Text Analytics

Index-Structures for Information Retrieval

Ulf Leser

Content of this Lecture

- Inverted files
- Storage structures
- Phrase and proximity search
- Building and updating the index
- Using a RDBMS

Full-Text Indexing

- Fundamental operation for all IR models: find(q, D)
  - Given a term q, find all docs from D containing the term
- Can be implemented using online search
  - Boyer-Moore, Keyword-Trees, etc.
- But
  - We generally assume that D is stable (compared to q)
  - We only search for terms (after tokenization)
  - The number of unique terms does not grow much with growing D
- These properties can be exploited to pre-compute a term-based index over D
  - Also called “full-text index”

Inverted Files (or Inverted Index)

- Simple and effective index structure for terms
- Builds on the Bag of words approach
  - We give up on order of terms in docs (reappears later)
  - We cannot reconstruct docs based on index only
- Start from "docs containing terms" (~ "docs") and invert to "terms appearing in docs" (~ "inverted docs")

```
d1: t1,t3
d2: t1
d3: t2,t3
d4: t1
d5: t1,t2,t3
d6: t1,t2
d7: t2
d8: t2
```

→

```
t1: d1,d2,d4,d5,d6
t2: d3,d5,d6,d7,d8
t3: d1,d3,d5
```

Building an Inverted File [Andreas Nürnberger, IR-2007]

Doc1:
Now is the time for all good men to come to the aid of their country.

Doc2:
It was a dark and stormy night in the country manor. The time was past midnight.

Term	Doc ID
now	1
is	1
the	1
time	1
for	1
all	1
good	1
men	1
to	1
come	1
to	1
the	1
aid	1
of	1
their	1
country	1
it	2
was	2
a	2
dark	2
and	2
stormy	2
night	2
in	2
the	2
country	2
manor	2
the	2
time	2
was	2
past	2
midnight	2

Sort

Term	Doc ID
a	2
aid	1
all	1
and	2
come	1
country	1
country	2
dark	2
for	1
good	1
in	2
is	1
it	2
manor	2
men	1
midnight	2
night	2
now	1
of	1
past	2
stormy	2
the	1
the	1
the	2
the	2
their	1
time	1
time	2
to	1
to	1
was	2
was	2

Merge

a	2
aid	1
all	1
and	2
come	1
country	1,2
dark	2
for	1
good	1
in	2
is	1
it	2
manor	2
men	1
midnight	2
night	2
now	1
of	1
past	2
stormy	2
the	1,2
their	1
time	1,2
to	2
was	2

Boolean Retrieval

- For each query term k_i, look-up doc-list D_i containing k_i
- Evaluate query in the usual order
  - $k_i \wedge k_j$: $D_i \cap D_j$
  - $k_i \vee k_j$: $D_i \cup D_j$
  - NOT k_i: $D \setminus D_i$
- Example

a	2
aid	1
all	1
and	2
come	1
country	1,2
dark	2
for	1
good	1
in	2
is	1
it	2
manor	2
men	1
midnight	2
night	2
now	1
of	1
past	2
stormy	2
the	1,2
their	1
time	1,2
to	2
was	2

(time AND past AND the) OR (men)

$$= (D_{time} \cap D_{past} \cap D_{the}) \cup D_{men}$$
$$= (\{1,2\} \cap \{2\} \cap \{1,2\}) \cup \{1\}$$
$$= \{1,2\}$$

Necessary and Obvious Tricks

- How do we efficiently look-up doc-list D_i?
  - Bin-search on inverted file: O(log(|K|))
  - Inefficient: Random access on IO
  - Better solutions: Later
- How do we support union and intersection efficiently?
  - Naïve algorithm requires $O(|D_i|*|D_j|)$
  - Better: Keep doc-lists sorted
  - Intersection $\mathbf{D_i \cap D_j}$: Sort-Merge in $O(|D_i| + |D_j|)$
  - Union $\mathbf{D_i \cup D_j}$: Sort-Merge in $O(|D_i| + |D_j|)$
  - If $|D_i| << |D_j|$, use binsearch in D_j for all terms in D_i
    - Whenever $|D_i| + |D_j| > |D_i|*\log(|D_j|)$

Less Obvious Tricks

- Define selectivity sel(k_i) = DF_i / |D|
- Expected size of result is $|q| = |D| * sel(q) = |D| * \prod_i sel(k_i)$
  - Assuming AND and independence of terms
- Intermediate result sizes vary greatly with different orders
  - These sizes have a large influence on runtime
  - How to keep size of intermediate results small?
  - Consider terms in order of increasing selectivity
- General queries
  - Optimization problem: Find optimal order of evaluation
  - $sel(k_i \cap k_j) = sel(k_i) * sel(k_j)$
  - $sel(k_i \cup k_j) = sel(k_i) + sel(k_j) - (sel(k_i) * sel(k_j))$

Adding Frequency

- VSM with TF*IDF requires term frequencies
- Split up inverted file into dictionary (with term and DF value) and posting list (with docID and TF values)

Term	docIDs	DF
a	2	1
aid	1	1
all	1	1
and	2	1
come	1	1
country	1,2	2
dark	2	1
…	…	…
of	1	1
past	2	1
stormy	2	1
the	1,2	2
their	1	1
time	1,2	2
to	1	1
was	2	1

→

Dictionary — Postings

Term	DF	Posting
a	1	(2,1)
aid	1	(1,1)
all	1	(1,1)
and	1	(2,1)
come	1	(1,1)
country	2	(1,1), (2,1)
dark	1	(2,1)
…	…	…
of	1	(1,1)
past	1	(2,1)
stormy	1	(2,1)
the	2	(1,2), (2,1)
their	1	(1,1)
time	2	(1,1), (2,1)
to	1	(1,2)
was	1	(2,2)

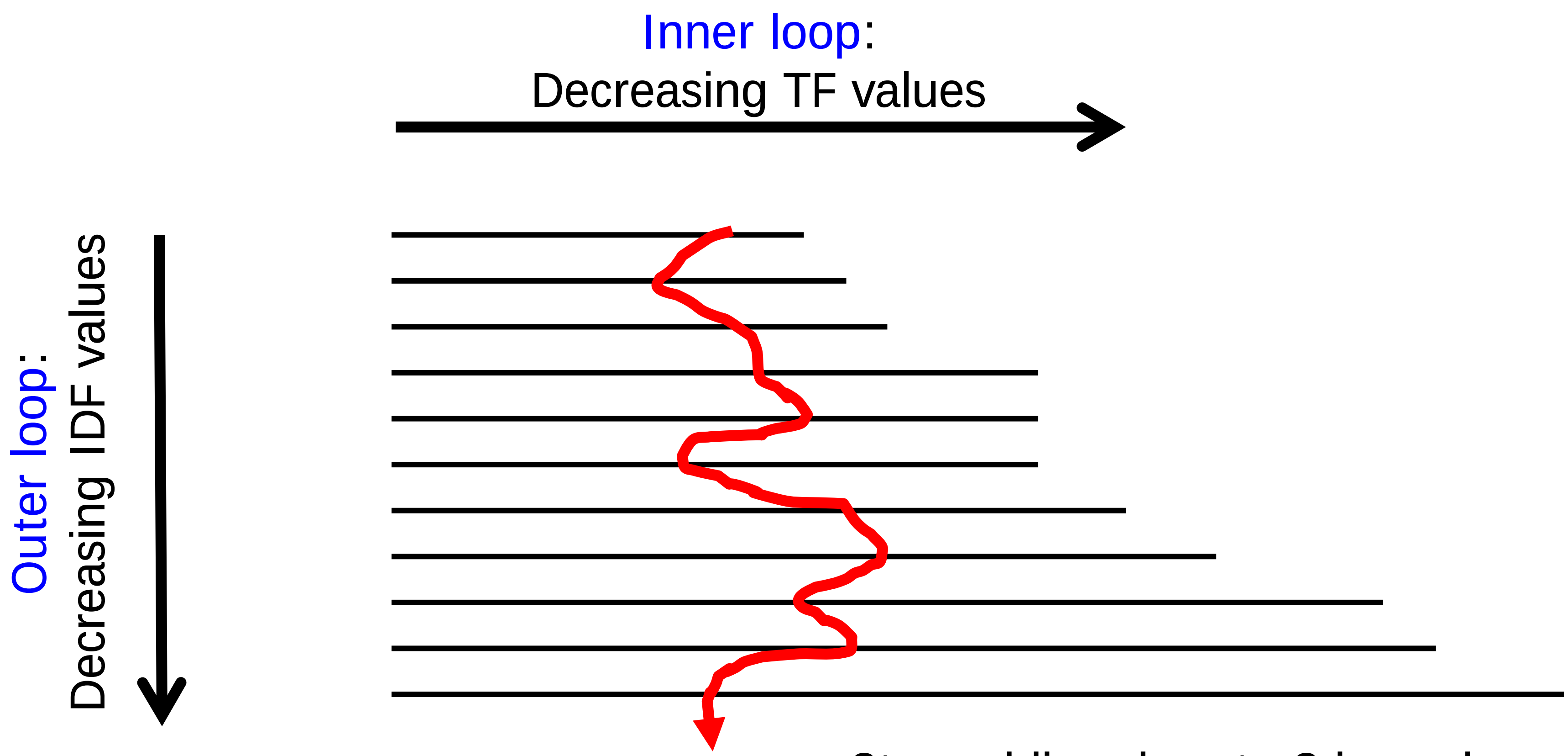
Searching in VSM

- Assume we want to retrieve the top-r docs
- Algorithm
  - Initialize an empty doc-list S (as hash table or priority queue)
  - Iterate through query terms k_i
    - Walk through posting list (elements (docID, TF))
      - If docID∈S: S[docID] =+ IDF[k_i]*TF
      - else: S = S.append((docID, IDF[k_i]*TF))
  - Return top-r docs in S
- S contains all and only those docs containing at least one k_i

Improvement

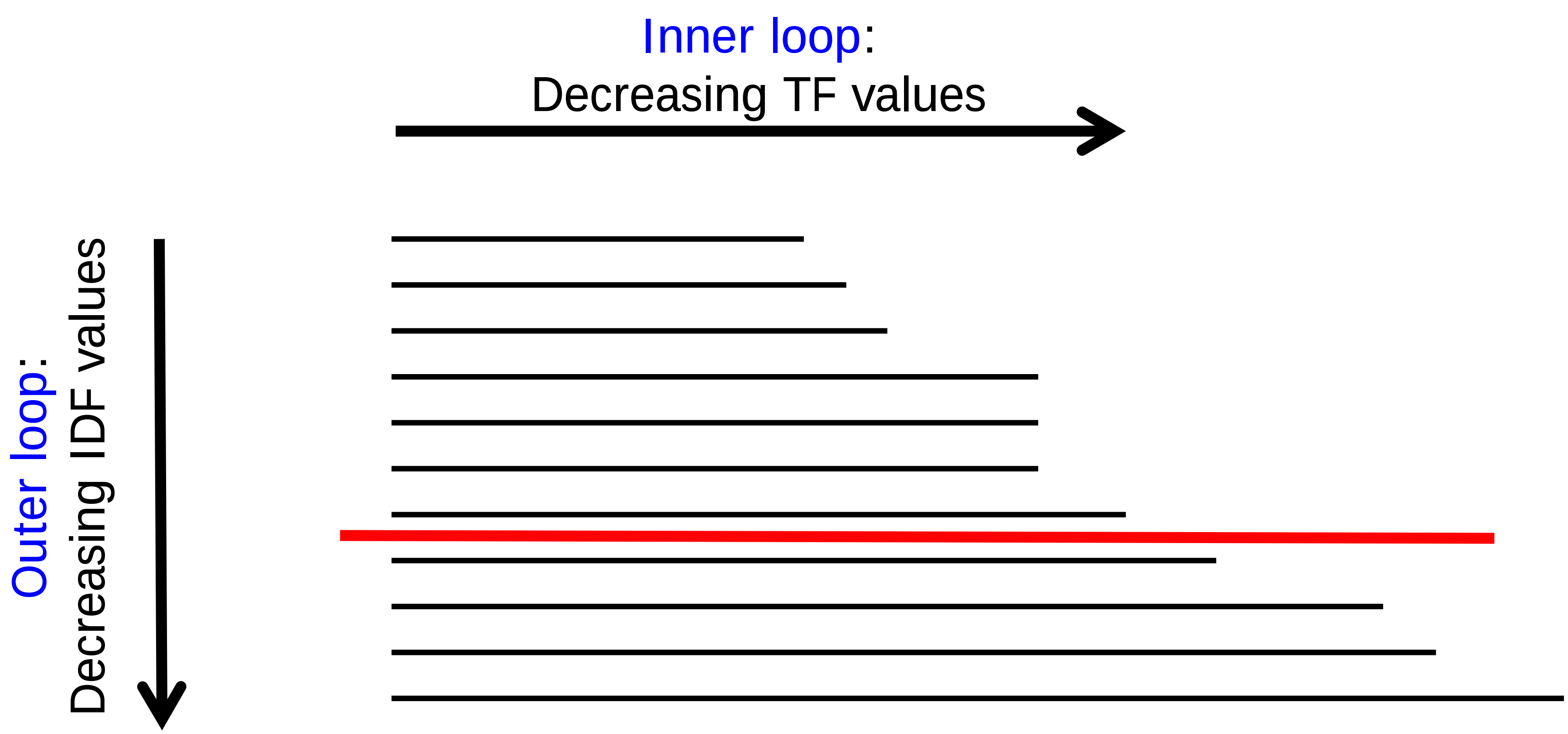
- Sort query terms by decreasing IDF Values – later terms have smaller IDF values – less weight
- Sort posting lists by decreasing TF values – later docs have smaller TF values – less weight
- Several heuristics to exploit these facts
  - Stop adding docs to S in each posting if current TF value too small
  - Drop query terms whose IDF value is too small
    - Typically stop words with long posting lists – much work, little effect
  - Compute $TF_{i\text{-max}}$ for each k_i; stop after $IDF_i * TF_{i\text{-max}}$ gets too small
  - Assume we look at term k_i and are at position TF_j in the posting list. If $s^r - s^{r+1} > IDF_i * TF_j$, stop searching this posting list
  - ...

Illustration



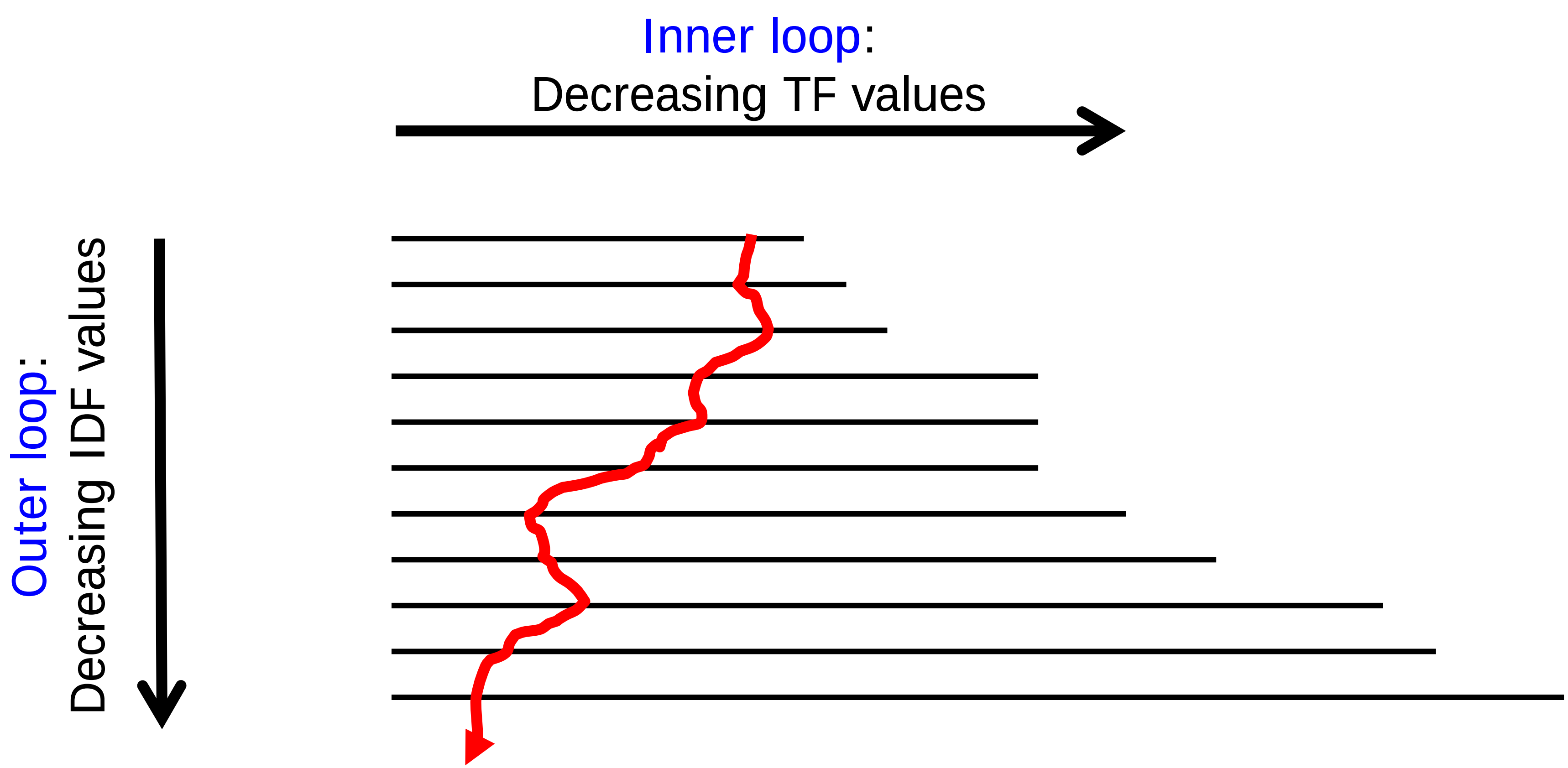
Stop adding docs to S in each posting if current TF value too small

Illustration



Drop query terms whose IDF value is too small

Illustration



If $s^r - s^{r+1} > IDF_i * TF_j$, stop searching this posting list

Space Usage

- Size of dictionary: |K|
  - Zipf's law: If |D| already is large, new terms appear only rarely
    - But there are always new terms, no matter how large D
    - Example: 1GB text (TREC-2) generates only 5MB dictionary
  - Typically: |K|<1 Million
    - Not true in multi-lingual corpora, web corpora, etc.
- Size of posting list
  - Theoretic worst case: O(|K|*|D|)
  - Average case analysis is difficult, but certainly still large (in |D|)
- Implementation
  - Dictionary should always fit into main memory
  - Posting lists remains on disk

Content of this Lecture

- General approach
- Storage structures
  - The dictionary
  - The posting lists
- Phrase and proximity search
- Building and updating the index
- Using a RDBMS

Storing the Dictionary

- Dictionary are always kept in main memory
- Suitable data structures?

Storing the Dictionary

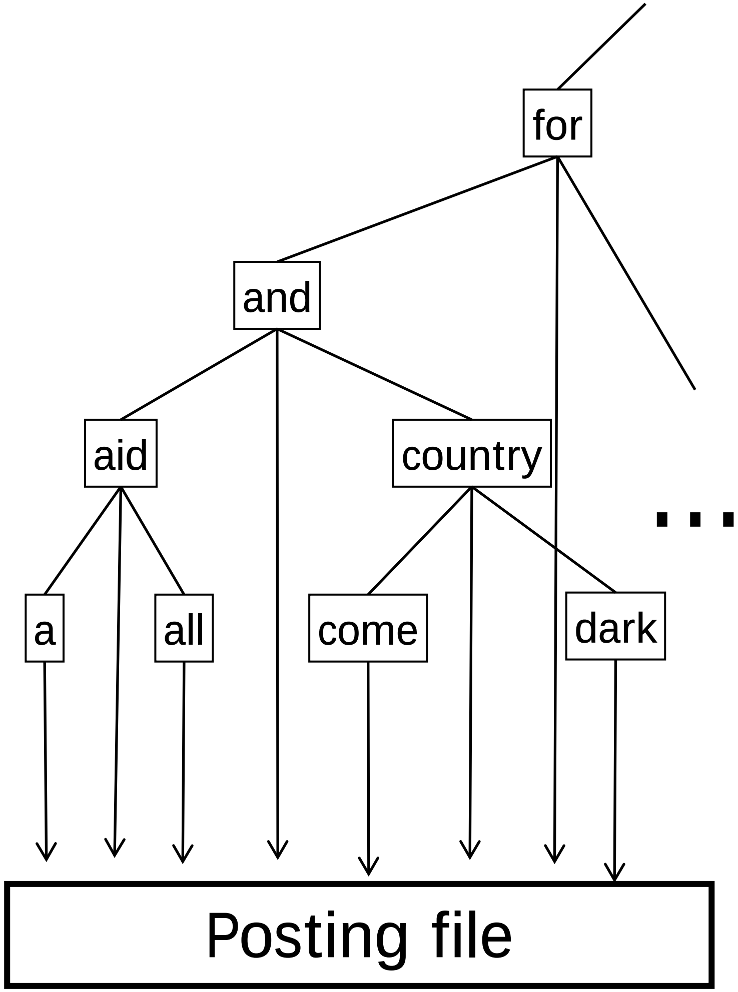
- Dictionary are always kept in main memory
- Suitable data structures?
  - Sorted keyword array: Small and fast (binsearch), static
  - Balanced binary (AVL) tree: Larger and fast, dynamic
  - Hashing: Either small and slow or large and very fast
  - (Compressed) Prefix-tree: Much larger and much faster
- In the following
  - Assume |ptr|=|DF|=4; |K|=1M
  - Let |q| be total length of query in characters
    - Usually small; use as upper bound on the number of char comparisons
  - Let n=8*|K|=8M be the sum of lengths of all keywords
    - Assuming average word length = 8

Dictionary as Sorted Array

- Elements: <keyword, DF, ptr>
- Since keywords have different lengths: Implementation will be (ptr1, DF, ptr2)
  - ptr1: To string (the keyword)
  - ptr2: To posting list
- Search: Compute log(|K|) memory addresses, follow ptr1, compare strings: O(log(|K|)*|q|)
- Construction: O(|K|*log(|K|))
- Space: (4+4+4)*1M +n ~ 20M bytes
- But: Adding keywords is painful

Term	DF	
a	1	ptr
aid	1	ptr
all	1	ptr
and	1	ptr
come	1	ptr
country	2	ptr
dark	1	ptr
for	1	ptr
good	1	ptr
in	1	ptr
is	1	ptr
it	1	ptr
manor	1	ptr
men	1	ptr
midnight	1	ptr
night	1	ptr
now	1	ptr

Dictionary as AVL-style Search Tree



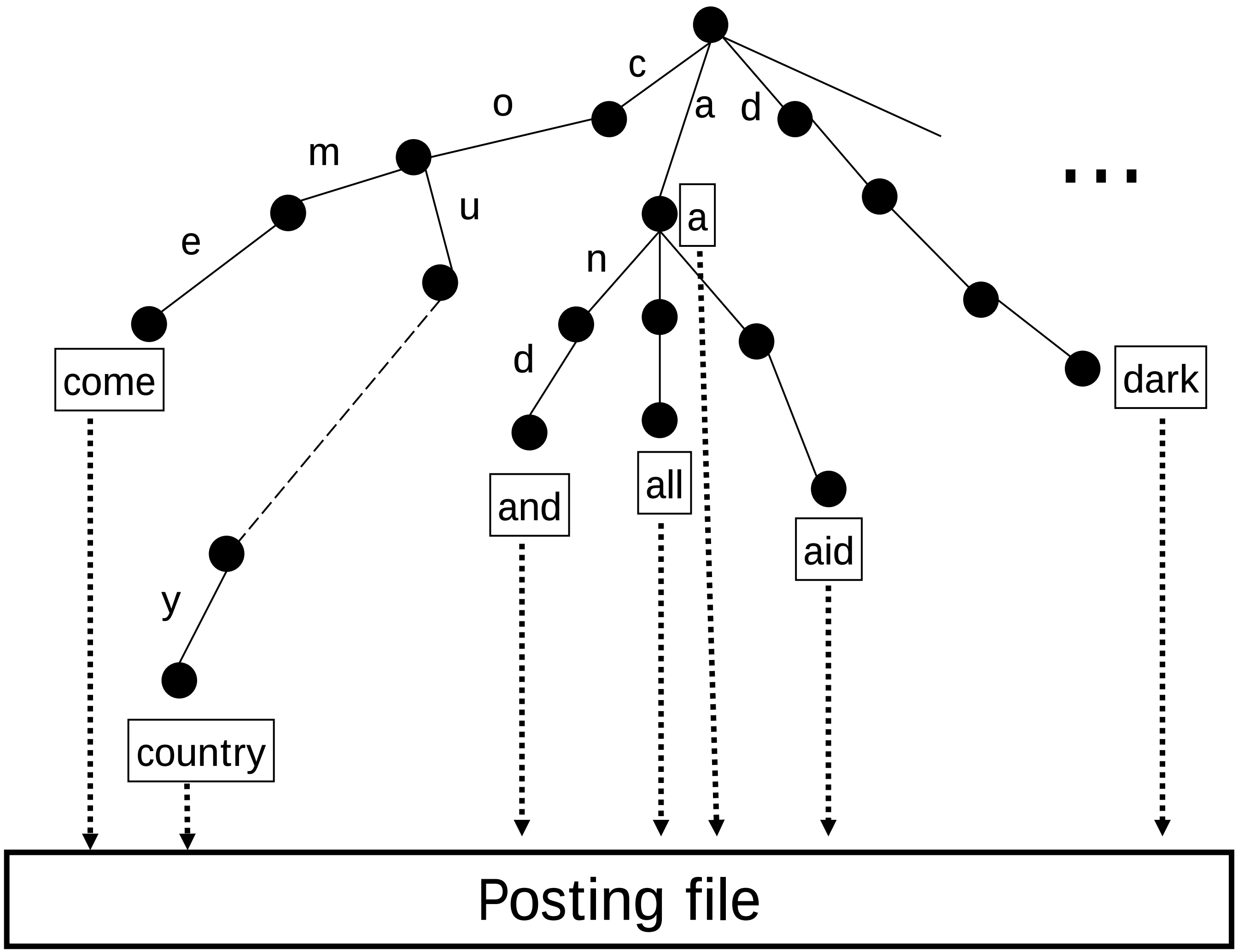
- Internal node: (ptr1, ptr2, ptr3, ptr4, DF)
  - String, posting, child1, child2
- Leaf: (ptr1, ptr2, DF)
- Search: Follow pointer, compare strings: O(log(|K|)*|q|)
- Construction: O(|K|*log(|K|))
- Space
  - Internal: 0.5M*(4+4+4+4+4)
  - Leaves: 0.5M*(4+4+4)
  - Together: 16M+n ~ 24MB
- Adding keywords is simple

Dictionary as Hash Table

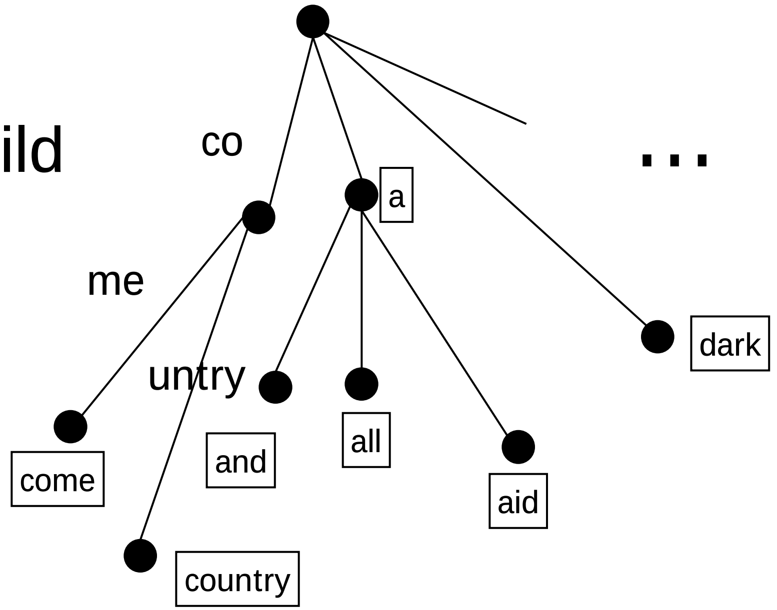
- Idea: Hash keywords into a hash table
  - Value is <ptr-to-posting-list,DF>
- In principle, O(1) access is possible ...
  - Construction: O(|K|)
  - Search time: O(|q|)
    - O(1) key comparisons, typical STRING hash functions look at all chars
  - Space: Difficult
    - Depends on size of hash table and expected length of overflow chains
- Only if collision-free hash function is used
  - Which requires hash tables much larger than |K|

Dictionary as Prefix Tree (TRIE: Information ReTRIEval)

Term	IDF
a	1
aid	1
all	1
and	1
come	1
country	2
dark	1
for	1
good	1
in	1
is	1
it	1
manor	1
men	1
midnight	1
night	1
now	1



Compressed Tries (Patricia Trees)



- Remove nodes with only one child
- Label edges with substrings, not single characters
- Saves space and pointers
- Search: O(|q|)
  - Maximally |q| char-comps + max |q| ptr to follow
  - Assumes O(1) for decision on child-pointer within each node
- Construction: O(n)
- Space ...

Space of a Trie

- Space: Difficult to estimate
- Assume 4 full levels, then each last inner node having two different suffixes (1M leaves, alphabet size 26)
  - 26 nodes in 1st, 26^2~700 in 2nd, 26^3~17.000 in 3rd, 26^4~450K in 4th
  - Assume each incoming edge stores only 1 character
  - Nodes in first 3 levels store 26 pointer, nodes in 4th only two
    - Beware: No O(|q|) search any more
- Inner: (26+700+17K)*(26*ptr+1)+450K*(2*ptr+1) ~ 6M
- Leaves: |K|*(string-ptr, posting-ptr, DF)+(n-|K|*4) ~ 16M
  - We only need to store a suffix of each string, prefix is in tree
- Together: ~22M
  - But assumptions are very optimistic
  - Prefix trees are typically very space-consuming

Content of this Lecture

- General approach
- Storage structures
  - The dictionary
  - The posting lists
- Phrase and proximity search
- Building and updating the index
- Using a RDBMS

Storing the Posting File

- Posting file is usually kept on disk
- Thus, we need an IO-optimized data structure
- Suggestions?

Storing the Posting File

- Posting file kept on disk: IO-optimized data structure
- Static
  - Store posting lists one after the other in large file
  - Posting-ptr is offset in this file
- Prepare for inserts
  - Reserve additional space per posting
    - Good idea: Large initial posting lists get large extra space
    - Many inserts can be handled internally
  - Upon overflow, append entire posting list at the end of the file
    - Place pointer at old position – at most two access per posting list
    - Or update pointer in dictionary – better if only one copy around
    - Generates unused space (holes) –regular reorganization
    - Reorganization requires updating all pointers in the dictionary

Content of this Lecture

- General approach
- Storage structures
- Phrase and proximity search
- Building and updating the index
- Using a RDBMS

Positional Information

- What if we search for phrases: “Bill Clinton”, “Ulf Leser”
  - ~10% of web searches are phrase queries
- What if we search by proximity “car AND rent/5”
  - “We rent cars”, “cars for rent”, “special care rent”, “if you want to rent a car, click here”, “Cars and motorcycles for rent”, ...
- We need positional information

Doc1:
Now is the time for all good men to come to the aid of their country.

s a dark and stormy night in the country manor. The time was past midnight.

Term	Doc #
a	1
aid	1
all	1
and	1
come	1
country	2
…	…
the	2
their	1
time	2
…	…

Doc #	TF	Pos
2	1	6
1	1	1
1	1	14
2	1	15
1	1	6
1	1	16
2	1	10
1	1	15
	…	
1	2	3,12
2	2	9,12
	…	

Answering Phrase Queries

- Search posting lists of all query terms
- During intersection, also positions must fit

Effects

- Dictionary is not affected
- Posting lists get much larger
  - Store many tuples (docID, pos)+TF instead of few docID+TF
  - Index with positional information typically 30-50% larger than the corpus itself
  - Especially frequent words require excessive storage
- One trick: Compression of docIDs (delta encoding)
  - In large corpora, docID is a large integer
  - In contrast, positions are small ints – no compression
  - Trick: Store length of gaps instead of docID
    - **`t1: 17654,3,17655,12,17862,8,17880,4,17884,9, …`**
    - **`t1: 17654,3,1    ,12,207  ,8,18   ,4,4    ,9, …`**

Encoding

- Only pays off if we need few bits for small numbers but still have many bits for large numbers
- Variable-byte encoding
  - Always use at least 1 byte
  - Reserve first bit as “continuation bit” (cb) and 7 bit as payload
  - If cb=1, also use payload of next byte
    - **`t1: 17654,3,1       ,12,207                 ,8, …`**
    - **`t1: 17654,3,00000001,12,11001111|00000001,8, …`**
  - Simple, small numbers not encoded optimally
- γ (gamma) codes (details skipped)
  - Always use minimal number of bits for value
  - Encode length in unary encoding

Bi-Gram Index

- Alternative for phrase queries: Index over bi-grams
  – „The fat cat ate a rat“ – „the fat“, „fat cat“, „cat ate“, ...
- Phrase query with |q| keywords gets translated into |q|-1 lookups
- Done?

Bi-Gram Index

- Alternative for phrase queries: Index over bi-grams
  - „The fat cat ate a rat“ – „the fat“, „fat cat“, „cat ate“, ...
- Phrase query with |q| keywords gets translated into |q|-1 lookups
- Done?
  - Bi-gram need not appear sequentially in the doc
  - Need to confirm match after loading the doc
  - But very high disambiguation effect due to regularities in natural languages
- Advantage: Simple, fast
- Disadvantage: Very large dictionary

Proximity Search

- Phrase search = proximity search with distance one
- Proximity search
  - Search doc-lists with positional information for each term
  - Upon intersection, consider doc-ID and position information
  - Can get quite involved for multi-term queries
    - “car AND rent/5 AND cheap/2 AND toyota/20” – “cheap” between 1 and 7 words from “car”, “toyota” between 1 and 22 words from rent ...
  - All conditions must be satisfied

Content of this Lecture

- General approach
- Storage structures
- Phrase and proximity search
- Building and updating the index
- Using a RDBMS

Building an Inverted File

- Assume a very large corpus: Trillions of documents
  - We still assume that dictionary fits in memory
- How can we efficiently build the index?

Blocked, Sort-Based Indexing

- Partition corpus in blocks fitting into memory
- Algorithm
  - Keep dictionary always in memory
  - For each block: Load, create postings, Flash to disk
  - Merge all blocks
    - Open all blocks at once
    - Skip through all files keyword-by-keyword in sort-order
    - Merge doc-lists of equal keywords and flash to disk
- Requires 2 reads and 2 writes of all data
  - If there are enough file handles to open all blocks at once
- Requires many large sorts in main memory

Updating an index: INSERT d_{new}

- What has to be done?
  - Foreach $k_i \in d_{new}$
    - Search k_i in dictionary
    - If present
      - Follow pointer to posting file
      - Add d_{new} to posting list of k_i
      - If list overflows, move posting list to end of file and place pointer
    - If not present
      - Insert k_i into dictionary
      - Add new posting list $\{d_{new}\}$ at end of posting file
- Disadvantage
  - Degradation: Many pointers in file, many terms require 2 IO
    - Especially the frequent ones
  - Index partly locked during updates

Using Auxiliary Indexes

- All updates are performed on a second, auxiliary index
  - Keep it small: Always in memory
- Searches need to search real and auxiliary index
- When aux index grows too large, merge into real index
  - Try to append in-file: Same problem with degradation
  - Or read both indexes and write a new real index
  - In both cases, the index is locked
  - Solution: Work on a copy, then switch file pointers
- Alternative: Ignore new docs, periodically rebuild index

Content of this Lecture

- General approach
- Storage structures
- Phrase and proximity search
- Building and updating the index
- Using a RDBMS

Implementing an Inverted File using a RDBMS

Term-ID	Term	IDF
T1	Night	1
T2	To	2
...	...	...

Term-ID	Doc-ID	TF
T1	2	1
T2	1	2
...	...	...

Term-ID	Doc-ID	Pos
T1	2	6
T2	1	9
T2	1	11
...	...	...

night	2
now	1
of	1
past	2
stormy	2
the	1,2
their	1
time	1,2
to	1,2
was	1,2

Doc #	TF	Pos
2	1	6
1	1	1
1	1	14
2	1	15
1	1	6
1	2	3
1	2	12
2	2	9
2	2	12
1	1	15
1	1	4
2	1	13
1	2	9
1	2	11

Example Query 1

- Boolean: All docs containing terms “night” and “to”
  - ```
    SELECT D1.docid
    FROM terms T1, terms T2, termdoc D1, termdoc D2
    WHERE   T1.term=‘night’ AND T2.term=‘to’ AND
            D1.termid=T1.termid AND
            D2.termid=T2.termid AND
            D1.docid = D2.docid;
    ```

terms

Term-ID	Term	IDF
T1	Night	1
T2	To	2

pos

Term-ID	Doc-ID	Pos
T1	2	6
T2	1	9
T2	1	11

termdoc

Term-ID	Doc-ID	TF
T1	2	1
T2	1	2
...	...	...
    ```

Example Query 2

- VSM queries
  - We need to compute the inner product of two vectors
    - We ignore normalization
    - We assume TF-values of query terms are 1, others are 0
  - It suffices to aggregate TF values of matching terms per doc
- Example: Compute score for “night rider” (two terms)
  - ```
    SELECT did, sum(tf)
    FROM (   SELECT D.docid did, T.term term, tf
             FROM terms T, termdoc D
             WHERE T.term=‘night’ AND D.termid=T.termid)
             UNION
             SELECT D.docid did, T.term term, tf
             FROM terms T, termdoc D
             WHERE T.term=‘rider’ AND D.termid=T.termid) docs
    GROUP BY did;
    ```
    ```

Access Methods in a RDBMS

- Use B*-Indices on ID columns
- Searching a term
  - Requires O(log(|K|) random-access IO
    - Mind the base of the logarithm: Block size
    - For <100M terms, this usually means <3 IO (cache!)
  - Accessing the posting list: O(log(n)) quasi-random-access IO
    - Where n is the number of term occurrences in D
    - Access is a lookup with term-ID, then seq. scan along the B*-leaves
  - Compared to IR: Dictionary in memory, posting is accessed by direct link, then only sequential IO
- Advantages: Simple, easy to build
- Disadvantages: Much slower
  - More IO, general RDBMS overhead, space overhead for keys, ...

Self Assessment

- Explain idea and structure of inverted files?
- What are possible data structures for the dictionary? Advantages / disadvantages?
- How can posting lists be managed?
- How much bigger is an inverted file with positions than without?
- How can one efficiently build a large inverted file from scratch?