CS6200
Information Retrieval

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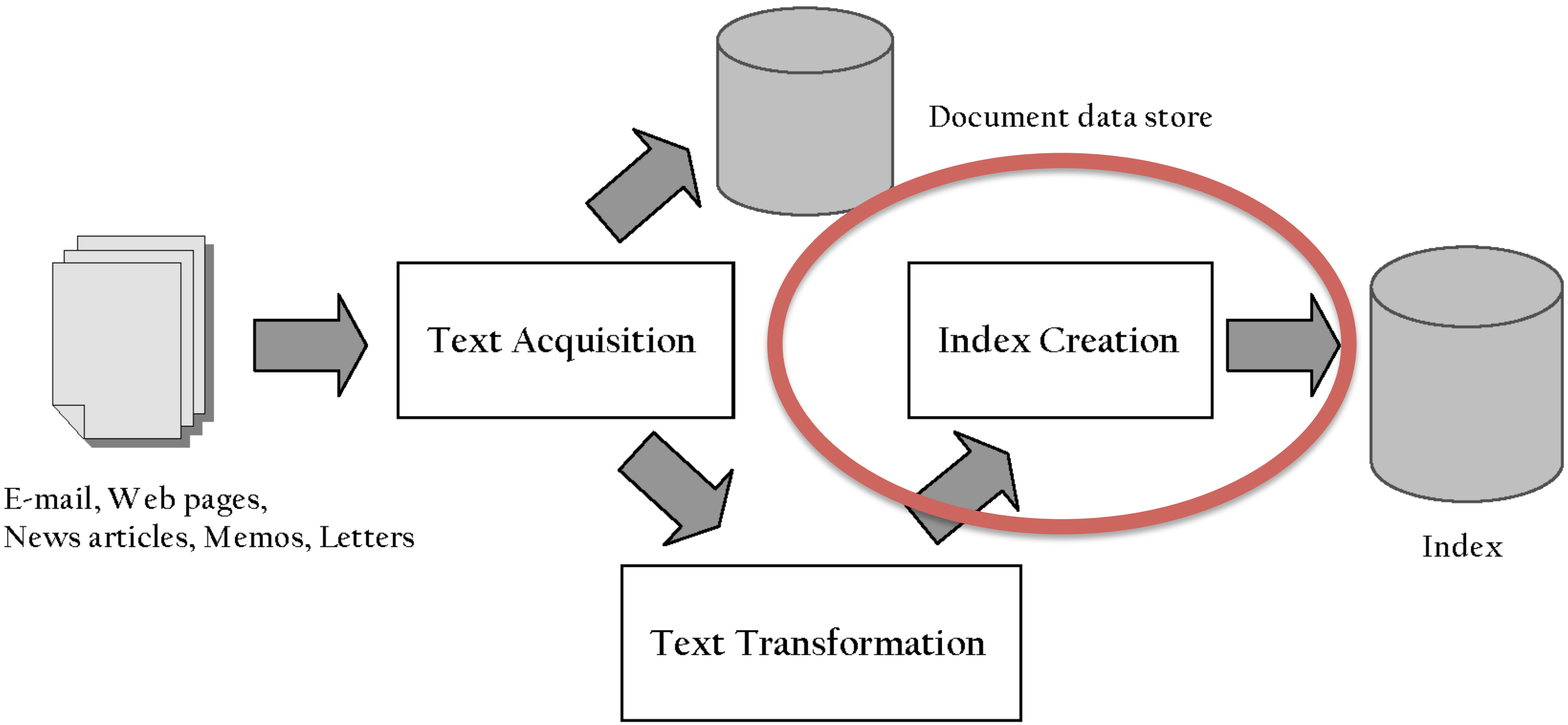
Indexing Process



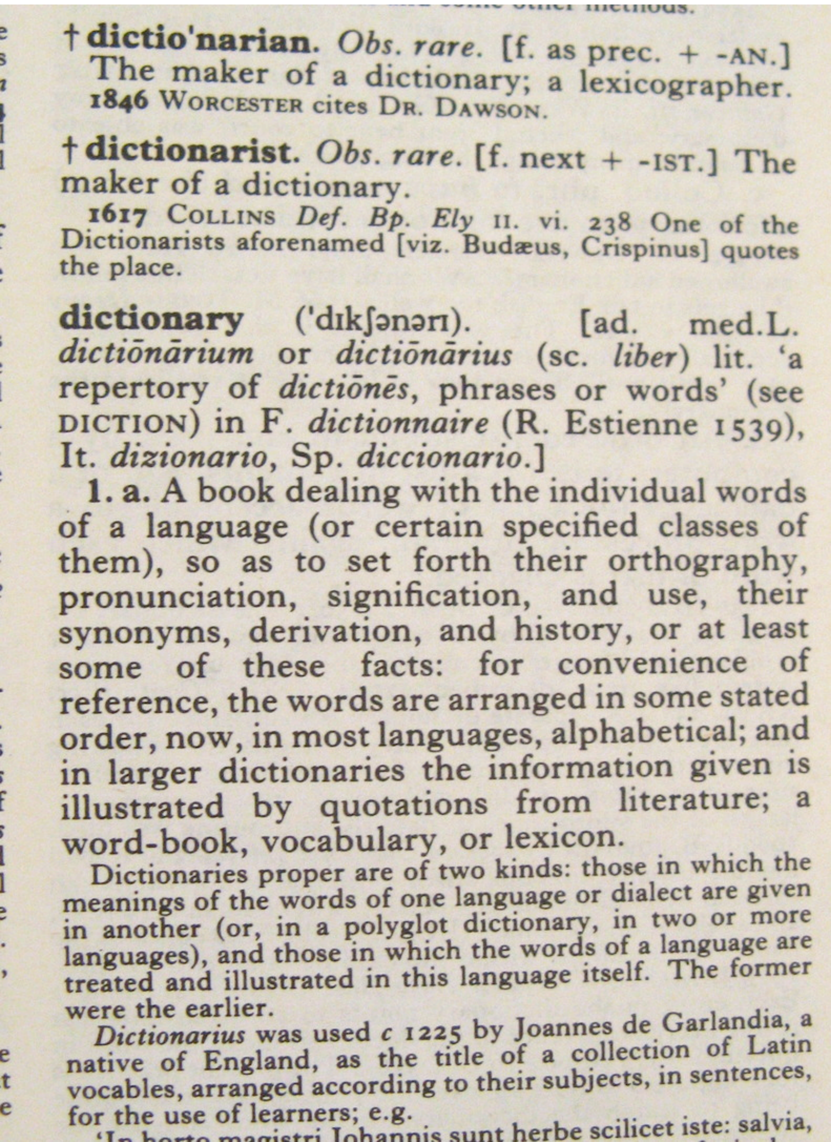
Indexes

- *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

IRISHMAN—an Irishman with....	*Merry Wives*,	ii. 2
altogether directed by an Irishman ..	*Henry V.*	iii. 2
IRISHMEN-against the Irishmen? .	2 *Henry VI.*	iii. 1
IRK—and yet it irks me............	*As you Like it*,	ii. 1
it irks his heart, he cannot	1 *Henry VI.*	i. 4
it irks my very soul	3 *Henry VI.*	ii. 2
IRKSOME—was irksome to me ..	*As you Like it*,	iii. 5
is an irksome brawling scold ..	*Taming of Shrew*,	i. 2
irksome is this music to my heart! ..	2 *Henry VI.*	ii. 1
IRON—to wear iron about you....	*Twelfth Night*,	iii. 4
my young soldier, put up your iron ..	—	iv. 1
before barred up with ribs of iron! ..	*Much Ado*,	iv. 1
runs not this speech like iron through	—	v. 1
but yet you draw not iron......	*Mid. N.'s Dream*,	ii. 2
the iron tongue of midnight hath	—	v. 1
iron may hold with her	*Taming of Shrew*,	ii. 1
fetch me an iron crow........	*Comedy of Errors*,	iii. 1
their iron indignation 'gainst your ..	*King John*,	ii. 1
with his iron tongue and brazen mouth	—	iii. 3
heat me these irons hot	—	iv. 1
must you with hot irons burn (*rep.*) ..	—	iv. 1
none, but in this iron age	—	iv. 1
stubborn hard than hammered iron?	—	iv. 1

How to Write a Dictionary



† **dictio'narian.** *Obs. rare.* [f. as prec. + -AN.] The maker of a dictionary; a lexicographer.
1846 WORCESTER cites DR. DAWSON.

† **dictionarist.** *Obs. rare.* [f. next + -IST.] The maker of a dictionary.
1617 COLLINS *Def. Bp. Ely* II. vi. 238 One of the Dictionarists aforenamed [viz. Budæus, Crispinus] quotes the place.

dictionary ('dɪkʃənərɪ). [ad. med.L. *dictiōnārium* or *dictiōnārius* (sc. *liber*) lit. 'a repertory of *dictiōnēs*, 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.

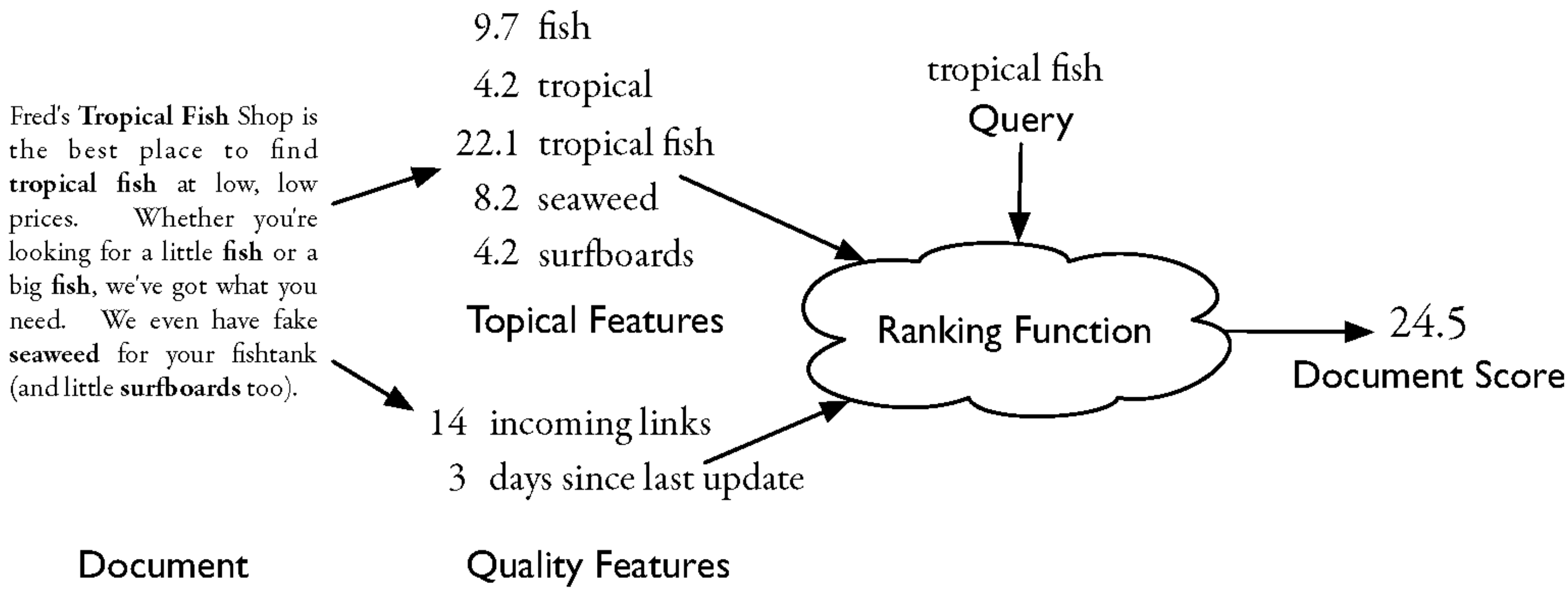
Dictionarius was used *c* 1225 by Joannes de Garlandia, a native of England, as the title of a collection of Latin vocables, arranged according to their subjects, in sentences, for the use of learners; e.g.

'In horto magistri Johannis 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

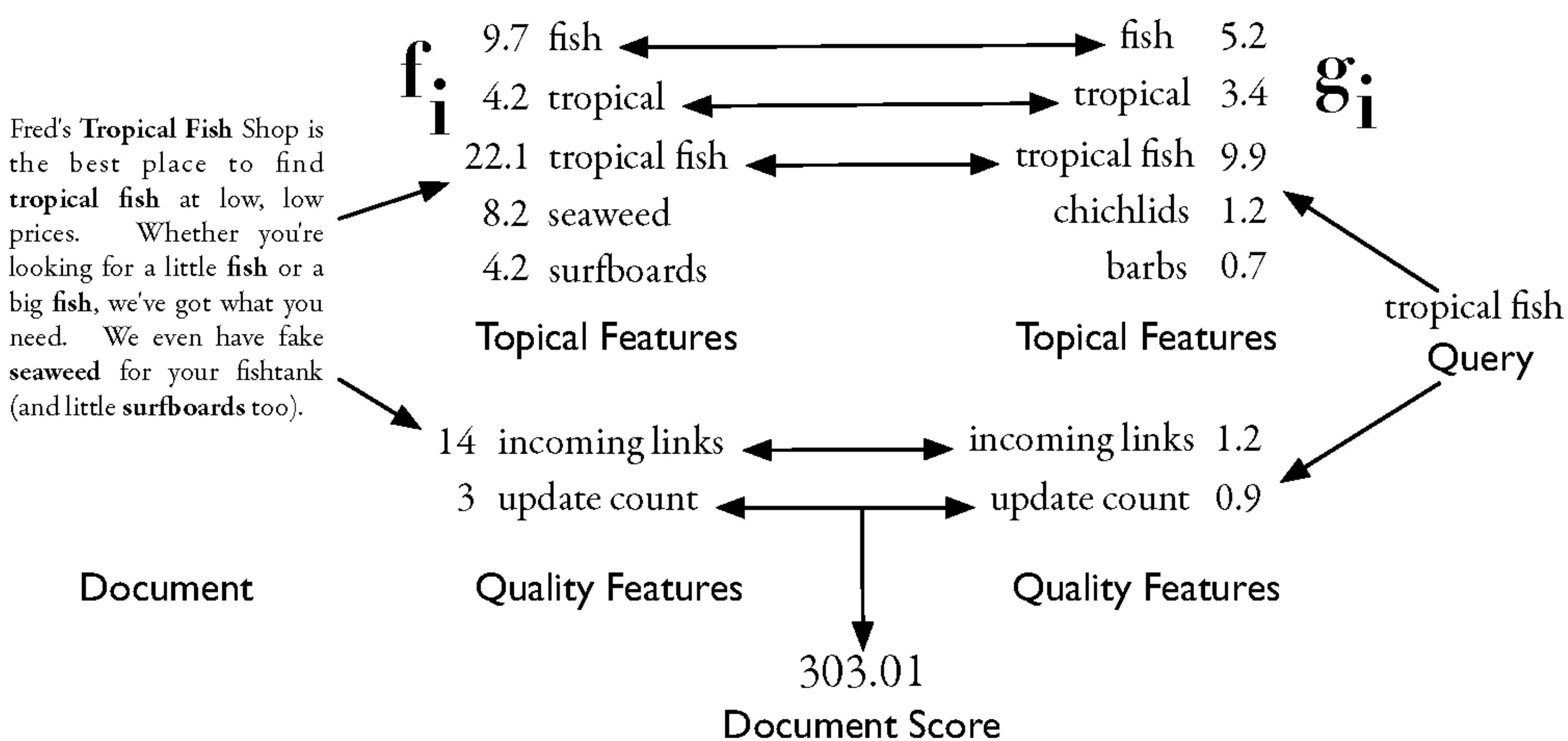
Abstract Model of Ranking



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



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

and	1
aquarium	3
are	3, 4
around	1
as	2
both	1
bright	3
coloration	3, 4
derives	4
due	3
environments	1
fish	1, 2, 3, 4
fishkeepers	2
found	1
fresh	2
freshwater	1, 4
from	4
generally	4
in	1, 4
include	1
including	1
iridescence	4
marine	2
often	2, 3
only	2
pigmented	4
popular	3
refer	2
referred	2
requiring	2
salt	1, 4
saltwater	2
species	1
term	2
the	1, 2
their	3
this	4
those	2
to	2, 3
tropical	1, 2, 3
typically	4
use	2
water	1, 2, 4
while	4
with	2
world	1

Inverted Index with counts

- supports better ranking algorithms

and	1:1
aquarium	3:1
are	3:1, 4:1
around	1:1
as	2:1
both	1:1
bright	3:1
coloration	3:1, 4:1
derives	4:1
due	3:1
environments	1:1
fish	1:2, 2:3, 3:2, 4:2
fishkeepers	2:1
found	1:1
fresh	2:1
freshwater	1:1, 4:1
from	4:1
generally	4:1
in	1:1, 4:1
include	1:1
including	1:1
iridescence	4:1
marine	2:1
often	2:1, 3:1
only	2:1
pigmented	4:1
popular	3:1
refer	2:1
referred	2:1
requiring	2:1
salt	1:1, 4:1
saltwater	2:1
species	1:1
term	2:1
the	1:1, 2:1
their	3:1
this	4:1
those	2:1
to	2:2, 3:1
tropical	1:2, 2:2, 3:1
typically	4:1
use	2:1
water	1:1, 2:1, 4:1
while	4:1
with	2:1
world	1:1

Inverted Index with positions

- supports proximity matches

Term	Postings
and	1,15
aquarium	3,5
are	3,3 4,14
around	1,9
as	2,21
both	1,13
bright	3,11
coloration	3,12 4,5
derives	4,7
due	3,7
environments	1,8
fish	1,2 1,4 2,7 2,18 2,23 3,2 3,6 4,3 4,13
fishkeepers	2,1
found	1,5
fresh	2,13
freshwater	1,14 4,2
from	4,8
generally	4,15
in	1,6 4,1
include	1,3
including	1,12
iridescence	4,9
marine	2,22
often	2,2 3,10
only	2,10
pigmented	4,16
popular	3,4
refer	2,9
referred	2,19
requiring	2,12
salt	1,16 4,11
saltwater	2,16
species	1,18
term	2,5
the	1,10 2,4
their	3,9
this	4,4
those	2,11
to	2,8 2,20 3,8
tropical	1,1 1,7 2,6 2,17 3,1
typically	4,6
use	2,3
water	1,17 2,14 4,12
while	4,10
with	2,15
world	1,11

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.,

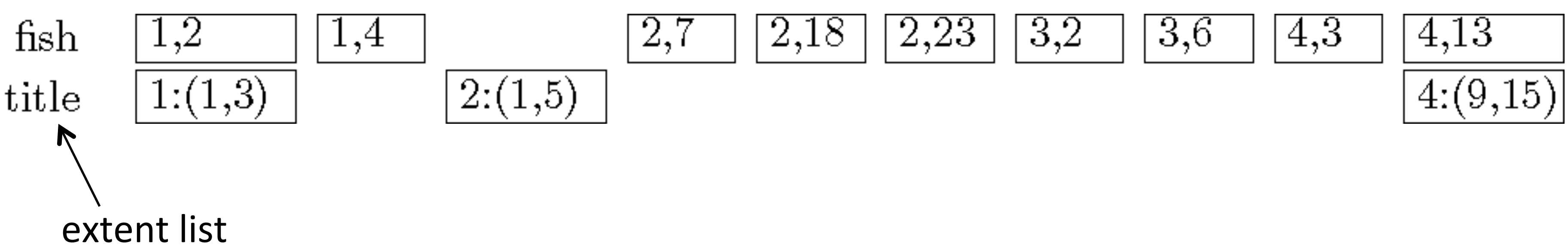
tropical	1,1		1,7	2,6	2,17		3,1			
fish	1,2	1,4		2,7	2,18	2,23	3,2	3,6	4,3	4,13

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.,



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 01 01 0 0 11 0
  - which represents: 0, 1, 1, 0, 0, 3, 0
  - use unambiguous code:

Number	Code
0	0
1	101
2	110
3	111

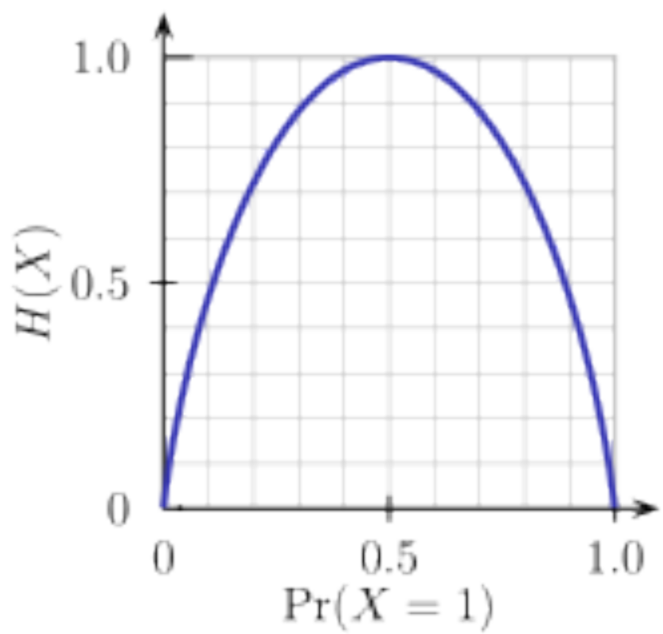
  - which gives: 0 101 0 110 0 110 0

Compression and Entropy

- **Entropy** measures “randomness”
  - Inverse of compressability

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

  - 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[|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[|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.,

$$1, 1, 2, 1, 5, 1, 4, 1, 1, 3, \ldots$$

- Differences for a low-frequency word are large, e.g.,

$$109, 3766, 453, 1867, 992, \ldots$$

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

Number	Code
0	0
1	10
2	110
3	1110
4	11110
5	111110

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

Number (k)	k_d	k_r	Code
1	0	0	0
2	1	0	10 0
3	1	1	10 1
6	2	2	110 10
15	3	7	1110 111
16	4	0	11110 0000
255	7	127	11111110 1111111
1023	9	511	1111111110 111111111

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

Number (k)	k_d	k_r	k_{dd}	k_{dr}	Code
1	0	0	0	0	0
2	1	0	1	0	10 0 0
3	1	1	1	0	10 0 1
6	2	2	1	1	10 1 10
15	3	7	2	0	110 00 111
16	4	0	2	1	110 01 0000
255	7	127	3	0	1110 000 1111111
1023	9	511	3	2	1110 010 111111111

```
#
# Generating Elias-gamma and Elias-delta codes in Python
#

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

k	Number of bytes
$k < 2^7$	1
$2^7 \leq k < 2^{14}$	2
$2^{14} \leq k < 2^{21}$	3
$2^{21} \leq k < 2^{28}$	4

k	Binary Code	Hexadecimal
1	1 0000001	81
6	1 0000110	86
127	1 1111111	FF
128	0 0000001 1 0000000	01 80
130	0 0000001 1 0000010	01 82
20000	0 0000001 0 0011100 1 0100000	01 1C A0

V-Byte Encoder

```
public void encode( int[] input, ByteBuffer output ) {
    for( int i : input ) {
        while( i >= 128 ) {
            output.put( i & 0x7F );
            i >>>= 7;
        }
        output.put( i | 0x80 );
    }
}
```

V-Byte Decoder

```
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:

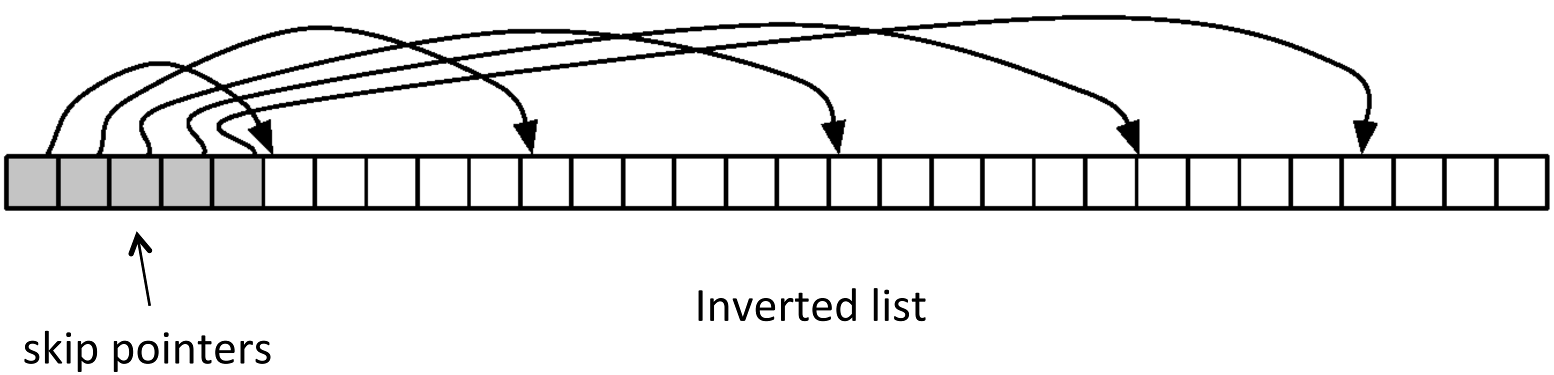
```
81 82 81 86 81 82 86 8B 01 B4 81 81 81
```

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 **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

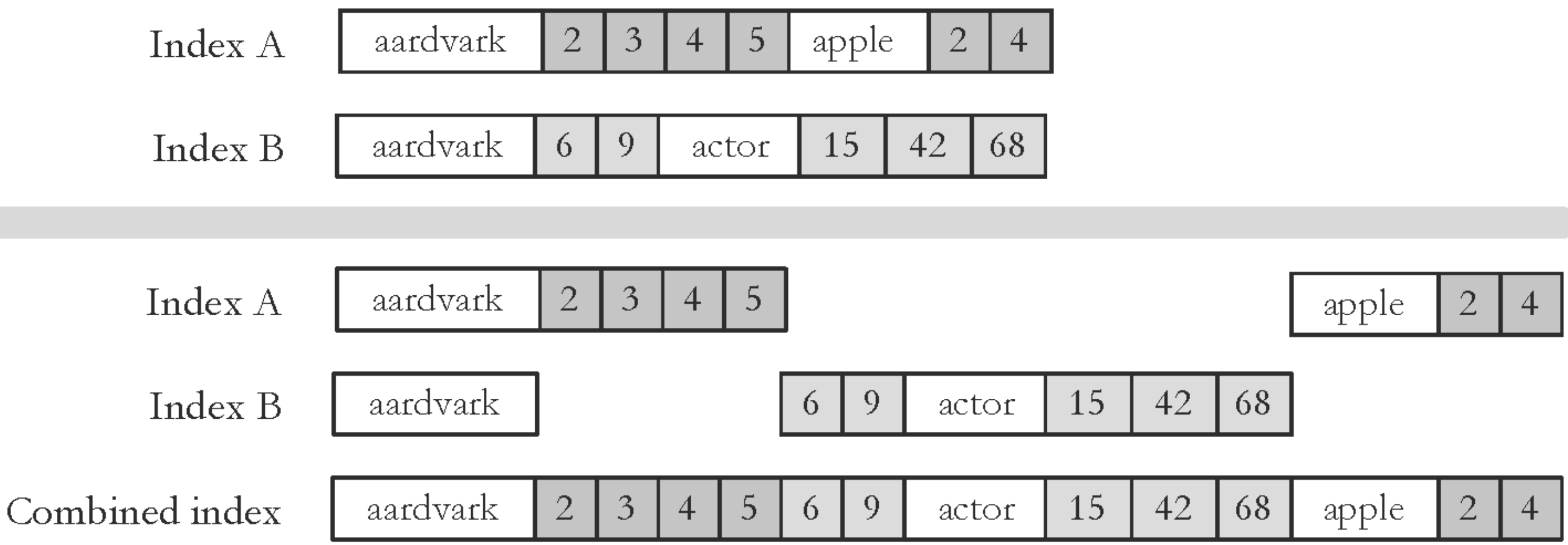
- Simple in-memory indexer

```
procedure BuildIndex(D)                          ▷ D is a set of text documents
    I ← HashTable()                              ▷ Inverted list storage
    n ← 0                                        ▷ Document numbering
    for all documents d ∈ D do
        n ← n + 1
        T ← Parse(d)                             ▷ Parse document into tokens
        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
```

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

Merging



Index A
aardvark 2 3 4 5 apple 2 4
Index B
aardvark 6 9 actor 15 42 68
Index A
aardvark 2 3 4 5
apple 2 4
Index B
aardvark
6 9 actor 15 42 68
Combined index
aardvark 2 3 4 5 6 9 actor 15 42 68 apple 2 4

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

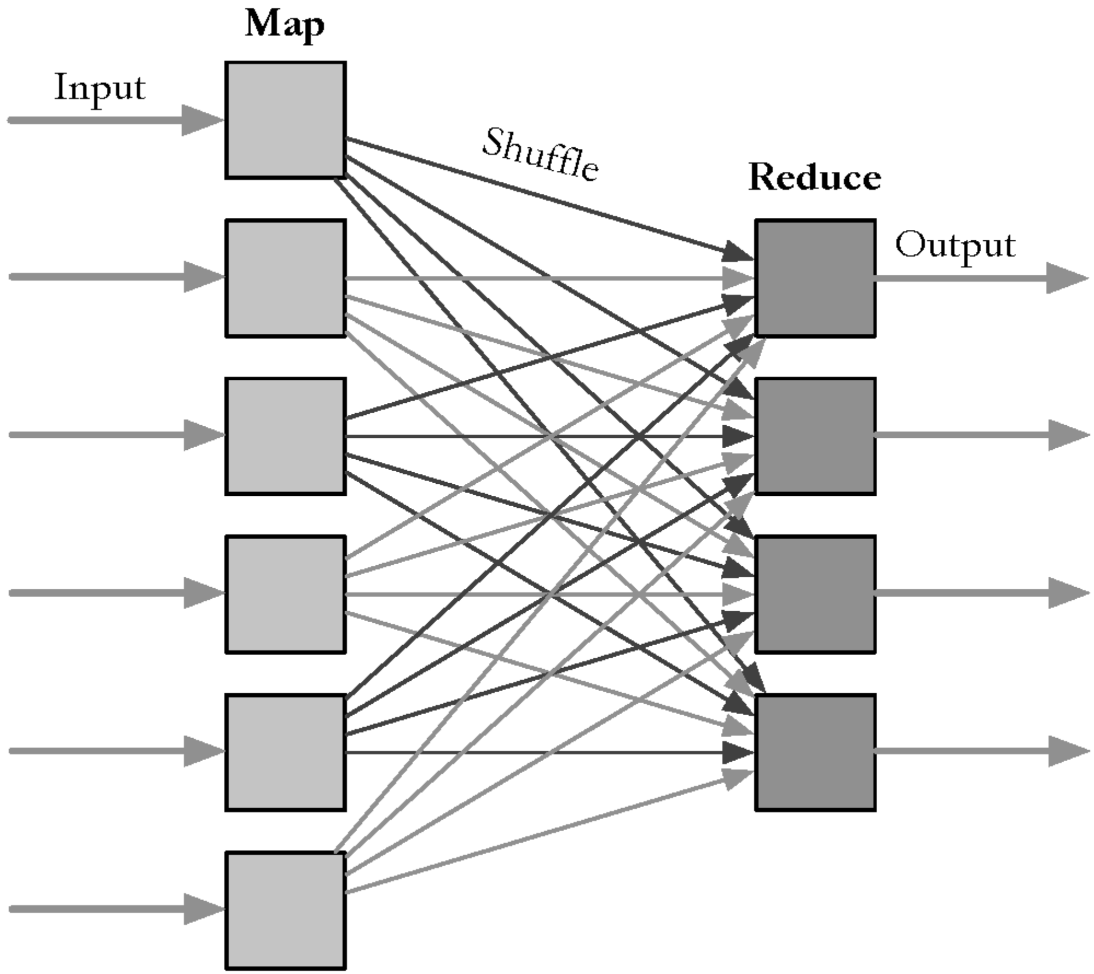
MapReduce

- 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

MapReduce



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
```

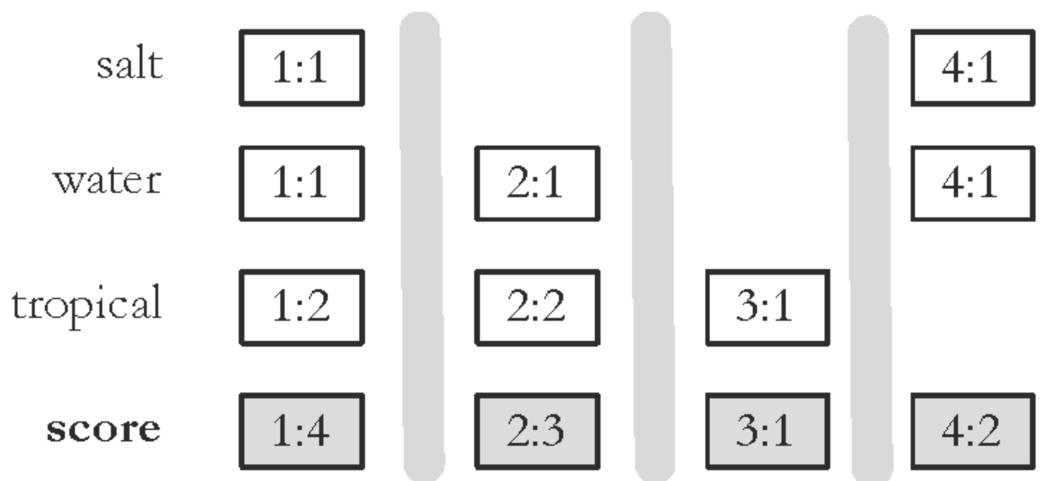
Result Merging

- 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 time required to generate scores

Document-At-A-Time



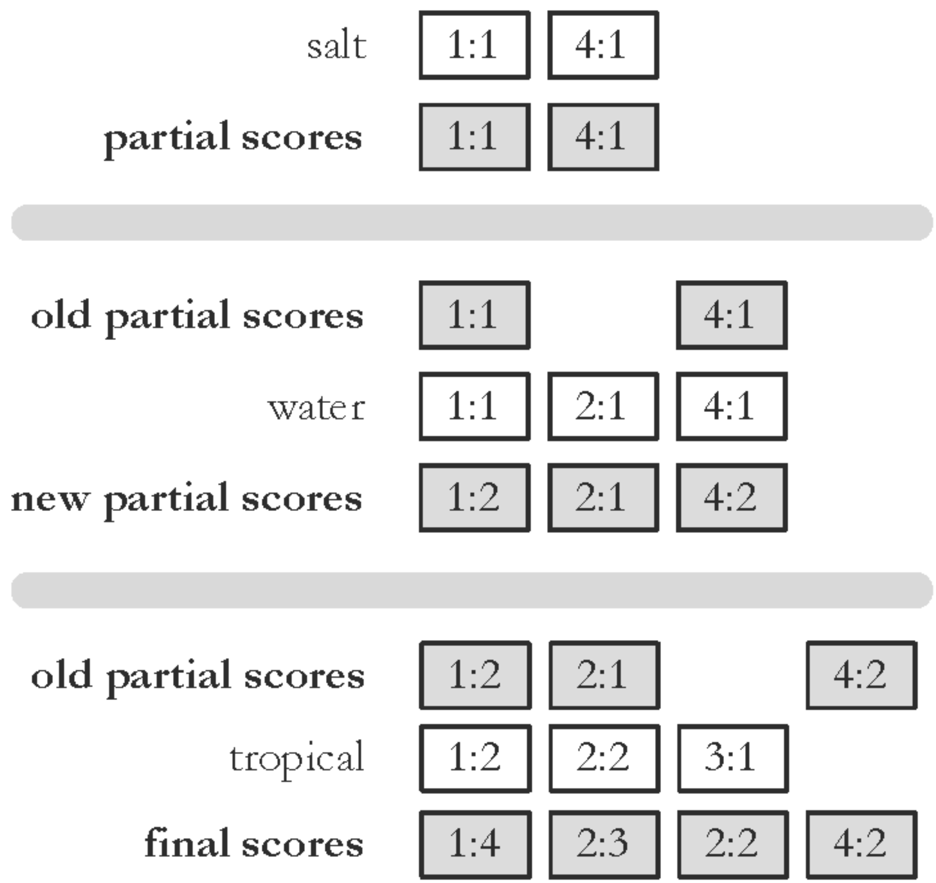
Pseudocode Function Descriptions

- 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()
  - Moves to the next document in the list. Equivalent to movePastDocument(getCurrentDocument()).
- 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 $a < d < b$.

Document-At-A-Time

```
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 ∈ 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



Term-At-A-Time

procedure TermAtATimeRetrieval(Q, I, f, g k)
  $A \leftarrow$ HashTable()
  $L \leftarrow$ Array()
  $R \leftarrow$ PriorityQueue(k)
  for all terms w_i in Q **do**
    $l_i \leftarrow$ InvertedList(w_i, I)
    L.add(l_i)
  end for
  for all lists $l_i \in L$ **do**
    while l_i is not finished **do**
      $d \leftarrow l_i$.getCurrentDocument()
      $A_d \leftarrow A_d + g_i(Q)f(l_i)$
      l_i.moveToNextDocument()
    end while
  end for
  for all accumulators A_d in A **do**
    $s_d \leftarrow A_d$ ▷ Accumulator contains the document score
    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

```
procedure TermAtATimeRetrieval(Q, I, f, g, k)
    A ← Map()
    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 lists l_i ∈ L do
        d_0 ← −1
        while l_i is not finished do
            if i = 0 then
                d ← l_i.getCurrentDocument()
                A_d ← A_d + g_i(Q)f(l_i)
                l_i.moveToNextDocument()
            else
                d ← l_i.getCurrentDocument()
                d′ ← A.getNextAccumulator(d)
                A.removeAccumulatorsBetween(d_0, d′)
                if d = d′ then
                    A_d ← A_d + g_i(Q)f(l_i)
                    l_i.moveToNextDocument()
                else
                    l_i.skipForwardToDocument(d′)
                end if
                d_0 ← d′
            end if
        end while
    end for
    for all accumulators A_d in A do
        s_d ← A_d                    ▷ Accumulator contains the document score
        R.add( s_d, d )
    end for
    return the top k results from R
end procedure
```

Conjunctive Document-at-a-Time

```
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
    d ← −1
    while all lists in L are not finished do
        s_d ← 0
        for all inverted lists l_i in L do
            if l_i.getCurrentDocument() > d then
                d ← l_i.getCurrentDocument()
            end if
        end for
        for all inverted lists l_i in L do
            l_i.skipForwardToDocument(d)
            if l_i.getCurrentDocument() = d then
                s_d ← s_d + g_i(Q)f_i(l_i)          ▷ Update the document score
                l_i.movePastDocument( d )
            else
                d ← −1
                break
            end if
        end for
        if d > −1 then R.add( s_d, d )
        end if
    end while
    return the top k results from R
end procedure
```

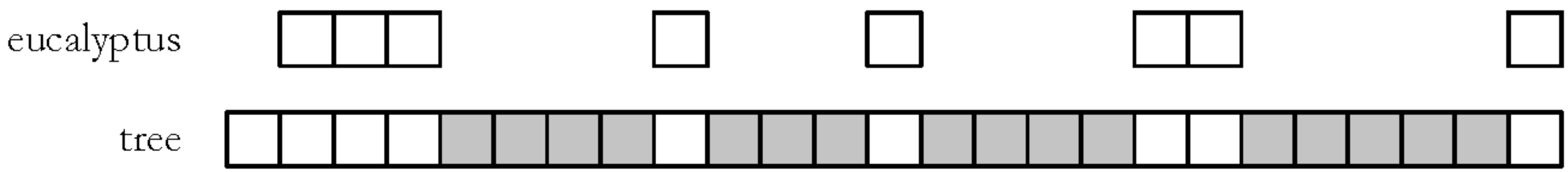
Threshold Methods

- 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* τ
  - optimization methods estimate τ' to ignore documents

Threshold Methods

- For document-at-a-time processing, use score of lowest-ranked document so far for τ'
  - 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 τ'
  - *safe* optimization in that ranking will be the same without optimization (cf. A* search)

MaxScore Example



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

Other Approaches

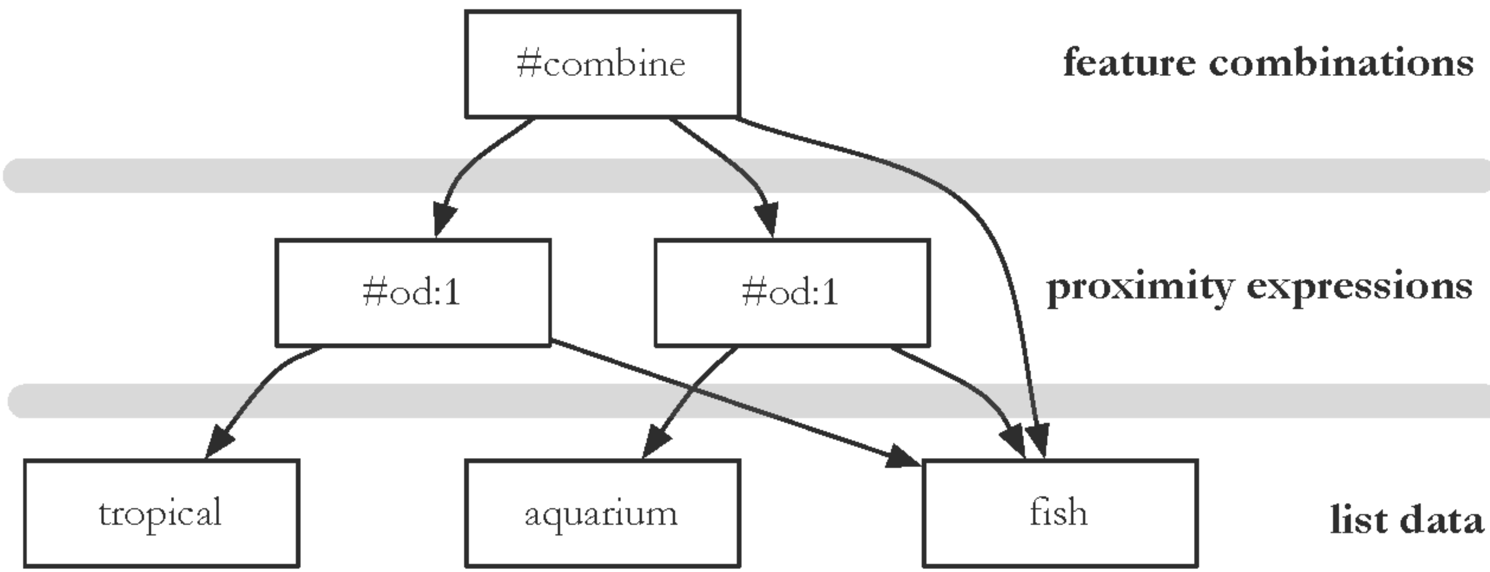
- Early termination of query processing
  - ignore high-frequency word lists in term-at-a-time
  - ignore documents at end of lists in doc-at-a-time
  - *unsafe* optimization
- List ordering
  - order inverted lists by quality metric (e.g., PageRank) or by partial score
  - makes unsafe (and fast) optimizations 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:

#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?