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Using Metafeatures to Increase the Effectiveness of Latent Semantic Models in Web Search

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ABSTRACT
In web search, latent semantic models have been proposed to bridge the lexical gap between queries and documents that is due to the fact that searchers and content creators often use different vocabularies and language styles to express the same concept. Modern search engines simply use the outputs of latent semantic models as features for a so-called global ranker. We argue that this is not optimal, because a single value output by a latent semantic model may be insufficient to describe all aspects of the model’s prediction, and thus some information captured by the model is not used effectively by the search engine.

To increase the effectiveness of latent semantic models in web search, we propose to create metafeatures—feature vectors that describe the structure of the model’s prediction for a given query-document pair—and pass them to the global ranker along with the models’ scores. We provide simple guidelines to represent the latent semantic model’s prediction with more than a single number, and illustrate these guidelines using several latent semantic models.

We test the impact of the proposed metafeatures on a web document ranking task using four latent semantic models. Our experiments show that (1) through the use of metafeatures, the performance of each individual latent semantic model can be improved by 10.2% and 4.2% in NDCG scores at truncation levels 1 and 10; and (2) through the use of metafeatures, the performance of a combination of latent semantic models can be improved by 7.6% and 3.8% in NDCG scores at truncation levels 1 and 10, respectively.

Categories and Subject Descriptors
H.3.3 [Information Storage and Retrieval]: Information Search and Retrieval—retrieval models

Keywords
Metafeatures; Latent Semantic Models; Web Search

1. INTRODUCTION
For the majority of cases in which search engine users complain that they cannot find information, while the information does exist in the system, the reasons are due to a mismatch between terms in queries and documents [24]. Term mismatch happens because searchers and content creators often use different vocabularies and language styles to refer to the same concepts [14]. To bridge this lexical gap between queries and documents, latent semantic models have been proposed [24].

Today, the use of latent semantic models by search engines is restricted to simply passing their outputs as features to a so-called global ranker, along with outputs of other models used for ranking. We argue that this is not optimal, because a single value output by a latent semantic model may be insufficient to describe all aspects of the latent semantic model’s prediction. Let us illustrate this using the Latent Semantic Indexing model [9].

The score produced by the Latent Semantic Indexing model is a sum of scores per latent space dimension. This is where potentially useful information for a global ranker may go missing as the model may assign similar scores to documents with radically different sets of per dimension scores. See Figure 1 for an example of this phenomenon: the sums of the per dimension scores are the same, but the lack of information about the distributions of their values, illustrated by this example, may hinder the global ranker when it attempts to reliably rank the two documents.

Figure 1: The plot shows the per dimension scores computed for two documents by the Latent Semantic Indexing model. The sums of the scores are the same, but the distributions of their values differ in interesting ways. (Best viewed in color.)

In previous work on latent semantic models in web search, comparisons of models are performed on a web document ranking task using the models’ scoring functions [1, 4, 8, 15, 16, 20, 29, 33–36]. While the scores produced by latent semantic models have demonstrated a strong correlation with document relevance, they are just the “tip of the iceberg” in capturing the relation between a query and document.

We argue that considering a latent semantic model’s score only is not enough to determine its effectiveness in search, and all potentially useful information captured by the model should be considered. To increase the effectiveness of latent semantic models in search engines, we propose to expose the structure of their predictions to the global ranker. This is done through the use of metafeatures—feature vectors that we construct for a latent semantic model to describe its prediction and the way it arrived at this prediction. The latent semantic models’ metafeatures are passed to the global ranker along with the models’ scores.
The problem of creating metafeatures requires a solid understanding of the model’s internal workings. However, as we will see, for many latent semantic models, their scoring functions give a good starting point. In particular, we provide two simple and broadly applicable guidelines for creating metafeatures based on the scoring functions used by latent semantic models, and demonstrate the effectiveness of these guidelines by inferring metafeatures from different latent semantic models in a systematic manner.

We test our ideas for complementing a latent semantic model’s scores with metafeatures on a web document ranking task, and demonstrate that metafeatures provide a means to improve the performance of both (1) individual latent semantic models and (2) combinations of multiple latent semantic models.

The proposed approach for creating and using metafeatures is substantially more than just feature engineering (where a significant part of the efforts of search engine employees go). The process of feature engineering described by Domingos [12] consists of three steps: (1) to choose a particular machine learning algorithm and a target evaluation criterion (i.e., the difference in NDCG scores between the global ranker trained with and without candidate features); (2) to generate a large number of candidate features; and (3) to select the best features according to the chosen criterion. However, this approach is difficult to apply in practice, because there are no clear guidelines for selecting the candidate features (and, thus, the effectiveness of features often depends more on an individual’s intuition rather than on a solid methodology). To alleviate this problem, we propose a methodology that guides the design choice of new features. Our proposal is both novel and ensures a broader impact of our technical contribution beyond the particular task setting (web search) that we consider.

We discuss related work in §2. Our method for creating metafeatures for latent semantic models and passing them along to a global ranker is detailed in §3. We detail our experimental setup in §4 and present our results and analysis in §5. We conclude in §6.

2. RELATED WORK

We discuss three types of related work: latent semantic models, ranking models based on latent semantic models, and combinations of latent semantic models.

Latent semantic models. Latent Semantic Indexing (LSI) [9] uses singular value decomposition (SVD) of a document-term matrix to map queries and documents to low-dimensional concept vectors. The relevance of a document to a query is assumed to be proportional to the cosine similarity between their concept vectors. A major limitation of LSI that prevents it from being used in very large scale applications, is the computational cost of SVD. To overcome this limitation, a Regularized Latent Semantic Indexing (RLSI) [33] with an efficient implementation in MapReduce has been proposed.

Probabilistic Latent Semantic Indexing (P-LSI) [18] views documents as mixtures of topics and ranks the documents by the probability of the query given the document distribution over topics. Latent Dirichlet Allocation (LDA) [6, 34] extends PLSI and assumes that topic distributions have a Dirichlet prior.

With increasingly large volumes of user logs, supervised latent semantic models trained on (clicked/not clicked) query-document pairs [1, 4, 8, 15, 16, 20, 29, 35, 36] have begun to outperform many unsupervised latent semantic models trained on documents only. Supervised Semantic Indexing (SSI) [1] and Regularized Mapping to Latent Spaces (RMLS) [35] learn weights for each query-document term pair using low rank matrix decomposition. The Bilingual Topic Model (BLTM) [16] is an extension of LDA, where queries and relevant documents are assumed to share the same distribution over topics, while they might use different topic word distributions for queries and documents.


Recently, latent semantic models based on neural networks [8, 16, 20, 28, 29, 36] have gained popularity. The Discriminative Projection Model (DPM) [16, 36] maps queries and document to concept vectors with the siamese network architecture [8]. Salakhutdinov and Hinton [28] propose a deep generative model that maps documents to memory addresses in such a way that semantically similar documents are located at nearby addresses. The Deep Structured Semantic Model (DSSM) [20] uses a deep feed-forward neural network to map queries and documents to the concept vectors. DSSM works at the level of character-trigrams, which allows generalization to unseen word forms. The performance of DSSM degrades as the text length increases, as its “bag of character-trigrams” representation leads to a combinatorial blow-up. The Convolutional Latent Semantic Model (CLSM) [29] mitigates this disadvantage by applying a DSSM-like model to word n-grams and combining their vectors at a later stage.

In our experiments we use LDA, WTM, DPM and DSSM as typical representatives of different families of models: topic models (PLSI, LDA, BLTM), translation models (WTM, PTM), conventional models based on matching in latent space (LSI, RLSI, SSI, RMLS, DPM) and recent models working at the level of character trigrams (DSSM, CLSM).

Ranking with latent semantic models. The training objective for LSI and RLSI is to minimize the reconstruction error of the document “bag of words” representation; PLSI and LDA (BLTM) minimize the perplexity of the document corpus (clicked query-document pairs); SSI, DPM minimize the ranking loss between clicked and unclicked documents. Common scoring functions used by the latent semantic models are (1) the cosine similarity between the query and document concept vectors (LSI, RLSI, SSI, RMLS, DPM, DSSM, CLSM) and (2) the query likelihood function (PLSI, LDA, BLTM, WTM, PTM). These scoring functions are simple and intuitive, but we argue that they are not expressive enough to tune latent semantic models for relevance prediction and that they do not use all potentially useful information from the model.

Combinations of latent semantic models. Most work on latent semantic models in search does not address the problem of combining latent semantic models and only provides a comparison of latent semantic models with each other [1, 2, 4, 8, 15, 16, 20, 29, 33, 34, 36]. Some work also uses linear interpolation with traditional retrieval models based on lexical matching (VSM, TFIDF, BM25) for comparison [2, 35, 36]. Wu et al. [35] test the performance of their proposed RMLS model by comparing the performance of a global ranker with baseline ranking models used as features against the global ranker with the baseline ranking models and RMLS. We provide an experimental analysis of the contribution of metafeatures to the combination of latent semantic models.

What we add on top of the work mentioned above is the following. First, we show that the common ways of using latent semantic models in web search (i.e., (1) to rank web documents by scores of the cosine similarity and query likelihood functions, and (2) to pass these scores as features to global ranker) are suboptimal. Second, we propose an approach that extracts more information from latent semantic models and leverages this information to improve...
3. METHOD

To increase the effectiveness of latent semantic models in (web) search engines, we propose to complement their outputs with metafeatures, feature vectors that describe the structure of the predictions of latent semantic models for a given query-document pair, and pass them to a global ranker together with the latent semantic models’ scores (see Figure 2).

We start with a disclaimer. There is no general algorithm for generating metafeatures for an arbitrary latent semantic model. However, as we will see, for many latent semantic models, their scoring functions provide a good starting point. In §3.1, we offer two guidelines for creating metafeatures for a latent semantic model based on its scoring function. We operationalize these guidelines in §3.2 using a diverse set of latent semantic models.

3.1 Guidelines for creating metafeatures

We use $Q$ to denote a query composed of terms $q_1, q_2, \ldots, q_\lvert Q \rvert$ and $D$ to denote a document composed of terms $w_1, w_2, \ldots, w_\lvert D \rvert$.

We write $MF_n((M, P))$ to denote the $n$-th group of metafeatures for a latent semantic model or a class of such models; $M; P$ denotes the parameters of the group of metafeatures. We use a compact form $MF_{\nu_1, \ldots, \nu_k}(M, P)$ to denote the metafeatures $MF_{\nu_1}(M, P), \ldots, MF_{\nu_k}(M, P)$.

**Guideline 1 (“Divide and Conquer”)**

The values making up the score produced by a latent semantic model capture more potentially useful information than the latent semantic model’s score by itself. They could, for instance, help to distinguish the two documents shown in Figure 1.

Below, we provide guidelines (a)–(c) for different types of scoring functions. We say that a scoring function $F(Q, D)$ can be expressed as a composition of functions $F = \{f_i(Q, D)\}$, if for all query-document pairs $(Q, D)$, it is possible to compute the value of $F(Q, D)$ by knowing the values of a subset of $F$. The values of some $f_i(Q, D)$ might be not defined for a given query-document pair $(Q, D)$, but it should still be possible to compute the value of $F(Q, D)$ using the values of other $f_i(Q, D) \in F$. The occurrence probability of $f_i(\cdot)$ is the probability that $f_i(\cdot)$ is defined for a query-document pair $(Q, D)$ randomly drawn from the (unknown) distribution of query-document pairs.

(a) For a scoring function $F(Q, D)$ that can be expressed as a composition of a fixed number ($N$) of functions $f_i(Q, D)$, define metafeatures $MF_1(F)$ by composing them of the values of the functions $f_i(Q, D)$ for a query-document pair $(Q, D)$:

\[
MF_1(F) = (f_1(Q, D), \ldots, f_N(Q, D)).
\]

(b) For a scoring function $F(Q, D)$ that can be expressed as a composition of a very large or unlimited number of functions $f_i(Q, D)$, define metafeatures $MF_1(F, N)$ of size $N$ by composing them of the values of $N$ functions $f_i(Q, D)$ that have the highest occurrence probabilities; if the value of function $f_i(Q, D)$ is not defined for a given query-document pair $(Q, D)$, set the metafeatures’ component that corresponds to the function $f_i(Q, D)$ with a NaN (Not a Number) value:

\[
MF_1(F, N) = (\hat{f}_1(Q, D), \ldots, \hat{f}_N(Q, D)),
\]

where $\hat{f}_i(Q, D)$ is $f_i(Q, D)$ if $f_i(Q, D)$ is defined, and NaN otherwise.

(c) For a scoring function $F(Q, D)$ that can be expressed as a composition of a very large or unlimited number of functions $f_i(Q, D)$ that have relatively high occurrence probabilities, define metafeatures $MF_1(F, k, p_1, \ldots, p_N)$ by composing them of the descriptive statistics of the distribution of values of the functions $f_i(Q, D)$ for a given query-document pair $(Q, D)$, e.g., the expected value $\mathbb{E}[f_i(Q, D)]$, variance $\text{Var}[f_i(Q, D)]$, $k$ min / max values of $f_i(Q, D)$ and percentiles $p_i$ of $\{f_i(Q, D)\}$. The default value of $k$ used in our study is 3; the default percentiles $p_i$ are 0.01, 0.03, 0.05, 0.125, 0.25, 0.5, 0.75, 0.875, 0.95, 0.97, 0.99.

**Note:** For a scoring function $F(Q, D)$ that can be expressed as a composition of functions $f_i(Q, D)$ that come from two or more different groups $G = \{g_k : k = 1, \ldots, |G|\}$, define $|G|$ scoring functions $F_{g_k}(Q, D)$ by setting the values of $f_i \notin g_k$ to constants, and construct metafeatures for $F_{g_k}(Q, D)$ using the guidelines (a)–(c).

**Guideline 2 (“Find the Strongest and Weakest Links”)**

For some latent semantic models, there is only a limited number of ways to express a scoring function $F(Q, D)$ as a composition of functions $f_i(Q, D)$. E.g., the scoring functions of WTM and DSSM cannot be expressed as a composition of per document term functions $f_1(Q, D), \ldots, f_{|D|}(Q, D)$, where the functions $f_i(Q, D)$ describe all relevant information about the $i$-th terms in the document $D$ for computing the scoring function $F(Q, D)$. But if such functions $f_1(Q, D), \ldots, f_{|D|}(Q, D)$ existed, their values could be regarded as contributions of the document terms to the scoring function $F(Q, D)$, and in this way, might help the global ranker to distinguish the documents that “answer” all query terms from those that match only some of them.

We suggest to create “surrogate functions” that perform the role of $f_i(Q, D)$. In particular, we propose to compute gradients of the scoring function $F(Q, D)$ with respect to the occurrences of document terms. This is a reasonable choice, because the components of these gradients measure how the score would change if we removed a small fraction of a term. Below, we capture this intuition more formally.

For a symmetric scoring function $F(Q, D)$ of query terms $Q$ and document terms $D$ (i.e., a function that takes the same value for any permutation of query terms and document terms), first define a function $F(q, d)$ of vectors $q$ and $d$ of vocabulary size $|V|$, whose $i$-th components are the number of occurrences of the $i$-th term in query $Q$ and document $D$, respectively. Then define a matrix $M_Q$ of size $|Q| \times |V|$, whose $i$-th row is a one-hot vector with the component corresponding to the $i$-th query term $q_i$ set to 1; and a matrix $M_D$ of size $|D| \times |V|$, whose $j$-th row is a one-hot vector with the component corresponding to the $j$-th document term $d_j$ set to 1. Finally, define the metafeatures $MF_1(F, N_1)$ and $MF_2(F, N_2)$ as gradients of $F(q, d)$ with respect to $q$ and $d$, $\nabla_Q F(q, d)$ and $\nabla_D F(q, d)$, multiplied by the matrices $M_Q(N_1)$ and $M_D(N_2)$.
and \( M_Q(N_2) \) composed of the first \( N_1 \) and \( N_2 \) rows of the matrices \( M_Q \) and \( M_D \):
\[
\begin{align*}
MF_1(F, N_1) &= M_Q(N_1) \nabla Q F(q, d), \\
MF_2(F, N_2) &= M_D(N_2) \nabla D F(q, d).
\end{align*}
\]

Sometimes, it is more convenient to apply a monotonic function \( g(x) \) to the scoring function \( F(\cdot) \), and use the resulting complex function \( g(F(\cdot)) \) instead of \( F(\cdot) \).

As we show in the next section, the presented guidelines help to extract a lot of potentially useful metafeatures from existing state-of-the-art latent semantic models.

### 3.2 Application of our guidelines

In this section we demonstrate how to apply the guidelines presented in Section 3.1 to different families of latent semantic models. Note that we do not aim to extract all possible metafeatures that could be extracted according to Guidelines 1 and 2, as the main purpose of our study is not an exhaustive search for all of them (which could potentially be a very large number), but a demonstration of the benefits of the methodology of metafeature extraction in general. Thus, we focus on the extraction of the most promising and interpretable metafeatures in this section.

#### 3.2.1 Latent semantic models based on the language modeling approach

We describe the metafeatures that we infer for topic models [6, 16, 18] and the Word-based Translation Model [4] that employ the language modeling approach. We start with the common metafeatures \( MF_2(QL, N) \) that capture the probabilities of the first \( N \) query terms given the document language model and the collection language model:
\[
\begin{align*}
MF_2(QL, N) &= \{P_{LM}(q_1 | C), \ldots, P_{LM}(q_N | C)\}, \\
MF_3(QL, N) &= \{P_{LM}(q_1 | D), \ldots, P_{LM}(q_N | D)\}.
\end{align*}
\]

These metafeatures provide extra information about the individual query terms that might help the global ranker to make better use of \( MF_3(QL, N) \). E.g., low query term probabilities given the latent semantic model \( P_{LM}(q_i | M_D) \) are less severe for query terms \( q_i \) for which \( P_{LM}(q_i | C) \) is high than for query terms \( q_i \) for which \( P(q_i | M_D) \) is low. A high query term probability given by the document model, \( P_{LM}(q_i | D) \), indicates that a high probability of a query term given the latent semantic model, \( P(q_i | M_D) \), is due to a lexical match. In this case, term-based models’ predictions might be more reliable for the global ranker.

**Topic models.** Topic models (e.g., PLSI, LDA, BLTM) view documents as mixtures of topics, i.e., \( M_D = \{P(t_j | D) : 1 \leq j \leq |T|\} \), where \( P(t_j | D) \) denotes the probability of topic \( t_j \) given the document \( D \), and \(|T|\) denotes the number of topics. The probability of a query term \( q_i \) given document model \( M_D \), \( P(q_i | M_D) \), is defined as the sum of the query term probabilities given the topic, \( P(q_i | t_j) \), weighted by topic probabilities, \( P(t_j | D) \):
\[
P(q_i | M_D) = \sum_{j=1}^{|T|} P(q_i | t_j) P(t_j | D).
\]

The document score is a function of (1) topic probabilities given the document, \( P(t_j | D) \) and (2) query term probabilities given the topic, \( P(q_i | t_j) \). Guideline 1 suggests that we define metafeatures \( MF_{1,2}(TM) \) that describe these values:
\[
\begin{align*}
MF_1(TM) &= \{P(t_1 | D), \ldots, P(t_{|T|} | D)\}, \\
MF_2(TM, N) &= \begin{pmatrix} P(q_1 | t_1), \ldots, P(q_N | t_1), \\
\cdots & \cdots & \cdots & \cdots \\
P(q_1 | t_{|T|}), \ldots, P(q_N | t_{|T|}) \end{pmatrix}.
\end{align*}
\]

However, the size of \( MF_2(TM, N) \) might be too large to train the global ranker without causing overfitting. In essence, \( MF_1(TM) \) and \( MF_2(TM, N) \) are meant to inform the global ranker about how well the document topic distribution helps to maximize the query probability. This can be achieved by comparing the document topic distribution with the query topic distribution—the query topic distribution is, by definition, the topic distribution that maximizes the query probability. This idea was originally proposed in [23], where the authors used Kullback-Leibler divergence between the query and document topic distributions as a scoring function:
\[
KL(Q, D) = \sum_{i=1}^{|T|} P(t_i | Q) \log \frac{P(t_i | Q)}{P(t_i | D)}
\]

Based on preliminary experiments, the Kullback-Leibler divergence scoring function (3) performed much poorer than the Query Likelihood scoring function (1), but it happened to be useful for creating metafeatures. Following Guideline 1 (a), we define metafeatures...
MF_3(TM) (defined earlier) and MF_3(TM) that capture the query and document topic distributions:

\[ MF_3(TM) = \{ P(t_1 \mid Q), \ldots, P(t_D \mid Q) \}. \]

The Word-based Translation Model. The Word-based Translation Model casts document ranking as a statistical machine translation problem, in which query Q is assumed to be a translation of document D. The document model MD is defined as a probability distribution of terms given a document. The probability of term w given document model MD is defined as the average translation probability of document terms \( w_1, \ldots, w_{|D|} \) into term w. So the probability of query term q_i given document model MD is:

\[ P(q_i \mid M_D) = \frac{1}{|D|} \sum_{j=1}^{|D|} P(q_i \mid w_j). \]

The document score is a function of the translation probabilities of a document term into a query term. Following Guideline 1 (b) we define metafeatures MF_1(WTM, N_1, N_2) that capture probabilities of the query terms given the document terms:

\[ MF_1(WTM, N_1, N_2) = \left\{ P(q_1 \mid w_1), \ldots, P(q_i \mid w_{N_2}), \ldots, P(q_q \mid w_{N_2}) \right\}. \]

As the number of \( P(q_i, w_j) \) that occur with a not low frequency is large, we also define metafeatures MF_2(WTM) from the set of translation probabilities of document terms into query terms \{P(q_i, w_j)\}_{1 \leq i \leq q, 1 \leq j \leq D}, following Guideline 1 (c). Guideline 2 suggests that passing on information about the query and document term contributions to the document score might be useful for the global ranker. The metafeatures MF_1(QL, N) that we have defined earlier (see (2)) describe the query term contributions. To define metafeatures that describe the document term contributions, we first apply a monotonic function \( g(x) = \log x \) to the scoring function \( P(Q \mid M_D) \) that gives a new scoring function

\[ F(Q, D) = g(P(Q \mid M_D)) = \sum_{i=1}^Q \log \frac{1}{|D|} \sum_{j=1}^{|D|} P(q_i \mid w_j). \]

Then we define a function \( F(q, d) \) of q and d:

\[ F(q, d) = q^T(\log A d - \log B d), \]

where A and B are matrices of size \(|V| \times |V|\) with \( A_{ij} = P(t_i, t_j) \), and \( B_{ij} = 1 \); \( \log(x) \) denotes the element-wise logarithm of vector x. Finally, we define the metafeatures that capture quantitative contributions of document terms as follows:

\[ MF_3(F, N_2) = M_Q(N_2) \nabla \nabla D F(q, d) = M_Q(N_2) (A^T \circ \text{inv}(A d) - B^T \circ \text{inv}(B d)) q, \]

where Z = X \circ Y denotes the element-wise multiplication of matrix X by vector Y: \( Z[i,j] = X[i,j] Y[i] \); and Z = \text{inv}(x) denotes the element-wise multiplicative inverse of vector x: \( z[i] = 1/x[i] \), if \( x[i] \neq 0 \) and 0 otherwise. Briefly, MF_1(WTM, N_2) are:

\[ \frac{|Q|}{|D|} \sum_{i=1}^{|Q|} P(q_i \mid w_1) - \frac{|Q|}{|D|} \sum_{i=1}^{|Q|} P(q_i \mid w_{N_2}) - \frac{|Q|}{|D|}. \]

The components of MF_3(WTM, N_2) characterize the contributions of document terms \( w_i \) with respect to the other terms in the document D: \( \alpha_k = \frac{\sum_{i=1}^{|Q|} P(q_i \mid w_k)}{\sum_{j=1}^{|D|} P(q_i \mid w_j)} \) is the actual quantitative contribution of the document term \( w_i \); \( \beta = \frac{|Q|}{|D|} = \frac{1}{|D|} \sum_{k=1}^{|D|} \alpha_k \) is the average contribution of the document terms \( w_{1}, \ldots, w_{|D|} \).

3.2.2 Latent semantic models based on the latent space matching approach

Next, we describe metafeatures that we infer for latent semantic models that employ the latent space matching approach. We start with the metafeatures shared by all models of this class and then take a closer look at the Deep Structured Semantic Model [20].

Latent semantic models based on the latent space matching approach learn vector representations for queries and documents, such that the distance between a query vector \( v_Q \) and a document vector \( v_D \) reflects the degree of relevance of the document D to the query Q. The standard choice for a distance function between the query and document vectors is the cosine similarity measure [25]:

\[ \cos(v_Q, v_D) = \frac{v_Q \cdot v_D}{\|v_Q\| \|v_D\|}. \]

where N denotes the dimensionality of the vector space and \( v(i) \) denotes the i-th component of vector v.

Following Guideline 1 (a), we use the terms under the summation sign in (4) to define metafeatures MF_1(COS) that capture per dimension matching scores:

\[ MF_1(COS) = \left( \frac{v_Q(1) v_D(1)}{\|v_Q\| \|v_D\|}, \ldots, \frac{v_Q(N) v_D(N)}{\|v_Q\| \|v_D\|} \right). \]

The rationale is analogous to the one underlying MF_1(QL, N): we want to be able to distinguish the two cases shown in Figure 1. One document has roughly the same scores in all dimensions, the other has much higher scores in two dimensions and lower scores in other dimensions.

Viewed differently, the document score is a function of both the query vector \( v_Q \) and the document vector \( v_D \). Hence, following Guideline 1 (a), we define metafeatures MF_2(COS) that capture the components of the query vector \( v_Q \) and document vector \( v_D \):

\[ MF_2(COS) = \left( v_Q(1), \ldots, v_Q(N) \right), \]

\[ MF_3(COS) = \left( v_D(1), \ldots, v_D(N) \right). \]

The Deep Structured Semantic Model. The Deep Structured Semantic Model (DSSM) uses a technique called word hashing, which represents queries and documents with letter-trigram vectors. For example, San Francisco is encoded with the following letter-trigrams #sa, san, an#, #fr, fra, ran, anc, nci, cis, isc, sco, co#, where # is a boundary symbol. These letter-trigram vectors are passed through the three fully connected layers of a feed-forward neural network to obtain vector representations \( v_Q \) and \( v_D \), as illustrated in Figure 3.

Guideline 2 suggests that we construct metafeatures that capture the quantitative contributions of query and document terms to the document score. But since DSSM works at the letter-trigram level, we consider letter-trigram contributions.\(^1\)

We use the following notation: \( |T|_c \) is the length of text T in characters; \( |L| \) is the total number of letter-ngrams; \( q_e \) and \( d_e \) are vectors of size \( |L| \), whose elements on the i-th position are the numbers of occurrences of the i-th letter-ngram in query Q and document D, respectively; \( v_Q(q_e) \) and \( v_D(d_e) \) are functions of \( q_e \) and \( d_e \) that return the semantic representations of query Q and document D.

\(^1\)In the case of the DSSM model, term contributions are the sums of the contributions of the letter-trigrams that constitute the term.
ment $D$ (these functions are learned by DSSM); $M_Q$ is a matrix of size $|Q| \times |V|$, whose i-th row is a one-hot vector with the component corresponding to the i-th query letter-trigram set to 1; $M_D$ is a matrix of size $|D| \times |V|$, whose i-th row is a one-hot vector with the component corresponding to the i-th document letter-trigram set to 1. We write $M_Q(N_1)$ and $M_D(N_2)$ for the matrices composed of the first $N_1$ and $N_2$ rows of the matrices $M_Q$ and $M_D$.

We define metafeatures that account for the contributions of the query and document letter-trigrams as follows:

$$MF_1(DSSM, N_1) = M_Q(N_1) \nabla_{q_k} \cos (v_Q(q_k), v_D(d_k)),$$

$$MF_2(DSSM, N_2) = M_Q(N_2) \nabla_{d_k} \cos (v_Q(q_k), v_D(d_k)).$$

Using the chain rule $\nabla_y F(y(x)) = J^T_y(y(x)) \nabla_x F(y)$, where $J_y(y(x))$ denotes the Jacobian matrix of a vector function $y(x)$ of a vector $x$ w.r.t. the vector $x$, and the equality $\nabla_x \cos(x, y) = \nabla_y x^T y = y - x^T y$, we rewrite $MF_{1,2}(DSSM, N_1)$ as follows:

$$MF_1(DSSM, N_1) = M_Q(N_1) J^T_{q_k} (v_Q(q_k)) \nabla_{v_Q} \cos (v_Q, v_D) = M_Q(N_1) J^T_{q_k} (v_Q(q_k)) \left( \frac{v_Q}{\| v_Q \|^2} \frac{v_D}{\| v_D \|^2} - \frac{v_D}{\| v_D \|^2} \frac{v_Q}{\| v_Q \|^2} \right).$$

$$MF_2(DSSM, N_2) = M_Q(N_2) J^T_{d_k} (v_D(d_k)) \nabla_{v_D} \cos (v_Q, v_D) = M_Q(N_2) J^T_{d_k} (v_D(d_k)) \left( \frac{v_D}{\| v_D \|^2} \frac{v_Q}{\| v_Q \|^2} - \frac{v_Q}{\| v_Q \|^2} \frac{v_D}{\| v_D \|^2} \right).$$

The elements of $J_{q_k} (v_Q(q_k))$ and $J_{d_k} (v_D(d_k))$ are the first derivatives of the functions in the output layer of the neural network w.r.t. the input vectors $q_k$ and $d_k$ (see e.g., [3] for the exact formulas).

The metafeatures $MF_1(DSSM, N_1)$ and $MF_2(DSSM, N_2)$ do not capture information about word boundaries. This might be a disadvantage because the importance of a letter-trigram, which we define as its expected contribution, varies with its position. E.g., letter-trigrams at the end of a term are typically less informative than those in the middle (for many European languages) [19].

To capture the boundaries between terms in the query and terms in the documents we define metafeatures $MF_{3,4,5,6}(DSSM, N)$:

$$MF_3(DSSM, N_1) = (\text{start}(Q, 1), \ldots, \text{start}(Q, N_1)),$$

$$MF_4(DSSM, N_1) = (\text{end}(Q, 1), \ldots, \text{end}(Q, N_1)),$$

$$MF_5(DSSM, N_2) = (\text{start}(D, 1), \ldots, \text{start}(D, N_2)),$$

$$MF_6(DSSM, N_2) = (\text{end}(D, 1), \ldots, \text{end}(D, N_2)).$$

Since DSSM uses weight sharing, $J_{a_k}(v_Q(q_k)) = J_{d_k}(v_D(d_k))$.

![Figure 3: The Deep Structured Semantic Model (DSSM) [20].](image)

**Figure 3:** The Deep Structured Semantic Model (DSSM) [20].

4. **EXPERIMENTAL SETUP**

4.1 **Research questions**

We seek to answer the following research questions.

**RQ1** Do metafeatures associated with latent semantic models help improve the performance of individual latent semantic models on a web document ranking task? In particular:

(a) Which of the metafeatures defined in Section 3.2 help to improve performance of the underlying latent semantic models?

(b) Does employing a combination of different metafeatures inferred from a single latent semantic model yield better performance than individual metafeatures?

(c) How does the performance of the global ranker, trained with metafeatures, vary with the size the training data set?

**RQ2** Do metafeatures associated with latent semantic models provide a means to improve the performance of a combination of latent semantic models on the web document ranking task?

4.2 **Data sets and evaluation methodology**

In modern search engines, a document is described by multiple fields, including body text, title, URL and anchor texts [30]. In our experiments, we focus on the title field. We do this for the following reasons. First, recent work on supervised latent semantic models in web search focuses on the title field [15, 16, 20, 29, 35]. Second, the title field gives better [29] or, at least, as effective [30] retrieval results as the body text field (using BM25). Third, some models achieve state-of-the-art performance using the title field, but do not

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2 Although our work targets supervised latent semantic models, we include a comparison with LDA, as a well-known baseline.
apply to other fields (e.g., it is not feasible to train DSSM [20] on the body text field, because of the extremely large number of non-zero elements in the word hashing layer).

To train latent semantic models, we collected a training data set that comprises 130,024,971 search sessions sampled from a commercial web search engine over a six months period. It contains a total of 51,117,758 unique user queries and 178,289,551 retrieved documents. Figures 5 and 6 show the query and document distributions of the number of words and characters in the training data set. We use these statistics to set the parameters of metafeatures in our experiments (Section 4.4).

To evaluate the performance of the models, we collected an evaluation data set that contains 111,203 queries sampled from the query-log files of a commercial web search engine. On average, each query is associated with 27 documents (URLs). Each query-document pair has a human-generated relevance label on a scale from 0 to 4, with 0 = bad, 1 = fair, 2 = good, 3 = excellent, 4 = perfect. Performance is measured using mean Normalized Discounted Cumulative Gain (NDCG) [21] at truncation levels 1, 3, 5 and 10, using k-fold cross-validation. We use (k − 1) folds to train the global ranker and 1 fold to evaluate the performance; the results over k folds are averaged. We perform significance testing using a paired t-test; differences are considered statistically significant for p-values lower than 0.001.

4.3 Model settings and baseline performance

We use four latent semantic models for which we infer metafeatures. The baseline performance achieved by the models after optimization is listed in Table 1. Below we describe how the models are trained. For comparison, we also list a state-of-the-art ranking model based on the global ranker trained with the latent semantic model’s score as features.

BM25 (row 1 in Table 1) is a state-of-the-art document ranking model based on lexical matching, BM25.

BM25 (row 1 in Table 1) is our MapReduce implementation of the topic model proposed in [6]. It is trained with 200 iterations of Gibbs sampling using α = 50/[T] and β = 0.01 (the default values used, e.g., in [34]). The number of topics [T] is set to 100

LDA (rows 2–3 in Table 1) is a state-of-the-art document ranking model based on lexical matching. The parameters k and b are optimized using Powell’s method [27].

DPM (row 6 in Table 1) is our implementation of the Discriminative Projection Model proposed in [13]. It is trained by maximizing the conditional likelihood of the clicked query-title pairs. We use the configuration proposed in [20] (the numbers of neurons in the hidden layers are (300, 300, 128)).

DSSM (row 7 in Table 1) is our implementation of the Deep Structured Semantic Model proposed in [20]. It is trained by maximizing the conditional likelihood of the clicked query-title pairs. We use the configuration proposed in [20] (the numbers of neurons in the hidden layers are (300, 300, 128)).

All ranking models based on latent semantic models outperform the BM25 ranking model by a large margin, on all metrics. DSSM is the best performing individual latent semantic model, again on all metrics. The two combination models outperform all individual models and GBRT outperforms the linear model. In the rest of the experiments, we use GBRT as our global ranker.

<table>
<thead>
<tr>
<th>#</th>
<th>Ranking model</th>
<th>@1</th>
<th>@3</th>
<th>@5</th>
<th>@10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BM25</td>
<td>0.520</td>
<td>0.583</td>
<td>0.631</td>
<td>0.709</td>
</tr>
<tr>
<td>2</td>
<td>LDA (w/o smoothing)</td>
<td>0.538</td>
<td>0.608</td>
<td>0.657</td>
<td>0.734</td>
</tr>
<tr>
<td>3</td>
<td>LDA (w/ smoothing)</td>
<td>0.552</td>
<td>0.619</td>
<td>0.667</td>
<td>0.741</td>
</tr>
<tr>
<td>4</td>
<td>WTM (w/o smoothing)</td>
<td>0.545</td>
<td>0.611</td>
<td>0.659</td>
<td>0.736</td>
</tr>
<tr>
<td>5</td>
<td>WTM (w/ smoothing)</td>
<td>0.560</td>
<td>0.626</td>
<td>0.673</td>
<td>0.746</td>
</tr>
<tr>
<td>6</td>
<td>DPM</td>
<td>0.537</td>
<td>0.602</td>
<td>0.648</td>
<td>0.724</td>
</tr>
<tr>
<td>7</td>
<td>DSSM</td>
<td>0.568</td>
<td>0.640</td>
<td>0.687</td>
<td>0.759</td>
</tr>
<tr>
<td>8</td>
<td>ALL (linear model)</td>
<td>0.580</td>
<td>0.649</td>
<td>0.694</td>
<td>0.764</td>
</tr>
<tr>
<td>9</td>
<td>ALL (GBRT)</td>
<td>0.604</td>
<td>0.664</td>
<td>0.706</td>
<td>0.772</td>
</tr>
</tbody>
</table>

4.4 Experiments

We design two experiments to answer our research questions.

Experiment 1. To answer RQ1, we compare the performance of each individual latent semantic model’s score against the output of the global ranker trained with the latent semantic model’s score as well as the metafeatures inferred from the latent semantic model used as features.
In Section 3.2 we have introduced some metafeatures together (e.g., MF2(COS) and MF3(COS)) and provided the intuitions why those metafeatures might be helpful for the global ranker. We evaluate the impact of the metafeatures within the groups where they were introduced (Table 2).

For the metafeatures MF1,2,3(QL, N), MF1(WTM, N1, N2) and MF1(WTM, N) we set N = N1 = N2 = 15, because less than 0.3% of the queries and 0.2% of the titles in the training set contain more than 15 words (Figure 5). For the metafeatures MF1,2,3,4,5,6(DSSM, N) we set N = 80 because less than 0.4% of the queries and 0.2% of the titles in the training set contain more than 80 characters (Figure 6).

Table 2: Experiment 1 (runs).

<table>
<thead>
<tr>
<th>Metafeatures</th>
<th>Latent semantic models</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF1,2,3(QL, 15)</td>
<td>LDA, WTM</td>
</tr>
<tr>
<td>MF1,3(TM)</td>
<td>LDA</td>
</tr>
<tr>
<td>MF1(WTM, 15, 15)</td>
<td>WTM</td>
</tr>
<tr>
<td>MF2(WTM)</td>
<td>WTM</td>
</tr>
<tr>
<td>MF1(QL, 15), MF3(WTM, 15)</td>
<td>WTM</td>
</tr>
<tr>
<td>MF1(COS)</td>
<td>DPM, DSSM</td>
</tr>
<tr>
<td>MF2,3(COS)</td>
<td>DPM, DSSM</td>
</tr>
<tr>
<td>MF1,2,3,4,5,6(DSSM, 80)</td>
<td>DSSM</td>
</tr>
</tbody>
</table>

Experiment 2. To answer RQ2, we compare the performance of the global ranker trained with the individual latent semantic models’ scores only (for LDA, WTM, DPM, DSSM) against the global ranker trained with those individual latent semantic models’ scores plus the metafeatures infered from those models.

5. RESULTS

We present the outcomes of the two experiments described in Section 4.4, and provide answers to our research questions.

5.1 Experiment 1

The results of Experiment 1 are given in Table 3 and Figure 7. Table 3 compares the performance of each individual latent semantic model and the global ranker trained using the latent semantic model’s score together with the metafeatures listed in Table 2 as features. Figure 7 plots the performance (in terms of NDCG@10) for the latent semantic models with the metafeatures listed in Table 2 vs. the number of queries used for training.

A first general observation from Table 3 is that for every latent semantic model, the addition of all metafeatures defined for that model yields the highest performance. We also see that combinations of metafeatures nearly always lead to performance increases. Let us now turn to each research question individually.

RQ1 (a). We find that all metafeatures defined in Section 3.2 yield statistically significant improvements in NDCG scores at truncation levels 1, 3, 5 and 10 over the underlying rankings produced by the latent semantic models’ scores, for all latent semantic models. The relative improvements in NDCG scores at truncation levels 1, 3, 5 and 10 are above 10.2%, 7.8%, 6.4% and 4.2%, respectively (Table 4). Hence, our metafeatures have a clear early precision enhancing effect.

RQ1 (b). We find that the best results for each latent semantic model are obtained by the combination of all latent semantic model metafeatures (“ALL MF”). However, combinations of metafeatures do not always lead to performance improvements. In particular, for DPM, the addition of MF1(COS) does not lead to a statistically significant improvement over the metafeatures MF2,3(COS). And for DSSM MF1,2,3(COS) does not outperform MF2,3(COS). This can be explained by the fact that the components of MF1(COS) are the products of the components of MF2(COS) and MF3(COS): MF1(COS) does not bring any new information to the global ranker trained with MF2,3(COS), but increases the number of features used by the global ranker, which results in a stronger overfitting of the global ranker.

RQ1 (c). We find that the gains obtained from metafeatures in terms of NDCG@10 are proportional to the logarithm of the size of the training data set: the average Pearson correlation coefficient, \( r = 0.860 \) (with all values in the interval [0.825; 0.921]). For some models, viz. LDA, WTM, DSSM, the performance achieved with a

Table 3: Performance of the ranking models based on the latent semantic models with different metafeatures (10-fold cross-validation). Highest scores per latent semantic model are indicated in boldface. The improvements of models with metafeatures over their respective baseline models (i.e., LDA, WTM, DPM and DSSM) are statistically significant (p < 0.001).

<table>
<thead>
<tr>
<th></th>
<th>NDCG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>@1</td>
</tr>
<tr>
<td>LDA</td>
<td>0.552</td>
</tr>
<tr>
<td>+ MF1,2,3(QL, 15)</td>
<td>0.564</td>
</tr>
<tr>
<td>+ MF1,3(TM)</td>
<td>0.619</td>
</tr>
<tr>
<td>+ ALL MF</td>
<td>0.625</td>
</tr>
<tr>
<td>WTM</td>
<td>0.560</td>
</tr>
<tr>
<td>+ MF1,2,3(QL, 15)</td>
<td>0.576</td>
</tr>
<tr>
<td>+ MF1(WTM, 15, 15)</td>
<td>0.599</td>
</tr>
<tr>
<td>+ MF2(WTM)</td>
<td>0.593</td>
</tr>
<tr>
<td>+ MF1(WTM)</td>
<td>0.605</td>
</tr>
<tr>
<td>+ MF1(QL, 15)</td>
<td>0.597</td>
</tr>
<tr>
<td>+ MF2(QL, 15)</td>
<td>0.617</td>
</tr>
<tr>
<td>DPM</td>
<td>0.537</td>
</tr>
<tr>
<td>+ MF1(COS)</td>
<td>0.605</td>
</tr>
<tr>
<td>+ MF2,3(COS)</td>
<td>0.614</td>
</tr>
<tr>
<td>+ MF1,2,3(COS)</td>
<td>0.615</td>
</tr>
<tr>
<td>(+ ALL MF)</td>
<td>0.634</td>
</tr>
</tbody>
</table>

Table 4: Relative improvements of the rankings given by the global ranker trained with the individual latent semantic models’ scores and all metafeatures defined for the model over the rankings given by the individual latent semantic models’ scores (10-fold cross-validation).

<table>
<thead>
<tr>
<th>Latent semantic model</th>
<th>@1</th>
<th>@3</th>
<th>@5</th>
<th>@10</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDA</td>
<td>+13.2%</td>
<td>+10.5%</td>
<td>+8.7%</td>
<td>+6.2%</td>
</tr>
<tr>
<td>WTM</td>
<td>+10.2%</td>
<td>+7.8%</td>
<td>+6.5%</td>
<td>+4.7%</td>
</tr>
<tr>
<td>DPM</td>
<td>+14.5%</td>
<td>+12.3%</td>
<td>+10.8%</td>
<td>+8.0%</td>
</tr>
<tr>
<td>DSSM</td>
<td>+11.6%</td>
<td>+8.0%</td>
<td>+6.4%</td>
<td>+4.2%</td>
</tr>
</tbody>
</table>
Deep Structured Semantic Model (DSSM)

Figure 7: Performance of the latent semantic models with different metafeatures for different sizes of training data. (Best viewed in color.)

relative small number of queries in the training set (i.e., < 12500) is below the performance of the baseline (not using metafeatures). This is apparently a result of overfitting, as we observed similar results for the global ranker trained with only one feature—the latent semantic model’s score. With more queries added for training, all metafeatures end up beating the baseline, and significantly so.

Together, the above results lead to the conclusion that the proposed metafeatures improve the performance of the latent semantic models on the web document ranking task that we consider. Interestingly, through the addition of metafeatures the ranking of latent semantic models has changed: from DSSM > WTM > LDA > DPM (on all metrics) we went to DSSM > LDA > DPM ≈ WTM (again, on all metrics) (Table 3). This reveals an important experimental issue: fair comparison of latent semantic models w.r.t. a document ranking task assumes utilizing all potentially useful knowledge mined during the building of these models.

5.2 Experiment 2

The outcomes of Experiment 2 are listed in Table 5. We find that the metafeatures yield a statistically significant improvement over the output of the global ranker trained with the latent semantic models’ scores only. The relative improvements in NDCG scores at truncation levels 1, 3, 5 and 10 are 7.6%, 6.17%, 5.38% and 3.75%, respectively.

Table 5: Performance of the model combinations with the latent semantic models’ scores only and the latent semantic models’ scores and metafeatures (10-fold cross validation). The improvements are statistically significant (p < 0.001).

<table>
<thead>
<tr>
<th>NDCG</th>
<th>@1</th>
<th>@3</th>
<th>@5</th>
<th>@10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global ranker features</td>
<td>0.604</td>
<td>0.664</td>
<td>0.706</td>
<td>0.772</td>
</tr>
<tr>
<td>models’ outputs</td>
<td>0.650</td>
<td>0.705</td>
<td>0.744</td>
<td>0.801</td>
</tr>
</tbody>
</table>

Next, we take a closer look at the changes brought about by the inclusion of metafeatures in the combination of latent semantic models. Table 6 provides a matrix of the changes in relevance labels for the documents returned in the top position for each query in the evaluation data set by the combination of the latent semantic models’ scores only (w/o MF) and by the combination extended with the metafeatures (w/ MF). We counted the number of times that the retrieved document is in each of the five relevance categories, from bad to perfect, for both combinations.

We observe that for 70% of the queries, the relevance labels of the documents returned in the top position did not change. For the remaining queries, the number of cases in which the highest ranked document returned by the combination w/ MF is more relevant than one returned by the combination w/o MF exceeds the number of cases in which the combination w/o MF returns a more relevant document than the combination w/ MF for all relevance label pairs. Furthermore, the relative number of cases in which the combination w/ MF returns a more relevant document than the combination w/o MF is smaller for low-performing queries (for which the retrieved documents’ labels fall into bad, fair or good categories) than for high-performing queries (for which the retrieved documents’ labels fall are excellent or perfect).

In sum, metafeatures help to bring high-quality documents to the top position rather than that they help to replace non-relevant documents with partially relevant ones.

6. CONCLUSION AND FUTURE WORK

In this paper, we have introduced an approach to increase the effectiveness of latent semantic models on a web document ranking task. The approach is based on so-called metafeatures—feature vectors that provide a fine-grained description of a latent semantic model’s prediction or some aspects of the prediction. We demonstrated our approach using four latent semantic models, two of which are traditional latent semantic models (Latent Dirichlet Allocation [6, 34] and Word-based Translation Model [4]) used in many IR applications, while the other two are recently proposed latent semantic models (Discriminative Projection Model [16, 36] and...
and Deep Structured Semantic Model [20]) that specialize on the web document ranking task.

Our experimental results show that through the use of metafeatures the performance of a combination of latent semantic models on the document ranking task can be improved by 7.6% and 3.8% in NDCG scores at truncation levels 1 and 10. Moreover, through the use of metafeatures we manage to achieve better performance for each individual latent semantic model by itself than the traditional way of combining all four latent semantic models’ scores.

We believe that a latent semantic model’s metafeatures along with its score provide a richer representation of the model’s prediction than the model’s score by itself. We expect metafeatures to be useful in other applications that use the scores of latent semantic models, e.g., online advertising [7], question answering [5], paraphrase detection [11], and textual entailment [31].

As to the limitations of our study, the large size of some metafeatures might increase the chances of overfitting for many machine learning algorithms. To mitigate the issue, dimensionality reduction techniques, such as Principal Component Analysis (PCA) [22], Autoencoder Neural Networks (AENNs) [10], Restricted Boltzmann Machines (RBMs) [17] and t-SNE [32], can be considered.

Our approach can be extended to other models whose scores are used as features for a machine learning algorithm. For instance, in web search, a similar approach can be applied to the PageRank model [26]. The score assigned to a document $D$ by the PageRank model is a sum of features over documents that contain a reference to $D$. Providing information about components of the sum (e.g., mean, variance) might help the global ranker when it attempts to rank documents that have received very similar PageRank scores.

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7. REFERENCES


