, B., and H. Garcia-Molina. 2002. “Improving Search in Peer-to-Peer Networks.” In *Proceedings 22nd International Conference on Distributed Computing Systems*, 5–14.