11-442 / 11-642:
Search Engines

Index Creation

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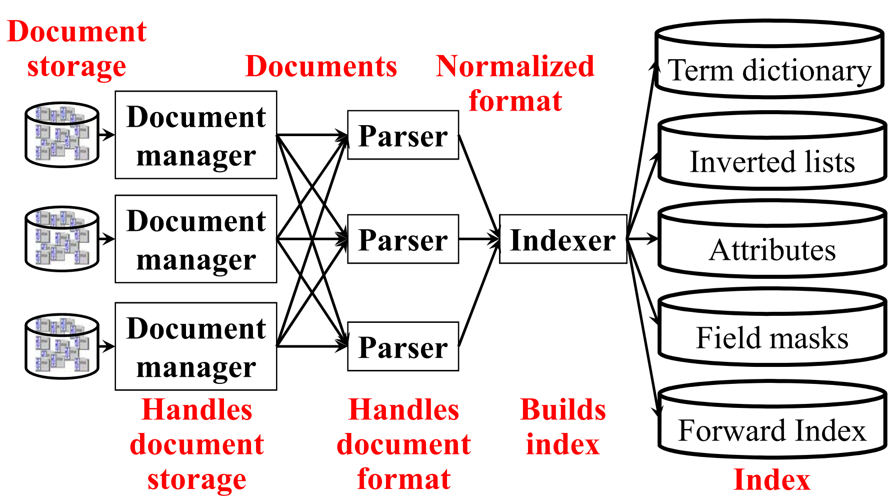
Overview of Index Construction



Lecture Outline

- **Building inverted lists on a single processor**
- **Inverted lists and inverted files**
  - – Inverted list compression
  - – Inverted list optimizations
- **Forward indexes**
- **Storing document structure**
- **Indri and Lucene indexes**
- **Index updates**

Basic Facts That Affect Indexing

Indexing architectures are designed to be very efficient

- Quickly turn a massive document corpus into an index
- Efficiency is the reason for many design decisions

Integers are usually preferred over strings

- Integers almost always take less space to store
- Integers can be compared more quickly

So…convert strings to integers whenever possible

Basic Facts That Affect Indexing

Usually the corpus is <u>much</u> bigger than the available RAM

- E.g., 10 million web documents is 250 GB
- You can't do the whole task in memory

Disks are slow compared to processors

- Only write to the disk when absolutely necessary
- Compress data to reduce I/O
- Sequential access is much faster than random access

Most of this is true for all parts of the search engine
…but it is especially important during indexing

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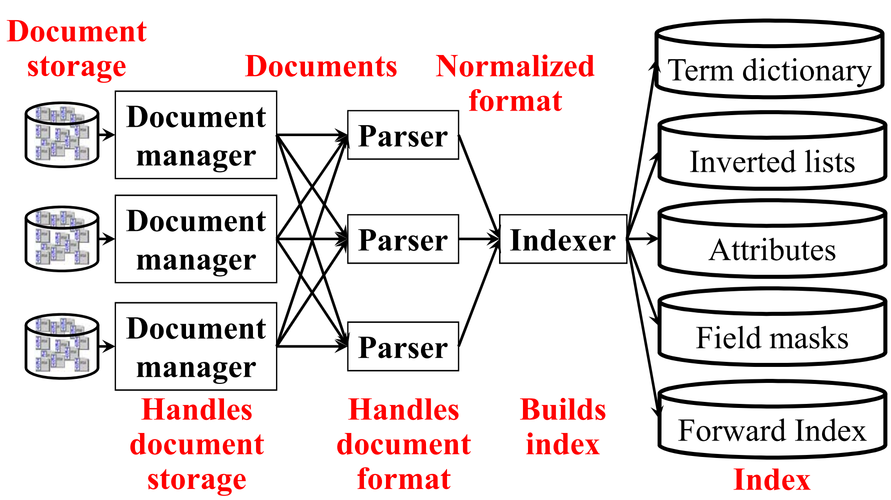


An Example Indexing API

Services that an indexing API might provide

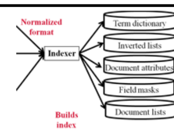
- documentBegin (externalId)
- documentEnd
- fieldBegin (fieldType)
- fieldBegin (fieldType, FieldId, parentFieldId)
- fieldEnd
- addAttribute (attributeType, value)
- addToken (tokenString, location)
- …

An Example Indexing API

Services that an indexing API might provide

- documentBegin (“http://www.cs.cmu.edu/~callan/”)
- documentEnd
- fieldBegin (TITLE)
- fieldBegin (TITLE, “21”, “18”)
- fieldEnd
- addAttribute (DATE, “09/30/2013”)
- addToken (“textbook”, 13)
- …

Indexing Text Tokens



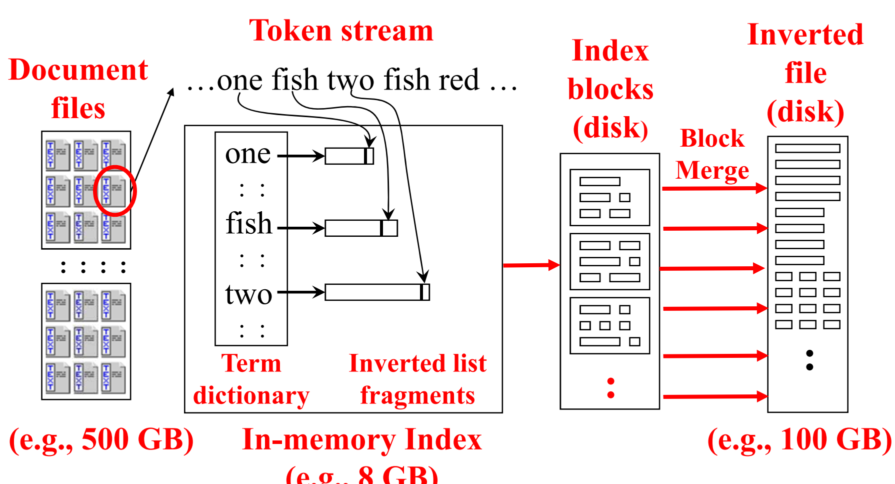
Most text representation tasks are done in the indexer

- Documents from different sources can be treated the same
- The indexer knows what data structures it needs

Typical text representation tasks (earlier lecture)

- Case folding (mixed case → lower case)
- Stopword removal
- Stemming (morphological processing / lemmatization)
- …

How Inverted Files are Built: Single Processor



(Adapted from Zobel & Moffat, 2006)

How Inverted Files are Built: Single Processor

The in-memory index buffers store

- Part of the term dictionary
- Fragments of inverted lists

The in-memory buffers are small compared to the final index

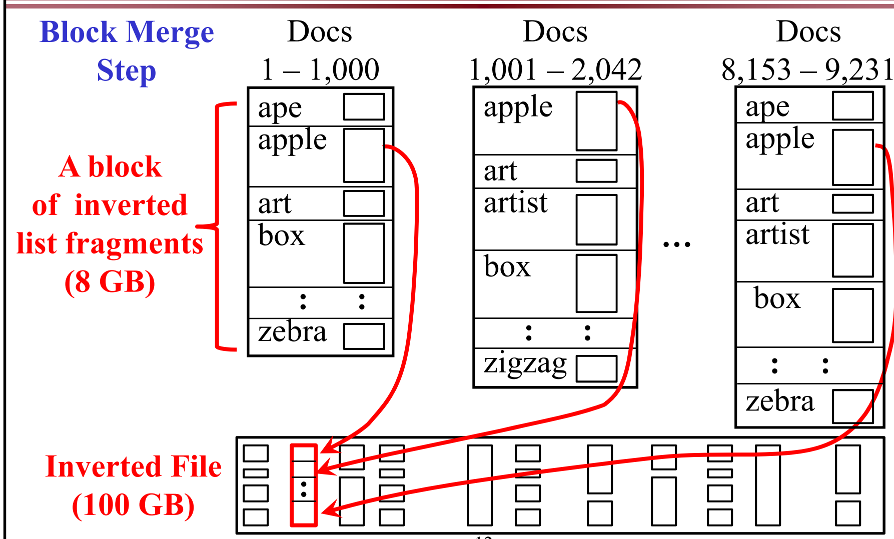
When in-memory buffers are full

- Flush in-memory buffers to disk and reinitialize them
- Continue parsing to refill the in-memory buffers

When all documents are parsed, merge index blocks on disk

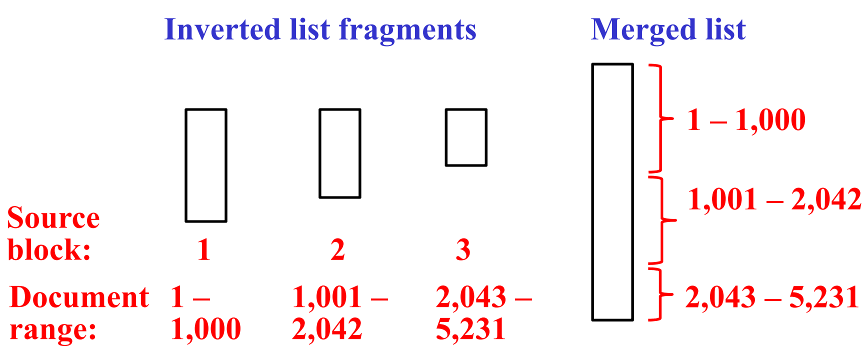
- Very fast – essentially a merge of sorted lists

How Inverted Files are Built: Single Processor



How Inverted Files are Built: Single Processor

Block merge of the inverted list for 'apple'



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  - Inverted list compression
  - Inverted list optimizations
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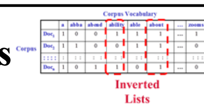
Different Types of Inverted Lists for the Term “Apple”



Binary

df:	4356
docid:	42
docid:	94
	:
	:

Frequency

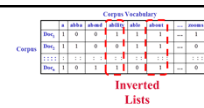
df:	4356
docid:	42
tf:	3
docid:	94
	:
	:

Positional

df:	4356
docid:	42
tf:	3
locs:	14
	83
	157
docid:	94
	:
	:

df: document frequency
tf: term frequency ($tf_{t,d}$)
doclen: document length (in terms)

Inverted Lists



Conceptually an inverted list looks like an object

apple

df:	**4356**
docid:	**42**
tf:	**3**
locs:	**14**
	83
	157
docid:	**94**
	:
	:

Usually it is stored on disk as a sequence of integers

apple

4356
42
3
14
83
157
94
:
:

Inverted List Indexes: Compression

Usually inverted lists are compressed – why?

- Save disk space? Favor aggressive compression algorithms
- Save time? Favor simple compression algorithms
  - I/O savings > CPU time required to uncompress

Today, the most common goal is to reduce query time

Algorithms:

- Gap encoding
- Restricted variable-length (RVL) encoding
- The book also covers slower, more aggressive algorithms

Inverted File Compression: Delta Gap ("DGap") Encoding

Store the differences between numbers ("DGaps")

- Increases probability of smaller numbers
- A more skewed distribution
- Lower entropy

Stemming also increases the probability of smaller numbers

- Why?

Before

Doc ID	121
TF	3
Loc	18
Loc	47
Loc	68
DocID	135
TF	2
Loc	22
Loc	35

After

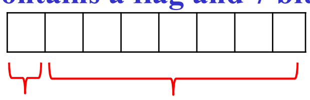
Doc ID	**121**
TF	3
Loc	18
Loc	29
Loc	21
DocID	**14**
TF	2
Loc	22
Loc	13

Inverted File Compression: Variable Byte Encoding

Variable byte encoding stores a number in a sequence of bytes

$byte_1$ **$byte_2$** …. **$byte_n$**

Each byte contains a flag and 7 bits of payload (the number)



The flag indicates whether this is the last byte in the sequence

0: Not the last byte 1: The last byte

Concatenate the payload bits to reconstruct the number

Inverted File Compression: Variable Byte Encoding

Decimal: 5

Binary: 00000000 00000000 00000000 $0\underbrace{0000101}_{\text{7 bits}}$

Compressed: 10000101

Decimal: 57

Binary: 00000000 00000000 00000000 $0\underbrace{0111001}_{\text{7 bits}}$

Compressed: 10111001

The flag identifies the last byte

Inverted File Compression: Variable Byte Encoding

					7 bits
Decimal:	127				
Binary:	00000000	00000000	00000000	01111111	
Compressed:	11111111				
			7 bits	7 bits	
Decimal:	128				
Binary:	00000000	00000000	00000000	10000000	
Compressed:	00000000	10000001			
	Byte$_0$	**Last byte**			
			7 bits	7 bits	
Decimal:	131				
Binary:	00000000	00000000	00000000	10000011	
Compressed:	00000011	10000001			

Inverted File Compression: Variable Byte Encoding

		7 bits	7 bits	7 bits
Decimal:	613,521			
Binary:	00000000	00001001	01011100	10010001
Compressed:	00010001	00111001	10100101	
	Byte$_0$	**Byte$_1$**	**Last byte**	

Inverted File Compression: Variable Byte Decoding

	$Byte_0$	$Byte_1$	$Byte_2$	
Compressed:	00010001	00111001	10100101	

Last? Payload

Initial:	00000000	00000000	00000000	00000000
After $Byte_0$:	00000000	00000000	00000000	00010001
After $Byte_1$:	00000000	00000000	00011100	10010001
After $Byte_2$:	00000000	00001001	01011100	10010001
Decimal:	613,521			

Inverted File Compression: Variable Byte Encoding

$[0 \ldots 2^7-1]$:	1 byte:	1xxxxxxx
$[2^7 \ldots 2^{14}-1]$:	2 bytes:	0xxxxxxx1xxxxxxx
$[2^{14} \ldots 2^{21}-1]$:	3 bytes:	0xxxxxxx0xxxxxxx1xxxxxxx
: :	:	: : :

Can store numbers of arbitrary size when needed

Advantages:

- Encoding and decoding can be done <u>very efficiently</u>
- Can find the n^th number without decoding the previous numbers

Inverted File Compression

There are other inverted list compression algorithms

- E.g., Gamma and Delta codes
  - See the textbook for details
  - **Note:** DGap Encoding ≠ Delta Code

The most effective compression algorithms are …

- About 15-20% smaller than variable byte encoding
- Slower than restricted variable length encoding

Disks are cheap, and speed is important

- So restricted variable length compression is a common solution

Inverted File Compression: Summary

A compressed inverted file, without positional information:

- Less than 10% the size of the original text

A compressed inverted file with positional information:

- 15-20% the size of the original text

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- **Inverted lists and inverted files**
  - Inverted list compression
  - Inverted list optimizations
- Forward indexes
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Inverted List Optimizations: Skip Lists

Skip lists are pointers that allow parts of the inverted list to be skipped

One heuristic

- List length: df_t
- A skip pointer every $\sqrt{df_t}$ documents

Purpose

- Avoid computation
- Avoid I/O

Inverted List With Skip Pointers

```
df   25
ctf  37
skip past doc 19
doc  3, tf 3 locs …
doc  7, tf 1, locs …
doc 10, tf 2, locs …
doc 13, tf 1, locs …
doc 19, tf 4, locs …
skip past doc 44
doc 23, tf 1, locs …
doc 27, tf 2, locs …
doc 32, tf 1, locs …
doc 41, tf 1, locs …
doc 44, tf 1, locs …
skip past doc 84
doc 57, tf 5, locs …
 :  :  :  :  :
```

Inverted List Optimizations: Skip Lists

When is a skip list useful? Consider #NEAR/3 (jamie apple)

42 ≠ 43, so advance the pointer with the smaller docid

jamie		apple	
df:	23	df:	1,033,436
→ docid:	42	→ docid:	43
tf:	3	tf:	3
docid:	59,356	docid:	49
tf:	1	tf:	1
:		:	

Document locations are not shown due to lack of space on the slide

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Inverted List Optimizations: Skip Lists

When is a skip list useful? Consider #NEAR/3 (jamie apple)

59,356 ≠ 43, so advance the pointer with the smaller docid

- But advancing to the next 'apple' document is inefficient

jamie		apple	
df:	23	df:	1,033,436
docid:	42	→ docid:	43
tf:	3	tf:	3
→ docid:	59,356	docid:	49
tf:	1	tf:	1
:		:	

- Better to advance the 'apple' pointer to at least docid 59,356
- **Note:** QryIop.java has docIteratorAdvanceTo (docid)
  – Advance to docid, or beyond if docid isn't in the list
  – It would be easy to add skip lists to the QryEval code

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Inverted List Optimizations: Skip Lists

Skip lists are useful for any query operator that needs all of its arguments to occur in a document

- #NEAR, #WINDOW, #SYN
- Boolean AND
- Document structure operators, e.g., jamie.title
  - A short jamie inverted list + a long title inverted list

Skipping can also occur when score calculations are complex

- Some query evaluation optimizations stop calculating a document score when it becomes obvious that the score is low
  - We may cover this later in the course, if there is time

Inverted List Optimizations : Top-Docs (Champion) Lists

Main idea

- Some inverted lists are long
- Most queries only need to return ≤ 100 documents
- Why rank all documents if only 100 are needed?

Top-docs lists:

- Truncated inverted lists that contain only the best docs
- Faster
- Lower recall

"apple" Inverted List

Doc 1 tf 2
Doc 2 tf 4
: : :
Doc 258392 tf 3
Doc 258393 tf 5
: : :
Doc 1025429 tf 6
Doc 1025430 tf 4

1,025,430 documents

"apple" Top-Docs List

Doc 1025429 tf 6
Doc 258393 tf 5
: : :
Doc 2 tf 4
Doc 1025430 tf 4

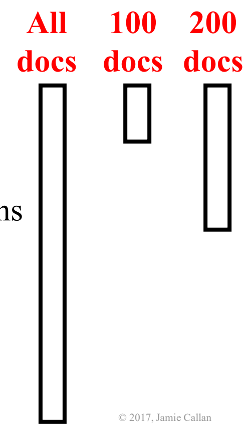
1,000 documents

Inverted List Optimizations : Top-Docs (Champion) Lists

How are top-docs lists constructed?

- **<u>Select</u> documents to go in the list by…**
  - tf
  - PageRank
  - …
- **<u>Order</u> the top-docs list by document id**
  - Faster, if the whole list is read
  - May require multiple lists of different lengths
- **<u>Order</u> the top-docs list by tf**
  - Supports reading variable amount of list
  - Requires just one list
- **…**

Inverted lists for "apple"



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Inverted List Optimizations : Top-Docs (Champion) Lists

How many terms are frequent enough to have a top-docs list?

- **How big is an average inverted list entry?**
- **Suppose 5 integers, on average**
  - Uncompressed: 16 bytes
  - Compressed: Assume 5 bytes
    - » 30% compression rate × 16 bytes = 5 bytes
- **Linux filesystem page size:** 4096 bytes
- **How many term inverted list entries fit in one page?**
  - 4096 / 5 = 819
  - Assume some overhead … 800 entries

docid
tf
loc
…
loc

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Inverted List Optimizations : Top-Docs (Champion) Lists

How many terms are frequent enough to have a top-docs list?

- **Zipf's Law:** Rank × Frequency$_c$ = A × N
- **Rank of a word that occurs once (ctf=1):** A × N / 1
  - Also an estimate of the vocabulary size
- **Rank of a word that occurs 800 times:** A × N / 800
- **The <u>percentage of terms</u> with ctf ≥ 800:**

  (A × N / 800) / (A × N) = 1 / 800 = 0.125%
- **So … if the vocabulary is 1,000,000 terms**
  - Probably fewer than 1,250 top-docs lists
  - Each list is perhaps 4-8 KB long
  - So … 5-10 MB

Ranking of terms by ctf

freq=800 →

freq=1 →

Inverted List Optimizations: Multiple Inverted Lists Per Term

Some common query operators do not use locations

- **Operators:** SUM, WEIGHT, AND, OR, ANDNOT, …
- Using inverted lists with locations causes wasted I/O

What are the I/O costs?

- **No location:** 2 integers per document
- **Locations:** Assume 1.5 extra integers per document

docid
tf
loc
…
loc
docid

So, 42% of the I/O is wasted effort

- Compression changes these numbers, but not the main idea

Inverted List Optimizations: Multiple Inverted Lists Per Term

Some common query operators do not use locations

- **Operators:** SUM, WEIGHT, AND, OR, ANDNOT, …
- Using inverted lists with locations causes wasted I/O

Solution: Store two types of inverted list for each term

I/O costs are reduced for queries that don't need locations

- **Cost:** Extra disk space

docid tf loc … loc docid

docid tf docid …

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Inverted List Optimizations: Multiple Inverted Lists Per Term

Is it worthwhile to store 2 inverted lists for every term?

- **How many terms have a topdocs / champion list?**
  - Only 0.125%
  - All other terms have 'short' inverted lists that fit in one disk page
- **What is the effect of making a 'short' inverted list shorter?**
  - Reduced computational effort
  - Probably no change in I/O
- **So … maybe have 2 inverted lists only for frequent terms**

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- Building inverted lists on a single processor
- Inverted lists and inverted files
  - Inverted list compression
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- **Forward indexes**
- Storing document structure
- Indri and Lucene indexes
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Forward Indexes

Suppose I want to know which words occur in documents about Microsoft … how would I do it?

- This is a common component of text mining tasks
- E.g., sentiment analysis of documents about Microsoft
- E.g., query expansion, relevance feedback

First step: Use an inverted list to find out which documents contain the word Microsoft

- Easy

Now what?

Forward Indexes

Sometimes your software needs to know what terms are in the document … how does it find out?

Parse the document again?

- A little slow (but not terrible, because indexing is fast)
- Done when storage is expensive
- But software evolves, so it might not be <u>exactly the same</u> parse

Store the parsed document?

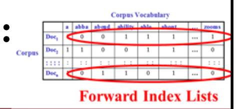
- Fast, and guaranteed to be accurate
- Done when storage is cheap

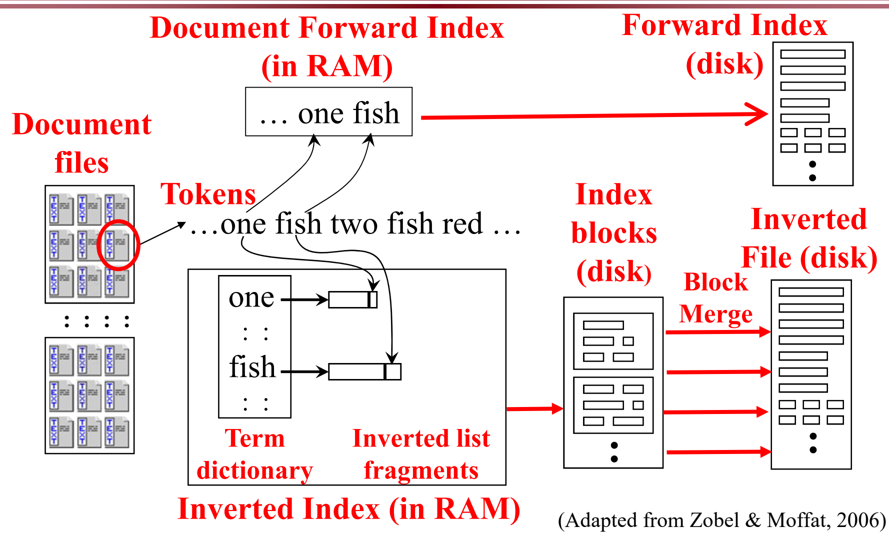
Forward Indexes

Forward indexes store the <u>indexed form of a document</u>

- **The location of every term that made it into the index**
  - Term id, location
  - Information about where stopwords appeared
- **Optionally: Information about document structure**
  - Field names and extents

How Forward Indexes are Built: Single Processor





(Adapted from Zobel & Moffat, 2006)

How Does Indri Do It? Two Different Approaches

Indri provides two classes for accessing forward indexes

- **Via the indri::index class**
  - A somewhat low-level access to the index
  - Very efficient, not always very friendly
- **Via the QueryEnvironment class**
  - Higher-level, more abstract access to the index
  - Somewhat less efficient, somewhat more user friendly

We start with the indri::index class because it exposes the data structures more clearly

How Does Indri Do It?
The indri::index::TermList Class

Text: "OBAMA STATE OF THE UNION SPEECH
President Barack Obama delivered …"

int terms [ ]

obama	41321
state	34127
OOV	0
OOV	0
union	25434
speech	9982
president	98476
barack	12653
obama	41321
deliver	34376
	: :

Term ids in the document.
0: stopword

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How Does Indri Do It?
The indri::index::TermList Class

Text: "OBAMA STATE OF THE UNION SPEECH
President Barack Obama delivered …"

int terms [ ]

obama	41321
state	34127
OOV	0
OOV	0
union	25434
speech	9982
president	98476
barack	12653
obama	41321
deliver	34376
	: :

Term ids in the document.
0: stopword

fields [ ]

int begin;
int end;
int id;

0, 5, 3	**title**
6, 99, 4	**body**
6, 16, 18	**sentence**
17, 34, 18	**sentence**
: : :	: : :

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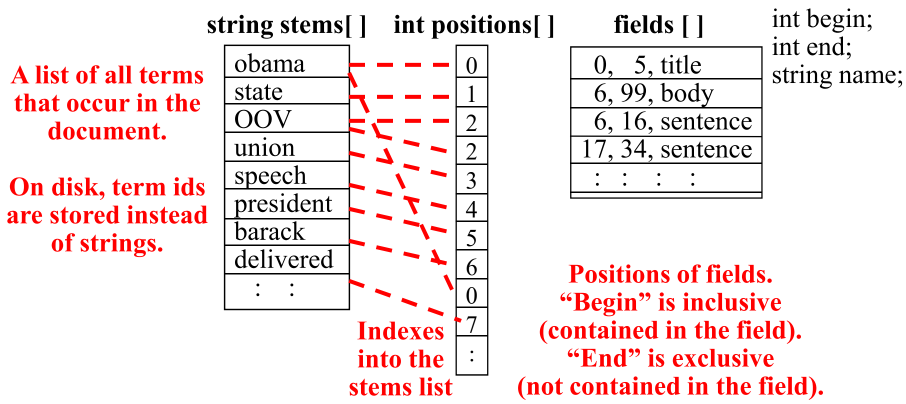
How Does Indri Do It?
The DocVector Class

Text: "OBAMA STATE OF THE UNION SPEECH
President Barack Obama delivered …"



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For More Information

- I.H. Witten, A. Moffat, and T.C. Bell. "Managing Gigabytes." Morgan Kaufmann. 1999.
- G. Salton. "Automatic Text Processing." Addison-Wesley. 1989.
- J. Zobel and A. Moffat. "Inverted files for text search engines." *ACM Computing Surveys*, 38 (2). 2006.