



Processamento
e Recuperação
de Informação

Generic
Document
Model

The Boolean
Model

The Vector
Space Model

Probabilistic
Models

Comparison of
the Different
Models

Processamento e Recuperação de Informação

Information Retrieval Models

Departamento de Engenharia Informática
Instituto Superior Técnico

1º Semestre
2018/2019



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Bibliography

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Retrieval Models

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Index Terms

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In the classic IR models, documents are represented by **index terms**

- full text/selected keywords
- structure/no structure

Not all terms are equally useful

- index terms can be **weighted**

We assume that terms are **mutually independent**

- this is, of course, a simplification



Definition of a Document Model

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Definition

Let t be the number of index terms in the collection of documents, and let k_i be a generic index term.

- $K = \{k_1, \dots, k_t\}$ is the set of all index terms.
- A weight $w_{i,j} \geq 0$ is associated with each index term k_i of a document d_j .
- For an index term which does not appear in the document text, $w_{i,j} = 0$.
- Each document d_j is associated a term vector \vec{d}_j , represented by $\vec{d}_j = (w_{1,j}, w_{2,j}, \dots, w_{t,j})$.
- Function $g_i(\vec{d}_j)$ returns the weight of index term k_i in vector \vec{d}_j .



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Boolean Model Queries

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- Follows Boolean algebra syntax and semantics
- Term weights are binary
 - $w_{i,j} \in \{0, 1\}$
 - $w_{i,j} = 1$ — term present,
 - $w_{i,j} = 0$ — term not present
- Queries are Boolean expressions
 - E.g., $q = k_a \wedge (k_b \vee \neg k_c)$
- Documents are considered **relevant** if the query evaluates to 1 (true)



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d_1

That government is best which
governs least

d_2

That government is best which
governs not at all

d_3

When men are prepared for it,
that will be the kind of
government which they will have



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That government is best which
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d_3

When men are prepared for it,
that will be the kind of
government which they will have

$q = \text{government} \wedge \text{best}$

answer: d_1, d_2



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d_1

That government is best which
governs least

$q = \text{government} \wedge \text{best}$

answer: d_1, d_2

d_2

That government is best which
governs not at all

$q = \text{government} \wedge \text{best} \wedge \neg \text{all}$

answer: d_1

d_3

When men are prepared for it,
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d_1

That government is best which
governs least

$q = \text{government} \wedge \text{best}$

answer: d_1, d_2

d_2

That government is best which
governs not at all

$q = \text{government} \wedge \text{best} \wedge \neg \text{all}$

answer: d_1

d_3

When men are prepared for it,
that will be the kind of
government which they will have

$q = \text{government} \vee \text{best} \wedge \neg \text{all}$

answer: d_1, d_2, d_3



Document-Query Similarity

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- Queries can be translated to a disjunction of conjunctive vectors

$$\vec{q} = k_a \wedge (k_b \vee \neg k_c) \Leftrightarrow (1, 1, 1) \vee (1, 1, 0) \vee (1, 0, 0)$$

each tuple corresponds to a vector (k_a, k_b, k_c)

- Similarity of a document to a query is defined as:

$$\text{sim}(d_j, q) = \begin{cases} 1 & \text{if } \exists \vec{q}_c \in \vec{q} | \forall_i, g_i(\vec{d}_j) = g_i(\vec{q}_c) \\ 0 & \text{otherwise} \end{cases}$$



The Boolean Model

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Why is it good?

- Simple model based on Boolean algebra
- Intuitive concept
- Precise semantics
- Clear formal basis
- Widely adopted by early information systems



Boolean Model

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Limitations:

- Retrieval based only on binary decisions
 - More similar to *data retrieval* than *information retrieval*
 - Can retrieve too many, or too little documents
 - Some documents may be more relevant than others
- How do you translate a query to a Boolean expression?
 - Non-expert users may not be able to represent their information needs using Boolean expressions
- Terms are all equally important
 - Index term weighting can bring great improvements in performance



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Documents as Vectors

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- Documents are represented as vectors
 - $\vec{d}_j = (w_{1,j}, w_{2,j}, \dots, w_{t,j})$
 - $w_{i,j}$ is the weight of term i in document j
- Queries are also vectors
 - $\vec{q} = (w_{1,q}, w_{2,q}, \dots, w_{t,q})$
- Vector operations can be used to compare queries×documents (or documents×documents)



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Defining Document Vectors

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Two questions are still unanswered:

- 1 How do we define term weights?
- 2 How do we compare documents to queries?



Defining Term Weights — TF

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Term frequency

Term frequency is a measure of term importance **within a document**

Definition

Let N be the total number of documents in the system and n_i be the number of documents in which term k_i appears. The **normalized frequency** of a term k_i in document d_j is given by:

$$f_{i,j} = \frac{freq_{i,j}}{\max_l freq_{l,j}}$$

where $freq_{i,j}$ is the number of occurrences of term k_i in document d_j .



Defining Term Weights — IDF

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(Inverse) Document frequency

Document frequency is a measure of term importance **within a collection**

Definition

The **inverse document frequency** of a term k_i is given by:

$$idf_i = \log \left(\frac{N}{n_i} \right)$$



Defining Term Weights — TF-IDF

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Definition

The weight of a term k_i in document d_j for the vector space model is given by the **tf-idf** formula:

$$w_{i,j} = f_{i,j} \times \log \left(\frac{N}{n_i} \right)$$



Components of TF-IDF

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Different TF-IDF formulations consider alternative approaches for the TF and IDF components, and also for normalizing the resulting vectors.

Term frequency		Document frequency		Normalization	
n (natural)	$tf_{t,d}$	n (no)	1	n (none)	1
l (logarithm)	$1 + \log(tf_{t,d})$	t (idf)	$\log \frac{N}{df_t}$	c (cosine)	$\frac{1}{\sqrt{w_1^2 + w_2^2 + \dots + w_M^2}}$
a (augmented)	$0.5 + \frac{0.5 \times tf_{t,d}}{\max_t(tf_{t,d})}$	p (prob idf)	$\max\{0, \log \frac{N - df_t}{df_t}\}$	u (pivoted unique)	$1/u$
b (boolean)	$\begin{cases} 1 & \text{if } tf_{t,d} > 0 \\ 0 & \text{otherwise} \end{cases}$			b (byte size)	$1/CharLength^\alpha$, $\alpha < 1$
L (log ave)	$\frac{1 + \log(tf_{t,d})}{1 + \log(\text{ave}_{t \in d}(tf_{t,d}))}$				



Document Similarity

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- Similarity between documents and queries is a measure of the correlation between their vectors
- Documents/queries that share the same terms, with similar weights, should be more similar
- Thus, as similarity measure, we use the **cosine of the angle between the vectors**

$$\text{sim}(d_j, q) = \frac{\vec{d}_j \cdot \vec{q}}{|\vec{d}_j| \times |\vec{q}|} = \frac{\sum_{i=1}^t w_{i,j} \times w_{i,q}}{\sqrt{\sum_{i=1}^t w_{i,j}^2} \times \sqrt{\sum_{i=1}^t w_{i,q}^2}}$$



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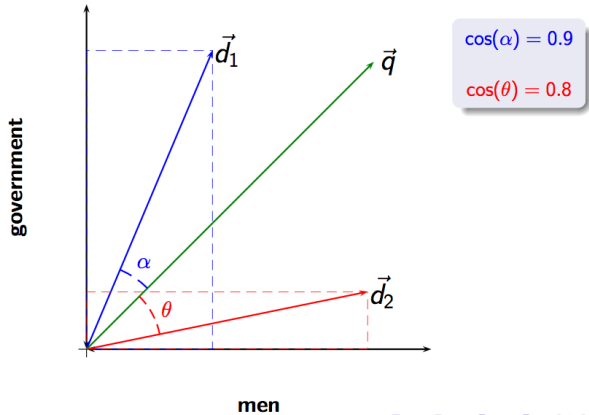
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The Vector Space Model

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Why is it so good?

- Simple model, based on linear algebra
- Term weights are not binary
- Allows computing a continuous **degree of similarity** between queries and documents
- Thus, allows **ranking** documents according to their possible relevance



Improving the VSM (1)

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The BM25 Model

Consider not only the term frequency and inverse document frequency heuristics, but also the **document length as a normalization factor** for the term frequency

$$TF_{i,j} = \frac{f_{i,j} \times (k_1 + 1)}{f_{i,j} + k_1 \times \left(1 - b + b \frac{|d_j|}{avgdl}\right)}$$

$$IDF_i = \log \frac{N - n_i + 0.5}{n_i + 0.5}$$

$$sim(d_j, q) = \sum_{i \in q} IDF_i \times TF_{i,j}$$

To be detailed in the next lecture



Improving the VSM (2)

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Latent Semantic Indexing

- Find a low-rank approximation of the matrix which describes the occurrences of terms in documents
 - Singular Value Decomposition
 - Compare the documents in the low-dimensional space
- The consequence of the rank lowering is that some dimensions are combined (e.g., **mitigates the problem of identifying synonymy**)
- To be detailed latter in the course



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Probabilistic Models for IR

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TF-IDF and VSM produces sufficiently good results in practice, but often criticized for being **too ad-hoc** or **not principled**

- Typically outperformed by probabilistic retrieval models and statistical language models in IR benchmarks
- Probabilistic retrieval models
 - use generative models of documents as bags-of-words
 - explicitly model probability of relevance $P(R|d_j, q)$
 - probabilistic justification for TF-IDF-like approaches
- Statistical language models
 - use generative models of documents and queries as sequences-of-words
 - consider likelihood of generating query from document model or divergence of document model and query model



Probabilistic Retrieval Models

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Bayes optimal decision rule for set retrieval

d_j is relevant iff $P(R|d_j, q) > P(\bar{R}|d_j, q)$

- Model the IR problem in a probabilistic framework
- Estimate the probability of document d_j being relevant to the user that submitted the query q
- When considering ranked retrieval, present documents in decreasing order of their estimated probability of relevance



Binary Independence Model (BIM)

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Simplifying assumptions for $P(R|d_j, q)$

- A simple probabilistic model can assume that:
 - ① probability depends only on query and document
 - ② there is a subset R of relevant documents
 - ③ index terms are independent
 - ④ non-query terms are equally likely to appear in relevant and non-relevant documents
- Use **binary term weights**
 - documents and queries as binary term incidence vectors
 - terms not appearing in the query do not affect the ranking



Document Query Similarity

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- As a similarity measure, we can use the ratio between the probability of finding the relevant documents and the probability of finding the non-relevant documents

$$\text{sim}(d_j, q) = \frac{P(R|\vec{d}_j, \vec{q})}{P(\bar{R}|\vec{d}_j, \vec{q})}$$

- Often referred to as the **Retrieval Status Value (RSV)**



Similarity Probabilities (1)

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Initial Equation

We can simplify the expression leveraging Bayes' theorem and rank equivalence (i.e., remove query-independent constants)

$$\text{sim}(d_j, q) = \frac{P(R|\vec{d}_j, \vec{q})}{P(\bar{R}|\vec{d}_j, \vec{q})} = \frac{P(\vec{d}_j, \vec{q}|R) \times P(R)}{P(\vec{d}_j, \vec{q}|\bar{R}) \times P(\bar{R})} \sim \frac{P(\vec{d}_j, \vec{q}|R)}{P(\vec{d}_j, \vec{q}|\bar{R})}$$

Assuming term independence...

$$\text{sim}(d_j, q) \sim \frac{(\prod_{g_i(\vec{d}_j)=g_i(\vec{q})=1} P(k_i|R)) \times (\prod_{g_i(\vec{d}_j)=0 \wedge g_i(\vec{q})=1} P(\bar{k}_i|R))}{(\prod_{g_i(\vec{d}_j)=g_i(\vec{q})=1} P(k_i|\bar{R})) \times (\prod_{g_i(\vec{d}_j)=0 \wedge g_i(\vec{q})=1} P(\bar{k}_i|\bar{R}))}$$



Similarity Probabilities (2)

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Taking logs and removing constant factors...

$$\text{sim}(d_j, q) = \sum_{i=1}^t w_{i,q} \times w_{i,j} \times \left(\log \frac{P(k_i|R)}{1 - P(k_i|R)} + \log \frac{1 - P(k_i|\bar{R})}{P(k_i|\bar{R})} \right)$$

Blind assumptions

$$\begin{aligned} P(k_i|R) &= 0.5 \\ P(k_i|\bar{R}) &= \frac{n_i}{N} \end{aligned}$$

- $P(k_i|R)$ reflects that we have no information about relevant documents (i.e., each query term is equally likely to occur in a relevant document)
- $P(k_i|\bar{R})$ reflects a much smaller number of relevant documents than the collection size



Similarity Probabilities (3)

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After document retrieval or leveraging training data...

- Let V be the number of returned documents (i.e., number of documents estimated to be relevant)
- Let V_i be the number of returned docs with term k_i

$$\begin{aligned}P(k_i|R) &= \frac{V_i}{V} \\P(k_i|\overline{R}) &= \frac{n_i - V_i}{N - V}\end{aligned}$$



Similarity Probabilities (4)

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Avoiding small values when using blind assumptions...

- With **zero counts** probability is not well-defined
- Maximum likelihood estimates do not work for rare events
- To avoid zeros add 0.5 to each count (expected likelihood estimation) or use a different type of smoothing

$$\begin{aligned}P(k_i|R) &= 0.5 \\P(k_i|\bar{R}) &= \frac{n_i+0.5}{N+1}\end{aligned}$$

Avoiding small values with estimates after retrieval...

$$\begin{aligned}P(k_i|R) &= \frac{V_i + \frac{n_i}{N}}{V+1} \\P(k_i|\bar{R}) &= \frac{n_i - V_i + \frac{n_i}{N}}{N - V + 1}\end{aligned}$$



Problems of this Simple Probabilistic Model

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- There is no accurate estimate for the first run probabilities
- Index terms are not weighted
- Terms are assumed mutually independent

In fact, **many different probabilistic retrieval models** have been proposed, some addressing the aforementioned limitations!



Another Look at the BIM (1)

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Recall the log odds ratio for computing RSV

$$\text{sim}(d_j, q) = \sum_{i=1}^t w_{i,q} \times w_{i,j} \times \left(\log \frac{P(k_i|R)}{1 - P(k_i|R)} + \log \frac{1 - P(k_i|\bar{R})}{P(k_i|\bar{R})} \right)$$

Denoting $p_i = P(k_i|R)$ and $u_i = P(k_i|\bar{R})$

$$\text{sim}(d_j, q) = \sum_{i=1}^t w_{i,q} \times w_{i,j} \times \left(\log \frac{p_i}{1 - p_i} + \log \frac{1 - u_i}{u_i} \right)$$



Another Look at the BIM (2)

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With the blind estimates, does the equation look familiar?

$$P(k_i|R) = p_i = 0.5$$

$$P(k_i|\bar{R}) = u_i = \frac{n_i}{N}$$

Replacing p_i and u_i in the previous equation...

$$\log \frac{p_i}{1 - p_i} = 0$$

$$\log \frac{1 - u_i}{u_i} = \log \frac{N - n_i}{n_i} \approx \log \left(\frac{N}{n_i} \right)$$



Another Look at the BIM (3)

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- The BIM can be seen as TF-IDF with binary term frequencies and logarithmically dampened inverse document frequencies
- The score for document d_j is just **IDF weighting of the query terms present in the document**

$$\text{sim}(d_j, q) = \sum_{i=1}^t w_{i,q} \times w_{i,j} \times \log \left(\frac{N}{n_i} \right)$$

- Alternative formulation using smoothing

$$\text{sim}(d_j, q) = \sum_{i=1}^t w_{i,q} \times w_{i,j} \times \log \left(\frac{N - n_i + 0.5}{n_i + 0.5} \right)$$



The Okapi BM25 Model (1)

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- Inspired by the BIM probabilistic formulation
- Considering an alternative for term weighting
- Captures various aspects in a simple formula, tuning each component
 - Inverse Document Frequency (IDF)
 - Term Frequency (TF)
 - Document length
 - Query term frequency (*in some formulations*)
- BM25 (BestMatch25) is an effective and widely used model for full-text retrieval over large collections



The Okapi BM25 Model (2)

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$$TF_{i,j} = \frac{f_{i,j} \times (k_1 + 1)}{f_{i,j} + k_1 \times \left(1 - b + b \frac{|d_j|}{avgdl}\right)}$$

$$IDF_i = \log \frac{N - n_i + 0.5}{n_i + 0.5}$$

$$sim(d_j, q) = \sum_{i \in q} IDF_i \times TF_{i,j}$$

- Postulates Poisson (or 2-Poisson-mixture) distributions for terms, instead of Binomial distributions as in BIM
- Parameters k_1 and b need to be tuned
 - k_1 controls impact of term frequency
 - b controls impact of document length
 - Setting $k_1 = 1.5$ and $b = 0.75$ are common defaults



Extending BM25 to Consider Document Fields

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- Textual data often found in some sort of structural form
- Retrieval effectiveness can be improved by taking the structure into account
- Simple solution: calculate score for each field and combine the different fields linearly

$$\text{sim}(d_j, q) = \sum_{z \in F} \alpha^z \times \text{sim}(d_j^z, q)$$

Problems of linear combination

- With similarities per field, IDF can vary highly in different fields (e.g. stopwords scoring highly in the title)
- TF usually non-linear and information gained by observing a term for the first time is greater than observing subsequent occurrences



BM25F and Combining Term Frequencies

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$$TF_{i,j} = \sum_{z \in F} \alpha^z \times \frac{f_{i,j}^z \times (k_1 + 1)}{f_{i,j}^z + k_1 \times \left(1 - b^z + b^z \frac{|d_j^z|}{avgdl^z}\right)}$$

$$IDF_i = \log \frac{N - n_i + 0.5}{n_i + 0.5}$$

$$sim(d_j, q) = \sum_{i \in q} IDF_i \times TF_{i,j}$$



Probabilistic Language Models

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- Another simple probabilistic retrieval formulation
- Each document d is treated as (the basis for) a **probabilistic language model**
- Given a query q rank documents based on $P(d|q)$

$$P(d|q) = \frac{P(d) \times P(q|d)}{P(q)}$$

- The evidence $P(q)$ is the same for all documents, so ignore
- $P(d)$ is the prior
 - often treated as the same for all d
 - we can give a higher prior to “high-quality” documents (e.g., those with high PageRank – to be seen latter)
- $P(q|d)$ is likelihood, i.e. the probability of q given d



How to compute $P(q|d)$

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- Conditional independence assumption

$$P(q|d) = P(\{t_1, \dots, t_{|q|}\}|d) = \prod_{1 \leq i \leq |q|} P(t_i|d)$$

- $|q|$ is length of q
- t_i is the token occurring at position i in q

- The above multinomial model is equivalent to:

$$P(q|d) = \prod_{\text{distinct term } t \in q} P(t|d)^{TF_{t,q}}$$

- Component $TF_{t,q}$ is the term frequency of t in q
- Parameters $P(t|d)$ computed through maximum likelihood estimates

$$P(t|d) = \frac{TF_{t,d}}{|d|}$$



Types of Language Models

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- The unigram language model (show before)

$$P(d) = P(t_1 t_2 t_3 \dots) = P(t_1)P(t_2)P(t_3) \dots$$

- n -gram language models (e.g. *bigram* language models)

$$P(d) = P(t_1 t_2 t_3 \dots) = P(t_1)P(t_2|t_1)P(t_3|t_2) \dots$$

- More complex language models, e.g. using *probabilistic context-free grammars*
 - Used for tasks like speech recognition, spelling correction, and machine translation



LM Retrieval and Naïve Bayes

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The next class will introduce a simple probabilistic document classifier, known as the **Naïve Bayes** approach

- We want to classify document d .
We want to classify a query q
- Human-defined classes: e.g., politics, economics, sports.
Each document in the collection is a different class
- Assume that d was produced by the generative model.
Assume that q was generated by a generative model
- Which of the classes (= class models) is most likely to have generated the document d ?
Which document (=class) is most likely to have generated the query q ?
- For which class do we have the most evidence?
For which document (as source for query) do we have the most evidence?



More on computing $P(q|d)$

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Problems with the aforementioned unigram model

$$P(q|d) = P(\{t_1, \dots, t_{|q|}\}|d) = \prod_{1 \leq i \leq |q|} P(t_i|d)$$

- A document with a single missing query-term will receive a score of zero (similar to Boolean AND)
- Where is the equivalent of the IDF?

Linear interpolation smoothing

$$P(q|d) = \prod_{1 \leq i \leq |q|} (\alpha \times P(t_i|d)) + ((1 - \alpha) \times P(t_i|c))$$



Query Likelihood Retrieval with Linear Interpolation Smoothing

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- Helps us avoid zero-probabilities
- Another added benefit...
 - Without smoothing, the query-likelihood model ignores how frequently the term occurs in general
 - Interpolation smoothing introduces IDF-like scoring

$$\begin{aligned}P(q|d) &= \prod_{1 \leq i \leq |q|} (\alpha \times P(t_i|d)) + ((1 - \alpha) \times P(t_i|c)) \\&= \prod_{1 \leq i \leq |q|} ((\alpha \times P(t_i|d)) + ((1 - \alpha) \times P(t_i|c))) \times \left(\frac{(1-\alpha) \times P(t_i|c)}{(1-\alpha) \times P(t_i|c)} \right) \\&= \prod_{1 \leq i \leq |q|} \left(\frac{\alpha \times P(t_i|d)}{(1-\alpha) \times P(t_i|c)} + 1 \right) \times (1 - \alpha) \times P(t_i|c) \\&= \prod_{1 \leq i \leq |q|} \left(\frac{\alpha \times P(t_i|d)}{(1-\alpha) \times P(t_i|c)} + 1 \right) \times \prod_{1 \leq i \leq |q|} (1 - \alpha) \times P(t_i|c) \\&\approx \prod_{1 \leq i \leq |q|} \left(\frac{\alpha \times P(t_i|d)}{(1-\alpha) \times P(t_i|c)} + 1 \right)\end{aligned}$$



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What makes these Models Work?

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Three main term weighting normalization driving features:

- TF - Term Frequency
- IDF - Inverse Document Frequency
- DL - Document Length



Comparison of the Different Models

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Generic
Document
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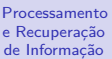
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- Boolean model is considered the weakest
- There is some controversy over which shows better performance: vector space or probabilistic
 - Simple BIM is just IDF weighting of the terms
 - BIM originally designed for short catalog records of fairly consistent length, working reasonably in these contexts
 - BM25 or language models offer a better performance (e.g., paying attention to term frequency and document length)
- Nowadays, BM25 is perhaps the most widely used approach
- Several other families of probabilistic models
 - Divergence from randomness
 - Markov random fields (e.g., account with term proximity)



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Questions?