CS3245

Information Retrieval

Lecture 6: Index Compression

6

Live Q&A
https://pollev.com/jin

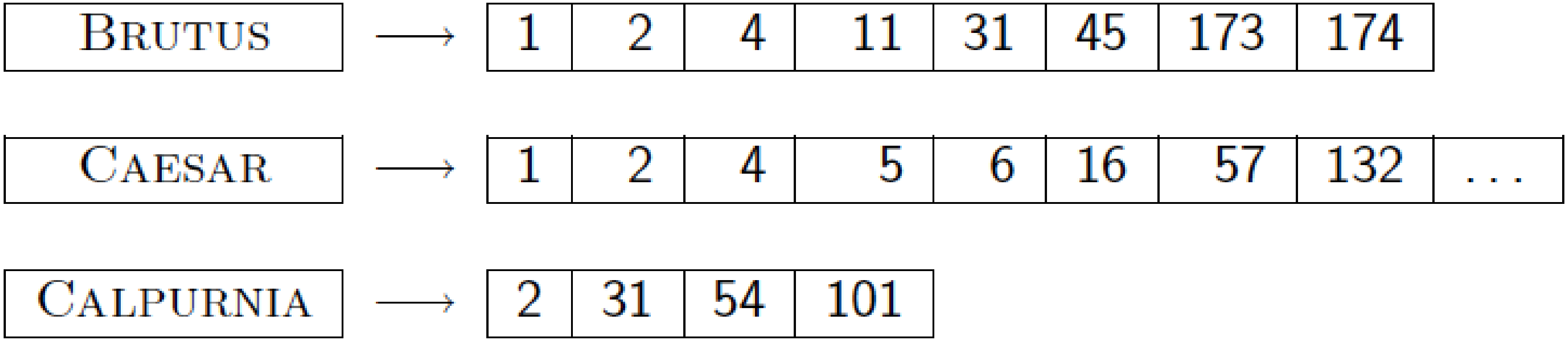
Last Time: index construction

- Sort-based indexing
  - Blocked Sort-Based Indexing
    - Merge sort is effective for disk-based sorting (avoid seeks!)
  - Single-Pass In-Memory Indexing
    - No global dictionary - Generate separate dictionary for each block
    - Don't sort postings - Accumulate postings as they occur
- Distributed indexing using MapReduce
- Dynamic indexing: Multiple indices, logarithmic merge

Why compression?

- Use less disk space
- Keep more data (e.g., **the dictionary**) in memory
- Increase the speed of data (e.g., **the posting lists**) transfer from disk to memory

Today: Idx Cmprssn



BRUTUS ⟶ 1 | 2 | 4 | 11 | 31 | 45 | 173 | 174

CAESAR ⟶ 1 | 2 | 4 | 5 | 6 | 16 | 57 | 132 | . . .

CALPURNIA ⟶ 2 | 31 | 54 | 101

- Empirical laws on collection statistics (with RCV1)
- Dictionary compression
- Postings file compression

Reuters RCV1 statistics

symbol	statistic	value
N	documents	800,000
L	avg. # tokens per doc	200
M	terms (= vocabulary size = # of entries in the dictionary)	400,000
	avg. # bytes per term	7.5
T	term-docID pairs (= tokens)	100,000,000

Where do all those extra terms come from if English vocabulary is only ~30K?

Heaps' Law

$$M = kT^b$$

- M is the size of the vocabulary, T is the number of tokens in the collection
- Typical values: $30 \leq k \leq 100$ and $b \approx 0.5$
- An empirical finding ("empirical law")
- In a log-log plot of vocabulary size M vs. T, Heaps' law predicts a line with slope about ½

Heaps' Law

For RCV1, the dashed line

$\log_{10} M = 0.49 \log_{10} T + 1.64$

is the best least squares fit.

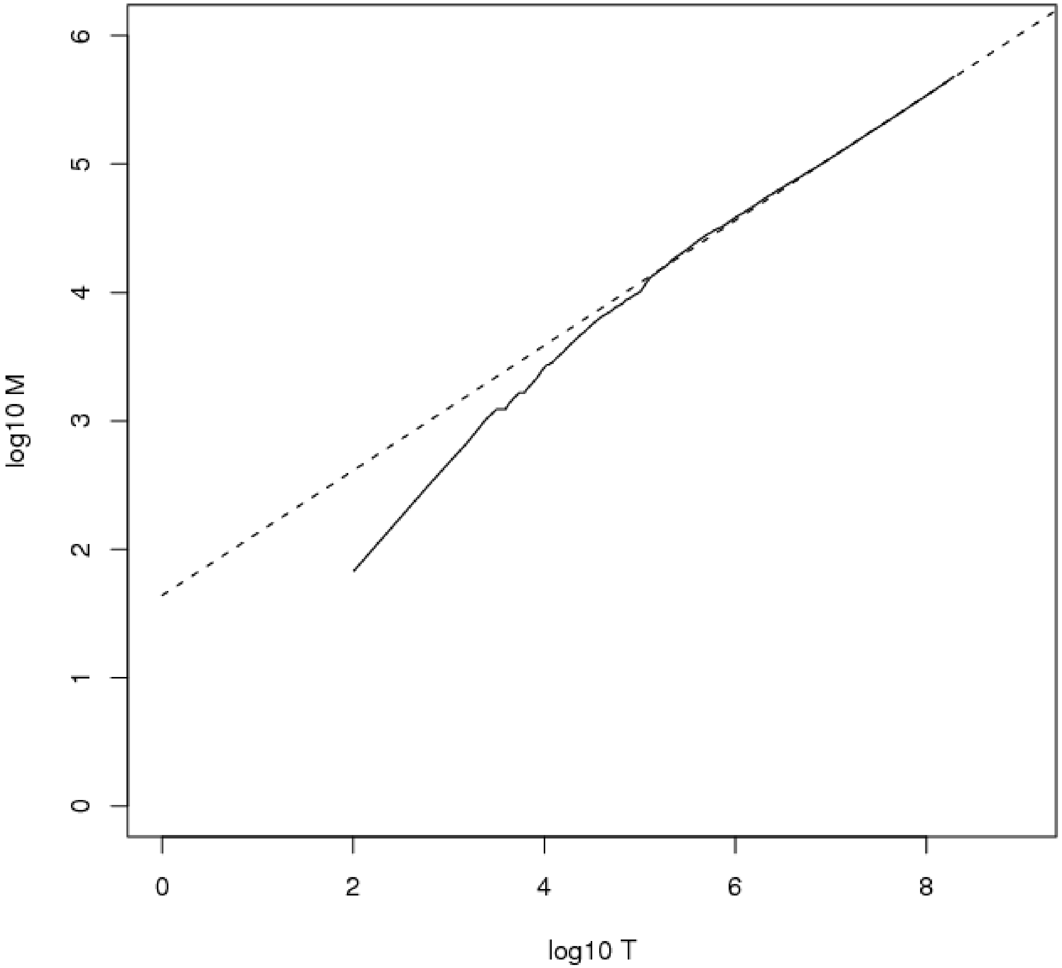
Thus, $M = 10^{1.64} T^{0.49}$ so $k = 10^{1.64} \approx 44$ and $b = 0.49$.

Good empirical fit for Reuters RCV1 !

For first 1,000,020 tokens,

law predicts 38,323 terms;

actually, 38,365 terms



Collection frequency

- Some terms are common and some others are rare…
- Collection frequency (cf)
  - The number of occurrences of a term in the **collection**.
  - NOT the same as **document frequency** (df)
- Example
  - Collection D_1: a a a b and D_2: a b c
  - $cf_a = 4$, $df_a = 2$.
- Nevertheless, cf is positively correlated with df in general.

Zipf's law

$$cf_i = K/i$$

- cf_i is the cf of the i-th most frequency term
- K is a normalizing constant, $cf_1 = K / 1 = K$

- Example:
  - Collection D_1: a a a b and D_2: a b c
  - Estimated collection frequency (with $cf_1 = K = 4$):
    - For a, the 1st most frequent term, $cf_1 = K / 1 =$ **4**
    - For b, the 2nd most frequent term, $cf_2 = K / 2 =$ **2**
    - For c, the 3rd most frequent term, $cf_3 = K / 3 =$ **1.33**

Zipf's law

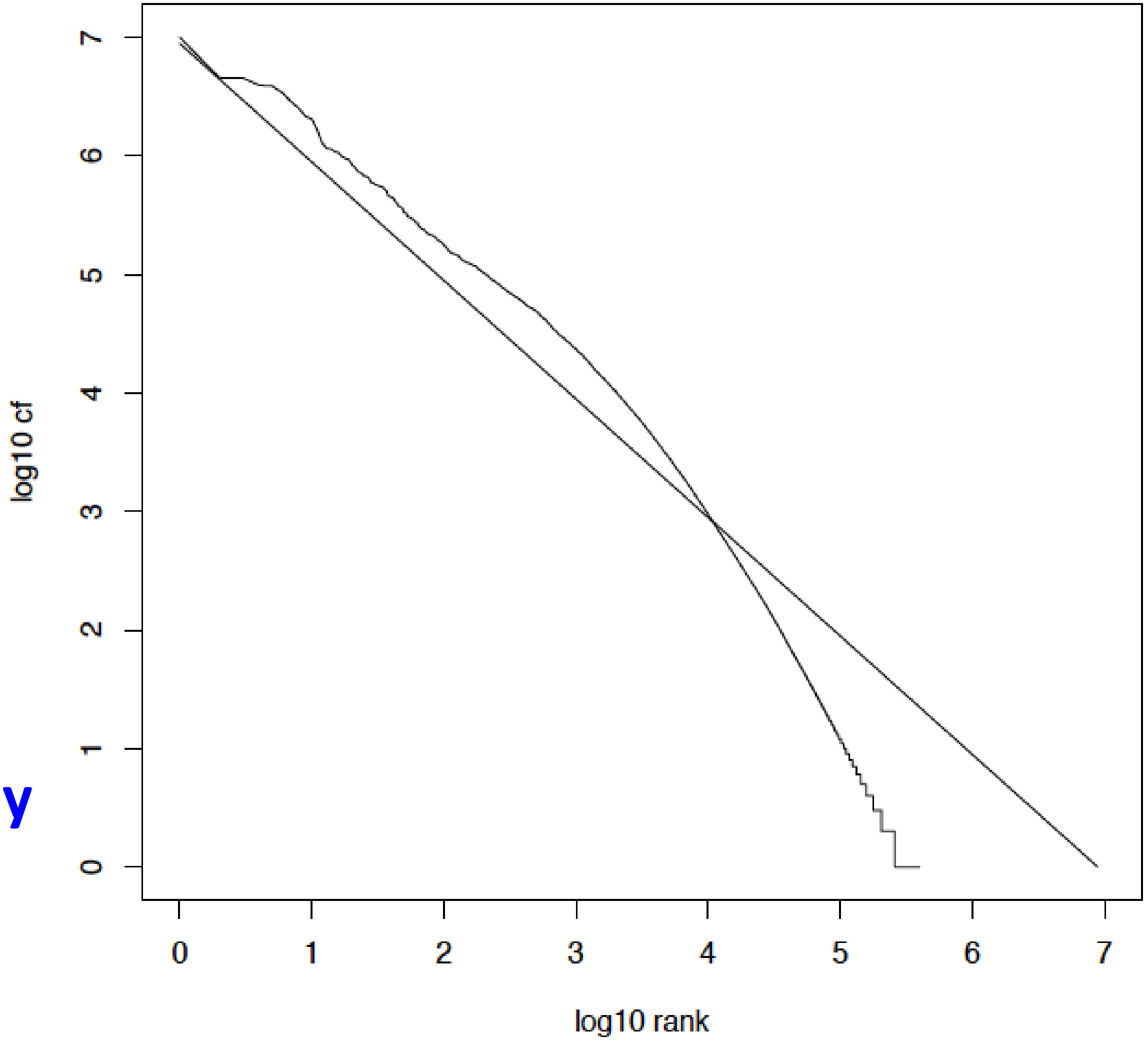
- If the most frequent term (*the*) occurs cf_1 times
  - then the second most frequent term (*of*) occurs $cf_1/2$ times
  - the third most frequent term (*and*) occurs $cf_1/3$ times …
- Equivalent: $\log cf_i = \log K - \log i$
  - Linear relationship between $\log cf_i$ and $\log i$
  - Another power law relationship

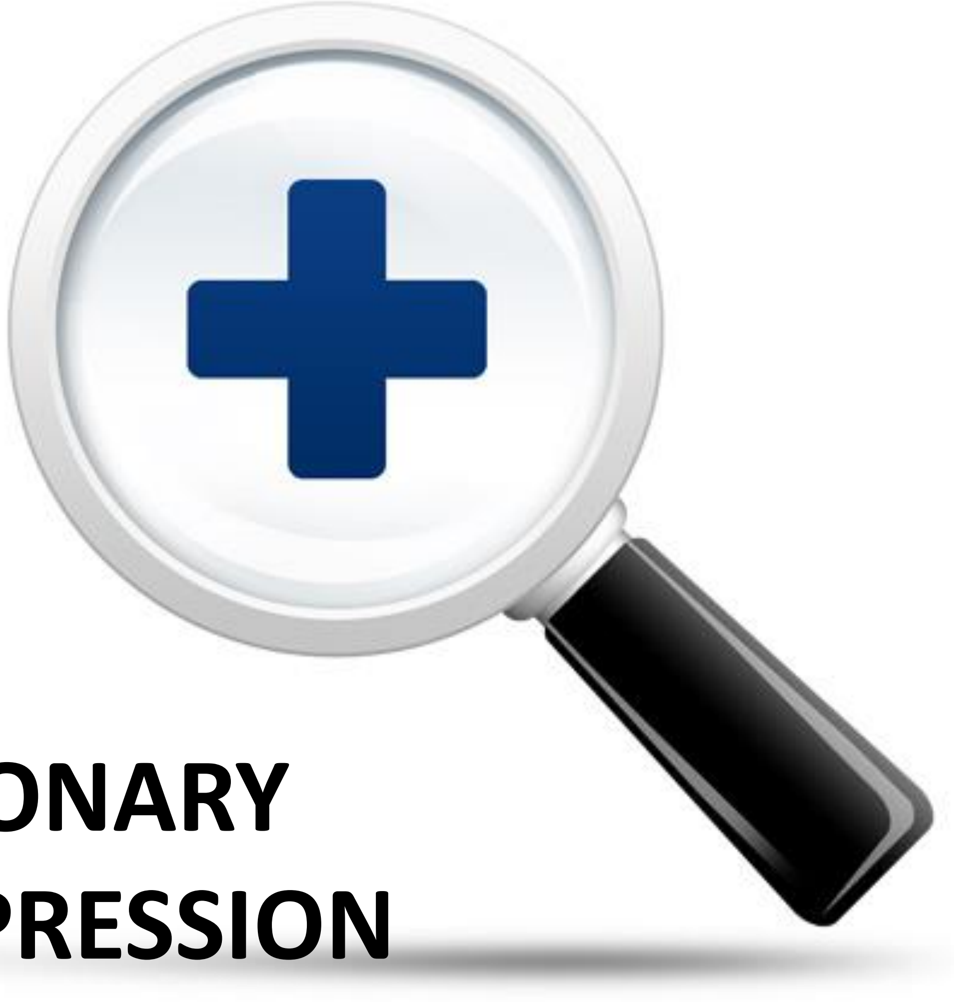
Zipf's law

Not a particularly good fit for RCV1…

But good enough as a rough model for calculations.

In general, there are **a few very frequent terms** and **very many very rare terms**.





DICTIONARY COMPRESSION

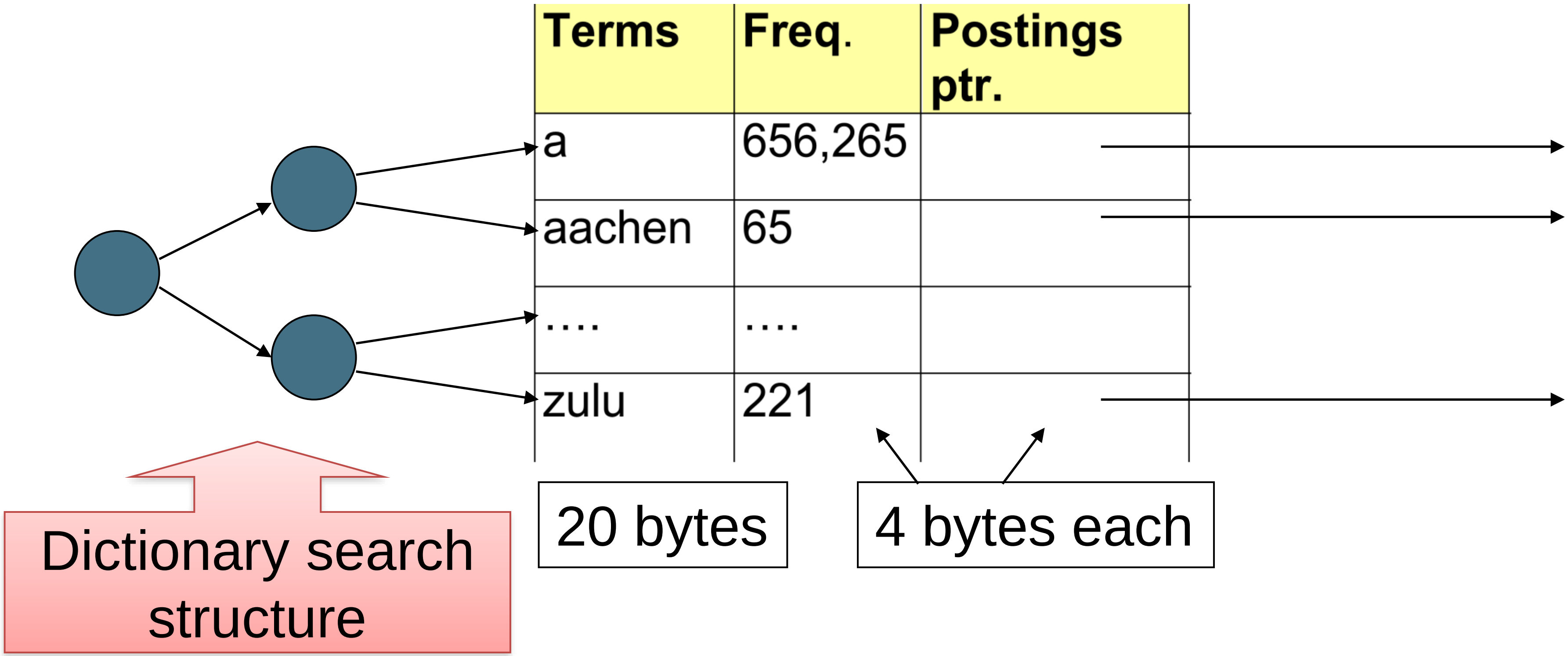
Why compress the dictionary?

- Search begins with the dictionary so we want to keep it in memory
- Memory footprint competition with other applications
  - Embedded/mobile devices may have very little memory
- Even if the dictionary isn’t in memory, we want it to be small for a fast search startup time

Compressing the dictionary is important

Dictionary storage - first cut

- Fixed-width entries indexed by a tree
  - ~400,000 terms; 28 bytes/term = 11.2 MB.



Terms	**Freq.**	**Postings ptr.**
a	656,265	
aachen	65	
….	….	
zulu	221	

Dictionary search structure

20 bytes

4 bytes each

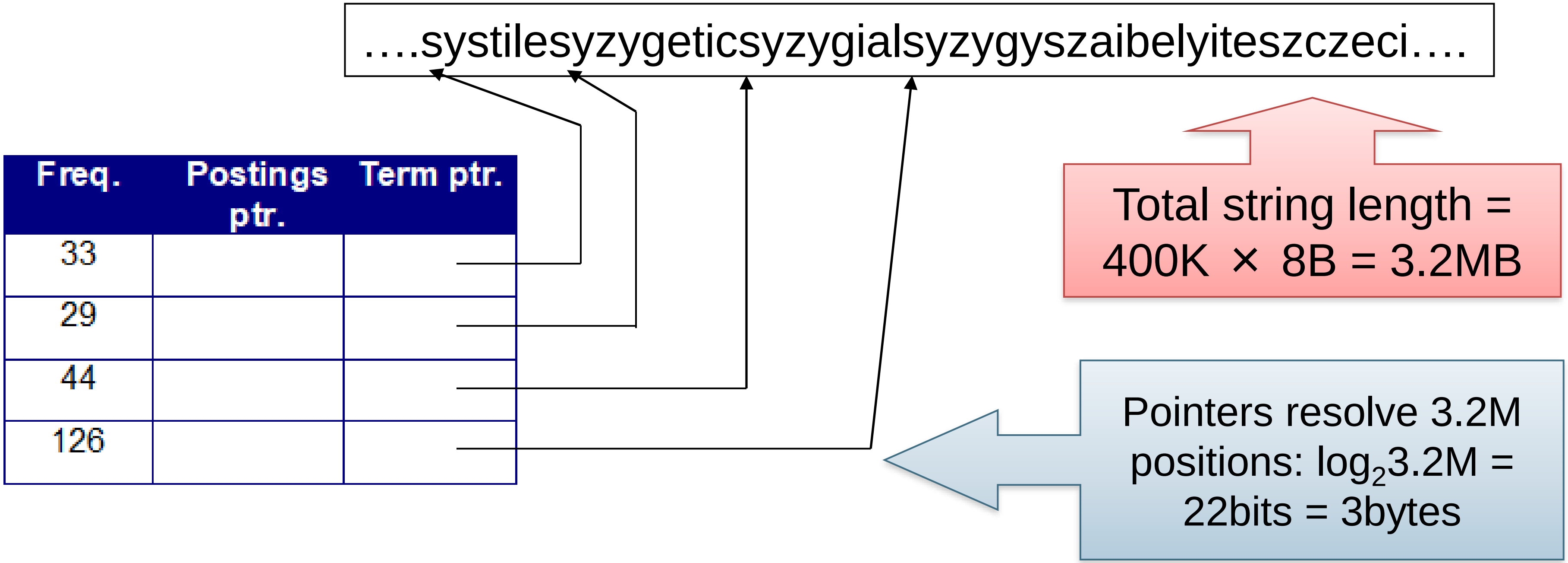
Fixed-width terms are wasteful

- Most of the bytes in the **Term** column are wasted
    - Average dictionary word in English: **~8** characters
    - And we still can’t handle *supercalifragilisticexpialidocious* or *hydrochlorofluorocarbons.*

- How to save space?

Compressing the term list: Dictionary-as-a-String

- Store dictionary as a (long) string of characters
- Add pointers to the start of every word



….systilesyzygeticsyzygialsyzygyszaibelyiteszczeci….

Freq.	Postings ptr.	Term ptr.
33		
29		
44		
126		

Total string length = 400K × 8B = 3.2MB

Pointers resolve 3.2M positions: $\log_2 3.2M$ = 22bits = 3bytes

Space for dictionary as a string

- Dictionary array of 400K terms of 11 bytes each
  - 4 bytes per term for frequency
  - 4 bytes per term for pointer to postings
  - 3 bytes per term pointer

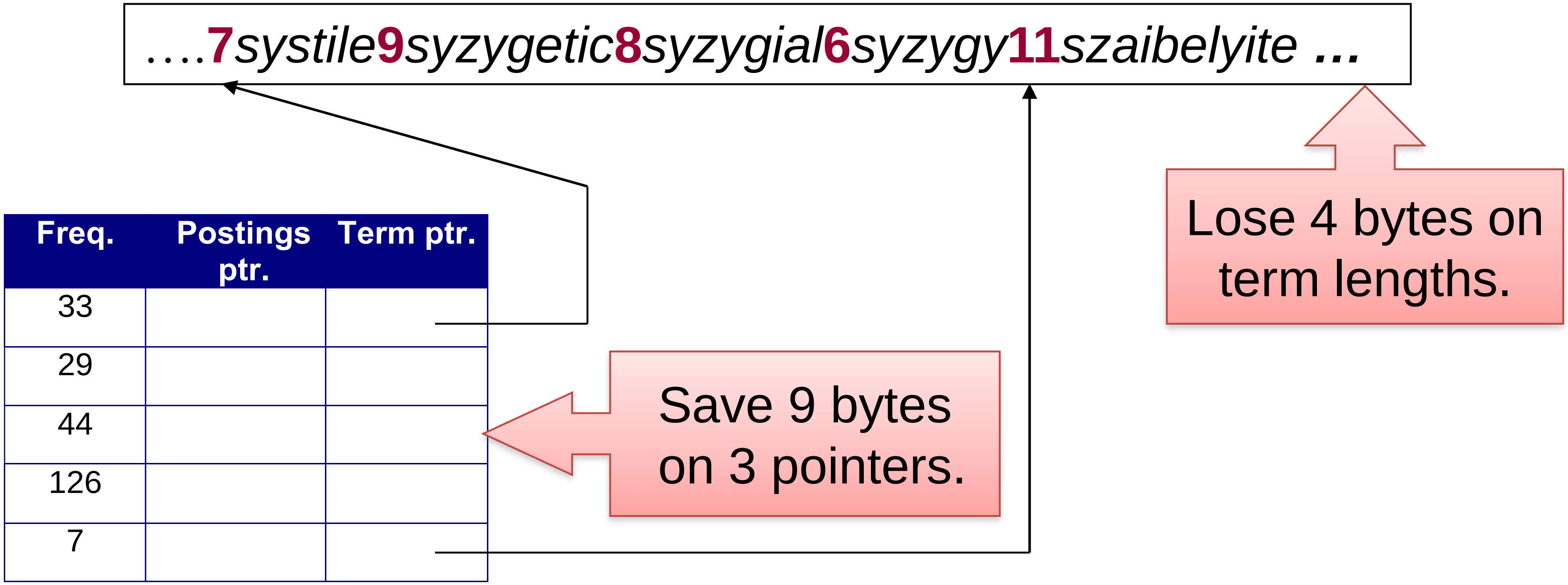
Now avg. 11 bytes/term, not 28.

- Dictionary string of 400K terms of 8 bytes on average

- Total size = 4.4 MB (dictionary array)
  + 3.2 MB (dictionary string)
  = 7.6 MB (3.6 MB less than the original size of 11.2MB)

Blocking

- Store pointers to every *k*th term string.
  - Example below: *k*=4.
- Need to store term lengths (1 extra byte)



….**7***systile***9***syzygetic***8***syzygial***6***syzygy***11***szaibelyite* **…**

Freq.	Postings ptr.	Term ptr.
33		
29		
44		
126		
7		

Save 9 bytes on 3 pointers.

Lose 4 bytes on term lengths.

Net Result

- Example for block size $k = 4$
- Where we used 3 bytes/pointer without blocking
  - 3 x 4 = 12 bytes,

now we use 3 + 4 = 7 bytes.

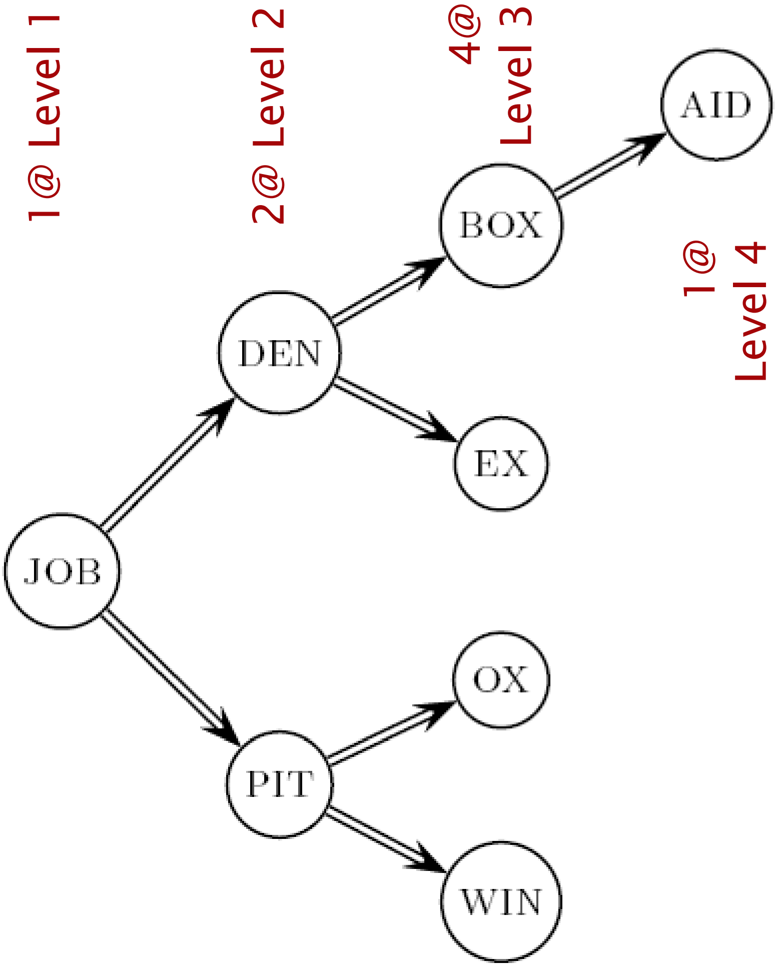
Shaved another ~0.5MB. This reduces the size of the dictionary from 7.6 MB to 7.1 MB.
We can save more with larger k.

Why not go with a larger k?

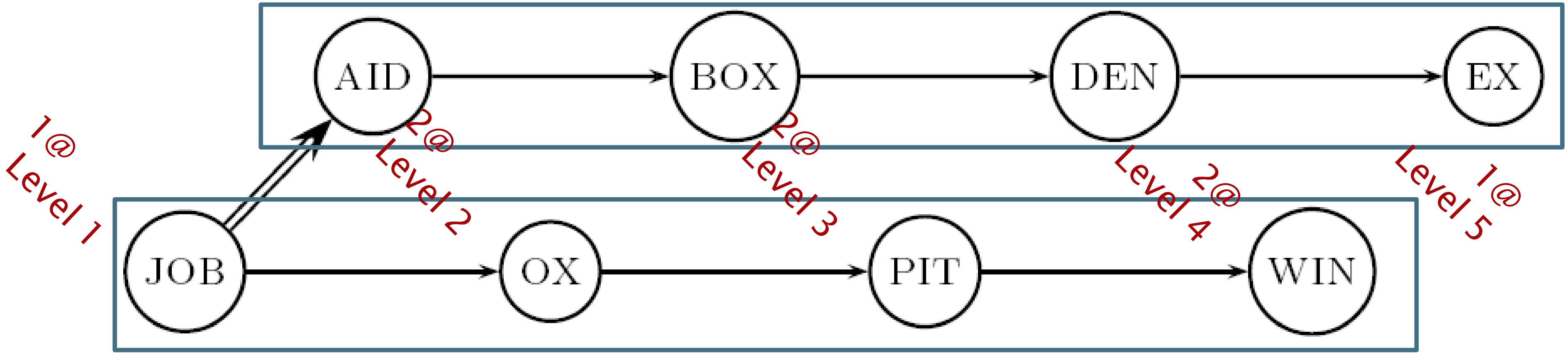
Dictionary search without blocking

- Assume that each dictionary term equally likely in query (not true in practice!)

- Average number of comparisons = (1*1 + 2*2 + 3*4 + 4*1)/8 = ~2.6



Dictionary search with blocking

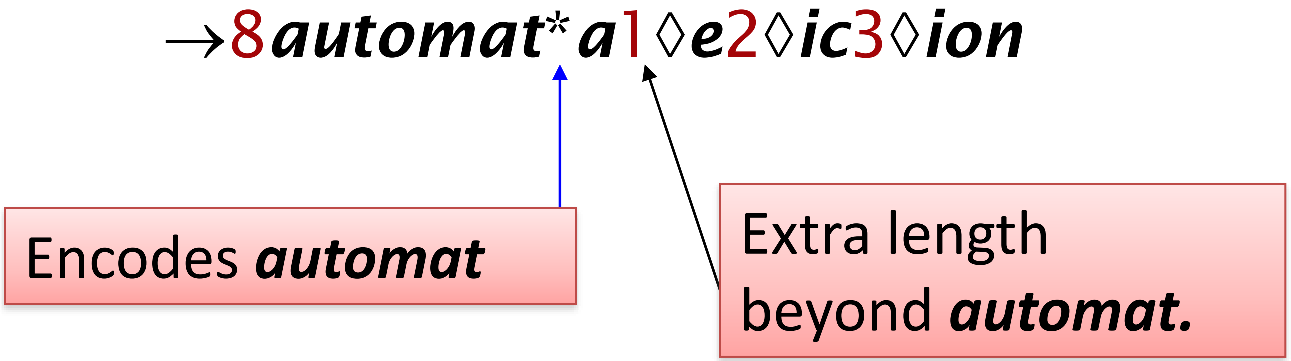


- Binary search down to 4-term block;
    - Then linear search through terms in block.
- Blocks of 4 (binary tree), average = (1*1 + 2*2 + 3*2 + 4*2 + 5*1)/8 = 3

Front coding

- Sorted words commonly have long common prefix – store differences only
  - Used for last *k-1* terms in a block of *k*

8***automata***8***automate***9***automatic***10***automation***



→8automat*a1◊e2◊ic3◊ion

Encodes ***automat***

Extra length beyond ***automat.***

Begins to resemble general string compression

RCV1 dictionary compression summary

Technique	**Size in MB**
Fixed width	11.2
Dictionary-as-String with pointers to every term	7.6
Also, blocking *k* = 4	7.1
Also, Blocking + front coding	5.9

POSTINGS FILE COMPRESSION

Postings file compression

- How to store postings (i.e., **docID**s) compactly?
  - *Computer, 34592*: **33,47,154,159,202** …

- For Reuters (800,000 documents)
  - Range of docIDs [1, 800,000]
  - $\log_2 800000$ ~= 20 bits ~= 3 bytes

- Let's try to make the numbers smaller!

Gap Encoding

- We store the list of docs containing a term in increasing order of docID.
  - *Computer, 34592*: **33,47,154,159,202** …
- Consequence: it suffices to store *gaps*.
  - 33,14,107,5,43 …

Gap Encoding

- As described by Zip's law, a small number of terms have a high *cf* and a lot of more words have a much lower *cf*.

- A high *cf* usually implies a high *df*, assuming the terms are evenly distributed across the documents.

- The gaps between the postings for a high *df* should be small.

Gap Encoding

	Encoding	Postings List					
the	docIDs	…	283042	283043	283044	283045	…
	gaps		…	1	1	1	
computer	docIDs	…	2803047	283154	283159	283202	…
	gaps		…	107	5	43	
arachnocentric	docIDs	252000	500100				
	gaps	…	248100				

Variable byte encoding

- Observation: it is wasteful and to use a fixed number of bits to store every number.
- Key challenge: encode every integer (gap) with about as little space as needed for that integer.
- This can be achieved by ***variable byte encoding,*** which uses *close to the fewest bytes* needed to store a gap.

Variable byte encoding

- Begin with one byte to store a gap G and dedicate 1 bit in it to be a continuation bit c
  - 0 (not ending) and 1 (ending)
- If $G \le 127$, binary-encode it in the 7 available bits and set $c = 1$
- Else encode G's lower-order 7 bits and then use additional bytes to encode the higher order bits using the same algorithm
- At the end set the continuation bit of the last byte to 1 ($c = 1$) – and for the other bytes $c = 0$.

Example

docIDs	824	829	215406
gaps		5	214577
VB code	00000110 10111000	10000101	00001101 00001100 10110001

824 = 1100111000 (binary)

5 = 101 (binary)

Postings stored as the byte concatenation

00000110 10111000 10000101 00001101 00001100 10110001

Key property: VB-encoded postings are uniquely prefix-decodable.

For a small gap (5), VB uses a whole byte.

Other variable unit codes

- Instead of bytes, we can also use a different "unit of alignment": 32 bits (words), 16 bits, 4 bits (nibbles).
- Variable byte alignment wastes space if you have many small gaps – nibbles do better in such cases.
- Variable byte codes:
  - Used by many commercial/research systems
  - Good blend of variable-length coding and sensitivity to computer memory alignment

RCV1 compression

Data structure	Size in MB
dictionary, fixed-width	11.2
dictionary, term pointers into string	7.6
with blocking, k = 4	7.1
with blocking & front coding	5.9
collection (text, xml markup etc)	3,600.0
collection (text)	960.0
Term-doc incidence matrix	40,000.0
postings, uncompressed (32 bits)	400.0
postings, uncompressed (20 bits)	250.0
postings, variable byte encoded	116.0

Summary: Index compression

- We can now create an index for highly efficient Boolean retrieval that is very space efficient
- Use the sorted nature of the data to compress
  - Variable sized storage
  - Encode common prefixes only once
  - Encode gaps to reduce size of numbers
- However, here we didn’t encode positional information
  - But techniques for dealing with postings are similar

Resources for today's lecture

- *IIR* 5
- *MG* 3.3, 3.4.
- F. Scholer, H.E. Williams and J. Zobel. 2002. Compression of Inverted Indexes For Fast Query Evaluation. *Proc. ACM-SIGIR 2002*.
  - Variable byte codes
- V. N. Anh and A. Moffat. 2005. Inverted Index Compression Using Word-Aligned Binary Codes. *Information Retrieval* 8: 151–166.
  - Word aligned codes