Vector Space Model Implementation

Presenter

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Slides are obtained from ChengXiang Zhai and Sean Massung book

Outline

1. Text Retrieval Problem
2. Vector Space Model
3. Vector Space Model Implementation
   - Term At A Time (TAAT) Query Processing
   - Document At A Time (DAAT) Query Processing

1. Text Retrieval Problem

Text Retrieval Problem

- **Query:** $q = q_1,\ldots,q_m$, where $q_i \in V$
- **Document:** $d = d_1,\ldots,d_n$, where $d_i \in V$
- **Ranking function:** $f(q, d) \in \Re$
- A good ranking function should rank relevant documents on top of non-relevant ones
- **Key challenge**: how to measure the likelihood that document d is relevant to query q
- **Retrieval model** = formalization of relevance (give a computational definition of relevance)

Common Form of a Retrieval Function

$f(q =$ "presidential campaign news", $\boxed{d})$

"Bag of Words"

$g($"presidential", $\boxed{d})$ $g($"campaign", $\boxed{d})$ $g($"news", $\boxed{d})$

How many times does "presidential" occur in d?
Term frequency (TF): $c($"presidential", $d)$

How long is d? **Document length:** $|d|$

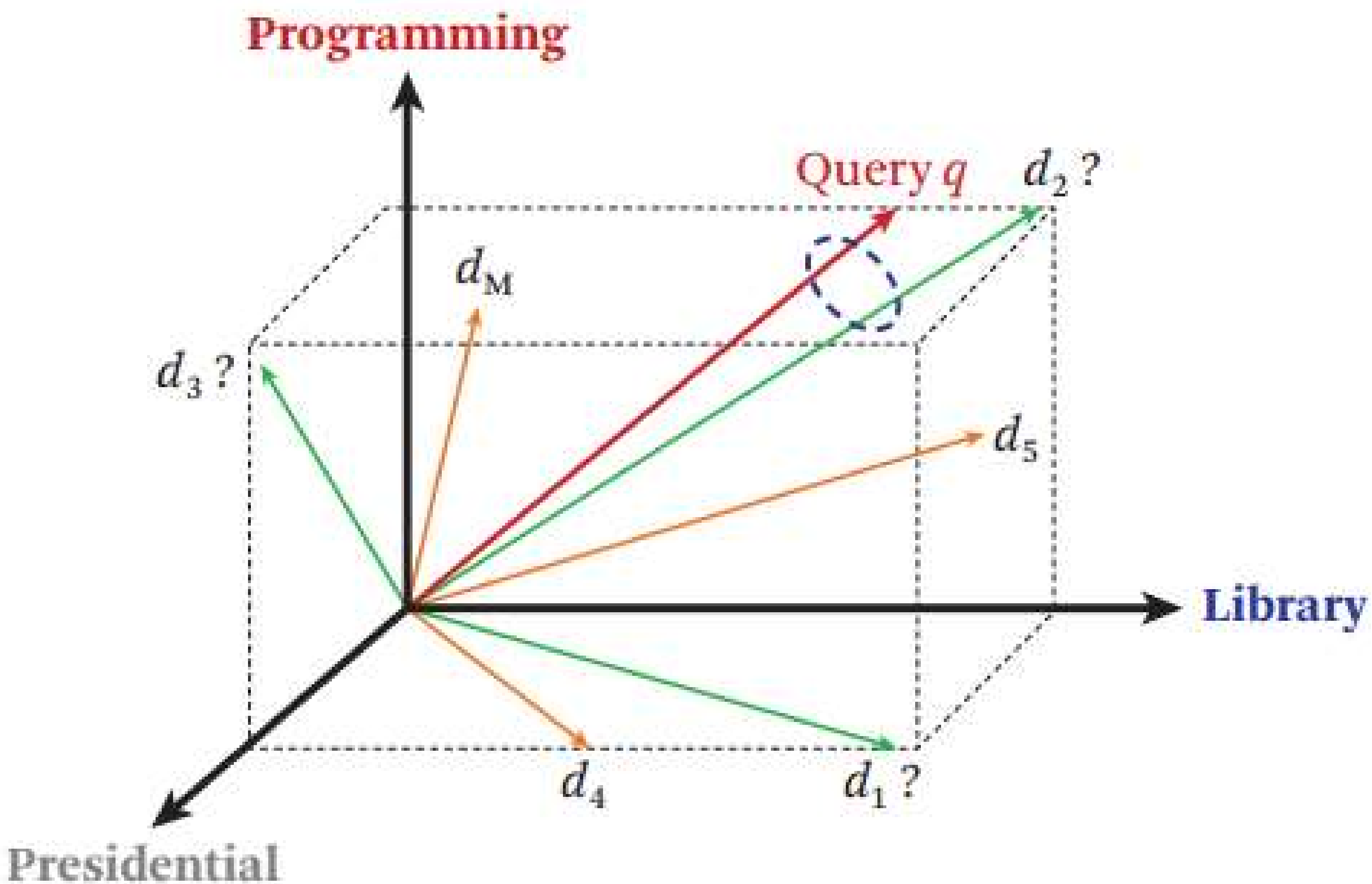
How often do we see "presidential" in the entire collection?
Document frequency: DF("presidential")
P("presidential"|collection)

2. Vector Space Model

Vector Space Model (VSM)

- Represent a document/query by a ***term vector***
  - ***Term***: basic concept, e.g., ***word*** or ***phrase***
  - Each term defines one dimension
  - N terms define a high-dimensional space
  - Element of vector corresponds to term weight
  - E.g., $d = (x_1,\ldots,x_N)$, x_i is "importance" of term i
- Measure relevance by the distance between the query vector and document vector in the vector space

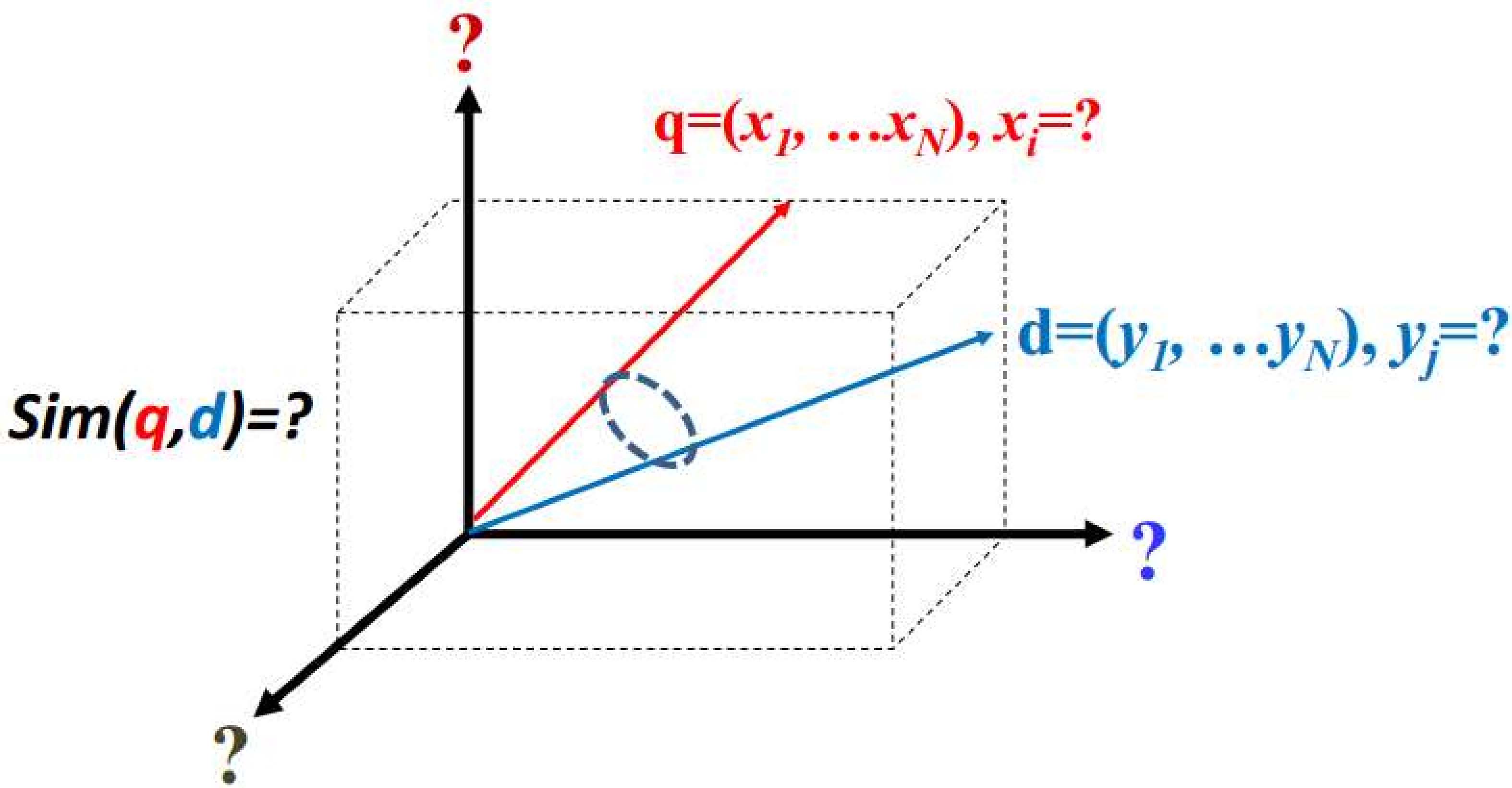
Vector Space Model (VSM) Illustration



VSM is a Framework

- How to define/select the terms
  - Terms are assumed to be linearly independent
- How to assign term weights
  - Weight in query indicates importance of term
  - Weight in doc indicates how well the term characterizes the doc
- How to define the similarity/distance measure

What VSM Doesn't Say



Term weighting

- Major term weighting heuristics
  - TF weighting and transformation
  - IDF weighting
  - Document length normalization

Term frequency		Document frequency		Normalization	
n (natural)	$\mathrm{tf}_{t,d}$	n (no)	1	n (none)	1
l (logarithm)	$1+\log(\mathrm{tf}_{t,d})$	t (idf)	$\log\frac{N}{\mathrm{df}_t}$	c (cosine)	$\frac{1}{\sqrt{w_1^2+w_2^2+\ldots+w_M^2}}$
a (augmented)	$0.5+\frac{0.5\times\mathrm{tf}_{t,d}}{\max_t(\mathrm{tf}_{t,d})}$	p (prob idf)	$\max\{0,\log\frac{N-\mathrm{df}_t}{\mathrm{df}_t}\}$	u (pivoted unique)	$1/u$ (Section 6.4.4)
b (boolean)	$\begin{cases}1 & \text{if } \mathrm{tf}_{t,d}>0\\ 0 & \text{otherwise}\end{cases}$			b (byte size)	$1/\mathit{CharLength}^{\alpha}$, $\alpha<1$
L (log ave)	$\frac{1+\log(\mathrm{tf}_{t,d})}{1+\log(\mathrm{ave}_{t\in d}(\mathrm{tf}_{t,d}))}$				

https://nlp.stanford.edu/IR-book/html/htmledition/document-and-query-weighting-schemes-1.html

State of the Art VSM Ranking Functions

Pivoted length normalization VSM

$$f(q,d) = \sum_{w \in q \cap d} c(w,q) \frac{\ln(1+\ln(1+c(w,d)))}{1-b+b\frac{|d|}{avdl}} \log \frac{M+1}{\mathrm{df}(w)} \quad b \in [0,1]$$

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$$f(q,d) = \sum_{w \in q \cap d} c(w,q) \frac{(k+1)c(w,d)}{c(w,d)+k(1-b+b\frac{|d|}{avdl})} \log \frac{M+1}{\mathrm{df}(w)} \quad b \in [0,1],\ k \in [0,+\infty)$$

3. Vector Space Model Implementation

Text Retrieval System Implementation

- Tokenizer
  - This determines how we represent a document
- Indexer
  - This convert documents to data structures that enable fast search
  - Compression when appropriate
- Scorer
  - This use inverted index for fast search

Inverted Index

- Fast access to all docs containing a given term (along with freq and pos information)
- For each term, we get a list of tuples (docID, freq, pos).
- Given a query, we can fetch the lists for all query terms and work on the involved documents.
  – Boolean query: set operation
  – Natural language query: term weight summing
- More efficient than scanning docs

Inverted Index Example

Doc 1

This is a sample document
with one sample sentence

Doc 2

This is another sample document

Dictionary

Term	# docs	Total freq
This	2	2
is	2	2
sample	2	3
another	1	1
…	…	…

Postings

Doc id	Freq
1	1
2	1
1	1
2	1
1	2
2	1
2	1
…	…

term|#docs|totalfreq|docID1:freq1;docID2:freq2;…

Positional Inverted Index Example

Doc 1

web retrieval
web search
information

Doc 2

search engine
web ranking

Doc 3

web search
course
information
search

Dictionary

Term	# docs	Total freq
course	1	1
engine	2	1
information	2	2
ranking	1	1
retrieval	1	1
search	3	4
web	3	4
…	…	…

Postings

Doc id	Freq	Pos
3	1	2
2	1	1
1	1	4
3	1	3
2	1	3
2	1	1
1	1	3
2	1	0
3	2	1, 4
1	2	0, 2
2	1	2
3	1	1
…	…	…

term|#docs|totalfreq|docID1:freq1,pos1,pos2;docID2:freq2,pos3,pos4,pos5;…

How to Score Documents Quickly with Inverted Index

General Form of Scoring Function

Final score **adjustment**

$$f(q,d) = f_a(\boldsymbol{h}(\boldsymbol{g}(\boldsymbol{t_1},\boldsymbol{d},\boldsymbol{q}),\ldots,\boldsymbol{g}(\boldsymbol{t_k},\boldsymbol{d},\boldsymbol{q})),f_d(d),f_q(q))$$

Weight **aggregation**

Weight a **matched** query term in d

TAAT vs DAAT Query Processing

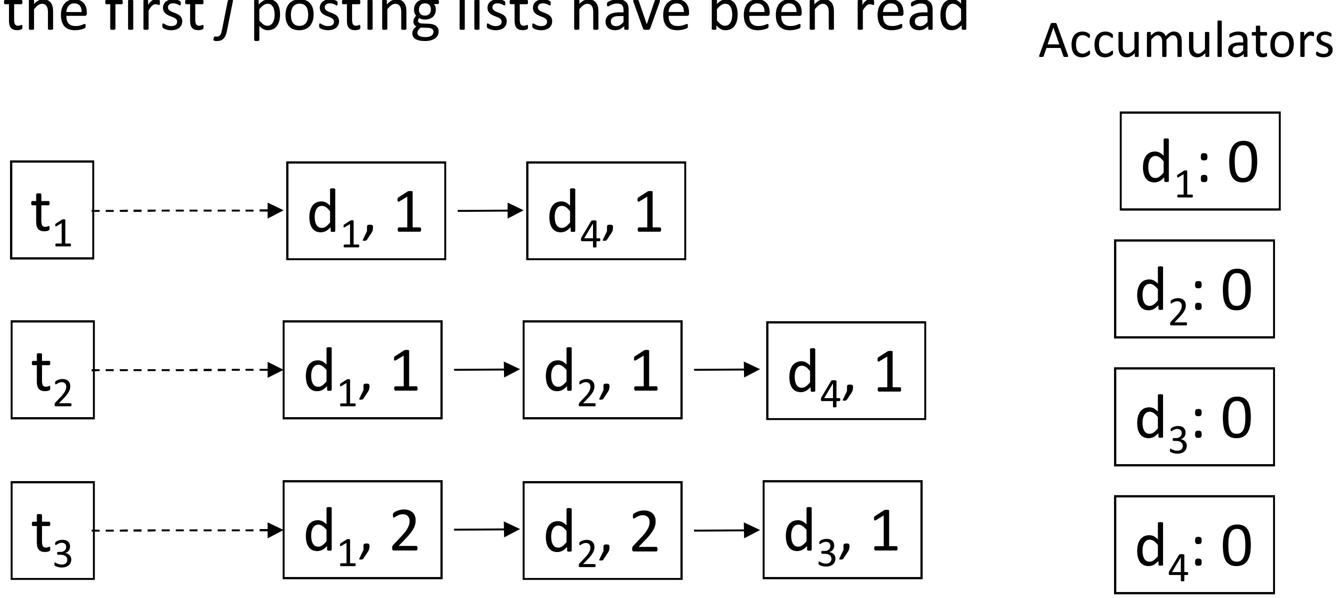
- **TAAT = "Term At A Time"**
  - Scores for all docs computed concurrently, one query term at a time
- **DAAT = "Document At A Time"**
  - Total score for each doc (include all query terms) computed, before proceeding to the next
- Each has implications for how the retrieval index is structured and stored

Term-at-a-time Ranking

- Read posting lists for query terms ($t_1, \ldots, t_{|q|}$) successively
- Maintains an accumulator for each result document with value

$$acc(d) = \sum_{i \leq j} score(t_i, d)$$

after the first *j* posting lists have been read



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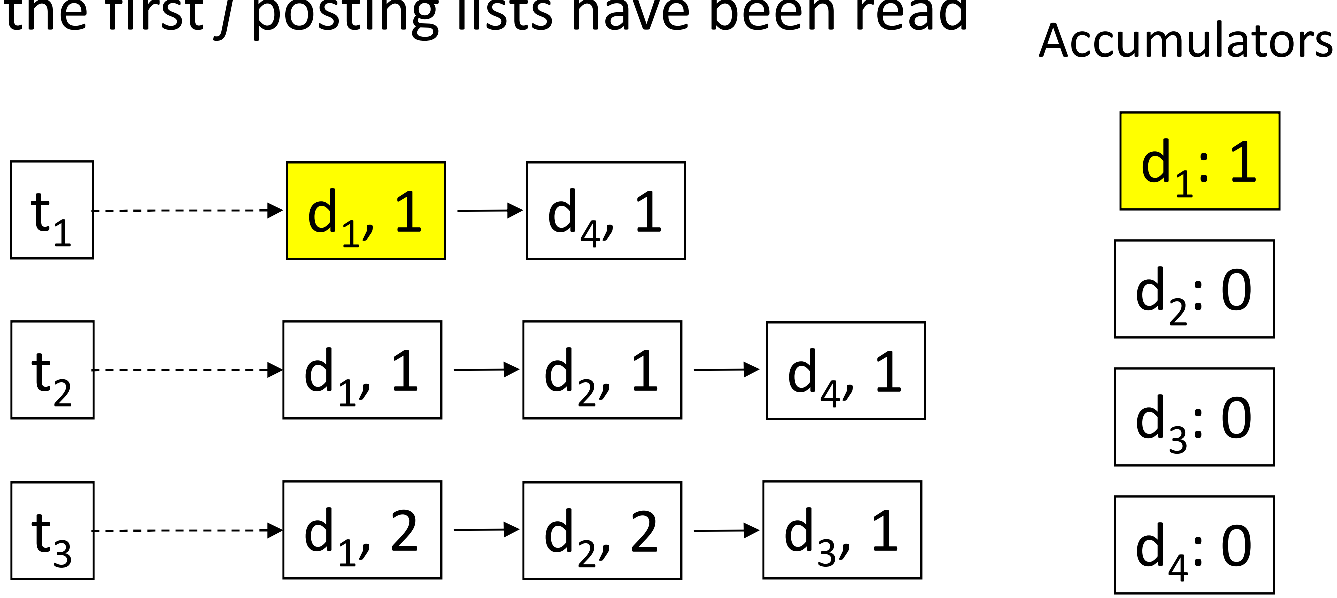

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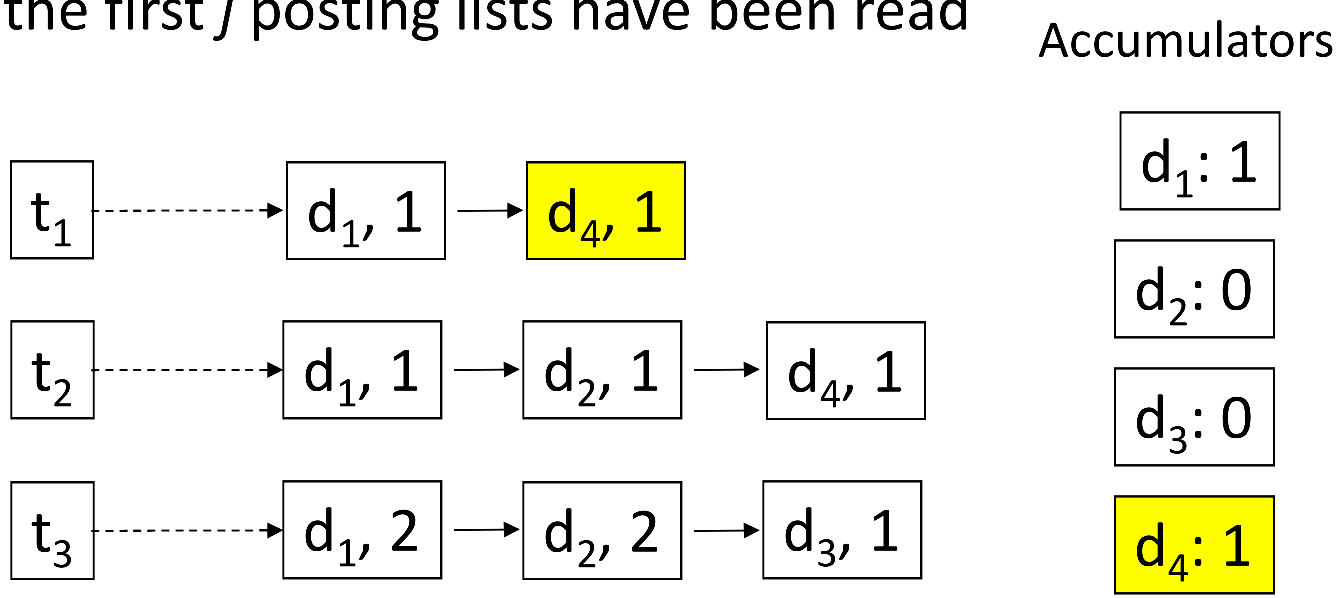

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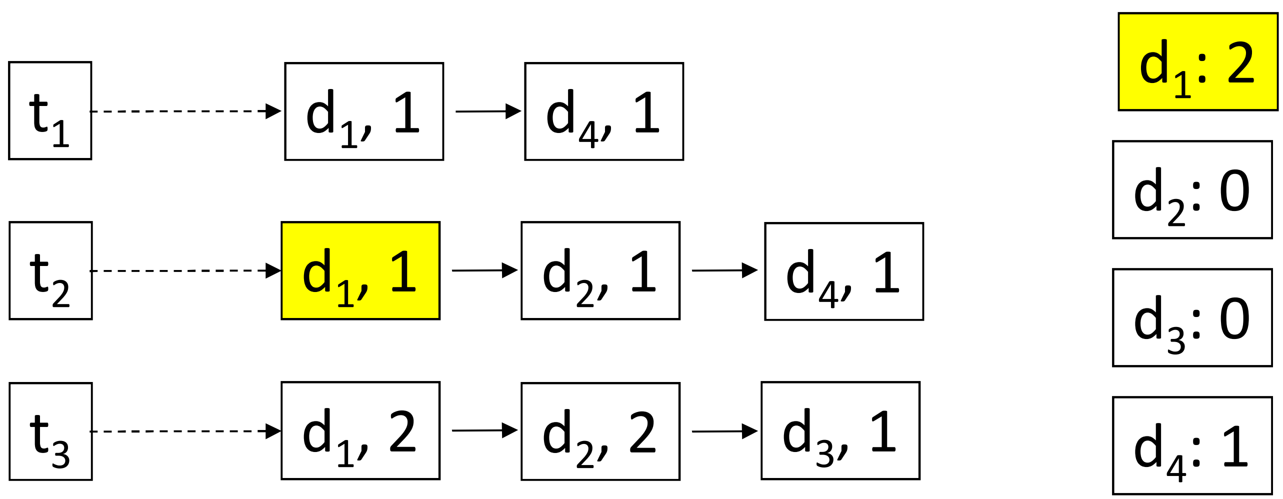
Accumulators



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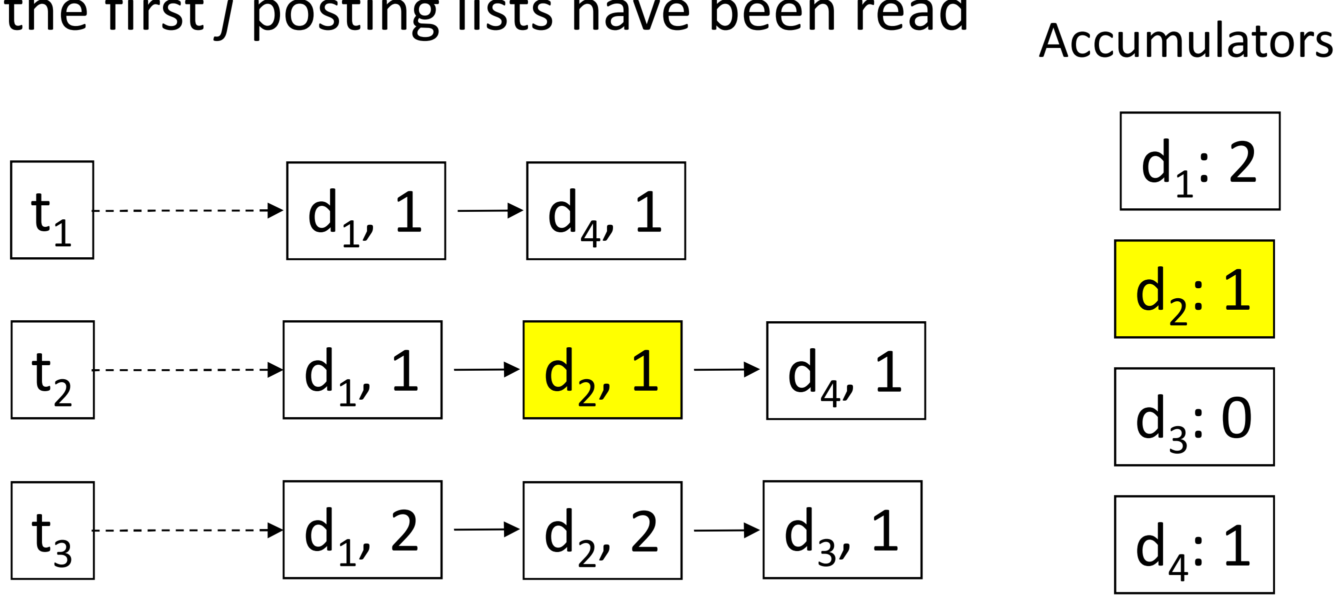

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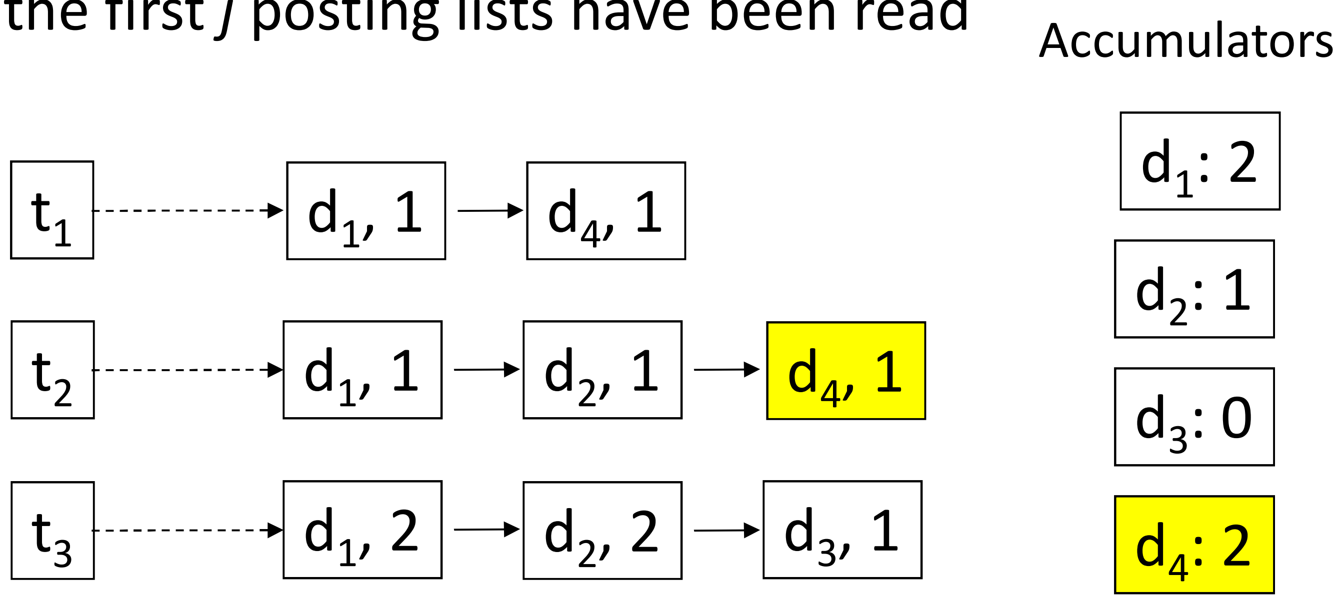

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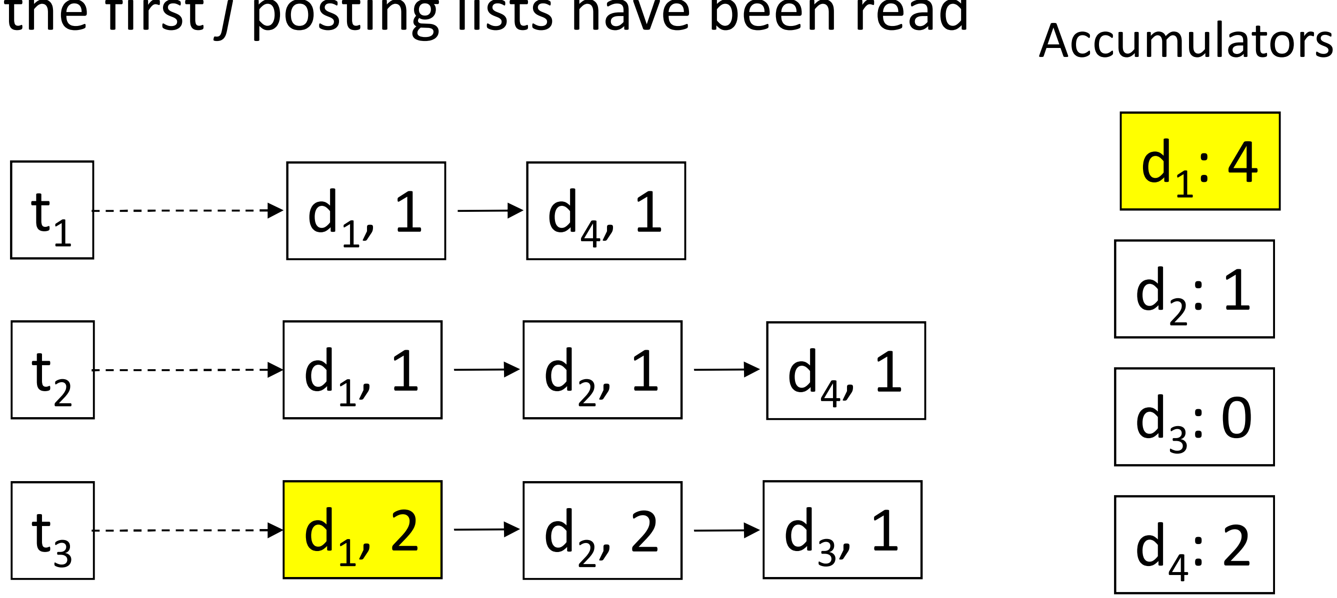

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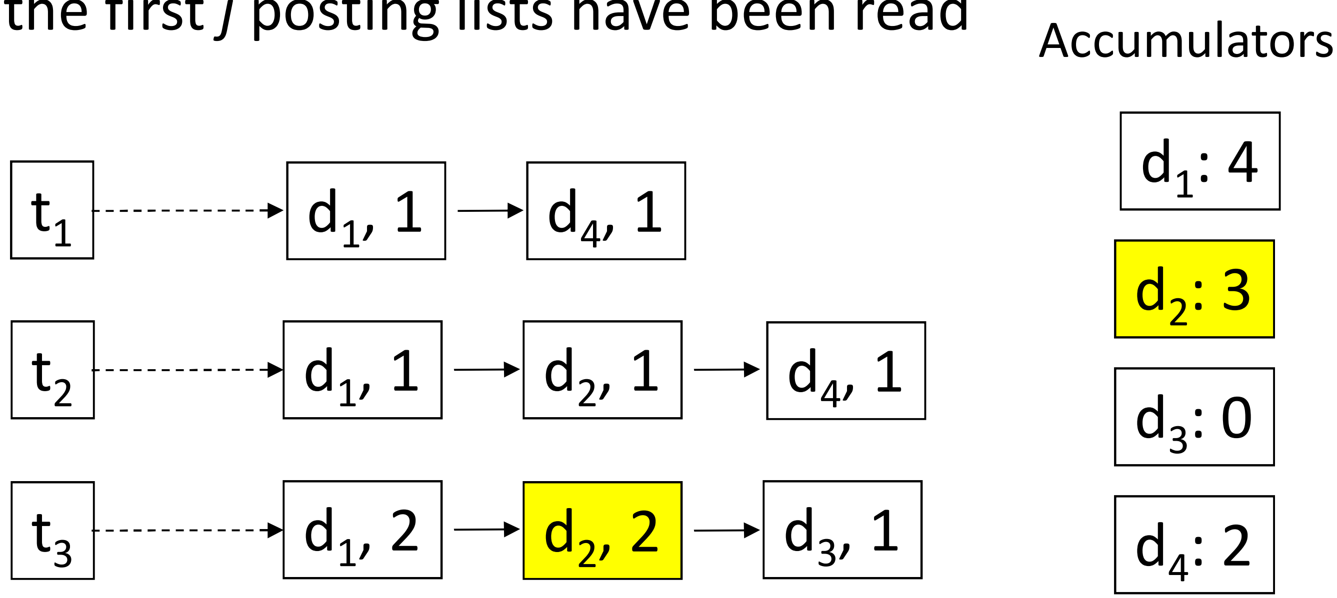

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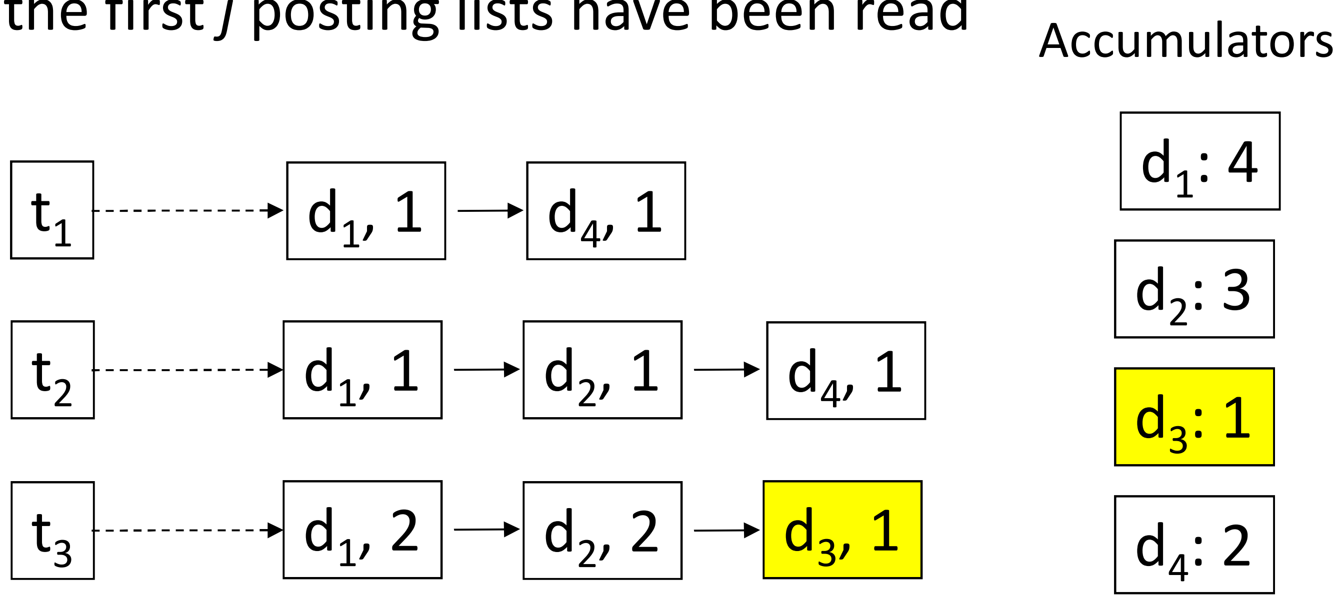

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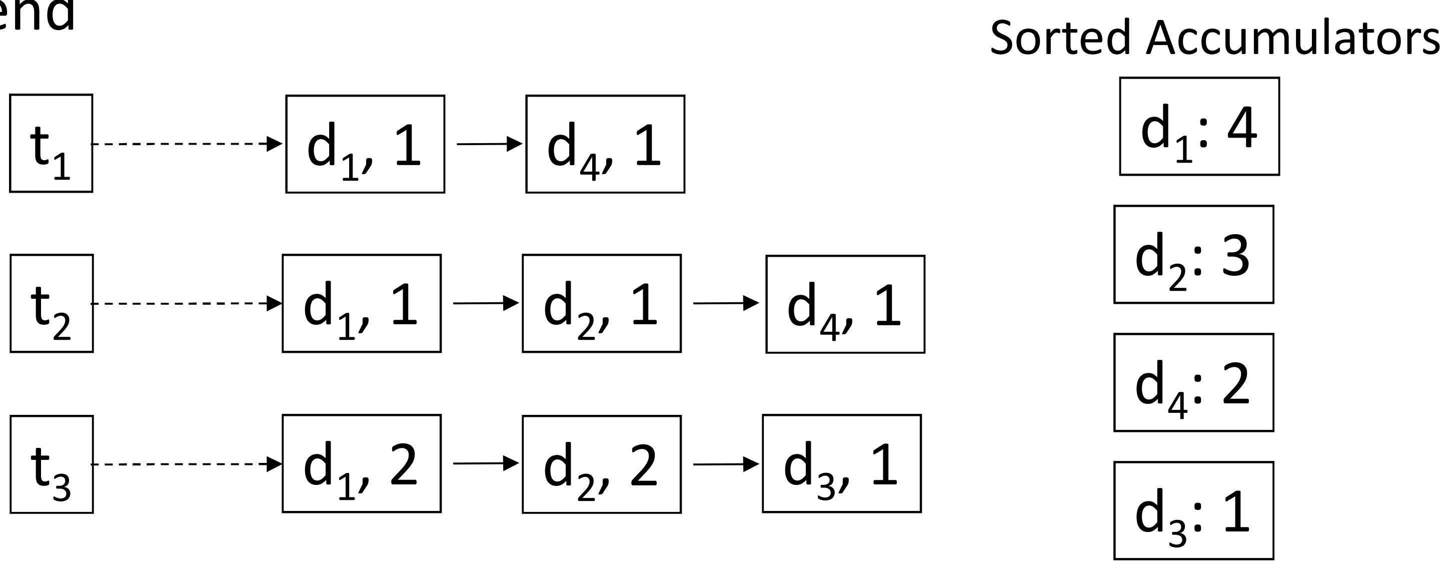
after the first *j* posting lists have been read

- Top-*k* results can be determined by sorting accumulators at the end



Term-at-a-time Ranking

```
scores = {}        // score accumulator maps doc IDs to scores
for w ∈ q do
    for d, count ∈ Idx.fetch_docs(w) do
        scores[d] = scores[d] + score_term(count)
    end for
end for
return top k documents from scores
```

Disadvantage of term-at-a-time ranking

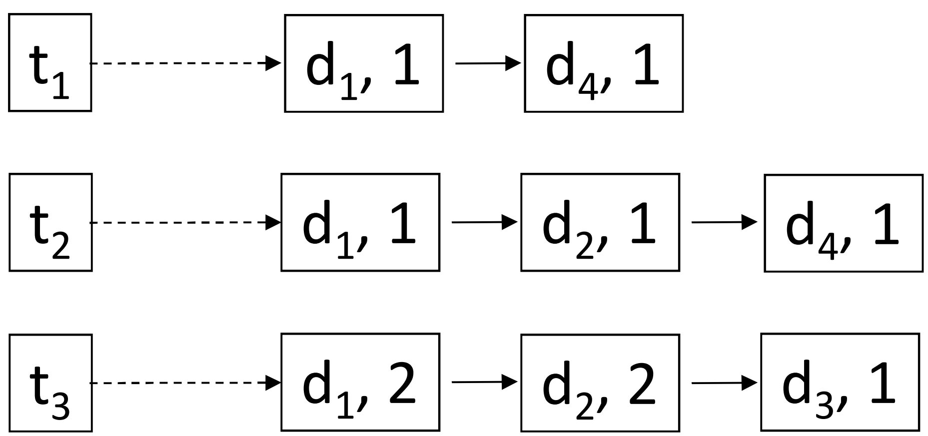
- The size of the score accumulators *scores* will be the size of the number of documents matching at least one term.
- This set is still large.

Document-at-a-time Ranking

- Since most searches are top-*k* searches, we can only keep the top-*k* documents at any one time.
- We can hold the *k* best completely scored documents with a priority queue.

Document-at-a-time Ranking

- Read posting lists for query terms (t_1, …, $t_{|q|}$) concurrently
- Computes score when same document is seen in one or more posting lists
- Always advances posting list with lowest current document id
- Top-k results can be determined by keeping results in priority queue



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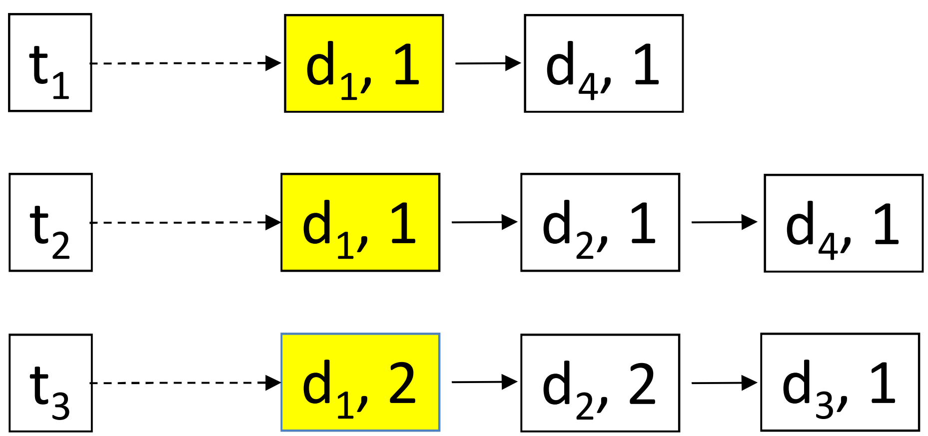

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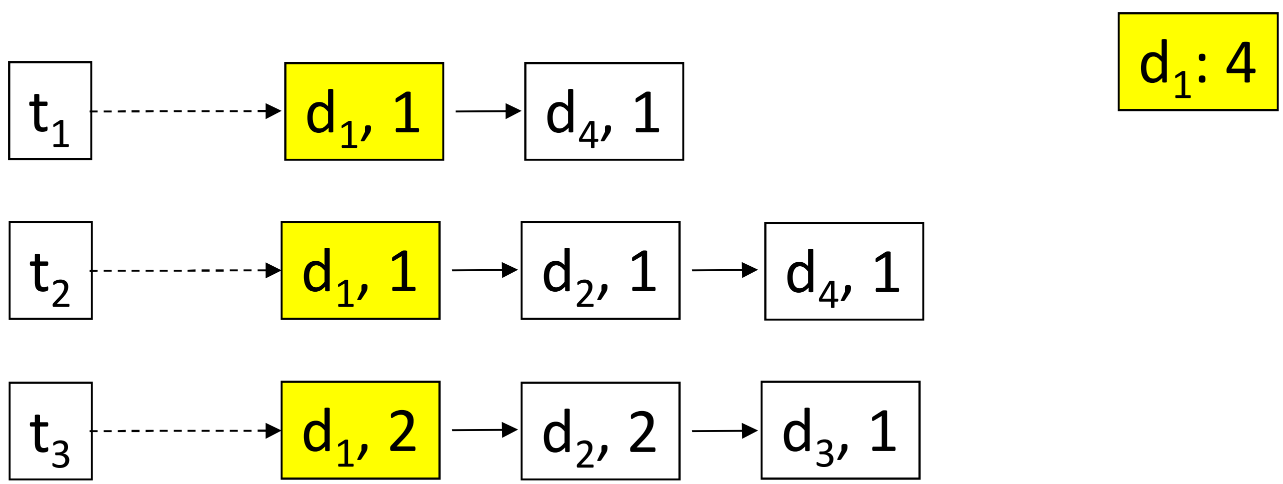

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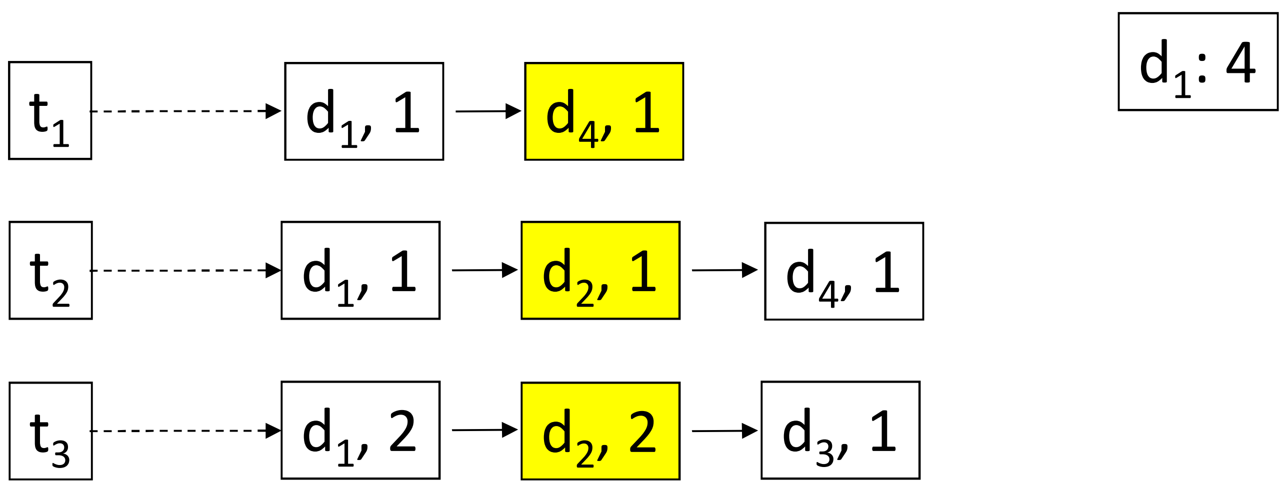

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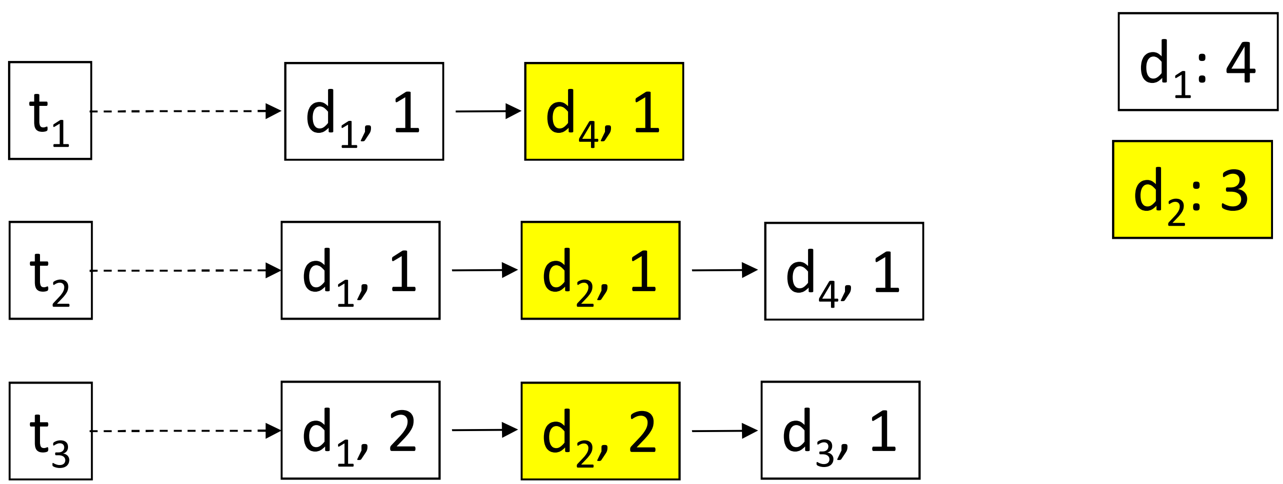

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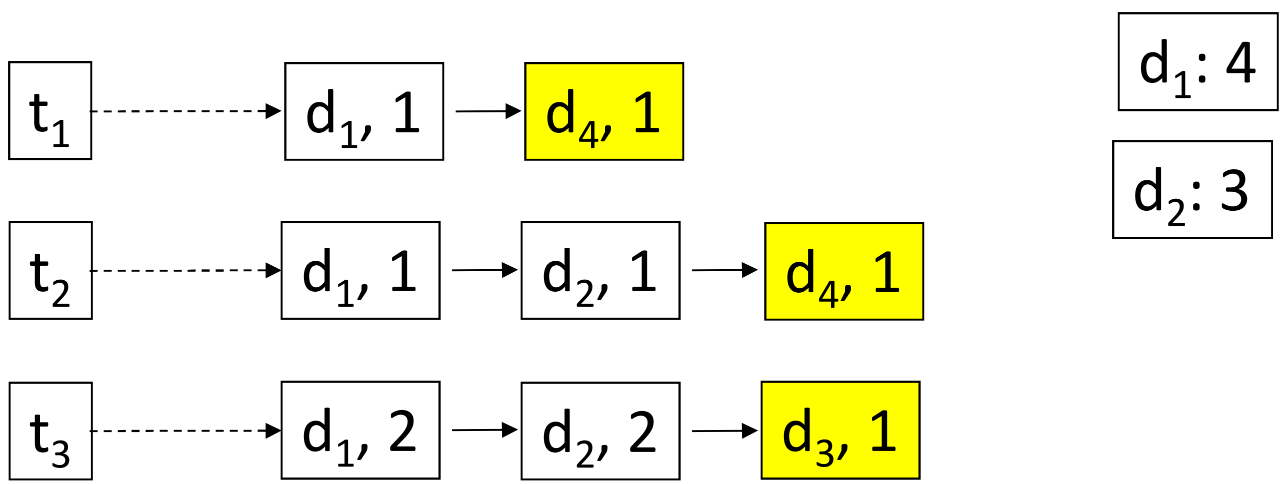

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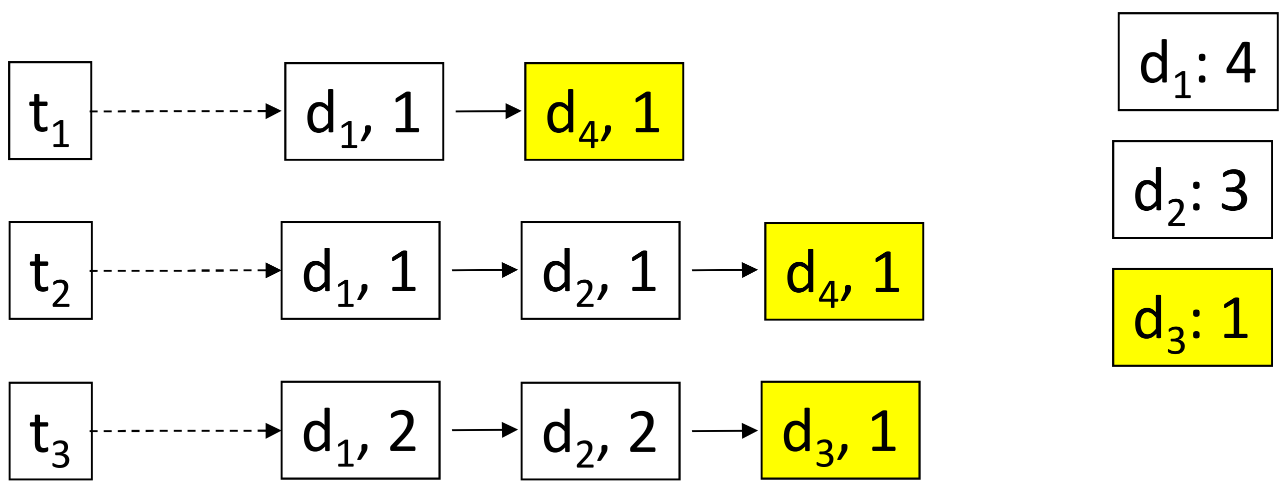

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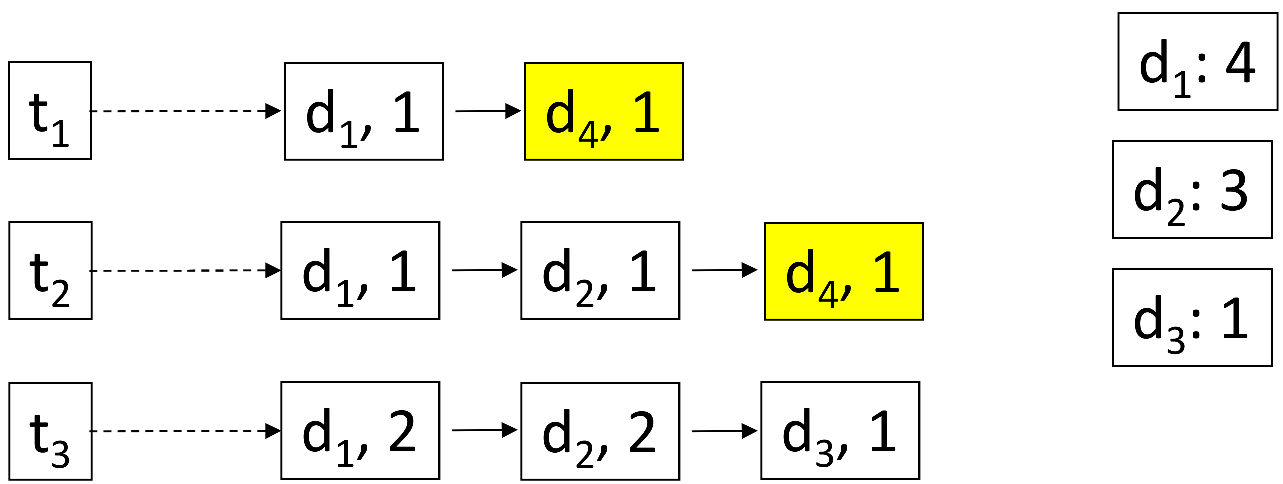

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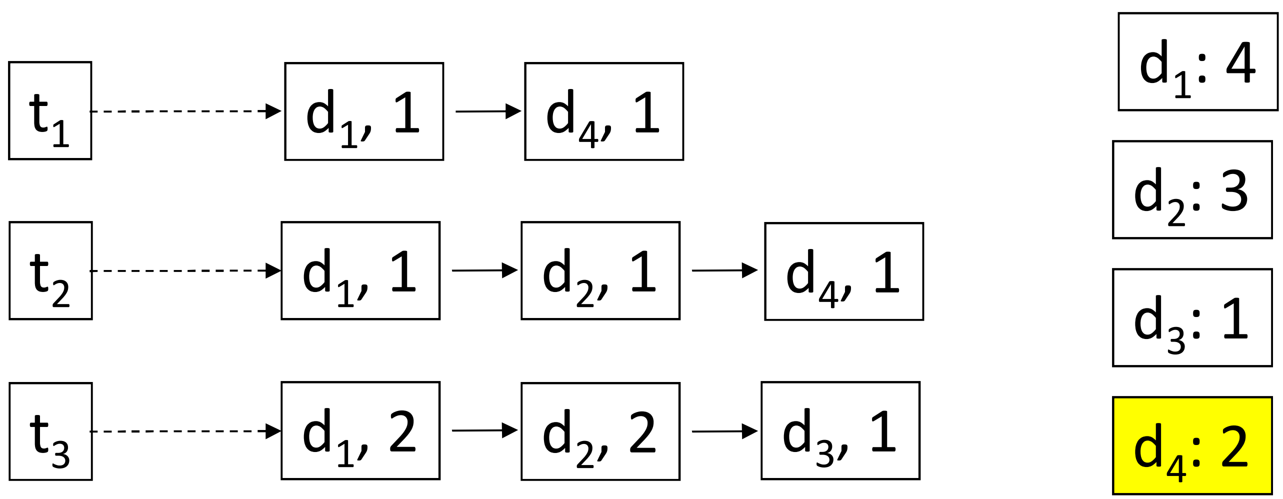

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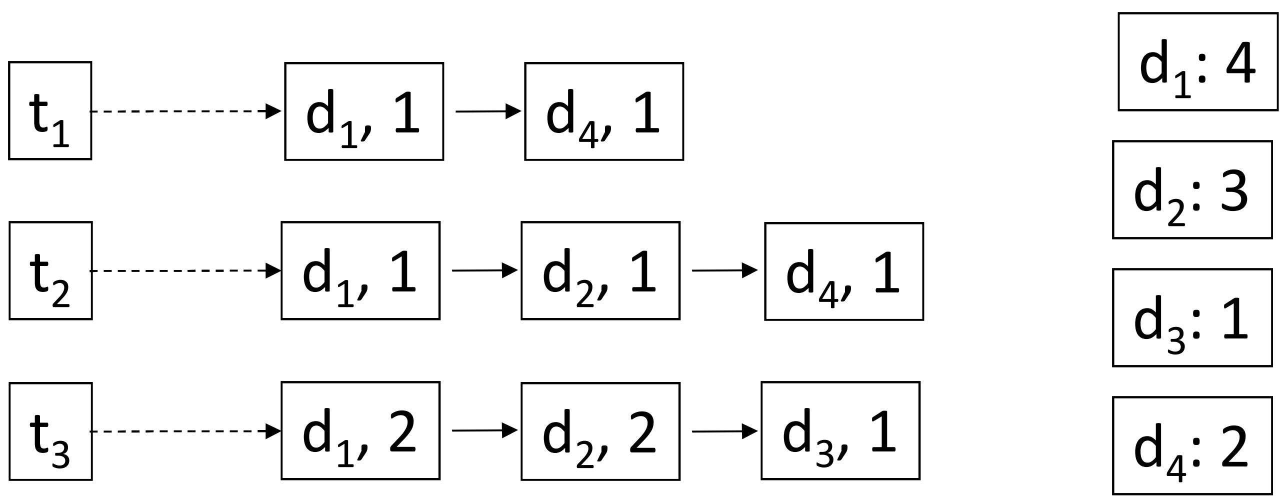

Document-at-a-time Ranking

```
context = {}        // maps a document to a list of matching terms
for w ∈ q do
    for d, count ∈ Idx.fetch_docs(w) do
        context[d].append(count)
    end for
end for
priority_queue = {}        // low score is treated as high priority
for d, term_counts ∈ context do
    score = 0
    for count ∈ term_counts do
        score = score + score_term(count)
    end for
    priority_queue.push(d, score)
    if priority_queue.size() > k then
        priority_queue.pop()        // removes lowest score so far
    end if
end for
Return sorted documents from priority_queue
```

References

- ChengXiang Zhai and Sean Massung, *Text Data Management and Analysis: A Practical Introduction to Information Retrieval and Text Mining*, ACM Books, 2016.
  - Chapter 6, Section 6.1-6.3 (Vector space model)
  - Chapter 8, Section 8.1-8.3 (Vector space model implementation)

Questions