# Topic 1: Indexing

## COMP3009J: Information Retrieval

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# Introduction: Indexing

- So that we can search a document collection, we must represent the documents in some type of data structure.
- We frequently refer to this data structure as an **index**.
- As we saw in the first lecture, an incidence matrix is one possibility, but does not scale well for larger document collections.

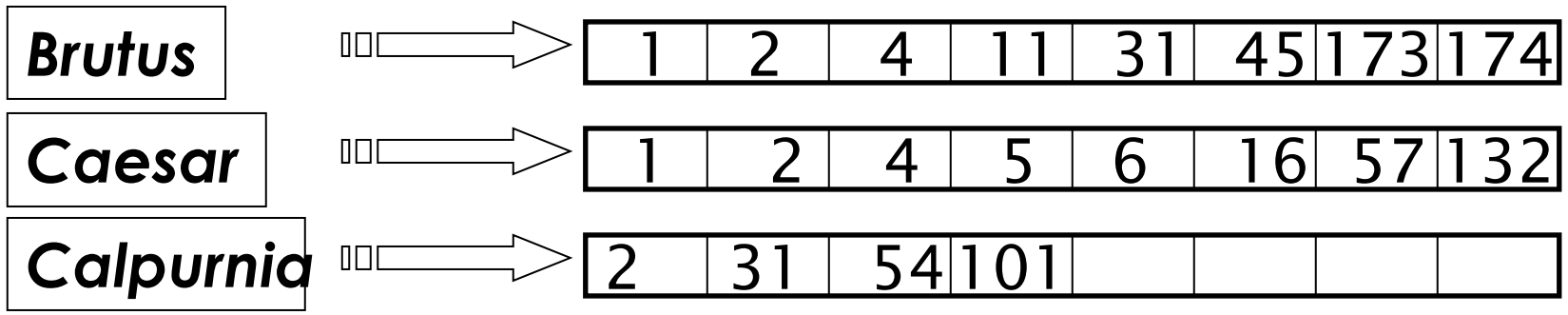
| | Antony and Cleopatra | Julius Caesar | The Tempest | Hamlet | Othello | Macbeth |
|---|---|---|---|---|---|---|
| Antony | 1 | 1 | 0 | 0 | 0 | 1 |
| Brutus | 1 | 1 | 0 | 1 | 0 | 0 |
| Caesar | 1 | 1 | 0 | 1 | 1 | 1 |
| Calpurnia | 0 | 1 | 0 | 0 | 0 | 0 |
| Cleopatra | 1 | 0 | 0 | 0 | 0 | 0 |
| mercy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

# Inverted Index

- An **inverted index** is a type of data structure where for each term *t*, we store a list of documents that contain *t*.
  - We identify each document using a **docID**: a unique identifier for each document.
- Can we use fixed-sized arrays for this?

What is a **term**?

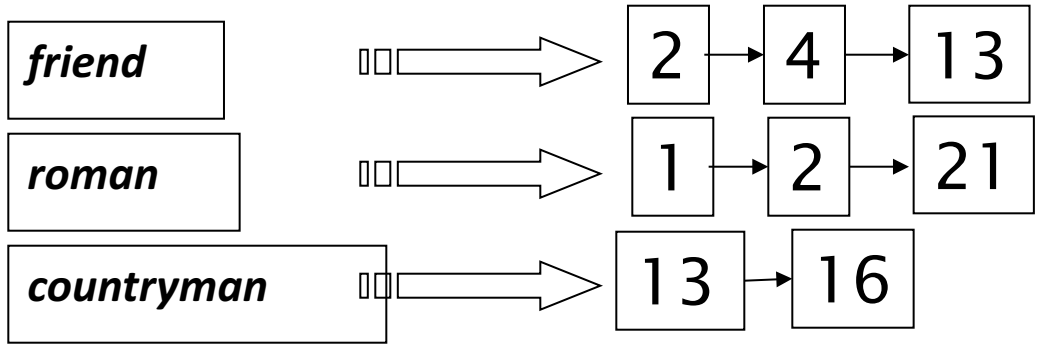
For now, we can think of a term as being a word. Later we will see that they are slightly different.



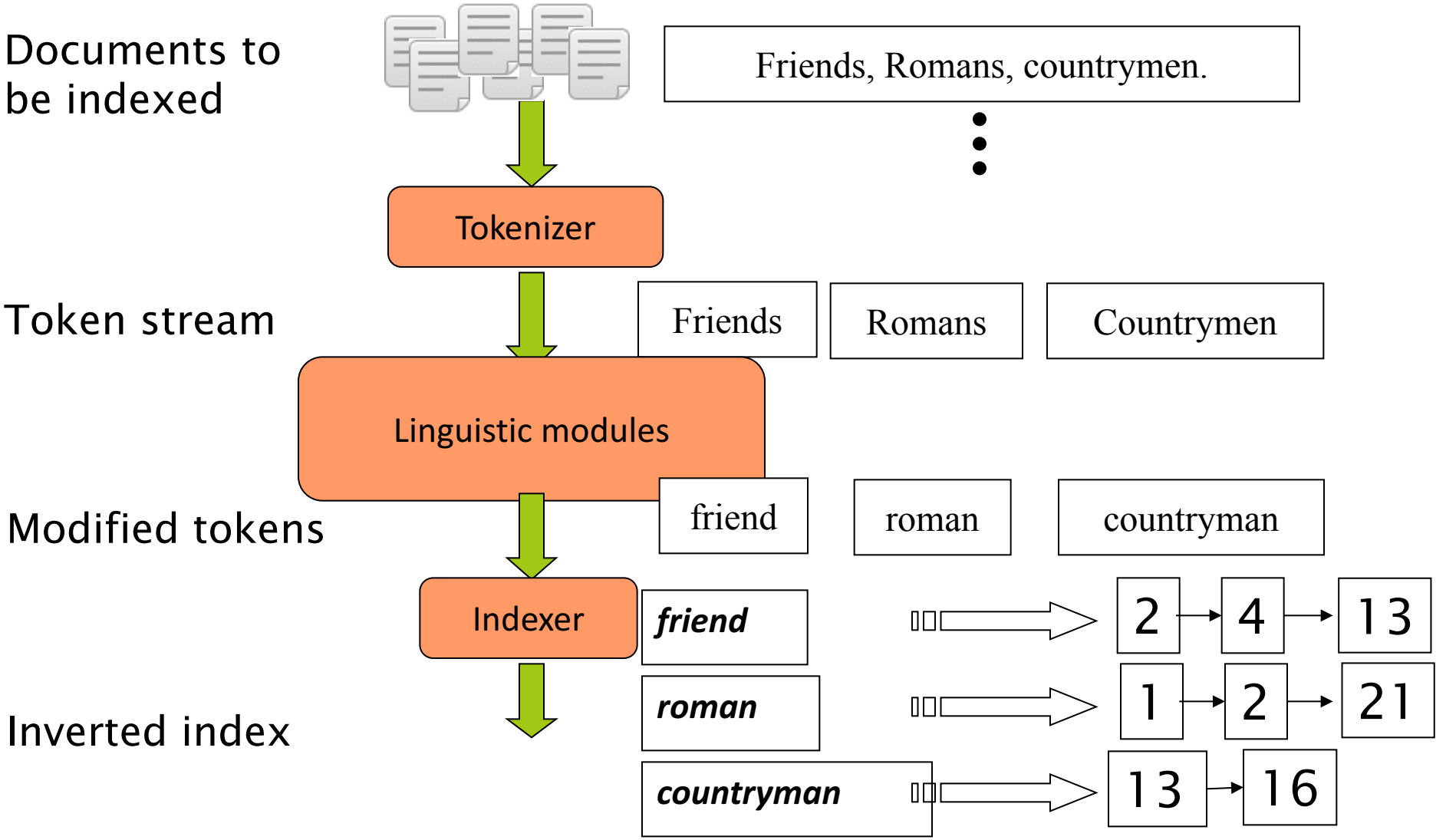

What happens if the word **Caesar** is added to document 14?

# Inverted Index

- So a fixed-sized array does not work well.
- We need variable-sized list for each term, called a **postings list**. A linked list would be suitable.
  - Each docID in the list is a **posting**.
- Each postings list should be **ordered** by the **docID.**
  - We will see the reason for this later.



# Construction of an Inverted Index




1. Split the text into **tokens** (generally words)

2. Tokens must be processed further, according to the language the text is in (more on this later).

   Here, we notice that they are converted to lowercase. Why?

3. Then, we create the inverted index.

# Indexer step 1: Token sequence

- Sequence (list) of pairs: (token, docID).
- As part of this process, punctuation is generally removed.
- In this example, we also convert to lowercase.

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 step 2: Sort

- Sort this sequence by the terms (alphabetically) and then by the docIDs.

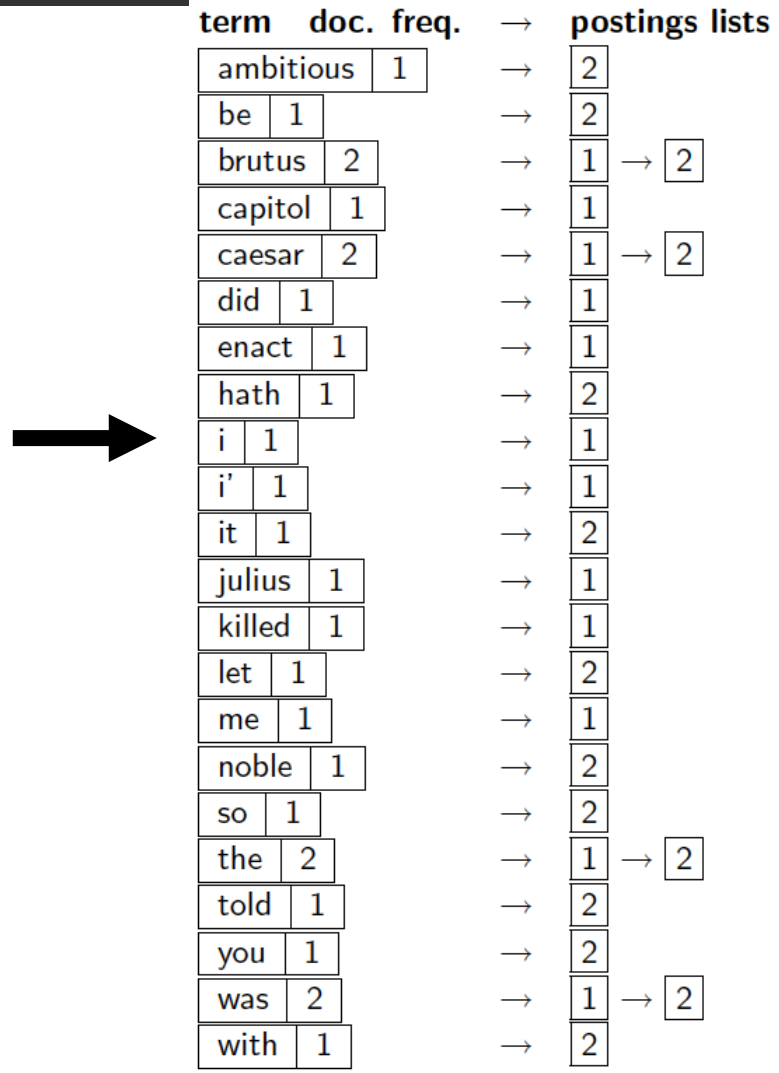
| Term | docID |
|---|---|
| I | 1 |
| did | 1 |
| enact | 1 |
| julius | 1 |
| caesar | 1 |
| I | 1 |
| was | 1 |
| killed | 1 |
| i' | 1 |
| the | 1 |
| capitol | 1 |
| brutus | 1 |
| killed | 1 |
| me | 1 |
| so | 2 |
| let | 2 |
| it | 2 |
| be | 2 |
| with | 2 |
| caesar | 2 |
| the | 2 |
| noble | 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 step 3: Dictionary & Postings

- If a term appears more than once in a document, these entries are merged (i.e. a term is recorded only once for each document).
- Split into a **dictionary** (alphabetical **order** of terms) and **postings** (**ordered** list of documents each term appears in).
  - Why is ordering important?
- We also record the **document frequency** of each term (the number of documents it appears in).
  - This information will be useful 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 |



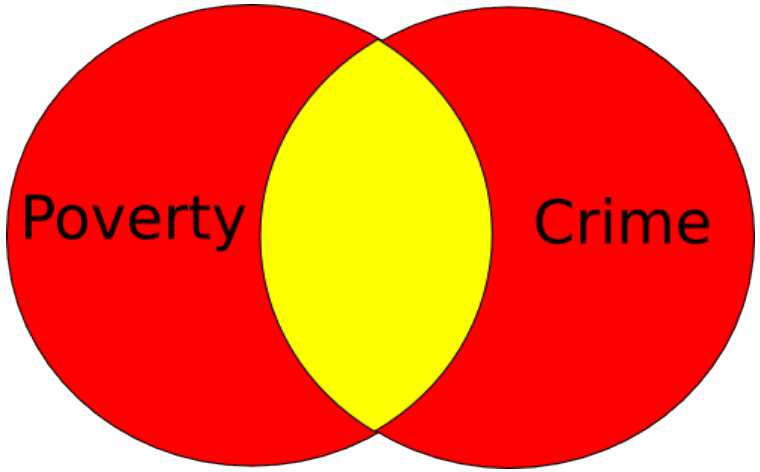
# Using the Inverted Index: How do we process a query?

- Consider the following query:
  - ***Brutus*** *AND* ***Caesar***

1. Locate ***Brutus*** in the dictionary and retrieve its postings.
   - What is the time complexity for finding ***Brutus*** in our dictionary?
2. Locate ***Caesar*** in the dictionary and retrieve its postings.
3. Merge the two postings (find the **intersection**) of the document sets.
   - Each of our boolean operators (AND, OR, NOT) is equivalent to a set operation.

# Set Theoretic Representation of AND

If *P* is the set of documents that contain the term "**poverty**" and *C* is the set of documents that contain the term "**crime**", the query "**poverty AND crime**" can be calculated by $P \cap C$ (i.e. the area in yellow).

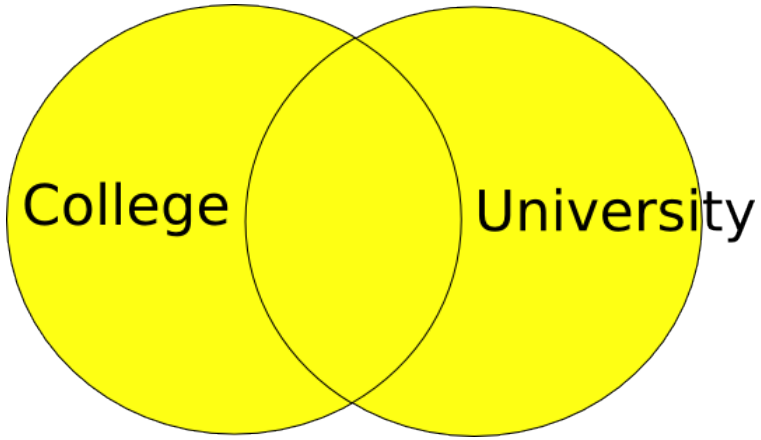


# Boolean Operators: AND

- **AND** is used to **narrow** a search by ensuring that all the search terms should appear in the results.
- It is commonly used to search for relationships between two concepts or terms, for example:
  - *poverty*: 783,447 results
  - *crime*: 2,962,165 results
  - *poverty* **AND** *crime*: 1,677 results
- The more terms or concepts combined in a search with AND, the fewer records that will be retrieved.

# Set Theoretic Representation of OR

If *C* is the set of documents that contain the term **"college"** and *U* is the set of documents that contain the term **"university"**, the query **"college OR university"** can be calculated by $C \cup U$. (i.e. the area in yellow)

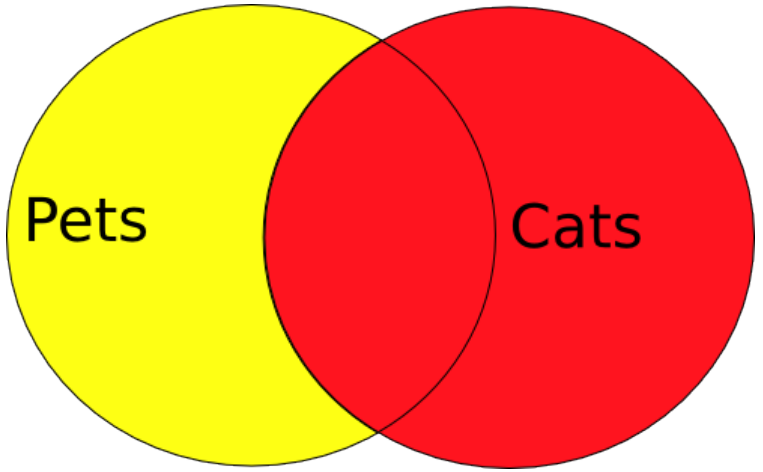


# Boolean Operators: OR

- **OR** is used to **broaden** a search by retrieving any, some or all of the keywords used in the search statement.
- It is commonly used to search for synonymous terms or concepts, for example:
  - *college*: 17,320,770 results
  - *university*: 33,685,205 results
  - *college* **OR** *university*: 38,702,660 results
- Note that the final result is not the same as the sum of the individual results: documents containing both terms (e.g. "University College Dublin") will only be counted once.
- The effect of using OR is that documents containing **any number of the terms specified** will be returned.

# Set Theoretic Representation of NOT

If *P* is the set of documents that contain the term "**pets**" and *C* is the set of documents that contain the term "**cats**", the query "**pets NOT cats**" can be calculated by P \ C (i.e. the area in yellow).

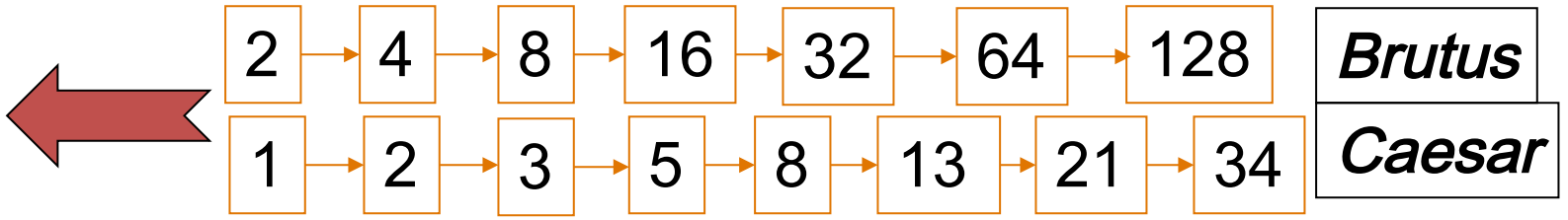


# Boolean Model Operators: NOT

- **NOT** is used to **specifically exclude** a term from your search, for example:
  - *pets*: 4,556,515 results
  - *cats*: 3,651,252 results
  - *pets* **NOT** *cats*: 81,497 results
- One difficulty with using NOT is that a document that is highly relevant to what you're searching for may also contain the term you had attempted to avoid.
- Again, the more terms or concepts combined in a search with NOT, the fewer records that will be retrieved.

# Merging postings lists

- How would you merge two postings lists into one?
  - **Hint:** Why is it important that the lists are sorted?



# Merging two postings lists: Intersection (AND)

```
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
```

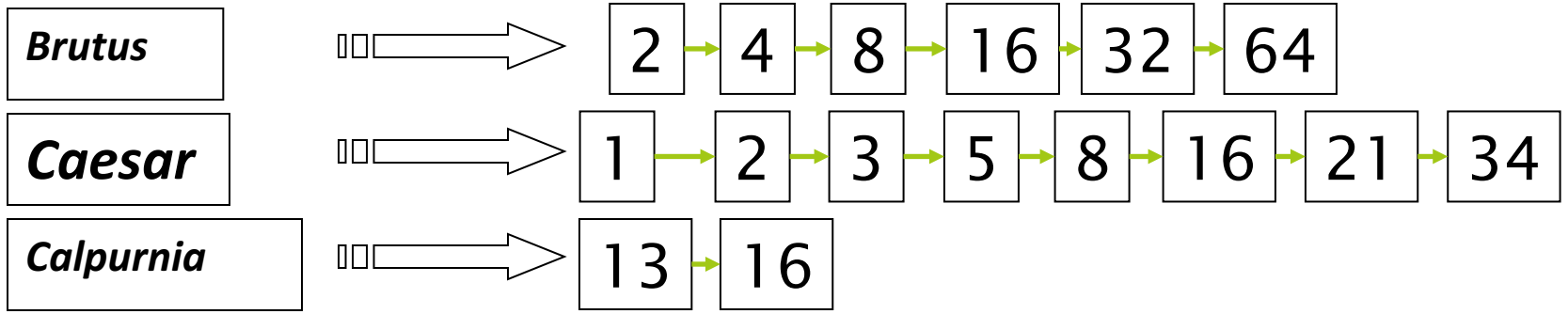
- If lengths are x and *y*, algorithm is O(x+y). **Why?**
- **Answer:**
  - Each iteration of the loop advances to the next document in at least one of the lists.
  - Worst case (two distinct lists with nothing in common):
    - x iterations to reach end of first list.
    - *y* iterations to reach end of second list.
    - *O(x+y)*
  - This **only** works because the lists are sorted by docID.

# Exercise

- Can we adapt the merge for the following query types? How?
  - ***Brutus*** *OR* ***Caesar***
    - Documents that contain either the term ***Brutus*** or the term ***Caesar****, or both.*
  - ***Brutus*** *AND NOT* ***Caesar***
    - Documents that contain the term ***Brutus*** but do not contain the term ***Caesar***.
  - ***Brutus*** *OR NOT* ***Caesar***
    - Documents that contain ***Brutus*** or do not contain ***Caesar***.
- If not, what else do we need?

# Query Optimisation

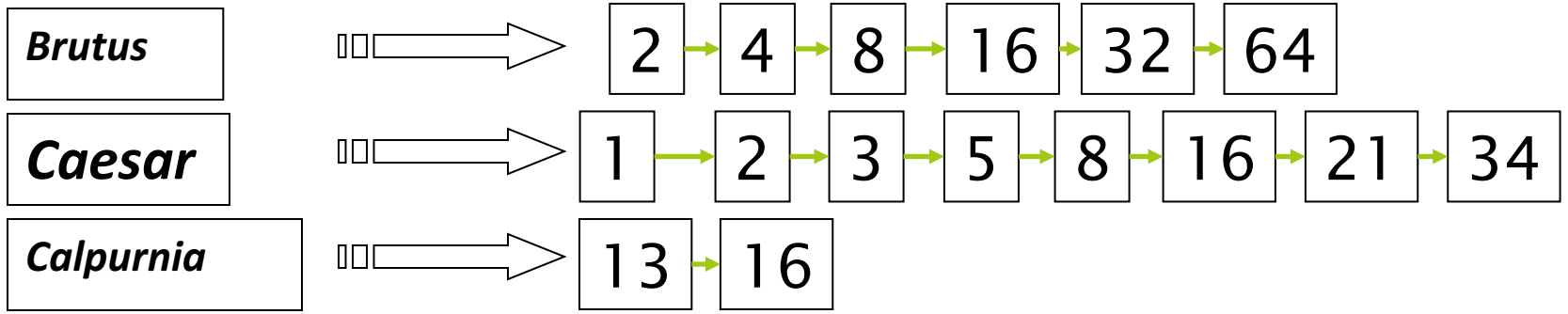
- What is the best order for query processing?
- For a query that is an AND of several terms:
  - For each of the terms, retrieve its postings list, and merge with the others.




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

# Query Optimisation

- Process in order of increasing frequency.
  - Start with the smallest set, then work towards the bigger ones.
    - **Why?** If we reach the end of the shorter list, we can stop!
    - For a very short list, this can save us a lot of time.
  - This is why we record document frequency in the dictionary.




- Query becomes : (***Calpurnia*** *AND* ***Brutus***) *AND* **Caesar**

# More complex optimisation

- What about a combination of *AND* and *OR* operations?
- E.g. (***madding*** *OR* ***crowd***) *AND* (***ignoble*** *OR* ***strife***)
  - Get the document frequencies for all terms.
  - Estimate the size of each *OR* operation.
    - Maximum possible size is the sum of the frequencies of the terms.
  - Process in increasing order of *OR* size.

# Exercise

- Recommend a query processing order for

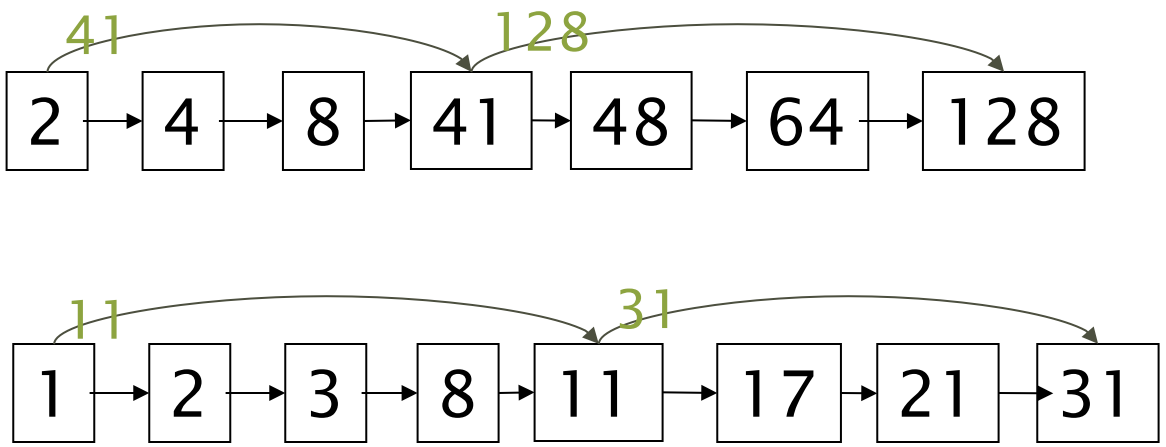
***(tangerine** OR **trees)** AND*
***(marmalade** OR **skies)** AND*
***(kaleidoscope** OR **eyes)***

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

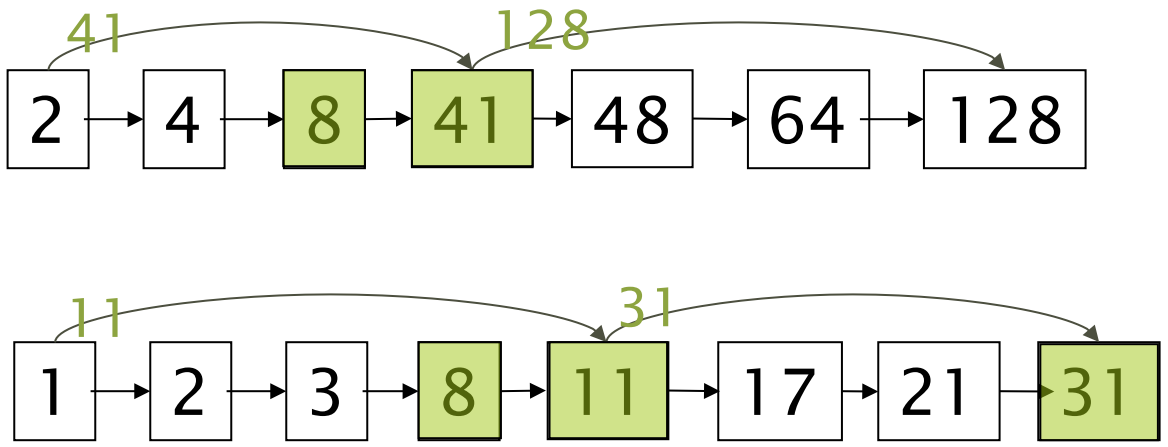
- Which two terms should we process first?

# A more optimised data structure: Skip Pointers

- In a regular linked list, each node (which in this case contains a posting) has a pointer/reference to the next node in the list.
- By introducing a second type of reference/pointer, called a **skip pointer**, we can reach later parts of the list without iterating through every element.
- This helps to skip postings that we know will not be in the final search results.



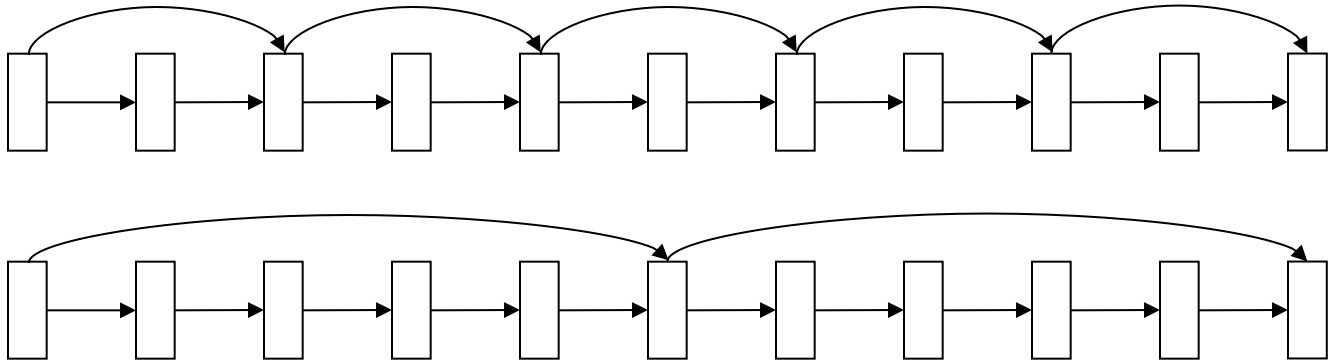
# Query processing with skip pointers




- Suppose we have stepped through both lists until we process **8** on each list. We match it and advance.
- We then have **41** on the upper list and **11** on the lower. **11** is smaller.
- But the skip pointer of 11 in the lower list is 31. This is still less than 41 so we can skip everything in between, since we know they cannot be part of the answer.
- Again, this only works if the list is **sorted**.

# 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 [Moffat and Zobel 1996]
- This ignores the distribution of query terms.
- Easy if the index is relatively static; harder if $L$ keeps changing because of updates.
- This definitely used to help; with modern hardware it may not unless you're memory-based [Bahle et al. 2002]
  - The I/O cost of loading a bigger postings list can outweigh the gains from quicker in memory merging!

# Summary

- We have examined how we might store document representations that allow us to run Boolean type queries.
- The process of **indexing** involves building a structure like this, after tokenising and processing the text.
  - We will look at text processing in more detail in the next topic.
- Postings lists can be merged in linear time, and we have a couple of strategies to help optimise query processing.