EXTENDING FACETED SEARCH TO THE OPEN-DOMAIN WEB

A Dissertation Presented

by

WEIZE KONG

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DEDICATION

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ABSTRACT

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Faceted search enables users to navigate a multi-dimensional information space by combining keyword search with drill-down options in each facets. It has been used successfully for many vertical applications, including e-commerce and digital libraries. However, this idea is not well explored for general web search in an open-domain setting, even though it holds great potential for assisting multi-faceted queries and exploratory search.

The goal of this work is to explore this potential by extending faceted search into the open-domain web setting, which we call Faceted Web Search. We address three fundamental issues in Faceted Web Search. First, to tackle the large and heterogeneous nature of the web, we propose a query-dependent approach for facet generation, which extracts facets for queries from their web search results. We further improve our facet generation model under a more practical scenario, where users care more

about precision of presented facets than recall. Second, to incorporate user feedback on facets into document ranking, we investigate both Boolean filtering and soft ranking models. Third, we propose both intrinsic evaluation, which evaluates facet generation on its own, and extrinsic evaluation, which evaluates an entire Faceted Web Search system by its utility in assisting search clarification. We also design a method for building reusable test collections for such evaluations.

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CHAPTER 1

INTRODUCTION

There are primarily two search paradigms in use since the very beginning of web search, navigational search and direct search. Navigational search uses a hierarchy structure (taxonomy) to enable users to browse the information space by iteratively narrowing the scope of their quest in a predetermined order, as exemplified by Yahoo! Directory[1] and DMOZ[2]. Taxonomies provide a guided search interface, and support abstractions that are easily understood by users. However, the strict ordering of a taxonomy can be too rigid, especially for large and heterogeneous corpora. The rapid decline of Yahoo! Directory as a primary web search engine provides pragmatic evidence.

Direct search instead allows users to specify their own queries as input, resorts to search systems for understanding search intents behind user queries, and returns search results that could best address the search intents. This approach has been made enormously popular by web search engines, such as Google[3]. However, in the basic search interface, users have to formulate their queries with no or limited assistance, and no exploration capability since results are presented as a flat list with no systematic organization. Recent advances, including query suggestions, query auto-completion, and search result clustering address part of these problems and will be reviewed in Chapter 2.

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[1]http://en.wikipedia.org/wiki/Yahoo!_Directory

[2]http://www.dmoz.org/

[3]http://www.google.com

A third approach that combines the two search paradigms emerged during the 1990s, namely faceted search. More specifically, faceted search enables users to navigate a multi-dimensional information space by combining direct search with narrowing choices in each dimensions, which are also called facets. For example, consider looking for a computer monitor in an e-commerce site like Amazon[4]. Users can directly search with the query "*computer monitor*". However, the number of computer monitors retrieved could be overwhelming. To assist users in refining and exploring the search results, the site provides refining choices in each facets. In this case, the facets are computer monitor attributes, such as "*brand*" with the choices {"*Dell*", "*ViewSonic*", "*HP*", ...}, "*display technology*" with the choices {"*LED-Lit*", "*LCD*", ...}, and "*condition*" with the choices {"*new*", "*used*", "*refurbished*"} , as illustrated in Figure 1.1. Then users can select some of the provided choices and combine them to refine the search results. For example, users can select the choice "*new*" from the facet "*condition*" to request only computer monitors in new conditions. Users can also combine the choice "*Dell*" in the facet "*brand*" with the choice "*LCD*" in the facet "*display technology*" to request only Dell computer monitors with LCD display technology.

Compared with direct search, faceted search provides additional search assistance for users. The facts provided in faceted search can assist users in clarifying their search intent and refining the search results, as already illustrated in the computer monitor example above. In addition, faceted search supports guided exploration over the complex information space. In the computer monitor example above, without the provided facets, users might have no clue about how to explore the large amount of returned results. By listing computer monitor attributes as facets, the site gives users an overview of the returned results, and provides them with the key factors they may need to consider when searching for a computer monitor. In other words, using facets,

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[4]http://www.amazon.com
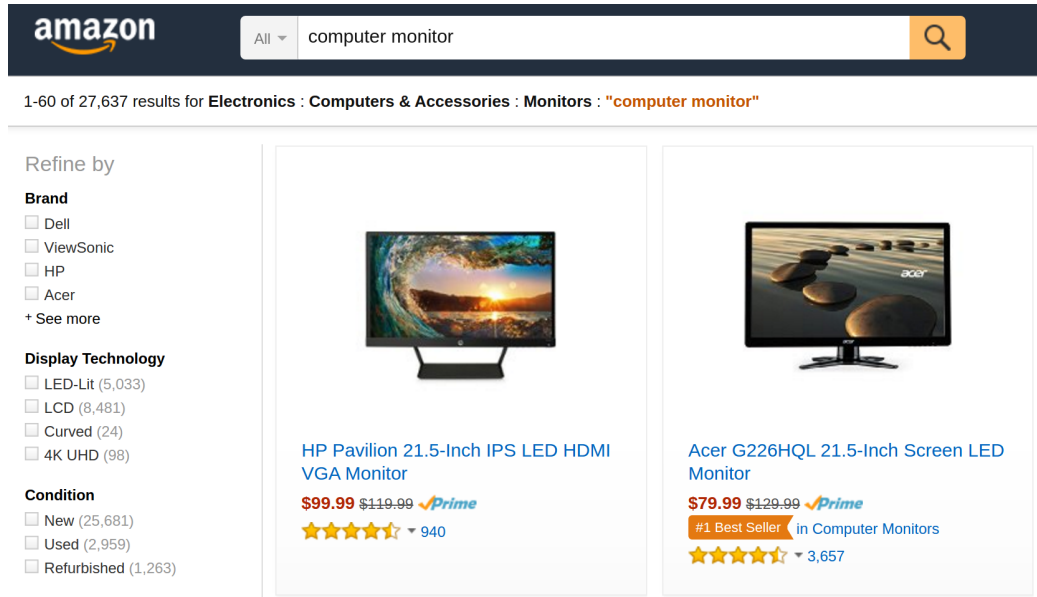
Figure 1.1: Faceted search illustrated by an example searching "computer monitor" in Amazon. The search interface shown has been simplified for the convenience of illustration.

the site summarizes the search space succinctly, and provides exploration suggestions organized in an systematic way. This exploration capability is especially important in exploratory search tasks, or when users are not exactly clear about what they are looking for.

Compared with navigational search, faceted search is different not only in its direct search capability, but also in its navigation mechanism. Navigation in navigational search is typically based on one single taxonomy that organizes information objects in a hierarchy structure. The key property of such a taxonomy is that, for every object in the taxonomy, there is precisely one unique path to it from the taxonomy root. For example, "*cancer*" can be classified in a taxonomy with a unique path "*disease*"→"*structural disease*"→"*tumor*"→"*cancer*". However, this strict ordering of a taxonomy can be too rigid when dealing with compound information objects. For example, should "*treatment of cancer*" be a child of "*treatment*" or of "*cancer*"? This strict ordering constraint limits expressibility and extensibility of taxonomy.

Instead, in faceted search, navigation is based on multiple independent taxonomies, called faceted taxonomies or multi-dimensional taxonomies. Each of the taxonomies organizes information objects from a different (preferably orthogonal) point of view, or equivalently in a different dimension of the multi-dimensional information space. The independent taxonomies in a faceted taxonomy can also be called "*facets*". However, "*facets*" are often used to indicate the part of independent taxonomies that are shown to users, and in many cases the taxonomies are often shown as shallow trees. In the computer monitor example above, the facets show only two-level taxonomies (*e.g.*, node "*Brand*" with children "*Dell*", "*ViewSonic*", etc.). We will provide a more detailed explanation of facets and related concepts in Chapter 2.

Combining these independent taxonomies, faceted taxonomies offers expressive power and flexibility beyond single taxonomy used in navigational search. In *Classification, Coding, and Machinery for Search*, Ranganathan (1950) provides an example that expresses the topic "*statistical study of the treatment of cancer of the soft palate by radium*" based on four constituent taxonomies in a faceted taxonomy as follows.

- Medicine $\rightarrow$ Digestive system $\rightarrow$ Mouth $\rightarrow$ Palate $\rightarrow$ Soft palate

- Disease $\rightarrow$ Structural disease $\rightarrow$ Tumor $\rightarrow$ Cancer

- Treatment $\rightarrow$ Treatment by chemical substances $\rightarrow$ Treatment by a chemical element $\rightarrow$ Treatment by a group 2 chemical element $\rightarrow$ Treatment by radium

- Mathematical study $\rightarrow$ Algebraical study $\rightarrow$ Statistical study

In the example, the four taxonomies ("*Medicine*", "*Disease*", "*Treatment*" and "*Mathematical study*") each represents one dimension of the information space. The foci in each of the taxonomies ("*Soft palate*", "*Cancer*", "*Treatment by radium*" and "*Statistical study*") are combined to express the compound topic, which is difficult in a single hierarchical taxonomy.

In summary, faceted search combines direct search with navigation based on a faceted taxonomy, providing assistance for users in clarifying search intent and exploration over a multi-dimensional information space. It has also been used successfully for many vertical applications, such as e-commerce and digital libraries.

1.1 Motivation for Faceted Web Search

While the principles of faceted taxonomy are widely applicable, faceted search has not been explored much for general web search in an open-domain setting. There is lots of work studying faceted search in fixed domain such as images (Cutrell et al., 2006), movies (Koren et al., 2008), houses (Shneiderman, 1994), and desktop content (Cutrell et al., 2006). However, there is limited work in successfully extending faceted search to the open-domain, due to the challenges of the large and heterogeneous nature of the web (Teevan et al., 2008).

Nevertheless, faceted search naturally suits and holds great potential for assisting multi-faceted queries and exploratory search in the open-domain web setting. We illustrate the idea with four example queries and their facets manually created in Table 1.1. For the first query "*baggage allowance*", the facet of different airlines (facet 1) can assist users to quickly compare baggage policies between different airlines. Users can also use other facets, such as flight types, flight classes and specifications to clarify this multi-faceted query. For the second query, "*Mars landing*", the facets list important information for exploring this topic, including Mars rovers (facet 1) and countries relevant to Mars landing (facet 2). Users can also combine multiple facets for search intent clarification (e.g., select "*Curiosity*" from facet 1 and "*pictures*" from facet 3 to find pictures of Mars rover Curiosity). The last query shows that faceted search is not limited to short queries. The facets succinctly summarize interesting aspects for the complex query "*Effect of building the three gorges dam in China*", including different types of effect (facet 1), related nature disasters (facet 2) and

different regions of the river (facet 3). This information could help users to learn and explore this topic.

Table 1.1: Examples facets for three web search queries.

Query 1: baggage allowance
Facet 1: AA, Delta, Jetblue, ...
Facet 2: international, domestic
Facet 3: first class, business class, economy class
Facet 4: weight, size, quantity
Query 2: Mars landing
Facet 1: Curiosity, Opportunity, Spirit
Facet 2: USA, UK, Soviet Union
Facet 3: video, pictures, news
Query 3: Effect of building the three gorges dam in China
Facet 1: environmental, social, economic
Facet 2: landslides, soil erosion, earthquake
Facet 3: lower, middle, upper

Faceted search when extended to the open-domain web setting can have several advantages over other related techniques developed for faceted queries or exploratory search. Search result diversification has been studied as a method of tackling ambiguous or multi-faceted queries while a ranked list of documents remains the primary output feature of web search engine today (Agrawal et al., 2009; Clarke et al., 2008; Santos et al., 2010; Sakai and Song, 2011; Dang and Croft, 2013). The purpose is to diversify the ranked list to account for different search intents or query subtopics. However, the query subtopics are hidden from the user, leaving him or her to guess at how the results are organized. Faceted search addresses this problem by explicitly presenting different facets for the search topic.

Search results clustering or organization is a technique that tries to organize search results by grouping them into clusters (Carpineto et al., 2009) or organizing them in a single hierarchical taxonomy (Lawrie et al., 2001; Lawrie and Croft, 2003; Nevill-Manning et al., 1999), very much like in navigational search. This offers a complementary view to the flat ranked list of search results. However, single taxonomies or

fixed clusters, as mentioned before, impose strict taxonomic ordering for the search results. Instead, faceted search allows users to explore the search space from multiple facets, offering flexibility beyond search results clustering or organization.

Query suggestion (Baeza-Yates et al., 2004; Cao et al., 2008) is a technique that generates alternative queries for users to helps them explore or express their information need. This technique is now widely used in commerce web search engine. However, the suggested queries are often provided in a flat list with no systematic organization and no capability of combining multiple suggestions. Instead, "suggestions" in faceted search are organized systematically into facets, which makes it conceptually easier to browse and select.

1.2 Faceted Web Search

In this thesis, we extend faceted search into the open-domain web setting, which we call Faceted Web Search (FWS). Similar to conventional faceted search, a FWS system will provide facets when a user issues a web search query. The user can then select some choices from the facets, which will be used by the FWS system to adjust the search results to better address the user's information need.

We illustrate the idea of FWS in Figure 1.2, supposing a user is preparing for an international flight and wants to find baggage allowance information. When the user searches "baggage allowance" in an FWS system (step 1 in the figure), in addition to the search result list (step 2), the system will provide a list of facets (step 3), such as a facet for different airlines, {*Delta, JetBlue, AA, ...*}, a facet for different flight types, {*domestic, international*}, and a facet for different classes, {*first, business, economy*}. When the user selects choices such as "Delta", "international" and "economy" in these facets (step 4), the system can ideally help to bring web documents that provide baggage allowance information for the economy class of Delta international flights to the top of the search results (step 5).
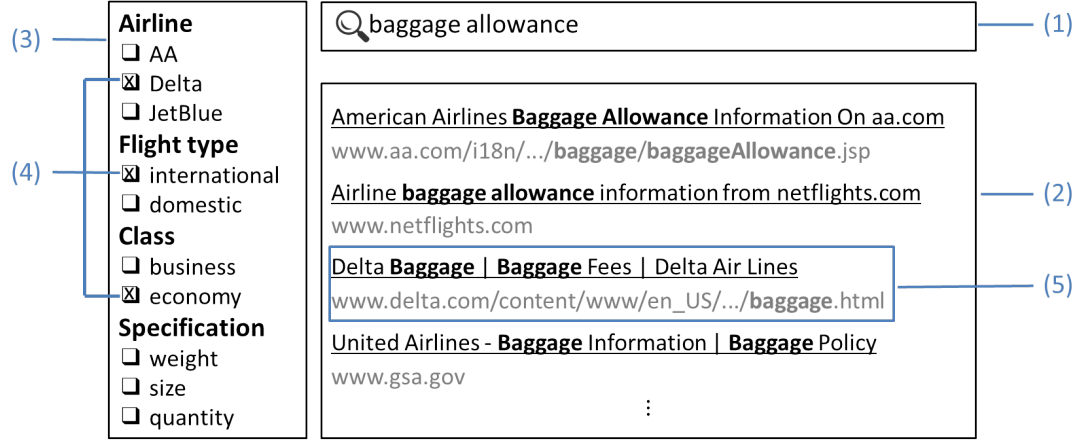
Figure 1.2: An example case of Faceted Web Search: (1) the user issues a query; (2) the system returns search results; (3) the system provides facets for the query; (4) the user selects terms in the facets; (5) the system re-ranks this relevant document to the top according to the selected terms.

This thesis address three fundamental issues of Faceted Web Search, including facet generation, facet feedback, and evaluation, as described further as follows.

1.2.1 Facet Generation

Facet generation is to identify facets for navigation (corresponding to step 3 in Figure 1.2). In conventional faceted search, facets are typically generated in advance for an entire corpus (Stoica and Hearst, 2007; Dakka and Ipeirotis, 2008) either manually or semi-automatically, and then recommended for particular queries. However, this approach is difficult to extend to the entire web due to the web's large and heterogeneous nature (Teevan et al., 2008). We instead propose a query-dependent approach, which extracts facets for a query from its search results, providing a promising direction for solving the problem.

We call the extracted items "query facets", defined as a set of coordinate terms (*e.g.*, {"*AA*", "*Delta*", "*JetBlue*",...}) that explicitly represent one facet (*e.g.*, "*airlines*") of the query (*e.g.*, "*baggage allowance*"). The coordinate terms share a semantic relationship by being grouped under a more general hypernym ("is a" relationship,

e.g., "*AA*", "*Delt*", "*JetBlue*" are all "*airlines*"). More examples for query facets are shown in Table 1.1. This definition of query facets corresponds to one-level taxonomies in faceted taxonomy, in which only information objects that belong to a same parent node are shown as a facet. We leave generating facets as two- or more level taxonomies as future work.

Because it is an automatic task, facet generation in FWS can be imperfect. The system can make mistakes in both precision and recall for generating facets. As in many precision-oriented information retrieval tasks, we believe users are likely to care more about "facet precision" than "facet recall". That is, users may care more about the correctness of presented facets (*e.g.*, are the terms in the airline facet indeed about airlines, and are the airline terms grouped together in a same facet) than the completeness of facets (*e.g.*, are all possible facets for that query presented, and are all possible airline terms included the results?). In other words, mistakes of presenting wrong terms in a facet, or grouping terms incorrectly are more severe than omitting some facets or terms in facets. Thus, we also study how to improve facet generation performance under precision-oriented scenarios, in order to make the technique more practical.

1.2.2 Facet Feedback

Facet feedback is to use selections on the facets to adjust (*e.g.*, filter or re-rank) the search results (corresponds to step 5 in Figure 1.2). In conventional faceted search, facet feedback is straightforward: as all information objects have been classified in the faceted taxonomy, when users make their selections on the facets, the search results can be easily filtered by requiring each objects belong to the restricted taxonomies according to the selection.

However, in FWS there is no explicit classification of webpages into the generated facets. One solution is Boolean filtering, which filters search results by the requiring

selected terms to appear. However, it turns out to be too strict when extended to the open-domain setting. Boolean filtering is based on two assumptions (Zhang and Zhang, 2010): (1) users are clear about what they are looking for, and thus are able to select proper terms to restrict the results; and (2) matching between a term and a document is accurate and complete. In FWS, that means a document that contains the selected term should be relevant to the term, and all documents relevant to that selected term should contain the term. Neither of the two assumptions are likely to hold reliably in FWS. Thus, we also investigate soft ranking models that expand original queries with user selection on the facets.

1.2.3 Evaluation

Evaluation for conventional faceted search mostly focuses on its user interface (Burke et al., 1996; English et al., 2002; Hearst, 2006, 2008; Kules et al., 2009). For FWS, there can be two types of evaluation according to the different focuses, namely intrinsic and extrinsic evaluation. Intrinsic evaluation only considers facet generation (i.e., the quality of generated facets). Extrinsic evaluation instead evaluates the effectiveness of the entire FWS system, combining both the facet generation and facet feedback components. We study both of them.

Most of the previous evaluations for faceted search are based on user studies (Dash et al., 2008; Li et al., 2010; Stoica and Hearst, 2007). However, user studies are often very expensive and more importantly difficult to extend for evaluating new systems. We instead use evaluation methods with higher reusability for both intrinsic and extrinsic evaluation.

In the following, we highlight the contributions of this thesis.

1.3 Contributions

- Faceted Web Search. We define Faceted Web Search, which extends faceted search into an open-domain web setting. We design a framework for an FWS system, which contains the facet generation and facet feedback components. We show that using this faceted search interface can significantly improve the original ranking if allowed sufficient time for user feedback: 18.0% in NDCG@10 if we allow users to examine 50 terms in facets, and 7.4% in NDCG@10 if we allow time for examining 10 terms.

- Query facet extraction. To cope with the large and heterogeneous nature of the web in facet generation, we develop a query-dependent approach, which generates facets for a query instead of the entire corpus. This query facet generation approach extracts facets from the top search results for the issued query. This not only makes the generation problem easier, but also addresses the facet recommendation problem at the same time. For query facet extraction, we develop a supervised approach based on a graphical model to recognize facets from the noisy candidates found. The graphical model learns how likely a candidate term is to be a facet term as well as how likely two terms are to be grouped together in a query facet, and captures the dependencies between the two factors. We propose two algorithms (QFI and QFJ) for approximate inference on the graphical model since exact inference is intractable. Compared with other existing methods, our models can easily incorporate a rich set of features, and learn for available labeled data.

- Intrinsic evaluation. We evaluate the quality of generated facets by comparing them with human-created ones. This can be measured from three aspects – precision and recall of extracted terms for facets, and the clustering quality of these facet terms. We design $PRF_{\alpha,\beta}$, a measure to combine three evaluation

factors together using weighted harmonic mean. This metric has the flexibility to adjust emphasis between the three factors for different applications. Experimental results based on this intrinsic evaluation show that our supervised methods (QFI and QFJ), can take advantage of a richer set of features and outperform other unsupervised methods, such as pLSA, LDA, and a variant of quality threshold clustering model (Dou et al., 2011).

- Precision-oriented query facet extraction. We improve query facet extraction performance under precision-oriented scenarios from two perspectives. First, we find that the likelihood objective used in the query facet extraction model can be loosely related to the performance measure in the precision-oriented scenario. Therefore, we directly optimize the performance measure instead of likelihood during training using a empirical utility maximization approach. However, exact optimization on the performance measure is difficult due to the non-continuous and non-differentiable nature of information retrieval measures. We address this problem by approximating the performance measure using its expectation. We show that this empirical utility maximization approach significantly improves over the models under precision-oriented scenarios, suggesting utility is a better learning objective than likelihood, and that our expectation-based approximation is effective.

- Second, we improve extraction performance by a selective method that shows facets for good performing queries and avoids doing so for poor performing ones. We find that extraction performance varies for different queries – some queries are naturally more difficult than others for extracting query facets. In the precision-oriented scenario, it may be more desirable to avoid showing facets for those poor performing queries and leave the users with a clean keyword-search interface. A key problem, however, is how to predict the extraction

performance. To solve this problem, we develop a simple and effective score based on the expectation of the performance measure. We find the score has a strong correlation with the performance measure, and when used in the selective method, it can significantly improve the average performance with fair coverage over the whole query set.

- Facet feedback. We find that Boolean filtering models are too strict for FWS, and propose soft ranking models that expand original queries with user selected terms for re-ranking. We show that the proposed soft ranking models are more effective than Boolean filtering models, which are widely used in conventional faceted search.

- Extrinsic evaluation. We develop an extrinsic evaluation method that evaluates FWS systems by their utility in assisting search clarification. This evaluation considers both gain in ranking improvement and cost in time for users to give feedback. Instead of performing user studies, we simulate the user feedback process, so that we can easily extend the evaluation for new models or systems. The simulation is based on a simple user model of the feedback process and limited human annotations.

- Building a reusable test collection. We describe a way of building reusable test collections for the intrinsic and extrinsic evaluation. We make our collected data set publicly available. The data set consists of annotated facets for 196 TREC Web Track queries from 2009 to 2012, and simulated user feedback for 678 corresponding query subtopics.

1.4   Outline

The remainder of this thesis is organized as follows. In Chapter 2, we provide background information related to this thesis. In Chapter 3, we present our query

facet extraction approach. In Chapter 4, we present our intrinsic evaluation that evaluates generated facets by comparing them with human-created ones. In Chapter 5, we investigate query facet extraction models under precision-oriented scenarios, and improve our models in such scenarios. In Chapter 6, we investigate both Boolean filtering and soft ranking models for facet feedback. In Chapter 7, we develop our extrinsic evaluation method that evaluates entire Faceted Web Search systems in terms of their utility in assisting search in an interactive search task. Lastly, in Chapter 8, we summarize the contributions made in this thesis and discuss potential future directions for more research in this area.

CHAPTER 2

BACKGROUND

In this chapter, we discuss background information and related work for Facet Search. We will provide additional related work for Faceted Web Search in each individual chapters when necessary.

2.1 Faceted Search

As faceted search is a heavily interdisciplinary topic, before introducing faceted search, we first provide necessary background information for it.

2.1.1 Direct Search and Navigational Search

Faceted search combines two search paradigms, direct search and navigational search. **Navigational search** (sometimes also called "*directory navigation*") uses a hierarchy structure to enable users to browse the information space by iteratively narrowing the scope of their quest in a predetermined order, as exemplified by Yahoo! Directory[1] and DMOZ[2]. Navigational search provides a guided search interface, and supports abstractions that are easily understood by users. However, the strict ordering imposed by the hierarchy structure can be too rigid, especially for large and heterogeneous corpora. The rapid decline of Yahoo! Directory as a primary web search engine provides pragmatic evidence.

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[1]http://en.wikipedia.org/wiki/Yahoo!_Directory

[2]http://www.dmoz.org/

Direct search instead allows users to specify their own queries as input. The queries are often keywords in web search scenarios, and thus, sometimes direct search is also called "*keyword search*". Direct search resorts to search systems for understanding search intents behind user queries, and returns search results that could best address the search intents. This approach has been made enormously popular by web search engines, such as Google[3]. However, in the basic search interface, users have to formulate their queries with no or limited assistance, and no exploration capability since results are presented as a flat list with no systematic organization. We discuss recent advances for addressing this problem in Section 2.2.

2.1.2 Taxonomy and Faceted Taxonomy

There are two types of information representation (or knowledge representation) related to this work, taxonomies and faceted taxonomies. A **taxonomy** is an organization of information objects or abstractions into a hierarchy or tree structure. Navigational search as described above is based on taxonomies. So we have seen two examples of taxonomies, Yahoo! Directory and the Open Directory Project. Taxonomy enables efficient navigation in the information space. Users start from the root node and iteratively discriminates among children, in order to find the appropriate one. Each time a node is selected for expansion, the total number of objects to be considered is reduced because the objects classified under discarded concepts need not be considered. Thus, users iteratively reduces the number of information objects to be manually inspected. (Sacco and Tzitzikas, 2009)

The key property of a taxonomy is that, for every information object or set of objects that corresponds to a node, there is precisely one unique path to it from the root node. Thus, a taxonomy imposes a strict logical ordering on the information that it represents (Tunkelang, 2009). For example, "*cancer*" can be classified in a

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[3]http://www.google.com

taxonomy with a unique path "*disease*"→"*structural disease*"→"*tumor*"→"*cancer*". However, this strict ordering of a taxonomy can be too rigid when dealing with compound information objects. For example, should "*treatment of cancer*" be a child of "*treatment*" or of "*cancer*"? This strict ordering constraint limits expressibility and extensibility of taxonomy.

Faceted search is based on another type of information representation, called faceted taxonomy (it is sometimes called multi-dimensional taxonomy (Sacco and Tzitzikas, 2009) or faceted classification (Tunkelang, 2009)). A **faceted taxonomy** is a set of independent taxonomies with each one organizes information objects from a different (preferably orthogonal) point of view, or equivalently base on a different dimension of the multi-dimensional information space. In *Classification, Coding, and Machinery for Search*, Ranganathan (1950) provides four constituent taxonomies in a faceted taxonomy, which are combined to expresses the topic "*statistical study of the treatment of cancer of the soft palate by radium*", as follows.

- Medicine → Digestive system → Mouth → Palate → Soft palate

- Disease → Structural disease → Tumor → Cancer

- Treatment → Treatment by chemical substances → Treatment by a chemical element → Treatment by a group 2 chemical element → Treatment by radium

- Mathematical study → Algebraical study → Statistical study

In the example, the four taxonomies ("*Medicine*", "*Disease*", "*Treatment*" and "*Mathematical study*") each represents one dimension of the information space. The foci in each of the taxonomies ("*Soft palate*", "*Cancer*", "*Treatment by radium*" and "*Statistical study*") are combined to express the compound topic, which is difficult in a single hierarchical taxonomy. Combining these independent taxonomies, faceted taxonomies offers expressive power and flexibility beyond single taxonomy used in navigational search.

From the example, we can also see that faceted taxonomy enables navigation over a multi-dimensional information, which is called **faceted navigation**. In faceted navigation, users can select multiple taxonomies for navigation. They can narrow the search space by iteratively select child nodes in each of taxonomies. Then the selections on the taxonomy are combined to restrict the matched information objects, as also illustrated in Ranganathan's example.

2.1.3 Facets

The term "*facet*" means "little face" and is often used to describe one side of a many-sided object, especially a cut gemstone (Teevan et al., 2008). In information science literature, "*facet*" is a overloaded term. The term has been used to refer both to the entire independent taxonomies in a faceted taxonomy, and to the part of independent taxonomies that are shown to users (as in most of our discussion). In many cases the taxonomies are often shown as shallow or two-level trees. In the computer monitor example in Figure 1.1, the facets are two-level (*e.g.*, parent node "*Brand*" with child nodes "*Dell*", "*ViewSonic*", etc.). We call the parent node (or more precisely, its presentation term) **facet label** (*e.g.*, "*brand*"), and the child nodes **facet terms** (*e.g.*, "*Dell*", "*ViewSonic*"). For the one-level case, a facet is consisted by only the facet terms (*e.g.*, {"*Dell*", "*ViewSonic*", "*HP*", ...}) with no facet label.

2.1.4 What is Faceted Search

Faceted Search combines direct search with faceted navigation, which enables users to navigate a multi-dimensional information space. We have provide an example in Figure 1.1. In the example, a user search with the query "*computer monitor*" in an e-commercial site, and the site provide two-level facet "*brand*", "*display technology*" and "*condition*".

Compared with direct search, faceted search provides additional search assistance for users through facets. Facets can assist users in clarifying their search intent

and refining the search results (*e.g.*, select "*new*" in facet "*condition*" to find only computer monitors in new conditions). Facets also summarizes the search space succinctly, and provides exploration suggestions organized in an systematic way (*e.g.*, the listed facet "*brand*", "*display technology*", "*condition*" give users an overview of the returned results, and provides them with the key factors they may need to consider when searching for a computer monitor). This exploration capability is especially important in exploratory search tasks, or when users are not exactly clear about what they are looking for.

Compared with navigational search, faceted search supports faceted navigation, which is especially useful for navigating a multi-faceted information space. In navigational search, the strict ordering imposed by a taxonomy is too rigid when dealing with compound information objects in the multi-faceted information space. Instead, in faceted search, users can combine facets to express complex information need (*e.g.*, "*statistical study of the treatment of cancer of the soft palate by radium*" in Ranganathan's example).

2.1.5 Automatic Facet Generation

Previous work on faceted search has studied automatic facet generation (Dakka and Ipeirotis, 2008; Li et al., 2010; Stoica and Hearst, 2007; Oren et al., 2006; Kohlschütter et al., 2006; Latha et al., 2010) and facet recommendation for a query (Dash et al., 2008; Koren et al., 2008). Most of the work is based on existing facet metadata or taxonomies, and extending faceted search to the general web is still an unsolved problem. The challenges stem from the large and heterogeneous nature of the web (Teevan et al., 2008): because the web is very large, it is difficult to assign quality facets to every document in the collection and to retrieve the full set of search results and their associated facets at query time; and because the web is heterogeneous, it is difficult to apply the same facets to every search result or every query.

2.1.6   Evaluation for Faceted Search

Most evaluations for facet generation/recommendation are either based on comparison between system generated and human created facets (Dakka and Ipeirotis, 2008; Dou et al., 2011) or user studies (Dash et al., 2008; Li et al., 2010; Stoica and Hearst, 2007). However, the former may not exactly reflect the utility in assisting users' search tasks, and the latter is expensive to extend for evaluating new systems. In a similar spirit to ours, some work (Schuth and Marx, 2011; Zhang and Zhang, 2010; Koren et al., 2008) also evaluates facets by their utility in re-ranking documents for users. The differences are their evaluation methods do not capture the time cost for users as explicitly as we do, and their experiments are based on corpora with human created facet metadata. Other evaluations (Burke et al., 1996; English et al., 2002; Hearst, 2006, 2008; Kules et al., 2009) for faceted search are mostly done from a user interface perspective, which is beyond the scope of this proposal.

2.2   Other Related Techniques

2.2.1   Query Subtopic/Aspect Mining

To address multi-faceted queries, much previous work studied mining query subtopics (or aspects). A query subtopic is often defined as a distinct information need relevant to the original query. It can be represented as a set of terms that together describe the distinct information need (Wang et al., 2009; Wu et al., 2011; Dang et al., 2011) or as a single keyword that succinctly describes the topic (Song et al., 2011). Different resources have been used for mining query subtopics, including query logs (Wang and Zhai, 2007; Hu et al., 2012; Xue and Yin, 2011; Wang et al., 2009; Wu et al., 2011; Yin and Shah, 2010), document corpus (Allan and Raghavan, 2002) and anchor texts (Dang et al., 2011).

Query subtopics and facets for a query are different in that the terms in a query subtopic are not restricted to be coordinate terms, or have peer relationships. Facets

for a query, however, organize terms by grouping "sibling" terms together. For example, {*news, cnn, latest news, mars curiosity news*} is a valid query subtopic for the query *mars landing*, which describes the search intent of Mars landing news, but it is not a valid facet. Instead, a valid facet that describes Mars landing news could be {*cnn, abc, fox*}, which includes different news channels.

2.2.2 Semantic Class Extraction

Semantic class extraction is to automatically mine semantic classes represented as their class instances from certain data corpora. For example, it may extract *USA*, *UK*, *China* as class instances of semantic class *country*. Due to the similar semantic relationships between terms inside a facet and a semantic class, semantic class extraction can be used for facet generation. Existing approaches can be roughly divided into two categories: distributional similarity and pattern-based (Shi et al., 2010). The distributional similarity approach is based on the distributional hypothesis (Harris, 1954), that terms occurring in analogous contexts tend to be similar. Different types of contexts have been studied for this problem, including syntactic context (Pantel and Lin, 2002) and lexical context (Pantel et al., 2004; Agirre et al., 2009; Pantel et al., 2009). The pattern-based approach applied textual patterns (Hearst, 1992; Pasca, 2004), HTML patterns (Shinzato and Torisawa, 2007) or both (Zhang et al., 2009; Shi et al., 2010) to extract instances of a semantic class from some corpus. The raw semantic class extracted can be noisy. To address this problem, Zhang et al. (2009) used topic modeling to refine the extracted semantic classes. Their assumption is that, like documents in the conventional setting, raw semantic classes are generated by a mixture of hidden semantic classes. In this work, we apply pattern-based semantic class extraction on the top-ranked Web documents to extract candidates for query facet generation.

2.2.3 Search Results Diversification

Search result diversification has been studied as a method of tackling ambiguous or multi-faceted queries while a ranked list of documents remains the primary output feature of Web search engine today (Agrawal et al., 2009; Clarke et al., 2008; Santos et al., 2010; Sakai and Song, 2011; Dang and Croft, 2013). The purpose is to diversify the ranked list to account for different search intents or query subtopics. A weakness of search result diversification is that the query subtopics are hidden from the user, leaving him or her to guess at how the results are organized. FWS addresses this problem by explicitly presenting different facets of a query using groups of coordinate terms for users to select.

2.2.4 Search Result Clustering/Organization

Search results clustering is a technique that tries to organize search results by grouping them into, usually labeled, clusters by query subtopics (Carpineto et al., 2009). It offers a complementary view to the flat ranked list of search results. Most previous work exploited different textual features extracted from the input texts and applied different clustering algorithms with them.

Instead of organizing search results in groups, there is also some work (Lawrie et al., 2001; Lawrie and Croft, 2003; Nevill-Manning et al., 1999) that summarizes search results or a collection of documents in a topic hierarchy. For example, previous studies (Lawrie et al., 2001; Lawrie and Croft, 2003) used a probabilistic model for creating topical hierarchies, in which a graph is constructed based on conditional probabilities of words, and the topic words are found by approximately maximizing the predictive power and coverage of the vocabulary.

FWS is different from these work in that it provides facets of a query, instead of directly organizing the search results. The facet interface allows users to filter/re-rank search results from multiple aspects, instead of a single, taxonomic order.

2.3   Summary

Faceted web search (FWS) we propose in this work is different from all the past work. It extends conventional faceted search from a commonly fixed-domain setting to an open-domain web setting. It is different from search result diversification in that instead of hiding those query subtopics from users, it explicitly presents different facets of a query. It is also different from search results clustering or organization in that instead of directly organizing the search results, the facet interface in FWS allows users to filter/re-rank search results from multiple aspects.

We study three main issues of FWS that have not been explored in previous work, including facet generation, facet feedback and evaluation for FWS. Facet generation for FWS is different from query subtopic mining due to the different nature of query subtopics and facets. It is also different from semantic class extraction in that it targets a general web query instead of a semantic class. Facet feedback for FWS is different from other user feedback due to their different purposes. Facet feedback targets at improving ranking with respect to the "query subtopic" specified by the feedback terms, instead of the query topic represented by the original query. Our evaluation for FWS is also different from previous ones for faceted search. We consider many different aspects (e.g., cost and gain), and the evaluation is based on simulations instead of user studies, which makes it relative cheap to extend for new systems.

CHAPTER 3
QUERY FACET EXTRACTION

3.1 Introduction

In conventional faceted search, facets are typically generated in advance for an entire corpus (Stoica and Hearst, 2007; Dakka and Ipeirotis, 2008) either manually or semi-automatically, and then recommended for particular queries. However, this approach is difficult to extend to faceted web search due to the large and heterogeneous nature of the web (Teevan et al., 2008): because the web is very large, it is difficult to assign quality facets to every document in the collection and to retrieve the full set of search results and their associated facets at query time; and because the web is heterogeneous, it is difficult to apply the same facets to every search result or every query.

To cope with this challenge, in this chapter, we propose an alternative solution, called **query facet extraction**, which extracts facets for queries from their web search results. For example, when users search with the query "*baggage allowance*", the system might extract query facets like airlines, {"*Delta*", "*JetBlue*", "*AA*", ...}, travel classes, {"*first*", "*business*", "*economy*"}, and flight types, {"*international*", "*domestic*"}. Changing from a global approach that generates facets in advance for an entire corpus to a query-based approach that extract facets from the top-ranked search results, query facet extraction appears to be a promising direction for solving the open-domain faceted search problem – it not only make the facet generation problem easier, but also addresses the facet recommendation problem at the same time.

We define a **query facet** as a set of coordinate terms (*e.g.*, {"*AA*", "*Delta*", "*Jet-Blue*",...}) that explicitly represent one aspect (*e.g.*, "*airlines*") of its query (*e.g.*, "*baggage allowance*"). The coordinate terms share a semantic relationship by being grouped under a more general hypernym ("is a" relationship, *e.g.*, "*AA*", "*Delt*", "*Jet-Blue*" are all "*airlines*"). In Table 3.1, we show query facets for three example queries. We will using the first query "*Mars landing*" as example for explanation. For the first query, the first query facet, {*Curiosity, Opportunity, Spirit*}, includes different Mars rovers. The second query facet, {*USA, UK, Soviet Union*}, includes countries relevant to Mars landings. These are both facets where the terms are instances of the same semantic class. Somewhat differently, the last facet, {*video, pictures, news*}, includes labels for different query subtopics. These labels can be viewed as instances of a special semantic class, the subtopics of the query *mars landing*.

Table 3.1: Query facet examples for three queries

Query 1: Mars landing
Query Facet 1: Curiosity, Opportunity, Spirit
Query Facet 2: USA, UK, Soviet Union
Query Facet 3: video, pictures, news
Query 2: baggage allowance
Query Facet 1: AA, Delta, Jetblue, ...
Query Facet 2: international, domestic
Query Facet 3: first class, business class, economy class
Query Facet 4: weight, size, quantity
Query 3: Mr Bean
Query Facet 1: comics, movies, tv, books
Query Facet 2: The Curse of Mr Bean, Mr Bean Goes to Town, ...
Query Facet 3: Rowan Atkinson, Richard Wilson, Jean Rochefort, ...
Query Facet 4: Mr Bean, Irma gobb, Rupert, Hubert, ...

In this work, we use query facet extraction to address the problem of facet generation in Faceted Web Search. This approach first extracts candidate facets from the top search results based on textual and HTML patterns, and then refines the extracted candidates, which are often very noisy, using clustering methods. We de-

velop a supervised method based on a graphical model for refining facet candidates. The graphical model learns how likely it is that a term should be selected from the candidates and how likely it is that two terms should be grouped together in a query facet. Further, the model captures the dependencies between the two factors. We propose two algorithms for approximate inference on the graphical model since exact inference is intractable. This proposed method can easily incorporate a rich set of features and learn from available human labels.

The rest of this chapter is organized as follows. We first define the task of query facet extraction and related concepts in Section 3.2, and then describe a general framework to solve this problem in Section 3.3. We propose a supervised clustering method based on a graphical model for refining extracted candidates in Section 3.6. Last, we describe other methods that can be used for refining extracted candidates, including topic modeling (e.g., pLSA, LDA) and a variation of quality threshold clustering model (Dou et al., 2011) in Section 3.7.

3.2   Task Description

3.2.1   Query Facet

To differentiate our work with facets in conventional faceted search, we call typically facets for a particular query "query facets". A query facet is a set of coordinate terms – i.e., terms that share a semantic relationship by being grouped under a more general hypernym ("is a" relationship), and they succinctly represent different options in the same category that a user can select to refine the issued query. This definition of query facets corresponds to one-level taxonomies in faceted taxonomy, in which only information objects that belong to a same parent node are shown as a query facet. We leave generating query facets as two or more level taxonomies in future work.

3.2.2 Facet Term

We call the terms inside facets "facet terms", which can be single words (e.g. "*international*", "*domestic*" in Table 3.1) or phrases (e.g. "*first class*", "*business class*" in Table 3.1). These facet terms can be instances of a semantic class, for example "*Curiosity*", "*Opportunity*", "*Spirit*" are all Mars rovers. They can be labels for query subtopics, such as "*video*", "*pictures*", "*news*" for the query "*mars landing*". Facet terms of a query succinctly represent different options in the same category that a user can select to refine the issued query.

When it is clear from context, we will simply use "facet" for "query facet", and "term" for "facet term" for convenience.

3.2.3 Query Facet Extraction

Based on the definitions above, query facet extraction is to extract query facets for a given query from certain resources. While a variety of different resources can be used for query facet extraction, such as a query log, anchor text, taxonomy and social folksonomy, In this work, we only focus on extracting query facets from the top ranked web search results, and and leave others as future work.

3.3 Solution Framework

The idea for solving query facet extraction is to leverage coordinate terms found in the web search results to build high-quality query facets. These coordinate terms can be found by looking into the list structures in webpages (*e.g.*, order lists, drop-down lists) or analyzing the linguistic list structures in the textual content (*e.g.*, "*airlines such as <u>AA</u>, <u>Delta</u>, <u>JetBlue</u>*"). Previous work in semantic class extraction (Hearst, 1992; Pasca, 2004; Kozareva et al., 2008; Shi et al., 2010) has studied patterns for extraction these structures.

This idea is based on the following two assumptions:

(1) The list structures are consisted by coordinate terms, or terms that share peering relationships. According to webpage design conversions, webpage editors often list peering information objects in the HTML list structures. Similarly, the linguistic list structures are often used to list peering information objects in writing.

(2) The list structures presents relevant and important aspects of the query. Assuming the search results are relevant to the query, those list structures extracted from the search result should also be related to the query. And, if they occurred frequently, it may also be important to that query.

Based on the idea, we develop the following general solution framework for query facet extraction, as also illustrated in Figure 3.1:
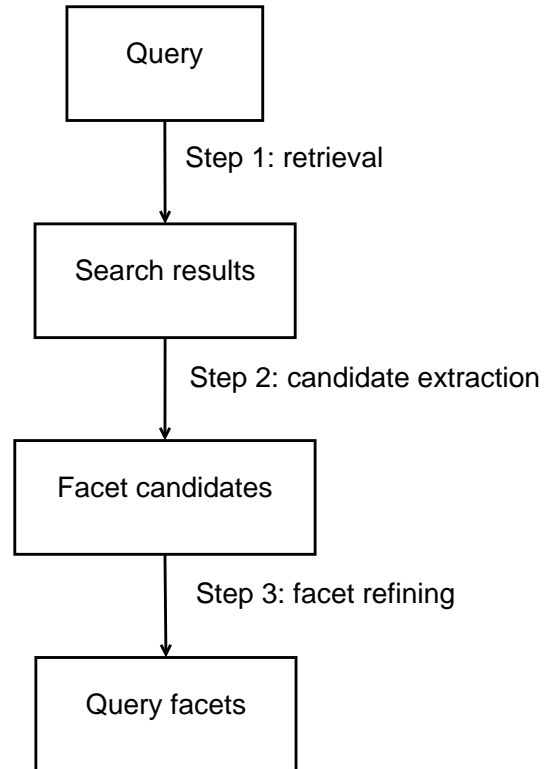
Figure 3.1: Query facet extraction framework

(1) **Retrieval**: in the first step, given a query, we retrieve the top search results.

(2) **Candidate extraction**: in the second step, we extract list structures as facet candidates from the search results based on pre-defined extraction patterns.

(3) **Facet Refining**: the facet candidates extracted are often very noisy, and cannot be directly used as query facets. In the last step, we refine the candidates to final query facets by re-clustering facets or terms in the candidate set.

We will describe candidate extraction and facet refining in more detail in the next two sections.

3.4 Candidate Extraction

Following Dou et al. (2011), we use pattern-based semantic class extraction approach (Shi et al., 2010) to extract lists of coordinate terms from search results as facet candidates. In pattern-based semantic class extraction, instances of a semantic class (*e.g.*, instance "*AA*", "*Delta*", "*JetBlue*" for class "*airlines*") are extracted from textual or webpage corpus based on lexical patterns (Hearst, 1992; Pasca, 2004), HTML patterns (Shinzato and Torisawa, 2007), or both (Shi et al., 2008; Zhang et al., 2009). For example, the pattern "*NP* such as *NP*, *NP*, ..., and *NP*", where "*NP*" stands for a noun phrase, can be used to extract coordinate terms (as instances) and their hypernyms (as the semantic class) from text. Besides lexical patterns, HTML patterns are often used on HTML documents to extract coordinate terms from some HTML structures, like unordered lists (*i.e.*, <UL>), drop-down lists (*i.e.*, <SELECT>) and tables (*i.e.*, <TABLE>). The coordinate terms extracted from each patterns form a candidate for query facets, which we call **candidate list**.

We apply both of the two types of patterns on the search results to extract candidate lists. These extraction patterns are summarized in Table 3.2. We describe them in details in the following two sections.

Table 3.2: Candidate list extraction patterns. All matched *items* in each pattern are extracted as a candidate list.

Type	Pattern
Lexical	*item*, {,*item*}*, (and|or) {other} *item*
HTML	\<select>\<option>*item*\</option>...\</select>
	\ \ *item*\ ...\
	\ \ *item*\ ...\
	\<table>\<tr>\<td>*item*\<td>...\</table>

3.4.1 Lexical Patterns

We use the following lexical pattern:

$$item, \{,item\}^*, (and|or) \{other\} \; item$$

We apply the pattern on the textual content (ignoring HTML tags and formatting in the webpage) of the search results, and extract matched *items* as a candidate list. To give an example, for the following sentence,

"... *Mars rovers such as Curiosity, Opportunity and Spirit.*"

For this lexical pattern, we also restrict those *items* to be siblings in the parse tree of that sentence in order to improve extraction quality. We use the PCFG parser (Klein and Manning, 2003) implemented in Stanford CoreNLP (Manning et al., 2014) for parsing documents.

3.4.2 HTML Patterns

We also extract candidate lists based on several HTML patterns that target list structures in HTML webpages, including drop-down lists, ordered list, unordered list and tables. Table 3.3 shows some HTML code examples for these list structures.

We extract those HTML list structures based on the HTML patterns listed in Table 3.2. Note that we do not match the HTML patterns with the HTML code exactly. Instead, we parse the HTML page into objects and extract textual content in the tags that we are interested in. We describe the extraction in details below:

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Table 3.3: HTML code examples for drop-down lists (SELECT), ordered lists (OL), unordered lists (UL) and tables (TABLE).

```
SELECT:
<select>
<option value="1">first class</option>
<option value="2">business class</option>
<option value="3">economy class</option>
</select>
```

```
OL:
<ol>
<li>checked baggage allowance</li>
<li>carry on baggage allowance</li>
<li>excess baggage allowance</li>
</ol>
```

```
UL:
<ul>
<li><a href="courtesy_bags.aspx">Courtesy bags</a></li>
<li><a href="dangerous.aspx">Dangerous goods</a></li>
<li><a href="devices.aspx">Electronic devices</a></li>
<li><a href="sports.aspx">Sports equipment</a></li>
</ul>
```

```
TABLE:
<table>
<tr><td></td><td>economy</td><td>business</td>first</li>
<tr>domestic<td>2 bags</td><td>3 bags</td><td>4 bags</td></li>
<tr>international<td>1 bag</td><td>2 bags</td><td>3 bags</td></li>
</table>
```

- **SELECT**: For the SELECT tag, we extract textual content in the OPTION tags as a candidate lists. For the example in Table 3.3, we will extract candidate list {"*first class*", "*business class*", "*economy class*"}.

- **OL**: For the OL tag, we extract textual content in the LI tags as a candidate lists. For the example in Table 3.3, we will extract candidate list {"*checked baggage allowance*", "*carry on baggage allowance*", "*excess baggage allowance*"}.

- **UL**: Similarly, for the UL tag, we also extract textual content in the LI tags as a candidate lists. For the example in Table 3.3, we will extract candidate list

{"*Courtesy bags*", "*Dangerous goods*", "*Electronic devices*", "*Sports equipment*"}. Note that in this case, when extracting textual content in the LI tags, we ignore other HTML tags/formatting (*i.e.*, "*<a>*").

- **TABLE**: for HTML tables, following Dou et al. (2011), we extract candidate lists from each columns and each rows. For the example in Table 3.3, we will extract 7 candidate lists. To list a few, {"*economy*", "*business*", "*first*"} and {"*domestic*", "*2 bag*", "*3 bags*", "*4 bags*"} are extracted from the first two rows. {conceptdomestic, "*international*"} and {"*economy*", "*2 bags*", "*1 bag*"} are extracted from the first two columns.

Ordered lists (OL) and unordered lists (UL) can be nested, as shown in Figure 3.2. For nested HTML lists, we extract all sibling items from each level. For the example in Figure 3.2, we will extract two lists, {"*Coffee*", "*Tea*", "*Milk*"} and {"*Black tea*", "*Green tea*"}.

```
<ul>
 <li>Coffee</li>
 <li>Tea
  <ul>
    <li>Black tea</li>
    <li>Green tea</li>
  </ul>
 </li>
 <li>Milk</li>
</ul>
```

Figure 3.2: An example for nested HTML lists.

3.4.3 Candidate List Cleaning

After extracting candidate lists from the top ranked search results, we further clean them as follows:

(1) First, all the list items are normalized by converting text to lowercase and removing non-alphanumeric characters.

(2) Then, we remove stopwords and duplicate items in each lists.

(3) Finally, we discard all lists that contain only one item or more than 200 items.

After the cleaning process, we harvest a set of candidate lists, from which we want to build high-quality query facets.

3.5   Facet Refining

The candidate lists extracted are usually noisy (Zhang et al., 2009), and could be non-relevant to the issued query, therefore they cannot be used directly as query facets. For example, Table 3.4 shows four candidate lists extracted for the query "*baggage allowance*". L_1 contains terms that are relevant to "*baggage allowance*", but they are not coordinate terms – "*delta*", "*france*" and "*round-trip*" are not members of the same class. L_2 is a valid query facet, but it is incomplete – another airline "*aa*" appears in L_3. L_3 is mixed with different facets, airlines and travel classes. L_4 is non-relevant to the query.

Table 3.4: Four candidate lists for the query "*baggage allowance*"

L_1: delta, france, round-trip
L_2: delta, jetblue, british airways
L_3: aa, first, business, economy
L_4: hard to remember, playing it by ear, ...

Since the candidate lists are frequently noisy, we need an effective way to refine extracted candidate lists into high-quality query facets. We call this problem **facet refining**, in which we take a set of candidate lists as input, and want to output high-quality query facets. This facet refining problem is the core issue in query facet

extraction, and the focus of our study. Existing query facet extraction models differ in how they refine candidate lists.

One related work about facet refining (Dou et al., 2011) clusters similarity candidate lists together as query facets (called query dimensions in their original paper), and then ranks/selects clusters and cluster items based on heuristics scores. We find this method is difficult to incorporate features. It also does not have the flexibility of breaking a candidate list into two query facets. We will describe more about this method and other related method for facet refining in Section 3.7. We will also compare these methods with our models in Chapter 4 and Chapter 7.

We instead treat the facet refining problem as a **selective clustering** problem. In the selective clustering problem, we do not cluster all given items, but only cluster a subset of the items. In the case of facet refining, we want to discard noisy terms, and cluster only facet terms in the candidate lists (*e.g.*, "*aa*", "*delta*", "*jetblue*", "*british airways*", "*first*", "*business*" and "*economy*" in Table 3.4) into query facets (*e.g.*, {"*aa*", "*delta*", "*jetblue*", "*british airways*"} and {"*first*", "*business*","*economy*"}). We will present this problem more formally in Section 3.6.1.

To address this problem, we develop a supervised method based on a graphical model, which will be presented in the next section.

3.6   Query Faceting Models

In this section, we describe query faceting (QF) models, our supervised methods based on a directed graphical model for facet refining. A directed graphical model (or Bayesian network) is a graphical model that compactly represents a probability distribution over a set of variables (Pearl, 1988). It consists of two parts: 1) a directed acyclic graph in which each vertex represents a variable, and 2) a set of conditional probability distributions that describe the conditional probabilities of each vertex given its parents in the graph.

We treat facet refining as a selective clustering problem (as described in Section 3.5), and solve it as a labeling problem, in which we are trying to predict 1) whether a list item is a facet term, and 2) whether a pair of list items is in a same query facet. Then, we used a directed graphical model to exploit the dependences that exist between those labels. Similar to conditional random fields (Lafferty et al., 2001), we directly model the conditional probability $P(y|x)$, where y is the label we are trying to predict and x is the observed data – list items and item pairs. Thus, it avoids modeling the dependencies among the input variables x, and can handle a rich set of features. For our graph model, exact maximum a posteriori inference is intractable; therefore, we approximate the results using two algorithms.

In the rest of this section, we will first describe the facet refining problem more formally in Section 3.6.1, and then present our graphical model in Section 3.6.2. We will describe how to train and perform inference on the model in Section 3.6.3 and Section 3.6.4 respectively.

3.6.1 Problem Formulation

Before diving into the QF method, we first define the facet refining problem more formally. We use $F = \{t_i\}$ to denote a query facet, consisted by a set of facet terms t_i. $\mathcal{F} = \{F_i\}$ denotes the set of query facets for the given query. $T_{\mathcal{F}} = \bigcup_i F_i$ denotes all the facet terms in $\mathcal{F}$. Candidate lists (or candidate facets) are just an imperfect version of query facets, and we substitute "F" with "L" to denote corresponding variables. $L = \{t_i\}$ denotes a candidate list. $\mathcal{L} = \{L_i\}$ denotes all the candidate lists extracted for the query. $T_{\mathcal{L}} = \bigcup_i L_i$ denotes all list items (or terms) in the candidate lists. Based on the formulation, the facet refining problem is simply to find $\mathcal{F}$ constrained with $T_{\mathcal{F}} \subseteq T_{\mathcal{L}}$, given $\mathcal{L}$ (and possibly other resources).

In our query faceting models, facet refining problem was treated as a label prediction problem. It aims to learn and predict jointly 1) whether a list item is a facet

term and 2) whether a pair of list items are in the same query facet. We denote the two types of labels as follows. The term/item labels are denoted by $Y = \{y_i\}$, where $y_i = 1\{t_i \in T_{\mathcal{F}}\}$ is a label indicating whether a list item t_i is indeed a facet term. Here $1\{\cdot\}$ is an indicator function which takes on a value of 1 if its argument is true, and 0 otherwise. The pair labels are denoted by $Z = \{z_{i,j}\}$, where $z_{i,j} = 1\{\exists\, F \in \mathcal{F},\, t_i \in F \wedge t_j \in F\}$ is a label indicates whether list item t_i and t_j are in a same query facet. Thus, the facet refining problem is now formulated as the problem of predicting labels Y and Z.

3.6.2 The Graphical Model

Our supervised method is based on a directed graphical model, aiming to capture the dependencies between the term and pair labels. The graphical model is shown in Figure 3.3. We further describe it as follows.
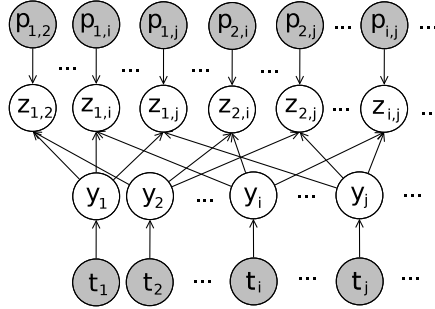
Figure 3.3: A graphical model for candidate list data

3.6.2.1 The Graph

First, we describes the four types of variables in the graphical model as follows. We use the formulation described in Section 3.6.1.

- list items: $t_i \in T_{\mathcal{L}}$, as defined before, are all the list items from the extracted candidate lists.

- item pairs: $p_{i,j} = (t_i, t_j)$ is simply a short name for term pair t_i and t_j. $P_{\mathcal{L}} = \{p_{i,j} \mid t_i, t_j \in T_{\mathcal{L}}, \ t_i \neq t_j\}$ are all the item pairs in $T_{\mathcal{L}}$.

- item labels: $y_i \in Y$, as defined before, are all item labels.

- pair labels: $z_{i,j} \in Z$, as defined before, are pair labels.

List items t_i and item pairs $p_{i,j}$ will be characterized by corresponding features (and will be described in Section 3.6.2.4). They are always observed. features (and will be described in Section 3.6.2.4). They are always observed. Item labels y_i and pair labels $z_{i,j}$ are what we are trying to predict. In summary, the vertices in our graphical model are $V = T_{\mathcal{L}} \cup P_{\mathcal{L}} \cup Y \cup Z$.

Second, as shown in Figure 3.3, there are three types of edges in the graph:

- edges from each list item t_i to its corresponding labels y_i.

- edges that point to each item pair label $z_{i,j}$ from the two corresponding list items y_i and y_j.

- edges from each item pair $p_{i,j}$ to its corresponding label $z_{i,j}$.

3.6.2.2 Conditional Probability Distributions

We use logistic-based conditional probability distributions (CPDs) for variable y_i and $z_{i,j}$, defined as in Equation 3.1 and Equation 3.2,

$$P(y_i = 1 \mid t_i) = \frac{1}{1 + \exp\{-\sum_k \lambda_k f_k(t_i)\}}, \tag{3.1}$$

$$P(z_{i,j} = 1 \mid p_{i,j}, y_i, y_j) = \frac{y_i y_j}{1 + \exp\{-\sum_k \mu_k g_k(p_{i,j})\}}, \tag{3.2}$$

where f_k and g_k are features that characterize a list item and a item pair respectively. λ and μ are the weights associated with f_k and g_k respectively. Compared to a conventional logistic function, Equation 3.2 has an extra term, $y_i y_j$, in the numerator.

When $y_i = 0$ or $y_j = 0$, we have $P(z_{i,j} = 1|p_{i,j}, y_i, y_j) = 0$. This means when either of the two list items is not a facet term, the two items can never appear in a query facet together. When both of the t_i and t_j are facet terms, $P(z_{i,j} = 1|p_{i,j}, y_i, y_j)$ becomes a conventional logistic function, which models the probability of t_i and t_j being grouped together in a query facet, given the condition that both t_i and t_j are facet term.

3.6.2.3 Joint Conditional Probability

Similar as in conditional random fields (Lafferty et al., 2001), we directly model the joint conditional probability $P(Y, Z|T_\mathcal{L}, P_\mathcal{L})$. Thus, it avoids modeling the dependencies among the input variables $T_\mathcal{L}, P_\mathcal{L}$, and can handle a rich set of features. The joint conditional probability for the graphical model is calculated as

$$P(Y, Z|T_\mathcal{L}, P_\mathcal{L}) = \prod_i P(y_i|t_i) \prod_{i,j} P(z_{i,j}|p_{i,j}, y_i, y_j), \qquad (3.3)$$

where the $P(y_i|t_i)$ and $P(z_{i,j}|p_{i,j}, y_i, y_j)$ are defined in Equation 3.1 and Equation 3.2 respectively.

3.6.2.4 Features

There are two types of features used in our graphical model, summarized in Table 3.5.

Item features, $f_k(t)$ in the graphical model, characterize a single list item. To capture the relevance of item t to the query, we use some TF/IDF-based features extracted from the top k search results, $\mathcal{D}$. For example, *snippetDF* is the number of snippets in top k search results that contain item t. *snippetDF* and other frequency-based features are normalized using $log(frequency + 1)$. To capture how likely item t is to be an instance of a semantic class, we use features extracted from candidate lists. For example, *listTF* is the frequency of t in the candidate lists extracted from $\mathcal{D}$. Some list items occur frequently in candidate lists across different queries, such

as *home*, *contact us* and *privacy policy*. They are treated as stopwords, and removed from the candidate lists. We also use $listIDF$ to cope with this problem. $listIDF$ is the IDF of a list item in a general collection of candidate lists we extracted (see Section 4.2). It is calculated as $listIDF(t) = \log\frac{N-N_t+0.5}{N_t+0.5}$, where N is the total number of lists in the collection, N_t is the number of lists contain t. The same form is used for *clueIDF*, IDF in ClueWeb09[1] collection.

Item Pair Features, $g(p_{i,j})$ in the graphical model, are used to capture how likely a pair of list items should be grouped into a query facet, given that the two list item both are facet terms. This can be measured by context similarity (Shi et al., 2010). For *textContextSim*, we use window size 25, and represent text context as a vector of TF weights. Cosine similarity is used as the similarity measure. Similarly, we use the candidate lists that contain the list item as its list context, and calculate *listContextSim* in the same way as *textContextSim*.

3.6.3   Maximum Likelihood Parameter Estimation

We estimate the parameters λ, μ in the model by maximizing the conditional likelihood of a giving training set. (Later in Chapter 5, we will present another method for parameter estimation by directly maximizing the performing measure.) The training set for the graphical model can be denoted as $\{T_{\mathcal{L}}^{(k)}, P_{\mathcal{L}}^{(k)}, Y^{*(k)}, Z^{*(k)}\}$, where $Y^{*(k)}$, $Z^{*(k)}$ are the ground truth labels for the list items $T_{\mathcal{L}}^{(k)}$ and item pairs $P_{\mathcal{L}}^{(k)}$. (We use superscript "*" to denote ground truth labels.) The conditional probability of the training set can be calculated according to Equation 3.4.

$$P(\lambda, \mu) = \prod_k P(Y^{*(k)}, Z^{*(k)} | T_{\mathcal{L}}^{(k)}, P_{\mathcal{L}}^{(k)}), \tag{3.4}$$

---

[1] http://lemurproject.org/clueweb09

Table 3.5: Item and item pair features

Item Features for list item t	
length	Number of words in t
clueIDF	IDF of t in ClueWeb09 collection
TF	Term frequency of t in $\mathcal{D}$
DF	Document frequency of t in $\mathcal{D}$
wDF	Weighted DF. Each document count weighted by $1/\sqrt{docRank}$
SF	Site frequency. Number of unique websites in $\mathcal{D}$ that contain t
titleTF	TF of t for the titles of $\mathcal{D}$
titleDF	DF of t for the titles of $\mathcal{D}$
titleSF	SF of t for the titles of $\mathcal{D}$
snippetTF	TF of t for the snippets of $\mathcal{D}$
snippetDF	DF of t for the snippets of $\mathcal{D}$
snippetSF	SF of t for the snippets of $\mathcal{D}$
listTF	Frequency of t in candidate lists extracted from $\mathcal{D}$
listDF	Number of documents that contain t in their candidate lists
listSF	Number of unique websites that contain t in their candidate lists
listIDF	IDF of t in a general candidate list collection
TF.clueIDF	TF $\times$ clueIDF
listTF.listIDF	listTF $\times$ lisIDF
Item Pair Features for item pair $p_{i,j} = (t_i, t_j)$	
lengthDiff	Length difference, $\|len(t_i) - len(t_j)\|$
listCooccur	Number of candidate lists extracted from $\mathcal{D}$, in which t_i, t_j co-occur
textContextSim	Similarity between text contexts
listContextSim	Similarity between list contexts

where $P(Y^{*(k)}, Z^{*(k)}|T_{\mathcal{L}}^{(k)}, P_{\mathcal{L}}^{(k)})$ is defined in Equation 3.3. Based on the condition probability, the conditional log-likelihood $l(\lambda, \mu)$, can be calculated as follows,

$$l(\lambda, \mu) = l_t(\lambda) + l_p(\mu), \qquad (3.5)$$

$$l_t(\lambda) = \sum_k \sum_i \log P(y_i^{*(k)}|t_i^{(k)}) - \frac{\sum_k \lambda_k^2}{2\sigma^2}, \qquad (3.6)$$

$$l_p(\mu) = \sum_k \sum_{i,j} \log P(z_{i,j}^{*(k)} | p_{i,j}^{(k)}, y_i^{*(k)}, y_j^{*(k)}) - \frac{\sum_k \mu_k^2}{2\gamma^2}, \tag{3.7}$$

where the last terms in Equation 3.6 and Equation 3.7 are served as regularizers, which penalize large values of λ, μ. σ and γ are regularization parameters that control the strength of penalty.

Notice that, in the train set, for those item pairs $p_{i,j}$ with any of its list item not being a facet term, their labels $z_{i,j}^* = 0$. According to Equation 3.2, for those item pairs, $\log P(z_{i,j}^* | p_{i,j}, y_i^*, y_j^*) = 0$, which makes no contribution to the conditional log-likelihood $l(\mu)$, and thus $l_p(\mu)$ can be simplified as

$$l_p(\mu) = \sum_k \sum_{i,j: y_i^{*(k)}=1, y_j^{*(k)}=1} \log P(z_{i,j}^{*(k)} | p_{i,j}^{(k)}, y_i^{*(k)}, y_j^{*(k)}) - \frac{\sum_k \mu_k^2}{2\gamma^2}, \tag{3.8}$$

where the i, j now indexes only item pairs with both of its list items being facet terms $(i.e., y_i^{*(k)} = 1, y_j^{*(k)} = 1)$.

We can see that Equations 3.6 and 3.8 are exactly the same as log-likelihoods for two separated logistic regressions. In fact, Equation 3.6 learns a logistic regression model for whether a list item is a facet term, and Equation 3.8 learns a logistic regression model for whether two facet terms should be grouped together. The parameter λ and μ can be learned by maximizing the log-likelihood using gradient descent, exactly same as in logistic regression.

3.6.4 Inference

When given a new labeling task, we could perform maximum a posteriori inference - compute the most likely labels Y, Z by maximizing the joint conditional probability $P(Y, Z | T_{\mathcal{L}}, P_{\mathcal{L}})$. After that, the query facet set $\mathcal{F}$ can be easily induced from the labeling Y, Z. (Collect list items with $y_i = 1$ as facet terms, and group any two of them into a query facet if the corresponding $z_{i,j} = 1$.) Note that the graphical model we designed does not enforce the labeling to produce strict partitioning for facet terms.

For example, when $Z_{1,2} = 1$, $Z_{2,3} = 1$, we may have $Z_{1,3} = 0$. Therefore, the labeling results may induce an overlapping clustering. Unfortunately, this optimization problem is NP-hard, which can be proved by a reduction from the Ising model (Barahona, 1982).

To facilitate developing solutions, we add the strict partitioning constraint that each facet term belongs to exactly one query facet. Also, to directly produce the query facets, instead of inducing them after predicting labels, we rephrase the optimization problem as follows. First, we use the following notations for log-likelihoods,

$$
\begin{aligned}
s_t(t_i) &= \log P(y_i = 1 | t_i) \\
\overline{s_t}(t_i) &= \log\left(1 - P(y_i = 1 | t_i)\right) \\
s_p(t_i, t_j) &= \log P(z_{i,j} = 1 | p_{i,j}, y_i = 1, y_j = 1) \\
\overline{s_p}(t_i, t_j) &= \log\left(1 - P(p_{i,j} = 1 | p_{i,j}, y_i = 1, y_j = 1)\right)
\end{aligned}
$$

Using the notations above, the log-likelihood $l(\mathcal{F})$ for a particular query facet set $\mathcal{F}$ formed from $\mathcal{L}$ can be written as

$$
\begin{aligned}
l(\mathcal{F}) &= l_t(\mathcal{F}) + l_p(\mathcal{F}) \\
l_t(\mathcal{F}) &= \sum_{t \in T_\mathcal{F}} s_t(t_i) + \sum_{t \notin T_\mathcal{F}} \overline{s_t}(t_i) \\
l_p(\mathcal{F}) &= \sum_{F \in \mathcal{F}} \sum_{t_i, t_j \in F} s_p(t_i, t_j) + \sum_{\substack{F, F' \\ \in \mathcal{F}}} \sum_{\substack{t_i \in F, \\ t_j \in F'}} \overline{s_p}(t_i, t_j)
\end{aligned}
\tag{3.9}
$$

In the right hand side of Equation 3.9, the first term is the intra-facet score, which sums up $s_p(\cdot, \cdot)$ for all the item pairs in each query facet. The second term is the inter-facet score, which sums up the $\overline{s_p}(\cdot, \cdot)$ for each item pair that appears in different query facets. Then the optimization target becomes $\mathcal{F} = \arg\max_{\mathcal{F} \in \mathfrak{F}} l(\mathcal{F})$, where $\mathfrak{F}$ is the set of all possible query facet sets that can be generated from $\mathcal{L}$ with the strict partitioning constraint.

This optimization problem, however, is still NP-hard, which can be proved by a reduction from the Multiway Cut problem (Bansal et al., 2002). Therefore, we propose two algorithms, **QF-I** and **QF-J**, to approximate the results.

3.6.4.1 QF-I

QF-I approximates the results by predicting whether a list item is a facet term and whether two list items should be grouped in a query facet independently, which is accomplished two phases. In the first phase, QF-I selects a set of list items as facet terms according to $P(y_i|t_i)$. In this way, the algorithm predicts whether a list item t_i is a facet term independently, ignoring the dependences between y_i and its connected variables in Z. In our implementation, we simply select list items t_i with $P(t_i) > w_{min}$ as facet terms. (For convenience, we use $P(t_i)$ to denote $P(y_i = 1|t_i)$.) In the second phase, the algorithm clusters the facet terms $T_{\mathcal{F}}$ selected in the first phase into query facets, according to $P(t_i, t_j)$. ($P(t_i, t_j)$ is used to denote $P(z_{i,j} = 1|p_{i,j}, y_i = 1, y_j = 1)$). Many clustering algorithm can be applied here, using $P(t_i, t_j)$ as the distance measure. For our implementation, we use a cluster algorithm based on WQT (Dou et al., 2011), because it considers the importance of nodes while clustering. We use $P(t_i)$ as the measure for facet term importance, and $d_t(t_i, t_j) = 1 - P(t_i, t_j)$ as the distance measure for facet terms. The distance between a cluster and a facet term is computed using complete linkage distance, $d_f(F, t) = max_{t' \in F} d(t, t')$, and the diameter of a cluster can be calculated as $dia(F) = \max_{t_i, t_j \in F} d_t(t_i, t_j)$. The algorithm is summarized in Algorithm 1. It processes the facet terms in decreasing order of $P(t)$. For each facet term remaining in the pool, it builds a cluster by iteratively including the facet term that is closest to the cluster, until the diameter of the cluster surpasses the threshold d_{max}.

Algorithm 1 WQT for clustering facet term used in QF-I
___
Input: $T_{\mathcal{F}}, P(t), d_f(F, t), dia(F), d_{max}$
Output: $\mathcal{F} = \{F\}$
 1: $T_{pool} \leftarrow \mathcal{F}$
 2: **repeat**
 3: $\quad t \leftarrow \arg\max_{t \in T_{pool}} P(t)$
 4: $\quad F \leftarrow \{t\}$
 5: $\quad$ iteratively include facet term $t' \in T_{pool}$ that is closest to F, according to $d_f(F, t')$, until the diameter of the cluster, $dia(F)$, surpasses the threshold d_{max}.
 6: $\quad \mathcal{F} \leftarrow \mathcal{F} \cup \{F\}, T_{pool} \leftarrow T_{pool} - F$
 7: **until** T_{pool} is empty
 8: **return** $\mathcal{F}$
___

3.6.4.2 QF-J

QF-I finds query facets based on the graphical model by performing inference of y_i and $z_{i,j}$ independently. The second algorithm, QF-J, instead tries to perform joint inference by approximately maximizing our target $l(\mathcal{F})$ with respect to y_i and $z_{i,j}$ iteratively. The algorithm first guesses a set of list items as facet terms. Then it clusters those facet terms by approximately maximizing $l_p(\mathcal{F})$, using a greedy approach. After clustering, the algorithm checks whether each facet term "fits" in its cluster, and removes those that do not fit. Using the remaining facet terms, the algorithm repeats the process (clustering and removing outliers) until convergence.

QF-J is outlined in Algorithm 2. The input to the algorithm are the candidate list item set $T_{\mathcal{L}}$, and the log-likelihoods $l(\mathcal{F})$, $l_p(\mathcal{F})$. In the first step, we select top n list items according to $s_t(t)$ as the initial facet terms, because it is less sensitive to the absolute value of the log-likelihood. In our experiment, n is set to 1000 to make sure most of the correct facet terms are included. Then, the algorithm improves $l(\mathcal{F})$ by iteratively performing functions CLUSTER and REMOVEOUTLIERS. CLUSTER performs clustering over a given set of facet terms. In step 10 to 12, it puts each facet terms into a query facet by greedily choosing the best facet, or creates a singleton for the list item, according to the resulting log-likelihood, $l_p(\mathcal{F})$. We choose to process these list items in decreasing order of $s_t(t)$, because it is more likely to form a good

query facet in the beginning by doing so. REMOVEOUTLIERS removes facet terms according to the joint log-likelihood $l(\mathcal{F})$. In step 20 to 22, it checks each facet term to see if it fits in the facet, and removes outliers. F' is the set of facet terms the algorithm selected when processing each facet F.

Algorithm 2 QF-J
___

Input: $T_{\mathcal{L}} = \{t\}, l, l_p$
Output: $\mathcal{F} = \{F\}$
 1: $T_{\mathcal{F}} \leftarrow$ top n list items from $T_{\mathcal{L}}$ according to $s_t(\cdot)$
 2: **repeat**
 3:     $\mathcal{F} \leftarrow$ CLUSTER$(T_{\mathcal{F}}, l_p)$
 4:     $T_{\mathcal{F}} \leftarrow$ REMOVEOUTLIERS$(\mathcal{F}, l)$
 5: **until** converge
 6: **return** $\mathcal{F}$
 7:
 8: **function** CLUSTER$(T_{\mathcal{F}}, l_p)$
 9:     $\mathcal{F} \leftarrow \emptyset$
10:     **for** each $t \in T_{\mathcal{F}}$ in decreasing order of $s_t(t)$ **do**
11:         Choose to put t into the best facet in $\mathcal{F}$ or add t as a singleton into $\mathcal{F}$, whichever that has the highest resulting $l_p(\mathcal{F})$.
12:     **end for**
13:     **return** $\mathcal{F}$
14: **end function**
15:
16: **function** REMOVEOUTLIERS$(\mathcal{F}, l)$
17:     $T_{\mathcal{F}} \leftarrow$ all facet terms in $\mathcal{F}$
18:     **for** each $F \in \mathcal{F}$ **do**
19:         $F' = \emptyset$
20:         **for** each $t \in F$ in decreasing order of $s_t(\cdot)$ **do**
21:             choose to add t into F' or not, whichever has the highest resulting $l(\{F'\})$
22:                 if not, $T_{\mathcal{F}} \leftarrow \mathcal{F} - \{t\}$
23:         **end for**
24:     **end for**
25:     **return** $T_{\mathcal{F}}$
26: **end function**
27: **return** $\mathcal{F}$
___

3.6.5 Ranking Query Facets

The output of QF-I and QF-J is a query facet set $\mathcal{F}$. To produce ranking results, we defined a score for a query facet as $score_F(F) = \sum_{t \in F} P(t)$, and rank the query facets according to this scoring, in order to present more facet terms in the top. Facet terms within a query facet are ranked according to $score_t(t) = P(t)$. We leave the investigation for more sophisticated ranking models as future work.

3.7 Other Approaches

In this section, we describe two alternative method for facet refining. They are used as baselines in our experiments.

3.7.1 QDMinder

Dou et al. (2011) developed QDMiner/QDM for query facet extraction, which appears to be the first work that addressed the problem of query facet extraction. To solve the problem of finding query facets from the noisy candidate lists extracted, they used an unsupervised clustering approach. It first scores each candidate list by combining some TF/IDF-based scores. The candidate lists are then clustered with bias toward important candidate lists, using a variation of the Quality Threshold clustering algorithm (Heyer et al., 1999). After clustering, clusters are ranked and list items in each clusters are ranked/selected based on some heuristics. Finally, the top k clusters are returned as results. This unsupervised approach does not gain by having human labels available. Also, by clustering lists, they lose the flexibility of breaking a candidate list into different query facets.

3.7.2 Topic modeling

In semantic class extraction, Zhang et al. (2009) proposed to use topic models to find high-quality semantic classes from a large collection of extracted candidate lists. Their assumption is, like documents in the conventional setting, candidate lists are

generated by a mixture of hidden topics, which are the query facets in our case. pLSA and LDA are used in their experiments. We find this approach can be directly used for finding query facets from candidate lists. The major change we need to make is that: in semantic class extraction, topic modeling is applied globally on the candidate lists (or a sample of them) from the entire corpus; in query facet extraction, we apply topic modeling only on the top k search results $\mathcal{D}$, assuming the coordinate terms in $\mathcal{D}$ are relevant to the query. Then, the topics are returned as query facets, by using the top n list items in each topic (according to the list item's probability in the topic). Though this topic modeling approach is more theoretically motivated, it does not have the flexibility of adding different features to capture different aspects such as query relevance.

3.8 Summary

In this chapter, we developed query facet extraction, which extracts facets for a given query from its search results. We developed a supervised approach based on a graphical model to recognize facets from the noisy candidates found. The graphical model learns how likely a candidate term is to be a facet term as well as how likely two terms are to be grouped together in a query facet, and captures the dependencies between the two factors. We proposed two algorithms (QFI and QFJ) for approximate inference on the graphical model since exact inference is intractable. Compared with other existing methods, our models can easily incorporate a rich set of features, and learn from available labeled data.

To evaluate our models, in the next chapter, we will develop an intrinsic evaluation method that compares extracted facets with human created ones.

CHAPTER 4

INTRINSIC EVALUATION

4.1   Introduction

Intrinsic evaluation is to evaluate the quality of query facet generation itself. We perform intrinsic evaluation by comparing system generated query facets with "gold standard" query facets. Note that this evaluation can be easily extended for evaluating new models (*i.e.*, compare the query facets generated by the new models with the existing "gold standard" query facets collected before). Later, in Chapter 7, we will carry out an extrinsic evaluation that evaluates the quality of generated facets by their utility in assisting search.

The "gold standard" query facets are constructed by human annotators and used as the ground truth to be compared with facets generated by different systems. The facet annotation is usually done by first pooling facets generated by the different systems. Then annotators are asked to group or re-group terms in the pool into preferred query facets, and to give ratings for each of them regarding how useful or important the facet is.

In intrinsic evaluation, the quality of generated query facets can be measured from two aspects. (1) How well does the model generate/find correct facet terms. This can be measured by standard classification measures, such as precision and recall. (2) How well does the model groups facet terms correctly. This can be measured by standard clustering measures, such as F-measures for clustering, Purity and Normalized Mutual Information.

However, a single performance measure that combines the different aspects can be desirable in many cases. First, such a single measure provides an overall measurement for effectiveness, which is often necessary for comparing different models. Second, such a single measure can be used for tuning or training models. For example, in Chapter 5, we propose a method that directly using a performance measure as the training object.

To combine the two evaluation aspects, we design a new measure called $PRF_{\alpha,\beta}$ (Kong and Allan, 2013). $PRF_{\alpha,\beta}$ combines TP, TR and PF using weighted harmonic mean, where TP, TR and PF are precision and recall for facet terms, and the F1 measure for facet term clustering. Parameters α and β can be used to adjust the emphasis of the three factors for different applications.

However, $PRF_{\alpha,\beta}$ does not directly account for facet ranking performance. Dou et al. (Dou et al., 2011) used some variations of nDCG to evaluate facet ranking. In the nDCG variation measures, system facets are mapped to truth facets, and assigned ratings according to their mapped truth facets. Then the ranked system facets are evaluated using nDCG, with the discounted gain further weighted by the precision and recall of the system facet and mapped truth facet. However, we will show that this metric can be problematic in some cases.

In the experiments of this chapter, we perform intrinsic evaluation on the different query facet extraction models described in Chapter 3. The experimental results show that our supervised method (QF-I and QF-J) proposed in Chapter 3 significantly outperforms other unsupervised methods, suggesting that query facet extraction can be effectively learned.

In the rest of this chapter, we will first described how we collect data and perform facet annotation for intrinsic evaluation in Section 4.2. Then, we will describe different evaluation metrics in Section 4.3, including $PRF_{\alpha,\beta}$ and other existing measures. We

will present our experiments for comparing different query facet extraction models in Section 4.4, followed by conclusions in Section 4.5.

4.2 Data

4.2.1 Query

We constructed a pool of 232 queries from different sources, including random samples from a query log, TREC 2009 Web Track queries [1], example queries appearing in related publications (Xue and Yin, 2011; Wang et al., 2009) and queries generated by our annotators. Annotators were asked to select queries that they are familiar with from the pool for annotating. Overall, we collect annotations for 100 queries (see Table 4.1).

Table 4.1: Query statistics

Source	#queries collected	#queries annotated
query log	100	30
related publications	20	10
TREC 2009 Web Track	50	20
annotators generated	62	40
sum	232	100

4.2.2 Search Results

For each query, we acquire the top 100 search results from a commercial Web search engine. A few search results were skipped due to crawl errors, or if they were not HTML Web pages. For the 232-query set, we crawled 22,909 Web pages, used for extracting feature $listIDF$ described in Section 3.6.2.4. For the 100 annotated queries, the average number of crawled Web pages is 98.7, the minimum is 79, both the maximum and the median are 100.

---

[1]http://trec.nist.gov/data/web/09/wt09.topics.queries-only
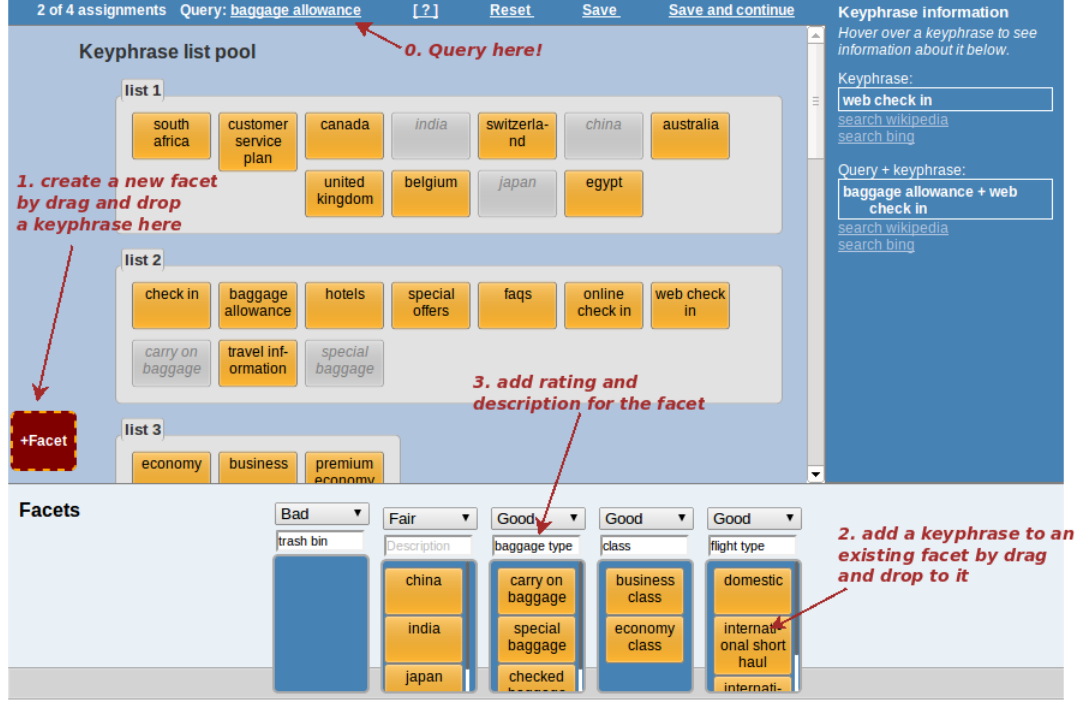
Figure 4.1: Annotation interface for query facet annotation.

4.2.3 Query facet annotations

We asked human annotators to construct query facets as ground truth, using the annotation interface shown in Figure 4.1. For each query, we first constructed a pool of terms by aggregating facet terms in the top 10 query facets generated by different models (corresponding to "keyphrase list pool" in Figure 4.1), including two runs from QDM, one run from each of pLSA and LDA using top 10 list items in each query facets, and one run for our graphical model based approach. Then, annotators were asked to group terms in the pool into query facets for each query they selected (corresponding to step 1 and 2 in Figure 4.1). Finally, the annotator was asked to give a rating for each constructed query facet, regarding how useful and important the query facet is (corresponding to step 3 in Figure 4.1). The rating scale of good=2/fair=1 is used. There are 50 query facets pooled per query, with 224.8 distinct facet terms per query. Annotation statistics for the good and fair facets, as well as the pooled facet, are given in Table 4.2. The table shows average number of facet terms per query, average

number of query facets per query, and average number of facet terms per facet, for each categories (fair, good, and pooled facets).

Table 4.2: Annotation statistics

	fair	good	pooled
#terms per query	26.6	55.8	224.8
#facets per query	3.1	4.8	50.0
#terms per facet	8.6	11.6	8.8

4.3 Metrics

Query facet extraction can be evaluated from different aspects. A good system should select "correct" facet terms from all the list items, therefore we use standard classification metrics, such as precision, recall and F-measures. A good system should also group those facet term correctly (i.e., in the same way as the annotators), therefore we use standard clustering metrics, such as F-measures for clustering, Purity and Normalized Mutual Information. To combine the different evaluation aspects, we design a new measure for this particular task.

4.3.1 Notations

We continue to use notations defined in Section 3.6.1 for a query facet (F), a query facet set ($\mathcal{F}$) and the set of all facet terms ($T_{\mathcal{F}}$) in a query facet set. We use "*" to distinguish between system generated results and human labeled results, which we used as ground truth. For example, $\mathcal{F}$ denotes the system generated query facet set, and $\mathcal{F}^*$ denotes the human labeled query facet set. For convenience, we use T to denote $T_{\mathcal{F}}$ in this section, omitting subscript $\mathcal{F}$. T^* denotes all the facet terms in human labeled query facet set. We use r_{F^*} to denote the rating score for a human labeled facet F^*.

4.3.2 Effectiveness in finding facet terms

One aspect of query facet extraction evaluation is how well a system finds facet terms. This can be evaluated using standard classification metrics as follows,

- facet term precision: $TP = \frac{|T \cap T^*|}{|T|}$

- facet term recall: $TR = \frac{|T \cap T^*|}{|T^*|}$

- facet term F1: $TF = \frac{2|T \cap T^*|}{|T|+|T^*|}$

where the "T" in measure names TP, TR, TF stands for facet *term*. It is used to distinguish the term based measures from term pair based measures as defined below. Note that these metrics do not take clustering quality into account.

4.3.3 Clustering quality

To evaluate how well a system groups facet terms correctly, similar to Dou et al. (Dou et al., 2011), we use several existing cluster metrics, namely, Purity, NMI/Normalized Mutual Information and pair-counting F1 measure. Here the pair-counting F1 measure treats term clustering as classification on whether each pairs of terms are in a same facet, and then combines pair precision and recall using F1 measure. We denote the pair-counting F1 measure as PF with "P" standing for term *pair*.

In our task, we usually have $T \neq T^*$. The facet terms in the system generated and human labeled clustering results might be different: the system might fail to include some human identified facet terms, or it might mistakenly include some "incorrect" facet terms. These standard clustering metrics cannot handle these cases properly. To solve this problem, we adjust $\mathcal{F}$ and $\mathcal{F}^*$ as if only facet terms in $T \cap T^*$ were clustered by the system, since we are only interested in how well the "correct" facet terms are clustered from these metrics. The adjusting is done by removing "incorrect" facet terms ($t \in T - T^*$) from $\mathcal{F}$, and removing missing facet terms ($t^* \in T^* - T$) in

$\mathcal{F}^*$. By this adjusting, we do not take into account the effectiveness of finding correct facet terms.

4.3.4 Overall quality

To evaluate the overall quality of query facet extraction, Dou et al. (Dou et al., 2011) proposed variations of nDCG (Normalized Discounted Cumulative Gain), namely fp-nDCG and rp-nDCG. They first map each system generated facet F to a human labeled facet F^* that covers the maximum number of terms in F. Then, they assign the rating r_{F^*} to F, and evaluate $\mathcal{F}$ as a ranked list of query facets using nDCG. The discounted gains are weighted by precision and/or recall of facet terms in F, against its mapped human labeled facet F^*. For fp-nDCG, only precision is used as weight, $\frac{|F^* \cap F|}{|F|}$. For rp-nDCG, precision and recall are multiplied as weight, $\frac{|F^* \cap F|^2}{|F^*||F|}$.

However, this these nDCG variation measures can be problematic in some cases. When two facets F_1 and F_2 are mapped to a same human labeled facet F^*, only the first facet F_1 is credited and F_2 is simply ignored, even if it is more appropriate to map F_2 to F^* (e.g., F_2 is exactly same as F^*, while F_1 contain only one facet term in F^*). Our proposed metric does not need to map facets, and thus does not have this problem.

The quality of query facet extraction is intrinsically multi-faceted. Different applications might have different emphasis in the three factors mentioned above - precision of facet terms, recall of facet terms and clustering quality of facet terms. We propose a metric $PRF_{\alpha,\beta}$ to combine the three factors together, using weighted harmonic mean, as follows

$$PRF_{\alpha,\beta}(TP, TR, PF) = \frac{(\alpha^2 + \beta^2 + 1)}{\frac{\alpha^2}{TP} + \frac{\beta^2}{TR} + \frac{1}{PF}}, \tag{4.1}$$

where $\alpha, \beta \in [0, +\infty)$ are used to control the weight between the three factors in the same way as "β" in F-measures (van Rijsbergen, 1979). α and β can be interpreted as

the importance of TP and TR compared to PF respectively. More formally, we have

$$\begin{aligned} when \ \alpha &= \frac{TP}{PF} \ , \frac{\partial PRF_{\alpha,\beta}}{\partial TP} = \frac{\partial PRF_{\alpha,\beta}}{\partial PF} \\ when \ \beta &= \frac{PR}{PF} \ , \frac{\partial PRF_{\alpha,\beta}}{\partial TR} = \frac{\partial PRF_{\alpha,\beta}}{\partial PF}. \end{aligned} \quad (4.2)$$

The intuition behind this is we want to specify the TP/PF ratio at which the user is willing to trade an increment in TP for an equal loss in PF, and similarly for TR/PF. For example, we can set $\alpha=2, \beta=1$ to evaluate the case where TP is twice important than TR and PF. When $\alpha = \beta = 1$, we omit the subscript part for simplicity, i.e. $PRF \equiv PRF_{1,1}$.

While $PRF_{\alpha,\beta}$ has the flexibility to adjust emphasis between the three factors, it does not take into account the different ratings associated with query facets. To incorporate ratings, we use a weighted version of TP, TR and PF in $PRF_{\alpha,\beta}$. We call the new metric $wPRF_{\alpha,\beta}$. The weighted facet term precision, recall and TF are defined as follows.

- weighted facet term precision: $wTP = \frac{\sum_{t \in T \cap T*} w(t)}{\sum_{t \in T} w(t)}$

- weighted facet term recall: $wTR = \frac{\sum_{t \in T \cap T*} w(t)}{\sum_{t* \in T*} w(t*)}$

- weighted facet term F1: $wTF = \frac{2wP(T,T^*)wR(T,T^*)}{wP(T,T^*)+wR(T,T^*)}$

where $w(t)$ is the weight for facet term t, and assigned as follows

$$w(t) = \begin{cases} r_{F^*} & \text{if } t \in T^* \\ 1 & \text{otherwise} \end{cases}$$

Similarly, wPF is computed by weighting its pairwise precision and recall in the same fashion as the weighted facet term precision and recall above. Instead of $w(t)$, we need weight for a pair of facet terms $w(t_1, t_2)$ in this calculation. We assign weight for facet term pair $w(t_1, t_2)$ using their sum, $w(t_1) + w(t_2)$.

4.4   Experiments

4.4.1   Experiment settings

We compare effectiveness of the five models, QDM, pLSA, LDA and QF-I, QF-J (described in Chapter 3), on the 100-query data set. All the models take the same candidate lists extracted/cleaned (see Section 3.4) as input. We perform 10-fold cross validation for training/testing and parameter tuning in all experiments and for all models (if applicable). When training the graphical model, we standardize features by removing the mean and scaling to unit variance. We set both of the two regularizers σ and γ to be 1. There are too many negative instances ($y_i = 0$, $z_{i,j} = 0$) in the training data, so we stratify samples by labels with the ratio of positive:negative to be 1:3. For QDM, we tune the two parameters used in the clustering algorithm Dia_{max} (the diameter threshold for a cluster) and W_{min} (the weight threshold for a valid cluster), as well as two parameters used for selecting facet terms in each facet ($S_{t|F} > \alpha|Sites(F)|$ and $S_{t|F} > \beta$). For pLSA and LDA, we tune the number of facet terms in a query facet. For QF-I, we tune the weight threshold for facet terms, w_{min}, and the diameter threshold, d_{max}. For QF-J, there are no parameter need to be tuned. We returned top 10 query facets from all the five models in all evaluation.

4.4.2   Finding Facet terms

To evaluate effectiveness in finding facet terms, we tune all the models on wTF, which combines both precision and recall, and takes into account facet term weighting.

Table 4.3: Facet term precision, recall and F1 tuned on wTF

Model	TP	wTP	TR	wTR	TF	wTF
pLSA	0.284	0.385	0.562	0.561	0.351	0.430
LDA	0.292	0.394	0.595	0.593	0.364	0.446
QDM	0.407	0.523	0.378	0.388	0.360	0.420
QF-I	0.347	0.458	**0.644**	**0.652**	0.427	**0.514**
QF-J	**0.426**	**0.534**	0.525	0.526	**0.449**	0.511

Table 4.4: Average number of facet terms in output per query for different models

Model	#terms/query
pLSA	153.1
LDA	154.8
QDM	68.0
QF-I	153.7
QF-J	97.8

Table 4.3 shows facet term precision, recall and F1 and their weighted version described in Section 4.3.1. QF-I and QF-J perform relatively well for both precision and recall. Their improvements over the other three models shown are all significant ($p < 0.05$, using paired t-test), except the improvements of QF-J over QDM for P and wP. The two topic model based approaches, pLSA and LDA, have relatively high recall and low precision. Contrarily, QDM has high precision and low recall. This difference can be explain by Table 4.4, which gives the number of facet terms output per query from each models. QDM only outputs 68 facet terms per query, while pLSA and LDA both output over twice that number. One possible reason for the low precision of pLSA and LDA is that they select facet terms solely according to term probabilities in the learned topics (query facets in our case) and do not explicitly incorporate query relevance. We find most of their facet terms are frequently-occurring list items, which are not necessary relevant to the query. While the number of facet terms QF-I outputs is similar to pLSA and LDA, QF-I obtain much higher precision and recall, likely due to the rich set of features used. Table 4.5 shows the five most important item features according to the absolute values of learned weights. Not surprisingly, list TF/IDF features which are used to capture the likelihood of being a coordinate term have relatively high weights, as well as some features that are used to capture query relevance, e.g. $TF.clueIDF$.

From Table 4.3, we also find the the weighted metrics are usually consistent with their corresponding unweighted metric. One exception is that QF-J performs better

Table 4.5: Top 5 item features, ranked by absolute weights

Feature	Weight
listTF.listIDF	2.6424
listSF	2.1374
wDF	-1.0754
TF.clueIDF	1.0115
SF	0.6873

than QF-I in FT, but it does slightly worse than QF-J in wFT. This is likely to be caused by the high recall for QF-I, which may include more highly rated facet terms.

4.4.3 Clustering Facet terms

Table 4.6 shows clustering performance of the five models, which are tuned on wFP. The improvements of QF-I and QF-J over the other three models shown are all significant ($p < 0.05$, using paired t-test). pLSA and LDA do not perform well in clustering, which could be caused by data sparsity. There are on average 5159 candidate lists per query, but only 3.9 items per list.

Table 4.6: Facet clustering performance tuned on wPF

Model	Purity	NMI	PF	wPF
pLSA	0.793	0.524	0.230	0.229
LDA	0.773	0.511	0.227	0.226
QDM	0.871	0.565	0.367	0.380
QF-I	0.843	0.606	**0.408**	**0.410**
QF-J	**0.922**	**0.631**	0.352	0.346

Table 4.7: Weights learned for item pair features

Feature	Weight
listContextSim	1.4944
textContextSim	0.7186
listCooccur	0.0817
lengthDiff	0.0563

The better performance in clustering for QF-I and QF-J can be explained by their incorporating factors other than list item co-occurrence information. In Table 4.7, we list the weights learned for item pair features. Besides one item co-occurrence related feature, *listContextSim*, we also find that *textContextSim* has a relatively high weight. *textContextSim* is used to capture the similarity of the two list items using their surrounding text, so it can help to group two facet terms together even if they might not co-occur a lot in candidate lists. As an example, for the query *baggage allowance*, we find different airlines do not co-occur a lot in candidate lists, (e.g. *delta* and *jetblue* only co-occur twice), but they tend to have high *textContextSim* (e.g. $textContextSim(delta, jetblue) = 0.81$), and are therefore grouped together by QF-I and QF-J.

4.4.4 Overall Evaluation

To compare overall effectiveness of the five models, we tune all the models on wPRF, and the results are reported in Table 4.8.

Table 4.8: Overall performance tuned on wPRF

Model	wTP	wTR	wPF	wPRF
pLSA	0.353	0.630	0.229	0.309
LDA	0.358	**0.670**	0.225	0.311
QDM	0.523	0.388	0.253	0.319
QF-I	0.450	0.667	**0.399**	**0.444**
QF-J	**0.534**	0.526	0.346	0.417

Unweighted metrics are very similar to their corresponding weighted metrics in terms of conclusions, and are omitted due to space limitation. Results here are consistent with the results that were tuned on wFT or wFP. pLSA and LDA have high recall, but low precision and FP. QDM has relatively high precision, but low recall and FP. It has on average 68 facet terms per query as output, and fails to

improve the overall effectiveness when including more facet terms in its output. QF-I and QF-J are among the best two models according to both PRF and wPRF.

Since wPRF does not account for facet ranking effectiveness, we also report fp-NDCG and rp-NDCG tuned on themselves in Table 4.9. QF-J gives the best performance for both fp-NDCG and rp-NDCG. The improvements of QF-I and QF-J over the other three models shown in the Table 4.8 and 4.9 are all significant ($p < 0.05$, using paired t-test), except the improvements of QF-J over QDM for wP and QF-I over QDM for fp-nDCG.

Table 4.9: fp-nDCG and rp-nDCG tuned on themselves

Model	fp-nDCG	rp-nDCG
pLSA	0.250	0.071
LDA	0.238	0.063
QDM	0.257	0.093
QF-I	0.290	0.157
QF-J	**0.336**	**0.193**

4.5 Summary

In this chapter, we designed intrinsic evaluation to directly evaluate generated query facets by comparing them with human created ones. We designed an new evaluation metric that combines recall and precision of facet terms with grouping quality. Experimental results show that our supervised method (QF-I/QF-J), described in Chapter 3, can take advantage of a richer set of features and outperforms other unsupervised methods.

One thing we note is that term precision tends to be low while recall is high in these results. In the next chapter, we explore methods for boosting precision on the assumption that it is often very important.

CHAPTER 5

PRECISION-ORIENTED QUERY FACET EXTRACTION

5.1 Introduction

While the query facet extraction approach presented in Chapter 3, provides a promising direction for solving the open-domain facet generation problem, it neglects the precision-oriented perspective of the task, which we believe is important in practical use. As in many precision-oriented information retrieval tasks, we believe users are likely to care more about "facet precision" than "facet recall". That is, users may care more about the correctness of presented facets (*e.g.*, are the terms in the airline facet indeed about airlines, and are the airline terms grouped together in a same facet) than the completeness of facets (*e.g.*, are all possible facets for that query presented, and are all possible airline terms included the results?). In other words, mistakes of presenting wrong terms in a facet, or grouping terms incorrectly are more severe than omitting some facets or terms in facets. The work presented in Chapter 3 and Chapter 4 does not consider this precision-oriented factor when designing query facet extraction models or evaluating extraction results. Therefore, it is unclear if these models can adapt to such scenarios.

In this chapter, we study query facet extraction under the precision-oriented scenario, and improve extraction performance under precision-oriented scenarios from two perspectives.

First, we find the learning objective used in our query faceting models are not ideal for the task especially under the precision-oriented scenario. The proposed model is trained by maximum likelihood estimation on labeled training data. However,

likelihood can be loosely related to the performance measure under the precision-oriented scenario. In this chapter, we propose to directly directly maximizing the performance measure $PRF_{\alpha,\beta}$ instead of likelihood during training using a empirical utility maximization (EUM) approach. However, exact optimization on the performance measure is difficult due to the non-continuous and non-differentiable nature of information retrieval measures. We address this problem by approximating the performance measure using its expectation. We show that this empirical utility maximization approach significantly improves over previous approaches under precision-oriented scenarios, suggesting utility is a better learning objective than likelihood, and our expectation-based approximation is effective.

Second, we improve extraction performance by an selective method that shows facets for good performing queries and avoid poor performing ones. We find that extraction performance varies for different queries – some queries are naturally more difficult than others for extracting query facets. In the precision-oriented scenario, it may be more desirable to avoid showing facets for those poor performing queries and leave the users with a clean keyword-search interface. A key problem, however, is how to predict the extraction performance. To solve this problem, we propose a simple and effective score based on the expectation of the performance measure. We find the score has a strong correlation with the performance measure, and when used in the selective method, it can significantly improve the average performance with fair coverage over the whole query set.

The rest of this chapter is organized as follows. In Section 5.2, we briefly review related work. In Section 5.3, we revisit the $PRF_{\alpha,\beta}$ measures used in intrinsic evaluation (Chapter 4) in order to help develop our empirical utility maximization approach in Section 5.4, and our selective method for query faceting in Section 5.5. We carry out experiments in Section 5.6.

5.2 Related Work

5.2.1 Directly Optimizing Performance Measures

Lots of previous work has proposed to directly optimize performance measures in learning for various information retrieval tasks, including ranking (Xu et al., 2008; Xu and Li, 2007; Cossock and Zhang, 2006; Quoc and Le, 2007; de Almeida et al., 2007) and classification (Musicant et al., 2003; Joachims, 2005; Jansche, 2005). While higher performance is expected by doing so, it is usually difficult due to the non-continuous and non-differentiable nature of information retrieval measures. From the perspective of the loss function optimization, existing solutions fall into three categories (Xu et al., 2008). First, one can minimize upper bounds of the basic loss function defined on the performance measures (Xu and Li, 2007; Joachims, 2005; Yue et al., 2007). Second, one can approximate the the performance measures with functions that are easy to handle (Jansche, 2005; Cossock and Zhang, 2006). Our work belongs to this category; it approximates the performance measure using a continuous function based on its expectation. Third, one can use specially designed technologies for optimizing the non-smooth performance measures (Quoc and Le, 2007; de Almeida et al., 2007).

More related to our problem, Jansche proposed to train a logistic regression model by directly optimizing F-measures (Jansche, 2005). The work approximated integer quantities in F-measures based on their probabilities, and thus made the optimization target continuous and differentiable. Then it trained the logistic regression model by optimizing the approximated F-measures on the training data. The method is also referred as empirical utility maximization (or empirical risk minimization) (Ye et al., 2012), which maximizes the expected utility (or performance) by its average utility on the training data as an approximation. The model and measure we study in this paper (see Section 3.6 and 4.3) is similar to Jansche's work, and we use similar approximation strategy in order to perform direct optimization on the performance measure.

5.2.2 Performance Prediction and Selective Methods

Previous work on performance prediction in information retrieval primarily focused on the core ranking problem. Many predictors/scores has been introduced for predicting retrieval performance, such as clarity score (Cronen-Townsend et al., 2002), average IDF (Tomlinson, 2004) and robustness score (Zhou and Croft, 2006). Learning methods, such as regression models, has also been used to combine different factors for predicting retrieval performance (Kwok et al., 2004; Balasubramanian et al., 2010; Yom-Tov et al., 2005).

One application of retrieval performance prediction is to allow the systems to invoke alternative retrieval strategies for different queries according to their performance. For example, Yom-Tov et al. (Yom-Tov et al., 2005) and Amati et al. (Amati et al., 2004) both showed that retrieval performance prediction can be used to improve the effectiveness of a search engine, by performing selective automatic query expansion for "easy" queries only. Our selective method for query facet extraction is similar as these methods in spirit – we want to selectively apply query facet extraction for "easy" queries only. However, to the best of our knowledge, no existing work has studied performance prediction for query facet extraction.

5.3 $PRF_{\alpha,\beta}$ Measure

Our empirical utility maximization approach and selective method for query faceting are based on the $PRF_{\alpha,\beta}$ measure that was introduced in Chapter 4. In this section, we revisit this measure, and formulate it in a way that will make the development for the utility maximization approach and the selective method easier. This measure will also be used for evaluating query facet extraction under precision-oriented scenarios in Section 5.6.

Recall that the $PRF_{\alpha,\beta}$ measure combines term precision, term recall, and term clustering perform. We will now re-formulate these factors in the following sections.

As before, to help describe the measure, we will use superscript "$*$" to distinguish ground truth from system output. For example, y_i^* is a ground truth term label, while y_i is a term label predicted by the system. $T_{\mathcal{F}}^*$ is a set consisted by all the terms in the ground truth facets, while $T_{\mathcal{F}}$ is consisted by all terms in the system extracted facets.

5.3.1 Term Precision and Recall

In $PRF_{\alpha,\beta}$, the classification performance is measured by term precision (*i.e.*, precision of the selected candidate terms being facet terms) and term recall (*i.e.*, recall of facet terms). They can be formulated as below, where subscript "c", "s", "g" stands for "correct", "system", "ground truth" respectively.

- term precision: $TP = \frac{T_c}{T_s}$, where T_c is the number of correct facet term selected, T_s is the number of terms select by the system.

- term recall: $TR = \frac{T_c}{T_g}$, where T_c is as defined above, T_g is the number of facet terms in the ground truth.

- term F1: $TF = \frac{2T_c}{T_s+T_g}$ is the F1 combination (or the harmonic mean) of TP and TR.

Quantity T_c, T_s, T_g can be more precisely defined using term labels y_i and y_i^* as

$$T_c = \sum_i y_i y_i^*, \;\; T_s = \sum_i y_i, \;\; T_g = \sum_i y_i^*. \tag{5.1}$$

5.3.2 Term clustering

system fails to find a facet term, by assuming it being a singleton, the clustering performance will be hurt (unless the facet term is a singleton in the ground truth). Empirically, we find systems return large sized facets when tuned on term clustering performance based on the adjusting. For example, on average, QFI returns 509.8

terms per query, while there is only 81.2 facet terms per query in the ground truth. Therefore by combining term precision, recall and clustering performance, $PRF_{\alpha,\beta}$ actually double-counts the term recall factor by this adjusting when measuring clustering performance.

In $PRF_{\alpha,\beta}$, term clustering performance is measured by pair-counting F1 measure after clustering adjusting 4.3.3. Here the pair-counting F1 measure treats term clustering as classification on whether each pairs of terms are in a same facet, and then combines pair precision and recall using F1 measure. Pair precision and recall can be formulate as below. (The subscripts carry the same meaning as in term precision and recall.)

- pair precision: $PP = \frac{P_c}{P_s}$, where P_c is the number of term pairs the model clustered together that are indeed in a same facet in the ground truth, P_s is the number of term pairs the model clustered together.

- pair recall: $PR = \frac{P_c}{P_g}$, where P_c is as defined above, T_g is the number of term pairs clustered together in the ground truth.

- pair F1: $PF = \frac{2P_c}{P_s + P_g}$ is the F1 combination (or the harmonic mean) of PP and PR.

Quantity P_c, P_s, P_g can be more precisely defined using term labels y_i, y_i^* and pair labels $z_{i,j}$, $z_{i,j}^*$ as

$$P_c = \sum_{i,j} z_{i,j} z_{i,j}^*, \; P_s = \sum_{i,j} z_{i,j} y_i^* y_j^*, \; P_g = \sum_{i,j} z_{i,j}^* y_i y_j, \tag{5.2}$$

where term labels y_i, y_i^* are used to perform the overlap adjusting as described previously.

5.3.3 Combining term precision, recall and clustering

The quality of query facet extraction is intrinsically multi-faceted. Different applications or scenarios might have different emphasis in the term precision, recall and clustering. To address this issue, $PRF_{\alpha,\beta}$ combines the three factors together, using weighted harmonic mean. We repeat its formulation as below,

$$PRF_{\alpha,\beta}(TP, TR, PF) = \frac{(\alpha^2 + \beta^2 + 1)}{\frac{\alpha^2}{TP} + \frac{\beta^2}{TR} + \frac{1}{PF}}. \tag{5.3}$$

Note that $\alpha, \beta \in [0, +\infty)$ are used to control the weight between the three factors. α and β can be interpreted as the importance of TP and TR compared to PF respectively (Section 4.3.4).

To evaluate query facet extraction under the precision-oriented scenario, we can set a high α and/or low β. For example, we can set $\alpha = 2, \beta = 1$ to evaluate the case where TP is twice important than TR and PF. Perhaps more reasonably, we can only down-weight the recall factor, by setting $\alpha = 1, \beta = 1/3$ to evaluate the case where TP and PF is three times important than TR.

To help develop our empirical utility maximization approach, we rewrite $PRF_{\alpha,\beta}$ as a function of term and pair quantities $(T_c, T_s, T_g, P_c, P_s, P_g)$ as

$$PRF_{\alpha,\beta}(T_c, T_s, T_g, P_c, P_s, P_g) = \frac{2(\alpha^2 + \beta^2 + 1)T_c T_p}{2\alpha^2 T_s P_c + 2\beta^2 T_g P_c + T_c P_s + T_c P_g}. \tag{5.4}$$

It is easy to see $PRF_{\alpha,\beta}$ can be also rewritten as a function of predicted labels and ground truth labels as $PRF_{\alpha,\beta}(Y, Z, Y^*, Z^*)$ by substituting term and pair quantities using Equation 5.1 and 5.2.

5.4 Empirical Utility Maximization

In this section, we describe our empirical utility maximization (EUM) approach that directly optimize $PRF_{\alpha,\beta}$ for training QF model (described in Section 3.6).

The QF model can be viewed as a model which takes in candidate terms and term pairs and predicts their labels, $(Y, Z) = h(T_{\mathcal{L}}, P_{\mathcal{L}}; \lambda, \mu)$. The parameters λ, μ are trained by maximizing the conditional likelihood of the labels, $l(\lambda, \mu)$ as defined in Equation 3.5. One problem with the maximum likelihood estimation is the likelihood target can be loosely related to performance measure $PRF_{\alpha,\beta}$, especially in the precision-oriented scenario, where term recall are less important than other factors (, as we will show in Section 5.6).

Therefore, we propose an alternative way of training the model $h(T_{\mathcal{F}}, P_{\mathcal{F}})$ by directly optimizing $PRF_{\alpha,\beta}$ measure. Our goal is to maximize the expected utility (or performance),

$$E_{\mathcal{P}}\big[PRF_{\alpha,\beta}(h(T_{\mathcal{L}}, P_{\mathcal{L}}), Y^*, Z^*)\big], \tag{5.5}$$

where $\mathcal{P}$ is the underlying and unknown distribution of our data $(T_{\mathcal{L}}, P_{\mathcal{L}}, Y^*, Z^*)$. In order to train the model, empirical utility maximization (or equivalently empirical risk minimization) is usually used, which tries to maximizes the above utility objective function over empirical data, $\mathcal{D} = \{T_{\mathcal{L}}^{(i)}, P_{\mathcal{L}}^{(i)}, Y^{*(i)}, Z^{*(i)} | i = 1...n\}$. The empirical utility is given below,

$$
\begin{aligned}
U(\lambda, \mu) &= E_{\mathcal{D}}\big[PRF_{\alpha,\beta}(h(T_{\mathcal{L}}, P_{\mathcal{L}}), Y^*, Z^*)\big] \\
&= \frac{1}{n}\sum_{i=1}^{n} PRF_{\alpha,\beta}(T_c^{(i)}, T_s^{(i)}, T_g^{(i)}, P_c^{(i)}, P_s^{(i)}, P_g^{(i)}),
\end{aligned}
\tag{5.6}
$$

where we use the uniform distribution over empirical data to replace the unknown distribution, and replace the $PRF_{\alpha,\beta}$ term with $PRF_{\alpha,\beta}$ calculation based on term and pair quantities $PRF_{\alpha,\beta}(T_c, T_s, T_g, P_c, P_s, P_g)$ as defined in Equation 5.4.

Our goal now is to find $(\lambda, \mu) = \text{argmax}_{\lambda,\mu} U(\lambda, \mu)$. Unfortunately, this objective is difficult to optimize. The basic quantities involved are integers, and the optimization objective is a piecewise-constant function of the parameters λ, μ. The non-smoothness

is due to that the dependent variable y_i and $z_{i,j}$ take only discrete values $\{0, 1\}$. For example, $U(\lambda, \mu)$ contains integer quantity $T_c = \sum_i y_i y_i^*$ that counts the correct facet terms labeled. According to QFI (see Section 3.6.4), y_i is predicted as either 1 or 0 by thresholding its term probability $P(y_i = 1|t_i)$ as:

$$y_i = 1\{P(y_i = 1|t_i) > w_{min}\}, \tag{5.7}$$

where $P(y_i = 1|t_i) = \frac{1}{1+\exp\{-\sum_k \lambda_k f_k(t_i)\}}$ (defined in Equation 3.1) involves parameter λ.

In generally, we can approximate discrete variables by their expectation to obtain a smooth objective function (Jansche, 2005). In our case, by assuming independence between all the labels, y_i can be approximated by its expectation as,

$$\widetilde{y}_i = E[y_i] = P(y_i = 1|t_i) = \sigma(\lambda^T f(t_i)), \tag{5.8}$$

where we use $\sigma(x) = \frac{1}{1+\exp\{-x\}}$ to denote the logistic function used in Equation 3.1, and use vector-representation for λ and feature $f(t_i)$ for convenience. Similarly, we approximate $z_{i,j}$ by its expectation assuming full independent condition as

$$
\begin{aligned}
\widetilde{z}_{i,j} = E[z_{i,j}] &= P(z_{i,j} = 1, y_i = 1, y_j = 1|t_i, t_j, p_{i,j}) \\
&= P(z_{i,j} = 1|p_i, y_i = 1, y_j = 1)P(y_i = 1|t_i)P(y_j = 1|t_j) \\
&= \sigma(\mu^T g(p_{i,j}))\sigma(\lambda^T f(t_i))\sigma(\lambda^T f(t_j)).
\end{aligned}
\tag{5.9}
$$

In the same way, we can approximate term and pair quantities (*i.e.*, T_c, T_s, P_c, P_s, P_g) by their expectation. It is easy to see that, under the full independence assumption between all labels, their expectation can be obtained by substituting y_i and $z_{i,j}$ in

Equation 5.1 and 5.2 with their expectation $E[y_i]$ and $E[z_{i,j}]$. For example, we can approximate $T_c \approx \widetilde{T}_c$ by

$$\widetilde{T}_c = E[T_c] = \sum_i E[y_i]y_i^* = \sum_i \sigma(\lambda^T f(t_i))y_i^*. \tag{5.10}$$

Based on the approximated term and pair quantities, we can rewrite our optimization objective as

$$\widetilde{U}(\lambda, \mu) = \frac{1}{n}\sum_{i=1}^n PRF_{\alpha,\beta}(\widetilde{T}_c^{(i)}, \widetilde{T}_s^{(i)}, T_g^{(i)}, \widetilde{P}_c^{(i)}, \widetilde{P}_s^{(i)}, \widetilde{P}_g^{(i)}), \tag{5.11}$$

which can now be maximized numerically. More specially, we used gradient ascent for maximizing $\widetilde{U}(\lambda, \mu)$. The derivatives of $\widetilde{U}(\lambda, \mu)$ can be easily obtained based on the derivatives of $\widetilde{y}_i$, $\widetilde{z}_{i,j}$, as we given below,

$$\begin{aligned}
\nabla_\lambda \widetilde{y}_i(\lambda) &= \sigma_i(1 - \sigma_i)\lambda, \\
\nabla_\lambda \widetilde{z}_{i,j}(\lambda) &= \sigma_{i,j}\sigma_i\sigma_j(2 - \sigma_i - \sigma_j)\lambda, \\
\nabla_\mu \widetilde{z}_{i,j}(\mu) &= \sigma_i\sigma_j\sigma_{i,j}(1 - \sigma_{i,j})\mu,
\end{aligned} \tag{5.12}$$

where $\sigma_i \equiv \sigma(\lambda^T f(t_i))$, $\sigma_{i,j} \equiv \sigma(\mu^T g(p_{i,j}))$. Note that the function $\widetilde{U}(\lambda, \mu)$ is generally not concave. We can deal with this problem by taking the maximum across several runs of the optimization algorithm starting from random initial values. After training, we use the original inference QFI and QFJ as describe in Section 3.6.4 to predict labels and induce facets.

5.5 Selective Query Faceting Based on Performance Prediction

In this section we describe selective query faceting – our selective method for query facet extraction. The idea is motived by the variance in extraction performance we

observed – depending on the nature of queries and extraction models, quality of the extracted facets varies drastically from excellent to poor and complete noise. For example, queries about products, such as "toilet" and "volvo", tend to have more high-quality candidate facets extracted and are therefore easier than other complex queries, such as "self motivation", to find query facets. In Figure 5.1, we show that $PRF_{\alpha,\beta}$ could range from 0 to above 0.8 with relatively high variance.

Figure 5.1: $PRF_{\alpha=1,\beta=1}$ performance distribution for QFI trained based on likelihood.
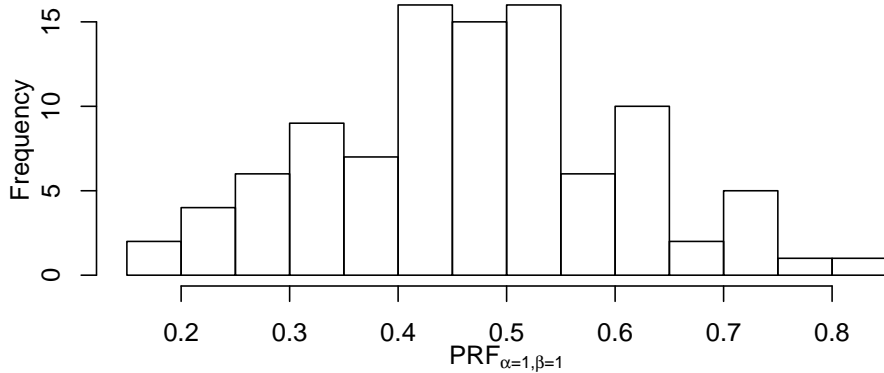
5.5.1 Selective Query Faceting

Similar as the idea of selective query expansion (Yom-Tov et al., 2005; Amati et al., 2004) we can selectively present facets to users based on the extraction performance of each queries. Ideally, we can only show facets for good performing queries and avoid bad ones to improve user satisfaction, as in the precision-oriented scenario, it may be more desirable to leave users with a clean keyword-search interface than showing poor-quality facets. To support this selective query faceting, a key problem need to be addressed is the prediction of extraction performance. We find a simple score based on the expectation of $PRF_{\alpha,\beta}$ could predict extraction performance fairly well. Next, we will describe our extraction performance prediction method.

5.5.2 Performance Prediction

In performance prediction, our goal is to predict the extraction performance for a given query with its extracted facets. We focus on predicting $PRF_{\alpha,\beta}$, and leave prediction of other measures as future work. The prediction could be done by using single indicator scores (like the clarity score in prediction retrieval performance (Cronen-Townsend et al., 2002)), or by combining different features using regression or classification models. No matter which approach, we first need to find good indicators/features for estimating the performance.

To find effective features, a natural way is to investigate the probabilistic model we have already learned in the QF method, because the learned probabilities already incorporate beliefs about the correctness of corresponding outputs. For example, we can use the term probability defined in Equation 3.1 to estimates the "likelihood" of the output terms are indeed facet terms, and use the pairs probability defined in Equation 3.2 to estimated the "likelihood" of the term pairs in a same extracted facets indeed belong to a query facet.

In order to use the term and pair probabilities as features, we need to aggregate them in some ways, because these probabilities are for terms and pairs, not directly for whole extracted facet set. We investigates two ways of aggregation. First, from the perspective of data fitness, we can directly use log-likelihood of extracted facets to measure the fitness. For example, we can use the whole log-likelihood based on Equation 3.5, and we can also use the log-likelihood for only the terms or only the pairs based on the first term and second terms in the equation respectively.

Second, from the perspective of directly estimating utility (performance), we can aggregate the probabilities for estimating $PRF_{\alpha,\beta}$ directly in a similar way as our empirical utility maximization approach. More specially, we can estimate $PRF_{\alpha,\beta}$ performance based on the expected term and pair quantities under the learned model. The estimates can be obtained as follows,

$$\widehat{TP} = \frac{\sum_i P(t_i)y_i}{\sum_i y_i}, \quad \widehat{TR} = \frac{\sum_i P(t_i)y_i}{\sum_i P(t_i)},$$
$$\widehat{PT} = \frac{\sum_{i,j} P(p_{i,j})z_{i,j}}{\sum_{i,j} z_{i,j}}, \quad \widehat{PR} = \frac{\sum_{i,j} P(p_{i,j})z_{i,j}}{\sum_{i,j} P(p_{i,j})y_i y_j},$$

$$(5.13)$$

where we use $P(t_i) \equiv P(y_i = 1 | t_i)$, $P(p_{i,j}) \equiv P(z_{i,j} = 1 | p_{i,j}, y_i = 1, y_j = 1)$ for simplification. Estimates of TF, PF and can be easily obtained by substitute TP, TR, PP, PR with their estimates in the corresponding equations in Section 5.3. Estimate of $PRF_{\alpha,\beta}$ can be obtained by substituting TP, TR and PF with their estimates in Equation 4.1. We call this estimate of $PRF_{\alpha,\beta}$ "PRF score".

To investigate the effectiveness of the two types of features, we analyze the correlation between extraction performance and each individual features. We show the correlation results for QFI's $PRF_{\alpha=1,\beta=1}$ performance in Table 5.1. (QFI is tested using cross-validation on QF13 dataset, which will be described in Section 5.6, under maximum likelihood estimation training. Observations are similar for other runs.)

In the table, utility-based feature TP, TR, PP, PR, TF, PF, PRF (PRF score) are estimated according to Equation 5.13 as described before. Likelihood-base feature $LL_{sum} = \sum_i \log P(y_i | t_i) + \sum_{i,j} \log P(z_{i,j} | p_{i,j}, y_i, y_j)$ calculates likelihood of extracted facets based on Equation 3.5. tLL_{sum} and pLL_{sum} separate log-likelihood that accounts for term and pair in LL_{sum}. Average log-likelihoods tLL_{avg}, pLL_{avg} are calculated by average tLL_{sum} and pLL_{sum} by the number of candidate terms $tSize$ and the number of pairs of selected terms (i.e., $y_i = 1$), $pSize$. In Table 5.1, first we can see that PRF score has strong correlation with the performance $PRF_{\alpha=1,\beta=1}$. This suggest 1) PRF score is a good indicator for extraction performance, and might be effective in performance prediction, and 2) our estimation of $PRF_{\alpha=1,\beta=1}$ based on its expectation is effective. Second, we can see utility-based features PRF, TF, TR correlate better with $PRF_{\alpha,\beta}$ performance than other likelihood-based features. This validates our assumption that likelihood can be loosely related to the performance measure, and utility could be a better optimization objective. First, we find that PRF score has

Table 5.1: The correlation of the individual features with QFI's $PRF_{\alpha=1,\beta=1}$ performance. QFI is tested using cross-validation on QF13 dataset under maximum likelihood estimation training. Feature name abbreviation explanation: initial "t" – "term", initial "p" – "pair", LL – "log-likelihood", avg – "average", "std" – "standard deviation", $tSize$ – $|T_{\mathcal{L}}|$, $pSize$ – $|P_{\mathcal{F}}|$.

Feature	Correlation	P-value
PRF	0.6249	3.6×10^{-12}
TF	0.5933	7.7×10^{11}
TR	0.5817	2.2×10^{-10}
tLL_{avg}	0.5709	5.5×10^{-10}
$tProb_{sum}$	0.5527	2.4×10^{-9}
$tSize$	0.5512	2.8×10^{-9}
PF	0.4962	1.5×10^{-7}
PR	0.4878	2.6×10^{-7}
pLL_{sum}	-0.4513	2.4×10^{-6}
$pSize$	0.4487	2.8×10^{-6}
$pProb_{sum}$	0.4435	3.8×10^{-6}
LL_{sum}	-0.4371	5.4×10^{-6}
PP	0.4015	3.4×10^{-5}
TP	0.3336	6.9×10^{-4}
pLL_{avg}	0.3329	7.1×10^{-4}
$pProb_{std}$	-0.3162	0.0014
tLL_{sum}	-0.2317	0.0203
$pProb_{min}$	-0.1984	0.0478
$tProb_{min}$	-0.1391	0.1674
$tProb_{std}$	-0.1094	0.2787
$tProb_{max}$	0.03447	0.7335

strong correlation (0.6249 with p-value 3.6×10^{-12}) with the performance $PRF_{\alpha=1,\beta=1}$. This suggest 1) PRF score is a good indicator for extraction performance, and might be effective in performance prediction, and 2) our estimation of $PRF_{\alpha=1,\beta=1}$ based on its expectation is effective. Second, we find utility-based features PRF scores, $\widehat{TF}, \widehat{TR}$ correlate better with $PRF_{\alpha,\beta}$ performance than other likelihood-based features. This validates our assumption that likelihood can be loosely related to the performance measure, and utility could be a better optimization objective.

We combine the proposed features in linear regression and logistic regression models. However, we find the results are not significantly better than simply using PRF

score for prediction, which could be caused by the linear dependence between those features. Thus, we propose to use only *PRF* score for extraction performance prediction, which is simple and effective as we will show in Section 5.6. We also test other features based on statistic aggregates of the term and pair probabilities, including minimum, maximum, mean, sum and standard deviation. However, they show relatively low correlation with $PRF_{\alpha,\beta}$, and thus we do not report the results here.

After choosing PRF score as the performance predictor, selective query faceting can be easily done by thresholding this score to decide to show or avoid showing query facet results for each query. We carry out experiments to evaluate its effectiveness in Section 5.6.

5.6 Experiments

Our experiments aim to investigate mainly three research questions. First, we want to test whether existing query facet extraction methods adapt to precision-oriented scenarios. Second, we want to test if our empirical utility maximization approach is effective in precision-oriented scenarios. Last, we want to test whether the PRF score can effectively predict extraction performance, and support selective query faceting. We will first describe our experimental settings, then present experiment results for each of the research questions.

5.6.1 Experimental Settings

5.6.1.1 Data

We use the same data set as in Chapter 4. We call the data set QF13. QF13 contains 100 web search queries, their top 100 web search results from a commercial web search engine, and their query facet annotation. The query facet annotation was done by pooling facet results from different models, and then having the pooled terms

re-grouped by human annotators into query facets. Our candidate lists are extracted as described in Chapter 3.

5.6.1.2 Evaluation

We use $PRF_{\alpha,\beta}$ as the evaluation measures, as well as term precision (*i.e.*, *TP*), term recall (*i.e.*, *TR*), and term clustering F1 (*i.e.*, *PF*). We choose this measure because it has the flexibility of adjusting emphasis between "facet precision" and "facet recall", which naturally suits well with the precision-oriented problem. When $\alpha = \beta = 1$, $PRF_{\alpha=1,\beta=1}$ is used to evaluate the case where term precision, term recall and term clustering are equally important. To evaluate facets under precision-oriented scenarios, we set high $\alpha \in \{2, 3, \ldots, 10\}$ with fixed $\beta = 1$. The settings correspond to the cases where term precision is twice to ten times important as both term recall and term clustering. Without any prior knowledge, it is more fair to assume that term precision and clustering are equally important (they are both "precision" factors for query facets), therefore we will focus more on only down-weight term recall by setting $\beta \in \{\frac{1}{2}, \frac{1}{3}, ..., \frac{1}{10}\}$ or equivalently $\frac{1}{\beta} \in \{2, 3, \ldots, 10\}$ with fixed $\alpha = 1$. The settings correspond to the case where term precision and clustering is twice to ten times importance as term recall. As before, we evaluate top 10 facets returned from each models.

We use 10-fold cross validation on QF13 for training, tuning (if applicable) and testing models. Models are tuned on the same $PRF_{\alpha,\beta}$ measure that they are tested on. Unless specified else, statistically significant test is performed by using paired t-test with 0.05 as the p-value threshold.

5.6.1.3 Methods

We study five query facet extraction models briefly summarized as below.

- pLSA and LDA (Section 3.7): pLSA and LDA was applied on candidate facets for facet refining. After training, the topics are returned as query facets, by

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using top terms in each topic. We tune the number of facets and number of facet terms in each facets. The topic model methods in facet refining only use term co-occurrence information.

- QDM (Section 3.7): this is an unsupervised clustering method that applies a variation of the Quality Threshold clustering algorithm (Heyer et al., 1999) to cluster the candidate facets with bias towards important ones. This method incorporates more information than just term co-occurrence, but it is not easy to add new features into the model to further improve the performance. We tune the diameter threshold, weight threshold for valid cluster and the threshold for selecting terms.

- QFI and QFJ (Section 3.6.4): the two models incorporate a rich set of features and learn from labeled data. They are reported to be the best across several evaluation measures in Chapter 4, therefore we primarily focus on them. Except for the difference of independent and joint inference, the two models are different in that QFI has tuning parameters that can be tuned for given measures, while QFJ do not, as it tries to optimize log-likelihoods. For QFI, we tune the weight threshold for facet terms w_{min}, and the diameter threshold d_{max}. There are no tuning parameters for QFJ.

We study two ways of training the graphical model (see Section 3.6) for QFI and QFJ.

- MLE (Section 3.6.3): Uses conditional likelihood as the optimization objective and performs maximum likelihood estimating for training.

- EUM (Section 5.4): since likelihood can loosely related to the performance measure, we propose to use empirical utility maximization to directly optimize the $PRF_{\alpha,\beta}$ measure during training. We approximate $PRF_{\alpha,\beta}$ by its expectation

in order to enable numerical optimization. With different α, β, we can use different versions of $PRF_{\alpha,\beta}$ as the optimization objective. We test three runs by setting $(\alpha=1, \beta=1)$, $(\alpha=2, \beta=1)$, $(\alpha=1, \beta=\frac{1}{2})$. We denote the different runs by add α, β subscript in "EUM" (*e.g.*, $EUM_{2,1}$ stands for EUM training using $PRF_{\alpha=2,\beta=1}$ as the optimization objective).

5.6.2 Existing Methods Under Precision-Oriented Scenarios

We first investigate if the five existing models can adapt to precision-oriented scenarios by evaluation based on $PRF_{\alpha,\beta}$ with different α, β settings. In Figure 5.2, we show $PRF_{\alpha,\beta}$ performance of different α (*i.e.*, term precision is more important than term recall and clustering) on the left, and of different β (*i.e.*, term precision and clustering are more important than term recall) on the right. We test all the five models with QFI, QFJ trained by MLE.

First, we find QFJ does not adapt well to precision-oriented scenarios. From the figure, we can see the superiority of QFJ over other models becomes less evident, when moving from the normal case to precision-oriented cases. This is due to that QFJ tries to optimize log-likelihood for inferencing, and it cannot be tuned on the performance measures like other models. So it returns the same results for the normal case and precision-oriented scenarios. Second, we find generally QFI and QDM can adapt better than the other models to the precision-oriented scenarios, with QFI consistently better than all the other models on both datasets. The adaptability of the two models can be explained by their tuning procedure. For example, depending on the target performance measure, QFI can set different threshold w_t for select facet terms. Overall, we find QFI (under MLE training) is the best among these existing models for the normal case, as well as precision-oriented cases.

To further analyze how QFI adapt to the precision-oriented scenarios, in Table 5.2, we report $PRF_{\alpha,\beta}$ together with *TP*, *TR*, *PF* and facet size (the total number of terms

Figure 5.2: $PRF_{\alpha,\beta}$ performance with different α (left, fixed $\beta=1$) and different β (fixed $\alpha=1$, right) settings for existing methods on QF13.

(a) QF13, $PRF_{\alpha,\beta=1}$
(b) QF13, $PRF_{\alpha=1,\beta}$
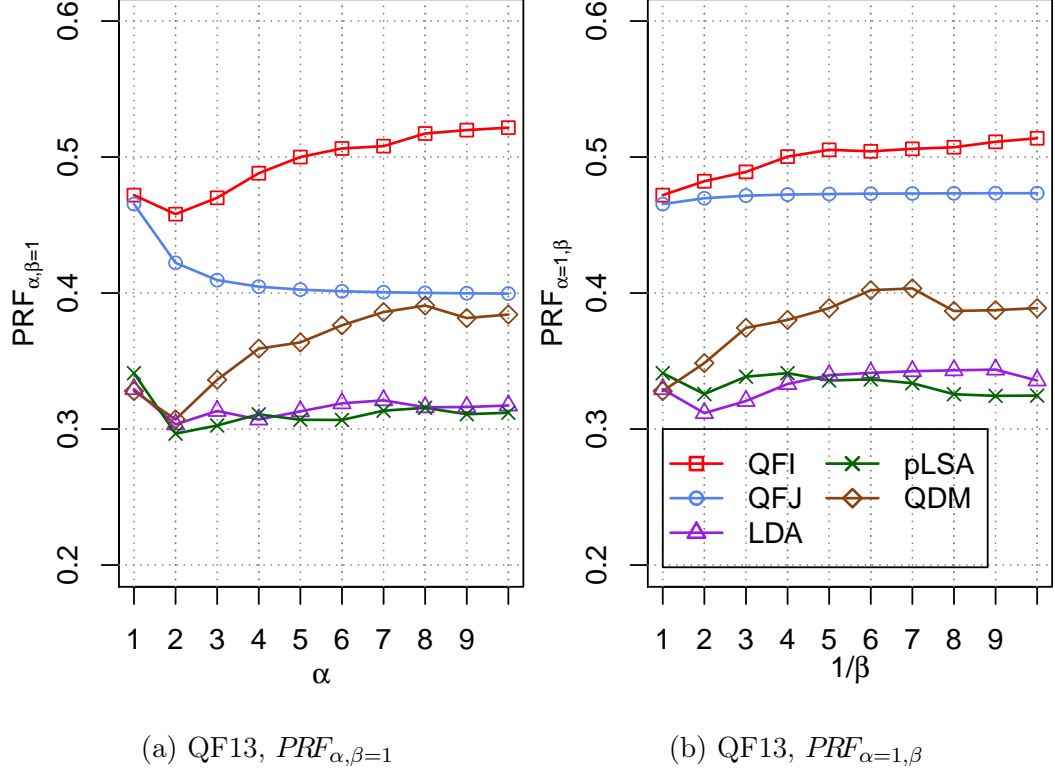
returned for a query) when setting different β in $PRF_{\alpha,\beta}$. From Table 5.2, we find

Table 5.2: $PRF_{\alpha,\beta}$ performance with its TP, TR, PF under different β settings (fixed $\alpha=1$) for QFI on QF13. "Size" reports the average number of terms returned for each queries.

$\frac{1}{\beta}$	$PRF_{\alpha,\beta}$	TP	TR	PF	Size
1	0.4720	0.4450	0.4881	0.6209	89.5
2	0.4822	0.4896	0.4186	0.6192	70.7
3	0.4891	0.5108	0.3574	0.5989	56.5
4	0.5003	0.5291	0.3498	0.5925	53.0
5	0.5053	0.5348	0.3306	0.5928	48.9
6	0.5042	0.5343	0.3194	0.5834	47.1
7	0.5060	0.5343	0.3194	0.5834	47.1
8	0.5072	0.5343	0.3194	0.5834	47.1
9	0.5112	0.5364	0.3172	0.5864	46.7
10	0.5138	0.5365	0.3097	0.5824	45.2

that as term recall factor becomes less and less important (or equivalently as the precision factors becomes more and more important), QFI becomes more and more conservative in selecting terms. The number of terms returned on average for each queries ("size" in the table) decreases from 89.5 to 45.2. Term precision TP thus increases significantly, while term recall TR and term clustering PF decreases. This indicates, by tuning on the performance measure, QFI tries to find a good balance between the tree factors for each scenarios.

5.6.3 Empirical Utility Maximization Performance

Next, we compare EUM and MLE training to test the effectiveness of the EUM approach we proposed. We first compare EUM and MLE training using both QFI and QFJ in Figure 5.3. We report results for $PRF_{\alpha=1,\beta}$ (*i.e.*, fixed $\alpha = 1$ with different β settings) on QF13. Observations are similar for other cases. The figure shows QFI with EUM and MLE training on the left, and QFJ results on the right. We report three runs of EUM, which use $PRF_{\alpha,\beta}$ under different α, β settings (specified in the legend) as the training target.

From Figure 5.3, for QFI, we find there are no statistically significant difference between MLE and EUM in most cases, even though generally EUM obtains slightly better $PRF_{\alpha,\beta}$ than MLE. This can be explained by that QFI under MLE has already incorporated the $PRF_{\alpha,\beta}$ learning target due to that it is tuned on $PRF_{\alpha,\beta}$. Essentially, we can view QFI (under MLE training) as a model that is trained on likelihood to find a small tuning space to enable optimization on given performance measures by hand tuning.

Differently, for QFI, we find EUM can improve over MLE largely under the precision-oriented scenarios. The difference between EUM and MLE are statistically significant for all $1/\beta > 2$ and for all the three EUM runs. This indicates 1)

utility (performance measure) is a better optimization objective than likelihood and 2) our approximation of $PRF_{\alpha,\beta}$ based on its expectation is effective.

Figure 5.3: $PRF_{\alpha=1,\beta}$ performance for MLE and EUM training using QFI (left) and QFJ (right) on QF13. The three EUM runs use $PRF_{\alpha,\beta}$ under different α,β settings (specified in the legend) as the training target.

(a) QFI

(b) QFJ
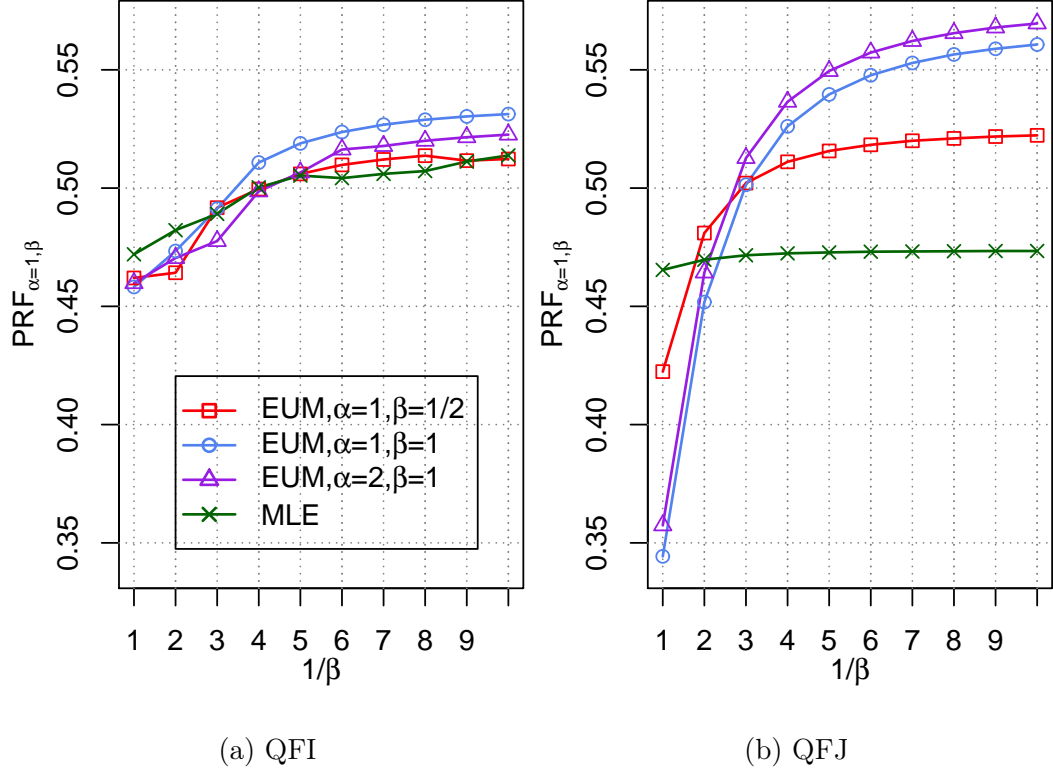
To study how EUM training affects QFJ in more details, as an example, we show $PRF_{\alpha=1,\beta=0.1}$ together with its TP, TR, PF and facet size in Table 5.3. From Table 5.3,

Table 5.3: $PRF_{\alpha=1,\beta=0.1}$ with TP, TR, PF for MLE and EUM training on QF13. Subscripts of EUM indicates the α,β setting used for its optimization target $PRF_{\alpha,\beta}$.

model	Training	$PRF_{\alpha,\beta}$	TP	TR	PF	Size
QFJ	MLE	0.4734	0.3986	0.4832	0.6961	97.0
QFJ	$EUM_{1,1}$	0.5223	0.4884	0.3341	0.6702	54.8
QFJ	$EUM_{2,1}$	0.5696	0.5711	0.2328	0.6705	33.9
QFJ	$EUM_{1,1}$	0.5607	0.5710	0.2229	0.6620	33.0

first, we can see when trained on EUM under precision-oriented settings ($i.e.$,$EUM_{2,1}$

and $EUM_{1,0.5}$), QFJ are more conservative in selecting terms than in MLE training. When moving from MLE to EUM training, its facet size becomes much smaller (*i.e.*, 97 to 33), *TP* increases largely while *TR* decreases largely. This effect is desirable under the precision-oriented scenarios, in which we care much more about precision than recall, as reflected by the improvement in $PRF_{\alpha=1,\beta=0.1}$ shown in the table.

Second, by comparing $EUM_{1,1}$ with $EUM_{2,1}$, $EUM_{1,0.5}$ in Table 5.3, we can see $EUM_{2,1}$, $EUM_{1,0.5}$ trained models behave more conservatively than $EUM_{1,1}$ trained models. This suggest our training is effective – as we change the training target $PRF_{\alpha,\beta}$ parameter from ($\alpha = 1, \beta = 1$) to ($\alpha = 2, \beta = 1$) and ($\alpha = 1, \beta = 0.5$)), it learns that we are putting more emphasis on precision, and thus behaves more conservatively.

Last, the improvement of QFJ in precision oriented scenarios raises a question – will it outperform previous best model QFI under precision-oriented scenarios? We test this in Figure 5.4. In the figure, we compare QFJ under EUM training with other baselines, including QFI under MLE (representing the state-of-the-art baseline) and EUM training. We report results under $EUM_{1,0.5}$ training on QF13 (results are similar in other cases). From the figure we find QFJ under EUM training outperforms other models in the precision-oriented scenarios. The difference between QFJ,EUM and the state-of-the-art method QFI,MLE are statistically significant for $PRF_{\alpha=1,\beta}$ when $\frac{1}{\beta} > 4$.

5.6.4 Extraction Performance Prediction

To predict query facet extraction performance, we build linear regression models using only PRF score (see Section 5.5) as the feature (with intercept). We test the models for predicting $PRF_{\alpha,\beta}$ under different α, β, based on 10-fold cross validation on QF13 for QFI in Table 5.4. We report root-mean-square deviation (RMSD), Pearson correlation (R), and p-values for the significance of correlation.

Figure 5.4: $PRF_{\alpha,\beta}$ performance with different α, β settings for QFI and QFJ under MLE and EUM training on QF13. $EUM_{1,0.5}$ run result is reported for EUM.

(a) $PRF_{\alpha,\beta=1}$ (b) $PRF_{\alpha=1,\beta}$
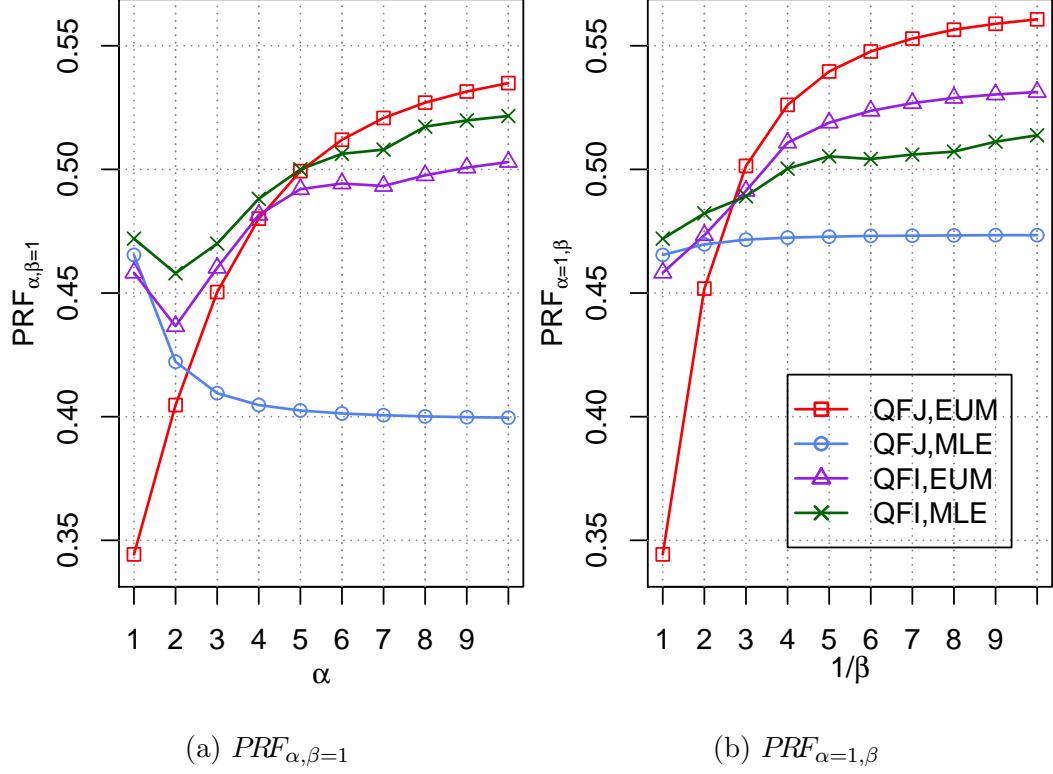
Table 5.4: Linear regression results based on 10-fold cross-validation for predicting $PRF_{\alpha,\beta}$ performance. RMSD – root-mean-square deviation, R – Pearson correlation.

Measure	RMSD	R	p-value
$PRF_{\alpha=1,\beta=1}$	0.1110	0.6112	1.4×10^{-11}
$PRF_{\alpha=1,\beta=0.2}$	0.1800	0.5745	4.1×10^{-10}
$PRF_{\alpha=1,\beta=0.1}$	0.1882	0.5566	1.8×10^{-9}
$PRF_{\alpha=5,\beta=1}$	0.2109	0.2958	0.0028
$PRF_{\alpha=10,\beta=1}$	0.2245	0.4028	3.2×10^{-5}

The results in Table 5.4 show fairly strong RMSD values and strong positive correlations between the predicted $PRF_{\alpha,\beta}$ and real $PRF_{\alpha,\beta}$ performance for most cases. For example, p-value 1.4×10^{-11} for the first row indicates that it is extremely unlike that the predicted $PRF_{\alpha=1,\beta=1}$ performance has no relationship with the actually performance. We also see one exception. For $PRF_{\alpha=5,\beta=1}$ we only see fair correlation,

which may due to that we use $\alpha = 1, \beta = 1$ for computing our PRF score, while in $PRF_{\alpha=5,\beta=1}$ the three factors are more unbalanced weighted.

5.6.5 Evaluating Selective Query Faceting

Next, we study the effectiveness of selective query faceting based on the predicted score (from cross validation). Recall that our selective method is done by thresholding the predicted performance for deciding show or avoid showing facets for each query (see Section 5.5). There is a trade-off between the performance of selected queries and the coverage on queries for query faceting. With a higher threshold, selective query faceting would select less queries to show facets, but users should obtain better performance for the facets that are presented to them. On the contrary, a lower threshold will result in selecting more queries to show facets, but the performance for the selected queries may be worse.

To evaluate selective query faceting, we plot the average $PRF_{\alpha,\beta}$ performance for queries selected by PRF score, when using different thresholds in Figure 5.5. The x-axis indicates the number of selected queries, while the y-axis indicates the average $PRF_{\alpha,\beta}$ performance for those selected queries. In addition to average $PRF_{\alpha,\beta}$, we also plot the standard error with 95% confidence intervals by the gray area (except for the case where only one query is selected). We report results on QF13 for a QFI run that are trained under MLE and evaluated on $PRF_{\alpha=1,\beta=1}$.

From Figure 5.5, we can see as we select less and less queries for presenting facets, generally the average performance for the selected queries increases. This indicates the query faceting method is fairly effective in selecting good performing queries and avoid bad ones. When 20 queries are selected, we obtain 0.5792 $PRF_{\alpha=1,\beta=1}$ for the selected queries, comparing to 0.4720 when the selective method is not performed (*i.e.*, showing facets for all queries). The difference are statistically significant according to two-tailed two-sample t-test (p-value = 0.0034).

Figure 5.5: Average $PRF_{\alpha,\beta}$ performance for selected queries. The gray area indicates standard error with 95% confidence intervals. Run: $PRF_{\alpha=1,\beta=1}$ as the measure with MLE trained QFI as the extraction model
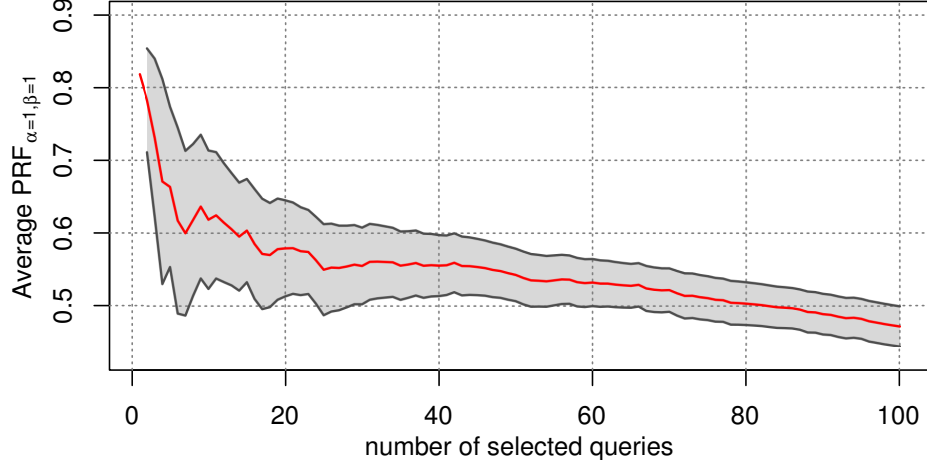
5.7 Summary

In this chapter, we studied and improved query facet extraction under precision-oriented scenarios, which could help this technique to be used practically. We find the performance expectation can be used as an approximation to directly optimize the performance measure, which significantly improves existing models under precision-oriented scenarios. We proposed a PRF score based on the expectation of $PRF_{\alpha,\beta}$ to predict extraction performance. We show this score has fairly good prediction performance which enables selective query faceting that selects good performing queries to show facets, and improves the average extraction performance.

In next chapter, we will consider how to re-organize search results based on users' selection on the extracted query facets.

CHAPTER 6

FACET FEEDBACK

6.1 Introduction

Facet feedback (Kong and Allan, 2014) is to adjust (filter or re-rank) the search results based on users' selections on the provided facets (corresponding to step 5 in Figure 1.2). Boolean filtering, which filters search results by requiring selected terms to appear, is the dominant facet feedback method used in conventional faceted search. However, it may be too strict when extended to the open-domain setting. Boolean filtering is based on two assumptions (Zhang and Zhang, 2010): (1) users are clear about what they are looking for, and thus are able to select proper terms to restrict the results; and (2) matching between a term and a document is accurate and complete. In FWS, that means a document that contains the selected term should be relevant to the term, and all documents relevant to that selected term should contain the term. Neither of the two assumptions are likely to hold in FWS. Therefore, we propose soft ranking models that expand original queries with user selected terms for re-ranking.

In this chapter we describe the two types of models we explore for facet feedback: Boolean filtering and soft ranking. We will first define notations used in facet feedback models in Section 6.3, and then present Boolean filtering and soft ranking models in Section 6.4 and Section 6.5 respectively. We will explore the effectiveness of these approaches in Chapter 7.

6.2   Related Work

There is a long history of using user explicit feedback to improve retrieval performance. In relevance feedback (Rocchio, 1971; Salton, 1997), documents are presented to users for judgment, after which terms are extracted from the judged relevant document, and added into the retrieval model. In the case where true relevance judgment is unavailable, top documents are assumed to be relevant, which is called pseudo relevance feedback (Buckley et al., 1995; Abdul-Jaleel et al., 2004). Because document is a large text unit, which can be difficult for users to judge and for the system to incorporate relevance information, previous work also studied user feedback on passages (Allan, 1995; Xu and Croft, 1996) and terms (Koenemann and Belkin, 1996; Tan et al., 2007). For faceted search, Zhang and Zhang (2010) study user feedback on facets, using both boolean filtering and soft ranking models. However, the study is based on corpora with human created facet metadata, which is difficult to obtain for the general web. One other difference between our work and most other user feedback work is that facet feedback in our work is used to improve ranking with respect to the query subtopic specified by the feedback terms, instead of the query topic represented by the original query. This presents the scenario in FWS, where users start with a less-specified query, and then use facets to help clarify and search for subtopic information.

6.3   Notations

We use t^u to denote a **feedback term** selected by a user u, $F^u = \{t^u\}$ to denote a facet that contains feedback terms (a **feedback facet**), and $\mathcal{F}^u = \{F^u\}$ to denote the set of feedback facets. Given those, a feedback model can be formally denoted as $S'(D, Q, \mathcal{F}^u)$, which gives a score for document D according to the original query Q and the user's feedback $\mathcal{F}^u$.

6.4 Boolean Filtering Model

The Boolean model filters documents based on Boolean operations using the feedback $\mathcal{F}^u$. Similar to Zhang and Zhang (2010), we study three different Boolean conditions for filtering. We use the AND condition to require that the document contains *all* of the feedback terms in $\mathcal{F}^u$. The AND condition might be too strict, so a relaxed alternative is to use the OR condition, which requires that the document contains *at least one* of the feedback terms. The last Boolean condition, A+O, is somewhere in between the two conditions above. It use AND across different feedback facets in $\mathcal{F}^u$, and OR for terms t^u inside each facet F^u. The Boolean feedback model scores a document by

$$S'_B(D, Q, \mathcal{F}^u) = \begin{cases} S(D, Q) & \text{if } D \text{ satisfies condition } B(\mathcal{F}^u) \\ -\infty & \text{otherwise} \end{cases} \tag{6.1}$$

where condition B can be either AND, OR, or A+O, and $S(D, Q)$ is the score returned by the original retrieval model. Notice that when there is only a single feedback term, the three conditions will be equivalent; when there is only one feedback query facet (group of feedback terms), OR and A+O will be equivalent.

6.5 Soft Ranking Model

While Boolean filter models are commonly used in faceted search, it may be too strict for FWS, as explained in Section 6.1. Therefore, we also use soft ranking models, which expand the original query with feedback terms, using a linear combination as follows

$$S'_E(D, Q, \mathcal{F}^u) = \lambda S(D, Q) + (1 - \lambda) S_E(D, \mathcal{F}^u) \tag{6.2}$$

where $S(D, Q)$ is the score from the original retrieval model as before, and $S_E(D, \mathcal{F}^u)$ is the expansion part which captures the relevance between the document D and

feedback facet $\mathcal{F}^u$, using expansion model E. λ is a parameter for adjusting the weight between the two parts.

We use two expansion models, a term and a facet expansion model. The term expansion model, ST, assigns equal weight for all the feedback terms, as follow,

$$S_{ST}(D, \mathcal{F}^u) = \frac{1}{N} \sum_{F^u \in \mathcal{F}^u} \sum_{t^u \in F^u} S(D, t^u) \tag{6.3}$$

where N is the total number of facet terms. $S(D, t^u)$ can be the original retrieval model used for the query or a different model.

The facet expansion model, SF, uses the facet structure information. It assigns equal weights between each feedback facets, and equal weights between feedback terms within the same facet, as shown below.

$$S_{SF}(D, \mathcal{F}^u) = \frac{1}{|\mathcal{F}^u|} \sum_{F^u \in \mathcal{F}^u} \frac{1}{|F^u|} \sum_{t^u \in F^u} S(D, t^u) \tag{6.4}$$

Notice that the two expansion models will be equivalent when there is only a single feedback term or when there is only one feedback facet. In our experiments, we use the Sequential Dependence Model (SDM) (Metzler and Croft, 2005) as the baseline retrieval model $S(D, Q)$, which incorporates word unigrams, adjacent word bigrams, and adjacent word proximity. For $S(D, t^u)$, we use the Query Likelihood model with Dirichlet smoothing as below,

$$S(D, t^u) = \sum_{w \in t^u} \log \frac{tf(w, D) + \mu \frac{tf(w, \mathcal{C})}{|\mathcal{C}|}}{|D| + \mu} \tag{6.5}$$

where w is a word in t^u, $tf(w, D)$ and $tf(w, \mathcal{C})$ are the number of occurrences of w in the document and the collection respectively; μ is the Dirichlet smoothing parameter; $|D|$ is the number of word in $|D|$, and $|\mathcal{C}|$ is the total number of words in the collection.

6.6 Summary

In this chapter, we described three Boolean filtering models (AND, OR, A+O) and proposed two soft ranking models (ST and SF) for facet feedback. In the next chapter, we will develop an extrinsic evaluation method for evaluating these feedback models.

CHAPTER 7

EXTRINSIC EVALUATION

7.1　Introduction

The intrinsic evaluation proposed in Chapter 4 is not based on any particular search task, and thus may not reflect the real utility of the generated facets in assisting search. Therefore, we describe an extrinsic evaluation method which evaluates a system based on an interactive search task that incorporates FWS. We believe the task is similar to a real application of FWS as illustrated in Figure 1.2: a user searches using an under-specified query, the FWS system provides query facets from which the user can select feedback terms that would help further specify the query, after which the FWS system uses the feedback terms for re-ranking documents.

For the extrinsic evaluation, ideally we could ask real users or carry out user studies to try each FWS systems, and measure the gain and cost for using them. The gain can be measured by the improvement of the re-ranked results using standard IR metrics like MAP or nDCG. The cost can be measured by the time spent by the users giving facet feedback. However this evaluation is difficult and expensive to extend for evaluating new systems rapidly.

We instead propose to *simulate* the user feedback process based on a user interaction model, using oracle feedback terms and facet terms collected from annotators. Both the oracle feedback and annotator feedback incrementally select all feedback terms that a user may select, which will then be used in simulation based on the user model to determine which subset of the oracle or annotator feedback terms are selected by a user and how much time is spent giving that feedback. Finally, the sys-

tems are evaluated by the re-ranking performance together with the estimated time cost.

For the simulated FWS task, we use the TREC Web track dataset of the diversification task (Clarke et al., 2009a,b,c,d). It includes query topics that are structured as a representative set of subtopics, each related to a different user need, with relevance judgment made at the subtopic level. In our task, each subtopic is regarded as the search intent of a user, and the corresponding topic title is used as the under-specified query issued to the FWS system. For example, for query number 10 in the TREC 2009 Web Track, the title "cheap internet" is used as the initial query, and its subtopic "I want to find cheap DSL providers" is regarded as the search intent of the user.

We conduct extrinsic evaluations on combinations of different query facet generation models and facet feedback models in our experiments. We show that , by using facet feedback from users, Faceted Web Search is able to assist the search task and significantly improve ranking performance. Comparing intrinsic evaluation and extrinsic evaluation on different facet generation models, we find that the intrinsic evaluation does not always reflect system utility in real application. Comparing different facet feedback models, we find that the Boolean filtering models, which are widely used in conventional faceted search, are too strict in Faceted Web Search, and less effective than soft ranking models.

In the rest of this Chapter, we will first describe how we collect simulated facet feedback in Section 7.2. Then, we will describe our user model for estimating the feedback time cost to users in Section 7.3. At last, we will present our experiments for conducting extrinsic evaluation on different faceted web search systems (different combinations of query facet generation models and facet feedback models) in Section 7.4, followed by conclusions in Section 7.5.

7.2 Oracle and Annotator Feedback

Oracle feedback presents an ideal case of facet feedback, in which only *effective* terms – those that improve the quality of the ranked list – are selected as feedback terms. We extract oracle feedback terms by testing each single term in the presented facets. Each single candidate term is used by a facet feedback model to re-rank the documents and the candidate term is selected for the oracle if the improvement of the re-ranked documents meets a threshold. In our experiment, we use MAP as the metric and set the threshold to be 0.01. Since we have two types of feedback models, there are two sets of oracle feedback terms – one uses the Boolean filter models, and one uses the soft ranking models.

Oracle feedback is cheap to obtain for any facet system (assuming document relevance judgments are available), however it may be quite different from what actual users may select in a real interaction. Therefore, we also collect feedback terms from annotators. Our annotation interface is shown in Figure 7.1. The facet feedback annotation is done by presenting the facets (corresponding to list 1 to 5 in Figure 7.1) to an annotator with description of the information need (corresponding to subtopic description in Figure 7.1) and the initial under-specified query. The annotator is asked to select all the terms from the facets that would help address the information need(corresponding to step 2 in Figure 7.1). Ideally, we could present all the facets generated from different FWS systems for this annotation, but it would be quite expensive. In our experiment, we only present annotator facets collected from the intrinsic evaluation. This assumes all other facet terms generated by systems are uninteresting to the user or at least not easy for the user to select.

7.3 User Model

The user model describes how a user selects feedback terms from facets, based on which we can estimate the time cost for the user. While any reasonable user model
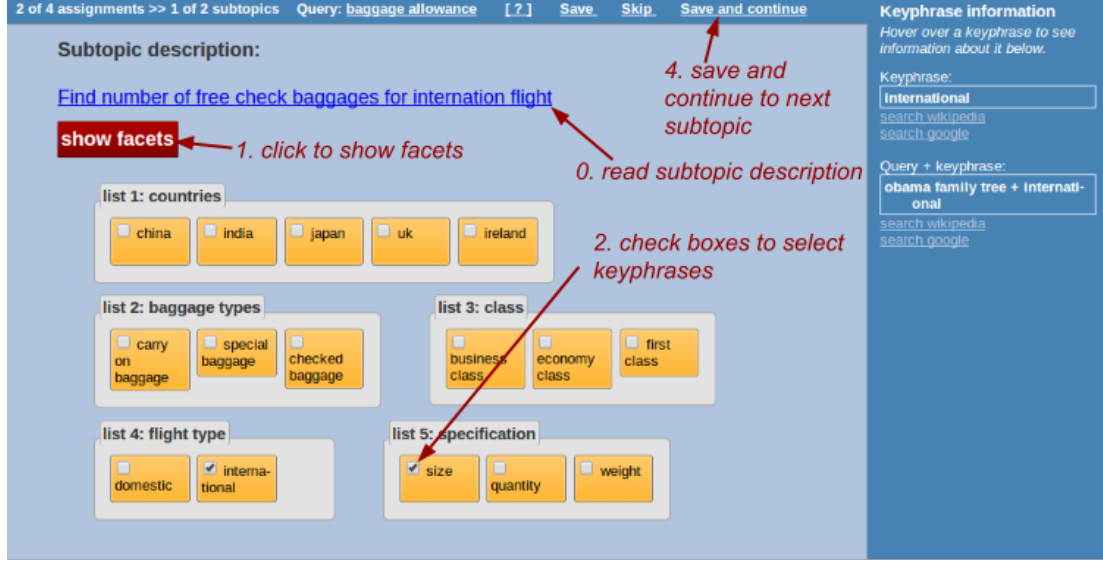
Figure 7.1: Annotation interface for facet feedback annotation.

can be brought to play here, we use a simple one, similar to the user model others have used for selecting suggestions from clusters of query auto-completions (Jain and Mishne, 2010).

Our user model is based on the structural property of facets. By grouping terms into facets, the facet interface essentially provides a skip list of these facet terms for users. More specifically, in the model, a user sequentially scans presented query facets and skips an entire facet if the user finds the facet irrelevant. Otherwise, the user will scan within the facet, sequentially reading and selecting desired facet terms, until the user finds the desired one or ones. Based on this user model, the time cost for giving facet feedback can be calculated as as,

$$T(\mathcal{F}^u) = \sum_{F^u \in \mathcal{F}^u} \left(T_f(F^u) + \sum_{t \in ts(F^u)} T_t(t) \right) \tag{7.1}$$

The righthand side of the equation contains two parts. The first part $T_f(F^u)$ is the time for scanning a facet and deciding relevance, and the second part is the time for scanning/selecting terms in the relevant facets. $ts(F^u)$ is the set of terms

scanned/selected in F^u's corresponding query facet, and $T_t(t)$ is the time used for scanning/selecting a term. Since we assume users sequentially scan the terms inside a facet, $ts(F^u)$ will include all the beginning terms in F^u's corresponding facet until the last selected term. This is based on the assumption that users are clear about what terms to select, and stop scanning after finding all of them.

To simplify the estimation, we further assume time costs are equal for scanning different facets, and equal for scanning/selecting different terms. Then the estimation becomes

$$T(\mathcal{F}^u) = |\mathcal{F}^u| \cdot T_f + |ts(\mathcal{F}^u)| \cdot T_t \tag{7.2}$$

where $|ts(\mathcal{F}^u)| = \sum_{F^u \in \mathcal{F}^u} |ts(F^u)|$ is the total number of term scanned/selected. T_f and T_t are now parameters representing the time for scanning a facet and time for scanning/selecting a term respectively.

To estimate parameters T_f and T_t, we tracked annotator behavior during the feedback annotation described in Section 7.2, including selecting / un-selecting terms and starting / exiting an annotation session. We only used annotation sessions which did not contain any un-selecting actions, and filter out some inappropriate sessions, e.g. the annotator dwells for a long time with no activity. This selection results in 274 annotator sessions. We then extracted $|\mathcal{F}^u|$ and $|ts(\mathcal{F}^u)|$ as well as the time cost $T(\mathcal{F}^u)$ for each session, and used linear regression to fit the model to the data. When using sessions from all annotators, T_f and T_t are estimated as 2.60 and 1.60 seconds respectively, with $R^2 = 0.089$. The low R^2 is partly due to the variance introduced by using sessions of different annotators. When using one single annotator we obtain a better fit with $R^2 = 0.555$, and $T_f = 1.51$, $T_t = 0.66$, for one of the annotators. Since the estimation for T_f is about twice of T_t, for simplicity, in our experiment, we set $T_f = 2 \cdot T_t$, and report the time cost in the time unit of reading/scanning a single term.

Based on this user model, given oracle/annotator feedback, which represents all the terms that a user may select, the extrinsic evaluation works as follows. We incrementally include each term in oracle/annotator feedback as a feedback terms, and measure how ranking performance changes together with the time cost estimated based on the user model.

7.4 Experiments

7.4.1 Experiment Settings

Data set. For the document corpus, we use the ClueWeb09 Category-B collection and apply spam filtering with a threshold of 60 using the Waterloo spam scores (Cormack et al., 2011). The spam-filtered collection is stemmed using the Krovetz stemmer (Krovetz, 1993). For the query topics and subtopics, we used those from TREC Web Track's diversity task from 2009 to 2012, which also contain relevance judgments for documents with respect to each subtopic. We constrain the subtopics to have at least one relevant document in the spam-filtered collection, and this results in 196 queries and 678 query subtopics in our experiment set. For the relevance judgment, any documents that are not in the spam-filtered collection are discarded.

Annotation. We collected facet annotations as described in Section 4.2 for all 196 queries. Facets are pooled from the top 10 facets generated by runs from QDM, pLSA, LDA, QF-I and QF-J. Then annotators are asked to group the terms in the pool into query facets, and to give a rating for the query facet using a scale of good (2) or fair (1). Facet annotation statistics for the good and fair facets, as well as the pooled facet, are given in Table 7.1. The table shows average number of facet terms per query, average number of query facets per query, and average number of facet terms per facet, for each categories (fair, good, and pooled facets).

Table 7.1: Facet annotation statistics

	fair	good	pooled
#terms per query	15.8	26.5	240.0
#facets per query	2.3	3.8	40.9
#terms per facet	6.8	6.9	5.9

For the extrinsic evaluation, we also collected facet feedback annotations as described in Section 7.1 for all 678 subtopics. The statistics are given in Table 7.2, which also includes statistics for oracle feedback. The table shows the number of feedback terms selected per subtopic and the number of feedback facets per subtopic. For some subtopics, there may be no feedback terms selected, so we also report feedback coverage over subtopics in the table.

Table 7.2: Oracle and annotator feedback statistics. oracle-b and oracle-s are oracle feedback based on the Boolean filter model and soft ranking model respectively.

	annotator	oracle-b	oracle-s
#fdbk terms/subtopic	4.10	7.83	5.24
#fdbk facet/subtopic	1.36	2.40	1.93
feedback coverage	0.80	0.74	0.72

Training/testing and parameter tuning are based on 4-fold cross validation for the same splits of the 196 queries.

Significance test is performed by using paired t-test, using 0.05 as the p-value threshold.

Facet Generation Models. We compare pLSA, LDA, QDM, QF-I and QF-J. $wPRF$ ($wPRF_{\alpha,\beta}$ with α and β set to 1.0) is used as the metric for parameter tuning. For pLSA and LDA, we tune the number of facets and the number of facet terms in a facet. For QDM we tune the two parameters used in the clustering algorithm, the diameter threshold for a cluster and the weight threshold for a valid cluster, as well as the parameters they used for selecting facet terms in each facet. For QF-I and QF-J, we do not use the features based on snippets (which was used in previous work (Kong

and Allan, 2013)), since snippets are not available in our system. For QF-I, we tune the weight threshold for facet terms, and the diameter threshold. For QF-J, there are no parameters that need to be tuned.

Baseline Retrieval Models and Facet Feedback Models. We use SDM as the baseline retrieval model with 0.8, 0.15, 0.05 weights for word unigrams, adjacent word bigrams, and adjacent word proximity respectively. SDM is also used as the initial retrieval model for facet generation and facet feedback. We compare different facet feedback models to SDM, including AND, OR, A+O for the Boolean filtering models, as well as ST and SF for the soft ranking models. λ in ST/SF is set to be 0.8. Dirichlet smoothing $\mu = 1500$ is used for both SDM and ST/SF. We also used other baselines including RM3 (Abdul-Jaleel et al., 2004), a pseudo relevance feedback model, tuned on MAP, and xQuAD (Santos et al., 2010), a diversification model, tuned on α-NDCG (Clarke et al., 2008).

7.4.2 Comparison to Baseline Retrieval Models

We first compare FWS with other baseline retrieval models in Table 7.3. QF-I is used as the FWS system here, with SF as the facet feedback model. Annotator feedback terms are used, which represents a real case (not oracle) of FWS application. In the table, QF-I:10 and QF-I:50 are QF-I runs allowed 10 and 50 time units for feedback respectively.

First, the table shows that using annotator feedback, QF-I can improve ranking over the initial retrieval model, SDM. QF-I also obtains better results than RM3, across all the metrics. It is also better than xQuAD for most metrics. The observations testify to the potential of FWS in assisting search. Last, when allowed more time, the results are further improved as shown by the change from QF-I:10 to QF-I:50.

Table 7.3: Retrieval effectiveness comparison with baselines. QF-I:10 and QF-I:50 are QF-I runs allowed 10 and 50 time units for feedback respectively. Statistically significant differences are marked using the first letter of the retrieval model name under comparison.

Model	MAP	MRR	nDCG@10
SDM	0.1854	0.3295	0.1997
RM3	0.1886	0.3124	0.2010
xQuAD	0.1822	0.3463^r	0.2191
QF-I:10	0.1918_x^s	$0.3476^{s,r}$	$0.2145^{s,r}$
QF-I:50	$0.2044_x^{s,r}$	$0.3736^{s,r}$	$0.2357^{s,r}$

7.4.3 Oracle and Annotator Feedback

In Figure 7.2, we compare the effectiveness of oracle and annotator feedback. It shows how ranking performance changes as time cost increases, when incrementally including terms from the two types of feedback as feedback terms. The time cost is estimated by the user model described in Section 7.3. MAP is calculated with respect to the subtopic level relevance, since we are evaluating the case where the user is looking for the subtopic information. MAP value is averaged by macro-averaging – averaging for subtopics within the same query first, and then across all the queries. [1] When time is zero, no feedback terms are used, which is then just the result for the initial ranking from SDM.

In Figure 7.2, MAP increases from the SDM baseline result for both oracle and facet feedback, with the oracle ones shown to be far more effective. This shows that annotators are able to identify some useful feedback terms, but not as effective as the ideal case: it seems people have a hard time knowing which terms are most likely to be successful. We further compare the feedback terms selected in oracle and annotator feedback in Table 7.4, which also supports this claim.

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[1]We also measured micro-averaging, but the results are similar.

Figure 7.2: MAP change over time for oracle and annotator feedback, based on annotator facets and SF feedback model. oracle-s and oracle-b are the oracle feedback based on the Boolean filtering model and soft ranking model respectively.
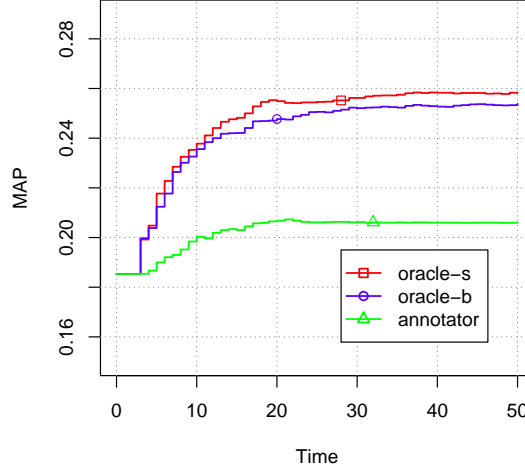

Table 7.4: Comparing feedback terms in annotator feedback and oracle feedback, using oracle-s as ground truth. This table shows that the annotator selects only 44% of the effective terms and that only 28% of the selected terms are effective.

Precision	Recall	F1
0.2817	0.4412	0.2179

Table 7.4 shows the overlap between oracle and annotator feedback is low according to F1. However, annotators are able to find almost half of the oracle feedback terms. Other oracle feedback terms are difficult for annotators (or users) to recognize, due to lack of background knowledge, or underlying statistical dependencies between words that are difficult to capture. For example, for the query subtopic, "find the TIME magazine photo essay Barack Obama's Family Tree", some names of family members are selected in oracle feedback, but not by the annotator. This is because the annotator is not able to capture the relevant relationship between the names of family members and the photo essay, or simply because the annotator does not know those family members' names.

7.4.4 Comparing Facet Generation Models

7.4.4.1 Intrinsic Evaluation

To compare intrinsic and extrinsic evaluation, we also report intrinsic evaluation on different facet generation models in Table 7.5. The table shows QF-I and QF-J outperform other models on the overall measure, wPRF. QF-I wins because of high recall of facet terms and high F1 of facet term clustering. For rp-nDCG, QF-J and QDM are more effective. These results are consistent with our previous results in Section 4.4.

Table 7.5: Intrinsic evaluation of facet generation models.

| Model	wTP	wTR	wPF	wPRF	rp-nDCG
pLSA	0.2198	0.6273	0.2541	0.2521	0.0561
LDA	0.2720	0.5578	0.2345	0.2571	0.0476
QDM	0.3253	0.4024	0.2492	0.2688	0.0908
QF-J	0.3525	0.4060	0.2779	0.2836	0.1359
QF-I	0.2729	0.7363	0.3859	0.3448	0.0825

7.4.4.2 Extrinsic Evaluation

Intrinsic evaluation may not reflect the utility of facets in assisting search. In Figure 7.3 we evaluate different facet generation models using extrinsic evaluation, by showing how MAP changes as time cost increases, similar to Figure 7.2.

First, Figure 7.3 shows all models are able to improve ranking from the baseline, which testifies to the potential of FWS. However, the automatically generated facets are less effective than annotator facets. MAP for annotator facets reaches 0.2 by 10 time units, while the models need much more time, ranging from 27 to 47. Second, QF-I is more effective than other models over the entire time span. This is consistent with the intrinsic evaluation. Third, the comparison results for other models are less clear. QF-J and QDM are better than pLSA and LDA before 20 time units, but MAP for pLSA and LDA increases much faster afterwards, and ends at a value similar to

QF-J. Comparing these results with Table 7.5, we find intrinsic metrics do not always reflect utility based on extrinsic evaluation, though the generally better performance of QF-I is clear in both.

Figure 7.3: MAP change over time for different facets generation models, based on annotator feedback and SF feedback model.
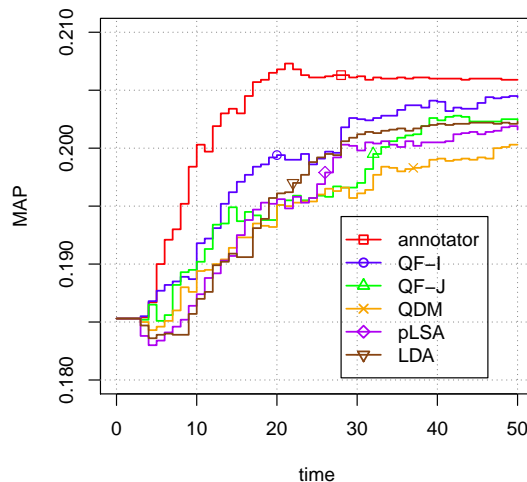
Another way to compare is to see how may terms in the presented facets are selected by annotators, as shown in Figure 7.4. The figure shows that with annotator facets a (simulated) user needs less time for selecting feedback terms. All the other facet generation approaches are similar to each other, with QDM having slightly more feedback terms at the beginning and QF-I having more for the rest. This explains why QF-I is the best system run in Figure 7.4 – for the same time cost, QF-I has more feedback terms selected by annotators.

If we switch to using the oracle feedback facets, the difference between different facet generation models and annotator facets are no longer that big, as shown in Figure 7.5. Annotator facets are better at the beginning, but the corresponding MAP stops growing at around 20 time units. We find this is due to there not being so many facets available in the annotator facets.
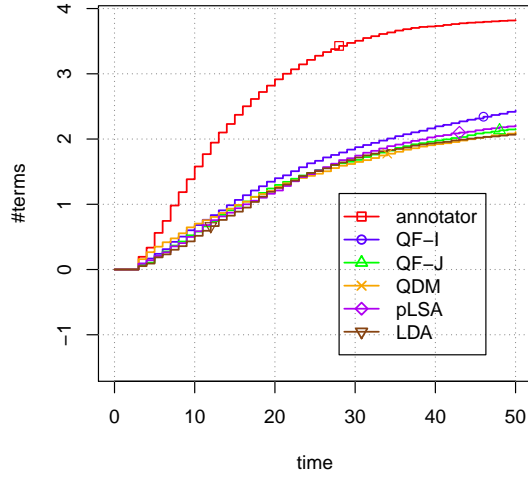
Figure 7.4: Number of feedback terms selected over time on facets generated by different models, based on annotator feedback.
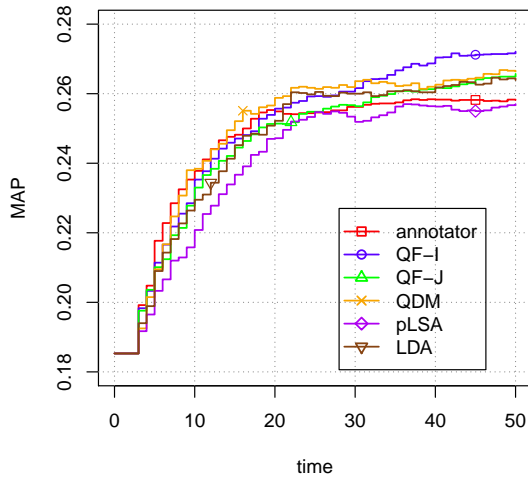
Figure 7.5: MAP change over time for different facets generation models, based on oracle feedback and SF feedback model.

The number of terms and facets presented to users will affect this evaluation. In the plot, when there is not a sufficient supply of facets at some time cost, the results from a smaller time cost is used. That is, if the user runs out of facet terms to consider, performance is stuck where it last left off. To validate the comparison in

Figure 7.3 and 7.5, we plot Figure 7.6 which shows the number of accumulated facet terms in the top facets generated by different models. Figure 7.6 shows all models

Figure 7.6: Accumulated number of facet terms in top facets generated from different facets generation models.
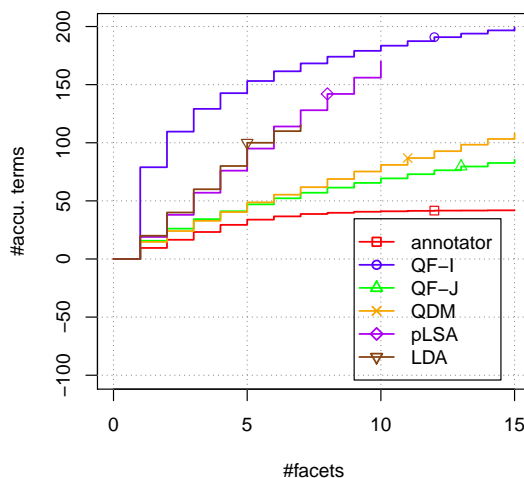
have a sufficient supply of facet terms for these evaluations. All of them present at least 50 facet terms (on average), which will need at least 50 time units for the user to process. This obviates the concern above. However, the annotator only has on average 42.3 facet terms selected, and therefore comparison at a time larger than that might unfairly penalize the annotator facets. We also notice that the first facet in QF-I is very large, and overall QF-I has more terms in top facets. Since the results are tuned on wPRF with equal weight for term precision and recall, this suggests it is very likely that too much weight is assigned for recall, and a more balanced weight between wP, wR and wFP should be used in wPRF.

7.4.5 Comparing Facet Feedback Models

We compare different facet feedback models in Figure 7.7. It shows soft ranking models are more effective than Boolean filter models. AND is too aggressive, which hurts the ranking performance as more and more feedback terms are used. The other

two Boolean filtering models, OR and A+O, are similar at the beginning. That is because in the beginning there is only one feedback facet, in which case OR and A+O will be equivalent. As more facet terms are selected, A+O performance decreases. For the two soft ranking model, SF and ST are very close, with SF slightly better as time progresses. This comparison suggests that Boolean filter models, AND and
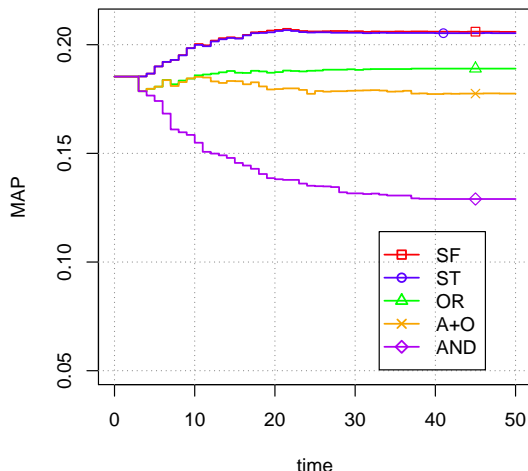
Figure 7.7: MAP change over time for different feedback models, based on annotator facets and annotator feedback.

A+O, are too strict for FWS, and a soft ranking model is more effective for FWS. This situation is probably because in FWS the mapping between facet term and document is incomplete; a document that does not contain the exact facet term may also be relevant.

7.4.6 Examples

In this section, we use some system generated facets as examples, to show how FWS can assist search. We find FWS can be helpful in exploratory search. For example, for the query "cheap internet", the facets generated by QDM includes a facet of different Internet service types, {*dial up*, *dsl*, *cable*}, and a facet of different ISPs, {*netzero*, *juno*, *copper*, *toast*}. These facets can assist the user to compare different

Internet service types and ISPs during his/her exploration of "cheap Internet". Another example is the query "lymphoma in dogs", in which the user may want to learn about different aspects of lymphoma in dogs. QF-J generates the facet {*treatment*, *diagnosis*, *prognosis*, *symptoms*, ...} which represents different aspects of the query. For this query, there is a query subtopic looking for symptoms of lymphoma in dogs, which can be directly answered by another facet found by QF-J, {*vomiting*, *diarrhea*, *weight loss*, *depression*, *fever*}.

7.5 Summary

In this chapter, we developed an extrinsic evaluation method for Faceted Web Search. The extrinsic evaluation method directly measures the utility in search instead of comparing system/annotator facets as in intrinsic evaluation. We described a way to build reusable test collection for the extrinsic evaluation, and make our collected data set publicly available[2].

We also investigated different facet generation and facet feedback models based on the extrinsic evaluation method. Our experiments show, by using facet feedback from users, Faceted Web Search is able to assist the search task and significantly improve ranking performance. Comparing intrinsic evaluation and extrinsic evaluation on different facet generation models, we find that the intrinsic evaluation does not always reflect system utility in real application. Comparing different facet feedback models, we find that the Boolean filtering models, which are widely used in conventional faceted search, are too strict in Faceted Web Search, and less effective than soft ranking models.

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[2]See http://ciir.cs.umass.edu/downloads

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

In this thesis, we investigated Faceted Web Search, an extension of faceted search to the open-domain web setting. We studied three fundamental problems in Faceted Web Search, namely (1) how to automatically generate facets, (2) how to re-organize search results with user feedback on facets and (3) how to evaluate generated facets and entire systems. To address these problems, we have: (1) developed query facet extraction for automatic facet generation; (2) developed an intrinsic evaluation method for evaluating generated facets; (3) developed an empirical utility maximization approach and a selective query faceting method for improving query facet extraction in precision-oriented scenarios; (4) investigated both Boolean filtering and soft ranking models for facet feedback; (5) developed an extrinsic evaluation method that evaluate entire systems in terms of their utility and cost in assisting search.

In Chapter 3, we developed query facet extraction, which extracts facets for a given query from its search results. Changing from a global approach that generates facets in advance for an entire corpus (Stoica and Hearst, 2007; Dakka and Ipeirotis, 2008) to a query-based approach, query facet extraction provides a promising direction for solving facet generation in Faceted Web Search. By focusing on the search results, query facet extraction avoids dealing with the entire web, which is large and heterogeneous. By directly generating facets for queries, it also addresses the facet recommendation problem at the same time.

For query facet extraction, we developed a supervised approach based on a graphical model to recognize facets from the noisy candidates found. The graphical model learns how likely a candidate term is to be a facet term as well as how likely two terms are to be grouped together in a query facet, and captures the dependencies between the two factors. We proposed two algorithms (QFI and QFJ) for approximate inference on the graphical model since exact inference is intractable. Compared with other existing methods, our models can easily incorporate a rich set of features, and learn from available labeled data.

In Chapter 4, we developed an intrinsic evaluation method that evaluates generated facets by comparing them with human-created ones. We described how to collect human annotations for query facets by a pooling method. We designed $PRF_{\alpha,\beta}$, an evaluation measure that combines precision and recall of facet terms with grouping quality, using weighted harmonic mean. The measure can adjust emphasis between the three factors for different application scenarios. Experimental results based on this intrinsic evaluation show that our supervised methods (QFI and QFJ), can take advantage of a richer set of features and outperforms other unsupervised methods.

In Chapter 5, we investigated query facet extraction models under precision-oriented scenarios, and improved our models in such scenarios. The precision-oriented scenarios consider a more practical setting, in which users care more about precision of presented facets than recall. From the investigation, we found that our model (QFJ), optimized based on likelihood, fails to adapt to the precision oriented scenarios, suggesting likelihood could be loosely related to the performance measure in such scenarios. Thus, we developed an empirical utility maximization approach to optimize the performance measure instead of likelihood. However, exact optimization on the performance measure is difficult due to the non-continuous and non-differentiable nature of the objective. We solved this problem by approximating the performance measure using its expectation. Our experiments show that this empirical utility

maximization approach significantly improves our query facet model (QFJ) under precision- oriented scenarios, suggesting utility is a better learning objective than likelihood, and our expectation-based approximation is effective.

Besides empirical utility maximization, we also improved query facet extraction performance in the precision-oriented scenarios by selective query faceting. In our investigation, We found query facet extraction quality varies drastically from excellent to poor and completely noisy. In the precision-oriented scenario, it may be more desirable to avoid showing facets for those poor performing queries and leave the users with a clean keyword-search interface. Thus, we proposed selective query faceting to show facets for good performing queries and avoid poor performing ones. A key problem, however, is how to predict the extraction performance. To solve the problem, we proposed a PRF score based on the expectation of $PRF_{\alpha,\beta}$ to predict the performance. We show this score has fairly good prediction performance which enables selective query faceting, and improves the performance for the selected queries with fair coverage over the entire query traffic.

In Chapter 6, we investigated both Boolean filtering and soft ranking models for facet feedback. The Boolean filtering models filter the search results based on users' selection on facets, which is the dominant feedback model in conventional faceted search. Instead, soft ranking models re-ranks the documents by expanding the original query with selected terms in facets. Our experiments (in Chapter 7) show that the Boolean filtering models are too strict in Faceted Web Search, and less effective than soft ranking models.

In Chapter 7, we developed our extrinsic evaluation method that evaluates entire Faceted Web Search systems in terms of their utility in assisting search in an interactive search task. In the search task, a user searches an under-specified query, the FWS system provides query facets from which the user can select terms in the facets that would help further specified the query, after which the FWS system uses the feedback

terms for re-ranking documents. Our extrinsic evaluation considers both gain in terms of the re-ranking performance and cost in terms of the time users spend for selecting feedback terms. The re-ranking gain can be measured by standard IR metrics like MAP or nDCG. The time cost ideally can be exactly measured by carrying out user studies.

However, we noticed the user-study-based time measurement would make the evaluation difficult and expensive to extend for evaluating new systems rapidly. Thus, we proposed to simulate the user feedback process based on a user interaction model, using oracle feedback terms and feedback terms collected from human annotators. Both the oracle feedback and annotator feedback incrementally select all feedback terms that a user may select, which will then be used in simulation based on the user model to determine which subset of facet terms are selected by a user and how much time is spent giving that feedback. We also describe a way to build reusable test collection for the extrinsic evaluation, and make our collected data set publicly available[1].

Our experiments show, by using facet feedback from human annotator, Faceted Web Search is able to assist the search task and significantly improve ranking performance if allowed sufficient time for user feedback: 18.0% in NDCG@10 if we allow users to examine 50 terms in facets, and 7.4% in NDCG@10 if we allow time for examining 10 terms. Comparing intrinsic evaluation and extrinsic evaluation on different facet generation models, we found that the intrinsic evaluation does not always reflect system utility in real application. Comparing different facet feedback models, as mentioned earlier, we found that the Boolean filtering models are too strict in Faceted Web Search, and less effective than soft ranking models.

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[1]See http://ciir.cs.umass.edu/downloads

8.2 Future Work

As a first extensive attempt at extending faceted search to the open-domain web, this work has some limitations, but also opens up many interesting directions for future work.

In this work, a query facet is defined as a set of coordinate terms (*e.g.*, {"*AA*", "*JetBlue*", "*Delta*"}), but with no label (*e.g.*, "*airlines*") for the set . This facet representation corresponds to one-level faceted taxonomies, in which information objects that belong to a same parent node are shown as a facet. However, explicitly showing labels for each query facets, or equivalently showing two-level faceted taxonomies, would be more desirable, as facet labels could help users quickly comprehend each query facets. There are two potential directions for solving this facet labeling problem. First, we could resort to some extraction patterns that extract facet candidates together with their labels. For example, from the sentence "*... <u>airlines</u> such as AA, Delta, and JetBlue.*", based on the pattern "*<u>NP</u> such as NP, NP, ..., and NP*", we can extract facet candidate {"*AA*", "*Delta*", "*JetBlue*"} together with the label "*airlines*". After candidate extraction, we need models for refining candidate facets with labels, which is also a very interesting problem. Second, we can resort to existing taxonomies. We can classify extracted query facets in to the taxonomies (*e.g.*, assign "*AA*", "*Delta*", "*JetBlue*" as child nodes for the node "*airlines*" in the taxonomy), and then use the assigned parent nodes as labels. One problem with this direction is that existing taxonomies will almost certainly have difficulties in covering all query facets web search users are interested in.

In Chapter 3, we used a heuristic score for ranking extracted query facets. The score is defined as $score(F) = \sum_{t \in F} P(t)$, which sums up the probabilities of each term t being facet term, in order to present more facet terms in top ranks. This ranking model might be far from optimal, and there are other ranking models that could potentially improve facet ranking performance. For example, learning-to-rank mod-

els (Liu, 2009) have been well-studied, and according to their success in information retrieval, they may also work for query facet ranking. However, one problem with using learning to rank is that we need to design informative features that measures the quality of a extracted query facet.

In this work, we focused on extracting query facet from search results. However, a variety of other resources can be useful for query facet extraction. For example, existing taxonomies or knowledge bases (*e.g.*, Freebase[2]) can be useful for extracting candidate facets. Ideally, we can identify concepts (or entities) in a taxonomy that are relevant to the query, and then use the concepts with their child nodes as facet candidates (or query facets directly). For example, if we find that the concept "*airline*" is relevant to our query "*baggage allowance*", and the taxonomy contains a node for "*airline*", then we can use the concept's child nodes ("*AA*", "*Delta*", "*JetBlue*") as facet candidates. We can also design features based on taxonomies to improve our models, such as the feature "*if two terms are assigned to the same parent node in a taxonomy*". Besides taxonomies or knowledge bases, query logs can also be helpful. They can be used to extract features to measure how useful and important facet terms or query facets are, and potentially improve term ranking within query facets, or facet ranking. For example, there may be many airlines extracted in the airline facet, based on statistics in query logs, we can easily find which airlines are more popular and rank them ahead in the query facet.

In Chapter 5, to improve the performance in precision-oriented scenarios, we used an empirical utility maximization approach that optimizes the performance measure for training our query faceting models. However, we have not investigated decision theoretic approaches, advocated by Lewis (1995), which try to optimize the performance measure during inferencing. Nan et al. (2012) compared both approaches for

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[2]www.freebase.com

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optimizing F-Measures. Their results suggest that the two approaches are asymptotically equivalent given large training and test sets. Nevertheless, their experiments show that the empirical utility maximization approach appears to be more robust against model misspecification, and given a good model, the decision-theoretic approach appears to be better for handling rare classes and a common domain adaptation scenario. It would be interesting to also develop decision theoretic approach for optimizing $PRF_{\alpha,\beta}$ measure, and compare with our proposed empirical utility maximization approach.

Lastly, in Chapter 7, we used a simple user interaction model based on some strong assumptions that may not hold in real scenarios. For example, in the user model, we originally model the time a user spends for scanning a facet F as $T(F)$. However, to simplify the estimation, we assumed time costs are equal for scanning different facets (*i.e.*, $T(F) = T_f$, where T_f is a constant). In reality, the time a user spends scanning a facet is highly dependent on the facet quality. Users may spend much more time for low-quality facets, in order to figure out what the facets are about. For example, the extracted facet {"*AA*", "*first*", "*Delta*", "*business*", "*JetBlue*"} mixes facet "*airline*" and facet "*flight classes*" together. When a user encounters this facet, he or she may be confused and take more time in scanning. To improve time estimation, we could model the time cost based on the facet quality.

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