Semantic Matching

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Abstract

We think of *match* as an operator that takes two graph-like structures (e.g., database schemas or ontologies) and produces a mapping between elements of the two graphs that correspond semantically to each other. The goal of this paper is to propose a new approach to matching, called *semantic matching*. As from its name, the key intuition is to exploit the model-theoretic information, which is codified in the nodes and the structure of graphs. The contributions of this paper are (i) a rational reconstruction of the major matching problems and their articulation in terms of the more generic problem of matching graphs; (ii) the identification of semantic matching as a new approach for performing generic matching; and (iii) a proposal of implementing semantic matching via SAT.

1 Introduction

The progress of information and communication technologies has made accessible a large amount of information stored in different application-specific databases and web sites. The number of different information resources is rapidly increasing, and the problem of semantic heterogeneity is becoming more and more severe, see for instance [Halevy, 2001], [Washe *et al.*, 2001], [Goh, 1997], [Giunchiglia and Zaihrayeu, 2002]. One proposed solution is matching. *Match* is an operator that takes two graph-like structures (e.g., database schemas or ontologies) and produces a mapping between elements of the two graphs that correspond semantically to each other. So far, with the noticeable exception of [Serafini *et al*, 2003], the key intuition underlying *all* the approaches to matching has been to map labels (of nodes) and to look for similarity (between labels) using syntax driven techniques and syntactic similarity measures; see for instance [Do and Rahm, 2002], [Madhavan *et al.*, 2001]. Thus for example, some of the most used techniques look for common substrings (e.g., ″phone″ and ″telephone″) or for strings with similar soundex (e.g., ″4U″ and ″for you″) or expand abbreviations (e.g., ″P.O″ and ″Post Office″). We say that all these approaches are different variations of *syntactic matching*. In syntactic matching semantics are not analyzed directly, but semantic correspondences are searched for only on the basis of syntactic features.

In this paper we propose a novel approach, called *semantic matching*, with the following main features:

- We search for semantic correspondences by mapping meanings (concepts), and not labels, as in syntactic matching. As the rest of the paper makes clearer, when mapping concepts, it is not sufficient to consider the meanings of labels of the nodes, but also the positions that the nodes have in the graph.
- We use semantic similarity relations between elements (concepts) instead of syntactic similarity relations. In particular, we consider relations, which relate the extensions of the concepts under consideration (for instance, more/less general relations).

The contributions of this paper are (i) a rational reconstruction of the major matching problems and their articulation in terms of the more generic problem of matching graphs; (ii) the identification of semantic matching as a new approach for performing generic matching; and (iii) a proposal of using SAT as a possible way of implementing semantic matching. It is important to notice that SAT is a correct and complete decision procedure for propositional logics. Using SAT allows us to find only and all possible mappings between elements. This is another major advantage over syntactic matching approaches, which are based on heuristics. The SAT-based algorithm discussed in this paper is a minor modification/extension of the work described in [Serafini *et al*, 2003].

The rest of the paper is organized as follows. Section 2 introduces some well-known matching problems and shows how they can be stated in terms of the generic problem of matching graphs. Section 3 defines the notion of matching and discusses the essence of semantic matching. Section 4 provides guidelines to the implementation of semantic matching. Section 5 overviews the related work. Section 6 reports some conclusions.

2 Matching Problems

Major data and conceptual models representing information sources across the WWW are database schemas, XML schemas, and ontologies.

2.1 Relational DB schemas

Let us consider the hypothetical relational database (RDB) BANK presented in Figure 1, storing information about the location of branches and of the staff that works at the BANK.

BRANCH

BN	Street	City	Zip
B8	Piazza Venezia	Trento	38100
B2	Piazza Cordusio	Milano	20123

STAFF

SN	F_Name	L_Name	Position	Salary	BN
S31	John	Dow	CFO	170	B2
S27	Eric	O'Neill	CTO	130	B8

Figure 1. RDB BANK

We can represent the schema and data instances of the above database as a graph in two possible ways. In the first case, starting from the name (root), the schema is partitioned into relations and further down into attributes and data instances. See Figure 2. Arcs of Level 1 encode relations; arcs of Level 2 stand for attributes, and arcs of Level 3 specify data instances. Blank nodes stand for primary keys. Blank nodes with dashed circles stand for foreign keys. Notice that we know in advance that the maximum height of the tree is 3.

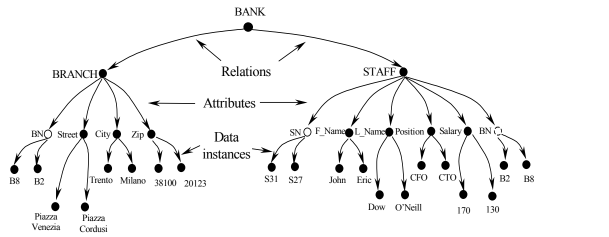

Figure 2. Tree representation 1 of the RDB BANK

In the second approach, as from [Buneman *et al.*, 1996], starting from the root, a database is partitioned into relations, then into tuples, and finally into attributes and data instances. See Figure 3. For lack of space not all attributes and their identifiers are presented in the diagram. Notice that the maximum height of the tree is 4.

The information about the structure of the database resides only at arcs' labels. Dashed arcs stand for primary keys. *R1* and *R2* denote relations of the database BANK. *ROOT.RI.TJ.AK* is a path to the *K-th* attribute of the *J-th* tuple of the *I-th* relation from the root of the tree. Data instances are presented as arcs at Level 4. Thus, the instances of the element BRANCH are represented by tuples: ("B8", "Piazza Venezia", "Trento", "38100") and ("B2", "Piazza Cordusio", "Milano", "20123").

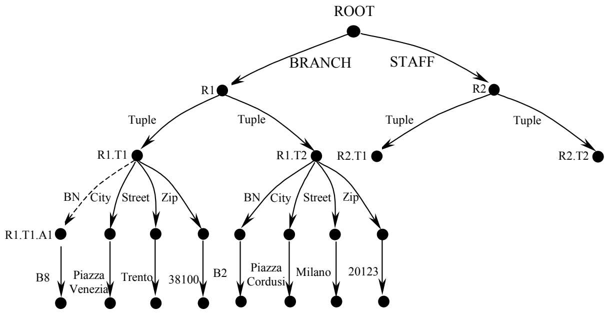

Figure 3. Tree representation 2 of the RDB BANK

Which of the two representations is more preferable depends on the concrete task, but its worth to note that it's always possible to transform one model into another.

Database schemas are seldom trees. If referential constraints are taken into account, schemas become DAGs. If we further consider recursive references we have cycles, see Figure 4. Referential constraints are shown as dashed arrows. Bold arrows represent recursive references, which appear if, for instance, we add to the relation STAFF the attribute Manager that expresses administrative relationships between employees.

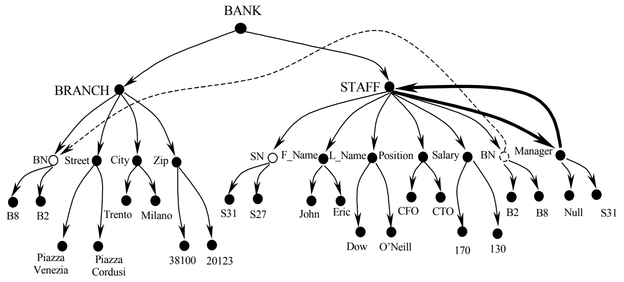

Figure 4. Graph representation of the RDB BANK

2.2 OODB schemas

Let us rebuild the relational database BANK example in terms of an object-oriented approach. Now, BANK consists of the three classes, expressing the same data as above:

BRANCH(Street, City, Zip)
PERSON(F_Name, L_Name)
STAFF:PERSON(Position, Salary, Manager).

A graph representation of the given OODB schema is shown in Figure 5. Arcs with blank arrows stand for the use case generalization; dashed arrows play notationally the same role as associations in UML.

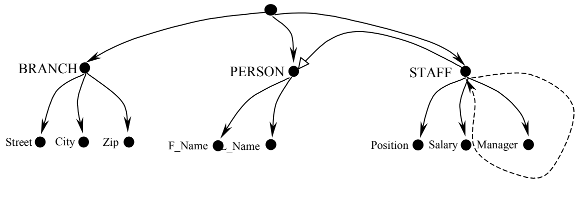

Figure 5. Digraph representation of the OODB BANK

The object-oriented data model captures more semantics than the relational data model. It explicitly expresses subsumption relations between elements, and admits special types of arcs for part/whole relationships in terms of aggregation and composition.

2.3 XML schemas

Neither the OO data model, nor the relational data model captures all the features of semistructured or unstructured data [Buneman, 1997]. Semistructured data don't possess regular structure; the structure could be partial or even implicit. Missing or duplicated fields are allowed. Semistructured data could be schemaless, or have a schema that poses only loose constraints on data. Typical examples are markup languages, e.g. HTML or XML.

XML schemas can be represented as DAGs. The graph in Figure 2 could also be obtained from an XML schema. Often, XML schemas represent hierarchical data models. In this case the only relationships between the elements are *{is-a}*. A DAG is obtained through the ID/IDREF mechanism. Attributes in XML are used to represent extra information about data. There are no strict rules telling us when data should be represented as elements, or as attributes.

2.4 Concept Hierarchies

A *concept hierarchy* is a way of defining a conceptualization of an application domain in terms of concepts and relationships expressed in a formal language. Concept hierarchies usually support *{is-a}* relations. Traditional examples of concept hierarchies are classifications, for instance, parts of Yahoo and Google electronic catalogs. Figure 6 presents a part of Google web directory devoted to business.

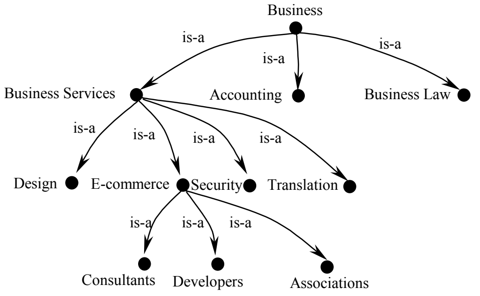

Figure 6. Google web directory

The concept hierarchy shown in Figure 6 consists of 11 concepts, and 10 subsumption relations, one per arc.

2.5 Ontologies

By an *ontology* we mean here a way of defining a conceptualization of an application domain in terms of concepts, attributes, and relations expressed in a formal language. Relations can be defined by the user, but there are some predefined relationships with known semantics, i.e., *{is-a; part-of; instance-of}*. A concept hierarchy is an ontology without attributes and only with *{is-a}* relations between elements.

One example of ontology can be constructed by complicating the concept hierarchy shown in Figure 6, by adding attributes to the concept Association, see Figure 7. Attributes of the concept Associations are BN, City, Street, Zip, while data instances are B8 and B2. Data instances have fixed attributes values: instance B8 has BN="B8", City="Trento", Street="Piazza Venezia", etc.

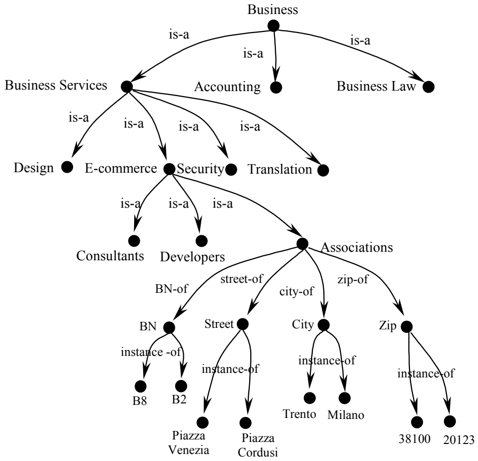

Figure 7. Example of ontology Business

3 Matching

All the data and conceptual models discussed in the previous section can be represented as graphs. Therefore, the problem of matching heterogeneous and autonomous information resources can be decomposed in two steps:

1. extract graphs from the data or conceptual models,
2. match the resulting graphs.

Notice that this allows for the statement and solution of a more *generic matching problem*, very much along the lines of what done in Cupid [Madhavan *et al*., 2001], and COMA [Do and Rahm, 2002]. However, as already discussed in some detail in Section 2, each of the five matching problems presented there, has different properties and it is still an open problem whether we will be able to develop a *general purpose matcher*, and exploit most (all?) the problem and domain dependent analysis in step (1).

Let us define the notion of matching graphs more precisely. *Mapping element* is a 4-tuple $< m_{ID}, N^i_1, N^j_2, R >$, $i=1...h; j=1..k$; where m_{ID} is a unique identifier of the given mapping element; N^i_1 is the *i-th* node of the first graph, h is the number of nodes in the first graph; N^j_2 is the *j-th* node of the second graph, k is the number of nodes in the second graph; and R specifies a *similarity relation* of the given nodes. A *Mapping* is a set of mapping elements. *Matching* is the process of discovering mappings between two graphs through the application of a matching algorithm. There exist two approaches to graph matching, namely *exact matching* and *inexact* or *approximate matching*. Both of them can be stated as subgraph matching problems: find all occurrences of a pattern graph P of m nodes as a subgraph of a graph G of n nodes, $m \leq n$. In the case of exact matching we look for subgraphs S of G that are identical to P. In inexact matching some errors are acceptable. For obvious reasons we are interested in inexact matching.

We classify matching into *syntactic* and *semantic matching* depending on how matching elements are computed and on the kind of similarity relation R used.

- In *syntactic matching* the key intuition is to map labels (of nodes) and to look for the similarity using syntax driven techniques and syntactic similarity measures. Thus, in the case of *syntactic matching*, mapping elements are computed as 4-tuples $< m_{ID}, L^i_1, L^j_2, R >$, where L^i_1 is the *label* at the *i-th* node of the first graph; L^j_2 is the *label* at the *j-th* node of the second graph; and R specifies a similarity relation in the form of a coefficient, which measures the similarity between the *labels* of the given nodes. Typical examples of R are coefficients in [0,1], for instance, *similarity* coefficients [Madhavan *et al*., 2001]. Similarity coefficients usually measure the closeness between the two elements linguistically and structurally. For instance, based on linguistic analysis, the similarity coefficient between elements "telephone" and "phone" from the two hypothetical schemas could be 0,7.
- As from its name, in *semantic matching* the key intuition is to map meanings (concepts). Thus, in the case of *semantic matching*, mapping elements are computed as 4-tuples $< m_{ID}, C^i_1, C^j_2, R >$, where C^i_1 is the *concept* of the *i-th* node of the first graph; C^j_2 is the *concept* of the *j-th* node of the second graph; and R specifies a similarity relation in the form of a semantic relation between the *extensions of concepts* at the given nodes. Possible R's between nodes are *equality* (=), *overlapping* ($\cap$), *mismatch* ($\perp$), or *more general/specific* ($\subseteq$, $\supseteq$).

These ideas are schematically represented in Figure 8. It is important to notice that all past approaches to matching we are aware of, with the exception of [Serafini *et al*, 2003], are based on syntactic matching.

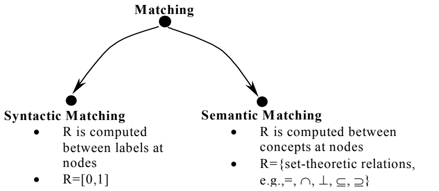
Matching
Syntactic Matching
• R is computed between labels at nodes
• R=[0,1]
Semantic Matching
• R is computed between concepts at nodes
• R={set-theoretic relations, e.g.,=, ∩, ⊥, ⊆, ⊇}

Figure 8. Matching problems

One of the key differences between syntactic and semantic matching is that in syntactic matching, when we match two nodes, we only consider the labels attached to them, independently of the position of the nodes in the graph. In semantic matching, instead, when we match two nodes, the concepts we analyse depend not only on the concept attached to the node (the concept denoted by the label of the node), but also on the position of the node in the graph. Let us consider the example in Figure 9. Numbers in circles are the unique identifiers of the nodes under consideration. A stands for the label at a node; A' stands for the concept denoted by A; $\boldsymbol{C_i}$ stands for the concept at the node i (in the following we sometimes confuse concepts with their extensions).

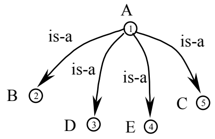

Figure 9. Syntactic vs. semantic matching

Let us consider for instance, the analysis carried out when the node numbered *5* is submitted to matching (against a node in another graph). In syntactic matching the matcher tries to match the label at node *5*, namely C. In semantic matching, instead, the matcher tries to match the concept at node *5,* namely $\boldsymbol{C}_5$, which is that subset of the extension of A' which is also in the extension of C'. Thus, $\boldsymbol{C}_5 = A' \cap C'$. A semantic matcher will therefore try to match $A' \cap C'$ and not (!) C.

Let us consider some more examples, which make the consequences of the observation described in the previous paragraph clearer. For any example we also report the results produced by the state of the art matcher, Cupid [Madhavan *et al*., 2001], which exploits very sophisticated syntactic matching techniques. Notationally in the following we write A_1 to mean that the string A occurs in the graph on the left, and A_2 to mean that A occurs in the graph on the right. We use the same notation also for nodes of graphs, concepts denoted by labels, and concepts at nodes. Thus for instance, 5_1 stands for the node *5* in the graph on the left, A'_1 is the concept denoted by the label A_1, while $\boldsymbol{C}_{5_1}$ is the concept at node 5_1.

Analysis of siblings. Let us consider Figure 10. Structurally the graphs shown in Figure 10 differ in the order of siblings. Suppose that we want to match node 5_1 with node 2_2.

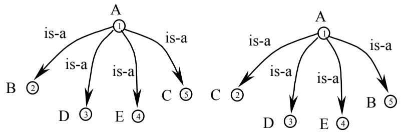

Figure 10. Analysis of siblings. Case 1

Cupid correctly processes this situation, and as a result, the similarity coefficient between labels at the given nodes equals to 0,8. This is because A_1=A_2, C_1=C_2 and we have the same structures on both sides. A semantic matching approach compares concepts $A'_1 \cap C'_1$ with $A'_2 \cap C'_2$ and produces $\boldsymbol{C}_{5_1} = \boldsymbol{C}_{2_2}$.

Analysis of ancestors. Let us consider Figure 11. Suppose that we want to match nodes 5_1 and 1_2.

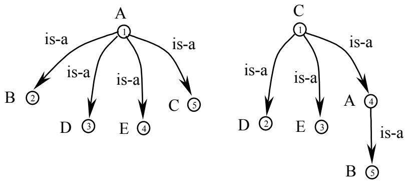

Figure 11. Analysis of ancestors. Case 1

Cupid does not find a similarity coefficient between the nodes under consideration, due to the significant differences in structure of the given graphs. In semantic matching, the concept denoted by the label at node 5_1 is C'_1, while the concept at node 5_1 is $\boldsymbol{C}_{5_1}=A'_1\cap C'_1$. The concept at the node 1_2 is $\boldsymbol{C}_{1_2}=C'_2$. By comparing the concepts denoted by the labels at nodes 5_1 and 1_2 we have that, being identical, they denote the same concept, namely $C'_1=C'_2$. Thus, the concept at node 5_1 is a subset of the concept at node 1_2, namely $\boldsymbol{C}_{5_1}\subseteq \boldsymbol{C}_{1_2}$.

Let us complicate the example shown in Figure 11 by allowing for an arbitrary distance between ancestors, see Figure 12. The asterisk means that an arbitrary number of nodes are allowed between nodes 1_2 and 5_2. Suppose that we want to match nodes 5_1 and 5_2.

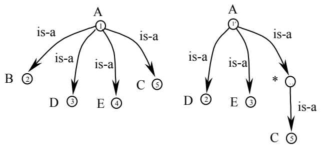

Figure 12. Analysis of ancestors. Case 2

Cupid finds out that the similarity coefficient between labels C_1 and C_2 is 0,86. This is because of the identity of labels ($A_1=A_2$, $C_1=C_2$), and due to the fact that nodes 5_1 and 5_2 are leaves. Notice how Cupid treats very differently the two situations represented here and in the example above, even if, from a semantic point of view, they are similar. Following semantic matching, the concept at node 5_1 is $\boldsymbol{C}_{5_1} = A'_1\cap C'_1$; while the concept at node 5_2 is $\boldsymbol{C}_{5_2} = A'_2\cap *\cap C'_2$. Since we have that $A'_1=A'_2$ and $C'_1=C'_2$, then $\boldsymbol{C}_{5_2}\subseteq \boldsymbol{C}_{5_1}$.

Enriched analysis of siblings. Suppose that we want to match nodes 2_1 and 2_2, see Figure 13.

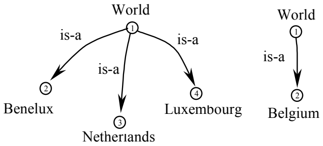

Figure 13. Analysis of siblings. Case 2.

Cupid without thesaurus doesn't find a match; with the use of thesaurus it finds out that the similarity coefficient between nodes with labels $Benelux_1$ and $Belgium_2$ is 0,68. This is mainly because of the entry in the thesaurus specifying *Belgium* as a part of *Benelux,* and due to the fact that the nodes with labels $Benelux_1$ and $Belgium_2$ are leaves. Following semantic matching, both concepts $Belgium'_1$ and $Benelux'_2$ are subsets of the concept $World'_{1,2}$. Let us suppose that an oracle, for instance WordNet, states that *Benelux* is a name standing for *Belgium*, *Netherlands* and *Luxembourg*. Therefore, we treat $\boldsymbol{C}_{2_1}$ in Figure 14 as $Benelux'_1 \cap Netherlands'_1 \cap Luxembourg'_1 = Belgium$. Thus, $\boldsymbol{C}_{2_1} = \boldsymbol{C}_{2_2}$.

Analysis of attributes. Let us consider Figure 14. On the left we have a graph, which represents an ontology *World*, where *State* and *Square* are attributes of the concept *Europe*. *State* has two sets of items corresponding to *Italy* and *Belgium*. On the right we have a graph, which represents the concept hierarchy *World*, where the concept *Italy* is populated with a set of items about Italy. Attributes can be matched with attributes, but also with concepts. Suppose that we want to match nodes 7_1 and 4_2.

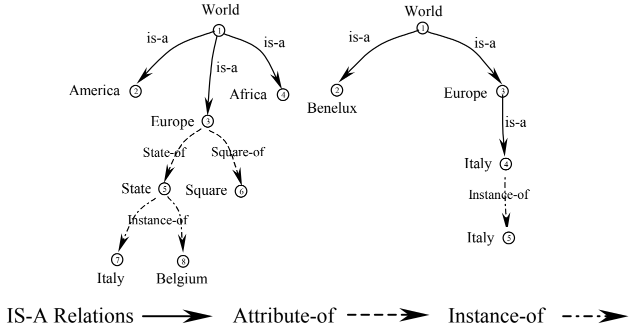

Figure 14. Analysis of attributes

Cupid does not find a match, due to the significant differences in structure of the given graphs. Following semantic matching, in our case, we can notice that we can substitute the path $World_1{:}Europe_1{:}State_1{:}Italy_1$ with $Italy_1$ (by taking the proper subset of items relating to Italy) and matching it with $Italy_2$. In this case we obtain $\boldsymbol{C}_{7_1} = \boldsymbol{C}_{4_2}$

4 Implementing Semantic Matching

There are two levels of granularity while performing semantic (and also syntactic matching) matching: *element-level* and *structure-level*. Element-level matching techniques compute mapping elements between individual labels/concepts at nodes; structure-level techniques compute mapping elements between subgraphs.

4.1 Element-level Semantic Matching

Element-level semantic techniques analyze individual labels/concepts at nodes. At the element-level we can exploit all the techniques discussed in the literature, see for instance [Do and Rahm, 2002], [Melnik *et al.*, 2002], [Rahm and Bernstein, 2001]. The main difference here is that, instead of a syntactic similarity measure, these techniques must be modified to return a semantic relation R, as defined in Section 3. We distinguish between *weak semantics* and *strong semantics* element-level techniques. *Weak semantics* techniques are syntax driven techniques: examples are techniques, which consider labels as strings, or analyze data types, or soundex of schema elements. Let us consider some examples.

Analysis of strings. String analysis looks for common prefixes or suffixes and calculates the distance between two strings. For example, the fact that the string "phone" is a substring of the string "telephone" can be used to infer that "phone" and "telephone" are synonyms. Before analyzing strings, a matcher could perform some preliminary parsing, e.g., extract tokens, expand abbreviations, delete articles and then match tokens. The analysis of strings discovers only equality between concepts.

Analysis of data types. These techniques analyze the data types of the elements to be compared and are usually performed in combination with string analysis. For example, the elements "phone" and "telephone" are supposed to have the same data type, namely "string" and therefore can be found equal. However, "phone" could also be specified as an "integer" data type. In this case a mismatch is found. As another example the integer "Quantity" is found to be a subset of the real "Qty". This kind of analysis can produce any kind of semantic relation.

Analysis of soundex. These techniques analyze elements' names from how they sound. For example, elements "for you" and "4 U" are different in spelling, but similar in soundex. This analysis can discover only equality between concepts.

Strong semantics techniques exploit, at the element-level, the semantics of labels. These techniques are based on the use of tools, which explicitly codify semantic information, e.g. thesauruses [Madhavan *et al.*, 2001], WordNet [Miller, 1995] or combinations of them [Castano *et al.*, 2000]. Notice that these techniques are also used in syntactic matching. In this latter case, however, the semantic information is lost before moving to structure-level matching and approximately codified in syntactic relations.

Precompiled thesaurus. A precompiled thesaurus usually stores entries with synonym and hypernym relations. For example, the elements "e-mail" and "email" are treated as synonyms from the thesaurus look up: *syn key* - "e-mail:email"=1. Precompiled thesauruses (most of them) identify equivalence and more general/specific relations. In some cases domain ontologies are used as precompiled thesauruses [Mena *et al.*, 1996].

WordNet. WordNet is an electronic lexical database for English (and other languages), where various *senses* (namely, possible meanings of a word or expression) of words are put together into sets of synonyms (synsets). Synsets in turn are organized as hierarchy. Following [Serafini *et al*, 2003] we can define the semantic relations in terms of senses. *Equality*: one concept is equal to another if there is at least one sense of the first concept, which is a synonym of the second. *Overlapping*: one concept is overlapped with the other if there are some senses in common. *Mismatch*: two concepts are mismatched if they have no sense in common. *More general / specific*: One concept is more general than the other iff there exists at least one sense of the first concept that has a sense of the other as a hyponym or as a meronym. One concept is less general than the other iff there exists at least one sense of the first concept that has a sense of the other concept as a hypernym or as a holonym. For example, according to WordNet, the concept "hat" is a holonym for the concept "brim", which means that "brim" is less general than "hat".

4.2 Structure-level Semantic Matching

The approach we propose is to translate the matching problem, namely the two graphs and our *mapping queries* into a propositional formula and then to check it for its validity. By mapping query we mean here the pair of nodes that we think will match and the semantic relation between them. We check validity by using SAT. Notice that SAT is a correct and complete decision for propositional satisfiability and therefore will exhaustively check for all possible mappings. Being complete, SAT automatically implements all the examples described in the previous section, and more. This is another advantage over syntactic matching, whose existing implementations are based only on heuristics.

Our SAT based approach to semantic matching incorporates six steps. We describe below its intended behavior by running these six steps on the example shown in Figure 11 and by matching nodes 5_1 and 1_2 (steps 2-5 are taken from [Serafini *et al*, 2003]).

1. **Extract the two graphs.** Notice that during this step, in the case of DB, XML or OODB schemas, it is necessary to extract useful semantic information, for instance in the form of ontologies. There are various techniques for doing this, see for instance [Mena *et al.*, 1996]. The result is the graph in Figure 11.
2. **Compute element-level semantic matching.** For each node, compute semantic relations holding among all the concepts denoted by labels at nodes under consideration. In this case A'_1 has no semantic relation with C'_2 while we have that $C'_1 = C'_2$.
3. **Compute concepts at nodes.** Starting from the root of the graph, attach to each node the concepts of all the nodes above it. Thus, we attach $\boldsymbol{C}_{1_1} = A'_1$ to node 1_1; $\boldsymbol{C}_{5_1} = A'_1 \cap C'_1$ to node 5_1; $\boldsymbol{C}_{1_2} = C'_2$ to node 1_2. As it turns out we have that $\boldsymbol{C}_{5_1} \subseteq \boldsymbol{C}_{1_2}$.
4. **Construct the propositional formula**, representing the matching problem. In this step we translate all the semantic relations computed in step 2 into propositional formulas. This is done according to the following transition rules:

$$\begin{gathered} A'_1 \supseteq A'_2 \Rightarrow A'_2 \rightarrow A'_1 \\ A'_1 \subseteq A'_2 \Rightarrow A'_1 \rightarrow A'_2 \\ A'_1 = A'_2 \Rightarrow A'_1 \equiv A'_2 \\ A'_1 \perp A'_2 \Rightarrow \neg(A'_1 \wedge A'_2) \end{gathered}$$

Subset translates into implication; equality into equivalence; disjointness into the negation of conjunction. In the case of Figure 11 we have that $C'_1 \equiv C'_2$ is an axiom. Furthermore, since we want to prove that $\boldsymbol{C}_{5_1} \subseteq \boldsymbol{C}_{1_2}$, our goal is to prove that $((A'_1 \wedge C'_1) \rightarrow C'_2)$. Thus, our target formula is $((C'_1 \equiv C'_2) \rightarrow (A'_1 \wedge C'_1 \rightarrow C'_2))$.

5. **Run SAT.** In order to prove that $((C'_1 \equiv C'_2) \rightarrow (A'_1 \wedge C'_1 \rightarrow C'_2))$ is valid, we prove that its negation is unsatisfiabile, namely that a SAT solver run on the following formula $(C'_1 \equiv C'_2) \wedge \neg ((A'_1 \wedge C'_1) \rightarrow C'_2)$ fails. A quick analysis shows that SAT will return FALSE.
6. **Iterations.** Iterations are performed re-running SAT. We need iterations, for instance, when matching results are not good enough, for instance no matching is found or a form of matching is found, which is too weak, and so on[1]. The idea is to exploit the results obtained during the previous run of SAT to tune the matching and improve the quality of the final outcome. Let us consider Figure 15.

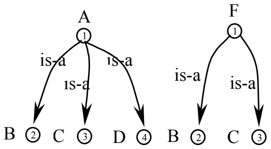

Figure 15. Not good enough answer

Suppose that we have found out that $\boldsymbol{C}_{2_1} \cap \boldsymbol{C}_{2_2} \neq \emptyset$, and that we want to improve this result. Suppose that an oracle tells us that $A'_1 = F'_2 \cup G'_2$. In this case the graph on the left in Figure 15 can be transformed into the two graphs in Figure 16.

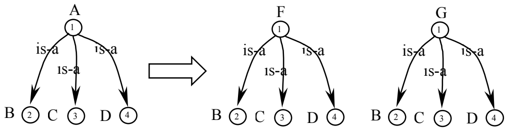

Figure 16. Extraction of additional semantic information

After this additional analysis we can infer that $\boldsymbol{C}_{2_1} = \boldsymbol{C}_{2_2}$. Another motivation for multiple iterations is to use the result of a previous match in order to speed up the search of new matches. Consider the following example.

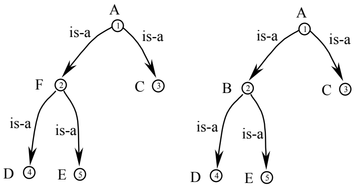

Figure 17. Iterations

Suppose that $F'_1 \subseteq B'_2$. Having found that $\boldsymbol{C}_{4_1} \subseteq \boldsymbol{C}_{4_2}$, we can automatically infer that $\boldsymbol{C}_{5_1} \subseteq \boldsymbol{C}_{5_2}$, without rerunning SAT, for obvious symmetry reasons.

5 Related Work

At present, there exists a line of semi-automated schema matching and ontology integration systems, see for instance [Madhavan *et al.*, 2001], [Do and Rahm, 2002], [Li and Clifton, 2000], [Castano *et al.*, 2000], [Arens *et al.*, 1996], [Mena *et al.*, 1996], [Doan *et al.*, 2002], etc. Most of them implement syntactic matching. A good survey, up to 2001, is provided in [Rahm and Bernstein, 2001]. The classification given in this survey distinguishes between individual implementations of match and combinations of matchers. Individual matchers comprise instance- and schema-level, element- and structure-level, linguistic- and constrained-based matching techniques. Individual matchers can be used in different ways, e.g. simultaneously (hybrid matchers), see [Li and Clifton, 2000], [Castano *et al.*, 2000], [Madhavan *et al.*, 2001] or in series (composite matchers), see for instance [Doan *et al.*, 2002], [Do and Rahm, 2002].

The idea of generic (syntactic) matching was first proposed by Phil Bernstein and implemented in Cupid system [Madhavan *et al.*, 2001]. Cupid implements a complicated hybrid match algorithm comprising linguistic and structural schema matching techniques, and computes normalized similarity coefficients with the assistance of a precompiled thesaurus. COMA [Do and Rahm, 2002] is a generic schema matching tool, which implements more recent composite generic matchers. With respect to Cupid, the main innovation seems to be a more flexible architecture. COMA provides an extensible library of matching algorithms; a framework for combining obtained results, and a platform for the evaluation of the effectiveness of the different matchers.

A lot of state of the art syntactic matching techniques exploiting weak semantic element-level matching techniques have been implemented. For instance, in COMA, schemas are internally encoded as DAGs, where the elements are the paths, which are analyzed using string comparison techniques. Similar ideas are exploited in Similarity Flooding (SF) [Melnik *et al.*, 2002]. SF is a hybrid matching algorithm based on the ideas of similarity propagation. Schemas are presented as directed labeled graphs; the algorithm manipulates them in an iterative fix-point computation to produce mappings between the nodes of the input graphs. The technique uses a syntactic string comparison mechanism of the vertices' names to obtain an initial mapping, which is further refined within the fix-point computation.

Some work has also been done in strong semantics element-level matching. For example, [Castano *et al.*, 2000] utilizes a common thesaurus, while [Madhavan *et al.*, 2001] has a precompiled thesaurus. In MOMIS [Castano *et al.*, 2000] element-level matching using a common thesaurus is carried out through a calculation of the name, structural and global affinity coefficients. The thesaurus presents a set of intensional and extensional relations, which depict intra- and inter-schema knowledge about classes, and attributes of the input schemas. All these systems implement syntactic matching and, when moving from element-level to structure-level matching, don't exploit the semantic information residing in the

[1] [Giunchiglia and Zaihrayeu, 2002] provides a long discussion about the importance of dealing with the notion of "good enough answer" in information coordination in peer-to-peer systems.

graph structure, and just translate the element-level semantic information into affinity levels.

As far as we know the only example where element-level and a simplified version of structure- level strong semantics matching have been applied is CTXmatch [Serafini *et al*, 2003]. In this work SAT is used as the basic inference engine for structure-level matching. The main problem of CTXmatch is that its rather limited in scope (it applies only to concept hierarchies), and it is hard to see the general lessons behind this work. For instance, the authors have made no attempt to do a thorough comparison of their approach with the other matching techniques, or to highlight its strengths and weaknesses. This paper provides the basics for a better understanding of the work on CTXmatch.

6 Conclusions and Future Work

In this paper we have stated and analyzed the major matching problems e.g., matching database schemas, XML schemas, conceptual hierarchies and ontologies and shown how all these problems can be defined as a more generic problem of matching graphs. We have identified semantic matching as a new approach for performing generic matching, and discussed some of its key properties. Finally, we have identified SAT as a possible way of implementing semantic matching, and proposed an iterative semantic matching approach based on SAT.

This is only very preliminary work, some of the main issues we need to work on are: develop an efficient implementation of the system, do a thorough testing of the system, also against the other state of the art matching systems, study how to take into account attributes and instances, analyze how to extract semantics from schemas (also taking into account integrity constraints), and so on.

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