Effectively Mining and Using Coverage and Overlap Statistics for Data Integration

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Abstract

Recent work in data integration has shown the importance of statistical information about the coverage and overlap of sources for efficient query processing. Despite this recognition there are no effective approaches for learning the needed statistics. The key challenge in learning such statistics is keeping the number of needed statistics low enough to have the storage and learning costs manageable. Naive approaches can become infeasible very quickly. In this paper we present a set of connected techniques that estimate the coverage and overlap statistics while keeping the needed statistics tightly under control. Our approach uses a hierarchical classification of the queries, and threshold based variants of familiar data mining techniques to dynamically decide the level of resolution at which to learn the statistics. The learnt statistics are effectively used by the query optimizer using our residual coverage computing algorithm. We describe the details of our method, and present experimental results demonstrating the efficiency of the learning algorithms and the effectiveness of the learned statistics over both controlled data sources and in the context of *BibFinder* with autonomous online sources.

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1 Introduction

With the vast number of autonomous information sources available on the Internet today, users have access to a large variety of data sources. Data integration systems [CGHI94, LRO96, ACPS96, LKG99, PL00] are being developed to provide a uniform interface to a multitude of information sources, query the relevant sources automatically and restructure the information from different sources. In a data integration scenario, a user interacts with a mediator system via a mediated schema [LKG99;DGL00]. A mediated schema is a set of virtual relations, which are effectively stored across multiple and potentially overlapping data sources, each of which only contain a partial extension of the relation. Early work on query optimization in data integration [FKL97, NLF99, DH02] thus focused on techniques for figuring out what sources are relevant to the given query, with the assumption that they will all be accessed.

Calling all potentially relevant sources is an untenable strategy in the long run as it increases network traffic, and leads to higher source access and processing costs to the mediator. We thus assume that the users are likely to be willing to sacrifice completeness of their answers for efficiency. Consider, for example, a situation where the mediator is trying to reduce the costs by calling just k of the N available and potentially relevant data sources. The question is how does the mediator efficiently pick these k sources. We argue that to do an effective job of source selection, the query optimizer needs to access statistics about the coverage of the individual sources with respect to the given query, as well as the degree to which the answers they export overlap. The main contribution of this paper is the development and evaluation of a framework for gathering and using such statistics. We start by illustrating the need for these statistics with an example scenario.

1.1 Motivating Scenario

Consider *BibFinder* (http://rakaposhi.eas.asu.edu/bibfinder), a publicly available computer science bibliography mediator that we have been developing. *BibFinder* integrates several online Computer Science bibliography sources. It currently covers *CSB, DBLP, Network Bibliography, ACM Digital Library, ACM Guide, ScienceDirect, IEEExplore* and *CiteSeer.* Since its unveiling in December 2002, *BibFinder* has been getting on the order of 200 queries a day.

BibFinder offers interesting contrast with respect to other bibliography search engines like CiteSeer [CIT]. First of all, because it uses online integration approach (rather than a data warehouse one), user queries are sent directly to the integrated Web sources and the results are integrated on the fly to answer a query. This obviates the need to store and maintain the paper information locally. Secondly, the sources integrated by *BibFinder* are autonomous and partially overlapping. By combining the sources, *BibFinder* can present a unified and more complete view to the user.

However it also brings some interesting optimization challenges. Let us assume that the global

schema exported by *BibFinder* includes just the relation:

paper(title, author, conference/journal, year)

Each of the individual sources only export a subset of the global relation. For example, *Network Bibliography* only contains publications in Networks, *DBLP* gives more emphasis on Database related publications, while *ScienceDirect* has only archival journal publications etc. To efficiently answer users' queries, we need to find and access the most relevant subset of the sources for the given query. Suppose, the user asks a selection query:

Q(title,author) :− **paper**(title, author, conference/journal, year), conference="AAAI".

To answer this query efficiently, *BibFinder* needs to know the *coverage* of each source S with respect to the query Q, i.e. $P(S|Q)$, the probability that a random answer tuple for query Q belongs to source S. Given this information, we can rank all the sources in descending order of $P(S|Q)$. The first source in the ranking is the one that *BibFinder* should access first while answering query Q. Although ranking seems to provide the complete order in which to access the sources, this is unfortunately not true in general. It is quite possible that the two sources with the highest coverage with respect to Q happen to mirror each others' contents. Clearly, calling both sources is not going to give any more information than calling just one source. Therefore, after we access the source S' with the maximum coverage $P(S'|Q)$, we need to access as the second source, the source S'' that has the highest *residual coverage* (i.e., provides the maximum number of those answers that are not provided by the first source S'). Specifically we need to pick the source S'' that has next best rank to S' in terms of $P(S|Q)$ but has minimal *overlap* (common tuples) with S'.

Given that sources tend to be autonomous in a data integration scenario and that the mediation may or may not be authorized, it is impractical to assume that the sources will automatically export coverage and overlap statistics. Consequently, data integration systems should be able to learn the necessary statistics. Although previous work has addressed the issue of how to model these statistics (c.f. [FKL97]), and how to *use* them as part of query optimization (c.f. [NLF99],[NK01],[DH02]), there has not been any work on effectively learning the statistics in the first place.

1.2 The *StatMiner* approach

In this paper, we address the problem of learning the coverage and overlap statistics for sources with respect to user queries. A naive approach may involve learning the coverages and overlaps of all sources with respect to all queries. This will necessitate $N_q * 2^{N_S}$ different statistics, where N_q is the number of different queries that the mediator needs to handle and N_S is the number of data sources that are integrated by the mediator. An important challenge is to keep the number of statistics under control, while still retaining their advantages.

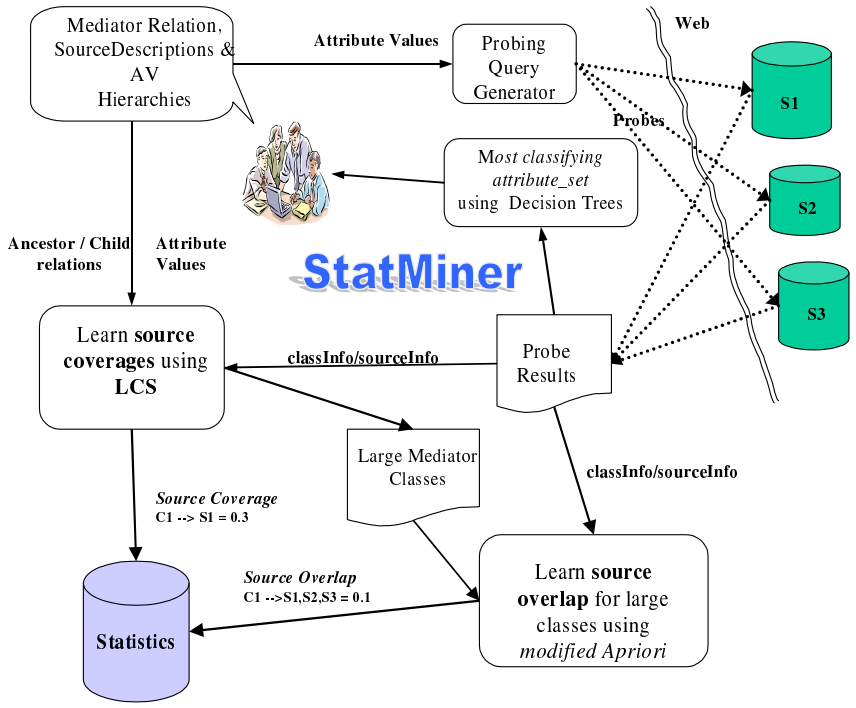


Figure 1: *StatMiner Architecture*

In this paper, we present *StatMiner* (see Figure 1), a statistics mining module for web based data integration. *StatMiner* is being developed as part of the *Havasu* data integration project at Arizona State University [KNNV02]. *StatMiner* comprises of a set of connected techniques that help a mediator estimate the coverage and overlap of a set of sources with respect to a user given query while keeping the amount of needed statistics tightly under control. Since the number of potential user queries can be quite high, *StatMiner* aims to learn the required statistics for *query classes* i.e. groups of queries. A *query class* is an instantiated subset of the global relation and contains only the attributes for which a hierarchical classification of instances (values) can be generated. Thus for the global relation *paper* in our *BibFinder*scenario, *StatMiner* may generate query classes using the attributes $conference$ and $year$. By selectively deciding the level of generality of the query classes with respect to which the coverage statistics are learnt, *StatMiner* can tightly control the number of needed statistics (at the expense of loss of accuracy). The loss of accuracy may not be a critical issue for us as it is the *relative* rather than the *absolute* values of the coverage statistics that are more important in ranking the sources.

The coverage statistics learning is done using the LCS algorithm, and the overlap statistics is learned using a variant of the Apriori algorithm [AS94]. LCS algorithm does two things: it identifies the query classes which have large enough support, and it computes the coverages of the individual

sources with respect to these identified large classes. The resolution of the learned statistics is controlled in an adaptive manner with the help of two thresholds. The threshold τ_c is used to decide whether a query class has large enough support to be remembered. When a particular query class doesn't satisfy the minimum support threshold, *StatMiner*, in effect, stores statistics only with respect to some abstraction (generalization) of that class. Another threshold τ_o is used to decide whether or not the overlap statistics between a set of sources and a remembered query class should be stored.

Specifically, *StatMiner* probes the Web sources exporting the mediator relation. Using LCS we then classify the results obtained into the query classes and dynamically identify "large" classes for which the number of results mapped are above the specified threshold τ_c. We learn and store statistics only w.r.t. these identified large classes. When the mediator encounters a new user query, it maps the query to one of the query classes for which statistics are available. Since we use thresholds to control the set of query classes for which statistics are maintained, it is possible that there is no query class that exactly matches the user query. In this case, we map the query to the nearest abstract query class that has available statistics. The loss of accuracy in statistics entailed by this step should be seen as the cost we pay for keeping the amount of stored statistics low. Once the query class corresponding to the user query is determined, the mediator uses the learned coverage and overlap statistics to rank the data sources that are most relevant to answering the query.

1.3 Challenges & Organization

In order to make this approach practical, we need to carefully control three types of costs: (1) cost of getting the training data from the sources (i.e., "probing costs") (2) the cost of processing the data to compute coverage and overlap statistics (i.e., "mining costs") and (3) the online cost of *using* the coverage and overlap statistics to rank sources. In the rest of the paper, we shall explain how we control these costs. Briefly, the probing costs are controlled through sampling techniques. The "mining costs" are controlled with the help of support and overlap thresholds. The "usage costs" are controlled with the help of an efficient algorithm for computing the residual coverage. We will demonstrate the effectiveness of these mechanisms through empirical studies. We will also empirically demonstrate that the statistics we learn and use for ranking and selecting sources significantly improve the precision and coverage of the top-K source query plans.

The rest of the paper is organized as follows. In the next section, Section 2 gives an overview of *StatMiner*. Section 3 describes the methodology used for extracting and processing training data from autonomous Web sources. Section 4 describes the details of learning AV hierarchies. In Section 5, we give the algorithms for learning coverage and overlap statistics. Then, in Section 6, we discuss how to efficiently use the leaned statistics to rank the sources for a given query. This is followed, in Section 7, by a detailed description of our experimental setup, and in Section 8, by the results we

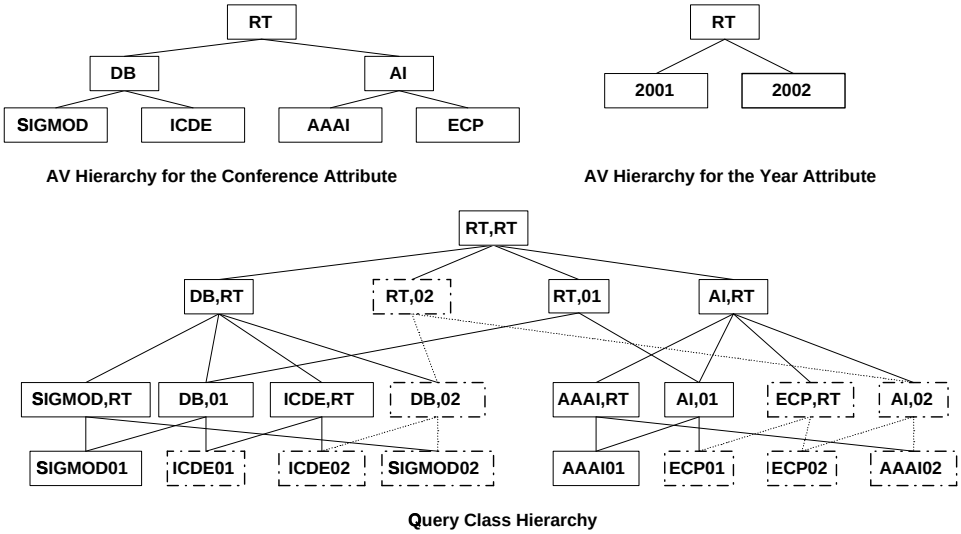


Figure 2: *AV Hierarchies and the Corresponding Query Class Hierarchy*

obtained demonstrating the efficiency of our learning algorithms and the effectiveness of the learned statistics. In Section 9, we discuss the related work. Section 10 contains a discussion of some practical issues regarding the realization of the *StatMiner* approach. We present our conclusions in Section 11.

2 Modeling Coverage and Overlap w.r.t. Query Classes

2.1 Classifying Mediator Queries

In this paper, we will limit our attention to selection queries.[1] Our approach consists of grouping queries into abstract classes. Since we focus on selection queries in this paper, the values for some attributes would be bound for a typical query. We classify the queries in terms of the selected attributes and their values. To abstract the classes further we assume that the mediator has access to the so-called "attribute value hierarchies" for a subset of the attributes of each mediated relation.

Attribute Value Hierarchies: An *AV hierarchy* (or attribute value hierarchy) over an attribute A is a hierarchical classification of the values of the attribute A. The leaf nodes of the hierarchy correspond to specific concrete values of A (Note that, for numerical attributes, we can take value ranges as leaf nodes), while the non-leaf nodes are abstract values that correspond to the union of values below them. Figure 2 shows the AV hierarchies for the "conference" and "year" attributes of the "paper" relation. It is instructive to note that AV hierarchies can exist for both categorical and quantitative

[1] See Section 10 for a discussion on how our techniques can be extended to handle join queries.

(numerical) attributes. In the case of the latter, the abstract values in the hierarchy may correspond to ranges of attribute values.

Note that hierarchies do not have to exist for every attribute, but rather only for those attributes over which queries are classified. We call these attributes the **classificatory attributes**. If we know the domains (or representative values) of multiple attributes, we can choose as the classificatory attribute the best k attributes whose values differentiate the sources the most, where the number k is decided based on a tradeoff between prediction performance versus computational complexity of learning the statistics by using these k attributes.

The selection of the classificatory attributes may either be done by the mediator designer or using automated techniques. In the latter case, we can, for instance, use decision tree learning techniques [HK00] to rank attributes in terms of their information gain in classifying the sources. For example, suppose *BibFinder* just has three sources: source S_1 only has papers in conference AAAI, S_2 only has papers in conference IJCAI, and S_3 only has papers in conference SIGMOD. In order to rank access to these sources, we need only choose the "conference" attribute as the classificatory attribute, even if we know the domain of the "year" attribute.

Once the classificatory attributes are selected, the AV hierarchies for those attributes can either be provided by the mediator designer (using existing domain ontologies, c.f.[WMY00;IGS01]), or be automatically generated through clustering techniques (See Section 4).

Query Classes: Since we focus on selection queries, a typical query will have values of some set of attributes bound. We group such queries into query classes using the AV hierarchies of the classificatory attributes that are bound by the query. To classify queries that do not bind any classificatory attribute, we would have to learn simple associations [2] between the values of the non-classificatory and classificatory attributes. A query class **feature** is defined as the assignment of a specific value to a classificatory attribute from its AV hierarchy. A feature is "abstract" if the attribute is assigned an abstract (non-leaf) value from its AV hierarchy. Sets of features are used to define query classes. Specifically, a query class is a set of (selection) queries sharing a particular set of features. A query class having no abstract features is called a *leaf class*, similarly a query having concrete features for all the classificatory attributes is called a *leaf query*. The space of query classes over which we learn the coverage and overlap statistics is just the cartesian product of the AV hierarchies of all the classificatory attributes. Specifically, let H_i be the set of features derived from the AV hierarchy of the i^{th} classificatory attribute. Then the set of all query classes (called $classSet$) is simply $H_1 \times H_2 \times ... \times Hn$.

[2] A simple association would be $Author = J.Ullman \rightarrow Conference = Databases$ where $Author$ is non-classificatory while $Conference$ is a classificatory attribute

2.2 Coverage and Overlap w.r.t Query Classes:

The *coverage* of a data source S with respect to a query Q, denoted by $P(S|Q)$, is the probability that a random answer tuple of query Q is present in source S. The *overlap* among a set $\widehat{S}$ of sources with respect to a query Q, denoted by $P(\widehat{S}|Q)$, is the probability that a random answer tuple of the query Q is present in each source $S \in \widehat{S}$. The overlap (or coverage when $\widehat{S}$ is a singleton) statistics w.r.t. a query Q are computed using the following formula

$$P(\widehat{S}|Q) = \frac{N_Q(\widehat{S})}{N_Q}$$

Here $N_Q(\widehat{S})$ is the number of answer tuples of Q that are in all sources of $\widehat{S}$, N_Q is the total number of answer tuples for Q. We assume that the union of the contents of the available sources within the system covers 100% of the answers of the query. In other words, coverage and overlap are measured relative to the available sources.

We also define coverage and overlap with respect to a query class C rather than a single query Q. The overlap of a source set $\widehat{S}$ (or coverage when $\widehat{S}$ is a singleton) w.r.t. a query class C, $P(\widehat{S}|C)$, is just the weight sum of all the statistics for leaf queries subsumed by C:

$$P(\widehat{S}|C) = \frac{N_C(\widehat{S})}{N_C} = \frac{\sum_{Q_{leaf} \in C}(N_{Q_{leaf}} \times P(\widehat{S}|Q_{leaf}))}{N_C} = \sum_{Q_{leaf} \in C}(w_{Q_{leaf}} \times P(\widehat{S}|Q_{leaf}))$$

Here Q_{leaf} denotes a leaf query, $N_{Q_{leaf}}$ is the number of answer tuples for Q_{leaf}, $N_{Q_{leaf}}(\widehat{S})$ is the number of answer tuples of Q_{leaf} that are in all sources of $\widehat{S}$, $N_C(\widehat{S})$ equals to $\sum_{Q_{leaf} \in C} N_{Q_{leaf}}(\widehat{S})$, N_C equals to $\sum_{Q_{leaf} \in C} N_{Q_{leaf}}$, and $w_{Q_{leaf}}$ equals to $\frac{N_{Q_{leaf}}}{N_C}$.

The coverage and overlap statistics w.r.t. a class C is used to estimate the source coverage and overlap for all the queries that are mapped into C. These statistics can be conveniently computed using an association rule mining approach as discussed in the next subsection.

2.3 Class-Source Association Rules:

A *class-source association rule* represents strong associations between a query class and a source set (which is some subset of sources available to the mediator). Specifically, we are interested in the association rules of the form $C \rightarrow \widehat{S}$, where C is a query class, and $\widehat{S}$ is a source set (possibly singleton). The *support* of the class C (denoted by $P(C)$) refers to the class probability of the class C, and the overlap (or coverage when $\widehat{S}$ is a singleton) statistic $P(\widehat{S}|C)$ is simply the *confidence* of such an association rule (denoted by $P(\widehat{S}|C) = \frac{P(C \cap \widehat{S})}{P(C)}$). Examples of such association rules include: $AAAI \rightarrow S_1$, $AI \rightarrow S_1$, $AI\&2001 \rightarrow S_1$ and $2001 \rightarrow S_1 \wedge S_2$.

2.4 Controlling the amount of stored statistics

From the foregoing, we see that all we need to do to gather the coverage and overlap statistics is to (a) get some representative data from the sources, and categorize the data into query classes (b) mine the class source association rules from this base data. We introduce two important changes to this basic plan to control the amount of statistics learned:

Limiting statistics to "large" classes: As we discussed in Section 1, it may be prohibitively expensive to learn and store the coverage and overlap statistics for every possible query class. In order to keep the number of association rules low, we would like to prune "small" classes. We use a threshold on the support of a class (i.e., percentage of the base data that falls into that class), called τ_c, to identify large classes. Coverage and overlap statistics are learned only with respect to these large classes. In this paper we present an algorithm to efficiently discover the large classes by using the *anti-monotone property*[3]([HK00]).

Ideally, we would like to measure the importance of a class in terms of the frequency of user queries to that class. However, initially, we do not have any information about the distribution of user queries. We thus make an implicit assumption that query frequency is correlated with the size of the class (see Section 10 for a discussion on the large versus frequent query classes). Thus, discovery of important classes boils down to discovery of "large" classes.

For queries belonging to a non-large class, we use the statistics of the root class to estimate the coverage and overlap of the sources. Although the statistics of the root class are at the highest level of abstraction, they do represent the average coverage and overlap of the integrated sources w.r.t. all the queries. So we can still improve the average efficiency of answering queries belonging to non-large classes. The statistics of the root class will be particularly useful in scenarios where some sources are significantly more complete than others for most of the queries.

Limiting Coverage and Overlap Statistics: Another way we use to control the number of statistics is to only remember coverage and overlap statistics only when they are above a threshold parameter, τ_o. While the thresholds τ_c and τ_o reduce the number of stored statistics, they also introduce complications when the mediator is using the stored statistics to rank sources with respect to a query.

Briefly, when a query Q belonging to a class C is posed to the mediator, and there are no statistics for C (because C was not identified as a large class), the mediator has to make do with statistics from a generalization of C that has statistics. Similarly, when a source set $\widehat{S}$ has no overlap statistics with respect to a class C, the mediator has to assume that the sources in set $\widehat{S}$ are in effect disjoint with respect to that query class. In Section 6, we describe how these assumptions are used in ranking the sources with respect to a user query. Before doing so, we first give the specifics of base data generation, AV hierarchy generation, discovering large classes, and computing their statistics.

[3]If a set cannot pass a test, all of its supersets will fail the same test as well.

3 Gathering Base Data

In order to use association rule mining approach to learn the coverage and overlap statistics, we need to first collect a representative sample of the data stored in the sources. Since the sources in the data integration scenario are autonomous, this will involve "probing" the sources with a representative set of "probing queries." The results of the probing queries need to be organized into a form suitable for statistics mining. We discuss both these issues in this section.

3.1 Probing queries

We note at the outset, that the details of the rest of the steps of statistics mining do not depend on *how* the probing queries are selected. The probing queries can, however, affect the accuracy of the learned statistics in answering the queries encountered in actual practice. There are two possible ways of generating "representative" probing queries. We could either (1) pick our sample of queries from a set of "spanning queries"–i.e., queries which together cover all the tuples stored in the data sources or (2) pick the sample from the set of actual queries that are directed at the mediator over a period of time. Although the second approach is more sensitive to the actual queries that are encountered, it has a "chicken-and-egg" problem as no statistics can be learned until the mediator has processed a sufficient number of user queries. For the purposes of this paper, we shall assume that the probing queries are selected from a set of spanning queries (the second approach can still be used for "refining" the statistics later, see [NK04]).

For scenarios where AV hierarchies are available, spanning queries can be generated by considering a cartesian product of the leaf node features of all the classificatory attributes (for which AV hierarchies are available), and generating selection queries that bind attributes using the corresponding values of the members of the cartesian product. Every member in the cartesian product is a "least general query" that we can generate using the classificatory attributes and their AV-hierarchies. Given multiple classificatory attributes, such queries will bind more than one attribute and hence we believe they would satisfy the "binding restrictions" imposed by most autonomous Web sources. Although a query binding single classificatory attribute will generate larger result sets, most often such queries will not satisfy the binding restrictions of Web sources as they are too general and may extract a large part of the source's data. The "less general" the query (more attributes bound), the more likely it will be accepted by autonomous Web sources. But reducing the generality of the query does entail an increase in the number of spanning queries leading to larger probing costs if sampling is not done.

For scenarios where AV hierarchies are not available, we need to gather valid binding values for the attributes in the mediated relation to generate selection queries as spanning queries. For example, in our *BibFinder*scenario, we can get author names from CiteSeer and conference names from DBLP. We also know the values for the year attribute are in 1950-2004.

Once we decide the space from which the probing queries are selected (in our case, a set of spanning queries), the next question is how to pick a representative sample of these queries. Clearly, sending all potential queries to the sources is too costly. We use sampling techniques for keeping the number of probing queries under control. Two well-known sampling techniques are applicable to our scenario: (a) *Simple Random Sampling* and (b) *Stratified Random Sampling* [M82, C77]. Simple random sampling gives equal probability of being selected to each query in the collection of sample queries. Stratified random sampling requires that the sample population be divisible into several subgroups. Then for each subgroup a simple random sampling is done to derive the samples. If the strata are selected intelligently, stratified sampling gives statistics with higher precision than simple random sampling. We evaluate both these approaches experimentally to study the effect of sampling on our learning approach.

3.2 Efficiently managing results of probing

Once we decide on a set of sample probing queries, these queries are submitted to all the data sources. The results returned by the sources are then organized in a form suitable for generating AV hierarchies, and mining large classes and their statistics. Specifically the result dataset consists of two tables, **classInfo**(CID,A_{c_1},...,A_{c_n}, Count) and **sourceInfo**(CID, Source, Count), where A_{c_j} refers to the j^{th} classificatory attribute. The leaf classes with at least one tuple in the sources are given a class identifier, CID. The total number of distinct tuples for each leaf class are entered into **classInfo**, and a separate table **sourceInfo** keeps track of which tuples come from which sources. If multiple sources have the same tuples in a leaf class then we just need to remember the total number of common tuples for that overlapped source set. An entry in the table sourceInfo for a class C and sourceset $\widehat{S}$ keeps track of the number of objects that are not reported for any superset of $\widehat{S}$. In the worst case, we have to keep the counts for all the possible subsets for each class(2^n of them, where n is the number of sources which have answers for the query)[4].

Example 3: Continuing the example in Section 1, we shall assume the following query is the first probing query:

Q(title, author, conference, year) :− **paper**(title, author, conference, year), conference="ICDE".

Then we can update the answer tuples of the above query into the dataset: **classInfo**(see Figure 3(a)) and **sourceInfo** (see Figure 3(b)). In the table **classInfo**, we use attribute CID to keep the id of the class, attributes "conference" and "year" to keep the classificatory attribute values, and attribute Count to keep the total number of distinct tuples of the class. In the table **sourceInfo**, we use attribute

[4]Although in practice the worst case is not likely to happen, if the results are too many to remember, we can do one of the following: use a single scan mining algorithm(see Section 4.1.2), then we can count query by query during probing, in this way we just need to remember the results for the current query; just remember the counts for the higher level abstract classes; or just remember overlap counts for upto k-$sourceSet$s, where k is a predefined value($k < n$).

CID	Conference	Year	Count
1	ICDE	2002	79
2	ICDE	2001	67

(a) Tuples in the table classInfo

CID	Source	Count
1	(S_2, S_7)	79
2	(S_1, S_2, S_3)	38
2	(S_1, S_2)	20
2	S_3	9

(b) Tuples in the table sourceInfo

Figure 3: classInfo and sourceInfo

CID to keep the id of the class, attribute Source to keep the overlap sources in the class, and attribute Count to keep the number of overlapped tuples of the sources. For example, in the leaf class with class CID=2, we have three subsets of overlapped sources which disjointly export the total 67 tuples. As we can see, all the sources in the set (S_1, S_2, S_3) export 38 tuples in common, all the sources in the set (S_1, S_2) export another 20 tuples in common, and the single source S_3 itself export another 9 tuples.

4 Acquiring AV Hierarchies

As we mentioned earlier, AV hierarchies can either be provided by the user or generated automatically. While it's often possible to manually generate AV hierarchies, in some cases, manually generating high quality hierarchies may be very time consuming even with domain experts' help. In this section we discuss how to automatically build AV Hierarchies based on the probing results gathered by the mediator. We first define the distance function between two attribute values. Next we introduce a clustering algorithm to automatically generate AV Hierarchies. Finally we discuss how to flatten our automatically generated AV Hierarchies.

Distance Function: The main idea of generating an AV hierarchy is to cluster similar attribute values into classes in terms of the coverage and overlap statistics of their corresponding selection queries binding these values. The problem of finding similar attribute values becomes the problem of finding similar selection queries. In order to find similar queries, we define a distance function to measure the distance between a pair of selection queries (Q_1, Q_2):

$$d(Q_1, Q_2) = \sqrt{\sum_i [P(\widehat{S}_i|Q_1) - P(\widehat{S}_i|Q_2)]^2}$$

Where $\widehat{S}_i$ denotes the i^{th} source set of all possible source sets in the mediator. Although the number of all possible source sets is exponential in terms of the number of available sources, we only

need to consider source sets with answers for at least one of the two queries to compute $d(Q_1, Q_2)$.[5] Note that we are not measuring the similarity of the answers of Q_1 and Q_2, but rather the similarity of the way their answer tuples are distributed over the sources. In this sense, we may find that a selection query $conference =$ "$AAAI$" and another query $conference =$ "$SIGMOD$" to be similar in as much as the sources having tuples for the former also have tuples for the latter. Similarly we define a distance function to measure the distance between a pair of query classes (C_1, C_2):

$$d(C_1, C_2) = \sqrt{\sum_i [P(\widehat{S}_i|C_1) - P(\widehat{S}_i|C_2)]^2}$$

We compute a query class's coverage and overlap statistics $P(\widehat{S}|C)$ according to the definition of the overlap (or coverage) w.r.t. to a class given in Section 2.2. The statistics $P(\hat{S}|Q)$ for a specific query Q are computed using the statistics from the probing results gathered by the mediator.

Generating AV Hierarchies: For now we will assume that all classificatory attributes have a discrete set of values, and we will also assume that the corresponding coverage and overlap statistics are available. We now introduce GAVH (Generating AV Hierarchy, see Figure 8), an agglomerative hierarchical clustering algorithm ([7]), to automatically generate an AV Hierarchy for an attribute.

Algorithm *GAVH()*
  for (each attribute value)
    generate a cluster node C;
    feature vector $C.fv = (\overrightarrow{P(\widehat{S}|Q)}, N_Q)$;
    children $C.children = null$;
    put cluster node C into AVQueue;
  end for
  while (AVQueue has more than two clusters)
    find the most similar pair of clusters C_1 and C_2;
    /* $d(C_1, C_2)$ is the minimum of all $d(C_i, C_j)$ */
    generate a new cluster C;
    $C.fv = (\frac{N_{C_1} \times \overrightarrow{P(\widehat{S}|C_1)} + N_{C_2} \times \overrightarrow{P(\widehat{S}|C_2)}}{N_{C_1} + N_{C_2}}, N_{C_1} + N_{C_2})$;
    $C.children = (C_1, C_2)$;
    put cluster C into AVQueue;
    remove cluster C_1 and C_2 from AVQueue;
  end while
End *GAVH*;

Figure 4: The GAVH algorithm

[5]For example, suppose query Q_1 gets tuples form only sources S_1 and S_5, and Q_2 gets tuples from S_5 and S_7, we will only consider source sets $\{S_1\}$,$\{S_5\}$,$\{S_1, S_5\}$,$\{S_7\}$, and $\{S_5, S_7\}$. We will not consider $\{S_1, S_7\}$, $\{S_1, S_5, S_7\}$, $\{S_2\}$, and many other source sets without any answer for either of the queries.

The GAVH algorithm will build an AV Hierarchy tree, where each node in the tree has a feature vector summarizing the information that we maintain about an attribute value cluster. The feature vector is defined as: $(\overrightarrow{P(\widehat{S}|C)}, N_C)$, where $\overrightarrow{P(\widehat{S}|C)}$ is the coverage and overlap statistics vector of the cluster C for all the source sets and N_C is the number of answer tuples for the queries in cluster C. Feature vectors are only used during the construction of AV hierarchies and can be removed afterwards. As we can see from Figure 8, we can incrementally compute a new cluster's coverage and overlap statistics vector $\overrightarrow{P(\widehat{S}|C)}$ by using the feature vectors of its children clusters C_1, C_2:

$$\overrightarrow{P(\widehat{S}|C)} = \frac{N_{C_1} \times \overrightarrow{P(\widehat{S}|C_1)} + N_{C_2} \times \overrightarrow{P(\widehat{S}|C_2)}}{N_{C_1} + N_{C_2}}$$

$$N_C = N_{C_1} + N_{C_2}$$

Flattening Attribute Value Hierarchies: Since the nodes of the AV Hierarchies generated using our GAVH algorithm contain only two children each, we may get a hierarchy with a large number of layers. One potential problem with such kinds of AV Hierarchies is that the level of abstraction may not actually increase when we go up the hierarchy.

Algorithm *FAVH(clusterNode C)* //Starting from root;
  if(C has children)
    for (each child node C_{child} in C)
      put C_{child} into $Children\_Queue$
    for (each node C_{child} **in** $Children\_Queue$**)**
      if $(d(C_{child}, C) \leq \frac{1}{t(C_{child})})$
        put $(C_{child}).children$ into $Children\_Queue$;
        remove C_{child} from $Children\_Queue$;
      end if
    for (each children node C_{child} in $Children\_Queue$)
      FAVH(C_{child});
  end if
End *FAVH*;

Figure 5: The FAVH algorithm

In order to prune these unnecessary clusters, we use another algorithm called FAVH (Flattening AV Hierarchy, see Figure 5). FAVH starts the flattening procedure from the root of the AV Hierarchy, then recursively checks and flattens the entire hierarchy.

To determine whether a cluster C_{child} should be preserved in the hierarchy, we compute the *tightness* of the cluster, which measures the accuracy of its statistics. We consider a cluster is tight if all

the queries subsumed by the cluster (especially frequently asked ones) are close to its center. The *tightness* $t(C)$ of a class C is computed as following:

$$t(C) = \frac{1}{\sum_{Q \in C} w_Q \times d(Q, C)}$$

where $d(Q, C)$ is the distance between the query Q and the class center, and w_Q is the weight of the query.

If the distance, $d(C_{child}, C)$, between a cluster and its parent cluster C is not larger than $\frac{1}{t(C_{child})}$, then we consider the cluster as unnecessary and put all of its children directly into its parent cluster.

5 Algorithms for Learning Coverage and Overlap

In terms of the mining algorithms used, we already noted that the source overlap information is learned using a variant of the Apriori algorithm [AS94]. The source coverage as well as the large class identification is done simultaneously using the LCS algorithm which we developed. Although the LCS algorithm shares some commonalities with multi-level association rule mining approaches, it differs in two important ways. The multi-level association rule mining approaches typically assume that there is only one hierarchy, and mine strong associations between the items within that hierarchy. In contrast, the LCS algorithm assumes that there are multiple hierarchies, and discovers large query classes with one attribute value from each hierarchy. It also mines associations between the discovered large classes and the sources.

5.1 The LCS Algorithm

The LCS algorithm (see Figure 6) dynamically discovers the large classes inside a mediator system and computes coverage statistics for these discovered large classes. As mentioned earlier, in order to avoid too many small classes, we can set support count thresholds to prune the classes with support count below the threshold. We dynamically prune classes during counting and use the anti-monotone property to avoid generating classes which are supersets of the pruned classes. A procedure genClassSet is used to efficiently generate potentially large candidate ancestor class set for each leaf class by pruning small candidate classes using anti-monotone property.

The LCS algorithm requires the dataset: *classInfo* and *sourceInfo*, the AV hierarchies, and the minimum support as inputs. As we can see, the LCS algorithm makes multiple passes over the data. Specifically, we first find all the large classes with just one feature, then we find all the large classes with two features using the previous results and the anti-monotone property to efficiently prune classes before we start counting, and so on. We continue until we get all the large classes

Algorithm *LCS(classInfo; sourceInfo; τ_c : minimum support; n : # of classificatory attributes)*

$classSet = \{\}, ruleSet = \{\}$;
for*($k = 1; k <= n; k++$)*
  Let $classSet_k = \{\}$;
  for*(each leaf class $lc \in classInfo$)*
    $C_{lc} = genClassSet(k, lc, ...)$;
    for*(each class $c \in C_{lc}$)*
      if*($c \notin classSet_k$)*
      then $classSet_k = classSet_k \cup \{c\}$;
      $c.count = c.count + lc.Count$;
      for *(each source $S \in lc$)*
        if *(rule $r_{c \to s} \notin ruleSet$)*
        then $ruleSet = ruleSet \cup \{r_{c \to s}\}$;
        $r_{c \to s}.count = r_{c \to s}.count +$
          # of tuples from source S and in class lc;
      end for
    end for
  end for
  $classSet_k = \{c \in classSet_k | c.count >= \tau_c\}$;
  remove rules with low support classes from $ruleSet$;
  $classSet = classSet \cup classSet_k$;
end for
for*(each rule $r_{c \to s} \in ruleSet$)*
do $r_{c \to s}.confidence = \frac{r_{c \to s}.count}{c.count}$;
return $ruleSet$;
End *LCS*;

Figure 6: Learning Coverage Statistics algorithm

with all the n features. For each tuple in the k-th pass, we find the set of k feature classes it falls in, increase the count $support(C)$ for each class C in the set, and increase the count $support(r_{c \to s})$ for each source S with this tuple. We prune the classes with total support count less than the minimum support count. After identifying the large classes, we can easily compute the coverage of each source S for every large class C as follows:

$$confidence(r_{c \to s}) = \frac{support(r_{c \to s})}{support(C)}$$

In the genClassSet algorithm(see Figure 7), we find all the candidate ancestor classes with k features for a leaf class lc using procedure **genClassSet**. The procedure prunes small classes using the large class set $classSet$ found in the previous $(k-1)$ passes. In order to improve the efficiency of the algorithm, we dynamically prune small classes during the cartesian product procedure.

Procedure *genClassSet(k : number of features;lc : the leaf class; $classSet$: discovered large class set; AV hierarchies)*
  for *(each feature $f_i \in lc$)*
    $ftSet_i = \{f_i\}$;
    $ftSet_i = ftSet_i \cup (\{ancestor(f_i)\} - \{root\})$;
  end for
  candidateSet={};
  for *(each k feature combination $(ftSet_{j_1}, ..., ftSet_{j_k})$)*
    $tempSet = ftSet_{j_1}$;
    for *($i = 1; i < k; i++$)*
      remove any class $C \notin classSet_i$ from tempSet;
      $tempSet = tempSet \times ftSet_{j_{i+1}}$;
    end for
    remove any class $C \notin classSet_{k-1}$ from tempSet;
    $candidateSet = candidateSet \cup tempSet$;
  end for
  return $candidateSet$;
End *genClassSet*;

Figure 7: Ancestor class set generation procedure

Example 4: Assume we have a leaf class lc={1, ICDE, 2001, 67} and k=2. We first extract the feature values $\{A_{c_1} = ICDE, A_{c_2} = 2001\}$ from the leaf class. Then for each feature, we generate a feature set which includes all the ancestors of the feature. Then we will get two feature sets: $ftSet_1 = \{ICDE, DB\}$ and $ftSet_2 = \{2001\}$. Suppose the class with the single feature "ICDE" is not a large class in the previous results, then any class with the feature "ICDE" can not be a large class according to the anti-monotone property. We can prune the feature "ICDE" from $ftSet_1$, then we get the candidate 2-feature class set for the leaf class lc,

$$candidateSet = ftSet_1 \times ftSet_2 = \{DB\&2001\}.$$

In the LCS algorithm, we assume that the number of classes will be high. In order to avoid considering a large number of classes, we prune classes during counting. By doing so, we have to scan the dataset n times, where n is the number of classificatory attributes. The number of classes we can prune will depend on the threshold. A very low threshold will not benefit too much from the pruning. In the worst case where the threshold equal to zero, we still have to keep all the classes($\prod_{i=1}^{n} |H_i|$, where H_i is the i^{th} AV hierarchy.).

However if the number of classes are small and the cost of scanning the whole dataset is very expensive, then we can use a one pass algorithm. For each leaf class lc of every probing query's

results, the algorithm has to generate an complete candidate class set of lc, increase the counts of each class in the set. By doing so, we have to remember the counts for all the possible classes during the counting, but we don't need to remember all the probing query results.

5.2 Learning Overlap among Sources

Once we discover large classes in the mediator, we can learn the overlap between sources for each large class. Here we also use the dataset: **classInfo** and **sourceInfo**. In this section we discuss how to learn the overlap information between sources for a given class.

From the table *classInfo* we can classify the leaf classes into the large classes we learned using LCS. A leaf class can be mapped into multiple classes. For example, a leaf class about a publication in Conference:"AAAI", and Year:"2001", can be classified into the following classes: (AAAI,RT), (AI,RT), (RT,2001), (AAAI,2001), (AI,2001), (RT,RT), provided all these classes are determined to be large classes in the mediator by LCS.

After we classify the leaf classes in *classInfo*, for each discovered large class C, we can get its descendent leaf classes, which can be used to generate a new table $sourceInfo_c$ by selecting relative tuples for its descendent leaf classes from *sourceInfo*.

Next we apply the Apriori ([AS94]) algorithm to find overlapping sources. In order to apply the Apriori on our data in $sourceInfo_c$, we do a minor change to the algorithm. Usually Apriori takes as input a list of transactions, while in our case it is a list of source sets with common tuple counts. So every time when an itemset appears in a transaction, the count of the itemset is increased by 1, while in our case, every time we find a superset of a sourceSet in $sourceInfo_c$, the count of the sourceSet is increased by the actual count of the superset.

The candidate source sets will include all the combinations of the sources, with 1-$sourceSets$, 2-$sourceSets$,...,n-$sourceSets$, where n is the total number of sources. In order to use Apriori, we have to decide a minimum support threshold, which will be used to prune source sets with few overlapping answers.

Once the frequent source sets from the table $sourceInfo_c$ have been found, we can compute the overlap probability of the sources $\{S_1, S_2, ..., S_k\}$ in class C by using the following formula:

$$P((S_1 \wedge S_2 \wedge ... \wedge S_k)|C) = \frac{support\_count(\{S_1, S_2, ..., S_k\})}{support\_count(C)}$$

Here the $support\_count(C)$ is just the total number of tuples in the table $sourceInfo_c$.

6 Using the Learned Statistics

In this section, we consider the question of how, given a user query, we can rank the sources to be accessed, using the learned statistics.

6.1 Mapping users' queries to abstract classes

After we run the LCS algorithm, we will get a set of large classes and there is a hierarchical structure between these classes. The classes shown in Figure 2 with solid frame lines are discovered large classes. As we can see some classes may have multiple ancestor classes. For example, the class (ICDE,01) has both the class (DB,01) and class (ICDE,RT) as it's parent class. In order to use the learned coverage and overlap statistics of the large classes, we need to map a user's query to a discovered large class. Then the coverage and overlap statistics for the corresponding class can be used to predict the coverage of the sources and overlap among the sources for the query.

The mapping is done according to the following algorithm.

1. If the classificatory attributes are bound in the query, then find the lowest ancestor abstraction class with statistics[6] for the features of the query.

2. If no classificatory attribute is bound in the query, then we do one of the following,

   - Check whether we have learned some association rules between the non-classificatory features in the query with classificatory features[7]. If we did, we use these features as features of the query to get statistics, go to step 1;
   - Present the discovered classes to the user, and take the user's feedback to select a class;
   - Use the root of the hierarchy as the class of the query.

6.2 Computing residual coverage

In this section we discuss how we compute the residual coverages in order to rank the sources for the class C (to which the user's query has been mapped), using the learned statistics. In order to find a plan with top k sources, we start by selecting the source with the highest coverage ([FKL97]) as the first source. We then we use the overlap statistics to compute the residual coverages of the rest of the

[6] If we have multiple ancestor classes, the lowest ancestor class with statistics means the ancestor class with lowest support counts among all the discovered large classes.

[7] In order to simplify the problem, we did not discuss this kind of association rule mining in this paper, but it is just a typical association rule mining problem. A simple example would be to learn the rules like:$J.Ullman \rightarrow Databases$ with high enough confidence and support.

sources to find the second best, given the first; the third best, given the first and second, and so on, until we get a plan with the desired coverage.

In particular, after selecting the first and second best sources S_1 and S_2 for the class C, the residual coverage of a third source S_3 can be computed as:

$$P(S_3 \wedge \neg S_1 \wedge \neg S_2|C) = P(S_3|C) - P(S_3 \wedge S_1|C) - P(S_3 \wedge S_2|C) + P(S_3 \wedge S_2 \wedge S_1|C)$$

where, $P(S_i \wedge \neg S_j)$ is the probability that a random tuple belongs to S_i but not to S_j. In the general case, after we had already selected the best n sources $\widehat{S} = \{S_1, S_2, ..., S_n\}$, the residual coverage of an additional source S can be expressed as:

$$P(S \wedge \neg\widehat{S}|C) = P(S|C) + \sum_{k=1}^{n}[(-1)^k \sum_{\widehat{S}^k \subseteq \widehat{S} \wedge |\widehat{S}^k|=k} P(S \wedge \widehat{S}^k|C)]$$

where $P(S \wedge \neg\widehat{S}|C)$ is shorthand for $P(S \wedge \neg S_1 \wedge \neg S_2 \wedge ... \wedge \neg S_n|C)$.

A naive evaluation of this formula would require 2^n accesses to the database of learned statistics, corresponding to the overlap of each possible subset of the n sources with source S. It is however possible to make this computation more efficient by exploiting the structure of the stored statistics. Specifically, recall that we only keep overlap statistics for source sets with sufficient number of overlap tuples, and assume that source sets without overlap statistics are disjoint (thus their probability of overlap is zero). Furthermore, if the overlap is zero for a source set $\widehat{S}$, we can ignore looking up the overlap statistics for supersets of $\widehat{S}$, since they will all be zero by the anti-monotone property.

To illustrate the above, suppose S_1,S_2,S_3 andS_4 are sources exporting tuples for class C. Let $P(S_1|C)$, $P(S_2|C)$ $P(S_3|C)$ and $P(S_4|C)$ be the learned coverage statistics, and $P(S_1 \wedge S_2|C)$ and $P(S_2 \wedge S_3|C)$ be the learned overlap statistics. The expression for computing the residual coverage of S_3 given that S_1 and S_2 are already selected is:

$$P(S_3 \wedge \neg S_1 \wedge \neg S_2|C) = P(S_3|C) - \underbrace{P(S_3 \wedge S_1|C)}_{=0} - P(S_3 \wedge S_2|C) + \underbrace{P(S_3 \wedge S_1 \wedge S_2|C)}_{=0 \text{ since } \{S_3,S_1\} \subseteq \{S_2,S_1,S_2\}}$$

We note that once we know $P(S_3 \wedge S_1|C)$ is zero, we can avoid looking up $P(S_3 \wedge S_1 \wedge S_2|C)$, since the latter set is a superset of the former.

In Figure 8, we present an algorithm that uses this structure to evaluate the residual coverage in an efficient fashion. In particular, this algorithm will cut the number of statistics lookups from 2^n to $\mathcal{R} + n$, where $\mathcal{R}$ is the total number of overlap statistics remembered for class C and n is the total number of sources already selected. This consequent efficiency is critical in practice since computation of residual coverage forms the inner loop of any query processing algorithm that considers

Algorithm *residualCoverage (s: source; $\widehat{S}_s$: selected sources; $\widehat{S}_c$: constraint source set)*
  n = the number of sources in $\widehat{S}_s$;
  if $(\widehat{S}_c \neq \emptyset)$ **then** p = the position of $\widehat{S}_c$'s last source in $\widehat{S}_s$;
  else p=0;
  Let $resCoverage = 0$;
  if the overlap statistics for the source set $\widehat{S}_c \cup \{\mathrm{s}\}$
  are present in the learned statistics;
    //This means their overlap is $> \tau_o$.
    for $(i = p + 1; i \leq n; i++)$
      Let $\widehat{S}'_c = \widehat{S}_c \cup \{the\ i^{th}$ source in $\widehat{S}_s\}$;
      //keep order of sources in $\widehat{S}'_c$ same as in $\widehat{S}_s$
      $resCoverage = resCoverage$+*residualCoverage*$(\mathrm{s}, \widehat{S}_s, \widehat{S}'_c)$;
    end for
    $resCoverage = resCoverage + (-1)^{|\widehat{S}_c|} overlap$;
  end if
  return $resCoverage$;
End *residualCoverage*;

Figure 8: Algorithm for computing residual coverage

source coverage.

The inputs to the algorithm in Figure 8 are the source s for which we are going to compute the residual coverage, and the currently selected set of sources $\widehat{S}_s$. The auxiliary datastructure $\widehat{S}_c$, initially set to $\emptyset$, is used to restrict the source overlaps considered by the *residualCoverage* algorithm. In each invocation, the algorithm first looks for the overlap statistics for $\{s\} \cup \widehat{S}_c$. If this statistic is among the learned (stored) statistics, the algorithm recursively invokes itself on supersets of $\{s\} \cup \widehat{S}_c$. Otherwise, the recursion stops in that branch (eliminating all the redundant superset lookups).

7 Experimental Setup

Our statistics learning system *StatMiner* has been fully implemented and evaluated using both controlled datasets and *BibFinder*, a popular computer science bibliography mediator that we developed. In the experiment with controlled datasets, we focused on evaluating the efficiency and effectiveness of our approach for scenarios with large number of sources. In the *BibFinder* experiments, we show the effectiveness of our approach in a real scenario, where we can not control the data distribution over these online Web sources, and probing these sources is also very costly. We will start by describing the experimental setup for both scenarios.

7.1 Controlled Datasets

Given a global mediator schema and Web sources exporting the schema, our approach for learning source statistics aims at capturing an approximate distribution of the source data that would enable efficient processing of potential mediator queries. We use the AV hierarchies provided for the global schema to generate a hierarchical classification of potential queries and also to generate sample probing queries to learn the approximate data spread of the sources with respect to the classification. To evaluate our techniques we set up a set of "remote" data sources accessible on the Internet. The sources were populated with synthetic data generated using the data generator from TPC-W benchmark [TPC] (see below). The TPC sources support controlled experimentation as their data distribution (and consequently the coverage and overlap among web sources) can be varied by us.

We designed 25 sources using 200000 tuples for the relation Books. We chose **Books**(Bookid, Pubyear, Subject, Publisher, Cover) as the relation exported by our sources. The decision to use Books as the sample schema was motivated by the fact that multiple autonomous Internet sources projecting this relation exist, and in the absence of statistics about these sources, only naive mediation services are currently provided. Pubyear, Subject and Cover are used as the *classificatory* attributes in the relation Books. The hierarchies were designed as shown in Figures 9 and 10. To evaluate the effect of the resolution of the hierarchy on ranking accuracy we designed two separate hierarchies for Subject, containing 180 and 40 leaf nodes respectively. Leaf node values for Pubyear range from 1980 to 2001, while Cover is relatively small with only five leaf nodes. The Subject hierarchy was modeled from the classification of books given by the online bookstore Amazon [AM]. We populated the data sources exporting the mediator relation using DataGen, the data generator from TPC-W Benchmark [TPC]. The distribution of data in these sources was determined by controlling the values used to instantiate the classificatory attributes Pubyear, Subject and Cover. For example, two sources S_1 and S_2 both providing tuples under abstract feature "Databases" of Subject hierarchy, are designed to have varying overlap with source S_3, by selecting different subsets of features under "Databases" to instantiate the source tuples. These subsets may be mutually exclusive, but they overlap with the subset of features selected for populating source S_3. Since the actual generation of data sources is done by using DataGen, the above mentioned procedure gives us a macro level control over the design of overlap among sources. In fact DataGen populates the sources by initializing each attribute of the Books relation using a randomly chosen value from a list of seed values for that attribute. Hence we control the query classes for which the sources provide answer tuples and may overlap with other sources but not the actual values of coverage and overlap given by sources.

7.2 *BibFinder* testbed

We use *BibFinder* as a testbed to evaluate our ability to learn an approximate data distribution from real Web data and also to test the effect of various probing techniques we use.

Six structured Web bibliography data sources in *BibFinder* : DBLP, CSB, ACM DL, ACM Guide, Science Direct and IEEExplore are used in our experimental evaluation. We chose **paper(title, author, conference/journal, year)** as the mediated relation. conference/journal and year are chosen as the classificatory attributes. Since it's difficult to get a good AV hierarchy for the conference/journal attribute, we use the GAVH and FAVH described in Section 4 to automatically learn the conference/journal hierarchy. We gathered 604 conference and journal names from DBLP, ACM dl, and Science Direct Web pages. These names are used to generate probing queries and to generate AV hierarchy for the conference/journal attribute. The AV hierarchy for the year attribute is consisted of the years from 1954 to 2003 as leaf nodes. Every five years in first level of the hierarchy is subsumed by a second level ancestor node, and every ten years are subsumed by a third level ancestor node, and ROOT is the only node in the fourth level. The space of all the probing queries is the cartisian product of the 604 conference/journal names and the 50 years. We used a set of 578 real queries asked by *BibFinder* users as the test queries.

Probing Data Sources: To estimate the spread of data over autonomous Web sources we must probe these sources. As discussed earlier, we generate the sample queries by taking cartesian products of the conference/journal names and recent 50 years. At this time we are assuming that only queries binding both conference/journal and year will be considered "safe" by the Web sources.

Probing Web sources using all the queries we can generate will be too costly for large number of queries. Hence we use query sampling to select a smaller set of queries to generate the required data distribution of sources.

Query Sampling: As mentioned in Section 3.1, we generate the set of sample probing queries using both *Simple Random Sampling* and *Stratified Random Sampling*. After generating the set of spanning queries we use the two sampling approaches to extract a sample set of queries to probe the data sources. Simple Random sampling picks the samples from the complete set of queries, whereas to employ the Stratified Random sampling approach, we have to further classify the queries into various *strata*. The strata is chosen as the abstract feature of any one classificatory attribute say $A1$. All the queries that bind $A1$ using leaf values subsumed by a strata are mapped to that strata. A strata based on an abstract feature that only subsumes leaf nodes will have fewer queries mapped to it compared to the strata that is based on an abstract feature that subsumes both the leaf nodes and other abstract features. Thus the level of abstraction at which we decide a strata varies the number of queries that get mapped to the strata. The lowest abstraction is the leaf node, while the root gives highest abstraction. Selecting root as the strata will make Stratified Random Sampling equal to Simple Random, where selecting the leaf nodes as strata, will be equal to issuing all the spanning queries.

7.3 Algorithms and Evaluation Metrics

To evaluate the accuracy of the statistics learnt by *StatMiner* we tested them using two simple plan generation algorithms. Our mediator implements the **Simple Greedy** and **Greedy Select** algorithms described in [FKL97] to generate query plans using the source coverage and overlap statistics learnt by *StatMiner*. Given a query, Simple Greedy generates a plan by assuming all sources are independent and greedily selects top k sources ranked according to their coverages. On the other hand, Greedy Select generates query plans by selecting sources with high residual coverages calculated using both the coverage and overlap statistics (see Section 6.2).

We evaluate the plans generated by both the planners for various sets of statistics learnt by *StatMiner* for differing threshold values and AV hierarchies. We compare the precision of plans generated by both the algorithms. We define the *plan precision* to be the fraction of sources in the estimated plan, which turn out to be the real top k sources after we execute the query. Let $TopK$ refer to the real top k sources, and $Selected(p)$ refer to the k sources selected in the plan p. Then the $precision$ of the plan p is:

$$precision(p) = \frac{|TopK \cap Selected(p)|}{|Selected(p)|}$$

The average precision and number of answers returned by executing the plan are used to estimate the accuracy of the learned statistics.

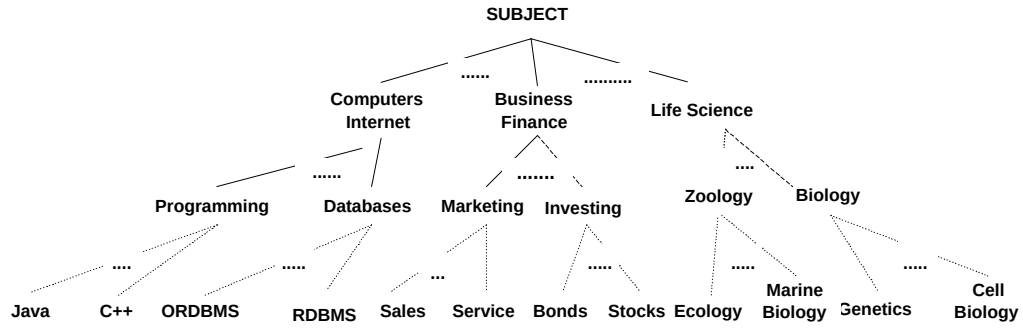


Figure 9: Subject Hierarchy

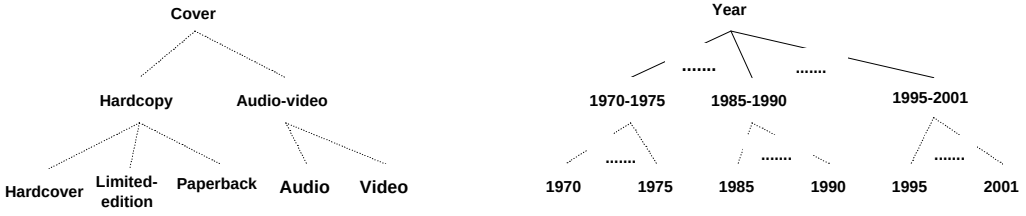


Figure 10: Cover and Year Hierarchy

8 Experimental Results

We now present the results of both experiments using controlled datasets and experiments using *BibFinder* as testbed.

8.1 Results over Controlled Data Sources

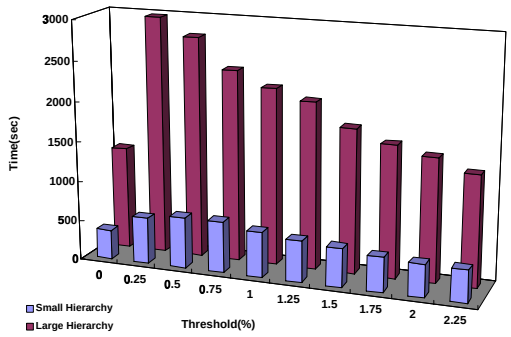
In this section we present results of experiments conducted to study the variation in pruning power and accuracy of our algorithms for different class size thresholds τ_c. In particular, given a set of sources and probing queries, our aim is to show that we can trade time and space for accuracy by increasing the threshold τ_c. Specifically by increasing threshold τ_c, the ***time*** (to identify large classes) and ***space*** (number of large classes remembered) usage can be reduced with a reduction in ***accuracy*** of the learnt estimates. All the experiments presented here were conducted on a 500MHZ Sun-Blade-100 systems with 256MB main memory running under Solaris 5.8. The sources in the mediator are hosted on a Sun Ultra 5 Web server located on campus.

Effect of Hierarchies on Space and Time: To evaluate the performance of our statistics learner, we varied τ_c and measured the number of large classes and the time utilized for learning source coverage statistics for these large classes. Figure 11(a) compares the time taken by LCS to learn rules for different values of τ_c. Figure 11(b) compares the number of pruned classes with increase in value of τ_c. We represent τ_c as a percentage of the total number of tuples in the relation. The total tuples in the relation is calculated as the number of unique tuples generated by the probing queries.

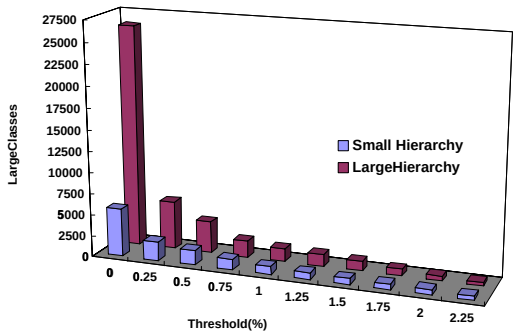
As can be seen from Figure 11(a), for lower values of threshold τ_c, LCS takes more time to learn the rules. For lower values of τ_c, LCS will prune less number of classes and hence for each class in ClassInfo, LCS will generate large number of rules. This in turn explains the increase in learning time for lower threshold values.

In Figure 11(b), with increase in value of τ_c, the number of small classes pruned increase and hence we see a reduction in the number of large classes. For any value of τ_c greater than the support of the largest abstract class in the classSet, LCS returns only the root as the class to remember. Figures 11(a) and 11(b) show LCS performing uniformly for both Small and Large hierarchy. For both hierarchies, LCS generates large number of classes for small threshold values and requires more learning time. From Figures 11(a) and 11(b), we can see that the amount of time used and classes generated (space requirement) for the Large hierarchy is considerably higher than for Small hierarchy.

Accuracy of Estimated Coverages: To calculate the error in our coverage estimates, we used the prototype implementations of "Simple Greedy" and "Greedy Select" algorithms and a subset of our spanning queries as test queries. Since the test queries will have classificatory attributes bound, from Section 6.1 we see that the mediator maps it to the lowest abstract class for which coverage statistics



(a) LCS learning time for various thresholds



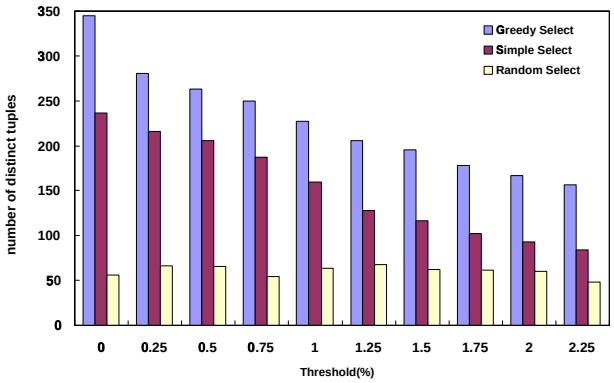
(b) Pruning of classes by LCS

Figure 11: Learning Efficiency

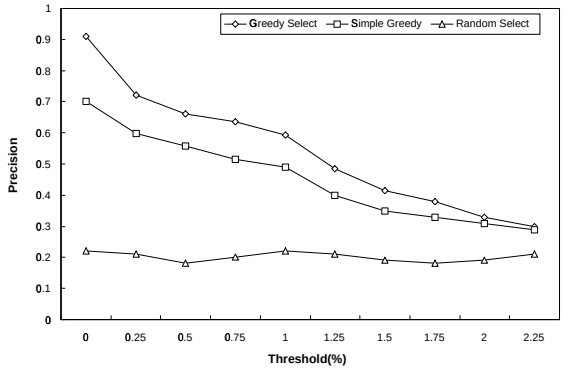
have been learnt. Once the query is mapped to a class, the mediator then generates plans using the ranking algorithms, Simple Greedy and Greedy Select as described in Section 7.3. We compare the plans generated by these algorithms with a naive plan generated by **Random Select**. Random select algorithm arbitrarily picks k sources without using any statistics. The source rankings generated by all the three algorithms is compared with the "true ranking" determined by querying all the sources. Figure 12(b) compares the precision of plans generated by the three approaches with respect to the true ranking of the sources.

As can be seen from Figure 12(a) for all values of τ_c Greedy Select gives the best plan, while Simple Greedy is close second, but the Random Select performs poorly. The results are according to our expectations, since Greedy Select generates plans by calculating residual coverage of sources and thereby takes into account the amount of overlap among sources, while Simple Greedy calls sources with high coverages thereby ignoring the overlap statistics and hence generates less number of tuples.

In Figure 12(b) we compare the precision of plans generated by the three approaches. We define the precision of a plan to be the fraction of sources in the estimated plan, which turn out to be the real top k sources after we execute the query. Figure 12(b) shows the precision for the top 5 sources in a plan. Again we can see that Greedy Select comes out the winner. The decrease in precision of plans generated for higher values of threshold can be explained from Figure 11(b). As can be seen, for larger values of threshold more number of leaf classes get pruned. A mediator query always maps to a particular leaf class. But for higher thresholds, the leaf classes are pruned and hence queries get mapped to higher level abstract classes. Therefore the statistics used to generate plans have lower accuracy and in turn generate plans with lower precision.



(a) Comparing Average Number of Answers by Executing Query Plans for Top 5 Sources Obtained by Different Planning Algorithms Using Learned Statistics



(b) Comparing Average Precision of Query Plans for Top 5 Sources Obtained by Different Planning Algorithms Using Learned Statistics

Figure 12: Effectiveness of the Learnt Statistics

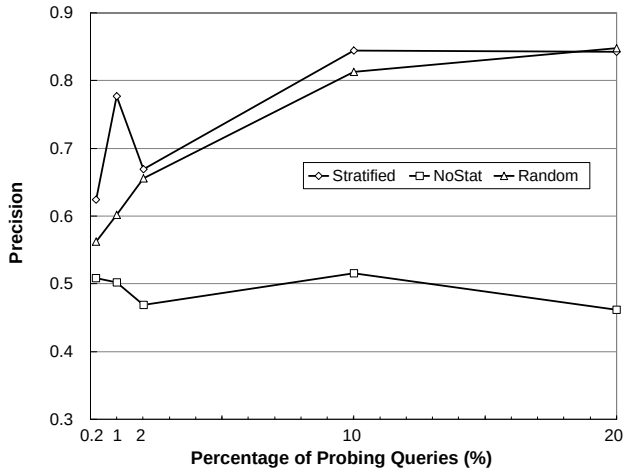
Altogether the experiments on these controlled datasets show that our LCS algorithm uses the association mining based approach effectively to control the number of statistics required for data integration. An ideal threshold for a mediator relation would depend on the number and size of AV hierarchies. For our sample Books mediator, an ideal threshold for LCS would be around 0.75%, for both the hierarchies, where LCS effectively prunes a large number of small classes and yet the precision of plans generated is fairly high. We also bring forth the problems involved in trying to scale up the algorithm to larger hierarchies.

8.2 Results over *BibFinder*

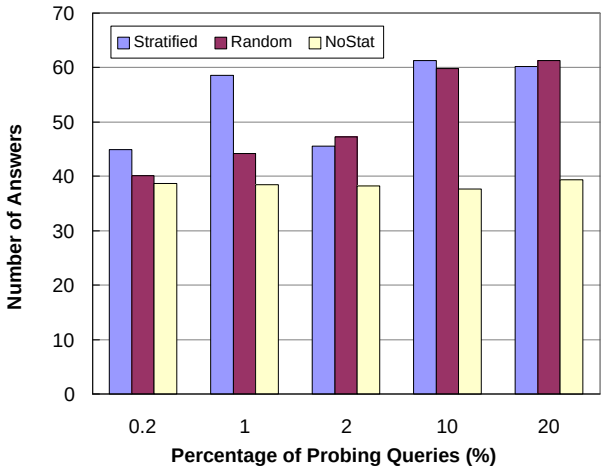
Given that the cost of probing tends to dominate the statistics gathering approach, we wanted to see how accurate the learned statistics are with respect to the two probing strategies. We used *BibFinder* sources for evaluating the probing strategies. The set of probing queries are generated by taking a cartesian product of the values of the conference/journal attribute and year attribute. The total number of queries generated is 30200. In order to be polite to the Web sources, we probe them at the rate of 3 queries per minute.

In the experiment we study the efficiency of different probing strategies and different number of probing queries by observing the effectiveness of the learned statistics through their probing results.

For each of these two probing strategies, we generate five sets of probing queries with different number of probing queries: 60 (0.2%), 302(1%), 604(2%), 3020(10%), 6040(20%). Specifically in the stratified sampling, the first set of 60 probing queries is generated by randomly selecting 60 conference/journal names without replacement and for each name randomly selecting a year from



(a) Comparing Average Precision of Query Plans for Top 3 Sources Obtained Using Statistics through Different Probing Strategies



(b) Comparing Average Number of Answers Returned by *BibFinder* by Executing Query Plans for Top 3 Sources Obtained Using Statistics through Different Probing Strategies

Figure 13: Effect of Probing Strategies in BibFinder

the 50 years; the second set of 302 queries is generated by randomly selecting 60 conference/journal names and for each names selecting 5 years (one from year ten year period); the third set of 602 queries is generated by selecting all names and for each names randomly selecting a year; the fourth set of 3020 queries is generated by selecting all names and for each names selecting 5 years (one year from each 10 year period); the fifth set of 6040 queries is generated by selecting all names, and for each name selecting 10 years (one year from each 5 year period). In the random sampling strategies, we generate the sets of queries by randomly selecting 60, 302, 604, 3020, and 6040 queries from all the 30200 queries.

We now describe the steps in the experimental procedure:

1. For each of the probing strategies and for each set of probing queries, we probe all the six online sources;

2. Generate conference/journal hierarchies using the probing results;

3. Discover large query classes using the learned conference/journal hierarchy and the year hierarchy using the probing results;

4. Learn coverage and overlap statistics for each discovered large classes using the probing results

5. Use a list of 578 real user queries submitted to *BibFinder* to evaluate the learned statistics.

In Figure 13(a), we observe the average precision of query plans for top 3 sources for different sampling strategies and different number of probing queries. Here we fix the thresholds $\tau_c = 0.1\%$ and $\tau_o = 1\%$. The query plans are generated by the greedy select algorithm using the learned coverage and overlap statistics. Different probing strategies and different number of probing queries affect the precision of the learned statistics, which affect the plan precision. From the figure, we can see that the stratified sampling is doing better than random sampling when the number of probing queries is small and the selection of strata is good, especially for the set of 302 probing queries. For each conference/journal, probing five years in each ten year period is much better than for each conference/journal randomly probing one year in a fifty year period. This is because the large classes discovered using 5 year probing results are more likely to be important conferences/journals than those using one year probing results. Learning the distribution over the sources for important conferences/journal will improve the precision, since users are more interested in these conferences/journals and the statistics for these conferences are more representative than that of random conferences/journals. However as the number of probing queries increases, the difference between random and stratified sampling becomes smaller (as to be expected).

In Figure 13(b), we observe the average number of answers from *BibFinder* when executing query plans for 3 sources for the 578 user queries. The figure illustrates results for different probing strategies and different number of probing queries. As we can see, the result is quite consistent with the plan precision. It is interesting to note that when using the statistics learned from the stratified probing results of 302 queries, *BibFinder* can actually provide about 50% more answers than by randomly querying 3 sources without using any statistics.

The above results are encouraging and show that our approach of leaning and using coverage and overlap statistics in *BibFinder* is able to give good results even for a very small sample of all probing queries. They also show that the stratified sampling is doing much better than random sampling when a good stratification strategy is chosen, and the number of probing queries is relatively small.

9 Related Work

Researchers in data integration have long noted the difficulty of obtaining relevant source statistics for use in query optimization. There have broadly been two approaches for dealing with this difficulty. Some approaches, such as those in [LRO96,DGL00,LKG99] develop heuristic query optimization methods that either do not use any statistics, or can get by with very coarse statistics about the sources. Others, such as [NLF99,NK01,DH02], develop optimization approaches that are fully statistics (cost) based. While these approaches assume a variety of coverage and response-time statistics, they do not however address the issue of learning the statistics in the first place–which is the main focus of the current paper.

There has been some previous work on using probing techniques to learn database statistics both in multi-database literature and data integration literature. Zhu and Larson [ZL96] describe techniques for developing regression cost models for multi-database systems by selective querying. Adali et. al [ACPS96] discuss how keeping track of rudimentary access statistics can help in doing cost-based optimizations. More recently, the work by Gruser et. al. [GRZ+00] considers mining response time statistics for sources in data integration scenario. Given that both coverage and response time statistics are important for query optimization (c.f. [NK01,DH02]), our work can be seen as complementary to theirs.

The utility of quantitative coverage statistics in ranking the sources is first explored by Florescu et. al. [FKL97], and more recently by Doan and Halevy [DH02]. The primary aim of both these efforts was however was on the "use" of coverage statistics, and they do not discuss how such coverage statistics could be learned. In contrast, our main aim in this paper is to provide a framework for learning the required statistics. We do share their goal of keeping the set of statistics compact. Florescu et. al. [FKL97] achieve the compactness by assuming that each source is identified with a single primary class of queries that it exports. They "factorize" the coverage of a source with respect to an arbitrary class in terms of (a) the coverage of that source with respect to its primary class and (b) the statistics about inter-class overlap. In contrast, we consider and learn statistics about a source's coverage with respect to any arbitrary query class. We achieve compactness by dynamically identifying "big" query classes, and keeping coverage statistics only with respect to these classes. From a learning point of view, we believe that our approach makes better sense since inter-class overlap statistics cannot be learned directly.[8]

There has also been a lot of work on selecting text collections in the domain of distributed information retrieval (or meta-search engines). To calculate the relevance of a text database to a keyword query, most of the work ([GG95],[XC98],[MLY+99],[C00],) uses the statistics about the document frequency of each single-word term in the query. The document frequency statistics are similar to our coverage statistics if we consider an answer tuple as a document. This suggests that an approach based on coverage and overlap statistics will also be beneficial in text databases. Indeed, recent work in our research group [HK04] adapted the ideas of *StatMiner* to the problem of text database ("collection") selection. The resulting approach has been shown to be superior to the traditional collection selection approaches such as CORI [C00].

Some recent work ([WMY00], [IG02]) also considers the problem of selecting text databases using a topic hierarchy. While our approach is similar to these approaches in terms of using hierarchies, and using probing and counting methods, it differs in several significant ways. First of all, we auto-

[8]They would have to be estimated in terms of statistics about the coverages of the corresponding query classes by various sources, as well as the inter-source overlap statistics. In this sense, the statistics in [FKL97] can be thought of as a post-processing factorization of the statistics learned in our framework.

matically learn such hierarchies while the existing work requires a pre-defined hierarchy. Secondly, the text database work uses a single topic hierarchy and does not have to deal with computation of overlap statistics. In contrast we deal with classes made up from the cartesian product of multiple AV hierarchies, and are also interested in overlap statistics. This makes the issue of space consumed by the statistics quite critical for us, necessitating our threshold-based approaches for controlling the resolution of the statistics.

10 Discussion and Future Directions

In this section, we will discuss some practical issues regarding the realization of the *StatMiner* approach, and outline several future directions for this work.

Large versus Frequent Classes: As we mentioned in Section 2.4, ideally we would like to measure the importance of a class in terms of the frequency of user queries to that class. This however requires that we have access to the distribution of user queries. In the absence of such information, we make the plausible assumption that the frequency with which a query class is accessed is correlated with the size of that query class.[9] Of course, if we have access to the distribution of queries, we could directly use them to learn coverage and overlap statistics in terms of "frequent" rather than "large" classes. In fact, in our more recent work [NK04], we present a complementary approach that assumes that the mediator will maintain a query list which records all the queries submitted to it, and use this real query distribution to discover frequent query classes and to learn statistics with respect to these classes. It is worth noting that even such a frequency-based approach can benefit from the "large class" assumption in the beginning stages where the mediator does not have a sufficiently large and representative query log.

Incremental Update of Statistics: Because of the dynamic nature of the sources, the coverage and overlap of the sources could change over time. We are currently developing and evaluating techniques to incrementally update statistics with respect to both the source updates and changes in the interests of the user population. In order to dynamically update the statistics with respect to the changes of the integrated sources, we propose to periodically probe all sources using the user queries and check the inconsistency between the estimated statistics and the current real coverage and overlap of the sources. If we find a large inconsistency, we relearn the statistics with respect to the corresponding query class by probing the sources using the queries subsumed by the class. To handle shifting interests of the user population, we propose to keep track of a sliding window of user queries (see previous para) and incrementally recompute the "frequent" query classes. This in turn

[9] For example, in the *BibFinder* scenario, if the number of papers for a conference is large, we assume the *BibFinder* users will be more interested in this conference than some small conferences. The reason why good conferences usually are large is that they usually exist longer. If a conference has been held for 30 years, then the number of the papers published by the conference will usually be larger than that by a conference with only several year history.

involves updating the AV-hierarchies (see Section 4).

Choosing the *StatMiner* threshold parameters: As discussed earlier, the *StatMiner* algorithms take two threshold parameters: τ_c and τ_o. Both the parameters can be set by the administrator to strike an appropriate balance between the amount of statistics remembered and the accuracy of the statistics. In the following, we summarize some guidelines for setting the parameters. The threshold τ_c is used to decide whether a query class has large enough support to be remembered. If τ_c is set to be 0, then every possible query class will be remembered. In this way we can get the most accurate coverage statistics. If τ_c is set to be 1, only the root class will be remembered. In this way all the queries will be mapped to the root class, and the coverage estimation of some queries may be very inaccurate. The administrator can select a number between 0 and 1 as τ_c according to the space available for remembering the coverage statistics and the performance tradeoffs between the additional time need for searching the statistics for a query and the time gained by using more accurate statistics to answer the query.

Another threshold τ_o is used to decide whether or not the overlap statistics between a set of sources and a remembered query class should be stored. If τ_o is set to be 0, then for each discovered large class, the overlap statistics for every source set will be remembered. If τ_o is set to be 1, then for a discovered large class, at most one source set (if all the sources are completely overlapped for the class) will be remembered. The above discussion for setting τ_c can also be applied to set the parameter τ_o.

Statistics for Handling Join Queries: In this paper, we focussed on learning learn coverage and overlap statistics of select and project queries. The techniques described in this paper can however be extended to join queries. Specifically, we consider the join queries with the same subgoal relations together. For the join queries with the same subgoal relations, we can classify them based on their bound values and use similar techniques for selection queries to learn statistics for frequent join query classes. Specifically, the following issues may have to be re-considered to support join queries:

1. Classificatory attributes selection: Instead of selecting classificatory attributes from a single relation, we will need to select attributes among all the relations in the join query;

2. Probing the sources: We can use the leaf nodes of a AV hierarchy to probe the sources of the first relation, and use the results of the first relation to probe the sources of the second relation, and so on. For each relation of the query, we use a classInfo and sourceInfo table to remember the counts of the relation. We count only the tuples that are the join results of the query. We can consider the join results as one big relation, and join query can be considered as the select and project query of this big relation.

3. Discovering large join query classes: Once we have the classificatory attributes and the join result relation, we can use the LCS algorithm to discover large classes.

4. Computing the coverage statistics for each relation: For each relation in the join query, we can compute the coverage and overlap statistics using the corresponding result relation.

Combining Coverage and Response-time Statistics: In the current paper, we assumed a simple coverage-based cost model to rank the available Websources for a query. However users may be interested in plans that are optimal w.r.t. any of a variety of possible combinations of different objectives. For example, some users may be interested in fast execution with reasonable coverage, while others may require high coverage even if with higher execution cost. Users may also be interested in plans that produce answer tuples at a steady clip (to support pipelined processing) rather than all at once at the end. In [NK01], we present the *Multi-R* query planning framework, that uses the gathered coverage and response time statistics to support multi-objective query optimization in data integration. The query planning techniques used in *Multi-R* are able to output query plans satisfying a variety of coverage and response-time tradeoffs, and still manage to keep "planning time" (i.e. search for query plans) within reasonable limits, despite the increased complexity of optimization. Our ongoing work on the *Havasu* prototype data integration system combines the *Multi-R* query planning framework and the *StatMiner* statistics learning approach to provide a comprehensive query processing methodology in the presence of Websources.

11 Conclusion

In this paper we motivated the need for automatically learning the coverage and overlap statistics of sources for efficient query processing in a data integration scenario. We then presented a set of connected techniques that estimate the coverage and overlap statistics while keeping the needed statistics tightly under control. Our specific contributions include:

- A model for supporting a hierarchical classification of the set of queries.
- An approach for estimating the coverage and overlap statistics using association rule mining techniques.
- A threshold-based modification of the mining techniques for dynamically controlling the resolution of the learned statistics.

We described the details and implementation of our approach. We also presented an empirical evaluation of the effectiveness of our approach in both controlled data sources and in the context of *BibFinder* with real online sources. Our experiments demonstrate that:

- We can systematically trade time and space consumption of the statistics computation for accuracy by varying the large class thresholds.

- The learned statistics provide tangible improvements in the source ranking, which in turn leads to improved plan precision in top-K source query plans. The improvement is proportional to the type (coverage alone vs. coverage and accuracy) and granularity of the learned statistics.

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