!Remark to reviewers: The manuscript is currently also under review of a native speaker to clean the language!

Lessons Learned from Applying AI to the Web

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Abstract. Ontobroker applies Artificial Intelligence techniques to improve access to heterogeneous, distributed and semistructured information sources as they are presented in the World Wide Web or organization-wide intranets. It relies on the use of *ontologies* to annotate web pages, formulate queries and derive answers. In the paper we will briefly sketch Ontobroker. Then we will discuss its main shortcomings, i.e. we will share the lessons we learned from our exercise. We will also show how On2broker overcomes these limitations. Most important is the separation of the query and inference engines and the integration of new web standards like XML and RDF.

1 Introduction

The World Wide Web (WWW) currently contains around 300 million static objects providing a broad variety of information sources (cf. [Bharat & Broder, 1998]). The early question of whether a certain piece of information is on the web has become the problem of how to find and extract it. The problem will become even more serious if the web continues to grow at the high speed expected by the W3C (the standardization committee of the WWW). Therefore, dealing with the problem of finding and accessing information in the WWW has become a key issue in overcoming the information overload, i.e. in preventing users from wasting hours in going through useless information and trying to find the piece of information they are interested in.

Artificial Intelligence (AI) has a strong tradition of developing methods, tools and languages for structuring knowledge and information. Therefore it is quite natural to apply its techniques to tackle the above problems. Viewing the web as a large knowledge-based system, however, makes aware of its very limited querying and inference interface at its current state. In the area of knowledge-based systems *ontologies* have been developed for structuring and reusing large bodies of knowledge (cf. CYC [Lenat, 1995], KIF/Ontolingua [KIF], and CommonKADS [Schreiber et al., 1994]). Ontologies are consensual and formal specification of a vocabulary used to describe a specific domain. Frame-based languages enriched by logical axioms are often used to formulate them (cf. LOOM [MacGregor, 1990] and Frame Logic [Kifer et al., 1995]). Roughly, ontologies correspond to generalized database schemata. However, ontologies can be used to describe the semantic structure of much more complex objects than common databases and are therefore well-suited for describing heterogeneous, distributed and semistructured information sources. The way ontologies are used in On2broker may rather be compared with mediating schemes as used in multi-database systems. There mediating schemes are used to provide an integrated view on the different local database schemes. However, these schema description languages are typically less expressive than our ontology specification language, especially with respect to the rule language part.[1] In the meantime a number of projects rely on such notions (cf. HERMES [Subrahmanian, to appear], Infomaster [Genesareth et al., 1997], and Information Manifold [Levy et al., 1996]) for integrating information sources. SHOE (cf. [Luke et al., 1996], [Luke et al., 1997]) and Ontobroker (cf. [Fensel et al., 1998a], [Decker et al., 1999]) use ontologies for information mediation focussing on the integration of HTML sources distributed throughout the WWW.

Ontobroker provides a broker architecture with 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. It provides a *representation* language for formulating ontologies. A subset of it is used to formulate queries, i.e. to define the *query language*. An *annotation* language is offered to enable knowledge providers to enrich web documents with ontological information. The strength of Ontobroker is the tight coupling of informal, semiformal and formal information and knowledge. This supports their maintenance and provides a service that can be used more generally for the purpose of *knowledge management* and for integrating knowledge-based reasoning and the semiformal representation of documents.

Applying these techniques to the web and to scenarios of realistic size, however, creates a couple of serious problems and brings up some interesting new insights. We will address the most interesting ones in this paper. Some of the above discussed problems and learned lessons could directly be addressed by Ontobroker and some of them required the redesign of the system now called On2broker. The major new design decisions in On2broker are the clear separation of query and inference engines and the integration of new web standards like XML and RDF. Both decisions are answers to two significant complexity problems of Ontobroker: the computational inference effort for a large number of facts and the human annotation effort for adding semantics to HTML documents.[2]

The content of the paper is organized as follows. First, we describe Ontobroker in section 2 and show how it enables integrated access to HTML pages distributed throughout the WWW. Then, we discuss in section 3 the limitations of this approach. These limitations illustrate the difficulties when making a step forward from solving toy examples to a

1. Also, ontologies have a much broader application context than database schemes. They are means to formalize joint domain theories and not necessarily reflects the conceptual or logical structure of a data store.

2. In terms of the database community On2broker is a kind of data warehouse for data on the Web. Queries are not run on the sources themselves to which On2broker provides access, but on a database into which the source content has been extracted. In addition to the facts that can be found explicitly in the sources, the system applies also rules to derive additional information.

system that is useful for solving real-world problems. Section 4 draws the consequences and introduces On2broker which overcomes most of the serious limitations of its predecessor. We will also show that such a system can successfully handle a much broader scope of tasks than intended at its inception. Section 5 provides the scope of tasks and domains, On2broker can be applied to. Our conclusions, and a discussion of related and future work are provided in section 6.

2 Ontobroker and its Merits

Ontobroker uses ontologies for information mediation focussing on the integration of HTML sources distributed over the WWW. To achieve this goal, Ontobroker provides three interleaved languages and two tools.

2.1 The Languages

Ontobroker provides an *annotation* language called HTML^A to enable the annotation of HTML documents with machine-processable semantics. For example, the following HTML page states that the text string „Richard Benjamins“ is the name of a researcher where the URL of his homepage is used as his object id.

```
<html><body><a onto="page:Researcher"><h2>Welcome to my homapge</h2>
My name is <a onto="[name=body]">Richard Benjamins</a>.</body></html>
```

An important design decision of HTML^A was

(1) to smoothly integrate semantic annotations into HTML and

(2) to prevent the duplication of information.

The reason for the former decision was to lower the threshold for using our annotation language. People who are able to write HTML can use it straightforwardly as a simple extension. The rationale underlying the second decision is more fundamental in nature. We do not want to add additional data, *instead we want to make explicit the semantics of already available data*. The same piece of data (i.e., „Richards Benjamins“) that is rendered by a browser is given a semantic in saying that this ascii string provides the name of a researcher. We will later show that this is a significant difference between our approach and approaches like SHOE, RDF, and annotations used in information retrieval.

In terms of a knowledge-based system, the annotation language provides the means to express factual knowledge (ground literals). Further knowledge in are provided by the ontology. The ontology defines the terminology (i.e., signature) and may introduce further rules (i.e., axioms) that allow the derivation of additional facts that are not stated extensionally.

A *representation* language is used to formulate an ontology. This language is based on Frame logic [Kifer et al., 1995]. Basically it provides classes, attributes with domain and range definitions, is-a hierarchies with set inclusion of subclasses and multiple attribute inheritance, and logical axioms that can be used to further characterize relationships

```
Object[].
  Person :: Object.
  Publication::Object.
Person[
   firstName =>> STRING;
   lastName =>> STRING;
   eMail =>> STRING;
   ...
   publication =>> Publication].
Publication[
author =>> Person;
title =>> STRING;
year =>> NUMBER;
abstract =>> STRING].
```

```
FORALL Person1, Person2
   Person1:Researcher [cooperatesWith ->> Person2]
  <-
   Person2:Researcher [cooperatesWith ->> Person1].

FORALL Person1, Publication1
   Publication1:Publication [author ->> Person1]
<->
  Person1:Person [publication ->> Publication1].
```

c_1 :: c_2 means that c_1 is a subclass of c_2.
c[*a* ==> *r*] means that an attribute *a* is of domain *c* and range *r*.
o : *c*[*a*->> *v*] means that *o* is element of *c* hand has the value *v* for *a*.
<- means logical implication and <-> logical equivalence.

Figure 1 An excerpt of an ontology (taken from [Benjamins et al., to appear])

between elements of an ontology and its instances. The representation language introduces the terminology that is used by the annotation language to define the factual knowledge provided by HTML pages on the web. A little example is provided in Figure 1. It defines the class *Object* and its subclasses *Person* and *Publication*. There some attributes are defined and some rules expressing relationships between them, for example, if a publication has a person as an author then the author should have it as a publication. Semantically, the language for defining rules is the fragment of first-order logic that can be transformed via Lloyd-Topor transformations [Lloyd & Topor, 1984] into Horn logic. Syntactically it differ as it incorporates object-oriented modeling primitives.

The *query* language is defined as a subset of the representation language. The elementary expression is:

$$x \in c \wedge attribute(x) = v$$

written in Frame logic:

x[*attribute* -> *v*] : *c*

In the head of F-Logic rules variables are all quantified. In the body variables may be either all or existentially quantified. All quantified variables must additionally be bound by a positive Atom in the body. Lloyd-Topor transformation handles these quantifications as following. Existential quantifiers in the body may be dropped, because in the body of a rule every variable is implicitly existentially quantified. An all quantification, *forall y p*(*y*), in the body is transformed to a $\neg$ *exists y* $\neg$ *p*(*y*). Then LLoyd-Topor transformation produces a set of rules out of this. Queries are handled as rules without head. Thus the above mentioned conditions for quantifications hold here too.

Complex expressions can be built by combing these elementary expressions with the usual logical connectives (∧, ∨, ¬). The following query asks for all abstracts of the publications of the researcher „Richard Benjamins“.

x[*name* -> „Richard Benjamins“; *publication* ->> { *y*[*abstract* -> *z*]}] : *Researcher*

The variable substitutions for *z* are the desired abstracts.

2.2 The Tools

Ontobroker relies on two tools that give it „life“: a *webcrawler* and an *inference engine*. The *webcrawler* collects web pages from the web, extracts their annotations, and parses them into the internal format of Ontobroker. The *inference engine* takes these facts together with the terminology and axioms of the ontology, and then derives the answers to user queries. To achieve this it has to do a rather complex job. First it translates Frame logic into Predicate logic and second it translates Predicate logic into Horn logic via Lloyd-Topor transformations [Lloyd & Topor, 1984]. The translation process is summarized in Figure 2

As a result we obtain a normal logic program. Standard techniques from deductive databases are applicable to implement the last stage: the bottom-up fixpoint evaluation procedure. Because we allow negation in the clause body we have to carefully select an appropriate semantics and evaluation procedure. If the resulting program is stratified, we use simple stratified semantics and evaluate it with a technique called dynamic filtering (cf. [Kifer & Lozinskii, 1986], [Angele, 1993]) which focuses the inference engine to the relevant parts of a minimal model required to answer the query. Dynamic filtering combines bottom-up and top-down evaluation techniques. The top-down part restricts the set of facts which has to be computed to a subset of the minimal model only. *Thus also infinite minimal models are possible because only this subset has to be finite* [Fensel et

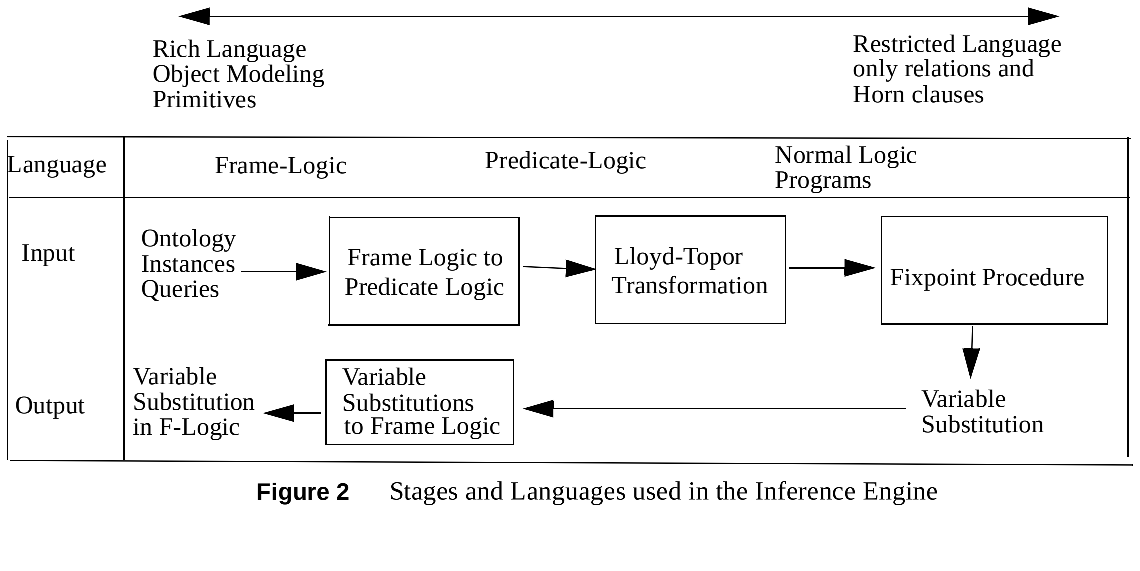
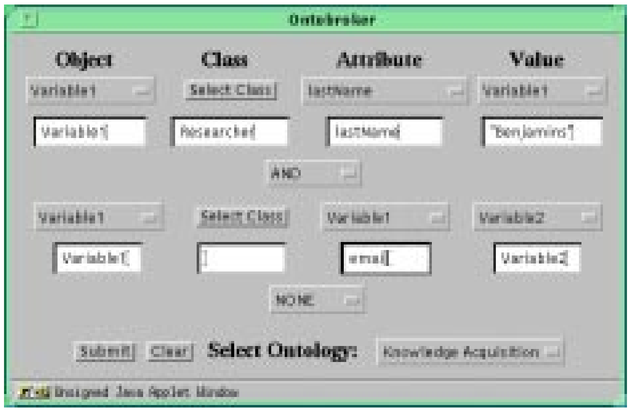


Figure 2 Stages and Languages used in the Inference Engine



Object	Class	Attribute	Value
Variable1	Select Class	lastName	Variable1
Variable1	Researcher	lastName	"Benjamins"
AND			
Variable1	Select Class	Variable1	Variable2
Variable1		email	Variable2
NONE			

Select Ontology: Knowledge Acquisition

Figure 3 The query interface.

al., 1998b].[3] The translation of Frame Logic usually results in a logic program with only a limited number of predicates, so the resulting program is often not stratified. In order to deal with non stratified negation we have adopted the *well-founded model semantics* [Van Gelder et al., 1991] and compute this semantics with an extension of dynamic filtering.

We developed a hyperbolic presentation of the ontology and a tabular interface to improve accessibility of the inference engine. Expecting a normal web user to type queries in a logical language and to browse large formal definitions of ontologies is not very practical. Therefore, we exploited the structure of the query language to provide a tabular query interface as shown in Figure 3. There we ask for the researchers whose last name is *Benjamins* and their email addresses. We also need support for selecting classes and attributes from the ontology. To allow the selection of classes, the ontology has to be presented in an appropriate manner. Usually an ontology can be represented as a large hierarchy of concepts. With regards to the handling of this hierarchy a user has at least two requirements: first he wants to scan the vicinity of a certain class looking for classes better suitable to formulate a certain query. Second a user needs an overview of the entire hierarchy to allow for a quick and easy navigation from one class in the hierarchy to another class. These requirements are met by a presentation scheme based on Hyperbolic Geometry [Lamping et al., 1995] where classes in the center are depicted with a large circle, whereas classes at the border of the surrounding circle are only marked with a small circle (see Figure 4). The visualization technique allows a quick navigation to classes far away from the center as well as a closer examination of classes and their vicinity. When a user selects a class from the hyperbolic ontology view, the class name appears in the class field of the tabular interface and the user can select one of the attributes from the attribute choice menu as the pre-selected class determines the possible attributes. Based on these interfaces Ontobroker automatically derives the query in textual form and presents the result of the query.

Ontobroker[4] is available on the web and has been applied in a few applications in the

3. Syntactical rules that ensure that the subset of minimal model that has to be computed remains finite are described in [Fensel et al., 1998b].

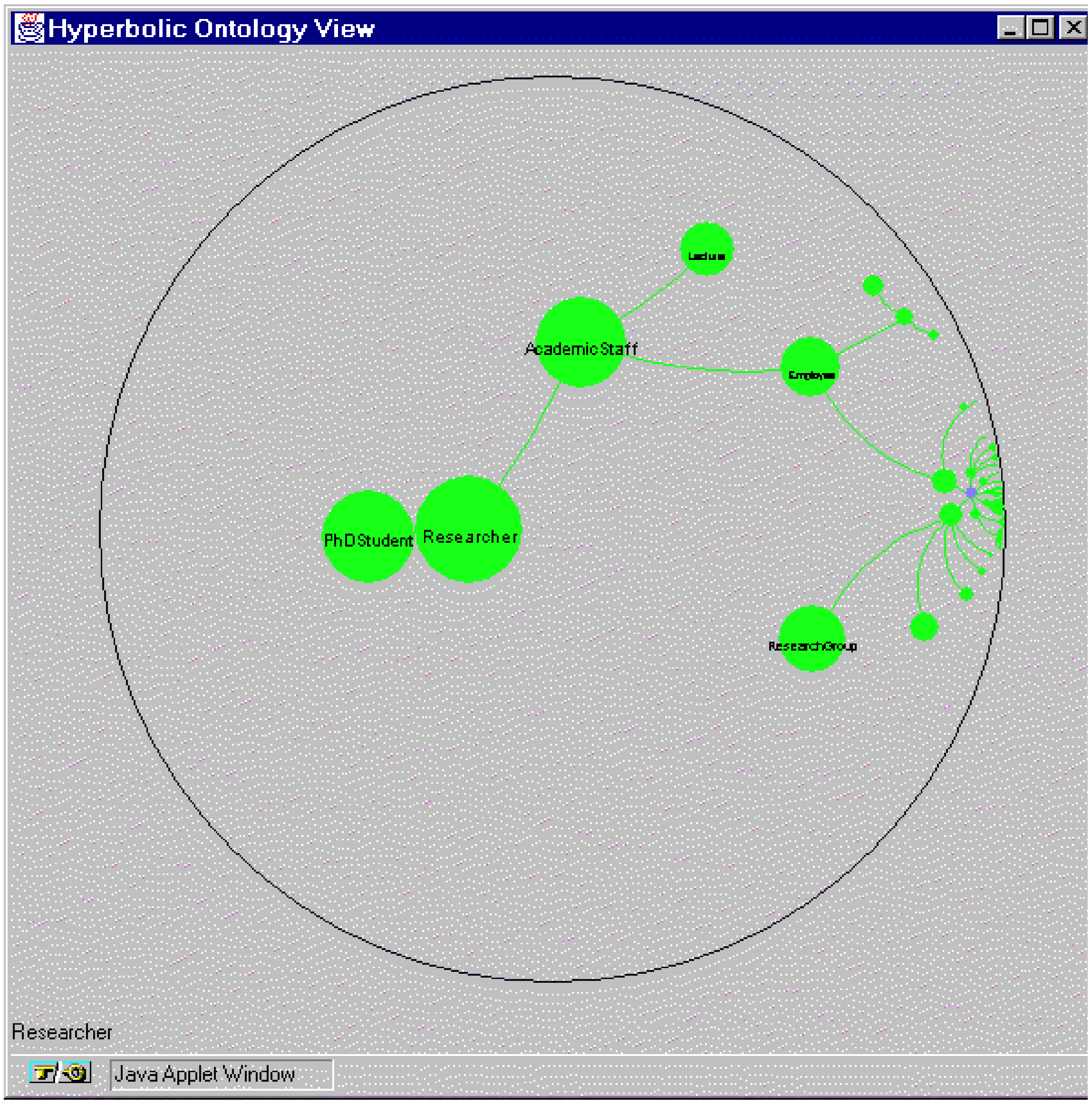


Figure 4 The hyperbolic ontology view.

meantime. The most prominent one is the (KA)^2 initiative[5] that develops an ontology for annotating web documents of the knowledge acquisition community [Benjamins et al., to appear].

4. http://www.aifb.uni-karlsruhe.de/www-broker.
5. The Knowledge Annotation Initiative of the Knowledge Acquisition Community (KA)^2.

3 Problems in Scaling Up Ontobroker

Ontobroker produces nice and convincing results for small-sized applications. However, there are serious bottlenecks when trying to apply it to larger case studies. Three main problems significantly reduce its usability. First, there is a high human annotation effort. It is hard to convince customers that this effort really pays back through the improved information access. Second, the inference engine becomes slow when the number of facts increases to realistic sizes. Then queries are no longer get answered or the answers arrive too late. Third, neither the query interface nor the way answers are presented fulfil the needs of information retrieval tools. We will discuss each of these problems in more detail in this section.

3.1 The Annotation Effort

Manually adding annotations to web sources requires human effort causing costs in terms of time and money. In an experiment we estimated that the average number of pages a person can annotate is around five per hour. Obviously this number significantly differs with the size of the pages, the quality, and the grainsize of annotations. Meanwhile we also developed a click-and-browse editor that lowers this effort (see Figure 5).[6] Still, annotating the entire web would require an unrealistic effort. This annotation effort may become less problematic by spreading it over the entire web community. Currently the Resource Description Framework (RDF) [Miller, 1998] arises as a standard for annotating web sources with machine-processable metadata.[7] Relating our approach to this standard significantly broadens the range of existing annotations it can be applied to. Another interesting possibility is the increased use of the eXtensible Markup language XML. In many cases, the tags defined by a Document Type Definition (DTD) may carry semantics that can be used for information retrieval. For example, assume a DTD that defines a person tag and within it a name and phone number tag.

```
<PERSON>
        <NAME>Richard Benjamins</NAME>
        <PHONE>+3120525-6263</PHONE>
</PERSON>
```

Then the information is directly accessible with its semantics and can be processed later by Ontobroker for query answering. Expressed in Frame logic, we get:

```
url[NAME --> „Richard Benjamins“; PHONE -->+3120525-6263] : PERSON
```

Annotation is a declarative way to specify the semantics of information sources. A procedural method is to write a program (called *wrapper*) that extracts factual knowledge from web sources. [Ashish & Knoblock, 1997] distinguish three types of information

6. The annotation tool presents a HTML page as it is presented by using a Web-browser. It also provides browsing facility for the ontology, where a user can select appropriate terms and the possibility to add annotations to the HTML code using the selected terms from the ontology.

7. For example, Netscape provides a Yahoo like index and categorized web sources in RDF, see directory.netscape.com.

sources on the web: multiple-instance sources, single-instance sources, and loosely-structured sources. The former two types have a stable format that can be used by a wrapper to extract information. Writing wrappers for stable information sources enable us to apply Ontobroker to structured information sources that do not make use of our annotation language. In fact, we applied Ontobroker to the CIA World Fact book (cf. Figure 6)[8]. The Fact book contains a page for each country in the world which presents some general information using a standardized layout. The wrapper program we developed (a one page phyton program) extracts around 40.000 facts providing around 4 MB of factual knowledge about these countries. The strategy of the wrapper is to use a key word based search combined with assumptions on the delimiters of information entries. This strategy was necessary because the pages are hand made and slightly differ in structure for different countries. Also the authors of these pages used HTML as a layout and not as a logical language.[9]

This experiment proved that it is already possible to exploit structure and regularity in current web sources (i.e., HTML documents) to extract semantic knowledge from it without any additional annotation effort. Successfully overcoming the annotation effort for this information source made us aware of a second bottleneck in Ontobroker, the query response time of inference engine for large sets of facts. We will discuss this

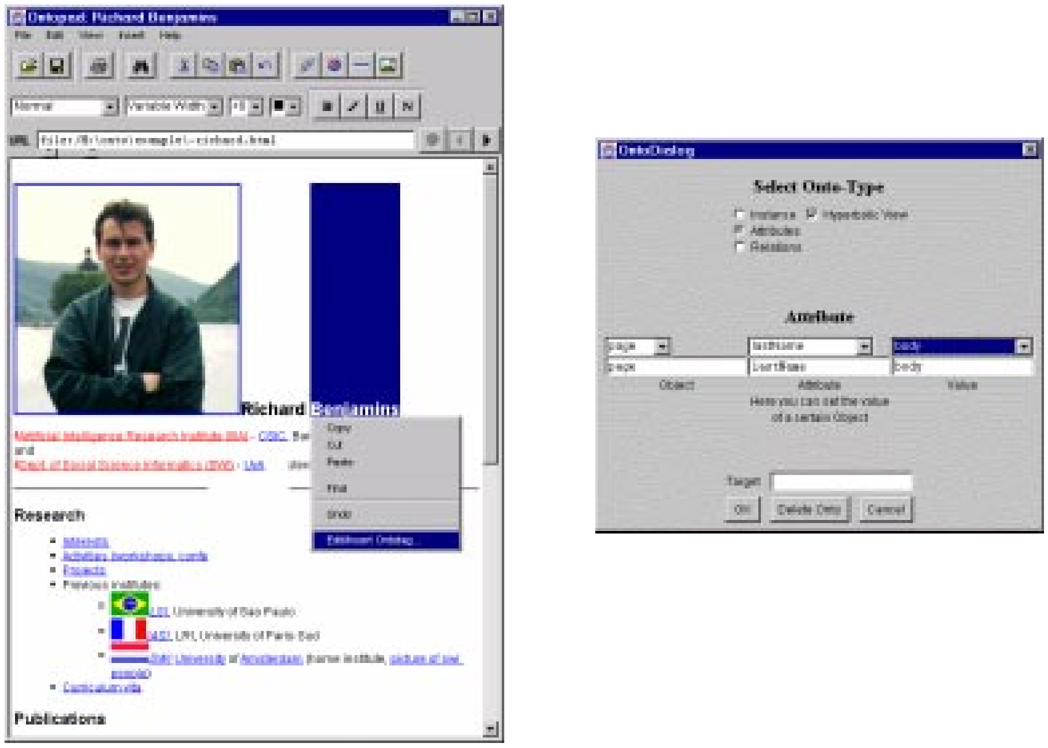


Figure 5 The annotation editor (it also includes the hperbolic representation of Figure 4).

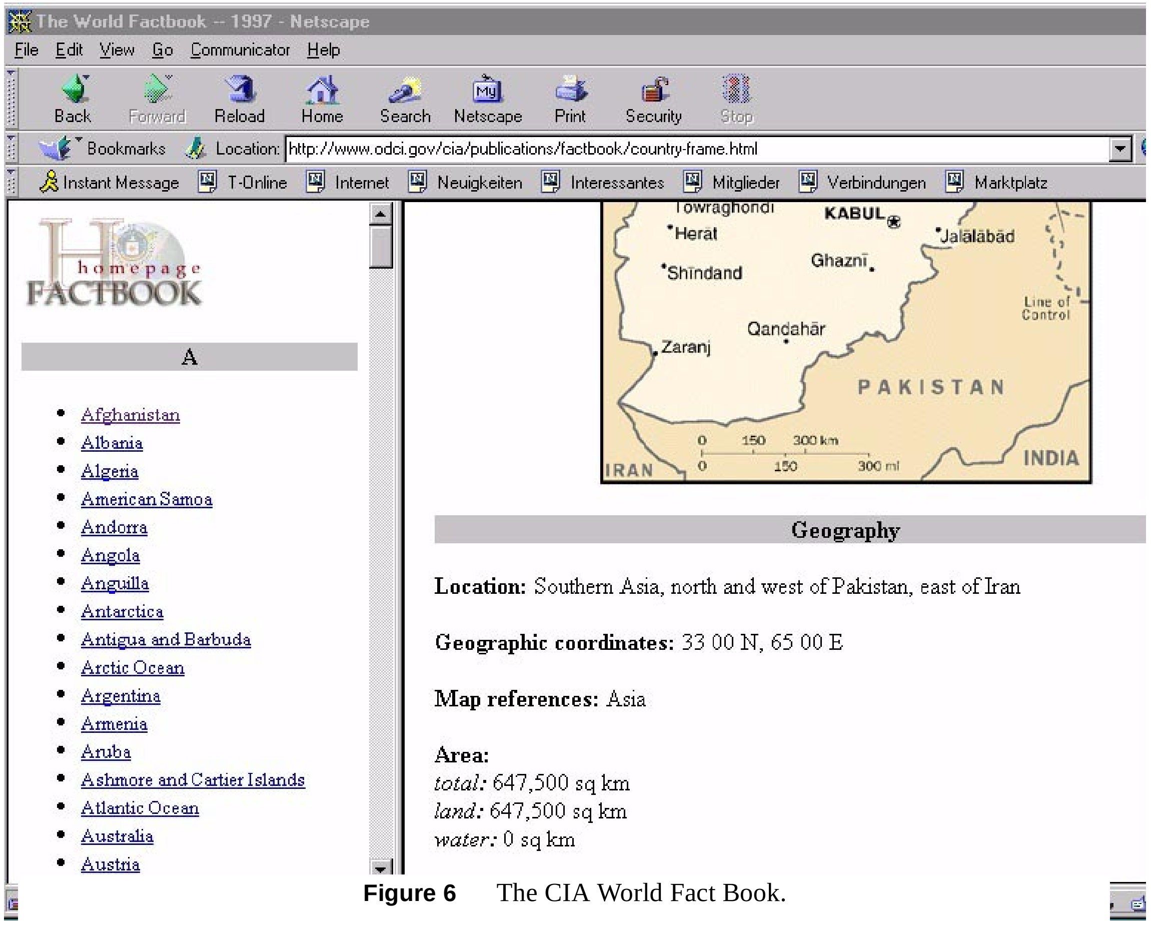
8. http://www.aifb.uni-karlsruhe.de/www-broker.

9. For example, they indicate headings by <bold> and not by <Heading$_i$>-tags.

problem in the next section.

3.2 The Inference Effort

In the worst case a query may lead to the evaluation of the entire minimal model. This is a computational hard problem (cf. [Brewka & Dix, 1999]). In other cases predicate symbols and constants are used to divide the set of facts into subsets in order to omit those subsets which can not contribute to the answer. This normally reduces the evaluation effort considerably. Ontobroker allows very flexible queries such as „which attributes has a class“. As a consequence the entire knowledge is represented by only a few predicates such as the predicate *value* which relates a class *c* to its attribute *att* and the corresponding attribute value *v* (*value*(*c*,*att*,*v*)). This reification strategy implies that the set of facts is divided into a few subsets only. The last version of our inference engine used the minimal model as semantics. If the set of rules is stratified [Ullman, 1988] an answer to a query may be evaluated efficiently using minimal model semantics. Using only few predicates has the consequence that nearly every rule set is not stratified if we allow negation in rules. This was the reason that we had to use the Wellfounded Semantics in our approach now (cf. [Van Gelder et al., 1991]). Wellfounded Semantics


The World Factbook -- 1997 - Netscape
File Edit View Go Communicator Help
Back Forward Reload Home Search Netscape Print Security Stop
Bookmarks Location: http://www.odci.gov/cia/publications/factbook/country-frame.html
Instant Message T-Online Internet Neuigkeiten Interessantes Mitglieder Verbindungen Marktplatz
homepage FACTBOOK
A
Afghanistan
Albania
Algeria
American Samoa
Andorra
Angola
Anguilla
Antarctica
Antigua and Barbuda
Arctic Ocean
Argentina
Armenia
Aruba
Ashmore and Cartier Islands
Atlantic Ocean
Australia
Austria
Towraghondi
KABUL
Herat
Jalalabad
Ghazni
Shindand
Line of Control
Qandahar
Zaranj
PAKISTAN
IRAN
INDIA
0 150 300 km
0 150 300 mi

Geography

Location: Southern Asia, north and west of Pakistan, east of Iran

Geographic coordinates: 33 00 N, 65 00 E

Map references: Asia

Area:
total: 647,500 sq km
land: 647,500 sq km
water: 0 sq km

Figure 6 The CIA World Fact Book.

coincides with Minimal Model Semantics in cases where the rule set is stratified. Beyond that the Wellfounded Model Semantics also allows us to evaluate non stratified rule sets.

Both points, the small number of predicates and the Wellfounded Model Semantics raised severe efficiency problems. Up to now we applied our inference engine only to knowledge bases with less than 100,000 facts. It is clear that our approach should be applicable to millions of facts in order to be of practical relevance. The problems in applying the inference engine to the full-sized applications pointed out a serious shortcoming of the overall system architecture of Ontobroker. Currently, the query engine and the inference engine are actually *one* engine. The inference engine receives a query and derives the answer. However, in the case of the CIA World Fact book there are no axioms present in the ontology (cf. Figure 7). And the query interface of Ontobroker is restricted to simple SQL-like queries (i.e., it can be used to ask for ground objects ids and ground attributes values fulfilling certain properties). That is, we applied a powerful inference mechanism to a problem that could be solved by much simpler means. The inference engine is necessary for deriving additional facts based on the annotations in the web and the rules of the ontology. But it is not necessarily required for deriving ground substitutions of our queries. The need to separate the query and inference engines was the clear lesson we learned from this exercise. The next section will provide further arguments for this need.

3.3 The Limited Query Interface

The query interface of Ontobroker lacks the standard capabilities of professional keyword-based web search engines and information retrieval systems. Terms must be typed precisely as they are stored (as facts or ontological expressions) into the system. Unification in logic programming assumes a perfect match of terms, i.e. Benjamins does not match with Benjamin. Similarly, Ontobroker does not allow the truncation of

```
Country :: Object.
Country[ has_name =>> string;
    has_geography =>> geography;
    has_people =>> people;
    has_government =>> government;
    has_economy =>> economy;
    has_communication =>> communications;
    has_transportation =>> transportation].
```

```
Geography :: Object.
geography[
    map =>> string;
    flag =>> string;
    location =>> string;
    geographic_coordinates =>> string;
    has_area =>> area;
    has_boundaries =>> boundaries;
    coastline =>> string;
    has_maritime_claims =>> maritime_claims;
    climate =>> string;
    terrain =>> string;
    has_elevation_extremes =>> elevation_extremes;
    natural_resources =>> string;
    has_land_use =>> land_use;
    irrigated_land =>> string;
    natural_hazards =>> string].
```

Figure 7 A snapshot of the ontology developed for describing the knowledge of the CIA World Fact Book.

expressions (i.e., Benjam*) and the ranking of the answers found is determined by the internal order of the inference process and does not make any sense to the user. In general, two strategies exist to deal with these shortcomings.

- First, the following features can be integrated into the inference process: (a) we could allow equality and express equality axioms for terms;[10] (b) we could include specific built-in predicates that externally define same term equalities (cf. [Cohen, 1998]); and (c) we could directly change the unification mechanism (for example, by including a truncation mechanism into it).
- Second, we could use the classical inference engine but provide additional post-processing service by the query interface. The query engine can decide how to deal with the results of the inference engine in a way that meets the user's needs. In On2broker we generally follow this second approach.

The choices we made in changing and extending Ontobroker to On2broker will be discussed in the following section.

4 On2broker: Lessons Learned and Problems Solved

On2broker takes two main lessons from the experiences we collected with Ontobroker. It overcomes the inference bottleneck and it broadens the scope of web sources it can be applied to. Both aspects will be discussed in this section. Finally we show how On2broker can communicate with other information mediators and softbots [Etzioni, 1997].

The overall picture of On2broker is provided in Figure 8 which includes four basic engines representing different aspects.

- The **info agent** is responsible for collecting factual knowledge from the web using various style of meta annotations and direct annotations like XML.
- The **inference agent** uses facts and ontologies to derive additional factual knowledge that is only provided implicitly. It frees knowledge providers from the burden of specifying each fact explicitly.
- The **query engine** receives queries and answers them by checking the content of the databases that were filled by the info and inference agents.
- The **database manager** receives facts from the Info agent, exchanges facts as input and output with the inference agent, and provides facts to the query engine.

Ontologies are the overall structuring principle. The info agent uses them to extract facts, the inference agent to infer facts, the database manager to structure the database and the query engine to provide help in formulating queries. On2broker has this architecture to overcome some serious shortcoming we encountered when applying AI techniques to the web environment with our prototypical system Ontobroker.

10. For reasons of computational complexity, Ontobroker does not provide equality reasoning.

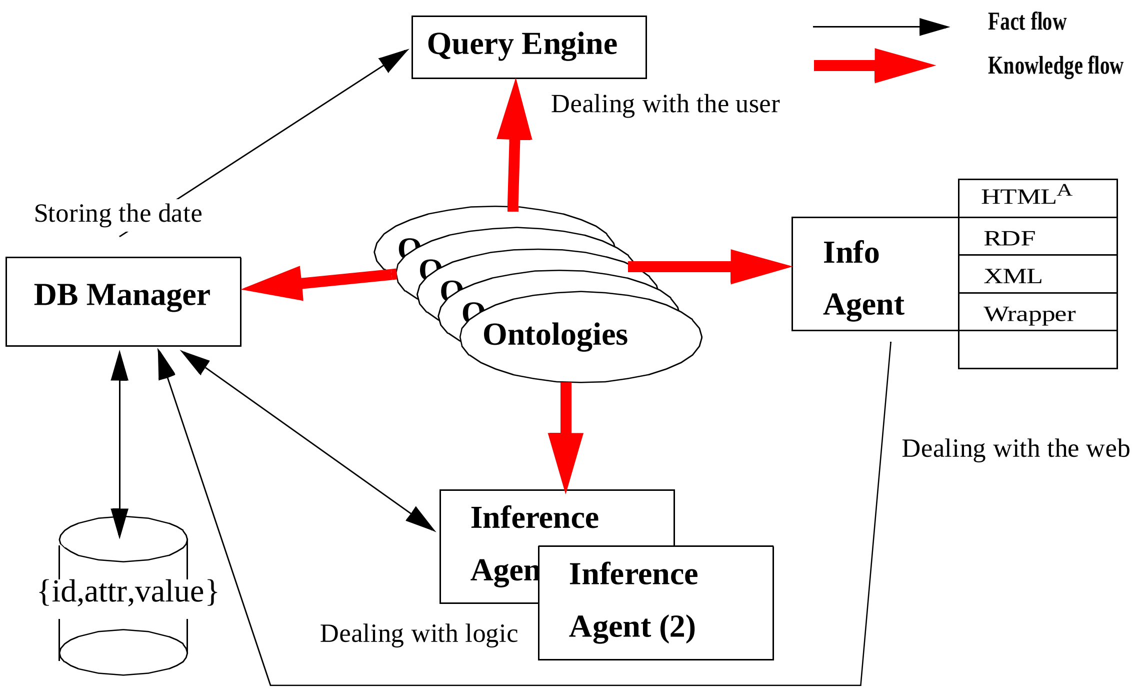


Figure 8 On2brokers Architecture.

4.1 Decoupling Inference and Query Response

In the design of Ontobroker we already made an important decision when we separated the web crawler and the inference engine. The web crawler periodically collects information from the web and caches it. The inference engine uses this cache when answering queries. The decoupling of inferencing and fact collection is done for efficiency reasons. The same strategy is used by search engines on the web. A query is answered with help of their indexed cache and not by starting to extract pages from the web. On2broker refines this architecture by introducing a second separation: *separating the query and inference engines*. The inference engine works as a demon in the background. It takes facts from a database, infers new facts and returns these results back into the database. The query engine does not directly interact with the inference engine. Instead it takes facts from the database. It is an SQL frontend to this database and the tabular and hyperbolic query interface of Figure 3 and Figure 4 can still be used for it. Separating query and inference engine has some clear advantages:

- Whenever inference is a time critical activity it can be performed in the background independently of the time required to answer the query.
- Using database techniques for the query interface and its underlying facts provides robust tools that can handle mass data.
- It is relatively simple to include things like truncation, term similarity and ranking in the query answering mechanism. They can now directly be integrated into the SQL

query interface (i.e., in part they are already provided by SQL) and does not require any changes to the much more complex inference engine.

For example, the ontology of the CIA World Fact Book does not contain any rules. It is therefore large overhead to use an inference engine for query answering. With Ontobroker, it takes a minute to read and translates all 40.000 facts before the inference engine even starts with its first inference. A simple database update in On2broker performs much faster.

In the simplest case the format in which the data are stored in the database is one large table with three columns: object-id, attribute (i.e., property), and value, and a row for each fact. This may cause new efficiency problems when millions of facts have been extracted. However, we can make use of several refinements to deal with this problem. First, we can define a database per ontology. Second, we can use one ontology to structure its database. Simplified, each concept in an ontology may correspond to a table and each attribute defines a column of this table.[11] Both strategies do not reduce the number of facts that need to be stored but the number of facts that need to be checked for answering a query.

More general, the strict separation of query and inference engines can be weakened for cases where this separation would cause disadvantages. In many cases it may not be necessary to enter the entire minimal model into a database. Many facts are of intermediate or no interest when answering a query. The inference engine of On2broker incorporates this in its dynamic filtering strategy which uses the query to focus the inference process. We can make use of this strategy when deciding which facts are to be put into the database. Either one limits the queries that can be processed by the system or one replaces real entries in the database with a virtual entry representing a query to the inference engine. The latter may require large delay in answering which, however, may be acceptable for user agents that collects information of the WWW in a background mode. Finally, we can cache the results of such queries to speed up the process in cases where it is asked again. One can even reduce the answering service to a set of predefined queries which are already materialized in the database. In many application contexts one does not need the full flexibility of the query interface but rather information answering for a set of predefined queries. This also holds for automatic generation of documents as discussed in the next section. Here the document results from a query that is executed when the document is retrieved by a user. Therefore, such a document corresponds to a predefined query. Refining the integration of database and inference techniques is an important line of the current work on On2broker. The dataware housing literature provides two alternatives:

- Materializing views (i.e., queries)
- Realizing views by run time queries

Both solutions are also present in the web (e.g., by the on-line store providers junglee and jango[12]) and both have their merits and shortcomings (cf. [Harinarayan et al., 1996]). By

11. The actual solution is more complex reflecting the is-a relationship between concepts including subset relationships of sub concepts and attribute inheritance.

making the architecture of On2broker more flexible as it was allows domain and task specific customization.

4.2 How to extend HTML^A

HTML^A is appealing because (1) it is a simple and straightforward extension of an existing technology and because (2) it prevents any duplication of information. However it is not a widely used standard. The actual annotations which we will find in the web will therefore be rather small. An alternative is to write wrappers for non-annotated sources. However, this burdens us with some programming effort. Therefore, we extended the webcrawler (called Info agent in On2broker) of Ontobroker to include two new web standards RDF and XML that both provide meta information in a complementary manner.

RDF[13] [Miller, 1998] provides means for adding semantics to a document without making any assumptions about the internal structure of this document. It is an XML application (i.e., its syntax is defined in XML) customized for adding meta information to Web documents. It is currently under development as a W3C standard for content descriptions of web sources and will be used by other standards like PICS-2, P3P, and DigSig.

The data model of RDF provides three object types: resources, property types, and statements (cf. [Lassila & Swick, 1998]):

- A *resource* (*subject*) is an entity that can be referred to by an address at the WWW (i.e., by an URI). Resources are the elements that are described by RDF statements.
- A *property type* (*predicate*) defines a binary relation between resources and / or atomic values provided by primitive datatype definitions in XML.
- A *statement* (*object*) specifies for a resource a value for a property. That is, statements provide the actual characterizations of the web documents.

A simple example is

Creator(http://www.w3.org/Home/Lassila) = *Ora Lassila*[14]

stating that the creator of the web document http://www.w3.org/Home/Lassila is Ora Lassila. Values can also be structured entities

Creator(http://www.w3.org/Home/Lassila) = $X \wedge$
Name(X) = *Ora Lassila* $\wedge$ *Email*(X) = lassila@w3.org

where X either denotes an actual (i.e., the homepage of Ora Lassila) or virtual URI. In addition, RDF provides bags, sequences, and alternatives to express collections of web sources. Finally, RDF can be used to make statements about RDF-statements, i.e. it provides meta-level facilities.

12. http://www.junglee.com and http://www.jango.com.
13. See http://www.w3c.org/RDF and http://www.cs.ukc.ac.uk/people/staff/djb1/research/metadata/rdf.shtml.
14. We skip the awkward syntax of RDF because a tool can easily present it as shown.

Claim(*Ralph Swick*) = (*Creator*(http://www.w3.org/Home/Lassila) = *Ora Lassila*)

states that Ralph Swick claims that Ora Lassila is the creator of the resource http://www.w3.org/Home/Lassila. The info engine of Onto2broker can deal with RDF descriptions. We make use of the RDF Parser SiRPAC[15] that translates RDF descriptions into triples that can directly be put into our database and used by our inference engine (cf. [Decker et al., 1998]). Actually, On2broker is the first inference engine for RDF.[16]

RDF still requires the annotation effort for creating metadata but this effort is now shared by the entire web community. XML provides the chance to get metadata „for free“, i.e. as side product of defining the document structure. XML allows the definition of new tags with the help of a DTD and provides semantic information as a by-product of defining the structure of the document. A DTD defines a tree structure to describe documents and the different leaves of the tree have tags that provides semantics of the elementary information units presented by them. That is, the structure and semantics of a documents are interleaved. In particular, a document must be written using XML and the specific tagging provided by its DTD. On2broker is able to read such DTD, to translate it into an ontology, and to translate XML documents into its internal triple representation (cf. [Erdmann & Studer, submitted]).

4.3 Enabling Agents to Access On2broker

In the effort to create efficient search mechanisms in the WWW information *mediators*, the like of Metacrawler[17], and softbots that access other search engines will become increasingly important. That is why in On2broker the decision was taken to implement the query interface as an Java™ *Remote Method Invocation (RMI) Server.* This allows us to make the Java™ interface publicly available and thus give meta search engines more efficient access to the database. While the current method, used by the query interface applet, returns the results in a HTML format as does the CGI script in Ontobroker, the interface can easily be extended to have methods return the result in any other format convenient to the invoking application. With the current release of Sun's JDK 1.2 an implementation of the query server with a CORBA interface will also be available to make accessibility even easier for applications not written in Java™.

5 Accessing, Creating, and Maintaining Semistructured Documents in Intranets and the Internet

Ontobroker was presented as a means to improve access to information provided in intranets and in the internet (cf. [Fensel et al., 1997]). Its main advantages compared to

15. http://www.w3.org/RDF/Implementations/SiRPAC/
16. http://www.w3.org/RDF, RDF Software and Products.
17. http://www.metacrawler.com.

keyword-based search engines are:

- Keyword-based search retrieves irrelevant information that use a certain word in a different meaning or it may miss information where different words about the desired content are used.
- The query responses require human browsing and reading to extract the relevant information from these information sources. This burdens web users with an additional loss of time and seriously limits information retrieval by automatic agents that miss all common sense knowledge required to extract such information from textual representations
- Key word based document retrieval fail to integrate information spread over different sources.
- Finally, each current retrieval service can only retrieve information that is represented by the WWW.[18]

Ontobroker uses semantic information for guiding the query answering process. It provides the answers with a well-defined syntax and semantics that can be directly understood and further processed by automatic agents or other software tools. It enables a homogeneous access to information that is physically distributed and heterogeneously represented in the WWW and it provides information that is not directly represented as facts in the WWW but which can be derived from other facts and some background knowledge. Still, the range of problems it can be applied to is much broader than information access and identification in semistructured information sources. On2broker is also used to create and maintain such semistructured information sources, i.e. it is a tool for web site construction and restruction.

Automatic document generation extracts information from weakly structured text sources and creates new textual sources. Assume distributed publication lists of members of a research group. The publication list for the whole group can automatically be generated by a query to On2broker. A background agent periodically consults On2broker and updates this page. The gist of this application is that it generates semistructured information presentations *from* other semistructured ones. The results of a query to On2broker may be inserted as Java-Script data structures into the HTML-Stream of a web page. So using Java-Script the query results may be presented in every desired form within this page. This allows to insert content into a web page which is dynamically generated by On2broker.

Maintenance of weakly structured text sources helps to detect inconsistencies among documents and to detect inconsistencies between documents and external sources, i.e., to detect incorrectness. WebMaster [van Harmelen & van der Meer, 1999] developed a constraint language for formulating integrity constraints for XML documents (for

18. This sounds trivially true, but it significantly limits query answering capability. Imagine that Feather writes on his homepage that he cooperates with another researcher E. Motta. You will completely miss this information for E. Motta if he does not repeat the information (with the reverse direction) on his homepage and you are only consulting his page. An answering mechanism that can make use of the implicit symmetry of cooperation could provide you with this answer.

example, a publication on a page of a member of the group must also be included in the publication list of the entire group). Again such a service can be provided by On2broker. We can either incorporate the inference of WebMaster in it or use the existing inference engine in a different way. We mentioned that we currently use the type system for abductively inferring new facts paying tribute to the sloppiness and openness of the WWW. Using the type system for checking integrity constraints may be the right way to make use of it for homogeneous and well designed intranets of companies and organizations. Maintaining intranets of large organizations and companies become a serious effort because such networks already provide several million documents. Therefore it is no surprise that first serious application projects of On2broker actually refer rather to intranet sides and not directly to the internet.

6 Conclusions

On2broker includes four basic engines representing different aspects. The info agent is responsible for collecting factual knowledge. The inference agent uses facts and ontologies to derive additional factual knowledge that is only provided implicitly. It frees knowledge providers from the burden of specifying each fact explicitly. The query engine is the user frontend and the database manager is the backbone of the entire system. It receives facts from the Info agent, exchanges facts as input and output with the inference agent, and provides facts to the query engine. *Ontologies* are the overall structuring principle. The info agent uses them to extract facts, the inference agent to infer facts, the database manager to structure the database and the query engine to provide help in formulating queries.

On2broker is the technology underlying the $(KA)^2$ initiative [Benjamins et al., to appear]. Here, a group of researcher works on a joined and shared ontology used to annotate information sources of the knowledge acquisition community. Achieving consensus in a world-wide and heterogeneous community on an ontology is a difficult process. Often it is not so much a pure technological problems (i.e., lacks of development tools) but rather highlights interesting aspects from a sociological point of view. In addition to this academic case study, On2broker is currently applied and evaluated in case studies with British Telecom (BT), DaimlerChrysler, and Swiss Life.

In the following we will compare On2broker with related work and outline directions of future work.

Current web standards like HTML are very limited in the access to information sources they provide. Therefore, many extensions of HTML are proposed in the literature. [Perkowitz & Etzioni, 1997b] propose A-HTML that extends HTML by the use of meta-information enabling adaptive web sites. This extension is close in spirit to our extensions of $HTML^A$. The main difference concerns the content and purpose of these annotations. A-HTML enables dynamic reconfiguration whereas $HTML^A$ supports query access to web pages. However, generating web pages via queries to On2broker brings both approaches together.

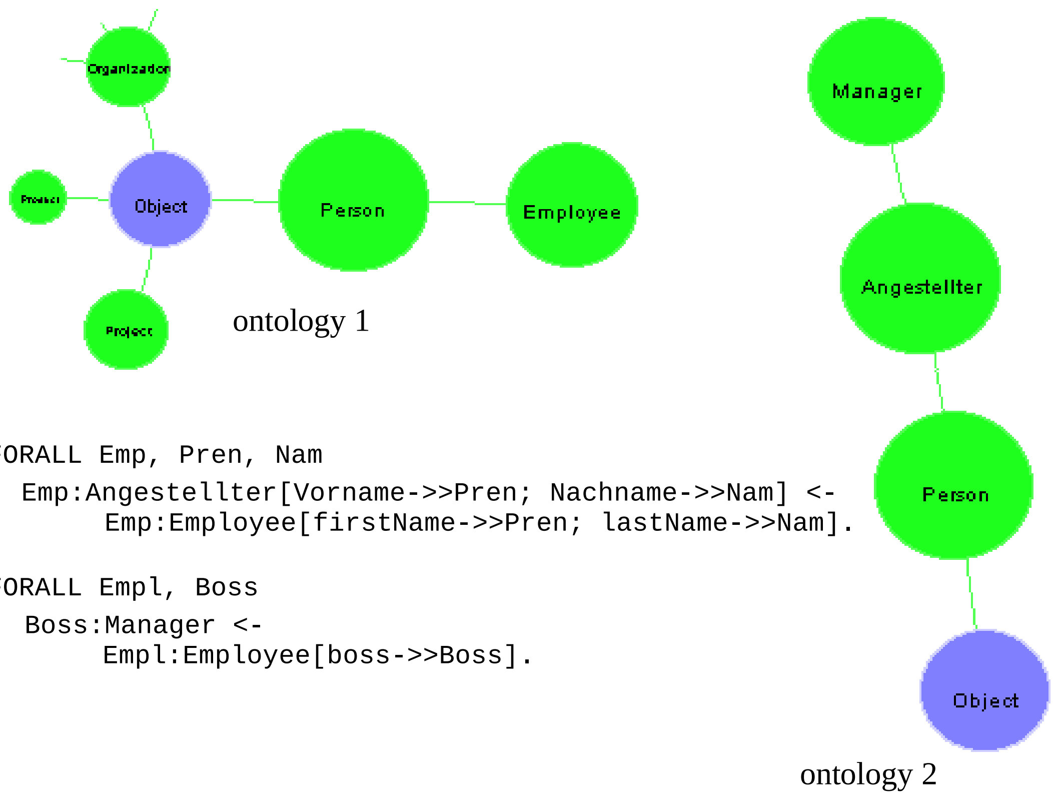
SHOE (cf. [Luke et al., 1996], [Luke et al., 1997]) introduced the idea of using ontologies for annotating web sources. There are two main differences to our approach. First, the annotation language is not used to annotate existing information in web pages but to add additional information and annotate them. That is, in SHOE the same information must be repeated and this redundancy may cause significant maintenance problems. For example, an affiliation must once be provided as a text string rendered by the browser and a second time as annotated meta information. In this respect, SHOE is close to meta tags in HTML. On2broker use the annotations to directly add semantics to textual information that is also rendered by a browser. A second difference is the use of inference techniques and axioms to infer additional knowledge. SHOE relies only on database techniques. Therefore, no further inference service is provided. Ontobroker uses an inference engine to answer queries. Therefore, it can make use of rules that provide additional information. However, this decision also limited the size of problems it can successfully be applied to. On2broker takes an intermediate position. It uses an inference engine to derive additional facts. Its query interface is, however, coupled to a database easily scaling up to large datasets.

An excellent survey of database techniques applied to the WWW is provided by [Florescu et al., 1998]. In their outline, they characterize a web site management system as consisting of wrappers, mediators, declarative web site specification, and an HTML generator. The Info agent of On2broker provides such a wrapper, and the ontology together with the inference agent and database manager provide the mediator. The query engine of On2broker allows the declarative specification of web site (relying also on additional axioms provided by the ontology).

FLORID [Ludäscher et al., 1998] uses Frame logic for defining access to web sources as does On2broker. However, FLORID directly relies on the syntactical structure of web sources and does not use any metadata approach. Simplified, a HTML page is an object and each tag (including links) is an attribute of this object. Therefore, it is possible to ask for headings of a page or for all pages reachable from it. On2broker lifts from this syntactical level and provides semantic access to facts spread over different web sources. This orientation on semantics rather than on syntax and the use of a logical background theory (i.e., an ontology) is also the main difference between On2broker and approaches like STRUDEL [Fernandez, 1998] and WebQQL [Aroneca, 1997].

The use of *one* ontology for annotating web documents will never scale up for the entire web. Neither will an ontology be suitable for all subjects and domains nor will ever such a large and heterogeneous community as the web community agree on a complex ontology for describing all their issues. For example, the Dublin Core community[19] has been working for years to establish a simple core ontology for adding some meta information to on-line documents. [Fensel et al., 1997] sketch out the idea of an *ontogroup*. Like a news groups, it is based on a group of people who are joined by a common interest and some agreement as to how to look at their topic. An ontology can be used by such a group to express this common ground and to annotate their information

19. http://purl.org/metadata/dublin_core.



```
FORALL Emp, Pren, Nam
  Emp:Angestellter[Vorname->>Pren; Nachname->>Nam] <-
       Emp:Employee[firstName->>Pren; lastName->>Nam].

FORALL Empl, Boss
  Boss:Manager <-
       Empl:Employee[boss->>Boss].
```

Figure 9 Ontology integration in On2broker.

documents. A broker can make use of these annotations to provide intelligent information access. The ontology describes the competence of the broker, i.e. the area in which it can provide meaningful query response. In consequence, several brokers will arise, each covering different areas or different points of views on related areas. Facilitators and softbots [Etzioni, 1997] guide a user through this knowledgeable network superimposed on the current internet (cf. [Dao & Perry, 1996], [Sakata et al., 1997]). Therefore, work on relating and integrating various ontologies (cf. [Jannink et al., 1998]) will become an interesting and necessary research enterprise which will also be addressed in the future course of the On2broker project helping to evolve „the Web from a Document Repository to a Knowledge Base.“ [Guha et al., 1998]

A first glance of how the inference engine of On2broker can be used to implement such ontology mappings is depictures in Figure 9. It shows two different ontologies and two rules which partially map the first ontology on the second. The first mapping rule solves a naming conflict between the two ontologies. It translates english named concepts and attributes of the first ontology to corresponding german named concepts in the second ontology. It maps the concept *Employee* to the concept *Angestellter* and the attributes *firstName* and *lastName* to the attributes *Vorname* and *Nachname*. The second rule solves a structure conflict by mapping the attribute *boss* of the concept *Employee* in the first ontology to the concept *Manager* in the second ontology.

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