

# Introduction to **Information Retrieval**

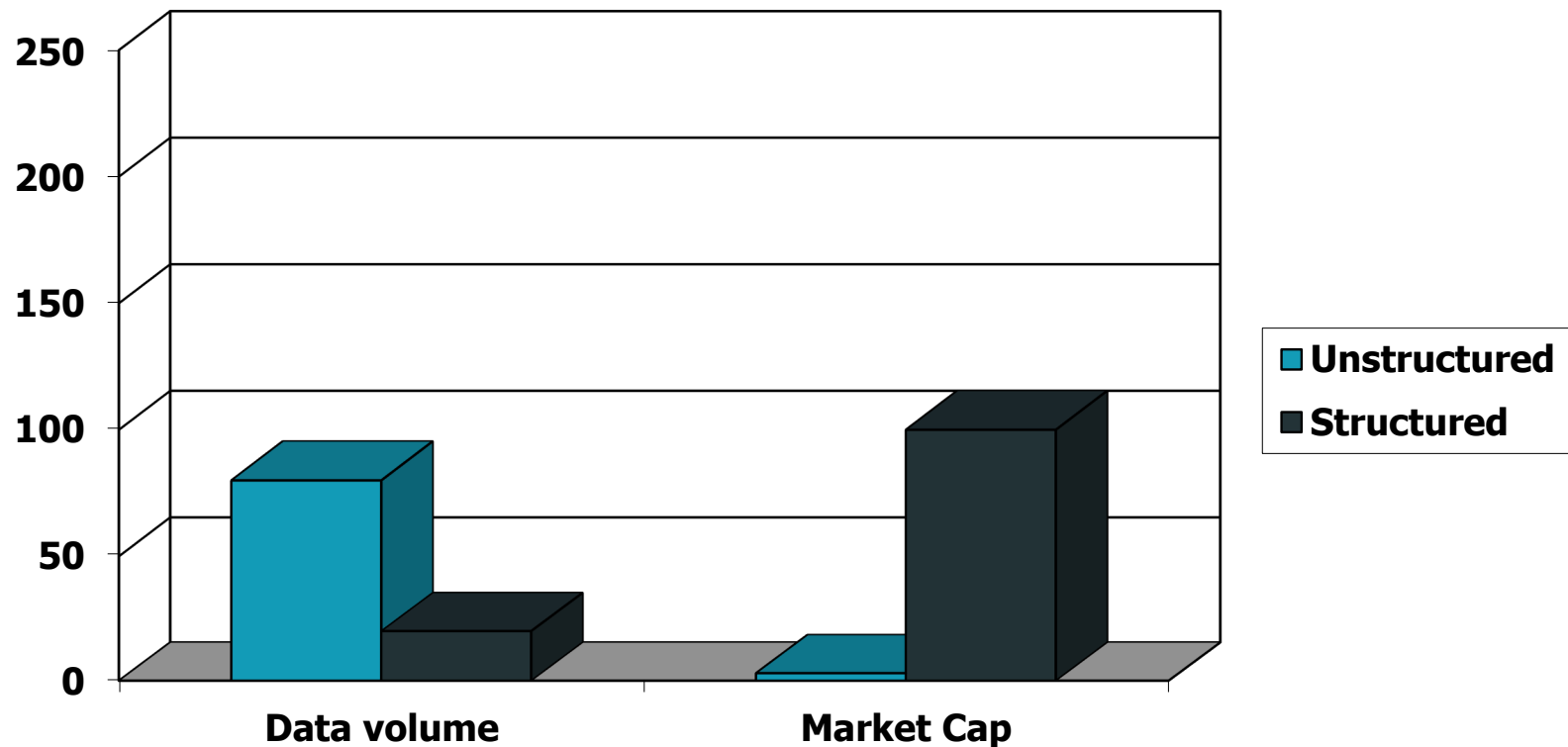
Introducing Information Retrieval  
and Web Search

# Information Retrieval

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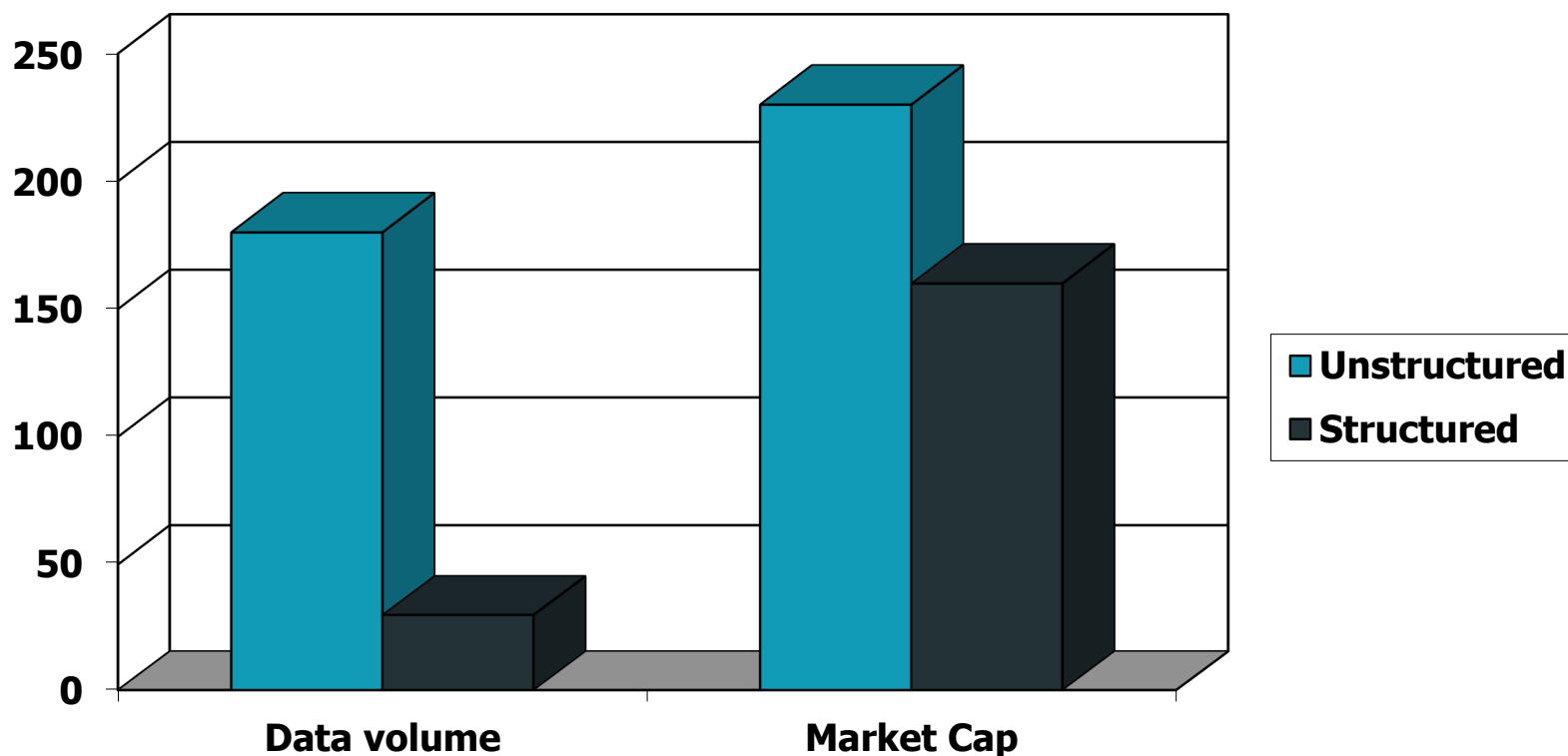
- Information Retrieval (IR) is **finding material** (usually documents) of an **unstructured** nature (usually text) that satisfies an **information need** from within **large collections** (usually stored on computers).
- These days we frequently think first of **web search**, but there are many other cases:
  - E-mail search
  - Searching your laptop
  - Corporate knowledge bases
  - Legal information retrieval

# Unstructured (text) vs. structured (database) data in the mid-nineties



# Unstructured (text) vs. structured (database) data today

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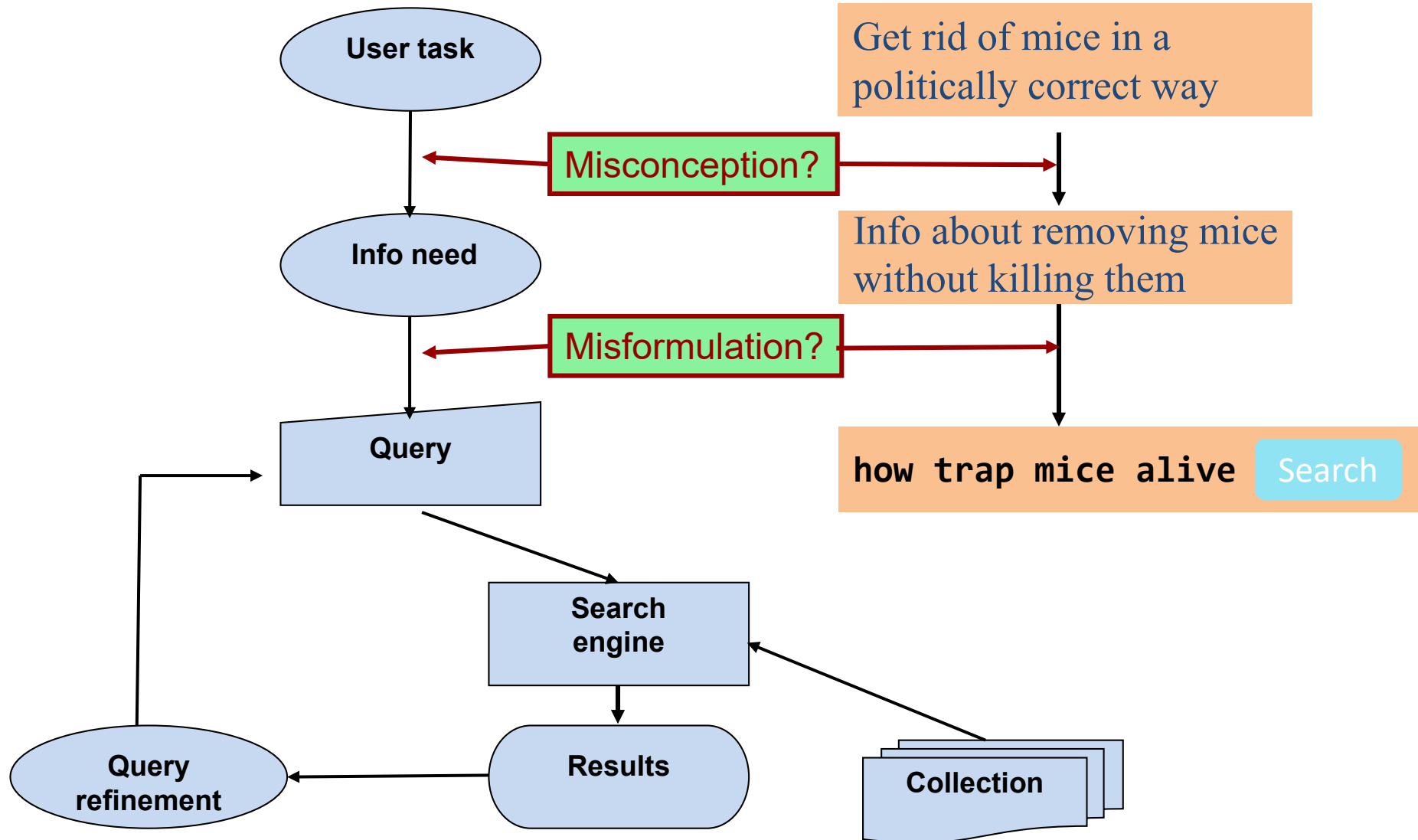


# Basic assumptions of Information Retrieval

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- **Collection:** A set of documents
  - Assume it is a static collection for the moment
- **Goal:** Retrieve documents with information that is **relevant** to the user's **information need** and helps the user complete a **task**

# The classic search model



# How good are the retrieved docs?

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- *Precision* : Fraction of retrieved docs that are relevant to the user's **information need**
- *Recall* : Fraction of relevant docs in collection that are retrieved
  - More precise definitions and measurements to follow later

# Introduction to **Information Retrieval**

Term-document incidence matrices



# Unstructured data in 1620

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- Which plays of Shakespeare contain the words *Brutus* *AND Caesar* but *NOT Calpurnia*?
- One could grep all of Shakespeare's plays for *Brutus* and *Caesar*, then strip out lines containing *Calpurnia*?
- Why is that not the answer?
  - Slow (for large corpora)
  - NOT *Calpurnia* is non-trivial
  - Other operations (e.g., find the word *Romans* near *countrymen*) not feasible
  - Ranked retrieval (best documents to return)
    - Later lectures

# Term-document incidence matrices

	Antony and Cleopatra	Julius Caesar	The Tempest	Hamlet	Othello	Macbeth
Antony	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: take the vectors for *Brutus*, *Caesar* and *Calpurnia* (complemented) → bitwise *AND*.
  - 110100 *AND*
  - 110111 *AND*
  - 101111 =
  - **100100**

	Antony and Cleopatra	Julius Caesar	The Tempest	Hamlet	Othello	Macbeth
Antony	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

# Answers to query

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- 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.

- Hamlet, Act III, Scene ii

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



# Bigger collections

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- Consider  $N = 1$  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.

# Can't build the matrix

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- 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 1 positions.



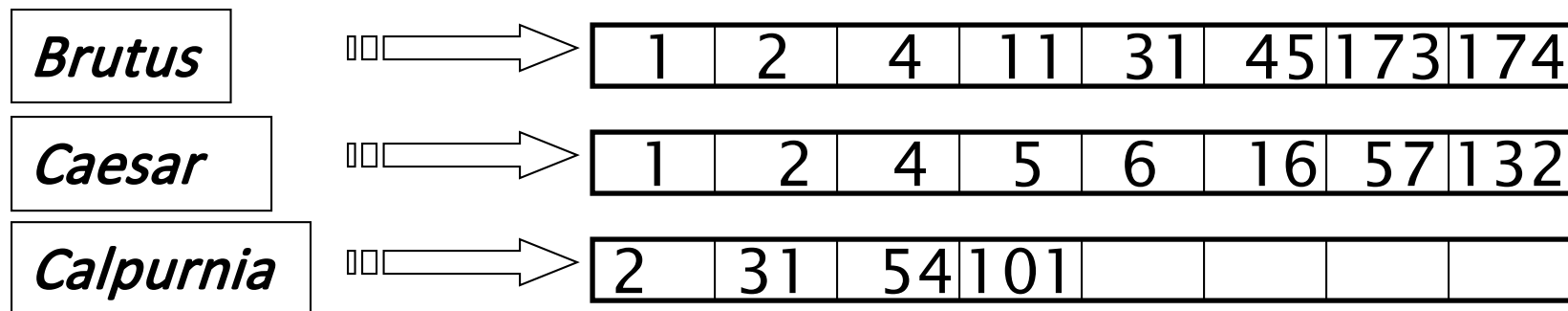
# Introduction to **Information Retrieval**

The Inverted Index

The key data structure underlying modern IR

# Inverted index

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

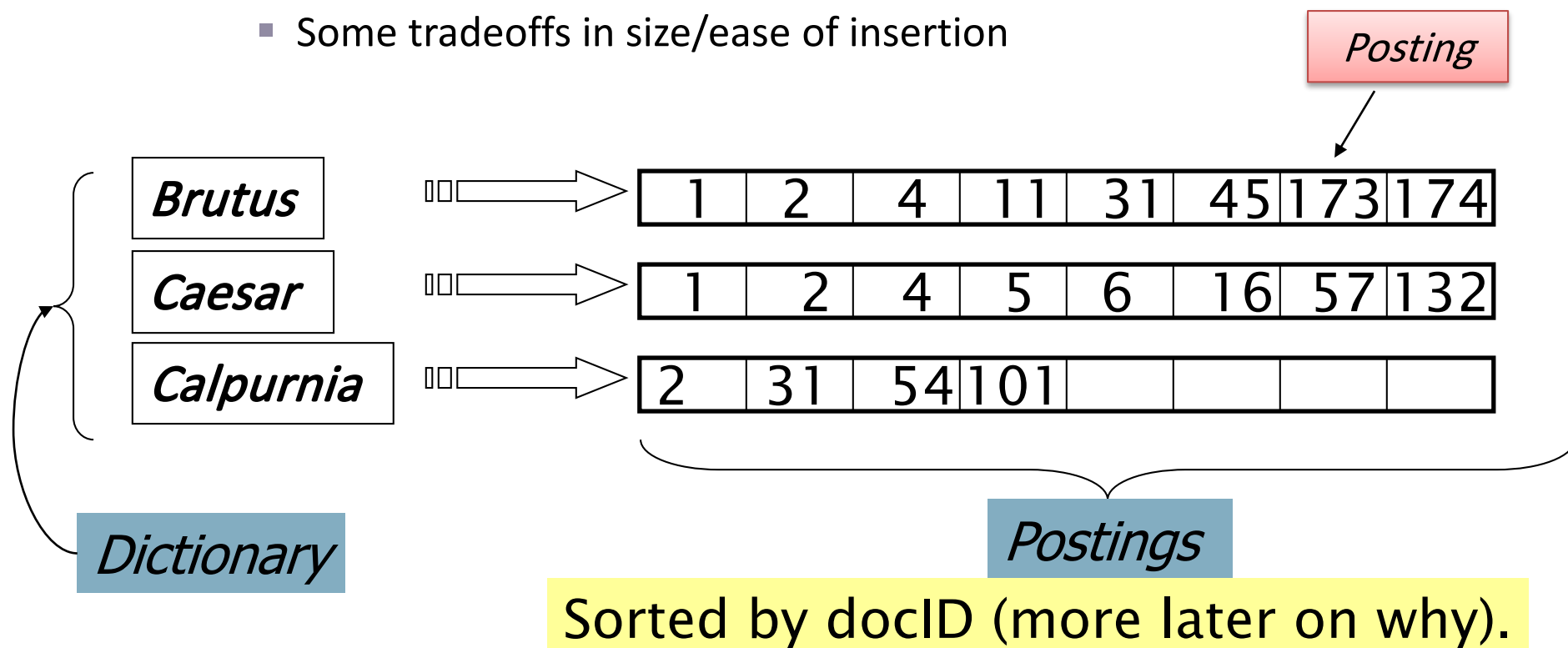


What happens if the word *Caesar* is added to document 14?

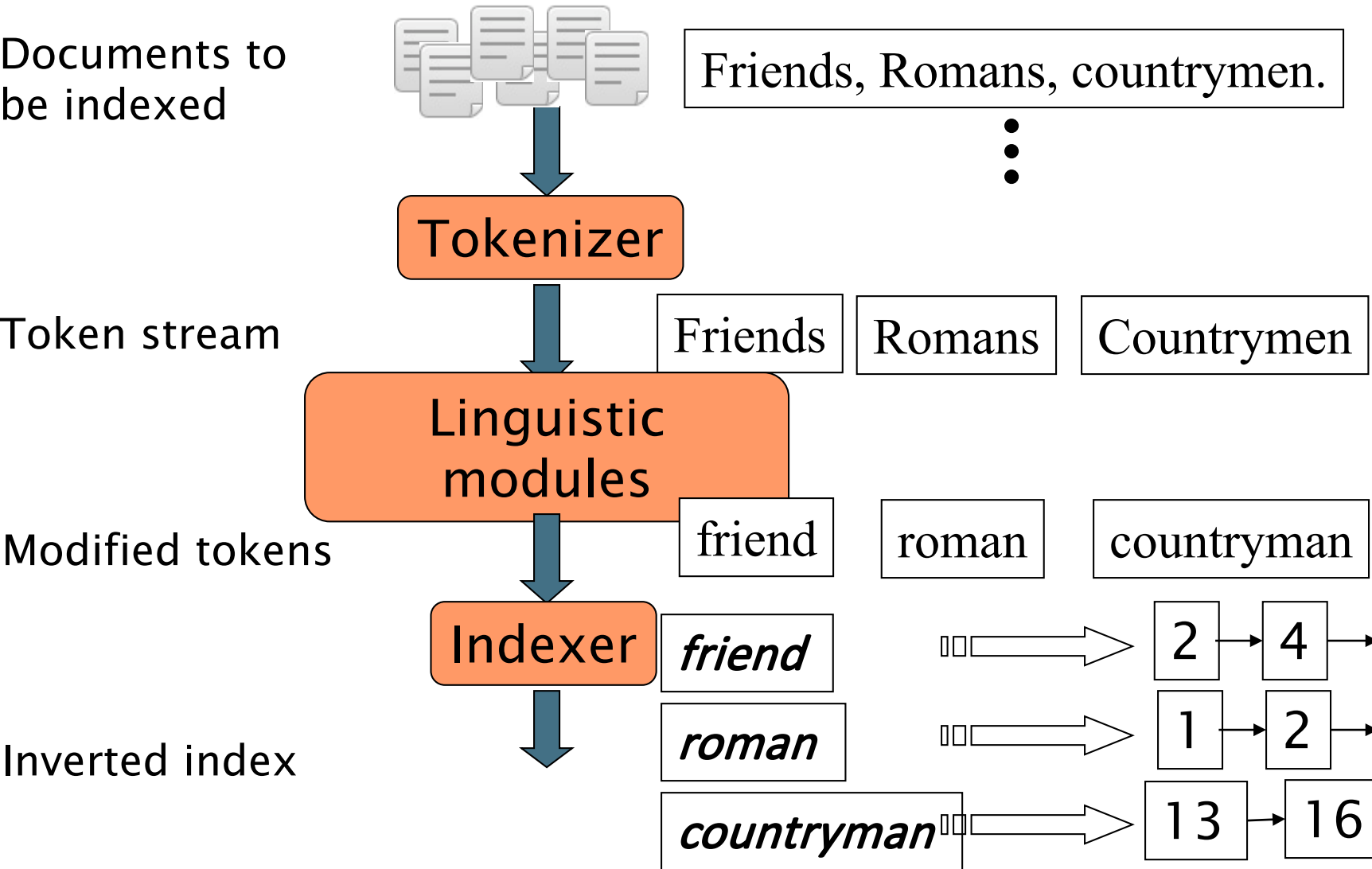


# Inverted index

- 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



# Initial stages of text processing

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- Tokenization
  - Cut character sequence into word tokens
    - Deal with *“John’s”, a state-of-the-art solution*
- Normalization
  - Map text and query term to same form
    - You want *U.S.A.* and *USA* to match
- Stemming
  - We may wish different forms of a root to match
    - *authorize, authorization*
- Stop words
  - We may omit very common words (or not)
    - *the, a, to, of*

# 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
  - At least conceptually
    - 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.

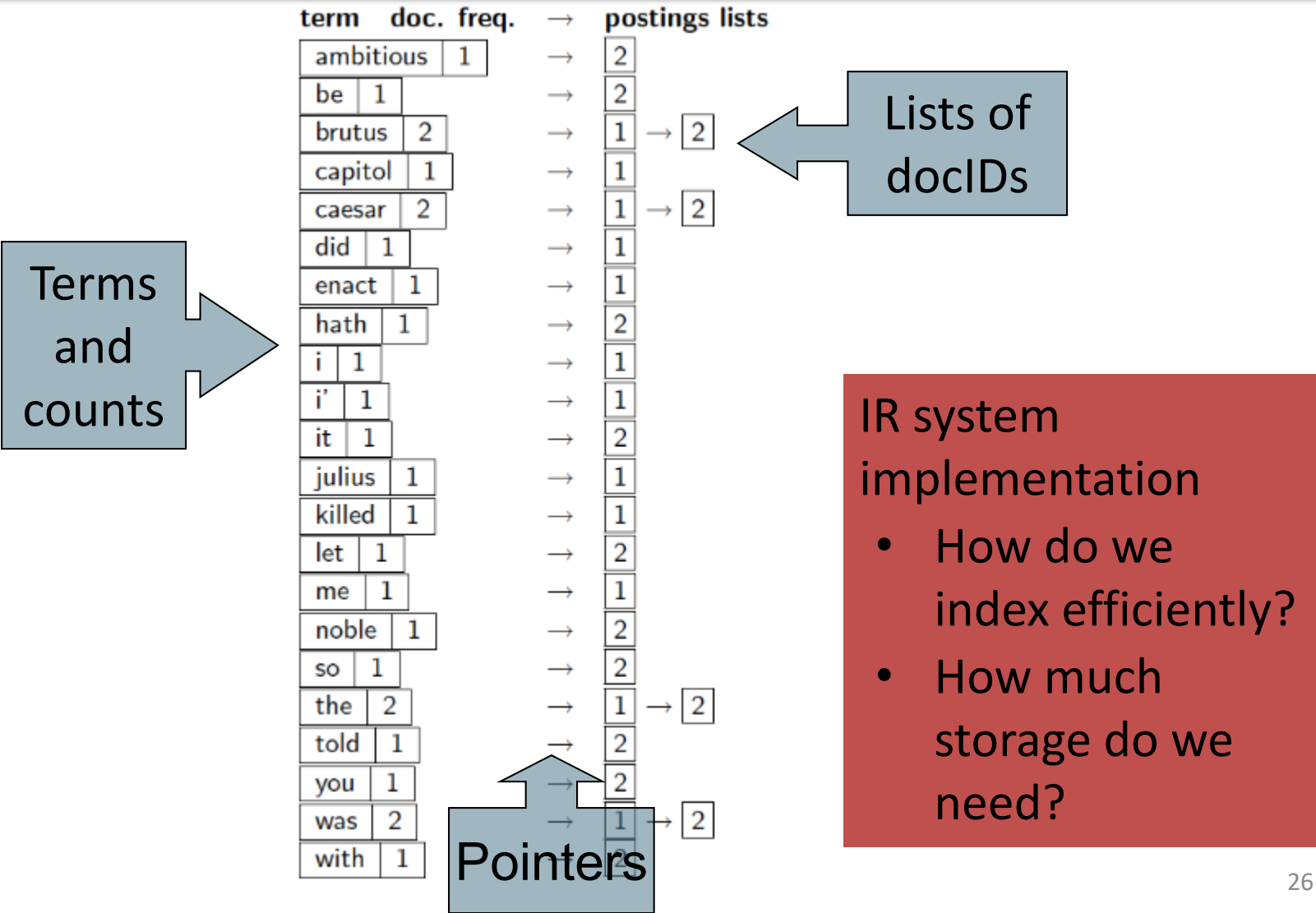
Why frequency?  
Will discuss later.

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?



# Introduction to **Information Retrieval**

Query processing with an inverted index



# The index we just built

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- How do we process a query?
  - Later – what kinds of queries can we process?

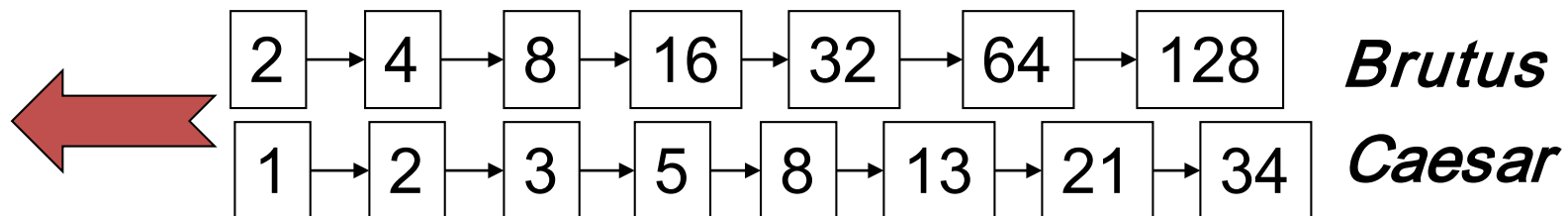


# Query processing: AND

- Consider processing the query:

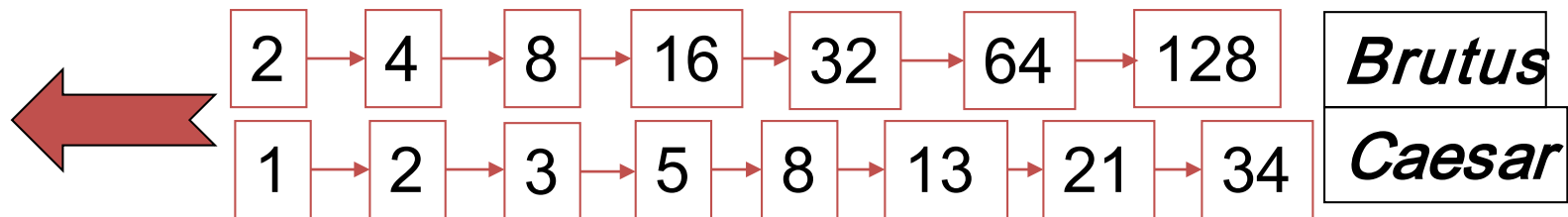
*Brutus AND Caesar*

- Locate *Brutus* in the Dictionary;
  - Retrieve its postings.
- Locate *Caesar* in the Dictionary;
  - Retrieve its postings.
- “Merge” the two postings (intersect the document sets):



# 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)

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```
INTERSECT( $p_1, p_2$ )  
  1   $answer \leftarrow \langle \rangle$   
  2  while  $p_1 \neq \text{NIL}$  and  $p_2 \neq \text{NIL}$   
  3  do if  $docID(p_1) = docID(p_2)$   
  4      then  $\text{ADD}(answer, docID(p_1))$   
  5           $p_1 \leftarrow next(p_1)$   
  6           $p_2 \leftarrow next(p_2)$   
  7      else if  $docID(p_1) < docID(p_2)$   
  8          then  $p_1 \leftarrow next(p_1)$   
  9          else  $p_2 \leftarrow next(p_2)$   
 10  return  $answer$ 
```

# Introduction to **Information Retrieval**

The Boolean Retrieval Model  
& Extended Boolean Models

# Boolean queries: Exact match

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- 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, macOS Spotlight

# Example: WestLaw <http://www.westlaw.com/>

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- Largest commercial (paying subscribers) legal search service (started 1975; ranking added 1992; new federated search added 2010)
- 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

# Example: WestLaw <http://www.westlaw.com/>

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- Another example query:
  - Requirements for disabled people to be able to access a workplace
  - `disabl! /p access! /s work-site work-place (employment /3 place`
- Note that SPACE is disjunction, not conjunction!
- Long, precise queries; proximity operators; incrementally developed; not like web search
- Many professional searchers still like Boolean search
  - You know exactly what you are getting
- But that doesn't mean it actually works better....



# Boolean queries: More general merges

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- Exercise: Adapt the merge for the queries:  
*Brutus AND NOT Caesar*  
*Brutus OR NOT Caesar*
- Can we still run through the merge in time  $O(x+y)$ ?  
What can we achieve?

# Merging

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What about an arbitrary Boolean formula?

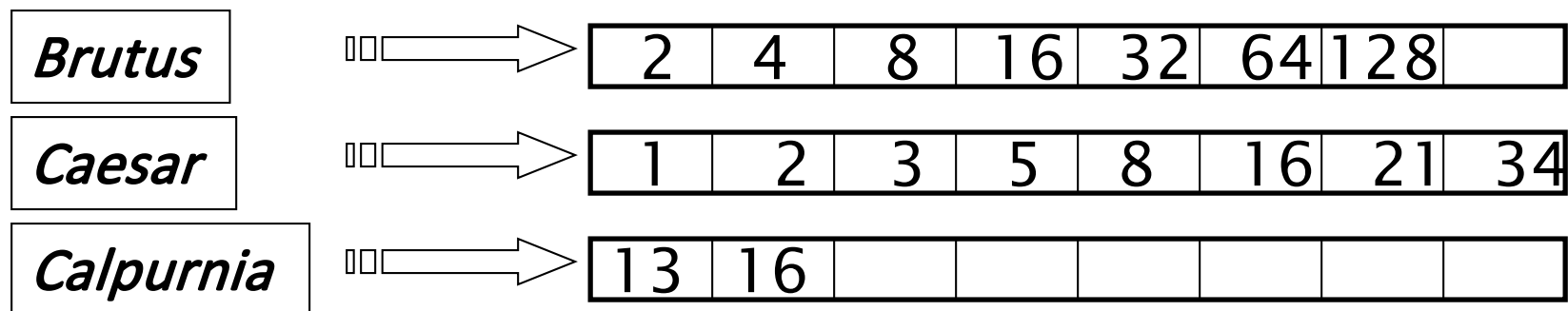
*(Brutus OR Caesar) AND NOT*

*(Antony OR Cleopatra)*

- Can we always merge in “linear” time?
  - Linear in what?
- Can we do better?

# 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.*

This is why we kept  
document freq. in dictionary

<b><i>Brutus</i></b>	⇒	2	4	8	16	32	64	128	
<b><i>Caesar</i></b>	⇒	1	2	3	5	8	16	21	34
<b><i>Calpurnia</i></b>	⇒	13	16						

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

# Exercise

- Recommend a query processing order for

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

- Which two terms should we process first?

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

# More general optimization

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- 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.

# Query processing exercises

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- **Exercise:** If the query is *friends AND romans AND (NOT countrymen)*, how could we use the freq of *countrymen*?
- **Exercise:** Extend the merge to an arbitrary Boolean query. Can we always guarantee execution in time linear in the total postings size?
- **Hint:** Begin with the case of a Boolean *formula* query: in this, each query term appears only once in the query.

# Exercise

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- Try the search feature at <http://www.rhymezone.com/shakespeare/>
- Write down five search features you think it could do better



# Introduction to **Information Retrieval**

Phrase queries and positional indexes



# Phrase queries

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- We want to be able to answer queries such as *“stanford university”* – as a phrase
- Thus the sentence *“I went to university at Stanford”* is not a match.
  - The concept of phrase queries has proven easily understood by users; one of the few “advanced search” ideas that works
  - Many more queries are *implicit phrase queries*
- For this, it no longer suffices to store only *<term : docs>* entries



# A first attempt: Biword indexes

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- Index every consecutive pair of terms in the text as a phrase
- For example the text “Friends, Romans, Countrymen” would generate the biwords
  - *friends romans*
  - *romans countrymen*
- Each of these biwords is now a dictionary term
- Two-word phrase query-processing is now immediate.



# Longer phrase queries

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- Longer phrases can be processed by breaking them down
- *stanford university palo alto* can be broken into the Boolean query on biwords:

*stanford university AND university palo AND palo alto*

Without the docs, we cannot verify that the docs matching the above Boolean query do contain the phrase.



Can have false positives!

# Issues for biword indexes

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- False positives, as noted before
- Index blowup due to bigger dictionary
  - Infeasible for more than biwords, big even for them
- Biword indexes are not the standard solution (for all biwords) but can be part of a compound strategy



## Solution 2: Positional indexes

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- In the postings, store, for each *term* the position(s) in which tokens of it appear:

<*term*, number of docs containing *term*;

*doc1*: position1, position2 ... ;

*doc2*: position1, position2 ... ;

etc.>



# Positional index example

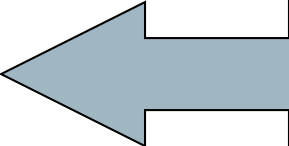
<*be*: 993427;

*1*: 7, 18, 33, 72, 86, 231;

*2*: 3, 149;

*4*: 17, 191, 291, 430, 434;

*5*: 363, 367, ...>



Which of docs *1,2,4,5*  
could contain “*to be*  
*or not to be*”?

- For phrase queries, we use a merge algorithm recursively at the document level
- But we now need to deal with more than just equality



# Processing a phrase query

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- Extract inverted index entries for each distinct term:  
*to, be, or, not.*
- Merge their *doc:position* lists to enumerate all positions with “*to be or not to be*”.
  - *to:*
    - 2:1,17,74,222,551; 4:8,16,190,429,433; 7:13,23,191; ...
  - *be:*
    - 1:17,19; 4:17,191,291,430,434; 5:14,19,101; ...
- Same general method for proximity searches





# Proximity queries

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- LIMIT! /3 STATUTE /3 FEDERAL /2 TORT
  - Again, here, / $k$  means “within  $k$  words of”.
- Clearly, positional indexes can be used for such queries; biword indexes cannot.
- Exercise: Adapt the linear merge of postings to handle proximity queries. Can you make it work for any value of  $k$ ?
  - This is a little tricky to do correctly and efficiently
  - See Figure 2.12 of *IIR*



# Positional index size

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- A positional index expands postings storage *substantially*
  - Even though indices can be compressed
- Nevertheless, a positional index is now standardly used because of the power and usefulness of phrase and proximity queries ... whether used explicitly or implicitly in a ranking retrieval system.



# Positional index size

- Need an entry for each occurrence, not just once per document
- Index size depends on average document size
  - Average web page has <1000 terms
  - SEC filings, books, even some epic poems ... easily 100,000 terms
- Consider a term with frequency 0.1%



Document size	Postings	Positional postings
1 000	1	1
1 00,000	1	1 00



# Rules of thumb

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- A positional index is 2–4 as large as a non-positional index
- Positional index size 35–50% of volume of original text
  - Caveat: all of this holds for “English-like” languages



# Combination schemes

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- These two approaches can be profitably combined
  - For particular phrases ( *“Michael Jackson”*, *“Britney Spears”* ) it is inefficient to keep on merging positional postings lists
    - Even more so for phrases like *“The Who”*
- Williams et al. (2004) evaluate a more sophisticated mixed indexing scheme
  - A typical web query mixture was executed in  $\frac{1}{4}$  of the time of using just a positional index
  - It required 26% more space than having a positional index alone



# Introduction to **Information Retrieval**

Structured vs. Unstructured Data



# What's ahead in IR?

## Beyond term search

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- 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

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- 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





# Ranking search results

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- Boolean queries give inclusion or exclusion of docs.
- Often we want to rank/group results
  - Need to measure proximity from query to each doc.
  - Need to decide whether docs presented to user are singletons, or a group of docs covering various aspects of the query.



# IR vs. databases:

## Structured vs unstructured data

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- Structured data tends to refer to information in “tables”

Employee	Manager	Salary
Smith	Jones	50000
Chang	Smith	60000
Ivy	Smith	50000

Typically allows numerical range and exact match (for text) queries, e.g.,

*Salary < 60000 AND Manager = Smith.*



# Unstructured data

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- Typically refers to free text
- Allows
  - Keyword queries including operators
  - More sophisticated “concept” queries e.g.,
    - find all web pages dealing with *drug abuse*
- Classic model for searching text documents



# Semi-structured data

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- In fact almost no data is “unstructured”
- E.g., this slide has distinctly identified zones such as the *Title* and *Bullets*
  - ... to say nothing of linguistic structure
- Facilitates “semi-structured” search such as
  - *Title* contains data AND *Bullets* contain search
- Or even
  - *Title* is about Object Oriented Programming AND *Author* something like stro\*rup
  - where \* is the wild-card operator



# Semi-structured data

---

- In fact almost no data is “unstructured”
- E.g., this slide has distinctly identified zones such as the *Title* and *Bullets*
- Facilitates “semi-structured” search such as
  - *Title* contains data AND *Bullets* contain search

... to say nothing of linguistic structure



# More sophisticated semi-structured search

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- *Title* is about Object Oriented Programming AND *Author* something like stro\*rup
- where \* is the wild-card operator
- Issues:
  - how do you process “about”?
  - how do you rank results?
- The focus of XML search (*IR* chapter 10)

