Abstract

Information Integration is a young and exciting field with enormous research and commercial significance in the new world of the Information Society. It stands at the crossroad of Databases and Artificial Intelligence requiring novel techniques that bring together different methods from these fields. Information from disparate heterogeneous sources often with no a-priori common schema needs to be synthesized in a flexible, transparent and intelligent way in order to respond to the demands of a query thus enabling a more informed decision by the user or application program. The field although relatively young has already found many practical applications particularly for integrating information over the World Wide Web. This paper gives a brief introduction of the field highlighting some of the main current and future research issues and application areas. It attempts to evaluate the current and potential role of Computational Logic in this and suggests some of the problems where logic-based techniques could be used.

1 Introduction

Over the years a vast and diverse amount of data has been collected or created and stored by different users for different purposes. In the last decade it has been realized that new information can be extracted from this data by synthesizing in an
advanced, sometimes referred to also as intelligent, way the available information from the initial separate sources. Such synthesis or integration of information would facilitate and enable high-level tasks such as planning and decision making.

The problem of information integration has its origins in the problems of multidatabases, federated databases and interscheme extraction for global schema construction. Recently, the need to address this problem has been further emphasized with the explosion in the amount of information that is now available on-line over the information networks such as the Internet and the World Wide Web. This development has given new dimensions to the task of information integration requiring the integration of non-structured, highly distributed autonomous and dynamic information sources. A flexible and scalable strategy for integrating these disparate information sources while respecting their autonomy is required. At the same time it has brought with it an enormous commercial potential that is already helping to drive research in the field.

The general task of Information Integration can be simply stated, in an informal way, as that of "getting information sources to talk to each other" in order to support some higher level goal. We want to achieve integration of information without integrating the information sources themselves. Thus an information integration system must provide a uniform interface to information sources allowing the user or application program to focus on specifying what they require rather than specifying how or where to find the information. Some of the basic technical problems that need to be addressed by such a system are: modeling of the information content, query reformulation with flexible selection of information sources and query optimization. For many of these problems it is possible to employ, together with database techniques, other techniques from Artificial Intelligence (AI) and soon it was realized that the field of Information Integration lies at the intersection of Databases with Artificial Intelligence and other areas such as Information Retrieval and Human Computer Interaction. This in turn has now given an excellent application domain for (weak) AI.

One of the major difficulties of information integration stems from the fact that the information sources involved employ different data models and are heterogeneous both semantically and syntactically. In addition, it is envisaged that information integration systems would be able to support in an integral way ad-
vanced applications exploiting the richness of the information made available by these systems. These two factors necessitate rich formalisms for semantic interpretation of the available information so that it can be understood by the other sources and the application programs. We are thus led to the need for semantic (or intelligent) information integration where, along with techniques from databases, Artificial Intelligence and Computational Logic can play a significant role in providing explicit and declarative representation frameworks for modeling the information and the complex behaviour of the system. The autonomous nature of the information sources, where we may only be able to represent partial information and where information from different sources may be overlapping or even inconsistent, increases the possibilities to apply techniques from the areas of Artificial Intelligence and Computational Logic.

In particular, a declarative logical representation can form the conceptual basis for the basic architecture of Information Integration systems. The primary role of Computational Logic transpires to be that of providing an overall cooperation layer that would link, through suitable forms of inference, the different information sources into an intermediate layer. This intermediate layer is called in the Information Integration literature, a mediator. Within this logical framework it would also be easy and natural to employ specific Computational Logic methods for particular subtasks required inside an information integration system. A hybrid computational model emerges where logic and its reasoning offer the computational link between high-level complex requirements and lower-level (typically non-logical) computational tasks such as searching, constraint solving, retrieval and various forms of manipulation of data.

The rest of the paper is organized as follows. Section 2, briefly reviews the main elements of Information Integration Systems and the current role of logic in them. Section 3 presents some of the Information Integration systems which use (to a varying extend) logic and discusses the current scope of application of such systems. Section 4 presents some of the future problems in the area and the challenges for Computational Logic stemming from these. The paper concludes with a short appraisal of the potential role of Computational Logic in the area.

Disclaimer: This paper is a survey written mainly for the non-specialist in the field of Information Integration and does not claim to provide a complete ac-
count of the area and its particular systems and applications. Furthermore, the presentation of the paper follows a particular view concerned with the possible role of Computational Logic in this new field attempting to show links between existing work in Computational Logic and problems arising in the area of Information Integration. In some cases, these potential links reflect the authors personal opinion.

2 State of the Art

The first roots of Information Integration can be found in the area of databases with the problem of constructing multilatabases [32, 24, 56]. This aspired to form databases where different sites of heterogeneous databases would cooperate and be updated together. In order to reduce the complexity of the problem the notion of Federated Databases [177, 186, 124] was proposed and later on Data warehousing [47, 185, 193] helped to simplify the problem even more by storing data in one site.

2.1 The Basic Architecture

To address the advanced requirements of future information systems, Wiederhold proposed [194] a general system architecture where a central role is assigned to software modules called mediators. A mediator is an information system component that lies between the data sources and the user and her applications. A mediator "exploits encoded knowledge about the data to create information for a higher layer of application”. Its added value is exactly this transformation of data to information. The tasks of a mediator according to [196] include:

- accessing and retrieving relevant data from multiple heterogeneous resources,
- abstracting and transforming retrieved data into a common representation and semantics,
- integrating the homogenized data according to matching keys, and
- reducing the integrated data by abstraction to increase the information density in the result to be transmitted.
The mediator-based architecture has been to a large extend adopted in the development of the reference architecture for Intelligent Information Integration (I3) supported by DARPA [8]. More importantly, the need for an intelligent middleware between the sources and the user is a common assumption in most of the work in I3. As already noticed in [194], to perform their functions effectively, mediators will embody techniques from logical databases and AI. It is inside the mediator, in its design and implementation, where logic can play an important role in the information integration systems of the future.

2.2 Inside the Mediator

Among the above mentioned tasks of the intelligent mediator middle-ware, the first, often called the information gathering problem, is the most studied. This task can be decomposed in the following sub-tasks.

- modeling the contents of information sources
- modeling the relation between sources and the mediator
- query reformulation (query planning)
- query optimization and execution

2.2.1 Modeling and Query Reformulation

As mentioned above a mediator needs to support adequately a wide range of tasks and provide a variety of functionality based on these tasks [8, 196]. In order to achieve this mediators need to use models of the various information sources that are available, referred to as the source model, as well as models of the users (or the applications) view of the problem world, referred to as the world model, and to link these models together. Among these modeling tasks of a mediator the linking of the world model to the source model is of central importance. In most of the early studies for developing such models the simplifying assumption is made that the sources can be modeled as relational databases. Similarly, it is assumed that the world model is captured by a set of relations. These relations are not stored in any of the information sources, but are those on which the user (or application
program) will pose queries. In DB terminology, we say that the world’s model relations define a *global mediated schema*.

Roughly speaking, the relations in the mediated schema are used by the user (or her/his application program) in order to specify *what* is the information s/he wants, while the source relations determine *where* the information is stored. To be able to answer user queries the mediator needs to know how the global schema relations are related to those of the information sources. Having this knowledge the middle-ware of an information integration system translates queries on the mediated schema to queries on the source relations.

There are basically two approaches to relate sources to the mediated schema. The first is the *local as view* approach and the second the *global as view* approach (also called *source definition* and *view definition* respectively). In the first approach sources are considered to be materialized views over the mediated schema. Datalog programs of the form

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source_relation :- global_relation_1, ..., global_relation_n
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are used to link source relations to the mediated schema describing in this way the contents of the source in terms of the global mediated schema. A datalog rule like this is called a *conjunctive query* expressing the fact that the query given by the body of this rule can be answered using the source relation found at the head of the rule. More generally, query translation can be seen as synthesizing queries from *views* [191], a problem that has been studied quite extensively [3, 53, 66, 119, 127, 124]. Levy [129] provides a thorough survey of this problem of answering queries using views in different application areas, including information integration.

In the global as view approach the mediated relations are considered as views over the source relations. Rules of the form

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global_relation :- source_relation_1, ..., source_relation_n
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relate the source relations to the global relations. Query translation then takes the form of simple view unfolding.

Ullman in [191] compares the two approaches, and identifies their advantages. The global as view approach makes the query translation problem easier. It can also draw from work on abduction [108], when we want to increase the expressive
power of the modeling language to include constraints, negation and other powerful modeling features. On the other hand, the local view approach simplifies adding and deleting sources and therefore it is particularly useful in dynamic environments. Moreover, it facilitates the specification of constraints on the content of the sources as we can attach such constraints in the conjunctive query that describes them. In the global view approach constraints on the contents of a source can be expressed separately as meta-level integrity constraints on the source relations.

Among the existing systems TSIMMIS [88], Disco [187], and Coin [25, 26, 27] adopt the second approach while Information Manifold [128, 129] and Infomaster [11, 64] follow the first. Moreover, recently there have been systems that combine the two approaches [85, 94]. We note here that description logics are also used as the underlying formalism for mediator modeling in some information integration systems, including SIMS [1] and PICSEL [94]. The general role of description logic in information integration has been studied in [43, 37, 39], while work on answering queries using views in the context of description logic is described in [14, 38, 93].

Once the mediator translates user queries to source relations, it has an information gathering plan, which in abstract terms can be seen as a conjunction over the source relations. At this stage the mediator knows what are the information sources that it needs to access in order to answer the query. Then it must retrieve the information form the sources by sending requests to them in a language that they understand. More importantly, the mediator should not post to the sources queries that are beyond their answering capabilities. Consequently the mediator must also model the query constraints of the sources. An important family of such constraints are binding restrictions, i.e. information that specifies that a certain source can only answer queries that have some of their attributes bound. Such query processing systems that take into account source capabilities are described in [84, 89, 168, 173, 188, 189, 202, 201].

Another important feature of a mediator at this stage is its capability to model various forms of local completeness of the sources, that is expressing the extend to which a source is complete for the domain that it covers. This information can help the system to restrict and improve access to the sources [70, 86, 63, 119, 122].
2.2.2 Query Optimization and Execution

Apart from being sound (the answers returned to the user are correct) and complete (all correct answers to the query are found) information gathering plans need also to be efficient. Query optimization in the context of information integration has several aspects. These can be divided into logical optimization and execution optimization. Logical optimization [119], seeks to eliminate redundancies from the information gathering plans possibly by exploiting local completeness information [70, 86, 119, 122]. Like in a traditional DB system, the resulting logically optimized plan is passed to a query optimizer that has to come up with an efficient query execution plan to achieve execution optimization. While this is a well-studied problem in the relation DB theory, information integration adds extra complexity [119, 123].

Garlic is one of the early integration systems that address logical and execution optimization by extending previous work in relational DB [19]. More recent work in the field is concerned with using local completeness and source overlap information for ordering source accesses in order to maximize the likelihood of obtaining answers as early as possible, and to minimize the access cost and the network traffic [82, 119, 190]. Another way to consider optimization is to add new sub-queries in the query plan specifically for the purpose of optimization [10].

The dynamic nature of the environment in which information integration systems operate require that their query execution engines have advanced capabilities. Information integration over a network like the Internet has to take into account that sources can become slow or unavailable during the execution of a information gathering plan. Query planning needs to be interleaved with query execution, and the system must be able to re-plan and re-optimize [112, 106].

2.3 Source Structure and Heterogeneity

The previous discussion makes the simplifying assumption that the contents of the information sources can be described by a set of relations. However, there are two separate problems with this approach [21]. The first is that sources can be physically semistructured, where the structure of the source information is obscured by the way that this information is stored e.g. in HTML file sources.
often the data is not stored directly in its structured form due to additional mark-up information used to make the source human readable. On the other hand data can be logically semistructured in the sense that the data does not necessarily fit in a schema. Data can be so irregular that the schema can be very large.

To cope with physically semistructured sources we add wrappers to them, while the problem of integrating logically semistructured sources is tackled through flexible data models and query languages. We discuss these important issues in the following two subsections.

2.3.1 Wrapper Technology

Sources often do not provide their data in a format, e.g. relational tuples, that can be directly manipulated by an integration system. For example, if the source is an HTML page, it can be the case that structured data (e.g. names, phones and emails of the faculty of a university department) is embedded in natural language text and graphical presentation objects. In such cases the integration system communicates with a wrapper, i.e. a program whose task is to translate the data in a form that can be further processed by the integration system, e.g. by removing all HTML markup information. Since sources usually store their data in different formats, each source often needs a different wrapper. However, writing wrappers can be a tedious task, therefore wrapper generation is an important issue. Wrapper generation can be semi-automatic, when support tools are used in their generation, or automatic, using machine learning techniques. The work of [38, 154] surveys the field and discusses the relation of wrapper generation to the more general problem of information extraction\(^1\). We should note however that the emergence of XML as a new standard for representing data in a machine readable way (in contrast to HTML which focuses on human readable representations) is expected to significantly mitigate the problem of physical data heterogeneity.

2.3.2 Semistructured Data

There are many interesting cases where the data can not be constrained by a rigid schema. Moreover, in an information integration application where data needs

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\(^1\) An information repository on information extraction and wrapper generation is maintained at [http://www.isi.edu/~muslea/RISE](http://www.isi.edu/~muslea/RISE).
to be exchanged and transformed among sources with different data models (e.g. relational and object oriented) we require very flexible data formats. These needs have led to the new research problem of modeling and querying *semistructured data* [31, 1, 184]. While there is no strict definition of the term, semistructured data is often described as *schemaless* or *self-describing* data, “terms that indicate that there is no separate description of the type or structure of data” [2].

Semistructured data is captured by flexible data models like the OEM model of the TSIMMIS project [88] or, more abstractly, by some form of *edge labeled directed graphs* [31]. All schema information moves to the data itself, i.e. to the graph, in the form of the labels attached to the nodes or edges of the graph (hence the term self-describing).

Flexible query languages like Lorel [4, 145] and UnQL [32] provide several required functionalities such as (i) the ability to query without knowing the exact structure of the data, (ii) the provision of navigation queries in the style of Web browsing and (iii) the ability to query both the data and the schema at the same time. The problem of answering queries using views in the context of semistructured data has also attracted attention recently [40, 41, 42, 169]. Motivated by the importance of schema information for efficient processing, storage and usability of data, recent research attempts to bring back some forms of structure or schema to semistructured data. Several schema formalisms have been considered in different approaches to this problem of extracting schema from semistructured data, e.g. in [33, 95, 158, 157]. Logical approaches to schema formulation from semistructured data include the use of Datalog rules [156], description logics [35] and mappings into the relational database model [60].

The semistructured data model represents a new paradigm and challenge in databases and therefore in Information Integration. The database community has already made significant progress towards linking semistructured data research to emerging standards for information exchange like XML [200, 45]. For instance, several of the query languages developed for XML [31, 174, 46, 22], bare a strong resemblance to query languages for semistructured data. A recent book [2] offers an extensive coverage of this research theme.
2.4 The Semantic Web

Recently, it has been realized that information integration over the Web can benefit significantly by adding extra semantic structure over these information sources, namely the web documents or web pages. This need for semantic information links information integration with the Semantic Web, a term coined by Tim Berners-Lee [16]. The Semantic Web is a vision for the next stage of the Web, described as a space of self-describing, machine-processable or "machine-understandable" fragments of information in which documents convey meaning. In contrast to the existing Web, whose content information is only human-readable, the Semantic Web aims to develop the technologies that will enable the machines themselves to make more sense out of it.

The Semantic Web is envisaged to have a multi-layer architecture which is based on the XML standard for semi-structured Web-Data and related technologies (e.g. Namespaces, XML-Schema) that support inter-operability mainly on a syntactic level. On top of XML lies the Resource Description Framework (RDF) [120], a key concept of the Semantic Web. Essentially, RDF is a simple data model for expressing metadata in the form of object-property-value triples, called statements. In RDF statements can be the object or value of a triple, allowing in this way the nesting of statements.

While RDF provides the model for describing resources and relationships between them, it does not support any mechanism for declaring properties or relationships between properties and other resources. For this RDF Schema (RDFS) [28], a schema specification language, is used. RDFS provides a basic type system, or vocabulary, for use in RDF models. Important modeling primitives it provides include class/subclass, instance-of, and range/domain restrictions. However, we should note that W3C recommendations follow a minimalistic approach, so neither RDF nor RDFS provide any formal semantics for the constructs they define, nor do they provide an inference system or a query language. This lack has motivated a number of works that attempt to relate RDF and RDFS to formalisms with clear semantics like conceptual graphs [52] or logical languages [7, 20, 29, 31, 40].

Hence although RDF/RDFS provide a powerful infrastructure for semantic inter-operability, they do not suffice to capture the advanced knowledge represen-

\(^2\)See www.semanticweb.org for a variety of information about the Semantic Web.
tation and reasoning needs of the Semantic Web. The Semantic Web architecture requires two additional layers, an ontology and a logic layer, that aim at accommodating richer forms of knowledge. One of the early attempts to employ ontologies on the Web were Ontobroker [74] (that will be described in some detail in the following) and the SHOE project [137] that allows authors to annotate their HTML pages with ontology-based knowledge about the page contents. More recent approaches are the Ontology Inference Layer - OIL [211] and the DARPA Agent Markup Language - DAML [212]. OIL [73, 101] is a system that combines the reasoning capabilities of description logics (more specifically that of FaCT [103, 104]), with the rich modeling of frame-based systems and the new Web standards of RDF and XML. The DAML Program [102, 146], which officially began in August 2000, is an “... effort to develop a language and tools to facilitate the concept of the semantic web.”. The DAML language also builds on top of XML and RDF, and its latest release called DAML+OIL is available from [213]. Two recent papers [72, 76] provide an up-to-date overview of languages, tools and services of the Semantic Web, and discuss new developments and current issues.

2.5 The Current Role of Logic

One of the basic requirements of Information Integration frameworks is to allow the user to specify what information she wants rather than how to get it. Such systems must rely, at least at some level of abstraction, on a declarative representation with a rich formalism for describing the available information. Logic can provide such a flexible representation and thus play an important role in the development of information integration systems. In the emerging future systems where an advanced form of sythesis of information would be facilitated through an application layer, above the mediator layer, Logic and Artificial Intelligence will have an ever increasing role to play. This wider role of AI in current and emerging Information integration systems has been recently presented in the survey paper [123].

Currently, the central role of logic rests on the fact that it provides a framework for specifying the mediator layer of an Information Integration system and the relation between the mediators and source information. Logic as a Knowledge Representation formalism facilitates this and provides (in some cases) techniques for
the computational process of the Information Integration system. Most systems indeed either use logic explicitly (e.g. COIN or Infomaster) as a KR technique or can be cast into this e.g. the MSL language of the TSIMMIS project. The work of [191] provides a survey of this role of logic showing how both the global as view and the local as view approaches for modeling the information sources and their relation to the mediator layer can be understood in terms of Logical views over Datalog programs. The extraction and integration of information by these systems is then seen as answering conjunctive queries over these programs.

A third approach to modeling the information in an Information Integration system is through the use of Description Logics3, (e.g. in Information Manifold, PICSEL, SIMS). This is used as a richer representational framework that can capture additional (meta-level) knowledge on the sources available primarily as contraints on the information in these sources. For example, the PICSEL system [94] which is based on the Description Logic language CARIN is able to combine the global as view and local as view approaches and to use the generic inference mechanisms of this logic. In particular, it avoids the problem of reformulation of the query required in the local as view approach.

At the level of computational methods used in information integration systems the problem of query answering can be directly related to logical inference for the reduction of the query to the mediator layer (often this is trivial) and then the further reduction of this to the information sources. Indeed, in the global as view approach one way to formalize this reduction is as a simple form of abductive reasoning [109]. In the local as view approach this can be seen as a problem of reformulating a query in terms of (materialized) views and in turn this is closely related to the problem of query containment in Datalog. Logic helps to study the theoretical issues concerning the question to what extent it is possible to do this reformulation. In Infomaster this query reformulation is achieved via first inverting the local as view description of sources in terms of mediator relations and then reducing, as in the global as view approach, the original query using logical inference techniques to do this reduction. Note that this inversion can bring us outside datalog with disjunction and recursion required.

3Description logic has also been used [166] in the related problem of interscheme extraction from database schemes.
Deductive databases with their strong logical basis can also play an important role in information integration, at the analysis and design level and also in the actual implementation. Indeed, Datalog-based formalisms are used by most approaches that build integrated systems and mediators for information taken from multiple heterogeneous data such as legacy databases, external views, and web sites \[123, 125\]. Furthermore, the query optimization problem for these systems is frequently solved by means of annotated plans where rules and goals are assigned bound/free annotations. This is the very approach developed and used by deductive database compilers and optimizers \[173, 126\]. The Deductive Database system of LDL++ \[203\] has been used as a component in the (early) information integration systems of Carnot \[155, 162\] and Infosleuth \[13, 160\]. LDL++ also proved very useful in an assortment of other tasks needed for information integration, such as the task of cleaning and converting legacy data \[178\].

In approaches that use description logics query processing is based in a general way on the underlying inference algorithm of the logic. This has the advantage that the development of a new application domain amounts to the design of a suitable knowledge base without the need to develop a specialized query engine. The description logic approaches also have a high degree of modularity. This stems from the fact that the representation of the sources is separated into two parts: (i) a theory that describes the relation between mediator and sources and (ii) declaratively stated integrity constraints that capture additional knowledge about the information in the sources.

The COIN framework \[25\] adopts a similar approach for its representation of the domain using integrity constraints to help resolve semantic conflicts between information that can be acquired from different sources, thus giving a form of semantic query optimization. This system is implemented on the ECLiPSe parallel constraint logic programming environment and relies on techniques of abduction and constraint propagation.

It is important though to note that despite the strong logical flavour that some of these information integration frameworks have many of the techniques that are used in these systems are specific to the particular needs of the systems. In particular, the problems of query optimization, source capabilities, local completeness of sources and use of other meta-level information about the source information
are typically handled with specific techniques that vary from system to system.

Some of these techniques e.g. for query planning, take input from AI and Logic (and Deductive databases) but there are no general methods of how logical techniques can be exploited in these important aspects of the general problem of information integration. Computational Logic needs to develop its own specific techniques suited for the particular problems of information integration. These techniques need not be (and in many cases should not be) entirely logical but they should have a hybrid nature of co-operation between logical reasoning and other computational methods.

The working assumption of much of the early research is that the information stored in the sources can be captured by a set of relations, i.e. it is assumed that sources are relational and can be described by some rigid schema. This assumption is not valid when working with semistructured data [2, 4, 78] and there is a current strong shift away from this assumption. It is therefore important for logical approaches to be able to adequately represent semistructured information sources. There are some studies towards this direction, where a logical theory is used to represent the labeled graph data model for semistructured data. The FLORID approach [136], described in more detail below, uses F-logic, a logical framework that combines techniques from object-oriented databases with the power of deductive rules for expressing complex queries. In [35, 36] the authors propose description logics as a logical formalism capable of capturing the labeled directed graphs model of [31] and extending it with various forms of constraints and the capability to deal with incomplete information. Finally, the MOMIS [15] approach, that also builds on work in description logics, also provides features that allow the representation of some forms of semistructured data.

3 Information Integration in Practice

Information integration has important practical applications particularly in view of the emerging need to integrate information distributed over the WWW. Several practical systems of Intelligent Information Integration have been developed. General information on these can be found at the following URL addresses [214, 215, 216]. We present here some of these systems whose development has to
a certain extend been influenced by Computational Logic either at the conceptual and/or the implementation level. Other systems that make use of methods from Computational Logic but to a lesser degree include the early systems of Information Manifold [21], TSIMMIS [88], SHOE [137], SIMS [9] and WHIRL [49].

**COIN** (COntext INterchange) [26, 27] is an Information Integration framework with emphasis on resolving problems arising from semantic heterogeneity, i.e. inconsistencies arising from differences in the representation and interpretation of data. This is accomplished using three elements: a shared vocabulary for the underlying application domain (in the form of a domain model), a data model (COIN), and an application/query language (COINL). Semantic inter-operability is accomplished by making use of declarative definitions corresponding to source and receiver contexts i.e. constraints, choices, and preferences for representing and interpreting data. The identification and resolution of potential semantic conflicts involving multiple sources is performed automatically by the context mediator. Users and application developers can express queries in their own terms and rely on the context mediator to rewrite the query in a disambiguited form.

The COIN data model is a deductive and object oriented model of the family of F-Logic [111]. The mediation engine’s main inference is implemented by means of a resolution based abductive procedure in the Constraint Logic Programming language of ECLiPSe [67]. Queries and subqueries are represented by the successive states of a constraint store along one branch of the resolution tree. Integrity constraints are translated into Constraint Handling Rules of ECLiPSe. Their propagation achieves a form of Semantic Query Optimization by rewriting the queries and subqueries in the store in between the resolution steps and by pruning the rewriting process. COIN has been used in various applications of e-commerce.

**FLORID** (F-LOGic Reasoning In Databases) [136] is a logic-based system for information extraction and integration from the Web. Web exploration, wrapping, mediation, and querying is done in a monolithic system where F-Logic serves as a data model and a uniform declarative programming language for Web access, data extraction, integration, and querying. The
Web and its contents are regarded as a unit, represented in an F-Logic data model. Based on the Web structure, given by its hyperlinks, and the parse-trees of Web pages, an application-level model is generated by F-Logic rules. For this, the F-Logic language is extended with Web access capabilities and structured document analysis. By retaining the declarative semantics of F-Logic also for the Web interface methods, Web data extraction can be programmed in a clear and natural way. In particular, generic rule patterns are presented for typical extraction, integration, and restructuring tasks [142], such as HTML lists and tables and syntactical markup.

Web access, wrapper and mediator functionality, restructuring, and querying can be arbitrarily combined, and thus FLORID can be used both for Web querying and for information extraction. The combination of Web access, Web data extraction, and interpretation rules allows for data-driven Web exploration: a priori unknown Web pages can be accessed and evaluated dependent on previously extracted information. Equipped with suitably intelligent evaluation rules, the system can explore hitherto unknown parts of the Web, coping with the steady growth of the Web. The practicability of FLORID has been shown in the case study [141] where geographic information from several sources on the Web has been integrated.

HERMES operates on the philosophy that the role of logic in applications is more that of providing a facilitator for cooperation between computational models rather than performing the actual computations itself. Logic is used to integrate computations in classical data structures with specialized data structures for computations been key to scalability.

In HERMES, external databases and software packages are assumed to either have a legacy Application Program Interface (API) (or have one built for them), and these sources are accessible via their API functions. HERMES mediators contain syntax to execute operations in these packages, and to return the answer in a set. HERMES rules are expressed in logic, and they allow us to execute boolean combinations of these API function calls. HERMES’ “base predicates” are just such boolean combinations of API calls – “derived predicates” may be defined (recursively or otherwise) in terms
of these “base” predicates. An HERMES query may involve accessing data in a distributed environment from a RDBS, a logistics database, a GIS, a route planning system and a linear optimizer. Over the years, HERMES has been used to integrate Oracle, Ingres, and Quad-tree databases, route planners, logistics databases, Dow Jones stock mediators, and intelligent travel agents.

**Infomaster** An essential feature of Infomaster as an Information Integration framework is its emphasis on semantic information processing. Infomaster integrates only structured information sources, sources in which the syntactic form reflects its semantic structure (in other words, databases and knowledge bases). This restriction enables Infomaster to process the information in these sources in a semantic fashion; information retrieval and distribution can be conducted on the basis of content as well as form.

The core of Infomaster is a facilitator that dynamically determines an efficient way to answer the user’s query using as few sources as necessary and harmonizes the heterogeneities among these sources. Infomaster connects, using wrappers, to a variety of databases such as for example any SQL database through ODBC and some World Wide Web sources. Infomaster contains a model-elimination resolution theorem for abduction which acts as a workhorse for the query planning process. The information sources are described in terms of rules and constraints which are stored in a knowledge base using Epilog, a main memory database system. Infomaster adopts mainly the local as view approach where sources are described as views of the mediator relations. It then employs an inversion mechanism to turn these into rules for the mediator (or query) predicates and uses its abductive theorem prover, together with constraint solving, to extract a query plan from this. Infomaster has been in production use on the Stanford campus since fall 1995 and is now commercially available.

**InfoSleuth** The InfoSleuth system architecture consists of a set of collaborating agents that work together at the request of the user. Users make requests to InfoSleuth from a domain-independent or domain-specific applet. Requests are made against an ontology specifying the users domain of
interest. An ontology agent together with a broker agent provide the basic support for enabling the agents to interconnect and intercommunicate. Ontology agents maintain a knowledge base of the different ontologies used for specifying requests, and returns ontology information as requested. The Broker agent maintains a knowledge base of information that all the other agents advertise about themselves, and uses this knowledge to match agents with requested services. In this way the broker performs a form of semantic matchmaking.

Within the InfoSleuth system, the agents themselves are organized into layers, with the broker and ontology agents serving all of the other agents. At the lower layers several other different types of agents for processing information within InfoSleuth exist: User agents, Resource agents, Task Execution agents and Multiresource Query agents. The latter process complex queries that span multiple resources. They may or may not allow the query to include logically derived concepts as well as slots in the ontology.

The Deductive Database system of LDL++ forms a component of the Infosleuth system. The main function of LDL++ in this system is implementing the articulation axioms that support the mapping between heterogeneous schemas. The advantages of LDL++ in this context are enhanced by the LDL++ system’s ability of translating rules (including those with aggregates) into equivalent SQL queries that are then offloaded for more efficient execution to remote database servers.

Infosleuth is used in applications for environmental data exchange, analysis of genetic information and business intelligence.

MedLan The underlying basis of MedLan is the framework of logic programming extended with: (i) the possibility of partitioning the code into separate programs, (ii) the ability of separate programs to interact, and (iii) the ability to answer queries with respect to a combination of programs denoted by so called program expressions.

The possibility of structuring logic programs into modules, that may interact, allows one to implement classical mediator based architectures, where the low-level modules can act as wrappers for different data sources, while
the intermediate level modules act as mediators. The possibility of a dynamic combination of programs by applying logic-based composition operators allows one to construct mediators as semantic views on the data provided by the wrappers. Among the operators for combining logic programs, the *constrain* operator is of special importance for the construction of mediators. It allows the use of a collection of rules as a set of constraints over a logic program.

The capabilities of MedLan for constructing mediators have been experimented in two application fields: semantic integration of deductive databases and the construction of a declarative analysis level on top of a traditional geographic information system. Currently MedLan is also studied as a candidate for expressing security levels for information systems.

Ontobroker The Ontobroker-system [74] is a WEB-based application for ontology based search aimed at small communities that are present in the internet or internet-like networks. Ontobroker consists of a number of languages that allow us to represent ontologies and to annotate web documents with ontological information. It also contains a set of tools that enhance query access and inference service in the WWW. This tool set allows us to access information and knowledge from the web and to infer new knowledge with an inference engine based on techniques from logic programming. It aims to use semantic information to guide the query answering process and to provide information that is not directly represented as facts in the WWW but which can be derived from other facts and some background knowledge.

The Ontobroker architecture consists of three core elements: a query interface for formulating queries, an inference engine used to derive answers, and a webcrawler used to collect the required knowledge from the web. Each of these elements is accompanied by a formalization language: the query language for formulating queries, the representation language for specifying ontologies, and the annotation language for annotating web documents with ontological information.

The inference engine of Ontobroker is given a formal semantics from Logic Programming. It uses generalized logic programs that are translated further
into normal logic programs via a Lloyd-Topor transformation. Negation in
the clause body that can be non-stratified is interpreted via the well-founded
model semantics \[90\]. Standard techniques from deductive databases, such
as the bottom-up fixpoint evaluation procedure, are also used in the imple-
mentation of Ontobroker.

Ontobroker has recently developed applications in the spirit of the Semantic
Web such as semantic community web portals and tools for human resource
knowledge management.

**PICSEL** \[94\] is an information integration system where the mediator is based
on the logical formalism of CARIN. This formalism combines the expressive
powers of Horn rules and description logics. CARIN is used as the core
logical formalism to represent both the domain of application and the con-
tents of information sources relevant to that domain. CARIN is a logical
formalism combining the expressive powers of function-free Horn rules and
description logics.

The strong use of a logical formalism allows PICSEL to have a declarative
definition of the relevant concepts for describing the application domain and
the information sources. This makes it easy to take into account changes
that can occur frequently e.g. when new sources are added, old sources are
removed, or when the capabilities of existing sources are modified. Also the
formal semantics of PICSEL helps the designers to express their knowledge
in an unambiguous and rigorous way and to define in a precise way the
problem of answering queries w.r.t to it.

In PICSEL the problem of answering queries can be identified as a general
problem of inference in a logical framework. Existing well established tech-
niques of this framework can help to determine decidability and complexity
results for the problem of information integration, and to design correct and
complete algorithms. These algorithms have the advantage to be generic,
i.e. not specific to the application domain and to the sources and therefore
they can be reused in another application setting.

PICSEL has been tested with applications from the travel and tourism do-
main. It is also used in electronic commerce applications where PICSEL is
employed as a tool for integrating different services.

### 3.1 Applications of Information Integration

Although the area of Information Integration is relatively young research in this field has had a strong emphasis on applications from the very beginning of its existence. This emphasis on practical aspects is growing with time. Much of the existing work is grounded by the development of prototype systems and their use for some specific application domain. Thus in many cases the research is that of the development of methodologies for information integration through principled engineering of applications.

Applications of Information Integration can be divided into two large classes: (a) integration of existing legacy heterogeneous databases and (b) integration of information available over the World Wide Web. At one end of the spectrum information integration systems are developed for a particular domain of interest. Examples include the Tambis [11] project concerned with the problem of integrating Bioinformatics Information Sources and the INEEL Data Integration System [167] that has been applied to problems of environmental restoration. The main purpose of these applications is to offer to the user an effective decision support tool through the provision of extensive but relevant (to the users needs) information. In such cases there is usually a rich amount of domain specific knowledge that can be exploited in various ways by the integration system e.g. in query optimization, providing easy query formation and mediator specification, identification and resolution of equivalences, etc.

At the other end of the application spectrum there is a fast growing class of applications focusing on integration of Web data resources. While Web-based integration systems usually provide generic tools, particular applications focus on specific domains of interest like entertainment [12], flight delay prediction [203], housing rentals ([204] and Federal Goverment Information System [205]. Moreover, information integration is an important enabling technology for a wide class of electronic commerce applications (see below for more details on this application domain). Issues like rapid development of wrappers, flexible data models and query languages that can easily accommodate semistructured data, and efficient query execution, are crucial for such applications.
Another emerging new application domain is that of integration of simulation results, so that we can also project information into the future [197]. These type of applications will complement existing applications, which only give a view into the past and present, and hence address only one part of the needs of decision-makers.

The web page of [http://www-db.stanford.edu/LIC/companies.html](http://www-db.stanford.edu/LIC/companies.html) maintained by Gio Wiederhold lists 41 commercial suppliers of Mediation Technology in the United States. Some of the more commercial products include OmniConnect [208], DataJoiner [207], Cross Access [209], and Enterworks [210].

### 3.2 Information Integration and E-commerce

One important application where the need for information integration would be ever growing is that of E-commerce over the web. The number of people that buy, sell or perform transaction on the Web is increasing at a phenomenal rate. Electronic commerce encompasses many issues, such as finding and filtering information, securing information, generating dynamic supply-chain links, online configuration of products and many others.

Many systems based on agent technology [98, 139, 153] are already present on the Web, *BargainFinder* [114] being the first agent for price comparison. Systems of this category, often called *Shopbots*, can be considered as a first attempt to link e-commerce with information integration and agent technology. Clearly these systems perform some form of integration of information at the different vendor sources, but as the information they return is rather limited (mainly price, availability, shipping time etc.) there is no need for a sophisticated query translation algorithm as we have described earlier. Other web-commerce agent systems like *Kasbah* [44] pro-actively search for products that may be of interest to the user, while *Firefly* [176] is one of the early systems that uses collaborative filtering to recommend musical albums to its user. Advanced agent systems like *AuctionBot* or *Kasbah*, are capable of negotiating on behalf of the user [98]. We therefore seem to be moving towards a form of information integration that emphasizes the aspect of personalization where the integration of information is performed to suit each time the needs of the particular user/buyer.

The functionality of current e-commerce agents is hindered by the fact that information on the Web is currently in HTML format. Agents use wrappers to
extract, in a heuristic way, product or other "content". Although there exist a number of approaches to semi-automate this process, such ad-hoc solutions do not seem to scale. Moreover, product information heterogeneity on the semantic level, seems to be a more serious obstacle to efficient business information exchange, than information representation heterogeneity. In general, there is no agreement on fundamental issues, such as what is included in a product domain, how to describe products or how to structure product catalogs.

Product information heterogeneity can be tackled either by standardization or integration [159]. Industry realizing the importance of resolving information heterogeneity has launched several standardization initiatives. Some of these develop horizontal standards (i.e. they cover all possible product areas) such as UN/SPSC (Universal Standard Products and Services Classification code, www.unspsc.org), while others develop vertical standards (focusing on products of certain type) such as RosettaNet for the area of hardware and software products(www.rosettanet.org).

Two modern technologies, XML and Ontologies, are playing an important role in these standardization efforts. XML has been put forward as an important tool for tackling inter-operability problems in e-commerce [12]. Indeed, today there is a growing number of XML standards for e-commerce capturing different aspects of business activities [130]. Although XML is a major step forward, it should not be regarded as a solution to all inter-operability problems, but more like a widely accepted layer on which to build appropriate semantic information. Although there is no single view on how to extend XML to support greater inter-operability in e-commerce, it seems that ontologies are becoming increasingly important as a component in semantically rich e-commerce services, as advocated in [71, 179, 144]. For instance, building consensual and reusable product catalogs is nothing more than building an ontology for a certain domain. Indeed, there is a strong interaction between the ontologies and online commerce communities. Examples include Interprice [217] and Content Europe [218] both providing ontology-based support for e-commerce [73].

Although standardization efforts are important, integration still remains an issue, as ”most industrial standards are not quite mature at the current stage, and there are no apparent leaders” [130]. The proliferation of standards threatens to create an electronic marketplace dominated by "commerce islands", markets that
have become isolated by differing proprietary protocols and domain standards. Therefore, it is inevitable that some form of integration will be required by the future e-commerce systems [159]. Logic could play an important role here in providing higher levels of inter-operability needed for the integration of information over different e-commerce markets.

Moreover, logics could contribute not only in solving product information heterogeneity problems, but also to other aspects of e-commerce. One such aspect is described in the recent work of [27] that uses Logic Programming to develop a framework for integrating business rules for electronic commerce. These rules are expressed in a generalized form of logic programs, called courteous logic programs, a framework that incorporates a form of conflict handling. The declarative semantics of this framework facilitates shared understanding and inter-operability between different rules. Pilot applications in e-commerce areas such as negotiations, catalogs and storefronts have been considered. The framework also supports an XML encoding of courteous logic programs. A prototype system called CommonRules is available at [219].

In addition, as the sophistication of e-commerce applications increases, we also expect to see a stronger interaction between the Semantic Web and E-commerce communities in the future. This interaction could reveal new roles for logic in e-commerce applications including the modeling of business rules [97], mentioned above, or the specification of workflow [28].

### 3.3 Logic Programming and the Web

In the last five years there has been a new interest in the field of Logic Programming aiming at linking Prolog languages to the Web e.g. the PiLLow library for Internet/WWW Programming [34]. The main idea is to provide a facility so that pages can be downloaded from the Web and turned into a corresponding Prolog program containing information extracted from these web pages. In general, this is an attempt to encode information pertaining to a web page, which can be either information within the page or meta information about the web page, into the declarative form of a Prolog program.

One can then view this as a mechanism for information integration under the paradigm of mediation as these logic programs define a common mediator
layer for the various web pages retrieved from the web in this way. Analyzing and synthesizing the information in these logic programs constitutes a primitive form of information integration over the web page sources. PrologCrawler [21] and ExpertFinder [30] are two such systems that use this "web page to prolog" approach in order to integrate information from various web pages. Similarly, WebLog [118] and D³Web [152] are Datalog based query languages for information held over several web pages.

The LogicWeb system [133, 55] converts web pages and their links into logic programs with the additional possibility for a web page itself to contain LogicWeb code. These logic programs can then be semantically composed together in several ways thus achieving the integration of information from the original web page sources. Applications of LogicWeb include a citation search tool [134] and a system for web-based guided tours [135].

These ideas to convert information from an HTML document of a web page to a logic program and utilize these programs to declaratively synthesize the information, extend from HTML web pages to XML documents [175] and RDF descriptions [57] thus enabling a higher-level of semantic form of information integration.

4 Challenges of CL in Information Integration

The problem of information integration has been the subject of intensive research activity over the recent years, with most of the work concentrating on modeling data sources in a single unified view. While significant progress has been made, many important problems remain unsolved. Future developments in information integration are expected to center around the following inter-related research themes as presented below. In the discussion of these problems we will focus particularly on the potential role that logic could play in addressing them. Some of these links to logic reflect the authors’ personal opinion.

Representation/Optimization: As noted earlier most of the early work on information integration has been carried out under the assumption that information sources can be modeled as relational databases. Logic based approaches have fol-
lowed to a large extend this line of research. However, nowadays interest is shifting fast towards semistructured data. Modeling, storing, managing and querying such data are emerging as important problems and will receive much attention in the years to come. Moreover, the development of standards for data representation and exchange on the Web, like XML, have already a strong impact on data modeling for information integration. The similarity between XML and data models like OEM developed independently by the DB community, will further facilitate the study of problems related to XML data management \[198\]. The role of CL in modeling semi-structured data is emerging as an important question that has received relatively little attention so far.

On the other hand, it is now clear that information integration in a dynamic environment like the internet, will need to employ effective query optimization and execution techniques. Richer forms of knowledge about the content and the structure of the sources as well as their inter-relations, are likely to be important elements in the design of future information integration systems facilitating new forms of semantic query optimization. Inductive learning and data mining techniques can further assist in the extraction of semantic knowledge for query optimization. Query optimization can also be enhanced within a logical framework with the further use of integrity constraints by interleaving their satisfaction with the query reformulation process. Integrity constraints can express information about completeness, preferences, inclusion and other properties of data sources.

The main focus of the modeling methods for information integration is on providing a mediated schema that defines the “semantics” of the underlying sources in the strict context of the mediated service that the global schema supports. Therefore, there is no need to define the intended meaning of the objects that make up the mediated schema. However, large scale information integration, as conceived for instance by the Semantic Web initiative, requires tackling data representation problems in a more global context, because ”...we expect this data, while limited within an application, to be combined later with data from other applications” \[17\].

Integration in the large calls for a semantically rich representation of the data that supports sharing, re-usability and extensibility. These requirements render metadata and ontologies, as key components of information integration systems
Metadata provides information about data, eg. information about database schemas and their intended meaning, which can be captured in an ontology that defines a common “vocabulary” for describing different information sources and services. The intended meaning of a database schema will be specified in terms of an ontology, and from this ontology (possibly together with some inter-ontology mappings) the mediator will be able to specify, automatically and through reasoning, the relationship between this schema and other schemata defined with respect to the same or related ontologies. Similarly, the user can use the same or related ontology to pose queries to the sources.

Several information integration systems including Information Manifold [121], OBSERVER [147], Ontobroker [74], InfoSleuth [13, 160] and SHOE [137] use ontologies strongly in their representation language. As noted earlier, ontologies also play a crucial role in the Semantic Web architecture. Logic, and in particular description logics, form an integral part of ontologies as most of these systems use them as their basic formalism for implementing ontologies. Formulating ontological context in logic (as in [77]) and reasoning about properties of ontologies using non-monotonic reasoning methods (e.g. default or hierarchical reasoning) seems a useful direction of research.

It is also expected that there will be a growing need for more advanced forms of application layers that would enable specialized and advanced forms of integration as compared with the relatively shallow integration that is carried out by todays systems. This will require declarative and more expressive mediator and application layers providing more flexible data models. Again the use of logic is one alternative for this purpose. For example, explicit negation in Logic Programming and constraints as in Constraint Logic Programming can be used to enrich the representation language. Current experience suggests that this use of logic will also need the use of other data models and computational methods in order to enhance the computational effectiveness of the overall framework. In such a hybrid model, logical reasoning can provide one of the main channels of cooperation between the different computational processes involved.

The work on Semantic Web services [146] is characteristic of the trends in the design of the next generation of advanced Web applications. Its main purpose is to provide declarative Application Program Interfaces that will enable apart from
service discovery, additional features such as automated service execution and more automated service composition and inter-operation. The solution proposed in [146] involves a combination of semantic markup of Web pages using DAML languages together with an agent infrastructure that uses situation calculus and the ConGolog agent programming language [58].

Two important technical problems that need to be addressed further irrespective of the particular form of more expressive language representation that we use are the problems of incomplete information and semantic conflicts or contradictory data. The problem of incompleteness can appear either at the level of the data sources themselves where some information is missing or at the level of the description of the mediator architecture as for example with semi-structured data. In the later case one issue to address is how we can use logic to describe the partial or uncertain information and then use mechanisms that are capable of reasoning under such incomplete information. The problem of incompleteness of data sources in information integration was studied in [70] and shown to be related to non-monotonic reasoning. As such the logical techniques of negation by failure, default reasoning and abduction could be useful in addressing this problem. In particular, constructive abduction that allows non-ground hypotheses seems to be well suited for query reduction under incomplete information. This can give existential answers conditional on an set of associated constraints expressing the range of values that a missing data entry can take.

It is inevitable that semantic conflicts or contradictory data will appear in information integration particularly when this is done over disparate sources over the WWW where there is no central control on the data available in these sources. The simplest form of this problem is that of naming mismatch where different syntactic names are given to the same semantic entity. WHIRL [49] combines techniques from information retrieval and AI to address this problem through an appropriate similarity measure. In this way it provides a system that is able to reason approximately (but with levels of confidence) with the partial information that it extracts from the unstructured textual form of the information sources.

These two inter-related problems of incomplete information and conflict resolution have been at the heart of many studies in Computational Logic, e.g. in default reasoning, extended logic programming, preference reasoning and argu-
mentation. We can then examine ways how these largely theoretical methods can be adapted and used in the more practical setting for applications of Information Integration.

**Automation:** For information integration systems to scale up we will need to automate at least some part of their development. Currently, the task of the description of the data sources that are available to a system is undertaken by the creator of the information integration system. But, when the number of sources grows, hand-coding the mapping between the mediated schema and the sources, is a major bottleneck in deploying large-scale integration systems. Therefore, there is a great need for methods and tools that assist or automate the process of generating source descriptions.

There are several places where machine learning can help in the automation of information integration. These include (i) the extraction of information from sources as for example in the process of automatic wrapper induction [68, 154, 113, 113, 180], (ii) learning mappings between mediator relations and source schemas thus automatically constructing part of the central mediator architecture [171, 62, 148, 164, 165] and (iii) extracting (additional) regularities over the data sources and mediator relations as meta-level integrity constraints that would be useful in the process of query planning and optimization. In many cases, these learning tasks take the usual concept learning paradigm of learning a set of concepts from given training examples e.g. learning concepts in the mediator schema from labeled sources of information as instances of these relations. This type of learning has been extensively studied in the field of Inductive Logic programming (ILP) and its methods have already began to be used in these problems [87, 53, 117]. The significance and potential of computational logic for these problems is high. Indeed, the inherent relational nature of any Information Integration framework makes the relational learning framework of ILP particularly appropriate for the aforementioned machine learning tasks within the general task of Information Integration.

As discussed in the previous section, the use of ontologies is an important approach to defining large-scale mediation services. They support sharing, reusability and extensibility, which are all important features for the rapid development of
information integration applications. It is therefore natural to expect that the different aspects of the problem of learning ontologies, as studied in [138, 69, 182, 183] and [161] where a review of existing approaches is given, will become important in the future. Relational learning can play a central role in this effort to automate the construction of the rich structure of ontology based mediators.

**Personalization:** In a mediator-based information integration system two interfaces have to be implemented, the mediator/source interface and the user-application/mediator interface. Indeed, the overall problem of information integration can be split into two levels:

- Interpret what the user (or application program) is asking for in her query (or high-level goal).
- Answer the query (or goal) through a suitable integration of information of various sources available.

While much work has been done at the second level based on a mediator architecture that describes sources, i.e. the mediator/source interface, the problem of modeling users/application for information integration is less well understood. This first level involves understanding the needs of each individual in a given context and satisfying these needs in the best possible way. This is a complicated problem with many different aspects. Existing user agent systems like Webwatcher [107] and Letizia [131] assist the user in locating information on the Internet, by tracking the users behaviour. On the information provider side, a current popular approach to personalization is the use of data mining techniques on Web-logs that track the users browsing behaviour represented as a clickstream [5, 181, 151]. The discovered patterns can be used in different ways such as changing the web structure for easier browsing, predicting future page requests, predicting user preferences for active advertising, or making recommendations to the user.

However, the above approaches either rely heavily on user browsing, or are restricted to individual web sites and therefore they do not adequately address all aspects and forms of information integration. The problem of personalization in a general information integration setting, involves understanding the user (or application) needs in a way that will allow the computation of the most appropriate
queries to the sources that would satisfy these needs. In other words, a *high-level query formation* is required that is sensitive to the particular users context and needs. In approaches where the user formulates her queries directly in the mediator language, it is assumed that she is familiar with the vocabulary available for posing queries, or with the range of information that is available to the mediator [77]. In application domains where this is not the case, the user should be assisted in formulating her queries [77, 96].

Moreover, answering user queries in a satisfactory way, involves in many cases a level of understanding that can not be reached without some semantic knowledge about the data and the context of the query. Although query answering can be seen as a process of matching the query description with the source description, in many interesting cases a simple syntactic matching is not adequate and semantic information is required. Ontology based query formulation is a first step towards providing some of the necessary functionality and has been employed in some of the existing systems [110, 144, 74]. On the other hand, we expect future work on personalization to be more tightly linked to the emerging metadata languages RDF and RDFS [48]. In addition, current approaches to personalization such as collaborative filtering or user clustering, will evolve to accommodate semantically richer forms of information that will become available on the internet.

In general, effective user profiling [172] and information brokering based on this, is a task that depends heavily on the existence and use of extensive background knowledge about the application domain and requires advanced techniques of knowledge representation and reasoning. "If we want our computers to understand us, we will need to equip them with adequate knowledge" [150]. Methods from ILP for knowledge intensive learning (e.g. [170]) and the use of CL for advanced forms of reasoning, such as default reasoning with (user) preferences and constraints, could prove useful in this task, especially in the context of the future Semantic Web services.

**Future Forms of Mediation:** Future developments will see an ever increasing number of applications that use information integration over the Web and in particular the emerging Semantic Web. This would range from more advanced search engines to applications for specific domains where integration of information rel-
ative to a user’s general needs is performed pro-actively. The two phases of query formation and query planning would then be strongly interleaved for this purpose.

As we automate more and more the construction process of a mediator this evolves into a facilitator as defined in [196]. A facilitator is dynamic and responsive to changing situation. It will be able to accept in a dynamic way meta-data about information sources and logical statements relating disparate concepts of an underlying ontology in order to automatically integrate a new resource into the system. There will also be an increasing need for abstraction where the volume of synthesized data is reduced while maintaining its essential (for the application) information content. For example, instead of responding to a query with a set of all answers we can use a rule or intentional answer that characterizes all the extensional answers. Clearly, logic can help realize these characteristics features of future mediators.

4.1 Multi Agent Systems for Information Integration

Information integration on the Web presents us with different challenges that require scalable, flexible and extensible solutions. Recent developments in agent systems seem to provide a promising supporting technology for realizing large scale information integration solutions. The Infosleuth approach [13, 160], and its predecessor Carnot project, pioneered the use of agent technology in information integration. In these systems CL had a significant role to play. The broker agent, who is responsible for pairing agents seeking for a service with agents that can perform that service, is partially implemented in the logical deductive Database language LDL++ [203]. More recently, the potential role of CL-based agents in information integration has been demonstrated by a number of works e.g. [54, 199].

The CL-agent approach brings together the benefits of declarative specification and rich level of expresiveness offered by computational logic, with a number of other benefits derived from the agent architecture. These additional benefits include: Reactivity: alertness to changes in the user requirements, and changes to the location, availability and content of information sources; Interactivity of the systems with the user; and Interleaving of query planning and query plan execution: the mediator can liaise with the information sources while it is constructing
a query plan, and before a complete plan is constructed. This has the advantage of pruning the search for a plan as early as possible. For example, it can alert the planning process of the unavailability of an information source, or it can find values for partial queries that will substantially reduce further search.

The approach of [199], uses the agent architecture of Kowalski and Sadri together with techniques of abduction. It adopts the global as view approach, where global relations are defined in terms of the information stored at the sources and incorporates the expression of functional dependencies which can be utilized in query planning. Furthermore it allows the expression and use of priorities amongst information sources in terms of their reliability and degree of completeness with respect to items of data.

We expect that in the near future, as applications become more complex, a closer link between information integration and agent technologies will be established. Future information integration systems will require agents for different activities, over and above those for the mediator, such as those for user profiling, symbolic learning and provision of user-friendly interfaces. The use of logic-based agents for information integration paves the way to the synthesis of information integration with other techniques to give such more powerful systems.

5 Conclusions

The area of Information Integration is a young but fast growing field that has emerged from the need to exploit more fully the available data spread over various databases of different type. It has been given a special impetus with the appearance of the World Wide Web where the need for new research on the problem of integration of information spread over the web is considered to be of paramount importance not least because of its enormous potential for commercial exploitation. This development has meant that together with new database techniques there is an ever growing need for the use of AI techniques such as those of multi-agent systems, knowledge representation (including in particular ontologies and hierarchies), natural language, resolution of conflict and machine learning. In fact, turning this around, the problem of information integration over the Web is providing an excellent opportunity for a new experimental arena where AI theory
and techniques can be applied and tested.

To the extent that Computational Logic belongs (also) to AI (see the recent book on "Logic-Based Artificial Intelligence" published after a meeting held in Washington in June 1999 [149]) we can see that Logic will also have a role to play in this new research area. A central role of logic in information integration concerns the problem of specifying a mediator. This is analogous to the problem of views in databases and, as exposed early in [191], it is possible to use logic to formalize most if not all mediator architectures that have been proposed. In some of these approaches logic is used explicitly to specify and to a certain extent implement the mediator architecture.

Indeed, the potential usefulness of logic was realized from the very beginning of investigations in this problem. As the work developed to address the problem in a more complete way the role of logic was exposed more clearly to be that of a facilitator for the cooperation between the different other computational processes involved in an information integration system. Logical inference can be used as the mechanism for communication and intelligent cooperation between these processes. We expect that this central role of logic will be further exposed as the ontologies used for mediation get richer and there is more scope for reasoning with these ontologies. This would help to develop more advanced forms of integration compared with the relatively shallow integration of today’s frameworks and systems. Also logic can be used to link the advanced and specialized (domain specific) needs of the application to the more general (problem independent) lower layers of the mediator architecture. An alternative way to formalize this upper application layer is using an algebra (see the SKC project [116]) and hence the merits of each approach, logical or algebraic, need to be compared.

A specific problem of immediate importance is that of rationalizing semi-structure data in the same way that logic rationalizes databases. This concerns the use of logic to formalize directed graphs of semi-structured data in the same way that we formalize in logic the (relational) tables of databases and their query language. Work in this direction has already started [136, 35], opening a new opportunity for logic-based databases. More generally, logic can help as a unifying basis with which we can add structure to the meaningful content of web pages so that a higher-level of semantic information integration can be performed over the
Web. Linking logical inference with ontological information is an important next development for building this vision of the Semantic Web.

Comparing the potential role of logic in Information Integration with its role in other areas in the past e.g. in the development of Constraint Programming, we see again that when we consider an application domain in its entirety the central role of logic is to provide a modeling environment for the problem (in our case the overall mediator architecture) and the link of this description to other computational methods needed to solve the problem. Of course, if and when some of these other computational processes can themselves be performed in a logical setting this central communicator role of logic can be implemented more tightly enabling more functionality. In the problem of information integration such cases are the use of (i) Inductive Logic Programming for the automatic generation of mediators, (ii) logic-based multi-agents as a framework for implementing the overall communication layers of a mediator architecture and (iii) Constraint Logic Programming to help address the scaling problem through the use of meta-level constraint information in query planning.

We would like to end this survey with a quote from a recent article [18] of Tim Bernels-Lee, James Hender and Ora Lassida: ”Adding logic to the Web ... is the task before the Semantic Web community at the moment”. This statement reveals succinctly the potential role of computational logic in the present and future development of Information Integration.

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