

# Index compression and efficient query processing

COMP90042 LECTURE 17, THE UNIVERSITY OF MELBOURNE

by

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# Index compression

# Inverted Index - Recap

term $t$	$f_t$	Postings list for $t$
and	6	$\langle 1, 6, 7, 8, 9, 12 \rangle, \langle 1, 2, 1, 3, 1, 2 \rangle$
big	3	$\langle 2, 5, 42 \rangle, \langle 1, 1, 1 \rangle$
old	1	$\langle 32 \rangle, \langle 4 \rangle$
in	7	$\langle 2, 3, 5, 6, 8, 14, 25 \rangle, \langle 1, 1, 4, 1, 5, 3, 1 \rangle$
the	52	$\langle 1, 2, 3, 4, 5, 7, 8, 9, \dots \rangle, \langle 10, 21, 10, 42, 12, 14, 12, 4, \dots \rangle$
night	4	$\langle 1, 12, 13, 14 \rangle, \langle 2, 2, 1, 3 \rangle$
house	5	$\langle 6, 21, 32, 33, 43 \rangle, \langle 2, 3, 4, 2, 1 \rangle$
sleep	3	$\langle 1, 51, 53 \rangle, \langle 1, 2, 3 \rangle$
where	4	$\langle 1, 3, 4, 6 \rangle, \langle 1, 1, 2, 1 \rangle$

# Index Compression - Motivation

Inverted Index size for 420GB of web data (tiny)

Documents	25 Million
Terms	35 Million
Postings	6 Billion
Uncompressed Storage Cost	$\approx$ 32 GB

- Inverted Index mostly stored in RAM (query performance)
- Companies run 1000s of machines to answer search queries
- Space reduction can lead to substantial cost reductions
- Saving 5% means shutting down 50/1000 machines!

# Index compression

## Benefits of index compression:

- Reduce storage requirements
- Keep larger parts of the index in memory
- Faster query processing

## Example

A state-of-the-art inverted index of 25 million websites (420GB) requires only 5GB (1.2%) and can answer queries in  $\approx 10$  milliseconds.

32GB  $\rightarrow$  5GB corresponds to a 700% space reduction!

# Compression Principles

- Compressibility is bounded by the information content of a data set
- Information content of a text  $T$  is characterized by its *Entropy*  $H$ :

$$H(T) = - \sum_{s \in \Sigma} \frac{f_s}{n} \log_2 \frac{f_s}{n}$$

where  $f_s$  is the frequency of symbol  $s$  in  $T$  and  $n$  is the length of  $T$ .

- For example,  $H(\text{abracadabra}) = 2.040373$  bits with  $n = 11, f_a = 5, f_b = 2, f_c = 1, f_d = 1, f_r = 2$ .
- Intuition: Spend less bits on items that occur often.

# Posting list Compression

- Minimize storage costs
- Fast sequential access
- Support  $GEQ(x)$  operation: Return the smallest item in the list that is greater or equal to  $x$

# Posting list Compression - Concepts

- Postings list corresponds to an increasing sequence of integers
- Each integer can be in  $[1, N]$  requiring  $\log_2(N)$  bits
- Idea: Gaps between two adjacent integers can be much smaller

the	ids:	25	26	29	...	12345	12347
	gaps:	25	1	3	...	1	2
house	ids:	5123	5234	5454	5591	...	
	gaps:	5123	1	220	137	...	
aeronaut	ids:	251235	251239	251239			
	gaps:	251235	4	34			



# Variable Byte Compression

## Idea

Use variable number of bytes to represent integers. Each byte contains 7 bits “payload” and one continuation bit.

## Examples

Number	Encoding	
824	00000110	10111000
5	10000101	

## Storage Cost

Number Range	Number of Bytes
0 – 127	1
128 – 16383	2
16384 – 2097151	3

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Compress number 512312 or 1111101000100111000 in binary.

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4. Discard lowest 7 bits.

$$4002 \div 128 = 31 \text{ (or } 4002 \gg 7)$$

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# Variable Byte - Algorithm

## Encoding

```
1: function ENCODE( $x$ )
2:   while  $x \geq 128$  do
3:     WRITE( $x \bmod 128$ )
4:      $x = x \div 128$ 
5:   end while
6:   WRITE( $x + 128$ )
7: end function
```

## Decoding

```
1: function DECODE(bytes)
2:    $x = 0, s = 0$ 
3:    $y = \text{READBYTE}(\text{bytes})$ 
4:   while  $y < 128$  do
5:      $x = x \wedge (y \ll s)$ 
6:      $s = s + 7$ 
7:      $y = \text{READBYTE}(\text{bytes})$ 
8:   end while
9:    $x = x \wedge ((y - 128) \ll s)$ 
10:  return  $x$ 
11: end function
```

# OptPForDelta Compression

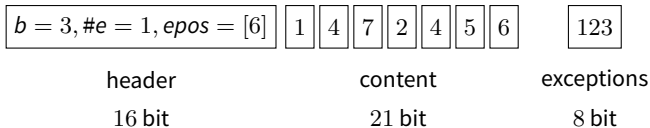
## Idea

Group  $k$  gaps and encode using fixed number of bits. Encode numbers  $> 2^b$  separately as an *exception*. Pick  $b$  “optimally” for each block so there are  $\approx 10\%$  exceptions.

## Example $k = 8$

[1 4 7 2 4 5 123 6]    [3 4 755 15 12 1 8 4]  
                                b=3                                  b=4

Encode [1 4 7 2 4 5 123 6] as:



# Decompression Speeds/Space Usage

Algorithm	Space [bits/int]	Speed [Million Integers/sec]
Uncompressed	32	$\approx 5400$
Variable Byte	8.7	$\approx 680$
OptPForDelta	4.7	$\approx 710$
Simple-8b	4.8	$\approx 780$
SIMD-BP128	11	$\approx 2300$
⋮	⋮	

Citation: Daniel Lemire, Leonid Boytsov: Decoding billions of integers per second through vectorization. Softw., Pract. Exper. 45(1): 1-29 (2015)



# Compression Optimizations

- Commonly lists are split into blocks of 128 integers
- Choose optimal compression for each block
- Often, long lists (“the”) are represented more efficiently using bitvectors of size  $N$
- State-of-the-art implementations use SIMD Instructions and bit-parallelism to increase decoding speed

# List Compression - Fast Searching

- Compress postings list in blocks of 128 integers at a time
- For each block store an uncompressed sample value representing the largest (or smallest) value in the block
- Use sample values to efficiently seek to any position in the postings list without decompressing everything

Operation  $GEQ(x)$  (Greater or Equal  $x$ ):

- Binary search over uncompressed sample values to find destination block
- Decompress destination block to determine final offset in postings list

# Postings Compression - Summary

- Compress increasing integer sequences
- Support iterating and searching the compressed sequence
- Store gaps between adjacent numbers
- Different compression schemes provide different time-space tradeoffs

# Efficient Query Processing

# Query Processing - Motivation

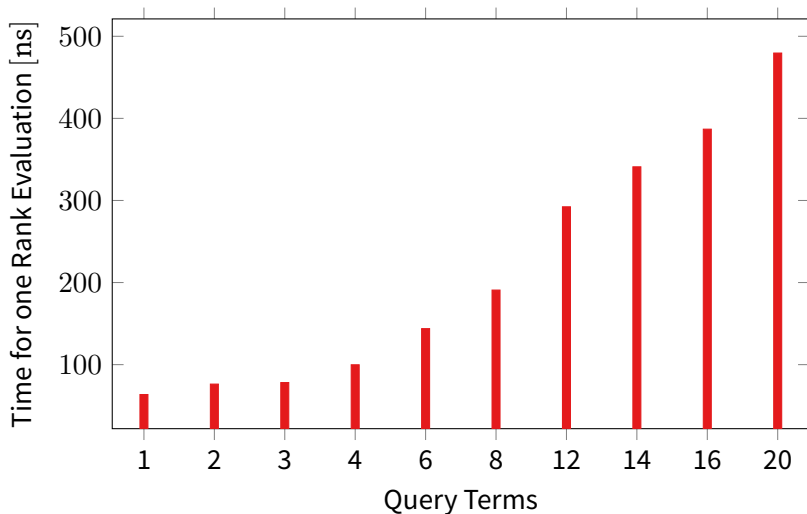
BM25 computation for one document:

$$S_{Q,d}^{\text{BM25}} = \sum_{q \in Q} \frac{(k_1 + 1)f_{d,q}}{k_1 \left(1 - b + b \frac{n_d}{n_{\text{avg}}}\right) + f_{d,q}} \cdot f_{Q,q} \cdot \ln \left( \frac{N - F_{\mathcal{D},q} + 0.5}{F_{\mathcal{D},q} + 0.5} \right)$$

Symbol	Description
$Q$	Multi set of query terms
$q$	Query term in $Q$
$d$	Evaluated document
$f_{d,q}$	Frequency of $q$ in $d$ (Term frequency)
$N$	Number of documents in the collection
$F_{\mathcal{D},q}$	Number of documents containing $q$ (Document frequency)
$f_{Q,q}$	Number of times $q$ occurs in $Q$
$n_d$	Length of document $d$
$n_{\text{avg}}$	Average document length in the collection
$k_1, b$	Constants

# Query Processing - Motivation II

BM25 computation speed:



# Query Processing - Motivation III

- Evaluating BM25 for one document takes 100 nanoseconds (Fast!).
- Assume query matches 25 million documents (term “the” contained in almost all documents).
- $25 \text{ million} \times 100 \text{ nanoseconds} \approx 2.5 \text{ seconds}$ .
- Is waiting 2.5 seconds for a search query acceptable?

# Query Processing - Motivation IV

- Google A/B tested the effect of latency on user satisfaction.<sup>1</sup>
  - Users are able to detect changes in latency by only 50 ms.
  - Users searched less when results took longer to be presented.
  - System abandonment was higher when results took longer to be presented.
  - Average revenue per user dropped by  $\approx 4\%$  when users had delayed results.
- Every 100 ms boost in latency increases annual revenue for Bing by  $\approx 0.6\%$ .<sup>2</sup>
  - In 2015, a 1% improvement in revenue per user at Bing was an increase of *tens-of-millions* of dollars per year.

<sup>1</sup> E. Schurman and J. Brutlag. "Performance related changes and their user impact". Velocity, 2009.

<sup>2</sup> R. Kohavi, A. Deng, B. Frasca, T. Walker, Y. Xu, and N. Pohlmann. "Online controlled experiments at large scale". In Proc. KDD, pages 1168–1176, 2013.



# Query Processing – Strategies

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  - Cannot scale infinitely: diminishing returns.
- Many improvements can still be made at the *software* level.
  - **Faster, cheaper algorithms for query processing.**

# Efficient Query Processing

## IDEA: Top- $k$ Retrieval

Retrieve the top  $k$  items for a given query without having to evaluate all documents.

- Web search engines return only the top-10 results to the user.
- For most queries most users generally do not retrieve more documents.
- No need to score all possible documents to produce a “complete” ranking.



# Top- $k$ Retrieval - Concepts

- Avoid scoring documents we know will not appear in the top- $k$  result list.
- For a given similarity metric (for example BM25), prestore some information for each term to avoid scoring.
- Incorporate with block based compression schemes for efficient query processing.
- Utilise the  $\text{GEQ}(x)$  operation to avoid decompression of large parts of postings lists.

# Inefficient Evaluation of BM25

BM25 computation for one document:

$$S_{Q,d}^{\text{BM25}} = \sum_{q \in Q} \underbrace{\frac{(k_1 + 1)f_{d,q}}{k_1 \left(1 - b + b \frac{n_d}{n_{\text{avg}}}\right) + f_{d,q}}}_{=w_{d,q}} \cdot \underbrace{f_{Q,q} \cdot \ln \left( \frac{N - F_{\mathcal{D},q} + 0.5}{F_{\mathcal{D},q} + 0.5} \right)}_{=w_{Q,q}}$$

Inefficient Evaluation:

- For each  $q$  in  $Q$  compute  $w_{Q,q}$  in  $O(|Q|)$  time.
- For each  $d$  in the document collection containing any  $q$  in  $Q$  evaluate  $w_{d,q}$ . (Potentially  $O(N)$  time!)
- Return the top- $k$  highest scoring documents.

# Top- $k$ - The WAND Algorithm

Basic Idea:

- Keep track of the top- $k$  highest scored documents.
- For each unique term in the collection store the **maximum contribution** it can have to *any* document score in the collection.
- Skip over documents that can not enter the top- $k$  highest results.

Citation: Andrei Z. Broder, David Carmel, Michael Herscovici, Aya Soffer, Jason Y. Zien: Efficient query evaluation using a two-level retrieval process. CIKM: 426-434 (2003)

# WAND - Maximum term contribution

## Maximum contribution

The **Maximum contribution** of a term  $q$  as the largest score **any** document in the collection can have for the query  $Q$  only consisting of  $q$ .

- Depends on the similarity measure.
- Can be computed at construction time of the index.
- Only requires storing a single floating point number for each list.
- Can be used to **overestimate** the score of a document in a multi term query.

# WAND - Example

Query  $Q$ : The quick brown fox

with  $k = 2$

The

2	3	7	8	9	10	11	12	13	17	18	19	...
---	---	---	---	---	----	----	----	----	----	----	----	-----

quick

5	6	9	11	14	18
---	---	---	----	----	----

brown

2	4	5	15	42	84	96
---	---	---	----	----	----	----

fox

5	7	8	13
---	---	---	----

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Query Q: The quick brown fox

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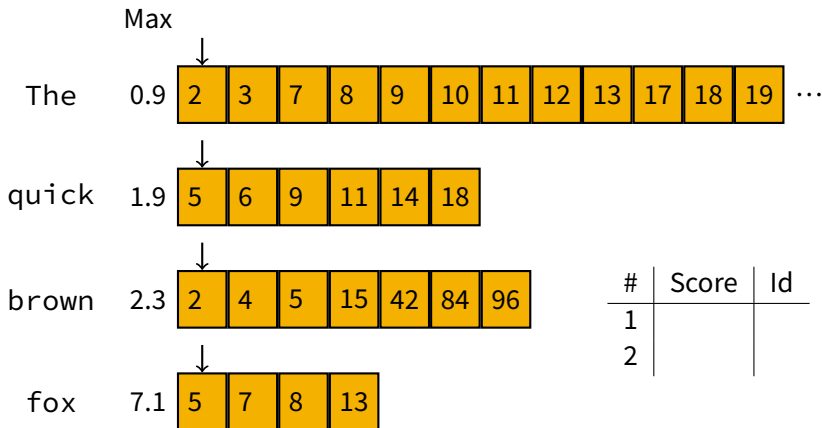
Maximum Contribution for each query term

	Max																
The	0.9	2	3	7	8	9	10	11	12	13	17	18	19	...			
quick	1.9	5	6	9	11	14	18										
brown	2.3	2	4	5	15	42	84	96									
fox	7.1	5	7	8	13												

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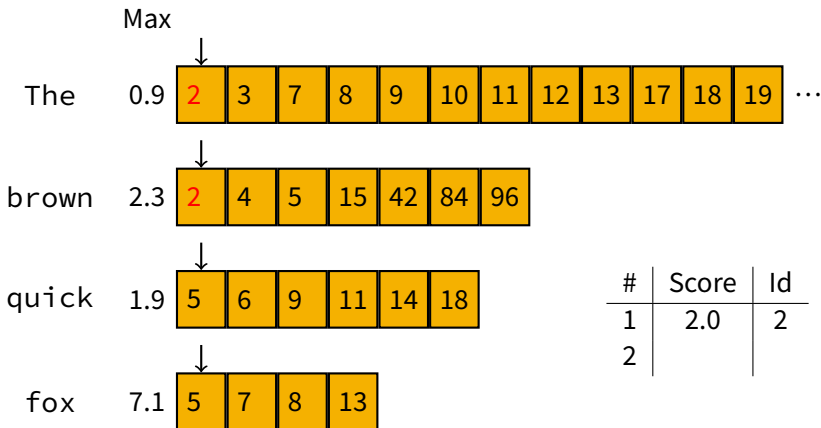


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Query Q: The quick brown fox

with  $k = 2$

(1) Reorder based on current id and score smallest.



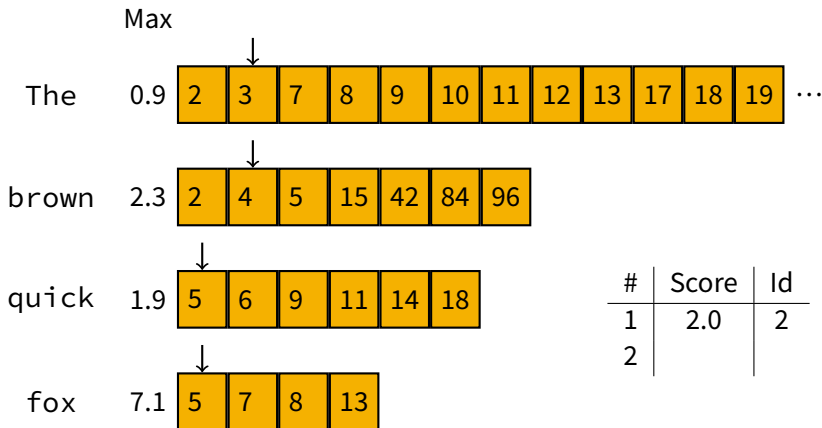


# WAND - Example

Query Q: The quick brown fox

with  $k = 2$

(2) Move pointer of scored elements.

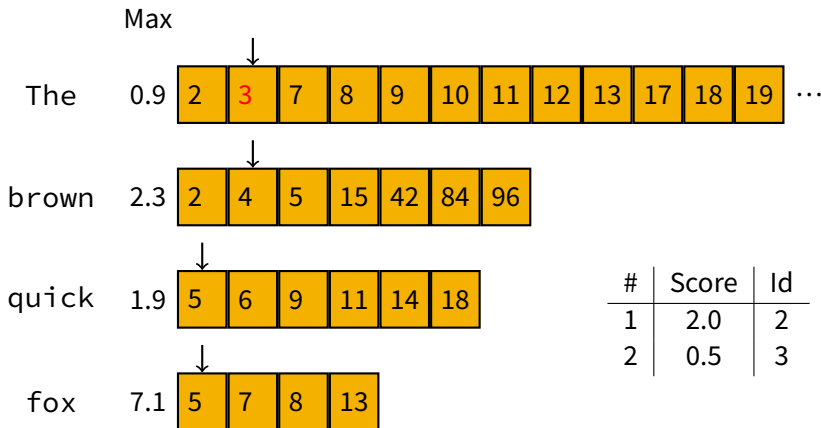


# WAND - Example

Query Q: The quick brown fox

with  $k = 2$

(3) Reorder based on current id and score smallest.

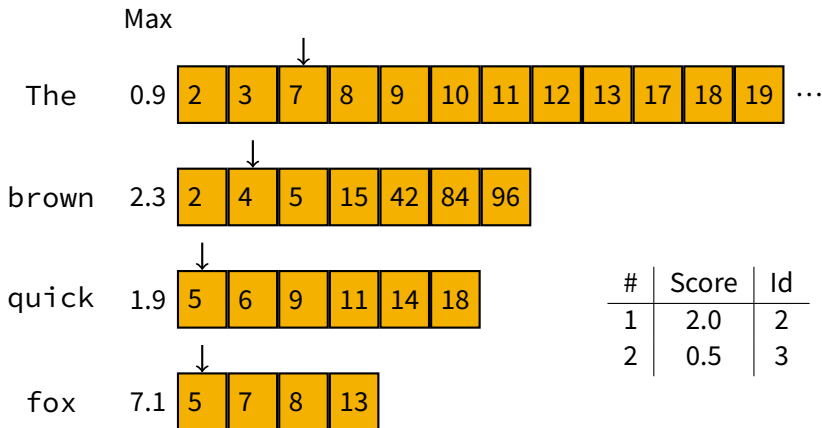


# WAND - Example

Query Q: The quick brown fox

with  $k = 2$

(4) Move pointer of scored elements

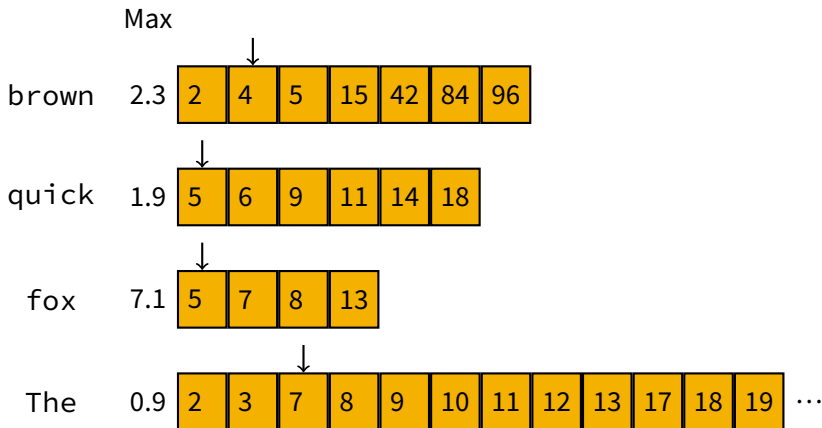


# WAND - Example

Query Q: The quick brown fox

with  $k = 2$

(5) Reorder based on current id and score smallest.

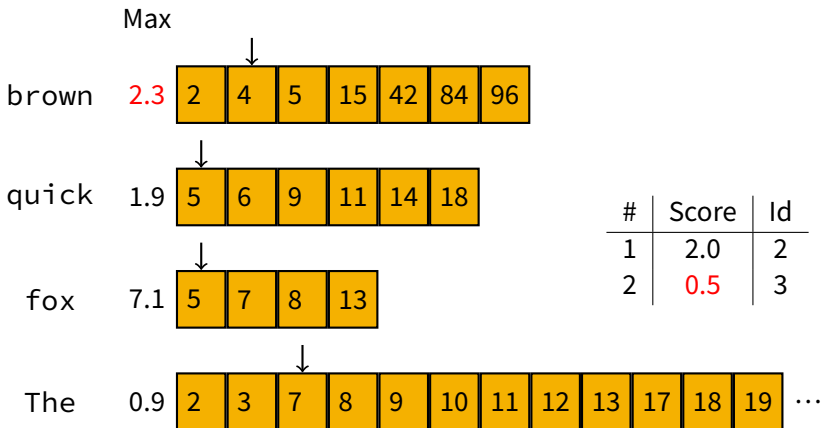


# WAND - Example

Query Q: The quick brown fox

with  $k = 2$

(6) Decide if we need to score smallest id.

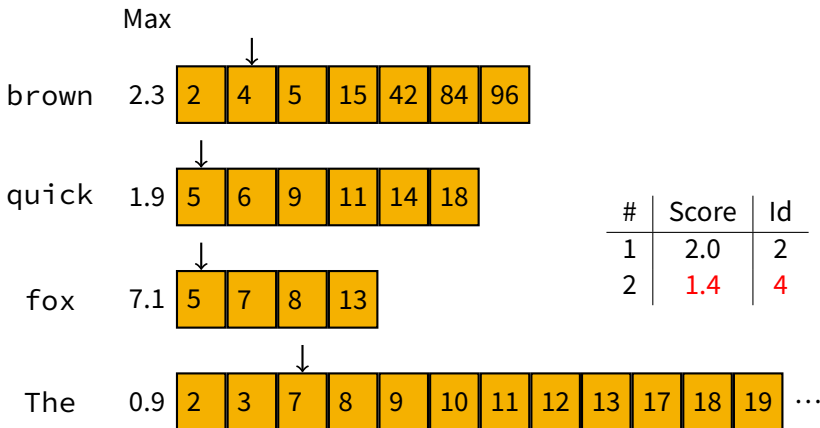


# WAND - Example

Query Q: The quick brown fox

with  $k = 2$

(7) Replace 3 with 4 on the heap.

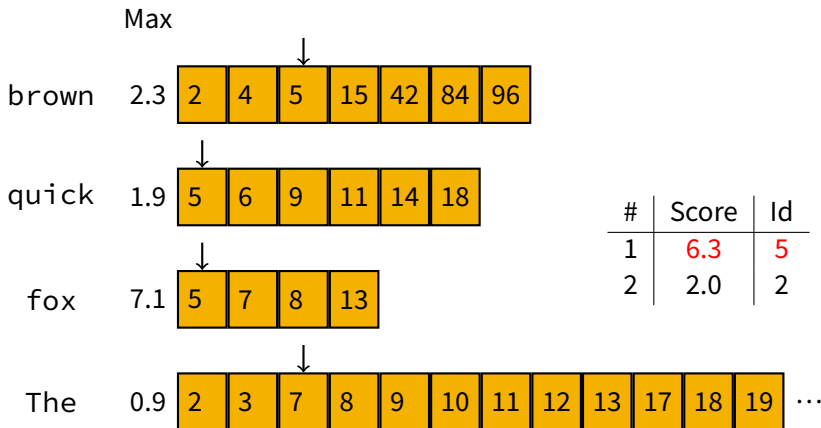


# WAND - Example

Query Q: The quick brown fox

with  $k = 2$

(8) Sort by current id. Evaluate 5. Add to Heap.

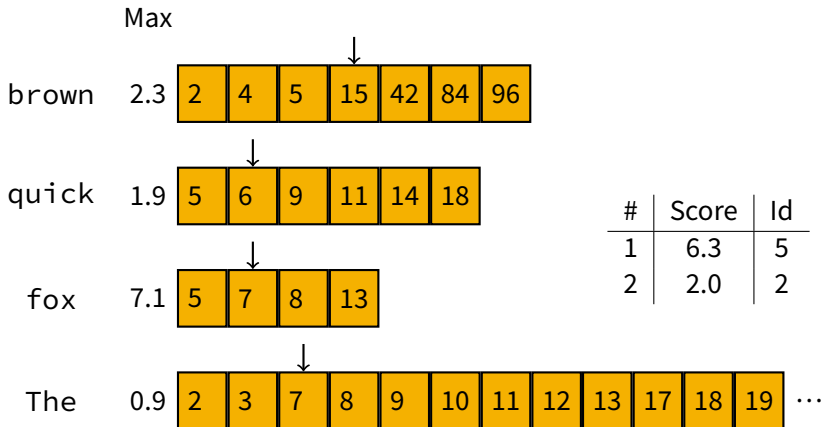


# WAND - Example

Query Q: The quick brown fox

with  $k = 2$

(9) Move pointers and sort.

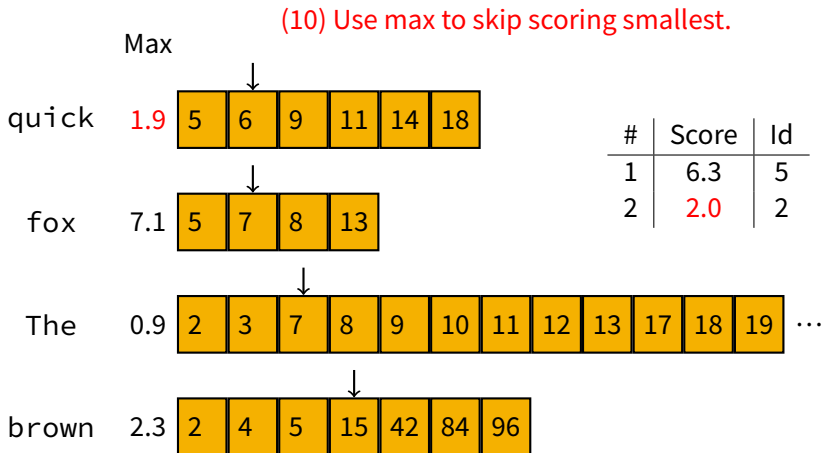




# WAND - Example

Query Q: The quick brown fox

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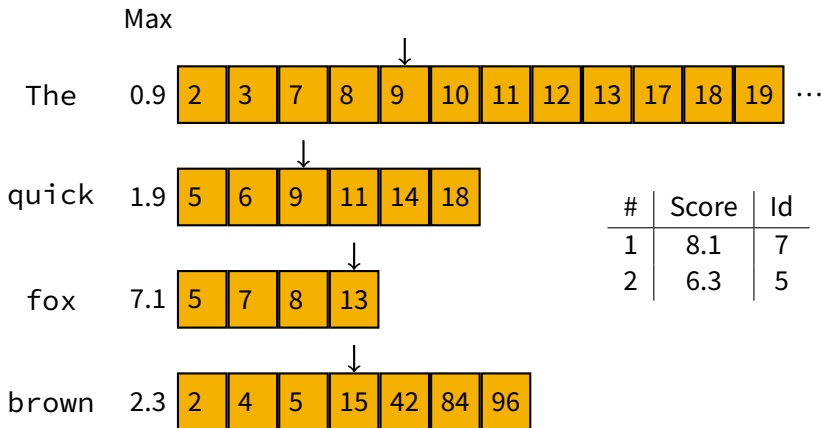


# WAND - Example - Fast Forward

Query Q: The quick brown fox

with  $k = 2$

Do we have to evaluate document 9?

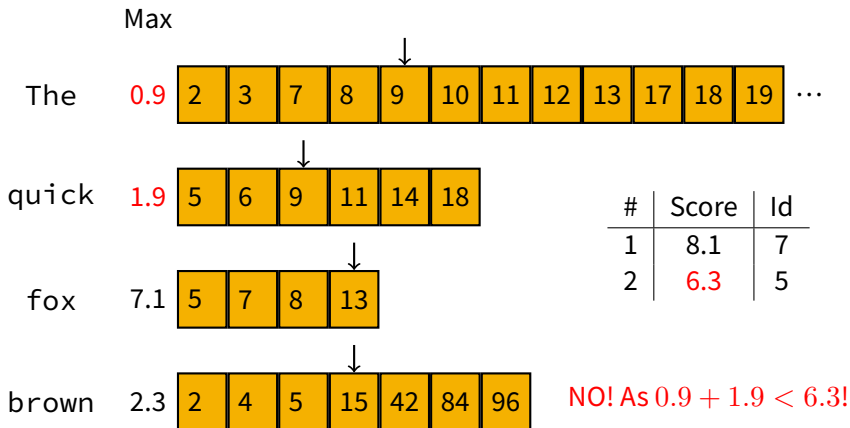


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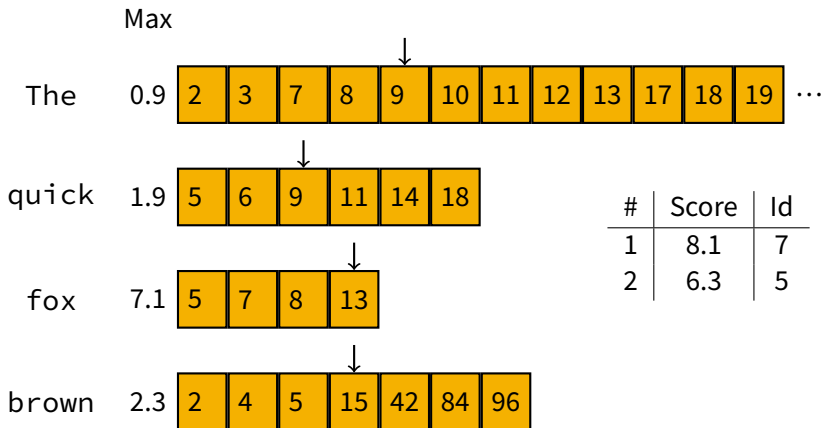


# WAND - Example - Fast Forward

Query Q: The quick brown fox

with  $k = 2$

What is the next document that has to be evaluated?



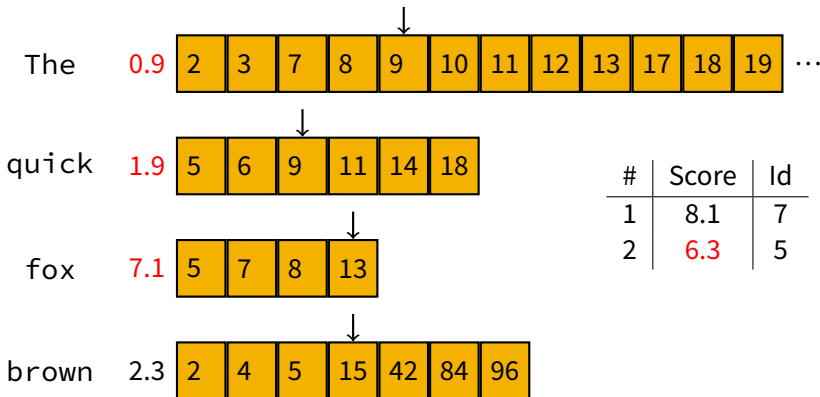
# WAND - Example - Fast Forward

Query Q: The quick brown fox

with  $k = 2$

What is the next document that has to be evaluated?

Max



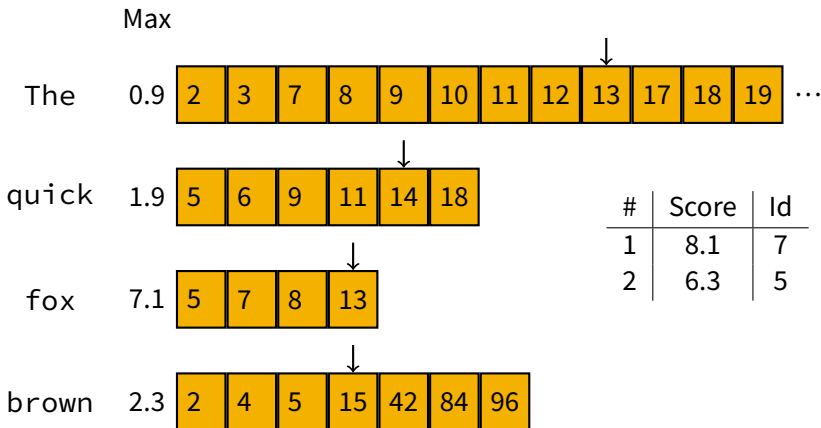
**13**, as  $0.9 + 1.9 + 7.1 > 6.3$ !

# WAND - Example - Fast Forward

Query Q: The quick brown fox

with  $k = 2$

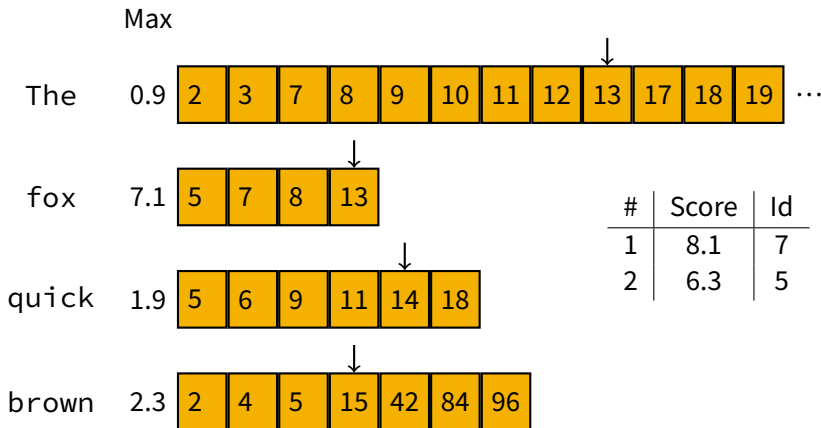
Fast forward smaller ids to 13 (GEQ) and sort.



# WAND - Example - Evaluate 13?

Query Q: The quick brown fox

with  $k = 2$



# WAND - Algorithm

Given  $Q, k$  and the postings lists  $L[0 \dots |Q| - 1]$  with:

$L[i].max \hat{=}$  the **maximum contribution** of the list

$L[i].cur \hat{=}$  the current element of the list

```
1: function WAND( $Q, k, L[0 \dots |Q| - 1]$ )
2:    $TopDocs = \emptyset$  ▷ Min Heap of size  $k$ 
3:   Threshold  $\Theta = 0$  ▷ Smallest score in  $TopDocs$ 
4:   while Not all lists are processed do
5:     Sort  $L$  based on  $L[i].cur$ 
6:     Select pivot list  $p$  such that  $\sum_0^{p-1} L[i].max \geq \Theta$ 
7:     Forward all lists  $L[0 \dots |p| - 1]$  to  $d_p = L[p].cur$ 
8:     Compute  $S_{Q, d_p}^{BM25}$  and insert into  $TopDocs$  if score  $> \Theta$ 
9:      $\Theta = \min(TopDocs)$  or 0 if  $|TopDocs| < k$ .
10:  end while
11:  Return  $TopDocs$ 
12: end function
```



# WAND - Discussion

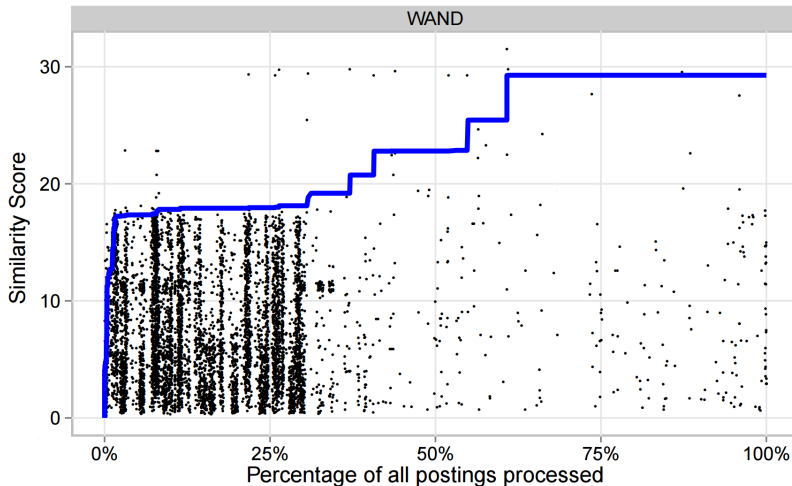
- Use max contribution of query term to overestimate score of a document.
- Do not score document if it can not enter the top- $k$  heap.
- Utilize GEQ function of compressed representation to skip over large parts of the postings lists.
- Similarity metric fixed at index construction time.
- Works very well in practice.

# WAND - Performance

Method	$k = 10$		$k = 1,000$	
	Avg.	Med.	Avg.	Med.
Exhaustive	100.0	100.0	100.0	100.0
BM25	3.5	1.0	28.0	11.7

Fraction of pointers processed as a percentage of the total number of pointers associated with each query, GOV2, using TREC topics 701–850. Across the set of queries, the average number of postings per query for exhaustive processing is 1,460,562, and the median number of postings is 1,080,008. The percentages shown in the table are relative to these two numbers.

# WAND - Performance II



Evaluation of one query “north korean counterfeiting” for  $k = 10$ .

# Further Reading

## Reading:

- Manning, Christopher D; Raghavan, Prabhakar; Schütze, Hinrich; Introduction to information retrieval, Cambridge University Press 2008. (Chapter 5)

## Additional References:

- Daniel Lemire, Leonid Boytsov: Decoding billions of integers per second through vectorization. Softw., Pract. Exper. 45(1): 1-29 (2015)
- Andrei Z. Broder, David Carmel, Michael Herscovici, Aya Soffer, Jason Y. Zien: Efficient query evaluation using a two-level retrieval process. CIKM: 426-434 (2003)