CS6200
Information Retrieval

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Indexing Process

Text Acquisition

E-mail, Web pages, News articles, Memos, Letters

Text Transformation

Index Creation

Document data store

Index
Indexes

• *Indexes* are data structures designed to make search faster

• Text search has unique requirements, which leads to unique data structures

• Most common data structure is *inverted index*
  – general name for a class of structures
  – “inverted” because documents are associated with words, rather than words with documents
    • similar to a *concordance*
A Shakespeare Concordance
How to Write a Dictionary

†dic\'tion\'narian. Obs. rare. [f. as prec. + -AN.] The maker of a dictionary; a lexicographer. 1846 Worcester cites Dr. Dawson.


dictionary ('dik\'si\'nər). [ad. med.L. dictionarium or dictionarius (sc. liber) lit. 'a repertory of dictiones, phrases or words' (see DICTION in F. dictionnaire (R. Estienne 1539). It. dizionario, Sp. diccionario.]

1. a. A book dealing with the individual words of a language (or certain specified classes of them), so as to set forth their orthography, pronunciation, signification, and use, their synonyms, derivation, and history, or at least some of these facts: for convenience of reference, the words are arranged in some stated order, now, in most languages, alphabetical; and in larger dictionaries the information given is illustrated by quotations from literature; a word-book, vocabulary, or lexicon.

Dictionaries proper are of two kinds: those in which the meanings of the words of one language or dialect are given in another (or, in a polyglot dictionary, in two or more languages), and those in which the words of a language are treated and illustrated in this language itself. The former were the earlier.

Dictionarius was used c 1225 by Joannes de Garlandia, a native of England, as the title of a collection of Latin vocables, arranged according to their subjects, in sentences, for the use of learners; e.g.

'In horto magistri Iohannis sunt herbe scilicet iste: salvia,
Indexes and Ranking

• Indexes are designed to support *search*
  – faster response time, supports updates

• Text search engines use a particular form of search: *ranking*
  – documents are retrieved in sorted order according to a score computing using the document representation, the query, and a *ranking algorithm*

• What is a reasonable abstract model for ranking?
  – enables discussion of indexes without details of retrieval model
Abstract Model of Ranking

Fred's Tropical Fish Shop is the best place to find tropical fish at low, low prices. Whether you're looking for a little fish or a big fish, we've got what you need. We even have fake seaweed for your fishtank (and little surfboards too).

Document

Quality Features

9.7 fish
4.2 tropical
22.1 tropical fish
8.2 seaweed
4.2 surfboards
Topical Features
14 incoming links
3 days since last update

Query

tropical fish

Ranking Function

24.5 Document Score
More Concrete Model

\[ R(Q, D) = \sum_i g_i(Q) f_i(D) \]

- \( f_i \) is a document feature function
- \( g_i \) is a query feature function

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Inverted Index

• Each index term is associated with an inverted list
  – Contains lists of documents, or lists of word occurrences in documents, and other information
  – Each entry is called a posting
  – The part of the posting that refers to a specific document or location is called a pointer
  – Each document in the collection is given a unique number
  – Lists are usually document-ordered (sorted by document number)
Example “Collection”

$S_1$ Tropical fish include fish found in tropical environments around the world, including both freshwater and salt water species.

$S_2$ Fishkeepers often use the term tropical fish to refer only those requiring fresh water, with saltwater tropical fish referred to as marine fish.

$S_3$ Tropical fish are popular aquarium fish, due to their often bright coloration.

$S_4$ In freshwater fish, this coloration typically derives from iridescence, while salt water fish are generally pigmented.

Four sentences from the Wikipedia entry for *tropical fish*
## Simple Inverted Index

<table>
<thead>
<tr>
<th>Word</th>
<th>Count</th>
<th>Word</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>and</td>
<td>1</td>
<td>only</td>
<td>2</td>
</tr>
<tr>
<td>aquarium</td>
<td>3</td>
<td>pigmented</td>
<td>4</td>
</tr>
<tr>
<td>are</td>
<td>3</td>
<td>popular</td>
<td>3</td>
</tr>
<tr>
<td>around</td>
<td>1</td>
<td>refer</td>
<td>2</td>
</tr>
<tr>
<td>as</td>
<td>2</td>
<td>referred</td>
<td>2</td>
</tr>
<tr>
<td>both</td>
<td>1</td>
<td>requiring</td>
<td>2</td>
</tr>
<tr>
<td>bright</td>
<td>3</td>
<td>requiring</td>
<td>2</td>
</tr>
<tr>
<td>coloration</td>
<td>3</td>
<td>salt</td>
<td>1</td>
</tr>
<tr>
<td>derives</td>
<td>4</td>
<td>saltwater</td>
<td>2</td>
</tr>
<tr>
<td>due</td>
<td>3</td>
<td>species</td>
<td>1</td>
</tr>
<tr>
<td>environments</td>
<td>1</td>
<td>term</td>
<td>2</td>
</tr>
<tr>
<td>fish</td>
<td>1</td>
<td>the</td>
<td>1</td>
</tr>
<tr>
<td>fishkeepers</td>
<td>2</td>
<td>their</td>
<td>2</td>
</tr>
<tr>
<td>found</td>
<td>1</td>
<td>this</td>
<td>3</td>
</tr>
<tr>
<td>fresh</td>
<td>2</td>
<td>those</td>
<td>2</td>
</tr>
<tr>
<td>freshwater</td>
<td>1</td>
<td>to</td>
<td>2</td>
</tr>
<tr>
<td>from</td>
<td>4</td>
<td>tropical</td>
<td>1</td>
</tr>
<tr>
<td>generally</td>
<td>4</td>
<td>typically</td>
<td>2</td>
</tr>
<tr>
<td>in</td>
<td>1</td>
<td>use</td>
<td>2</td>
</tr>
<tr>
<td>include</td>
<td>1</td>
<td>water</td>
<td>1</td>
</tr>
<tr>
<td>including</td>
<td>1</td>
<td>while</td>
<td>4</td>
</tr>
<tr>
<td>iridescence</td>
<td>4</td>
<td>with</td>
<td>2</td>
</tr>
<tr>
<td>marine</td>
<td>2</td>
<td>world</td>
<td>1</td>
</tr>
<tr>
<td>often</td>
<td>2</td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>
Inverted Index with counts

- supports better ranking algorithms
Inverted Index with positions

- supports proximity matches
Proximity Matches

• Matching phrases or words within a window
  – e.g., "tropical fish", or “find tropical within 5 words of fish”

• Word positions in inverted lists make these types of query features efficient
  – e.g.,

<table>
<thead>
<tr>
<th>tropical</th>
<th>1,1</th>
<th>1,7</th>
<th>2,6</th>
<th>2,17</th>
<th>3,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>fish</td>
<td>1,2</td>
<td>1,4</td>
<td>2,7</td>
<td>2,18</td>
<td>2,23</td>
</tr>
</tbody>
</table>
Fields and Extents

• Document structure is useful in search
  – field restrictions
    • e.g., date, from:, etc.
  – some fields more important
    • e.g., title

• Options:
  – separate inverted lists for each field type
  – add information about fields to postings
  – use extent lists
Extent Lists

• An *extent* is a contiguous region of a document
  – represent extents using word positions
  – inverted list records all extents for a given field type
  – e.g.,

\[
\begin{array}{c|c|c|c|c|c|c|c}
\text{fish} & 1,2 & 1,4 & 2,7 & 2,18 & 2,23 & 3,2 & 3,6 & 4,3 & 4,13 \\
\hline
\text{title} & 1:(1,3) & 2:(1,5) & 4:(9,15) \\
\end{array}
\]
Other Issues

• Precomputed scores in inverted list
  – e.g., list for “fish” [(1:3.6), (3:2.2)], where 3.6 is total feature value for document 1
  – improves speed but reduces flexibility

• Score-ordered lists
  – query processing engine can focus only on the top part of each inverted list, where the highest-scoring documents are recorded
  – very efficient for single-word queries
Compression

• Inverted lists are very large
  – e.g., 25-50% of collection for TREC collections using Indri search engine
  – Much higher if n-grams are indexed

• Compression of indexes saves disk and/or memory space
  – Typically have to decompress lists to use them
  – Best compression techniques have good compression ratios and are easy to decompress

• *Lossless* compression – no information lost
Compression

• **Basic idea**: Common data elements use short codes while uncommon data elements use longer codes
  – Example: coding numbers
    • number sequence: 0, 1, 0, 2, 0, 3, 0
    • possible encoding: 00 01 00 10 00 11 00
    • encode 0 using a single 0: 0 01 0 10 0 11 0
    • only 10 bits, but...
Compression Example

• *Ambiguous* encoding – not clear how to decode
  - another decoding: 0 0 1 0 1 0 0 1 1 0
  - which represents: 0, 1, 1, 0, 0, 3, 0
    - use unambiguous code:
      - which gives: 0 1 0 1 0 1 1 0 0 1 1 0 0

<table>
<thead>
<tr>
<th>Number</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>101</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
</tr>
<tr>
<td>3</td>
<td>111</td>
</tr>
</tbody>
</table>
Compression and Entropy

• **Entropy** measures “randomness”
  – Inverse of compressability

\[ H(X) = - \sum_{i=1}^{n} p(X = x_i) \log_2 p(X = x_i) \]

  – Log2: measured in *bits*
  – Upper bound: log \( n \)
  – Entropy = log(perplexity)
  – Example curve for binomial
Compression and Entropy

• Entropy bounds compression rate
  – Theorem: $H(X) \leq E[ |\text{encoded}(X)| ]$
  – Recall: $H(X) \leq \log(n)$
  – $n$ is the size of the domain of $X$

• Standard binary encoding of integers optimizes for the worst case where choice of numbers is completely unpredictable

• It turns out, we can do better. At best:
  – $H(X) \leq E[ |\text{encoded}(X)| ] < H(X) + 1$
  – Bound achieved by Huffman codes
Delta Encoding

• Word count data is good candidate for compression
  – many small numbers and few larger numbers
  – encode small numbers with small codes
• Document numbers are less predictable
  – but differences between numbers in an ordered list are smaller and more predictable
• *Delta encoding*:  
  – encoding differences between document numbers (*d-gaps*)
Delta Encoding

• Inverted list (without counts)
  1, 5, 9, 18, 23, 24, 30, 44, 45, 48

• Differences between adjacent numbers
  1, 4, 4, 9, 5, 1, 6, 14, 1, 3

• Differences for a high-frequency word are easier to compress, e.g.,
  1, 1, 2, 1, 5, 1, 4, 1, 1, 3, ...

• Differences for a low-frequency word are large, e.g.,
  109, 3766, 453, 1867, 992, ...
Bit-Aligned Codes

- Breaks between encoded numbers can occur after any bit position
- *Unary code*
  - Encode $k$ by $k$ 1s followed by 0
  - 0 at end makes code unambiguous

<table>
<thead>
<tr>
<th>Number</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
</tr>
<tr>
<td>3</td>
<td>1110</td>
</tr>
<tr>
<td>4</td>
<td>11110</td>
</tr>
<tr>
<td>5</td>
<td>111110</td>
</tr>
</tbody>
</table>
Unary and Binary Codes

• Unary is very efficient for small numbers such as 0 and 1, but quickly becomes very expensive
  – 1023 can be represented in 10 binary bits, but requires 1024 bits in unary

• Binary is more efficient for large numbers, but it may be ambiguous
Elias-γ Code

- To encode a number $k$, compute
  \[ k_d = \lfloor \log_2 k \rfloor \]
  \[ k_r = k - 2^{\lfloor \log_2 k \rfloor} \]

- $k_d$ is number of binary digits, encoded in unary

<table>
<thead>
<tr>
<th>Number ($k$)</th>
<th>$k_d$</th>
<th>$k_r$</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>101</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2</td>
<td>11010</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>7</td>
<td>1110111</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>0</td>
<td>111100000</td>
</tr>
<tr>
<td>255</td>
<td>7</td>
<td>127</td>
<td>11111110 1111111</td>
</tr>
<tr>
<td>1023</td>
<td>9</td>
<td>511</td>
<td>111111110 11111111</td>
</tr>
</tbody>
</table>

Elias-δ Code

• Elias-γ code uses no more bits than unary, many fewer for $k > 2$
  – 1023 takes 19 bits instead of 1024 bits using unary
• In general, takes $2 \lfloor \log_2 k \rfloor + 1$ bits
• To improve coding of large numbers, use Elias-δ code
  – Instead of encoding $k_d$ in unary, we encode $k_d + 1$ using Elias-γ
  – Takes approximately $2 \log_2 \log_2 k + \log_2 k$ bits
Elias-δ Code

• Split $k_d$ into:
  
  $k_{dd} = \lfloor \log_2 (k_d + 1) \rfloor$

  $k_{dr} = k_d - 2^{\lfloor \log_2 (k_d + 1) \rfloor}$

  – encode $k_{dd}$ in unary, $k_{dr}$ in binary, and $k_r$ in binary

<table>
<thead>
<tr>
<th>Number $(k)$</th>
<th>$k_d$</th>
<th>$k_r$</th>
<th>$k_{dd}$</th>
<th>$k_{dr}$</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1000</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1001</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1010</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>7</td>
<td>2</td>
<td>0</td>
<td>1100</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1101</td>
</tr>
<tr>
<td>255</td>
<td>7</td>
<td>127</td>
<td>3</td>
<td>0</td>
<td>1110</td>
</tr>
<tr>
<td>1023</td>
<td>9</td>
<td>511</td>
<td>3</td>
<td>2</td>
<td>1110</td>
</tr>
</tbody>
</table>
import math

def unary_encode(n):
    return "1" * n + "0"

def binary_encode(n, width):
    r = ""
    for i in range(0, width):
        if ((1<<i) & n) > 0:
            r = "1" + r
        else:
            r = "0" + r
    return r

def gamma_encode(n):
    logn = int(math.log(n,2))
    return unary_encode( logn ) + " " + binary_encode(n, logn)

def delta_encode(n):
    logn = int(math.log(n,2))
    if n == 1:
        return "0"
    else:
        loglog = int(math.log(logn+1,2))
        residual = logn+1 - int(math.pow(2, loglog))
        return unary_encode( loglog ) + " " + binary_encode( residual, loglog ) + " " + binary_encode(n, logn)

if __name__ == "__main__":
    for n in [1,2,3, 6, 15,16,255,1023]:
        logn = int(math.log(n,2))
        loglogn = int(math.log(logn+1,2))
        print n, "d_r", logn
        print n, "d_dd", loglogn
        print n, "d_dr", logn + 1 - int(math.pow(2,loglogn))
        print n, "delta", delta_encode(n)
        print n, "gamma", gamma_encode(n)
        print n, "binary", binary_encode(n)
Byte-Aligned Codes

• Variable-length bit encodings can be a problem on processors that process bytes
• v-byte is a popular byte-aligned code
  – Similar to Unicode UTF-8
• Shortest v-byte code is 1 byte
• Numbers are 1 to 4 bytes, with high bit 1 in the last byte, 0 otherwise
## V-Byte Encoding

<table>
<thead>
<tr>
<th>$k$</th>
<th>Number of bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k &lt; 2^7$</td>
<td>1</td>
</tr>
<tr>
<td>$2^7 \leq k &lt; 2^{14}$</td>
<td>2</td>
</tr>
<tr>
<td>$2^{14} \leq k &lt; 2^{21}$</td>
<td>3</td>
</tr>
<tr>
<td>$2^{21} \leq k &lt; 2^{28}$</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$k$</th>
<th>Binary Code</th>
<th>Hexadecimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 00000001</td>
<td>81</td>
</tr>
<tr>
<td>6</td>
<td>1 0000110</td>
<td>86</td>
</tr>
<tr>
<td>127</td>
<td>1 1111111</td>
<td>FF</td>
</tr>
<tr>
<td>128</td>
<td>0 00000001 1 0000000</td>
<td>01 80</td>
</tr>
<tr>
<td>130</td>
<td>0 00000001 1 0000010</td>
<td>01 82</td>
</tr>
<tr>
<td>20000</td>
<td>0 00000001 0 0011100 1 0100000</td>
<td>01 1C A0</td>
</tr>
</tbody>
</table>
V-Byte Encoder

```java
public void encode( int[] input, ByteBuffer output ) {
    for( int i : input ) {
        while( i >= 128 ) {
            output.put( i & 0x7F );
            i >>>= 7;
        }
        output.put( i | 0x80 );
    }
}
```
public void decode( byte[] input, IntBuffer output ) {
    for( int i=0; i < input.length; i++ ) {
        int position = 0;
        int result = ((int)input[i] & 0x7F);

        while( (input[i] & 0x80) == 0 ) {
            i += 1;
            position += 1;
            int unsignedByte = ((int)input[i] & 0x7F);
            result |= (unsignedByte << (7*position));
        }

        output.put(result);
    }
}
Compression Example

• Consider inverted list with counts & positions:
  \((1, 2, [1, 7])(2, 3, [6, 17, 197])(3, 1, [1])\)

• Delta encode document numbers and positions:
  \((1, 2, [1, 6])(1, 3, [6, 11, 180])(1, 1, [1])\)

• Compress using v-byte:
  81 82 81 86 81 82 86 8B 01 B4 81 81 81
Skipping

• Search involves comparison of inverted lists of different lengths
  – Can be very inefficient
  – “Skipping” ahead to check document numbers is much better
    – Compression makes this difficult
      • Variable size, only d-gaps stored
• Skip pointers are additional data structure to support skipping
Skip Pointers

• A skip pointer \((d, p)\) contains a document number \(d\) and a byte (or bit) position \(p\)
  – Means there is an inverted list posting that starts at position \(p\), and the posting \textbf{before} it was for document \(d\)
Skip Pointers

• Example
  – Inverted list
    5, 11, 17, 21, 26, 34, 36, 37, 45, 48, 51, 52, 57, 80, 89, 91, 94, 101, 104, 119
  – D-gaps
    5, 6, 6, 4, 5, 9, 2, 1, 8, 3, 3, 1, 5, 23, 9, 2, 3, 7, 3, 15
  – Skip pointers
    (17, 3), (34, 6), (45, 9), (52, 12), (89, 15), (101, 18)
Auxiliary Structures

• Inverted lists usually stored together in a single file for efficiency
  – Inverted file

• Vocabulary or lexicon
  – Contains a lookup table from index terms to the byte offset of the inverted list in the inverted file
  – Either hash table in memory or B-tree for larger vocabularies

• Term statistics stored at start of inverted lists
• Collection statistics stored in separate file
Index Construction

• Simple in-memory indexer

```plaintext
procedure BUILD_INDEX(D)
    I ← HashTable()
    n ← 0
    for all documents d ∈ D do
        n ← n + 1
        T ← Parse(d)
        Remove duplicates from T
        for all tokens t ∈ T do
            if I_t ∉ I then
                I_t ← Array()
            end if
            I_t.append(n)
        end for
    end for
    return I
end procedure
```

▷ D is a set of text documents
▷ Inverted list storage
▷ Document numbering

▷ Parse document into tokens
Merging

• Merging addresses limited memory problem
  – Build the inverted list structure until memory runs out
  – Then write the partial index to disk, start making a new one
  – At the end of this process, the disk is filled with many partial indexes, which are merged

• Partial lists must be designed so they can be merged in small pieces
  – e.g., storing in alphabetical order
Distributed Indexing

• Distributed processing driven by need to index and analyze huge amounts of data (i.e., the Web)
• Large numbers of inexpensive servers used rather than larger, more expensive machines
• *MapReduce* is a distributed programming tool designed for indexing and analysis tasks
Example

• Given a large text file that contains data about credit card transactions
  – Each line of the file contains a credit card number and an amount of money
  – Determine the number of unique credit card numbers

• Could use hash table – memory problems
  – counting is simple with sorted file

• Similar with distributed approach
  – sorting and placement are crucial
MapReduce

• Distributed programming framework that focuses on data placement and distribution

• Mapper
  – Generally, transforms a list of items into another list of items of the same length

• Reducer
  – Transforms a list of items into a single item
  – Definitions not so strict in terms of number of outputs

• Many mapper and reducer tasks on a cluster of machines
MapReduce

• Basic process
  – *Map* stage which transforms data records into pairs, each with a key and a value
  – *Shuffle* uses a hash function so that all pairs with the same key end up next to each other and on the same machine
  – *Reduce* stage processes records in batches, where all pairs with the same key are processed at the same time

• *Idempotence* of Mapper and Reducer provides fault tolerance
  – multiple operations on same input gives same output
Example

procedure MAPCREDITCARDS(input)
    while not input.done() do
        record ← input.next()
        card ← record.card
        amount ← record.amount
        Emit(card, amount)
    end while
end procedure

procedure REDUCECREDITCARDS(key, values)
    total ← 0
    card ← key
    while not values.done() do
        amount ← values.next()
        total ← total + amount
    end while
    Emit(card, total)
end procedure
Indexing Example

procedure MapDocumentsToPostings(input)
  while not input.done() do
    document ← input.next()
    number ← document.number
    position ← 0
    tokens ← Parse(document)
    for each word w in tokens do
      Emit(w, number:position)
      position = position + 1
    end for
  end while
end procedure

procedure ReducePostingsToLists(key, values)
  word ← key
  WriteWord(word)
  while not input.done() do
    EncodePosting(values.next())
  end while
end procedure
Result Merging

• Index merging is a good strategy for handling updates when they come in large batches

• For small updates this is very inefficient
  – instead, create separate index for new documents, merge *results* from both searches
  – could be in-memory, fast to update and search

• Deletions handled using *delete list*
  – Modifications done by putting old version on delete list, adding new version to new documents index
Query Processing

• Document-at-a-time
  – Calculates complete scores for documents by processing all term lists, one document at a time

• Term-at-a-time
  – Accumulates scores for documents by processing term lists one at a time

• Both approaches have optimization techniques that significantly reduce the time required to generate scores
Document-At-A-Time

salt
water
tropical
score
Pseudocode Function Descriptions

• `getCurrentDocument()`
  – Returns the document number of the current posting of the inverted list.
• `skipForwardToDocument(d)`
  – Moves forward in the inverted list until `getCurrentDocument() <= d`. This function may read to the end of the list.
• `movePastDocument(d)`
  – Moves forward in the inverted list until `getCurrentDocument() < d`.
• `moveToNextDocument()`
• `getNextAccumulator(d)`
  – Returns the first document number d' >= d that has already has an accumulator.
• `removeAccumulatorsBetween(a, b)`
  – Removes all accumulators for documents numbers between a and b. \( A_d \) will be removed iff \( a < d < b \).
procedure DOCUMENTATATIMERETRIEVAL(Q, I, f, g, k)

    L ← Array()
    R ← PriorityQueue(k)

    for all terms $w_i$ in $Q$ do
        $l_i$ ← InvertedList($w_i$, I)
        L.add($l_i$)
    end for

    for all documents $d \in I$ do
        $s_d$ ← 0
        for all inverted lists $l_i$ in $L$ do
            if $l_i$.getCurrentDocument() = $d$ then
                $s_d$ ← $s_d + g_i(Q) f_i(l_i)$  // Update the document score
            end if
            $l_i$.movePastDocument($d$)
        end for
        R.add($s_d$, $d$)
    end for

    return the top $k$ results from $R$

end procedure
## Term-At-A-Time

<table>
<thead>
<tr>
<th>Salt</th>
<th>1:1</th>
<th>4:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial scores</td>
<td>1:1</td>
<td>4:1</td>
</tr>
</tbody>
</table>

| Old partial scores | 1:1 | 4:1 |
| Water             | 1:1 | 2:1 | 4:1 |
| New partial scores | 1:2 | 2:1 | 4:2 |

| Old partial scores | 1:2 | 2:1 | 4:2 |
| Tropical          | 1:2 | 2:2 | 3:1 |
| Final scores      | 1:4 | 2:3 | 2:2 | 4:2 |
procedure TERMAtATimeRETRIEVAL($Q, I, f, g k$)
    $A \leftarrow \text{HashTable}()$
    $L \leftarrow \text{Array}()$
    $R \leftarrow \text{PriorityQueue}(k)$
    for all terms $w_i$ in $Q$
        $l_i \leftarrow \text{InvertedList}(w_i, I)$
        $L.add(l_i)$
    end for
    for all lists $l_i \in L$
        while $l_i$ is not finished do
            $d \leftarrow l_i.get\text{CurrentDocument}()$
            $A_d \leftarrow A_d + g_i(Q)f(l_i)$
            $l_i.move\text{ToNextDocument}()$
        end while
    end for
    for all accumulators $A_d$ in $A$
        $s_d \leftarrow A_d$
        $R.add(s_d, d)$
    end for
    return the top $k$ results from $R$
end procedure
Optimization Techniques

• Term-at-a-time uses more memory for accumulators, but accesses disk more efficiently

• Two classes of optimization
  – Read less data from inverted lists
    • e.g., skip lists
    • better for simple feature functions
  – Calculate scores for fewer documents
    • e.g., conjunctive processing
    • better for complex feature functions
Conjunctive Term-at-a-Time

```python
1: procedure TermAtATimeRetrieval(Q, I, f, g, k)
2:       A ← Map()
3:       L ← Array()
4:       R ← PriorityQueue(k)
5:       for all terms w_i in Q do
6:           l_i ← InvertedList(w_i, I)
7:           L.add(l_i)
8:       end for
9:       for all lists l_i ∈ L do
10:          d_0 ← -1
11:          while l_i is not finished do
12:             if i = 0 then
13:                 d ← l_i.getCurrentDocument()
14:                 A_d ← A_d + g_i(Q)f(l_i)
15:                 l_i.moveToNextDocument()
16:             else
17:                 d ← l_i.getCurrentDocument()
18:                 d' ← A.getNextAccumulator(d)
19:                 A.removeAccumulatorsBetween(d_0, d')
20:                 if d = d' then
21:                     A_d ← A_d + g_i(Q)f(l_i)
22:                     l_i.moveToNextDocument()
23:                 else
24:                     l_i.skipForwardToDocument(d')
25:                 end if
26:             end if
27:             d_0 ← d'
28:          end while
29:       end for
30:       for all accumulators A_d in A do
31:           s_d ← A_d  \quad \triangleright \text{Accumulator contains the document score}
32:           R.add(s_d, d)
33:       end for
34:       return the top k results from R
35: end procedure
```
Conjunctive Document-at-a-Time Retrieval

1: procedure DOCUMENTATATIMERETRIEVAL(Q, I, f, g, k)
2:   L ← Array()
3:   R ← PriorityQueue(k)
4:   for all terms \( w_i \) in \( Q \) do
5:       \( l_i \) ← InvertedList(\( w_i \), I)
6:       L.add( \( l_i \) )
7:   end for
8:   \( d \) ← -1
9:   while all lists in \( L \) are not finished do
10:      \( s_d \) ← 0
11:      for all inverted lists \( l_i \) in \( L \) do
12:          if \( l_i \).getCurrentDocument() > \( d \) then
13:              \( d \) ← \( l_i \).getCurrentDocument()
14:          end if
15:      end for
16:      for all inverted lists \( l_i \) in \( L \) do
17:          \( l_i \).skipForwardToDocument(\( d \))
18:          if \( l_i \).getCurrentDocument() = \( d \) then
19:              \( s_d \) ← \( s_d \) + \( g_i(Q)f_i(l_i) \) > Update the document score
20:              \( l_i \).movePastDocument( \( d \) )
21:          else
22:              \( d \) ← -1
23:              break
24:          end if
25:      end for
26:      if \( d > -1 \) then \( R \).add( \( s_d \), \( d \) )
27:   end if
28:   end while
29: return the top \( k \) results from \( R \)
30: end procedure
Threshold Methods

• Threshold methods use number of top-ranked documents needed \((k)\) to optimize query processing
  – for most applications, \(k\) is small

• For any query, there is a minimum score that each document needs to reach before it can be shown to the user
  – score of the \(k\)th-highest scoring document
  – gives threshold \(\tau\)
  – optimization methods estimate \(\tau'\) to ignore documents
Threshold Methods

• For document-at-a-time processing, use score of lowest-ranked document so far for $\tau'$
  – for term-at-a-time, have to use $k_{th}$-largest score in the accumulator table

• MaxScore method compares the maximum score that remaining documents could have to $\tau'$
  – safe optimization in that ranking will be the same without optimization (cf. A* search)
MaxScore Example

- Indexer computes $\mu_{tree}$
  - maximum score for any document containing just “tree”
- Assume $k = 3$, $\tau'$ is lowest score after first three docs
- Likely that $\tau' > \mu_{tree}$
  - $\tau'$ is the score of a document that contains both query terms
- Can safely skip over all gray postings
Other Approaches

• Early termination of query processing
  – ignore high-frequency word lists in term-at-a-time
  – ignore documents at end of lists in doc-at-a-time
  – *unsafe* optimization

• List ordering
  – order inverted lists by quality metric (e.g., PageRank) or by partial score
  – makes unsafe (and fast) optimizations more likely to produce good documents
Structured Queries

• *Query language* can support specification of complex features
  – similar to SQL for database systems
  – *query translator* converts the user’s input into the structured query representation
  – Galago query language is the example used here
  – e.g., Galago query:
    \[
    \texttt{#combine(\#od:1(tropical fish) \#od:1(aquarium fish) fish)}
    \]
Evaluation Tree for Structured Query
Distributed Evaluation

• Basic process
  – All queries sent to a director machine
  – Director then sends messages to many index servers
  – Each index server does some portion of the query processing
  – Director organizes the results and returns them to the user

• Two main approaches
  – Document distribution
    • by far the most popular
  – Term distribution
Distributed Evaluation

• Document distribution
  – each index server acts as a search engine for a small fraction of the total collection
  – director sends a copy of the query to each of the index servers, each of which returns the top-$k$ results
  – results are merged into a single ranked list by the director

• Collection statistics should be shared for effective ranking
Distributed Evaluation

- Term distribution
  - Single index is built for the whole cluster of machines
  - Each inverted list in that index is then assigned to one index server
    - in most cases the data to process a query is not stored on a single machine
  - One of the index servers is chosen to process the query
    - usually the one holding the longest inverted list
  - Other index servers send information to that server
  - Final results sent to director
Caching

• Query distributions similar to Zipf
  – About ½ each day are unique, but some are very popular
• Caching can significantly improve effectiveness
  – Cache popular query results
  – Cache common inverted lists
• Inverted list caching can help with unique queries
• Cache must be refreshed to prevent stale data
The Future

• When are inverted indices helpful?
• When are they not helpful?
• What IR models are not well-served by inverted indices?
• What architectures do not serve inverted indices well?