Data-driven optimization of search service composition for answering multi-domain queries

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ABSTRACT

Answering multi-domain queries requires the combination of knowledge from various domains. Such queries are inadequately answered by general-purpose search engines, because domain-specific systems typically exhibit sophisticated knowledge about their own fields of expertise. Moreover, multi-domain queries typically require combining in the result domain knowledge possibly coming from multiple web resources, therefore conventional crawling and indexing techniques, based on individual pages, are not adequate. In this paper we present a conceptual framework for addressing the composition of search services for solving multi-domain queries. The approach consists in building an infrastructure for search service composition that leaves within each search system the responsibility of maintaining and improving its domain knowledge, and whose main challenge is to provide the "glue" between them; such glue is expressed in the format of joins upon search service results, and for this feature we regard our approach as "data-driven". We present an overall architecture, and the work that has been done so far in the development of some of the main modules.

1. INTRODUCTION

The current evolution of the Web is characterized by an increasing availability of online services (e.g., book search services provided by online stores or libraries) and novel search facilities (e.g., flight search Web sites, provided by most commercial airlines or travel package integrators). Being specific to a restricted domain, the quality of their answers goes much beyond what can be achieved via conventional, general purpose search engines. The overall amount of data that can contribute to such queries is continuously growing, mainly within the so-called deep Web, i.e., in a form not immediately indexable by search engines.

In light of these considerations, multi-domain queries, i.e., queries that can be answered by combining knowledge from two or more domains (i.e., commercial sectors, cultural fields, and so on), no longer represent a mere academic exercise; rather, they demonstrate how intricate real life queries may be, and what a user would like to find available in order to fulfill real needs. However, we are still lacking effective query systems on the Web allowing users even to ask similar queries.

Answering multi-domain queries requires the combination of knowledge from various domains. These queries are hardly managed by general-purpose search engines, because domain-specific systems exhibit more sophisticated knowledge about their own field of expertise. Examples include expertise about cultural events, medical specializations, popular rock songs, and so on; knowledge can be contributed through social processes (e.g., rating, tagging, commenting) or through a long and careful process of knowledge construction by experts.

With the advent of service oriented architectures and the growing interest for the Web as the predominant interface for any human activity, we expect such knowledge to become more and more exposed in the form of search services. But typically a user is not only concerned with queries about a single domain; while current technological limitations confine a user to such interaction, in reality users' need for information typically spans over multiple semantically connected domains. At the current state of the art, the above needs can be answered only by patient and expert users, whose strategy is to interact with specialized services one at a time and then feed the result of one search in input to another one, reconstructing answers in their mind.

In this paper, we present a conceptual framework for addressing the composition of search services for solving multi-domain queries. Our approach consists in building an infrastructure for search service composition that leaves within each search system the responsibility of maintaining and improving its domain knowledge, and whose main challenge is to provide the glue between search service competences; such glue is expressed in the format of joins upon search service results, and for this feature we regard our approach as "data-driven". This research is carried on within "Search Computing" (SeCo), a five-year project sponsored by the ERC. We present here a preliminary vision on the constellation of problems to be solved and of software components to be developed. We give a high-level description of the approach in terms of an overall architecture, and present the work done so far in the development of some of the core models and software modules of the architecture.

We are aware that the general formulation of the search computing problem, going from registration of arbitrary services and acquisition of arbitrary queries to the production of sensible results, is very complex; many simplifying assumptions can be used to reduce the problem complexity, ranging from a preselection of the domains of interest and of the search engines, to a progressive reduction of the expressive power of the query. Ultimately, vertical solutions combining a limited number of domains, could be realized by predetermining the domains of interest and building suitable query interfaces with search fields statically associated to search domains. However, at least in this early phase of the search computing project, we like to explore the problem in its full complexity, and approach it with an experimental attitude, knowing that the most difficult tasks can be addressed in a simplified way, and yet attempting general solutions.

To overcome the difficulties of addressing a full English vocabulary and natural language understanding we resort to the use of consolidated resources, such as WordNet [8][22] and the Stanford Natural Language Parser **Error! Reference source not found.**. We attempt a *lightweight semantic approach*, which does not rely on the expressive power of domain-specific ontologies and on reasoning techniques, but instead leverages on WordNet and its functionalities for the annotation of queries, services, and domains. Given that semantics provided in this way is too limited, we add a significant amount of user's feedback and manual refinement in the definition of services, domains, and queries. Indeed, our framework, once developed in all its components, will be a very interesting testbed for tuning the level of feedback and refinement, and for measuring, at the same time, the deviation between automatic processing and processing driven by human feedback.

To better appreciate the approach, we consider a running example, consisting of the domain, service, and query analysis steps required to answer the query: *Where can I attend a DB scientific conference close to a beautiful beach reachable with cheap flights?*

2. OVERALL ARCHITECTURE AND EXECUTION FLOWS

Within the multi-domain query answering problem we identify two main activity flows: the ***registration flow*** - that deals with the declaration and description of domains, and the registration of search services and their association to domains- and the ***query execution flow*** - that deals with the actual processing of the queries. Figure 1 shows the overall architecture of the system, together with the two main execution flows.

The objects managed by the activity flows are represented by a conceptual model that describes: (1) domains and their properties (classification taxonomies and associated concepts); (2) search services (request/response interfaces with annotations for in/out parameters and response description, including functional and non functional properties); (3) high level multi-domain user queries (simplified natural language queries, composed by subqueries); (4) low-level queries (adorned conjunctive datalog queries); (5) query plans (descriptions of query execution strategies, using coarse-granularity operations which comply with access limitations and define ranking-aware strategies for building results); and (6) query execution schedules (well-defined schedules of fine-granularity operations, including service invocations, which embody the execution control flow, possibly exploiting parallelism).

In the registration flow, we address the following problems: (a) semantic representation, storage, management, and access to domains and their descriptions; (b) semantic description, storage, management, and access to search services; (c) clustering of services based on similarity; (d) mapping of services to domains; and (e) definition of admissible join conditions between services.

In the query execution flow we address the following problems: (f) definition of proper interfaces for submission of multi-domain user queries; (g) splitting of the query into subqueries; (h) mapping of subqueries to domains; (i) mapping of subqueries on given domains to associated search services, for defining low-level queries; (j) generation of query plans and therr evaluation against several cost metrics so as to choose the most promising one for execution; (k) generation and processing of query execution plans; and (l) transformation and rendering of the results for user consumption.

The next two sections describe a general architecture for addressing the multi-domain query problem, define its decomposition into sub-problems, assign each sub-problem to a component, and sketch a technical solution for developing each of them. Registration (addressed in Section 3) is performed by developers, and the framework helps them in selecting the domains and services, annotating them, and creating mappings between them. Queries are performed by users, whose feedback helps in resolving ambiguities and confirming interpretations. Query execution is addressed in Section 4.

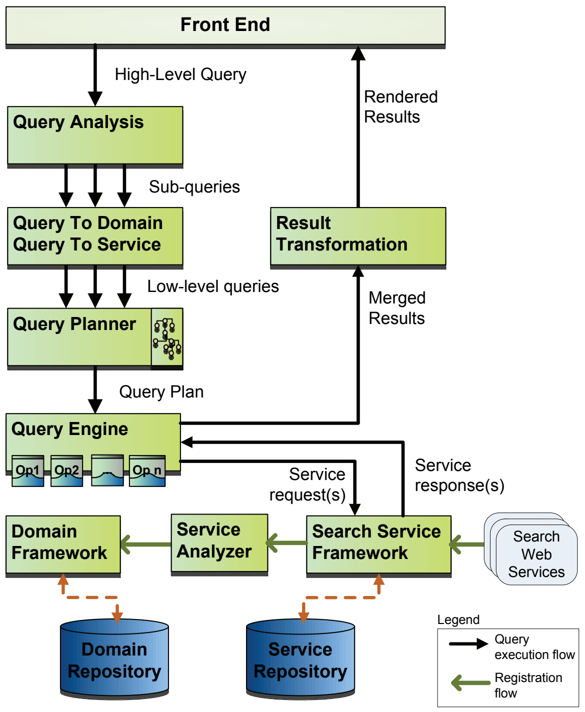

Figure 1. Overall architecture and execution flows.

3. REGISTRATION FLOW

The registration flow comprises all the activities involved in the registration of (1) domains, (2) domain descriptions, and (3) search services, addressed by the components described next.

3.1 Domain framework

The domain framework deals with domains and their definitions (1) and addresses the problems of semantic annotation, storage, management, and access to domains and their descriptions (a).

The whole infrastructure of the multi-domain search engine is based on the concept of **domain**. Intuitively, we consider a domain as a self-standing field of interest for the user, such as music, sport, arts, tourism, computer science, and so on. Every domain is associated to a distinctive **label** and associated with a bag of **Wordnet synsets**[1]; each synset can be associated with multiple domains, and such association is further characterized by a probability distribution. This allows us to characterize a domain based on the most frequently used terms for describing concepts in that domain, and viceversa to identify for each synset the list of domains it refers to. Moreover, domain definition will take advantage of *Wordnet Domains* [23], a definition of about 200 domains which have been produced in order to partition the Wordnet vocabulary and to associate each part with a specific domain of interest. One of the most interesting task in search computing is to investigate if Wordnet Domains have sufficient discrimination power to help partitioning queries and associating them to specific search engines and data sources.

The domain repository is a data structure that stores domains as described above. We assume that domains are organized as a taxonomy, representing a tree of domain-subdomain relationships. Information about the domains is made available to the other components through an API that exposes interfaces for querying and updating the domain structure (i.e., creation, deletion, and update of domain information, including associated synsets and services).

In the proposed example, domains concerning Scientific Conferences, Beaches, and Flights are required. Beach is included within a more general domain of Geographic Resource, and both Geographic Resource and Flight are found as sub-domains of Travel.

3.2 Search service framework

The search service framework defines a conceptual model of *search service* (2) and addresses the semantic annotation, storage, management, and access to search services (b). The core function performed by the framework is to enable the annotation of the request/response interface of the services. Such annotation phase uses the Wordnet vocabulary and labels each service, its operations, and the input - output parameters of each operation. In our framework, we are concerned only with those operations belonging to a Web service which perform data retrieval, and particularly in those operations that return itemized and ranked information.

The service repository exposes services in terms of operations; each operation is described by means of a set of functional or non-functional attributes. The qualifying attributes are the id, the name, the descriptor (Wordnet annotation), the serviceName (the name of the service exposing the operation), the input and output descriptors and types, the average response time and cost of interacting with the operation. In addition, several parameters describe the qualifying aspects of search services: the *ranking description* (a parameter indicating if the result is ranked), the *caching description* (an indication whether the service results can be cached, and of the validity time of cached data), the *decay description* (an indication of the decay trend of service results), the *chunking description* (an indication whether service results are returned as a single result set or by chunks, where every chunk contains a given number of result items that can be requested by means of an iteration-based interface).

[1] A Synset, or Synonym ring, is a group of data elements considered semantically equivalent for the purposes of information retrieval.

The above parameters are essential to our framework, which could be augmented with more information as in classical service repositories. According to [19], the most important QoS parameters are scalability, capacity (describing the limit of concurrent requests for guaranteed performance), performance (a measure of the speed in completing a service request), response time, latency, throughput, reliability (expressed in terms of mean time between failure and of mean time to failure), robustness, accuracy (defines the error rate produced by the service), and completeness. This information is crucial when it comes to choosing among different services and optimizing the query execution based on some cost model.

The registration process is semi-automatic: a user interacts with the service registration framework for adding a specific service. If he WSDL description is not available (e.g., because the service has a REST interface or is a wrapping of a web form), a description must be explicitly defined. The system analyzes the name of the service, of the operations and of the parameters, and tries to assign them to a domain, by associating one possible term and one possible synset in WordNet. This process is semi-automatic since it requires different interactions with the user (for example for each term the system shows to the user different possible synsets and asks him/her to choose the most appropriate). Once this phase is ended, the system automatically collects further implicit or hidden information [21].

It is important to note that, the information in a given domain could be available on the Web, but not necessarily exposed by means of a proper web service. Thus, an extension of the registration process covers the aspect of wrapping existing data sources so that the wrapper eventually exhibits some of the mentioned properties of a service – most important, offers a request-response interface and is capable of some form of aggregation, chunking, ranking, and caching of results. We aim at providing developers with tools that will make such wrapping rather easy in the classical case of web sites which are accessible through entry forms, thereby assuming that the form can provide the same information as a service request, and that the results, extracted from one or more result pages, can be structured as a set or list of result items, each described by a given number of attributes.

In the proposed example, registration of services relative to conferences may lead to integrating several services, e.g. with different choices of input and output parameters, since conferences can be searched by topic, name, place, start date, or some of these inputs in combination. One such service, relevant to our running example, could be:

```
ConfSearch(topic,nameX,placeX,dateY)
```

where topic is an input parameter, name, place and dates are output parameters, and the service and parameters are further annotated through Wordnet descriptors. Results are collections of triples of names, places, and dates, associated to a given input topic, results can be either ranked or not ranked; ranking may take into account the relative importance given by a community of users to the conference itself; the service may be characterized in terms of availability and of accuracy.

3.3 Service analyzer

The service analyzer will primarily address the following problems: the clustering of the available services, based on their similarity (c); the mapping of services to domains (d); and the definition of join connections between services (e). This part of the framework requires the other parts to be prototyped, hence it is in a very early stage.

Items (c) and (d) above require the use of clustering algorithms, such as *Lingo* [14], in order to gather together similar web services and to map them to domains on the basis of their content description.

The aim of the clustering process is the grouping of all the available web services and their probabilistic association with a set of domains. The clustering process will take advantage of the availability of synset annotations for services and their input/output parameters, and will also exploit the presence of a light weight semantic associated with registered web service in order to associate them to one of the *Wordnet Domains*. While the clustering process will be periodically performed, we also envision an incremental process of adding a service to an existing cluster. Developers will be asked to verify the correctness of the choices made by the system. In addition, they will be offered the possibility to expand the domain ontology of Wordnet Domains with other terms and relationships.

While clustering the services and associating them to domains, we will also build information about the "degree of membership" of each service to the corresponding cluster, evaluated as the cosine distance between the vectorial representation of the service in a term vectorial space, and the centroid of the cluster. This information can be seen as an expression of how much a specific service is correlated to the domain/s identified from its cluster/s of belonging. We will then see if this information can be pragmatically used in the selection of search services.

The second major task of the service analyzer is the definition of admissible join paths between services. The goal of this task is to identify, for every pair of services that can be invoked for answering a query, the join attributes that will be used for composing their results. A possible solution to this problem requires first the classification of the services within each cluster, computed on the basis of their operations interfaces (name and parameters annotations and types). In this way, for each pair of classes belonging to different domains, we can identify parameters having the same type and annotations, which are candidates for being qualified as join attributes. Then, the process of pairing services is progressively performed, with the help of developers, who can tell if the join paths identified by the system can indeed be used for connecting domains, and, if so, how elements of join paths should be paired and join conditions be fully qualified.

In the running example, the goal of this step is to identify that services such as ConfSearch (describing conferences) and Flights (defining available flights) can be connected by matching place, start and end dates of the conference and of a roundtrip flight; furthermore, the conference location is used as destination of a roundtrip from a user designated location, the starting date is used to designate the date for the first trip, and the termination date is used as return date. Finally, the flight service is identified as one associated with ranking, and specifically with a ranking criterion based on the total cost of the flight.

4. QUERY EXECUTION FLOW

4.1 Query analysis

In this section we discuss the conceptual model of high level multi-domain user queries (3) and address the problem of splitting the high-level query into subqueries (g). A high level query is the specification of an information need of a user at a high level of abstraction. We assume high level queries to be quasi-natural language descriptions of the user's need, which may require information from multiple domains. The only restriction we impose on the queries is that they must consist of a set of *noun phrases*, i.e., phrases whose head is a noun or a pronoun, optionally accompanied by modifiers (e.g., adjectives).

The query analysis component decomposes the high-level queries into sub-queries, each representing one search objective in a specific domain. As an example, a query like "Where can I attend a DB scientific conference close to a beautiful beach reachable with cheap flights?" would be split into Q1= "DB scientific conference?", Q2="Place close to a beautiful beach?", and Q3="Place reachable with a cheap flight?".

For processing the natural language query, we exploit an open source tool developed by the Stanford Natural Language Processing Group. The tool implements a probabilistic lexical parser of English natural language sentences [13]. The outcome of the parser is a tree representation of the sentences that is suitable for the problem of splitting the queries into subqueries to be assigned to different domains.

The most promising approach seems to consist in applying a first splitting of the sentence, and then assessing whether the generated subqueries map consistently to separate domains, by invoking the Query-Domain mapper. If the mapping is incoherent (e.g., several very different domains refer to the same subquery), we conjecture that the splitting may not be solid enough, and therefore we: (i) ask for feedback from the user; or (ii) try a different splitting based on cohesion of words w.r.t. domains. The final result of the splitting in (high-level) subqueries is therefore just a first step towards the mapping of subqueries to domains.

4.2 Query to domain and service mapping

This component addresses the problems of mapping subqueries to domains (h) and of mapping subqueries to associated search services, for defining low-level queries (i). The operation of mapping a query to a domain can be successful only if: (i) each subquery comprises only requests to one domain; and (ii) the words used in the subquery are unambiguous, thus allowing a crisp identification of their semantics (and therefore a correct mapping to the domains).

Several techniques can be applied to optimize the recognition of query-subquery structures which comply with the separation into distinct domains of concern so as to achieve the objective (i); these include:

- iterative invocation of the NLP tool based on defined lexical interpretation obtained from feedback from user, or feedback from other components;
- exploitation of annotations of search services or domains for assessing the correctness of the query splitting;
- syntax/logic analysis results on the sentence.

The second precondition can be satisfied by replacing all the words in the query with the correct synsets. The latter task is in general hard. We apply some heuristics for reaching the goal:

- synset domain coherence: as a first step, we try to infer the correct meaning of the word by (1) extracting all the synsets of the words used in the queries; (2) calculating the groups of synsets that better map to one domain (or to nearest domains); and (3) selecting one synset per word, according to the grouping defined before.
- user feedback: in case no final decisions can be taken in the selection of a group of synsets for the words, the user feedback is requested.

To clarify the approach, consider the following query: "rainy US states". The problem of identifying the domain of this query can be reduced to:

- identifying the synsets of the words: rainy has just one synset (ADJ: (1) showery, rainy); US has four synsets (NOUN: (2) uracil, (3) uranium, (4) U, (5) United States); state has several synsets, we report only a few here (NOUN: (6) state, province; (7) the way something is; (8) group of people comprising the government of a sovereign state; (9) state of matter).
- grouping the synsets by domain: for the example, we assume that: synset (1) is associated to the domain "weather"; synsets (2), (3), (9) are associated to "chemistry"; synsets (4), (7) are associated to "grammar"; synsets (5),(6),(8) are associated to "geography".
- selecting one synsets for each word: considering the closeness of the domains, we can infer that probably the significant synsets involved here are: (1) (5) (6/8) (related to the geographical domain, which is the correct interpretation of the sentence), or (1) (2/3) (9) (related to the chemical domain, which is not correct and indeed has a lower probability because of the high distance of (1) from (2/3/9)).
- if the probability difference between the two options is not so high, the user feedback could be requested in terms of a question like: "are you asking information about geography or chemistry?".

Once the domain is identified, analogous techniques can be applied for mapping the query to the services. The ultimate goal of this task is to match each of the identified subqueries to one or more services, so that the following processing of the query can take place according to a well-defined query execution strategy. Of course, this step is extremely difficult, and therefore users' feedback may be required at various levels, in particular regarding the query rewriting, the domain selection, and the mapping to specific services with well identified join paths connecting them.

By taking again as input the running query about conferences near to beaches, already broken down into Q1 = "DB scientific conference?", Q2 = "Place close to a beautiful beach?", and Q3 = "Place reachable with a cheap flight?", the ultimate result of such processing is the selection of services:

```
S1 = ConfSearch("DB",Title,Place,StartDate, EndDate);
S2 = PhotoSearch("Beach",Stars, PhotoID,Place);
S3 = RoundTripFlight(From,To,FromDate,ToDate,TotalTime,
                                TotalCost, RounTripID)
```

With joins pairing S1 to S2 by Place and S1 to S3 by Place=To, StartDate=FromDate, and EndDate=ToDate. Moreover, the word "cheap" indicates interest in a ranking of flights, and the word "beautiful" indicates an interest in an evaluation of the beach's beauty, that can be obtained by an indication of the "number of stars" that the beach has been given, and by linking the result to a photo of the beach so as to enable an individual evaluation. While we understand that doing all such steps dynamically, at query presentation time, and without help from the user goes beyond the current state-of-art, we envision progressive steps to achieve this result at least in part through a well-designed user interaction. We therefore anticipate a huge amount of experimentation in this component, leading us to draw conclusions concerning the practicability of the approach; of course, the complexity of this step can be arbitrarily reduced by constraining the choice of queries, domains, search systems, and their pairing through join connections.

We also designed and partially implemented a visual language, in the form of mash-up, for query plan specification that allows designers to submit low-level queries [3], thereby substituting in full steps 4.1 and 4.2.

4.3 Query planner

A *low-level query* is a conjunctive query over services. A *query plan* is a well-defined scheduling of service invocations, possibly parallelized, that complies with their access modes and exploits the ranking order in which search services return individual results to rank the global query results. The Query Planner addresses the problem (j) of generating query plans and evaluating them against a cost metric so as to choose the most promising one for execution. A preliminary version of query planner was presented in [2], while we are currently engineering an extended version.

The Query Planner accepts as input low-level queries, i.e., conjunctive queries that list the specific services to be invoked, already chosen at the Query-To-Domain Mapper. It is assumed that each such service is associated with a description in the service repository.

The originality of the model resides in introducing a simple and yet effective classification of services: *exact services* have a "relational" behavior and return either a single answer or a set of unranked answers, *search services* return a list of answers in ranking order, according to some measure of relevance.

Query plans schedule the invocations of Web services and the composition of their inputs and outputs. A plan is defined as the orchestration of service invocations, possibly in parallel, which takes into account the most significant features of the service, including its ability to chunk the results (i.e., to return a given number of answers with a single request-response). Within plans, the main operations are joins between Web service results, whose execution can take place according to several join strategies, already investigated in [1].

The Query Planner relies on the concept of access pattern, which is a sequence of access modes to the services, i.e., each service attribute is marked as either input or output. The planner progressively refines choices through the following steps:

1. Given that services may be accessed according to different patterns, the Query Planner chooses specific access patterns for each of the services involved in the query, provided that they are compatible with the query.
2. Once the access patterns are fixed, there may still be some indeterminacy on the order of invocation of the different services, some of which may be invoked in parallel. The Query Planner fixes such order.
3. The main operation for combining search services in our conjunctive setting is the join. The Query Planner selects an execution strategy for each join.

4. Optimality of execution primarily depends upon the cost and time of execution of request/responses to services. The Query Planner determines the expected number of requests associated with each service in order to obtain the desired number of results, so as to associate to each plan an execution cost.

The Query Planner searches for an optimal query plan by considering all feasible choices in the above context, yet reducing its search space by a branch-and-bound exploration that associates expected costs with every choice. A suitable cost metrics is the total execution time, but others are possible.

An example of complex query that can be considered by the optimizer is:

BestMatch(ConfTitle, Place, Stars, DateStart, DateEnd,
TotalCost, TripId, PhotoID) :-
ConfSearch("DB", ConfTitle ,Place, DateStart, DateEnd),
PhotoSearch("Beach", Stars, PhotoID, Place),
RoundTripFlight("[*InputCity*]", Place, DateStart, DateEnd,
TotalTime, TotalCost, TripID),
DateStart>[*InputPeriodStart*], DateEnd<[*InputPeriodEnd*]

This query is presented with parametric user input indicating the city and period of interest. One can think of addressing progressively more contexts in which such formalization can be used, starting from one where the query is installed and made available to users within a vertical application (e.g., offered to the university's travel agent) leaving the initial city of the user and the period description as the only variable parts of the query, up to a context where the query is dynamically presented, understood, mapped, and executed. Of course, in a fully dynamic setting, there would be no difference between the "input" values (user's city of residence and suggested period) and the other constants in the query (such as "beach" and "DB"), therefore the complete query to be considered in such case is "Where can I attend a DB scientific conference close to a beautiful beach reachable with cheap flights, starting from Milano, in the next 4 months?"; "Milano" and suitable dates would then be included in the query.

The outcome of the query planner is the selection of the access plan that minimizes the cost of interaction with the services, while producing a given expected number of results in output; results are lists of entries, ranked by the combination of low cost and high number of beach stars (which are clearly independent criteria). An example of access plan, taken from [2] for a slightly different version of this same query, is given in Figure 2. In the model:

- All service invocations are marked with an expected number of items provided in input (t^{in}) and in output (t^{out});
- Exact services (conf and weather) are represented as simple boxes, chunked services (flight and hotel) are segmented by vertical lines. The latter are also search services, marked with a grey triangle recalling the decay of the ranking of their results, the former are exact services (conf is marked with a * because it is a proliferative service, i.e. in average it returns several items in response to every input, whereas weather is a selective service which selects some of the input items; all search services are proliferative);
- The number F of subsequent invocations to be performed on each chunked service is specified;
- Join nodes are marked with a join strategy (MS stands for Merge-Scan, see [1]) and are also marked with estimations of the size of their input and their output (derived by applying the expected reduction due to the selectivity of the join predicate).

The aforementioned annotations result from the static optimization criteria applied by the query planner, and if the runtime behavior strictly matches the expected one the query will return exactly the top K results (in the example, K=15).

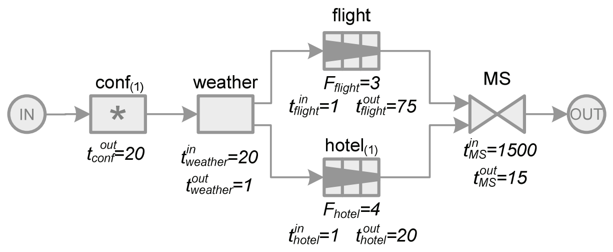

Figure 2. A fully specified query plan

While query plan designate the orchestration of several services and the methods used for their integration, we are studying more sophisticated methods for their join, including methods which guarantee the optimality of top-k result extraction. More specifically, for point 3 we recently described a join strategy suitable for the case of Web services that output data objects ranked by score, which adapts to the join of ranked services the FA method designed by Fagin [9]. The ranked lists may contain a high number of objects, typically presented in pages, and accessing such pages is costly. Moreover, objects can be accessed according to various methods, broadly classified as *sorted*, producing a very long ranked list of objects, or *attribute-based*, producing a narrower set of objects, normally not ranked, which satisfy a selection over the attributes. The query planner formulates the problem of optimal extraction of top-k combinations, whereby the optimization is performed with respect to the access costs involved with the different services and the available access methods. For the specific case of the binary join between two Web services (e.g. finding the top ranked hotel-restaurant combinations, i.e. with highest combined score, in the same city district), we devise an iterative execution strategy that, at each step, determines the way of accessing services, such that the probability of obtaining the combinations with the highest combined scores is maximized, while the overall cost of accessing the services is minimized. Such optimization strategy can be practically deployed in a search computing setting, since it requires a minimal set of parameters that characterizes the joined services, which can be obtained at the time of service registration and possibly refined during the execution of queries involving those services. These parameters include, for example, estimates of sorted and attributed-based access costs, cardinality of objects returned by the services (e.g. total number or hotels/restaurants), average number of distinct join attributes (e.g. average number of hotels/restaurant per district). We are currently working towards the extension of the aforementioned optimization strategy to the case of joins involving more than two services.

4.4 Query engine

The query engine deals with the generation and processing of query execution schedules (k); these include fine-granularity operations, like service invocations, and thus facilitate execution controls, also in the presence of parallelism. The input of this step is a query plan generated by the planner, like the one in Figure 2.

- The execution schedule is a lower level representation of the visual language that we use to specify the behavior of joins in terms of number of iterations and interleaving of fetches from the different input items. A very simple example is in Figure 3, where a Nested Loop option for the join between the results of flight and hotel is expanded into a specification in which:
- Iterators are represented by "circle" units with the specification of the iteration range (in this case, simply chunks 1-to-4 and 1-to-3 for hotel and flight respectively);
- Fetching of pages of results is represented by units with the upgoing arrow as icon;
- Dashed arrows represent the control flow in the execution, whereas regular lines represent the data flow.
- The join node represents a simple operation that applies the join predicate to the data items it gets in input in the order in which they are provided.

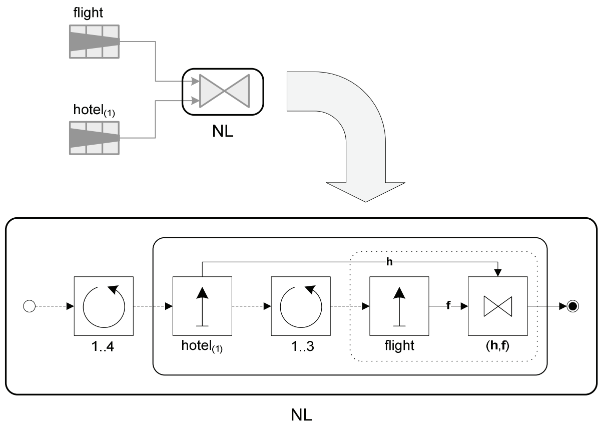

Figure 3. Unit-based specification of the Nested Loop join

At this level, the plan could include an explicit allocation of cache memory to store partial results of sub-queries and portions of pre-computed joins between the results of frequently invoked services with the most frequent inputs, as well as the specification of exploration strategies for the join search space that are not simply expressed by combination of simple iterations, but follow sophisticated methods like the FA method extension, discussed in the previous section. We are currently working on the selection of a limited number of nodes representing reusable operations and on efficient schemes for parameter passing between nodes, so as to give to the language, at the same time, high expressive power and good ability of being used for join strategy generation and testing. The results generated by the service nodes and the combinations returned by join nodes are collected in their "raw" format of tuples of values, and passed to the Result Transformation module, to be processed in order to be presented to the user.

Apart from enacting the execution and orchestrating the prescribed service invocations, it is the query engine responsibility, instead, to cope with any unexpected behavior, and apply correction policies. We are currently investigating:

- Anticipated stopping policies if the query shows to be likely to generate more than K results. Whenever a service that is "initial" in the query graph provides more results than expected, this heuristically allows for limiting the search space of the subsequent ones;
- Heuristically effective strategies to restart the computation of "completed" nodes when the query returns fewer results than expected;
- Dynamic change of the join strategy in the presence of trends in the scoring functions that clearly contradict the expected ones.

All these issues also correspond to situations in which the planning was not accurate enough, and feedback to the planner has to be provided. The optimal balance between heuristic deviations from the optimized plan and continuous feedback (which may even be pushed to halt the execution and request a new overall optimization with new parameters) is, in turn, a challenging research problem.

In order to leverage parallel execution as much as possible, invocations are all performed by different threads (normally one per node in the query plan) and results are pushed forward in a continuous way, as soon as they are available. Nodes that accept input from more than one node (all join nodes, but possibly service nodes as well) may be blocked waiting for delayed data, but his doesn't prevent other branches from proceeding with the computation. It is worth noting that this "operational semantics" ideally leads itself to be deployed on highly parallel computing infrastructures.

We will work on the deployment of execution environments which will initially support simple schedule executions, and will then be augmented to deal with exception handling and dynamicity, and finally support optimal caching, pipelining, and parallelism.

4.5 Human-computer interface

This component will address the following problems: (f) definition of proper interfaces for submission of multi-domain user queries; (k) transformation and rendering of the results for user consumption; it will deal with:

- building a interface for the user to express multi-domain queries in a facilitated way, by also providing hints about his expected semantics (e.g., personal service preferences, a priori disambiguation of terms, etc.)
- building an interface for presenting results, incorporating an explanation facility, whereby the user can drill down the result set and understand where each piece of information comes from
- enabling query refinement, whereby the user can peruse the results of past queries to better reformulate his information need (e.g., using a faceted query modality over the result set to narrow down the scope of query processing to selected services/domains, adding terms to the query to make it more precise, etc..)

5. RELATED WORK

A great deal of interest is being devoted to extending service-orientation capabilities of software systems, as testified to by current research trends [17]. Search computing is an approach meant to mark the transition towards better behaved and more reliable systems thanks to a better use of search and composition. Foreseeable extensions include, e.g., achieving better guarantees that can be given to users in the context of dynamically assembled systems, where unsatisfactory or failing services can be changed and when user's requests may vary at each time. We now propose an overview of the most closely related fields.

Web service composition provides the basis to be used in search computing to translate a user query into calls to several existing services. At the current state-of-art, composition is mostly the result of human selection, but we can envision systems that will be able to perform composition either partially or fully automatically. Research on automatic Web service compositions exploits different notions, such as functional substitutability [4], semantic annotation based on ontologies [17], and others.

Meta-search consists in a shallow-level integration of search engines working in restricted domains (e.g. searching the best fare for books or flights). Meta-search engines are Web applications that aim at integrating the results of several search engines that are queried with the same search string. The user typically submits a search request in the meta-search submission form, and the meta-search system forwards the search simultaneously to several individual search engines, whose responses are then shown together in a single result page. A comprehensive review of meta-search (discussing its qualities and limitations) can be found in [14]. Albeit related to search computing, meta-search profoundly differs from it. The set of search engines used by a meta-search system is fixed and predefined, while search computing will foster context-based dynamic selection of search engines as well as source ranking; each source is queried with the specific part of the query that is pertinent to its domain. In meta-search, results are merged with no composition, possibly after sorting based on single-domain common information (e.g., price, departure time, etc.). Search computing comprises a rich compositional framework that allows several strategies to deal with the results of multiple search engines included in a query, and supports several operations other than the simple merge. Moreover, user interaction is articulated through protocols rather than the simple result presentation.

Top-k query answering is a topic that has been addressed by a large body of recent research (see [10] for a survey). The topic is very relevant, as it shows how ranking has been managed in the simpler context of database management. Top-k queries produce results that are ordered on some computed score. Typically, these queries involve joins, where users are usually interested only in the top-k join results. Top-k queries are dominant in many emerging applications, e.g., multimedia retrieval by content, Web databases, data mining, middleware, and most information retrieval applications. The foundations of top-k queries are rooted in the simpler problem of rank aggregation, i.e., the problem of combining several ranked lists of objects in a robust way to produce a single consensus ranking of the objects [6]. Rank aggregation has resulted in a number of algorithms, such as the so-called Fagin's algorithm [5], and the threshold [7], which have been adapted to various extents to the context of top-k queries. Under suitable assumptions, some of these extensions can be proved to be *instance optimal*, in the sense that the cost incurred by their execution is the smallest possible in every database (modulo a fixed constant). Among these, we mention [9][12].

A known approach to answering queries that pursue optimality with respect to more than one criterion is that of *skyline queries*. The skyline of a set of d-dimensional points is the locus of the points that are not dominated by any other point on all dimensions. A point dominates another point if it is as good or better in all dimensions and better in at least one dimension. Skyline computation has recently received considerable attention, especially for progressive (or online) algorithms that can quickly return the first skyline points (e.g., Nearest Neighbors [11] and the IO-optimal Branch-and Bound Skyline [16]).

6. CONCLUSIONS

This paper presented a set of problems that need to be addressed when addressing multi-domain queries, an architectural view of the problems, and a sketch of the solution techniques adopted for each of them. Future works include the implementation of the different components of the architecture and their validation within a set of realistic scenarios.

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