Boolean Retrieval

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Most of these slides comes from the course:
Information Retrieval and Web Search,
Christopher Manning and Prabhakar Raghavan

Content

- Information needs and evaluation of IR
- Term document matrix
- Inverted index
- Processing Boolean queries
- The merge algorithm
- Query optimization
- Skip pointers
- Dictionary data structures
  - Hash tables
  - Binary trees

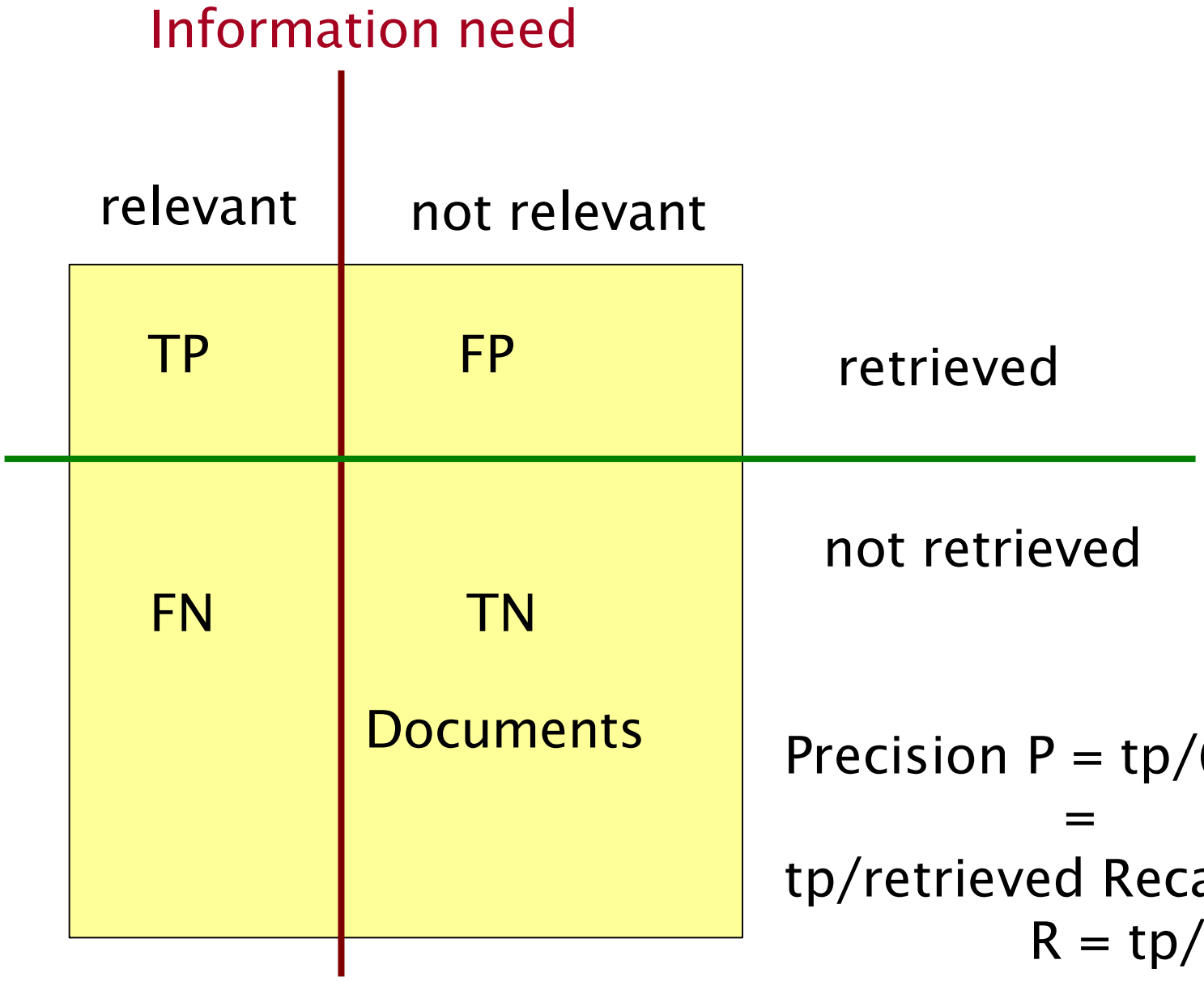
Basic assumptions of IR

- **Collection:** fixed set of documents
- **Goal:** retrieve documents with information that is relevant to the user's information need and helps the user complete a task
- Using the **Boolean Retrieval Model** means that the information need must be translated into a **Boolean expression:**
  - terms combined with AND, OR, and NOT operators

How good are the retrieved docs?

- *Precision* : Fraction of retrieved docs that are relevant to user's information need
- *Recall* : Fraction of relevant docs in collection that are retrieved

Relevance and Retrieved documents



Precision P = tp/(tp + fp)
=
tp/retrieved Recall
R = tp/(tp + fn)
= tp/relevant

Term-document incidence

Antony	Antony and Cleopatra	Julius Caesar	The Tempest	Hamlet	Othello	Macbeth
	1	1	0	0	0	1
Brutus	1	1	0	1	0	0
Caesar	1	1	0	1	1	1
Calpurnia	0	1	0	0	0	0
Cleopatra	1	0	0	0	0	0
mercy	1	0	1	1	1	1
worser	1	0	1	1	1	0

Brutus AND Caesar BUT NOT Calpurnia

1 if play contains word, 0 otherwise

Incidence vectors

- So we have a 0/1 vector for each term
- To answer query:
  - ***Brutus, Caesar*** and NOT ***Calpurnia***
  - take the vectors for
    - ***Brutus*** 110100
    - ***Caesar*** 110111
    - ***Calpurnia*** (complemented) 101111
  - Bitwise *AND*
    - 110100 *AND* 110111 *AND* 101111 = 100100

Answers to query

[J Antony and Cleopatra, Act III, Scene ii

Agrippa [Aside to DOMITIUS ENOBARBUS]: Why, Enobarbus,
When Antony found Julius ***Caesar*** dead,
He cried almost to roaring; and he wept
When at Philippi he found ***Brutus*** slain.

[J Hamlet, Act III, Scene ii

Lord Polonius: I did enact Julius ***Caesar*** I was killed i' the Capitol; ***Brutus*** killed me.

http://www.rhymezone.com/shakespeare/

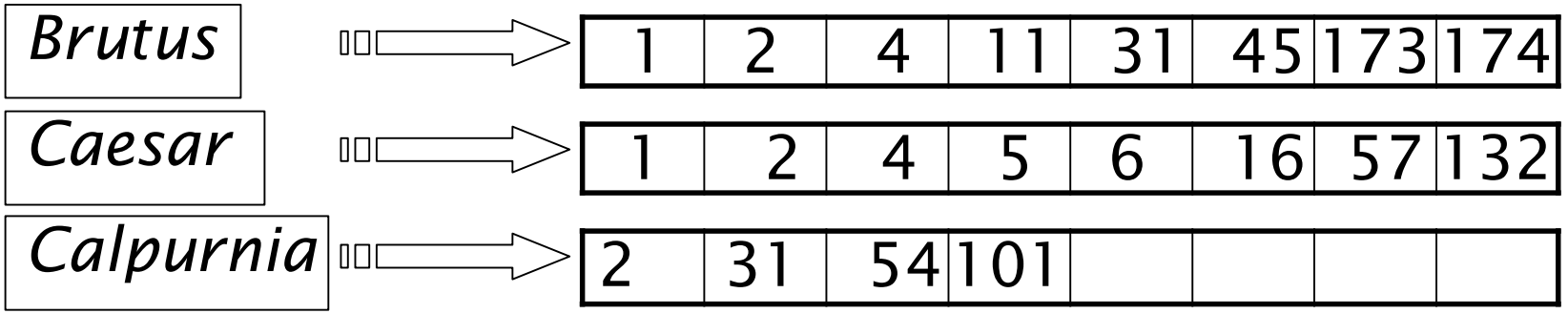
Bigger collections

- Consider a more realistic case
- N = 1 million documents, each with about 1000 words
- Avg 6 bytes/word including spaces/punctuation
  - 6GB of data in the documents.
- Say there are M = 500K *distinct* terms among these
- 500K x 1M matrix has half-a-trillion 0's and 1's
- But it has no more than one billion 1's
  - matrix is extremely sparse

- What's a better representation?
  - We only record the positions of the 1's.

Inverted index

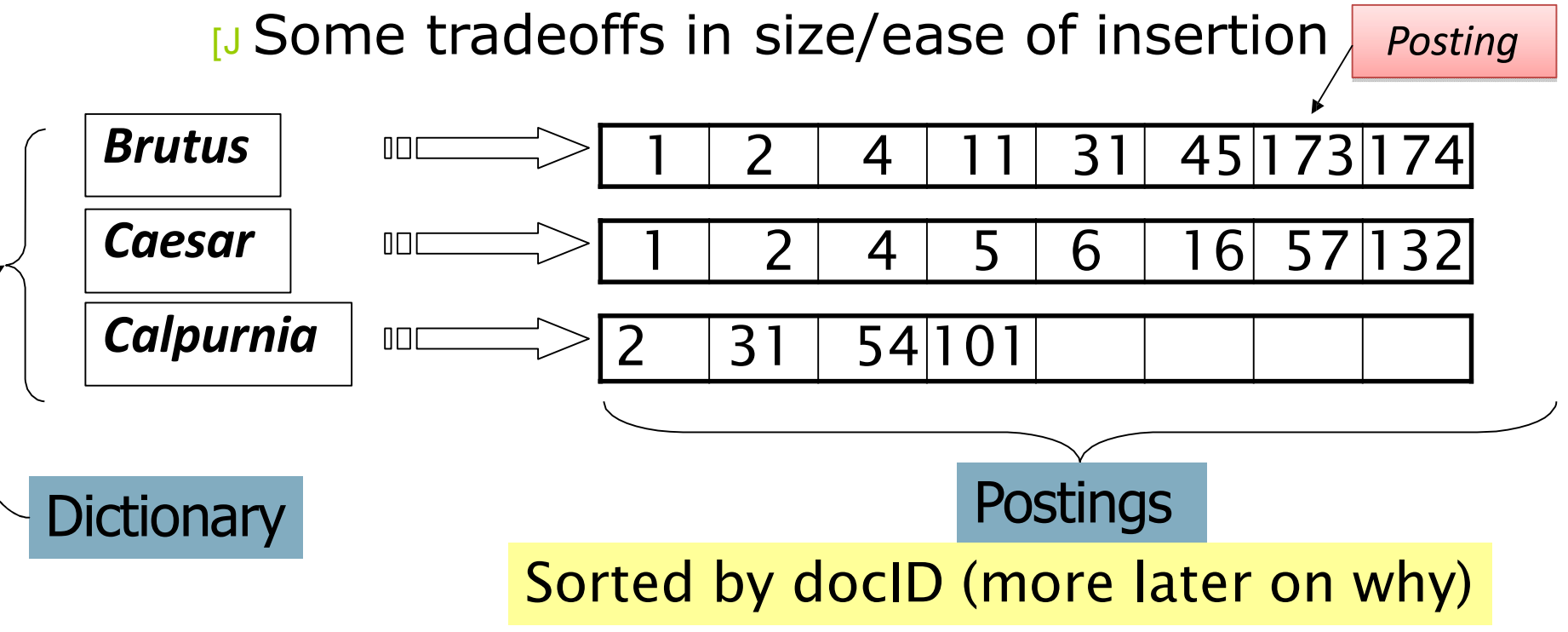
- For each term *t*, we must store a list of all documents that contain *t*
  - Identify each by a **docID**, a document serial number
- Can we used fixed-size arrays for this?



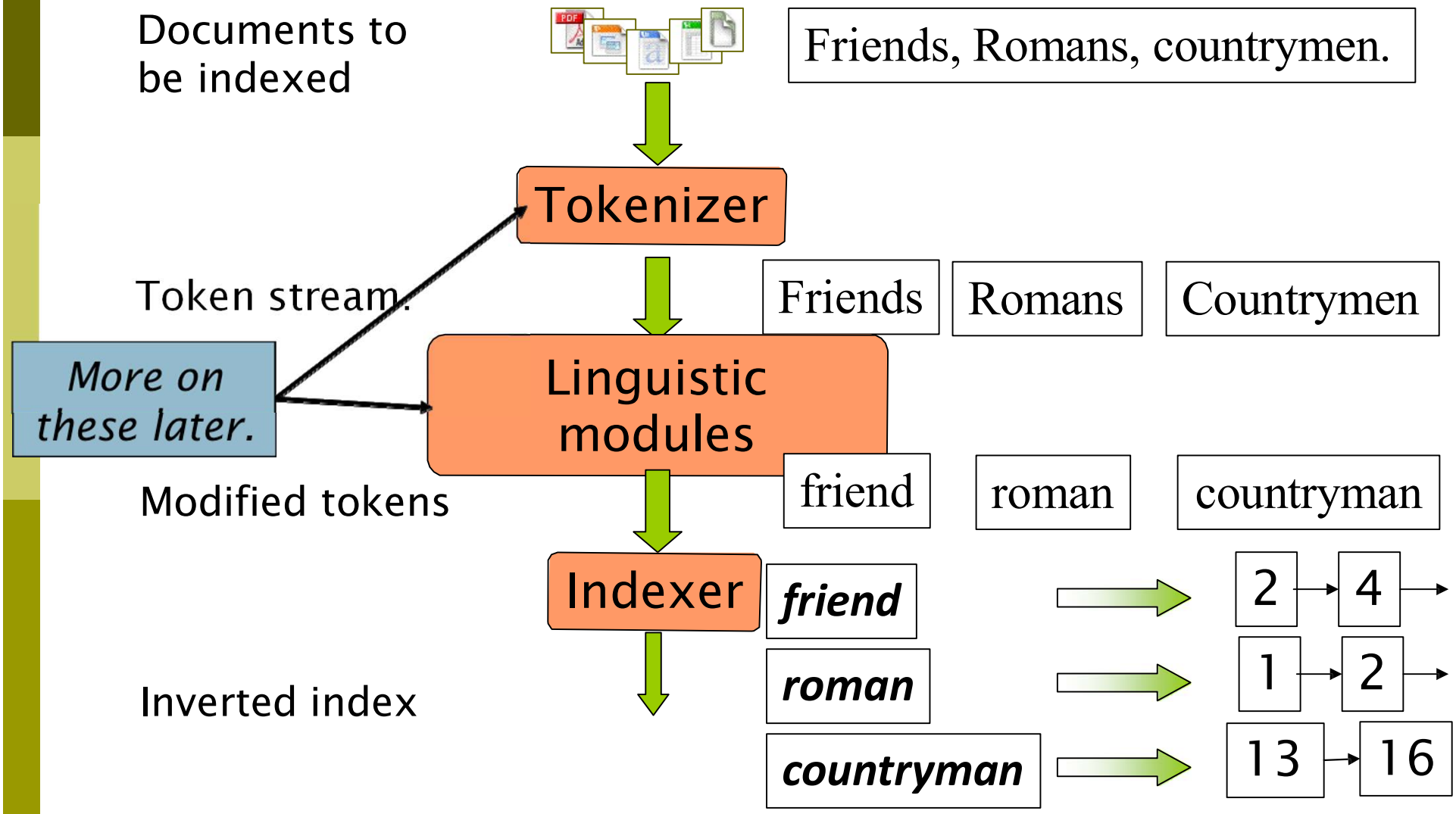
What happens if the word *Caesar* is added to document 14?

Inverted index

- We need variable-size postings lists
  - On disk, a continuous run of postings is normal and best
  - In memory, can use linked lists or variable length arrays
    - Some tradeoffs in size/ease of insertion



Inverted index construction



Indexer steps: Token sequence

- Sequence of (Modified token, Document ID) pairs.

Doc 1

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

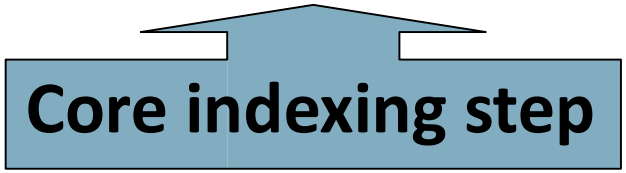
Doc 2

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

Term	docID
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

Indexer steps: Sort

- Sort by terms
  - And then docID



Term	docID
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	docID
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

Indexer steps: Dictionary & Postings

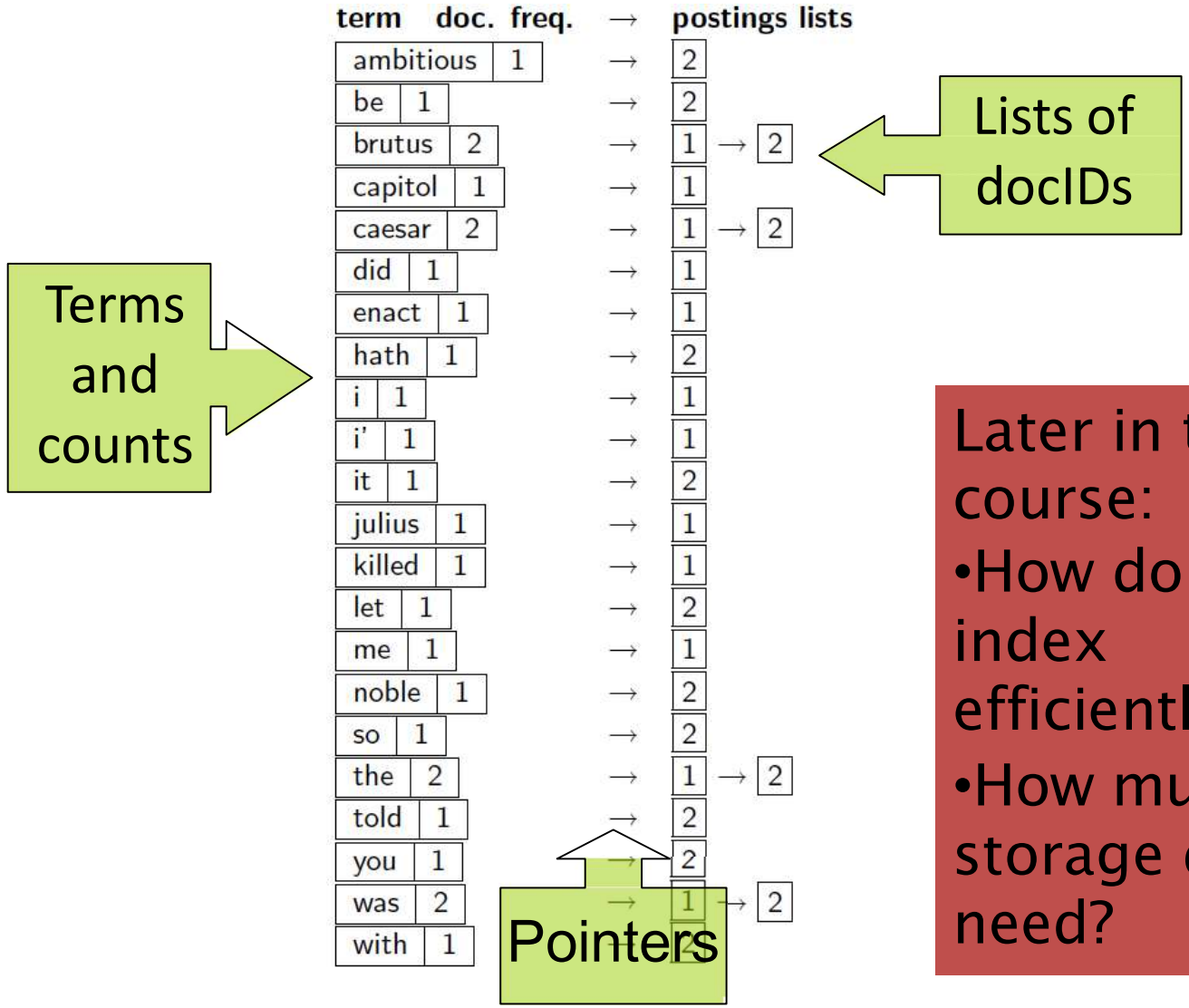
- Multiple term entries in a single document are merged
- Split into Dictionary and Postings
- Doc. frequency information is added.

Why frequency?
Will discuss later

Term	docID
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

term	doc. freq.	→	postings lists
ambitious	1	→	2
be	1	→	2
brutus	2	→	1 → 2
capitol	1	→	1
caesar	2	→	1 → 2
did	1	→	1
enact	1	→	1
hath	1	→	2
i	1	→	1
i'	1	→	1
it	1	→	2
julius	1	→	1
killed	1	→	1
let	1	→	2
me	1	→	1
noble	1	→	2
so	1	→	2
the	2	→	1 → 2
told	1	→	2
you	1	→	2
was	2	→	1 → 2
with	1	→	2

Where do we pay in storage?



Later in the course:

- How do we index efficiently?
- How much storage do we need?

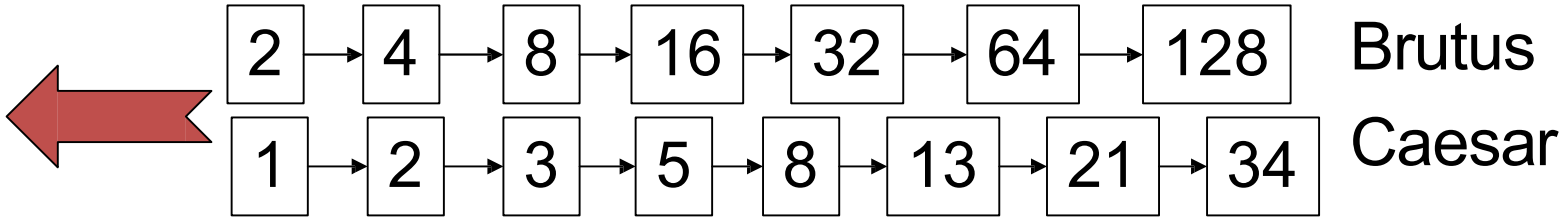
Query processing: AND

- Consider processing the query:

  Brutus *AND* ***Caesar***

  - Locate ***Brutus*** in the Dictionary
    - Retrieve its postings
  - Locate ***Caesar*** in the Dictionary
    - Retrieve its postings
  - "Merge" the two postings

How we can merge?



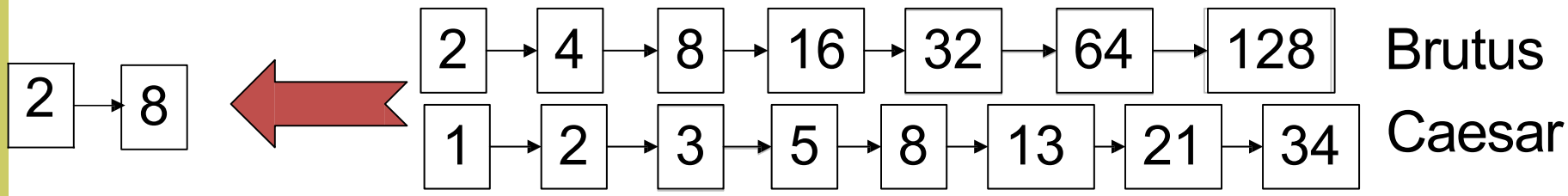
The idea

brutus	nn	02	nn	04	nn	nn	nn	nn	nn	nn	nn	nn	nn	nn	nn	16
cesar	01	02	nn	nn	05	nn	nn	08	nn	nn	nn	nn	13	nn	nn	nn
position	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16

- If we have the incidence vectors we scan in parallel the entries of the two vectors – starting from the first position *(here I wrote "02" instead of 1 and "nn" instead of 0)*
- Try to replicate this idea but imagine that in these two arrays you removed the "nn" entries ...
- Advance to the next entry in the smallest position, i.e., to the smallest docID.

The merge

- Walk through the two postings simultaneously, in time linear in the total number of postings entries



If the list lengths are *x* and *y*, the merge takes O(*x*+*y*) operations.

Crucial: postings sorted by docID.

Intersecting two postings lists (a "merge" algorithm)

```
INTERSECT(p1, p2)
 1  answer ← ⟨ ⟩
 2  while p1 ≠ NIL and p2 ≠ NIL
 3  do if docID(p1) = docID(p2)
 4        then ADD(answer, docID(p1))
 5             p1 ← next(p1)
 6             p2 ← next(p2)
 7        else if docID(p1) < docID(p2)
 8                then p1 ← next(p1)
 9                else p2 ← next(p2)
10  return answer
```

Boolean queries: Exact match

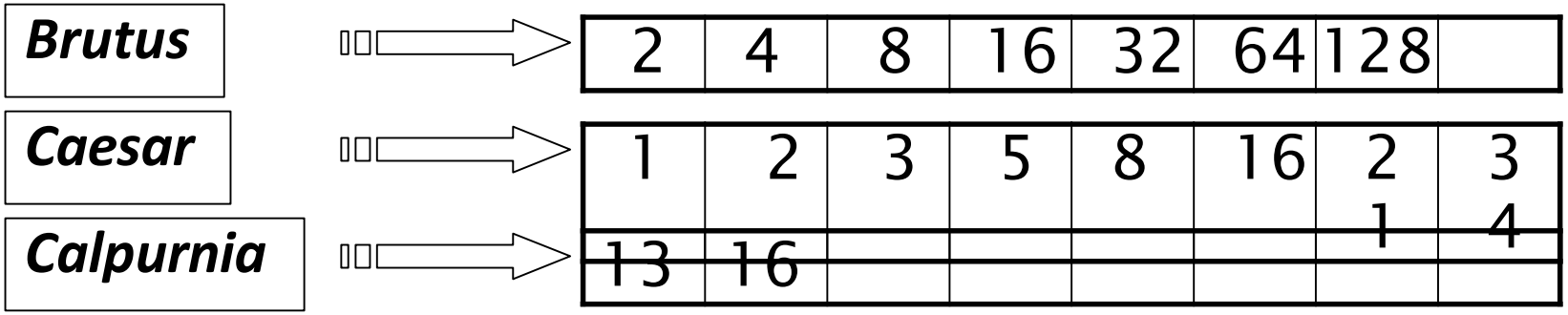
- The Boolean retrieval model is being able to ask a query that is a Boolean expression:
  - Boolean Queries are queries using *AND, OR* and *NOT* to join query terms
    - Views each document as a set of words
    - Is precise: document matches condition or not.
  - Perhaps the simplest model to build an IR system on
- Primary commercial retrieval tool for 3 decades
- Many search systems you still use are Boolean:
  - Email, library catalog, Mac OS X Spotlight.

Example: WestLaw http://www.westlaw.com/

- Largest commercial (paying subscribers) legal search service (started 1975; ranking added 1992)
- Tens of terabytes of data; 700,000 users
- Majority of users *still* use boolean queries
- Example query:
  - What is the statute of limitations in cases involving the federal tort claims act?
  - LIMIT! /3 STATUTE ACTION /S FEDERAL /2 TORT /3 CLAIM
    - /3 = within 3 words, /S = in same sentence

Query optimization

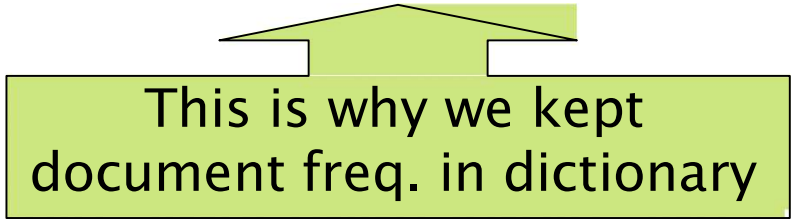
- What is the best order for query processing?
- Consider a query that is an *AND* of *n* terms
- For each of the *n* terms, get its postings, then *AND* them together

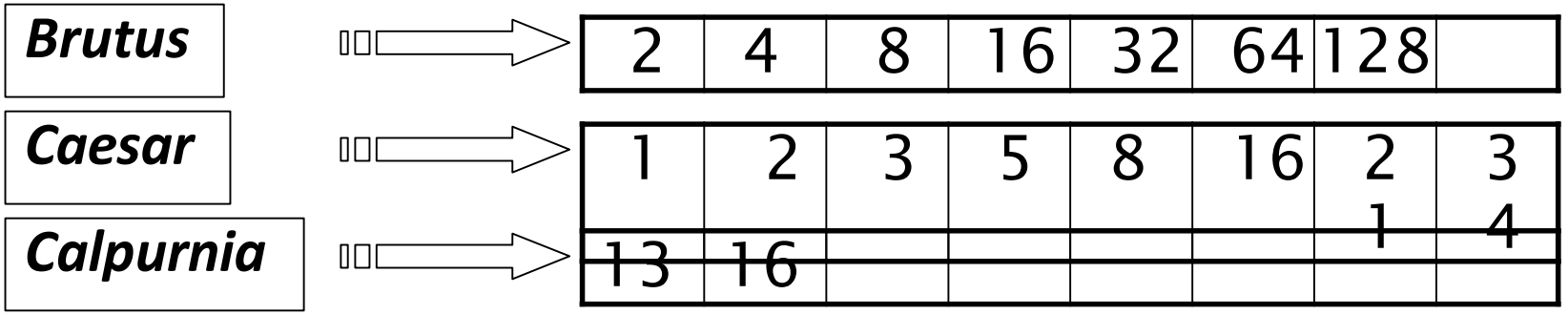


Query: ***Brutus*** *AND* ***Calpurnia*** *AND* ***Caesar***

Query optimization example

- Process in order of increasing freq:
  - *start with smallest set, then **keep cutting** further*.





Execute the query as (***Calpurnia** AND **Brutus)** AND **Caesar***.

Algorithm for conjunctive queries

```
INTERSECT(⟨t_1, ..., t_n⟩)
1  terms ← SORTBYINCREASINGFREQUENCY(⟨t_1, ..., t_n⟩)
2  result ← postings(first(terms))
3  terms ← rest(terms)
4  while terms ≠ NIL and result ≠ NIL
5  do result ← INTERSECT(result, postings(first(terms)))
6     terms ← rest(terms)
7  return result
```

- The intermediate result is in memory
- The list is being intersected with is read from disk
- The intermediate result is always shorter and shorter

More general optimization

- e.g., *(**madding** OR **crowd**) AND (**ignoble** OR **strife**)*
- Get doc. freq.'s for all terms
- Estimate the size of each *OR* by the sum of its doc. freq.'s (conservative)
- Process in increasing order of *OR* sizes.

Exercise

- Recommend a query processing order for

***(tangerine** OR **trees)** AND*
***(marmalade** OR **skies)** AND*
(kaleidoscope** OR **eyes)

Term	Freq
eyes	213312
kaleidoscope	87009
marmalade	107913
skies	271658
tangerine	46653
trees	316812

What's ahead in IR? Beyond term search

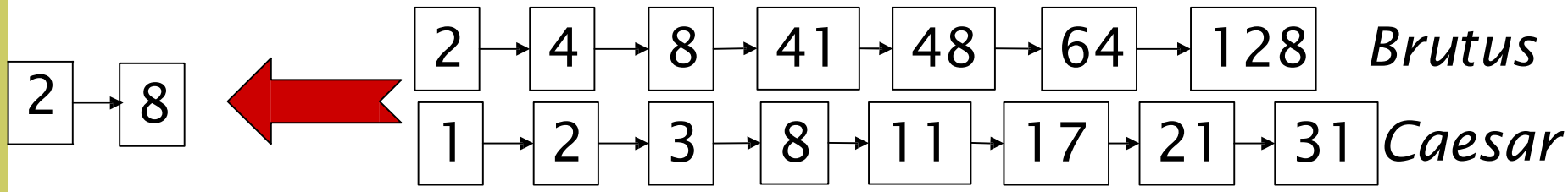
- What about phrases?
  - ***Stanford University***
- Proximity: Find ***Gates*** *NEAR* ***Microsoft***.
  - Need index to capture position information in docs.
- Zones in documents: Find documents with (*author* = ***Ullman***) *AND* (text contains ***automata***).

Evidence accumulation

- 1 vs. 0 occurrence of a search term
  - 2 vs. 1 occurrence
  - 3 vs. 2 occurrences, etc.
  - Usually more seems better
- Need term frequency information in docs

FASTER POSTINGS MERGES: SKIP POINTERS

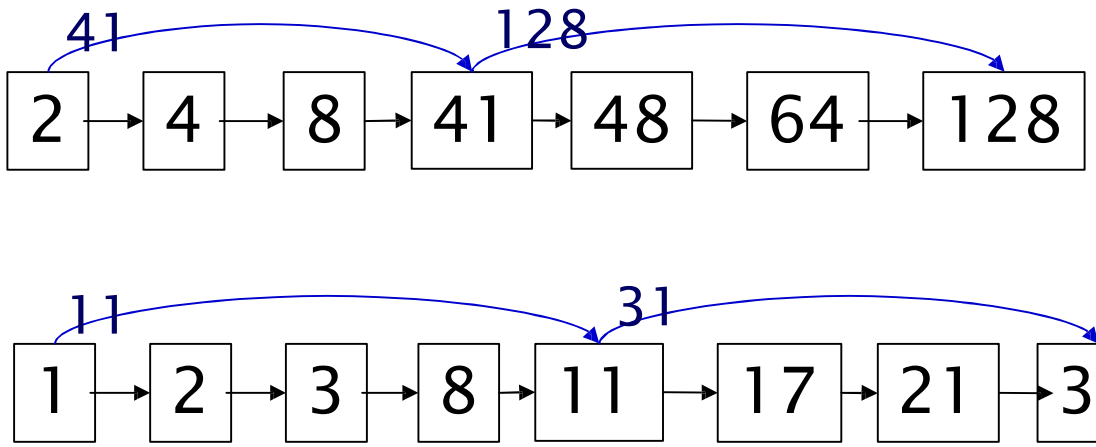
- Walk through the two postings simultaneously, in time linear in the total number of postings entries



If the list lengths are *m* and *n*, the merge takes O(*m*+*n*) operations.

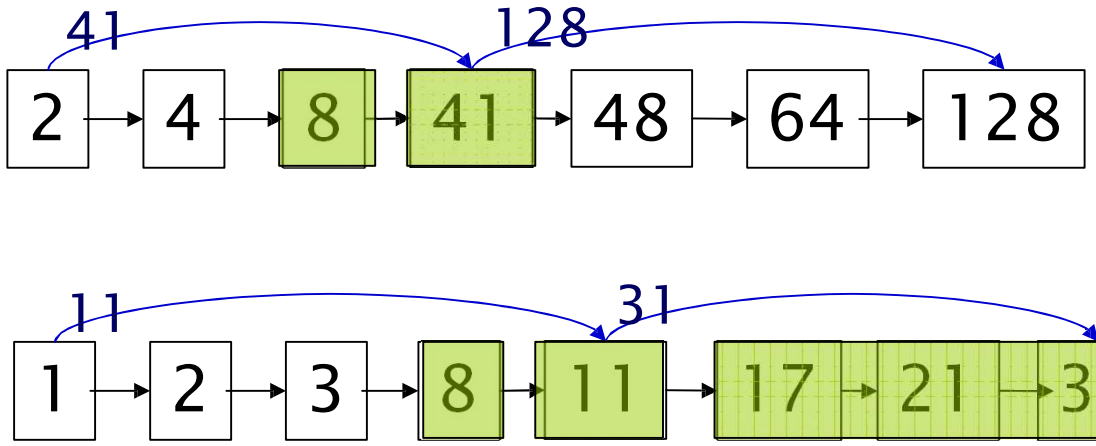
Can we do better?
Yes (if index isn't changing too fast).

Augment postings with skip pointers (at indexing time)



- Why?
- To skip postings that will not figure in the search results.
- How?
- Where do we place skip pointers?

Query processing with skip pointers



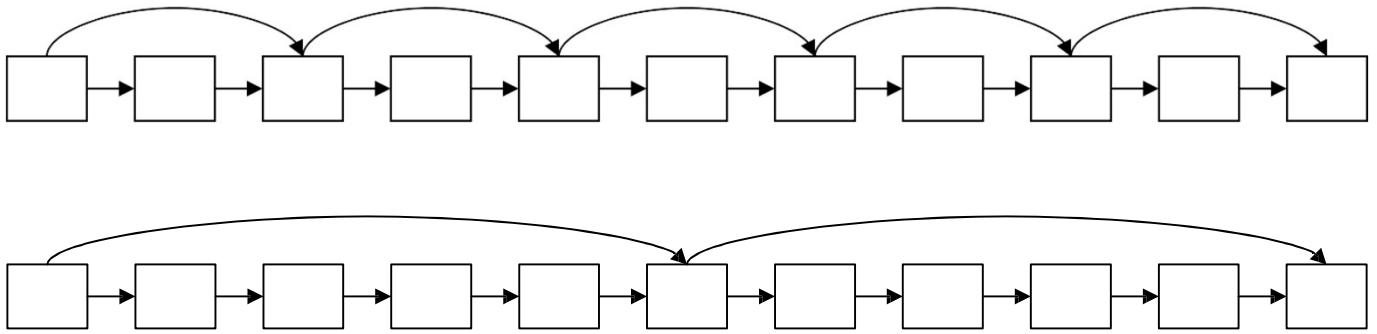
Suppose we've stepped through the lists until we process 8 on each list. We match it and advance.

We then have 41 and 11 on the lower. 11 is smaller.

But the skip successor of 11 on the lower list is 31, so we can skip ahead past the intervening postings.

Where do we place skips?

- Tradeoff:
  - More skips → shorter skip spans ⇒ more likely to skip. But lots of comparisons to skip pointers.
  - Fewer skips → few pointer comparison, but then long skip spans ⇒ few successful skips.

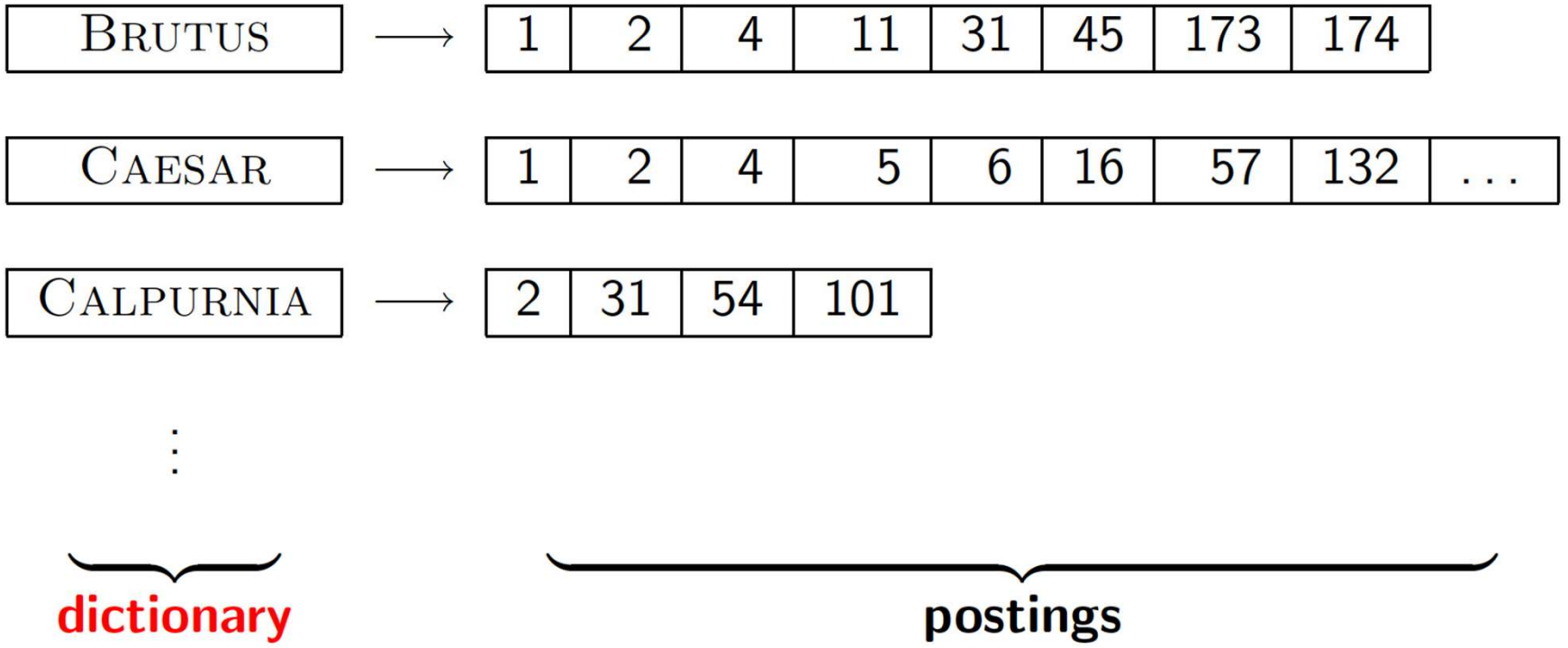


Placing skips

- Simple heuristic: for postings of length L, use $\sqrt{L}$ evenly-spaced skip pointers
- This ignores the distribution of query terms
- Easy if the index is relatively static; harder if L keeps changing because of updates

Dictionary data structures for inverted indexes

- The dictionary data structure stores the term vocabulary, document frequency, pointers to each postings list … in what data structure?



A naïve dictionary

- An array of struct:

term	document frequency	pointer to postings list
a	656,265	⟶
aachen	65	⟶
. . .	. . .	. . .
zulu	221	⟶

char[20]	int	Postings *
20 bytes	4/8 bytes	4/8 bytes

- How do we store a dictionary in memory efficiently?
- How do we quickly look up elements at query time?

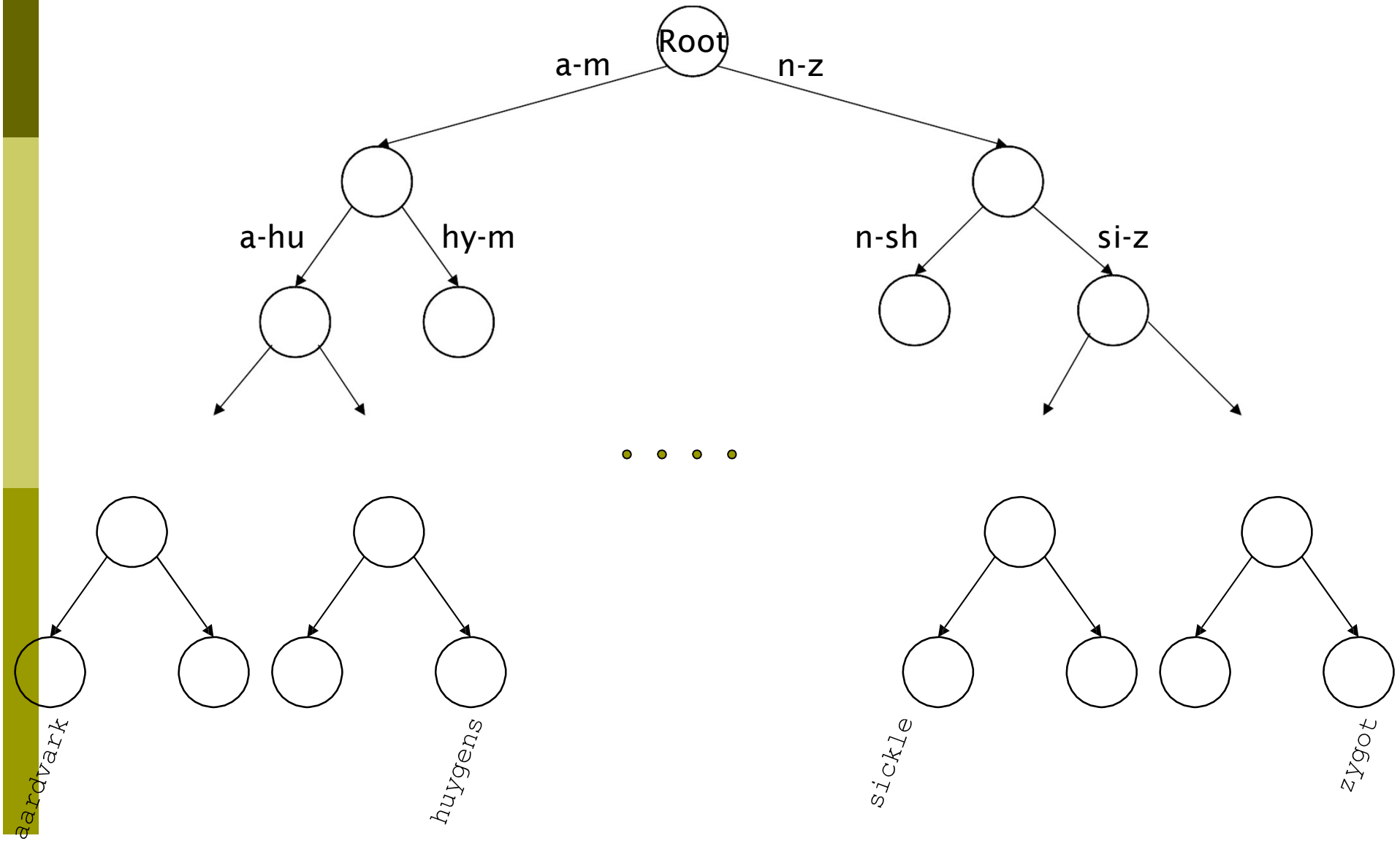
Dictionary data structures

- Two main choices:
  - Hash table
  - Tree
- Some IR systems use hashes, some trees

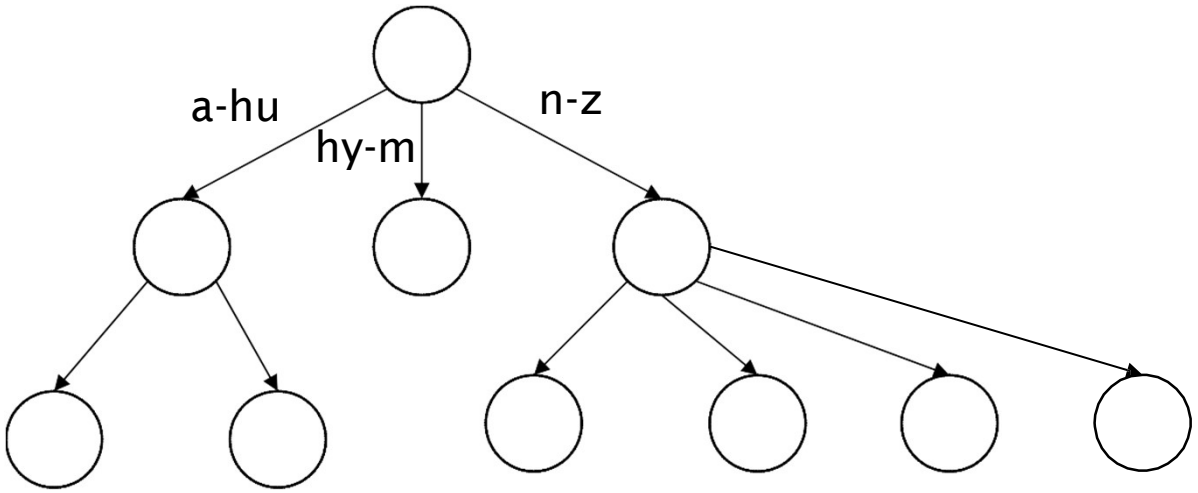
Hashes

- Each vocabulary term is hashed to an integer
  - (We assume you've seen hashtables before)
- Pros:
  - Lookup is faster than for a tree: O(1)
- Cons:
  - No easy way to find minor variants:
    - judgment/judgement
  - No prefix search [tolerant retrieval]
  - If vocabulary keeps growing, need to occasionally do the expensive operation of rehashing *everything*

Tree: binary tree



Tree: B-tree



- Definition: Every internal node has a number of children in the interval [*a*,*b*] where *a, b* are appropriate natural numbers, e.g., [2,4].

Trees

- *Simplest:* binary tree
- *More usual:* B-trees
- Trees require a standard ordering of characters and hence strings … but we have one – lexicographic
  - Unless we are dealing with Chinese (no unique ordering)
- *Pros:*
  - Solves the prefix problem (terms starting with 'hyp')
- *Cons:*
  - Slower: O(log M) [and this requires balanced tree]
  - Rebalancing binary trees is expensive
    - But B-trees mitigate the rebalancing problem.