Suffix and LCP Arrays

Recap from Last Time

Suffix Trees

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Suffix Trees

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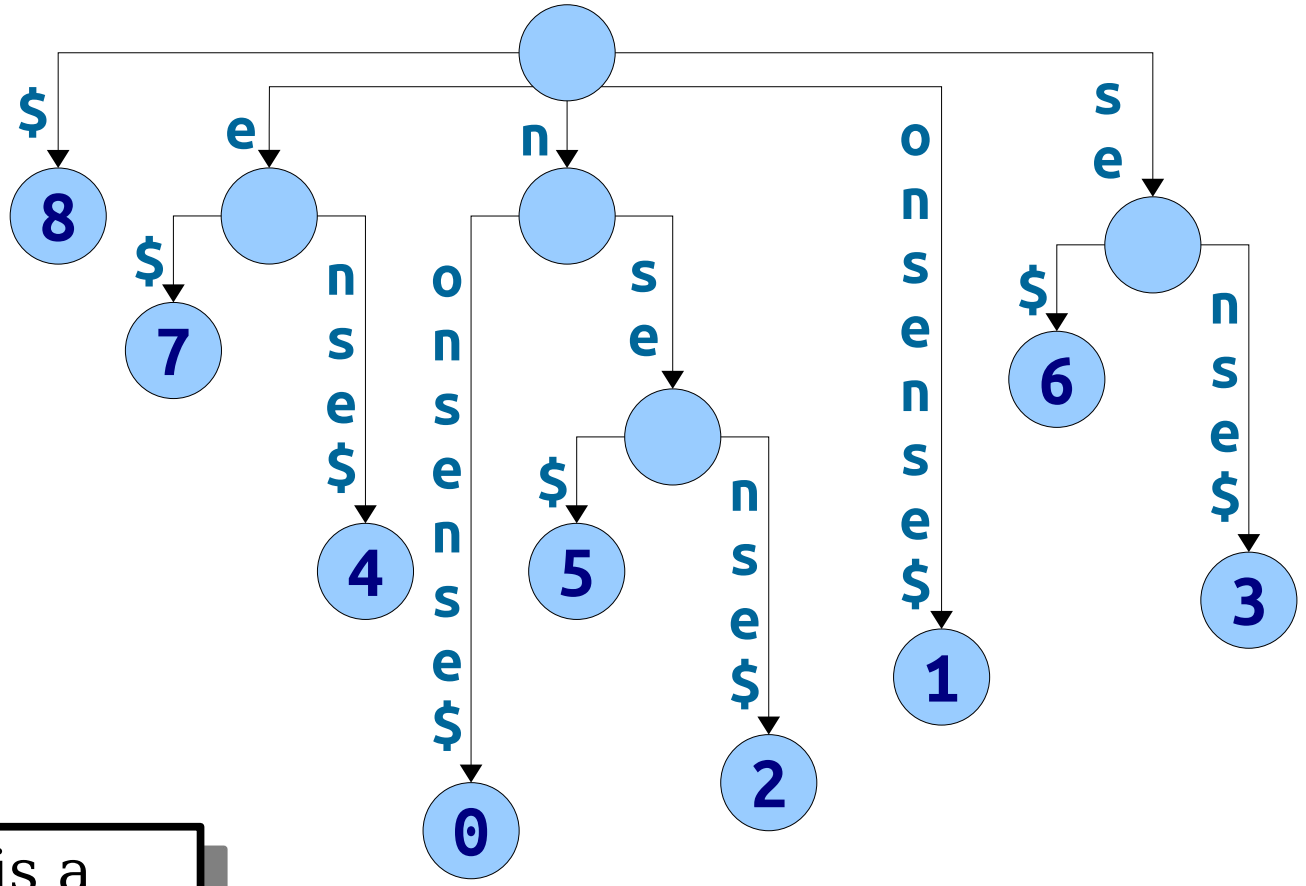

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Theorem: *w* is a substring of *x* if and only if *w* is a prefix of a suffix of *x*.

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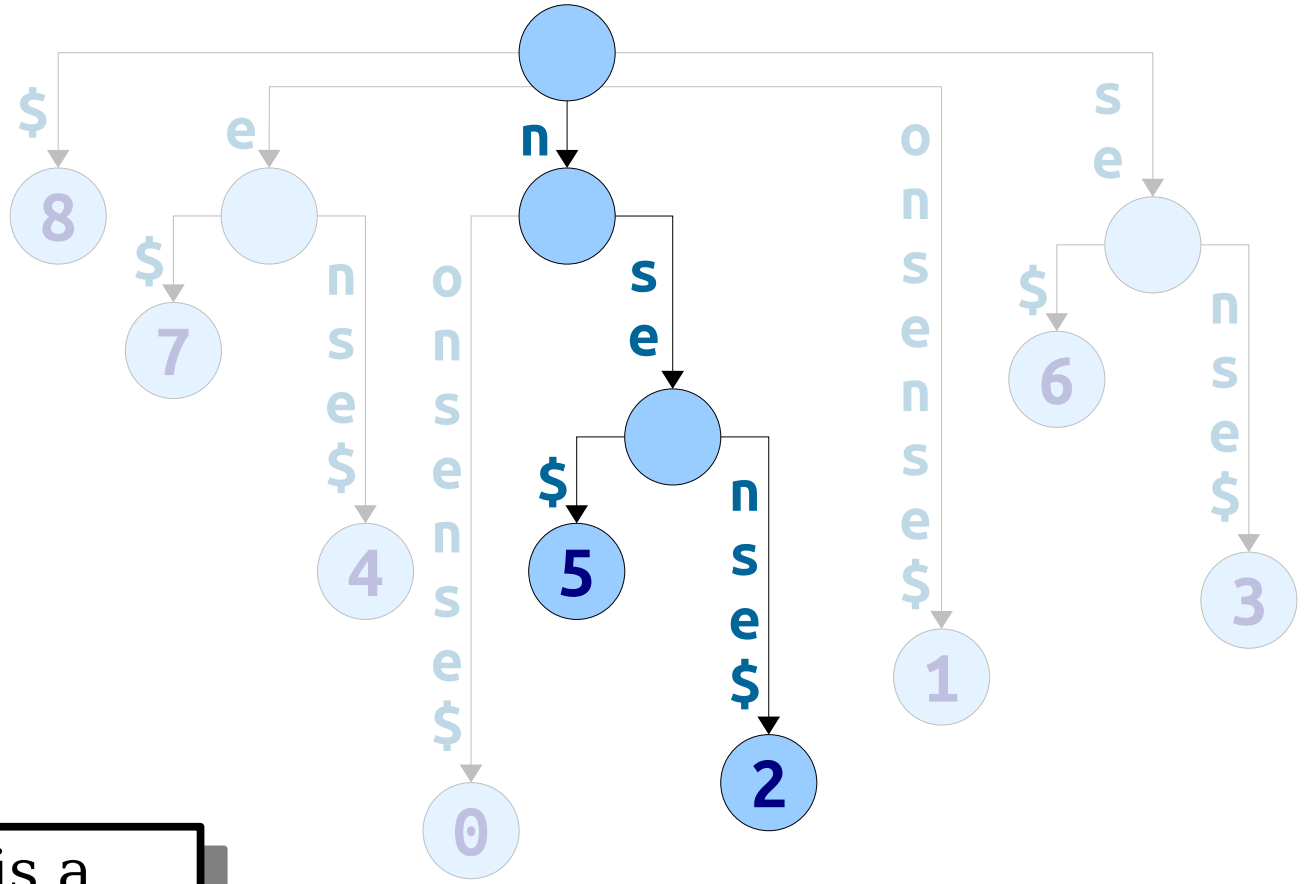

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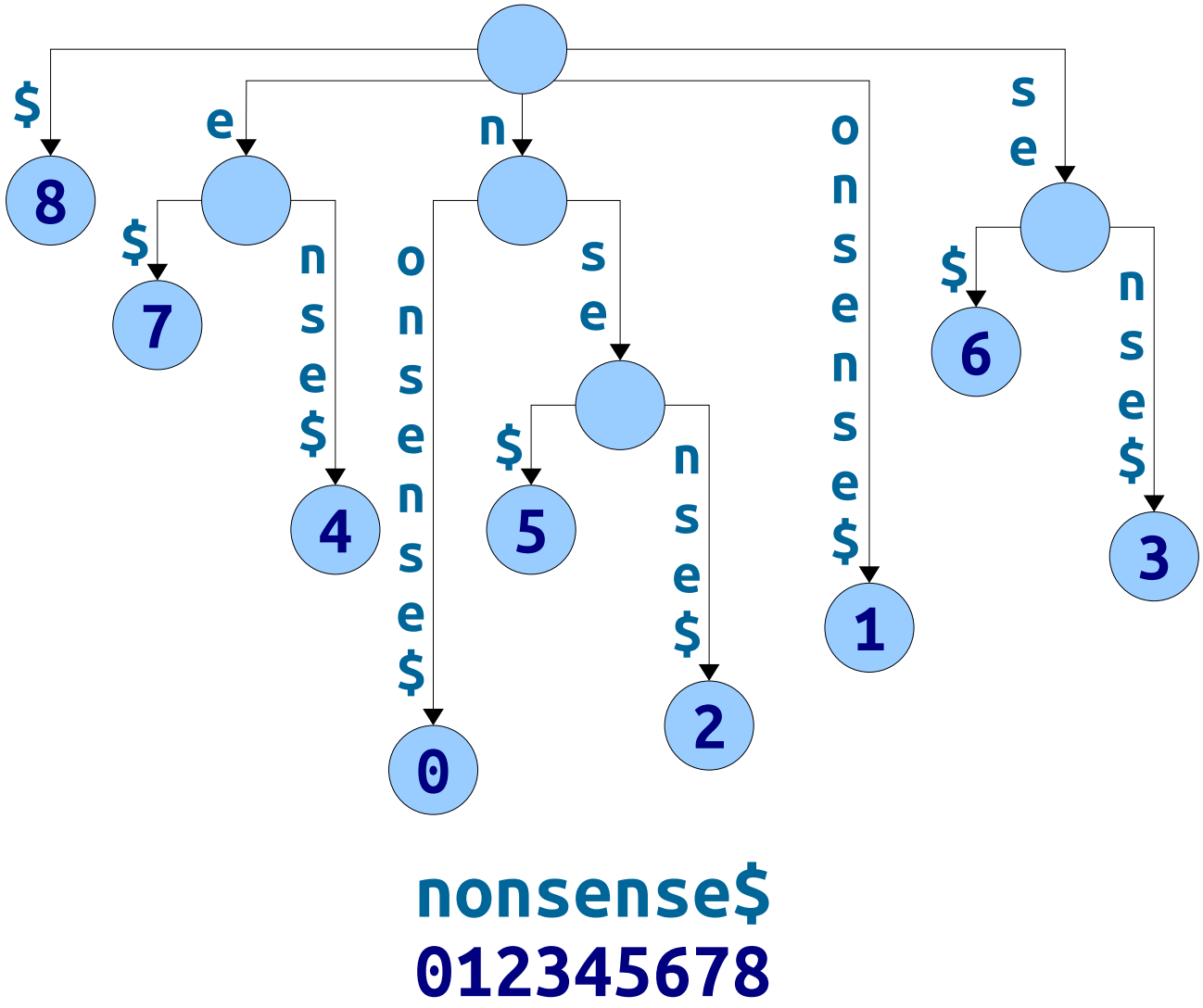
New Stuff!

Representing Suffix Trees

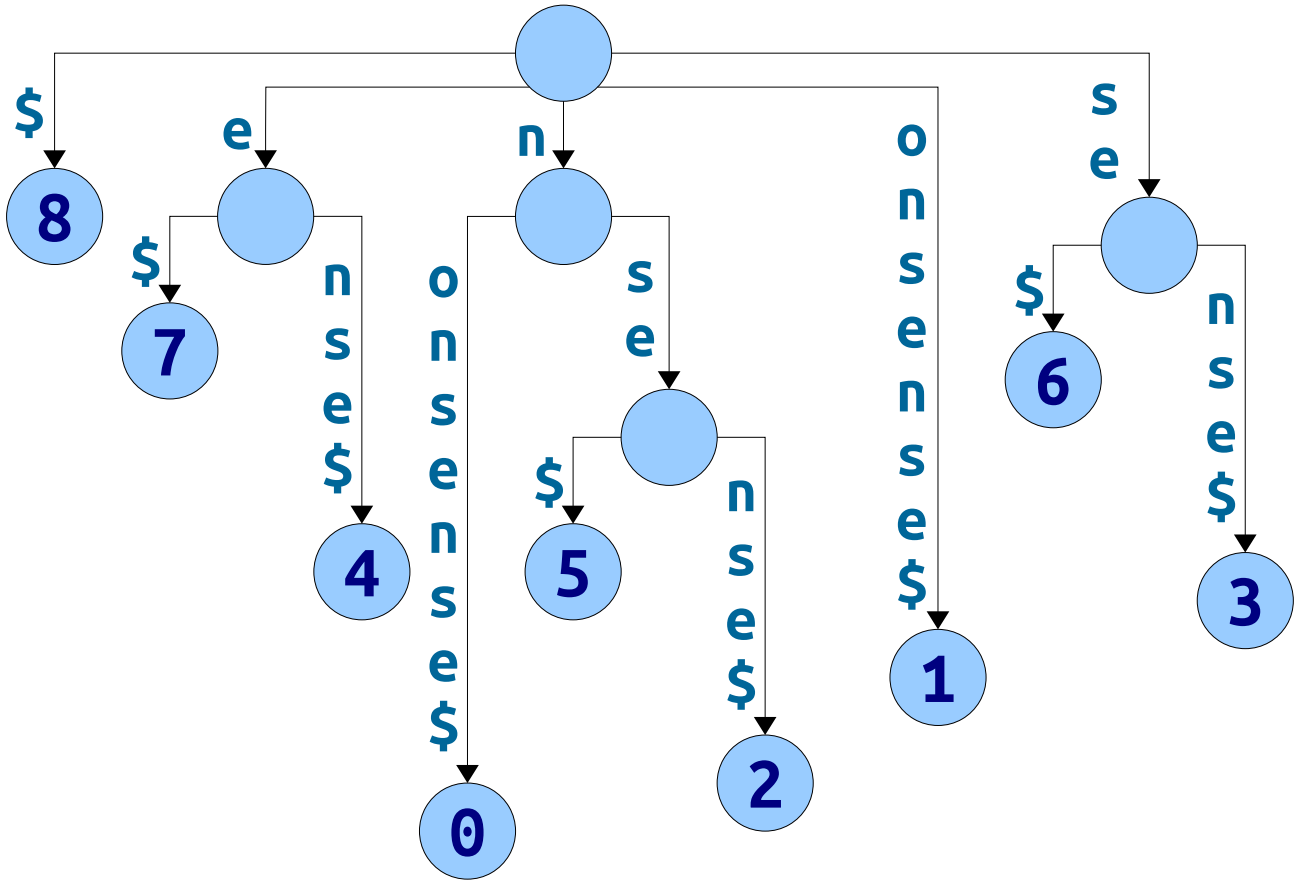
Representing a Suffix Tree

- We know that a suffix tree has O(***m***) nodes, where ***m*** is the number of characters in the input string.
- This means that there are O(***m***) edges.
- ***Question:*** Why can't we immediately claim that the space usage of the suffix tree is O(***m***)?



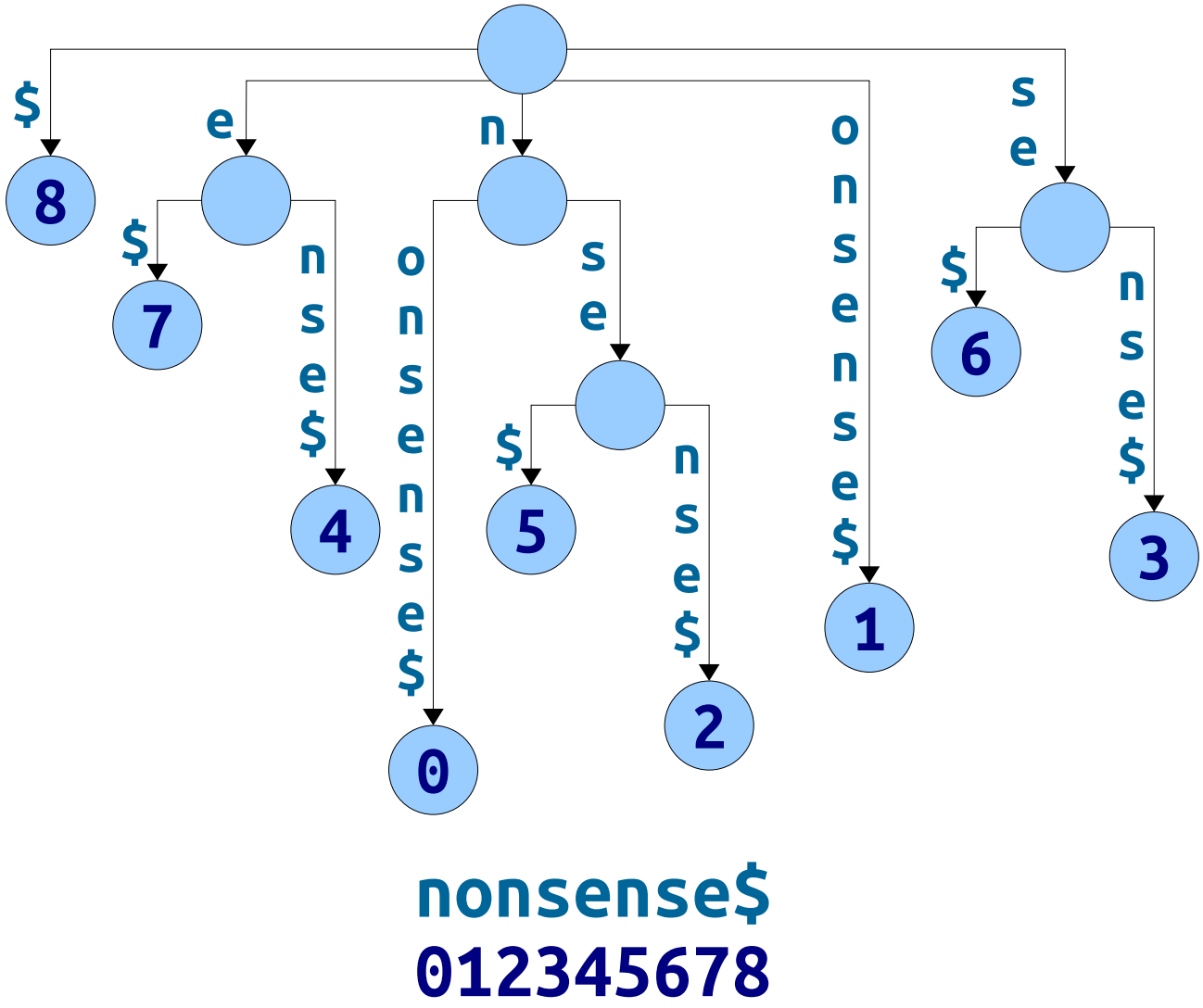
Representing a Suffix Tree

- ***Claim:*** Writing out all suffixes of a string of length m requires $\Theta(m^2)$ characters.
- ***Proof idea:*** Those suffixes have length $1 + 2 + \ldots + (m+1)$, factoring in the special **$** character.
- ***Problem:*** It is indeed possible to build a suffix tree with $\Theta(m^2)$ total letters on the edges.



Representing a Suffix Tree

- By being clever with our representation, we can guarantee that a suffix tree uses only $\Theta(m)$ space, regardless of the input string.
- ***Observation:*** Each edge is labeled with a substring of the original input string.
- ***Idea:*** Don't actually write out the labels on the edges. Just write down the start and end index!



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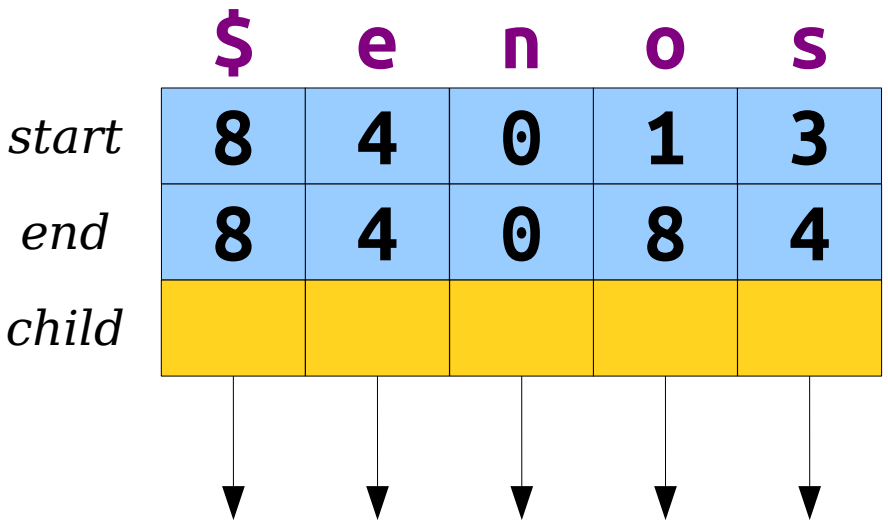

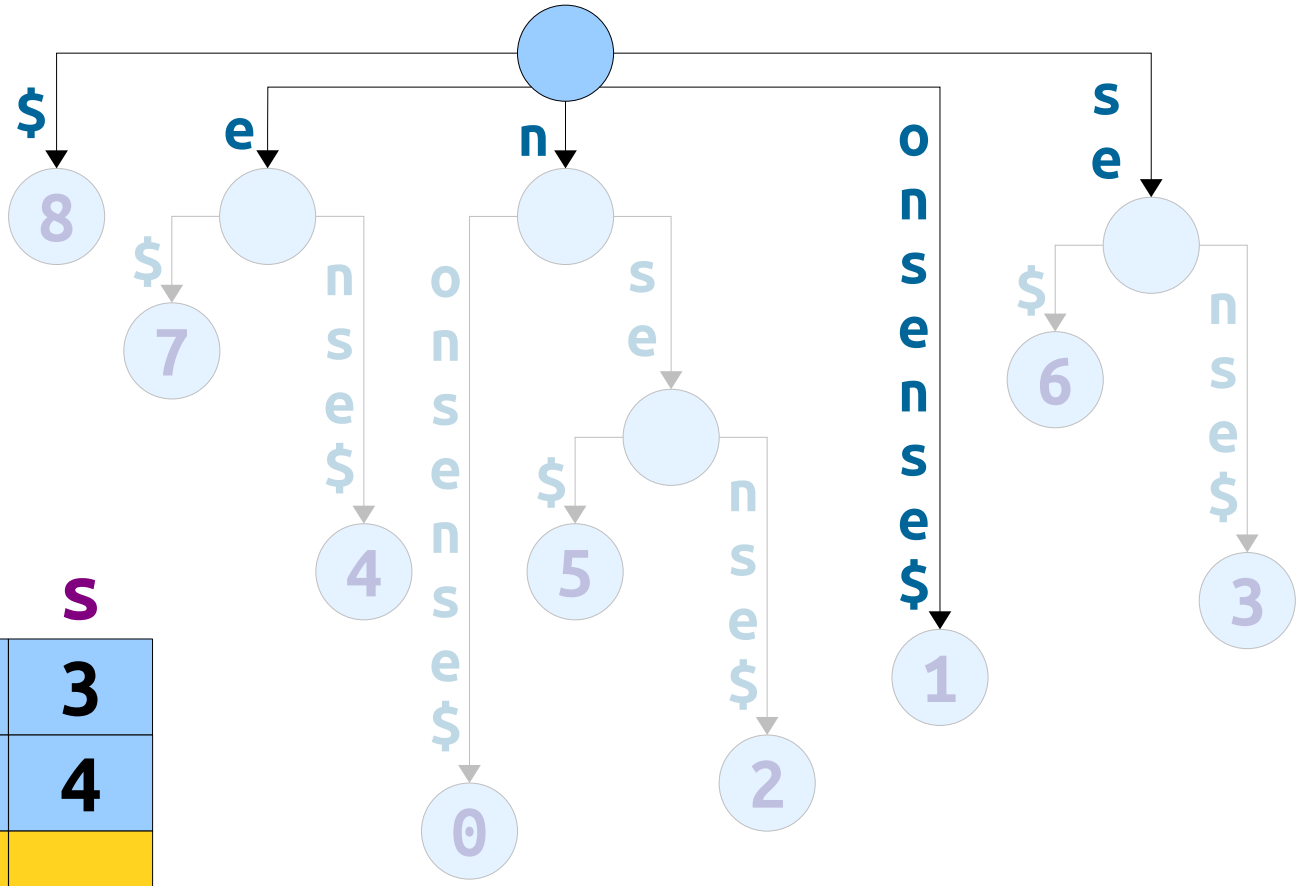

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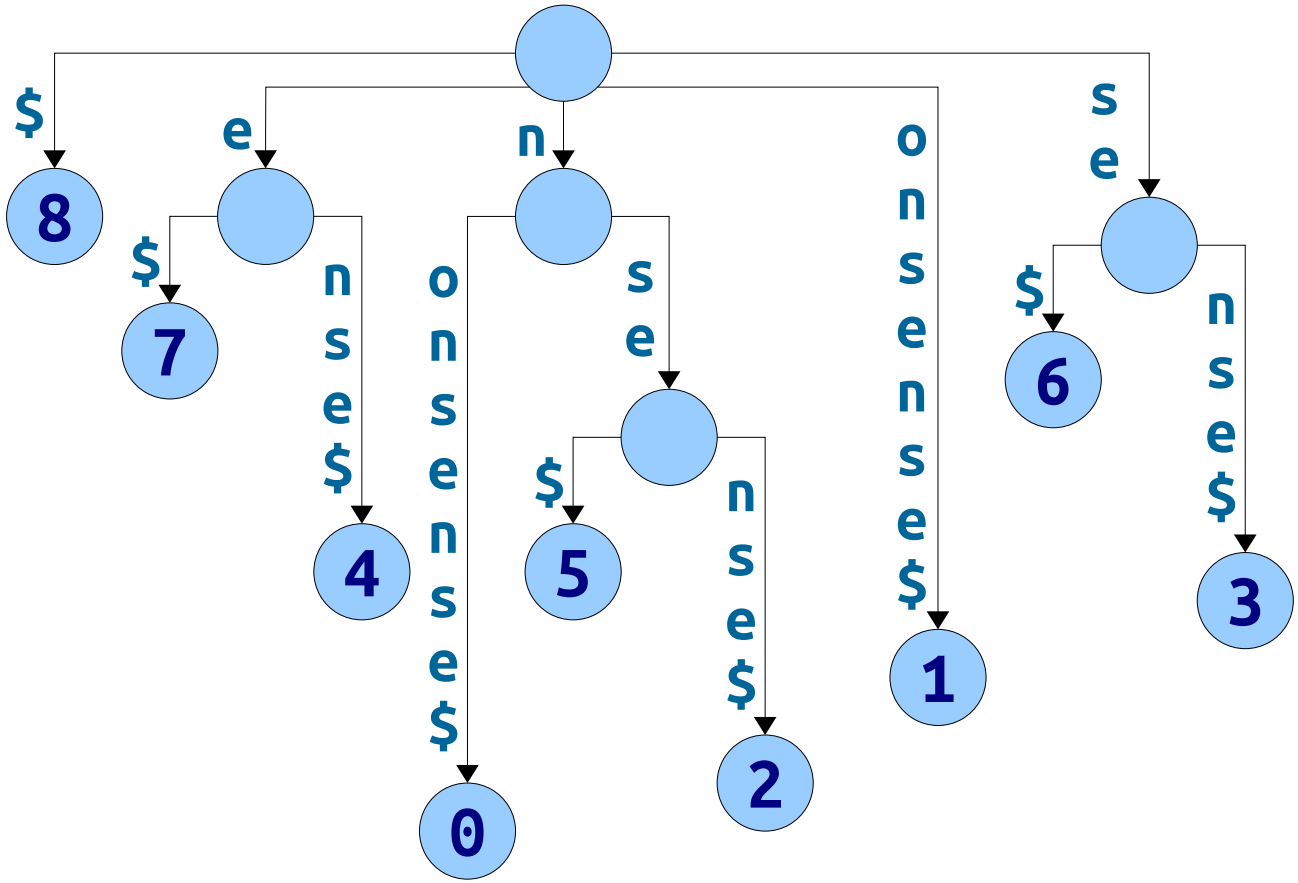
Representing a Suffix Tree

- Space usage required for a suffix tree:
  - O(***m***) space for all the nodes.
  - O(***m***) space for a copy of the original string.
  - O(***m***) space for the edges.
- Total space: O(***m***).



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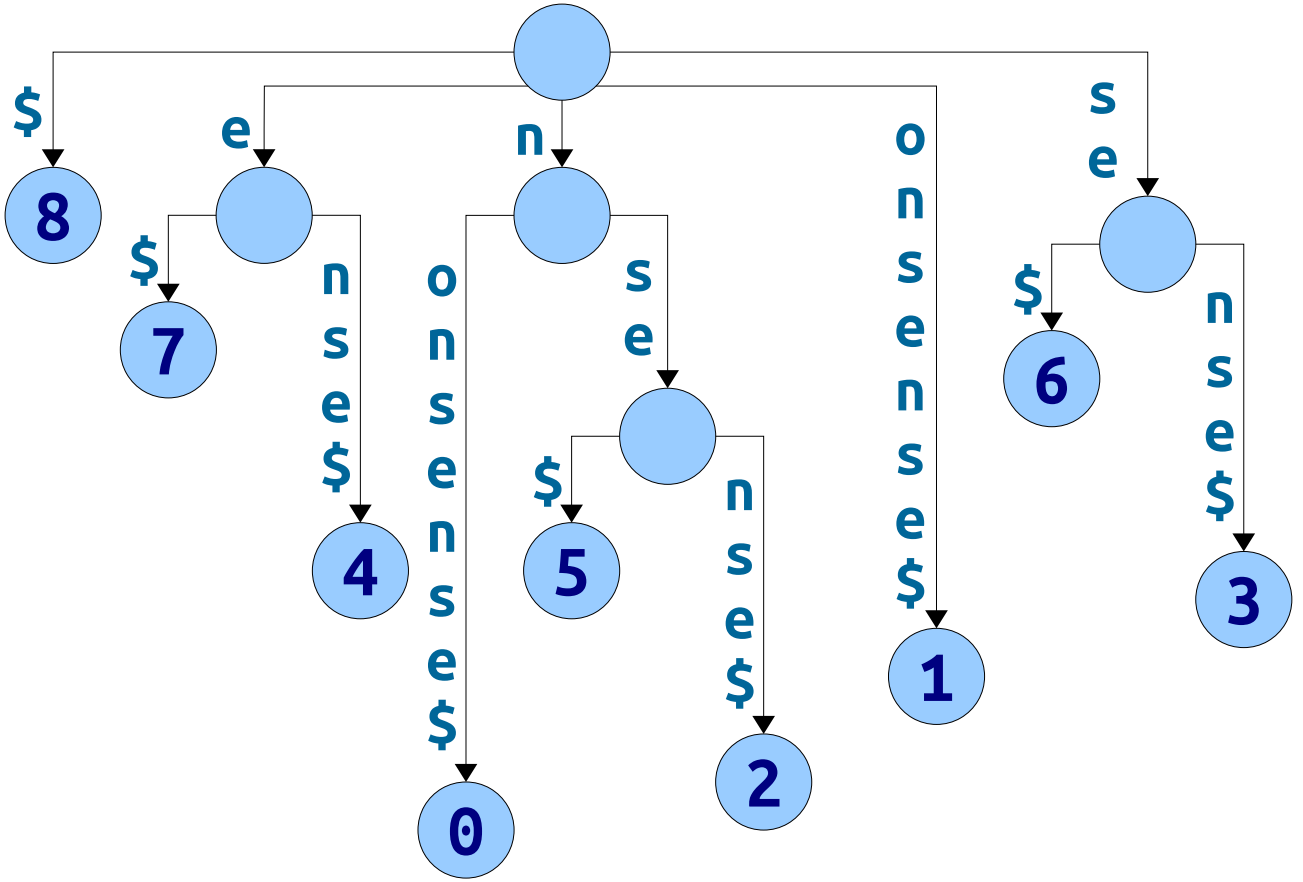
Suffix Tree Space Usage

- Suffix tree edges take up a *lot* of space.
  - Two machine words per edge to denote the range of characters visited.
  - One machine word per edge for the pointer itself.
  - Number of edges ranges from m to $2m - 1$, so this is between $3m$ and $6m$ machine words for the whole string!
- Example: a human genome is about three billion characters long.
  - With clever techniques, that can be packed into about 800MB.
  - On a 32-bit machine, the suffix tree needs about 48GB – too big to fit into memory!
  - On a 64-bit machine, the suffix tree needs about 96GB – way more than a typical machine can hold!

Key Question: Can we get the benefits of a suffix tree without the space penalty?

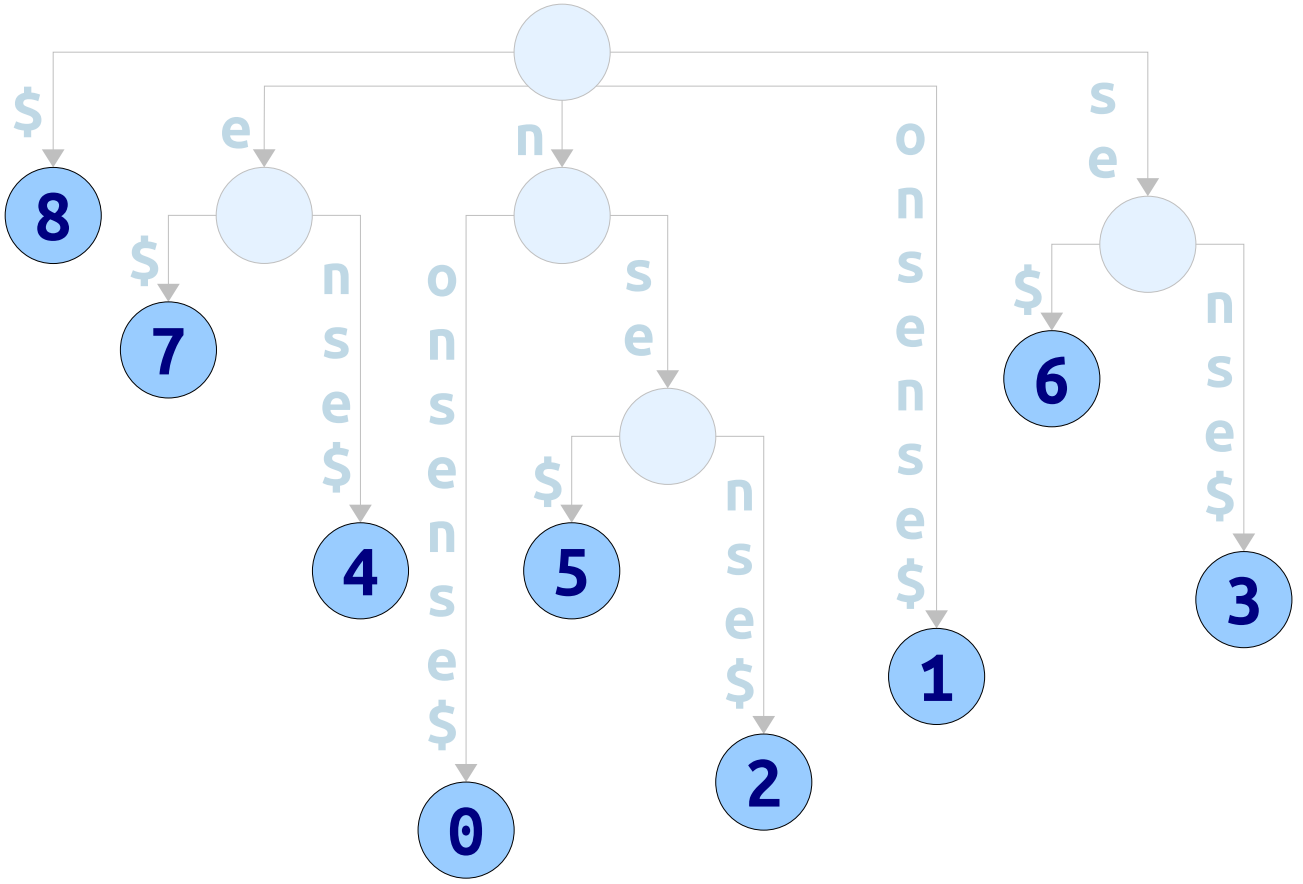
What is it about suffix trees that make them so useful algorithmically?



Theorem: There is a node labeled ω in a suffix tree for T

if and only if

ω is a suffix of T\$ or ω is a branching word in T\$.



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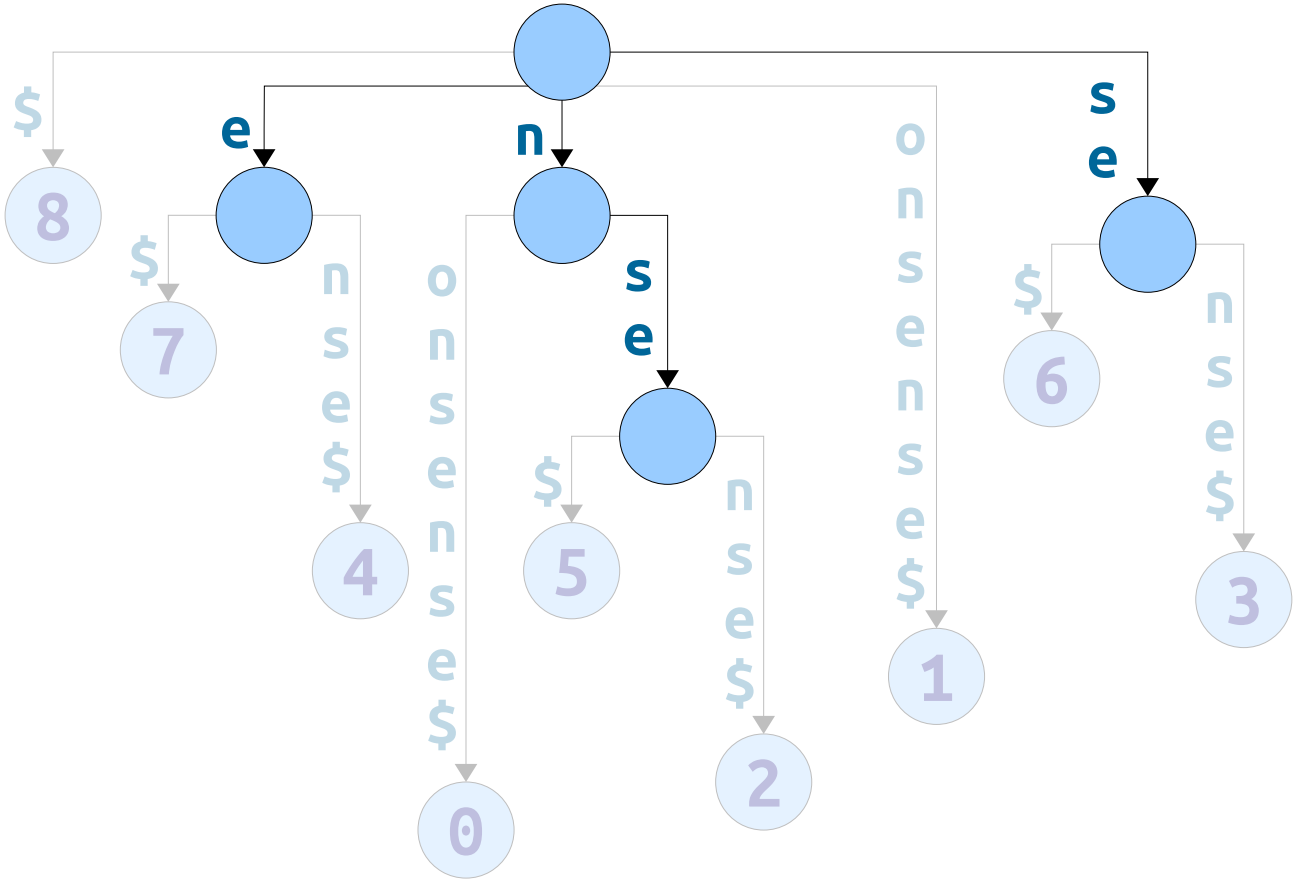

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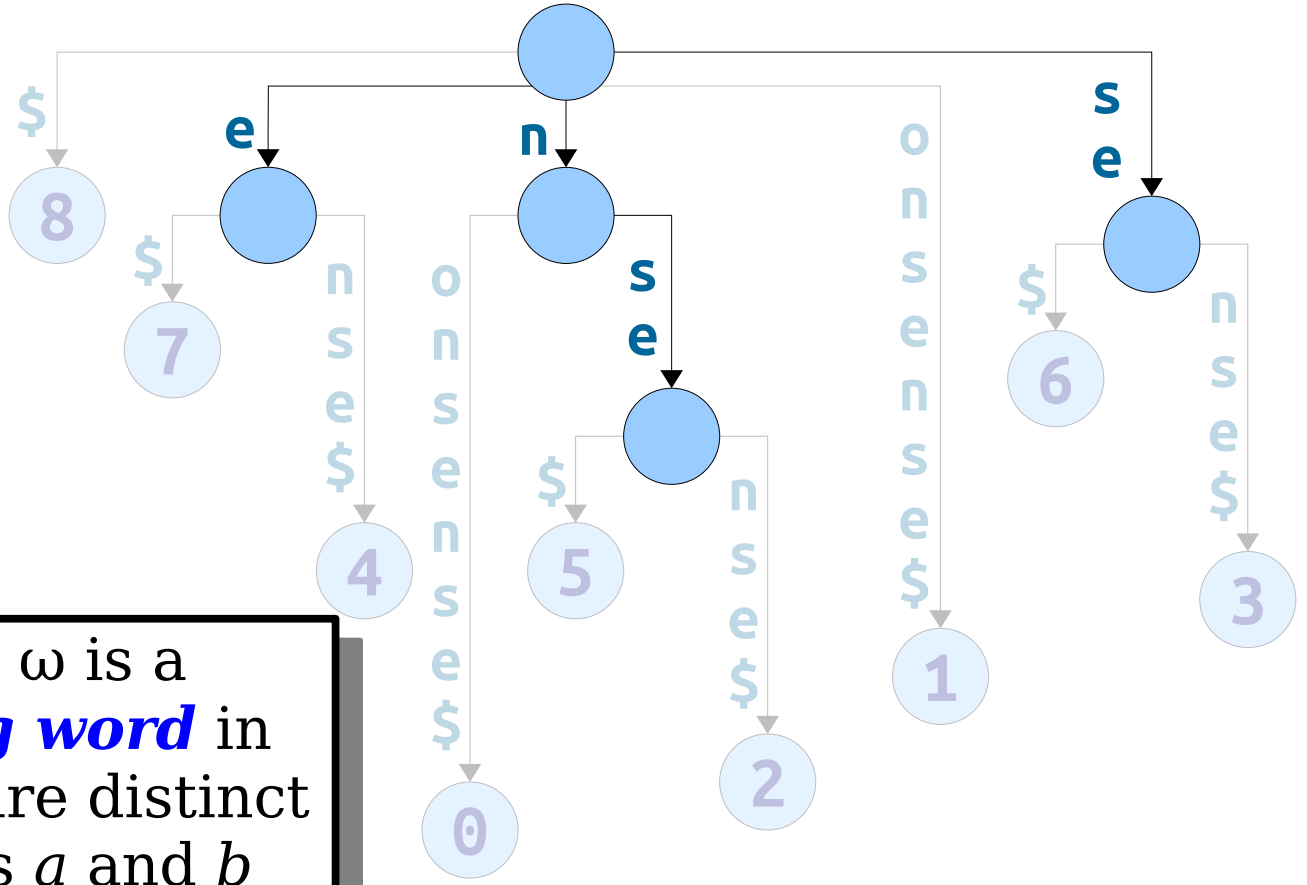

A string ω is a ***branching word*** in $T\$$ if there are distinct characters a and b where ωa and ωb are substrings of $T\$$.

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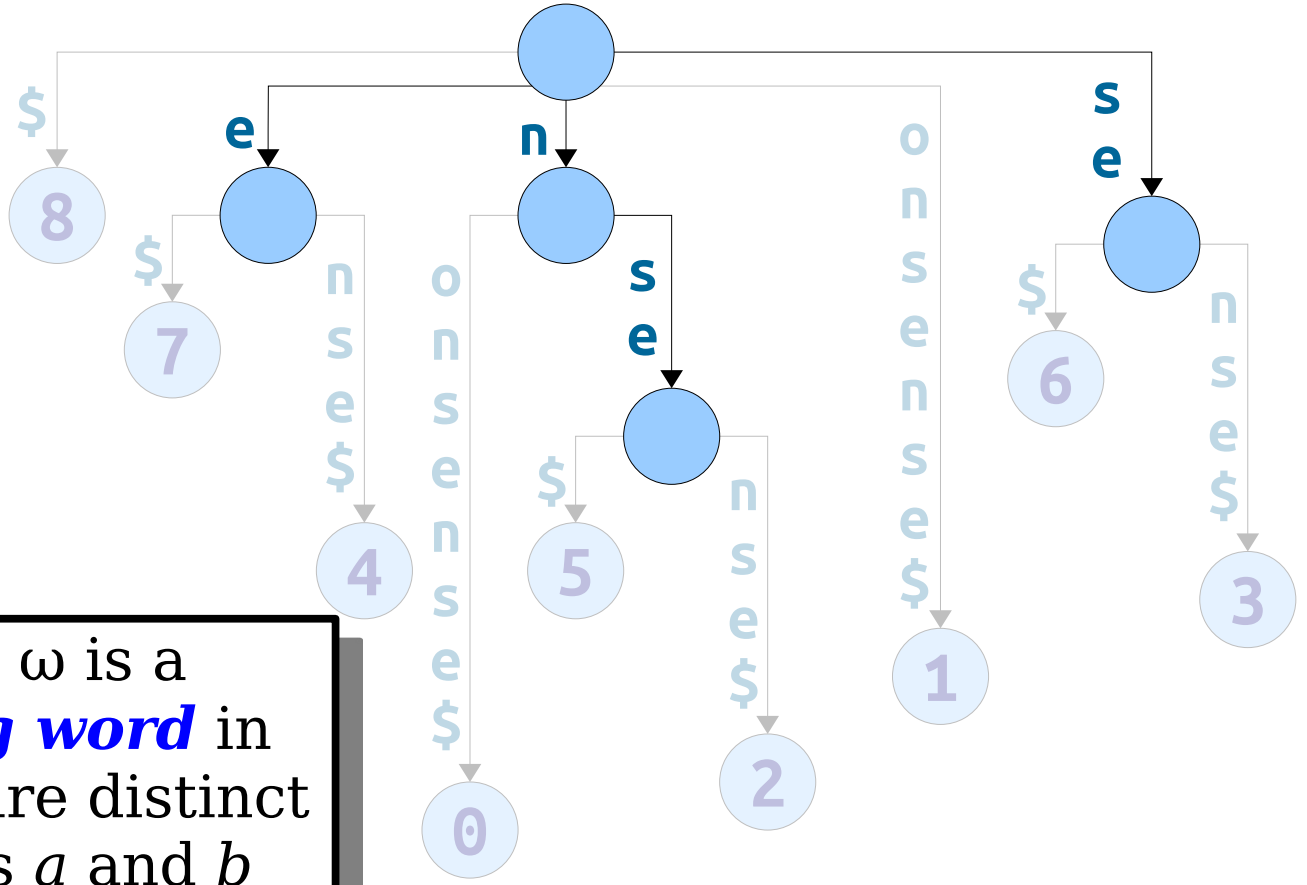

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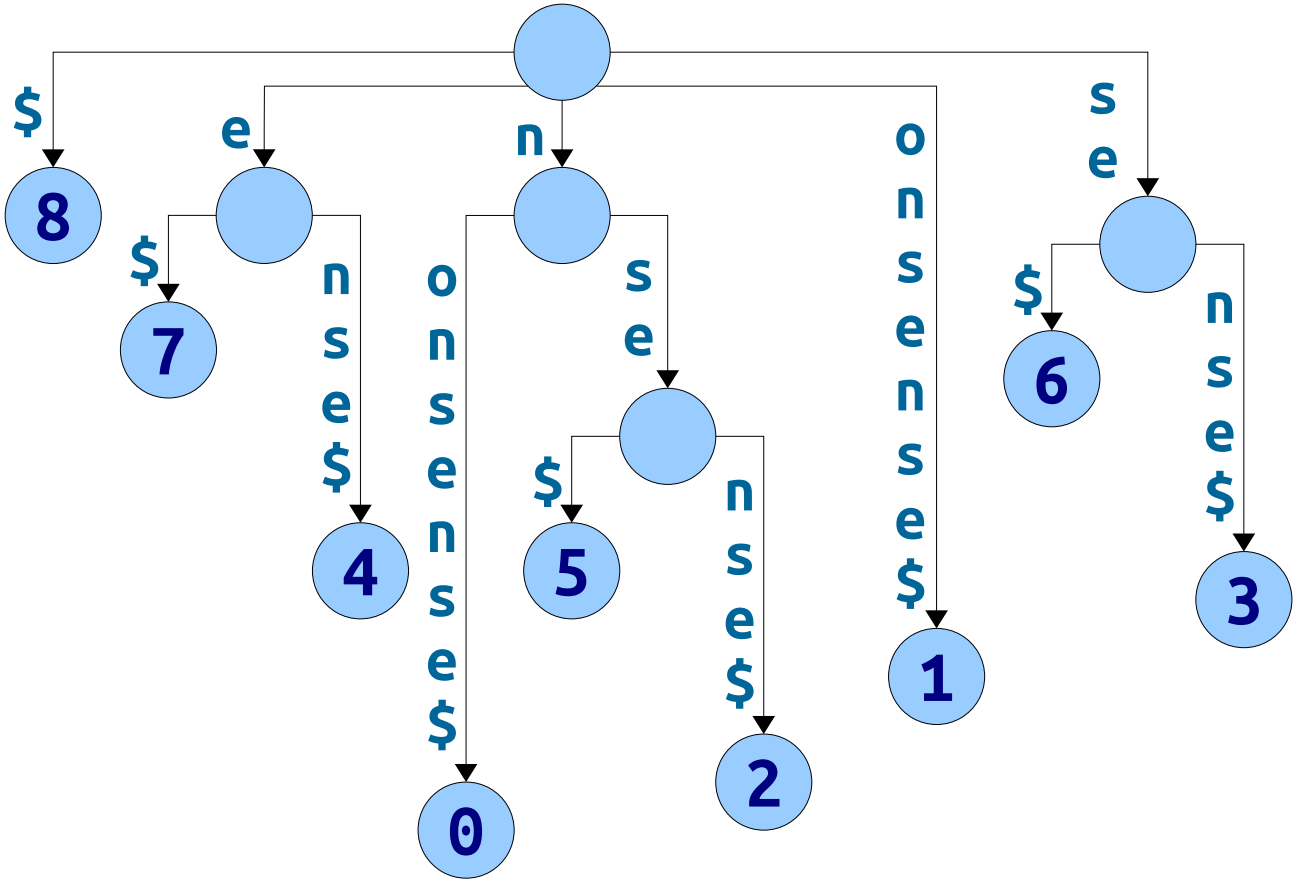


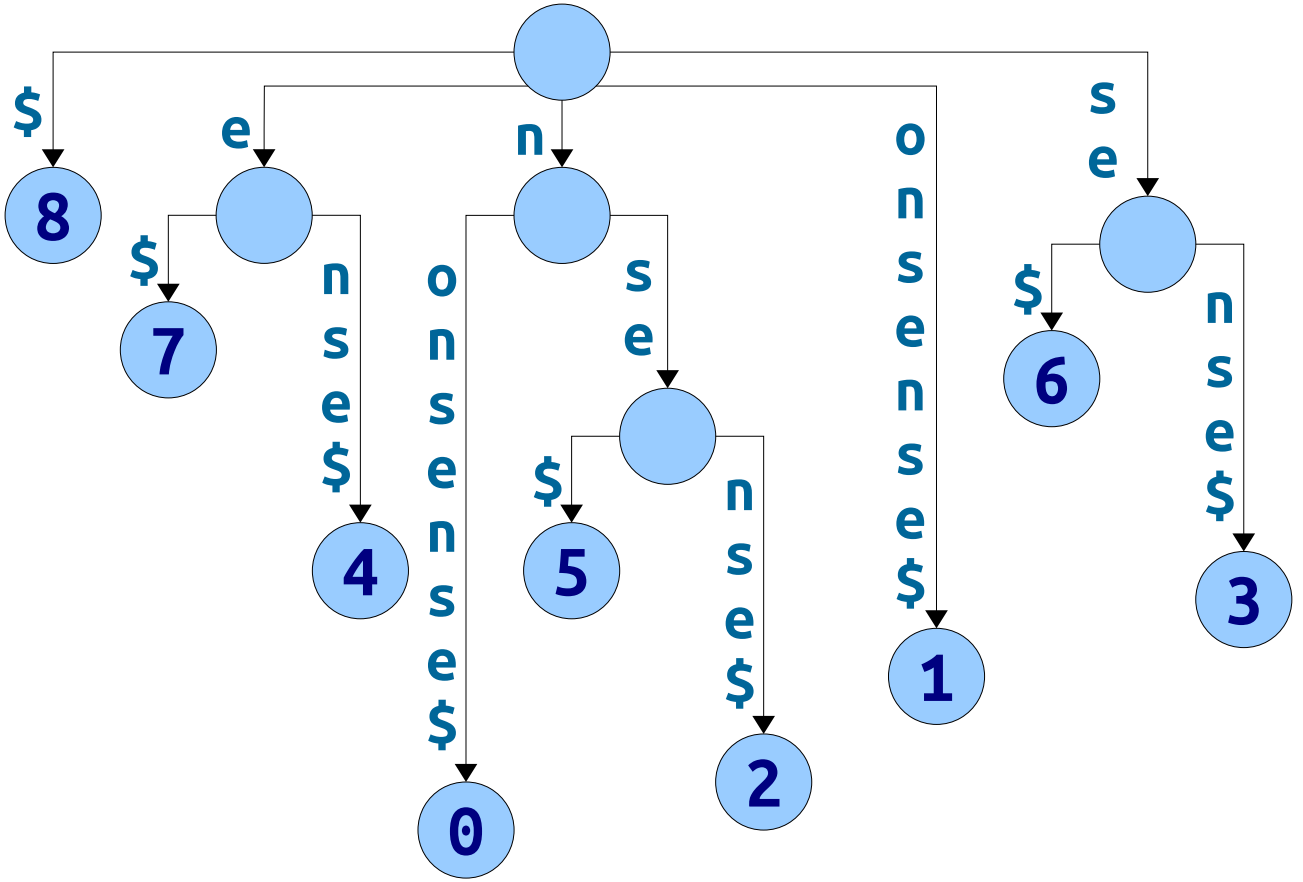
Key Intuition: The efficiency in a suffix tree is largely due to

1. keeping the suffixes in sorted order, and
2. exposing branching words.

Where We're Going

- Today, we'll see two data structures that encode much of the same information as suffix trees, but in much less space.
  - The ***suffix array*** stores information about the ordering of the suffixes of a string.
  - The ***LCP array*** stores information about the branching words of a string.
- Together, they'll provide algorithms that match or are comparable to the time bounds from last time.

Suffix Arrays



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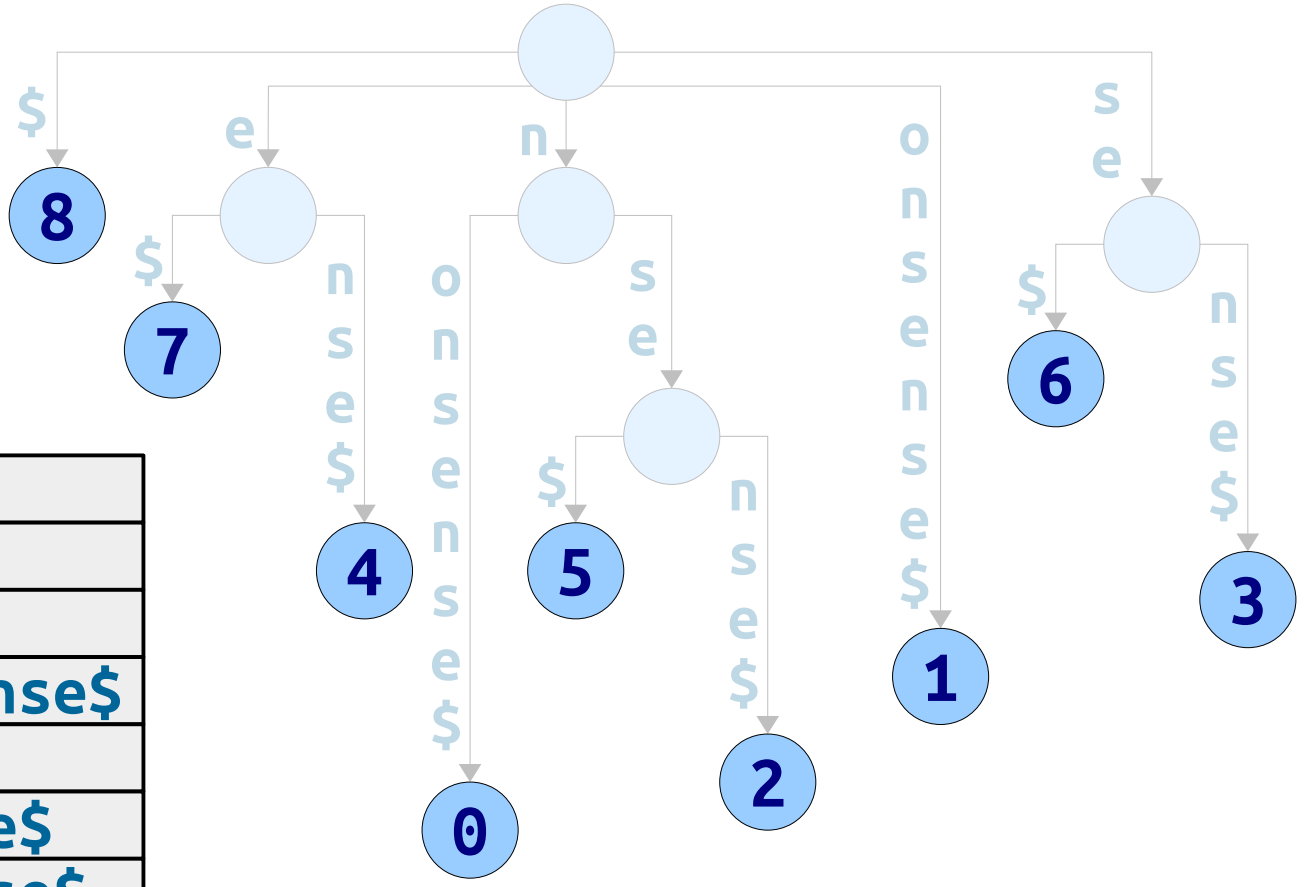

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Suffix Arrays

- A ***suffix array*** for a string T is a sorted array of the suffixes of the string T\$.
- Suffix arrays distill out just the first component of suffix trees: they store suffixes in sorted order.

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- A ***suffix array*** for a string T is a sorted array of the suffixes of the string T\$.
- Suffix arrays distill out just the first component of suffix trees: they store suffixes in sorted order.
- ***Non-obvious fact:*** Suffix arrays can be built in time O(***m***). We can cover this later in the quarter if you're interested.

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Suffix Arrays

- The way we've drawn suffix arrays is terribly space-inefficient.
  - It always uses space $\Theta(m^2)$, since that's how many total characters occur in all suffixes.
- Can we do better?

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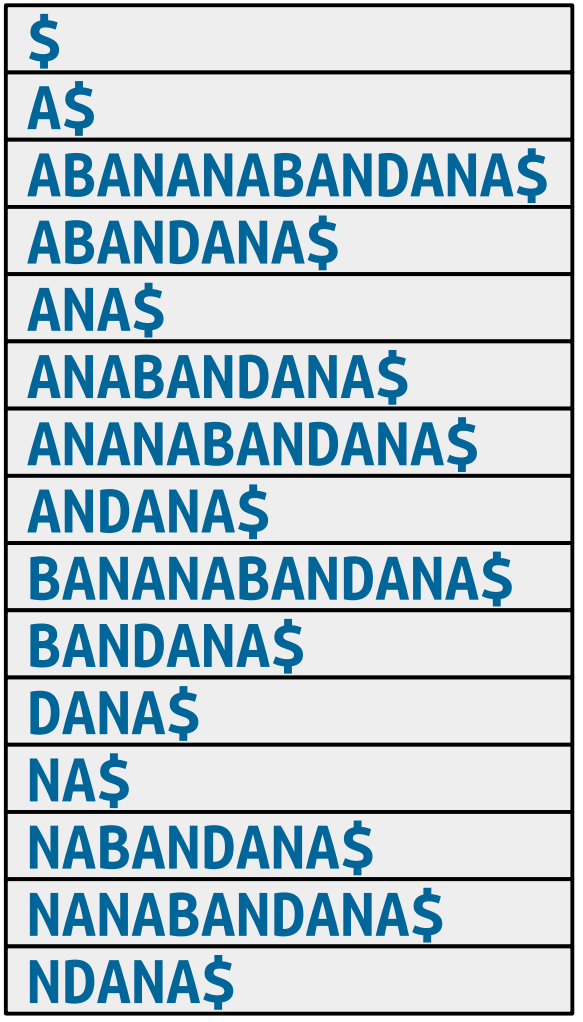
Suffix Arrays

- We reduced the space usage of suffix trees by representing substrings, implicitly, as ranges within the original string.
- ***Idea:*** Don't store the suffixes themselves. Just store the starting positions of the suffixes.
- Space: $\Theta(m)$, and with only one machine word used per character of input.



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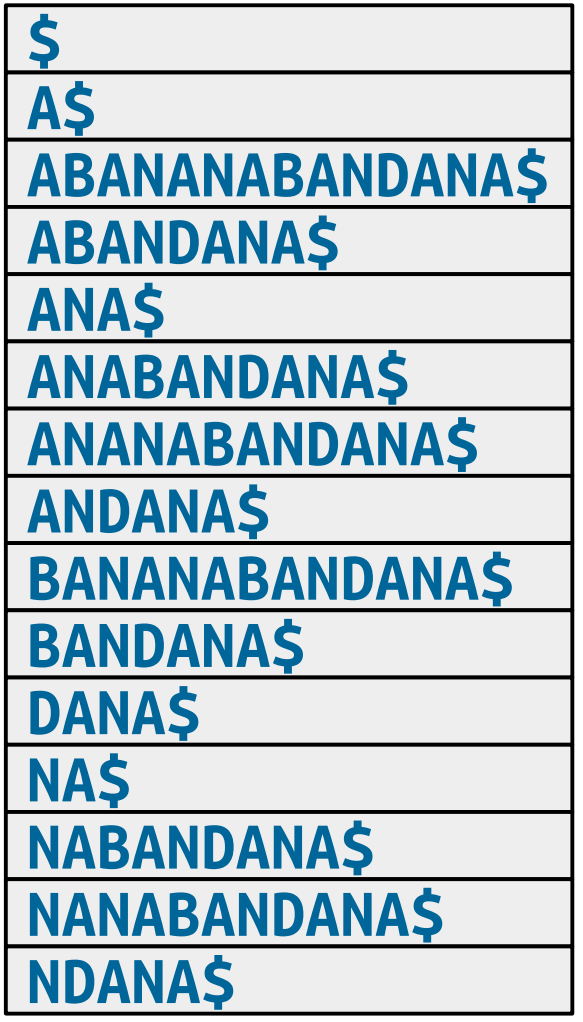

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Suffix Arrays

- Although the picture to the right is how we'd represent the suffix array in memory, for this lecture we'll draw things out the longer way.
- This is just to build intuition; we wouldn't actually do that in practice.

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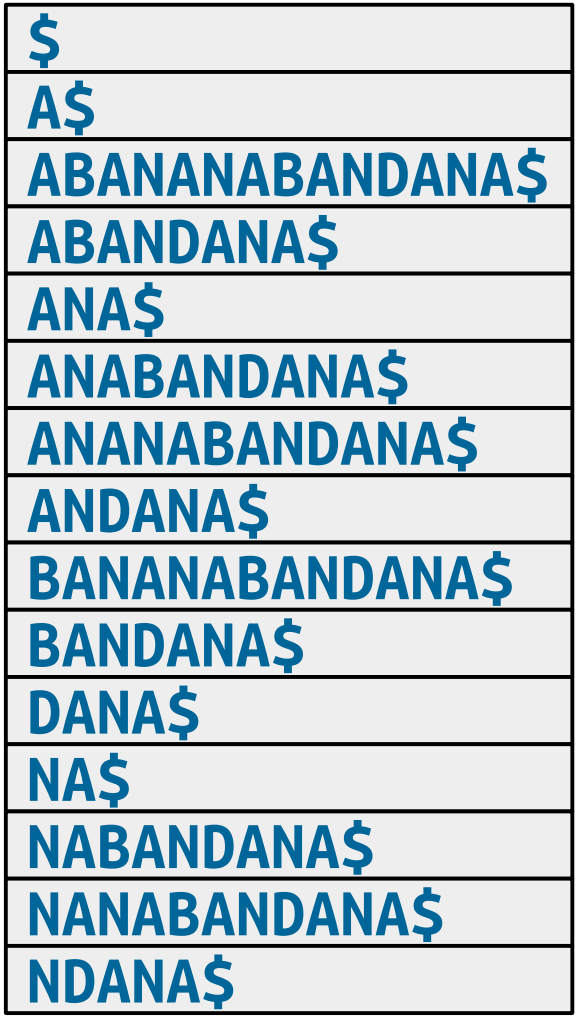
Using Suffix Arrays

- Last time, we saw how to find all instances of a pattern ***P*** in a text ***T*** using suffix *trees*.
- How could we do that with suffix *arrays*?



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Using Suffix Arrays

- ***Reminder:*** Our text string ***T*** has length ***m***. Our pattern string ***P*** has length ***n***.
- ***Claim:*** With a suffix array, we can determine whether ***P*** appears in ***T*** in time O(***n*** log ***m***).

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How?

Answer at
https://pollev.com/cs166spr23

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  - Binary search has O(log ***m***) rounds.
  - Each probe takes time O(***n***).
- This bound can be made tight. *(How?)*
- Figure that ***m*** is often much bigger than ***n***, so this is a huge win over a raw scan.

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Using Suffix Arrays

- ***Claim:*** With a suffix array, we can find all matches of a pattern ***P*** in ***T*** in time O(***n*** log ***m*** + ***z***), where ***z*** is the number of matches.
- ***Idea:*** Binary search can be used to find a range of values equal to some key. Adapt that idea to find all suffixes beginning with the same prefix.

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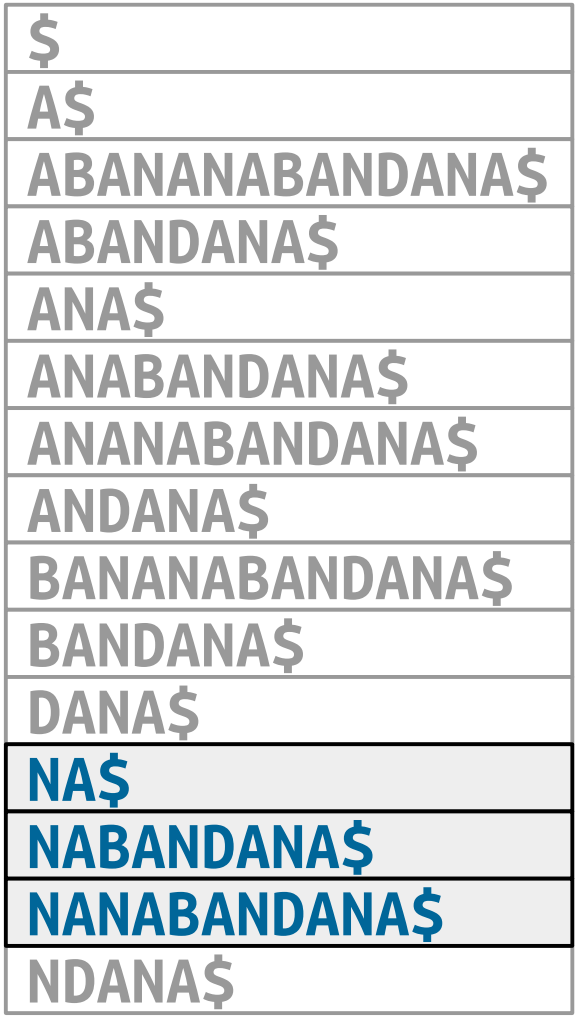

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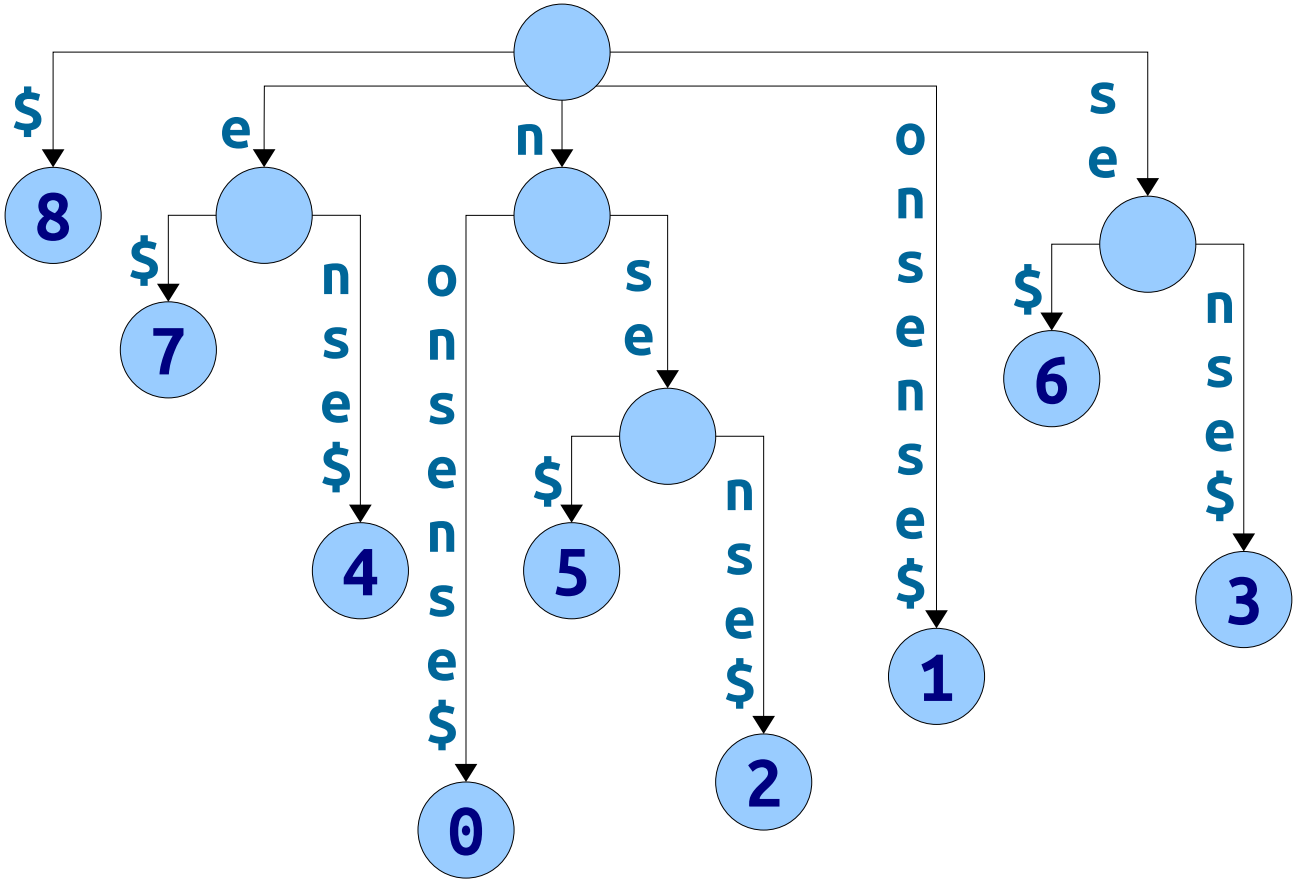
The Story So Far

- Suffix arrays store all the suffixes of a string in sorted order.
- They provide an

$$\langle O(m), O(n \log m + z) \rangle$$

  solution to the substring search problem.
- ***Intuition:*** Suffix trees are valuable in large part because they just keep the suffixes sorted.
- What else are suffix trees doing?



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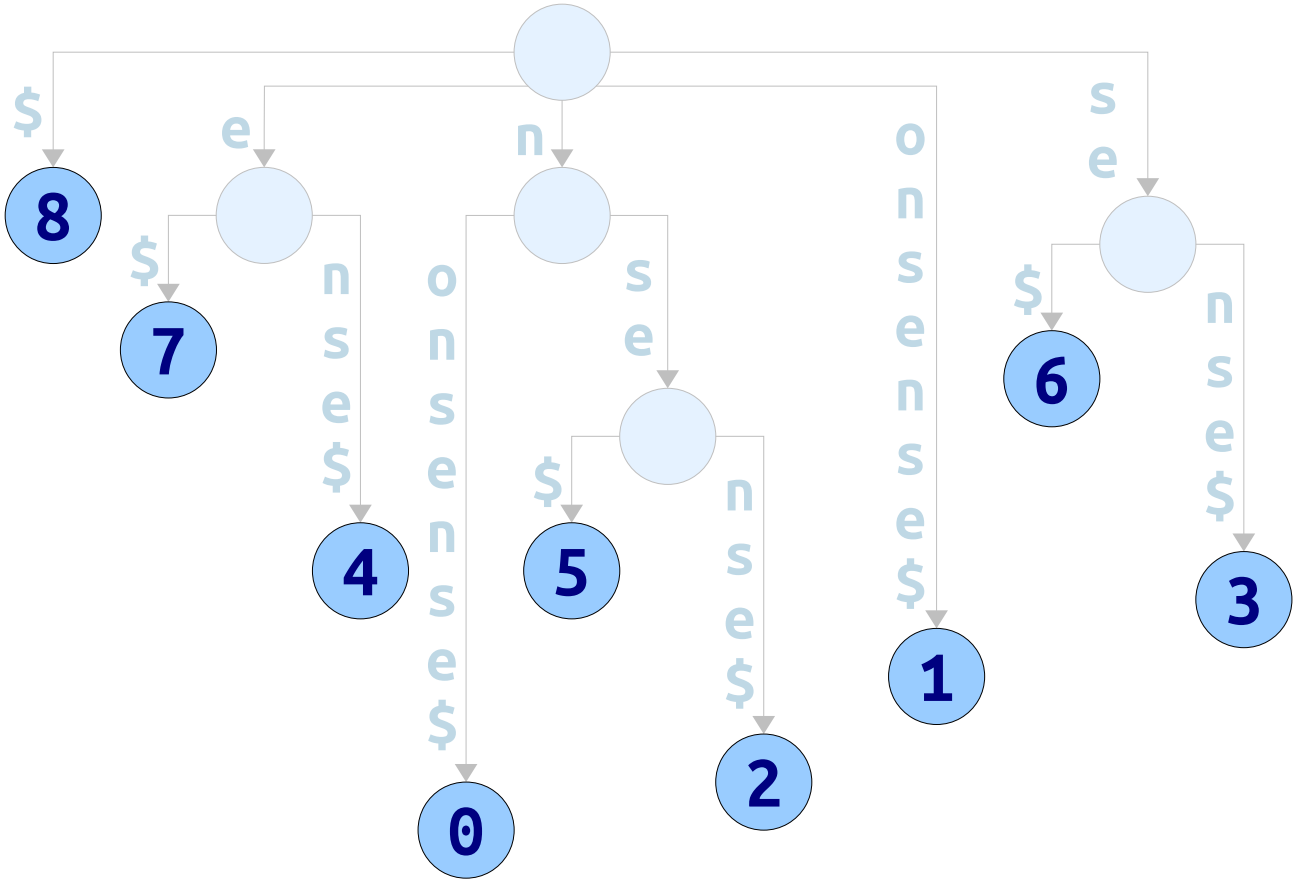

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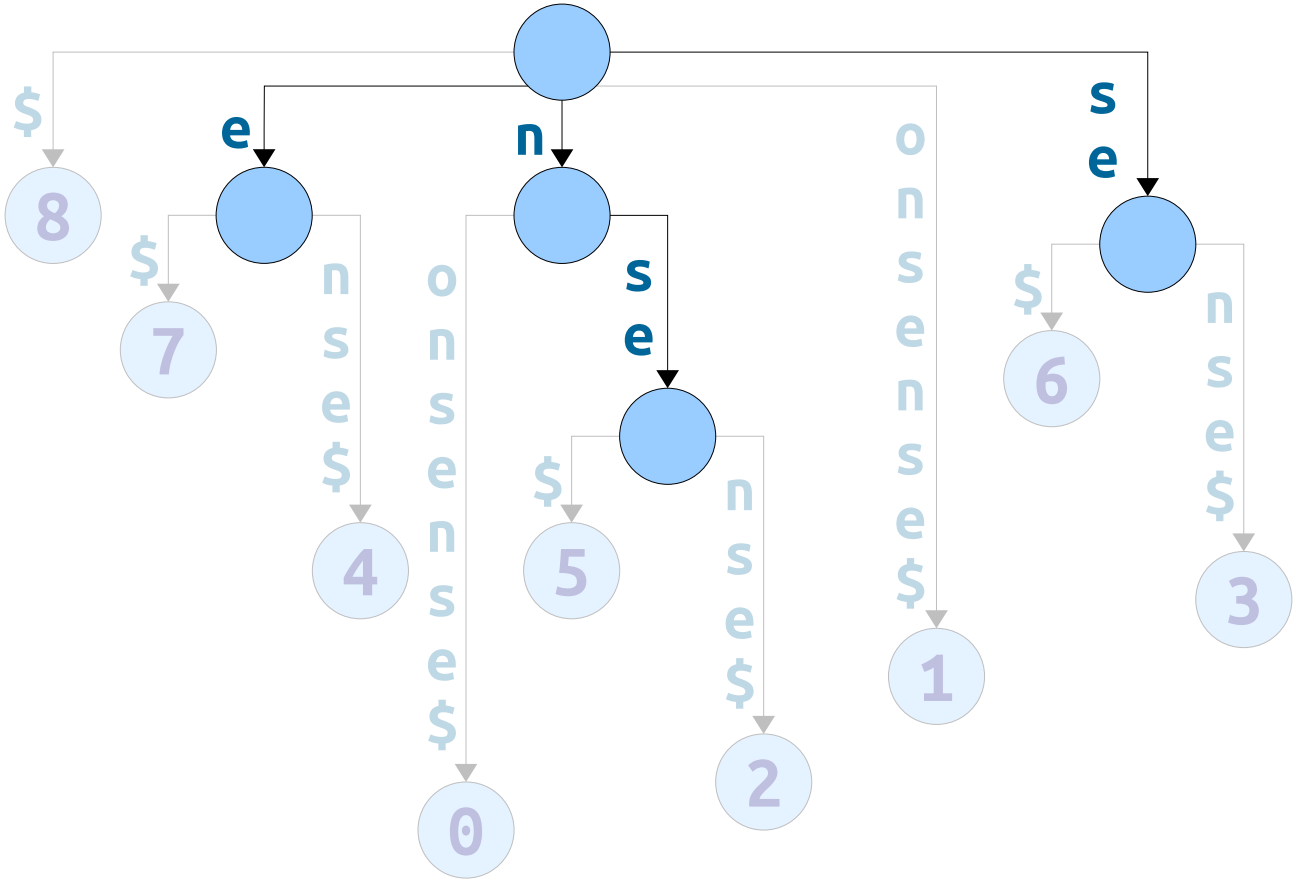

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Branching Words

- ***Recall:*** If T is a string, then ω is a ***branching word*** in $T\$$ if there are characters $a \neq b$ such that ωa and ωb are substrings of $T\$$.

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Although ABA is a repeated substring, it is not a branching word because all appearances are followed by N.

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Branching Words

- ***Recall:*** If T is a string, then ω is a ***branching word*** in $T\$$ if there are characters $a \neq b$ such that ωa and ωb are substrings of $T\$$.

ABANANABANDANA$

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The substring ANANA only appears once, so it's not a branching word.

ABANANABANDANA$

Branching Words

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Branching Words

- Notice that, by sorting suffixes, we've made it easier to spot branching words.
- Specifically, all suffixes starting with a branching word will be adjacent in the suffix array.
- The branching word will be the ***longest common prefix*** (or ***LCP***) of those adjacent suffixes.

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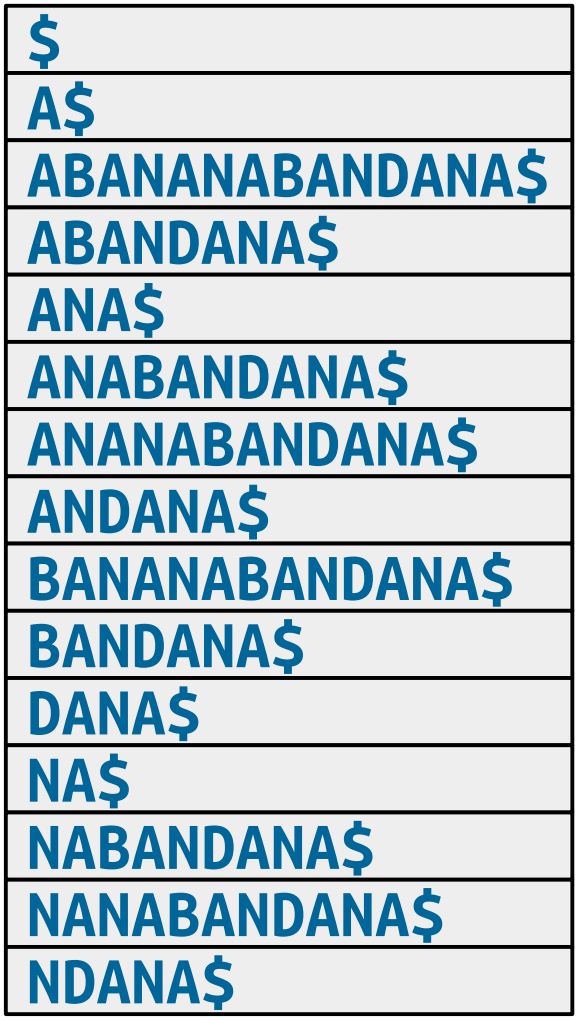

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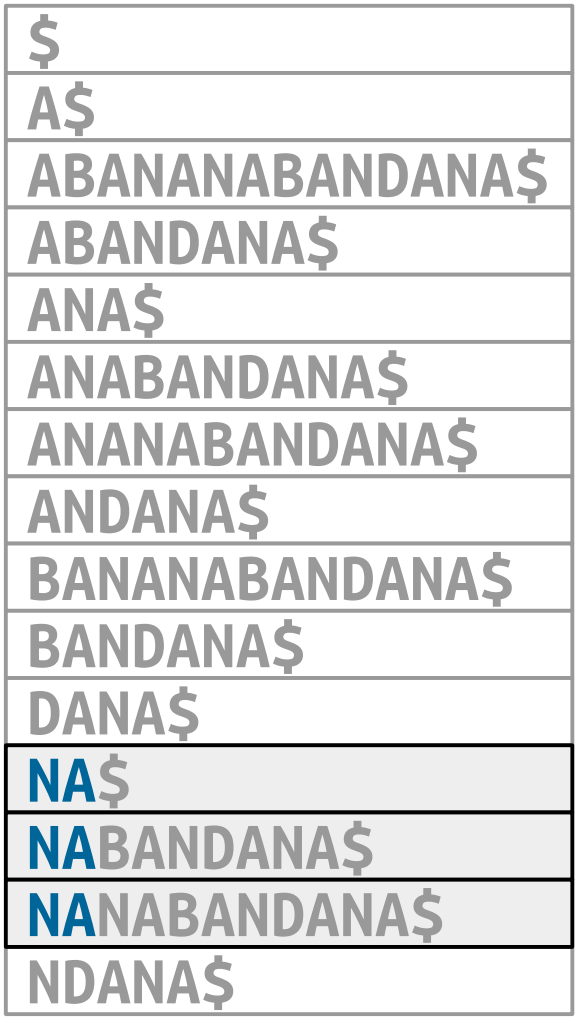

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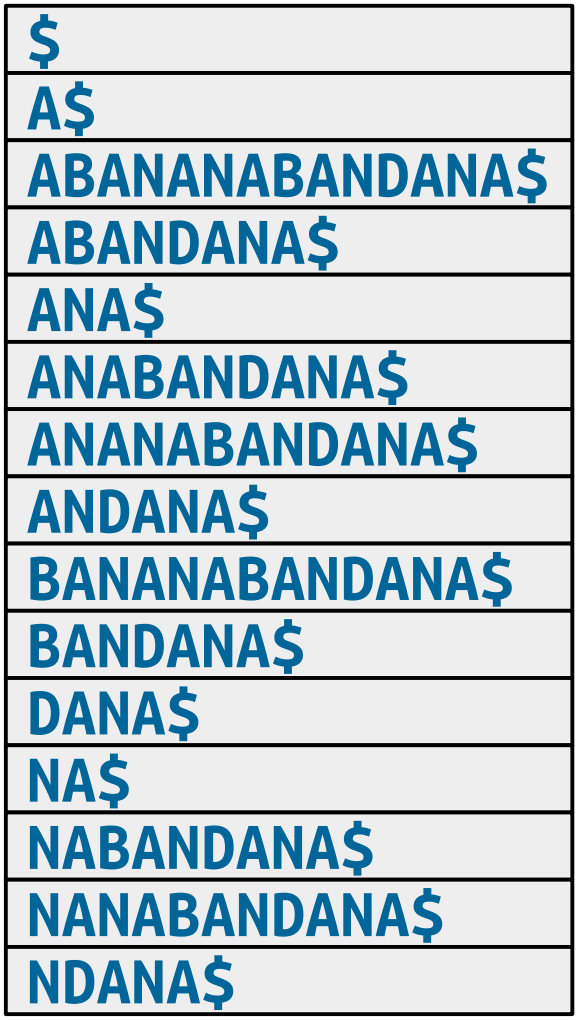

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Branching Words

- ***Theorem:*** A string ω is a branching word in string T\$ if and only if it's the longest common prefix of two adjacent suffixes in T's suffix array.
- ***Proof idea:*** If ω is the longest common prefix of two adjacent suffixes, let a and b be the characters immediately following ω in those two suffixes. Then ωa and ωb are substrings of T\$.

  If ω is branching, choose the lexicographically smallest a and b making the definition work. Then the last suffix starting with ωa and the first suffix starting with ωb are adjacent in the suffix array. ■

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A$
ABANANABANDANA$
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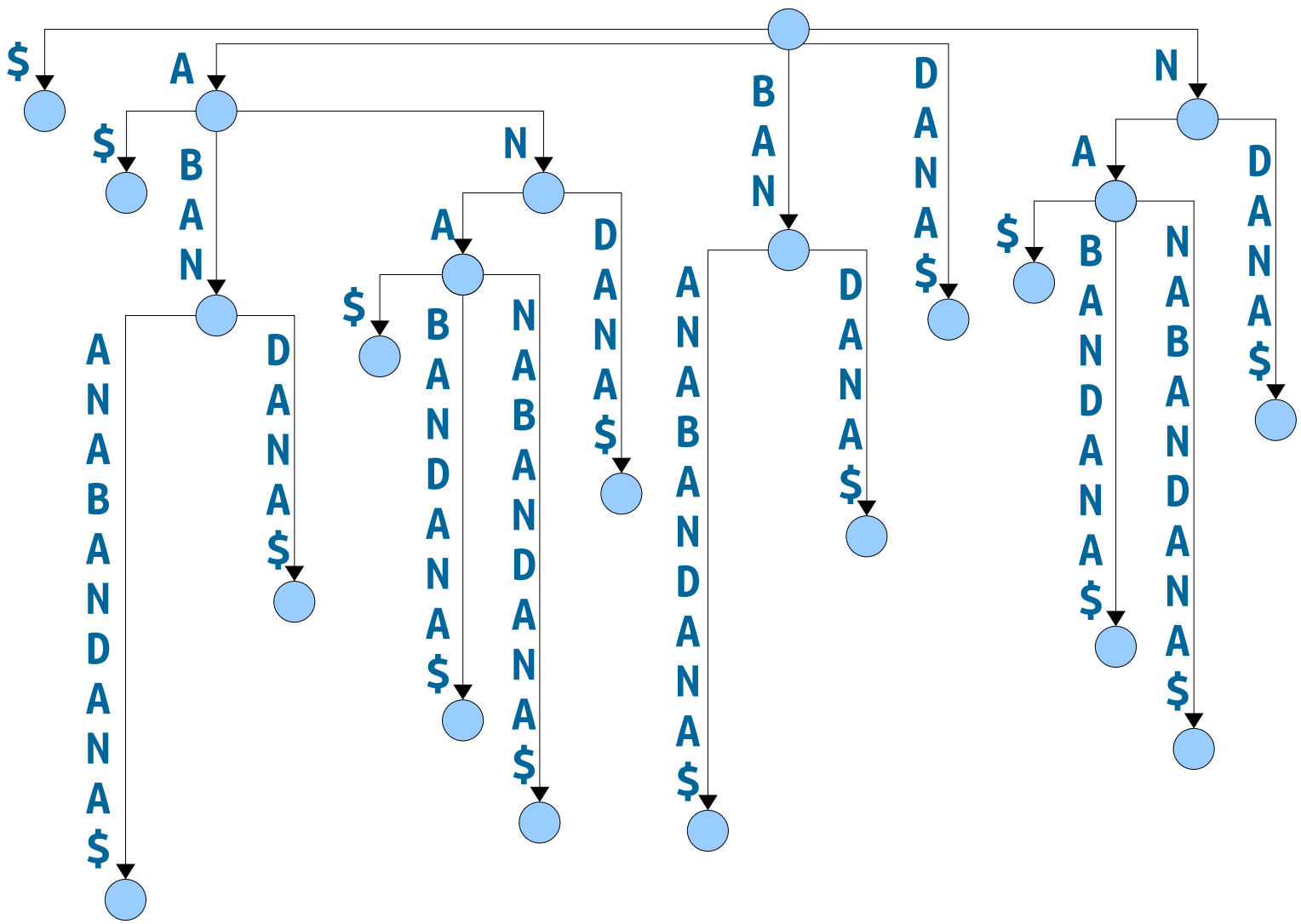

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DANA$
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NABANDANA$
NANABANDANA$
NDANA$

ABANANABANDANA$

ω is an internal node in the suffix tree for T

if and only if

ω is a branching word in T$

if and only if

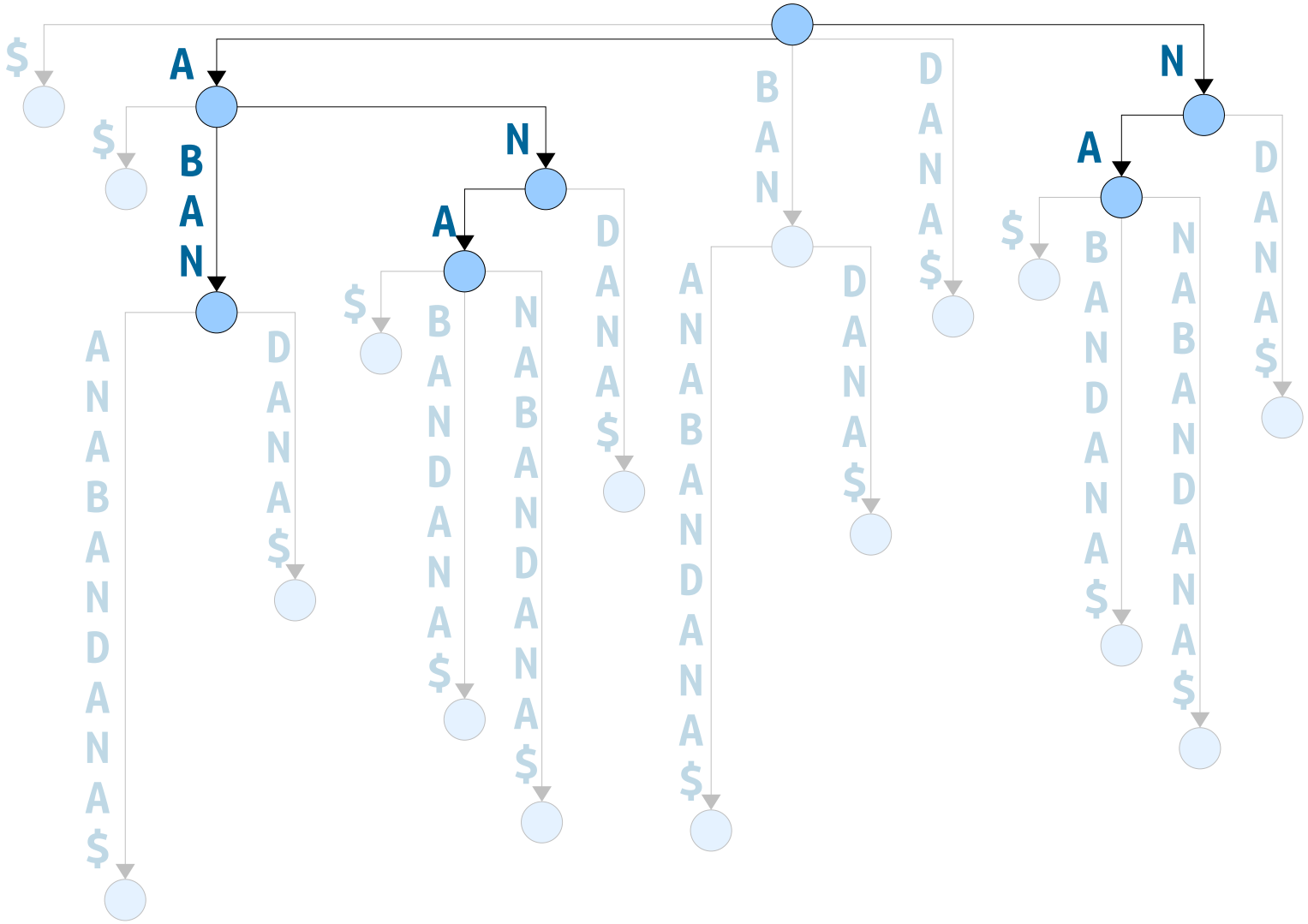
ω is the LCP of two adjacent suffixes in the suffix array for T

Key Intuition: Adjacent suffixes with long shared prefixes correspond to subtrees of the suffix tree.

Harnessing this Connection

Longest Repeated Substring

- Last time, we saw how to solve the longest repeated substring problem by using suffix trees.
- ***Algorithm:*** Find the internal node in the suffix tree with the longest label.
- ***Question:*** Can we do this with just a suffix array?



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Longest Repeated Substring

- We can list all branching words from a suffix array in time O(m^2).
  - O(m) pairs; each pair takes time O(m) to process.
- This worst-case bound can be realized.

$
A$
ABANANABANDANA$
ABANDANA$
ANA$
ANABANDANA$
ANANABANDANA$
ANDANA$
BANANABANDANA$
BANDANA$
DANA$
NA$
NABANDANA$
NANABANDANA$
NDANA$

How?

Answer at
https://pollev.com/cs166spr23

ABANANABANDANA$

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DANA$
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NANABANDANA$
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ABANANABANDANA$

Longest Repeated Substring

- We can list all branching words from a suffix array in time O(m^2).
  - O(m) pairs; each pair takes time O(m) to process.
- This worst-case bound can be realized.
- Contrast this with O(m) for a suffix tree.
- Can we do better?

$
A$
ABANANABANDANA$
ABANDANA$
ANA$
ANABANDANA$
ANANABANDANA$
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BANANABANDANA$
BANDANA$
DANA$
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NABANDANA$
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NDANA$

ABANANABANDANA$

Longest Repeated Substring

- ***Observation:*** We don't actually need to know what all the branching words are to find the longest repeated substring.
- We just need to know how long they are.
- That way, we can figure out which is longest.
- Is there some nice way to do this?

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A$
ABANANABANDANA$
ABANDANA$
ANA$
ANABANDANA$
ANANABANDANA$
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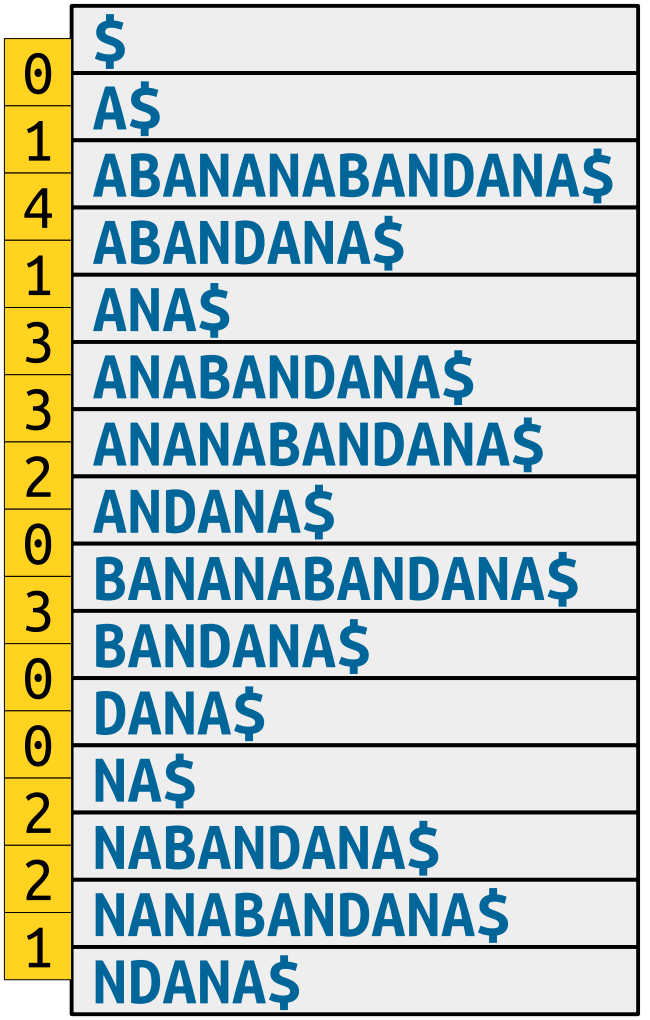
NABANDANA$
NANABANDANA$
NDANA$

ABANANABANDANA$

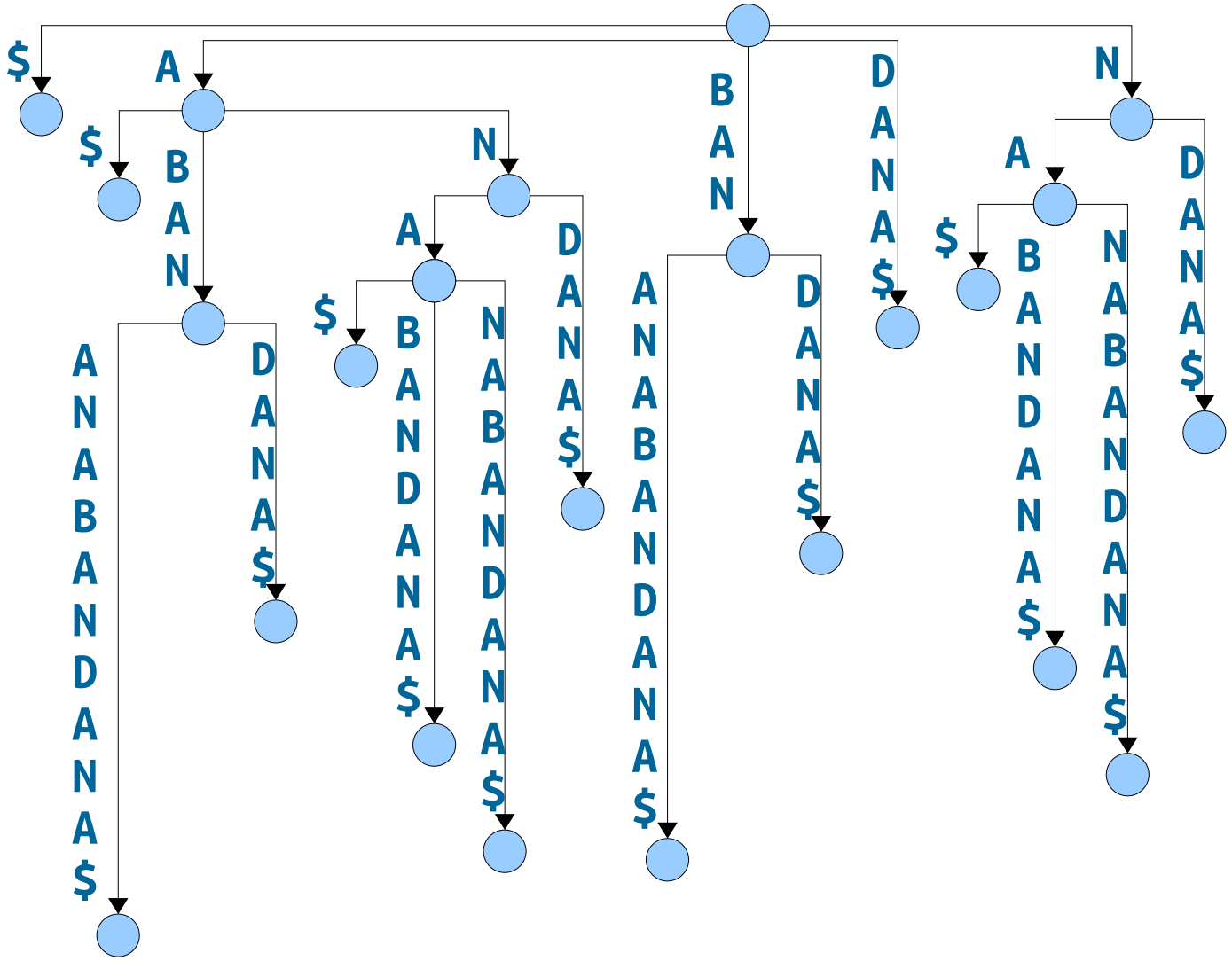
LCP Arrays

LCP Arrays

- The ***LCP array***, often denoted ***H***, is an array where $H[i]$ is the length of the LCP of the ith and $(i+1)$st suffixes in the suffix array.
- (The letter H comes from “height.”)



ABANANABANDANA$



0	$
1	A$
4	ABANANABANDANA$
1	ABANDANA$
3	ANA$
3	ANABANDANA$
2	ANANABANDANA$
0	ANDANA$
3	BANANABANDANA$
0	BANDANA$
0	DANA$
2	NA$
2	NABANDANA$
1	NANABANDANA$
	NDANA$

ABANANABANDANA$

Key intuition: The suffix array gives the leaves of the suffix tree. The LCP array gives the internal nodes of the suffix tree.

Using LCP Arrays

- If you already have a suffix array and LCP array, you can solve longest repeated substring in time O(***m***):
  - Find the largest element in the LCP array.
  - Return the string it corresponds to.
- ***Question:*** How fast can we construct an LCP array?

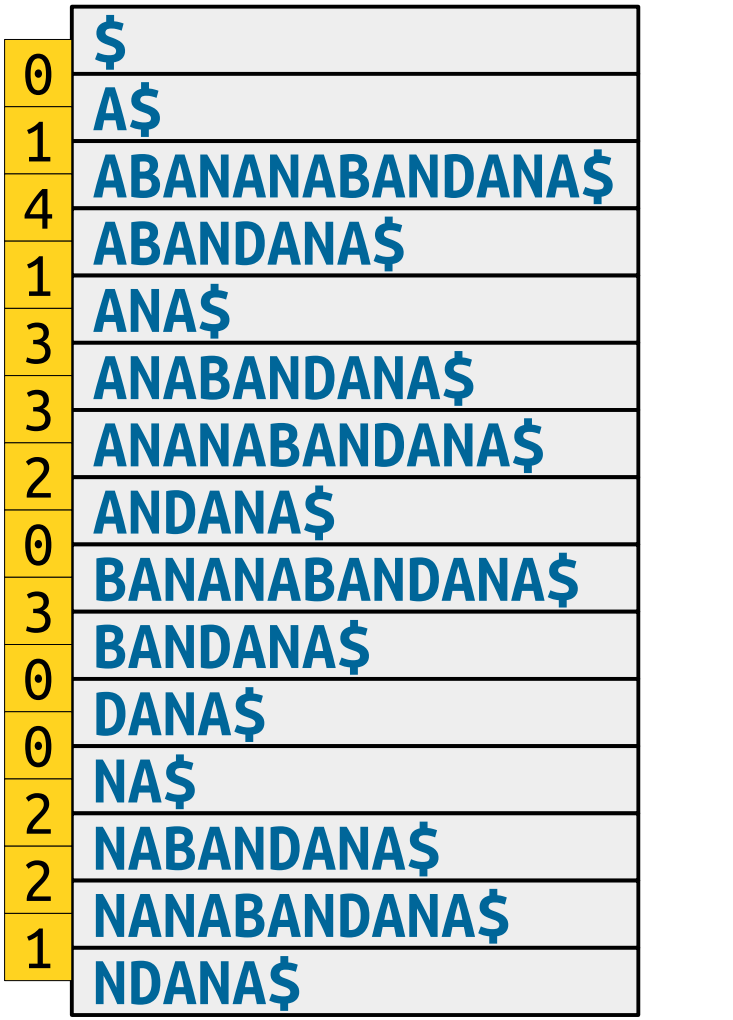
0	$
1	A$
4	ABANANABANDANA$
1	ABANDANA$
3	ANA$
3	ANABANDANA$
2	ANANABANDANA$
0	ANDANA$
3	BANANABANDANA$
0	BANDANA$
0	DANA$
2	NA$
2	NABANDANA$
1	NANABANDANA$
	NDANA$

ABANANABANDANA$

Building LCP Arrays

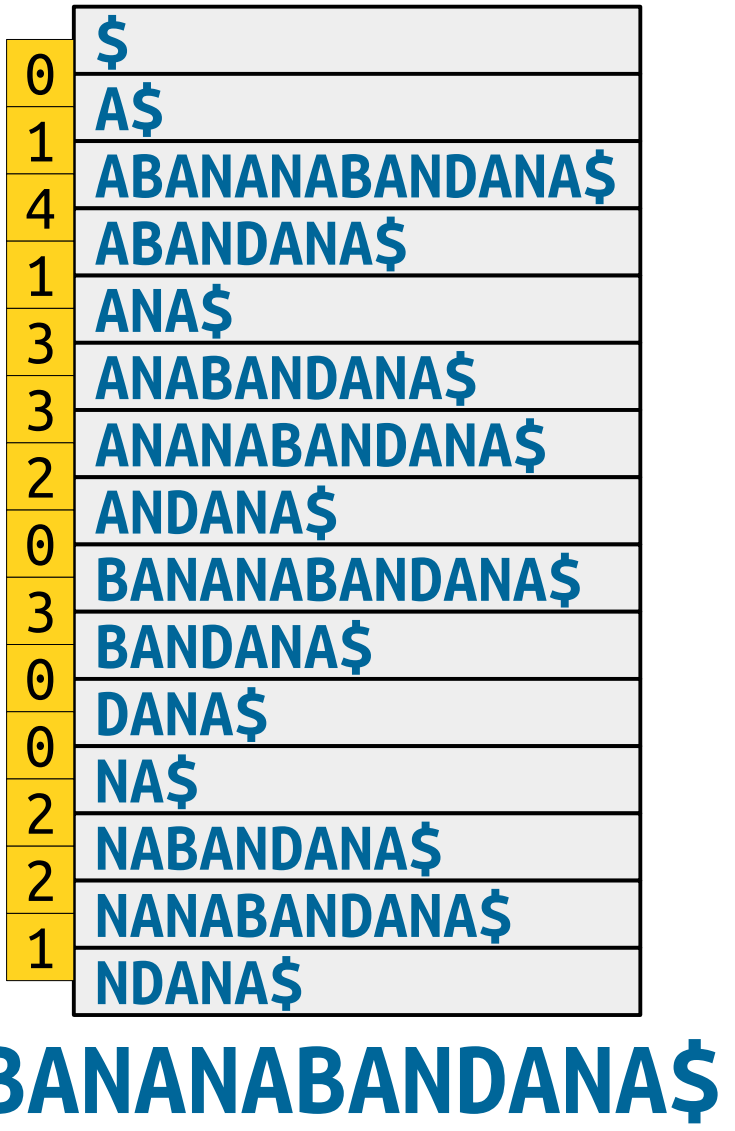
Building LCP Arrays

- It never hurts to start with the naive algorithm and see what happens!
- ***Algorithm:*** For each consecutive pair of strings in the suffix array, compute the length of their longest common prefix.
- We can upper-bound the runtime at $O(m^2)$.
- ***Question:*** Can we realize this upper bound?



Building LCP Arrays

- Why is our naive algorithm slow?
- ***Intuition:*** We aren't able to carry work from one suffix over to the next.



Building LCP Arrays

- ***Key intuition:*** Suffixes overlap one another! It should be possible to share LCP information across suffixes.

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A$
ABANANABANDANA$
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Building LCP Arrays

- ***Key intuition:*** Suffixes overlap one another! It should be possible to share LCP information across suffixes.
- For example, suppose we compute the LCP entry shown here.

$
A$
ABANANABANDANA$
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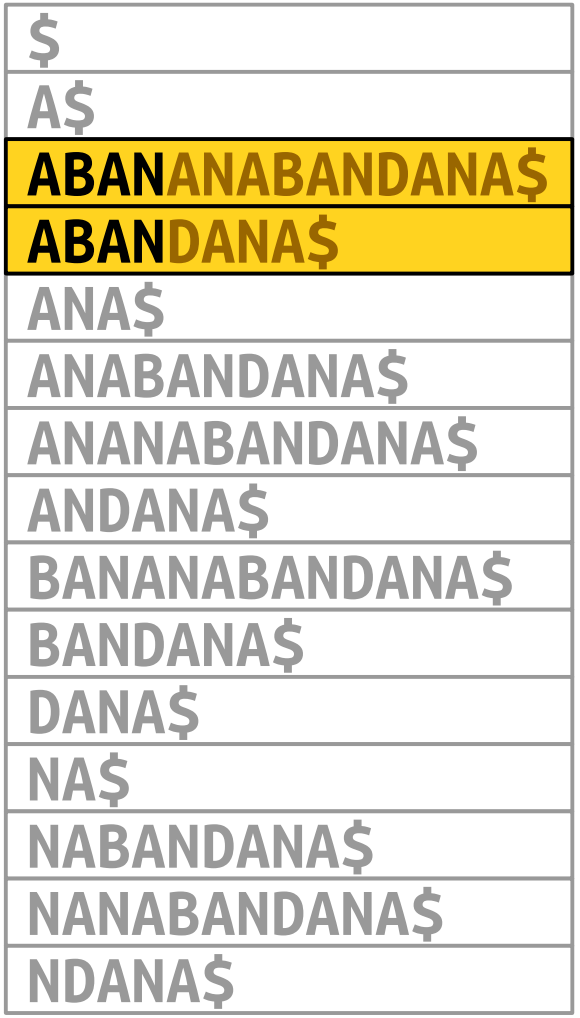

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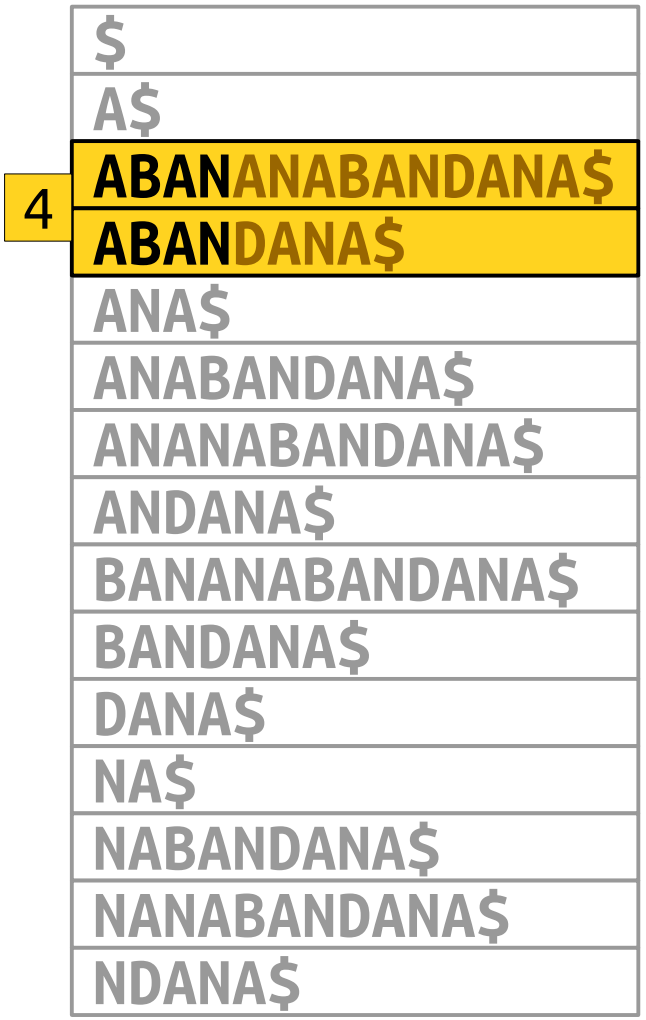

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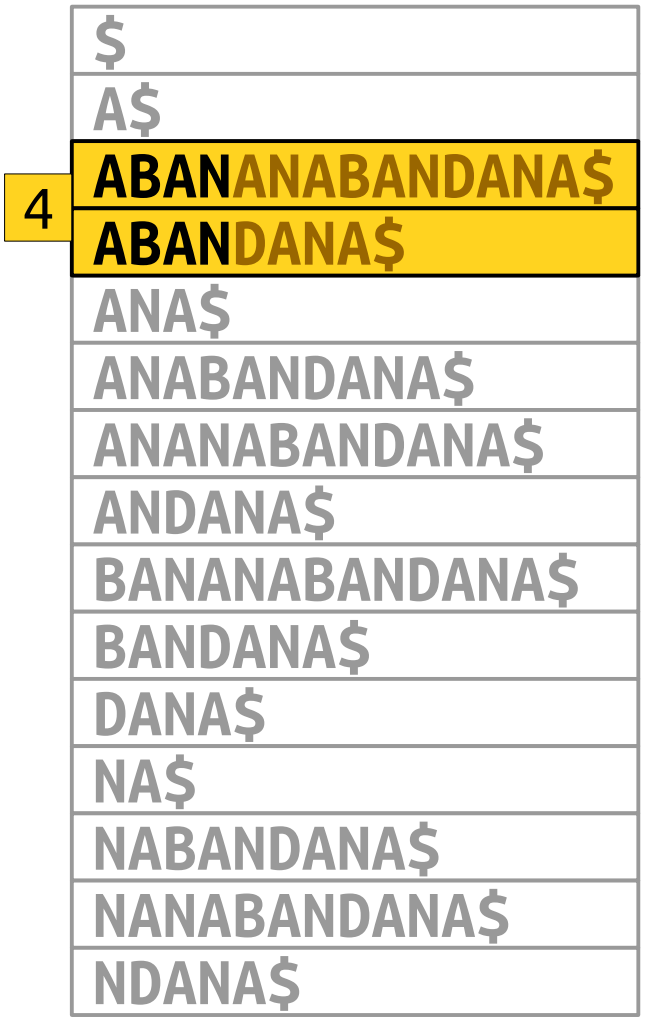
- ***Key intuition:*** Suffixes overlap one another! It should be possible to share LCP information across suffixes.
- For example, suppose we compute the LCP entry shown here.
- Look at the suffixes formed by dropping the first letter of these two suffixes.



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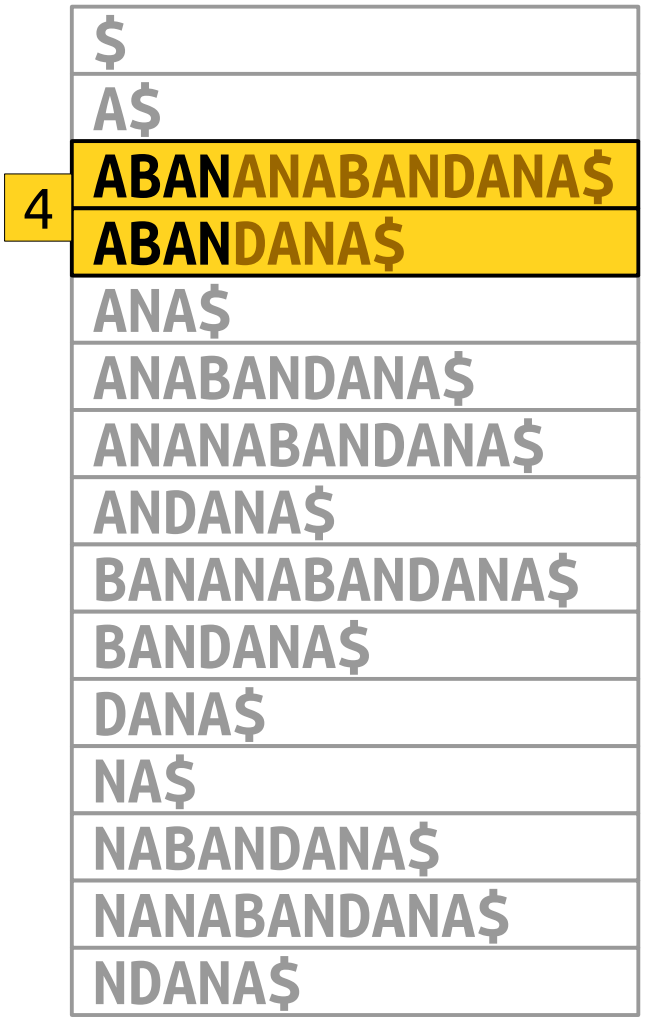

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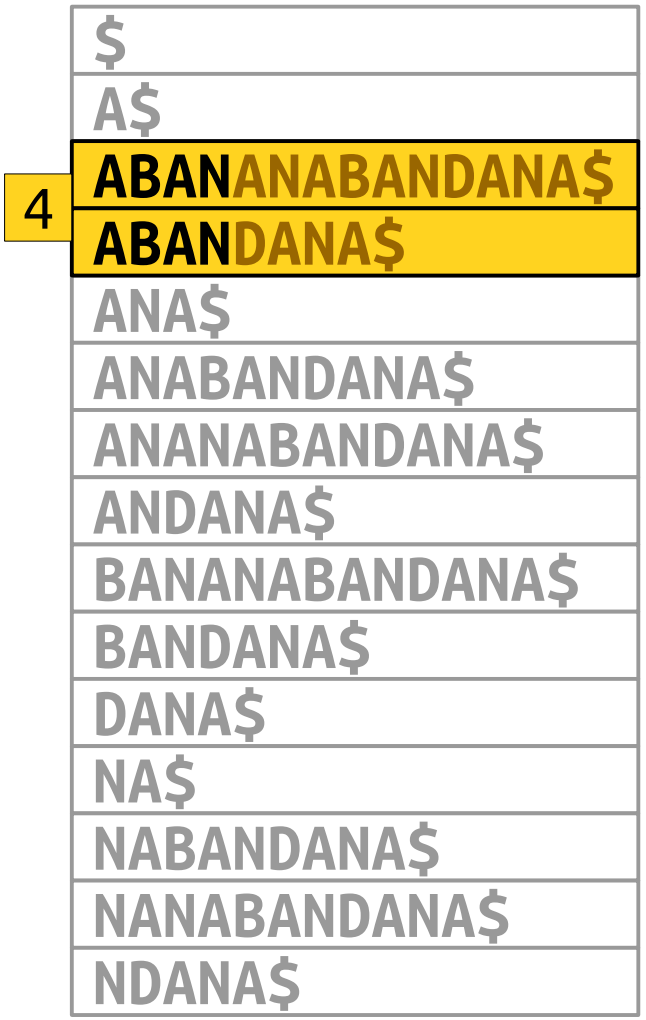

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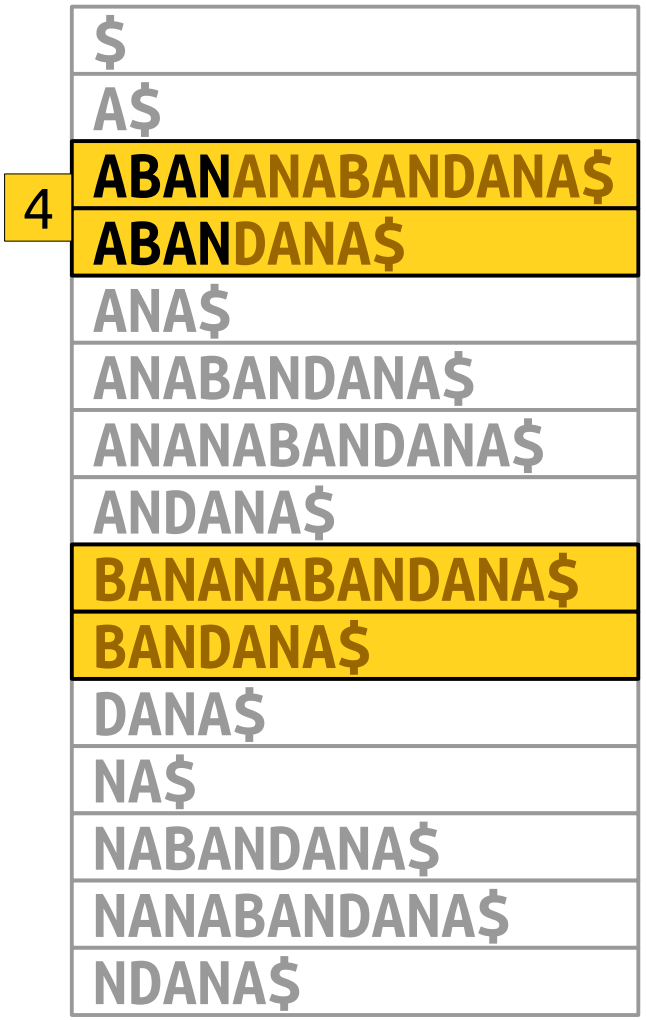

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ABANDANA$

Building LCP Arrays

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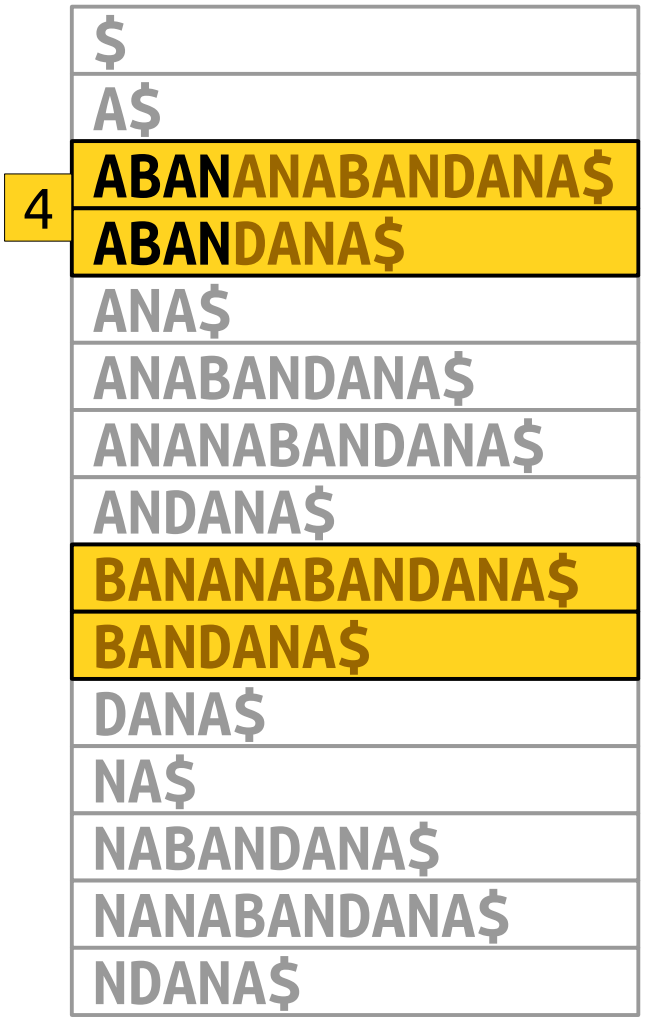
- Look at the suffixes formed by dropping the first letter of these two suffixes.
- What do we know about their LCP?



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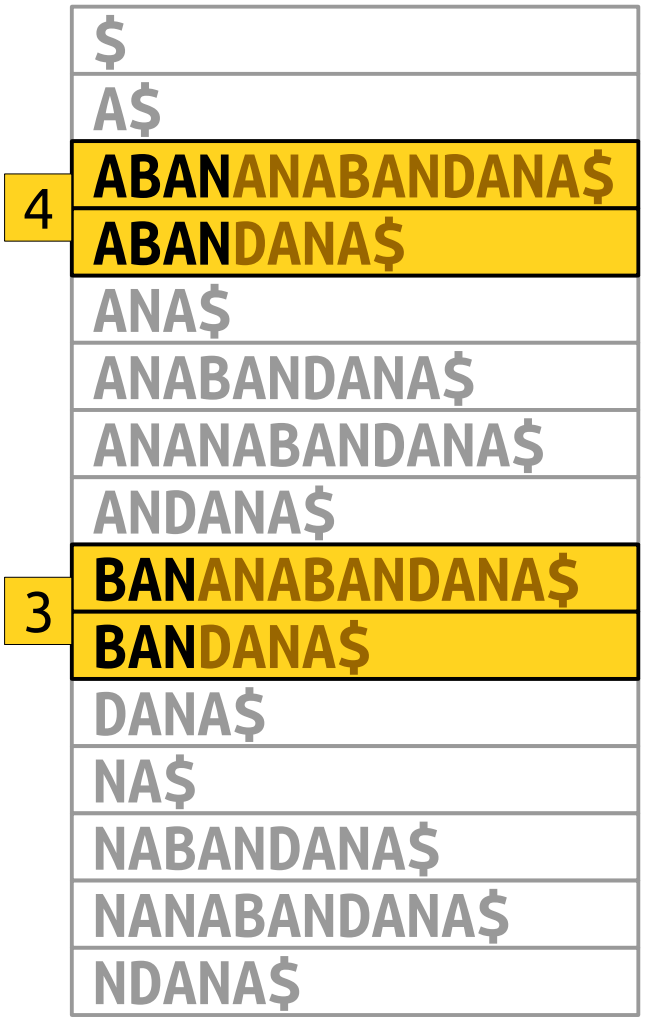

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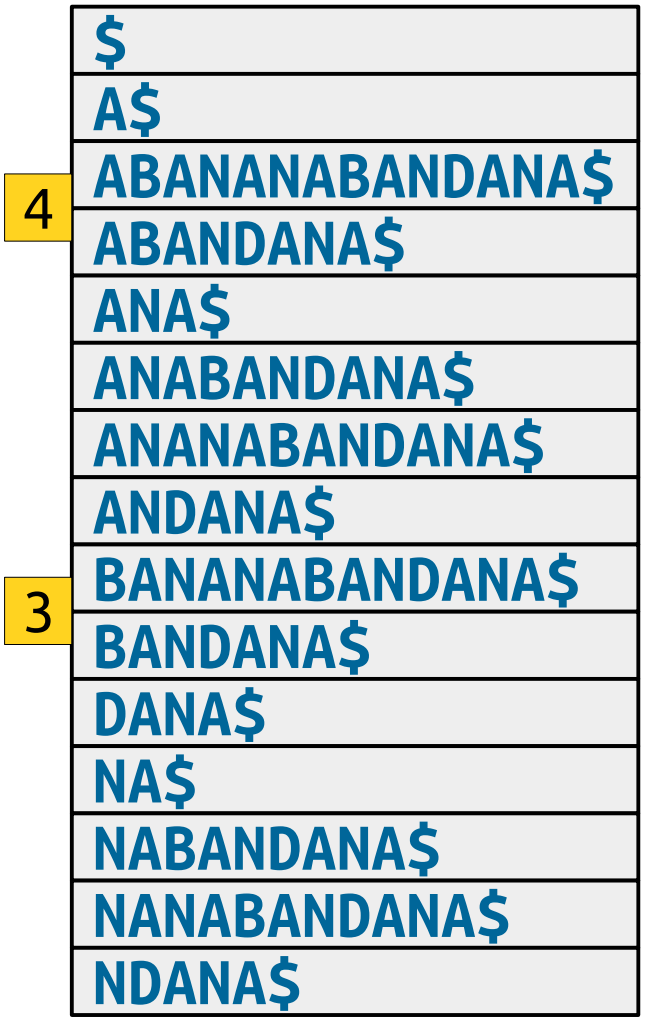

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Building LCP Arrays

- Let’s do another example. Suppose we know the LCP of these suffixes.

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A$
ABANANABANDANA$
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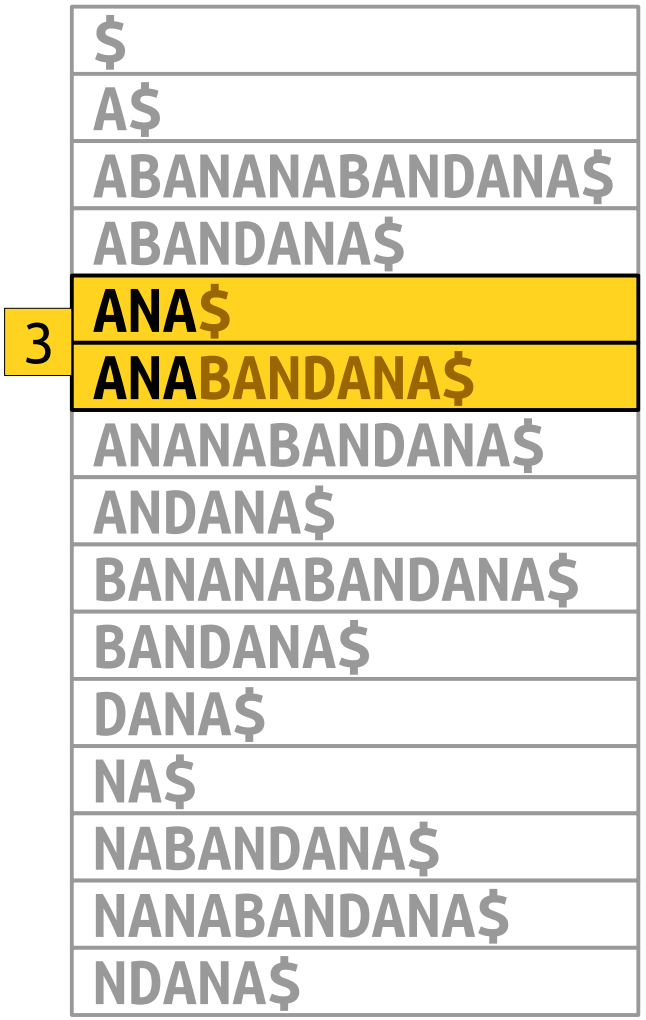

Building LCP Arrays

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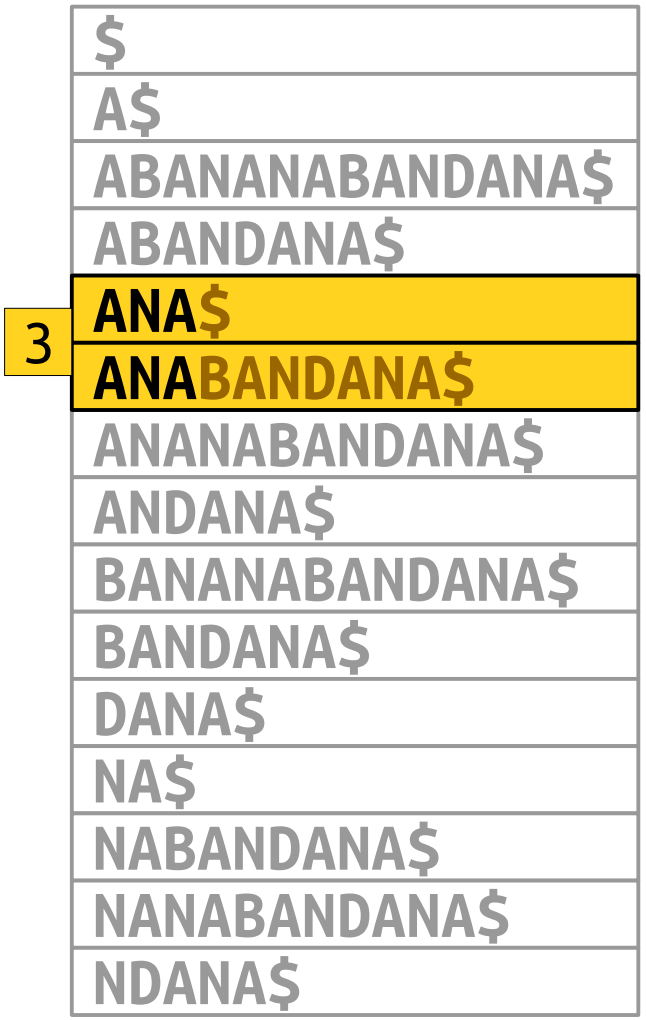
- As before, drop the first letter from each suffix.



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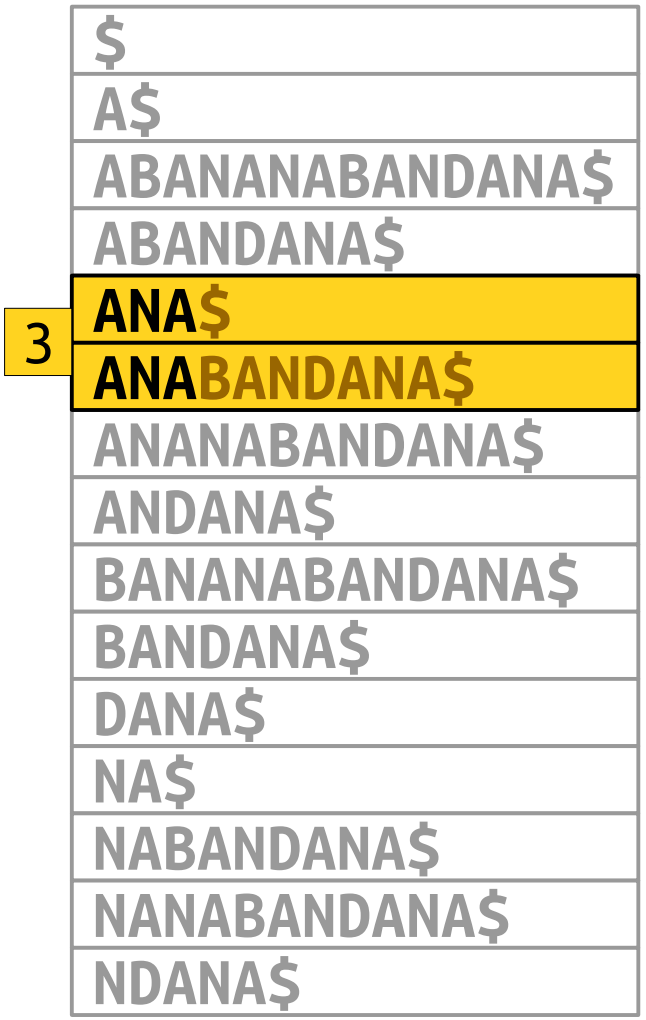

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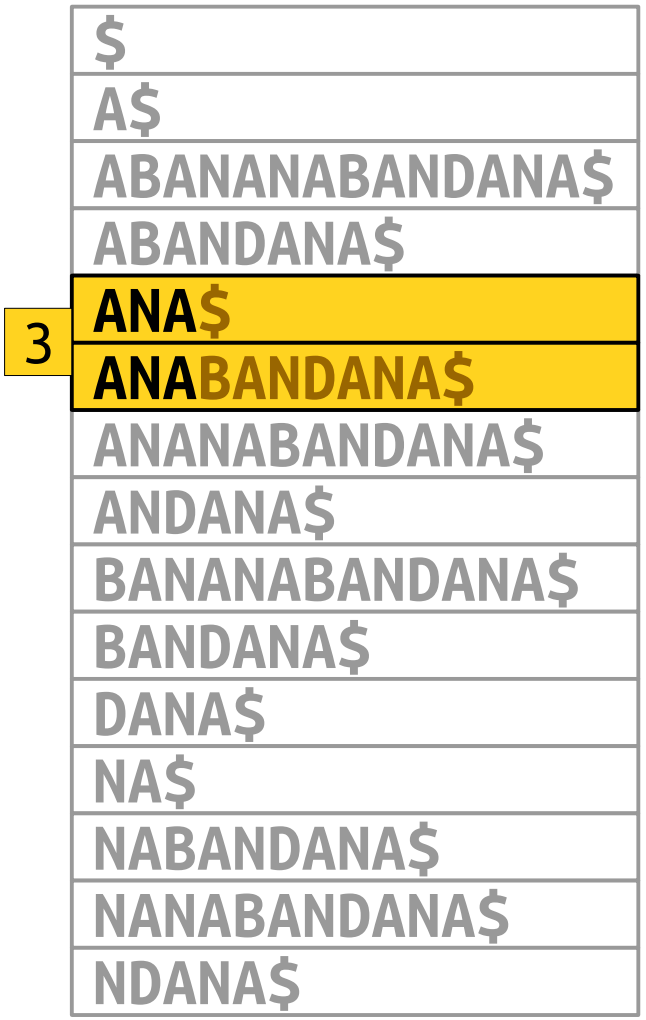

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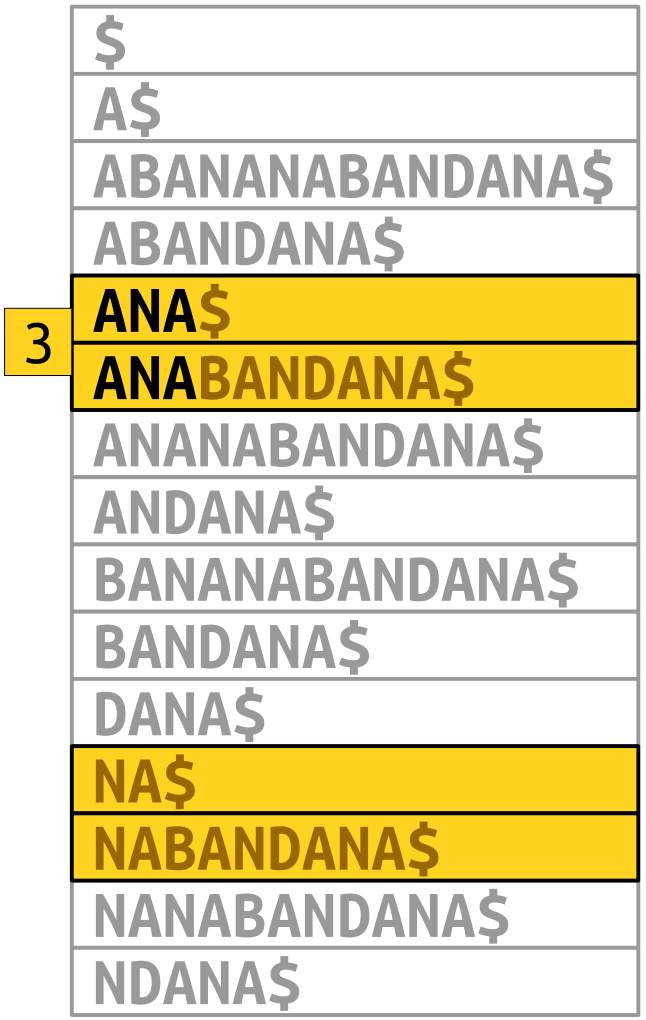
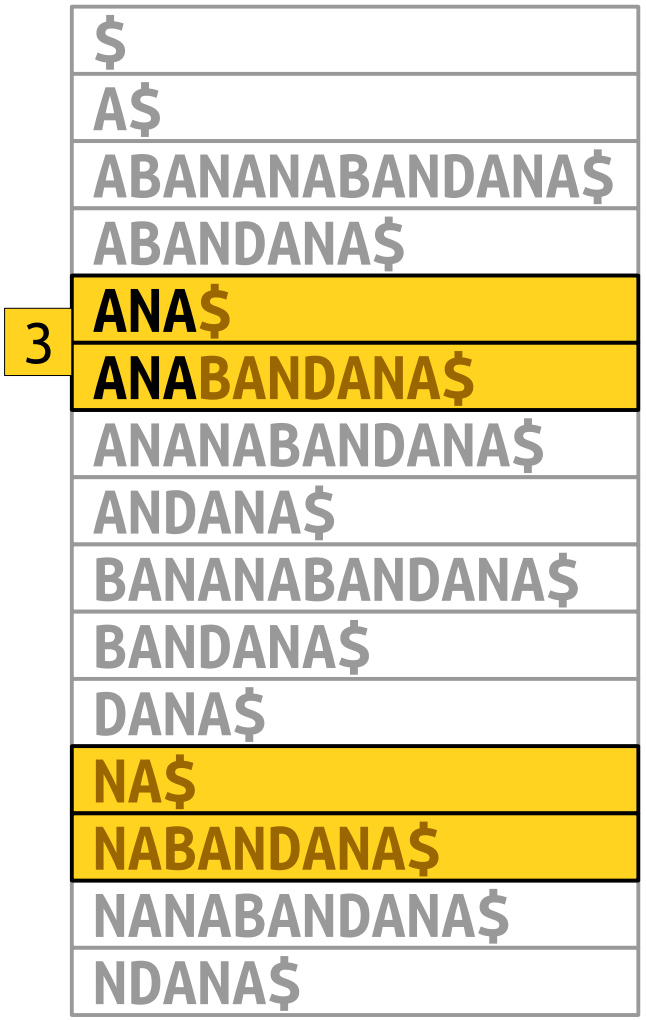


ANA$

ANABANDANA$

Building LCP Arrays

- Let’s do another example. Suppose we know the LCP of these suffixes.
- As before, drop the first letter from each suffix.
- What can we say about the LCP of the resulting suffixes?



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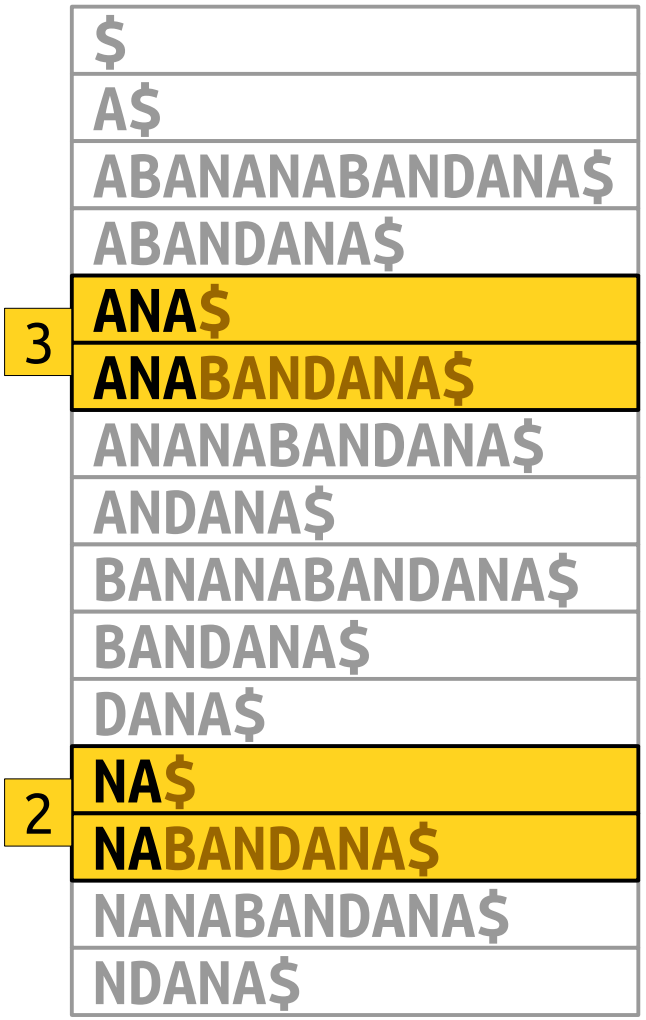

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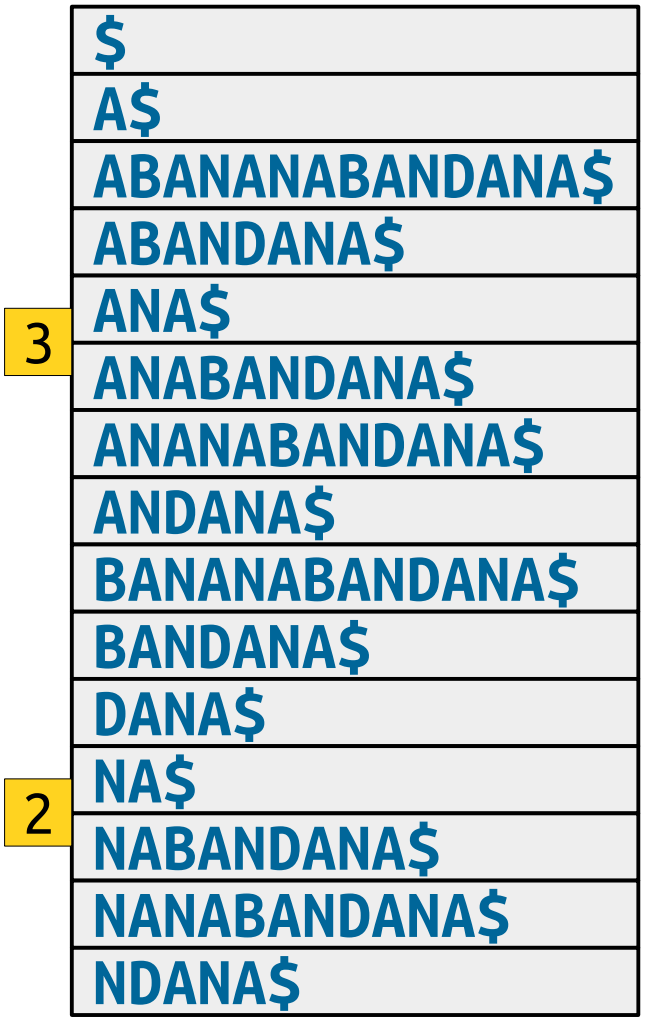

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Building LCP Arrays

- Sometimes, in dropping the first letter, two adjacent suffixes get spread out.

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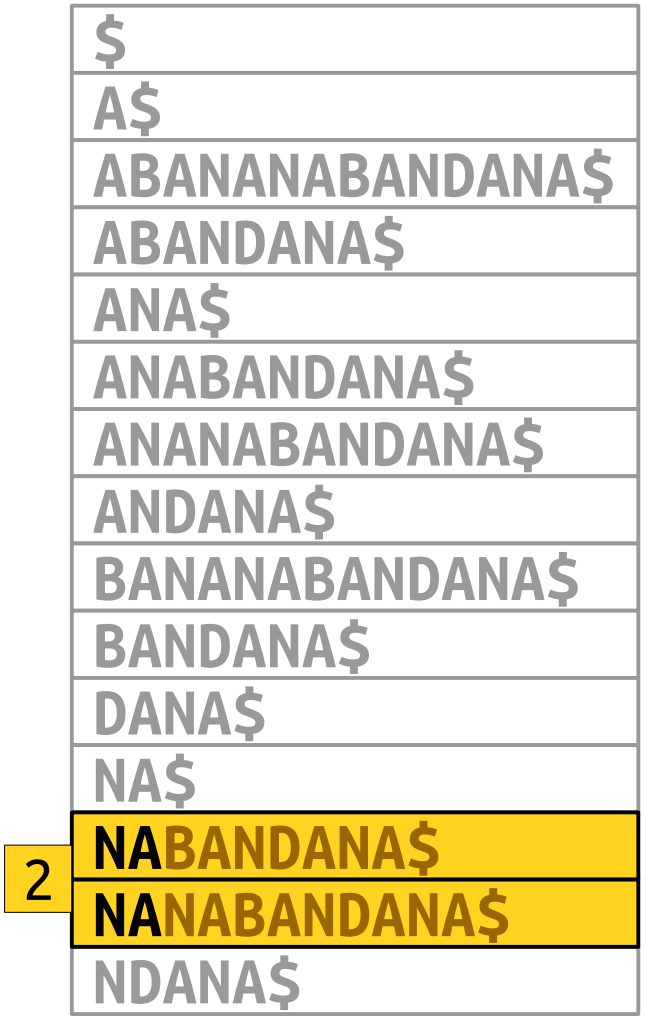

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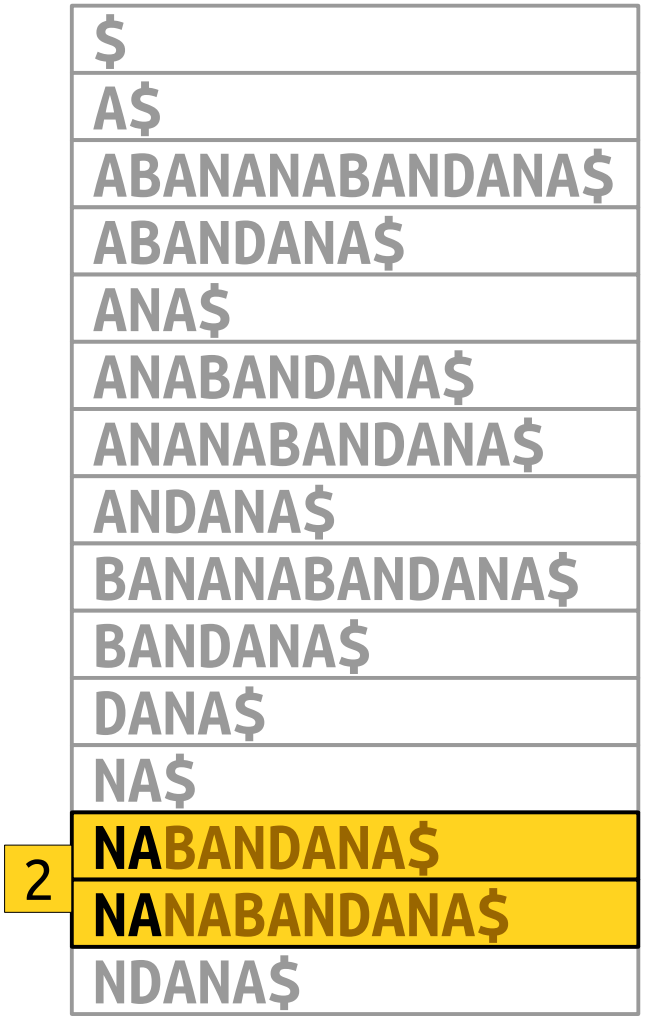

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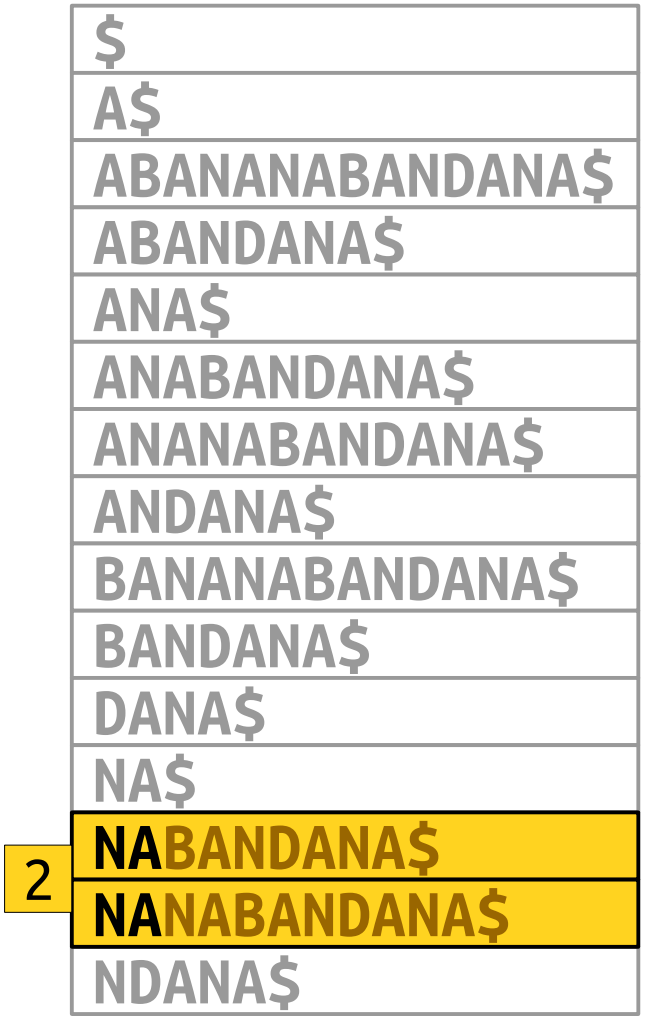

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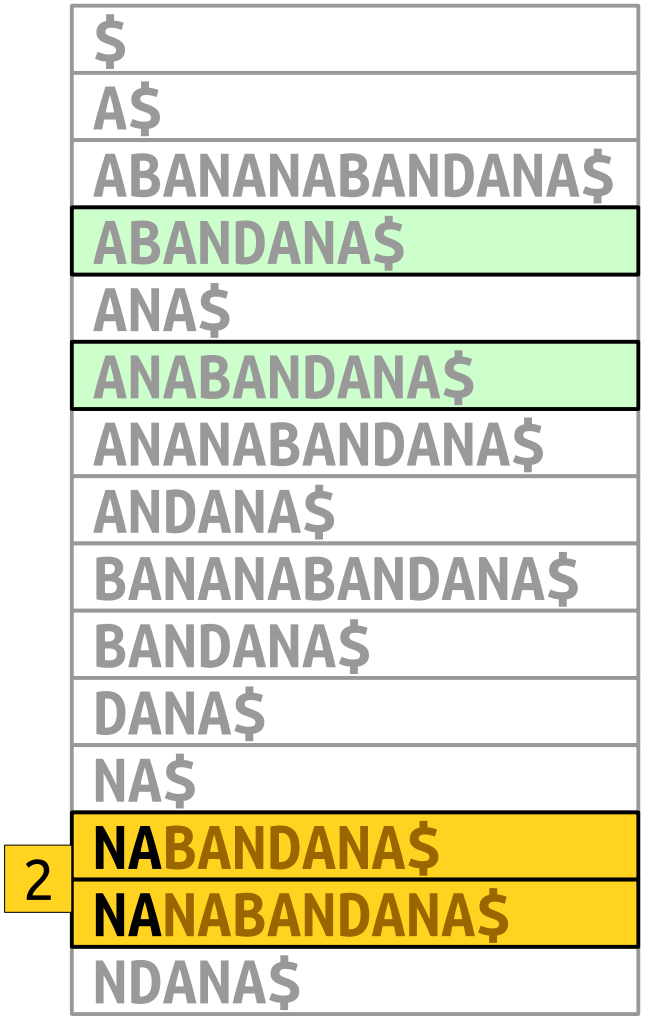

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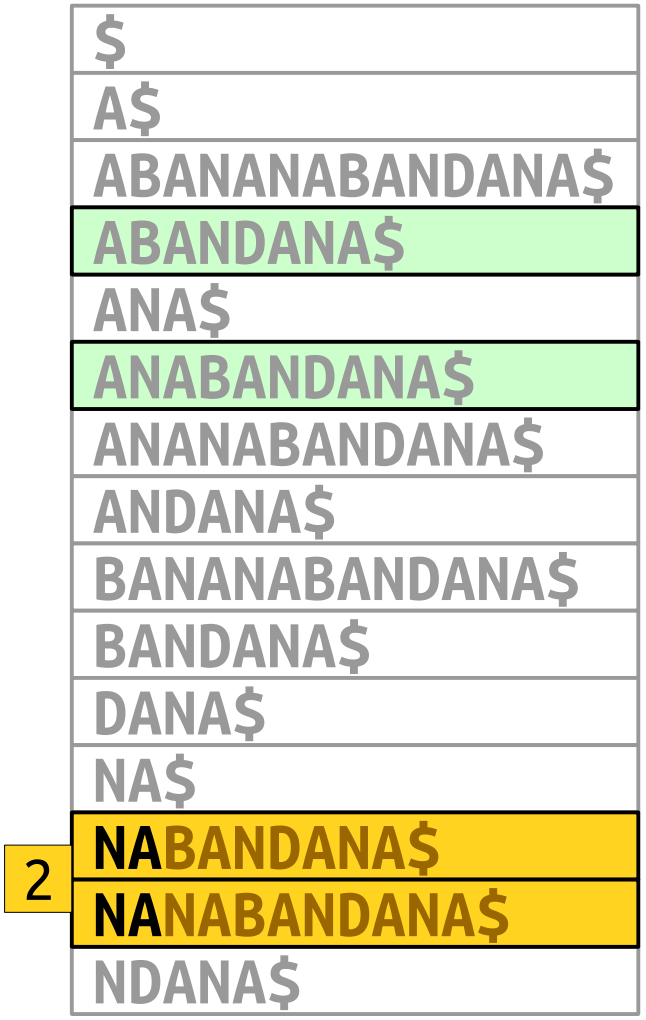

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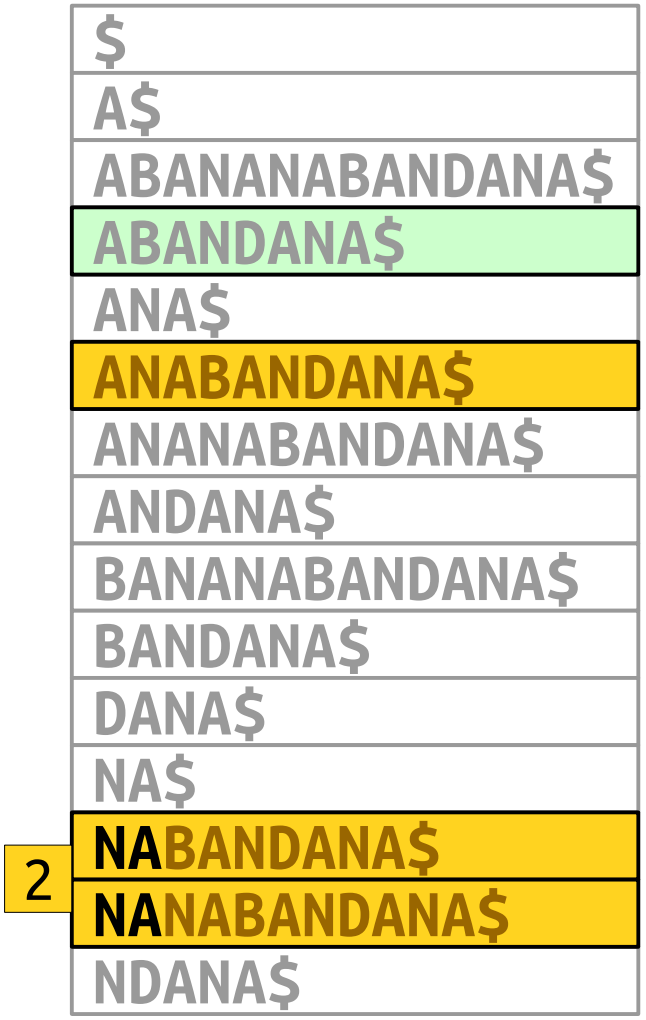

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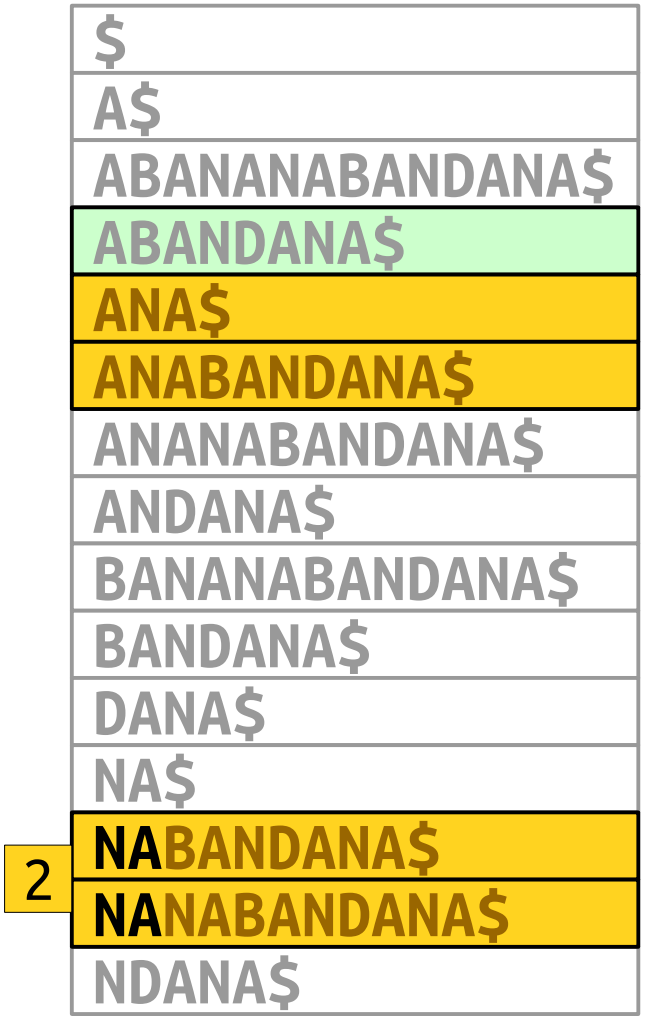

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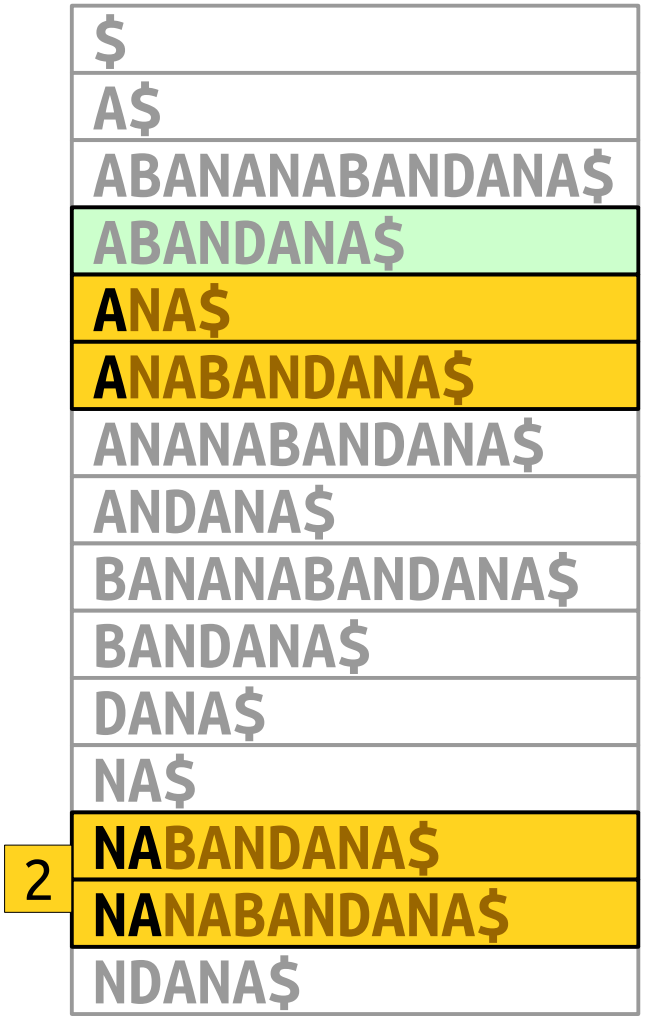

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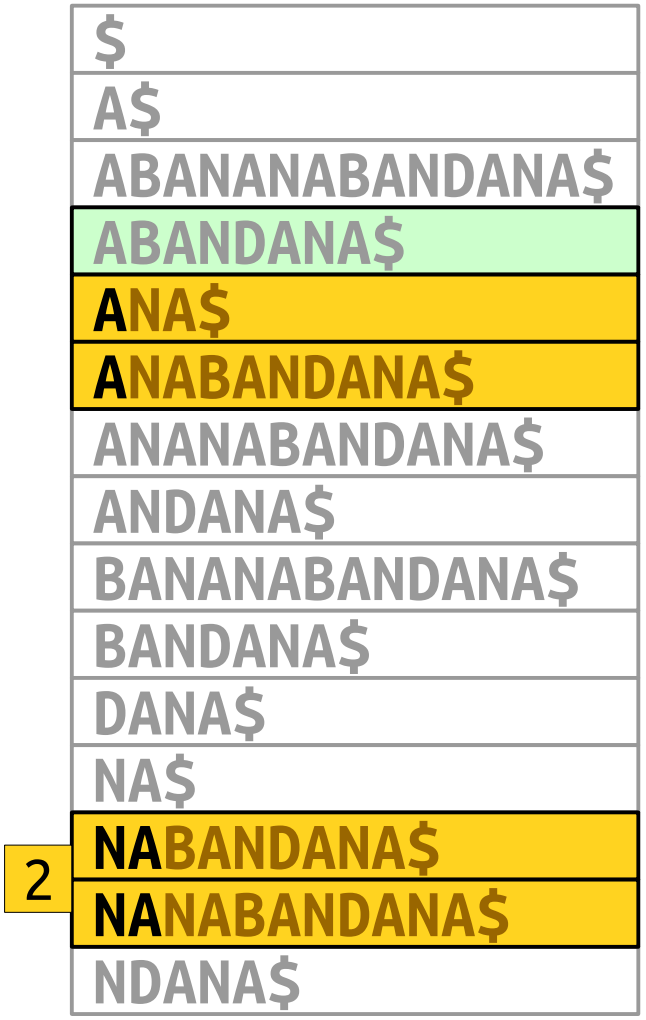
Why?

Answer at
https://pollev.com/cs166spr23



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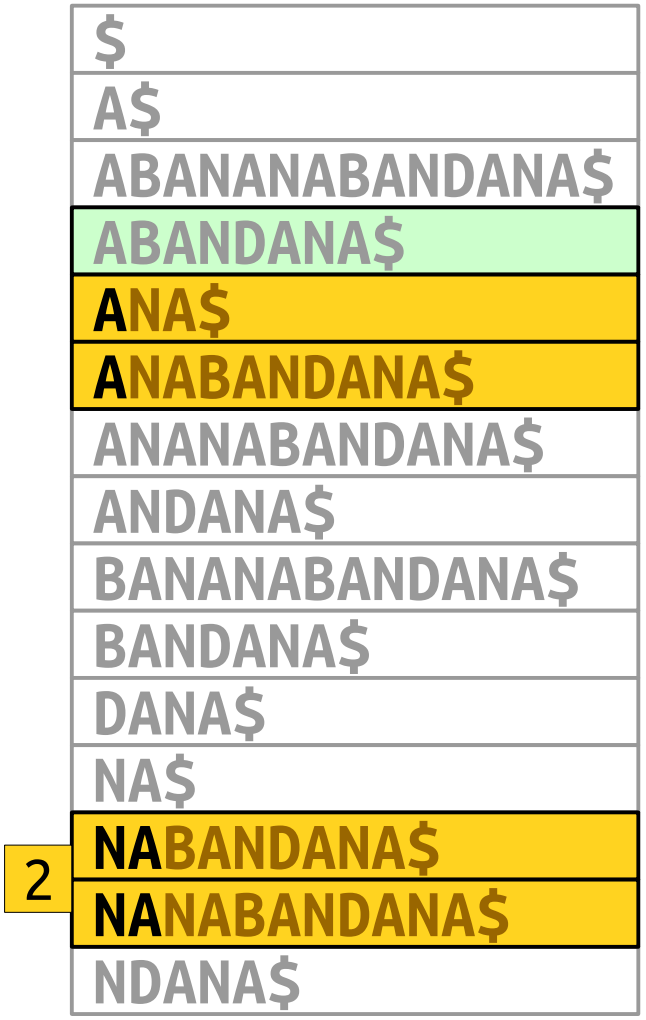

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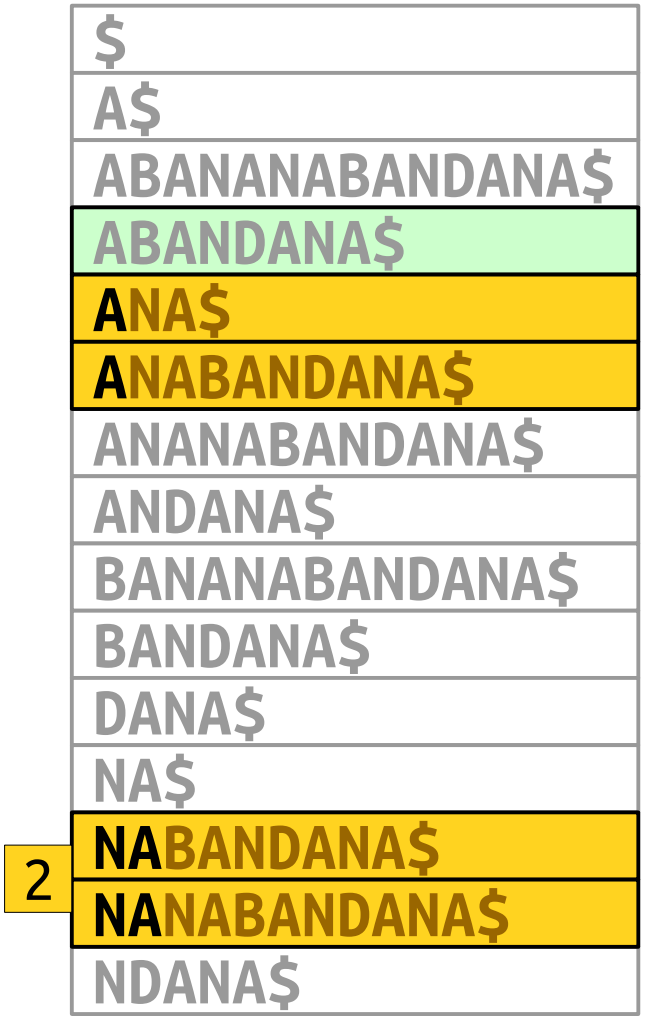

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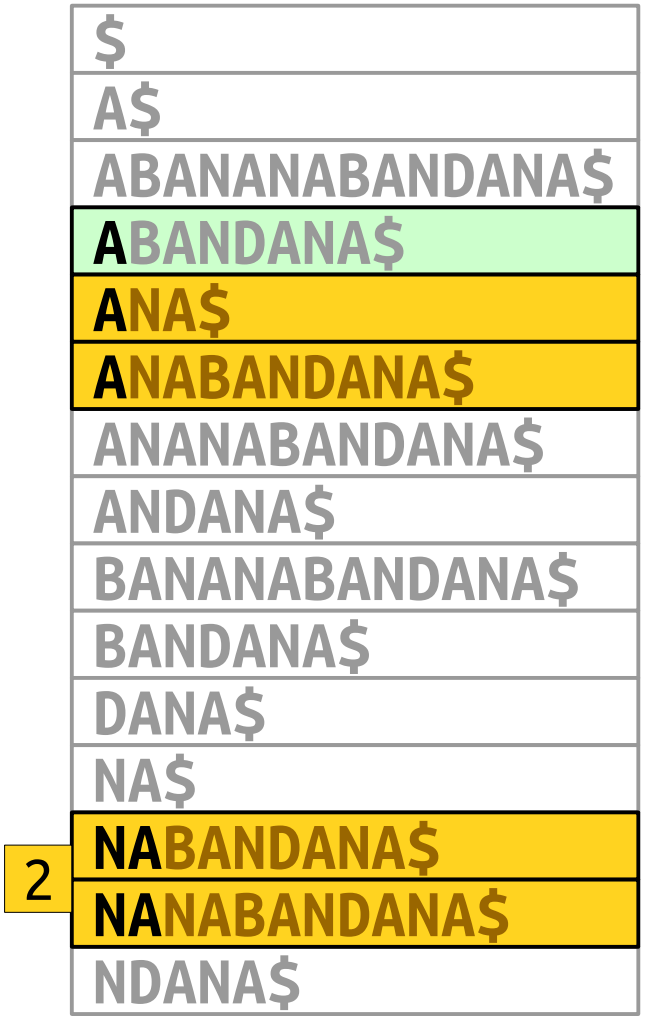

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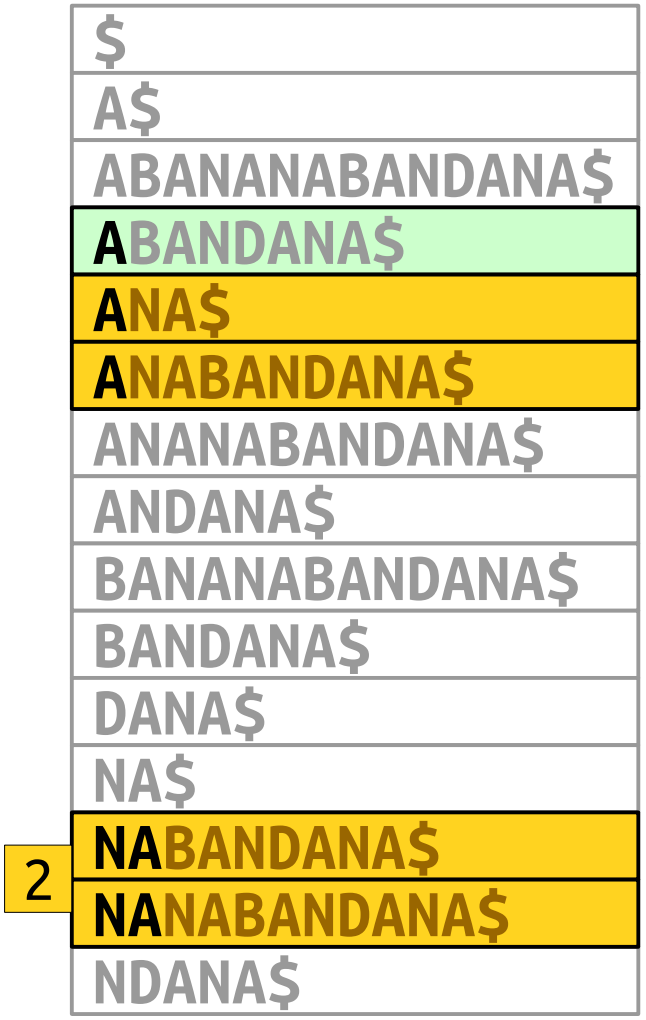
Building LCP Arrays

- We know that these two new suffixes must have an LCP of at least 1, because the two old suffixes have an LCP of 2.
- However, the LCP may be longer than 1, since we've never seen one of these two suffixes.
- We still need to some some scanning, but we won't necessarily have to rescan the entire suffix.



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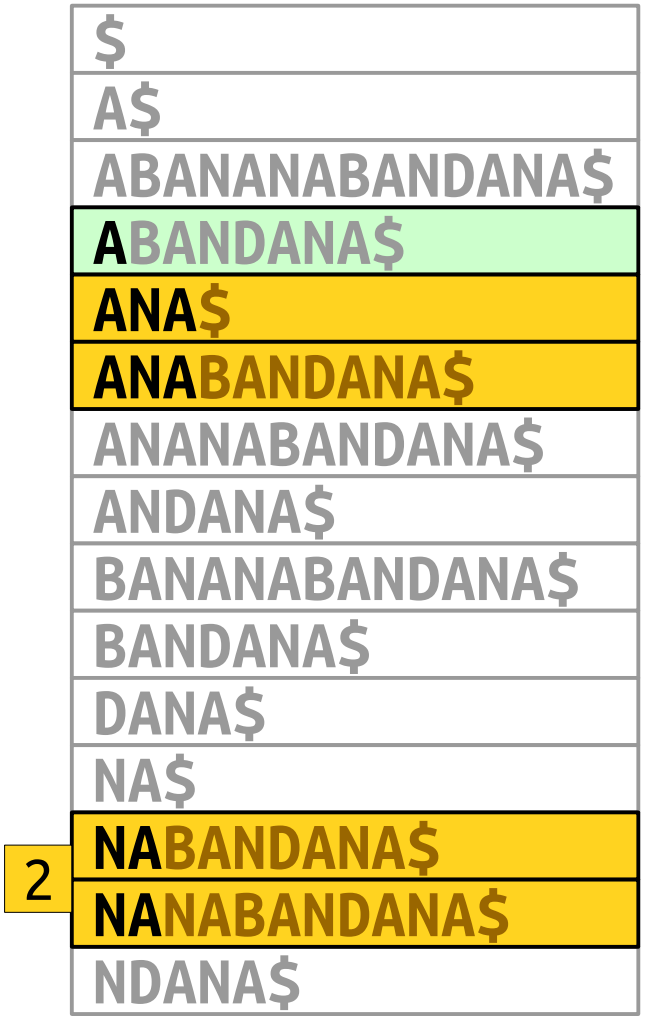

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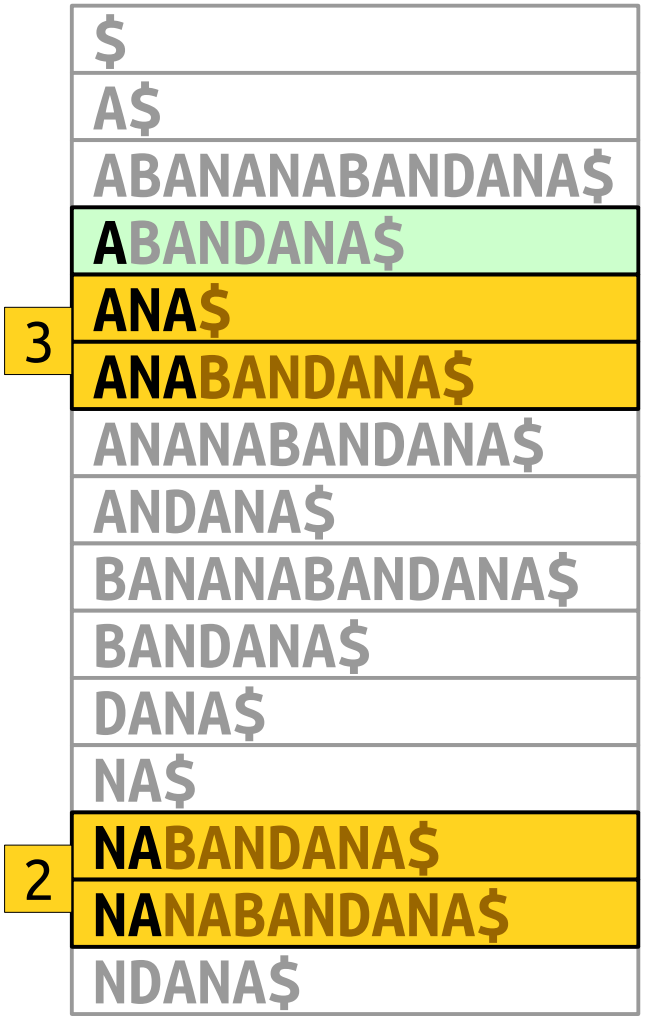

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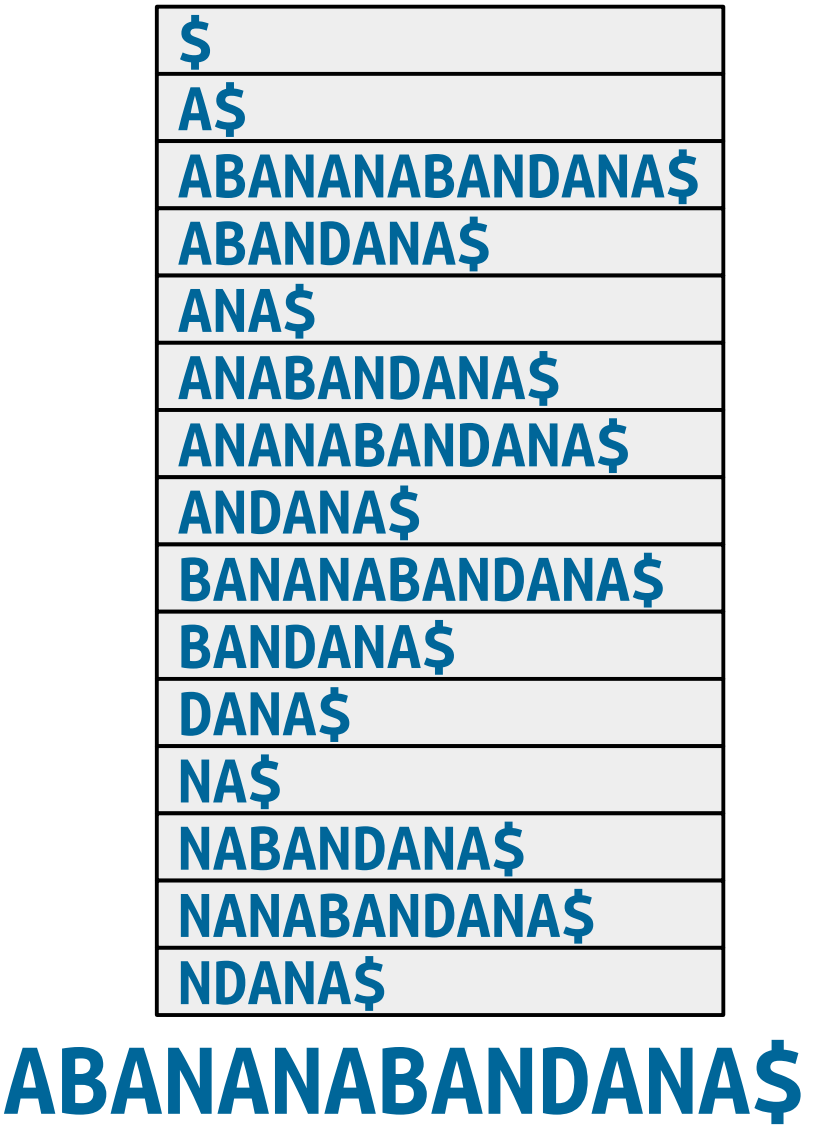

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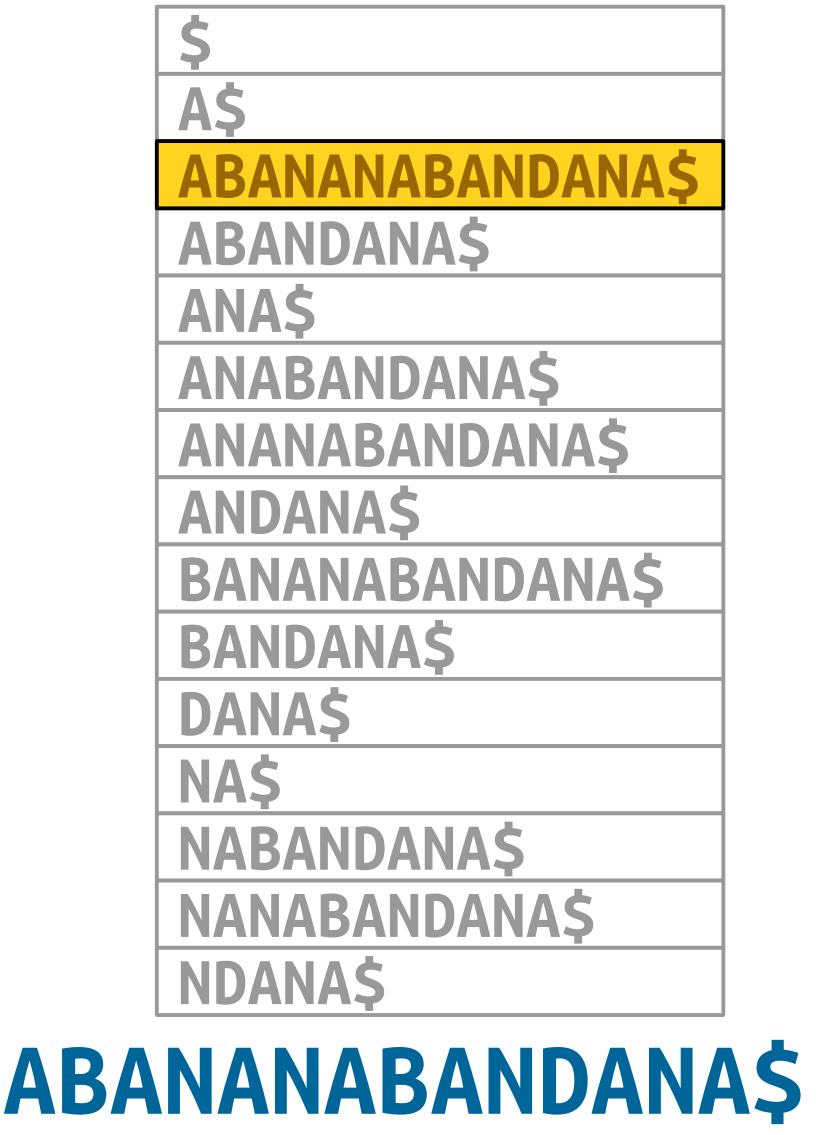

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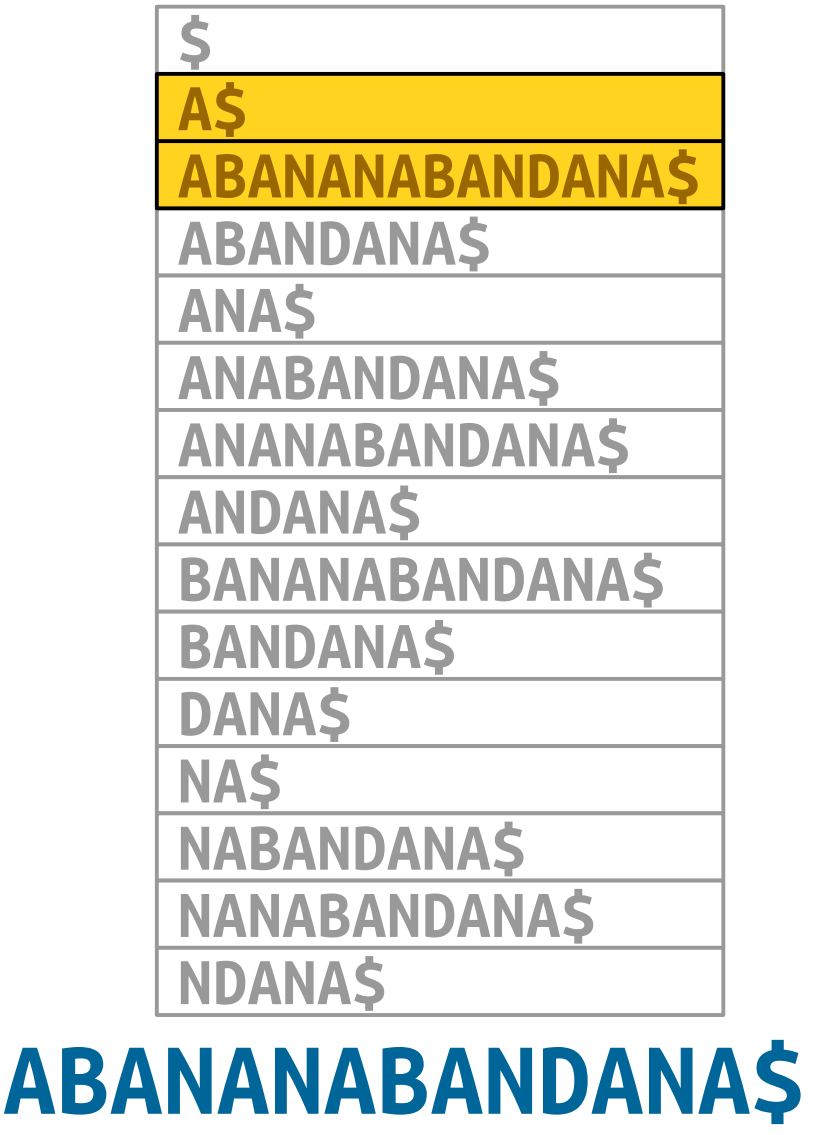

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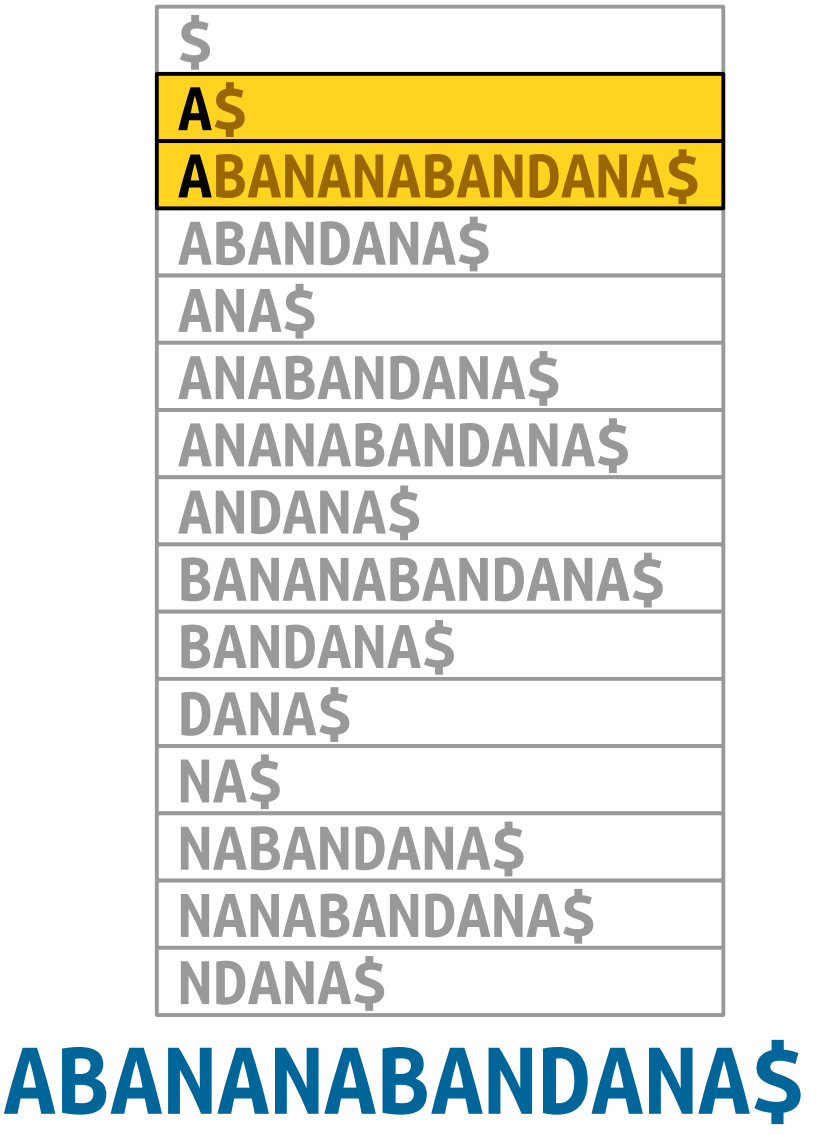

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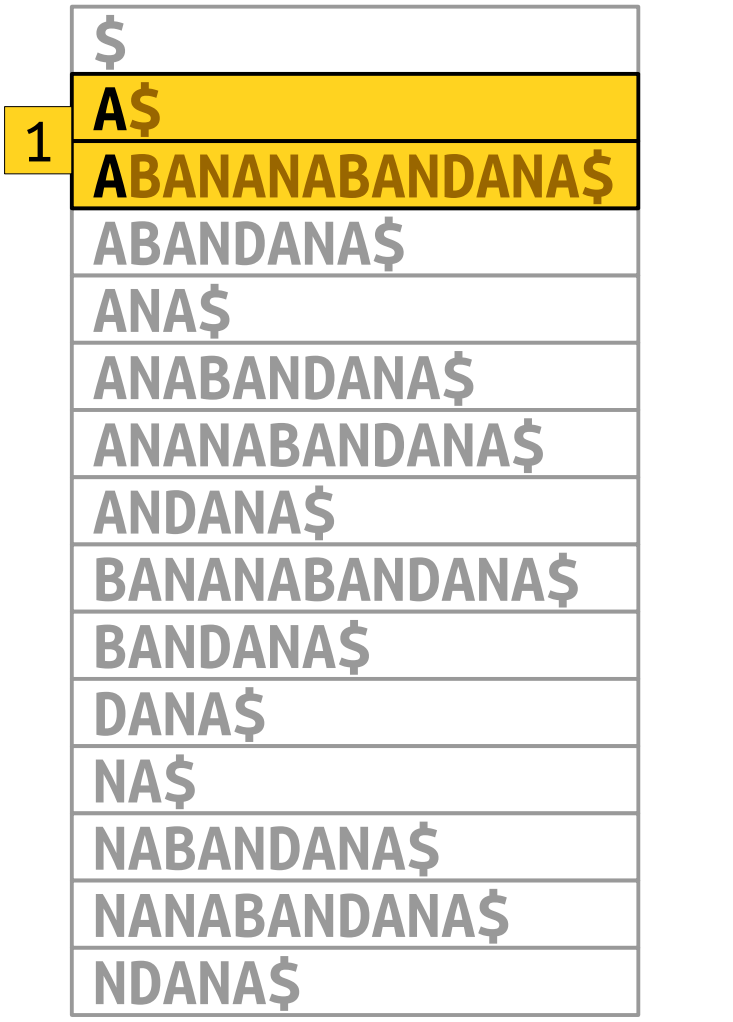

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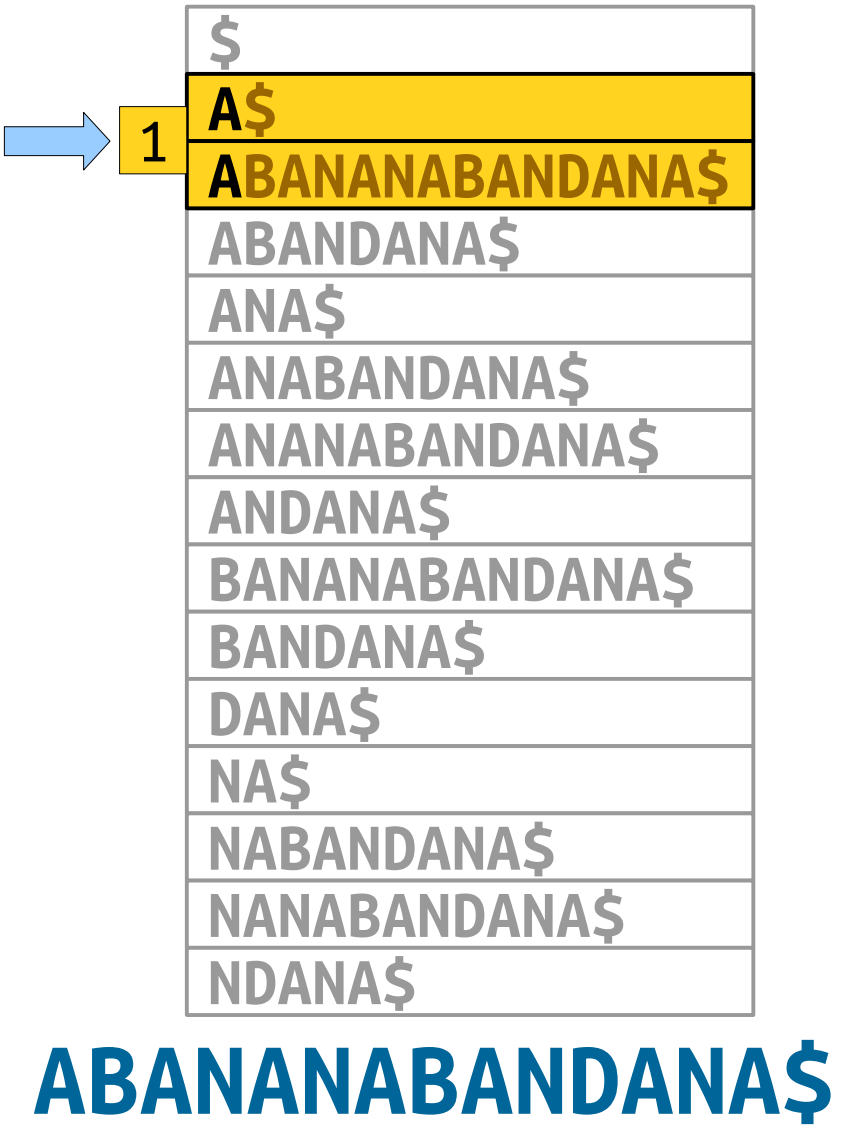

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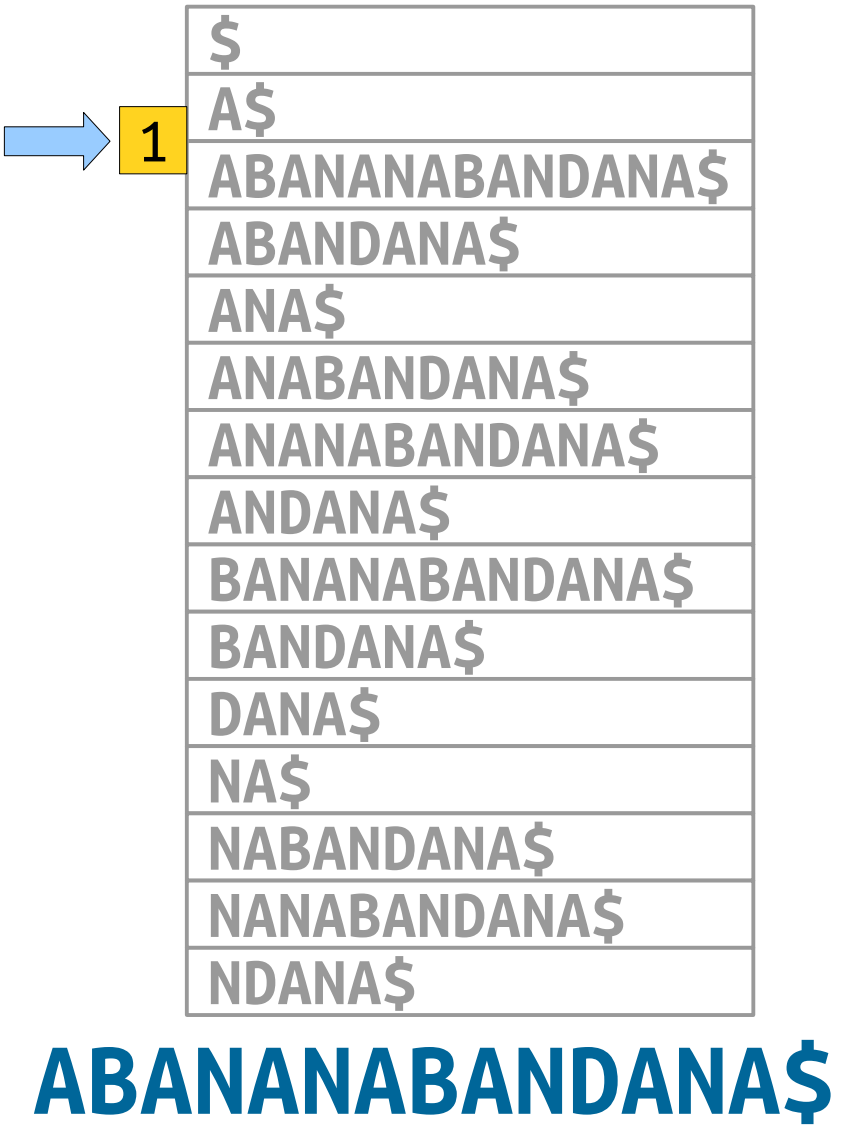

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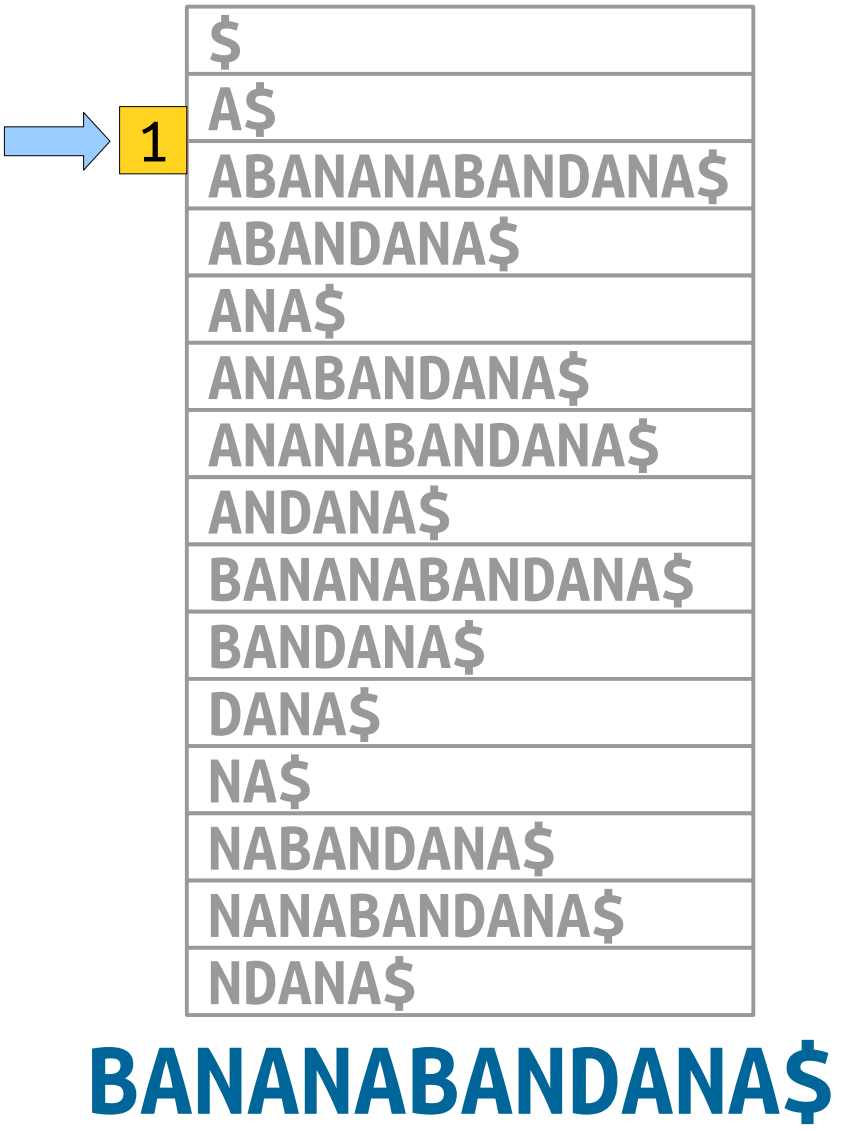

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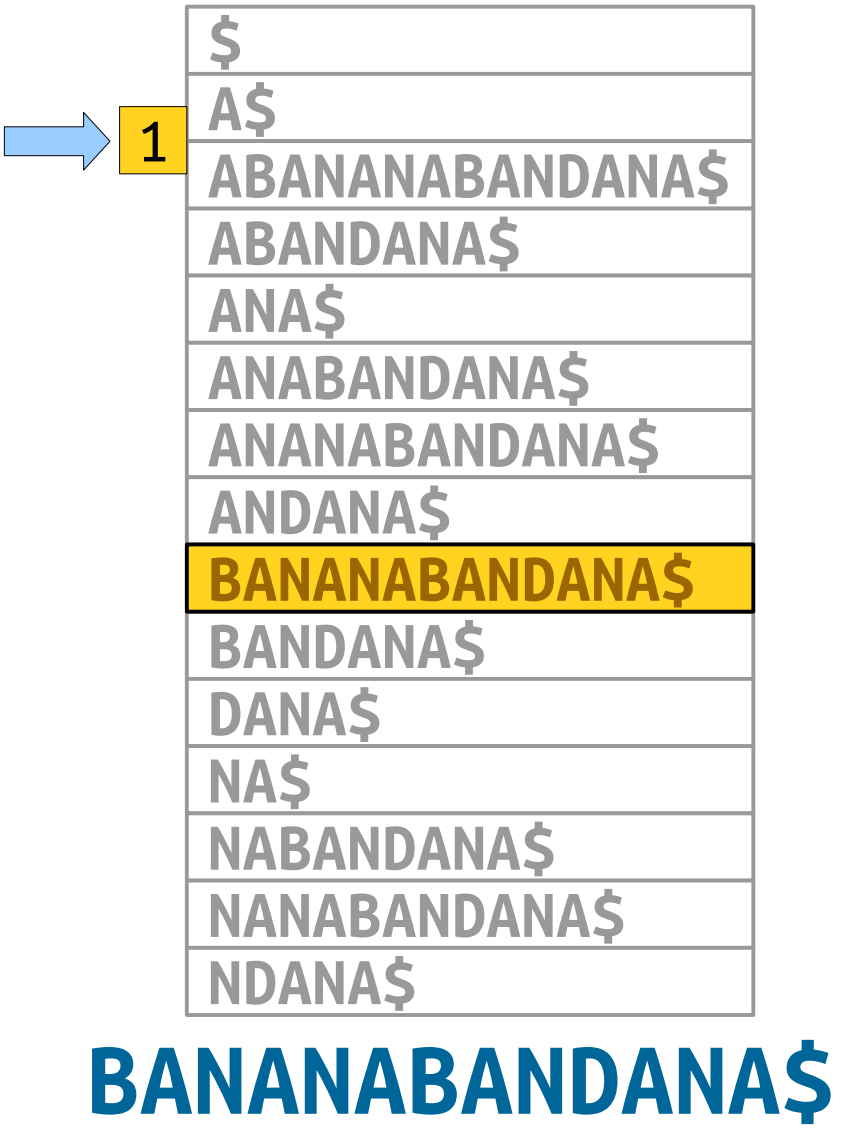

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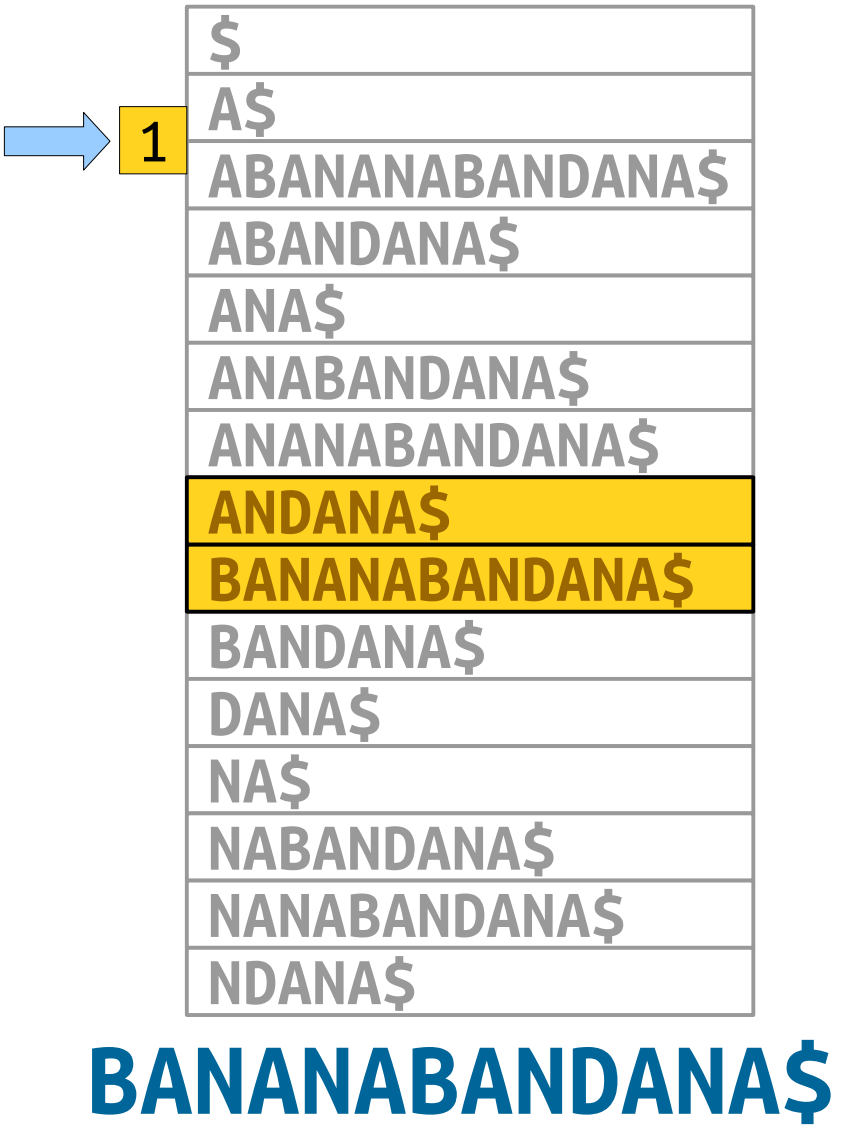

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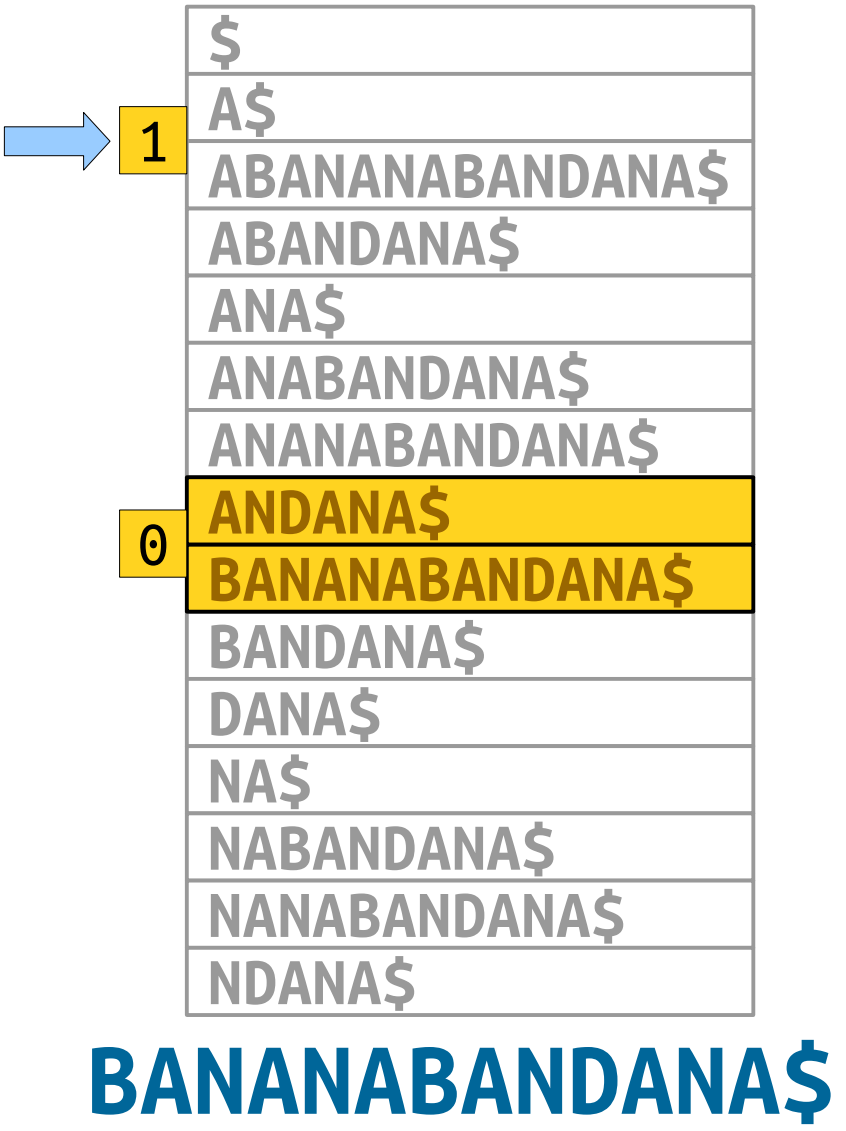

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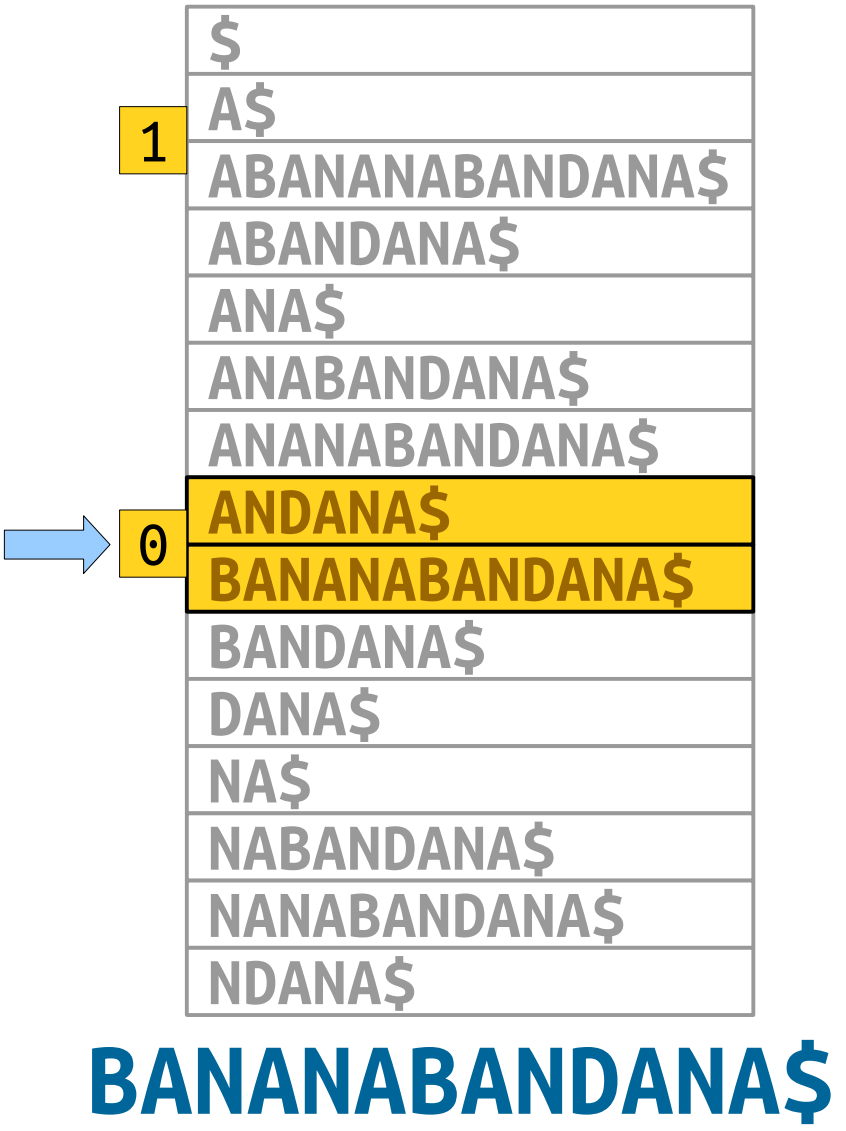

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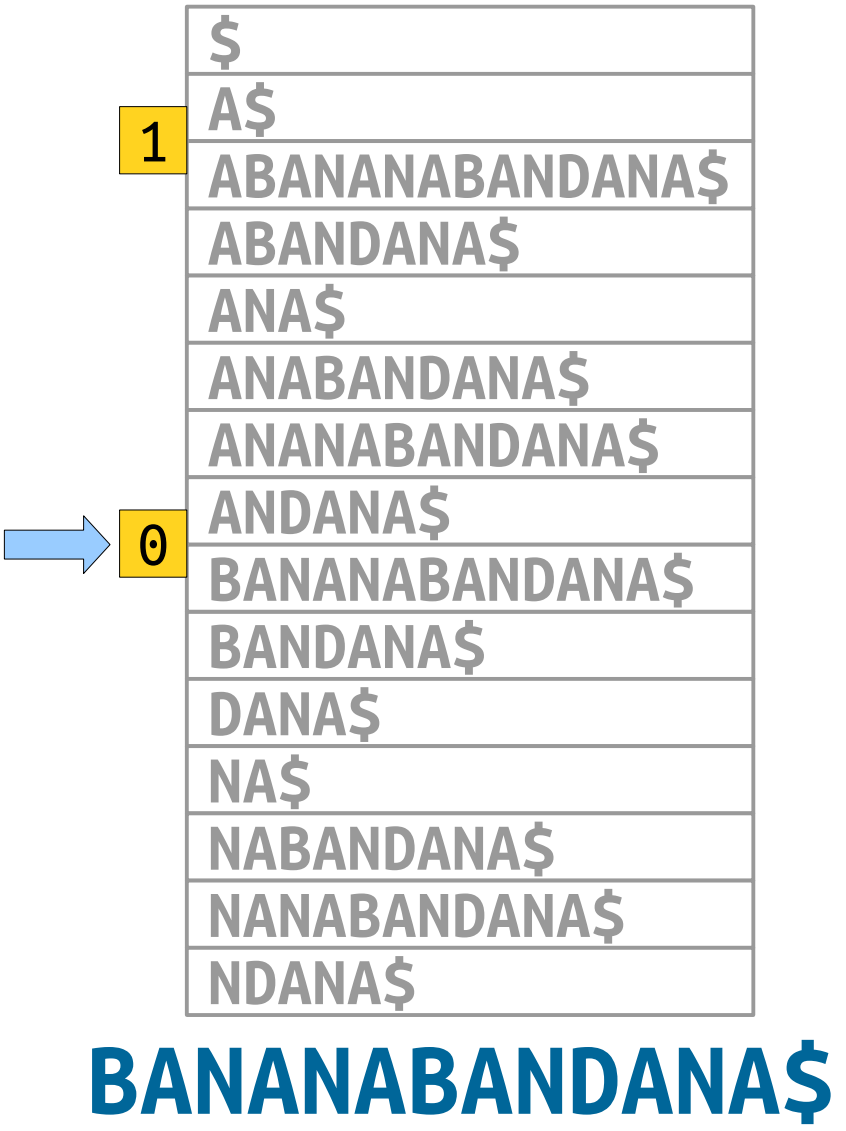

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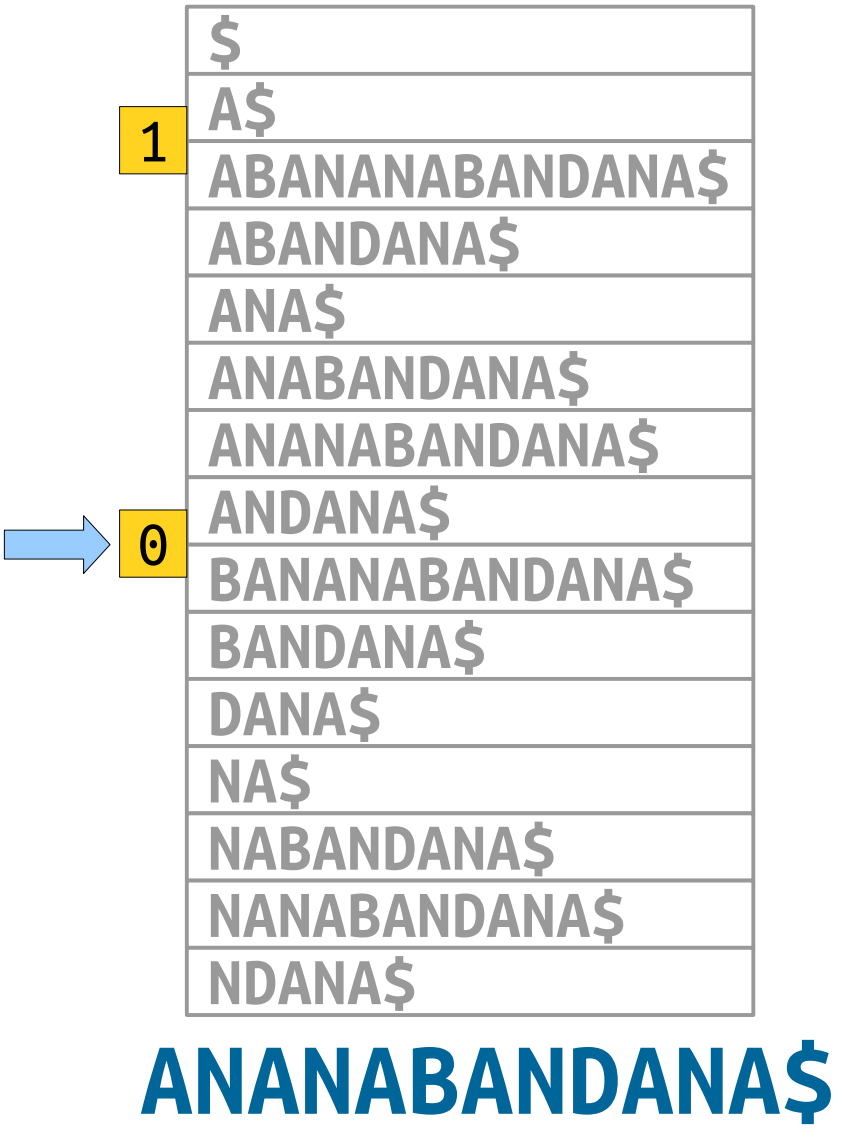

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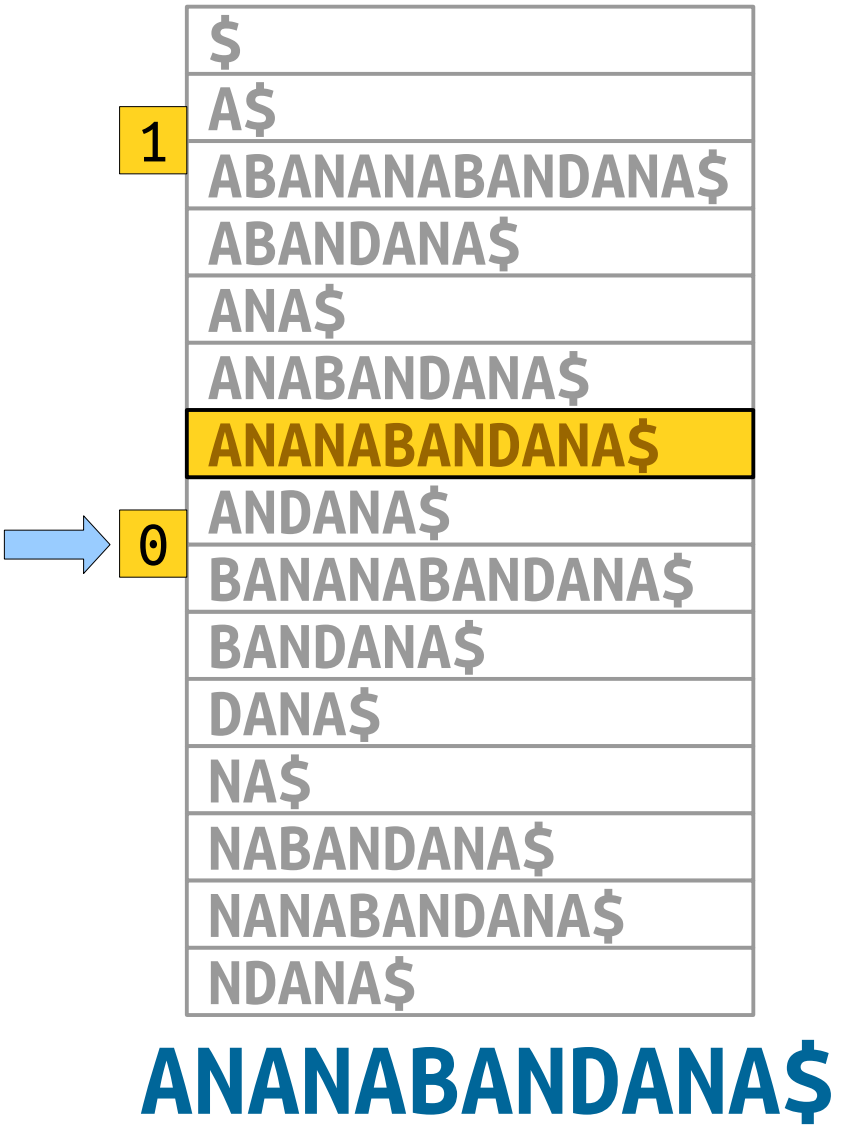

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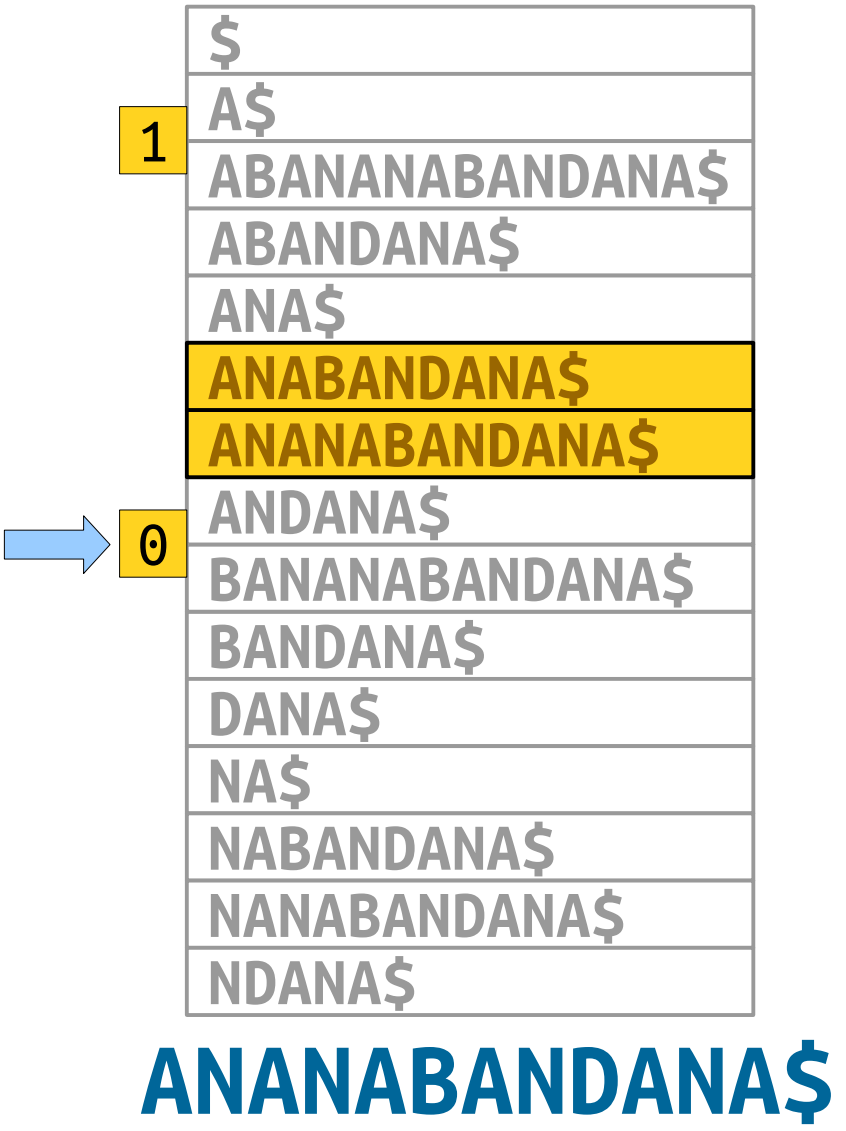

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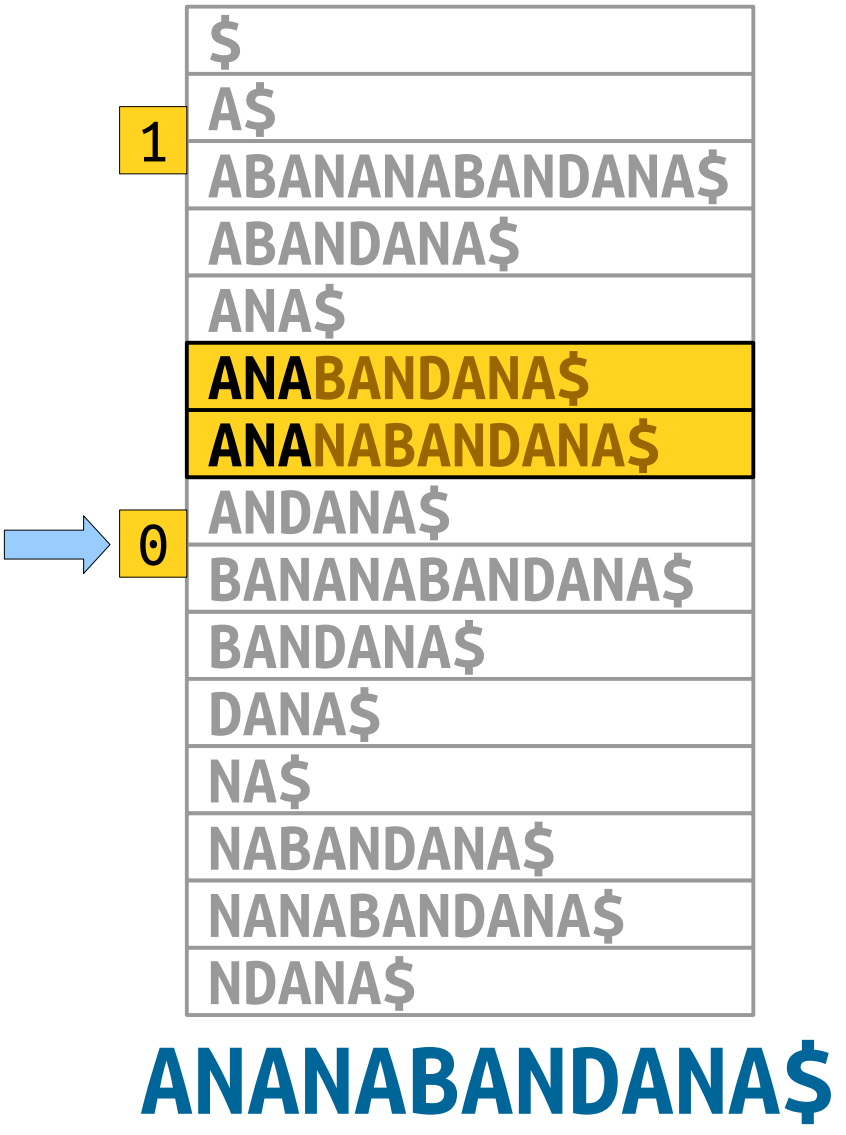

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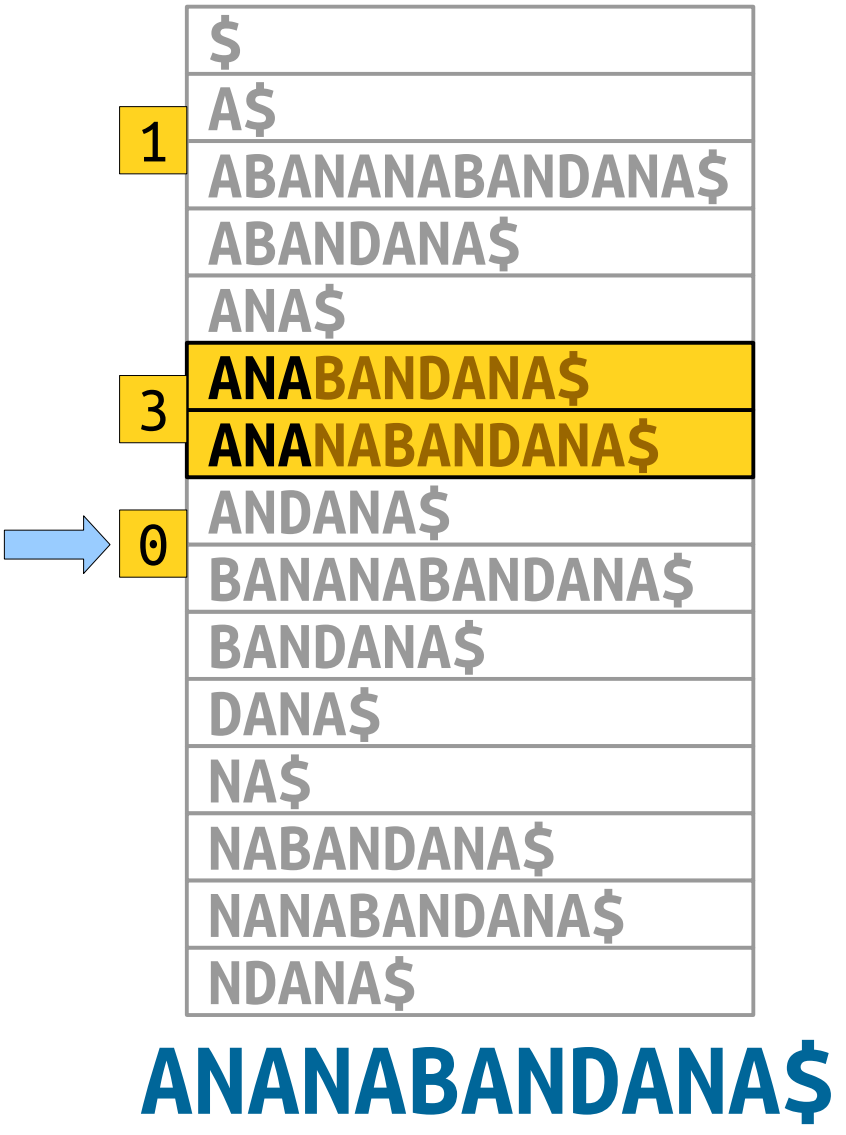

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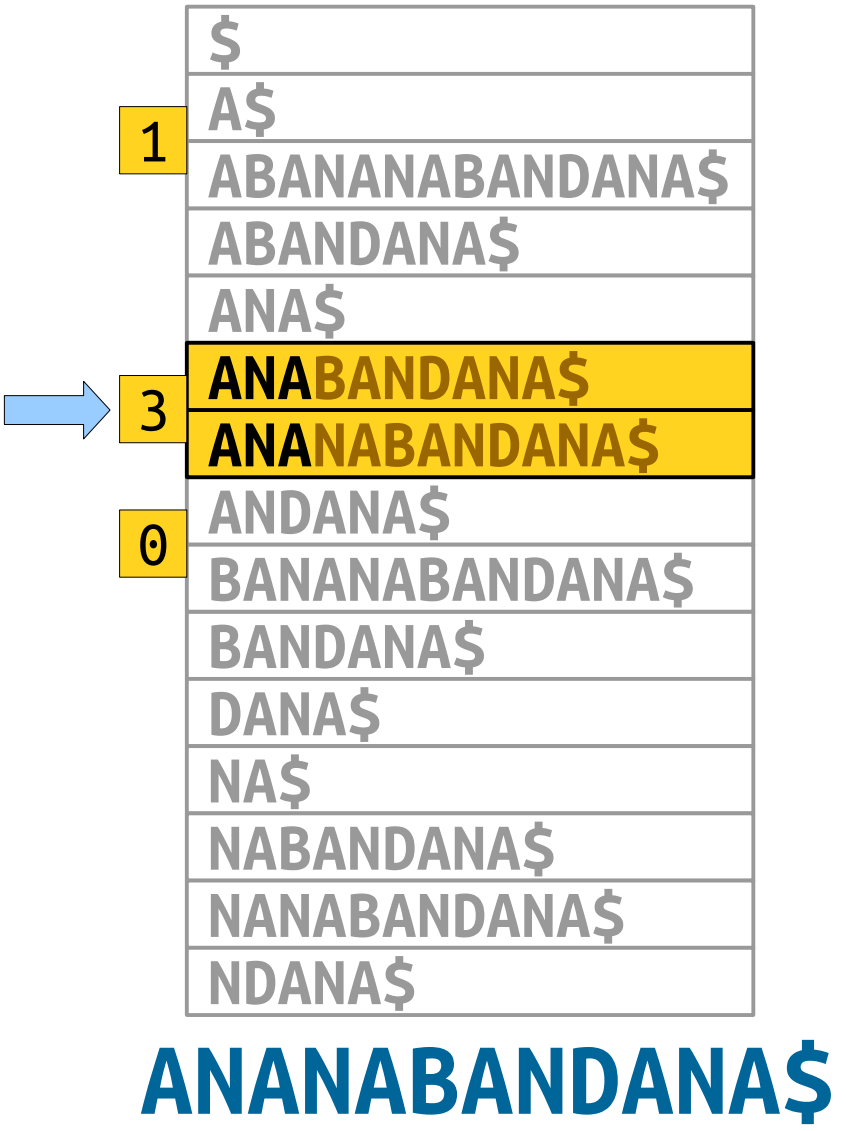

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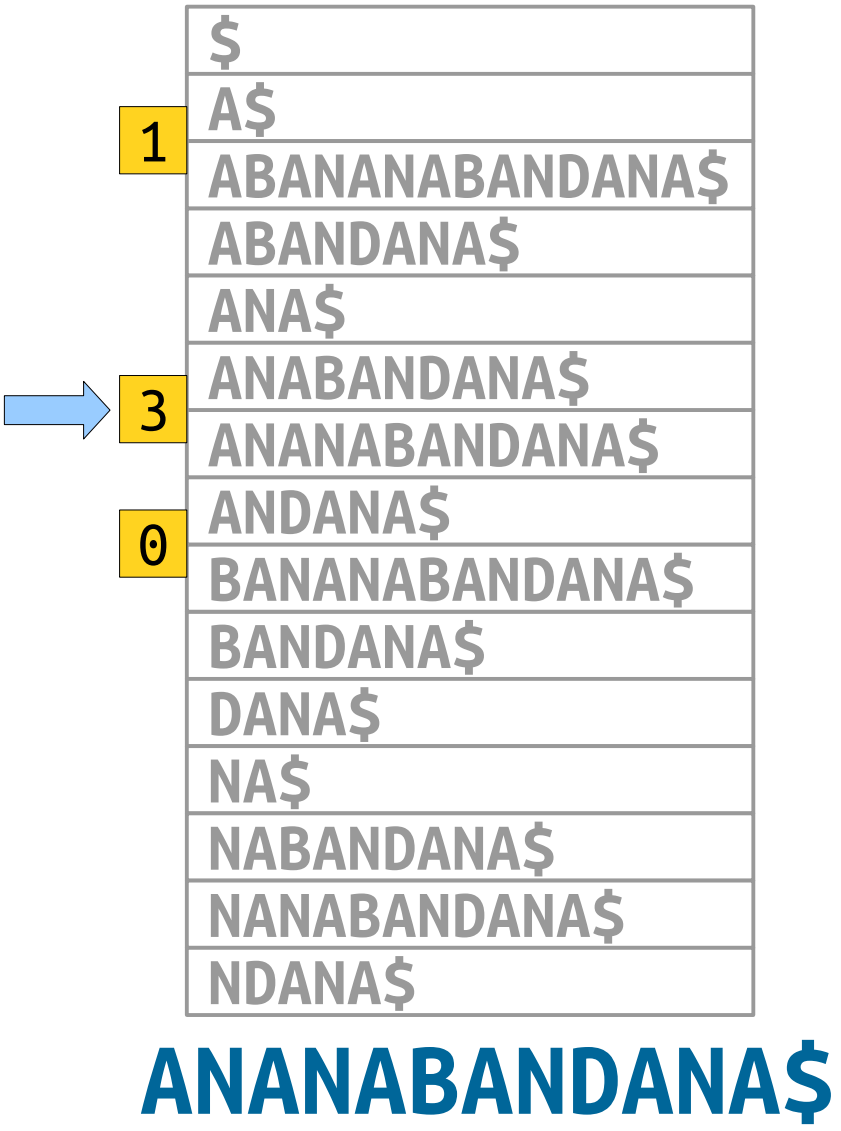

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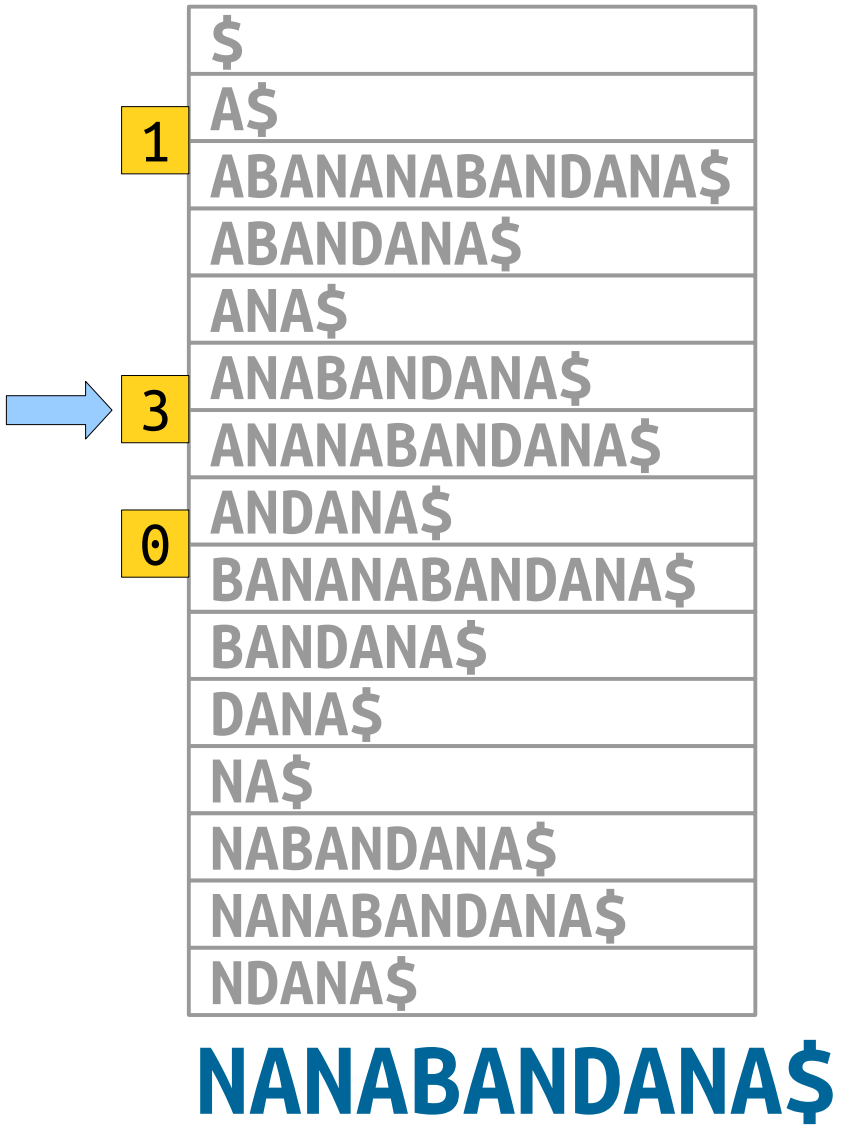

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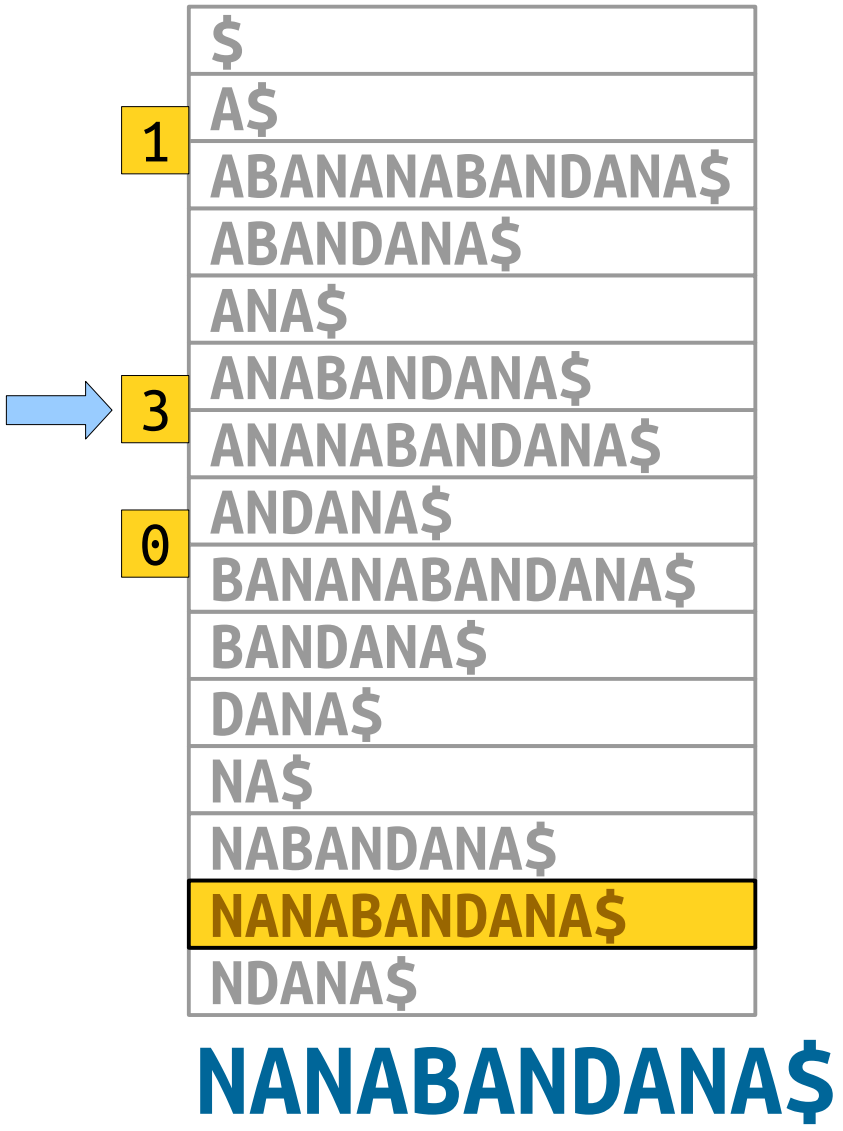

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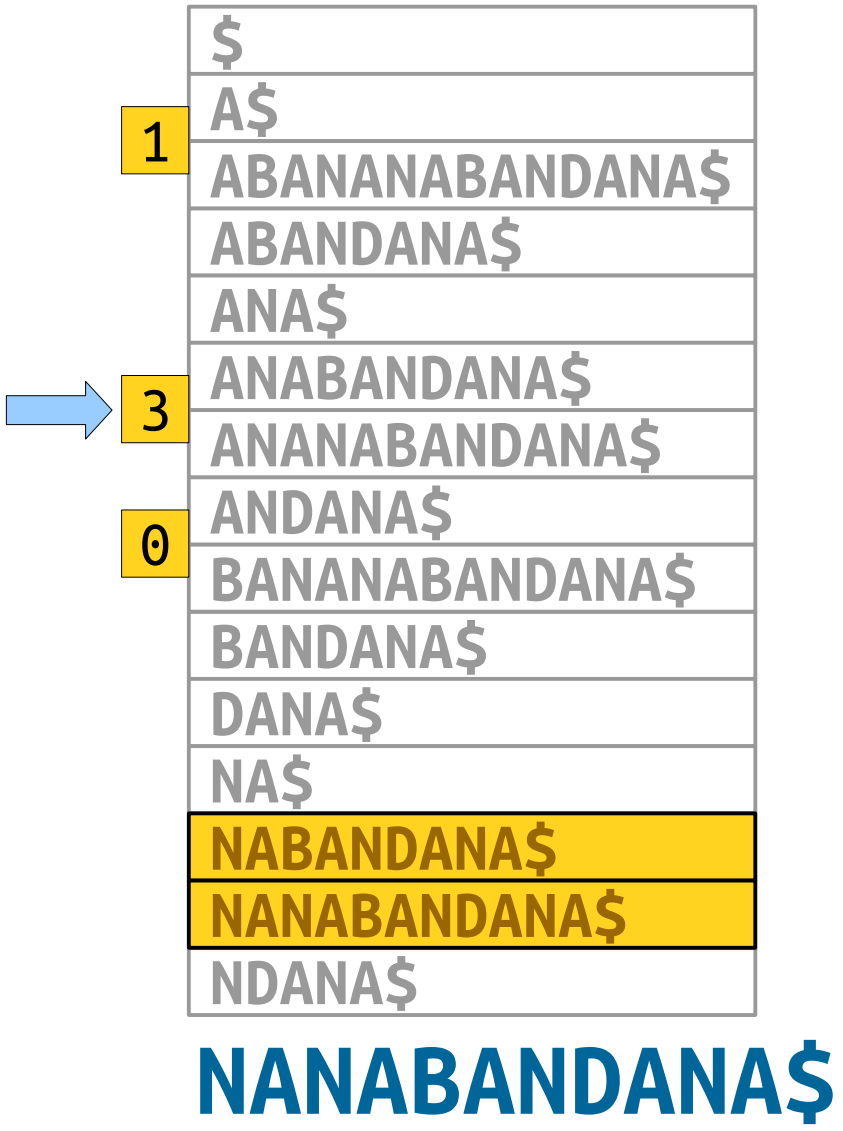

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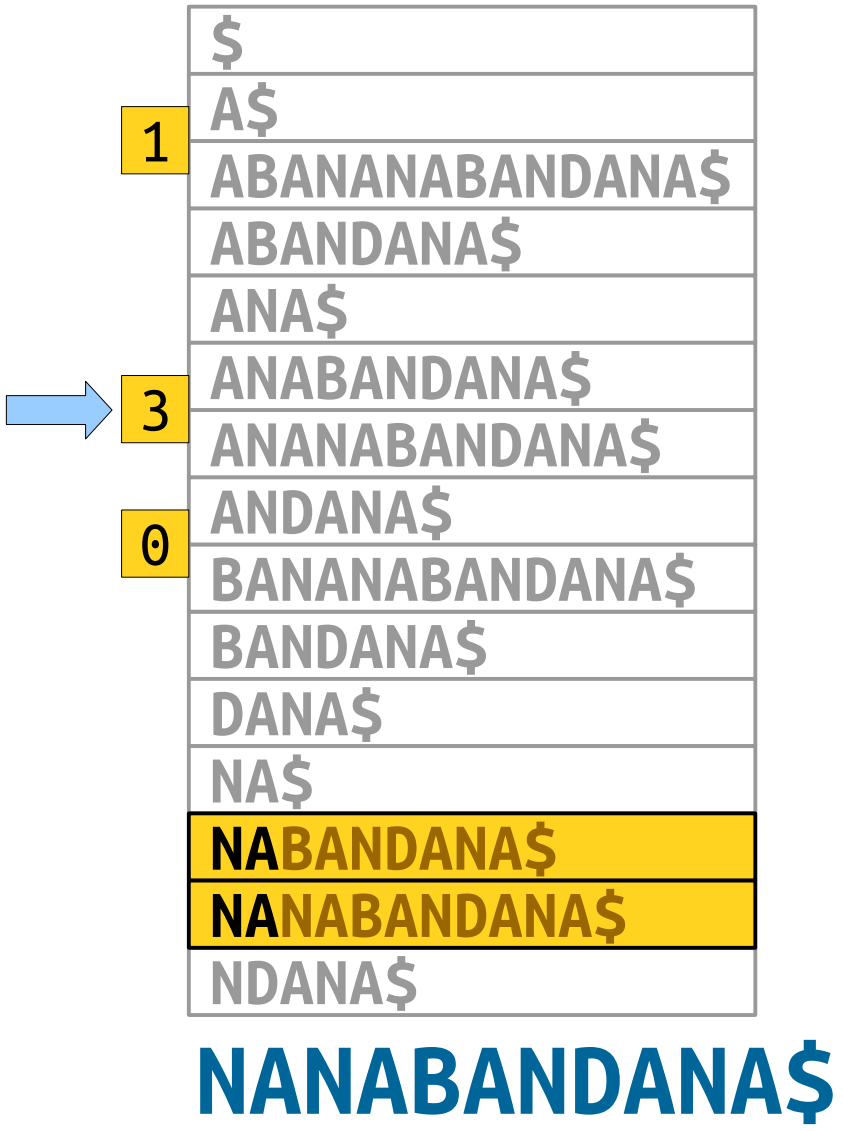

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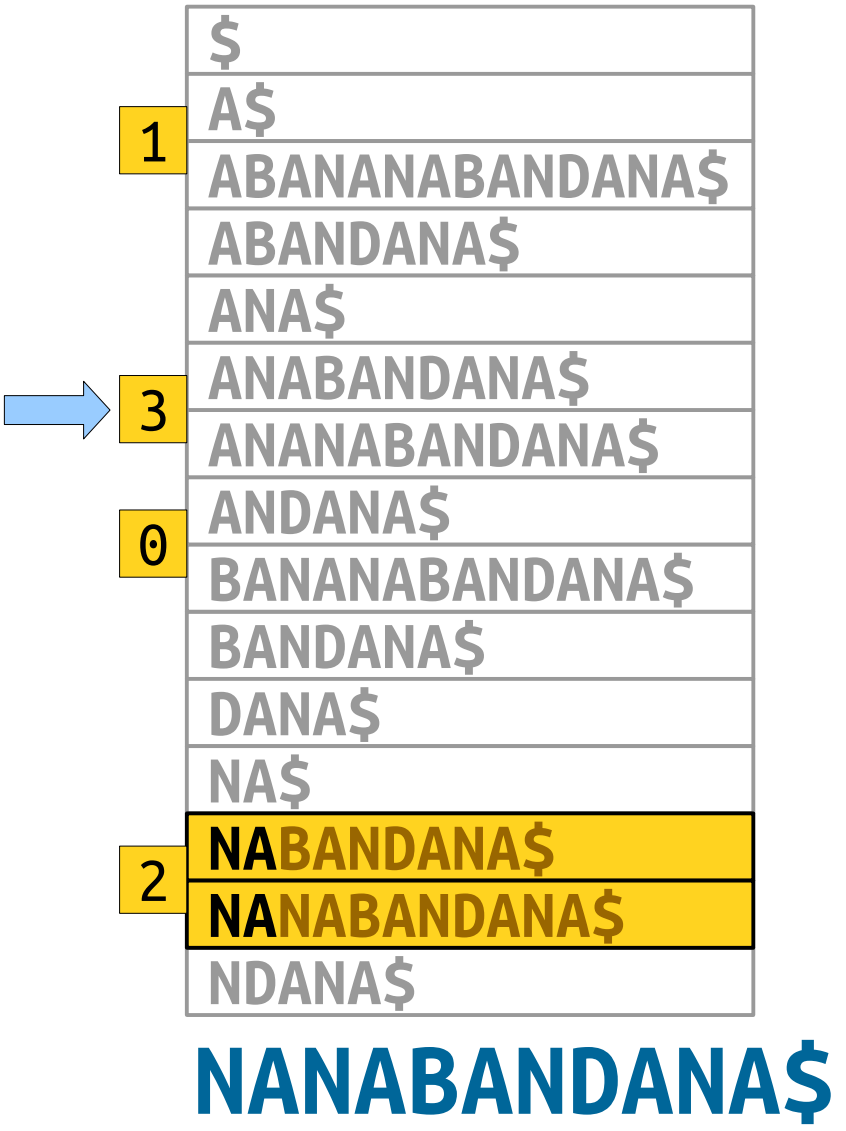

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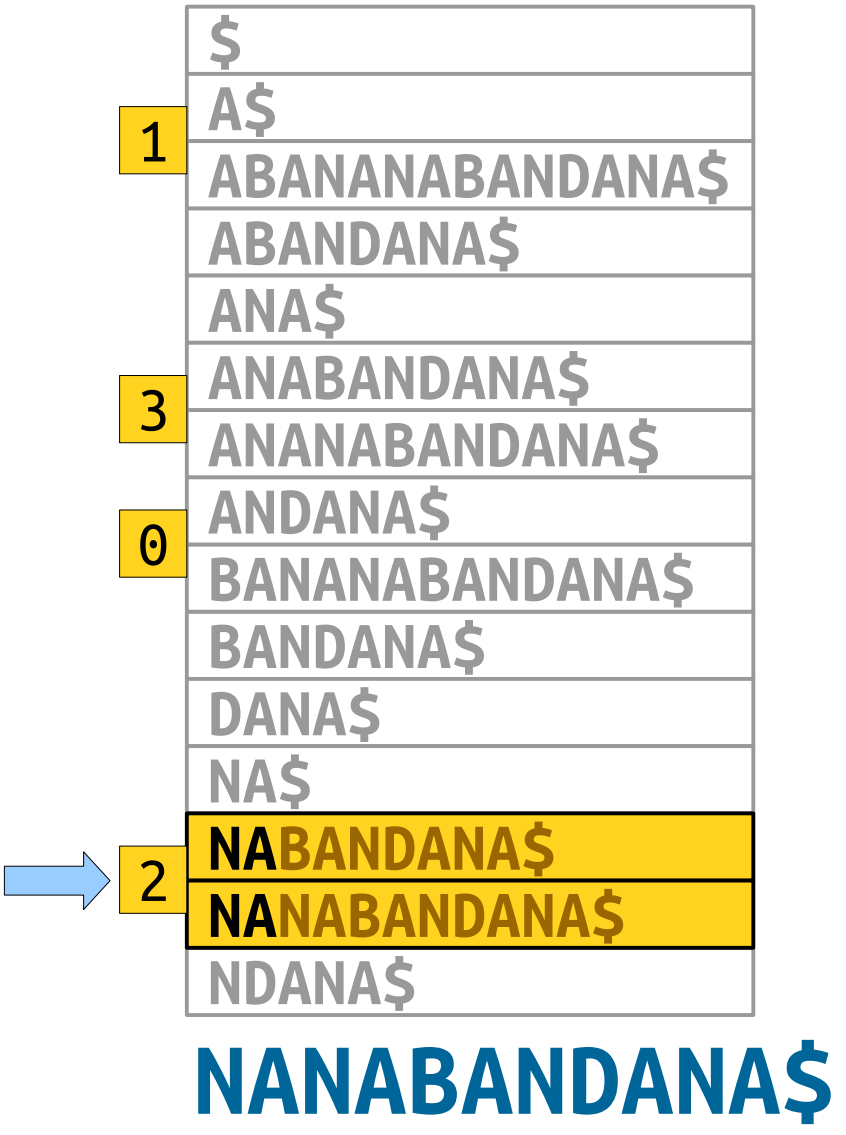

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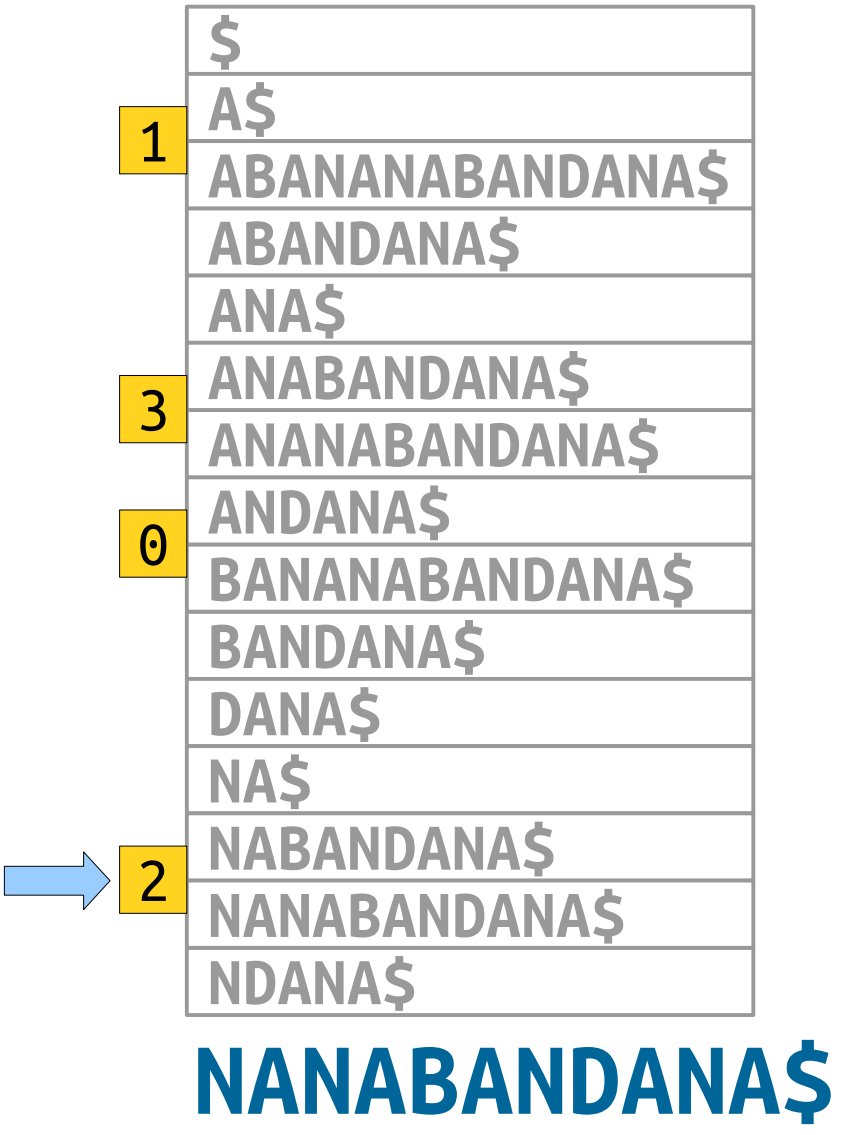

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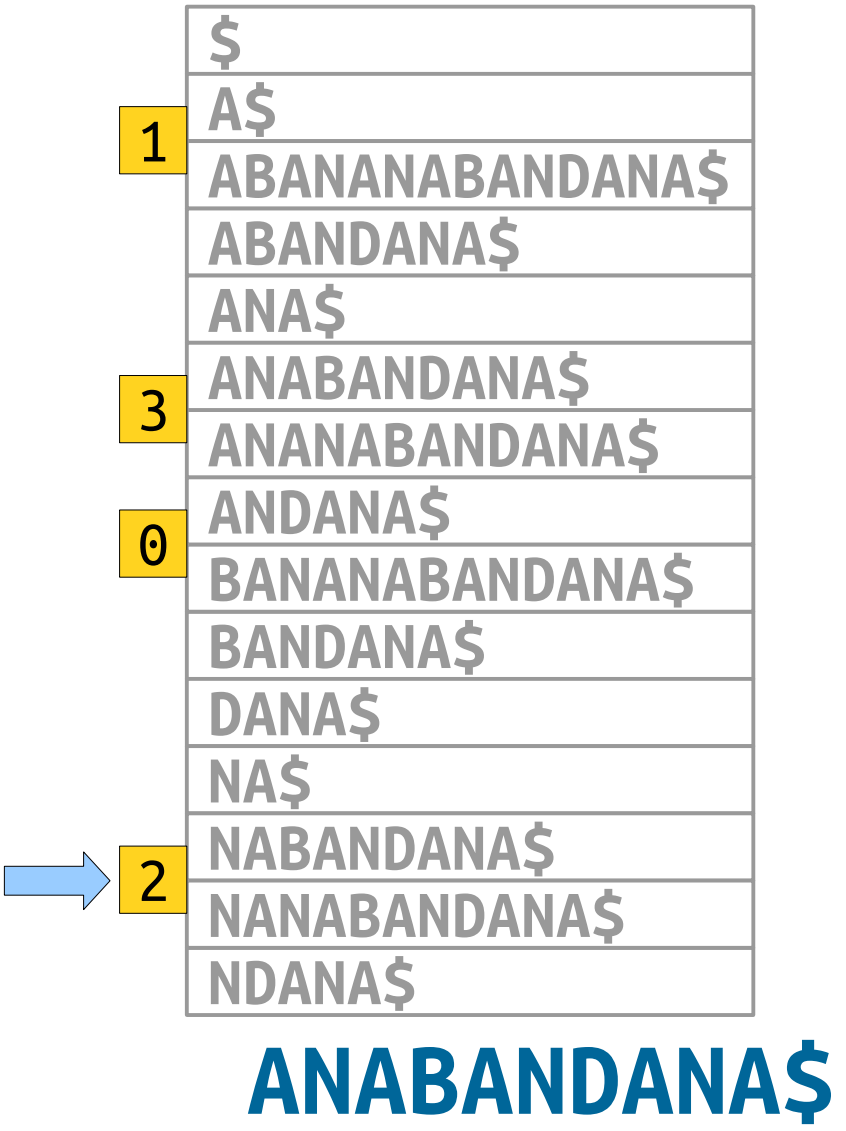

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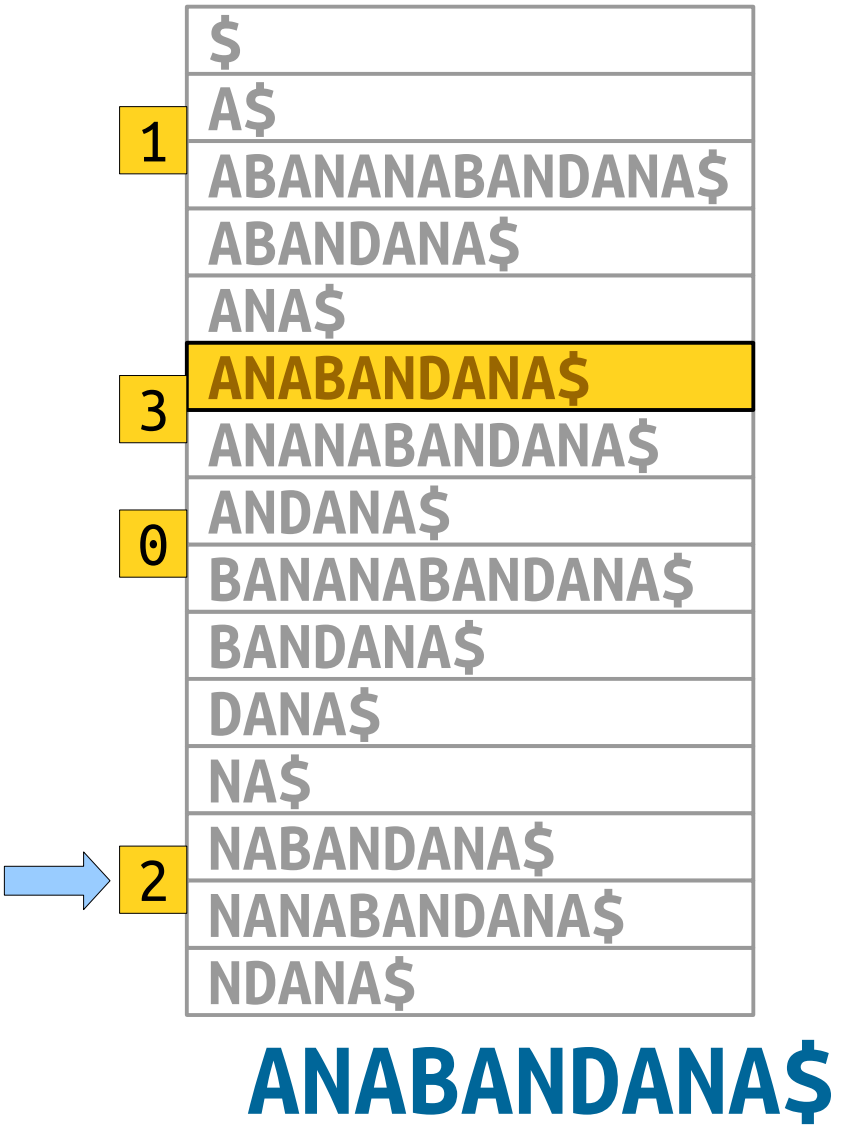

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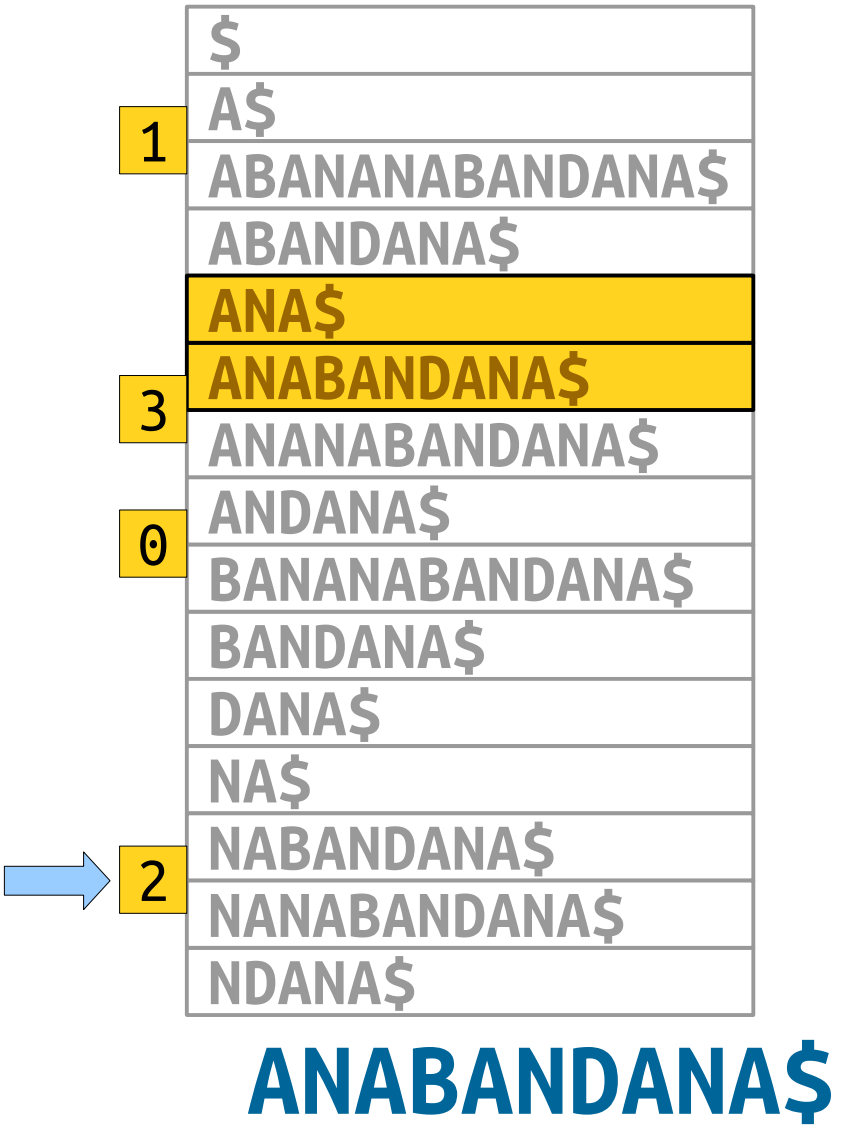

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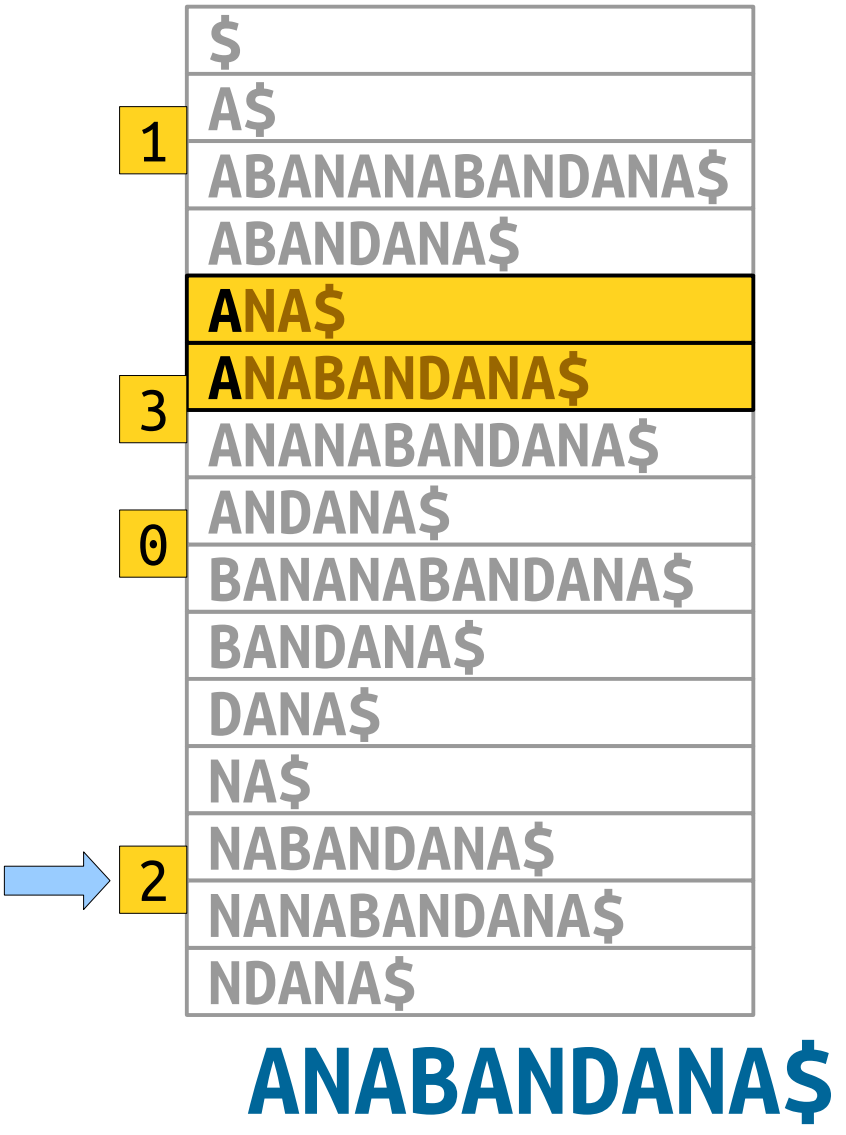

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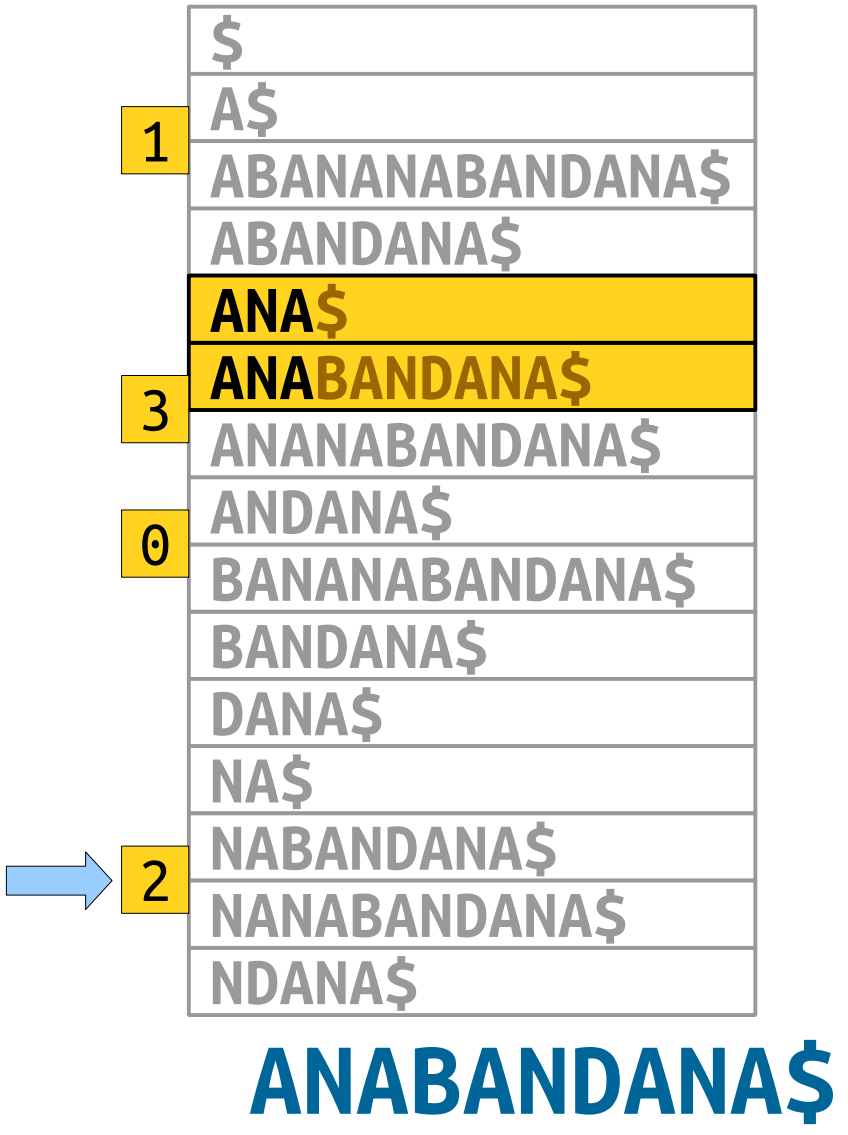

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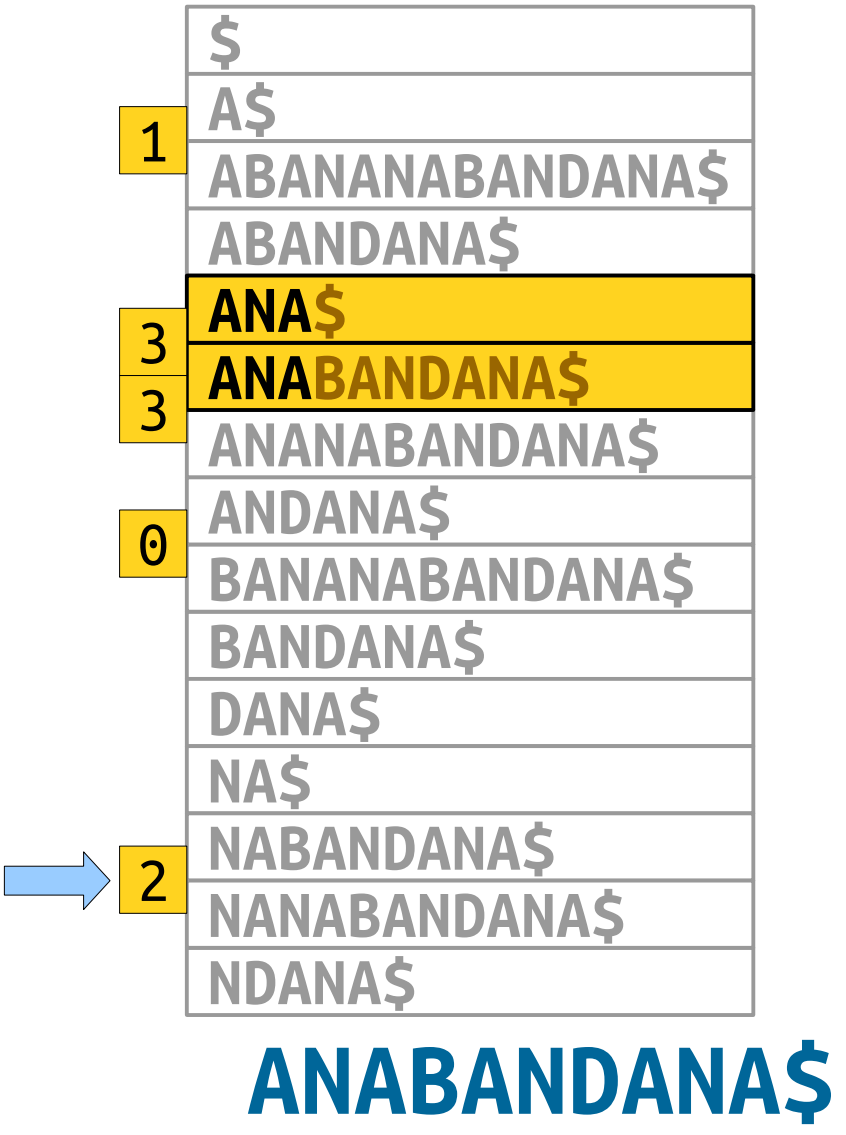

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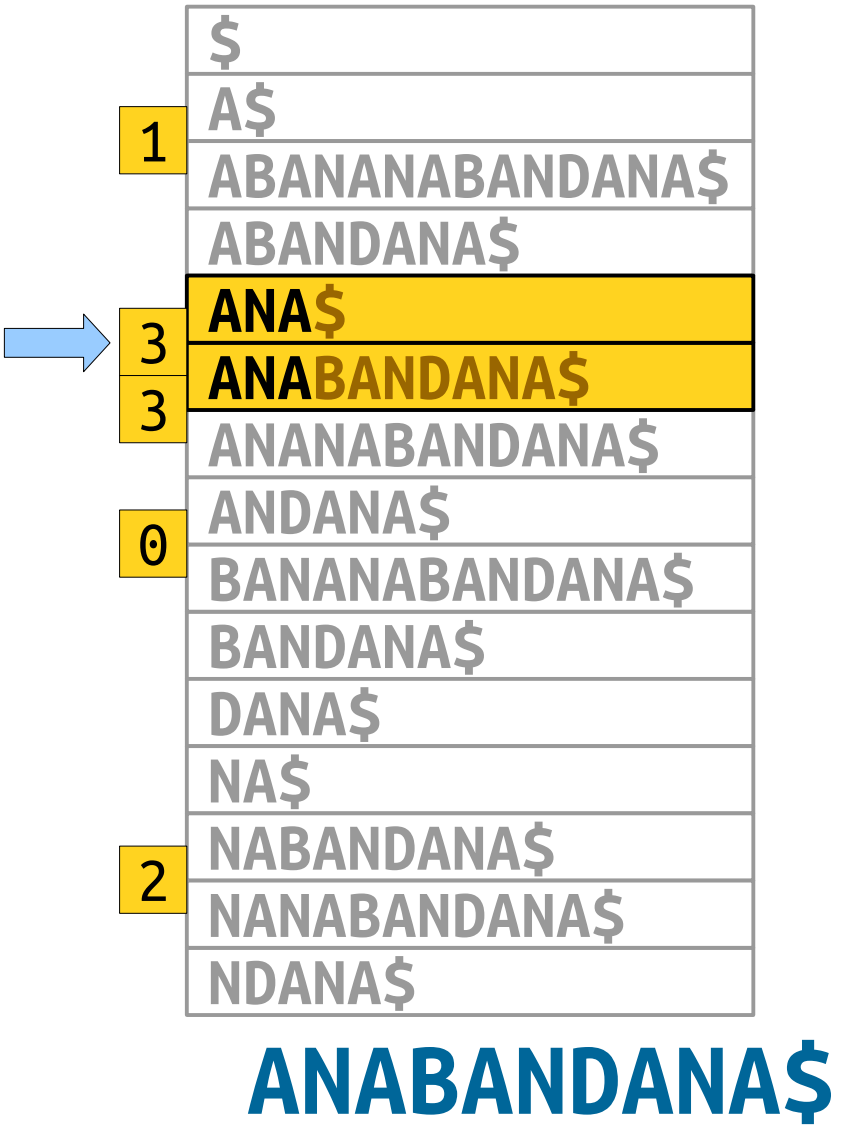

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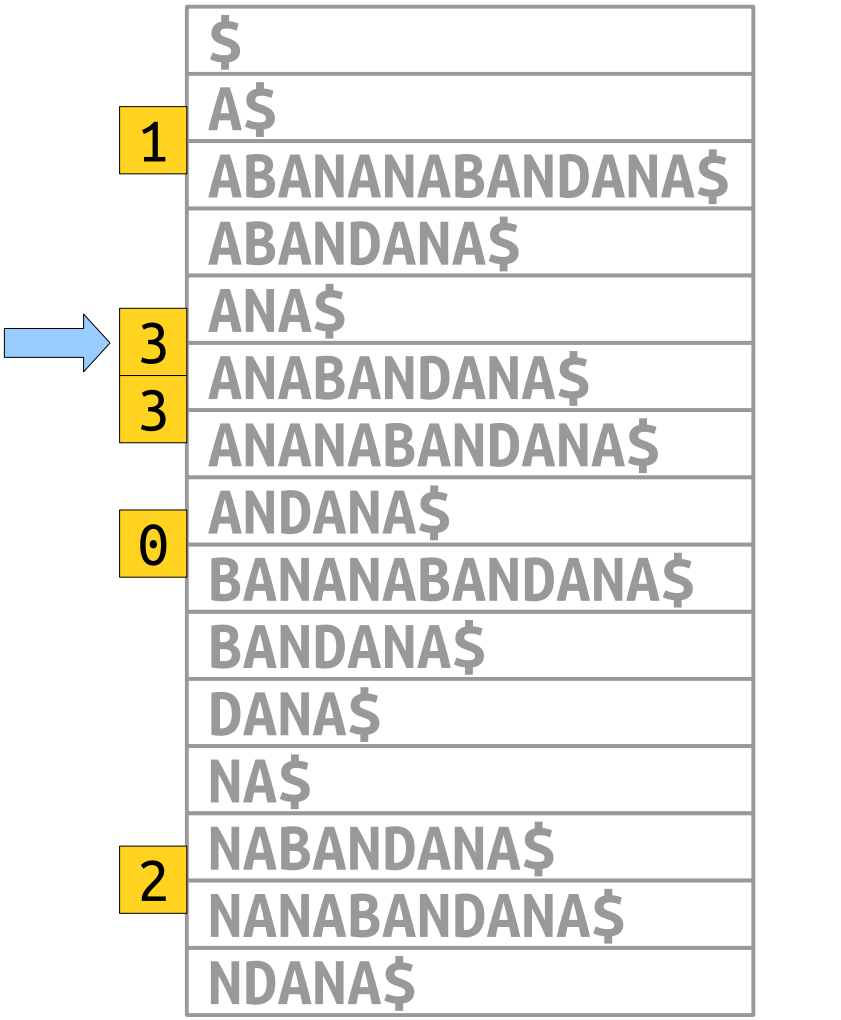

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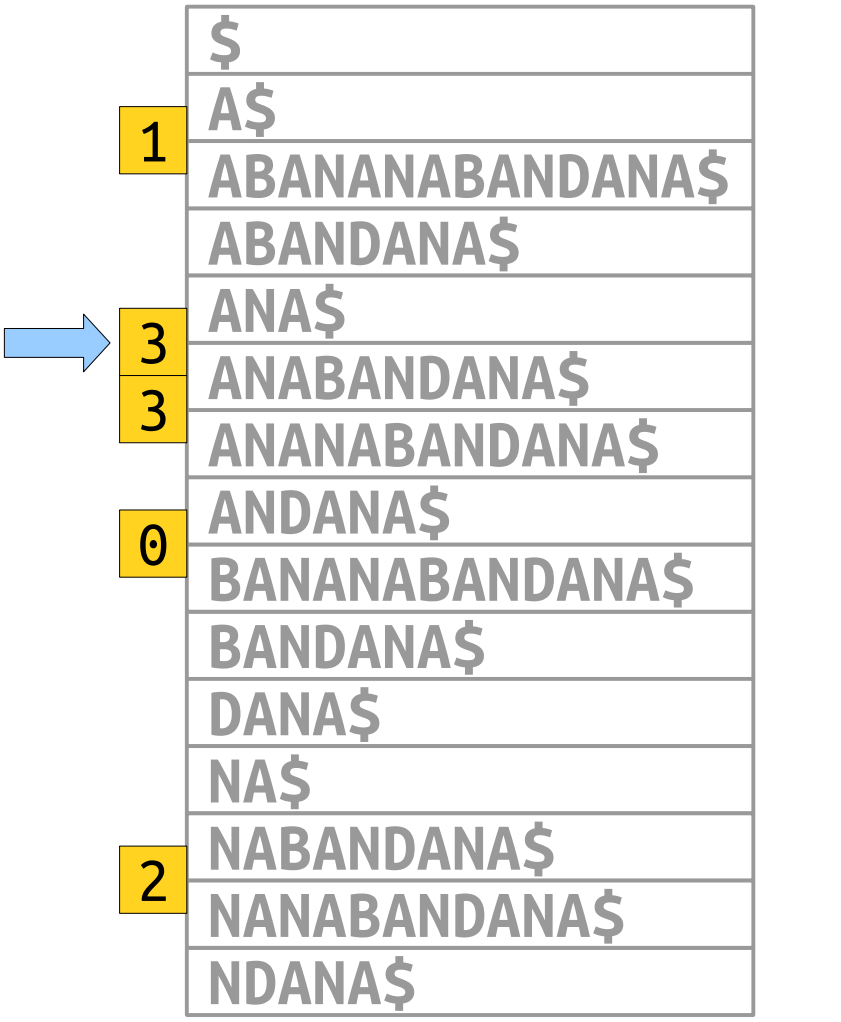

NABANDANA$

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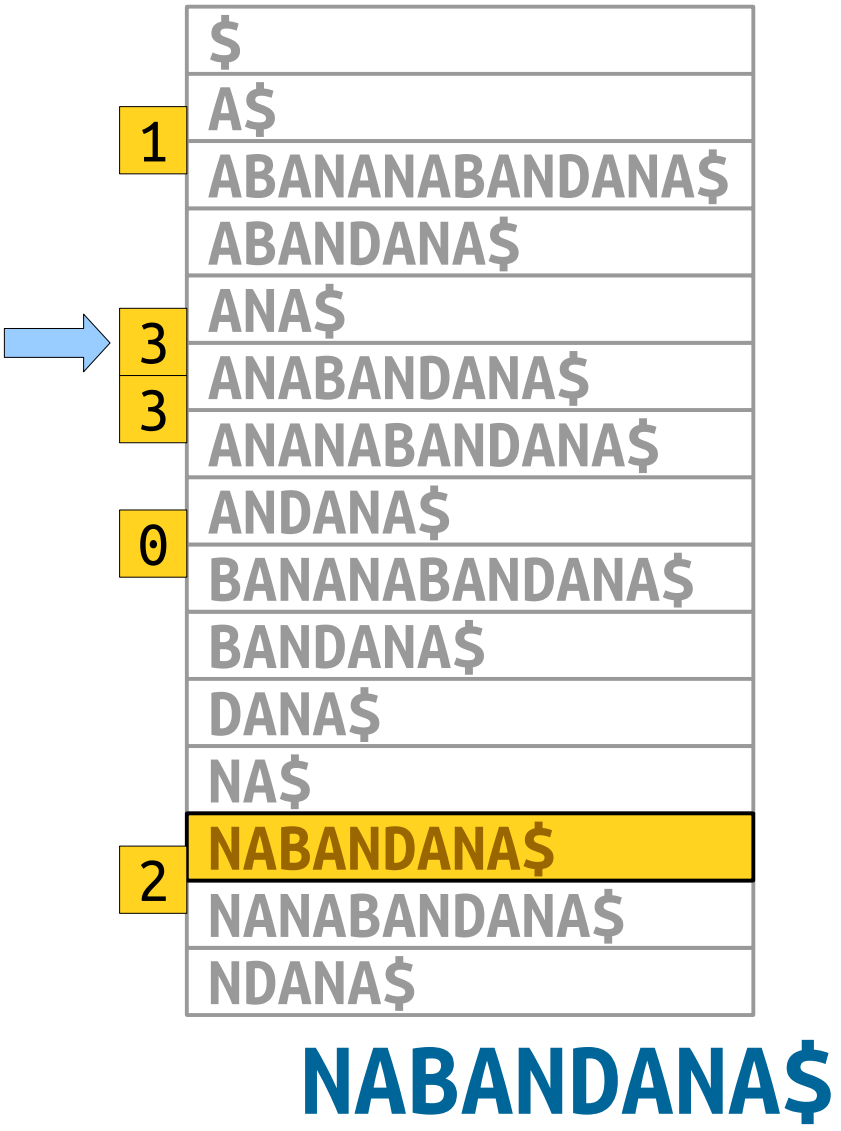

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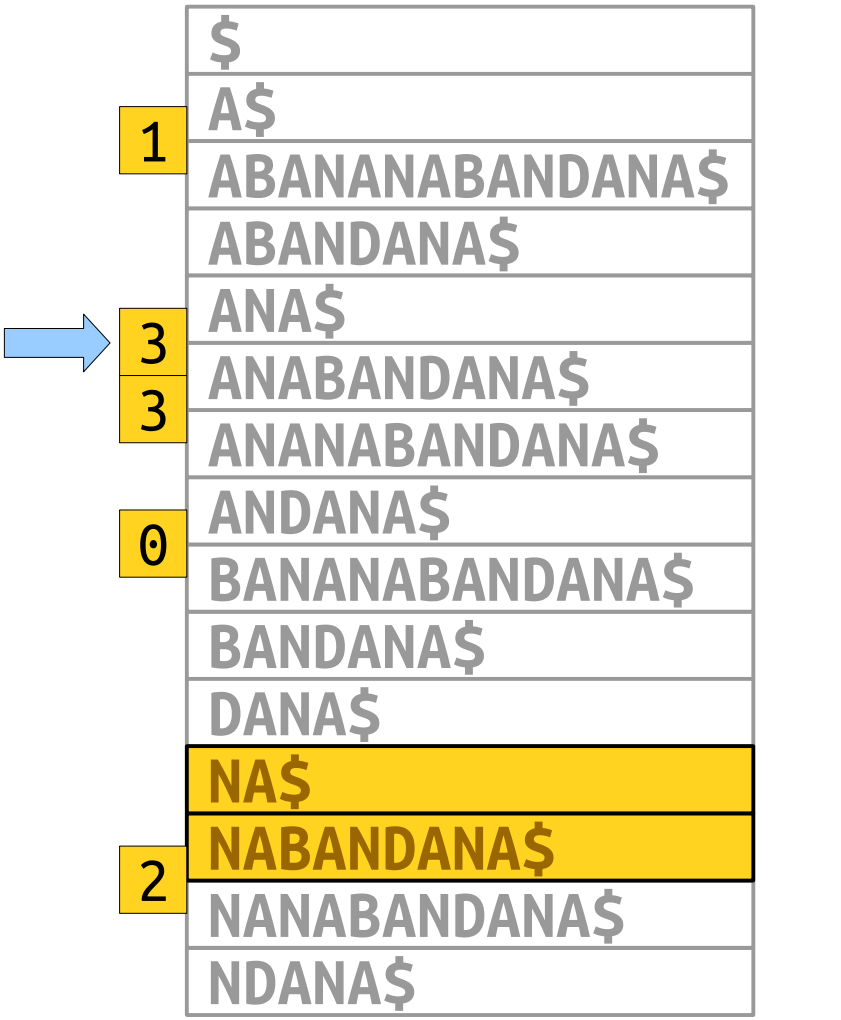

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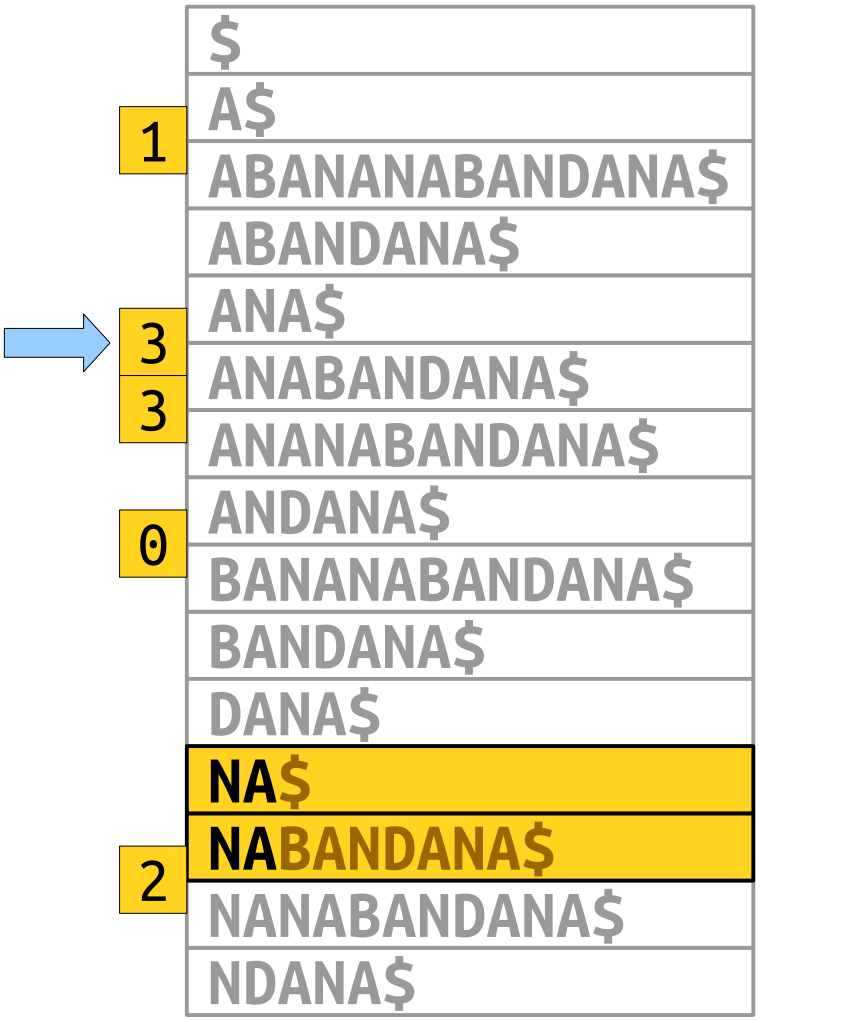

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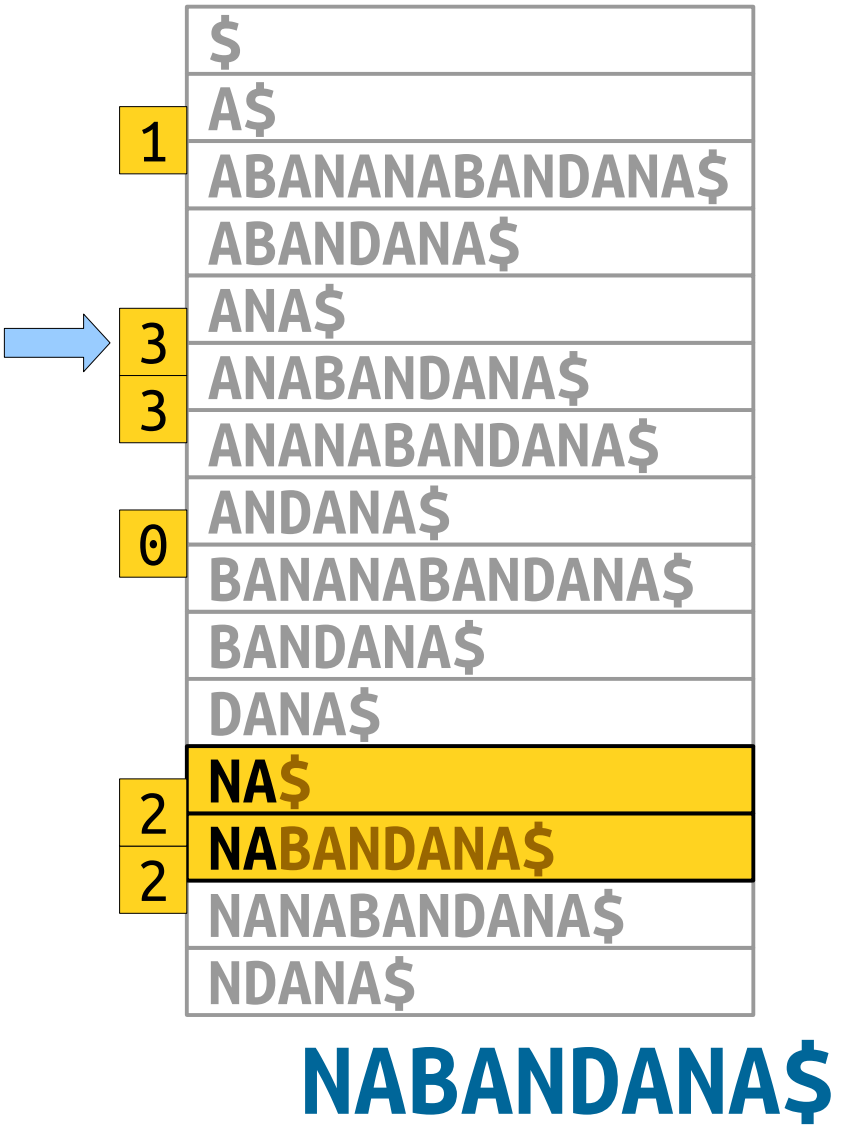

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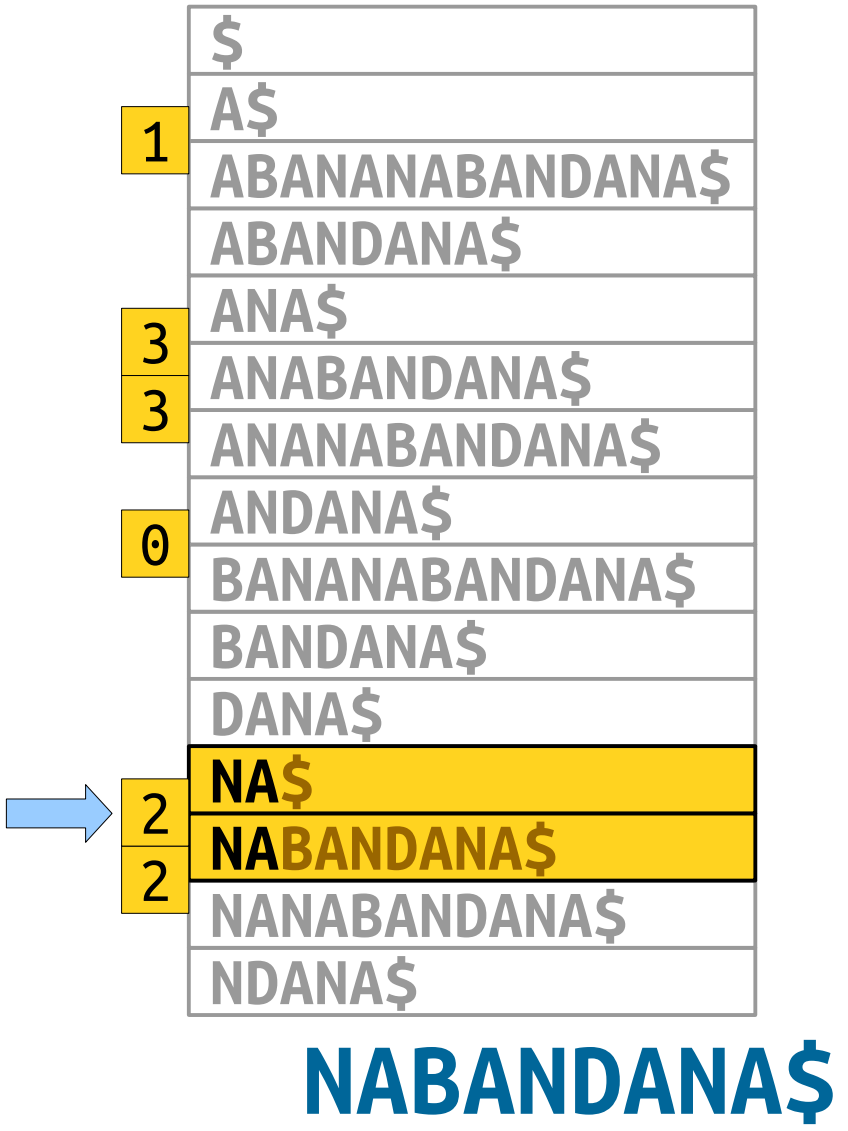

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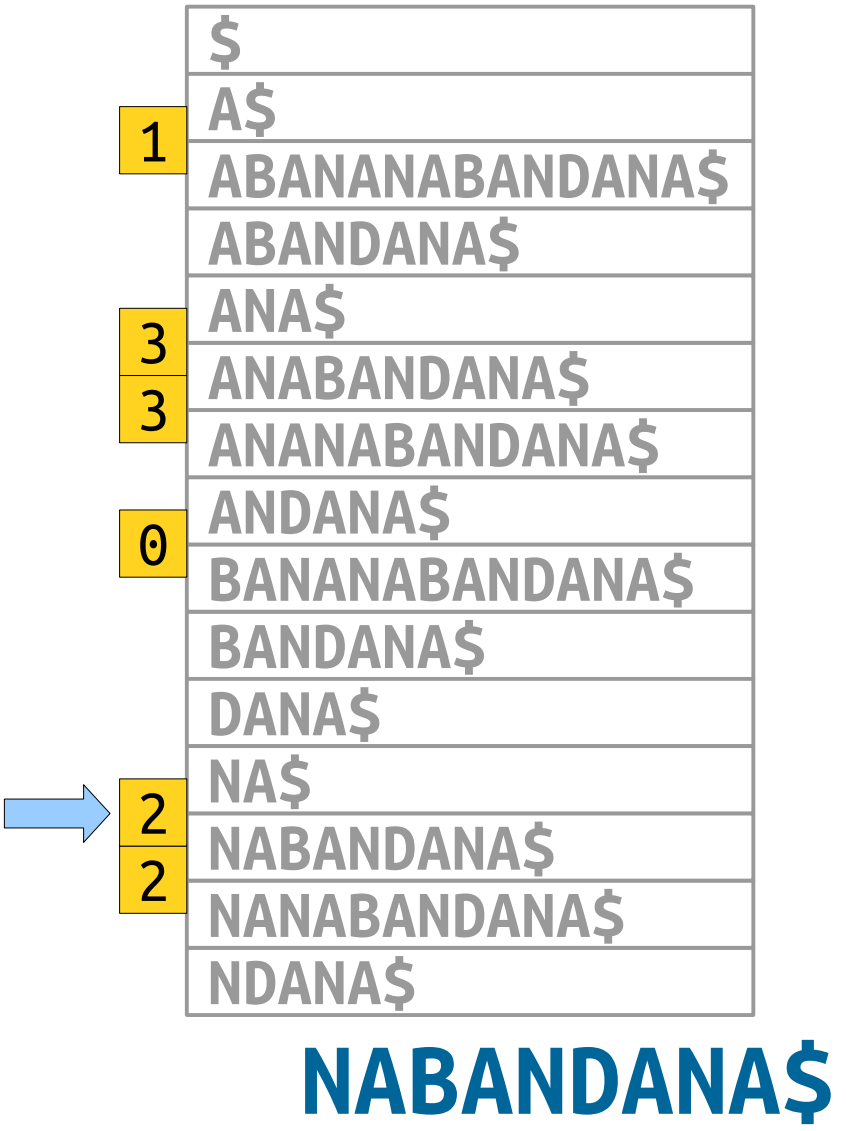

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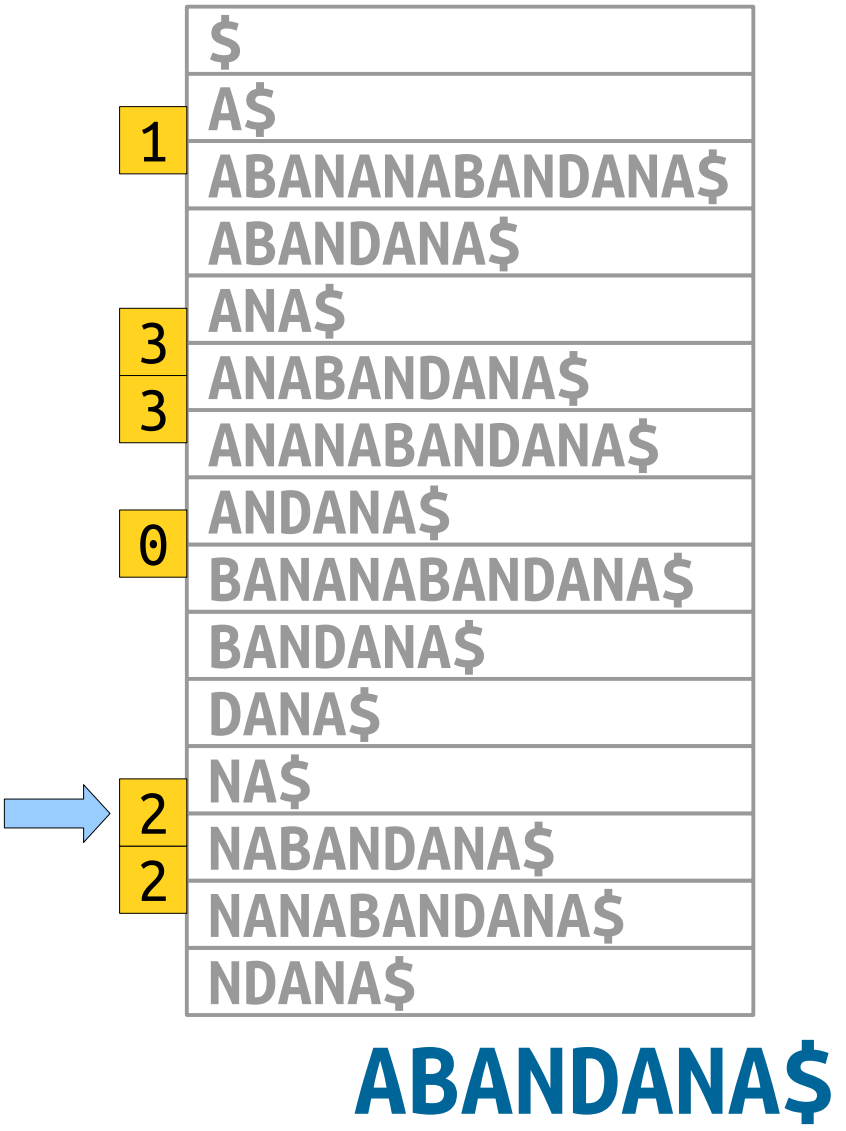

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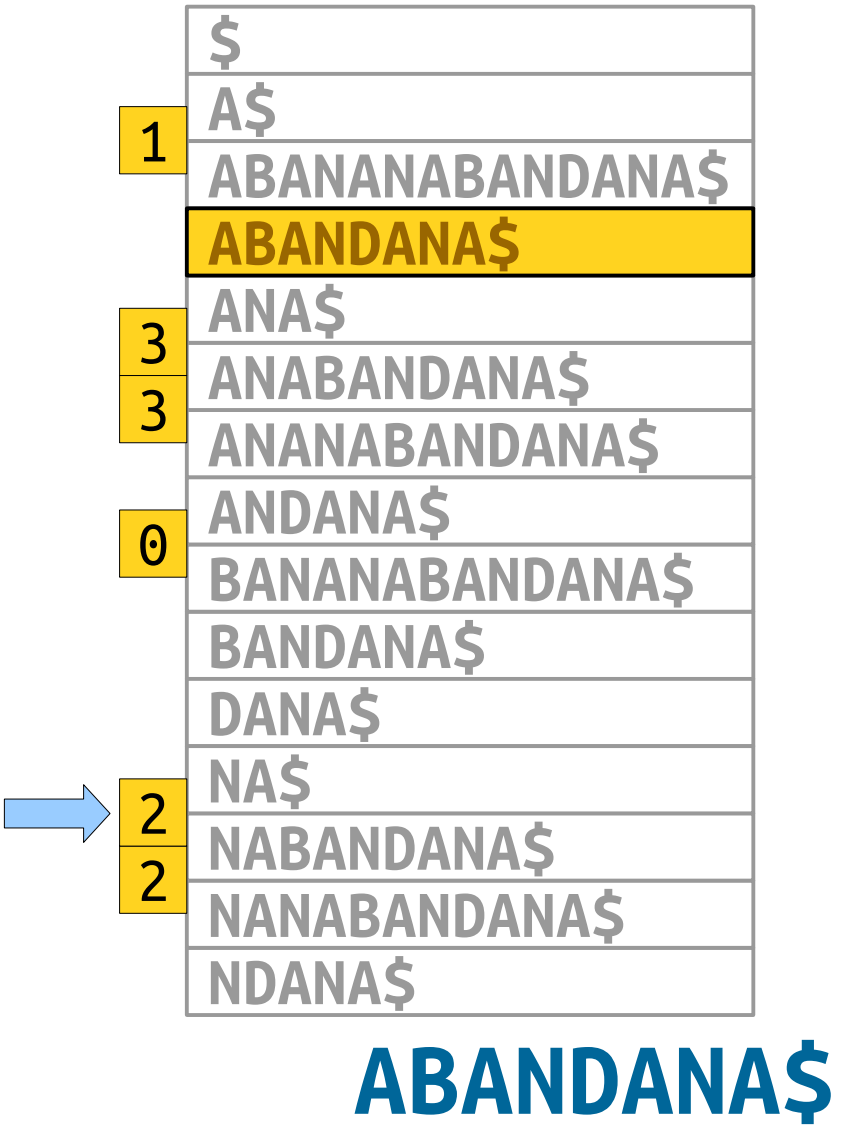

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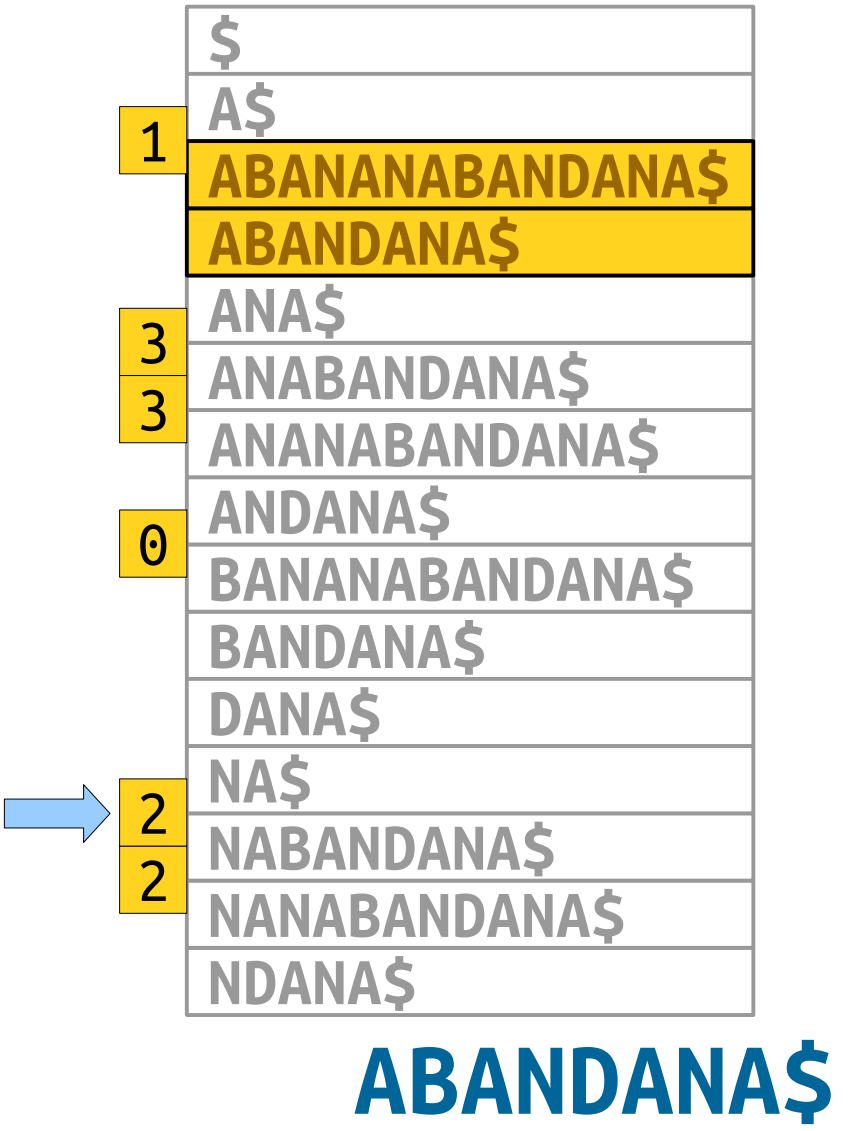

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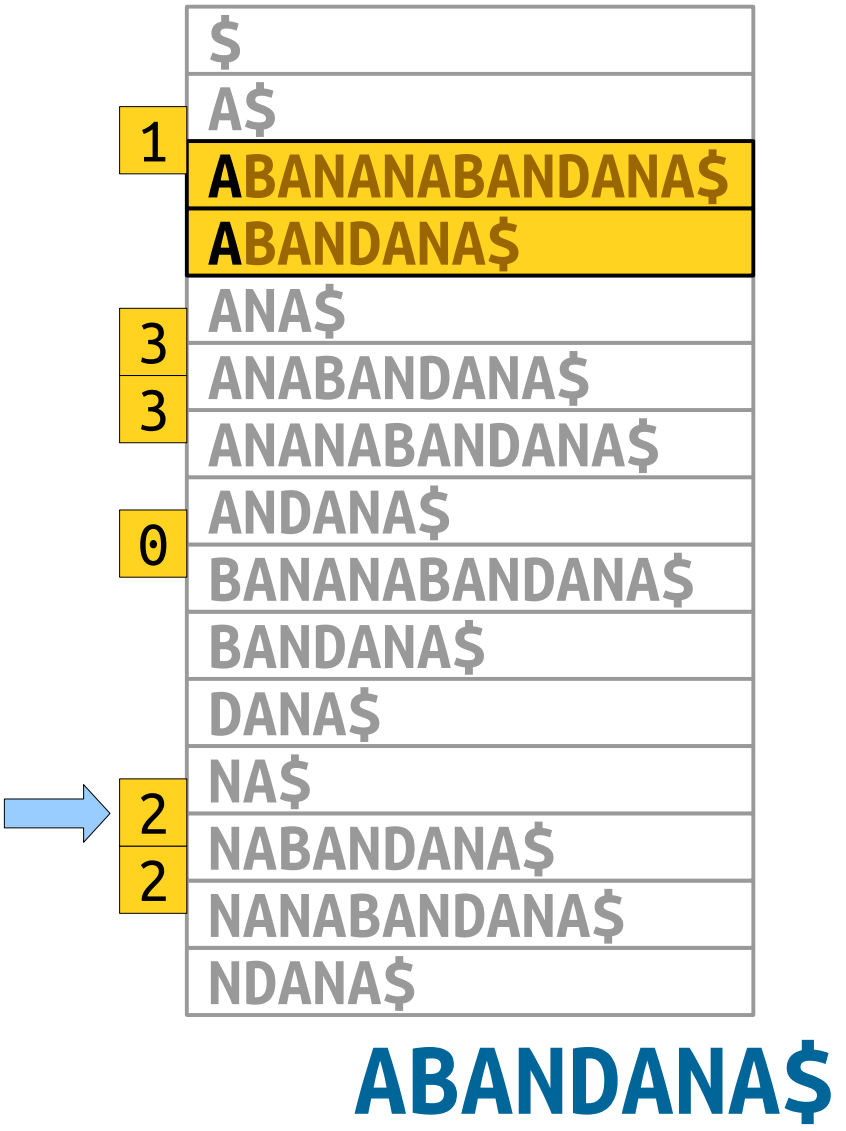

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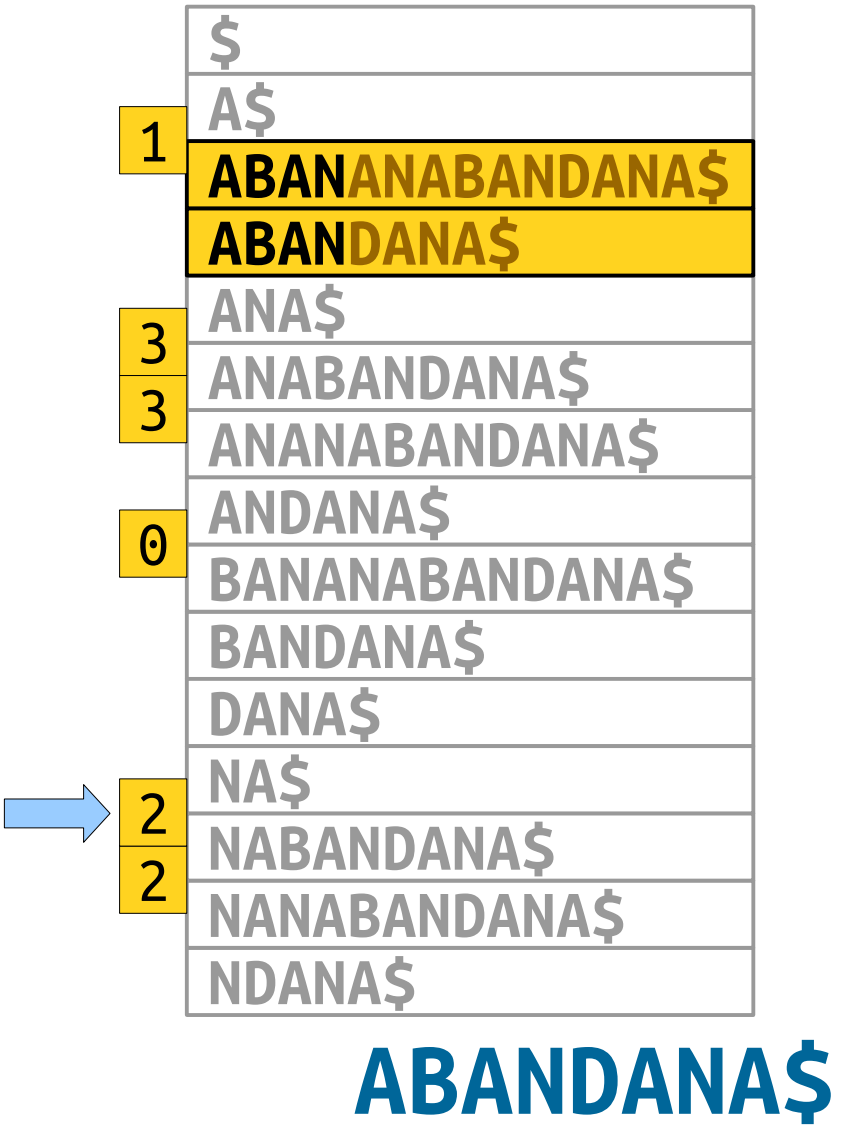

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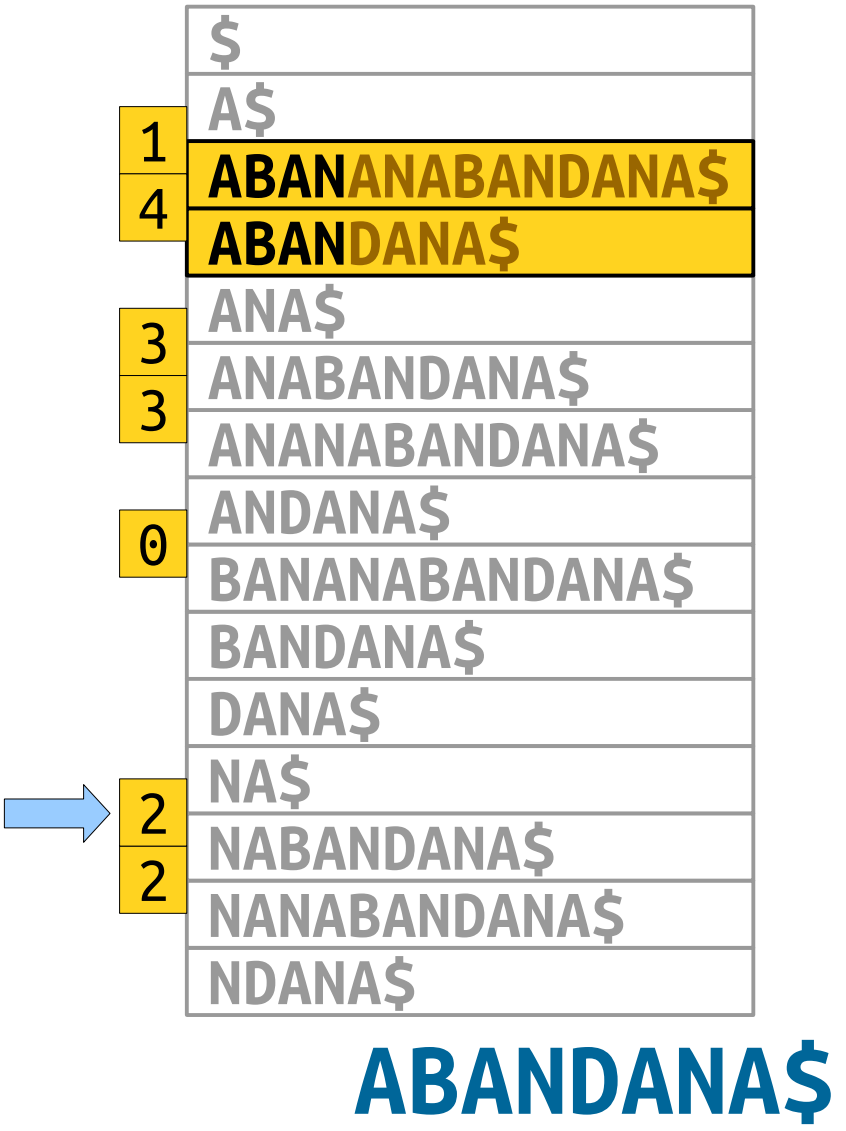

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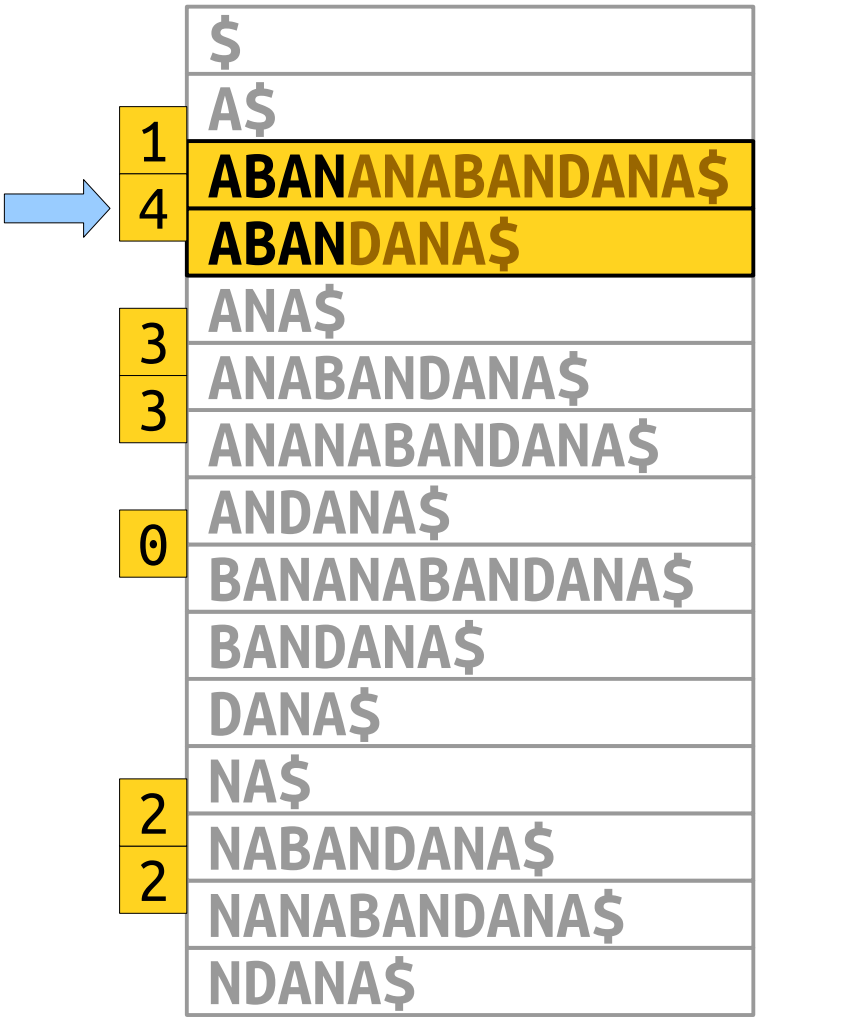

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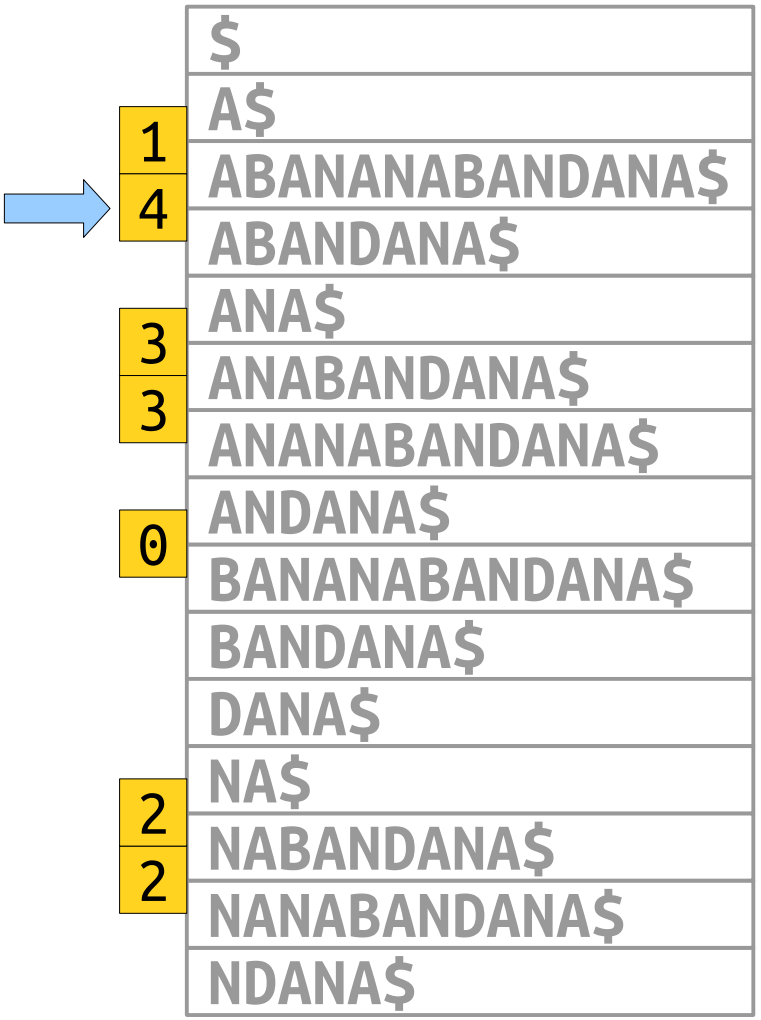

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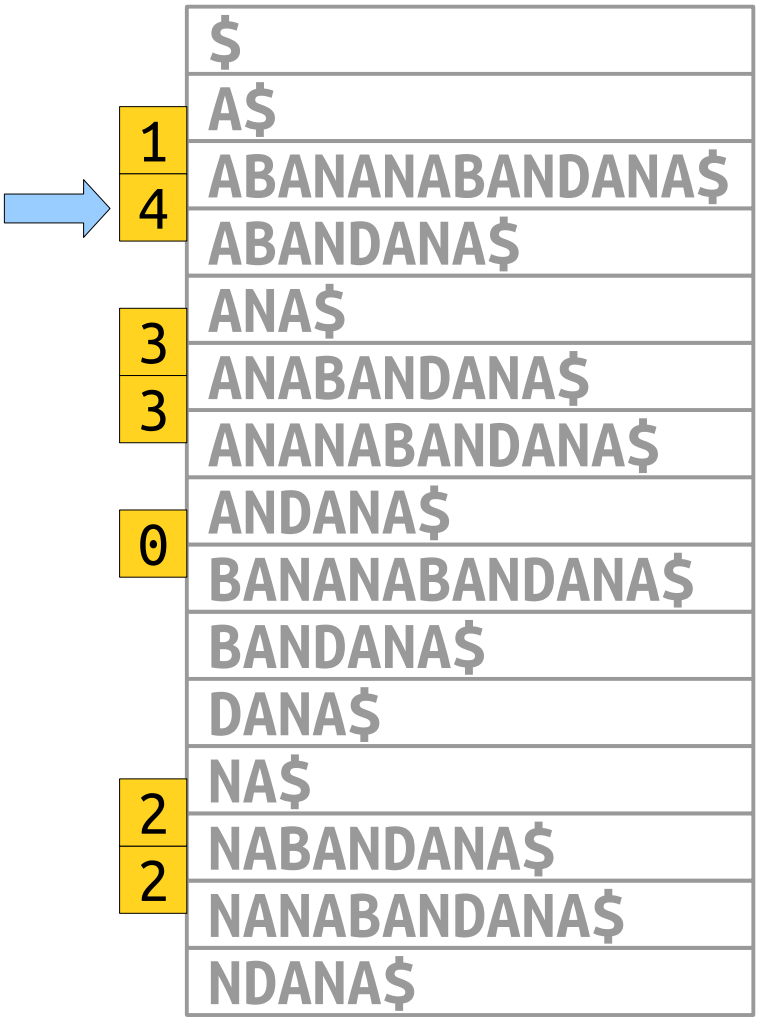

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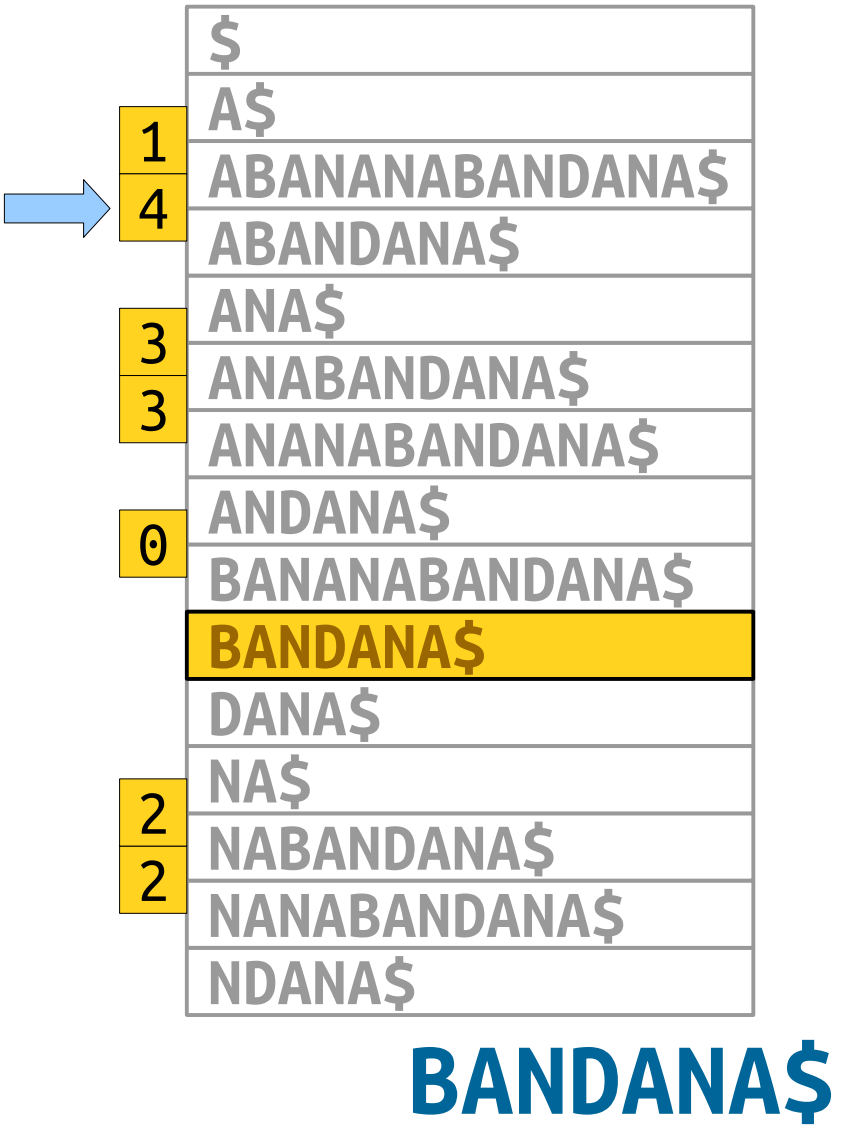

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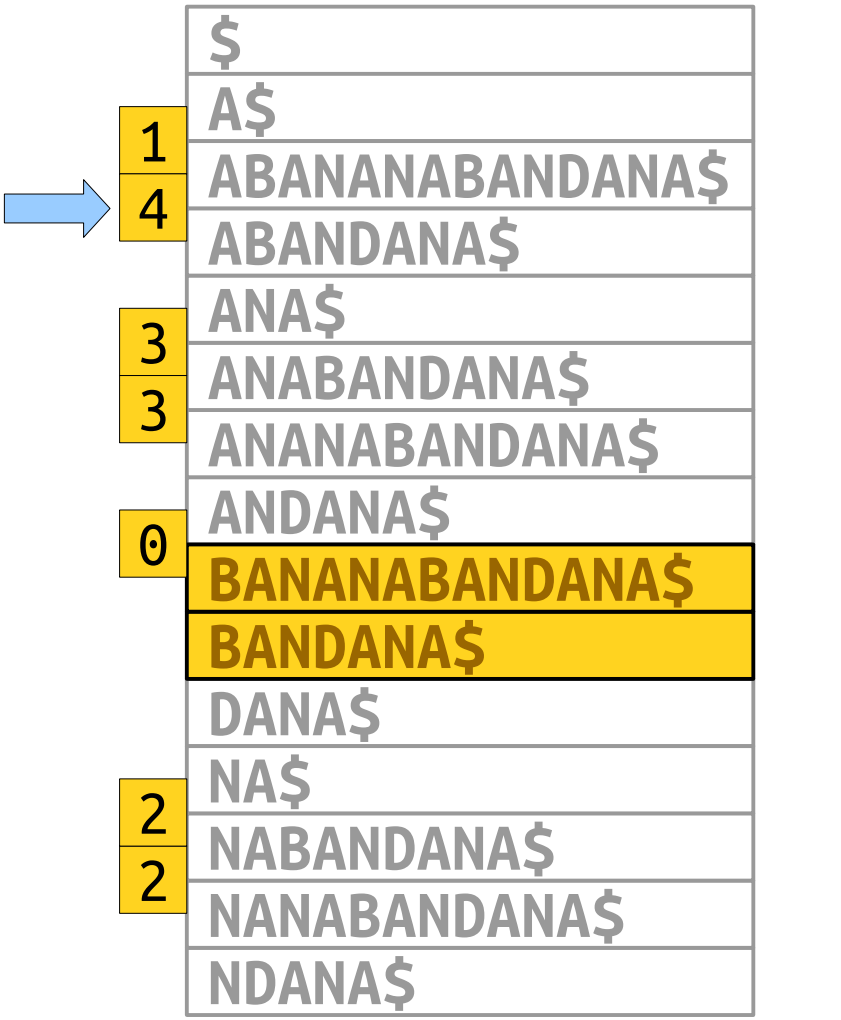

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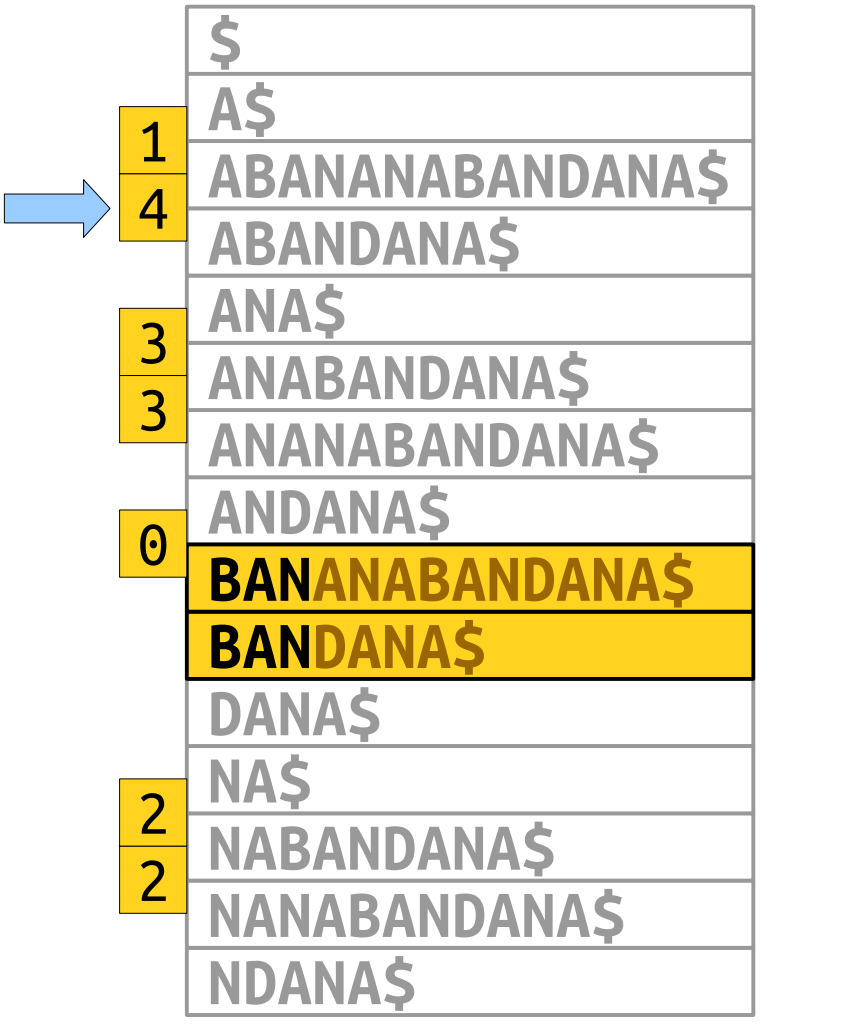

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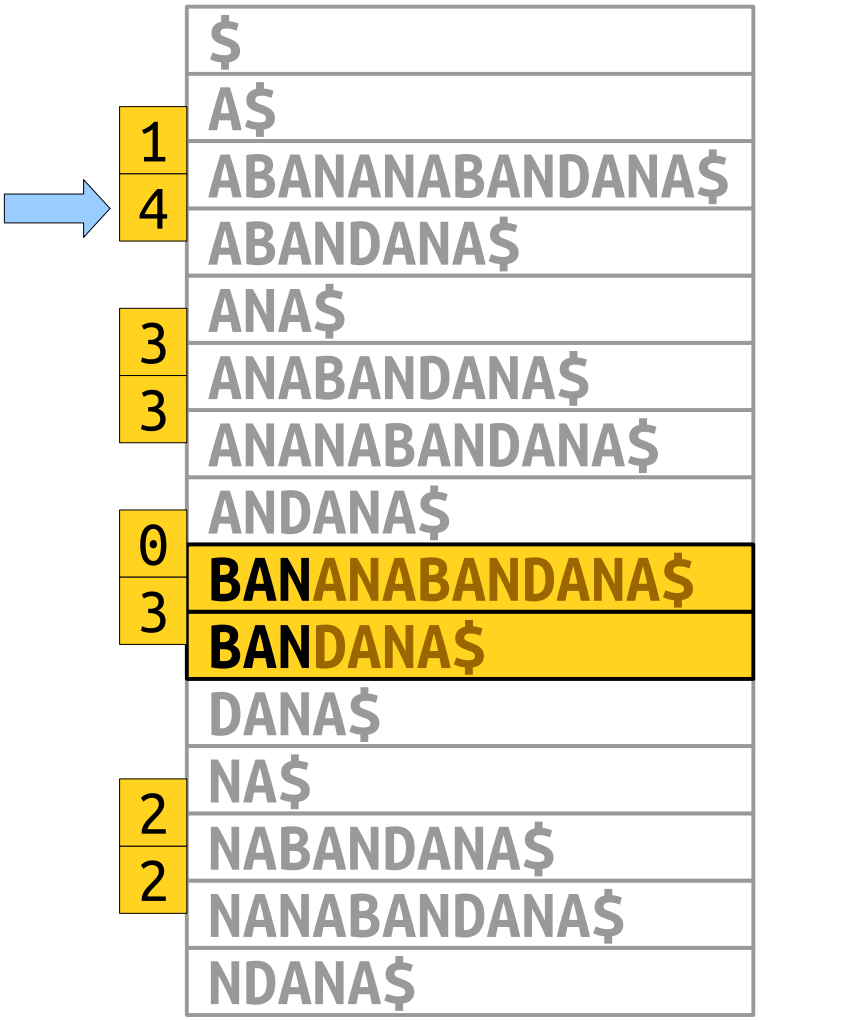

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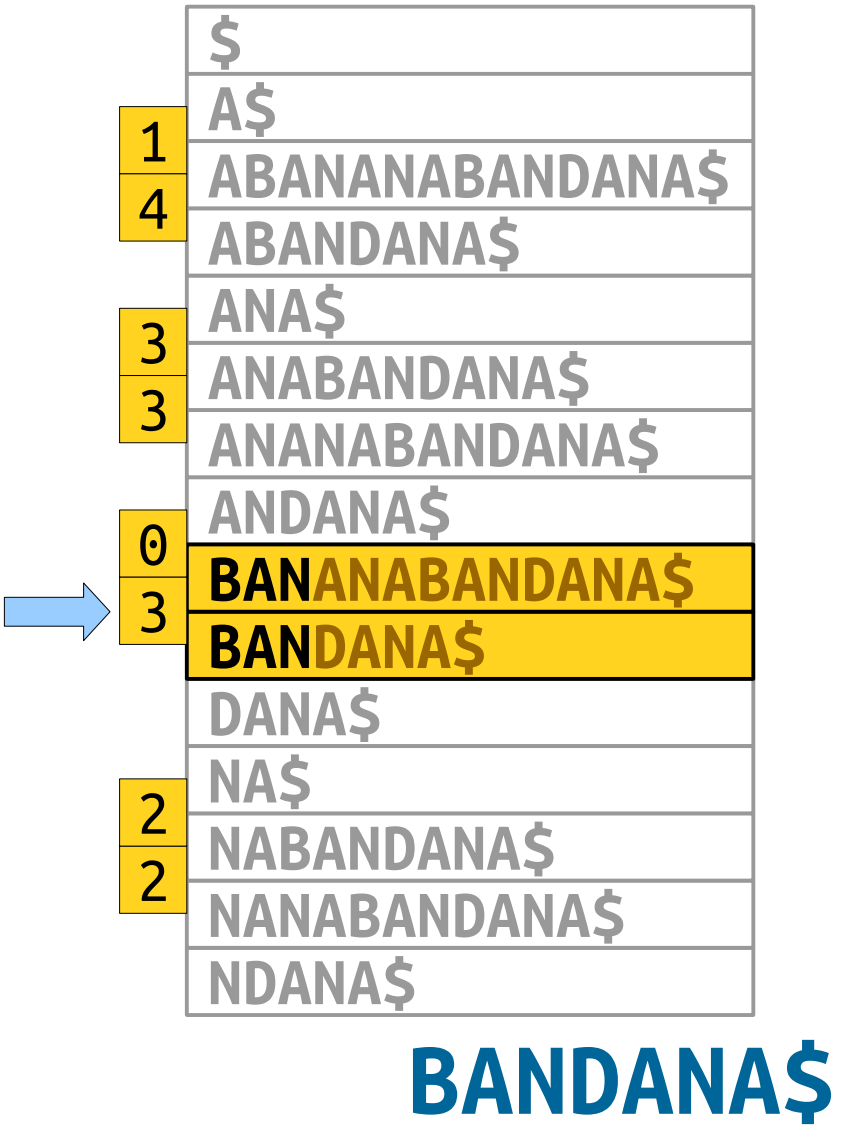

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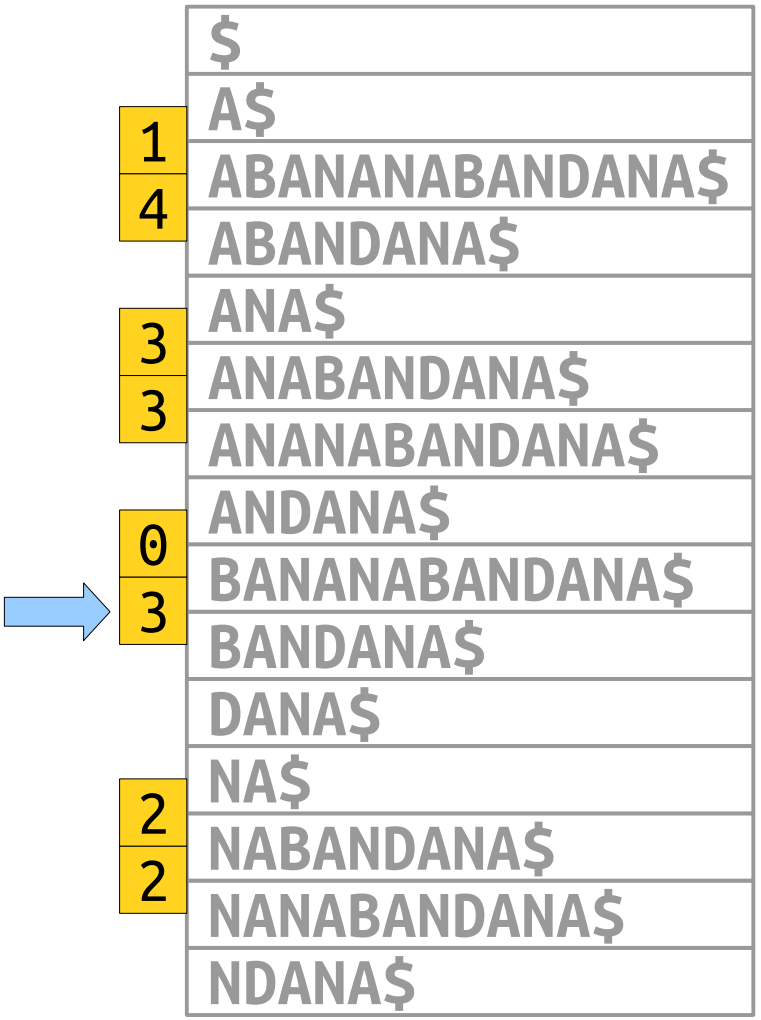

BANDANA$

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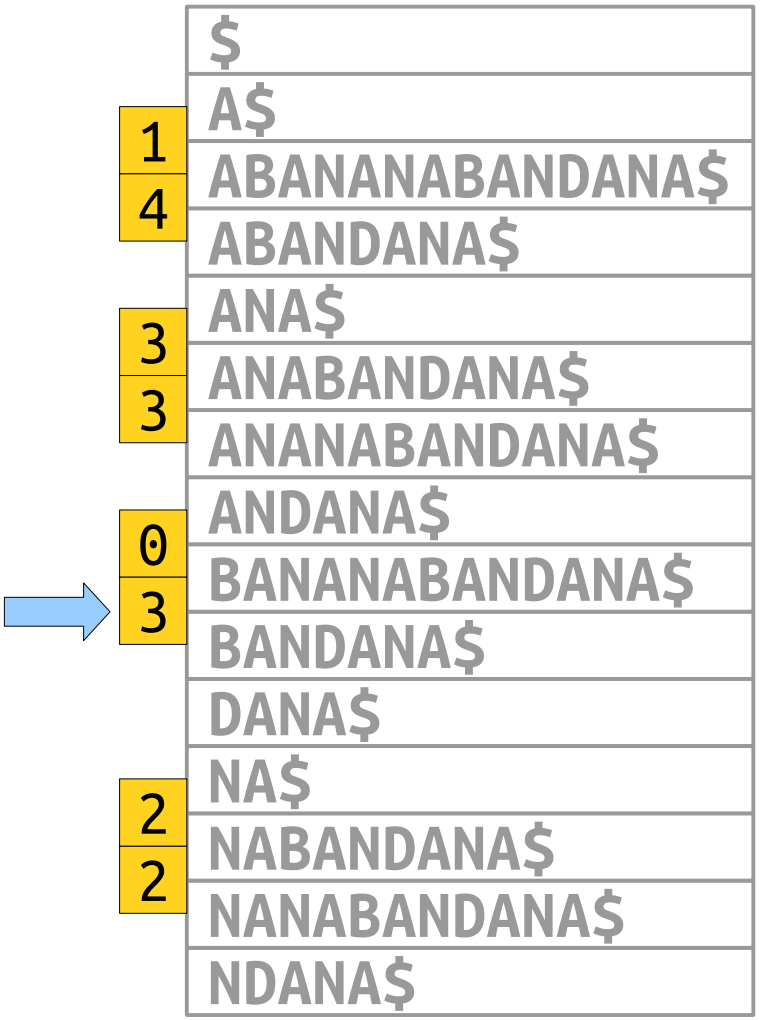

ANDANA$

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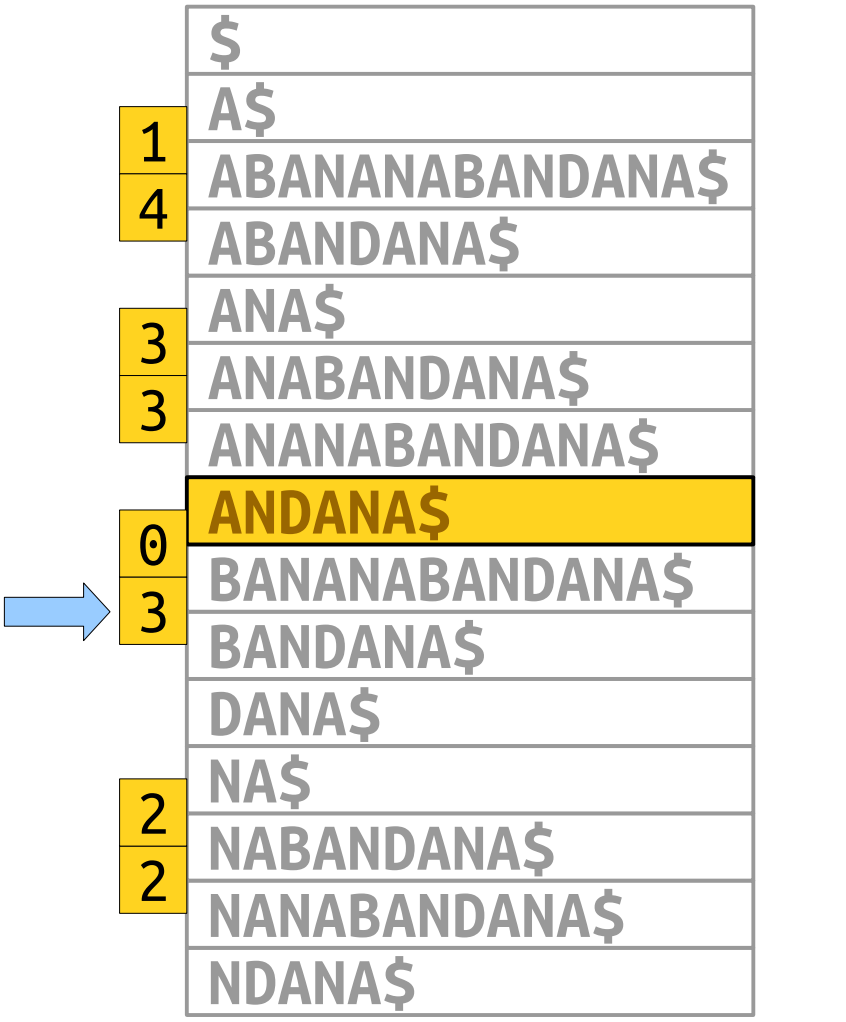

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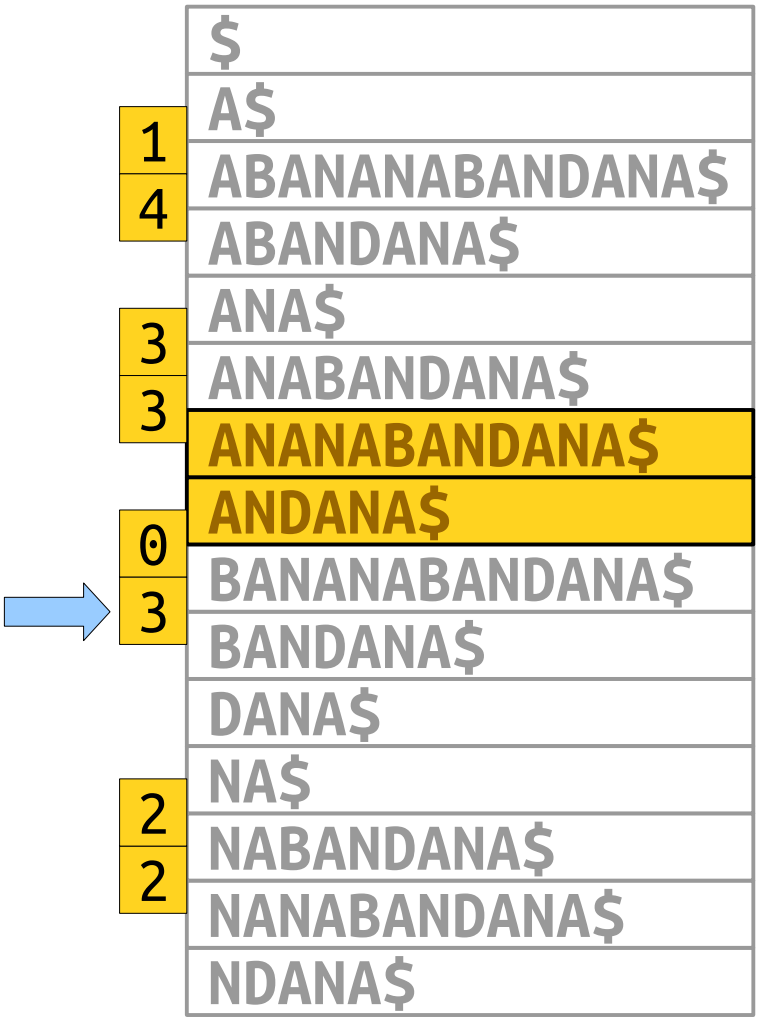

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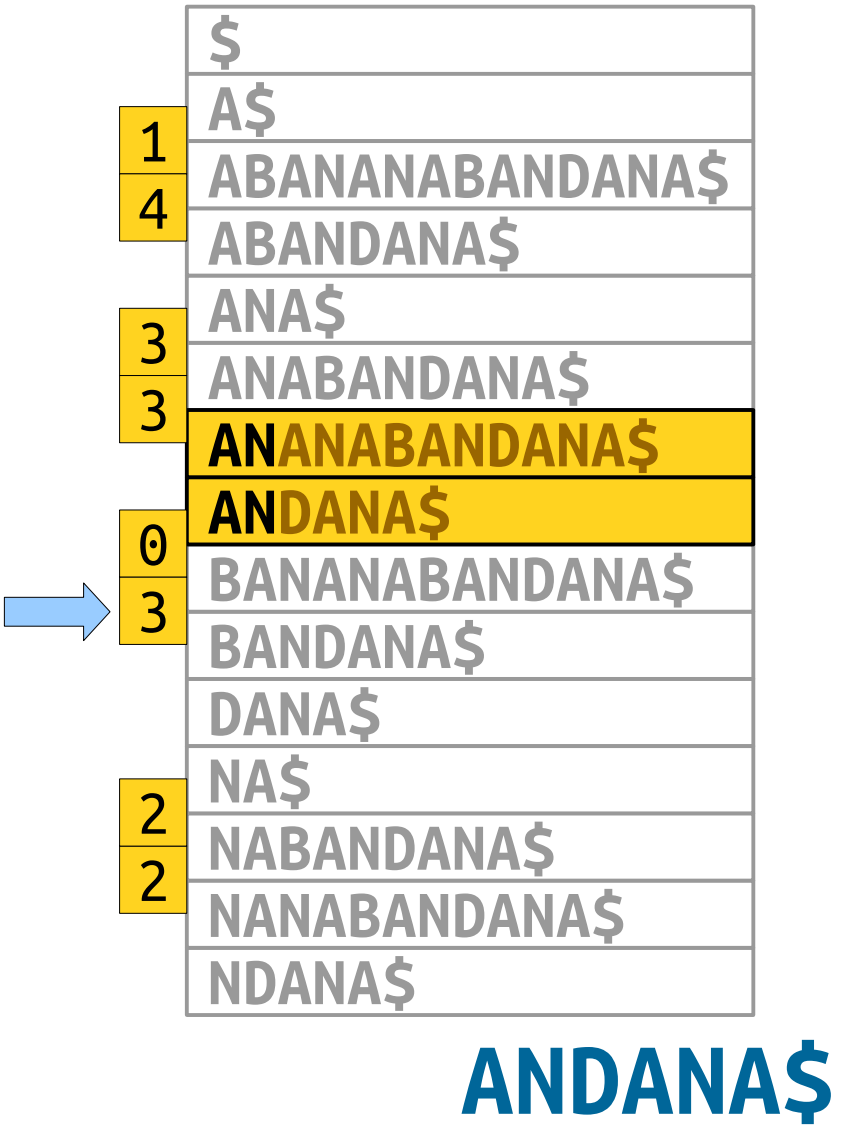

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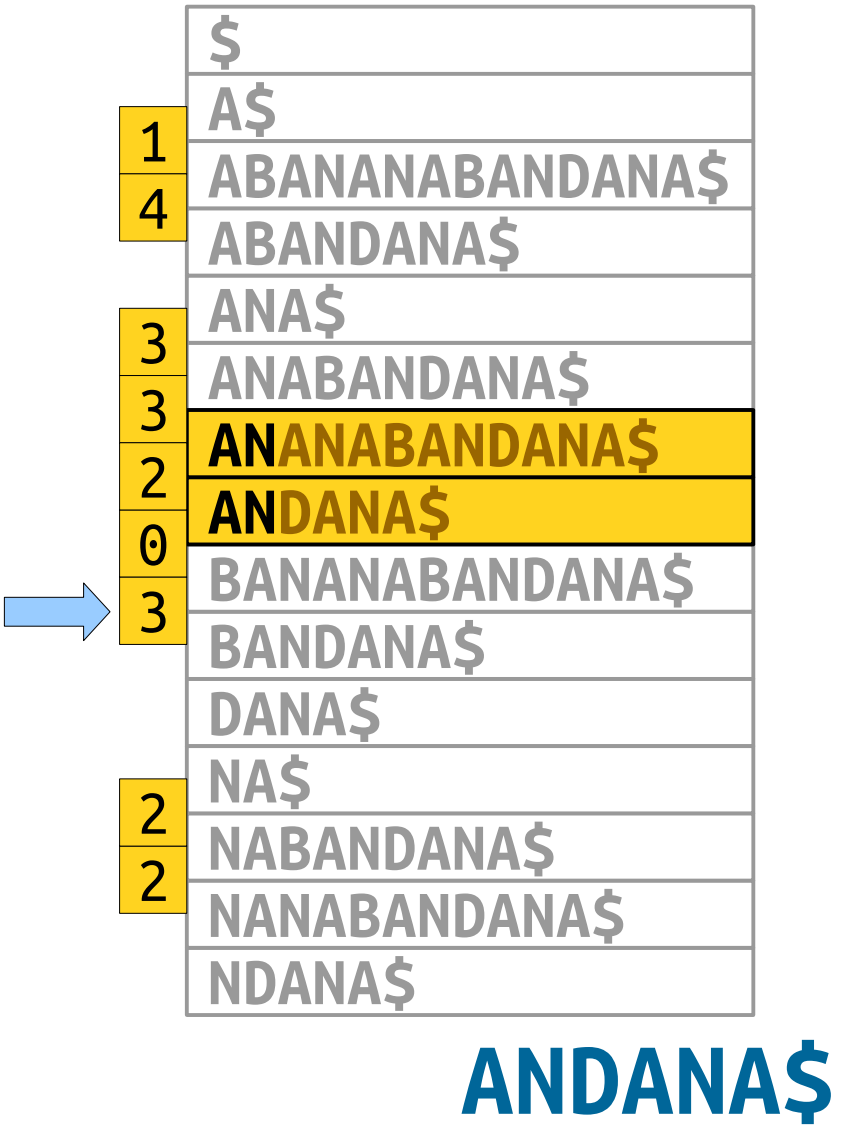

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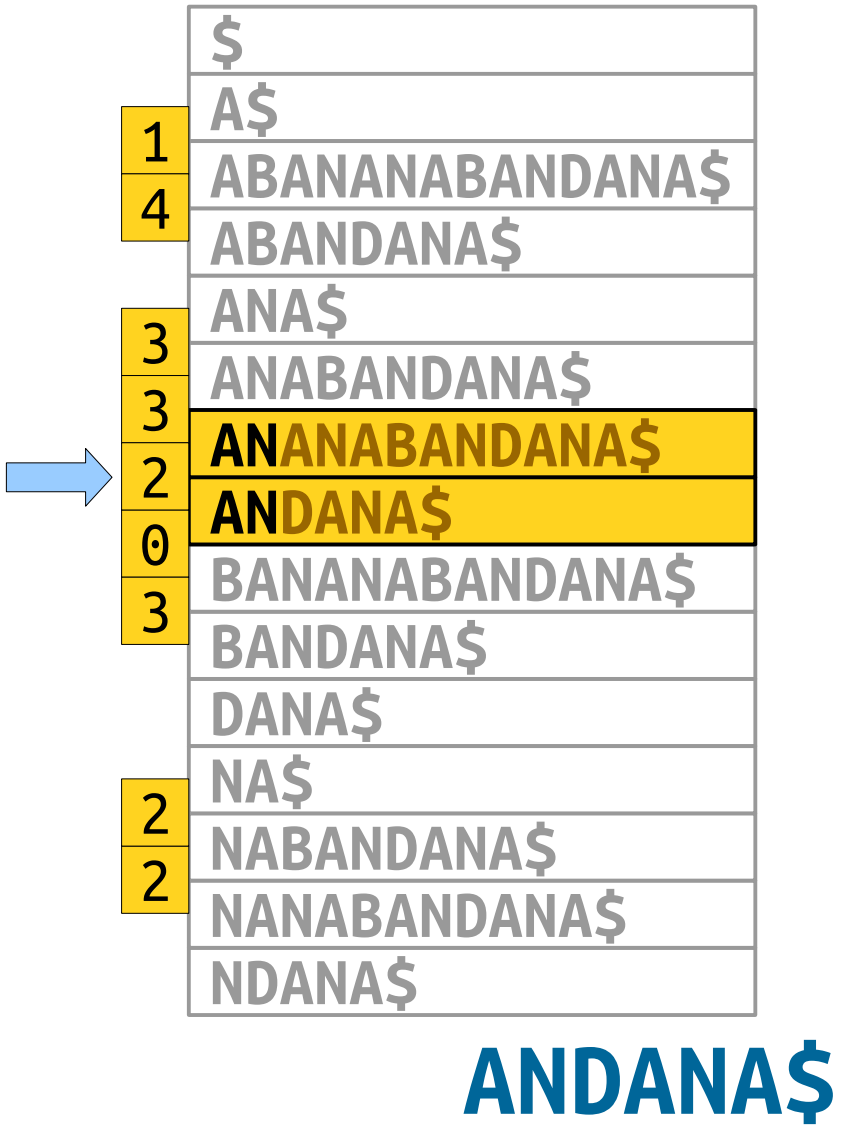

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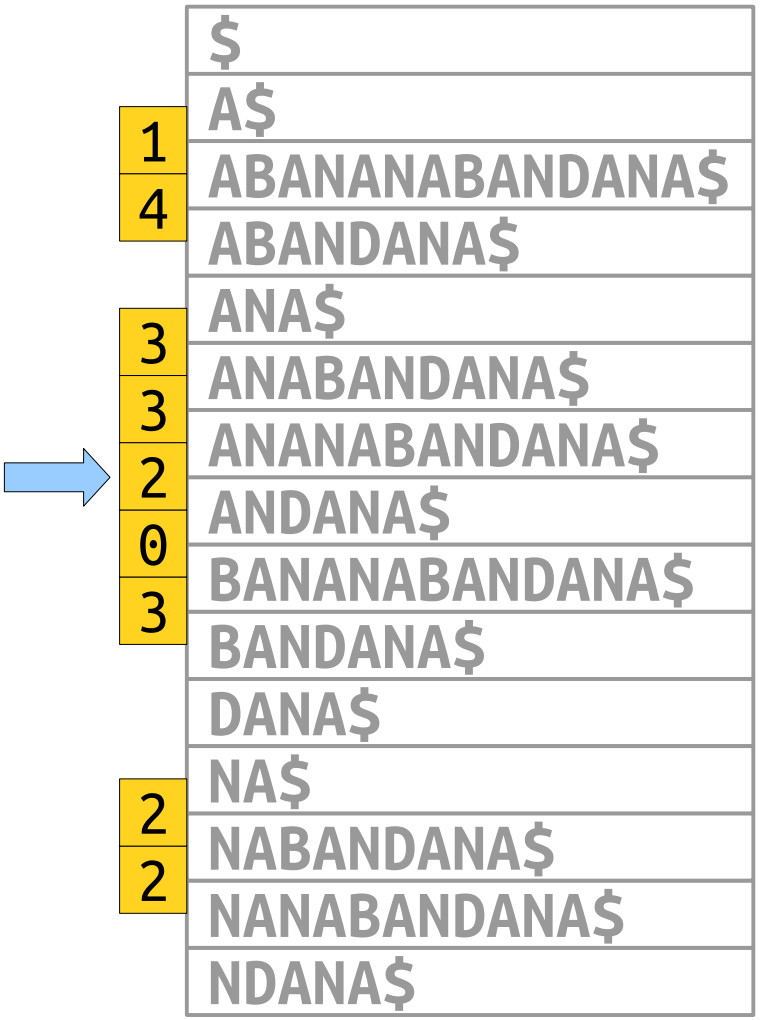

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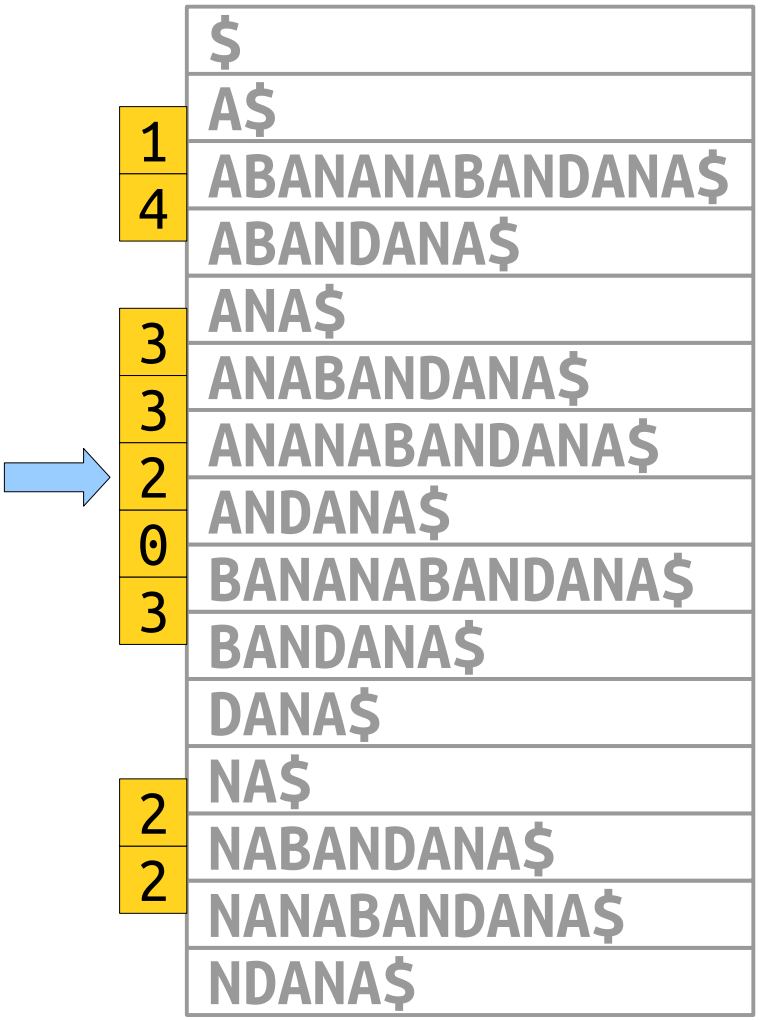

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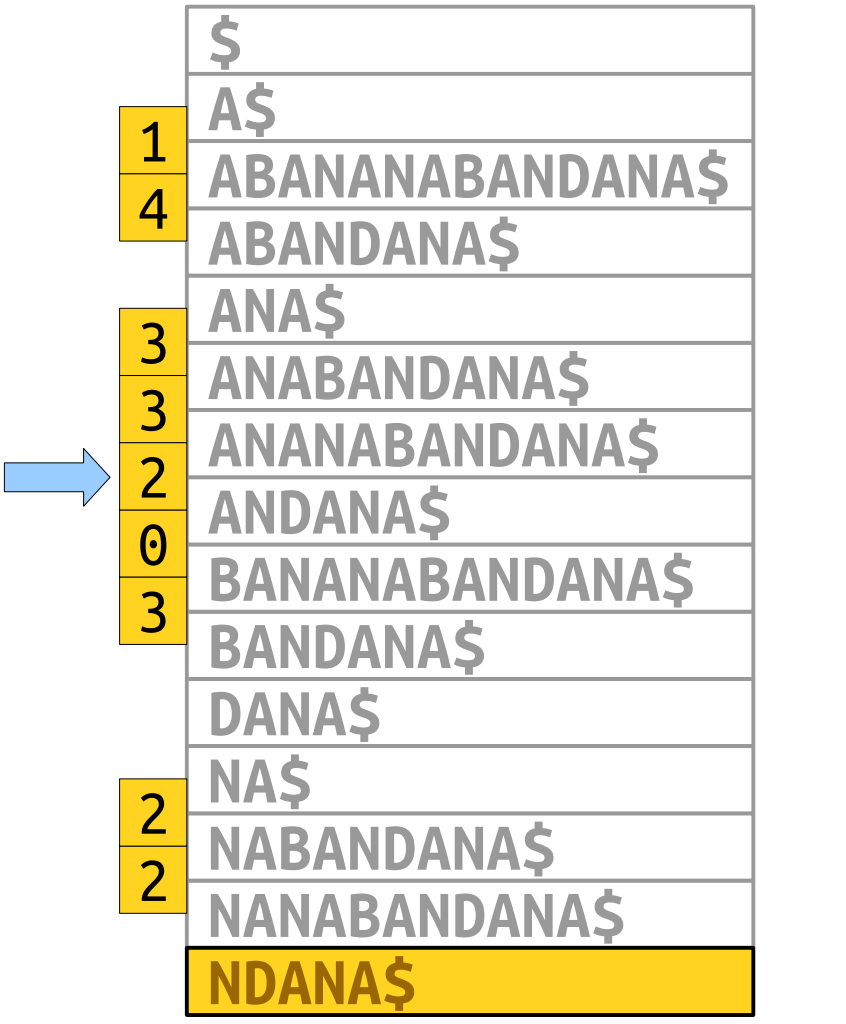

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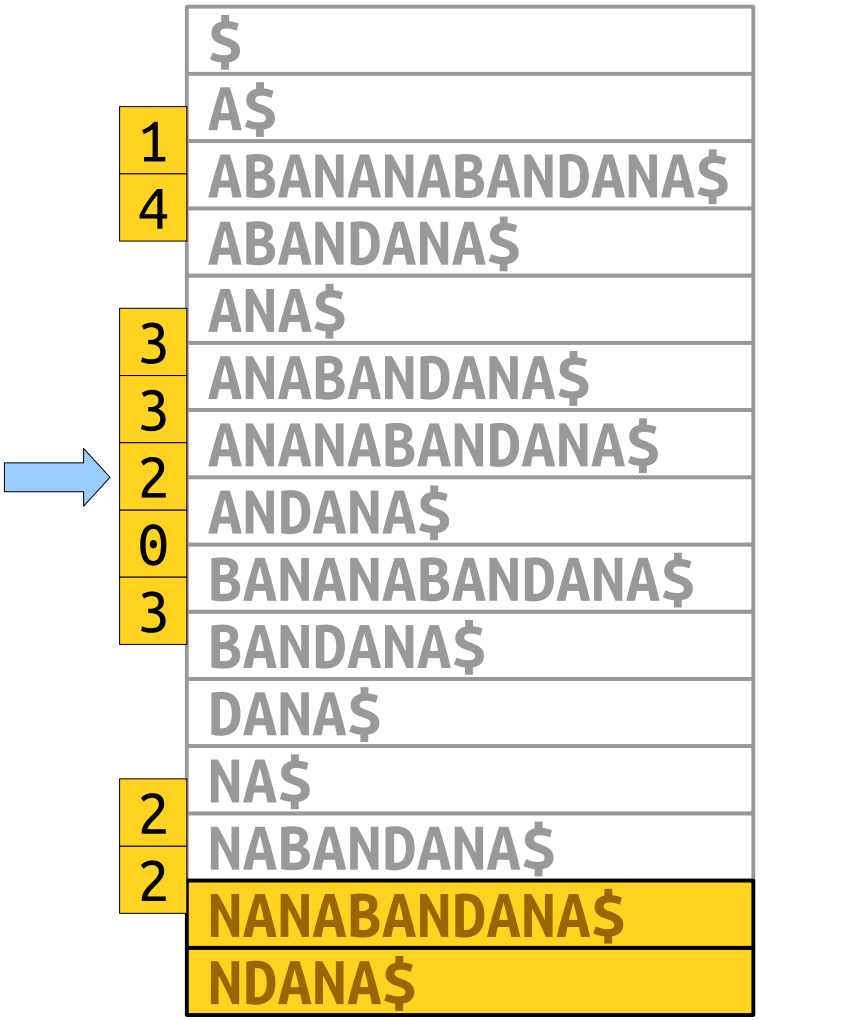

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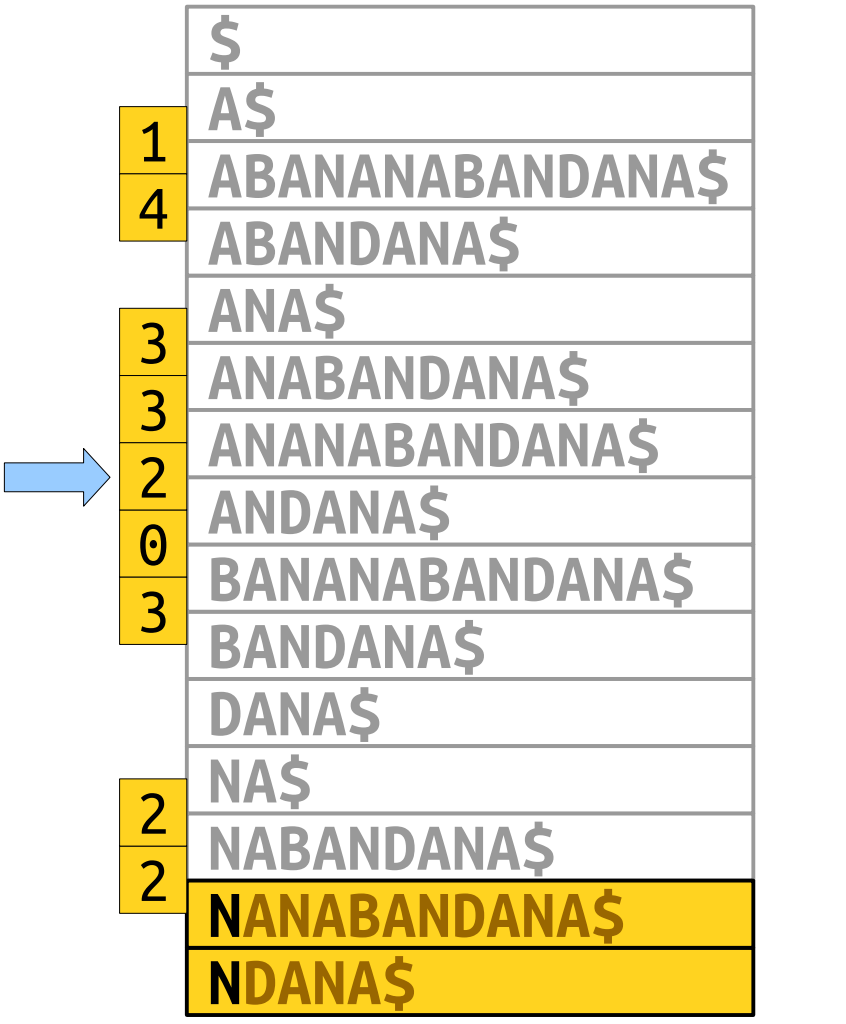

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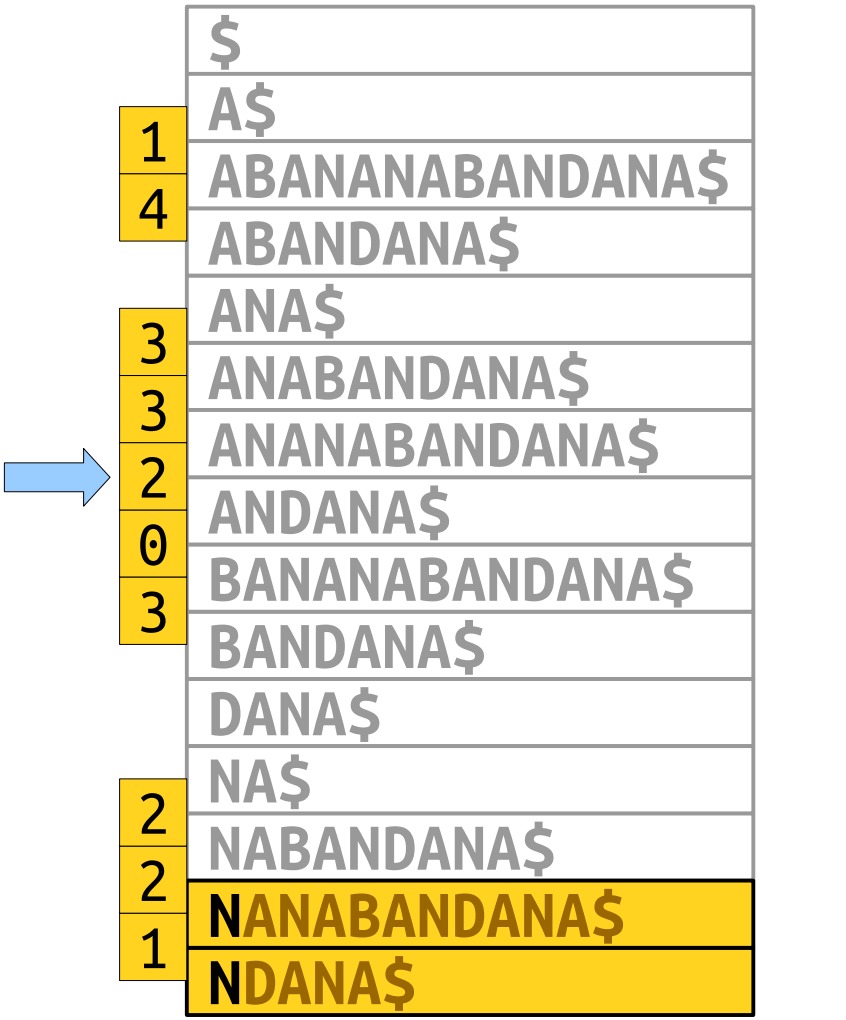

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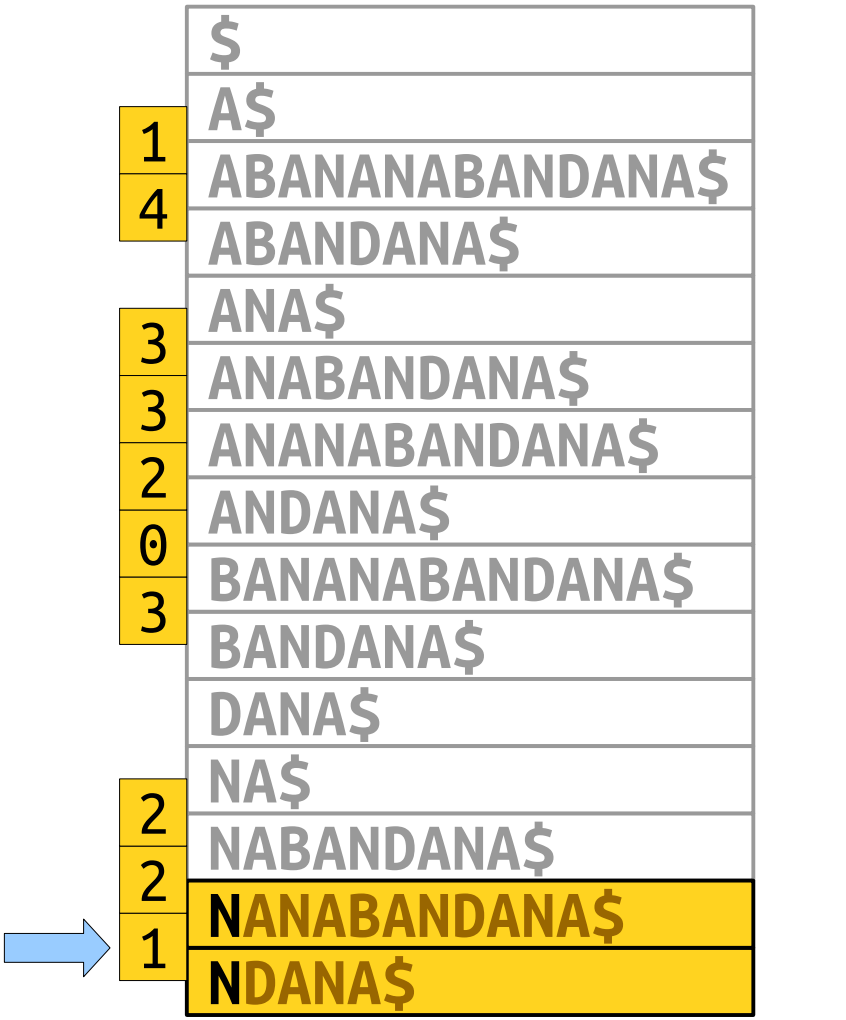

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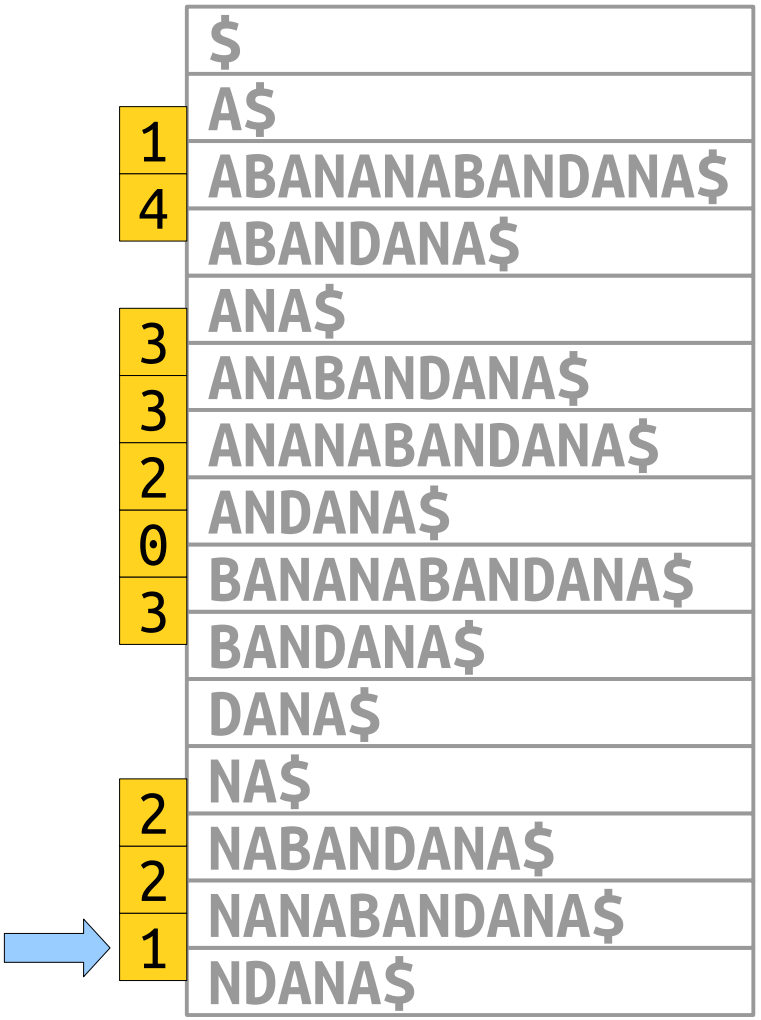

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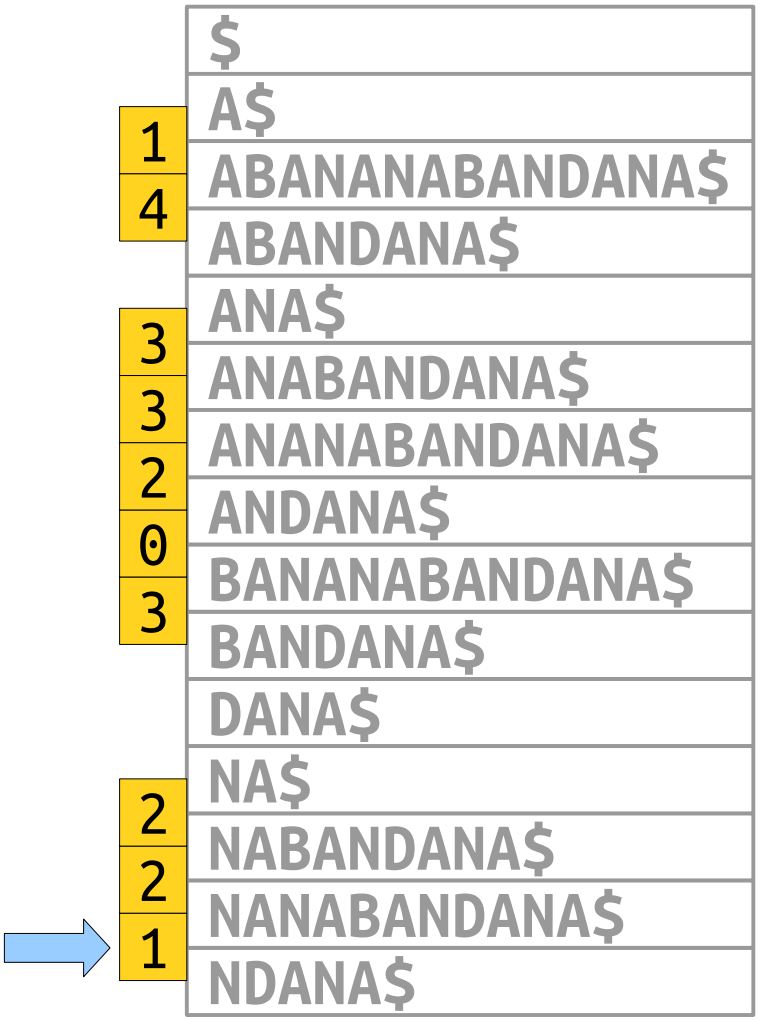

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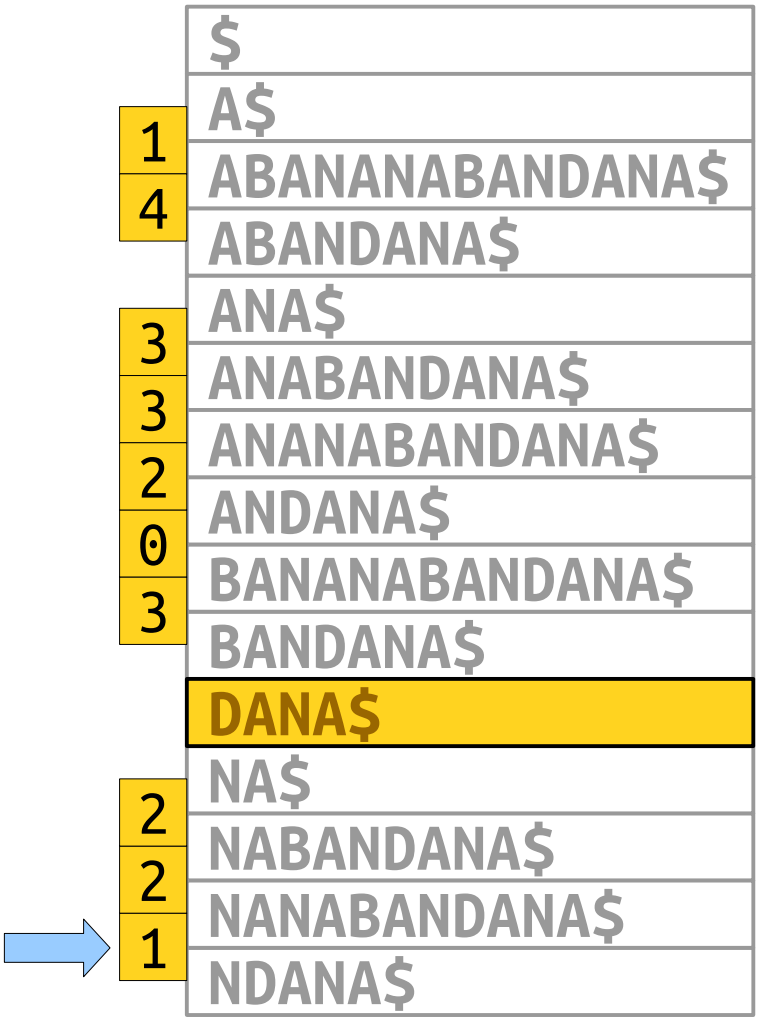

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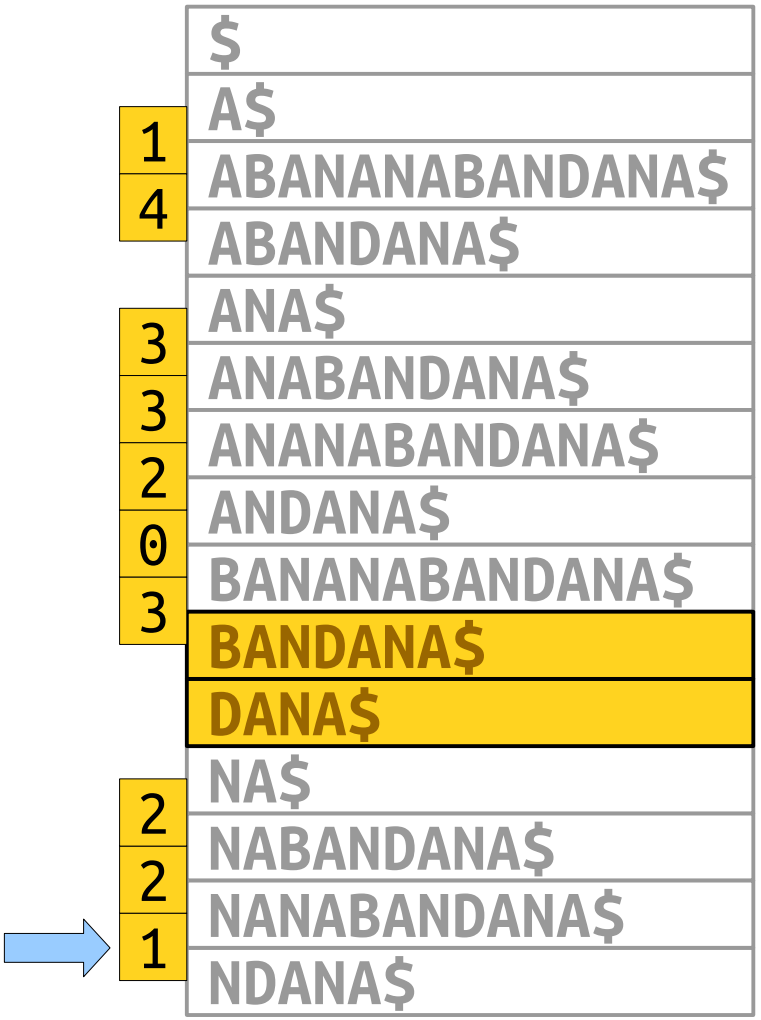

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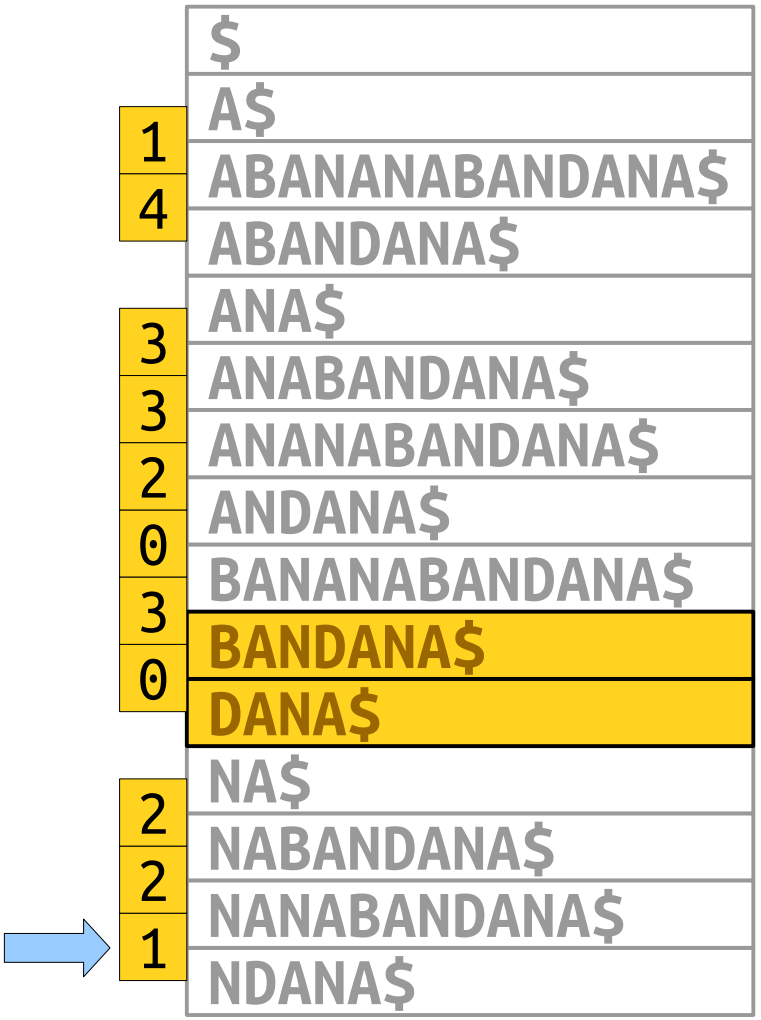

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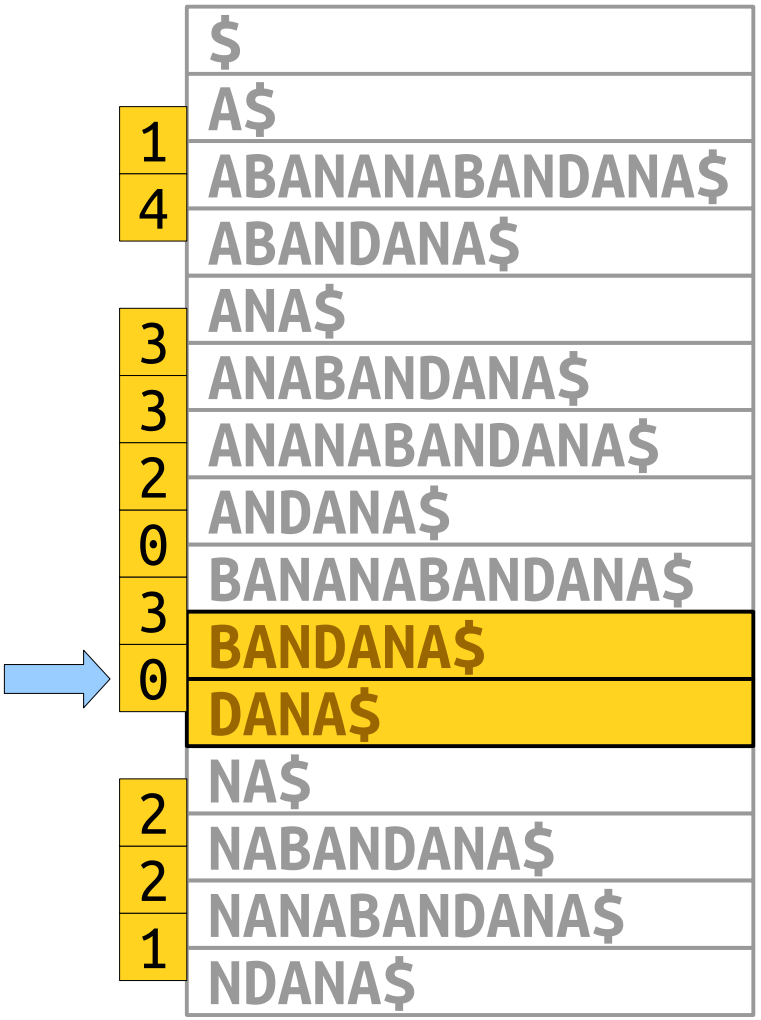

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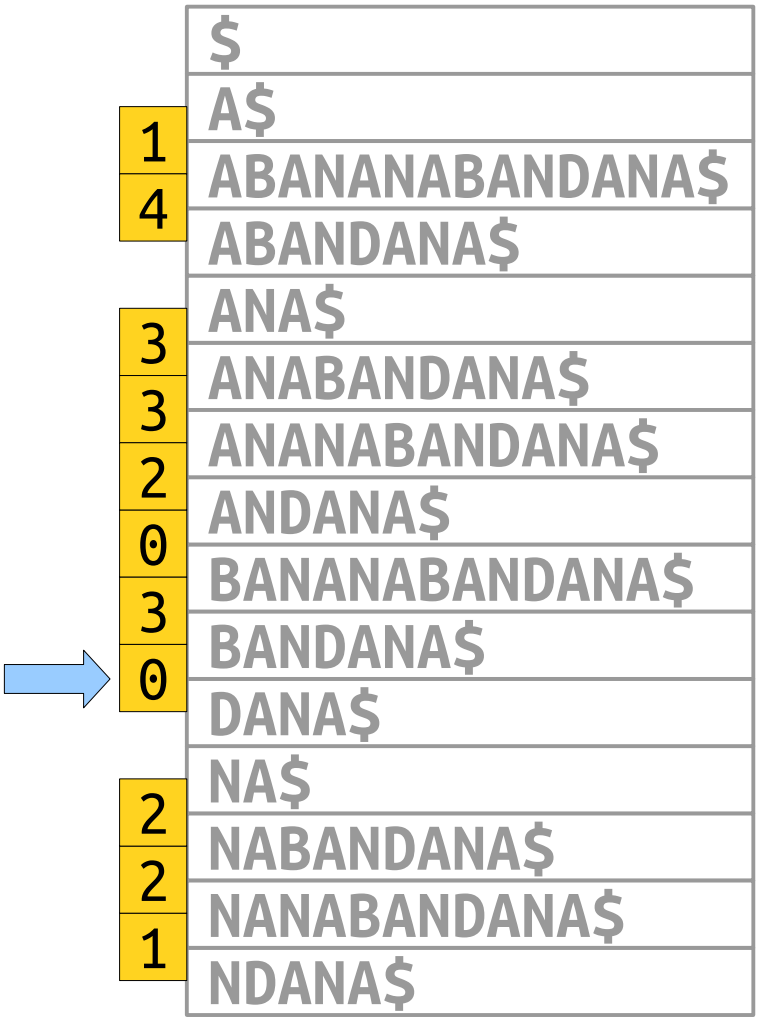

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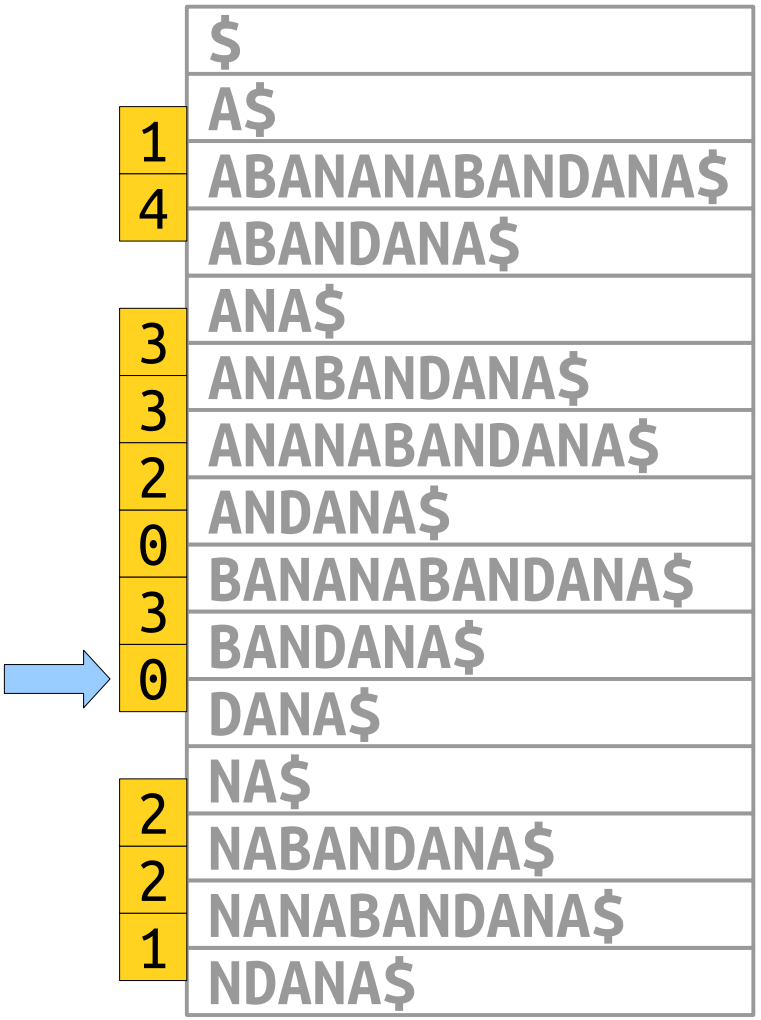

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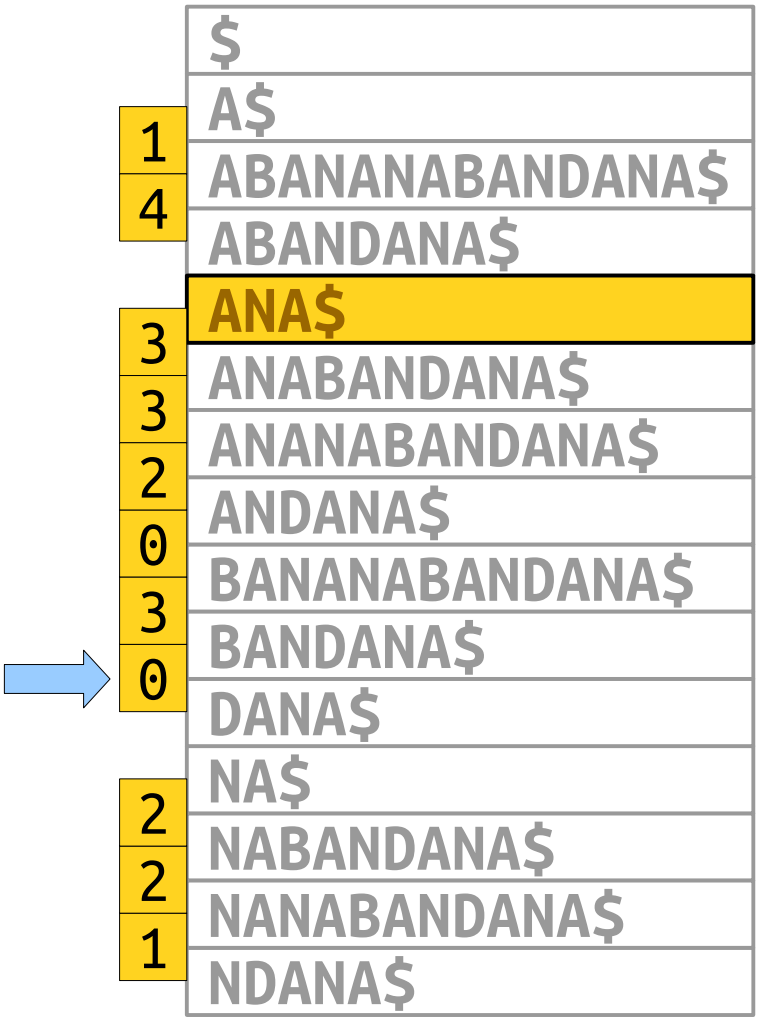

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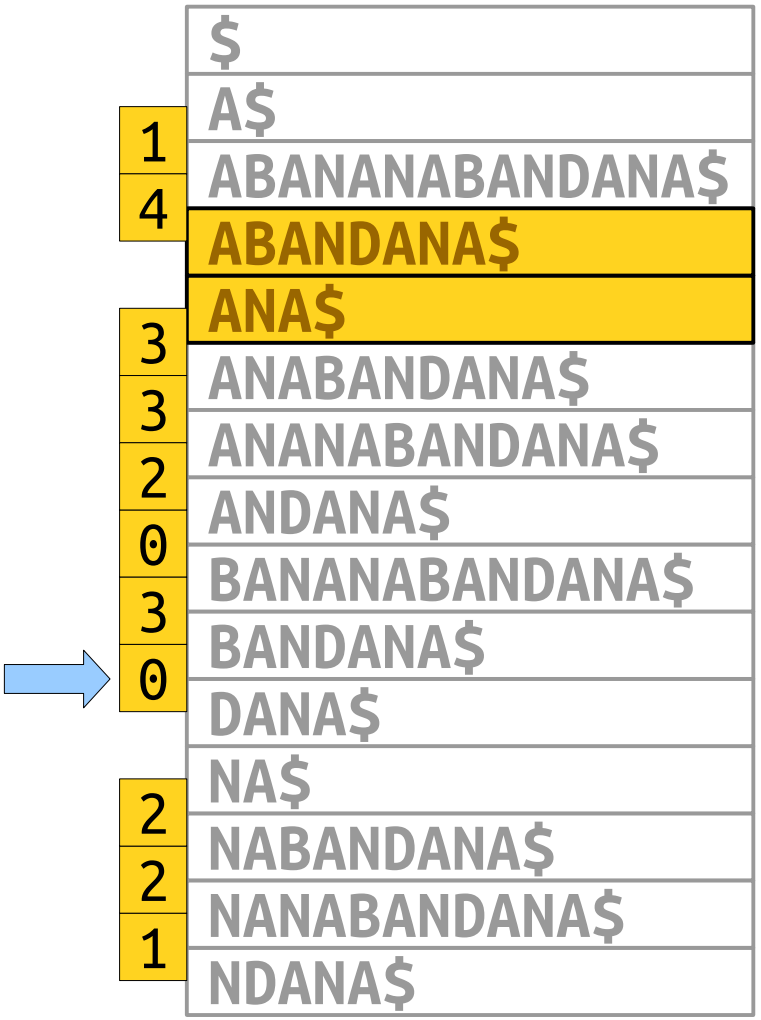

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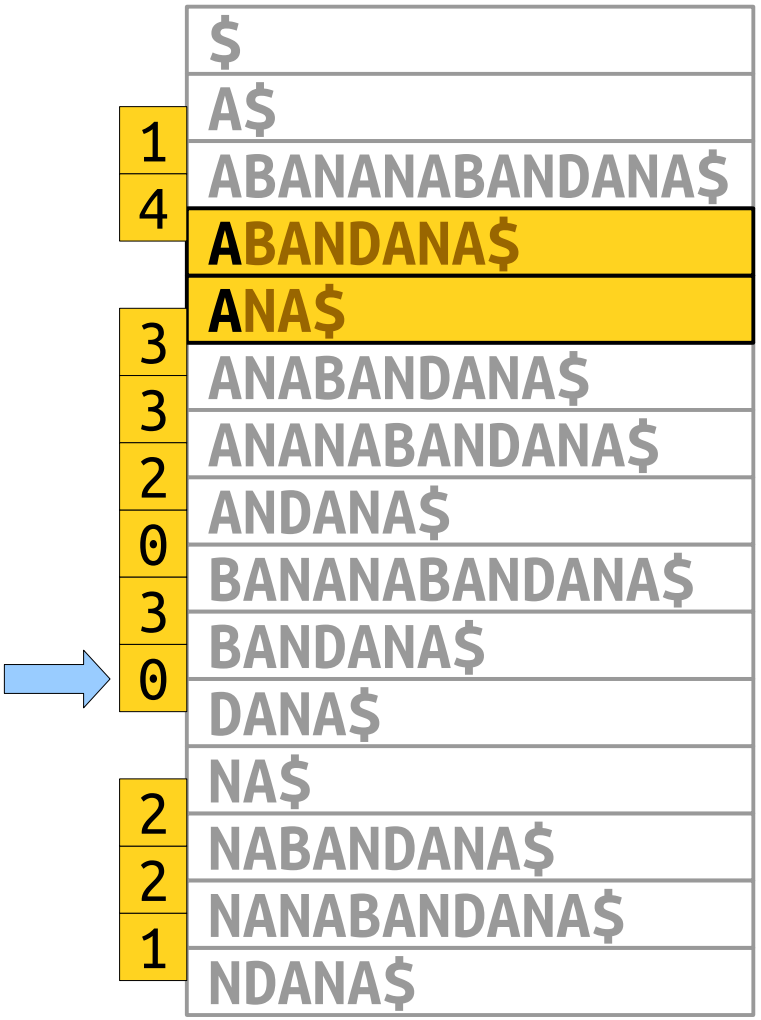

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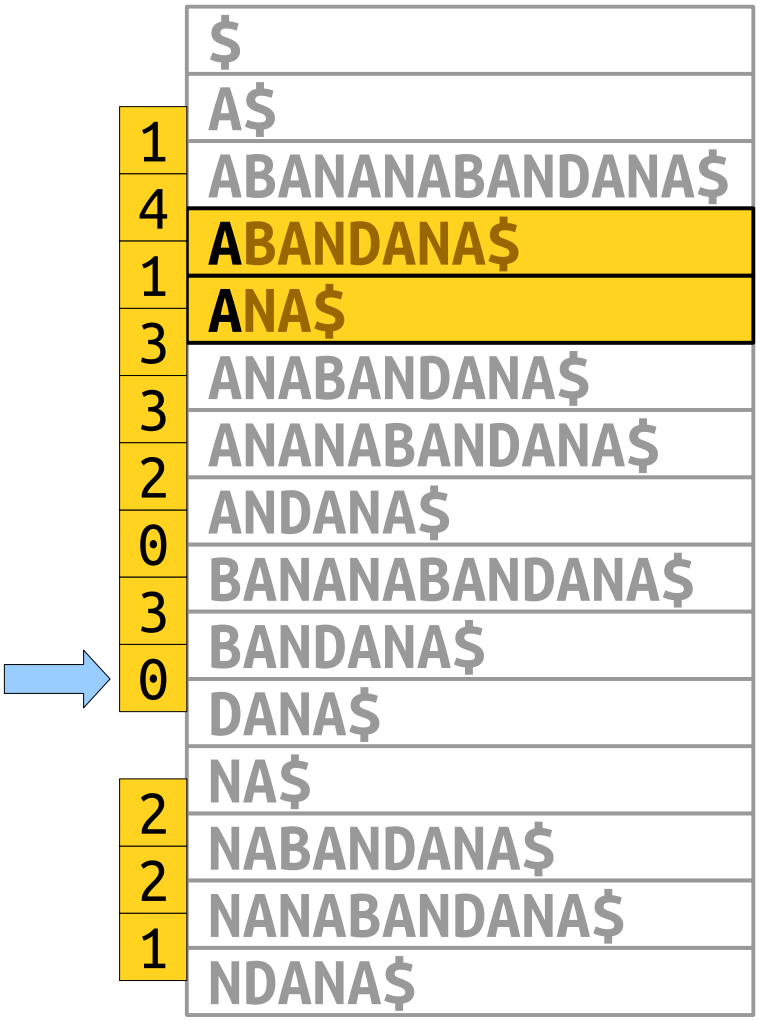

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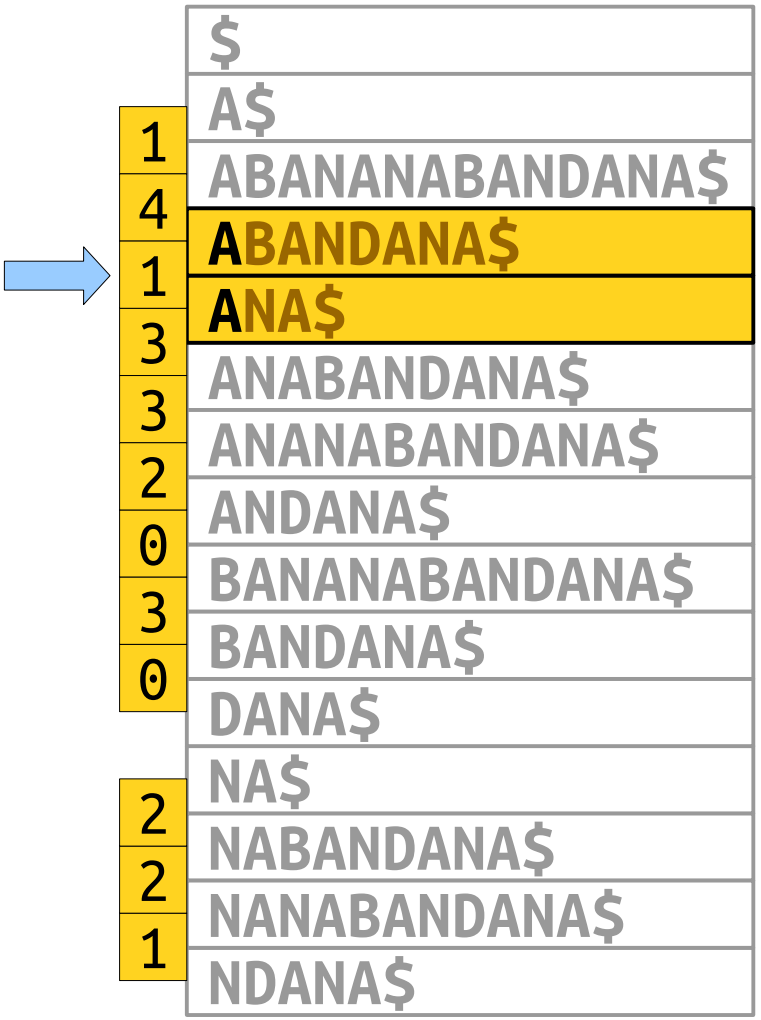

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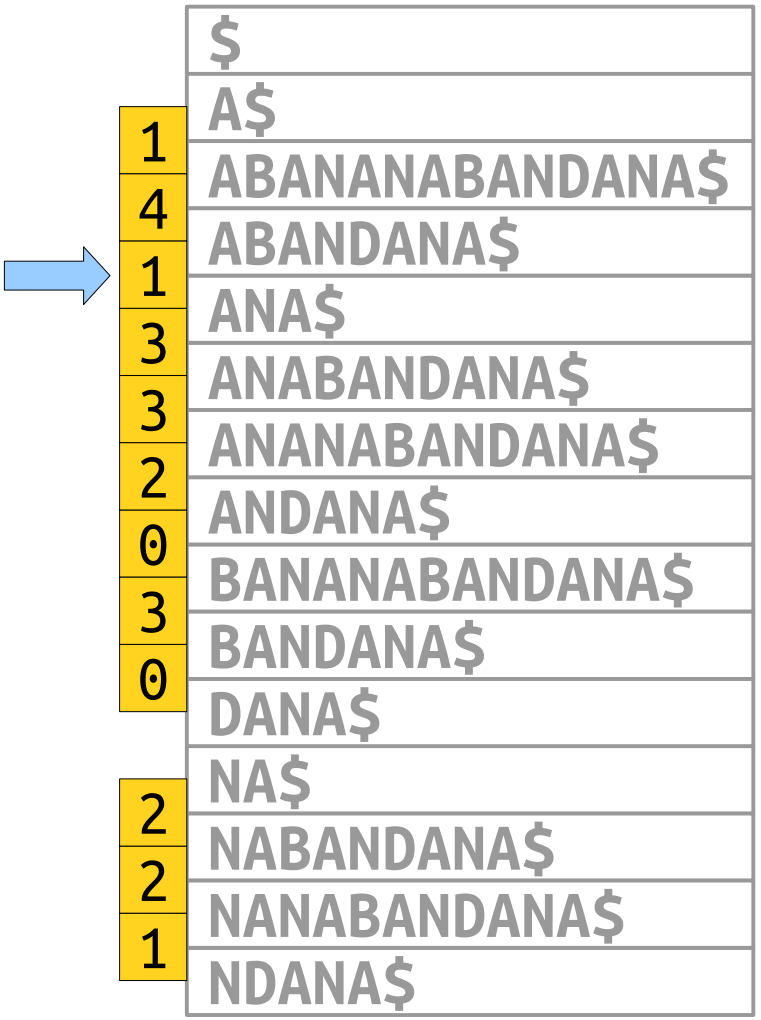

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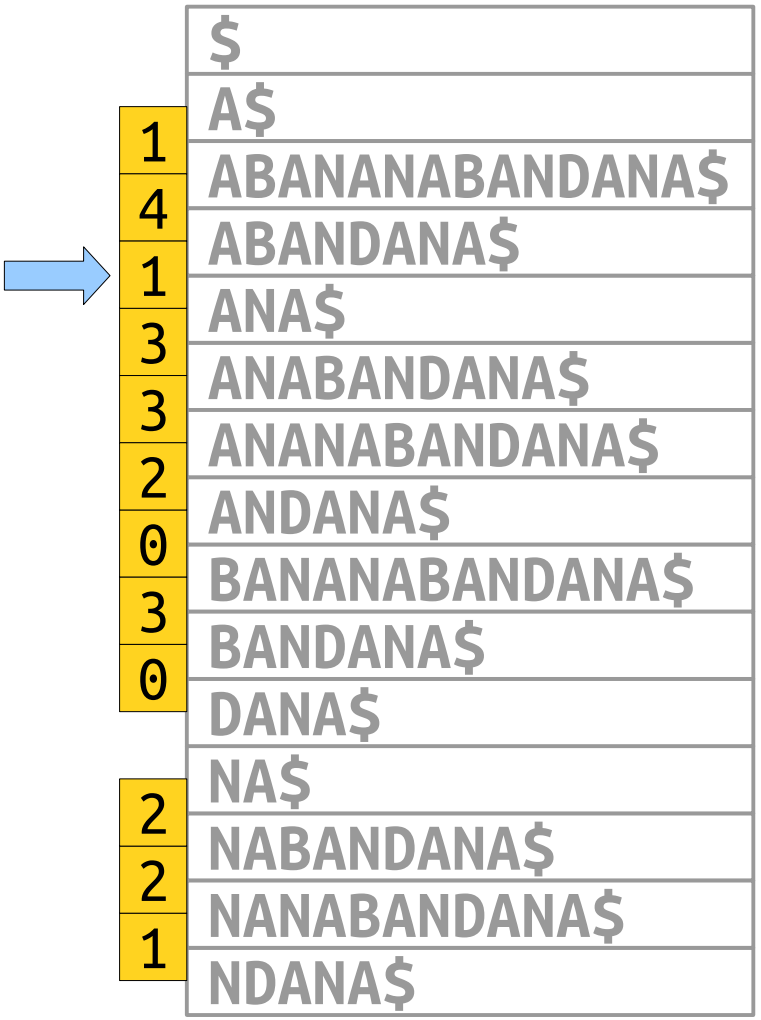

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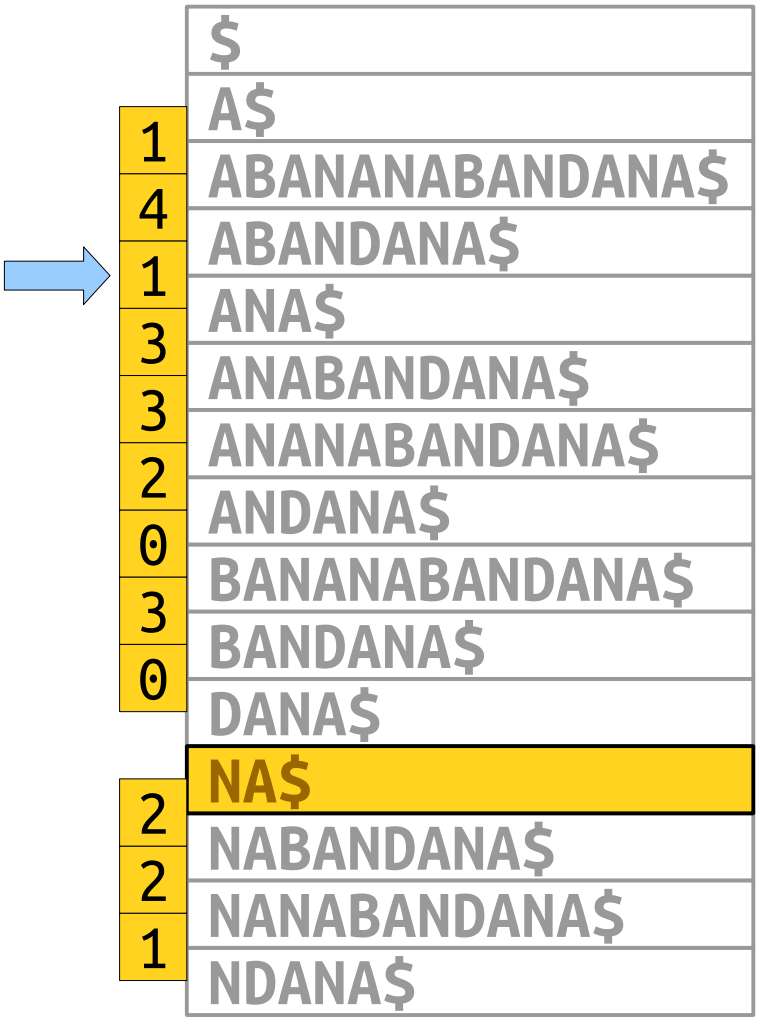

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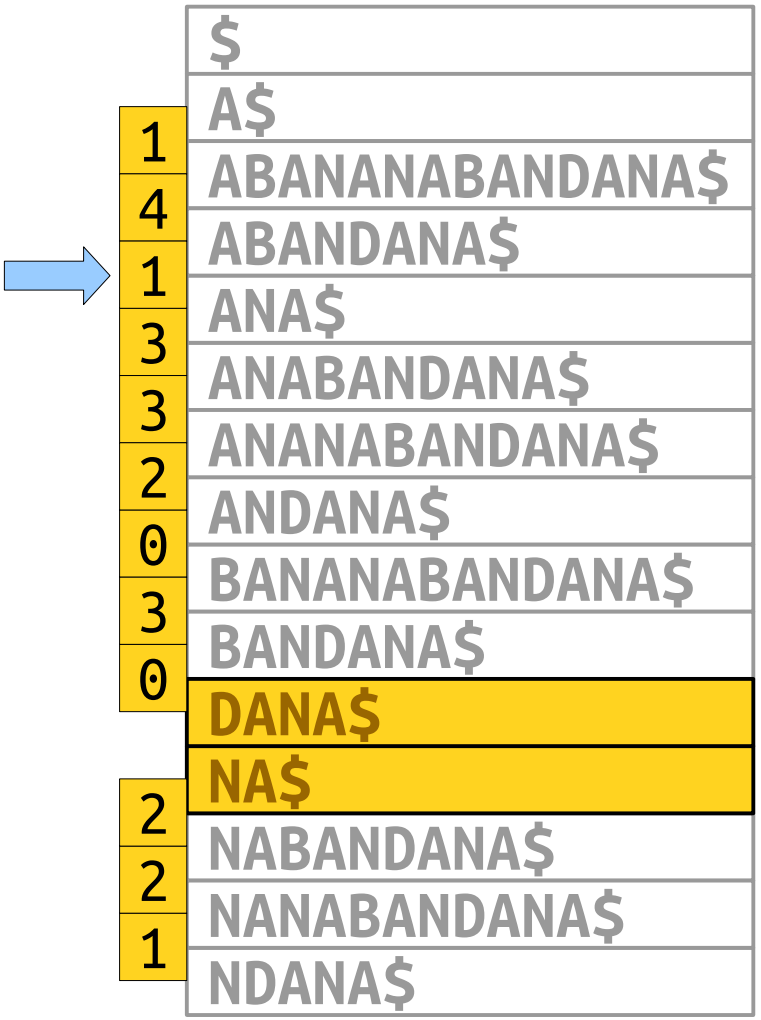

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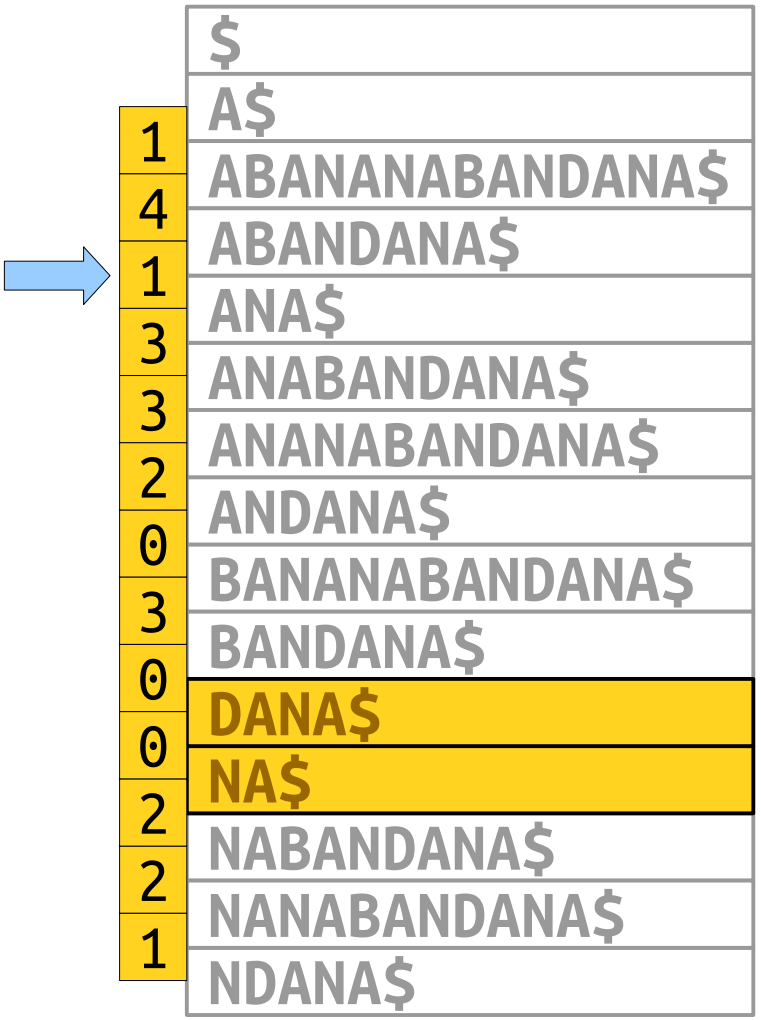

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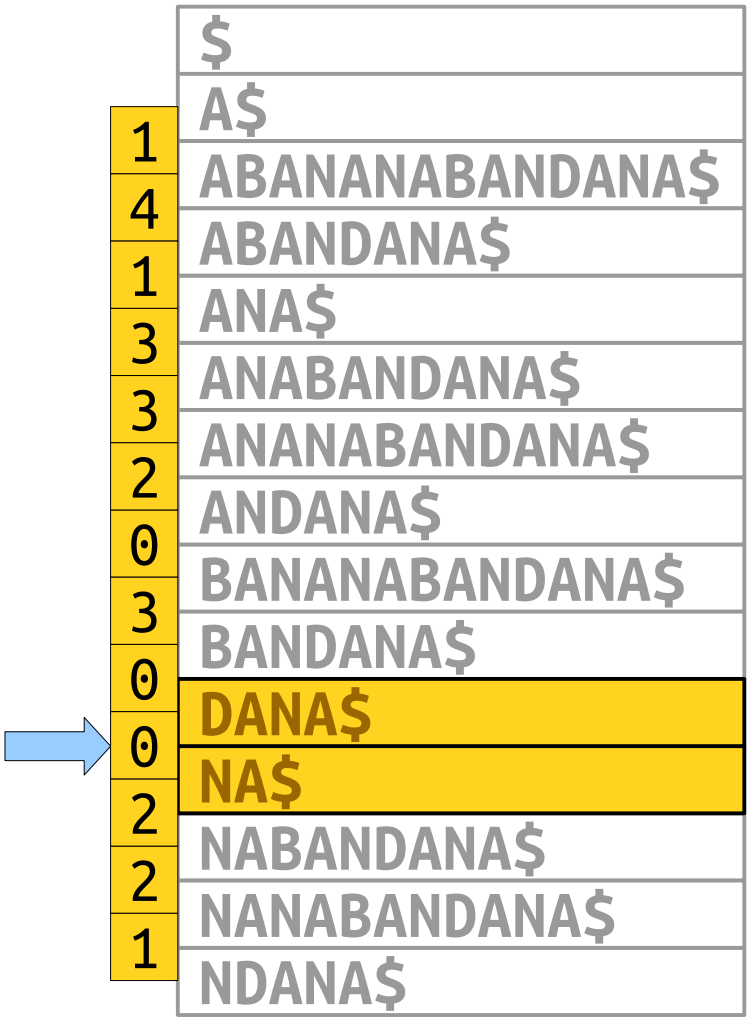

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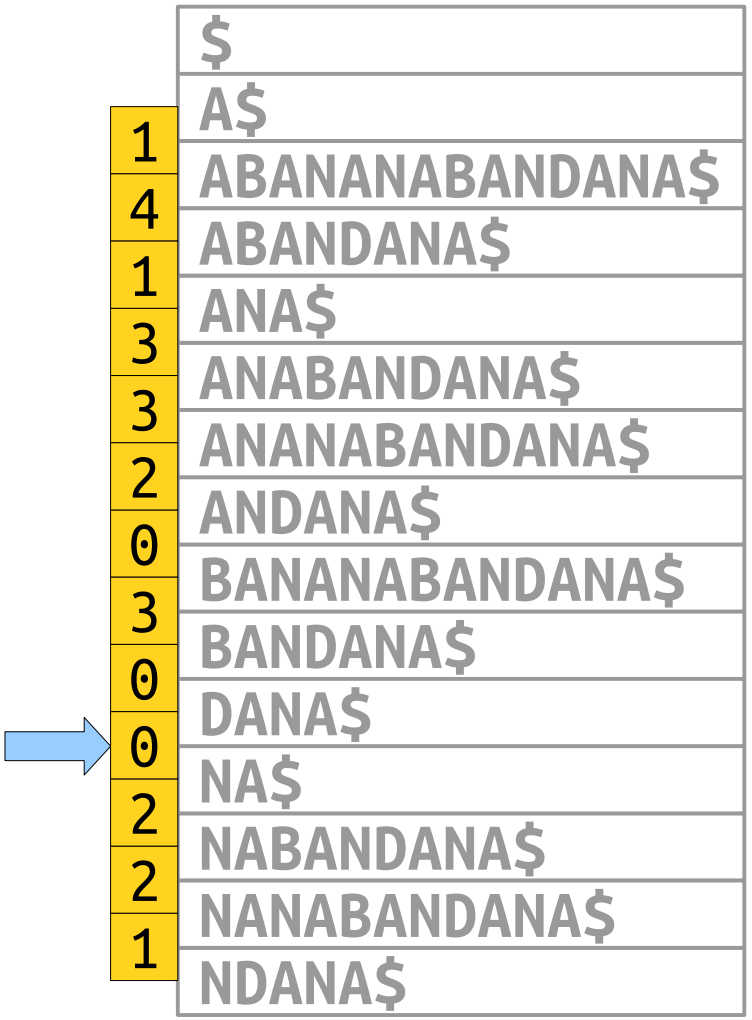

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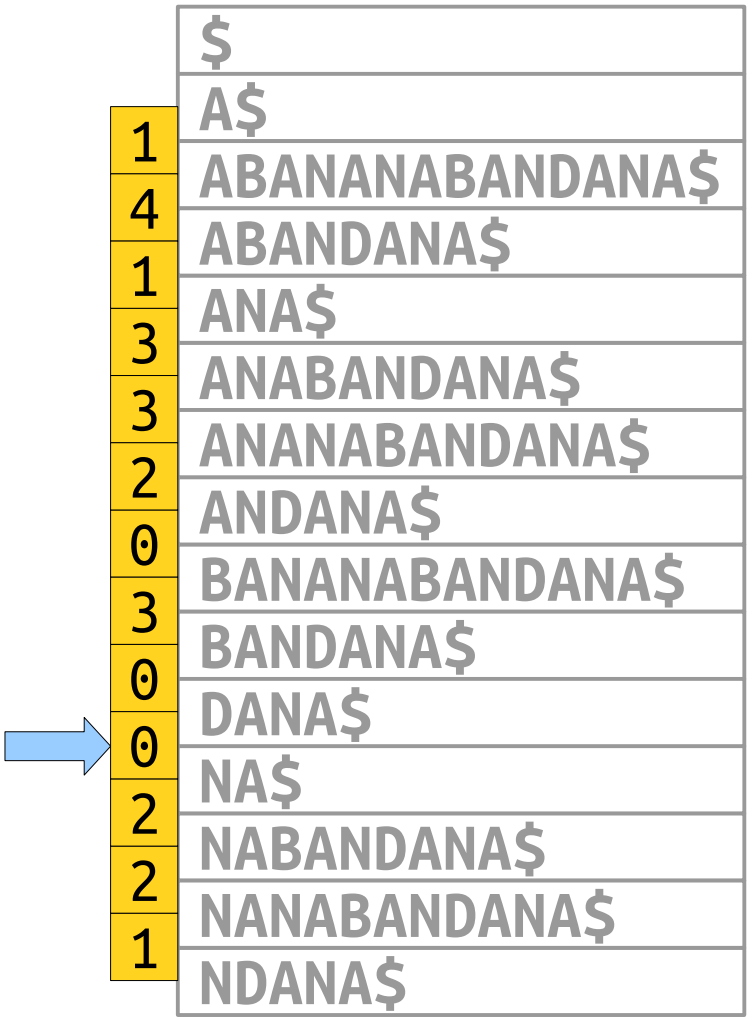

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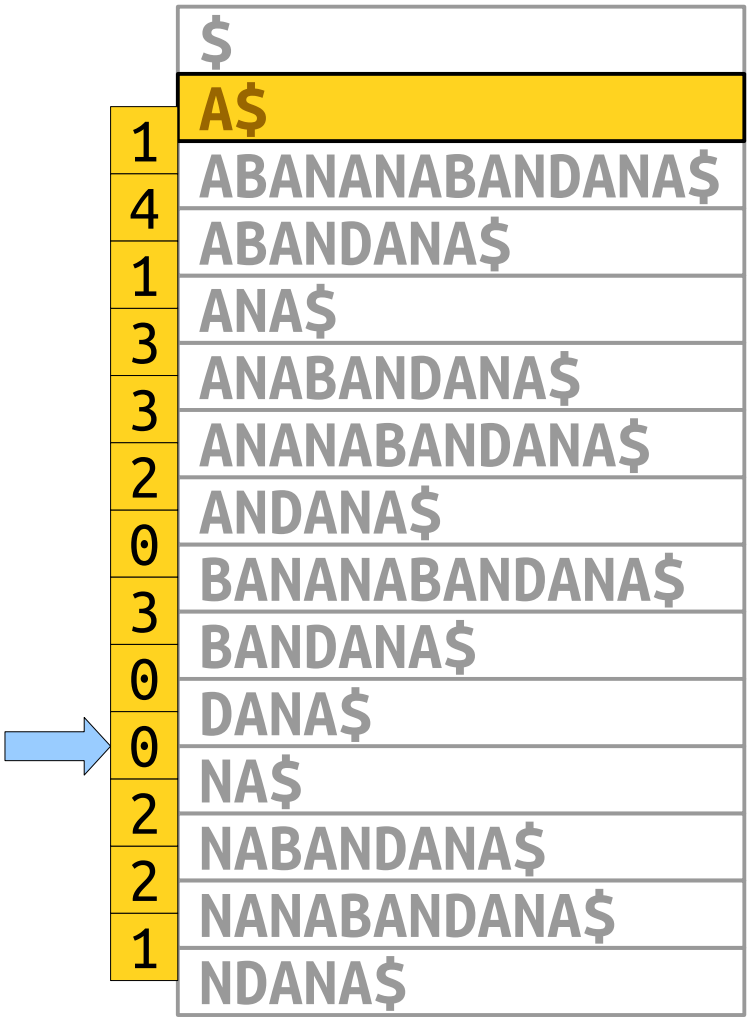

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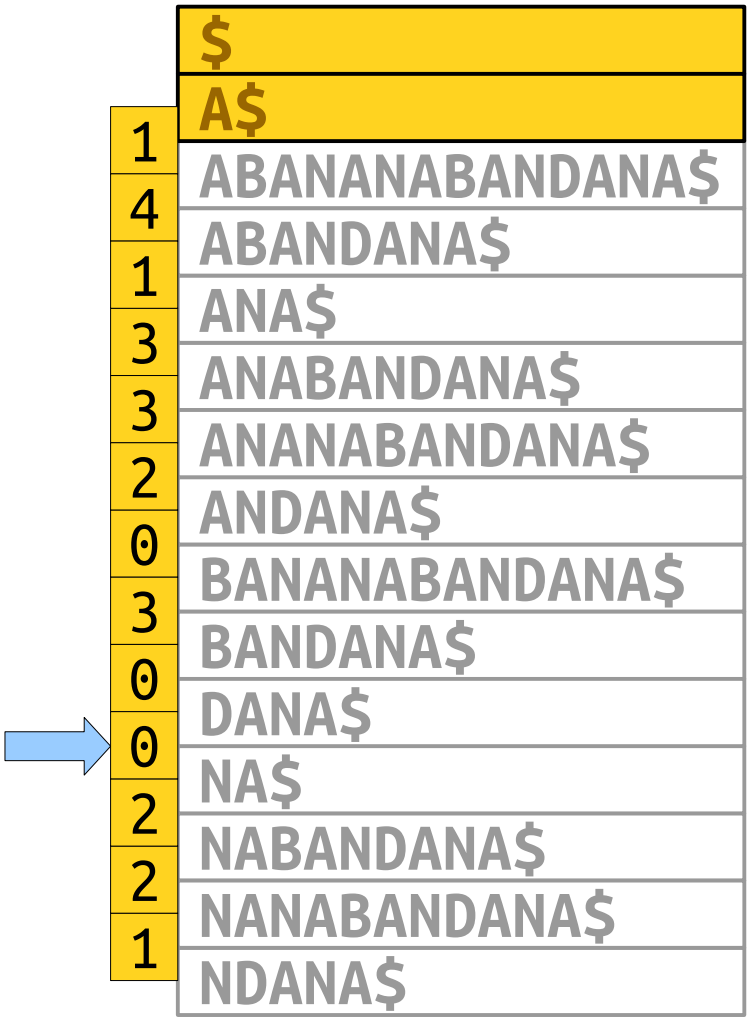

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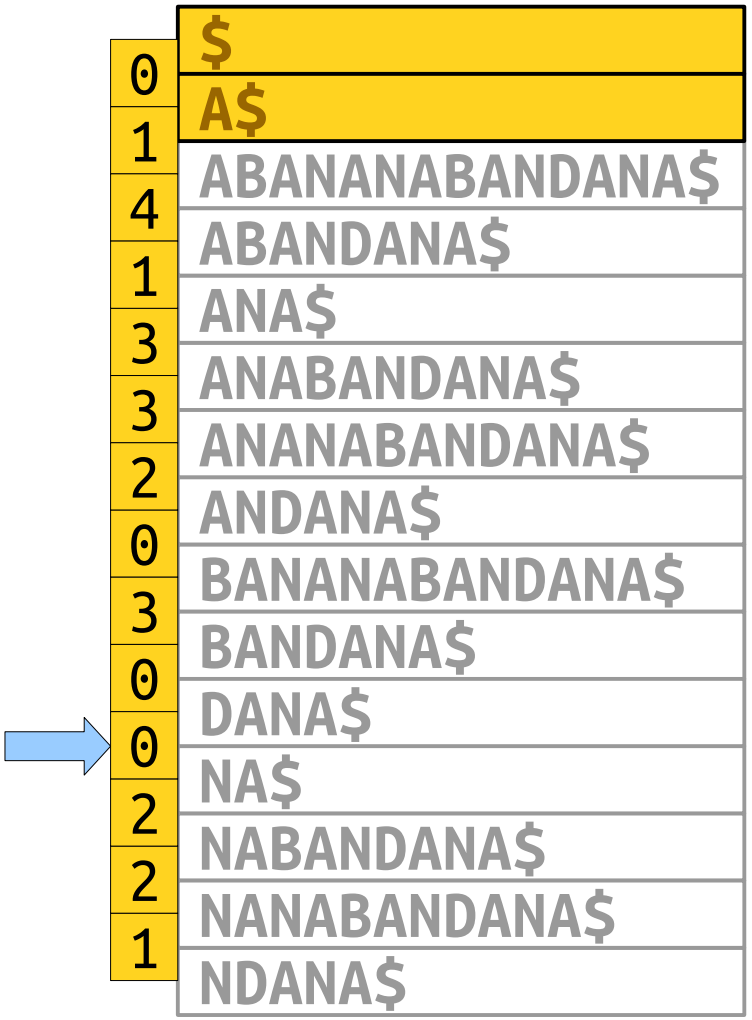

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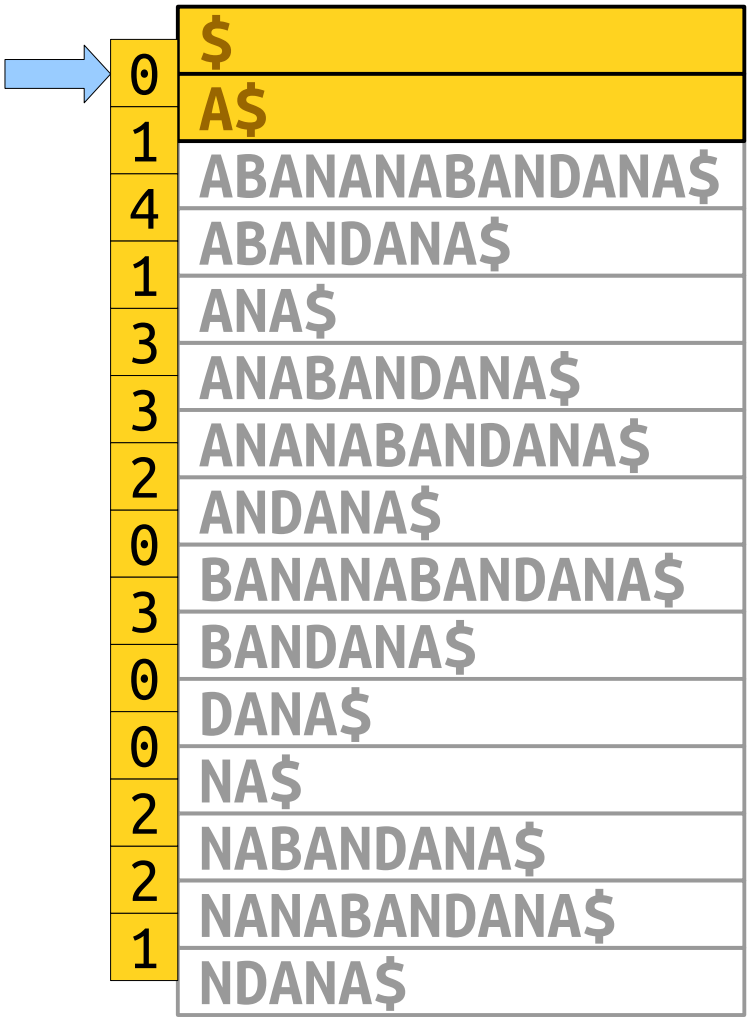

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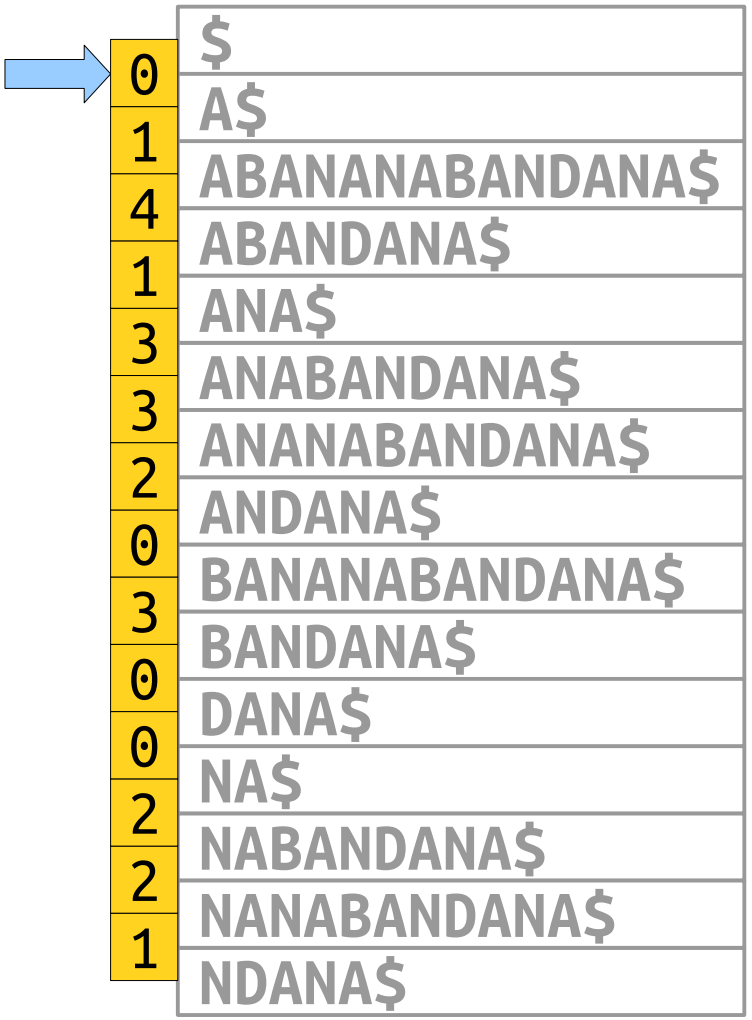

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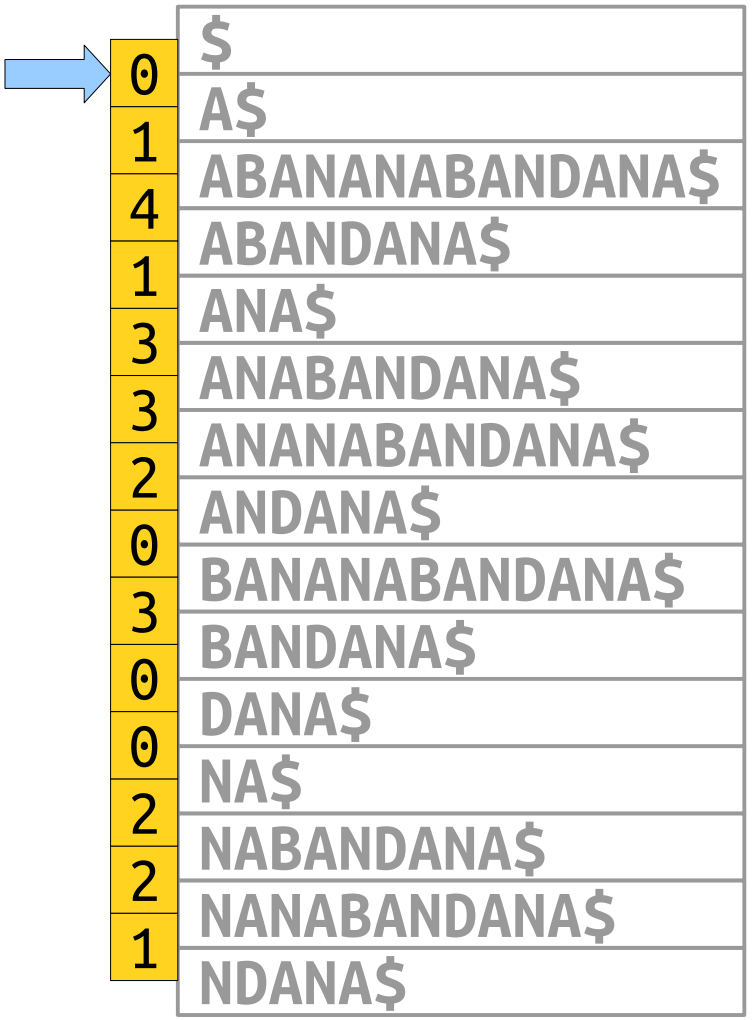

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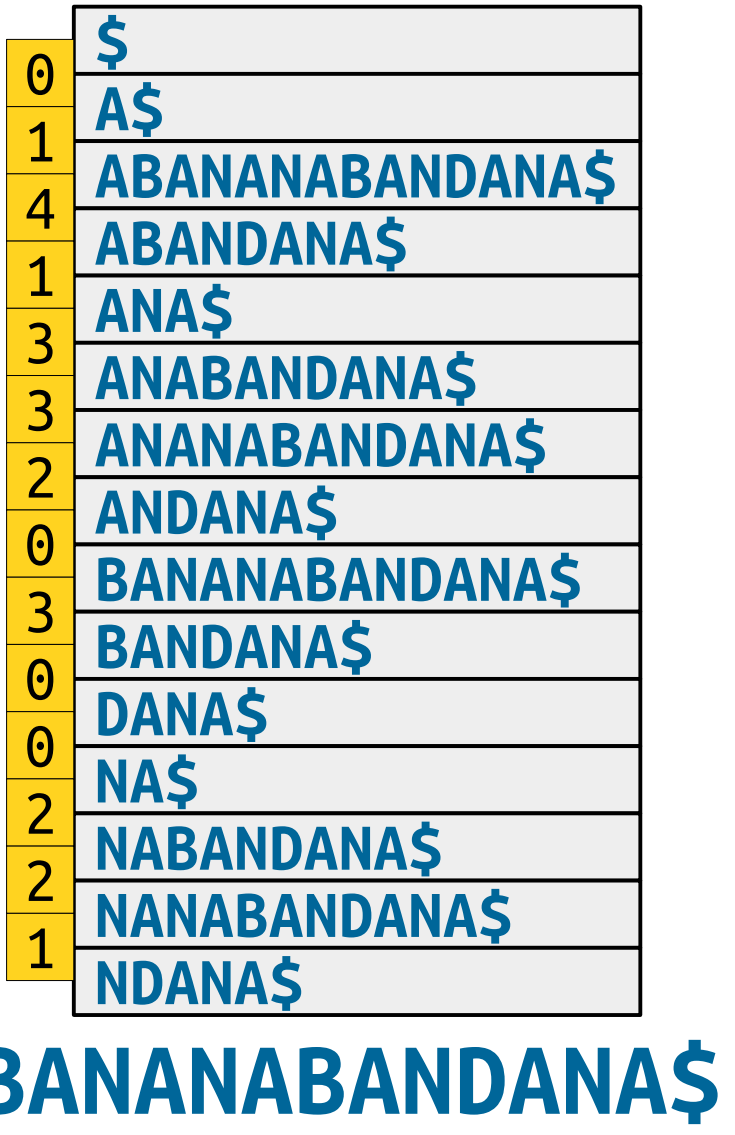

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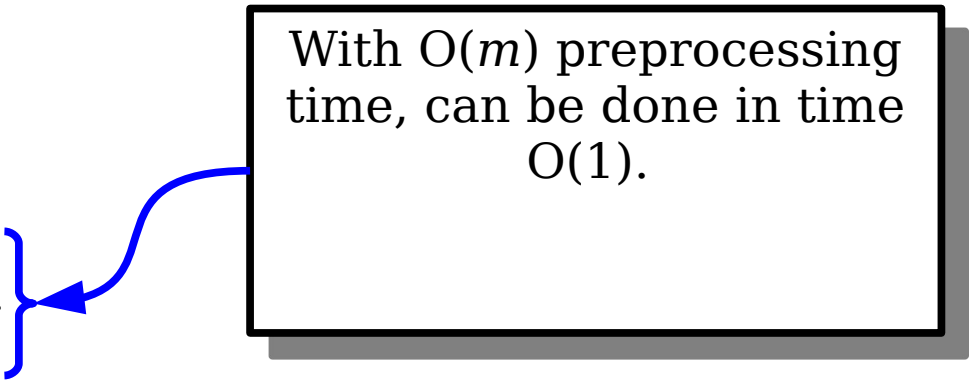

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How would you do this?

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Claim: Across all iterations, this step takes a total of O(*m*) time.

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Total runtime: O(***m***).

More to Explore

- We could easily spend a whole quarter talking about suffix arrays. Here's what we didn't cover:
  - ***Bottom-up tree simulations:*** Using LCP arrays, you can simulate any O(***m***)-time suffix tree algorithm that works with a bottom-up DFS in time O(***m***).
  - ***Faster substring searching:*** Using LCP arrays, plus RMQ, you can improve the cost of a substring search to O(***n*** + ***z*** + log ***m***).
  - ***Burrows-Wheeler transforms:*** Suffix arrays, plus LCP arrays, can be used to significantly improve the performance of text compressors.
- Check these out – they're super interesting!

Next Time

- ***Amortized Analysis***
  - Lying in a runtime analysis.
- ***The Potential Method***
  - Physics meets data structure design.