NPBibSearch - An Ontology Augmented Bibliographic Search

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Abstract. Ontologies are considered to be the state-of-the-art technology for the development and evolution of the Semantic Web. Today, the use of semantic markup in the World Wide Web (WWW) is rather poor. Therefore, search engines and software agents often use external ontologies for applying information retrieval tasks in the WWW. We have developed NPBibSearch, an ontology augmented search engine tool for bibliographical search in the restricted domain of NP-complete problems, an important subject in theoretical computer science. In connection with the keyword-based full-text retrieval of the Google web APIs service, NPBibSearch searches the database of the Electronic Colloquium of Computational Complexity (ECCC), guided by a simple ontology driven navigation tool that unfolds the domain of NP-complete decision problems to the user.

1 Introduction

The Semantic Web is an extension of the current World Wide Web (WWW), based on the concept of exchanging information with explicitly expressed, formal descriptions of meaning, in a manner understandable by machines [1]. This additional semantic information will enable applications to understand the information they process, and thus, to provide more accurate operations. In order to exchange the meaning of information, it is important to agree on how to explicitely model its semantics. Ontologies as an explicit and formal specification of a conceptualization are a widely used mechanism for representing such domain descriptions [16]. Ontologies represent a domain of discourse and allow the definition of classes, relations, and functions, while providing a great deal of flexibility. In the Semantic Web, ontologies are shared vocabularies that are used for defining how to understand data and metadata of the WWW.

The WWW of today mainly consists out of HTML encoded documents with an emphasis on machine readable formating information and human readable semantics. This lack of machine understandable semantic information necessitates the employment of information retrieval techniques to guess right the meaning of WWW documents. For this reason, WWW applications working on documents that are purely encoded in HTML must be less accurate than applications that use formalized semantic information provided by the author.

Search engines are one of the many applications that will benefit from the new way of information processing in the Semantic Web. Today, general search engines are producing endless lists of search hits and it is up to the user to refine his query until the expected results are among the first page of hits. Ontologies may help search engines in two ways at the same time: Additional semantic information provided by the author and encoded within or being linked to the WWW document, and the connection of regular information retrieval techniques on WWW documents to external ontologies, for better content categorization and thus, for providing more accurate search results.

Among the billions of WWW documents, there is also an increasing number of scientific papers, often organized in electronic journals, as e.g. *Electronic Colloquium on Computational Complexity* (ECCC) [3], or bibliographic databases, as e.g. *Digital Bibliography and Library Project* (DBLP) [9], or the *Scientific Literature Digital Library* (CiteSeer.IST)[7]. In this paper we describe how to improve bibliographic search applied to a restricted domain by deploying ontologies. As a testbed for our research we focused on the domain of NP-complete decision problems, one of the most important topics in computer science. NP-complete decision problems are considered to be very hard to solve and thus, they are subject of ongoing research. The *Electronic Colloquium on Computational Complexity* (ECCC) is an electronic journal covering the subject of computational complexity and thus, it is related to NP-complete decision problems. It provides a bibliographic database including all volumes of ECCC since its start in 1993 (for a detailed description see [3]). We improved the regular, keyword-based bibliographic search of ECCC by adding an ontology representation of NP-complete decision problems and their relationships to each other. With the help of this ontology the user is able to navigate within the search domain. It facilitates the resolution of disambiguities among query keywords, and allows simple cross-referencing between the search results. Convenient keyword-based full-text retrieval inside the ECCC documents via Google Web APIs Services [15] is connected to additional semantic information only available inside the ECCC databases.

The paper is structured as follows: Section 2 briefly presents the ontology for NP-complete decision problems, while section 3 explains, how to improve bibliographical search by using ontologies. Section 4 shows an outline of our search engine implementation, followed by a comparison of achieved results with Google and ECCC. Section 6 concludes the paper with an outlook on future work.

2 An Ontology for NP-complete Decision Problems

In computer science, an ontology is the product of an attempt to formalize an exhaustive and rigorous conceptual schema about a domain. Typically, ontologies can be represented as a hierarchical data structure containing all the relevant entities and their relationships and rules within the domain. For the Semantic Web, ontologies can be formulated with the help of the *Web Ontology Language* (OWL) [22], a simple vocabulary extension of RDF (*Resource Description Framework*) derived from the DAML+OIL Web Ontology Language.

For our work, we focused on the narrow, but nevertheless for computer science very important topic of NP-complete decision problems. The "P vs. NP-problem", i.e. the question, whether NP-complete problems are *easy* to solve, is one of the unsolved questions among the famous *Millenium Prize problems* [4], being rewarded with 1 million US$ for a commonly accepted solution. In computational complexity (a sub-domain of theoretical computer science) **NP** (*Non-deterministic Polynomial time*) is the set of decision problems solvable in polynomial time on a non-deterministic Turing machine. It is not known, whether all problems that belong to NP are also deterministically solvable in polynomial time, i.e. belong to **P** (*deterministic Polynomial time*). On the other hand, the solution of a decision problem in NP can simply be verified deterministically in polynomial time. The importance of this class of decision problems is that it contains many interesting searching and optimization problems where we want to know if there exists a certain solution for a certain problem. For example, the SAT problem is to decide whether a given Boolean formula has any satisfying truth assignments. SAT belongs to NP. It is difficult to find a satisfying assignment, but a satisfying assignment can simply be proved by just evaluating the formula. A decision problem is called **NP-complete**, if it belongs to NP, and any other problem in NP can be *reduced* to it (with the help of an resource restricted algorithm). NP-complete problems are considered to be the most difficult problems in NP. To *reduce* a problem A to problem B, a polynomial-time algorithm is given as input an instance of problem A, and must produce as output an instance of problem B.

In 1971 Cook proved that SAT is NP-complete [5]. Since Cook's original result, thousands of other problems have been shown to be NP-complete by reductions from other decision problems previously shown to be NP-complete. Many of these decision problems have been published by Garey and Johnson in 1979 [13]. Following their manual we have structured the domain of NP-complete problems into different subsets (see fig. 1). The basic term in the ontology for NP-complete problems is the *decision problem* as some kind of problem that can only be answered with *yes* or *no*. Besides other characteristics the relationships between different decision problems have to be considered: By changing a single parameter of a decision problem, it may change its membership to some complexity class. E.g. the 3-SAT decision problem testing the satisfiability of a Boolean formula in conjunctive normal form with at most three variables per clause is an NP-complete decision problem, while 2-SAT, where only clauses with at most two variables are considered belongs to P (i.e. can be decided deterministically in polynomial time). Thus, decision problems can be related to *stronger* or *weaker* decision problems of the same kind that belong to different complexity classes. On the other hand introducing a new parameter or fixing a given parameter of a decision problem can result in a special case of decision problem. Thus, deci-

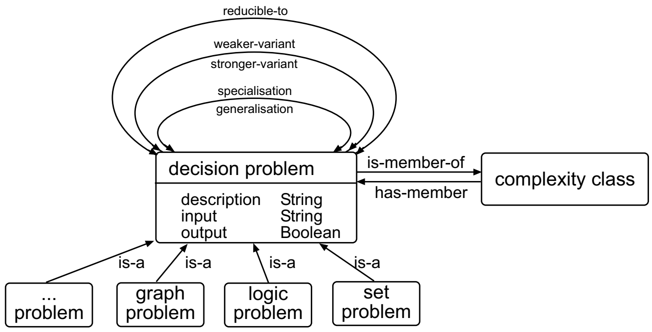

Fig. 1. Simplified Ontology for NP-complete Problems.

sion problems can be related to each other by *generalization* or *specialization*, e.g. SAT is a generalization of 3-SAT or 2-SAT, while 2-SAT is a special case of SAT. Finally, NP-complete decision problems are also related to each other by *reductions*, e.g. SAT can be reduced to 3-SAT in linear time simply by using auxiliary variables. See figure 1 for a simplified outline of the ontology for the domain of NP-complete decision problems and figure 2 for the instance of the 3-SAT decision problem and its relationship to other decision problems.

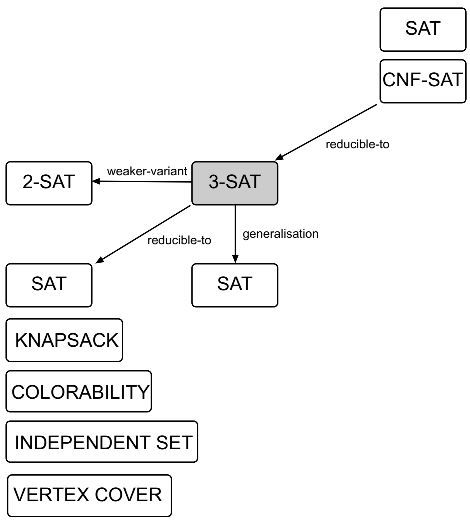

Fig. 2. 3-SAT Decision Problem and its Relationships to other Decision Problems.

3 How to Improve Bibliographic Search by Using Ontologies

Since *Callimachus of Cyrene* (305–240 B.C) wrote the first bibliographic catalog, the so called *Pinakes* for the legendary great library of Alexandria [2], the use of bibliographic information for conventional libraries has become a useful standard for centuries. Following the media evolution, bibliographies moved from books to card catalogs over microfilm to digital storage. Bibliographies accumulate descriptions of autonomous publications, as e.g. books or journals, as well as descriptions of non-autonomous publications such as e.g. journal articles or scientific papers published in conference proceedings. Typically, bibliographies contain information such as author, title, subject, content description, keywords, or even location of the referenced publications. With the arrival of the internet digital bibliographies including various search possibilities became available worldwide. Retrieval of bibliographic information in the internet can be performed by using general search engines as e.g. Google, specialized search engines as e.g. CiteSeer.IST, or also by accessing special bibliographic databases as e.g. DBLP.

General search engines allow search restrictions such as choosing a special file type (e.g. postscript or pdf for scientific publications in the WWW), performing domain searches on restricted URLs (e.g. restricting the search domain to a special database or electronic journal), or restricting the search domain by stating several topic specific keywords within the query string. Many times, it will not be possible to find all papers related to a special topic, because most general search engines rely on keyword-based full text search, such that the term stated in the user's query string must also be part of the paper's text.

In most cases, **specialized search engines** rely on the cooperation of its users (i.e. for a bibliographic search engine the authors of the maintained publications). For being incorporated into the bibliographic search engine the scientific paper often has to be registered by the author, who has to provide additional semantic information such as the paper's topic, keywords, a brief content description, etc. Specialized search engines also rely on keyword-based full text retrieval such that the user's query string has to be either part of the paper's text or within semantic information provided by the author. Most times, this semantic information does not follow a general accepted standard, i.e. authors often might use different expressions for the same subject. Therfore, ambiguities or syntactical errors will cause obstructions and thus, incomplete or even wrong search results.

Bibliographic databases are often maintained by editors, registering relevant scientific publications and providing formalized bibliographic information. Although relying on keyword-based full text retrieval the formalized semantic information provided by the editors anticipates ambiguities such that bibliographic databases are able to deliver more accurate search results than the other mentioned search engine types. But, the user often is not aware of using the right predefined standard search terms when searching a specific topic such that ambiguities might occur in the evaluation of the user provided query string and thus, incomplete or even wrong results will be returned.

Ontologies as a mechanism of representing formal and shared data descriptions can help in different ways to improve bibliographic search: Of course all scientific papers published over the internet can be endorsed with additional semantic annotations. This might include classic DublinCore descriptions [10] as well as ontology based information describing the paper's content. In any case providing this semantic information is accomplished best by the authors themselves. But, standardized methods and interfaces for providing semantic annotations are not yet established or commonly accepted. Therefore, we have concentrated on a different approach, applying ontologies locally on top of a general search engine and a bibliographic database for augmenting bibliographic search [14]. Similar to Mayfield and Finnin [19] we combine ontology-based techniques with standard text-based retrieval. We agree that as long as not enough metadata are available semantic search should work as a supplement to keyword-based search.

Query string evaluation. When performing a bibliographic search the user has to enter a query string consisting of one or several keywords that can be connected by logical expressions or special control characters. A well known problem is the assignment of an appropriate category according to which to evaluate the given keywords. In our case, authors often don't use unique names for specific NP-complete decision problems (e.g. 3-SAT can also be referred to as 3SAT, 3-Satisfiability, 3-CNF-SAT, or even as LO2, i.e. the notation used in [13]). On the other hand, users often encounter difficulties when having to provide terms that describe their information need best. To overcome ambiguities and other vocabulary related problems, ontologies can provide synonyms and alternative spellings. Thus, we are able to refer to a unique NP-complete decision problem whenever one of the terms provided by the ontology's vocabulary is part of (or even resembles) the query string.

Query string expansion. According to the user's evaluation of the search result, we can use the ontology provided vocabulary for broadening or narrowing the scope of the current search. We do this simply by adding synonyms and other related keywords that refer to the NP-complete problem under consideration to the search string and joining them together with a logical operator. Joining the keywords together with a logical "OR" will extend the scope, while by using "AND" the opposite effect of narrowing the search result's scope is achieved. In difference to statistical query string expansion methods as proposed by [8] and [6], for our application the inclusion of synonyms and hyponyms is sufficient for query expansion, because we are only searching in a limited and predefined domain. For extending the scope of our search from a single database as ECCC to the WWW as a whole, more semantic information on the query subject is required to achieve word sense disambiguation.

Domain navigation and cross-referencing. The major benefit of ontologies for searching is the possibility to find new cross references between topics or between individual documents that are not apparent without using the ontology.

Without ontologies cross connections between documents are only available, if e.g. the document itself contains links or references to other related documents. In our case, we can cross connect different NP-complete decision problems according to the different relationships between the individual decision problems given by the ontology, as e.g. *is-weaker-variant-of* or *can-be-reduced-to*. In this way we are able to cross reference from SAT to 3-SAT, because SAT can be reduced to 3-SAT, or we can cross reference from 3-SAT to the KNAPSACK problem, because 3-SAT can be reduced to KNAPSACK.

Additional information. In addition, ontologies can be used to provide supplementary information that is also important for bibliographic search. For an individual decision problem, we can reference to canonical resources, e.g. the first or the most important paper addressing the problem, or the paper proofing the NP-completeness of the decision problem. This additional information can also comprise links to the authors of the canonical resources.

Thus, the use of ontologies for guiding bibliographic search performed on top of a keyword-based search engine can improve accuracy as well as completeness of the accomplished search results providing additional information by cross referencing semantically related documents.

4 Implementation of an Ontology Enhanced Bibliographic Search - NPBibSearch

The ontology for NP-complete decision problems was implemented with the Web Ontology Language (OWL) [22] and with the ontology editor protege [20]. The associated file *NPTheory.owl* is available at [23]. The ontology enhanced bibliographic search *NPBibSearch* is implemented as a Java Servlet using the JENA Semantic Web Framework [21]. The prototype can be tested at [24]. See figure 3

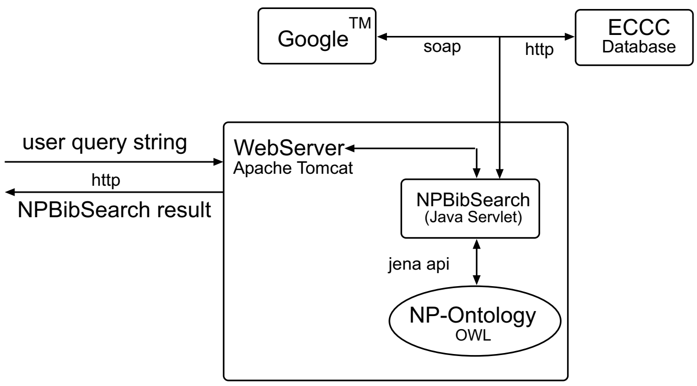

Fig. 3. Schematic Overview of NPBibSearch.

for an overview of the implementation of NPBibSearch. To explain how NPBibSearch works we consider a brief usage scenario. Let's assume the user starts a bibliographic search related to the SAT problem and enters the query string *sat*.

Query string evaluation. The query string is transferred via the web server to the java servlet and first, the associated ontology has to be found. The string *sat* occurs to be among the synonyms of *SAT* but it is also found for *3-SAT*, *CNF-SAT*, etc. Thus, the user has to decide, which of the referred decision problems to choose from a given selection list.

Searching Google and ECCC. After the SAT problem has been fixed, the next step would be a keyword-based full text search in the ECCC database. ECCC only allows full text search in titles, keywords, or abstracts, but not inside the text body. For ECCC resources being also available as static HTML files, they are on-hand for web robots of general search engines. Therefore, a keyword-based full text search via Google restricted only to the ECCC web site with the search string *SAT* is conducted. The user may choose between the original Google results, where only the paper's title and a short text snipped is shown, and the ECCC results that provide much more useful information. For ECCC results, the search results provided by Google are directly retrieved from the ECCC database and presented to the user. In addition to the information provided by Google, the authors of the paper, a part of the papers abstract, and the list of keywords are shown, while occurrences of the query string among the results are displayed highlighted. ECCC provides also a list of homepages of people working in the field of computational complexity. If the author of a paper in the search results is listed among these homepages, the author's name will be linked with his homepage. The title of the paper itself is linked with the ECCC cover page related to the paper providing additional information about the paper.

Navigation. Furthermore, the ontology is used for cross reference navigation. As stated in section 3, cross references between individual decision problems are provided within the ontology, available via an extra navigation element on top of the displayed search results (see figure 4). According to the three defined relationships among decision problems (stronger/weaker, generalization/specialization, reduced to/from) we charted three axes for navigating the ontology domain. With the help of this very simple navigation tool the user can choose to switch to a related weaker, stronger, general, or special decision problem. At the same time the user can switch to decision problems, where there exists a reduction to or from the current problem. If the user decide to switch to a related decision problem, his choice will be transferred to the query string and a new search will be performed

Query string refinement. To refine or to broaden the current search, the user has the possibility to add additional terms to the search string, either by providing a supplementary query string, or by choosing one or more entries from the list of synonyms and alternative names (displayed below the query string on top of the search results). The result page of our example, where the current

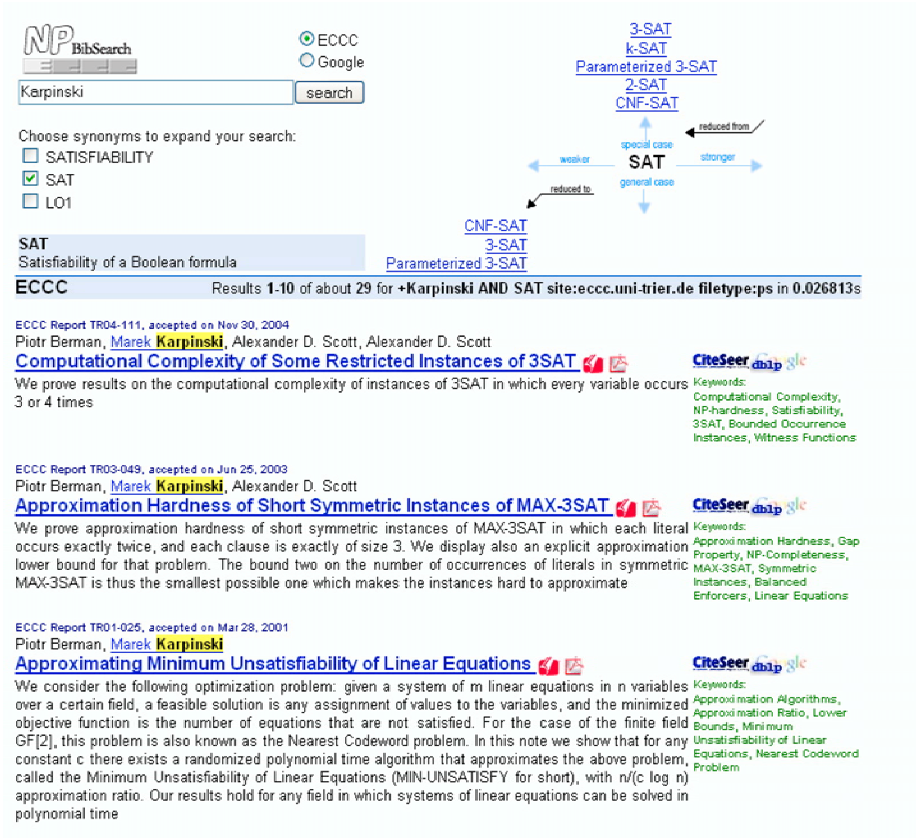

Fig. 4. Results Provided by NPBibSearch for searching *Karpinski* related to the *SAT* Decision Problem. On to right the tool for navigating through the domain of NP-complete decision problems is displayed.

search is refined by referring only papers written by Marek Karpinski is shown in figure 4.

Additionaly, the user can extend his search to other databases and services. For each document among the search results of NPBibSearch a link to Cite-Seer.IST and to DBLP is provided. Thus, the user is able to gather more information about the specific document, where it is referrenced, or about the document's author.

5 Comparison and Results

In this section we compare the bibliographic search of NPBibSearch with the search possibilities of Google and ECCC alone. We distinguish two different usage scenarios: direct search and cross referencing.

Direct search. One of the typical scenarios in bibliographic search is to find reference papers for a given subject. For NP-complete decision problems, the search task may comprise first, a listing of available papers for a given NP-complete decision problem and afterwards, maybe to refine the search by restricting the results to one or several authors. For each enlisted decision problem our ontology provides synonyms, alternative spellings, and acronyms. If using only Google without NPBibSearch, the user has to give the correct name of the decision problem, or at least the name variant used in the paper he is looking for. Of course, if the user himself is an expert, he might construct the query string in the same way as NPBibSearch by including a set of possible names and spellings. If the user's query string matches different problems, Google will show all matches without any differentiation, while NPBibSearch offers a selection of different matching decision problems. E.g. for the search string *sat* restricted to the domain `eccc.uni-trier.de` and to the filetype *postscript* Google presents 272 results (november 2005). NPBibSearch presents the same results while offering different refinements as e.g. *3-SAT*, *CNF-SAT*, or also *Parameterized 3-SAT*. Google provides all the correct references, but it is not able to provide any other content related information such as coauthors, abstract, or keywords. Also Google's text snippets displayed for each search result do not really give sufficient clues about the retrieved papers. While for Google the user has to keep track of the keywords being used and how to combine them, NPBibSearch provides a special user interface for that task. For further refinement, in both cases the user can restrict the result set by adding the name of one or more authors to the query string.

Searching ECCC without Google becomes even more difficult, because ECCC does not provide full-text search in the text body, or the arbitrary combination of the user's query strings. We take the simple example from section 4, i.e. searching all *SAT* related papers with *Karpinski* as author or cited in other papers also published in ECCC. ECCC provides two possibilities to accomplish this search task:

1. Search for the author *Karpinski* and in a second step, search the results manually or with the help of your browser for *SAT*. The result will be 6 papers.
2. Search in title or abstract the term *SAT* and in a second step, search the results manually or with the help of the browser for *Karpinski*. The result will be 20 papers. The additional results are achieved, because in the first variant *SAT* has to appear in the title text while the second variant also examines the abstract.

Performing the same search with NPBibSearch on the same data, 29 resulting papers are reported. NPBibSearch also includes citations of *Karpinski* or references of *SAT* in the text body that is not examined if using ECCC alone.

Cross Referencing. When comparing *NPBibSearch* with Google or ECCC, we have to consider that the benefit of *NPBibSearch* is not necessarily assembled from merely better recall or precision. The difference arrises in the ability to cross reference to other topics, i.e. to other decision problems related to the problem under current consideration. If using Google or ECCC, the user has to provide knowledge about the search domain himself for drawing cross references between related subjects. With the help of its simple navigation tool, NPBibSearch allows the user to navigate through related decision problems to find out, e.g. whether the author *Karpinski* was also publishing on other subjects.

6 Conclusions and Outlook

We have developed an ontology augmented bibliographic search engine NPBibSearch operating in the domain of NP complete decision problems. Ontologies are used to improve search results obtained from the general search engine Google and our reference bibliographic database ECCC. Ontologies help to improve recall and precision of the obtained search results and enable cross references to other topics, thus facilitating navigation within the search domain.

One of the most expensive tasks in the development of NPBibSearch was the design and ongoing refinement of the ontology for NP complete decision problems. Several experts had to agree on a common design of a rather complex topic. Subsequently filling the ontology with different instances of decision problems was time-consuming, but did not require expert advice. The ontology comprises about 60 different problems and is subject of ongoing completion.

Several extensions of NPBibSearch are subject of current work. First, NP-complete decision problems are of course a rather restricted domain. The topic served well as a first testbed to develop and debug new ideas. Now, ontologies for other topics related to computer science are developed or adopted, and will be included. NP-complete decision problems belong to the domain of computational complexity theory, that is besides formal languages, automata theory, graph theory, e.a. part of theoretical computer science, which is part of computer science. This tree-like order facilitates the design of a hierarchical ontology comprising all subjects related to computer science. Broadening the scope and connecting several ontologies of different subjects requires an advanced navigation element. Arranging subjects in an hierarchical way can be directly transposed into a graphical layout for navigation.

Lessons learned from the development of a bibliographic search engine may facilitate an ontology augmented general search engine, providing more accurate and self-contained results compared to the general search engines today..

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