Introduction to

Information Retrieval

CS276: Information Retrieval and Web Search

Basic inverted index construction

Index construction

- How do we construct an index?
- What strategies can we use with limited main memory?

Recall index construction

- Documents are parsed to extract words and these are saved with the Document ID.

Doc 1

I did enact Julius Caesar I was killed i' the Capitol; Brutus killed me.

Doc 2

So let it be with Caesar. The noble Brutus hath told you Caesar was ambitious

Term	Doc #
I	1
did	1
enact	1
julius	1
caesar	1
I	1
was	1
killed	1
i'	1
the	1
capitol	1
brutus	1
killed	1
me	1
so	2
let	2
it	2
be	2
with	2
caesar	2
the	2
noble	2
brutus	2
hath	2
told	2
you	2
caesar	2
was	2
ambitious	2

Key step

- After all documents have been parsed, the inverted file is sorted by terms.

We focus on this sort step.

Term	Doc #
I	1
did	1
enact	1
julius	1
caesar	1
I	1
was	1
killed	1
i'	1
the	1
capitol	1
brutus	1
killed	1
me	1
so	2
let	2
it	2
be	2
with	2
caesar	2
the	2
noble	2
brutus	2
hath	2
told	2
you	2
caesar	2
was	2
ambitious	2

→

Term	Doc #
ambitious	2
be	2
brutus	1
brutus	2
capitol	1
caesar	1
caesar	2
caesar	2
did	1
enact	1
hath	1
I	1
I	1
i'	1
it	2
julius	1
killed	1
killed	1
let	2
me	1
noble	2
so	2
the	1
the	2
told	2
you	2
was	1
was	2
with	2

RCV1: Our collection for this lecture

- As an example for applying scalable index construction algorithms, we will use the Reuters RCV1 collection.
  - This is one year of Reuters newswire (part of 1995 and 1996)

- The collection isn't really large enough, but it's publicly available and is a plausible example.

A Reuters RCV1 document

REUTERS

You are here: Home > News > Science > **Article**

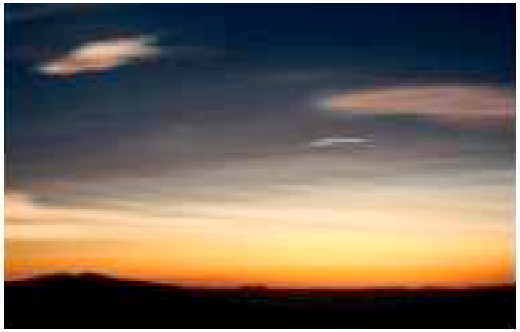
Go to a Section: U.S. International Business Markets Politics Entertainment Technology Sports Oddly Enoug

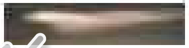
Extreme conditions create rare Antarctic clouds

Tue Aug 1, 2006 3:20am ET

Email This Article | Print This Article | Reprints

[-] Text [+]





SYDNEY (Reuters) - Rare, mother-of-pearl colored clouds caused by extreme weather conditions above Antarctica are a possible indication of global warming, Australian scientists said on Tuesday.

Known as nacreous clouds, the spectacular formations showing delicate wisps of colors were photographed in the sky over an Australian meteorological base at Mawson Station on July 25.

Reuters RCV1 statistics

symbol	statistic	value
N	documents	800,000
L	avg. # tokens per doc	200
M	terms (= word types)	400,000
	avg. # bytes per token (incl. spaces/punct.)	6
	avg. # bytes per token (without spaces/punct.)	4.5
	avg. # bytes per term	7.5
	non-positional postings	100,000,000

4.5 bytes per word token vs. 7.5 bytes per word type: why?

Sort-based index construction

- As we build the index, we parse docs one at a time.
  - The final postings for any term are incomplete until the end.
- At 8 bytes per *(termID, docID)*, demands a lot of space for large collections.
- T = 100,000,000 in the case of RCV1
  - So … we can do this in memory today, but typical collections are much larger. E.g., the *New York Times* provides an index of >150 years of newswire
- Thus: We need to store intermediate results on disk.

Scaling index construction

- In-memory index construction does not scale
  - Can’t stuff entire collection into memory, sort, then write back
- How can we construct an index for very large collections?
- Taking into account hardware constraints. . .
  - Memory, disk, speed, etc.

- Let’s review some hardware basics

Hardware basics

- Servers used in IR systems now typically have several GB of main memory, sometimes tens of GB.
- Available disk space is several (2–3) orders of magnitude larger.
- Fault tolerance is very expensive: It's much cheaper to use many regular machines rather than one fault tolerant machine.

Hardware basics

- Access to data in memory is ***much*** faster than access to data on disk.
- Disk seeks: No data is transferred from disk while the disk head is being positioned.
- Therefore: Transferring one large chunk of data from disk to memory is faster than transferring many small chunks.
- Disk I/O is block-based: Reading and writing of entire blocks (as opposed to smaller chunks).
- Block sizes: 8KB to 256 KB.

Hardware assumptions (circa 2007)

symbol	statistic	value
s	average seek time	5 ms = 5 x 10^{-3} s
b	transfer time per byte	0.02 μs = 2 x 10^{-8} s
	processor's clock rate	10^{9} s^{-1}
p	low-level operation (e.g., compare & swap a word)	0.01 μs = 10^{-8} s
	size of main memory	several GB
	size of disk space	1 TB or more

Sort using disk as "memory"?

- Can we use the same index construction algorithm for larger collections, but by using disk instead of memory?
- No: Sorting T = 100,000,000 records on disk is too slow – too many disk seeks.
- We need an *external* sorting algorithm.

Introduction to

Information Retrieval

CS276: Information Retrieval and Web Search

External memory indexing

BSBI: Blocked sort-based Indexing (Sorting with fewer disk seeks)

- 8-byte records *(termID, docID)*
- These are generated as we parse docs
- Must now sort 100M such 8-byte records by *termID*
- Define a <u>Block</u> ~ 10M such records
  - Can easily fit a couple into memory
  - Will have 10 such blocks to start with
- Basic idea of algorithm:
  - Accumulate postings for each block, sort, write to disk
  - Then merge the blocks into one long sorted order

```
BSBIndexConstruction()
n ← 0
while (all documents have not been processed)
do n ← n + 1
    block ← ParseNextBlock()
    BSBI-Invert(block)
    WriteBlockToDisk(block, f_n)
MergeBlocks(f_1, ..., f_n; f_merged)
```

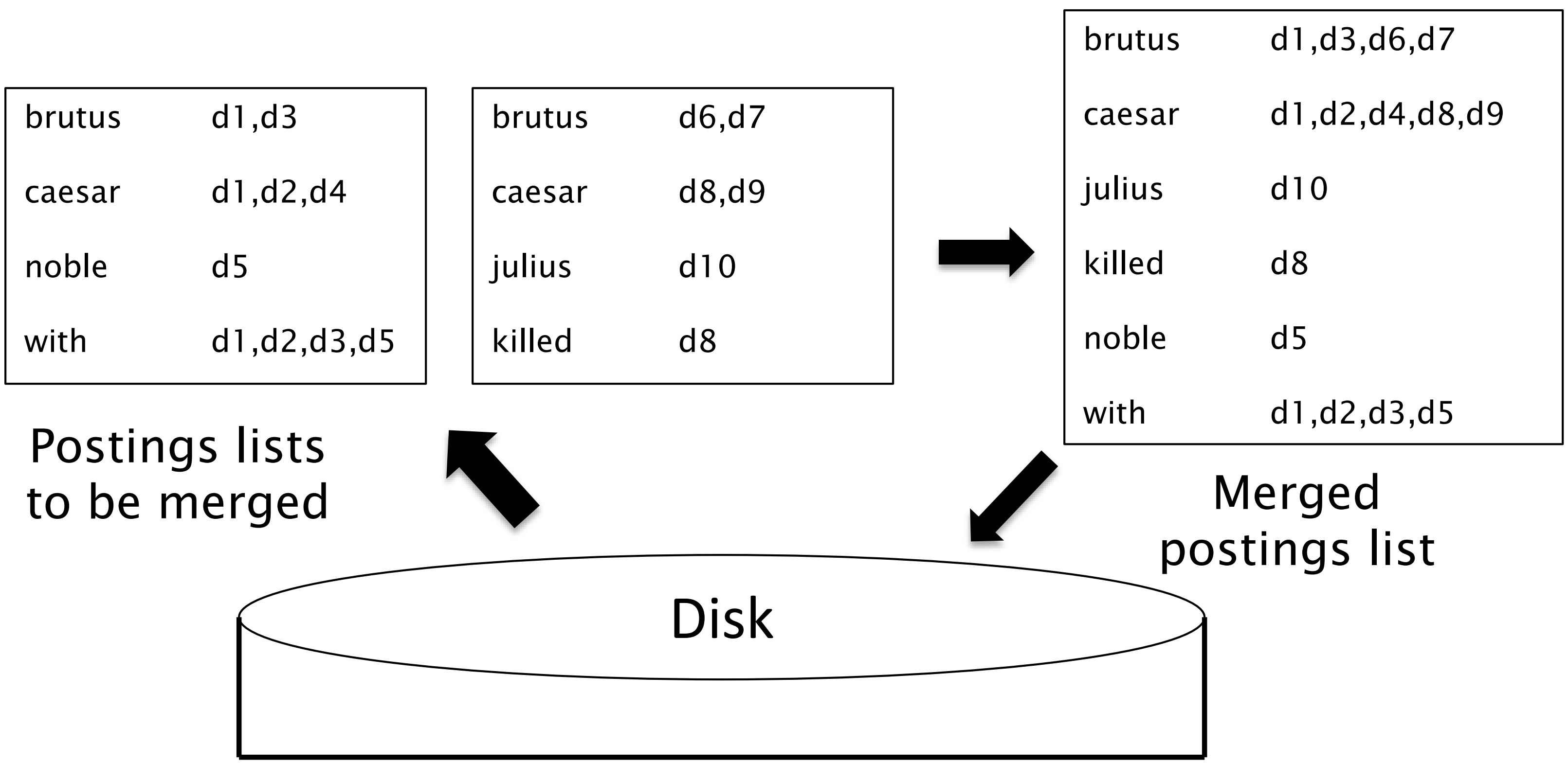
Sorting 10 blocks of 10M records

- First, read each block and sort within:
  - Quicksort takes O(*N* ln *N)* expected steps
  - In our case *N=10M*

- 10 times this estimate – gives us 10 sorted *runs* of 10M records each.
- Done straightforwardly, need 2 copies of data on disk
  - But can optimize this

How to merge the sorted runs?

- Can do binary merges, with a merge tree of $\log_2 10 = 4$ layers.
- During each layer, read into memory runs in blocks of 10M, merge, write back.



How to merge the sorted runs?

- But it is more efficient to do a multi-way merge, where you are reading from all blocks simultaneously
  - Open all block files simultaneously and maintain a read buffer for each one and a write buffer for the output file
  - In each iteration, pick the lowest termID that hasn't been processed using a priority queue
  - Merge all postings lists for that termID and write it out

- Providing you read decent-sized chunks of each block into memory and then write out a decent-sized output chunk, then you're not killed by disk seeks

Remaining problem with sort-based algorithm

- Our assumption was: we can keep the dictionary in memory.
- We need the dictionary (which grows dynamically) in order to implement a term to termID mapping.

SPIMI: Single-pass in-memory indexing

- Key idea 1: Generate separate dictionaries for each block – no need to maintain term-termID mapping across blocks.
- Key idea 2: Don't sort. Accumulate postings in postings lists as they occur.
- With these two ideas we can generate a complete inverted index for each block.
- These separate indexes can then be merged into one big index.

SPIMI-Invert

```
SPIMI-Invert(token_stream)
  output_file = NewFile()
  dictionary = NewHash()
  while (free memory available)
  do token ← next(token_stream)
     if term(token) ∉ dictionary
       then postings_list = AddToDictionary(dictionary, term(token))
       else postings_list = GetPostingsList(dictionary, term(token))
     if full(postings_list)
       then postings_list = DoublePostingsList(dictionary, term(token))
     AddToPostingsList(postings_list, docID(token))
  sorted_terms ← SortTerms(dictionary)
  WriteBlockToDisk(sorted_terms, dictionary, output_file)
  return output_file
```

- Merging of blocks is analogous to BSBI.

SPIMI in action

Input token	Dictionary	Sorted dictionary
Caesar d1	brutus d1 d3	brutus d1 d3
with d1	with d1 d2 d3 d5	caesar d1 d2 d4
Brutus d1	noble d5	noble d5
Caesar d2	caesar d1 d2 d4	with d1 d2 d3 d5
with d2		
Brutus d3		
with d3		
Caesar d4		
noble d5		
with d5		

SPIMI: Compression

- Compression makes SPIMI even more efficient.
  - Compression of terms
  - Compression of postings
- More on this later …

Original publication on SPIMI: Heinz and Zobel (2003)

Introduction to

Information Retrieval

CS276: Information Retrieval and Web Search

Distributed indexing

Distributed indexing

- For web-scale indexing (don't try this at home!):
  must use a distributed computing cluster
- Individual machines are fault-prone
  - Can unpredictably slow down or fail
- How do we exploit such a pool of machines?

Web search engine data centers

- Web search data centers (Google, Bing, Baidu) mainly contain commodity machines.
- Data centers are distributed around the world.
- Estimate: Google ~1 million servers, 3 million processors/cores (Gartner 2007)

Massive data centers

- If in a non-fault-tolerant system with 1000 nodes, each node has 99.9% uptime, what is the uptime of the entire system?
- Answer: 37% - meaning, 63% of the time one or more servers is down.
- Exercise: Calculate the number of servers failing per minute for an installation of 1 million servers.

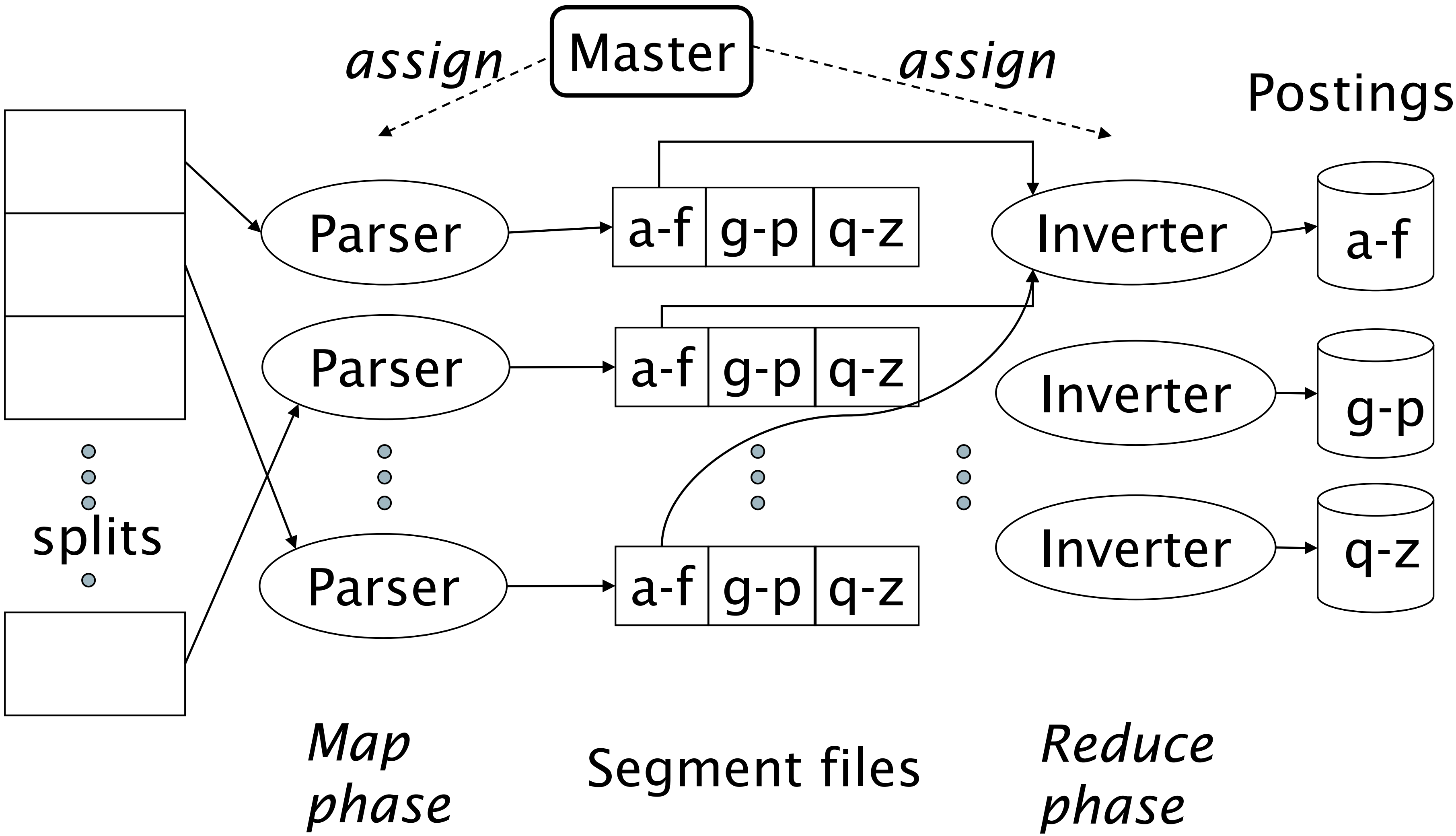
Distributed indexing

- Maintain a *master* machine directing the indexing job – considered "safe".
- Break up indexing into sets of (parallel) tasks.
- Master machine assigns each task to an idle machine from a pool.

Parallel tasks

- We will use two sets of parallel tasks
  - Parsers
  - Inverters
- Break the input document collection into *splits*
- Each split is a subset of documents (corresponding to blocks in BSBI/SPIMI)

Data flow


Master
assign
assign
Postings
Parser
Parser
Parser
a-f g-p q-z
a-f g-p q-z
a-f g-p q-z
Inverter
Inverter
Inverter
a-f
g-p
q-z
splits
Map phase
Segment files
Reduce phase

Parsers

- Master assigns a split to an idle parser machine
- Parser reads a document at a time and emits (term, doc) pairs
- Parser writes pairs into *j* partitions
- Example: Each partition is for a range of terms' first letters
  - (e.g., ***a-f, g-p, q-z***) – here *j* = 3.
- Now to complete the index inversion

Inverters

- An inverter collects all (term,doc) pairs (= postings) for <u>one</u> term-partition.
- Sorts and writes to postings lists

Example for index construction

Caesar

conquered

Map:

d1 : C came, C c’ ed.

d2 : C died.

→

<C,d1>, <came,d1>, <C,d1>, <c’ ed, d1>, <C, d2>, <died,d2>

Reduce:

(<C,(d1,d1,d2)>, <died,(d2)>, <came,(d1)>, <c’ ed,(d1)>)

→

(<C,(d1:2,d2:1)><died,(d2:1)>, <came,(d1:1)>,<c’ ed,(d1:1)>)

Index construction

- Index construction was just one phase.
- Another phase: transforming a term-partitioned index into a document-partitioned index.
  - *Term-partitioned:* one machine handles a subrange of terms
  - *Document-partitioned:* one machine handles a subrange of documents
- As we'll discuss in the web part of the course, most search engines use a document-partitioned index … better load balancing, etc.

MapReduce

- The index construction algorithm we just described is an instance of *MapReduce*.
- MapReduce (Dean and Ghemawat 2004) is a robust and conceptually simple framework for distributed computing …
- … without having to write code for the distribution part.
- They describe the Google indexing system (ca. 2002) as consisting of a number of phases, each implemented in MapReduce.

Schema for index construction in MapReduce

- **Schema of map and reduce functions**
- map: input → list(k, v)   reduce: (k,list(v)) → output
- **Instantiation of the schema for index construction**
- map: collection → list(termID, docID)
- reduce: (<termID1, list(docID)>, <termID2, list(docID)>, …) → (postings list1, postings list2, …)

Introduction to

Information Retrieval

CS276: Information Retrieval and Web Search

Dynamic indexing

Dynamic indexing

- Up to now, we have assumed that collections are static.
- They rarely are:
  - Documents come in over time and need to be inserted.
  - Documents are deleted and modified.
- This means that the dictionary and postings lists have to be modified:
  - Postings updates for terms already in dictionary
  - New terms added to dictionary

Simplest approach

- Maintain “big” main index
- New docs go into “small” auxiliary index
- Search across both, merge results
- Deletions
  - Invalidation bit-vector for deleted docs
  - Filter docs output on a search result by this invalidation bit-vector
- Periodically, re-index into one main index

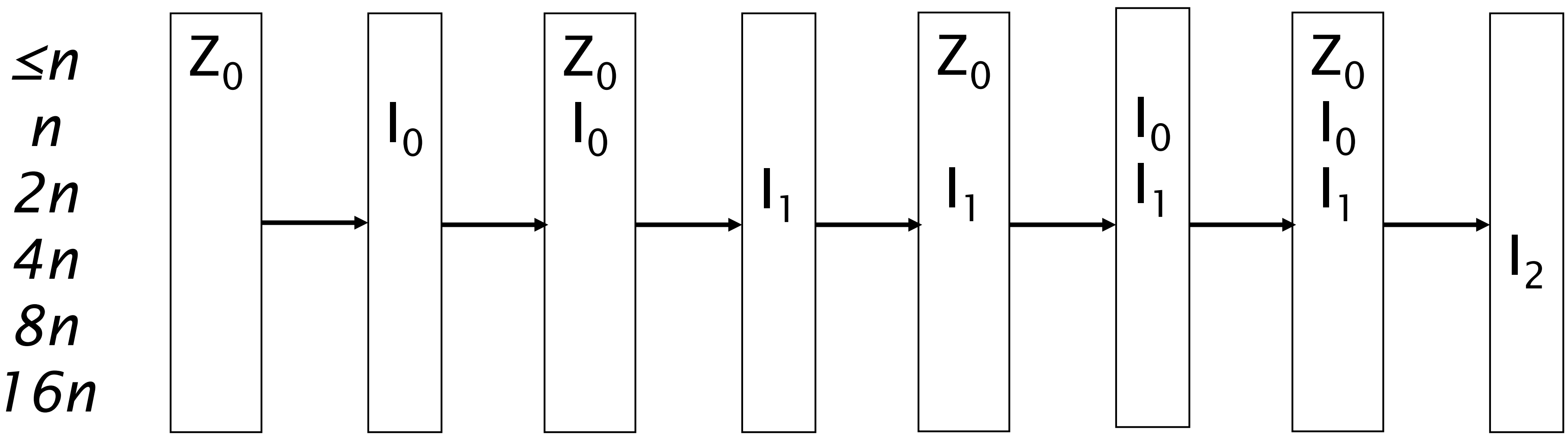
Issues with main and auxiliary indexes

- Problem of frequent merges – you touch stuff a lot
- Poor performance during merge
- Actually:
  - Merging of the auxiliary index into the main index is efficient if we keep a separate file for each postings list.
  - Merge is the same as a simple append.
  - But then we would need a lot of files – inefficient for OS.
- Assumption for the rest of the lecture: The index is one big file.
- In reality: Use a scheme somewhere in between (e.g., split very large postings lists, collect postings lists of length 1 in one file etc.)

Logarithmic merge

- Maintain a series of indexes, each twice as large as the previous one
  - At any time, some of these powers of 2 are instantiated
- Keep smallest (Z_0) in memory
- Larger ones (I_0, I_1, …) on disk
- If Z_0 gets too big (> *n*), write to disk as I_0
- or merge with I_0 (if I_0 already exists) as Z_1
- Either write merge Z_1 to disk as I_1 (if no I_1)
- Or merge with I_1 to form Z_2

Logarithmic merge in action



LMergeAddToken($indexes, Z_0, token$)
$Z_0 \leftarrow$ Merge($Z_0, \{token\}$)
if $|Z_0| = n$
  then for $i \leftarrow 0$ **to** ∞
    do if $I_i \in indexes$
      then $Z_{i+1} \leftarrow$ Merge(I_i, Z_i)
        (Z_{i+1} *is a temporary index on disk.*)
        $indexes \leftarrow indexes - \{I_i\}$
      else $I_i \leftarrow Z_i$ (Z_i *becomes the permanent index* I_i.)
        $indexes \leftarrow indexes \cup \{I_i\}$
        Break
    $Z_0 \leftarrow \emptyset$

LogarithmicMerge()
$Z_0 \leftarrow \emptyset$ (Z_0 *is the in-memory index.*)
$indexes \leftarrow \emptyset$
while true
do LMergeAddToken($indexes, Z_0,$ getNextToken())

Logarithmic merge

- Auxiliary and main index:
  - T/n merges where T is # of postings and n is size of auxiliary
  - Index construction time is $O(T^2/n)$ as in the worst case a posting is touched T/n times
- Logarithmic merge: Each posting is merged at most O(log (T/n)) times, so complexity is O(T log (T/n))
- So logarithmic merge is much more efficient for index construction
- But query processing now requires the merging of O(log (T/n)) indexes
  - Whereas it is O(1) if you just have a main and auxiliary index

Further issues with multiple indexes

- Collection-wide statistics are hard to maintain
- E.g., when we speak of spell-correction: which of several corrected alternatives do we present to the user?
  - We may want to pick the one with the most hits
  - How do we maintain the top ones with multiple indexes and invalidation bit vectors?
  - One possibility: ignore everything but the main index for such ordering
- Will see more such statistics used in results ranking

Dynamic indexing at search engines

- All the large search engines now do dynamic indexing
- Their indices have frequent incremental changes
  - News items, blogs, new topical web pages
- But (sometimes/typically) they also periodically reconstruct the index from scratch
  - Query processing is then switched to the new index, and the old index is deleted

Earlybird: Real-time search at Twitter

- Requirements for real-time search
  - Low latency, high throughput query evaluation
  - High ingestion rate and immediate data availability
  - Concurrent reads and writes of the index
  - Dominance of temporal signal

Earlybird: Index organization

- Earlybird consists of multiple index segments
  - Each segment is relatively small, holding up to 2^{23} tweets
  - Each posting in a segment is a 32 bit word: 24 bits for the tweet id and 8 bits for the position in the tweet
- Only one segment can be written to at any given time
  - Small enough to be in memory
  - New postings are simply appended to the postings list
  - But the postings list is traversed backwards to prioritize newer tweets
- The remaining segments are optimized for read-only
  - Postings sorted in reverse chronological order (newest first)

Other sorts of indexes

- Positional indexes
  - Same sort of sorting problem … just larger ← Why?
- Building character n-gram indexes:
  - As text is parsed, enumerate *n*-grams.
  - For each *n*-gram, need pointers to all dictionary terms containing it – the "postings"

Resources for today's lecture

- Chapter 4 of IIR
- MG Chapter 5
- Original publication on MapReduce: Dean and Ghemawat (2004)
- Original publication on SPIMI: Heinz and Zobel (2003)
- Earlybird: Busch et al, ICDE 2012