Indexing

(COSC 488)

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Efficiency

- Difficult to analyze sequential IR algorithms: data and query dependency (query selectivity).
- $O(q(cf_{max}))$ -- high estimate
- No standard analytical model to estimate query performance, hence empirical efforts.

Efficiency Techniques

- Indexing
- ➢ Compression
- Index Pruning (Top Doc)
- Efficient Query Processing
- Duplicate Document Detection

Indexing

- Scanning Text
  - Small document collection
- Inverted index [1960's]
  - Reducing I/O, thus, speeding query processing; storage overhead; time overhead to build index
- Signature files
  - Smaller and faster; less functionality
- Relational
  - Higher overhead; supports integration of structured data and text

Inverted Index

- Regardless of the retrieval strategy we need a data structure to efficiently store:
  – For each term in the document collection
    - The list of documents that contain the term
    - Number of documents having a term (df, idf)
    - For each occurrence of a term in a document
      – The frequency the term appears in the document (tf)
      – The position in the document for which the term appears (only needed if proximity search is supported).
        » Position may be expressed as section, paragraph, sentence, location within sentence.

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Inverted Index

- Associates a *posting list* with each term

a:	(D1,7) (D2,5) (D3,19) (D4,11)…
abacus:	(D7,1)
abatement:	(D15,1) (D23,2)
…	
zoology:	(D8,1) (D32,2)

- Inverted because it lists for a term, all documents that contain the term.

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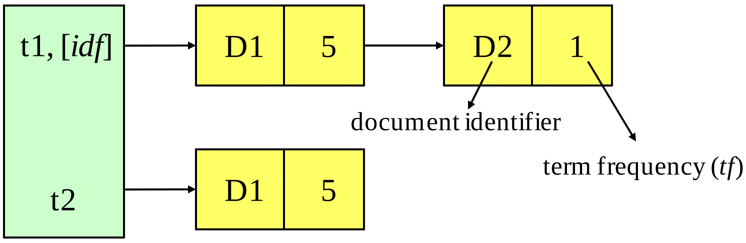
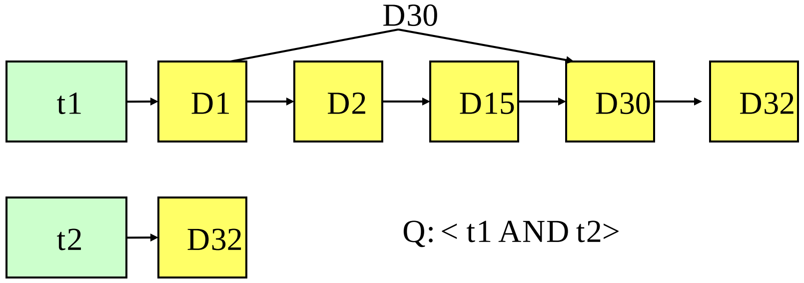
Inverted Index: Structure

- Document map (Document information: url, length, page rank,….)
- Term list/index (Lexicon/Vocabulary/Dictionary)- stores distinct terms and document frequency information (*df*, *idf*)
- Posting list- stores documents for a given term)



Skip Pointers

- To optimize
  - Join operation of O(m+n) for posting lists of size *m* and *n*
  - Search for a given document *d* in the PL *(will be discussed later)*



Query Processing using Inverted Index

- Term-at-a-time:
  - For each term, at a time, the inverted index is accessed to calculate scores
- Document-at-a-time:
  - All inverted lists (posting lists relevant to the query) are accessed concurrently. In case of intersections between PLs, forward-skip optimizations can be utilized.

Positional (Proximity) Index

- Posting List nodes may maintain position of terms in each document for Proximity search.

Apple, 3 ⟶ (D1,2, {1,5}) (D2,1, {10}) (D3,3, {1,7, 15}) …

- An alternative to phrasing
- Expands the PL storage requirements
- Using both phrase and proximity can be combined.

Term List
(Lexicon/Dictionary/Vocabulary)

- Usually we have enough memory to store the term list in memory.
- Various options
  - Sorted List: good for prefix lookup
    - Fixed length array -- wasteful
    - String of characters (primary array of integers pointing to string of terms)
    - Search tree (binary, b+trees, trie,….)
  - Hash table – with collision list; good for indexing (insert & lookup)
  - Hybrid Approach
- Can use *dictionary interleaving* if term index is too large (subset of terms in memory pointing to term index <*term*, *posting*> on disk)

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Posting List

- Mainly resides on disk
- Brought into memory for processing
- Contiguous posting entries for each term on disk
- In memory posting:
  - Array (variable length)
  - Linked List (single link)

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Memory Requirements
(single link list example)

- While in memory the posting list is not compressed.
- Typical entry

DocID (4 bytes)	tf (2 bytes)	nextPointer (4 bytes)

- For an 800,000,000 word collection, 400,000,000 posting list entries were needed (many terms did not result in a posting list entry because of stop words removal and duplicate occurrences of a term within a document).
- With 400,000,000 posting list entries, at 10 bytes per entry, we obtain a memory requirement of 4GB.

Index Construction Algorithms

All depends on the hardware availability

- Memory-based
  - Assumption: enough memory is available to construct and maintain the entire inverted index.
  - Good if enough memory and small collection
- Disk-based
  - No memory assumption; scaling to large collections
  - Various implementations exist

Memory-based Index Construction

- For each document *d* in the collection
  - For each term *t* in document *d*
    - Find term *t* in the lexicon
    - If term *t* exists, add a node to its posting list
    - Otherwise,
      - Add term *t* to the lexicon
      - Add a node to the posting list
- After all documents have been processed, write the inverted index to disk.

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Memory-based Inverted Index

- Phase I (parse and read)
  - For each document
    - Identify distinct terms in the document
    - Update, in memory the posting list for each term
- Phase II (write)
  - For each distinct term in the index
    - Write the inverted index to disk (feel free to compress the posting list while writing it)

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Memory Management

- We usually don't have more memory than the size of the document collection.
- Periodically must write inverted index to disk.
- Algorithm must be changed to periodically write to disk a subset of the inverted index *I* and then merge the subsets.

Disk based Index Construction (Sort/Merge-based)

- Read fixed chunk of data into memory
- Tokenize
- *If needed* create the *term* to *term id* mappings
- build <*term, doc*> pairs; or <*term, doc, tf*> triples; or <*term and its postings*> per implementation decisions
- Create intermediate sorted files and write on disk
- Perform m-way merging of intermediate files in memory and write onto the disk
- The outcome is one final inverted file on disk.

Disk based Index Construction (Sort/Merge-based)

- Phase I
  - Create temp files of triples (termID, docID, tf)
- Phase II
  - Sort the triples using external mergesort
- Phase III
  - Merge the sorted triples files (2-way; m-way)
- Phase IV
  - Build Inverted index from sorted triples

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Disk based Index Construction (Sort/Merge-based)

- Phase I (parse and build temp file)
  - For each document
    - Parse text into terms, assign a term to a termID (use an internal *index* for this)
    - For each distinct term in the document
      - Write an entry to a temporary file with only triples <*termID, docID, tf*>
- Phase II (make sorted *runs*, to prepare for merge)
  - Do Until End of Temporary File
    - Sort the triples in memory by term id and doc id.
    - Write them out in a sorted run on disk.

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Disk based Index Construction (Sort/Merge-based)

Run1:

tid	did	tf
1	d1	2
3	d1	1
5	d1	2
2	d1	4
4	d1	1
1	d2	1
2	d2	3
5	d2	3

Sorted:

tid	did	tf
1	d1	2
1	d2	1
2	d1	4
2	d2	3
3	d1	1
4	d1	1
5	d1	2
5	d2	3

Run2:

tid	did	tf
1	d3	2
2	d3	1
4	d3	3
2	d4	2
3	d4	1
5	d4	2
4	d4	1
1	d4	2

Sorted:

tid	did	tf
1	d3	2
1	d4	2
2	d3	1
2	d4	2
3	d4	1
4	d3	3
4	d4	1
5	d4	2

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Disk based Index Construction (Sort/Merge-based)

- Phase III (merge the runs)

  Repeat until there is only one *run*

  Merge pair-wise (2-way) or m-way sorted runs into a single run.
- Phase IV
  - For each distinct term in final sorted run
    - Start a new inverted file entry.
    - Read all triples for a given term (these will be in sorted order)
    - Build the posting list (feel free to use compression)
    - Write (append) this entry to the inverted index into a binary file.

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Disk based Index Construction (Sort/Merge-based)

Sorted Run1:

tid	did	tf
1	d1	2
1	d2	1
2	d1	4
2	d2	3
3	d1	1
4	d1	1
5	d1	2
5	d2	3

Sorted Run2:

tid	did	tf
1	d3	2
1	d4	2
2	d3	1
2	d4	2
3	d4	1
4	d3	3
4	d4	1
5	d4	2

Merged:

tid	did	tf
1	d1	2
1	d2	1
1	d3	2
1	d4	2
2	d1	4
2	d2	3
2	d3	1
2	d4	2
3	d1	1
3	d4	1
4	d1	1
4	d3	3
4	d4	1
5	d1	2
5	d2	3
5	d4	2

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Disk based Index Construction (Sort/Merge-based)

Final Sorted Run:

tid	did	tf
1	d1	2
1	d2	1
1	d3	2
1	d4	2
2	d1	4
2	d2	3
2	d3	1
2	d4	2
3	d1	1
3	d4	1
4	d1	1
4	d3	3
4	d4	1
5	d1	2
5	d2	3
5	d4	2

t1 → d1,2 | d2,1 | d3,2 | d4,2

t2 → d1,4 | d2,3 | d3,1 | d4,2

t3 → d1,1 | d4,1

t4 → d1,1 | d3,3 | d4,1

t5 → d1,2 | d2,3 | d4,2

Stream of Posting List Nodes

Inverted Index

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Alternatives

- Instead of triples:
  - <*term, doc*> pairs: after sorting then create the posting with *tf*
  - For each term create the posting directly in memory posting <*term and its postings*> triples -- Good for dynamic collection
- Instead of term id:
  - No need for *term id* at all. Lexicon keeps the *terms*
  - No need for extra structure for the term to term id mapping

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Disk-based Inverted Index Summary

- Pro
  - Not as fast as memory based, but it is scalable!
- Con
  - Requires significant additional space.

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Distributed Index

- Single index – traditional approach
  - Use single fast machine
  - Good for some applications (enterprise search)
- Distributed index
  - Use several/many fast machines (servers)
  - Good for indexing tens of billions of pages (large scale)

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Query Servers

- Each server has its own disk holding a portion of index
- Queries are distributed, via a centralized control, to servers that contain the related posting lists
- Common terms may map to many servers
- No single point of resource contention (*efficient*)
- If a server crashes, that portion of index is not available

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Distributed Index (Cont'd)

- Web search tools access data distributed on servers worldwide but indexed centrally.
- Most of these systems have a *partitioned index* with a *centralized control*.
- Partitioning of index across multiple machines, based on terms or documents
- Using content-index, sending requests to those server that have the data

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Partitioned Indexing

- Partitioning of index across multiple machines, based on either:
  - Terms (Global index organization)
    - Each node holds posting list for some terms
    - Using content-index, query terms sent to nodes having the terms
    - Higher concurrency level, but larger postings lists
  - Documents (Local index organization)
    - Each node holds a complete term index (shorter PLs)
    - Query terms sent to all nodes
    - Top k results from each node merged
    - Global statistics (e.g.. idf) must be calculated
  - Tiered Indexing may be used

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Index Tiering

- A popular *early termination* technique to improve the efficiency of query processing
- Dividing nodes into two tiers to allocate the index of most popular documents on tier 1 and the rest on tier 2.
- Search tier 1 first, if not enough results then search tier 2.
- Note: other popular early termination techniques (*top-doc* and *query pruning)* will be discussed!

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Distributed Index Construction

- Not possible on a single machine
- Various architecture for distributed indexing
- ***MapReduce*** architecture (a term-partitioned index)
  - Master node assigns tasks to worker nodes (*map workers* & *reduce workers*) to split up the computing jobs:
    - Map Phase: Parsing & building localized <term, doc> pairs
    - Reduce Phase: Combining/merging posting pairs for each term

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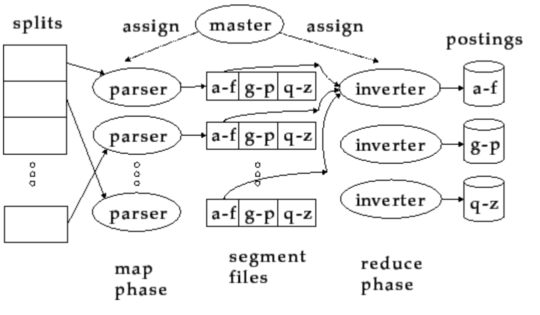
MapReduce (Cont'd)

- Map & reduce phases can be done in parallel on many machines
- A map machine can be a reducer machine in the process
- Data broken into pieces (*shards*)…generally 16M-64 M [128M] and send to map workers as they finish their job
- Map workers work on one shard at a time (generally), unless having more than one CPU, parse and generate <*term*,*doc*> pair (can be combined to <*term*,*doc*,*tf*>
- Sort based on term, and then secondary key (doc_id)
- The same keys (terms) are assigned to the same reduce worker
- Load should be balanced on the reducers

MapReduce (Cont'd)

Taken from: C. Manning, P. Raghavan & H. Schütze, Introduction to Information Retrieval, Cambridge University Press., 2008.



Index in Dynamic Environment

- Data collection is not static
  - Reconstruct the index periodically from scratch (many search engines use this)
  - Maintain an auxiliary index to store new document
  - Maintain multiple indexes - complicated in maintaining collection statistics

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Signature Files

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Signature Files

- A signature is an encoding of a document, using few bits.
- Each signature may represent multiple docs.
- Thus, Two-Phase query processing:
  - Phase 1: scan signatures and identify candidate signatures
  - Phase 2: scan original text of the candidate signatures

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Construction of Signatures

- Often using one or more hashing functions for each term to set a bit in a signature:
  - h(information): 0101;
  - h(retrieval): 1010;
  - h(security): 0011
- OR the term signatures of a document to build document signature
  - D1: Information retrieval: 1111
  - D2: security information: 0111

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Processing of Signatures

- Boolean AND between query and document

  Q> information: 0101
  - D1: Information retrieval: 1111
  - D2: security information: 0111

  ⇒match: D1 and D2

  Q> security: 0011
  - D1: Information retrieval: 1111
  - D2: security information: 0111

  => match: D1 and D2 - ***false positive (false drop)***

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Processing of Signatures

- Boolean AND queries: all query terms must return true
- Boolean OR queries: some query terms must return true

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Signature Files Summary

- Pros:
  - Useful if can fit into memory
  - Easy to add or remove documents (signatures) as compared to inverted index.
  - The order of signature in the signature file does not matter.
- Cons:
  - Two phased processing for false matches
  - Does not rank the retrieved documents

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Relational Approach will be discussed in a separate set of slides!

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References

- D. Grossman & O. Frieder, Information Retrieval Algorithms and Heuristics, 1998, 2nd Edition, Springer, 2004.
- C. Manning, P. Raghavan & H. Schütze, Introduction to Information Retrieval. Cambridge University Press., 2008.
- S. Buttcher, C. Clarke, G. Cormack, Information Retrieval: Implementing and Evaluating search Engines, Addison Wesley, 2010