

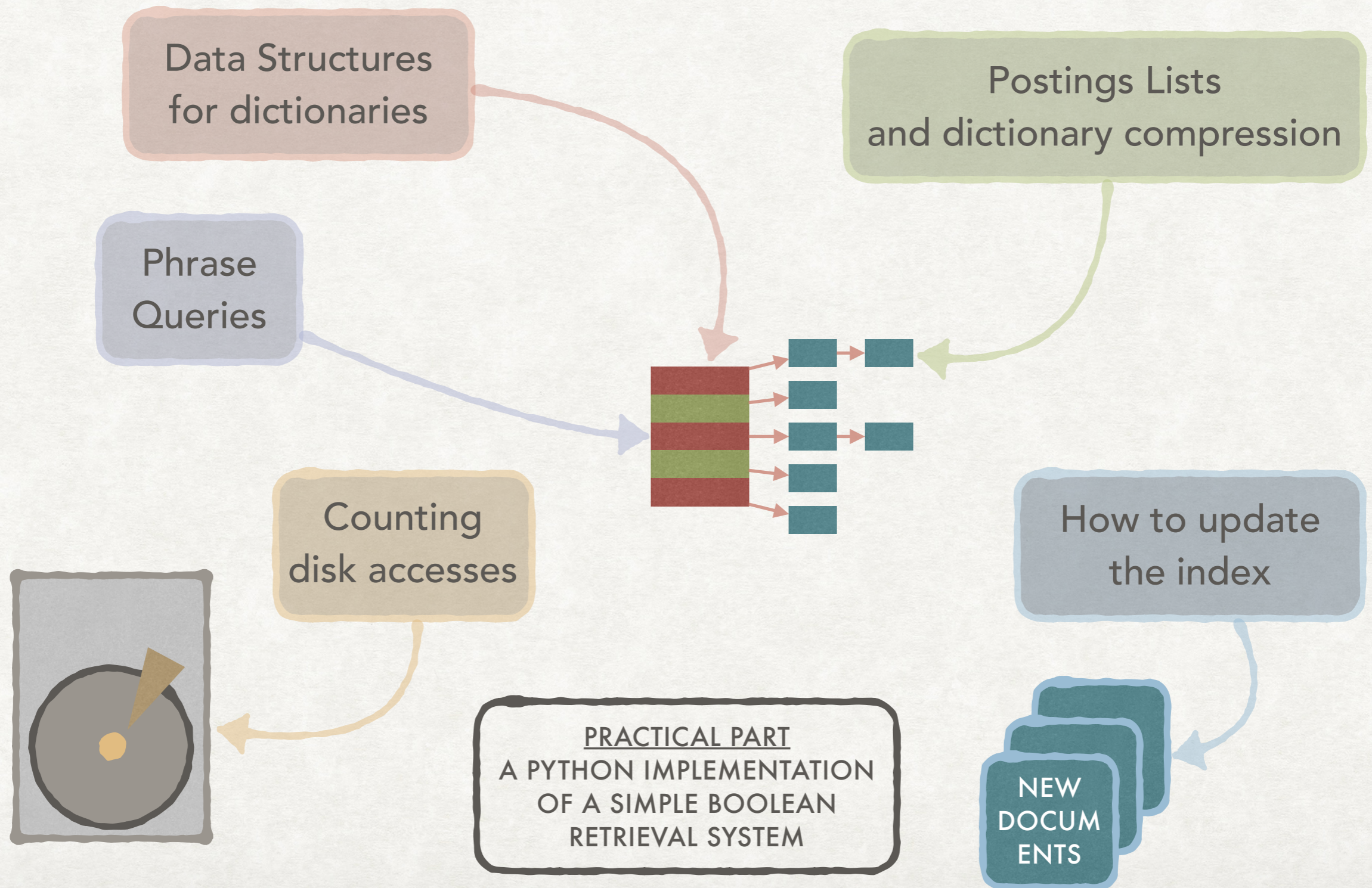
INFORMATION RETRIEVAL

Luca Manzoni

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LECTURE OUTLINE

*Now without asbestos



ANSWERING PHRASE QUERIES

OUR GOAL

EXTENDING THE QUERY LANGUAGE

- We want to be able to ask queries consisting of multiple consecutive words:
 - "calico cat"
 - "University of Trieste"
- A common syntax for this kind of queries is to enclose the words in double quotes.
- Two approaches shown: *biword indexes* and *positional indexes*.

BIWORD INDEXES

WORKING ON PAIRS OF WORDS

THE CAT IS INSIDE THE BOX

Text

THE CAT

CAT IS

IS INSIDE

INSIDE THE

THE BOX

Terms

- The terms are pairs of words
- Queries need to be "rewritten":

"inside the box" → "inside the" AND "the box"

BIWORD INDEXES

POSSIBLE PROBLEMS

Text: INSIDE THE HOUSE THERE IS THE BOX

Original Query: "inside the box" **No Match**

Rewritten Query: "inside the" AND "the box" **Match**

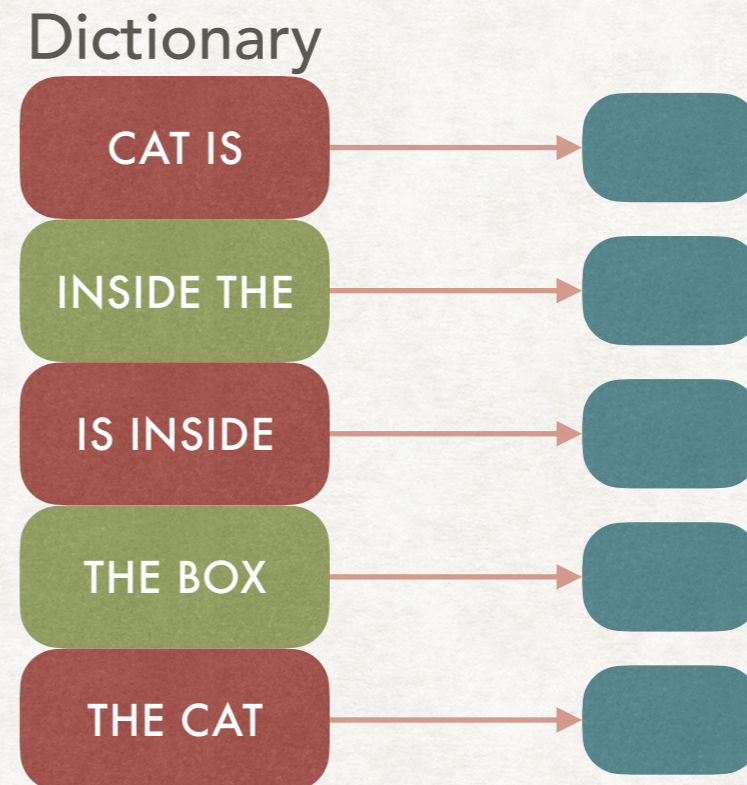
Rewriting the query might generate false positives
(but it works quite well in practice)

BIWORD INDEXES

POSSIBLE PROBLEMS



To answer the query
we would need to find
all terms containing "cat"



We also need an index of single-word terms!

BIWORD INDEXES

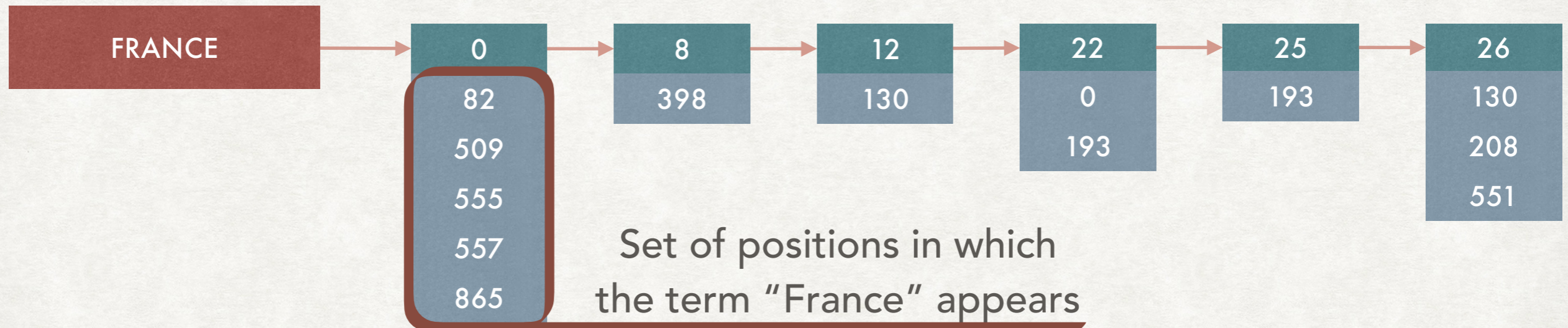
EXTENSIONS AND FURTHER OBSTACLES

- The idea of using pair of words as terms can be extended to any length, reducing the risk of false positives...
- ...but increasing the amount of space needed.
- If the number of words in a term is variable it is called *phrase index*.
- It is also possible to "tag" the part of speech (i.e., names, verbs, articles, prepositions, etc.) to add pairs of names separated by articles and prepositions to the index.
 - E.g., in "door at the entrance", "door entrance" is considered a term

POSITIONAL INDEXES

ADDING POSITIONS TO THE POSTINGS

One way to answer a phrase query is to add, for each posting, the set of positions in which the term appear in the document.

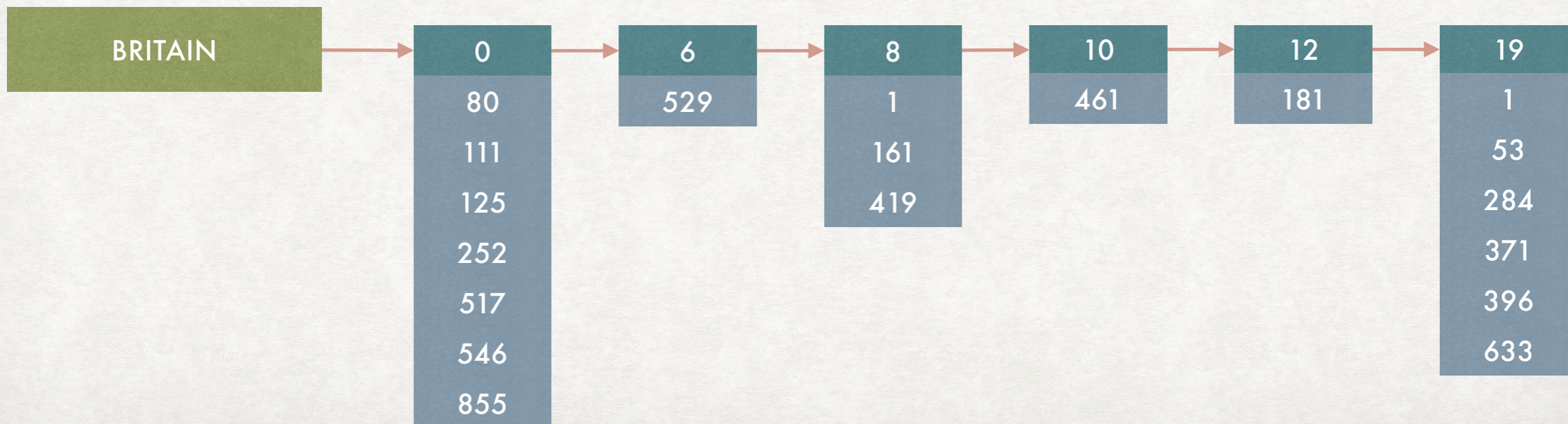
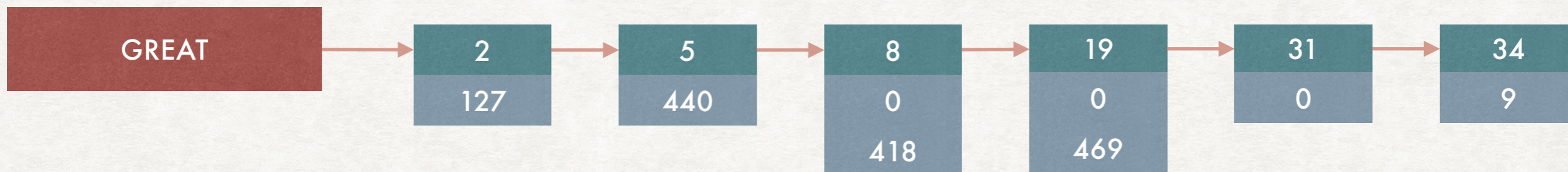


ANSWERING A PHRASE QUERY

WITH POSITIONAL INDEXING

QUERY "GREAT BRITAIN"

ANSWER

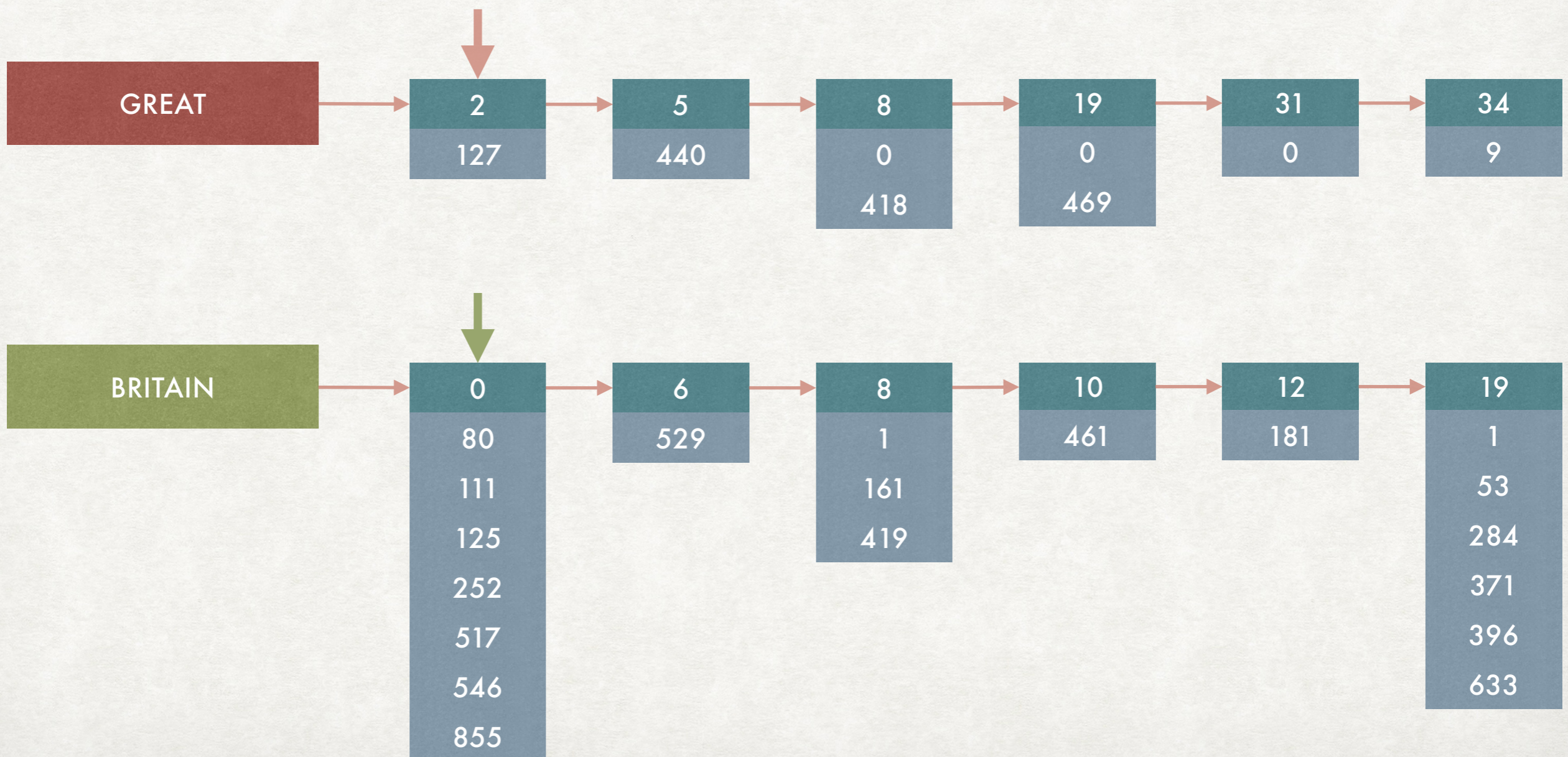


ANSWERING A PHRASE QUERY

WITH POSITIONAL INDEXING

QUERY "GREAT BRITAIN"

ANSWER

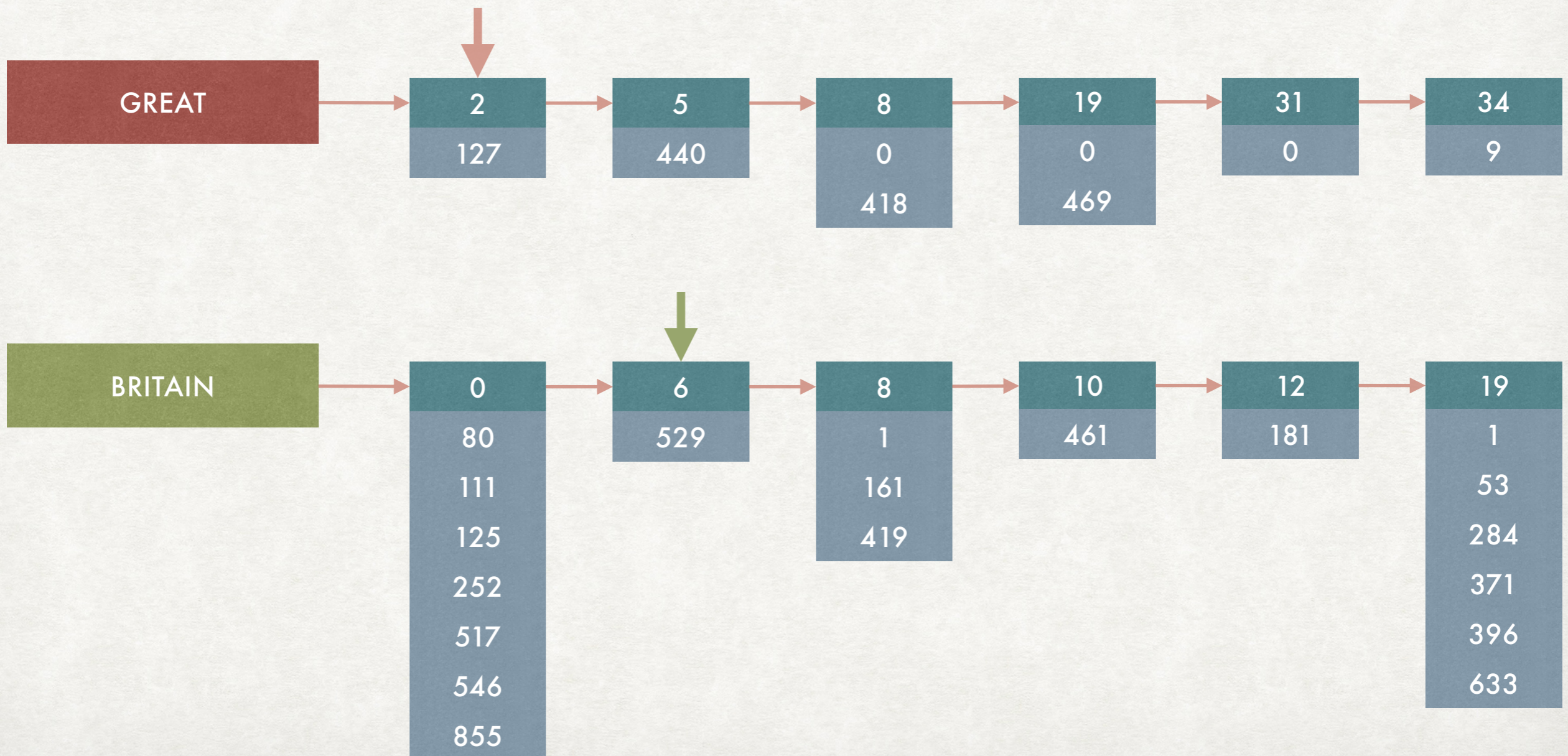


ANSWERING A PHRASE QUERY

WITH POSITIONAL INDEXING

QUERY "GREAT BRITAIN"

ANSWER

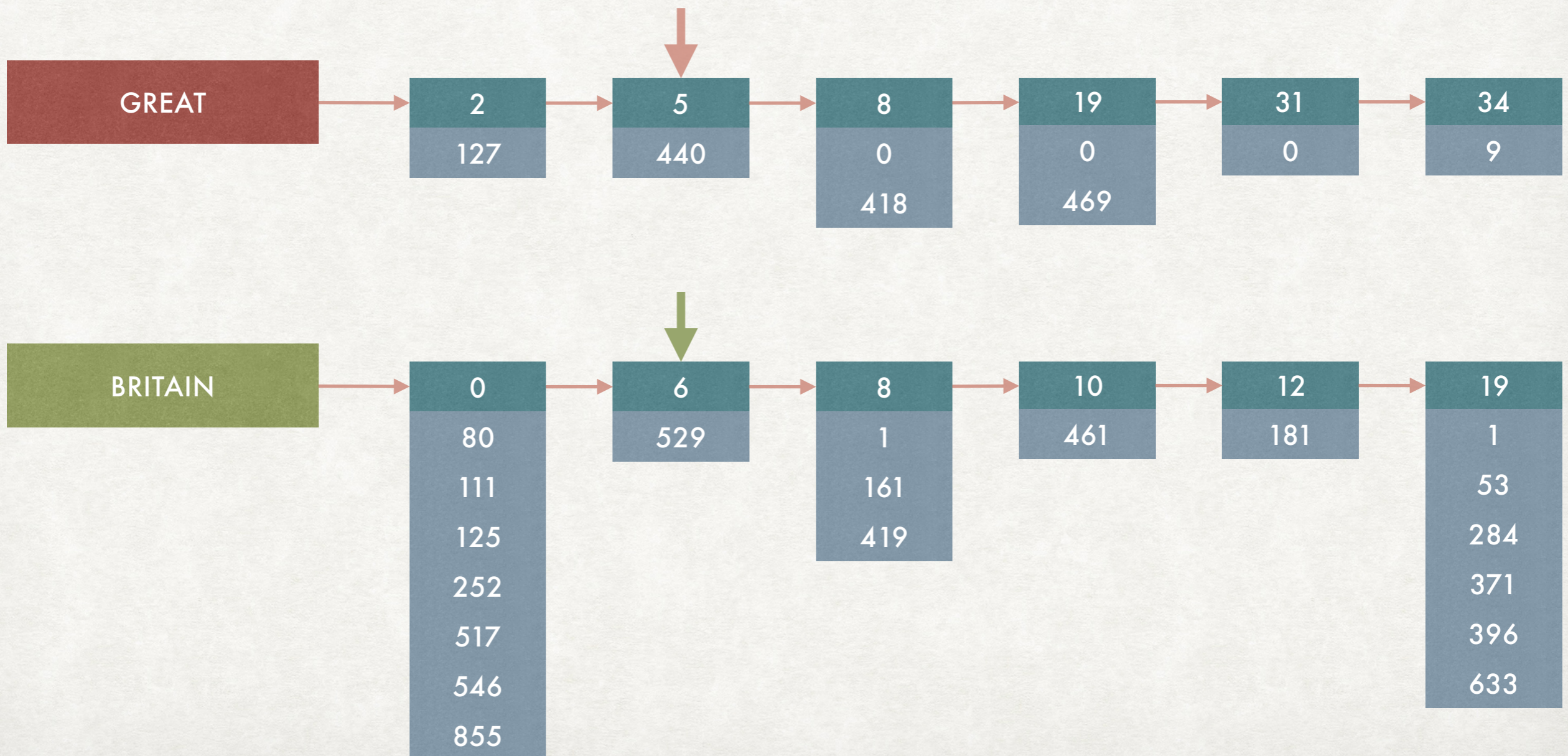


ANSWERING A PHRASE QUERY

WITH POSITIONAL INDEXING

QUERY "GREAT BRITAIN"

ANSWER

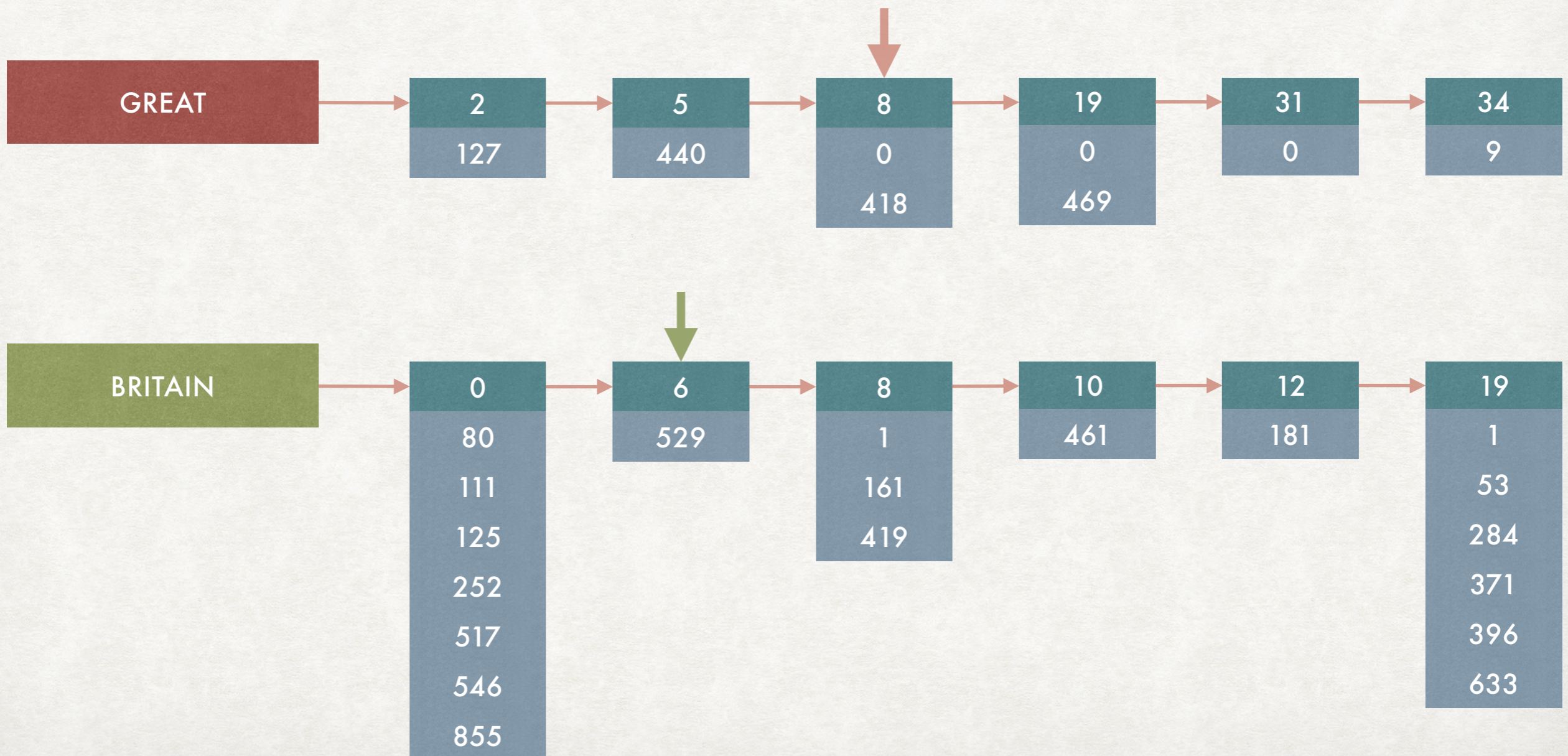


ANSWERING A PHRASE QUERY

WITH POSITIONAL INDEXING

QUERY "GREAT BRITAIN"

ANSWER

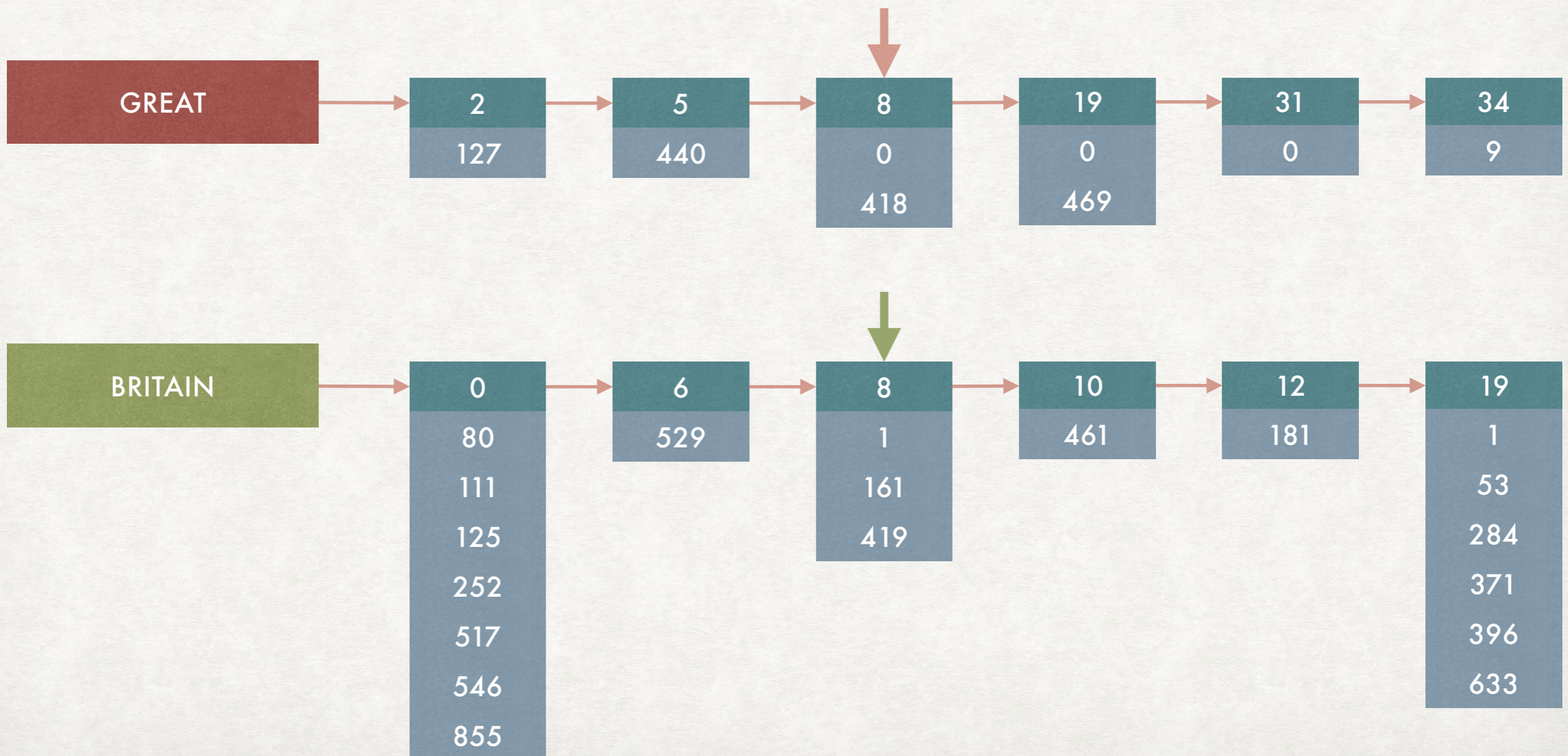


ANSWERING A PHRASE QUERY

WITH POSITIONAL INDEXING

QUERY "GREAT BRITAIN"

ANSWER

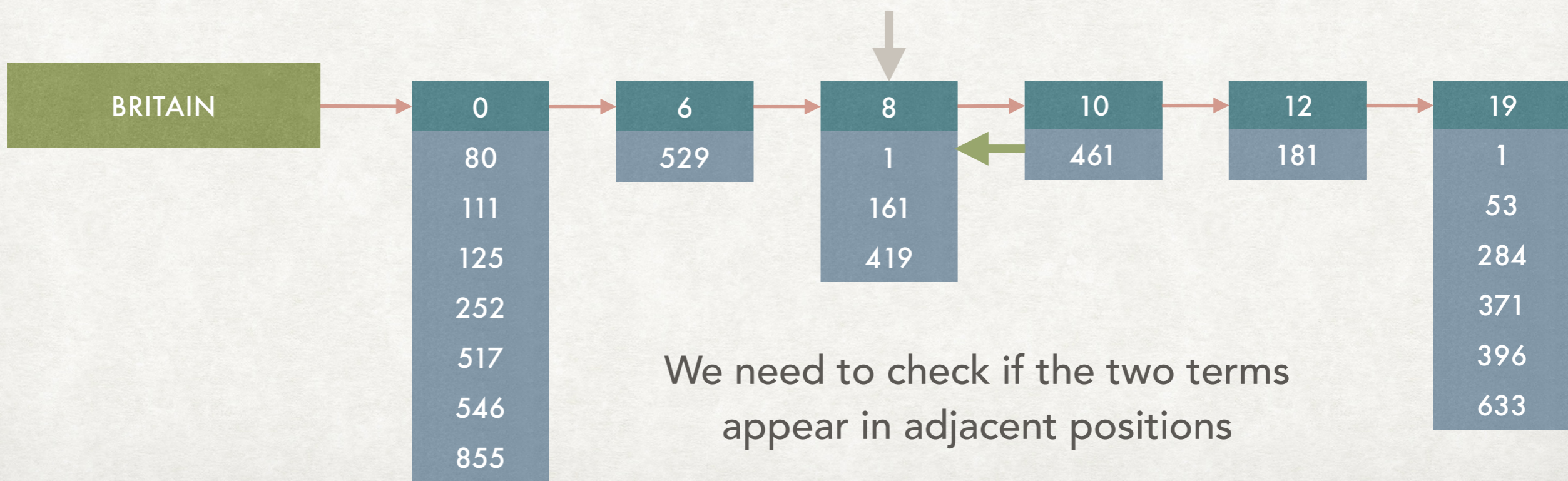
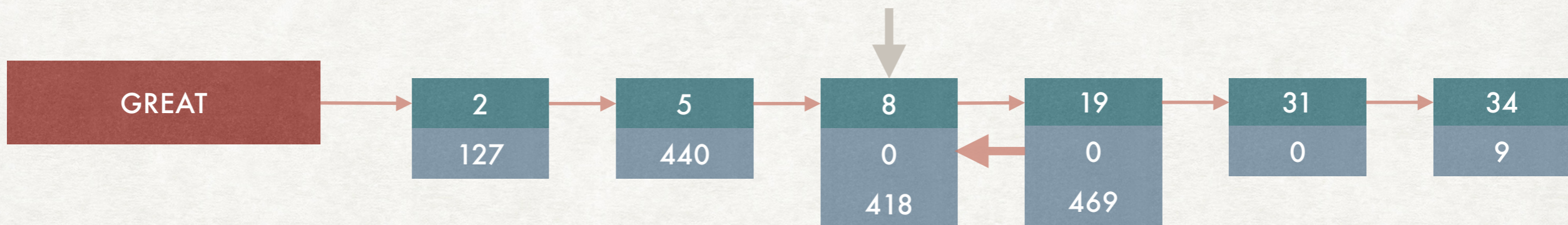


ANSWERING A PHRASE QUERY

WITH POSITIONAL INDEXING

QUERY "GREAT BRITAIN"

ANSWER



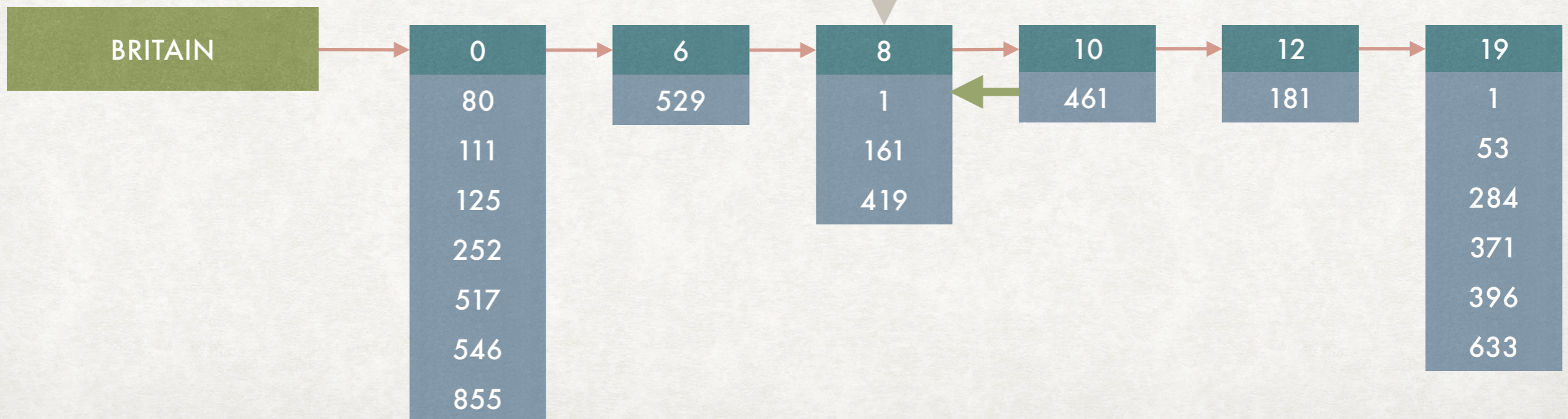
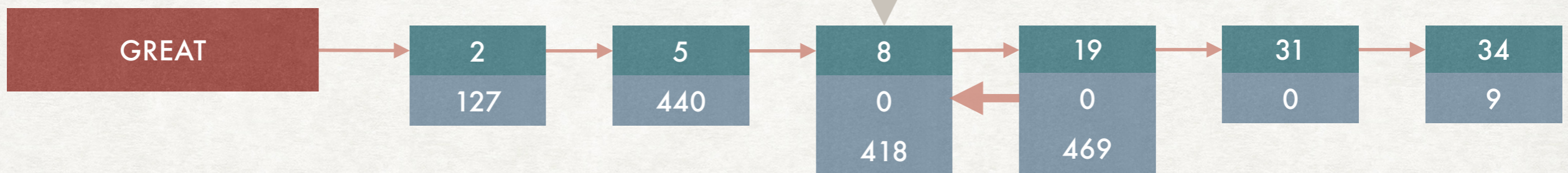
We need to check if the two terms appear in adjacent positions

ANSWERING A PHRASE QUERY WITH POSITIONAL INDEXING

QUERY "GREAT BRITAIN"

ANSWER

8
0

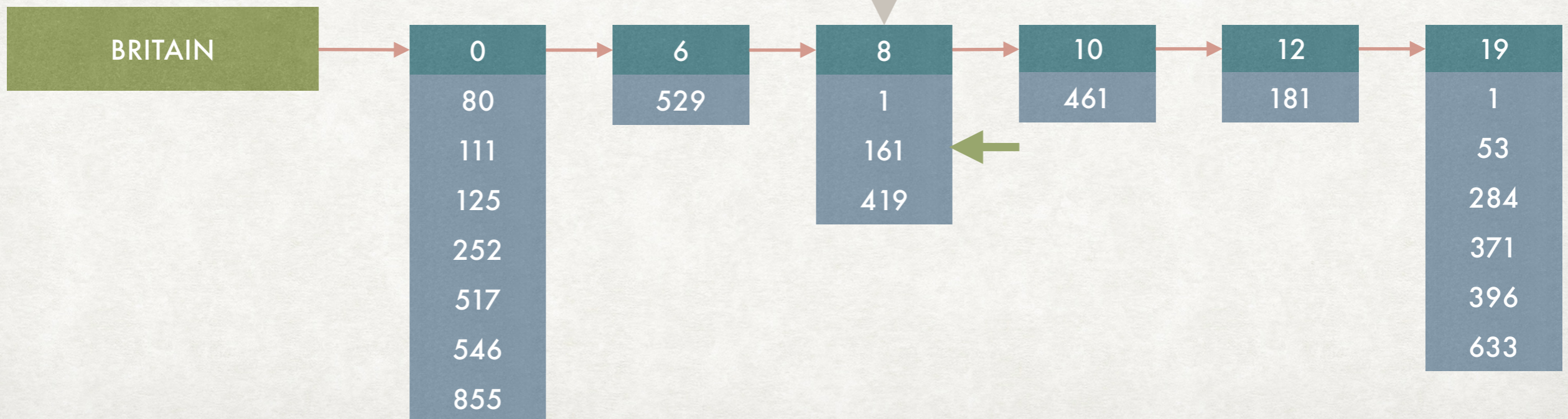
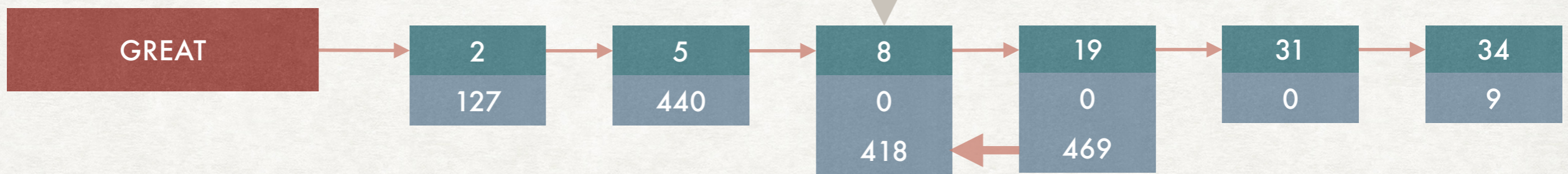


ANSWERING A PHRASE QUERY WITH POSITIONAL INDEXING

QUERY "GREAT BRITAIN"

ANSWER

8
0

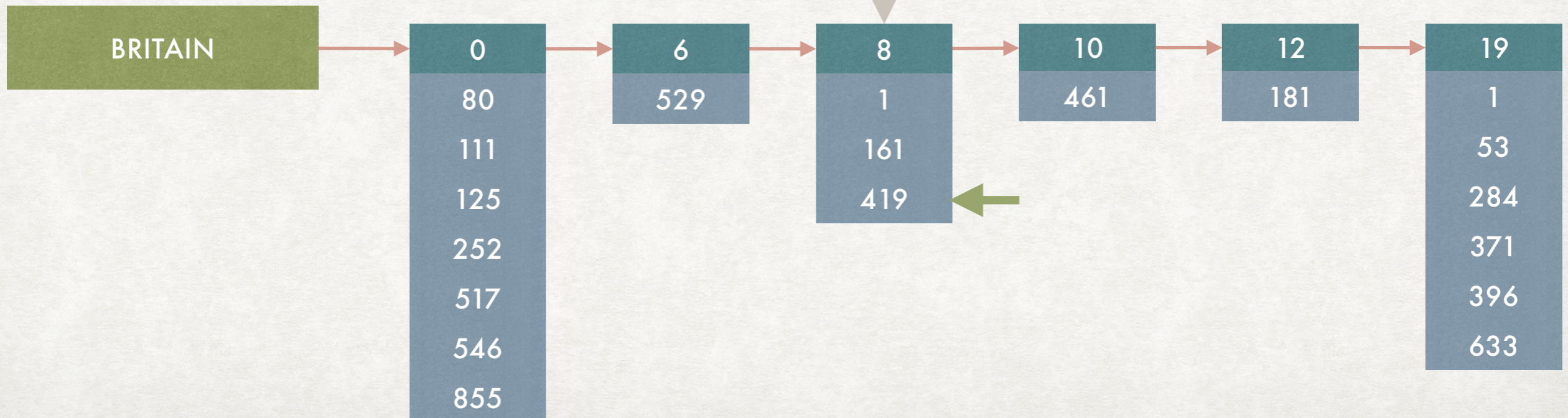
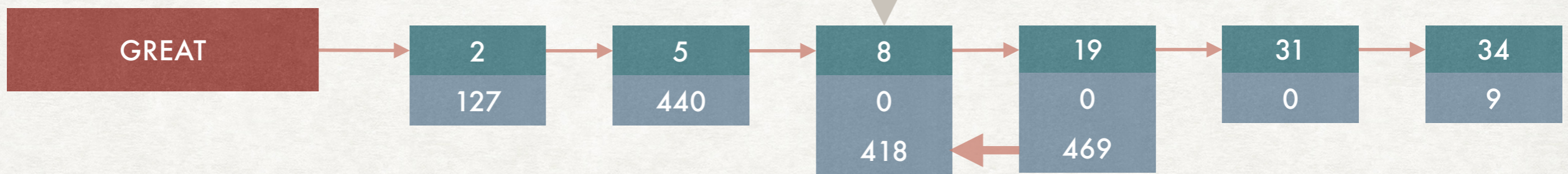


ANSWERING A PHRASE QUERY WITH POSITIONAL INDEXING

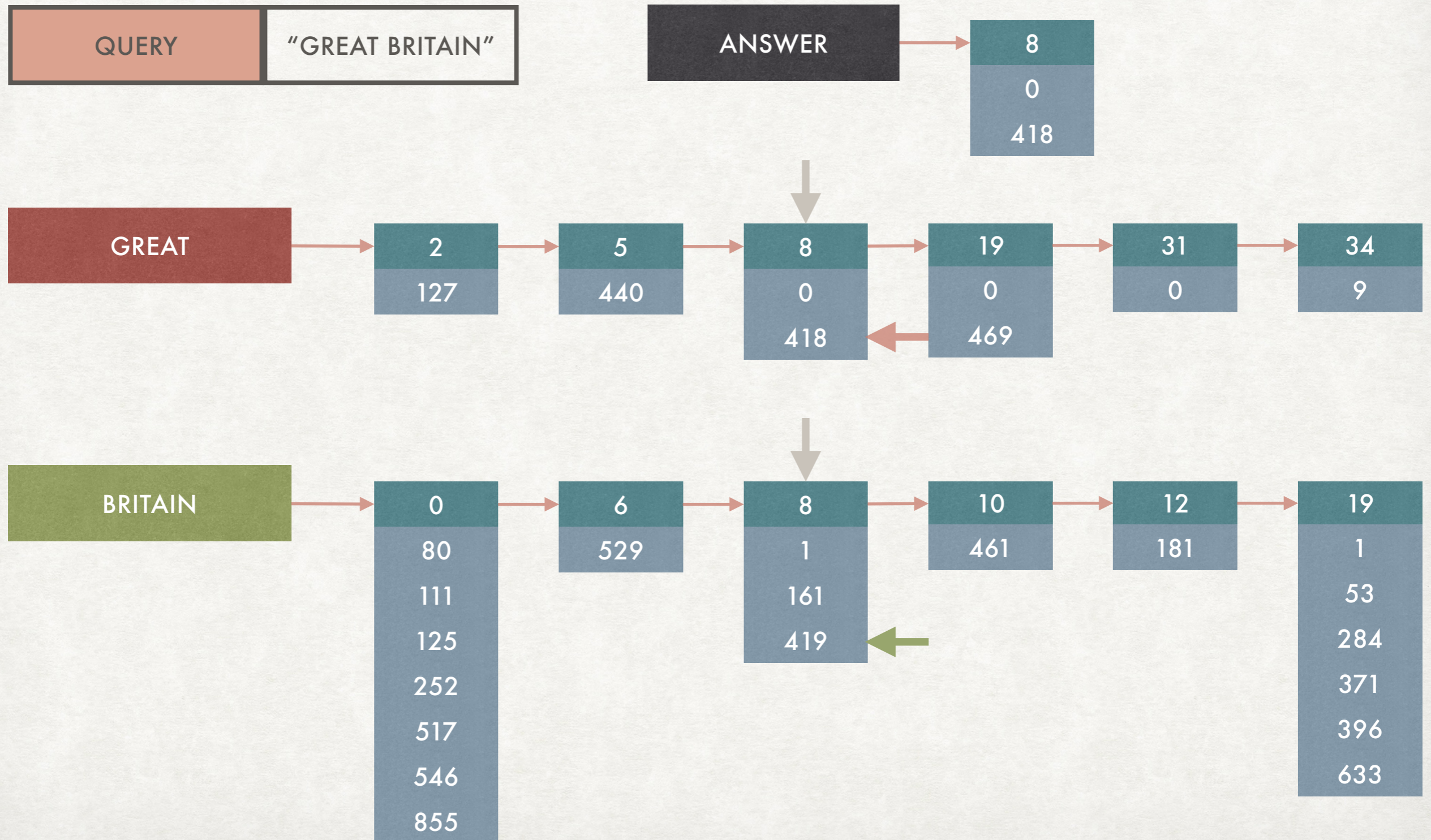
QUERY "GREAT BRITAIN"

ANSWER

8
0

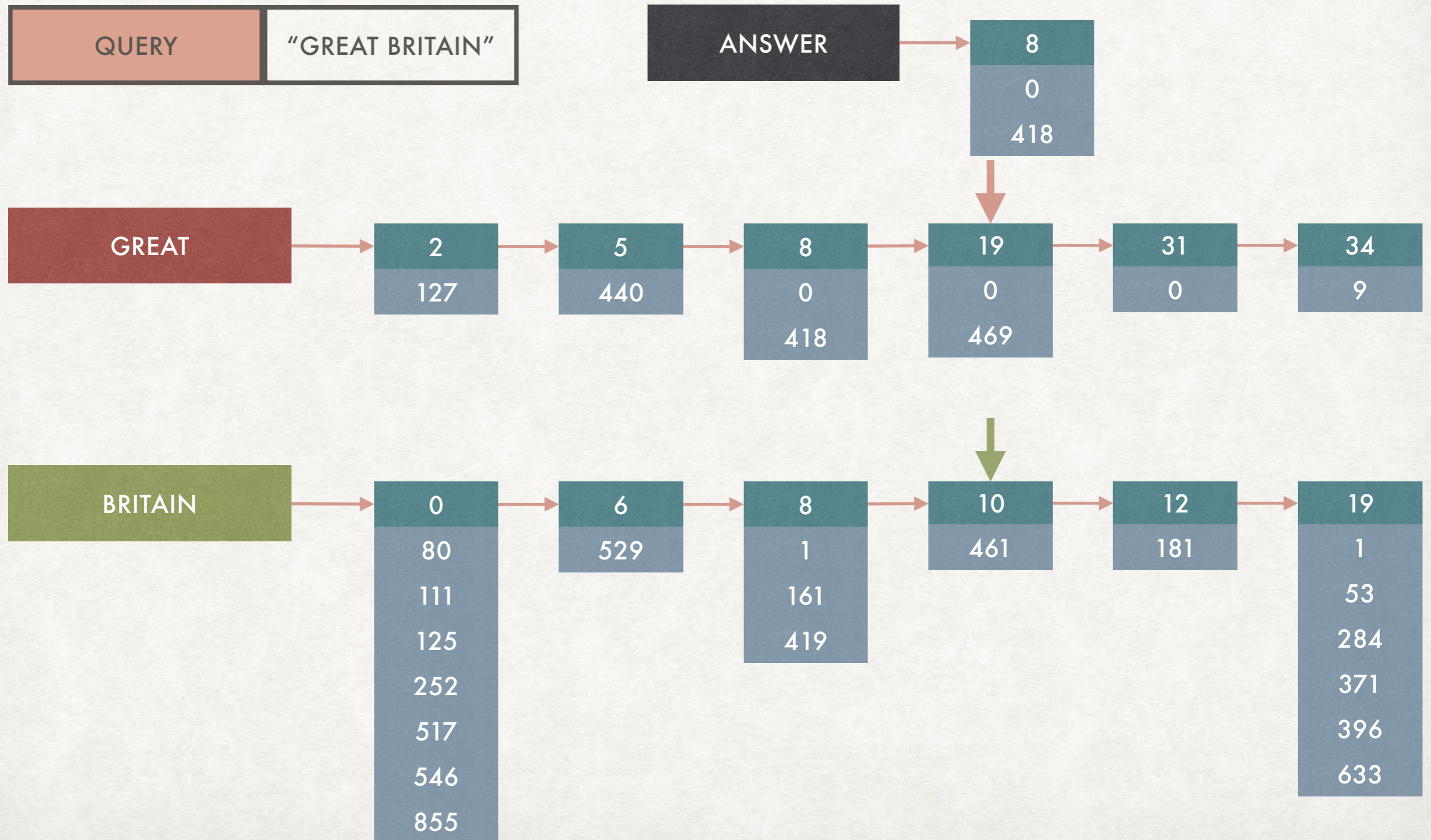


ANSWERING A PHRASE QUERY WITH POSITIONAL INDEXING



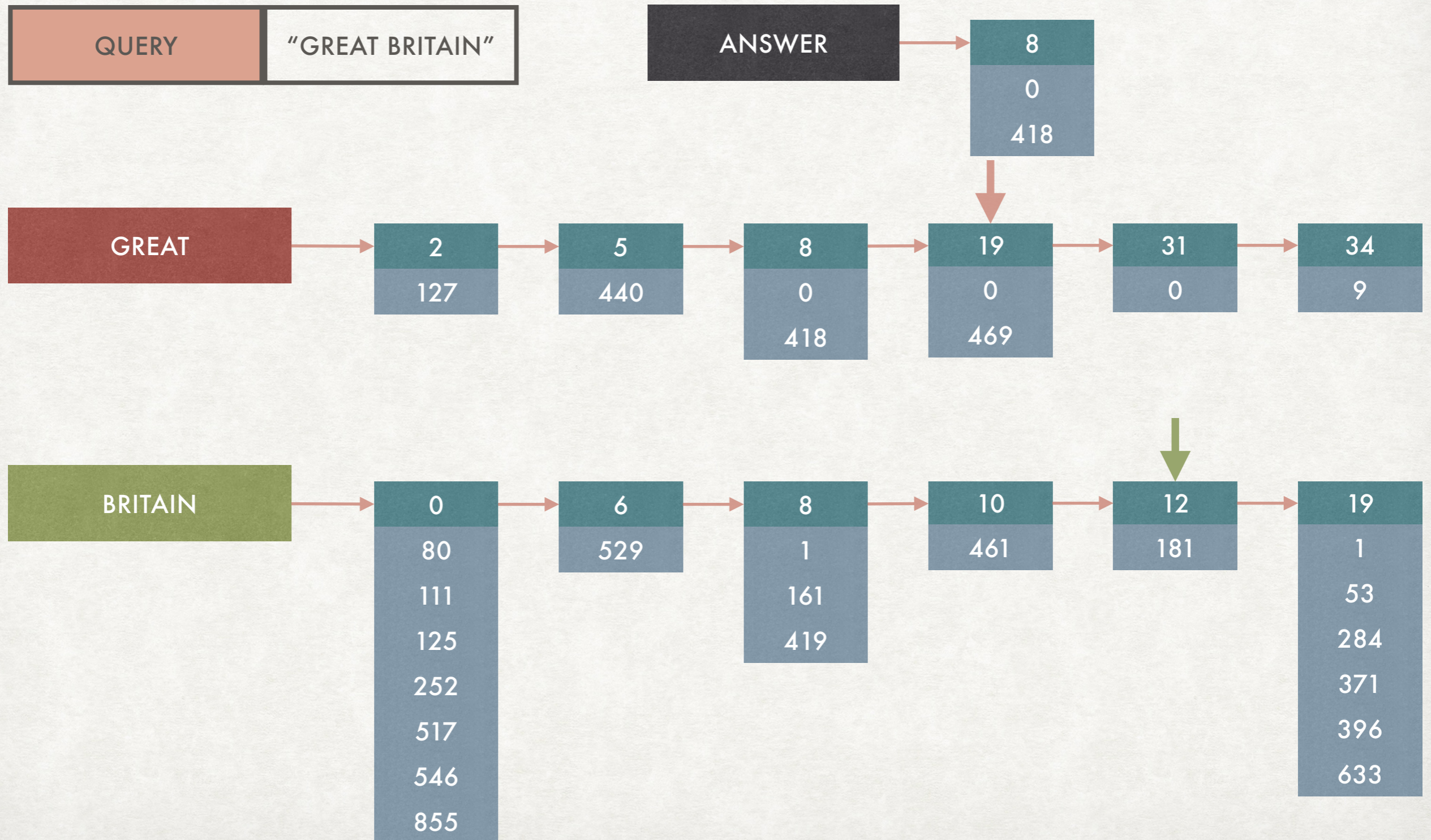
ANSWERING A PHRASE QUERY

WITH POSITIONAL INDEXING

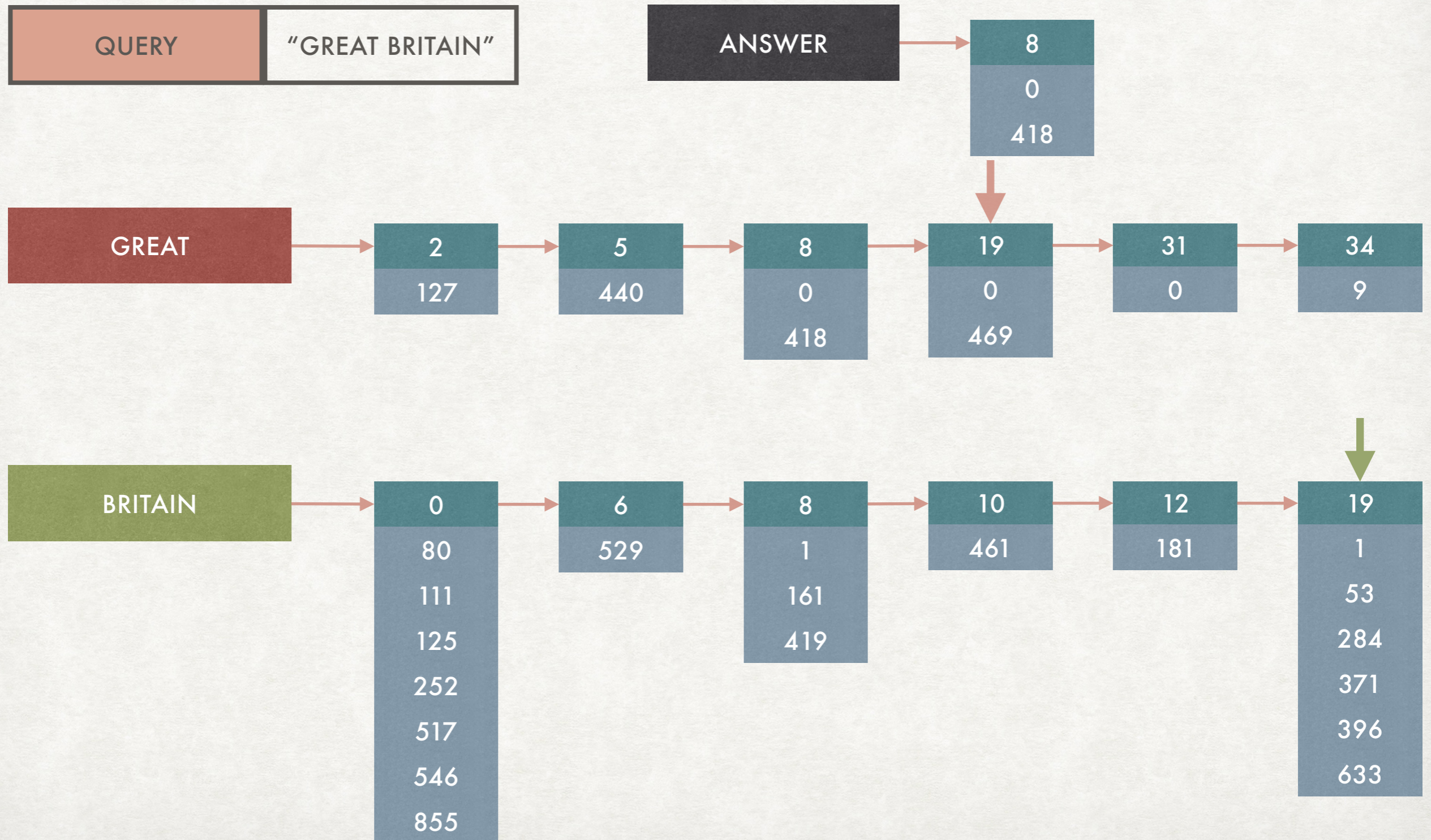


ANSWERING A PHRASE QUERY

WITH POSITIONAL INDEXING



ANSWERING A PHRASE QUERY WITH POSITIONAL INDEXING



ANSWERING A PHRASE QUERY WITH POSITIONAL INDEXING

QUERY "GREAT BRITAIN"

ANSWER

8
0
418

GREAT

2
127

5
440

8
0
418

19
0
469

31
0

34
9

BRITAIN

0
80
111
125
252
517
546
855

6
529

8
1
161
419

10
461

12
181

19
1
53
284
371
396
633

ANSWERING A PHRASE QUERY

WITH POSITIONAL INDEXING

QUERY "GREAT BRITAIN"

ANSWER

8
0
418

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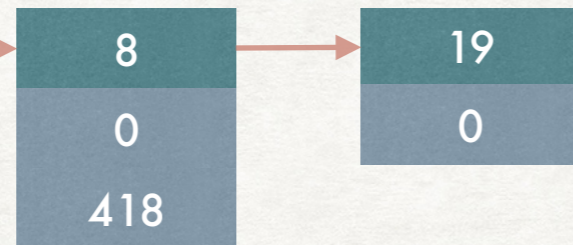
19
1
53
284
371
396
633

POSITIONAL INDEXING: SUMMARY

THE GOOD, THE BAD, AND THE UGLY

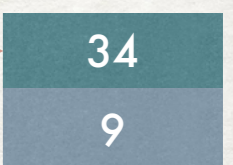
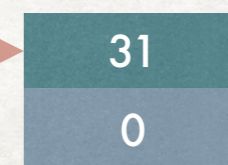
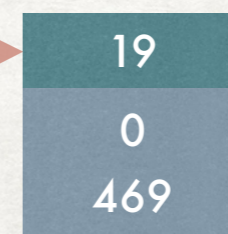
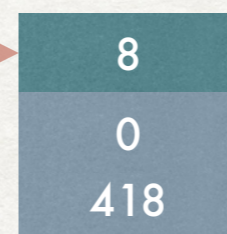
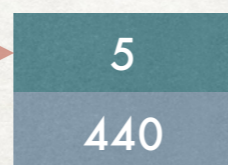
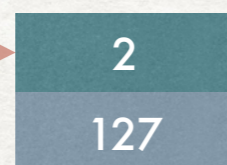
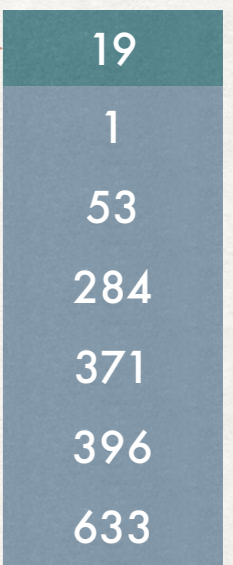
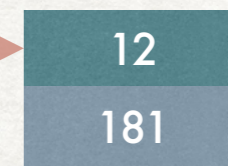
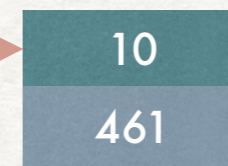
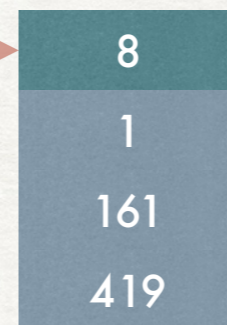
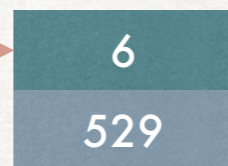
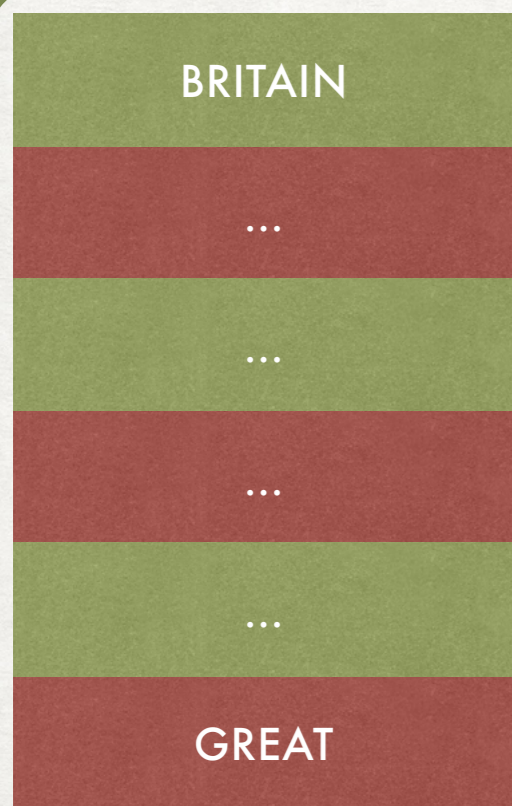
- The positional index can be used to support the operators of the form “term₁ /k term₂” with k an integer indicating the maximum number of words that can be between term₁ and term₂.
- The complexity of performing a query is not bounded anymore by the number of documents, but by the number of terms
- The size of the index now depends on the average document size.

COMBINING BIWORD AND POSITIONAL INDEXES



Phrase index for frequently asked queries

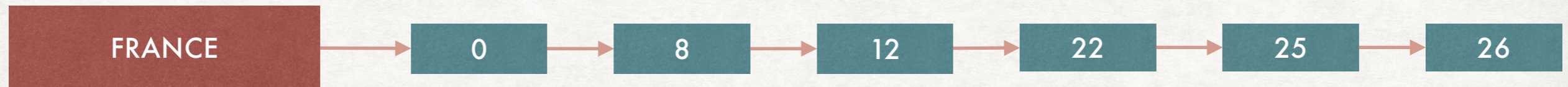
Positional index for all other queries



IMPROVING THE INVERTED INDEX

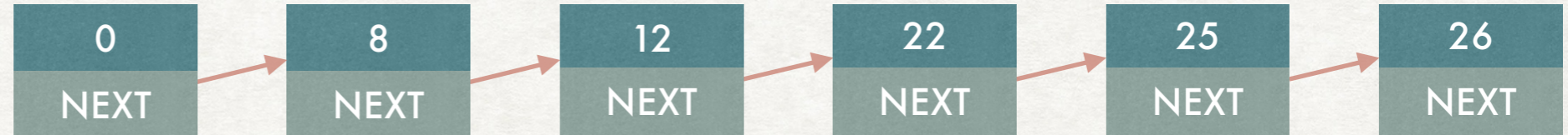
ARRAYS OR LINKED LISTS?

WHAT TO USE FOR THE POSTING LISTS?



Which data structures should we actually use for the postings list?

Singly linked lists



cheap insertion and updates

pointer overhead, poor memory locality (pointers chasing)

Variable length arrays



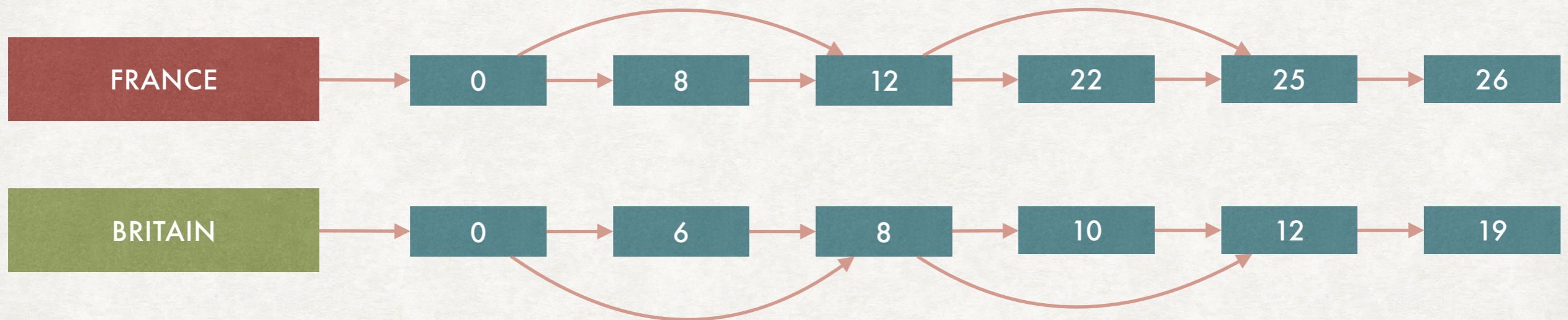
no pointers overhead, contiguous memory

difficult to update

SKIP LISTS

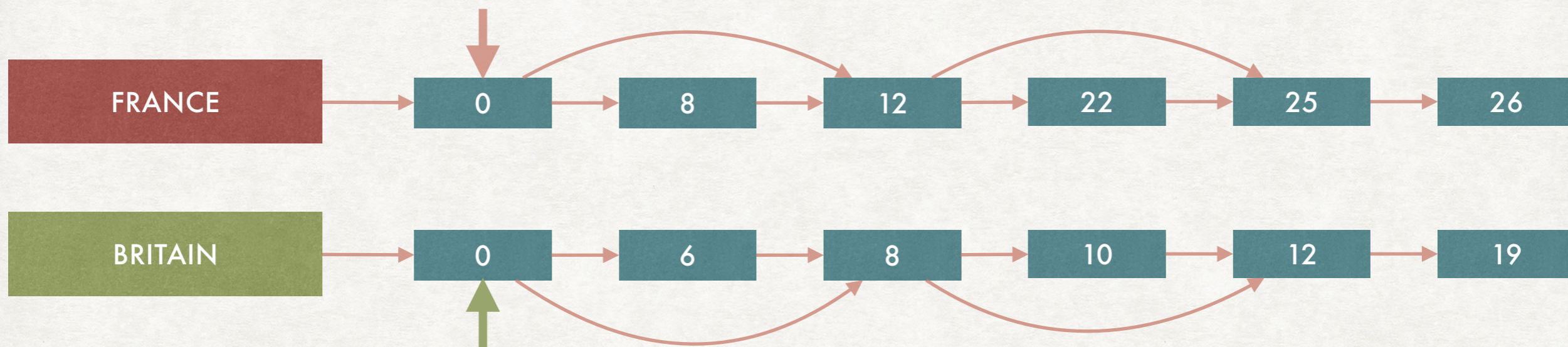
FASTER INTERSECTION

- We add additional forward pointers every k postings inside a list. The forward pointer "skips" a certain number of postings.
- A rule of thumb is, for a postings list of P postings to use \sqrt{P} evenly spaced skip pointers



AN EXAMPLE QUERY

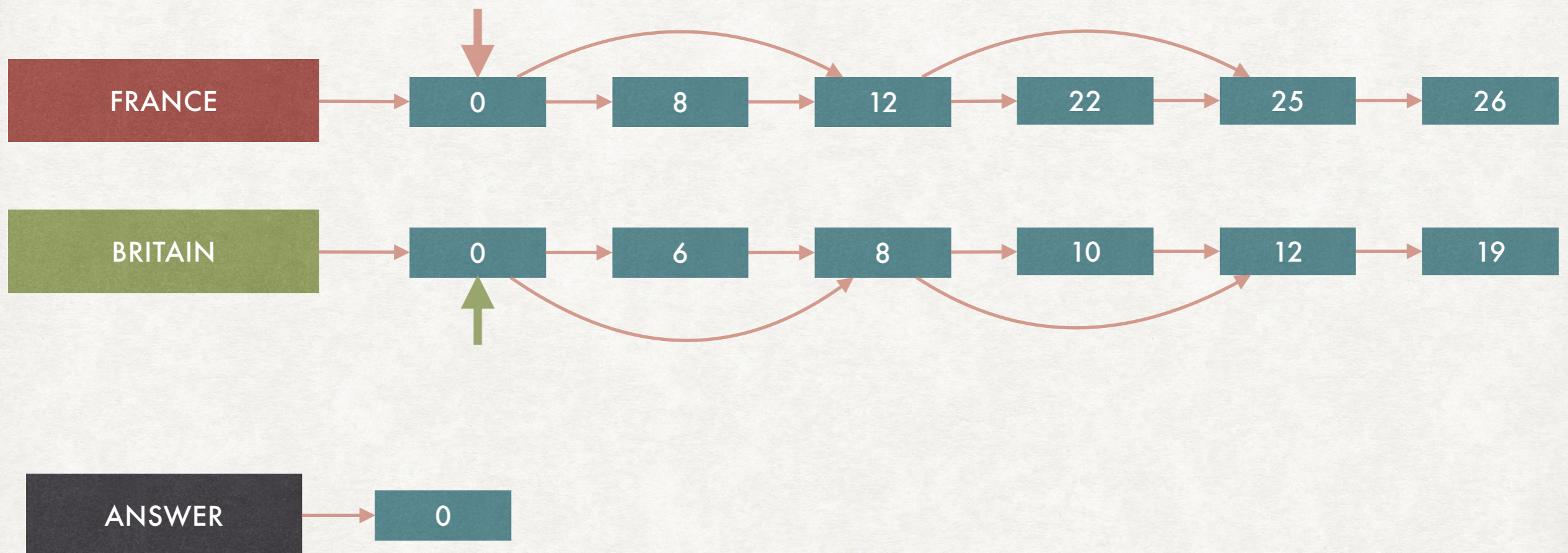
SAVING TIME WITH SKIP LISTS



ANSWER

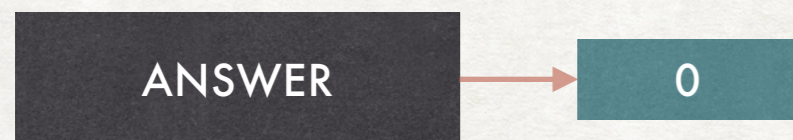
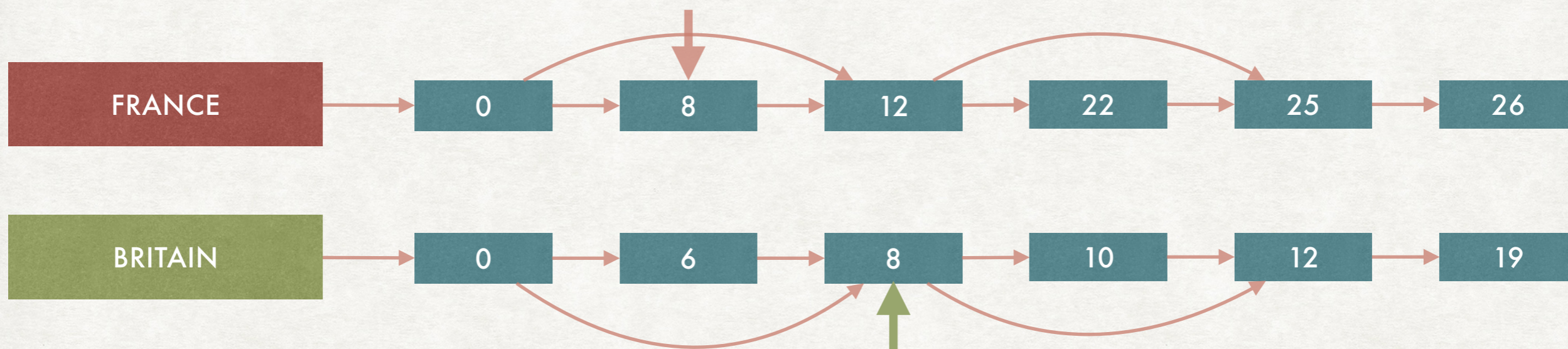
AN EXAMPLE QUERY

SAVING TIME WITH SKIP LISTS



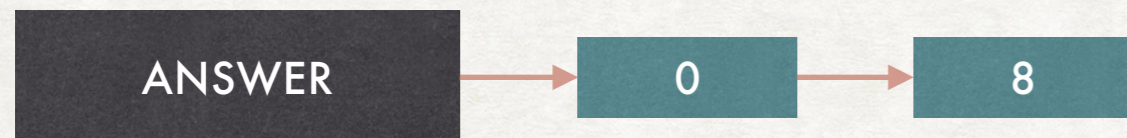
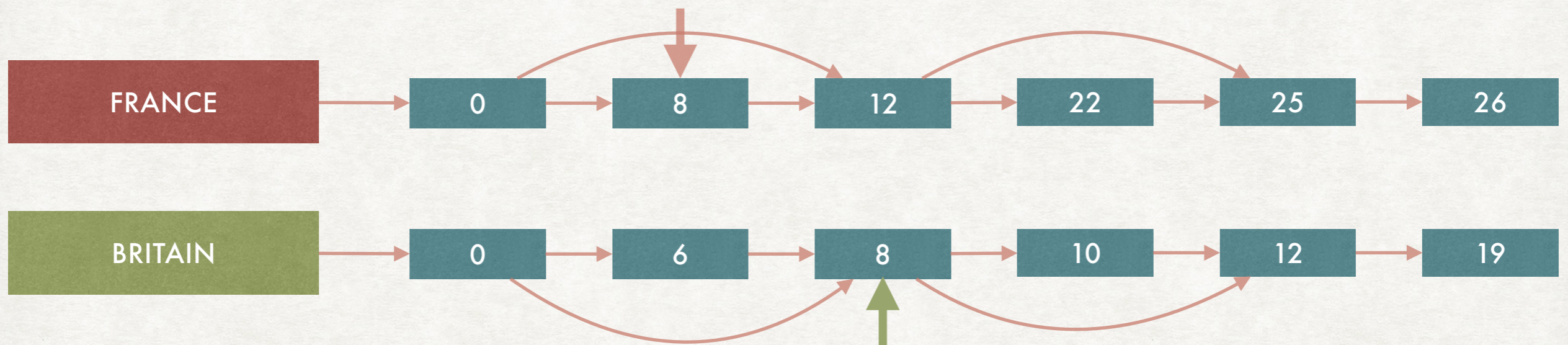
AN EXAMPLE QUERY

SAVING TIME WITH SKIP LISTS



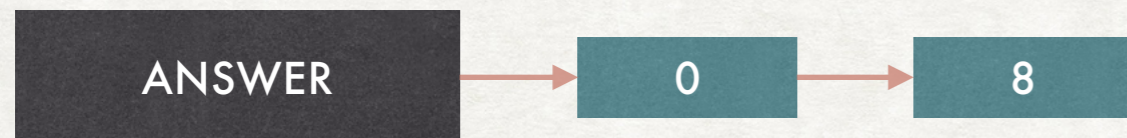
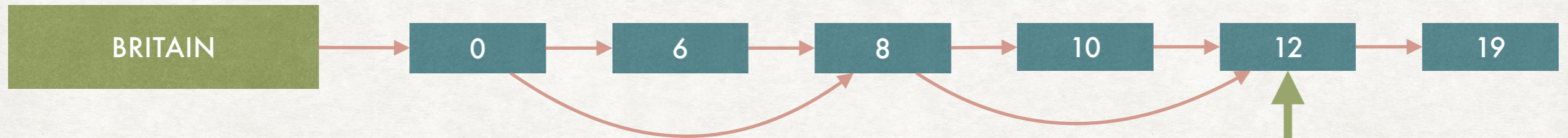
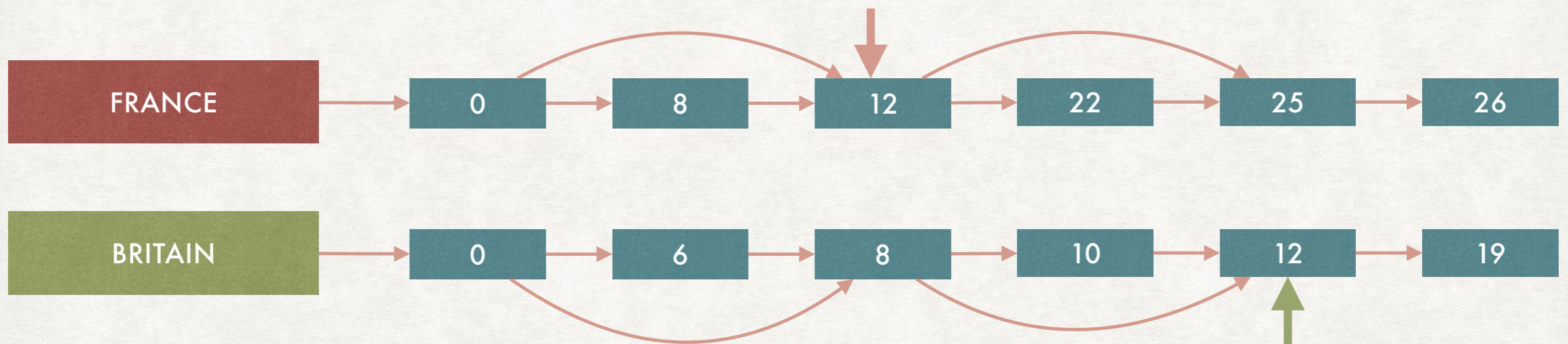
AN EXAMPLE QUERY

SAVING TIME WITH SKIP LISTS



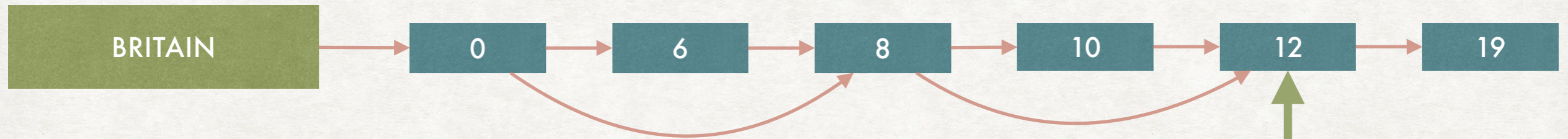
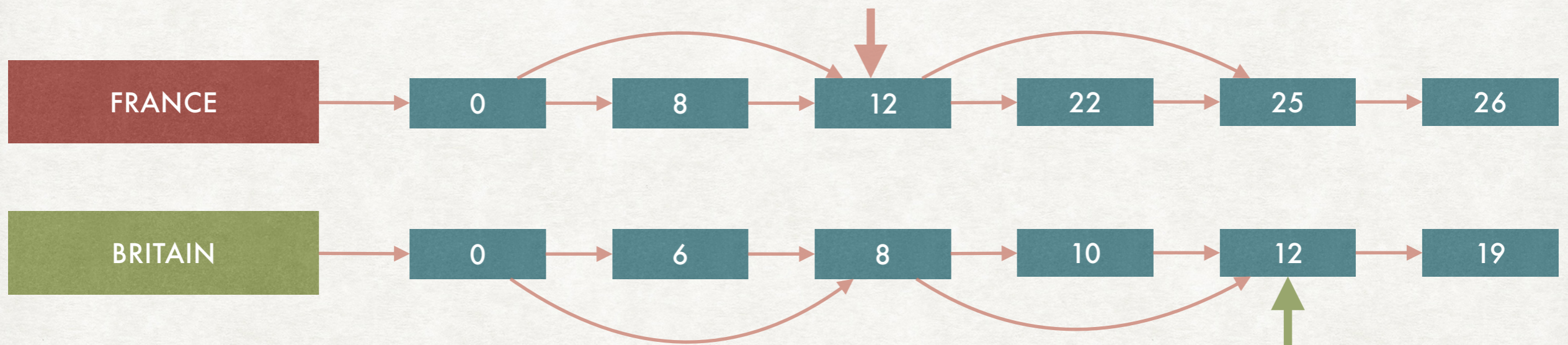
AN EXAMPLE QUERY

SAVING TIME WITH SKIP LISTS



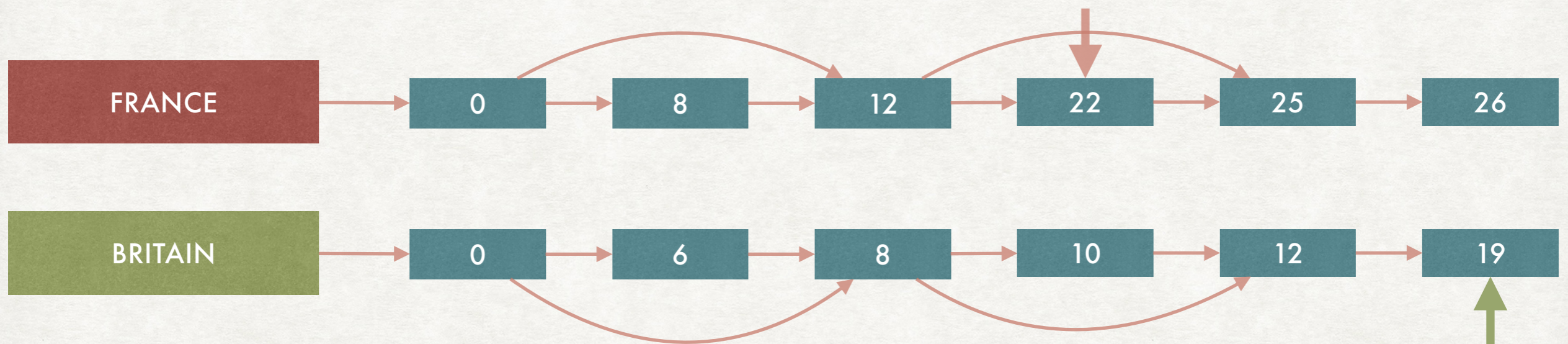
AN EXAMPLE QUERY

SAVING TIME WITH SKIP LISTS



AN EXAMPLE QUERY

SAVING TIME WITH SKIP LISTS



In some situations
we might only need
 $O(\sqrt{P})$ steps
to traverse a list

EXERCISES

THE PRACTICAL PART

- We are going to implement some of the algorithms and data structure described in this course
- We use Python 3, but you can follow along with any other programming language
- While IR systems must be efficient, we will sometimes allow for inefficiencies for the sake of more readable code
- Dataset that we use: <http://www.cs.cmu.edu/~ark/personas/>, more than 42k movie descriptions

EXTERNAL STORAGE

MAIN MEMORY AND EXTERNAL STORAGE

- When analysing the complexity of algorithms each step is considered as having the same cost.
- This is a reasonable assumption in many cases, especially if all the data fit in the main memory.
- When accessing storage this assumption is stretched too thin: the costs can be orders of magnitude greater than accessing the main memory.
- Similar considerations holds when using the network.

TIMING OF SOME STANDARD OPERATIONS

FROM NANoseconds TO MILLISECONDS

execute typical instruction	1 ns
fetch from L1 cache memory	0.5 ns
branch misprediction	5 ns
fetch from L2 cache memory	7 ns
Mutex lock/unlock	25 ns
fetch from main memory	100 ns
send 2K bytes over 1Gbps network	20,000 ns
read 1MB sequentially from memory	250,000 ns
fetch from new disk location (seek)	8,000,000 ns
read 1MB sequentially from disk	20,000,000 ns

From <http://norvig.com/21-days.html#answers>

COMPLEXITY: COUNTING DISK ACCESSSES

- We should take into account the number of disk accesses.
- Some effects of this choice are:
 - We might want to transfer data "in bulk". Since each read is costly, we want to read more than strictly necessary.
 - While asymptotic results are important, we might want to be do a finer analysis.
 - Since the access to external storage is expensive, we might decide to do more work "in memory" to minimise the number of accesses (e.g., compress and decompress data).

DATA STRUCTURES FOR DICTIONARIES

HOW IS A DICTIONARY ACTUALLY REPRESENTED?

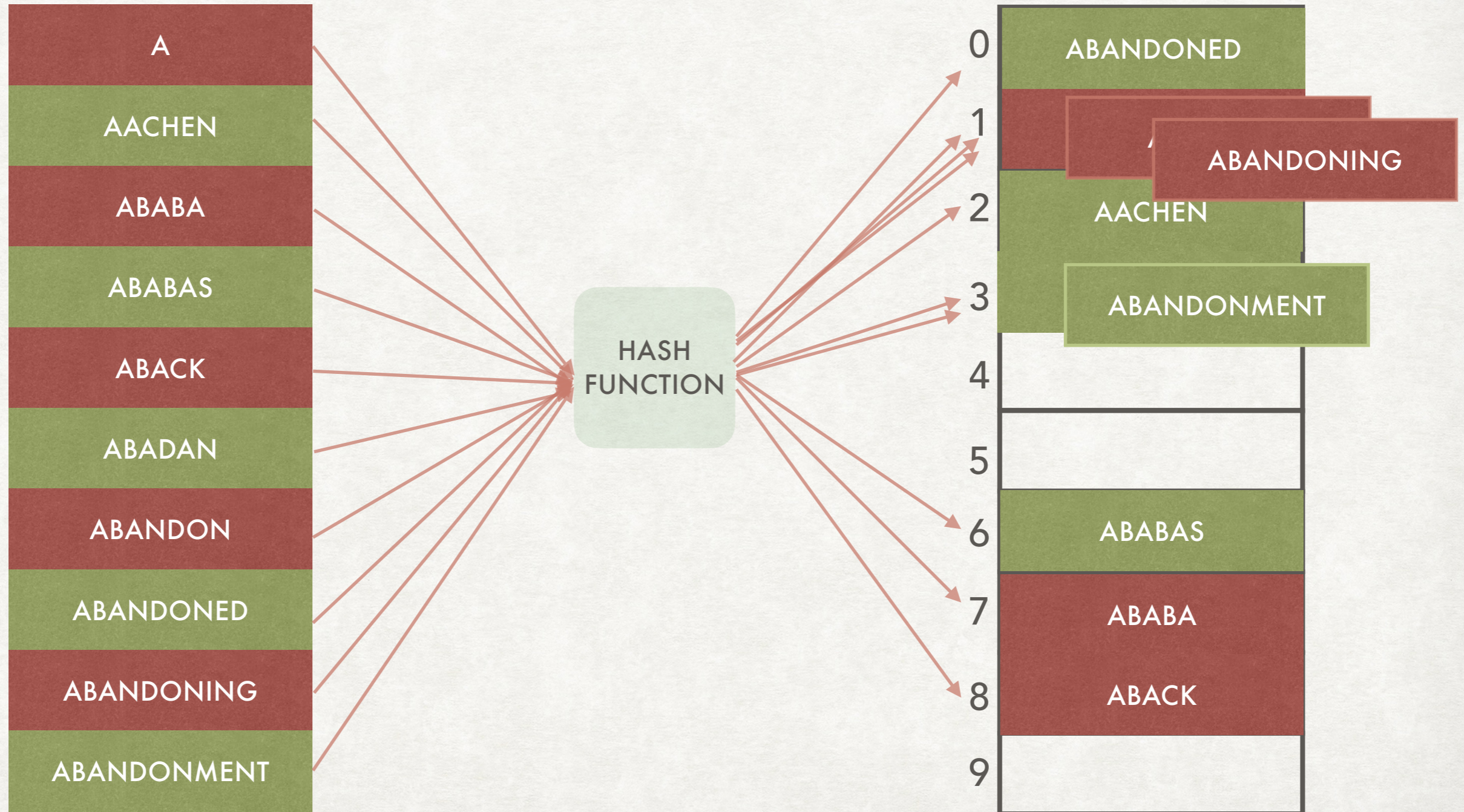
HASH TABLES & TREES



- It is necessary to search in a dictionary that can be quite large
- Something more efficient than a linear scan is needed
- Two main approaches:
 - Hash tables
 - Trees (binary trees, b-trees, tries, etc.)

HASH TABLES

A BRIEF RECAP



HASH FUNCTIONS

SOME EXAMPLES

Traditional for integers: $h(x) = x \bmod m$ where m is the size of the table

How to manage strings?



Component sum

split the string into chunks and sum (or xor) them.



104 + 101 + 108 + 108 + 111 = 532

Polynomial accumulation

consider each chunk as a coefficient of a polynomial, then evaluate it for a fixed value of the unknown



$104 + 101x + 108x^2 + 108x^3 + 111x^4$

for $x = 33$ it evaluates to 135639476

HASH TABLES

A BRIEF RECAP

- A hash function assigns to each input (term) an integer number, which is the position of the term in a table.
- **Collisions**: sometimes for two different inputs the hash function returns the same value.
- Load factor: $\frac{\text{\# elements}}{\text{size of the table}}$.
 - Lower load factor: **higher memory usage** but **less risk of collisions**
 - Higher load factor: **lower memory usage** but **higher risk of collisions**

HASH TABLES

MANAGING COLLISIONS

- **Open addressing.** All entries are stored in the table, in case of collision the first free slot according to some probe sequence is found (e.g., linear or quadratic probing).
- **Chaining.** Each "cell" is a list of all entries with the same hash.
- **Perfect hashing.** For a fixed set it is possible to compute an hashing function with no collisions.
- **Other collision resolution techniques, like cuckoo hashing.** It shares some characteristic of perfect hashing while allowing updates.

HASH TABLES

THE GOOD, THE BAD, AND THE UGLY

- Finding an element in a hash table requires $O(1)$ *expected* time.
- In some cases (e.g., perfect hashing) this can also be the worst case time.
- Adding new elements might require *rehashing* (i.e., reinsertion of all elements into a bigger table) which is costly. This is needed to keep the load factor low enough.
- Some kind of searches are not possible, like looking for a prefix. In general anything that requires something different from the exact term.

BINARY TREES

A BRIEF RECAP

A binary tree is a tree in which each node has at most two children

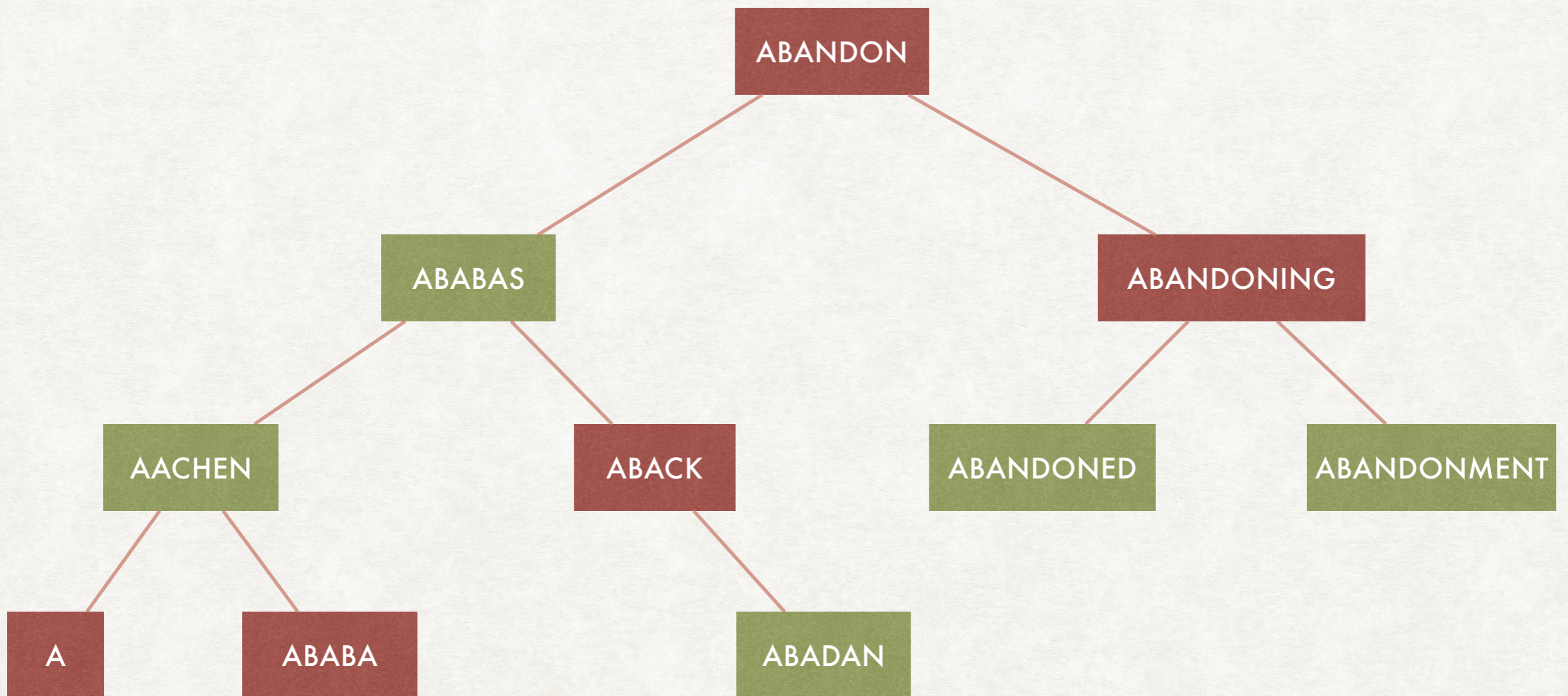
Each node has an associated value (a term in our case)

A *binary search* tree has the property that the left subtree has only values smaller than the value in the root and the right subtree only values that are larger.

This means that, if the tree is balanced, search can happen in $O(\log n)$ steps.



AN EXAMPLE OF BINARY SEARCH TREE



BINARY TREES

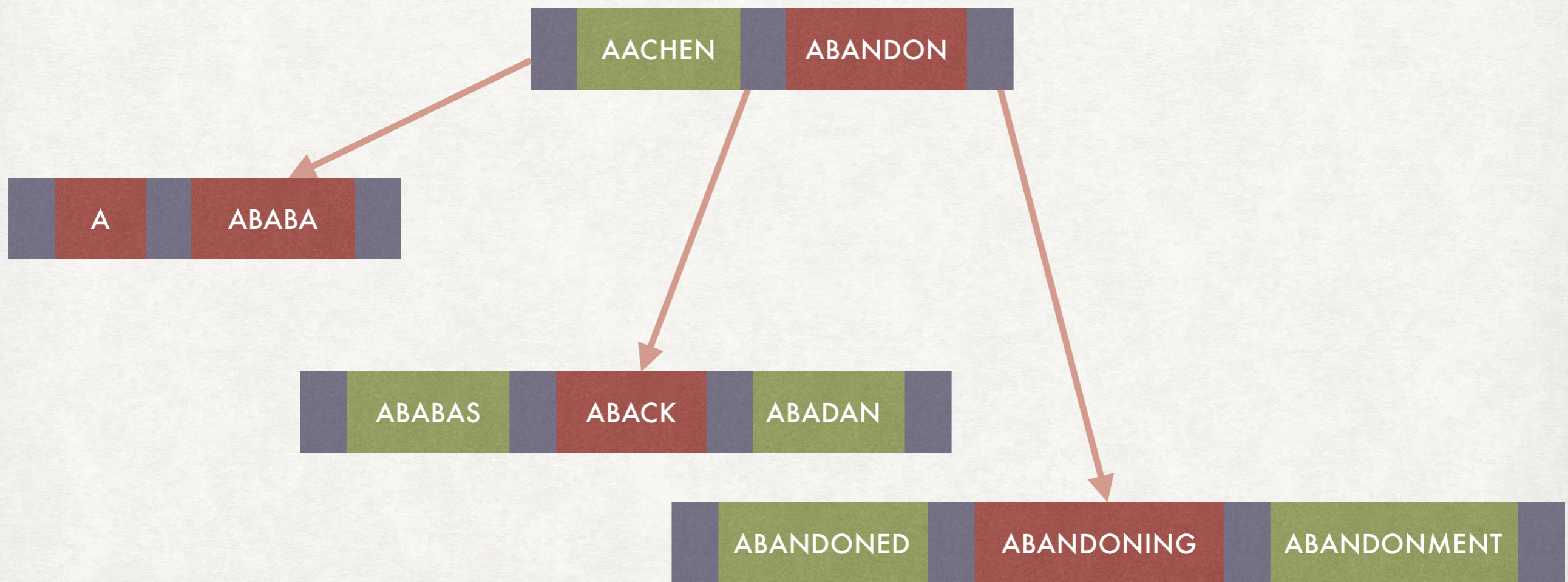
THE GOOD, THE BAD, AND THE UGLY

Binary search trees solve most of the problems of hash tables:

- Insertion (and deletion) are not expensive.
- Searching a prefix is possible.
- As long as the tree is kept balanced, search is efficient.
- But binary trees do not play well with disk access. $O(\log n)$ accesses to the main storage might be costly.
- A way to reduce the number of disk accesses while still using trees is via B-trees.

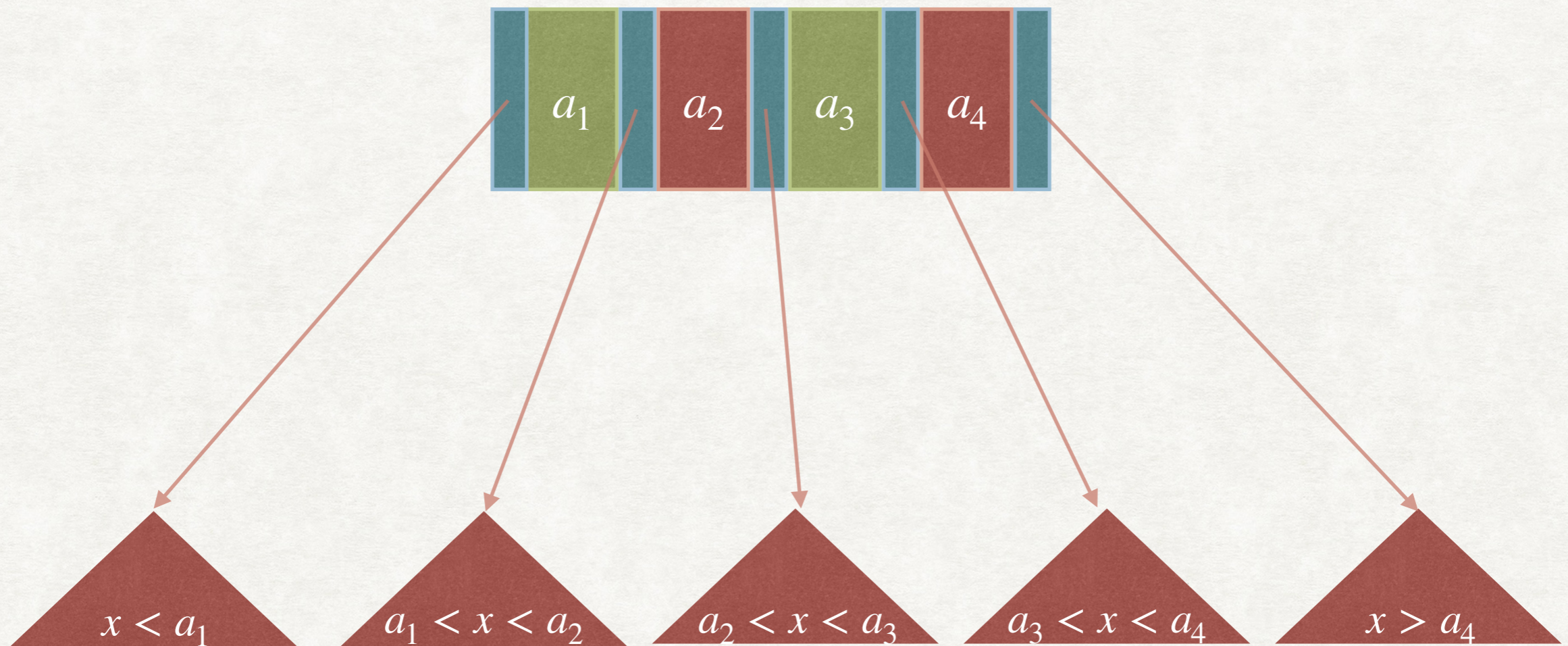
B-TREES

B-trees can be seen as a generalisation of binary search trees in which each node has between a and b children.



STRUCTURE OF A B-TREE NODE

The size of a node is usually selected to be a "block"



The node can contain up to four values and five pointers to subtrees each respecting a "generalised" version of the BST property

WHY B-TREES?

AND NOT SIMPLY BINARY SEARCH TREES?

- If you have to search across 10^6 elements then you need to go through at most:
 - $\lceil \log_2(10^6) \rceil = 20$ nodes in a binary search tree.
 - $\lceil \log_B(10^6) \rceil$ nodes in a B-tree, where B is the size of the block. Suppose $B = 100$, then $\lceil \log_{100}(10^6) \rceil = 3$.
- This number corresponds to the number of disk accesses, which are the ones dominating the running time.

TRIES

ALSO KNOWN AS PREFIX TREES

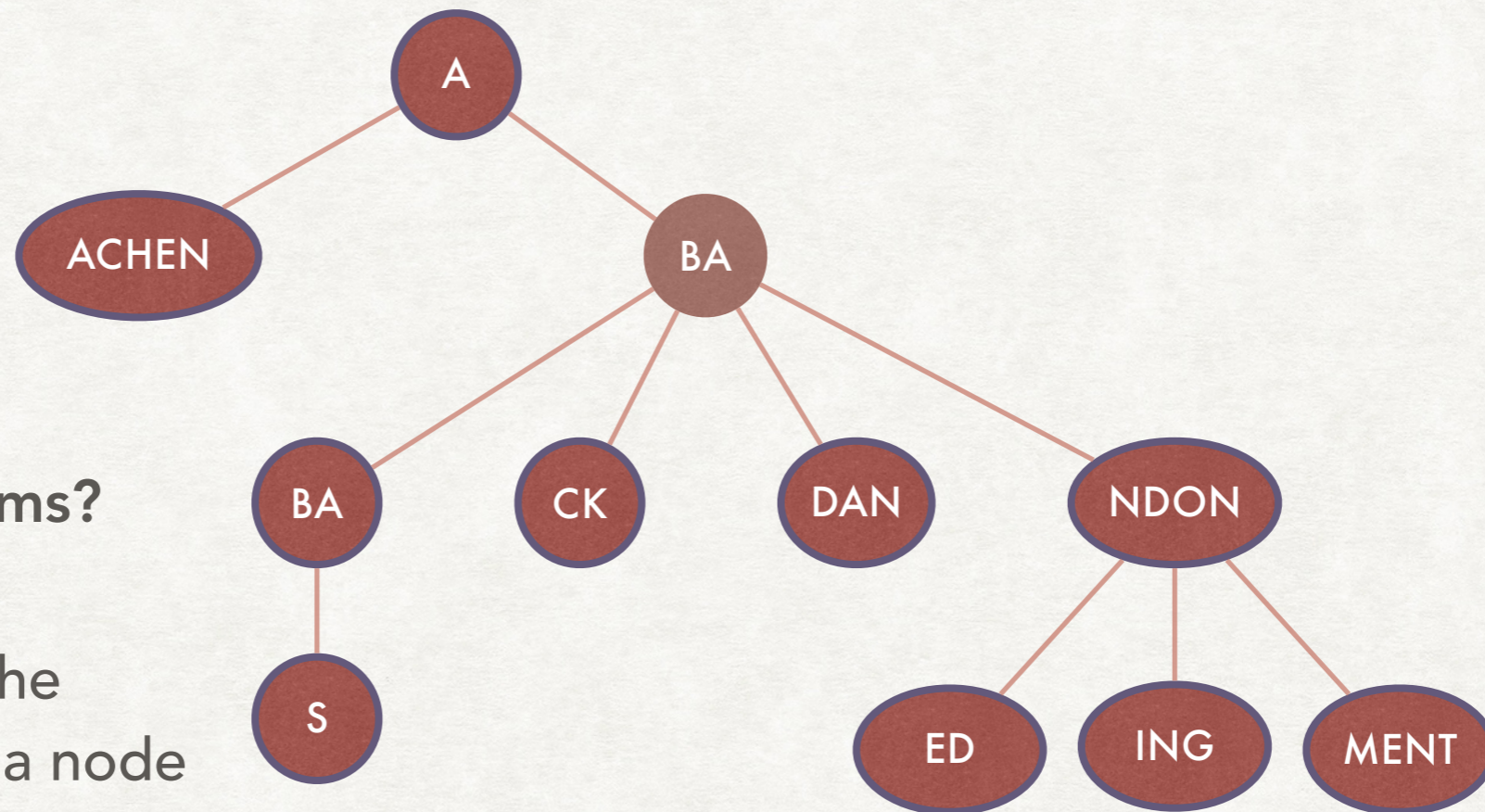
A **trie** is a special kind of tree based on the idea of searching by looking at the prefix of a key

The key itself (the term in our case) provides the path along the edges of the trie

Access time: worst case $O(m)$ where m is the size of the key. This is optimal because we must read the key.

Insertion is still possible and efficient.

TRIES: AN EXAMPLE



Where are the terms?

They are encoded
in the paths from the
root of the tree to a node

- There **is** a key corresponding to the path from the root to this node
- There **isn't** key corresponding to the path from the root to this node

TRIES: PROS AND CONS

- Tries have access time that is as good as hash tables (the $O(1)$ time for hash tables assumes a constant-length key)
- Differently from hash tables, there cannot be collisions.
- Insertion is still efficient.
- Search inside a range of key is very efficient.
- There can still be problems of too many accesses to disk.
- There are variants of tries for external storage that mitigate the problem

DICTIONARY AND INDEX COMPRESSION

WHY COMPRESSION?

SPEED IMPLICATIONS

- We can compress two things: the dictionary and the postings
- Why using compression?
 - To save disk space.
 - To keep the entire dictionary in memory.
 - To keep more data in the main memory.
 - It might be faster to read less data from disk and decompress it in memory than to read the non-compressed data.

ESTIMATION OF THE NUMBER OF TERMS

HEAPS' LAW

In a collection with T tokens the estimated size of the vocabulary is:

$$M = kT^b$$

Typical values for k are between 30 and 100

Usually, $b \approx 0.5$

HEAPS' LAW SUGGESTS THAT THE SIZE OF THE DICTIONARY INCREASES WITH THE SIZE OF THE COLLECTION

DISTRIBUTION OF TERMS

ZIPF'S LAW

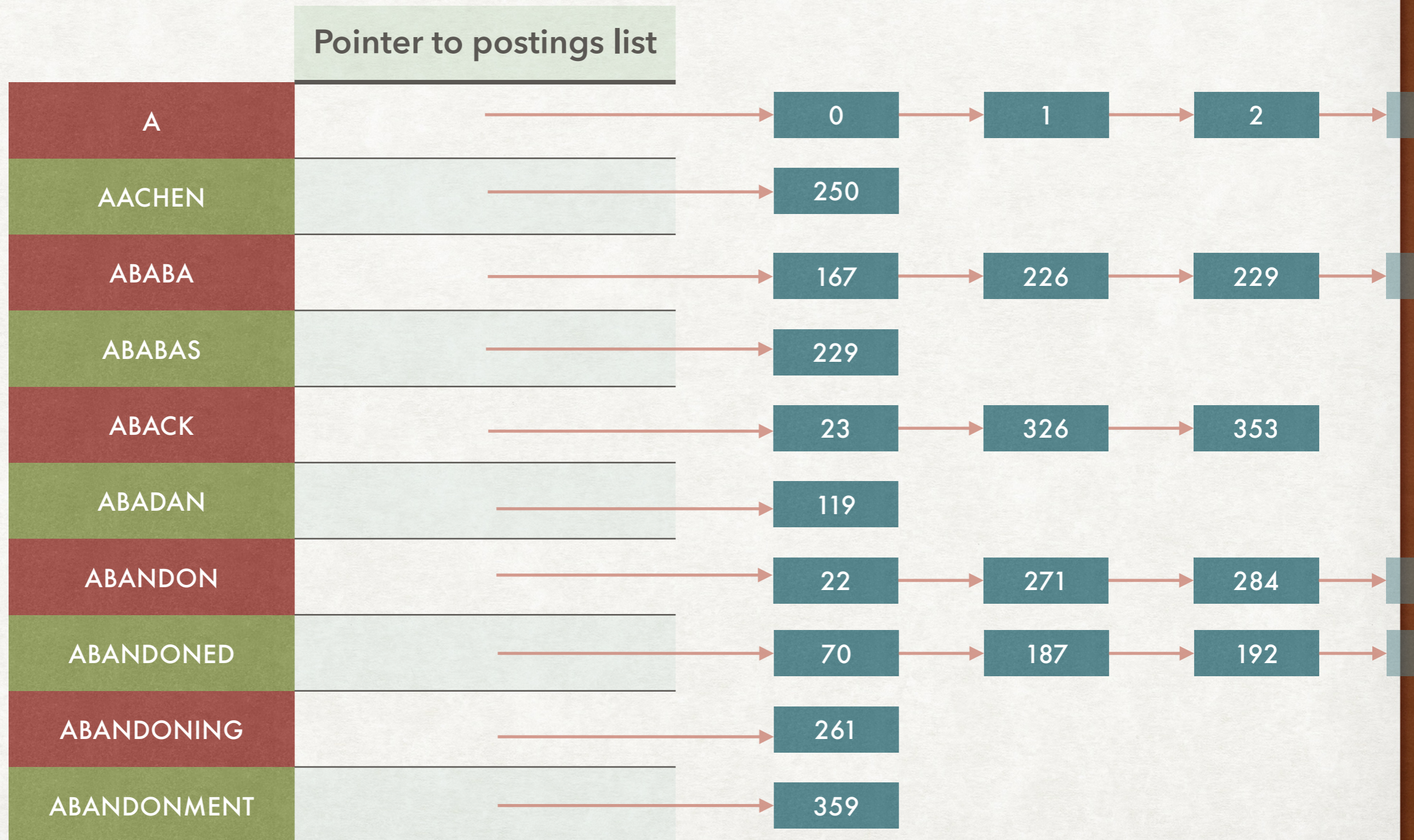
The i -th most common term in a collection appears with a frequency cf_i proportional to $\frac{1}{i}$:

$$cf_i \propto \frac{1}{i}$$

In other words, frequency of terms decreases rapidly with the rank.

Equivalent formulation: $cf_i = ci^k$ for some constants c and for $k = -1$.

DICTIONARY AS FIXED-WIDTH ENTRIES

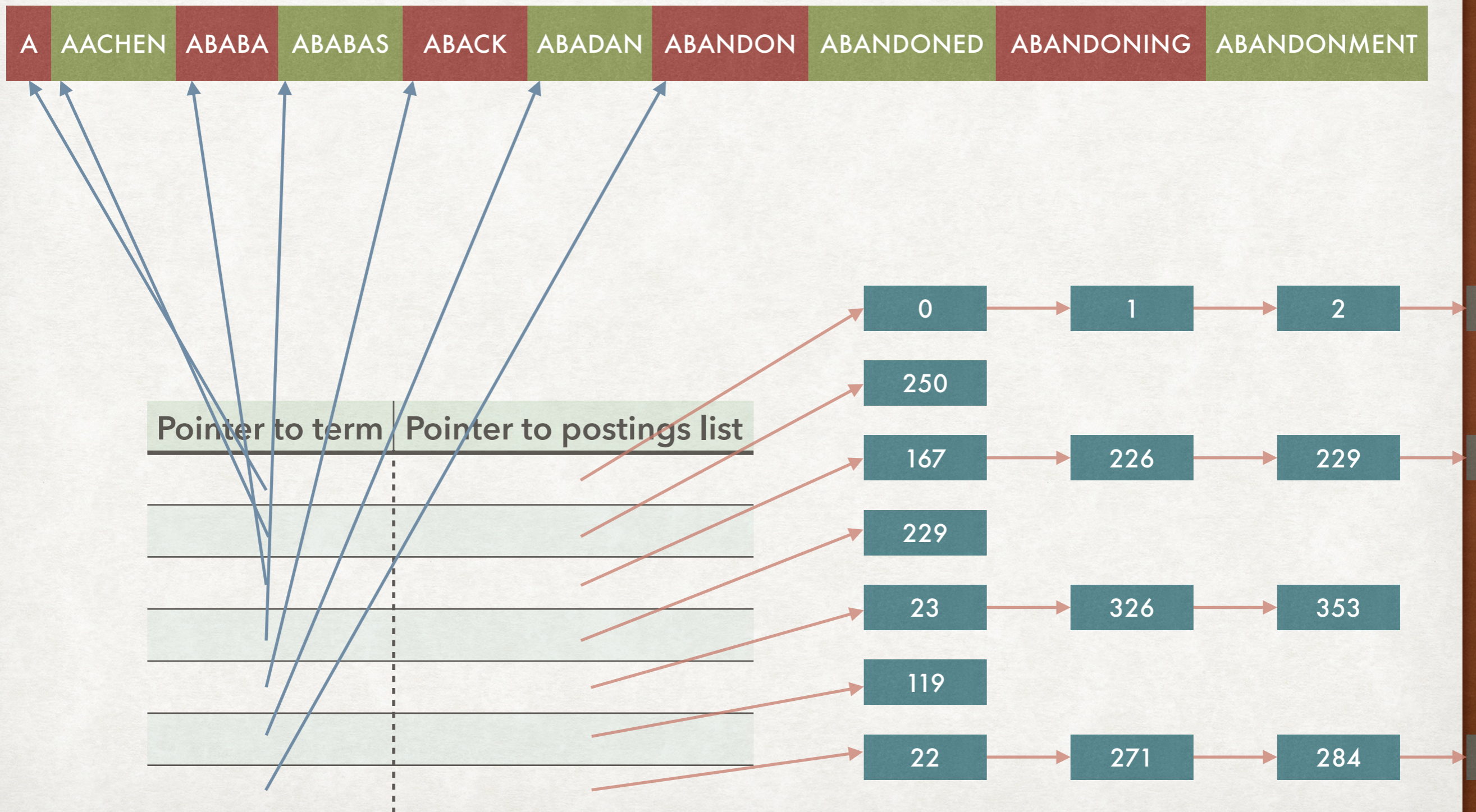


DICTIONARY AS FIXED-WIDTH ENTRIES

ADVANTAGES AND DISADVANTAGES

- Each entry consists of an entry of m characters and a pointer to the postings list.
- Words of length at most m can be stored.
- If we save a 40 characters string (i.e., $m \geq 40$) then every entry will require 40 characters, wasting a lot of space for short words.

DICTIONARY AS A SINGLE STRING

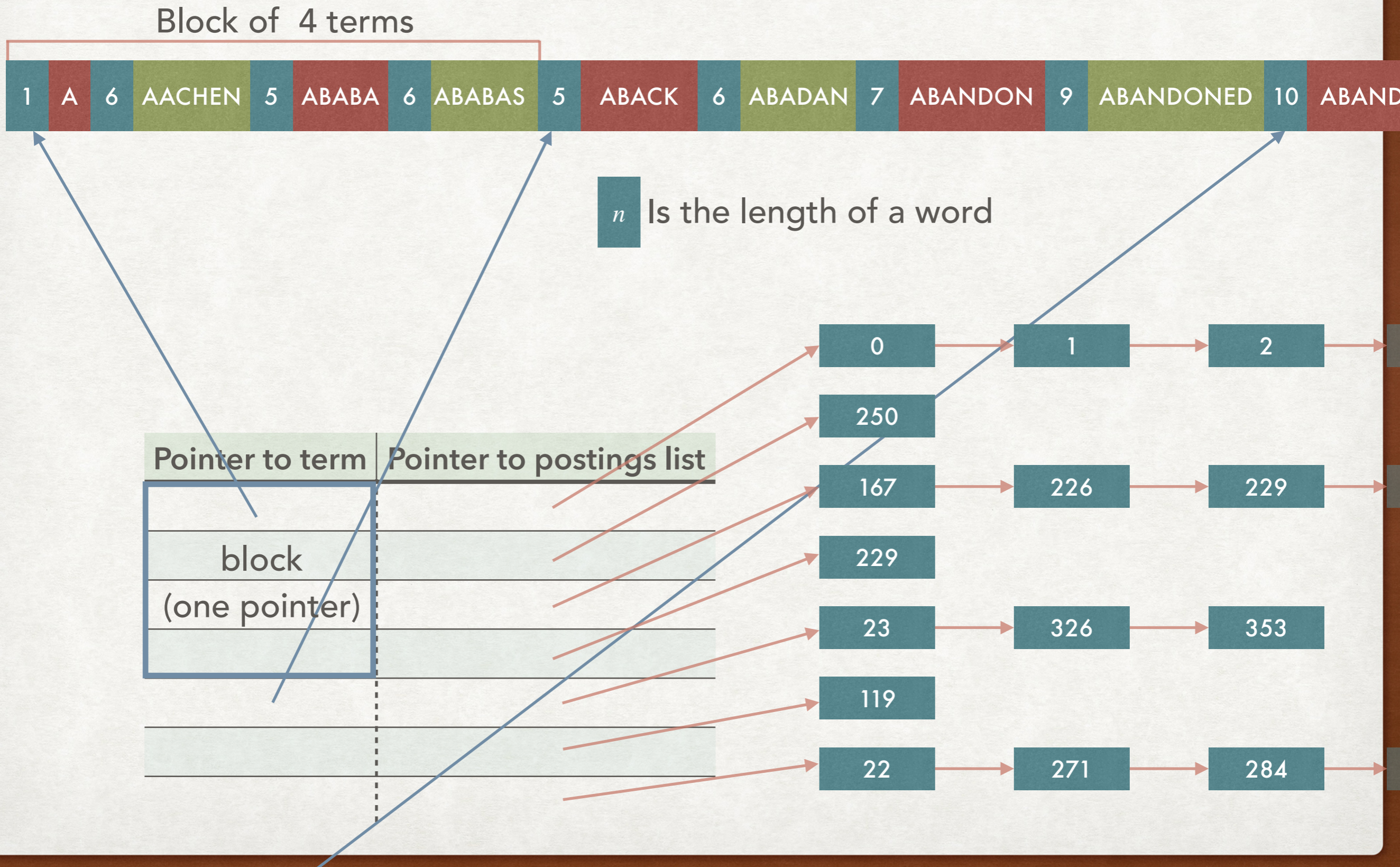


DICTIONARY AS A SINGLE STRING

DESCRIPTION AND ADVANTAGES

- Each entry consists of a pointer to the term that is part of a contiguous string and to the pointer to the postings list
- To know the end of the word it is necessary to look at the next pointer.
- There is no wasted space for the strings...
- ...but it is necessary to keep an additional pointer for each entry.
- We can reduce the space used for the pointers by using *blocked storage*.

BLOCKED STORAGE



BLOCKED STORAGE

ADVANTAGES AND DISADVANTAGES

- Now only one every k entries (the block size) has a pointer.
- The value of the others entries is determined by a linear scan of the block.
- The addition of the length of the string is needed to know where a string end.
- It is a trade-off between space and access time (which is increased due to the linear scanning inside a block).
- We are still not using the fact that the words in the dictionary are ordered alphabetically.

FRONT CODING



Length of the prefix shared with the previous word

In red the prefix shared by each word with the previous one in the block:

A
AACHEN
ABABA
ABABAS

ABACK
ABADAN
ABANDON
ABANDONED

This works because the dictionary is ordered alphabetically, thus many words share a prefix

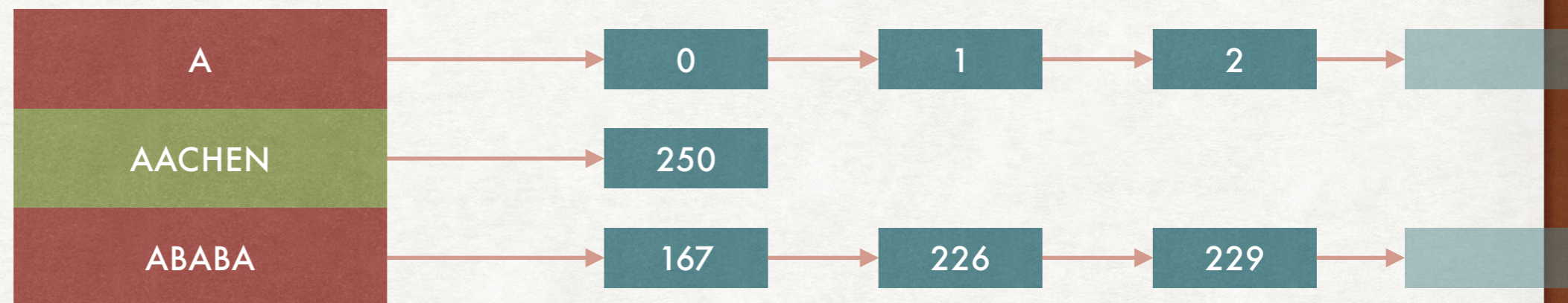
FRONT CODING

ADVANTAGES AND DISADVANTAGES

- Used inside a block reduces the size of the dictionary.
- Uses the fact that the dictionary is ordered.
- Requires, in addition to the linear scanning, a decoding phase.
- As before a trade-off between reducing size and incrementing the cost of retrieving a term.

POSTING FILE: ENCODING DIFFERENCES

AND THE USE OF VARIABLE BYTE CODES



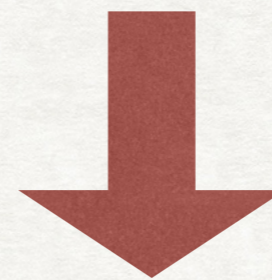
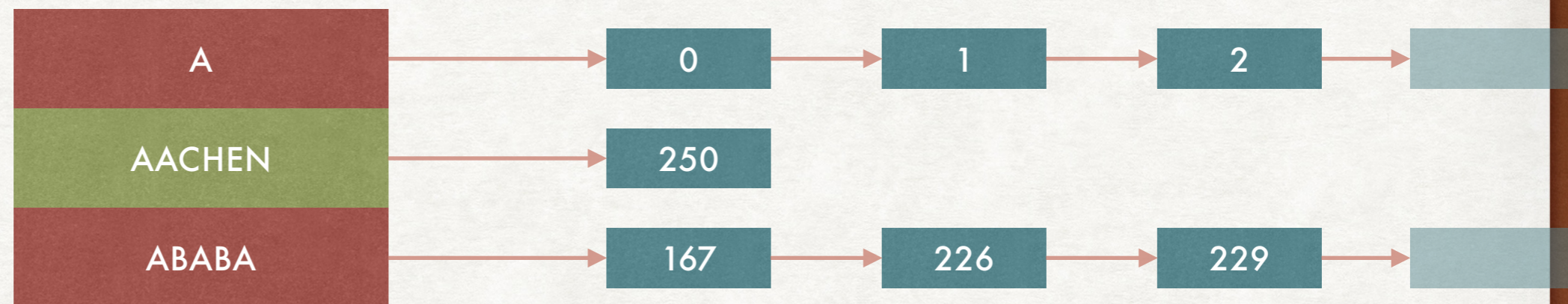
Can we use the fact that a postings list is ordered?

YES

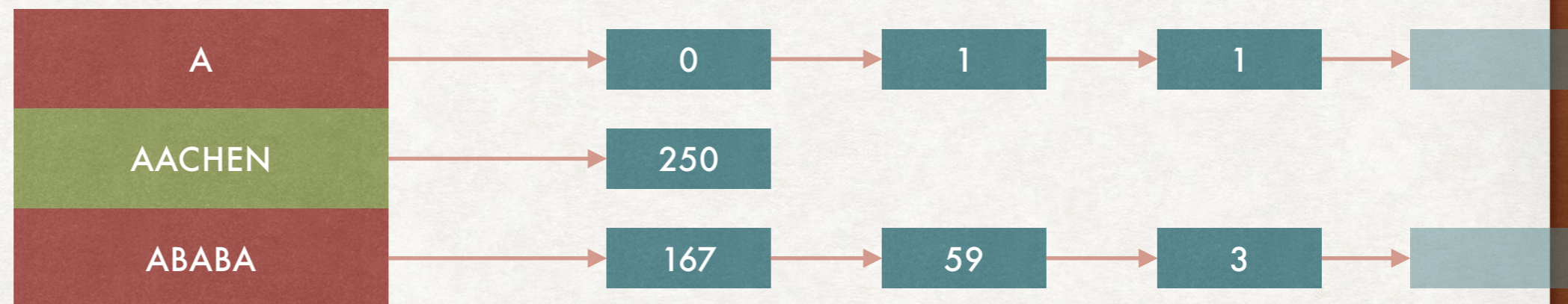
If we have a sequence $(a_0, a_1, a_2, a_3, \dots)$ with $a_i < a_{i+1}$ for all i , we can also encode it as a sequence of differences of consecutive terms: $(a_0, a_1 - a_0, a_2 - a_1, a_3 - a_2, \dots)$

POSTING FILE: ENCODING DIFFERENCES

AND THE USE OF VARIABLE BYTE CODES

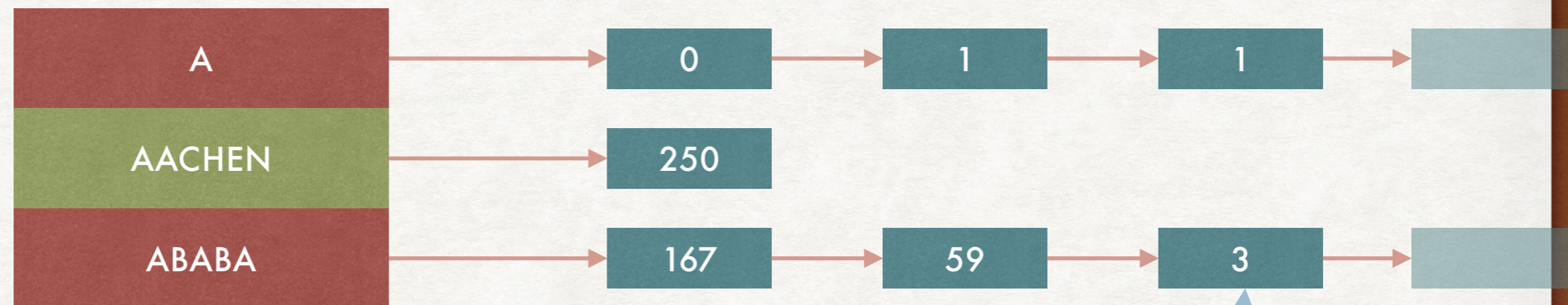


Encoding gaps instead of DocIDs



POSTING FILE: ENCODING DIFFERENCES

AND THE USE OF VARIABLE BYTE CODES



How can we recover this DocID?

$$167 + 59 + 3 = 229$$

In general, to recover the k -th DocID in list we sum all the values up to the k -th one:

$$a_0 + \sum_{i=0}^k (a_i - a_{i-1}) = a_0 + a_1 - a_0 + a_2 - a_1 + \dots = a_k$$


POSTING FILE: ENCODING DIFFERENCES

MOTIVATIONS FOR ENCODING THE GAPS

- The DocID can be arbitrarily large...
- ...but most of the gaps between two DocID will be small
- We can use *variable byte codes* to use less storage
- Still, recovering a DocID now is more complex.
- Most importantly, access to the list must be sequential: to recover a DocID we need to read all the previous ones.
- But the algorithms for union and intersection access the list sequentially.

VARIABLE BYTE CODES

ENCODE NUMBERS IN A VARIABLE NUMBER OF BYTES


$$2^6 + 2^3 = 72$$

One byte usually encodes $2^8 = 256$ different values

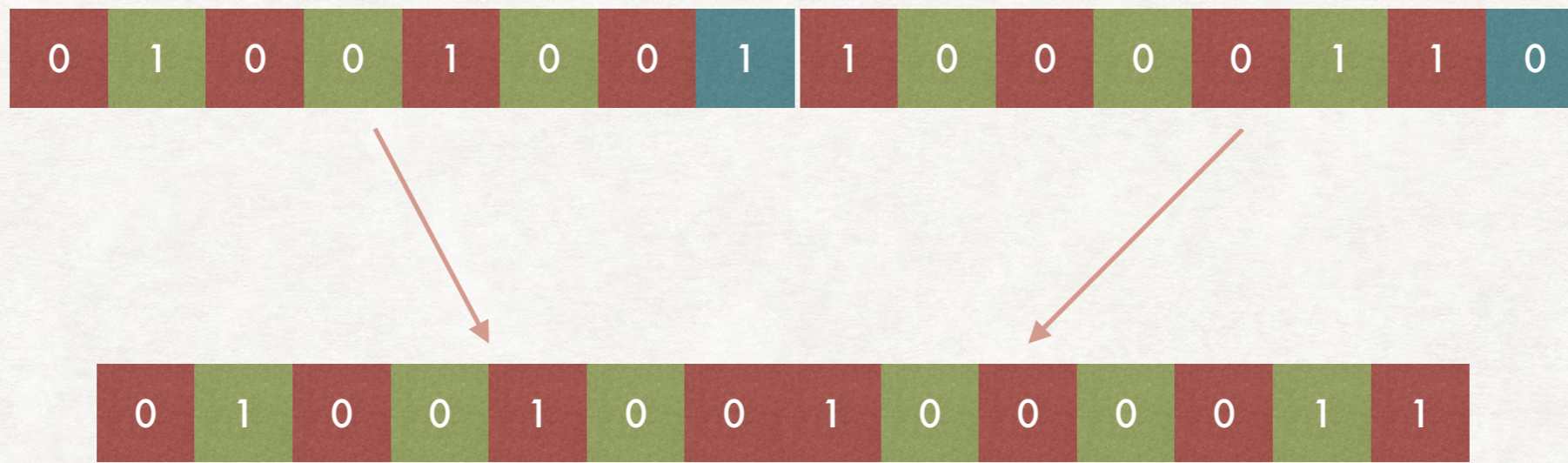

$$2^5 + 2^2 = 36$$

We encode $2^7 = 128$ different values in the first seven bits
the last bit is a *continuation bit*.

If it is 0 then we have completed reading the number
otherwise we must continue to read the next byte

VARIABLE BYTE CODES

ENCODE NUMBERS IN A VARIABLE NUMBER OF BYTES



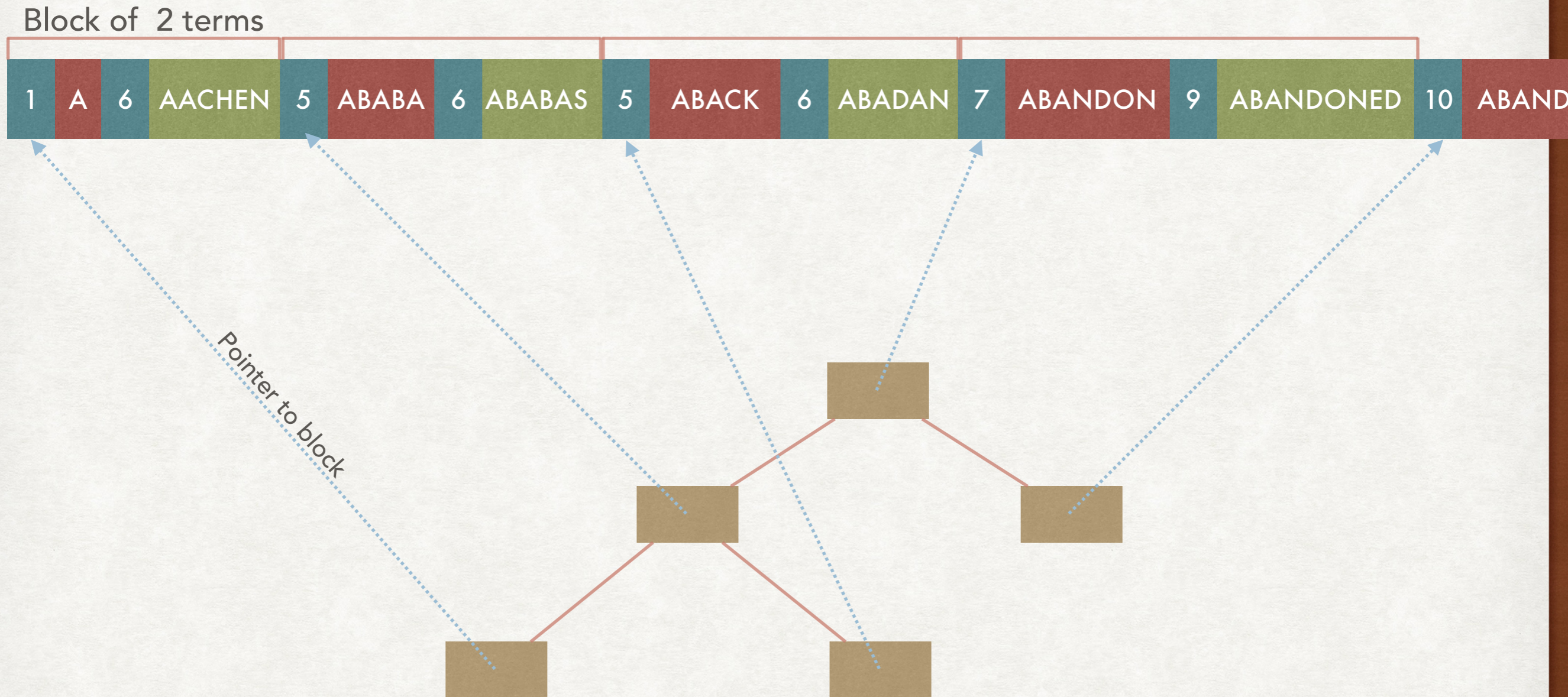
$$2^{12} + 2^9 + 2^6 + 2^1 + 2^0 = 4675$$

# of bytes	Max value
1	127
2	16383
3	2097152
4	268435456

The most frequent terms will have small gaps in their postings lists.

Hence, we can store the size of most gaps in only a few bytes

COMPRESSION + DATA STRUCTURES



A binary search on a compressed dictionary requires a linear search inside each block

UPDATING THE INDEX

STORING POSTINGS

HOW THE POSTINGS LISTS ARE ORGANISED ON DISK

- How are the postings stored on-disk?
- One file per postings list can lead to too many files for a filesystem to manage efficiently
- One single large file containing all the postings can be better (here we select this solution)
- In reality we can have a combination of both, with multiple large files each storing part of the postings

DYNAMIC INDEXING

FOR COLLECTIONS THAT CHANGE WITH TIME

- How can we insert new documents (or delete old ones) in an inverted index?
- We can rebuild the index:
 - Not very efficient.
 - Only useful when the number of changes is small.
 - To keep the system online while reindexing we need to keep the old index until new one is ready.

AUXILIARY INDEX

A MORE EFFICIENT SOLUTION

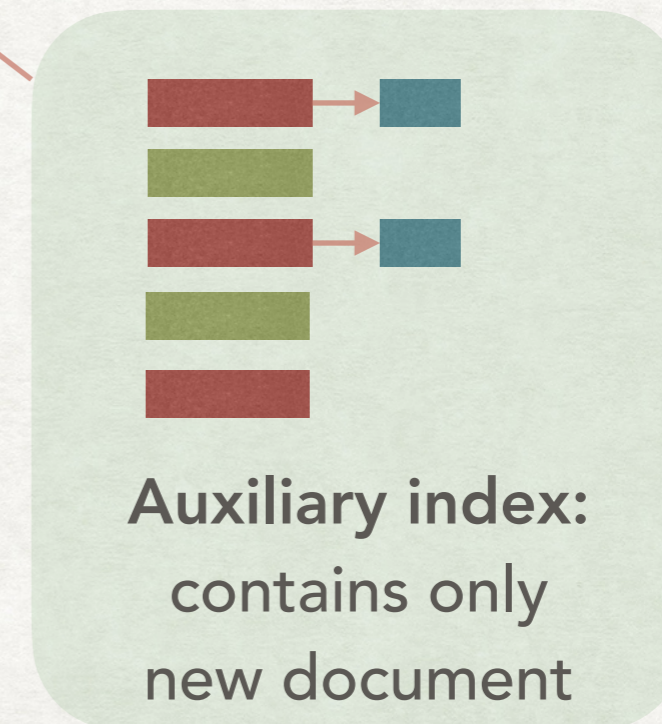
Queries merge
the results of
the two indices

+

Filtering using the
invalidation bit vector



Invalidation bit vector:
we save which documents
has been deleted
(one bit for each document)



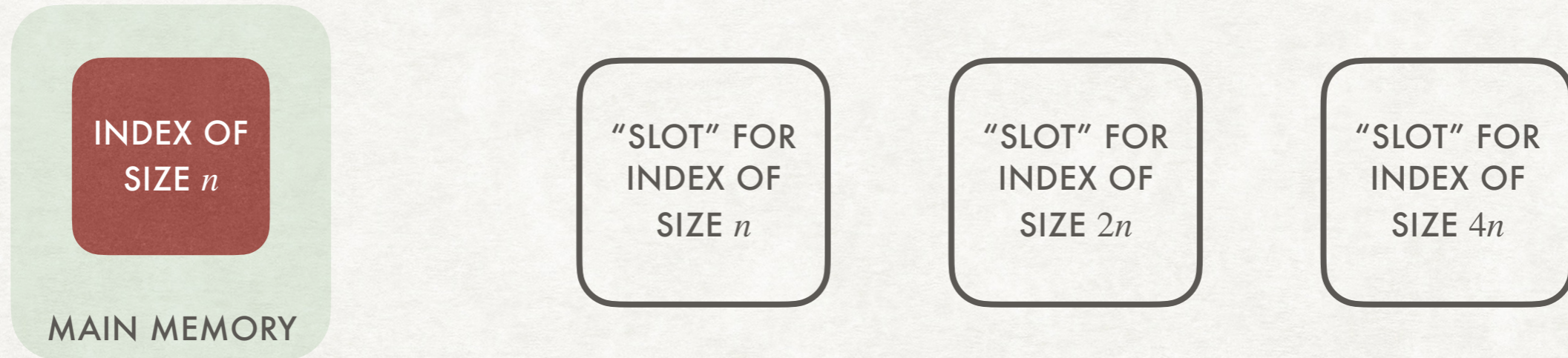
AUXILIARY INDEX

CAN WE DO BETTER?

- When the auxiliary index becomes too big we need to merge it with the main index.
- We can improve the efficiency by keeping $\log_2(T/n)$ auxiliary indices (each one of size double the previous one) where T is the total number for postings and n the size of the smaller auxiliary index.
- This increase the complexity of all algorithms used to answer queries, so it is a trade-off.

LOGARITHMIC MERGING

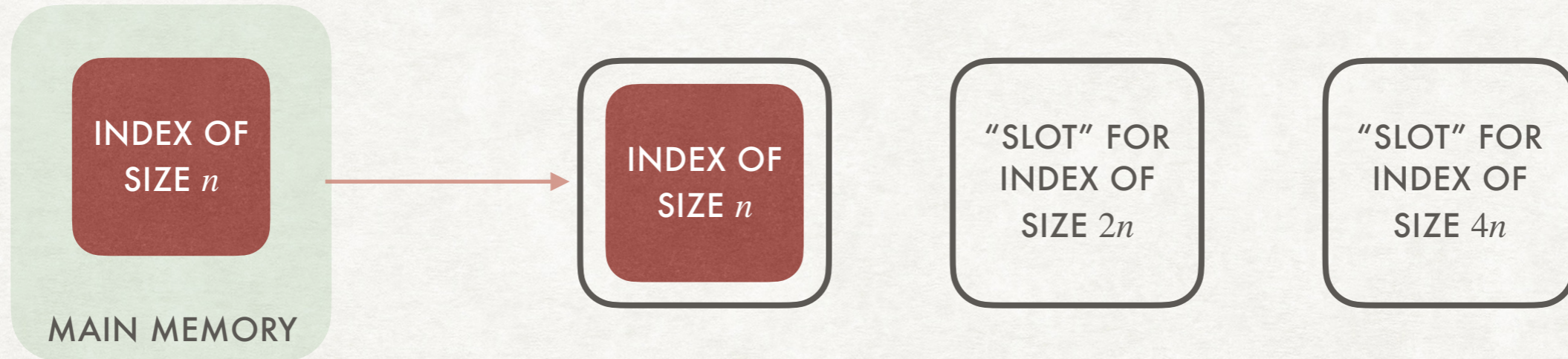
MAIN IDEAS



The smaller index is kept in memory

LOGARITHMIC MERGING

MAIN IDEAS

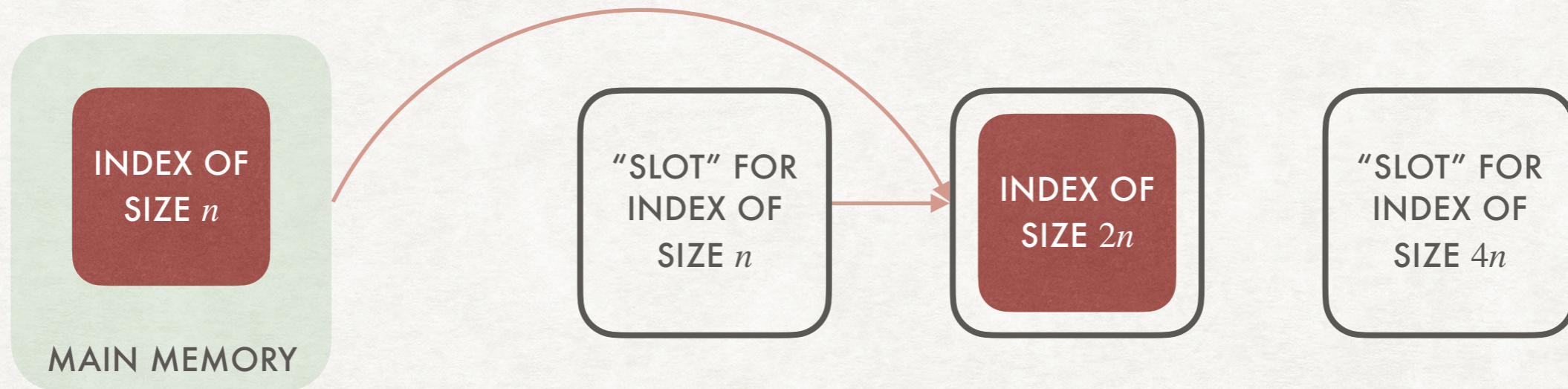


When full it is copied to disk.

A new (empty) index of size n is created in memory

LOGARITHMIC MERGING

MAIN IDEAS

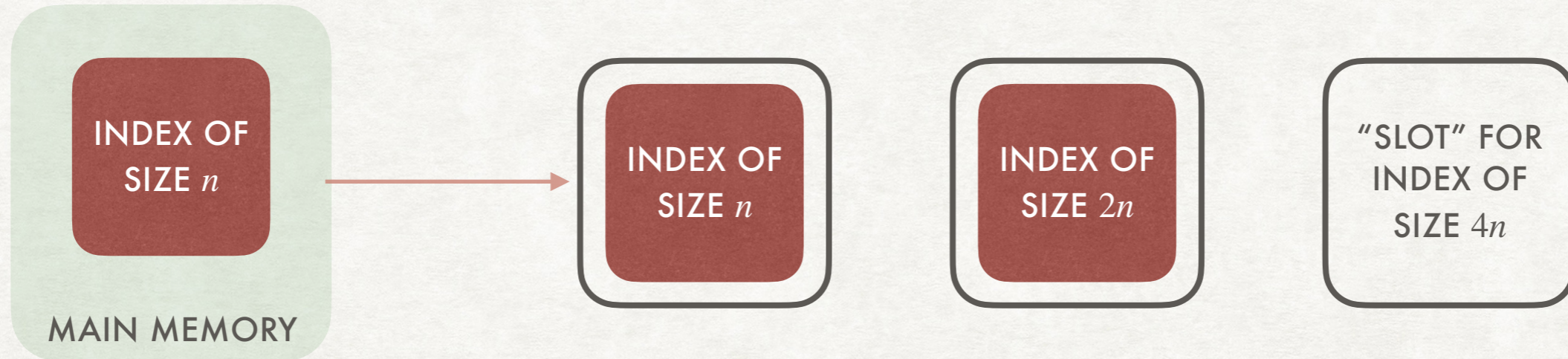


When it is full, since there is already an index of size n saved on disk, it is merged with it to form an index of size $2n$.

A new (empty) index of size n is created in memory

LOGARITHMIC MERGING

MAIN IDEAS

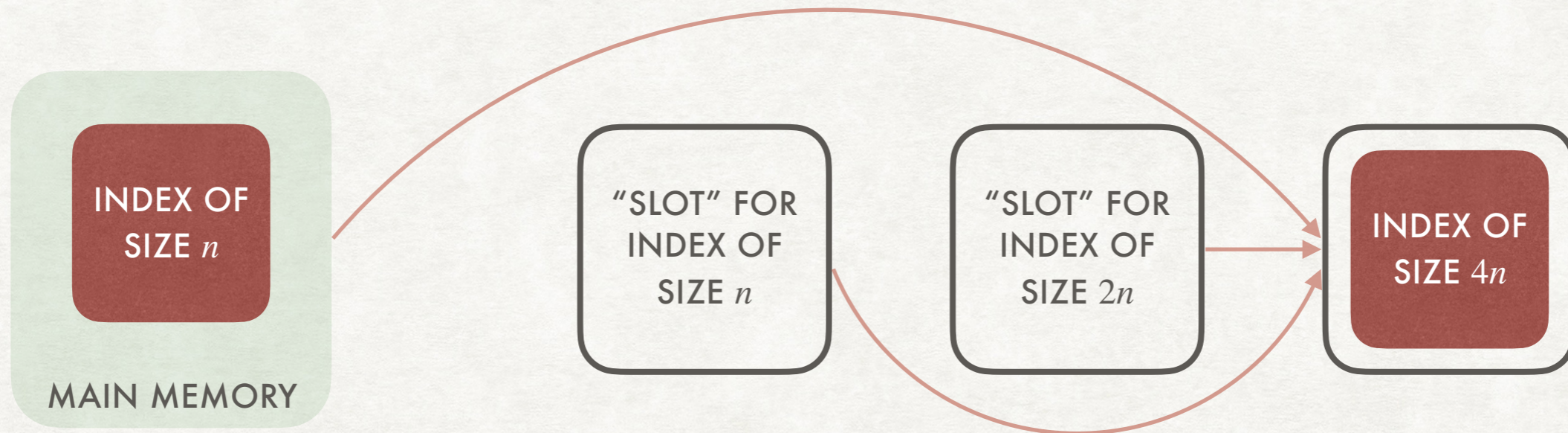


When full it is copied to disk. No merge is necessary (the "slot" is free)

A new (empty) index of size n is created in memory

LOGARITHMIC MERGING

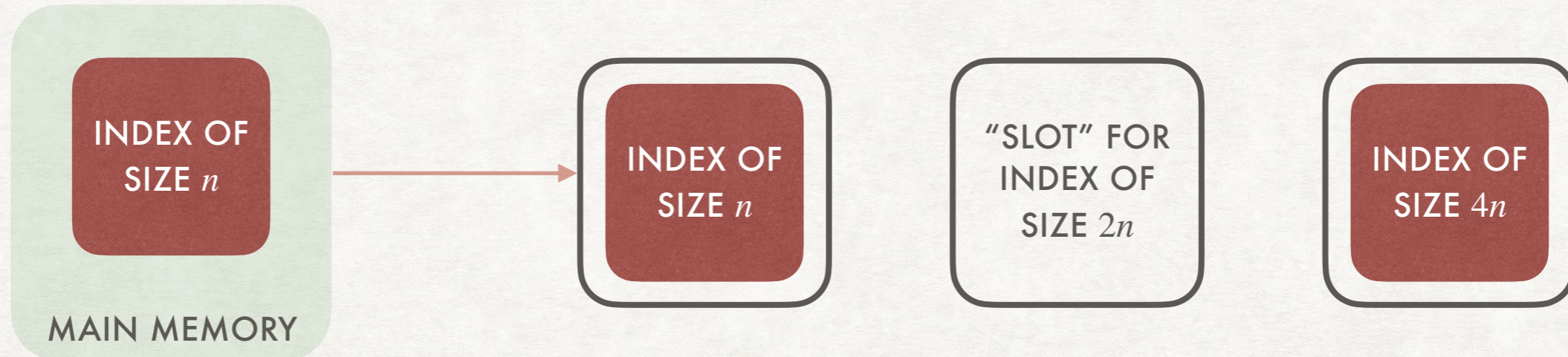
MAIN IDEAS



When it is full, since there is already an index of size n saved on disk, it is merged with it to form an index of size $2n$. Since there is already an index of size $2n$ saved on disk, it is merged with it to form an index of size $4n$. A new (empty) index of size n is created in memory.

LOGARITHMIC MERGING

MAIN IDEAS



When full it is copied to disk. No merge is necessary (the “slot” is free)

A new (empty) index of size n is created in memory

Most merges are of small indices, even if sometimes a series of more merge operations are necessary.