TRIE

Motivation:

- hashmaps are very efficient so far: we can achieve **O(1)** running time for the most important operations

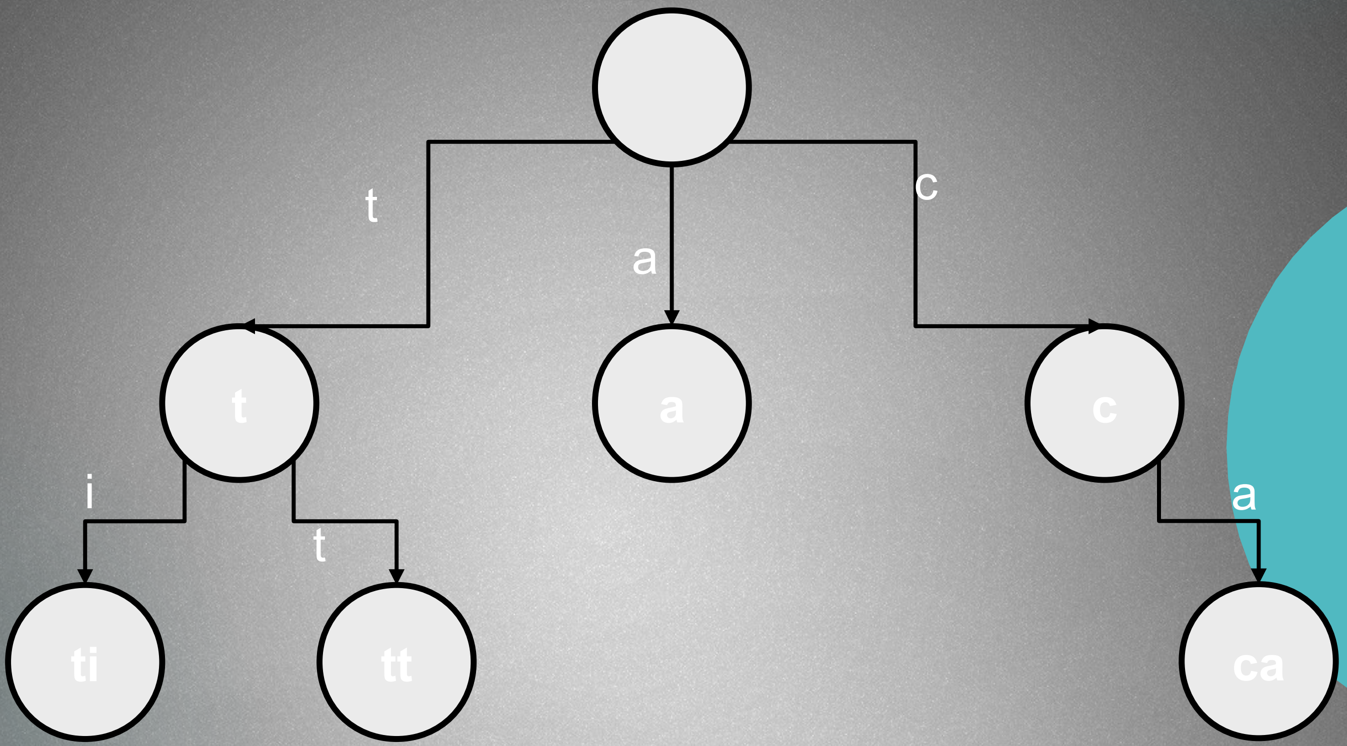
- does not support sorting + hashfunction is usually not perfect: we would like to construct a data structure where search and insert operations have running time proportional to the length of the key !!!

  ~ hashmap worst case search: **O(N)**

- we would like to get rid of collisions: this can be solved with tries + add another feature: sorting !!!

Tries

- Trie / radix tree / prefix tree
- It is a data structure to implement associative arrays
- The keys are usually strings
- Unlike BST no node in the tree stores the key associated with that given node → its position in the tree defines the key with which it is associated
- All the descendants of a node have a common prefix of the string associated with that node, and the root is associated with the empty string
- Values are not necessarily associated with every node // usually leaf nodes only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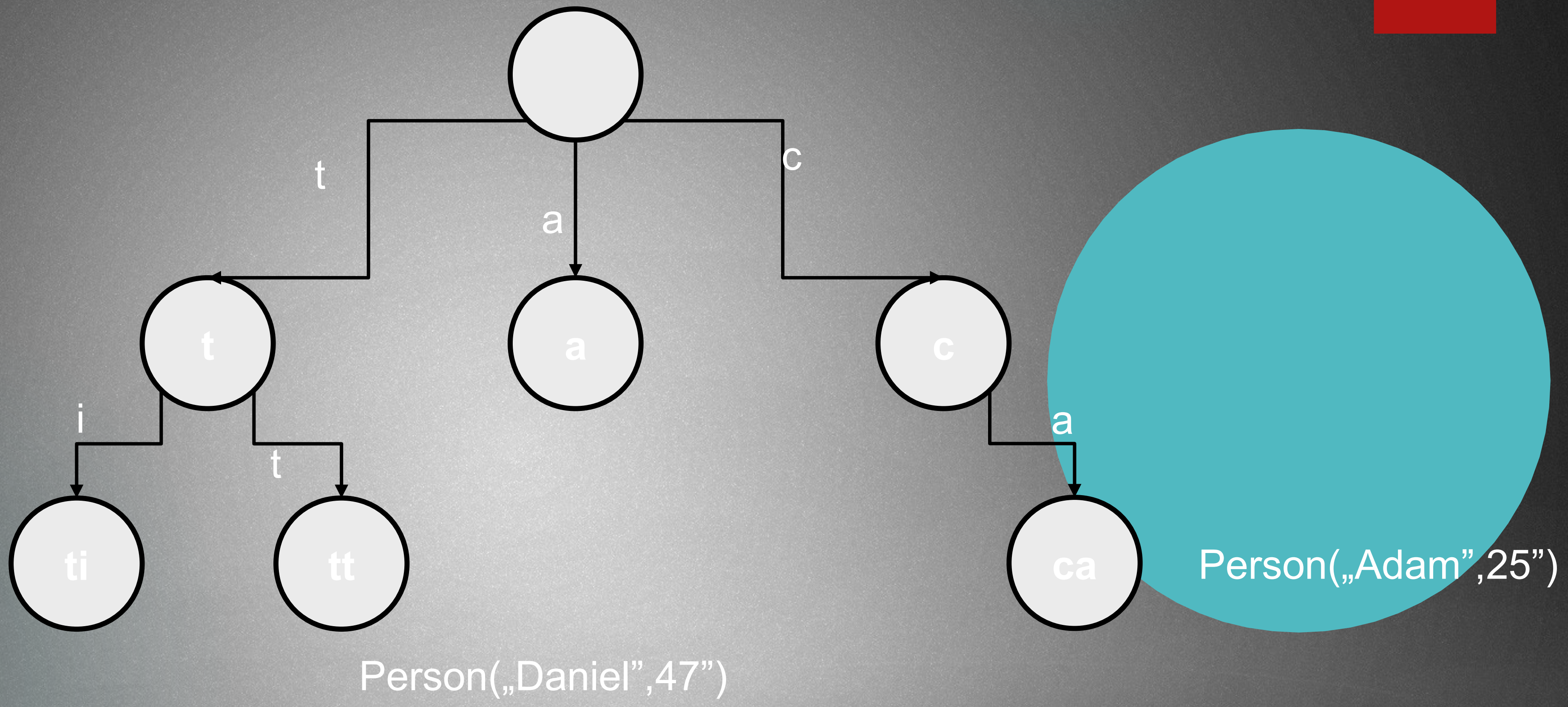
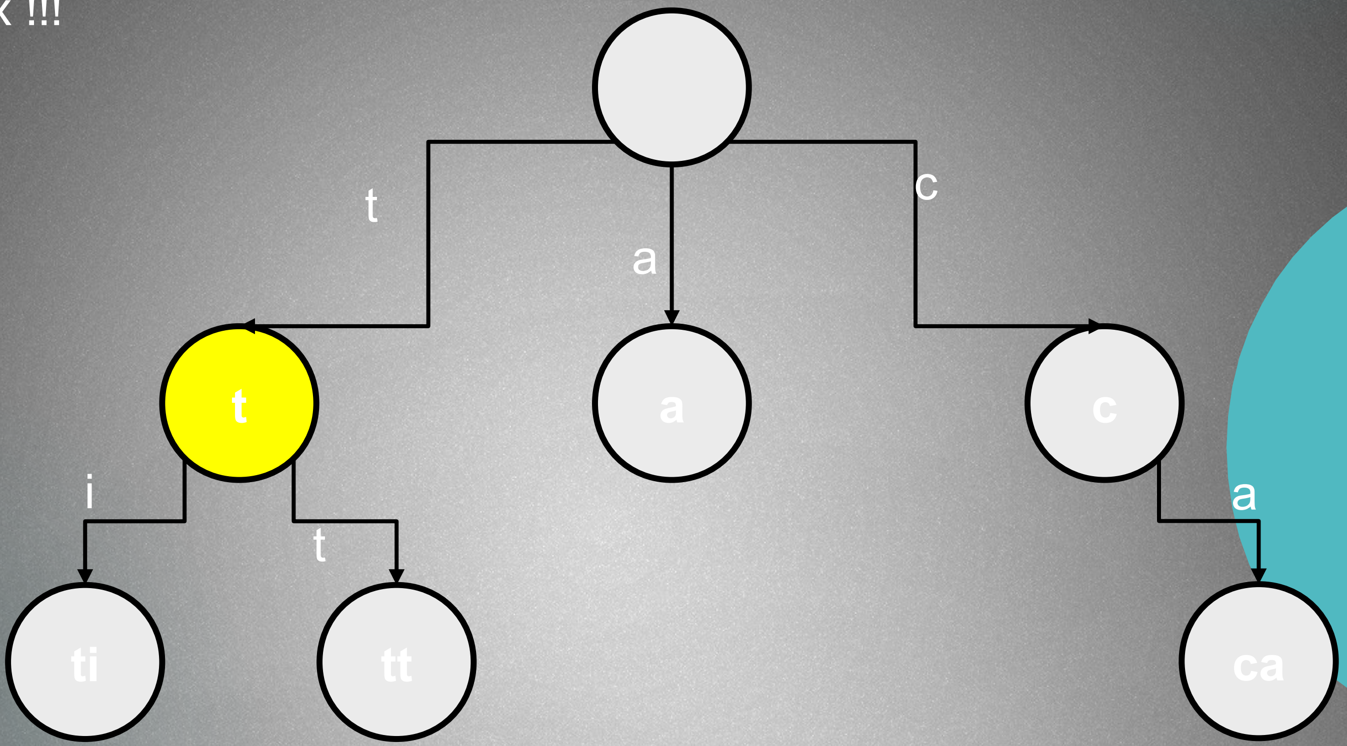


Like hashmaps: we have key-value pairs

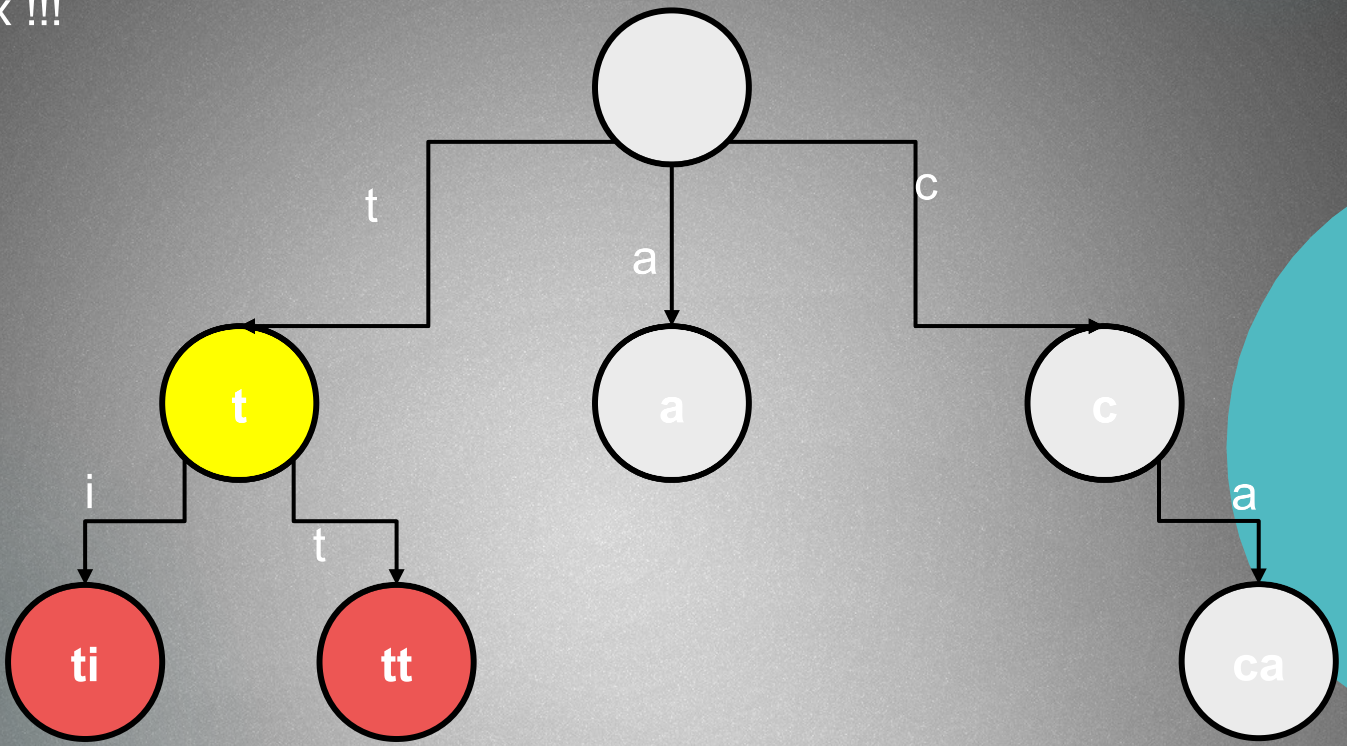
Key: tt → value: a person with name Daniel, age 47

Key: ca → value: a person with name Adam, age 25

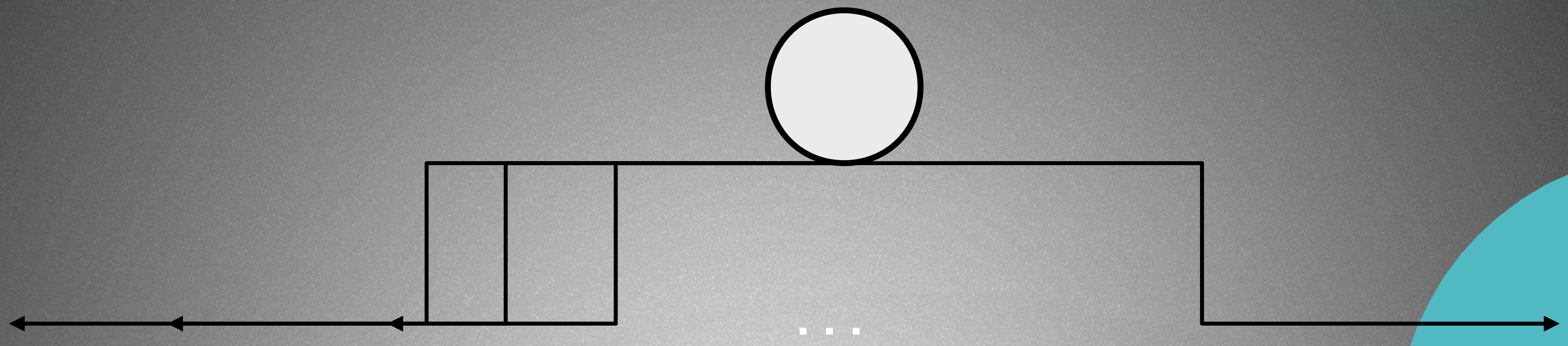
All the descendants of a node has a common prefix !!!



All the descendants of a node has a common prefix !!!



In general



In general we have as many pointers / edges from every node as the number of characters in the alphabet

We have to define an alphabet in advance + ALPHABET_SIZE

For example: in english alphabet there are 26 characters, so

ALPHABET_SIZE = 26 → 26 pointers from every node !!!

In general

```
class Node {
	value
	children Node[ALPHABET_SIZE]
}
```

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ALPHABET_SIZE = 26 → 26 pointers from every node !!!

MOST OF THE TIME, WE DO NOT NEED 26 CHILD NODES

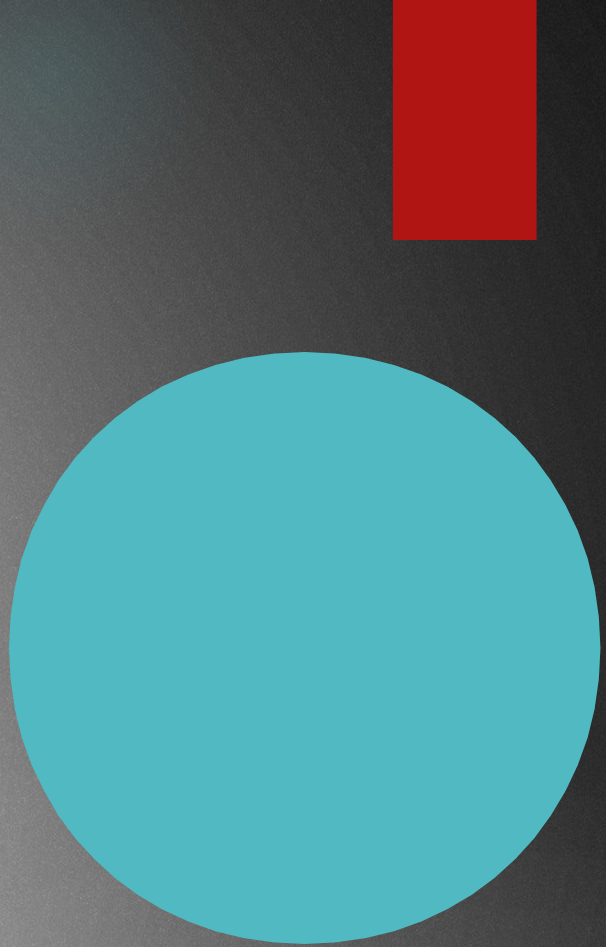
MEMORY INEFFICIENT !!!

Running time – memory tradeoff: it is fast but needs lots of memory (slow, but memory friendly)

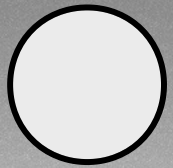
- With the help of tries we can search and sort strings very very efficiently
- The problem is that tries consume a lot of memory, so we should use ternary search trees instead which stores less references and null objects

INSERTION

<u>Insertion</u> insert(„apple”)



Insertion insert(„apple”)



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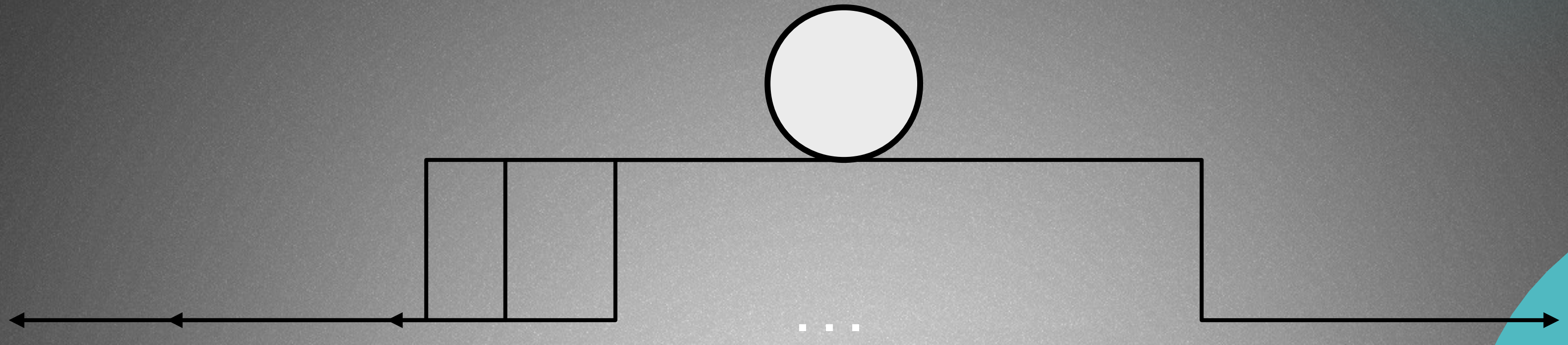
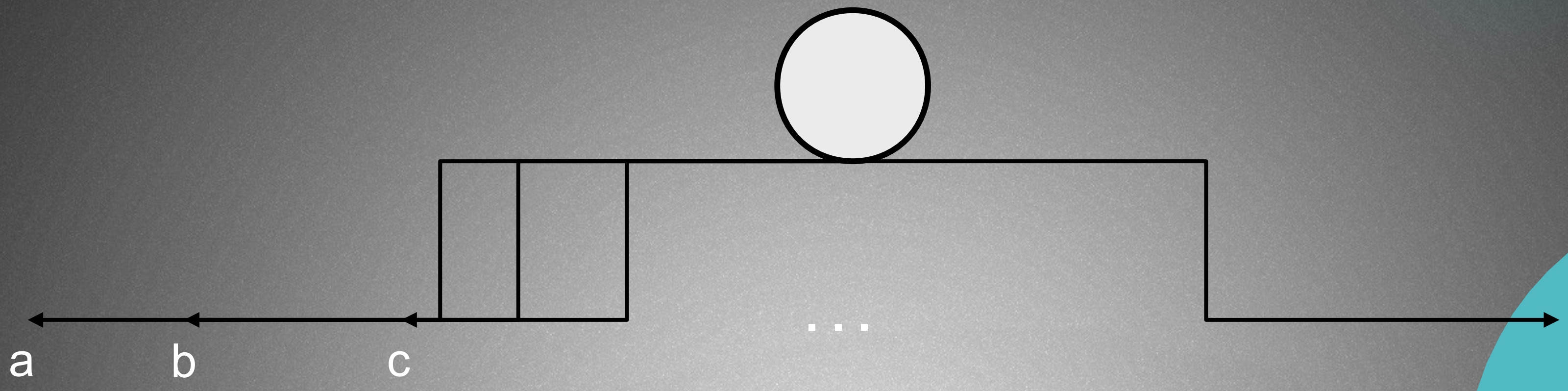


Basically it has 26 children pointing to all the characters in the alphabet → a, b, c …

Insertion insert(„apple”)



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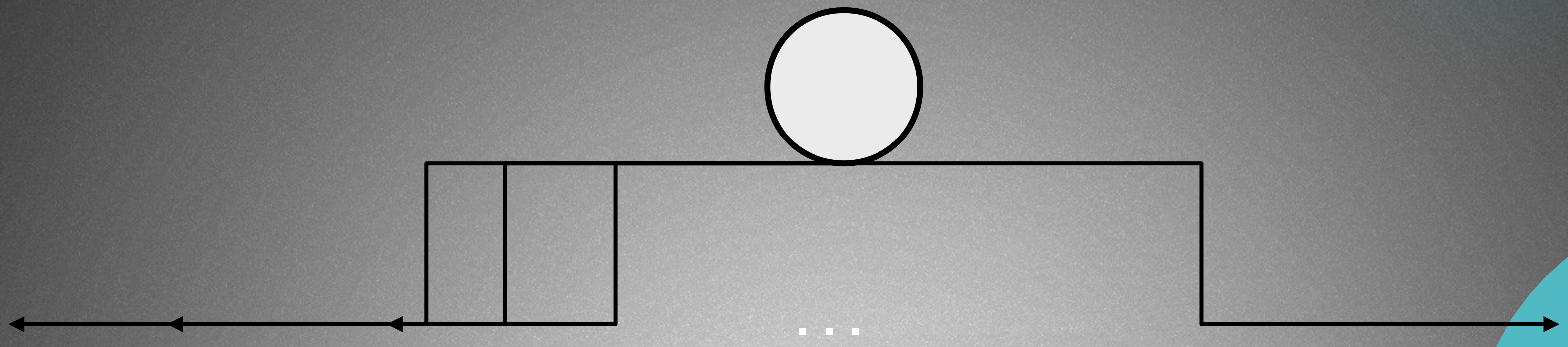
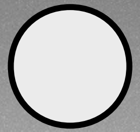


Basically it has 26 children pointing to all the characters in the alphabet → a, b, c …

BUT ther are null values at the beginning

When we insert a character → we insert to the right place

Insertion insert(„apple")



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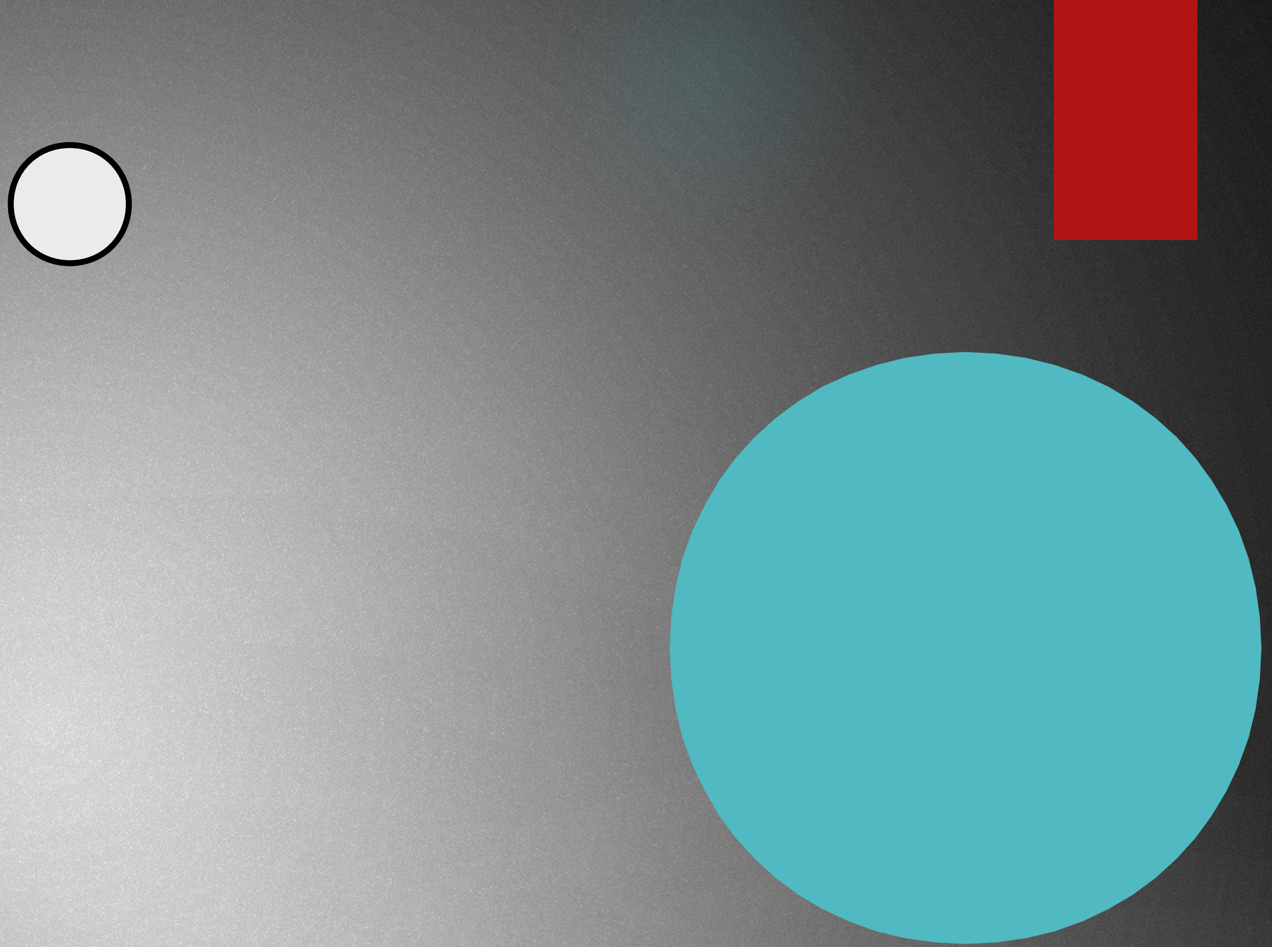

Insertion

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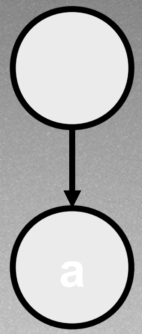
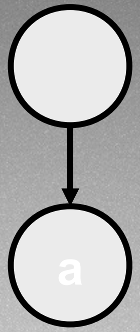


Insertion insert(„**ap**ple”)



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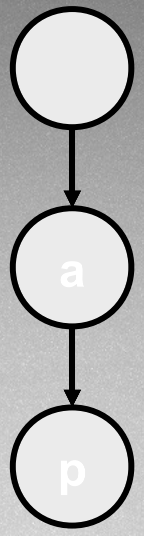

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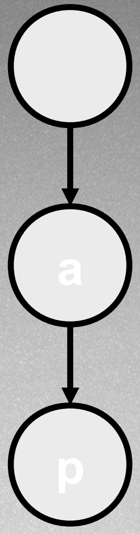

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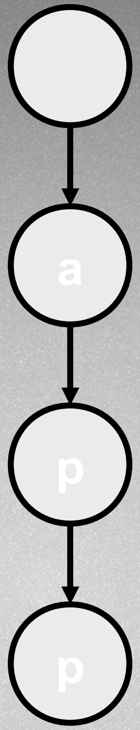

Insertion

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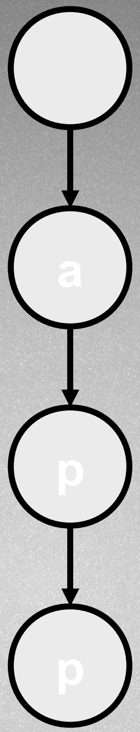

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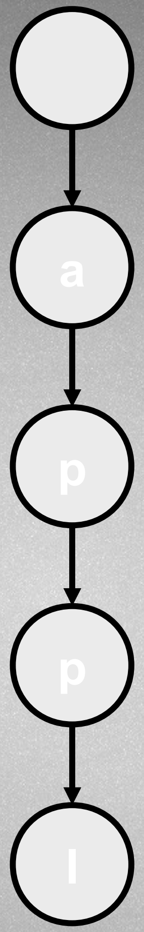

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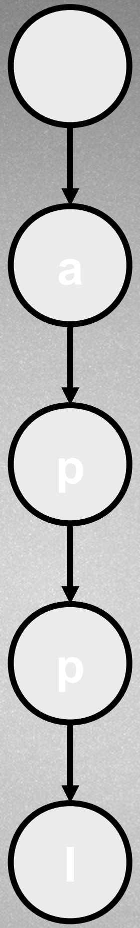

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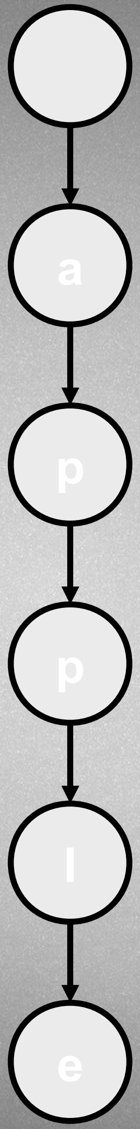

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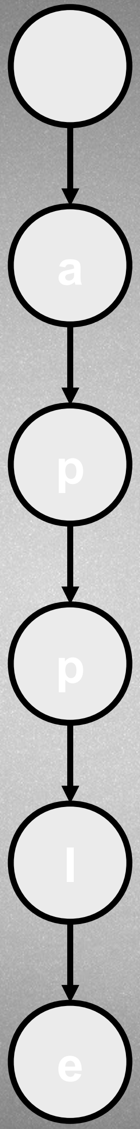
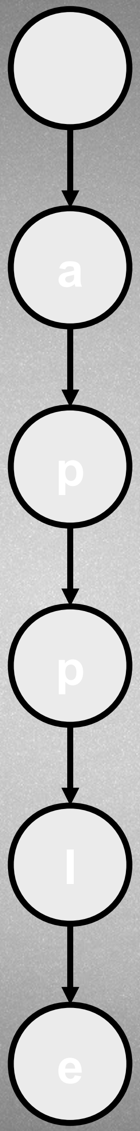


Insertion insert(„air”)



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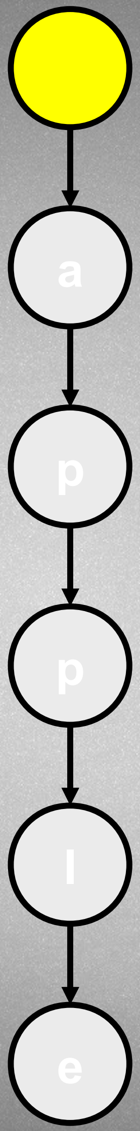

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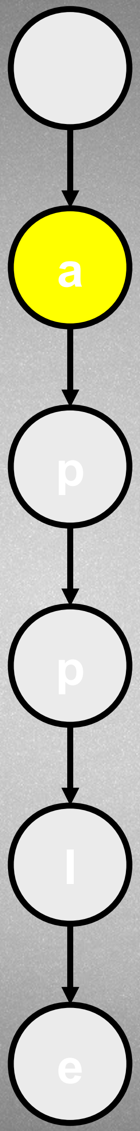

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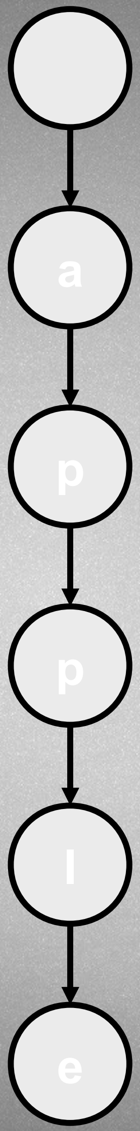

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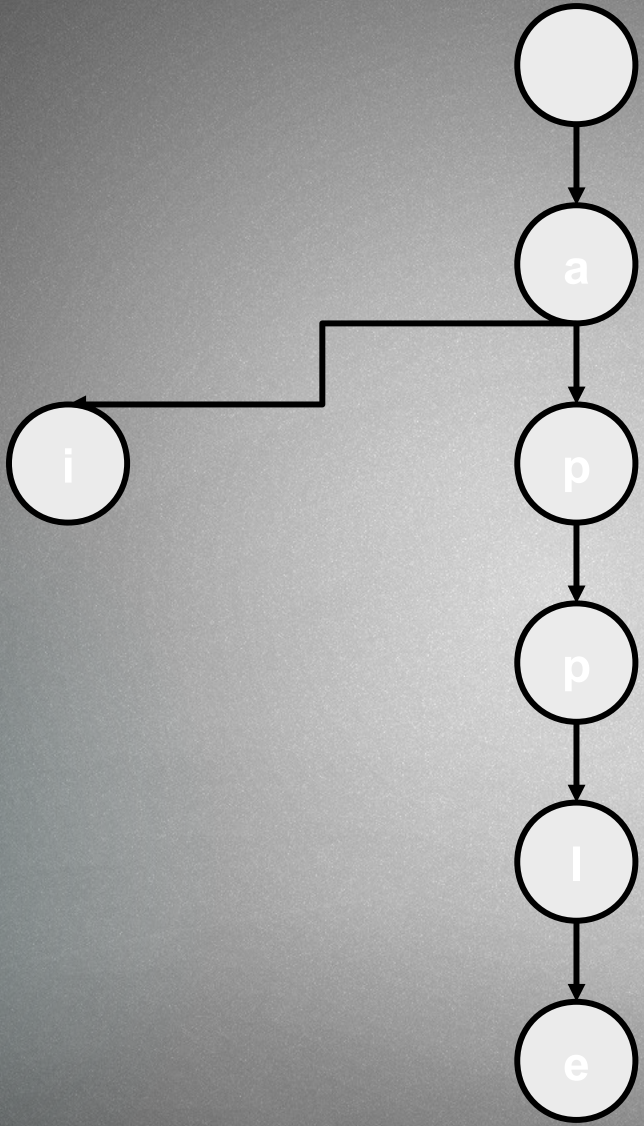

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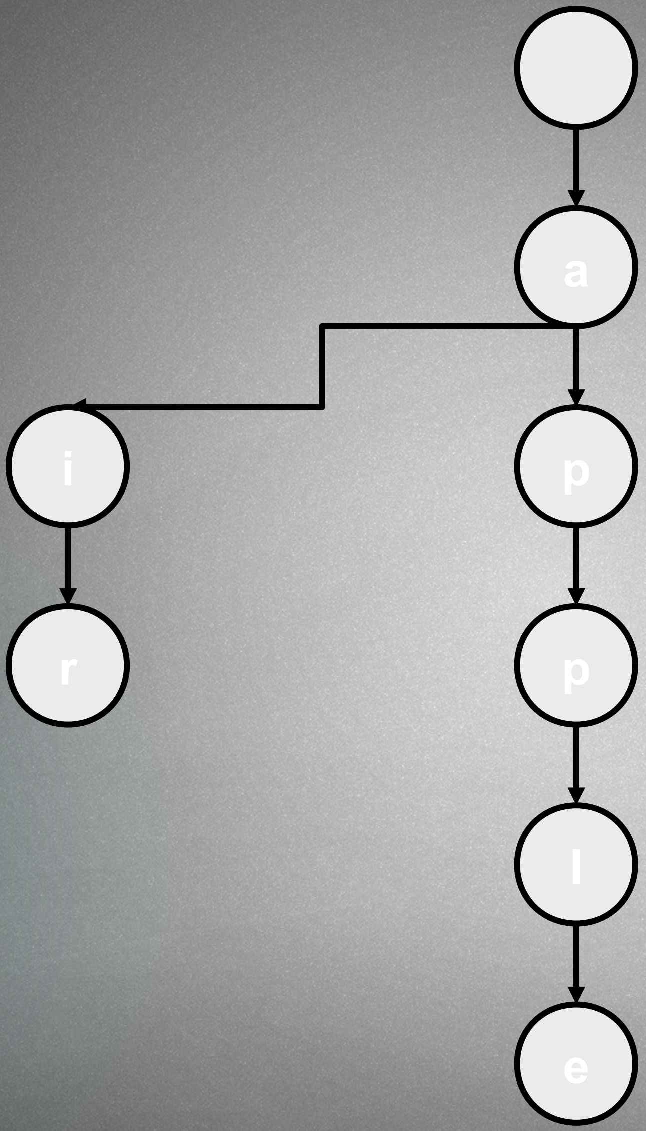

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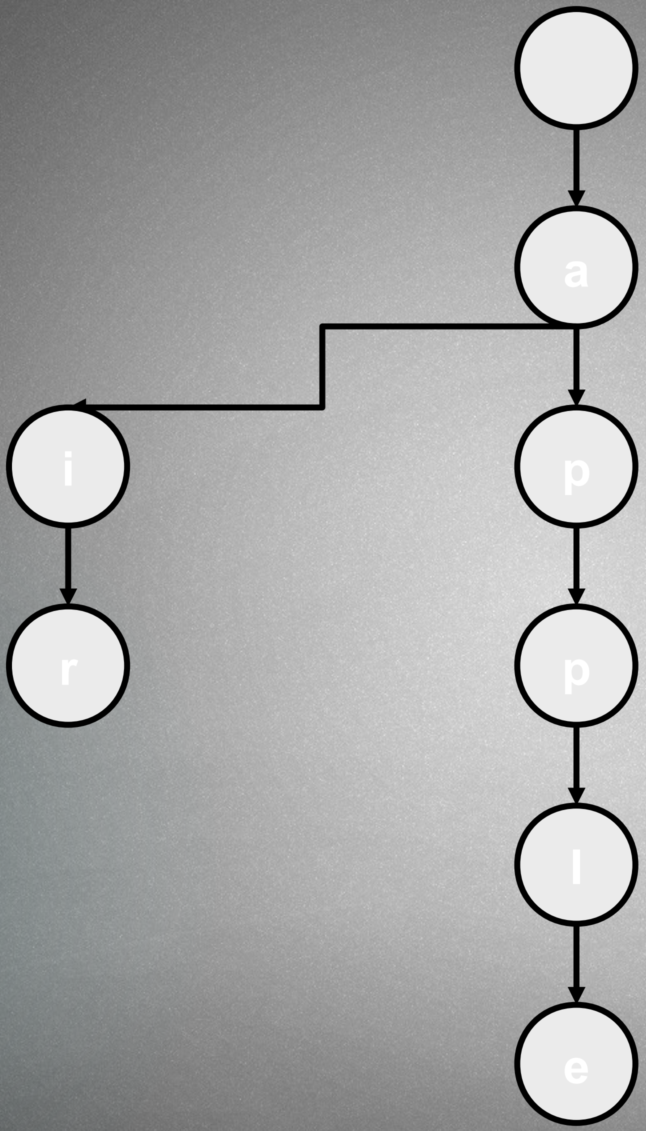

Insertion

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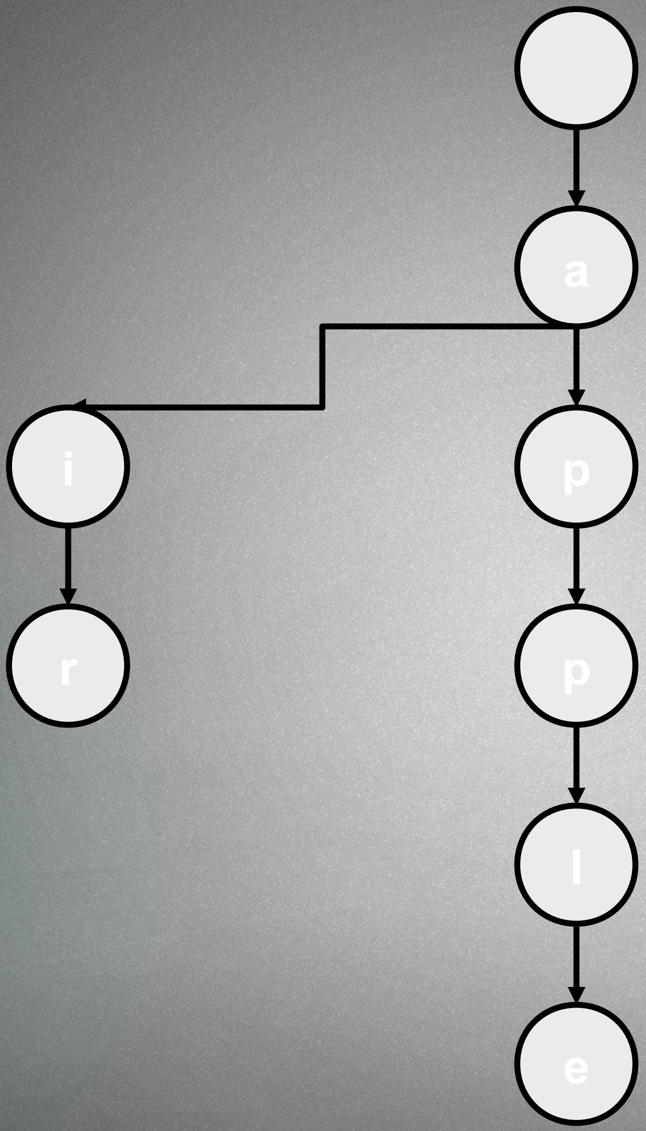

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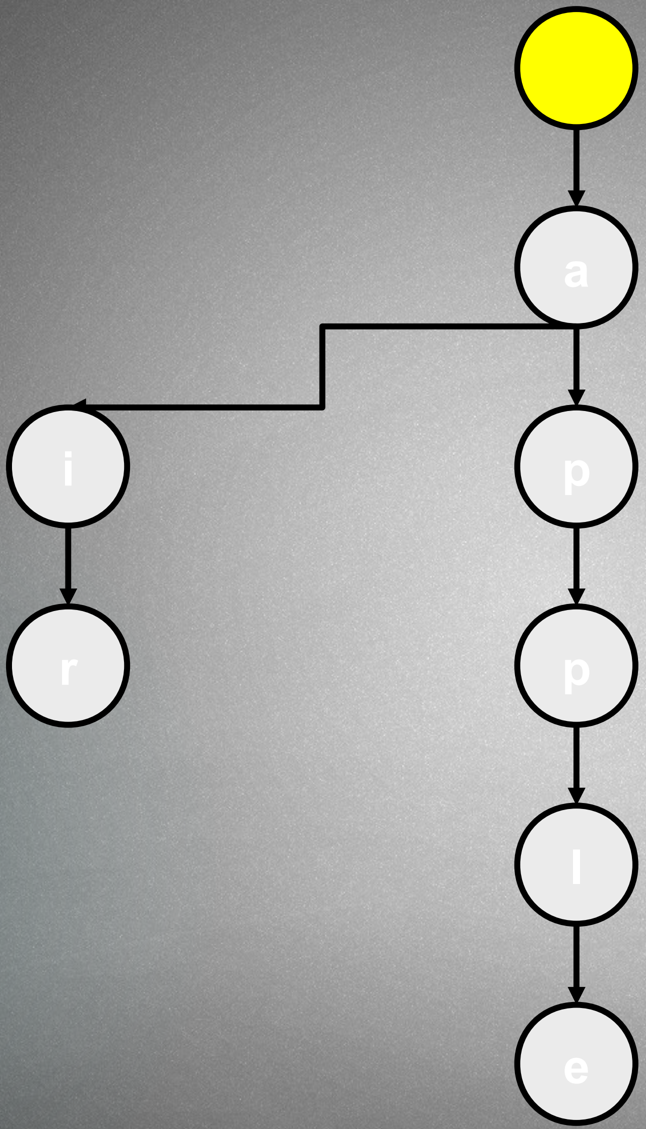

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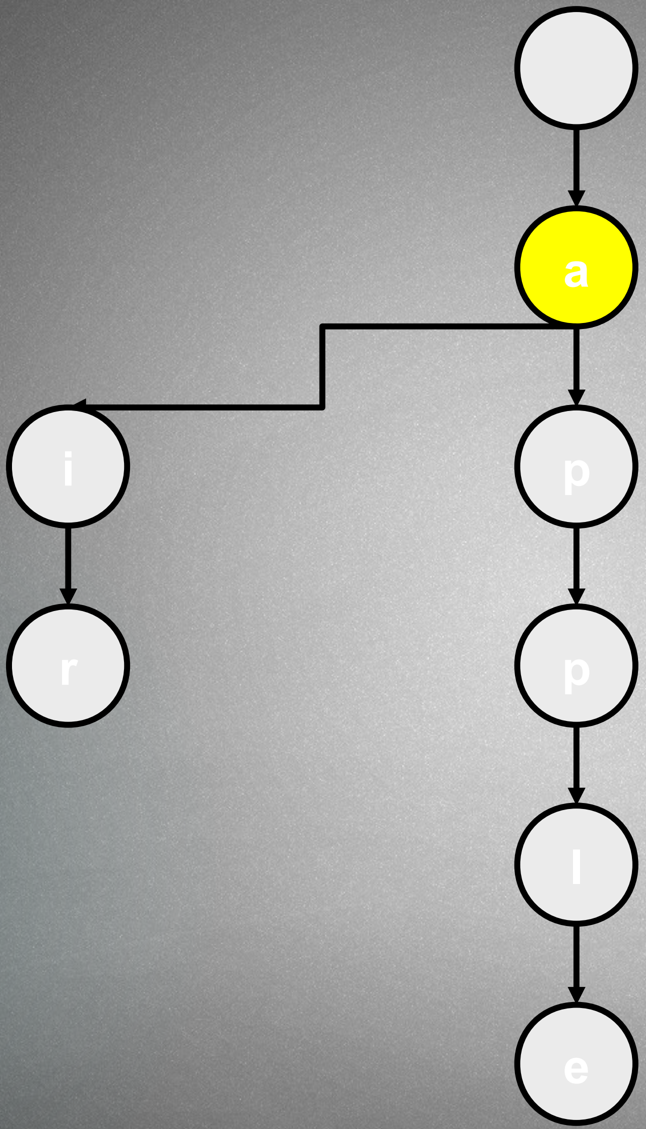
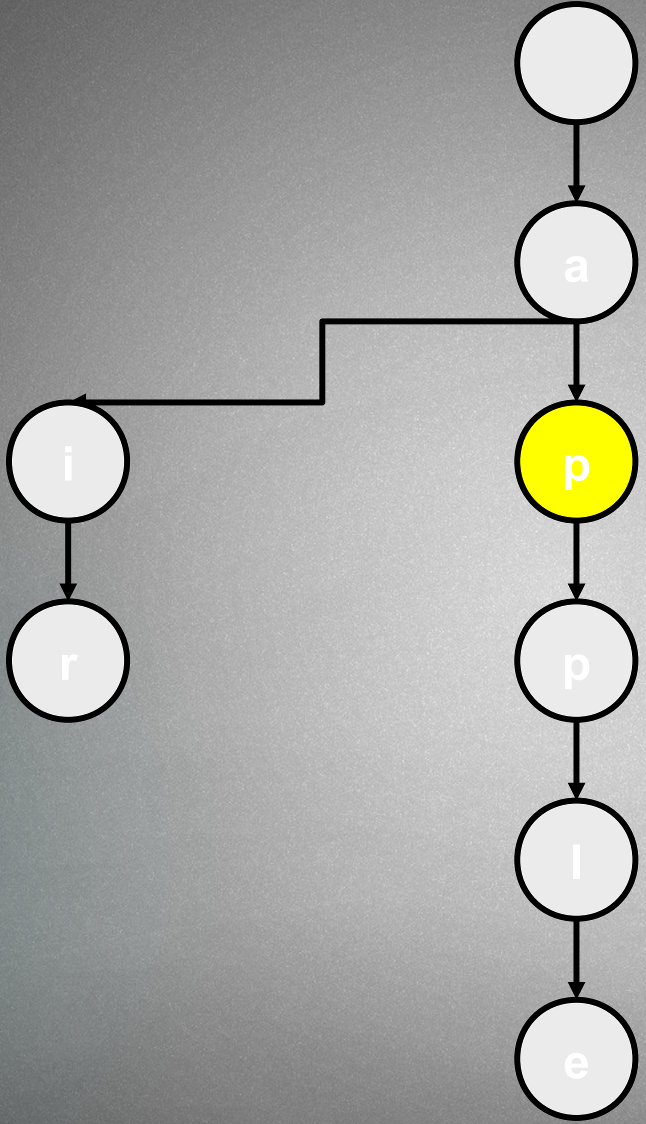


Insertion insert(„**ap**prove”)



Insertion

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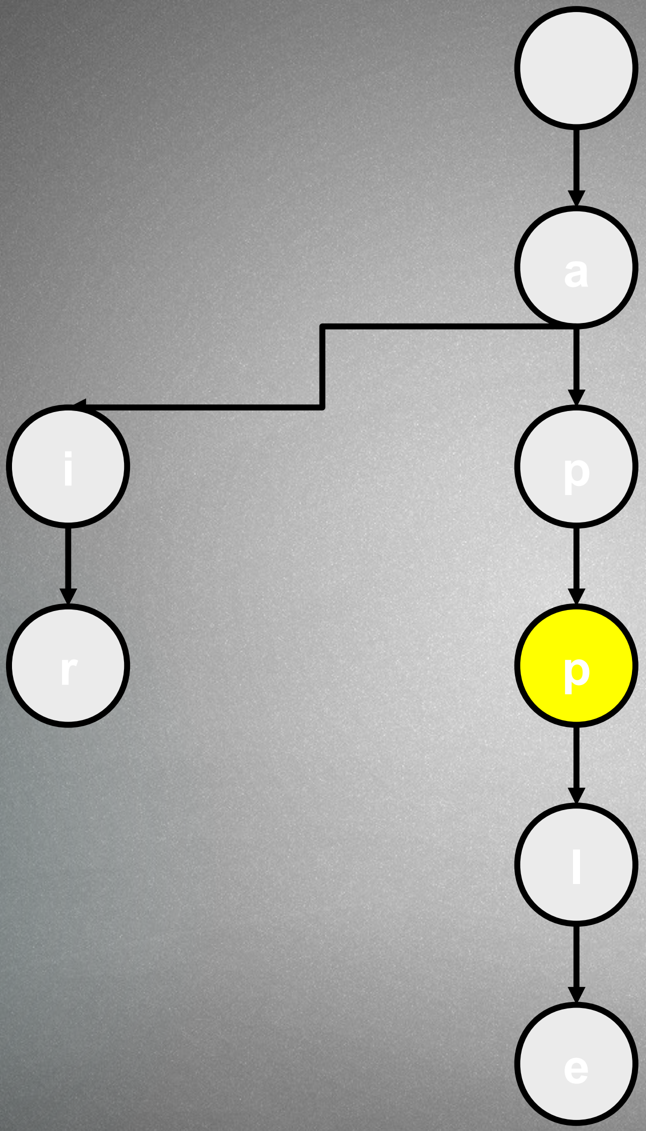

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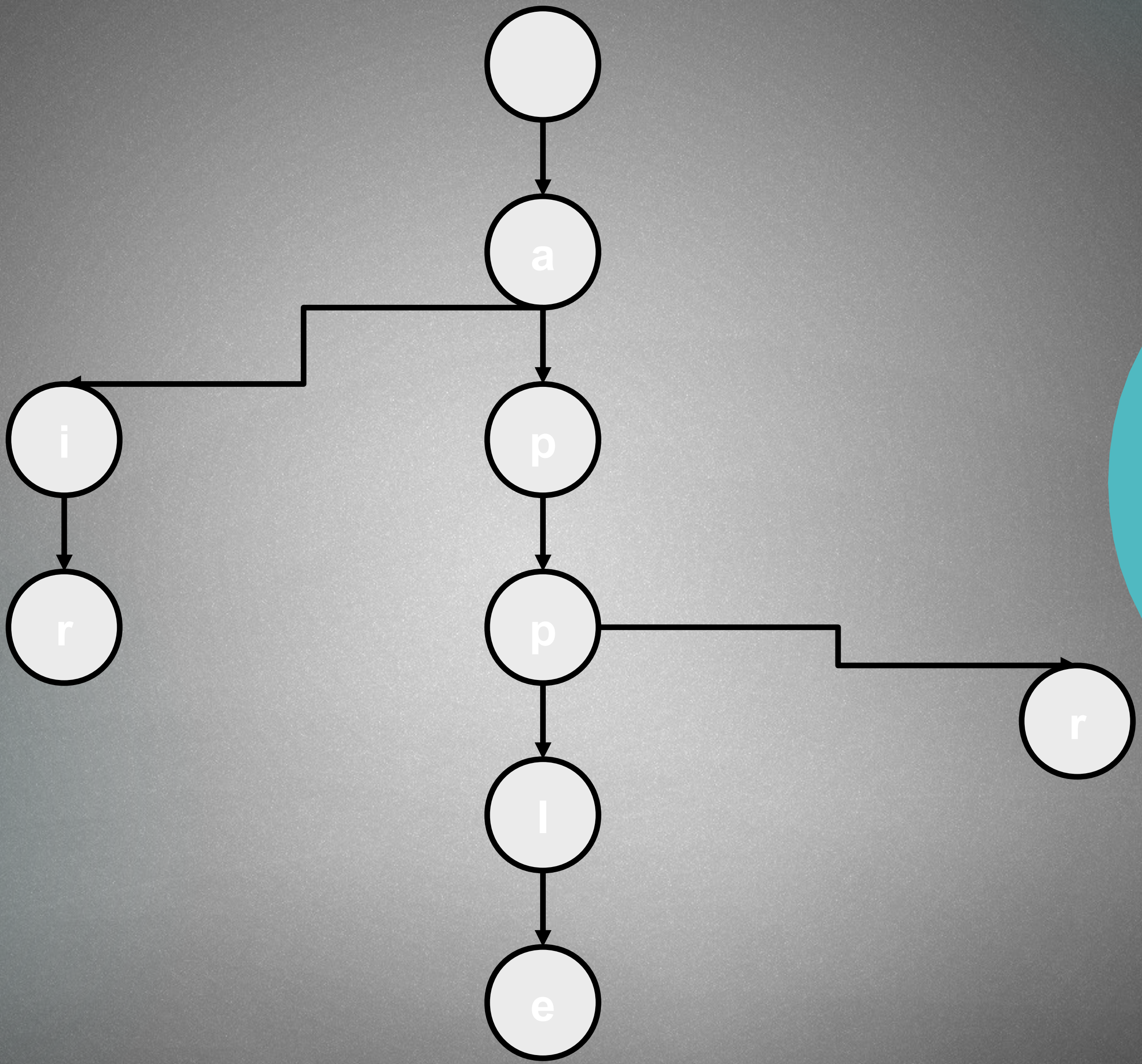

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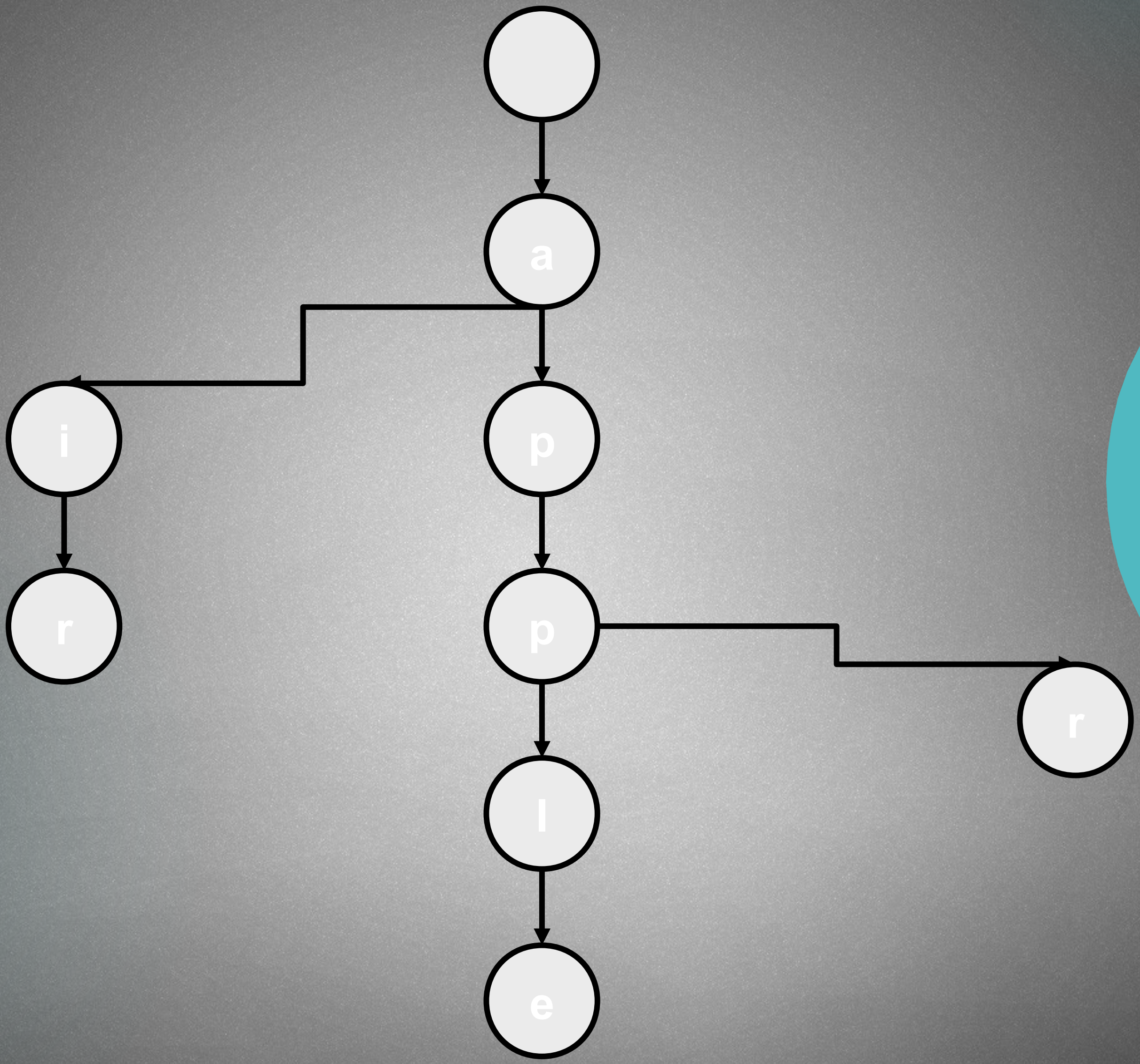

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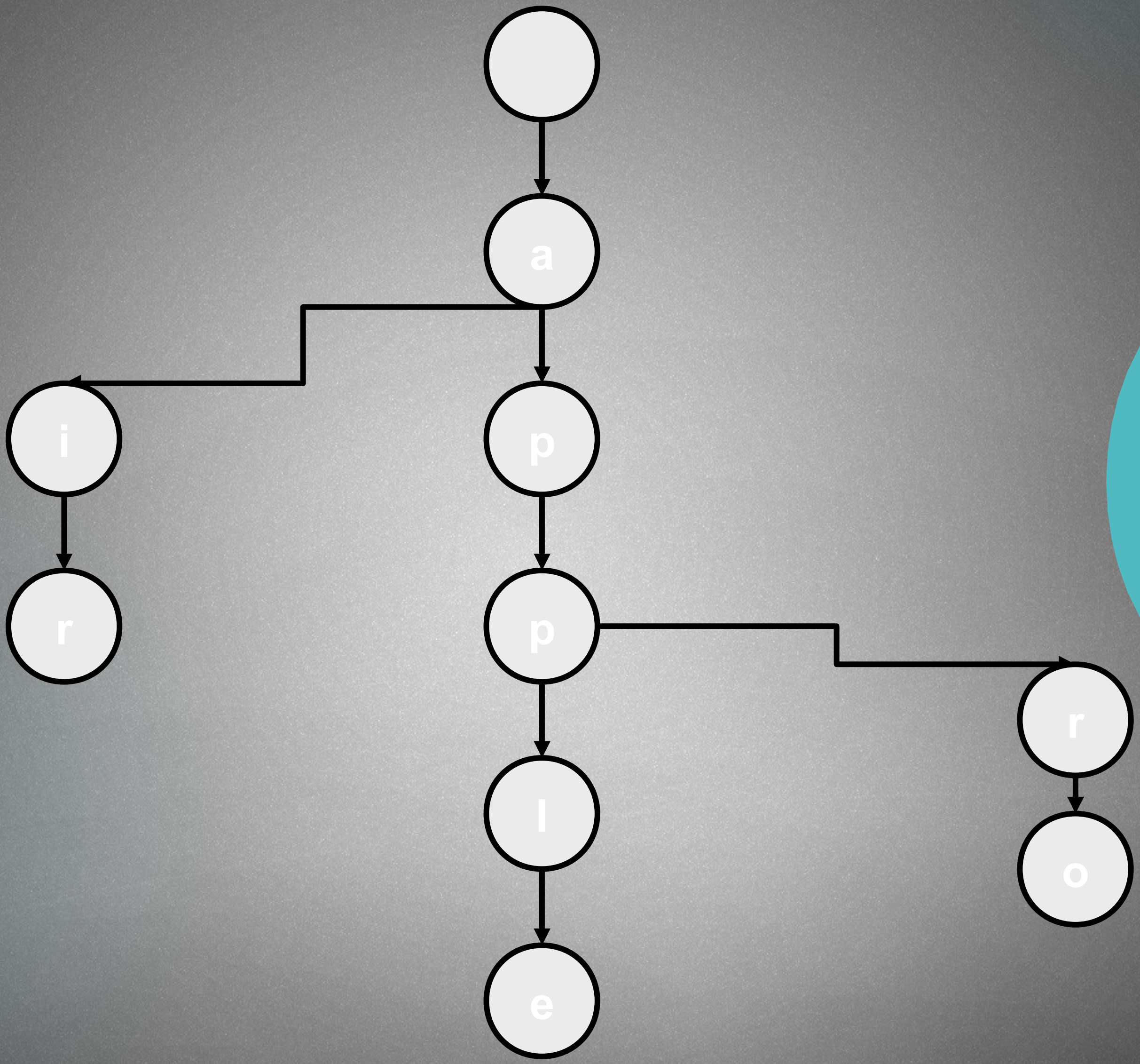

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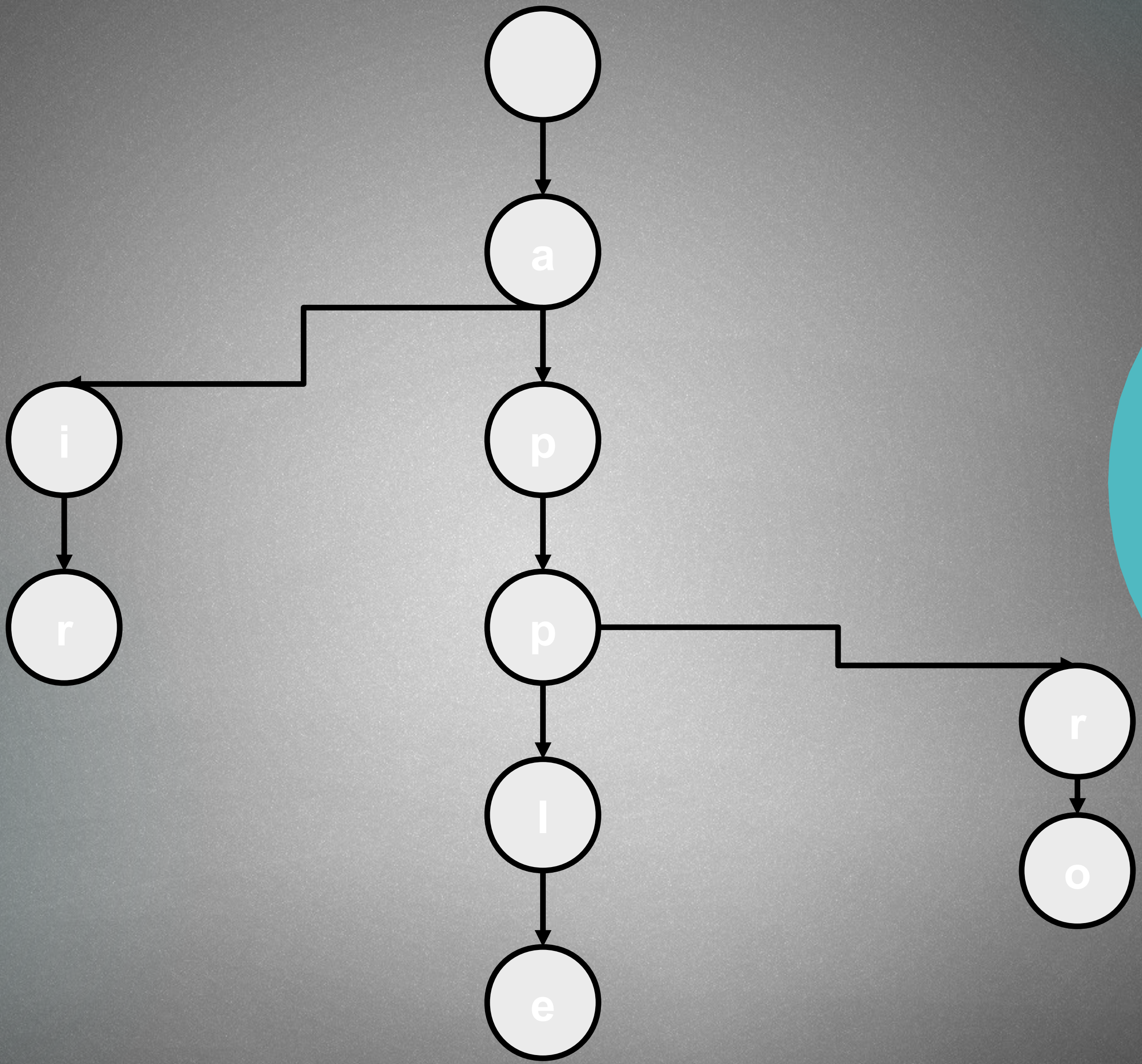

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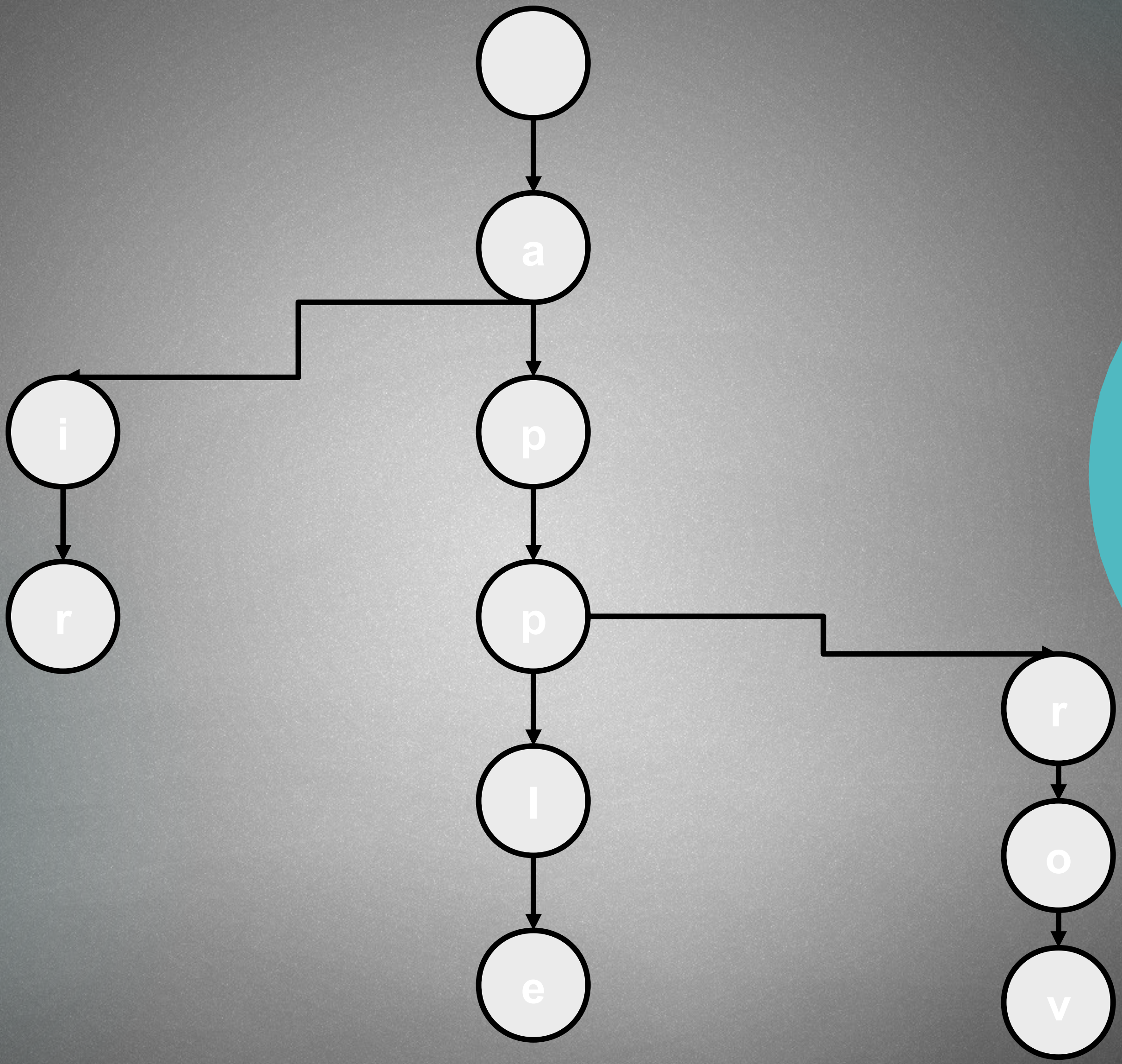

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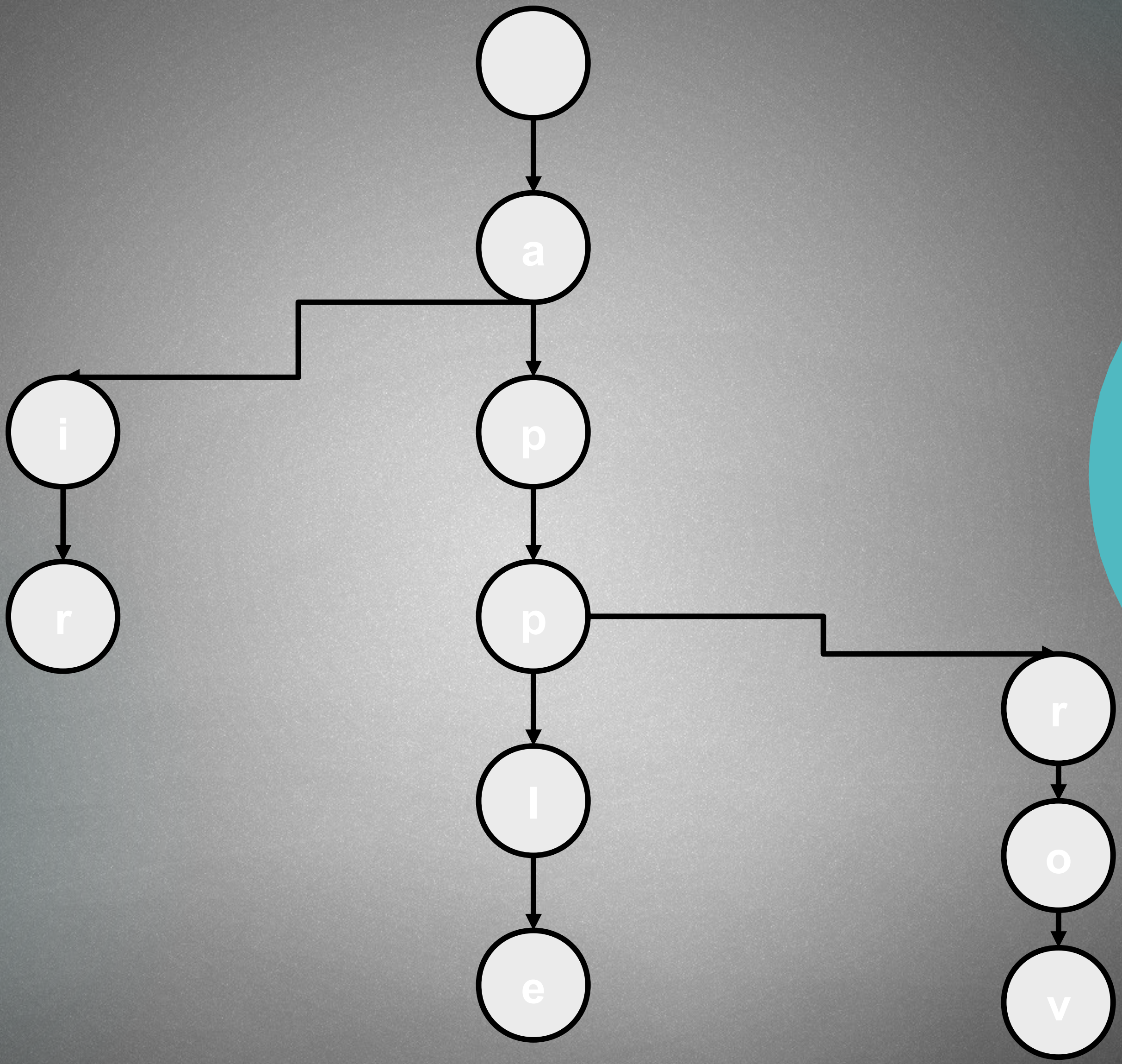

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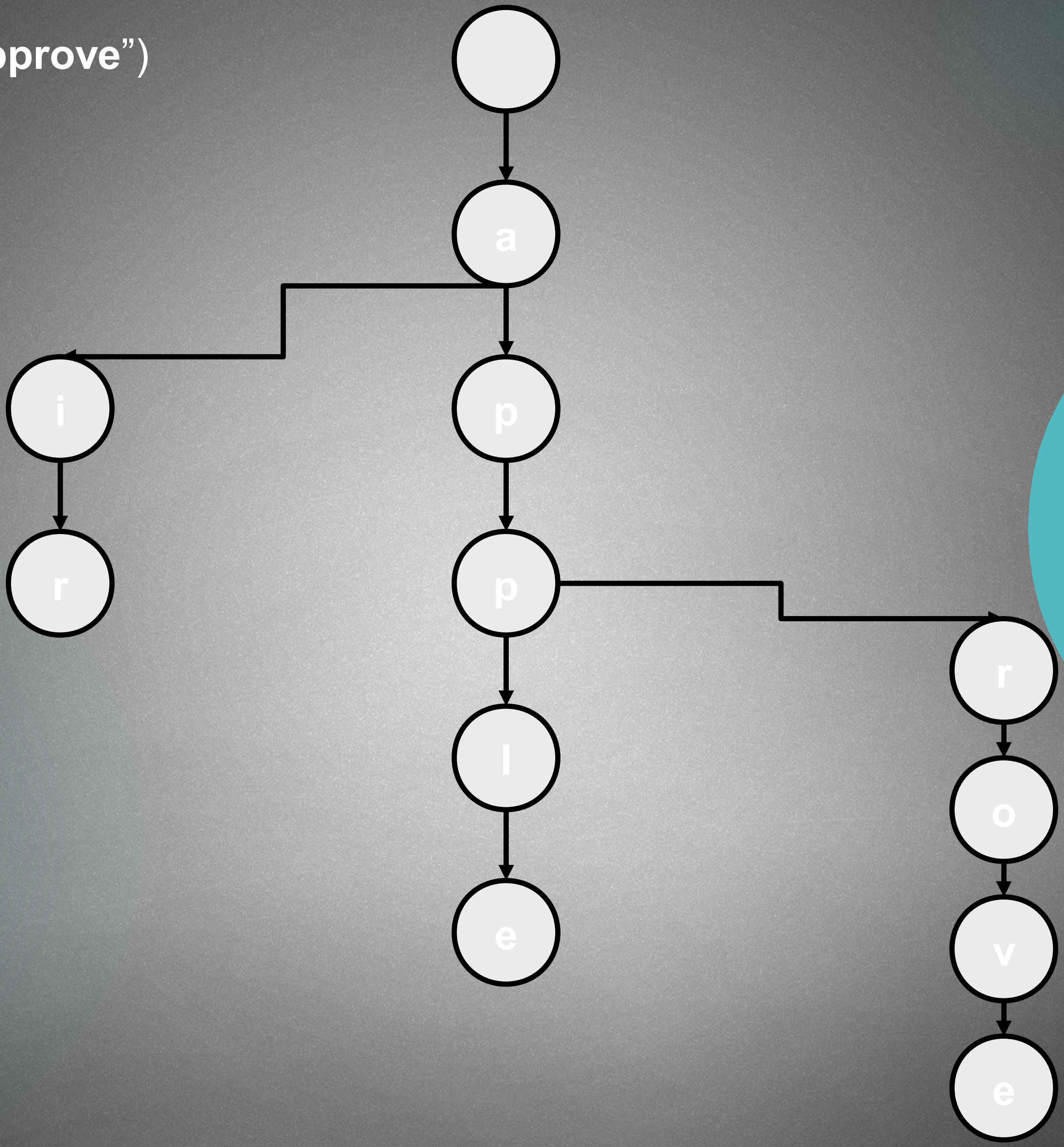

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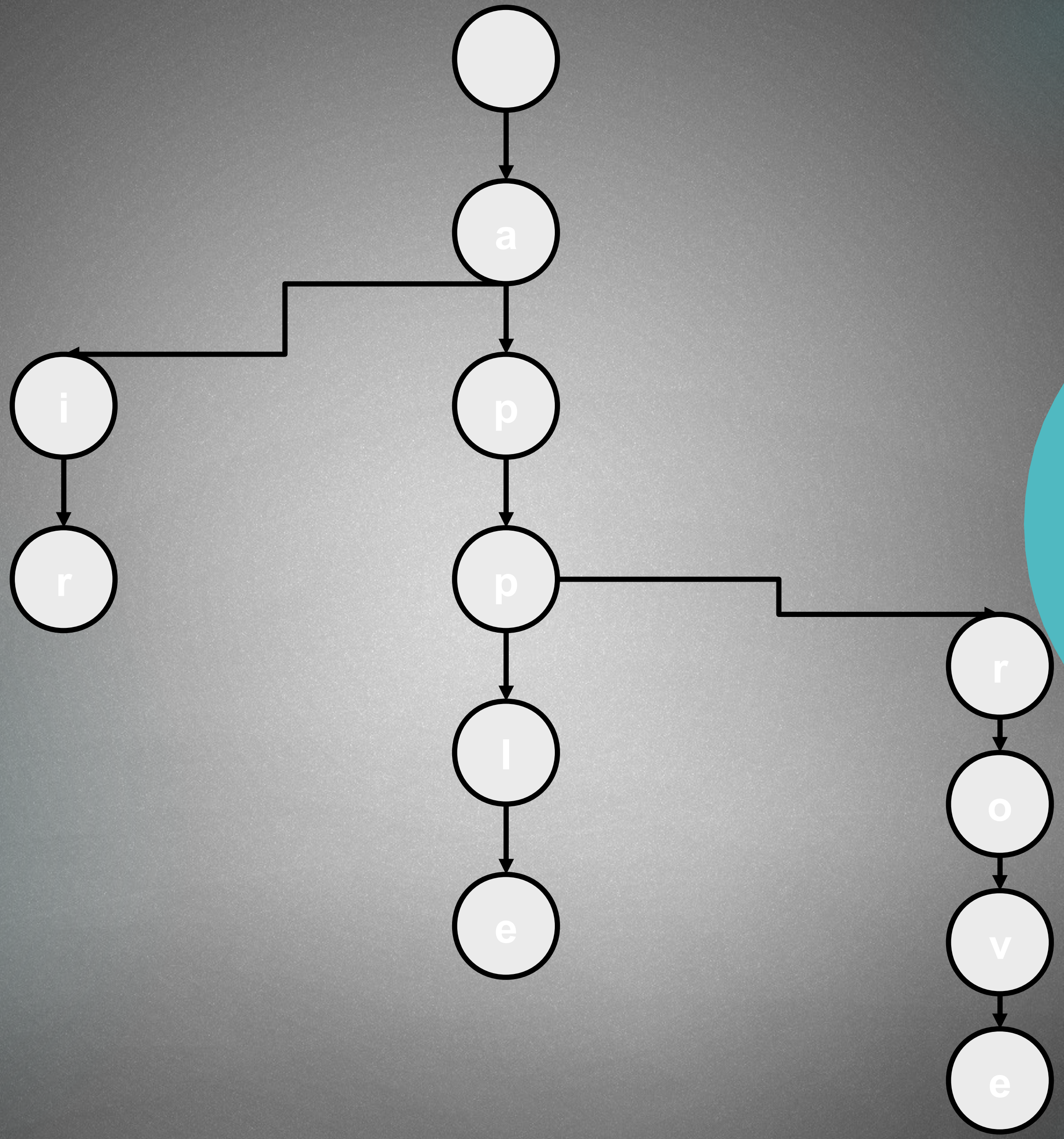

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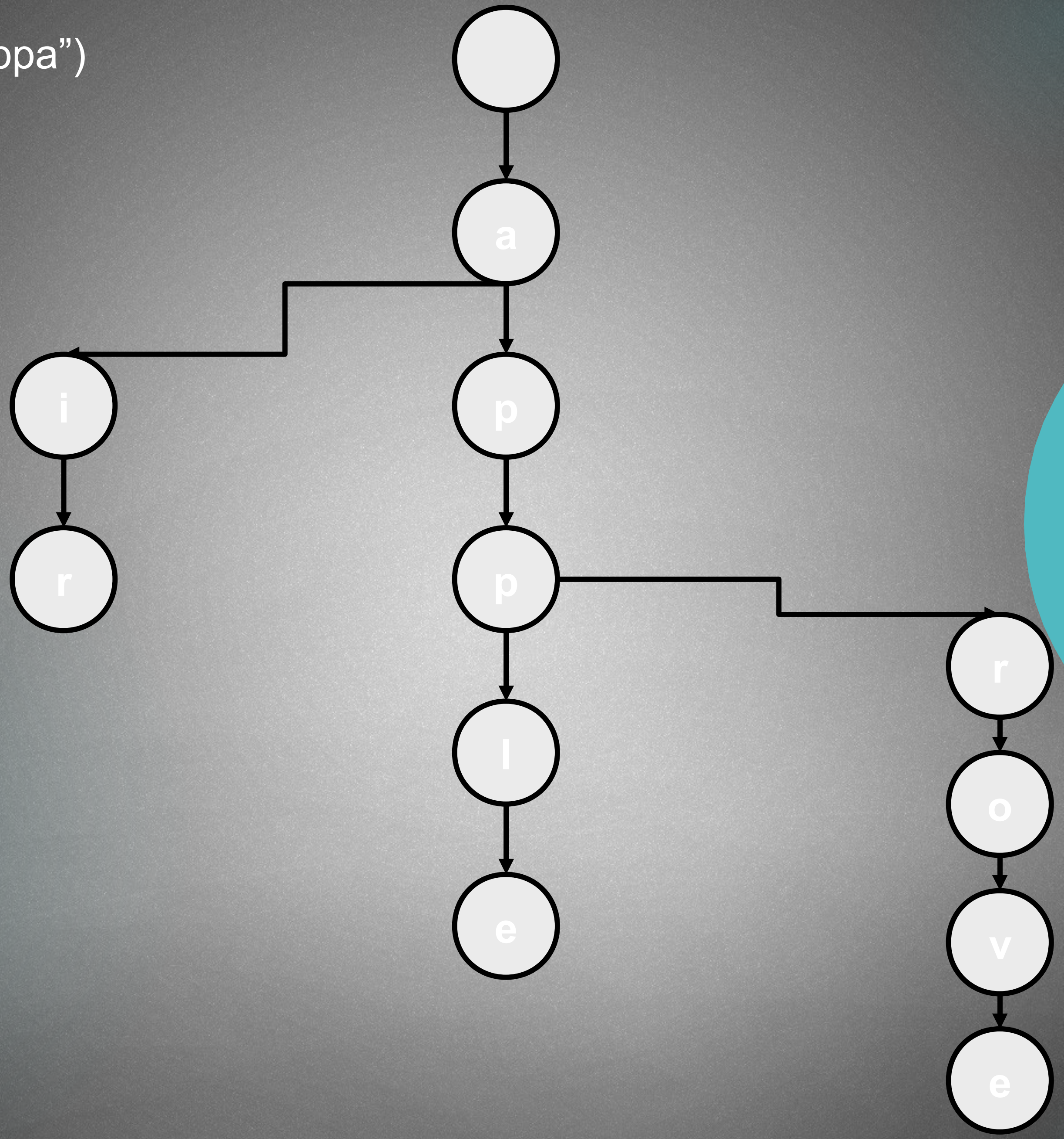

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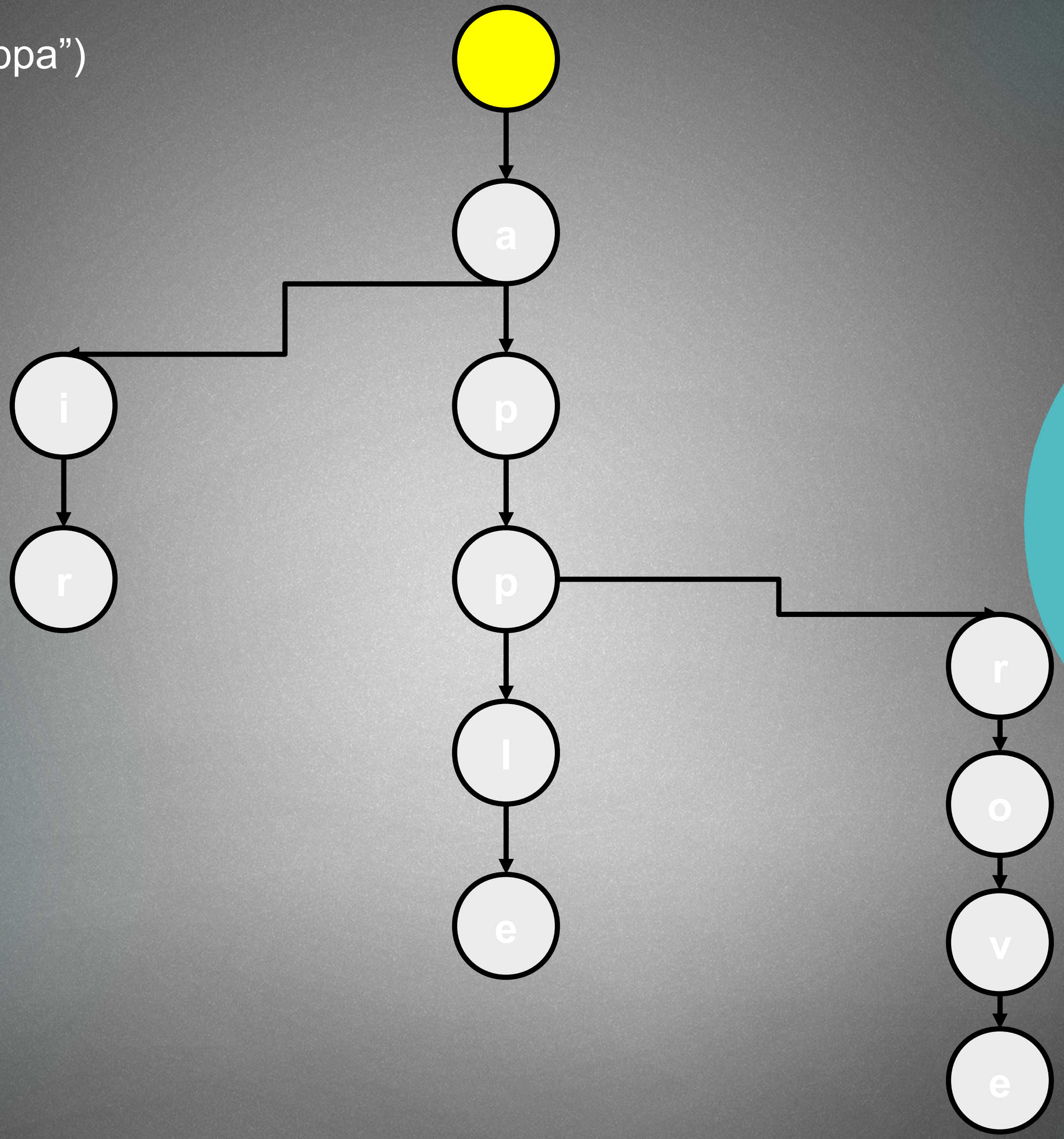

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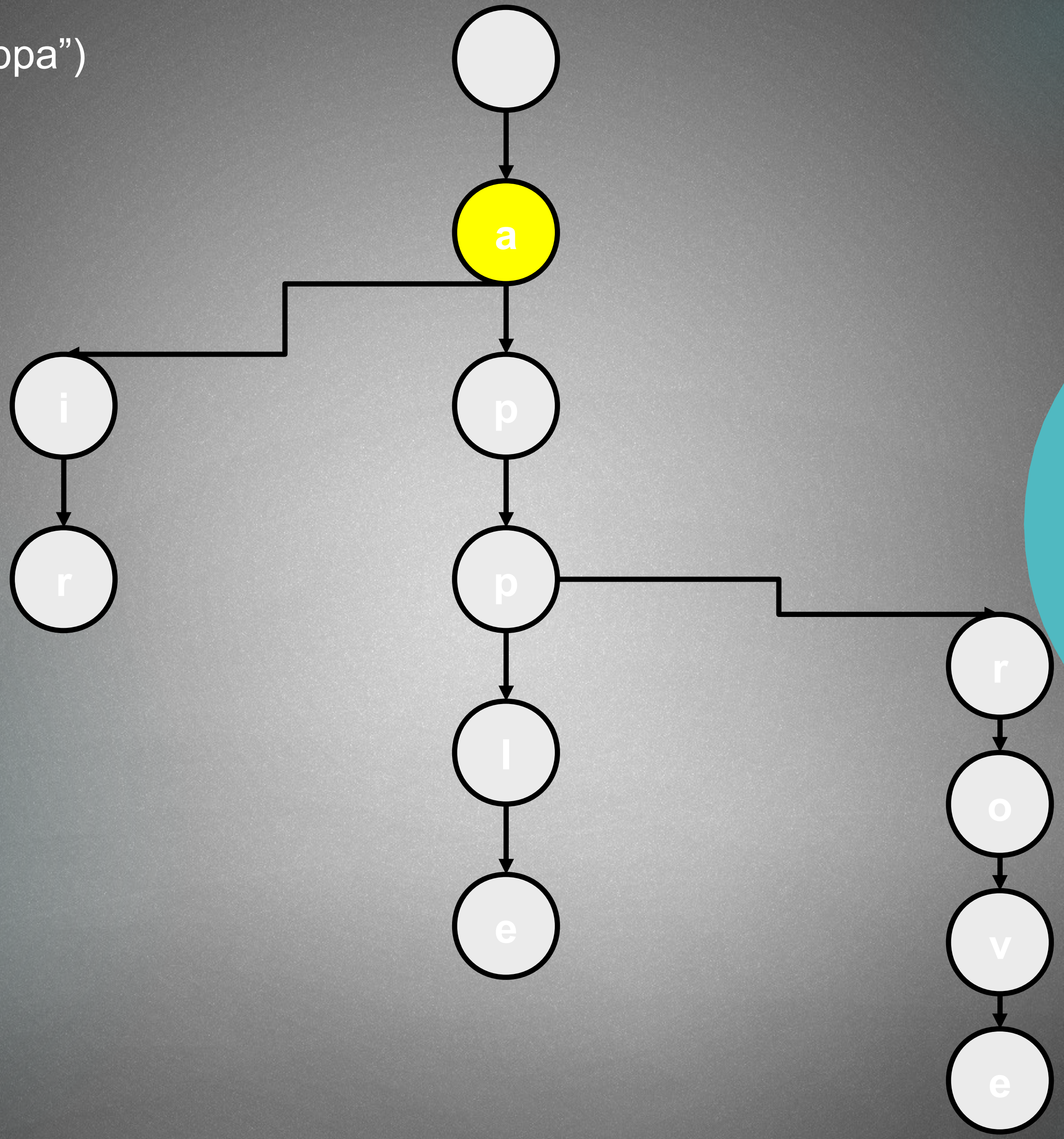

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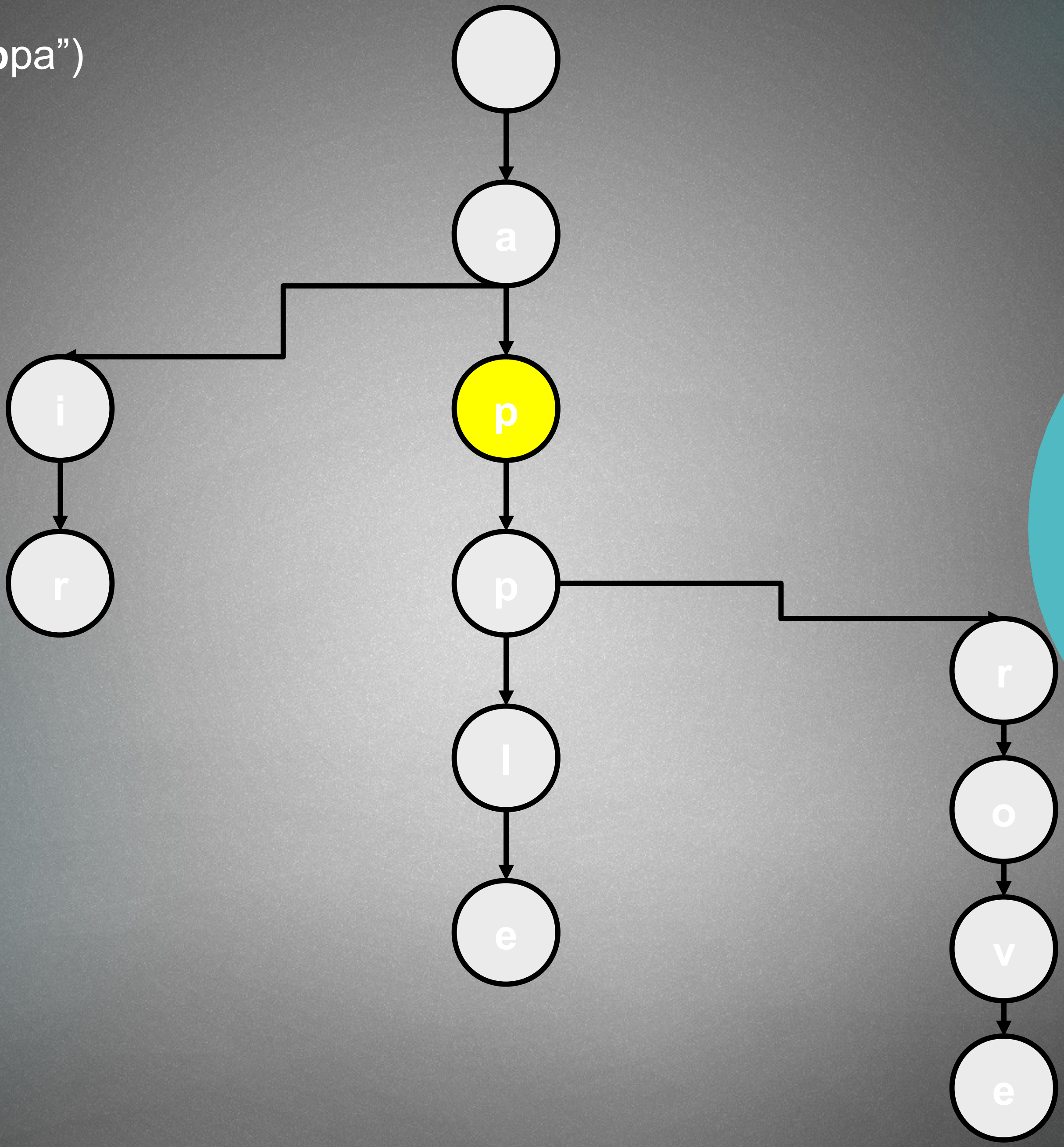

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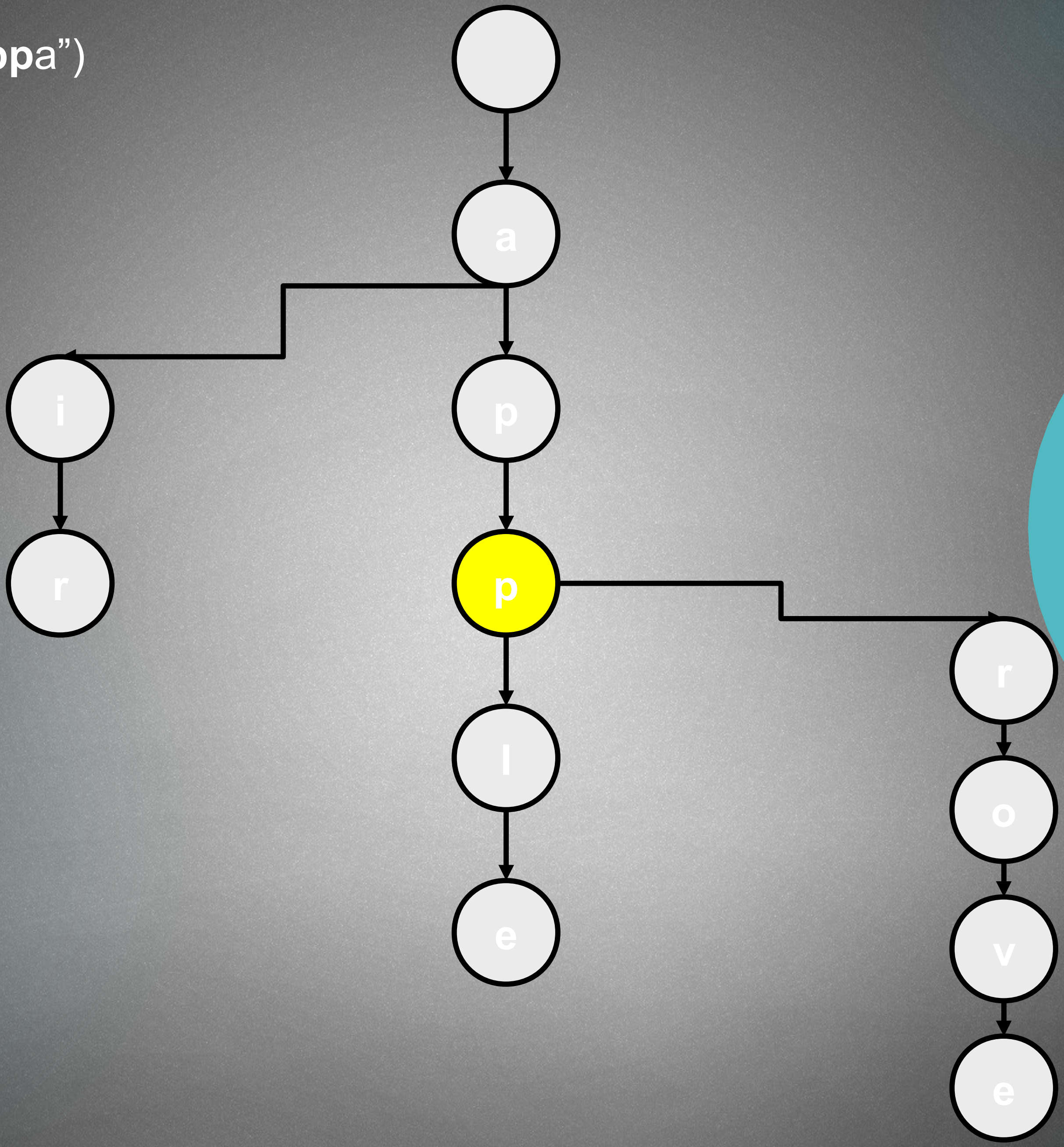

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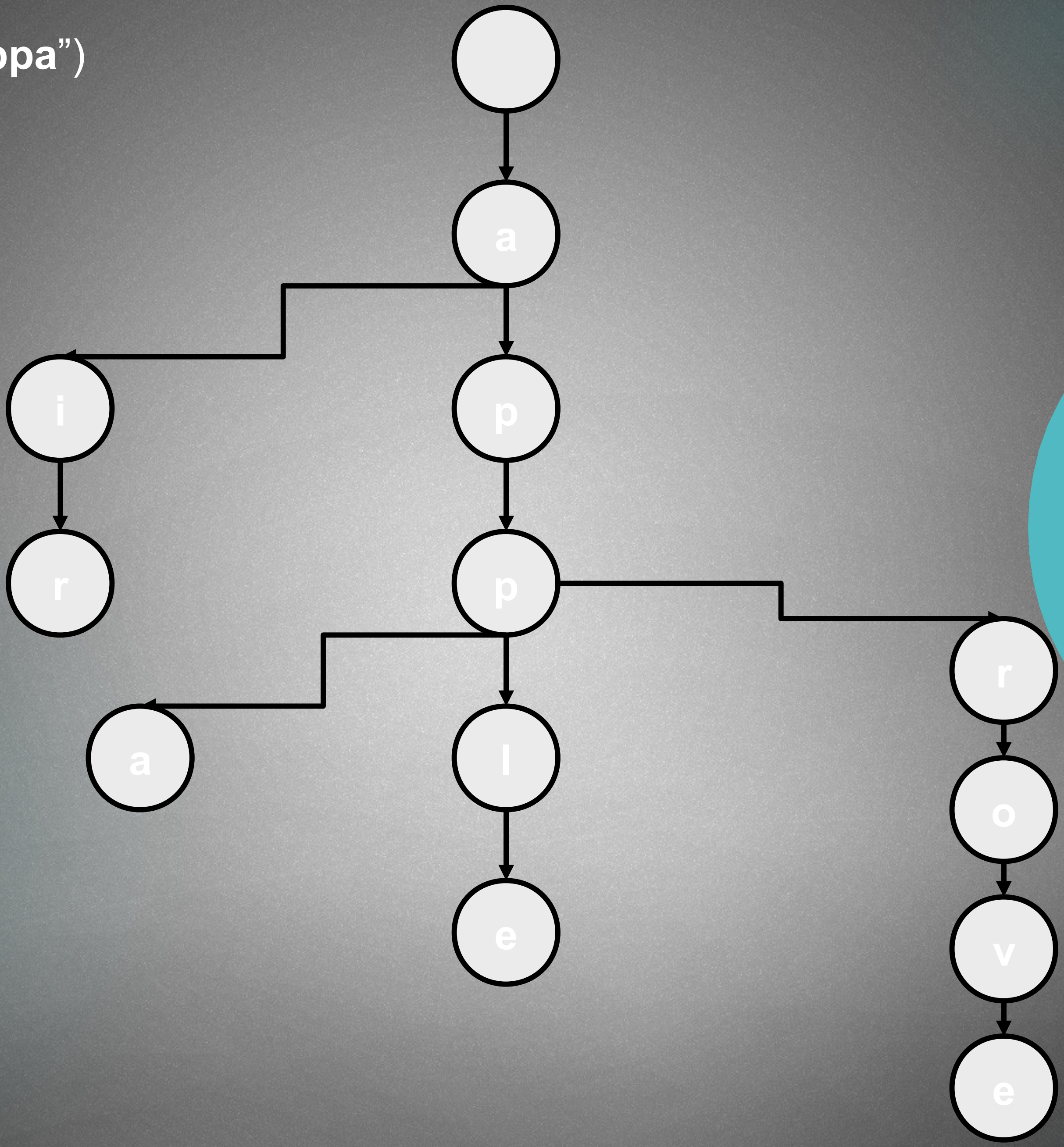

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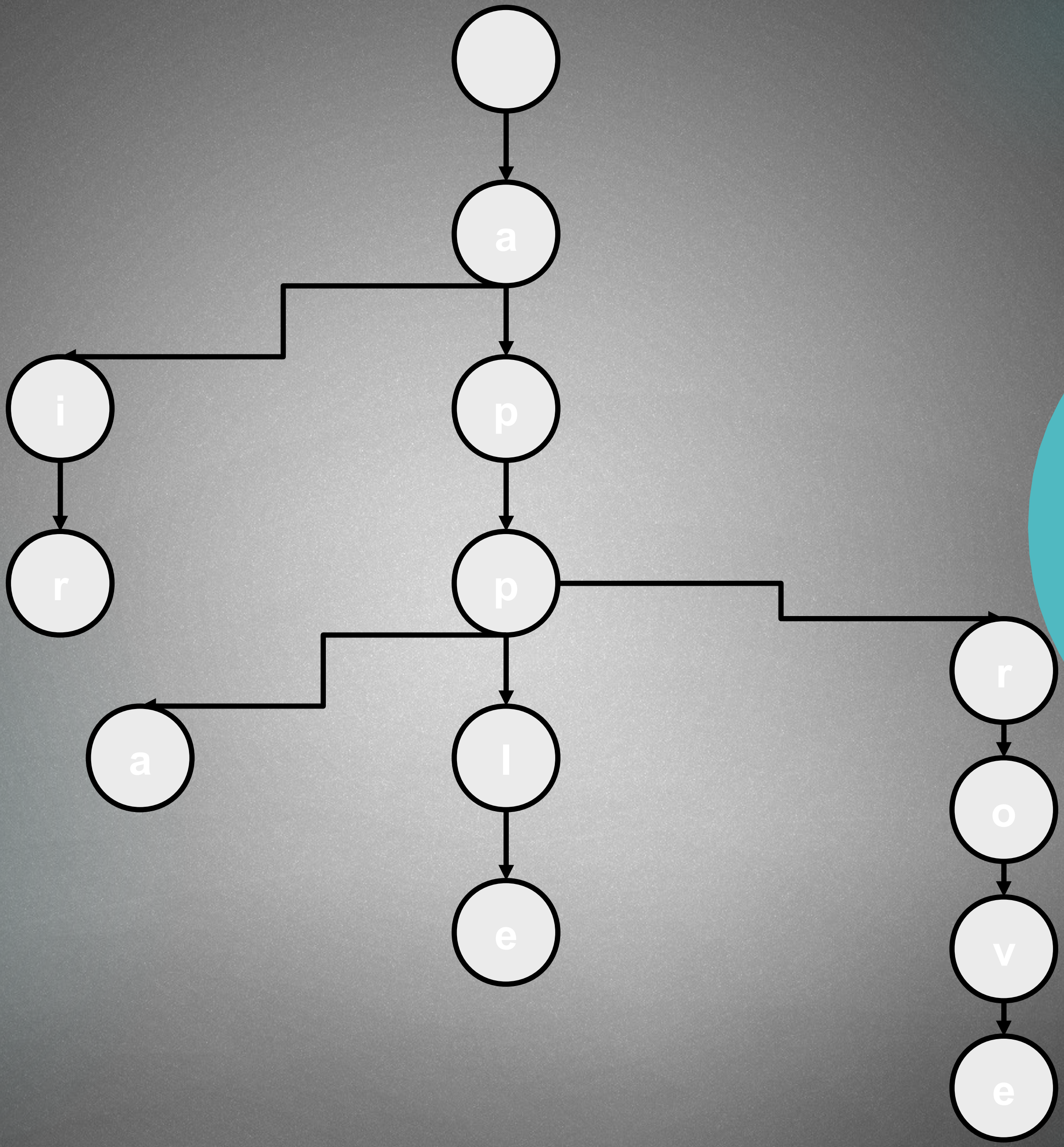

Insertion

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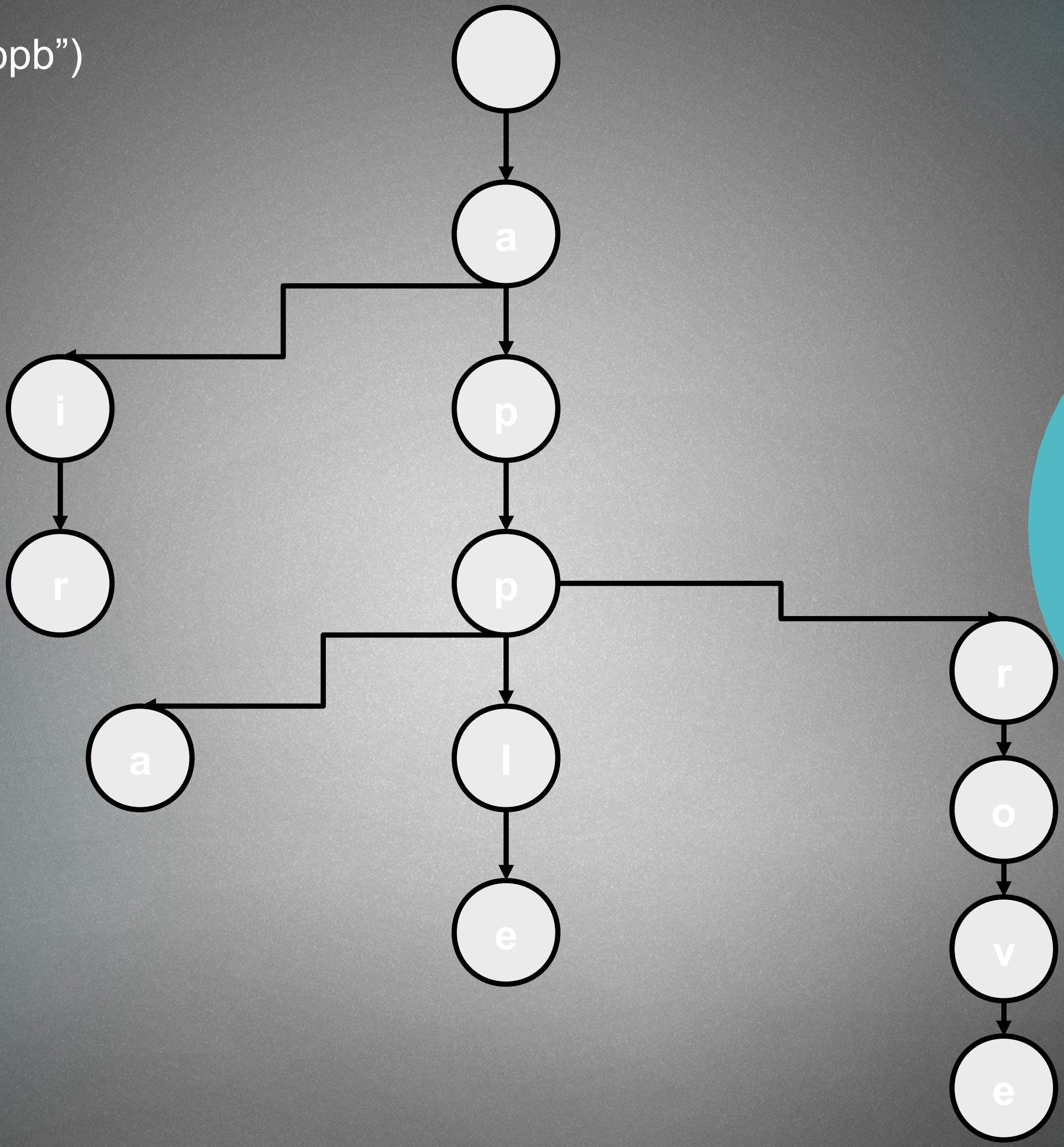

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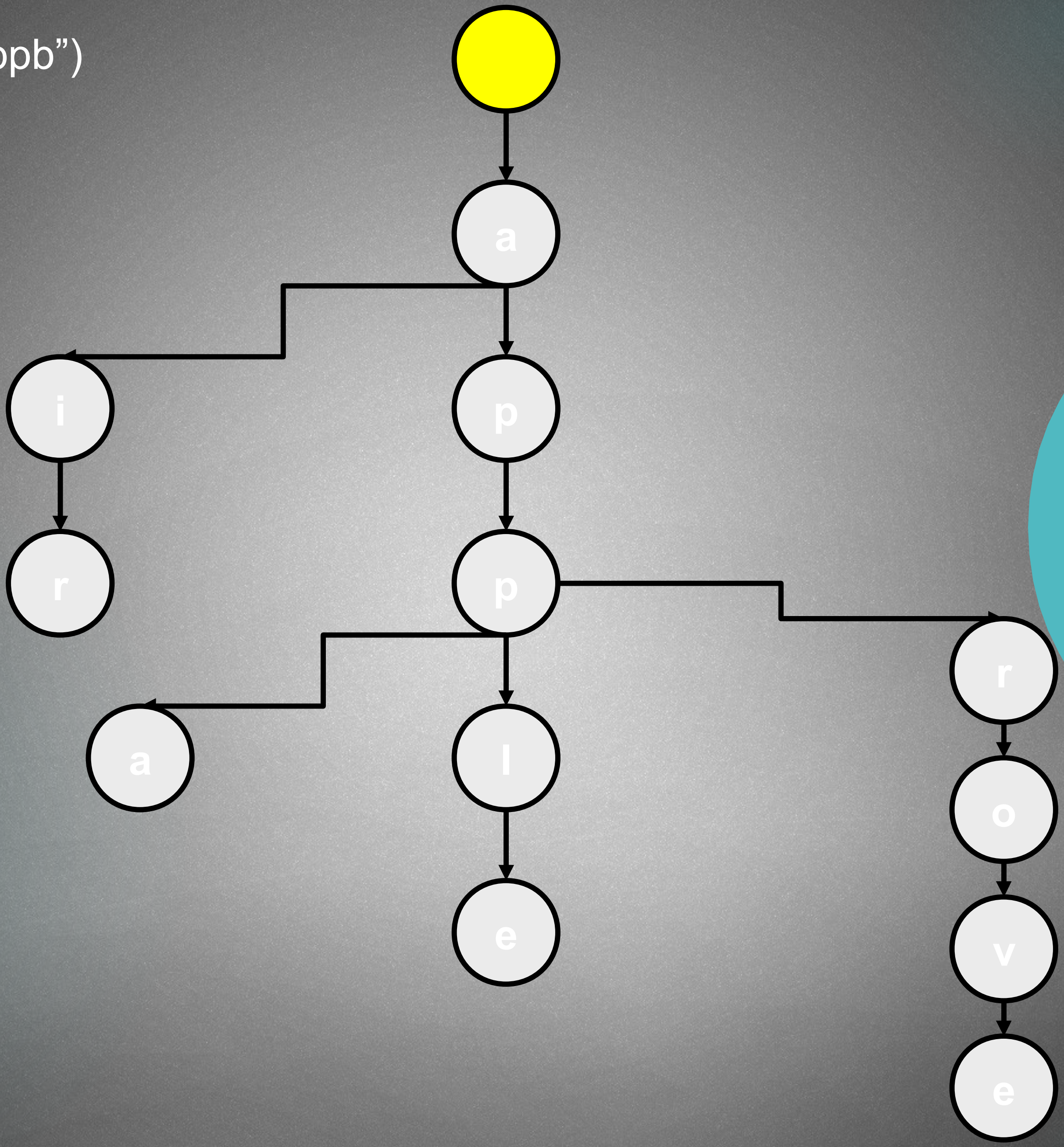

Insertion

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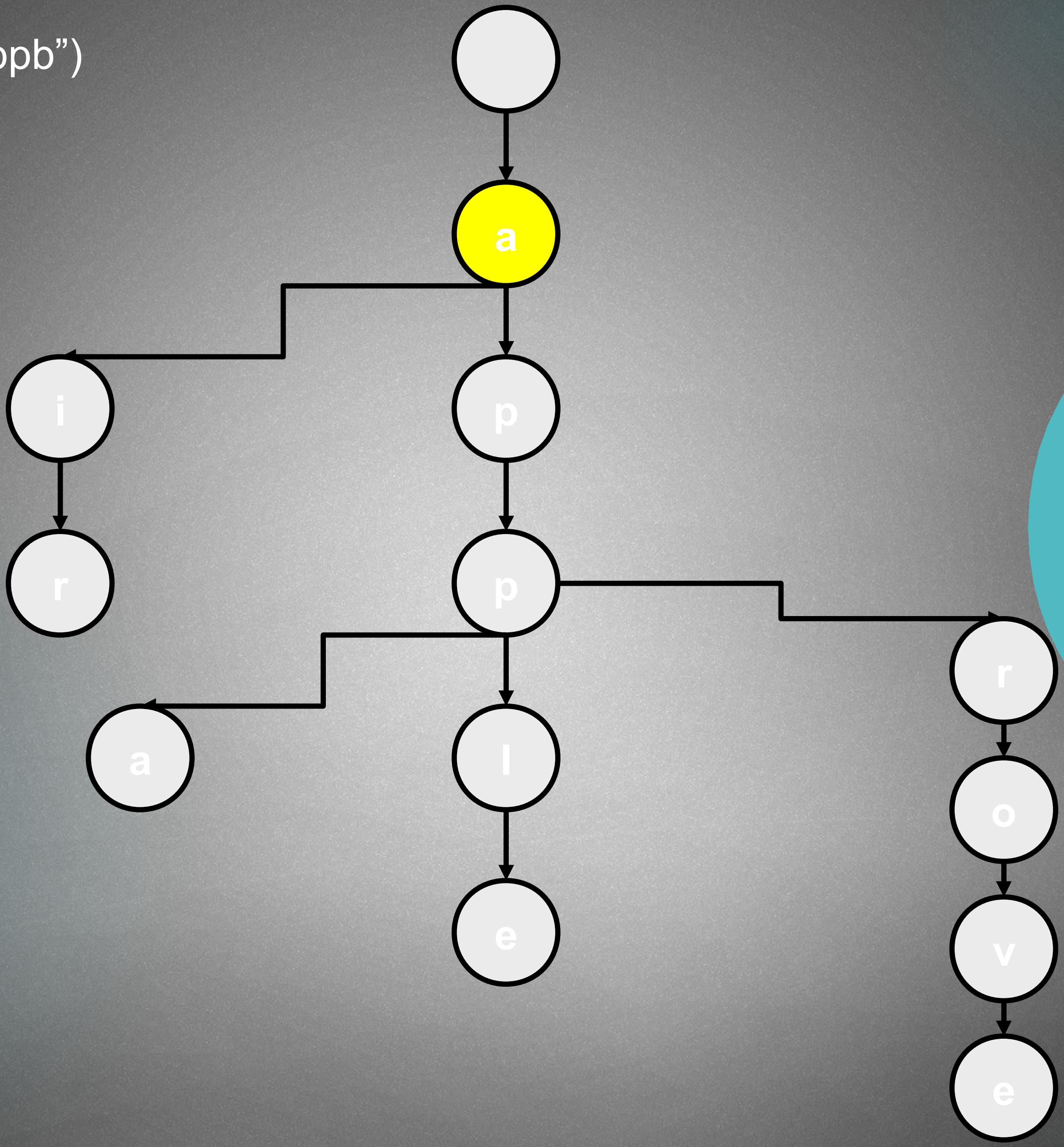

Insertion

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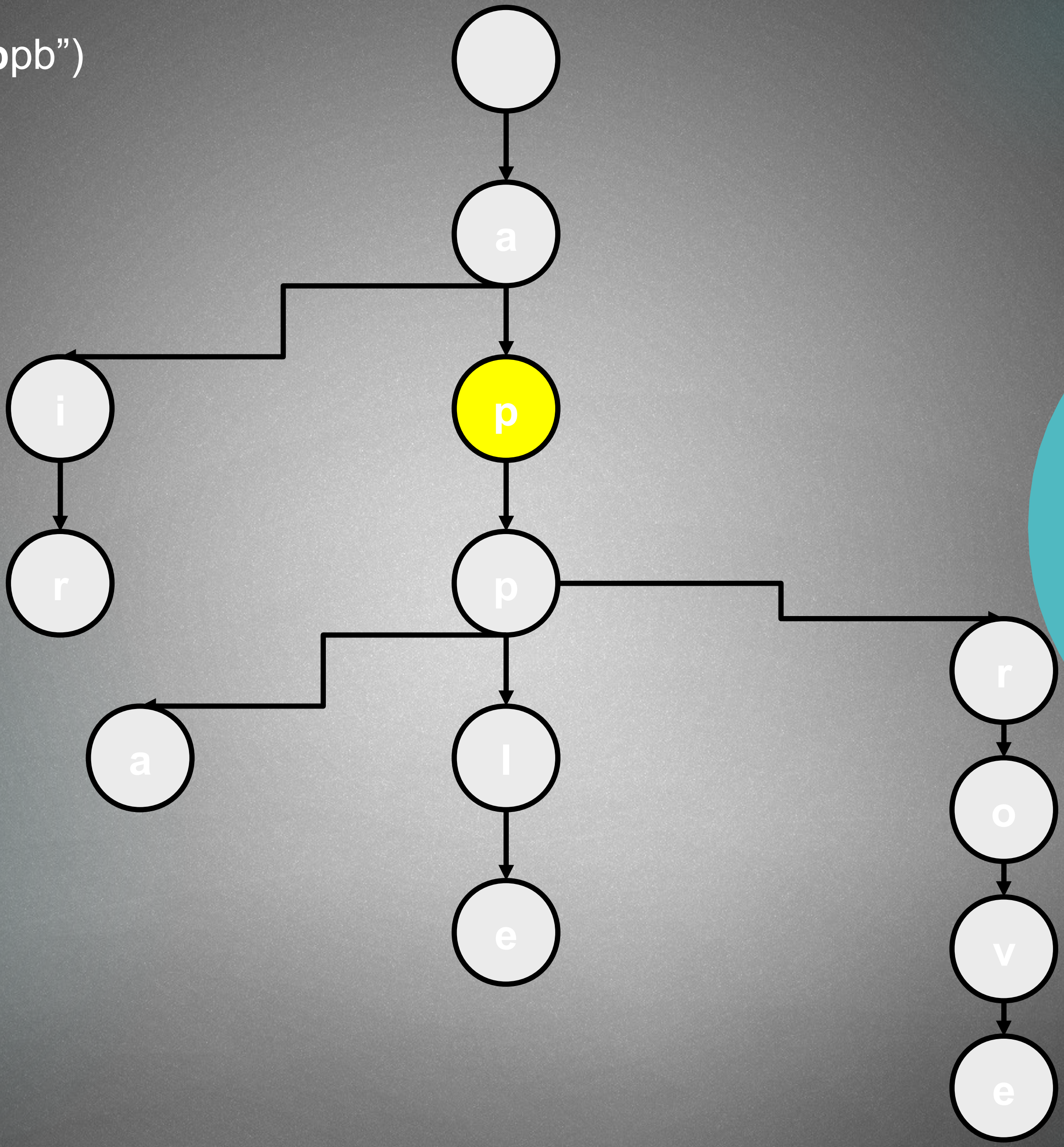

Insertion

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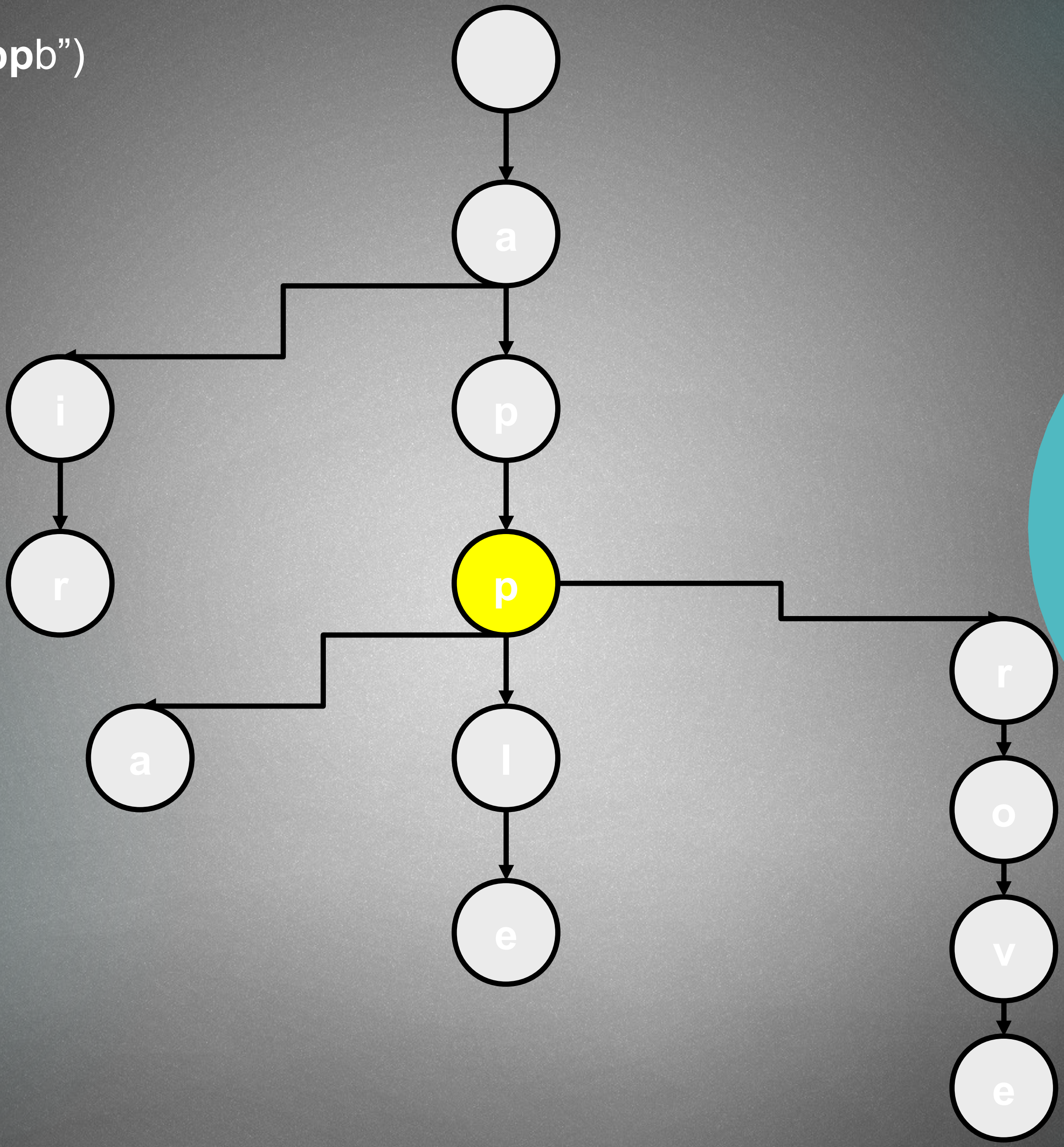

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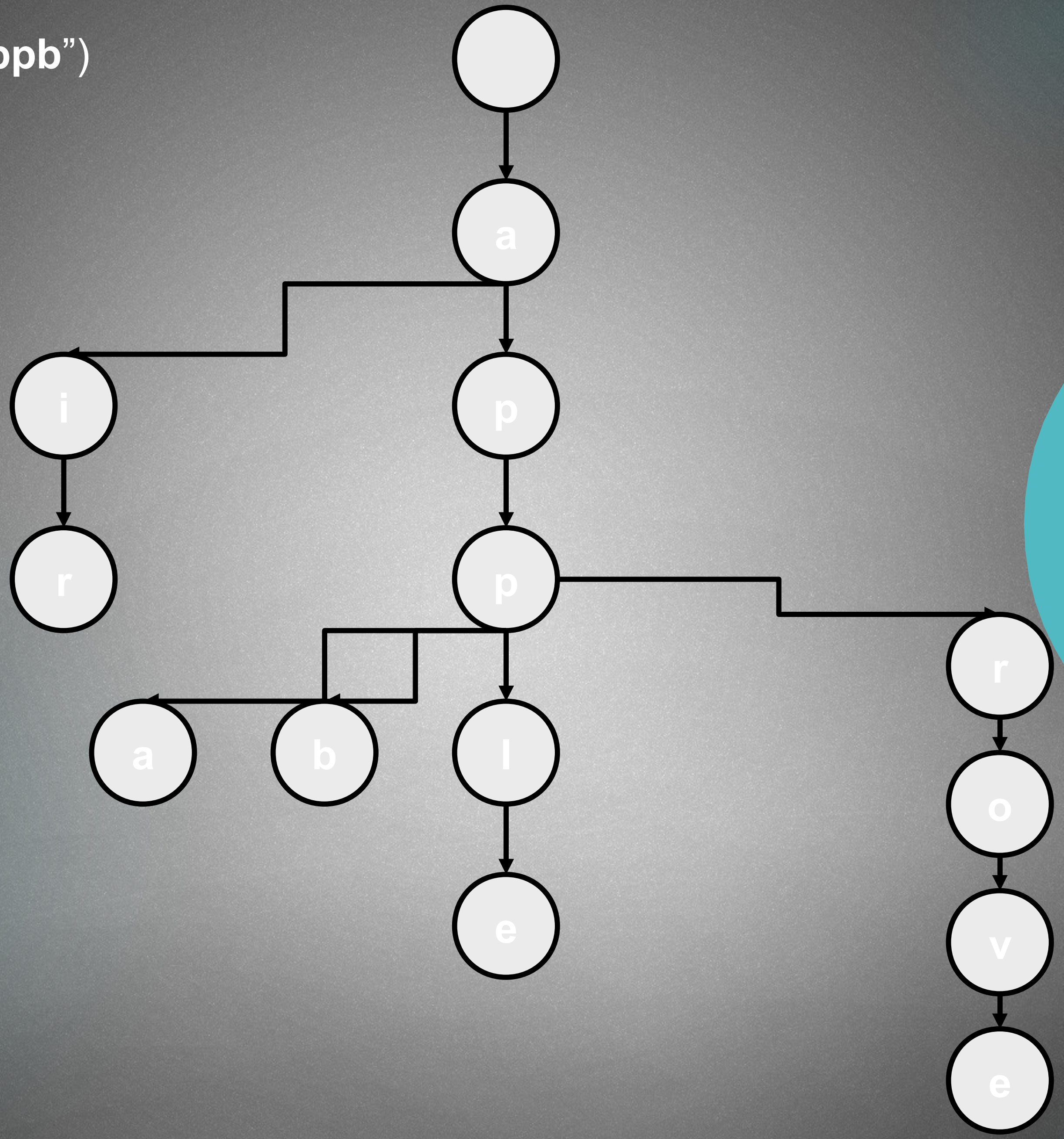
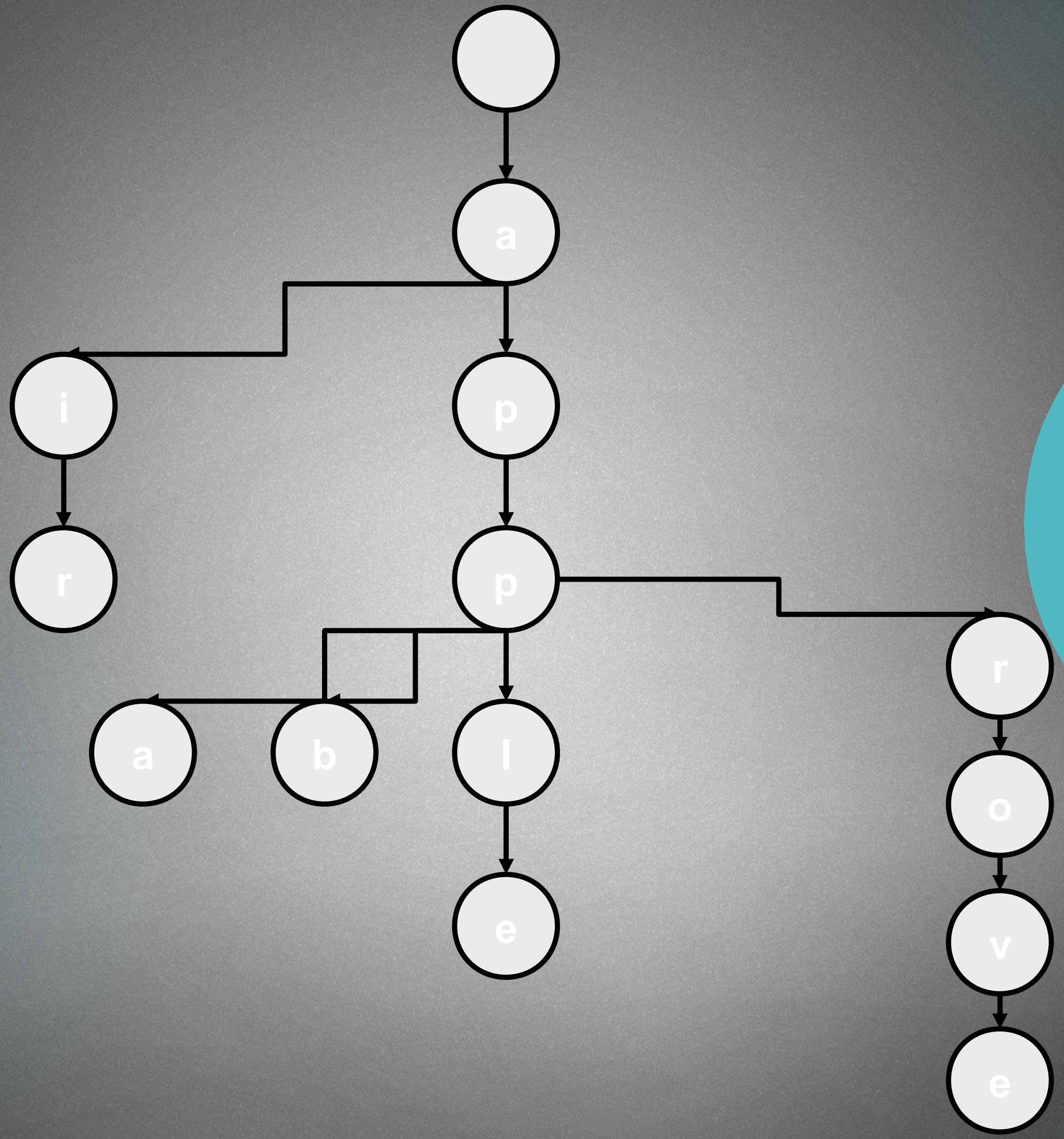
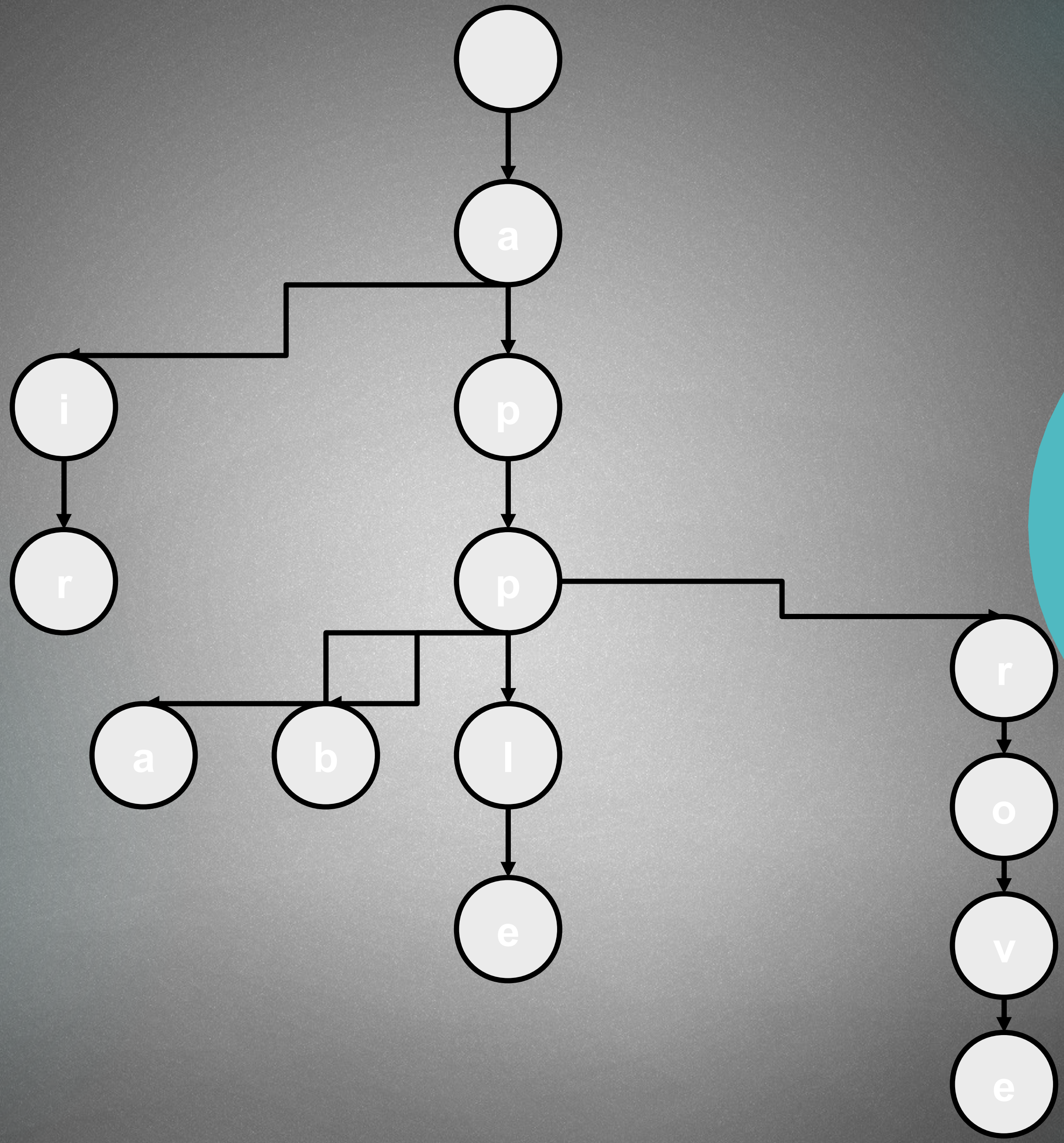


Insertion



Sorting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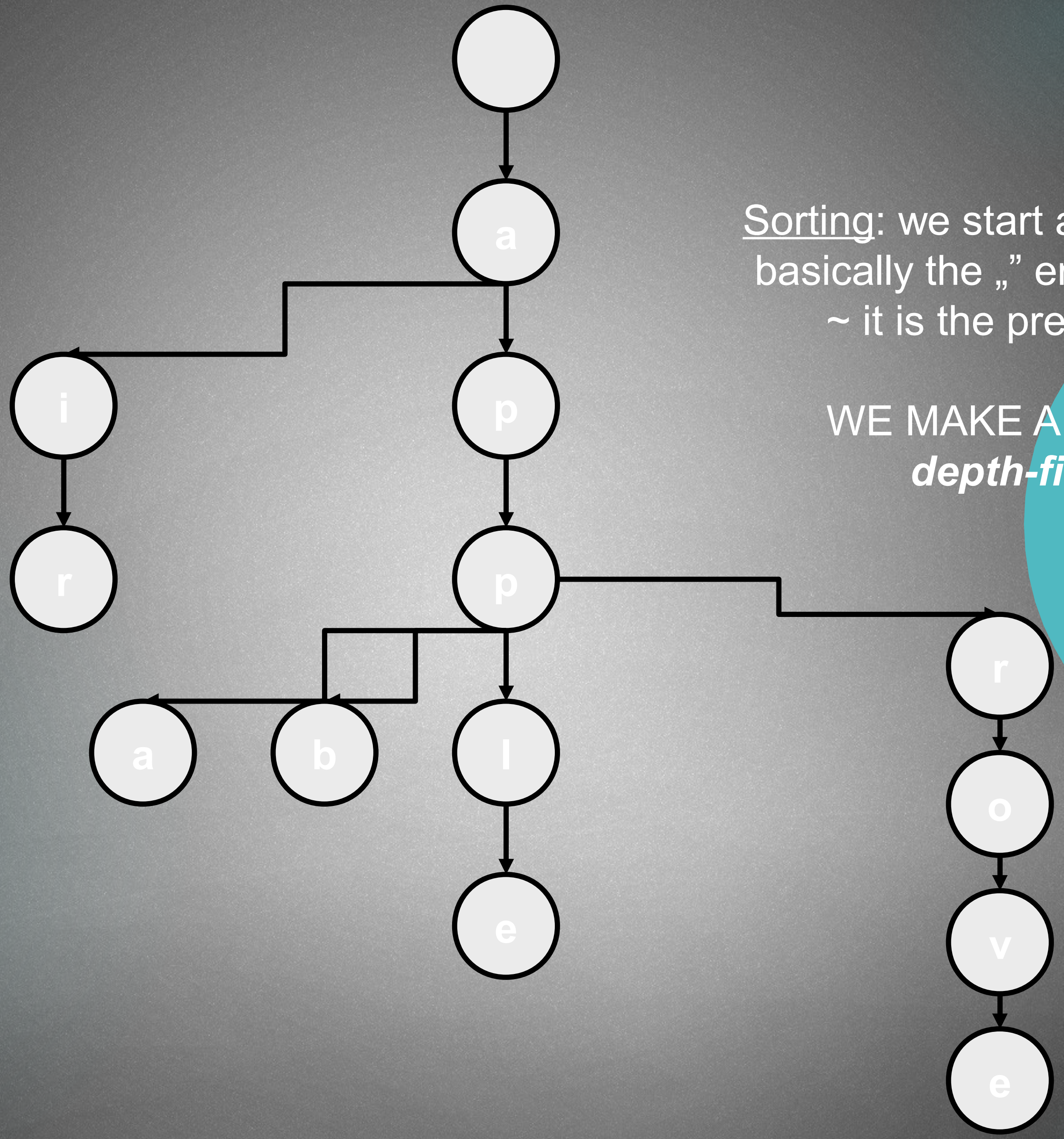


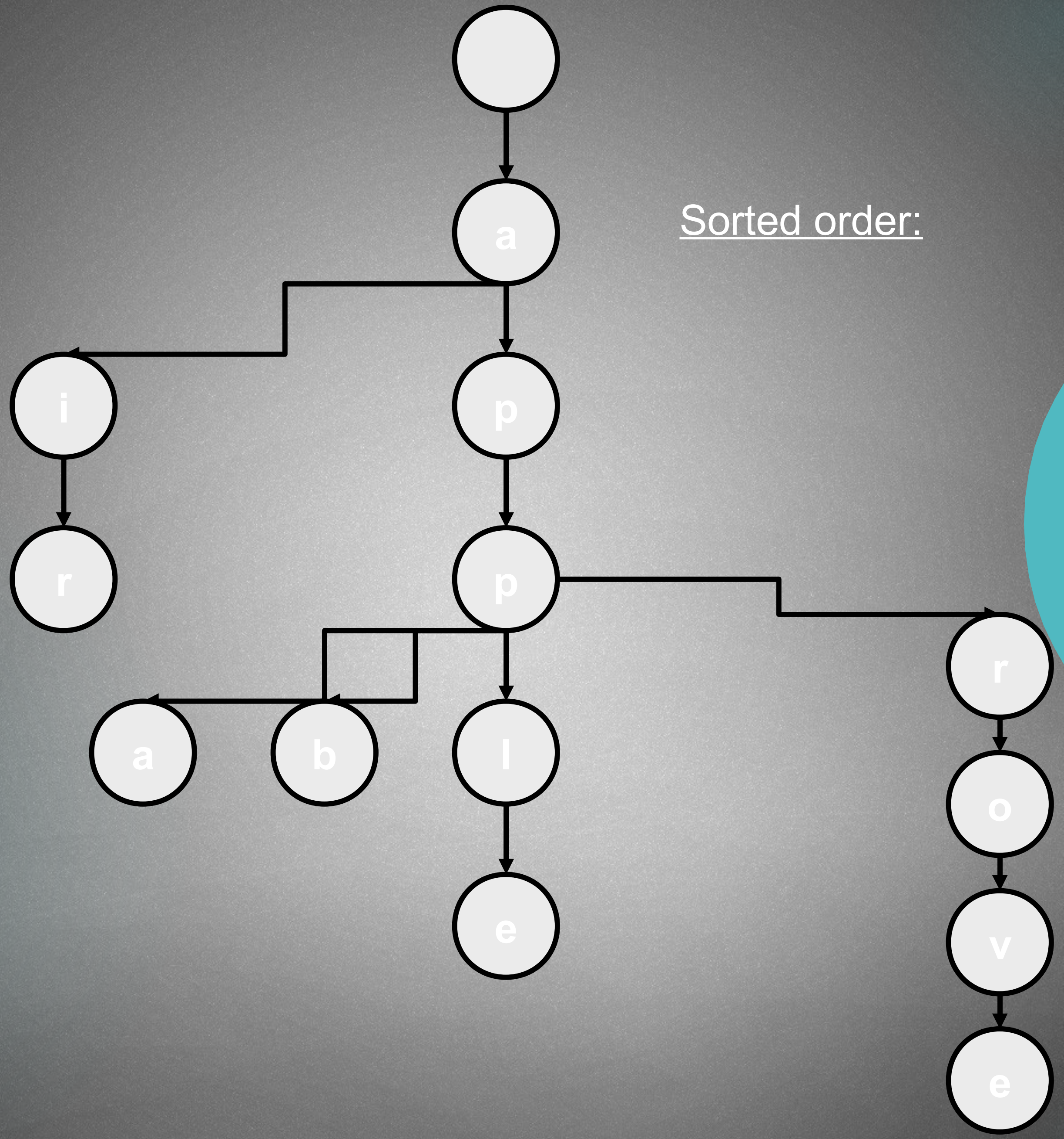
Sorting: we start at the root, which is basically the „” empty string

~ it is the prefix of every item in the trie

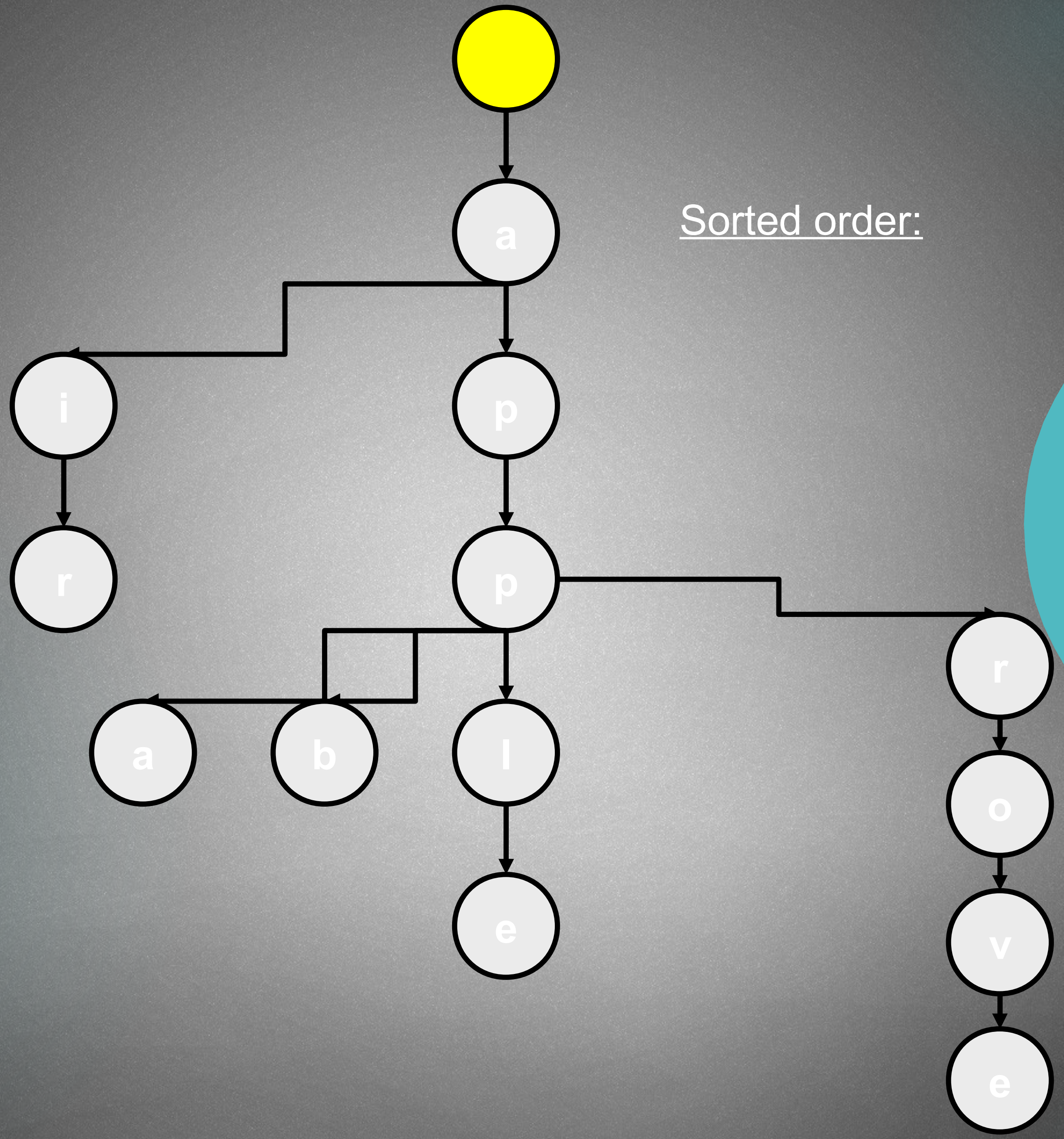
WE MAKE A SIMPLE DFS !!!

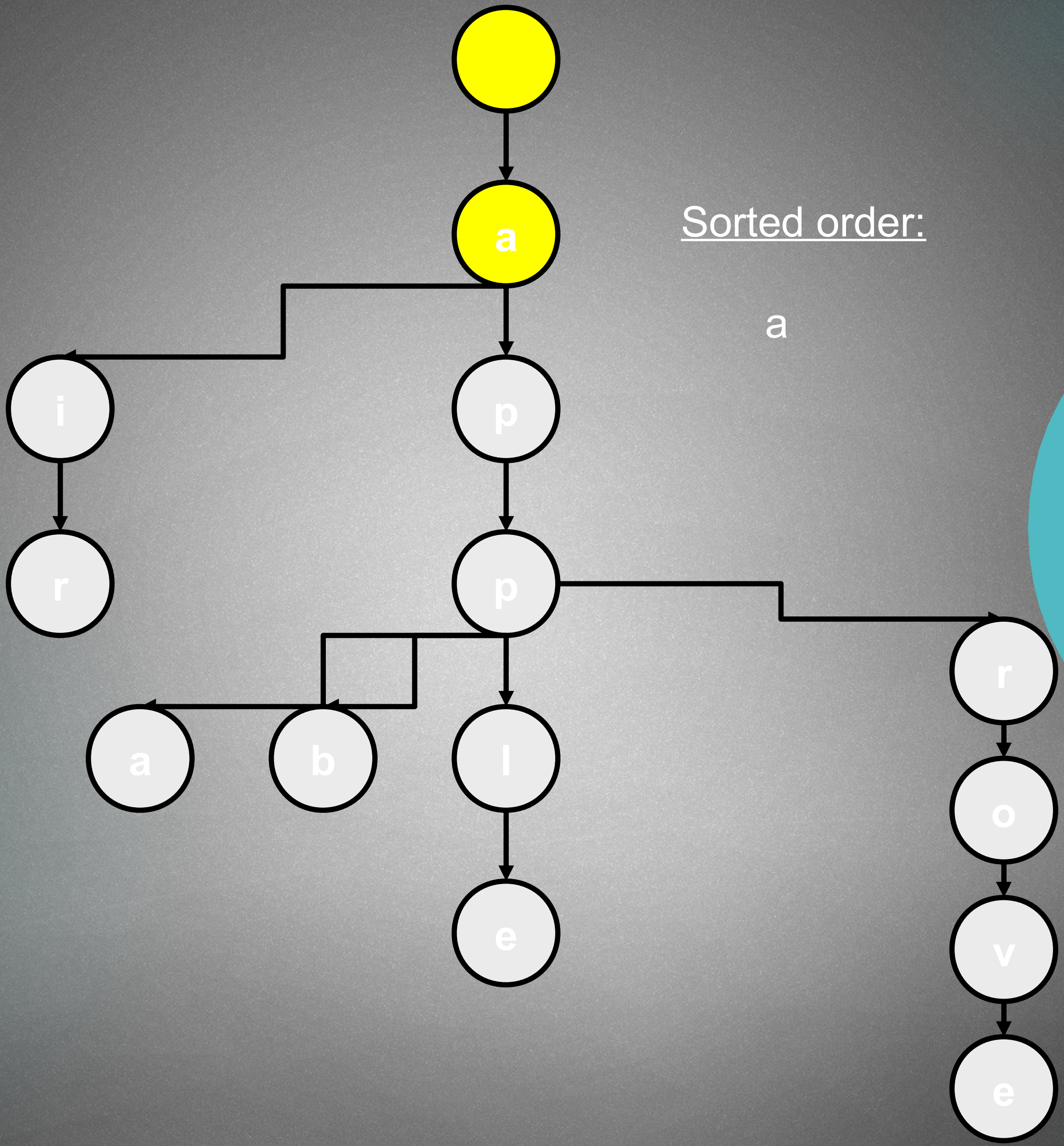
depth-first search

Sorted order:



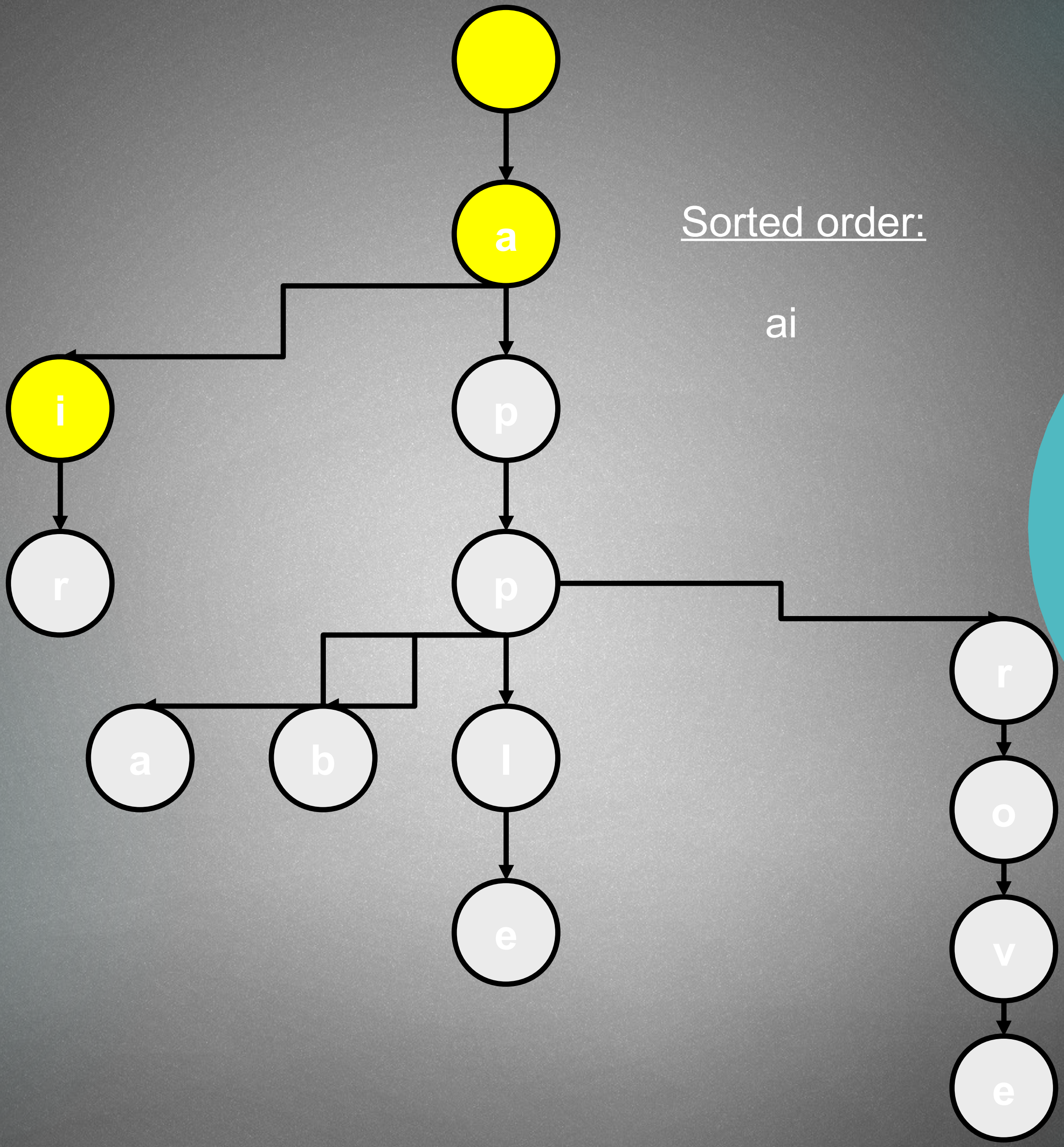
Sorted order:





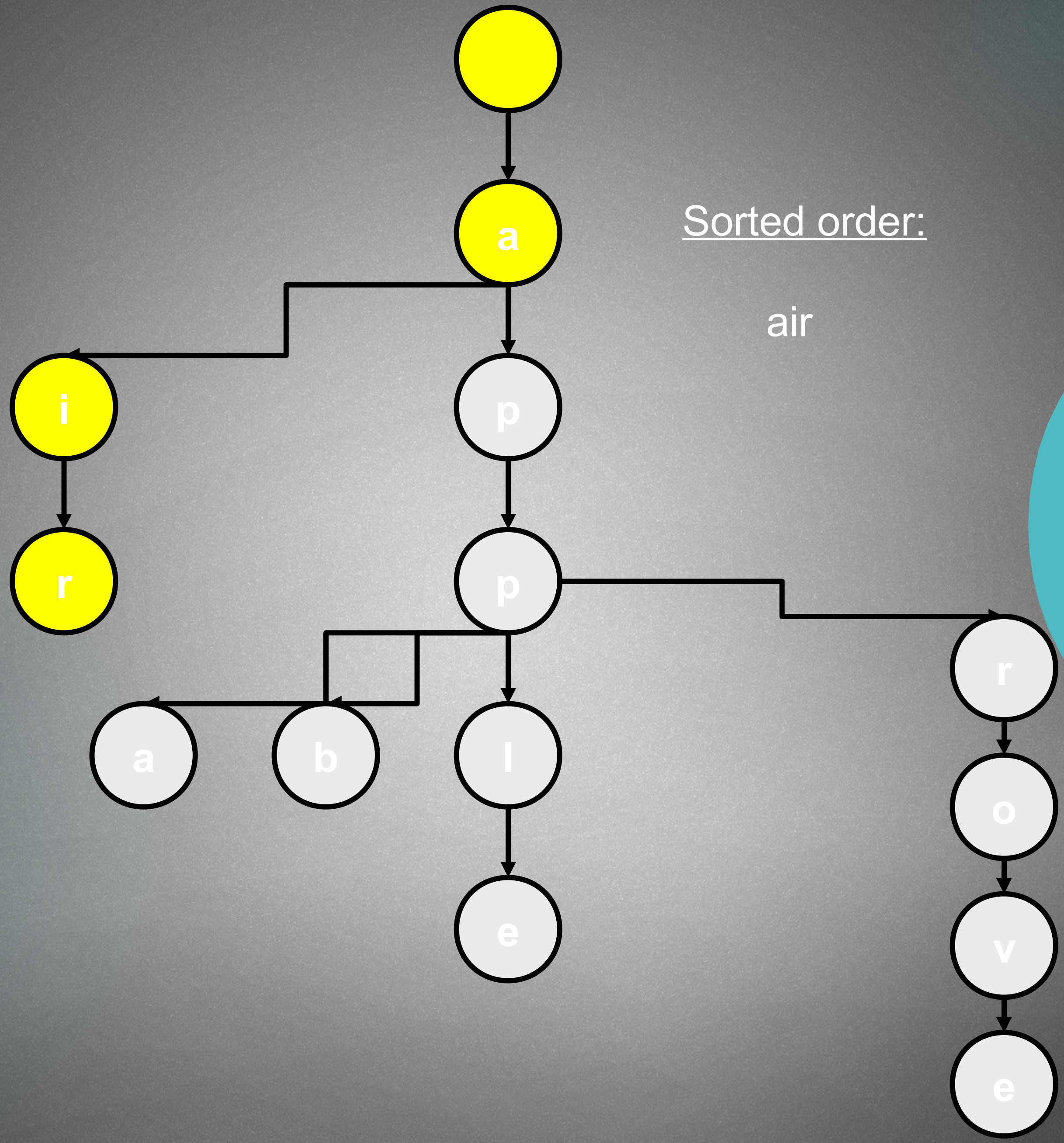
Sorted order:

a



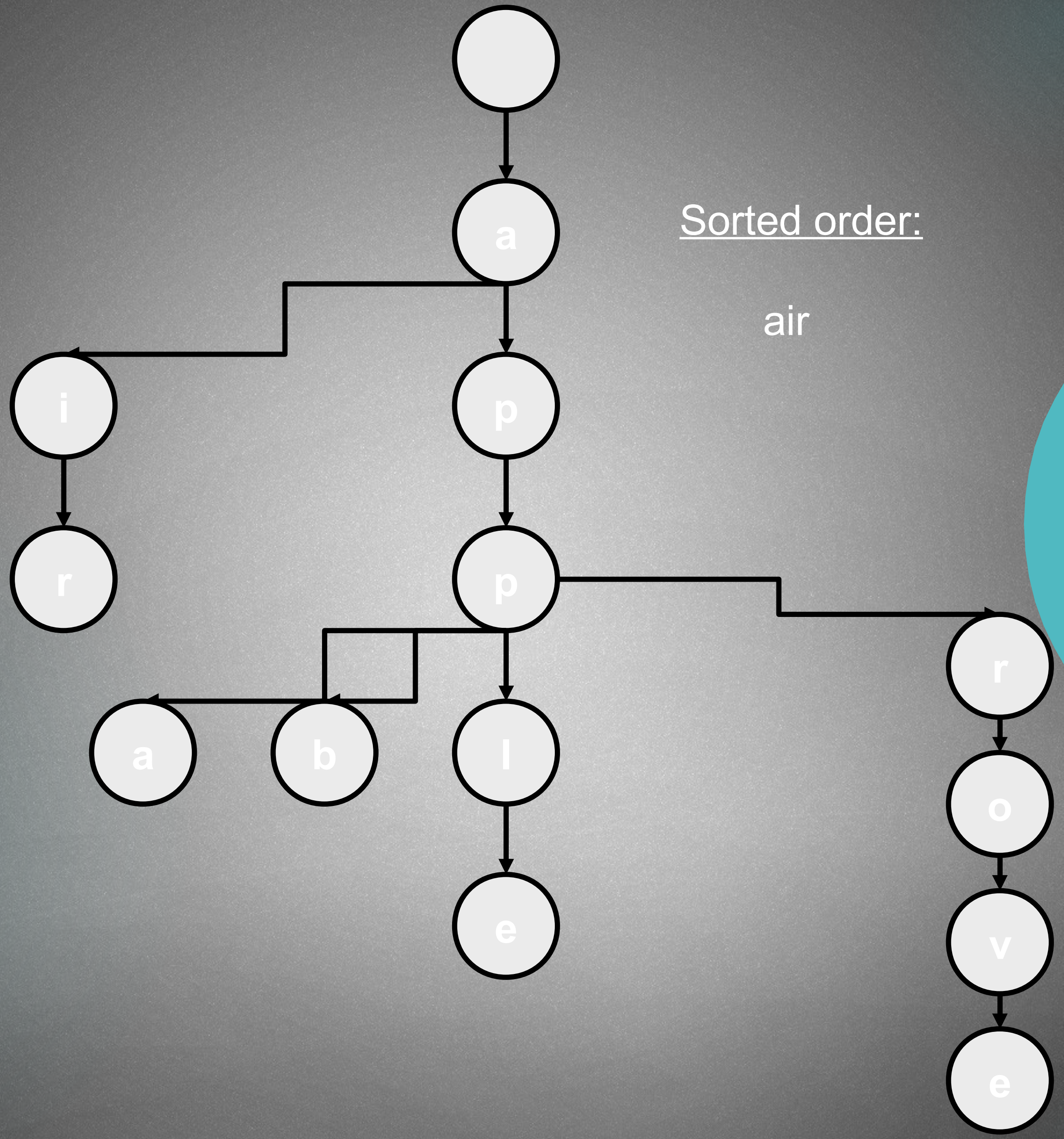
Sorted order:

ai



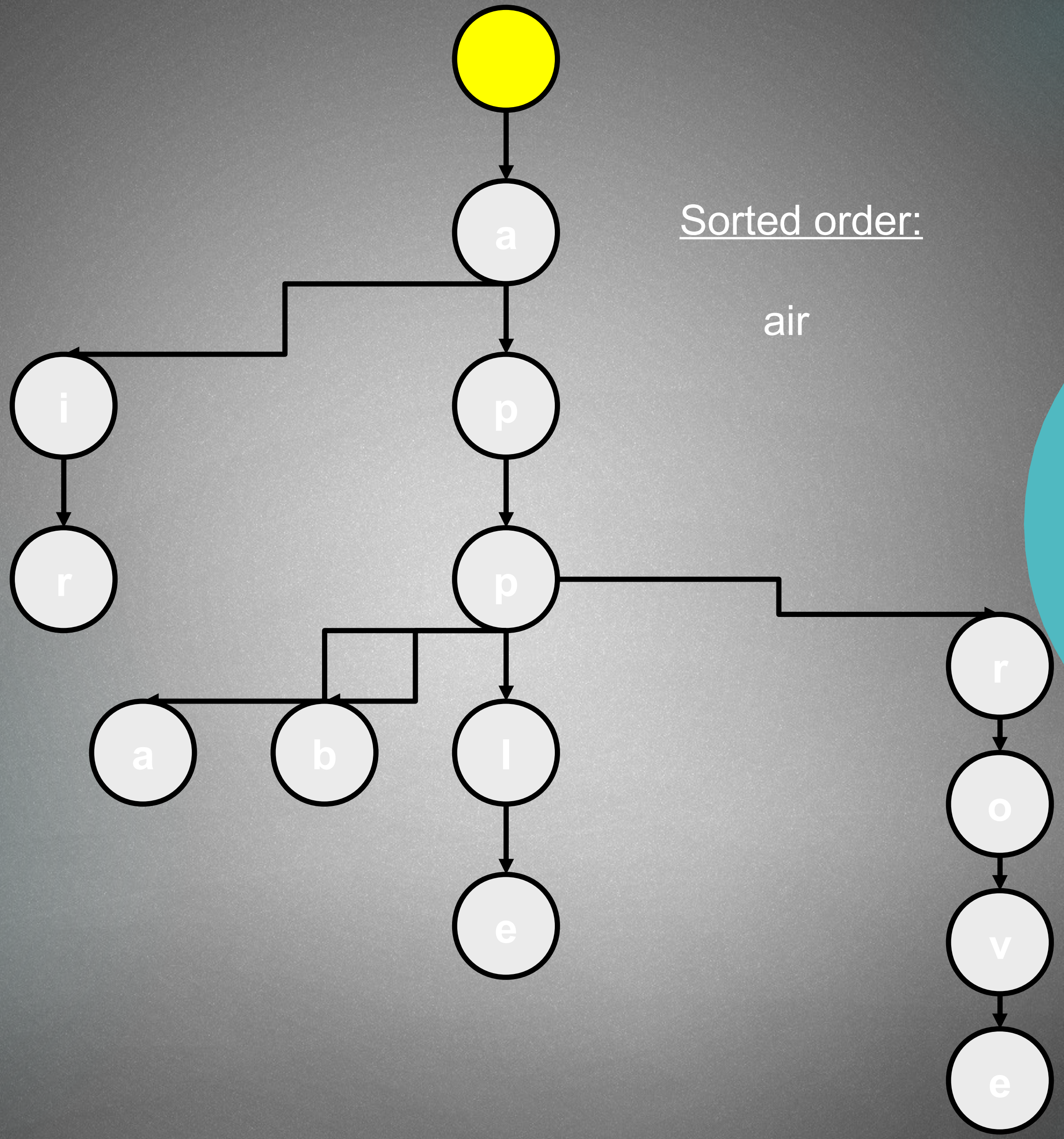
Sorted order:

air



Sorted order:

air



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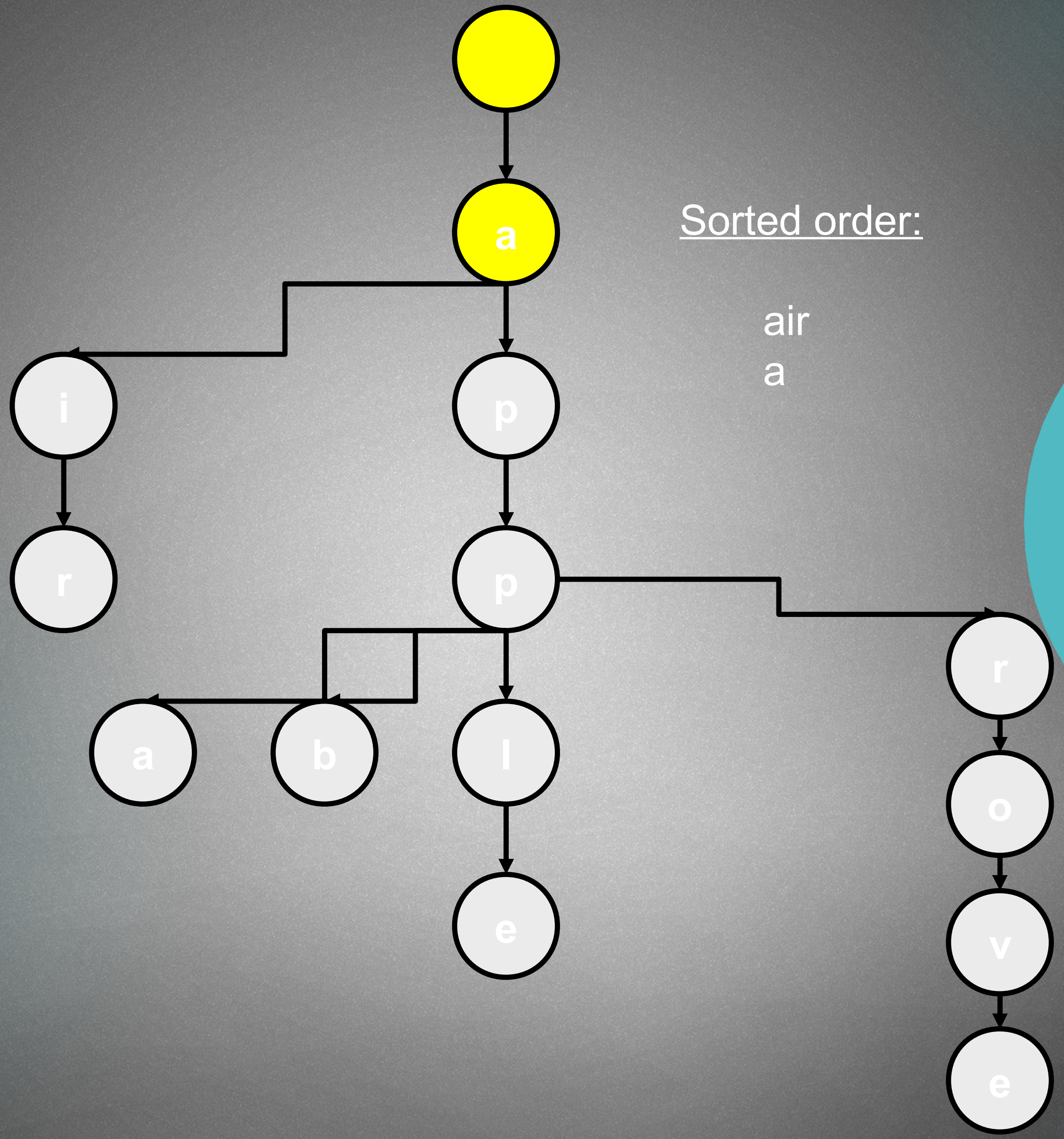

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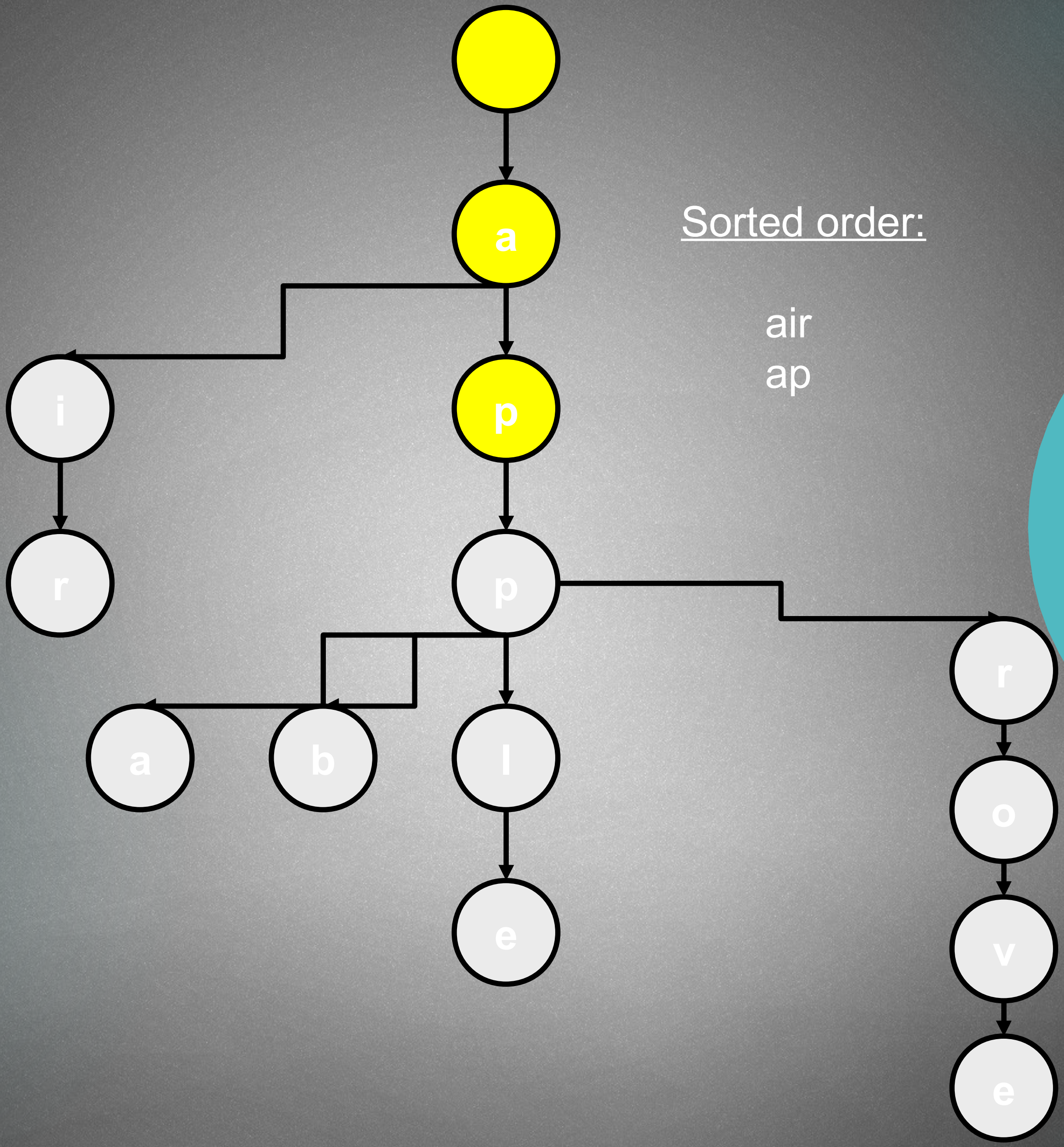

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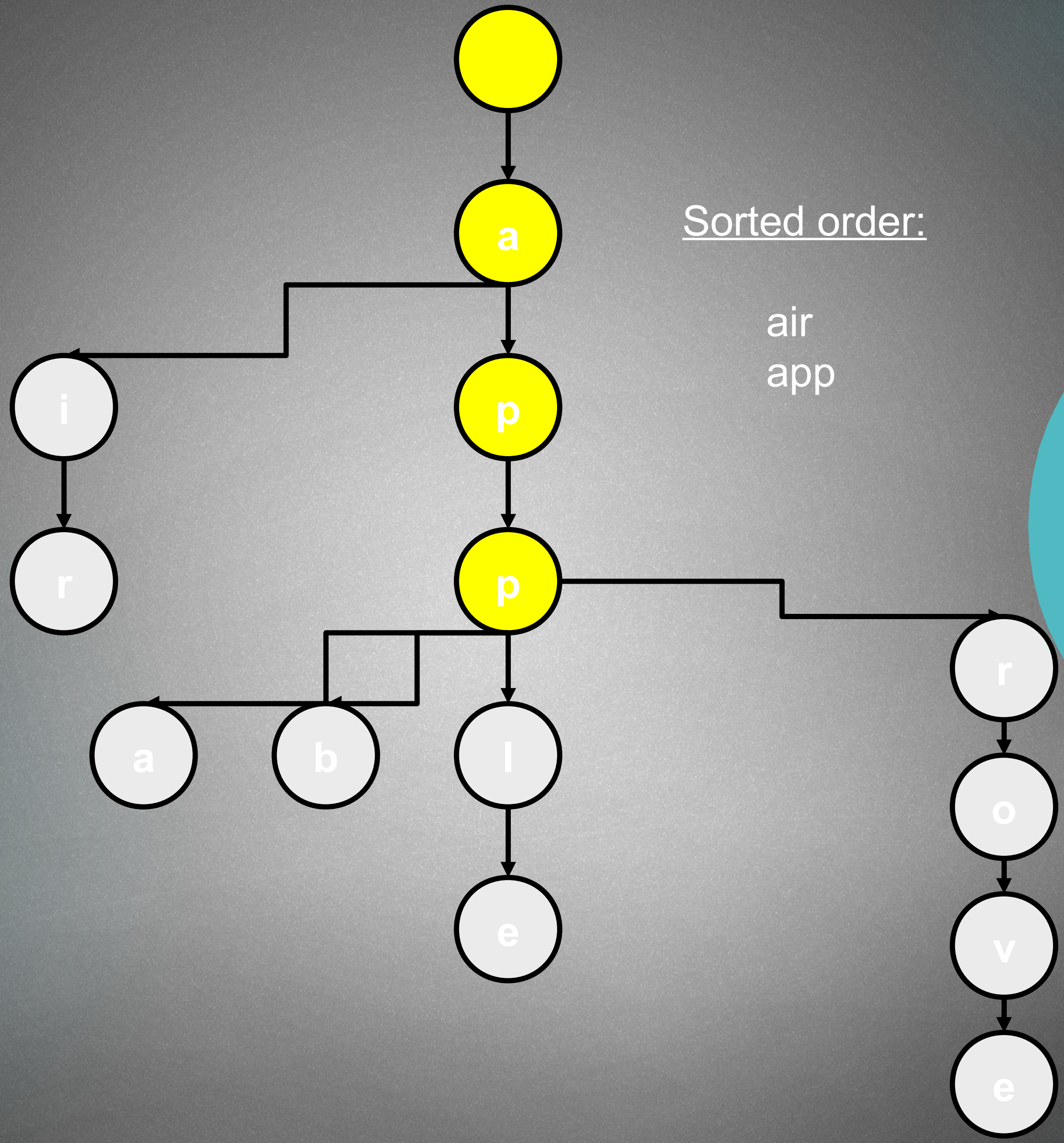

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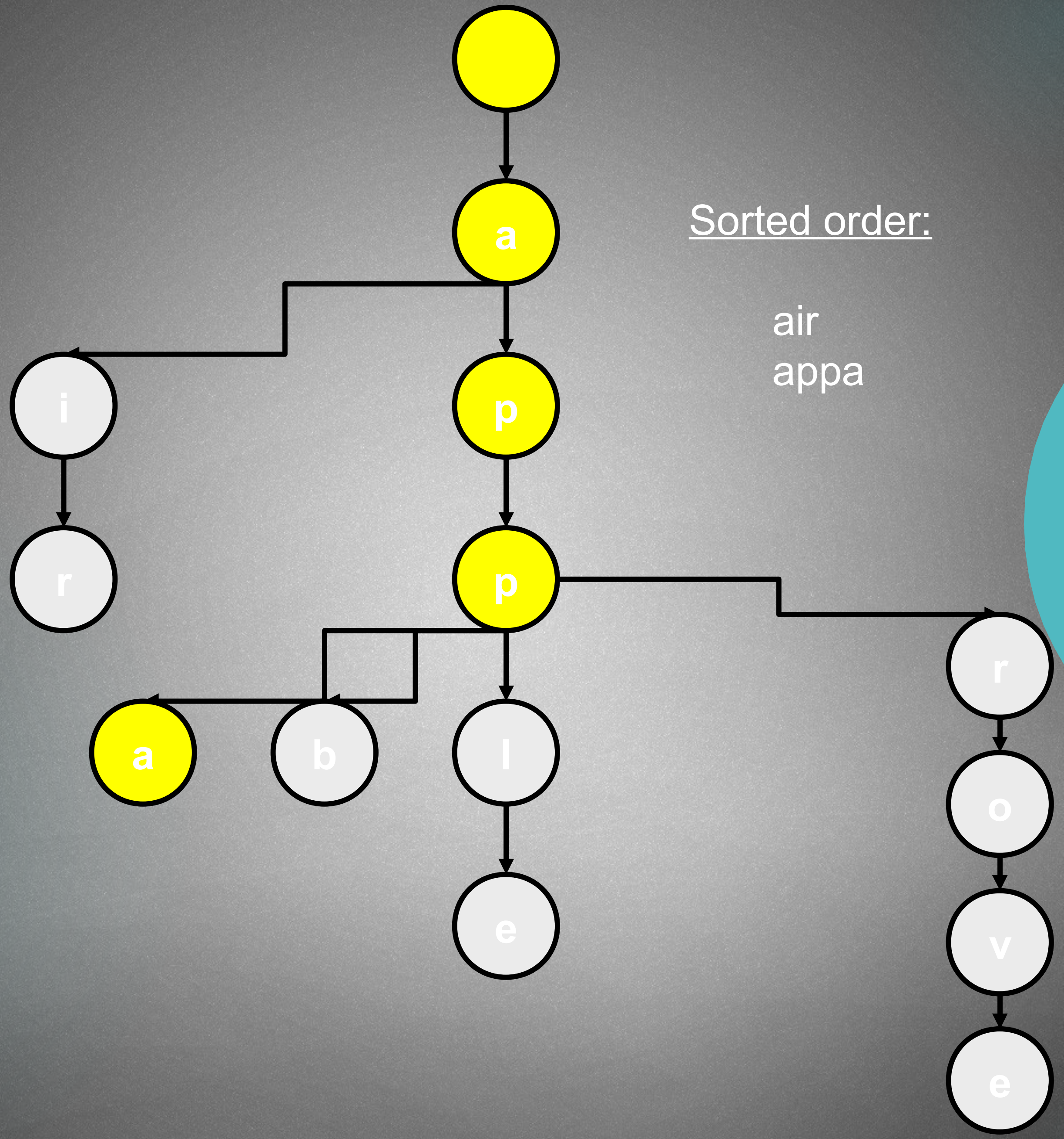

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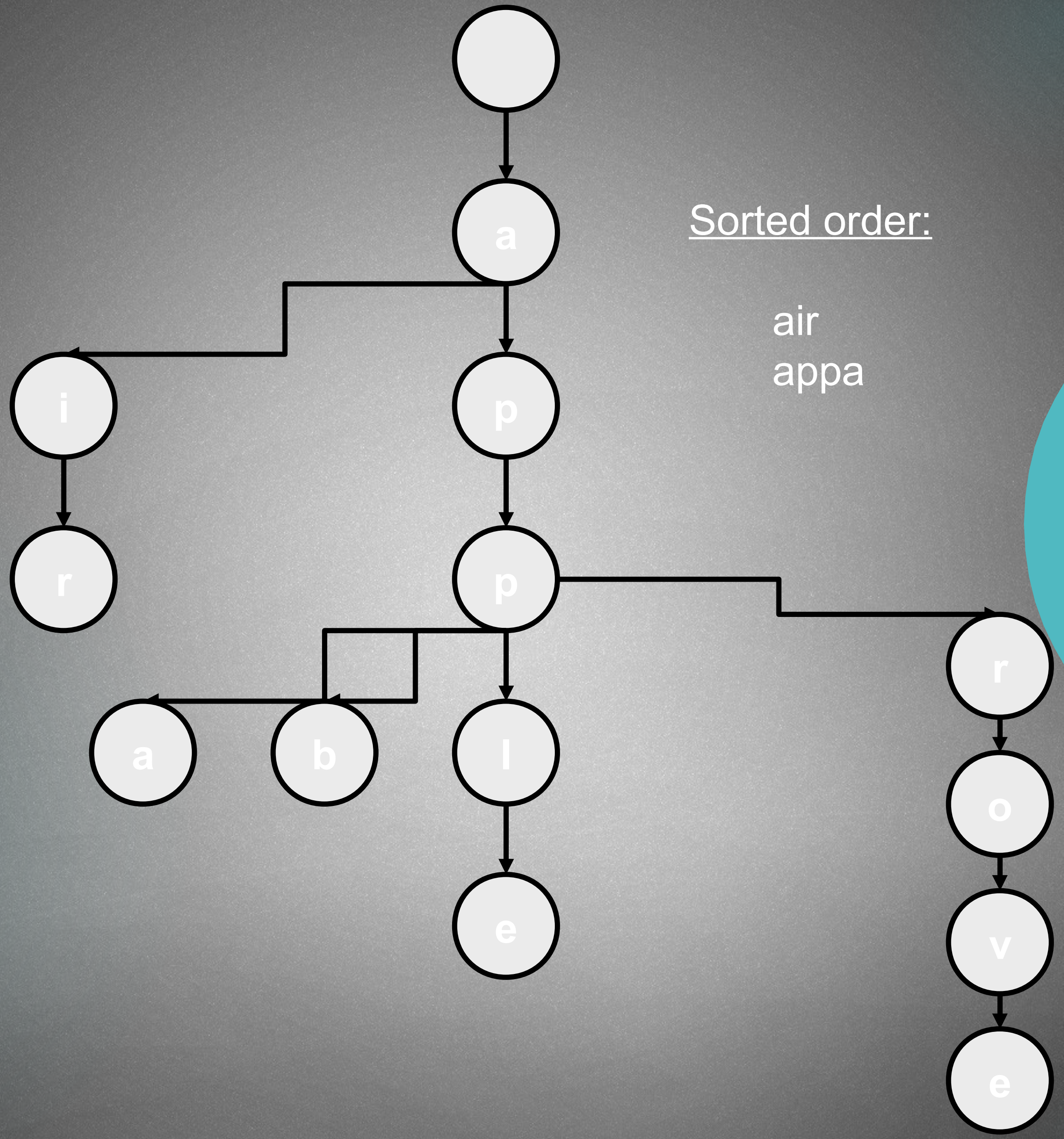

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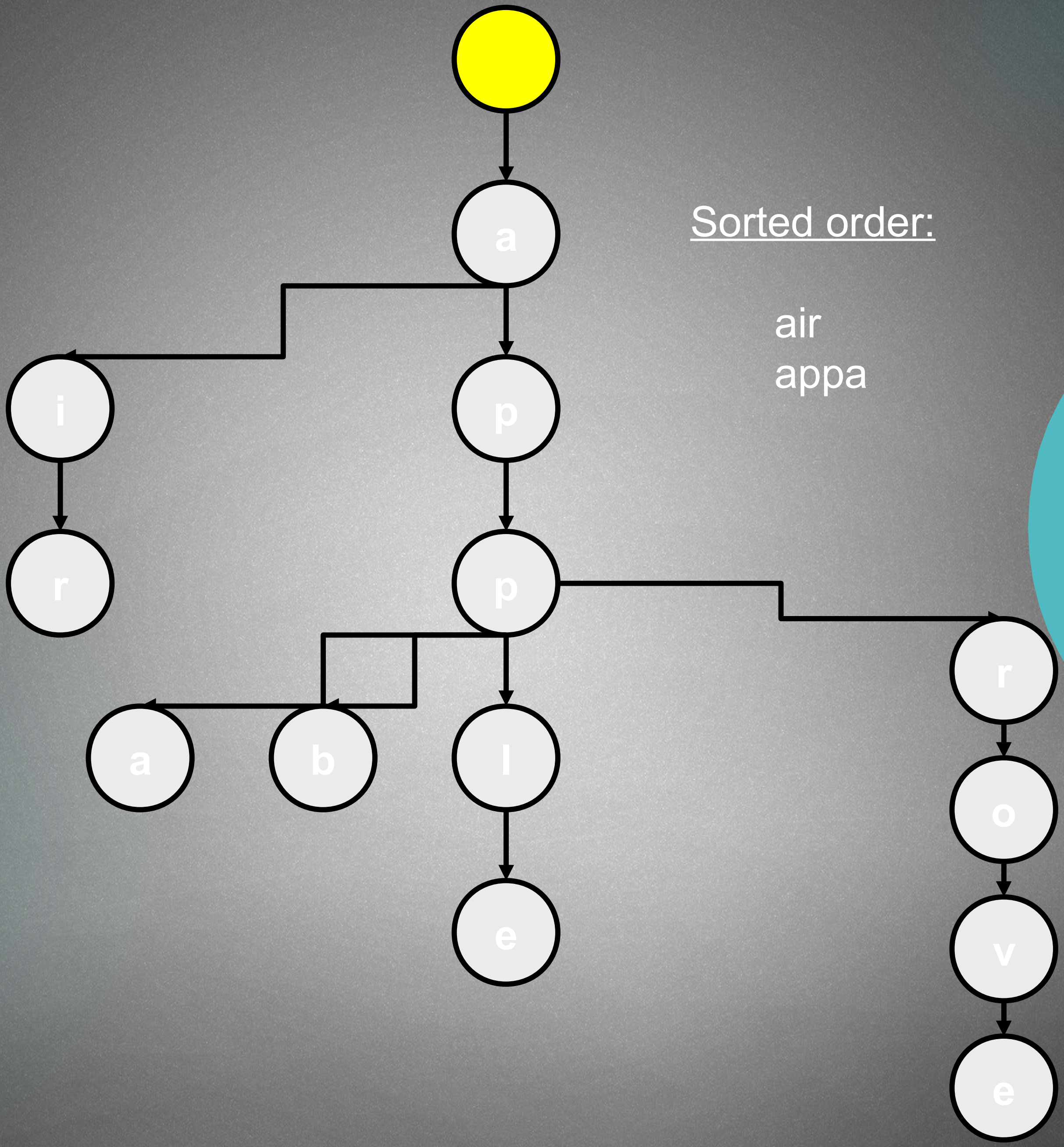

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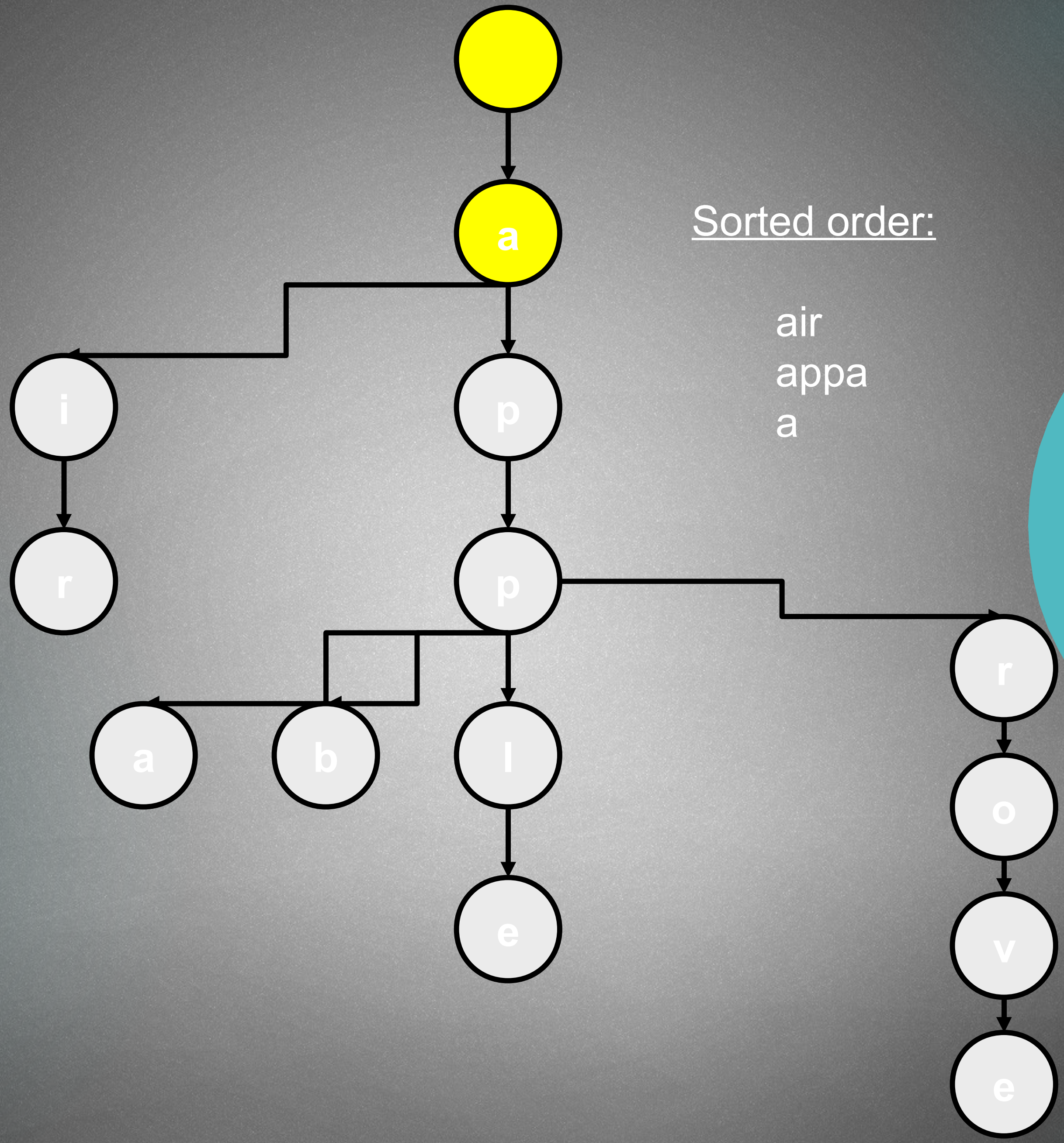

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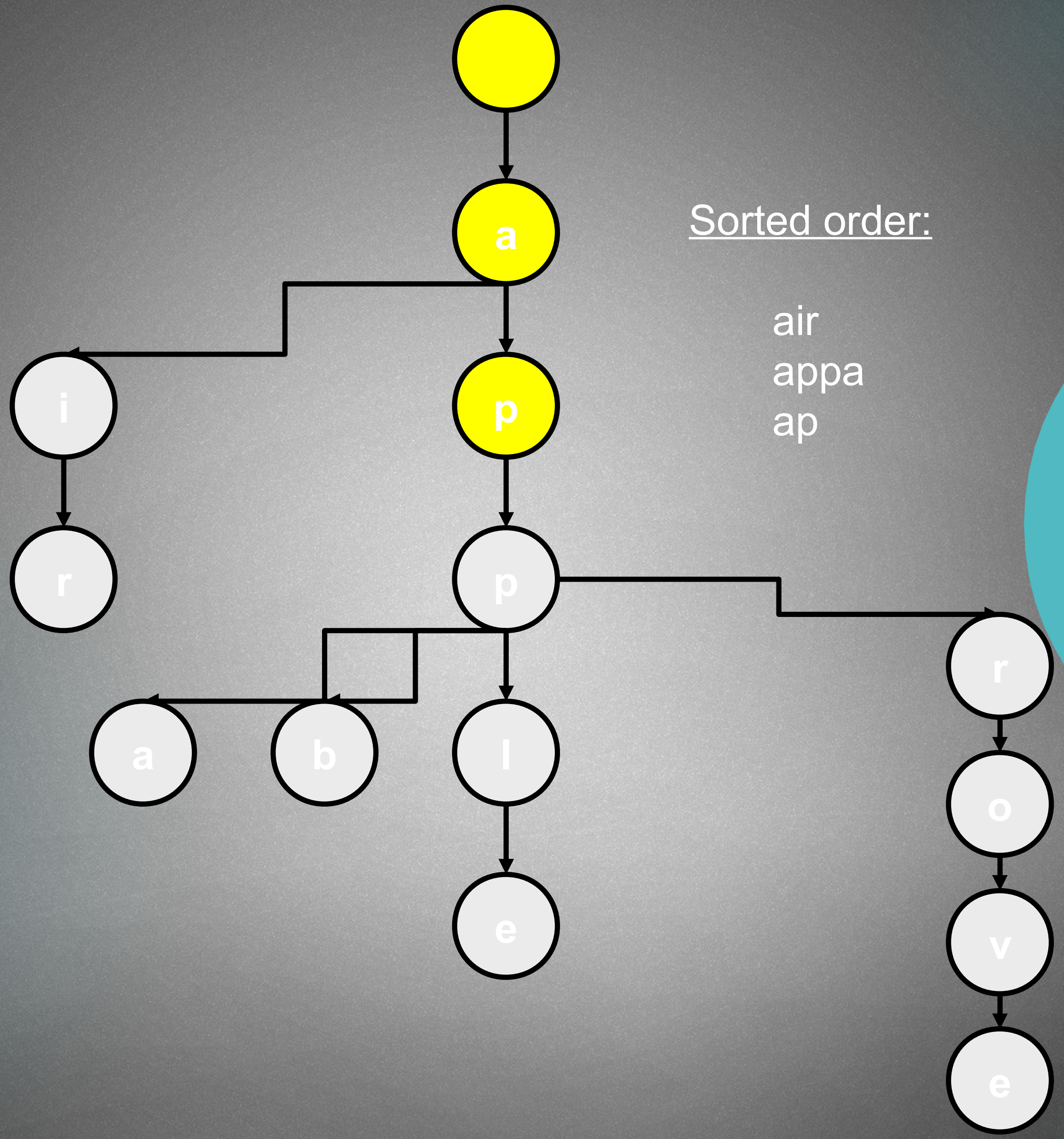

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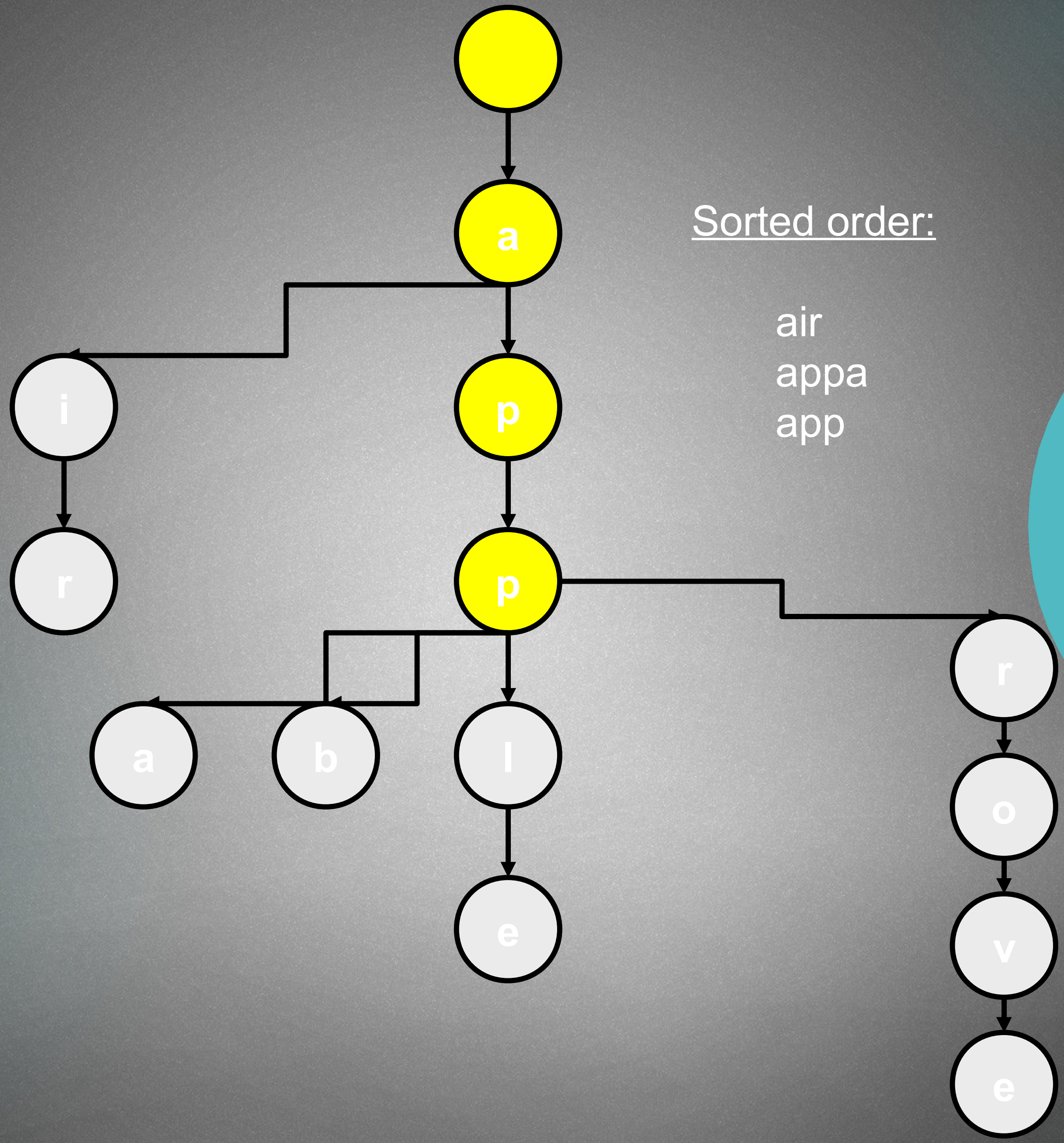

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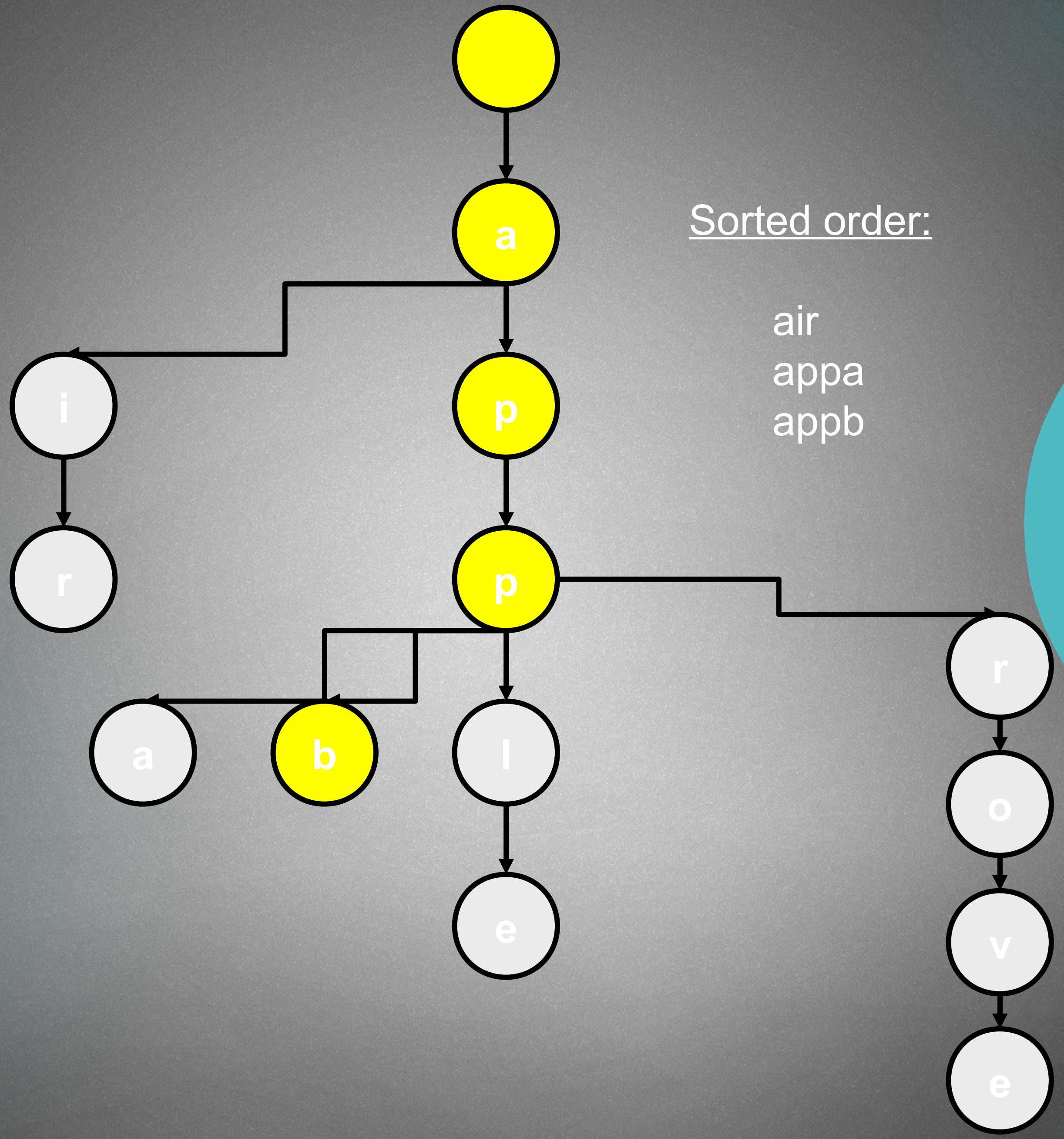

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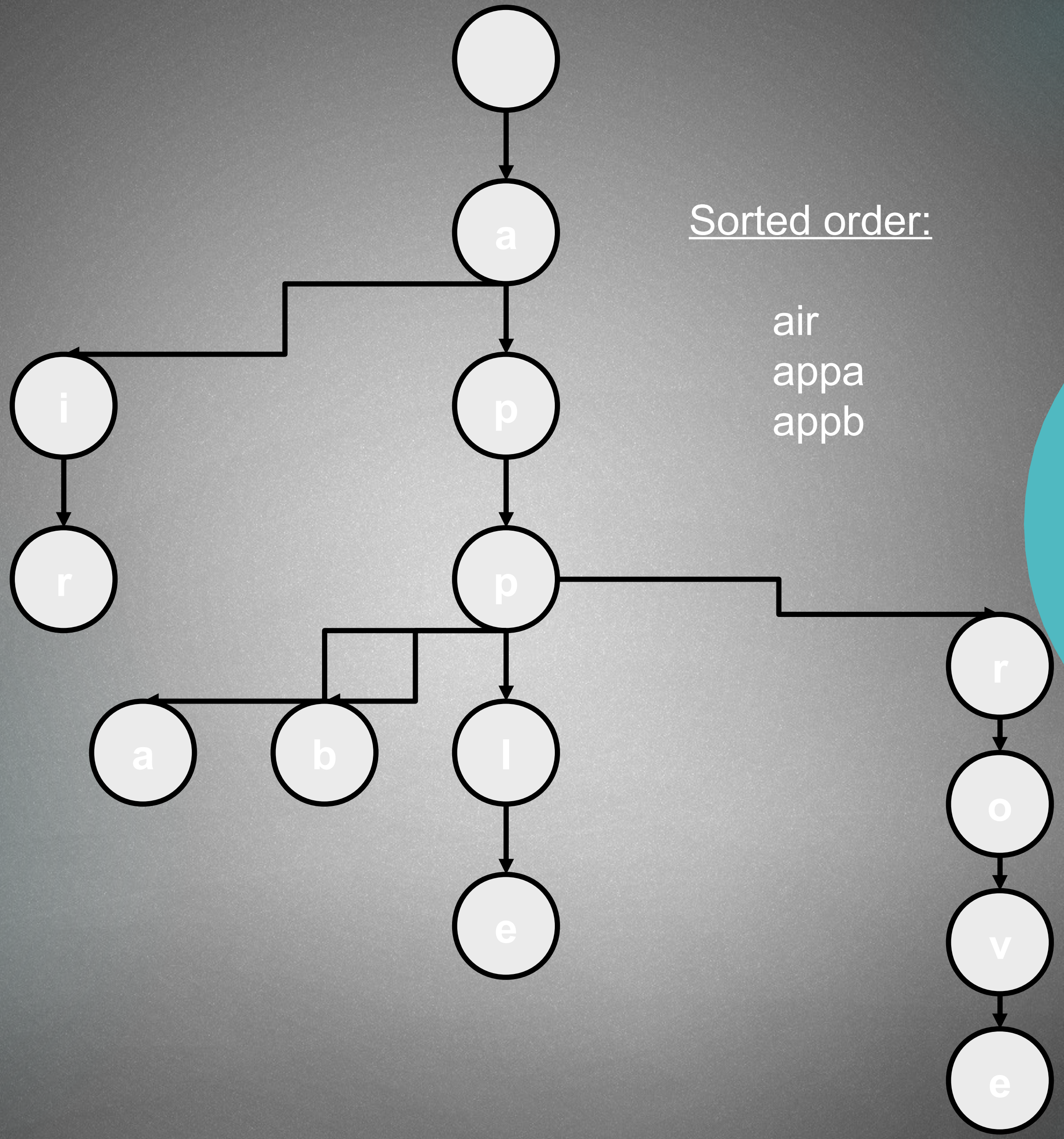

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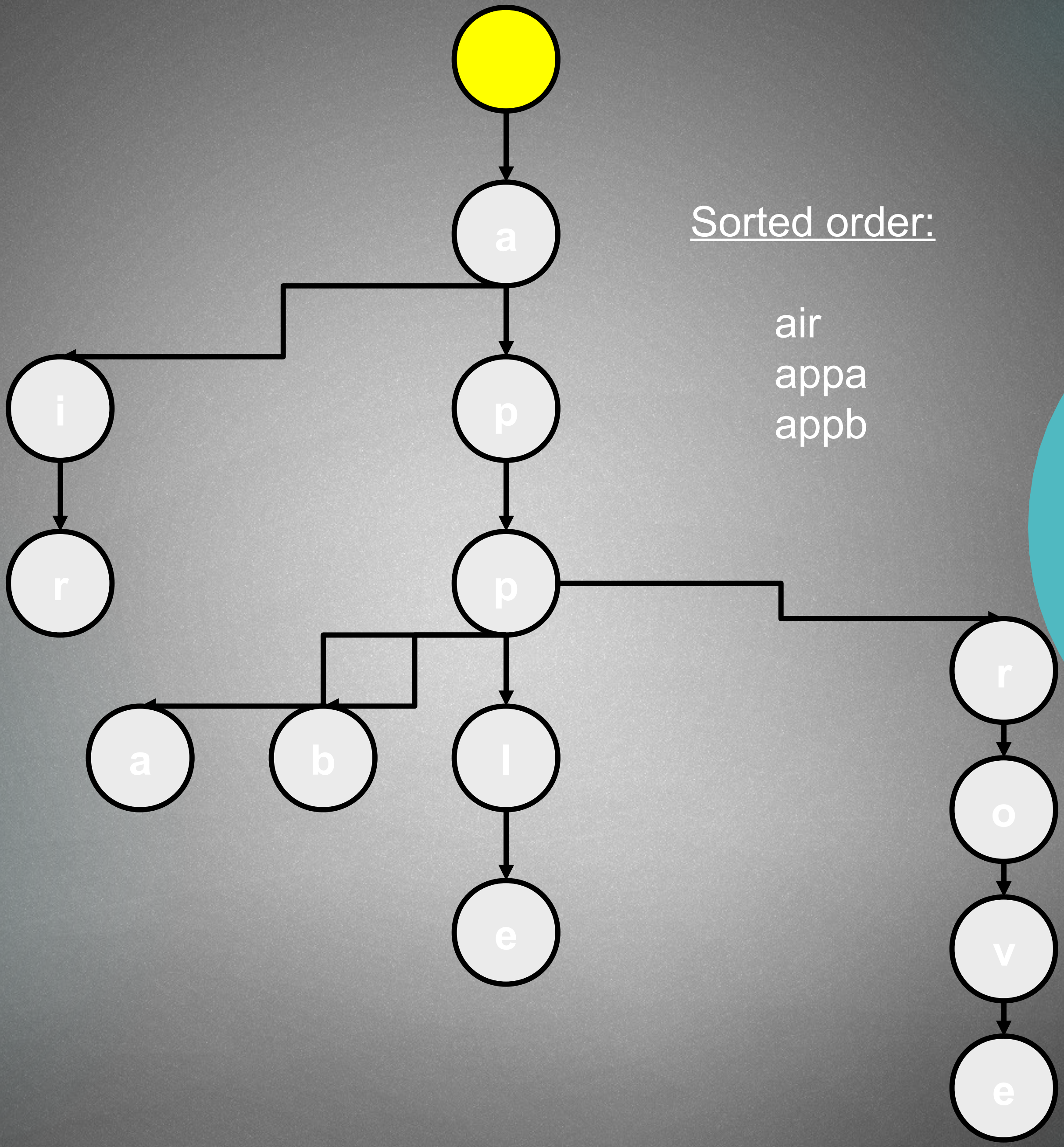

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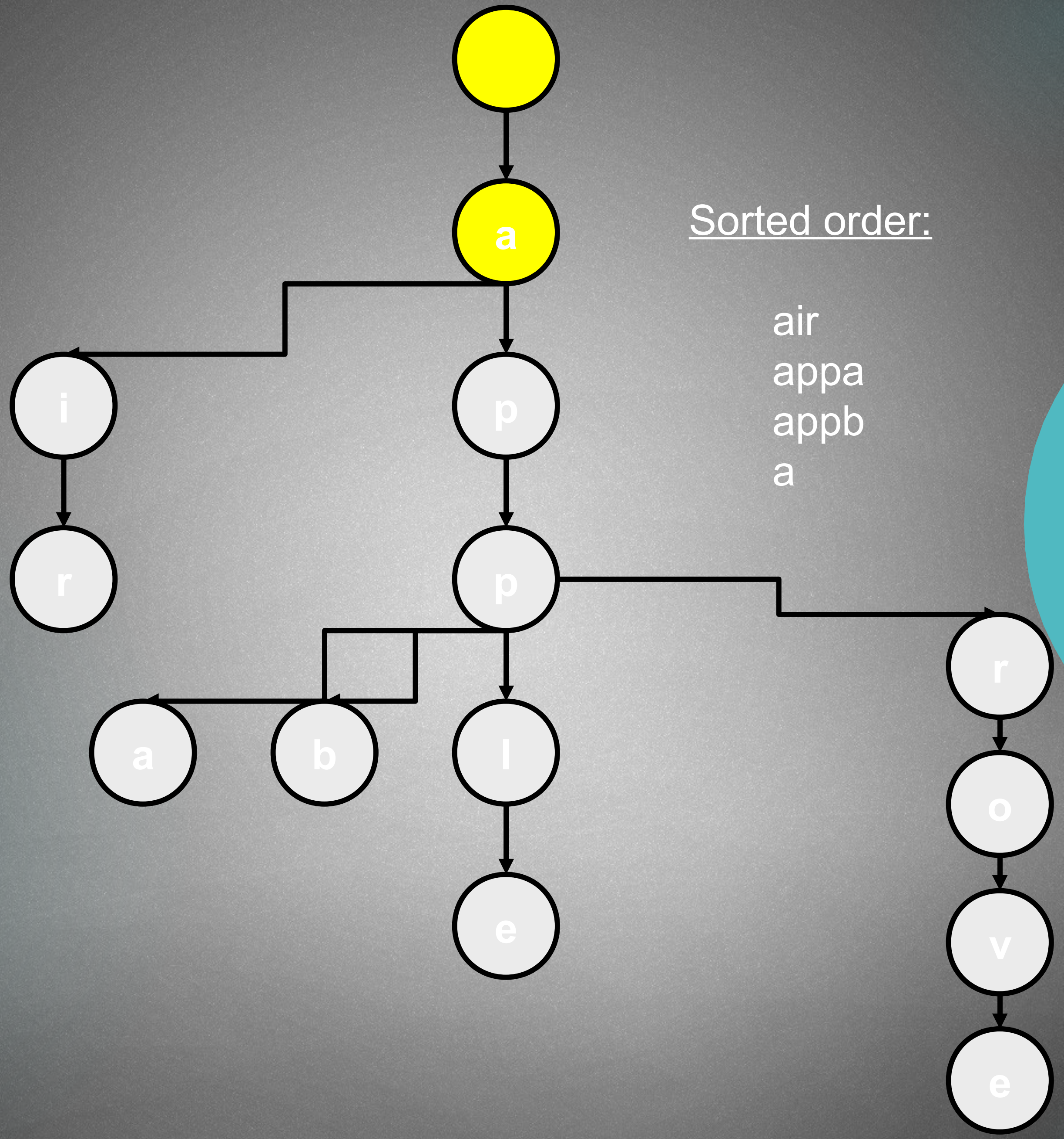

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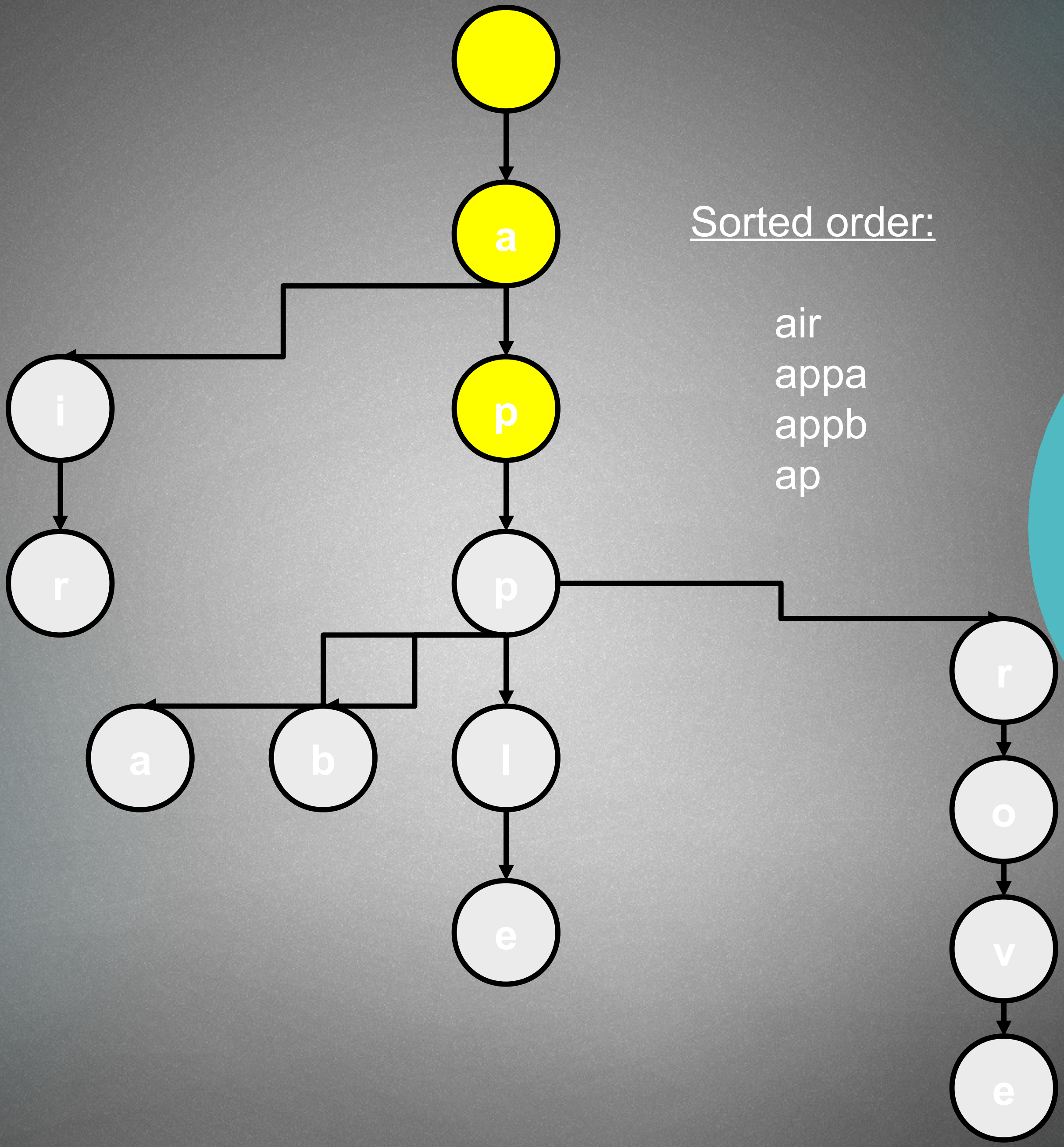

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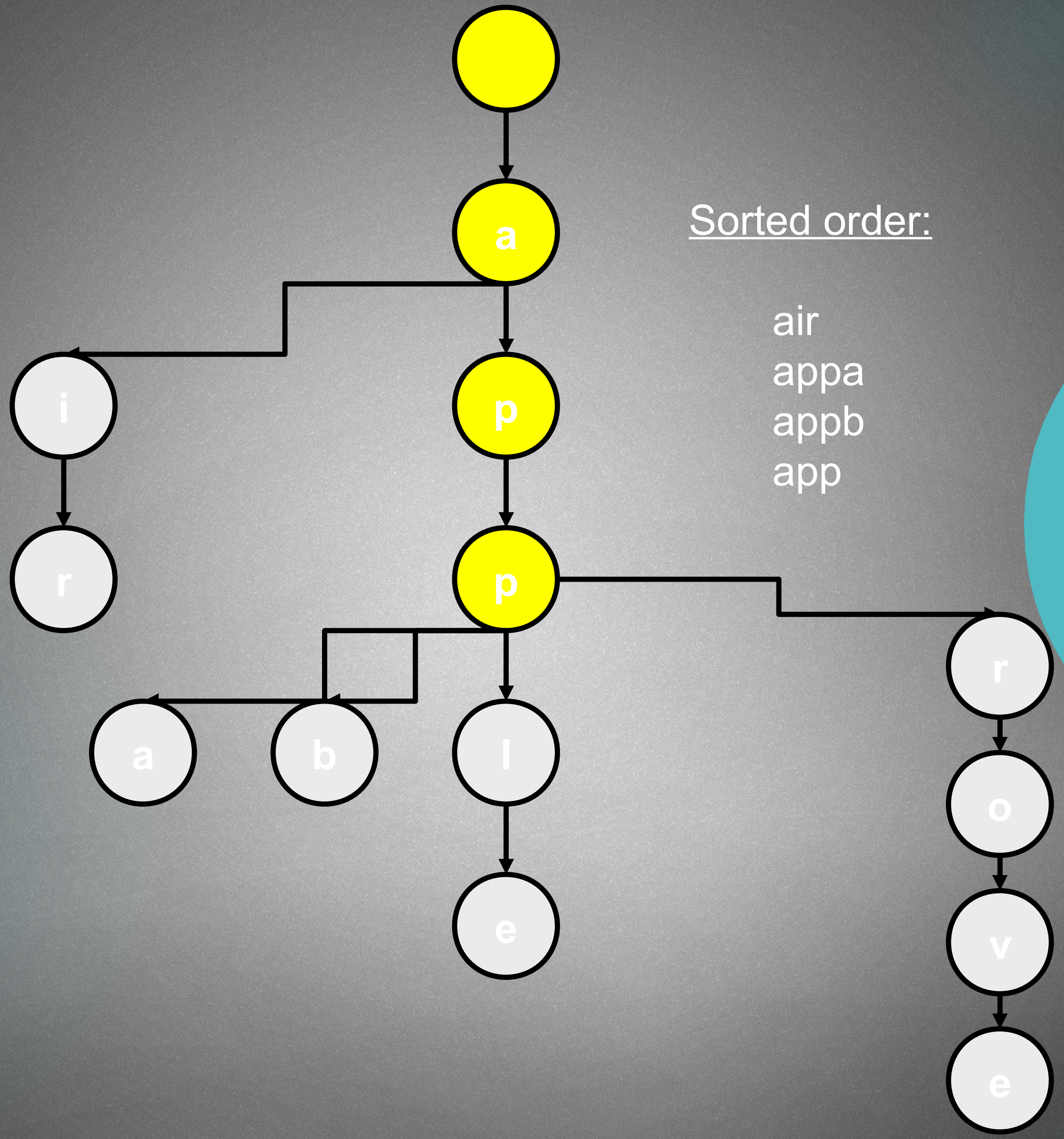

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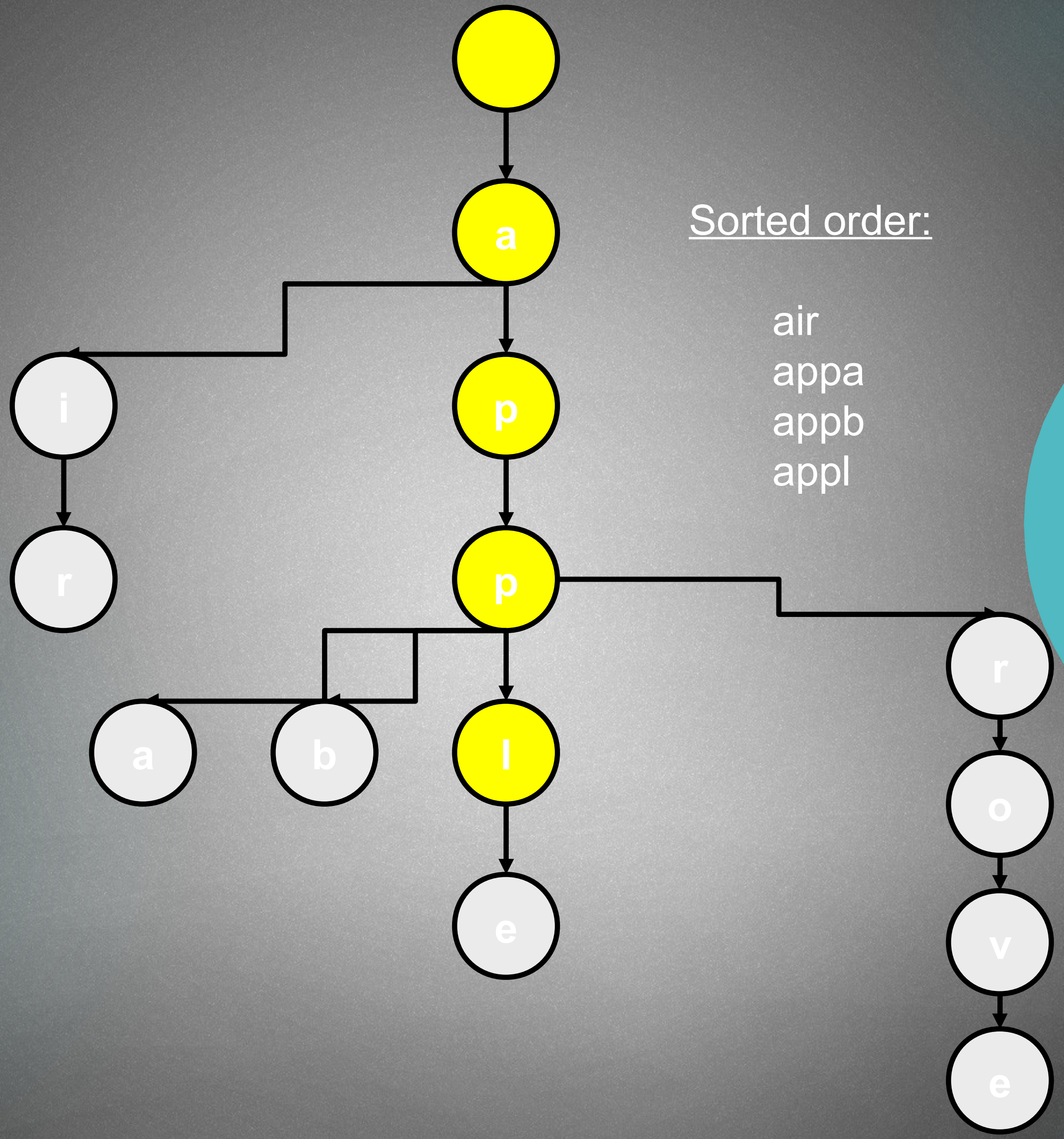

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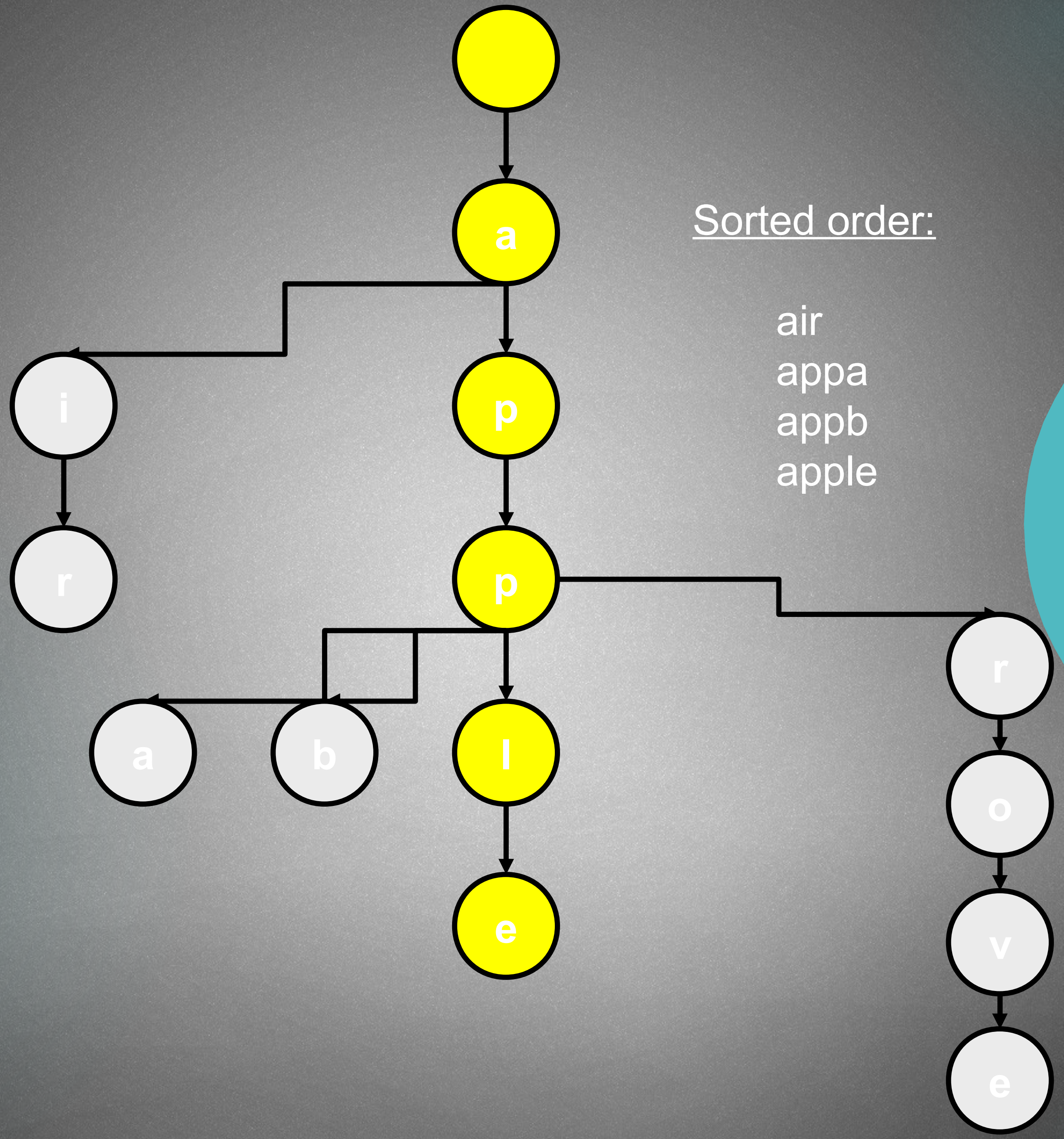

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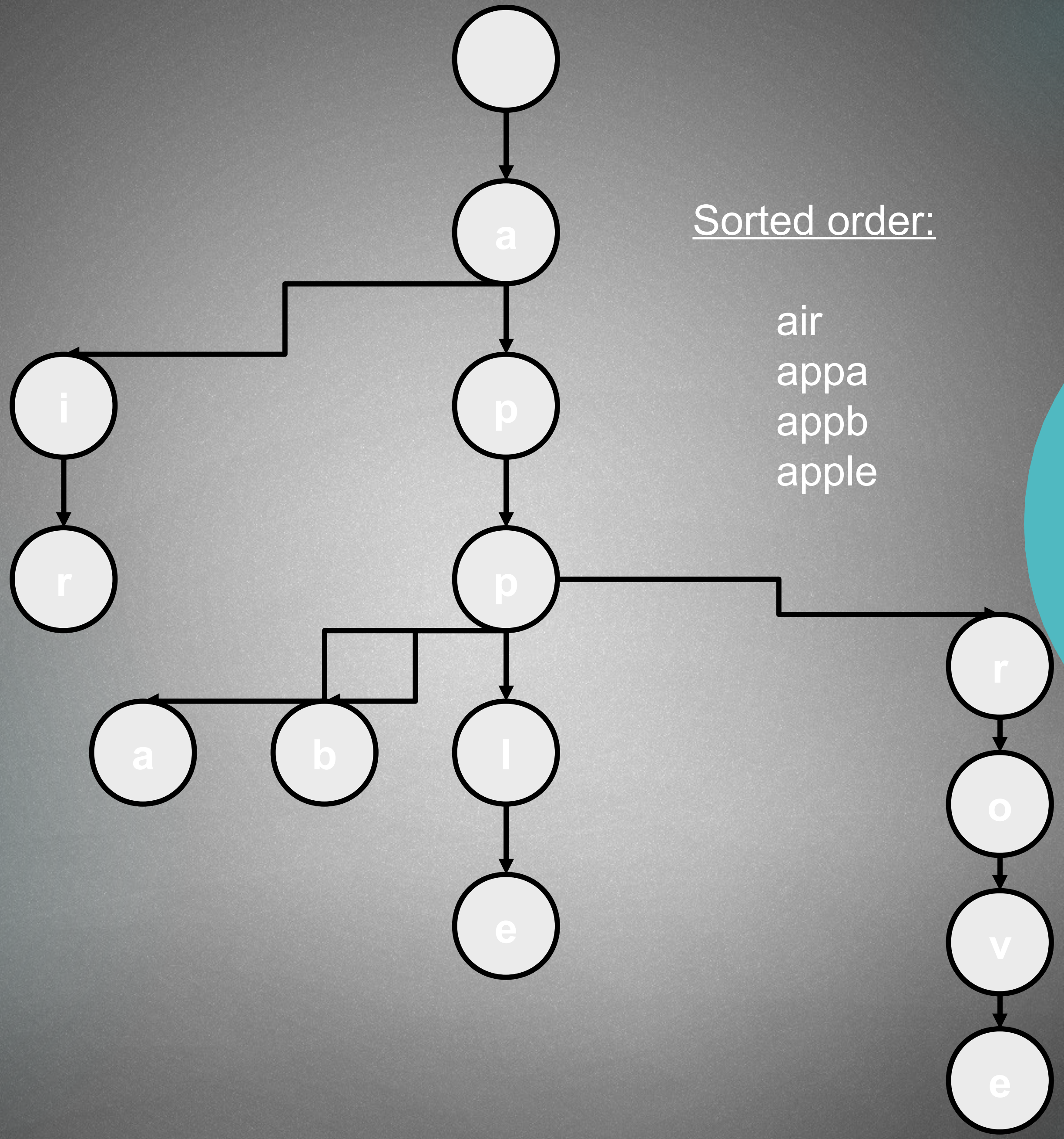

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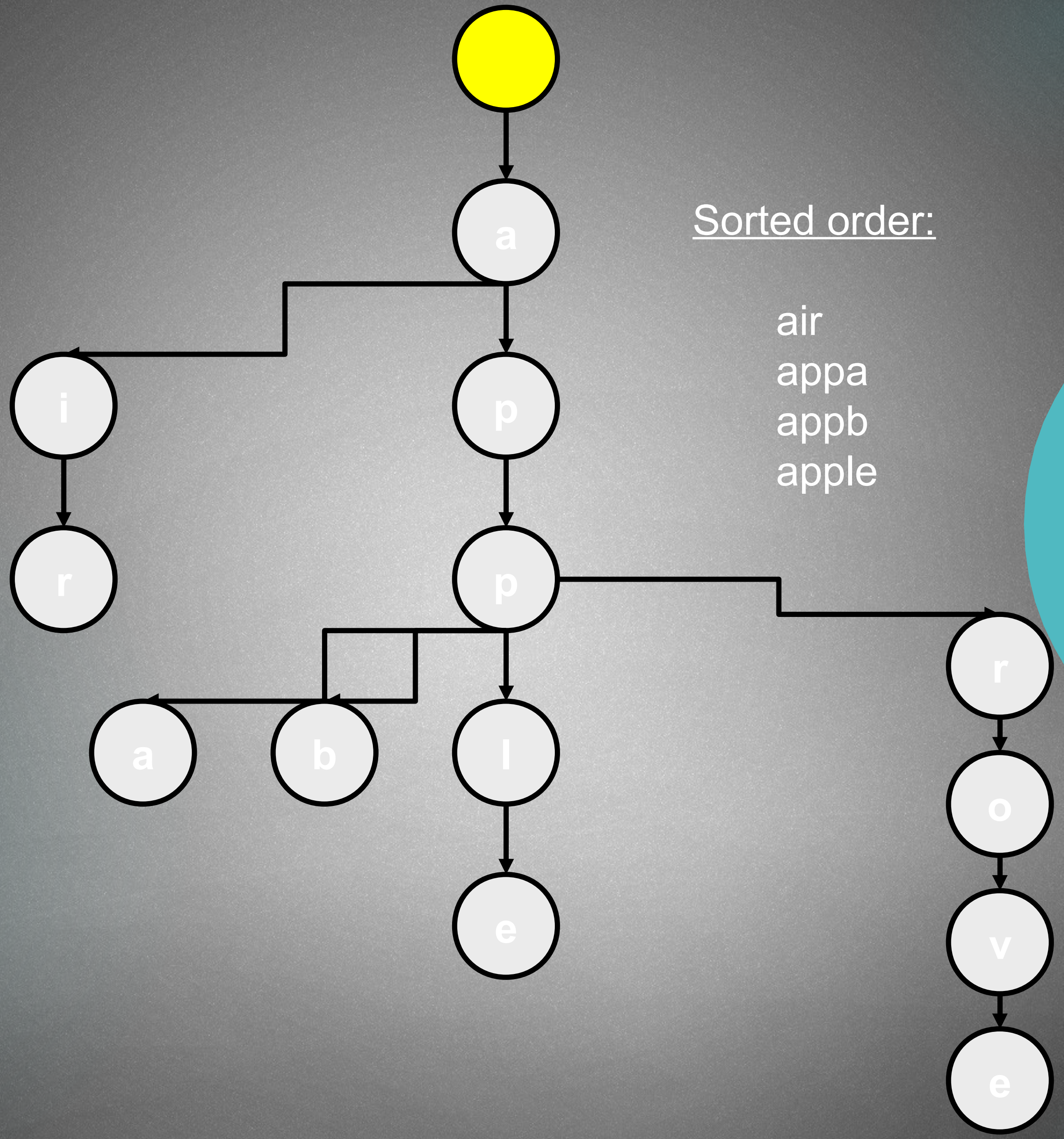

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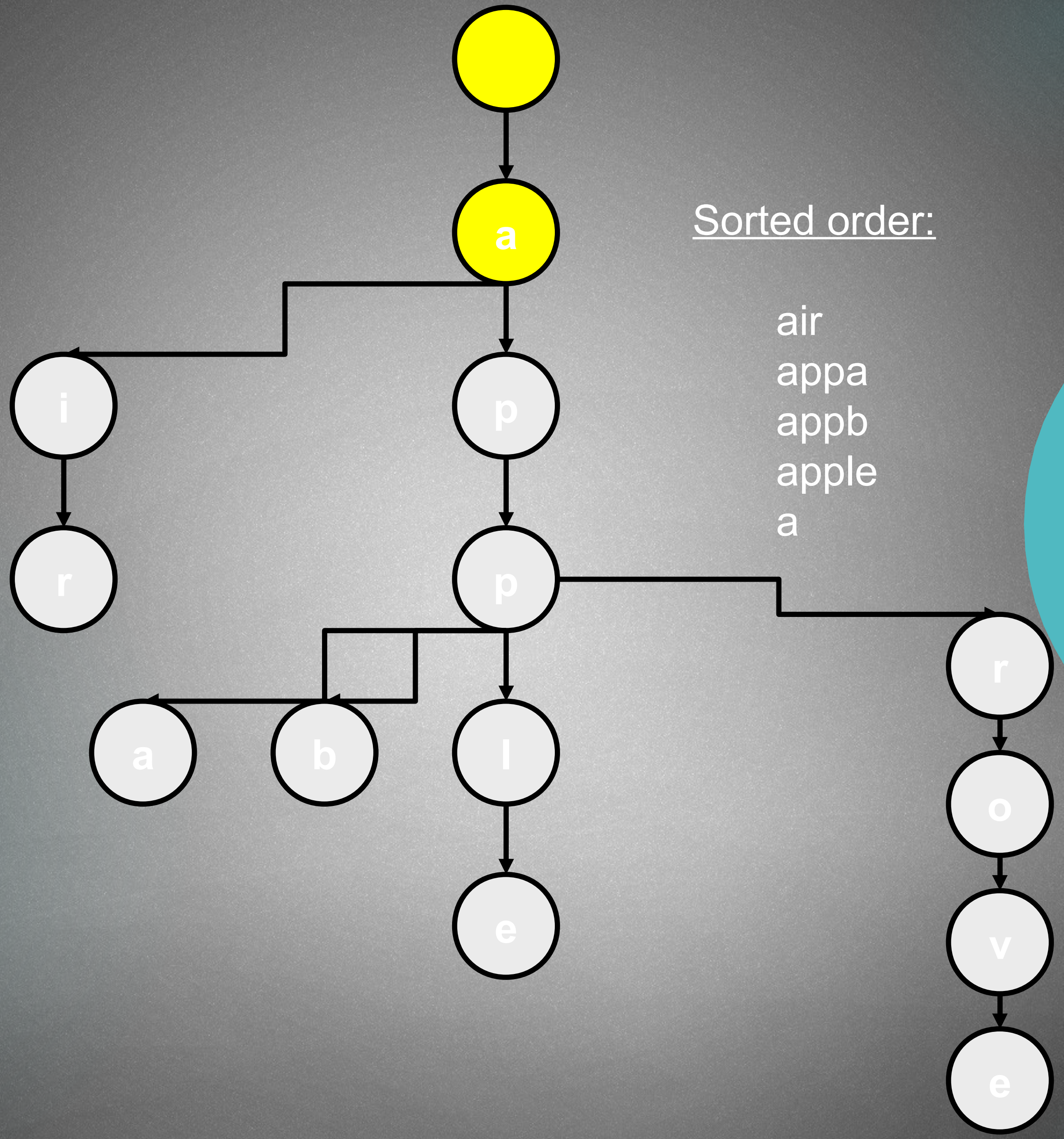

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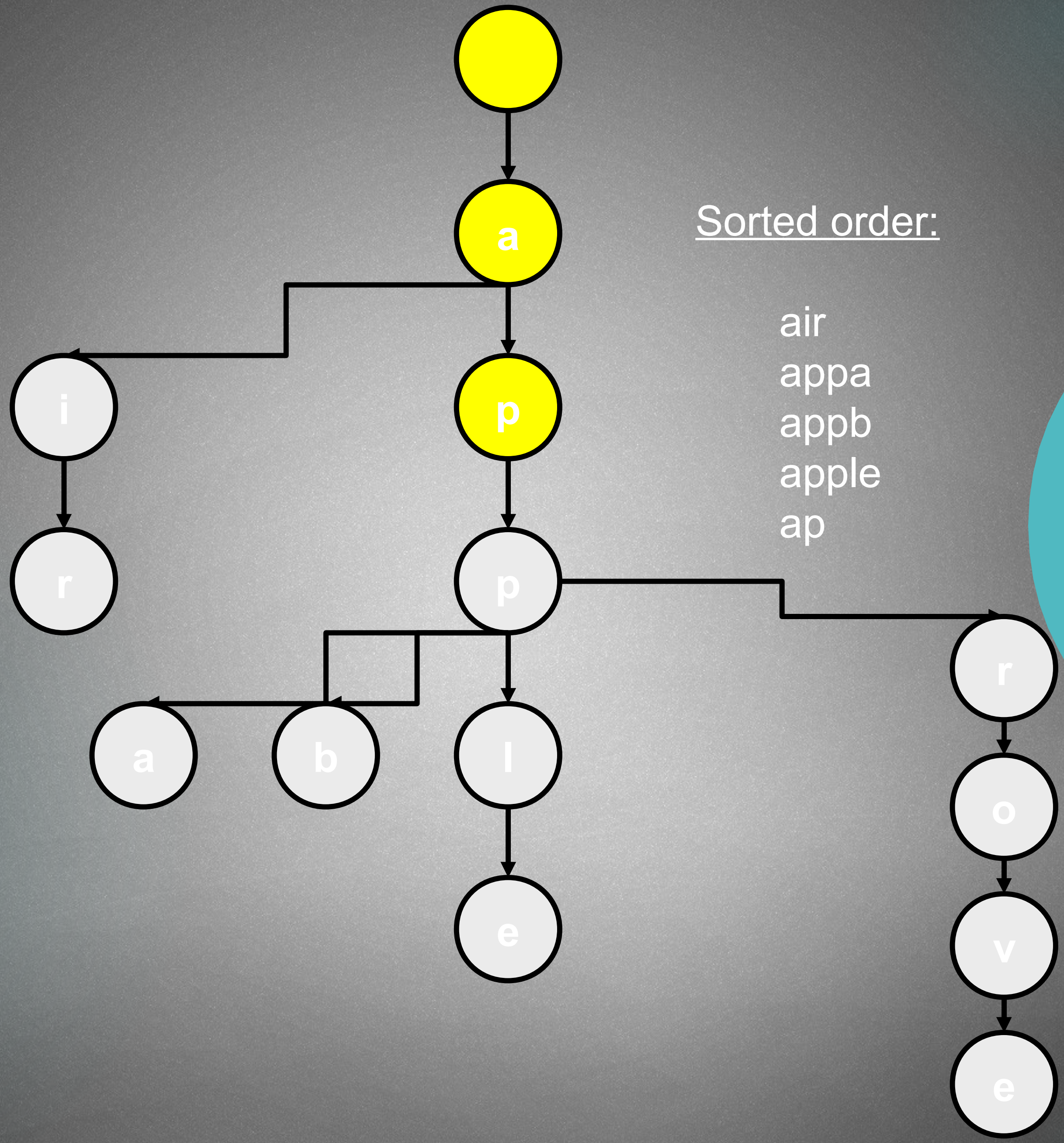

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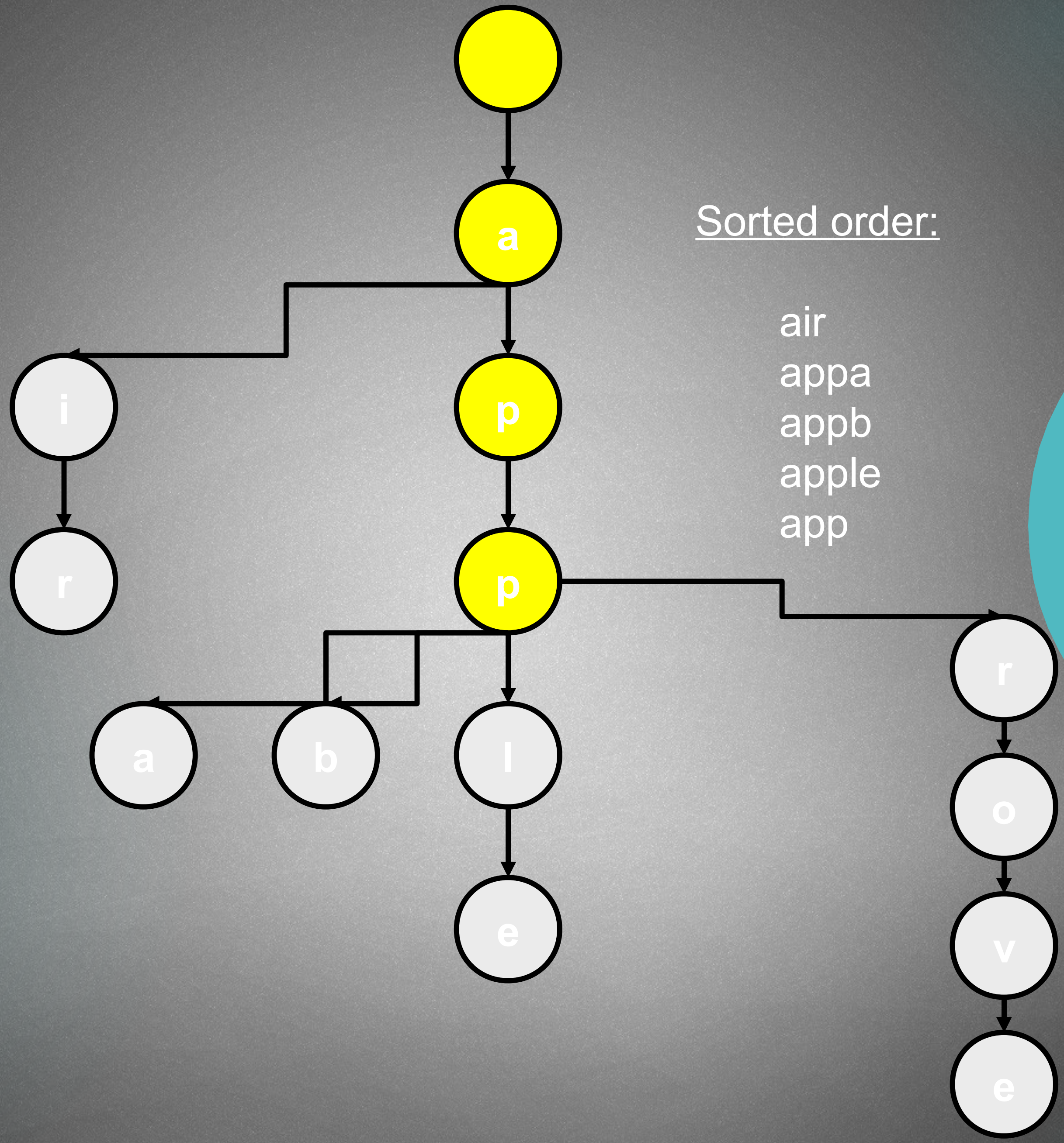

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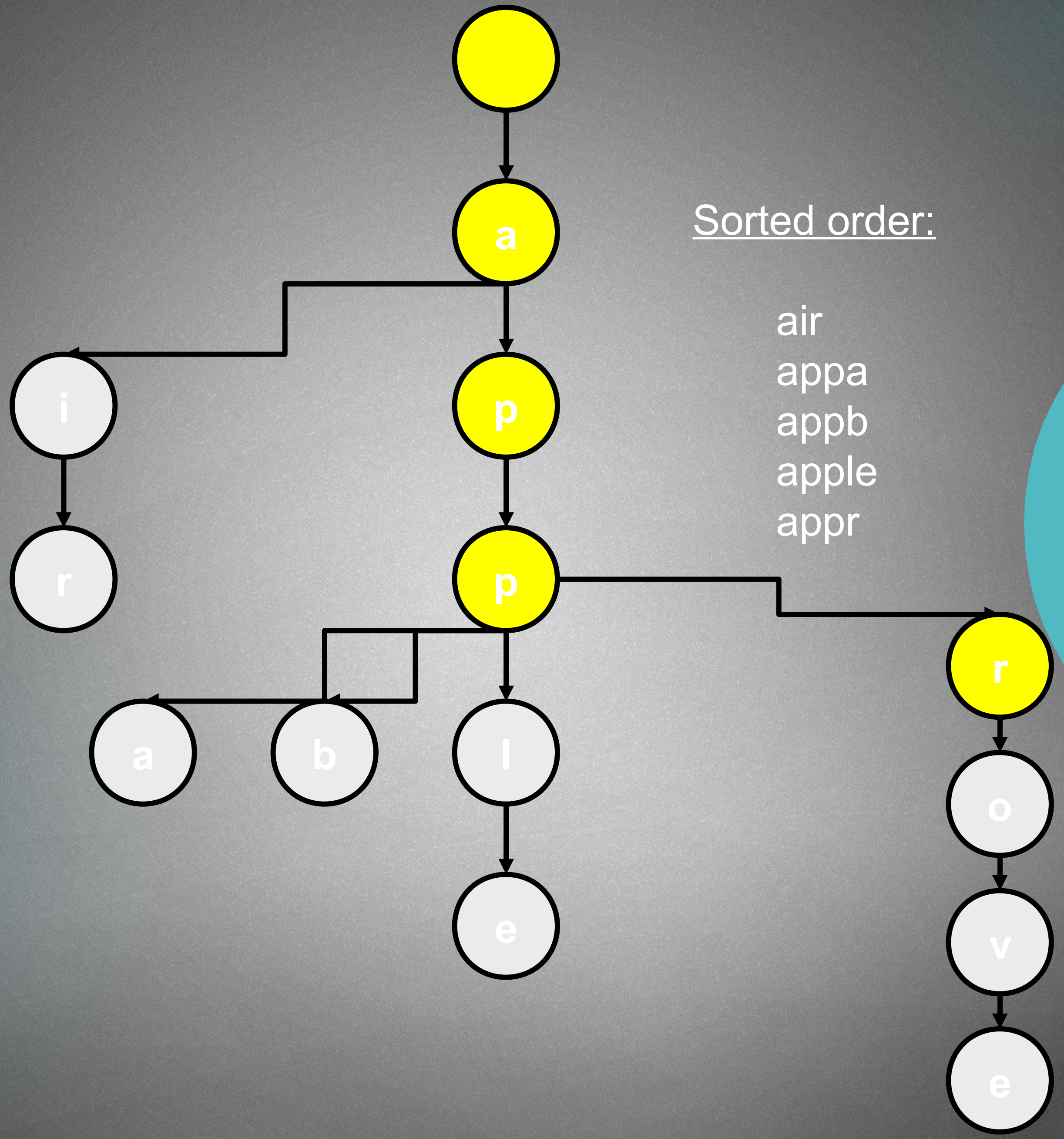

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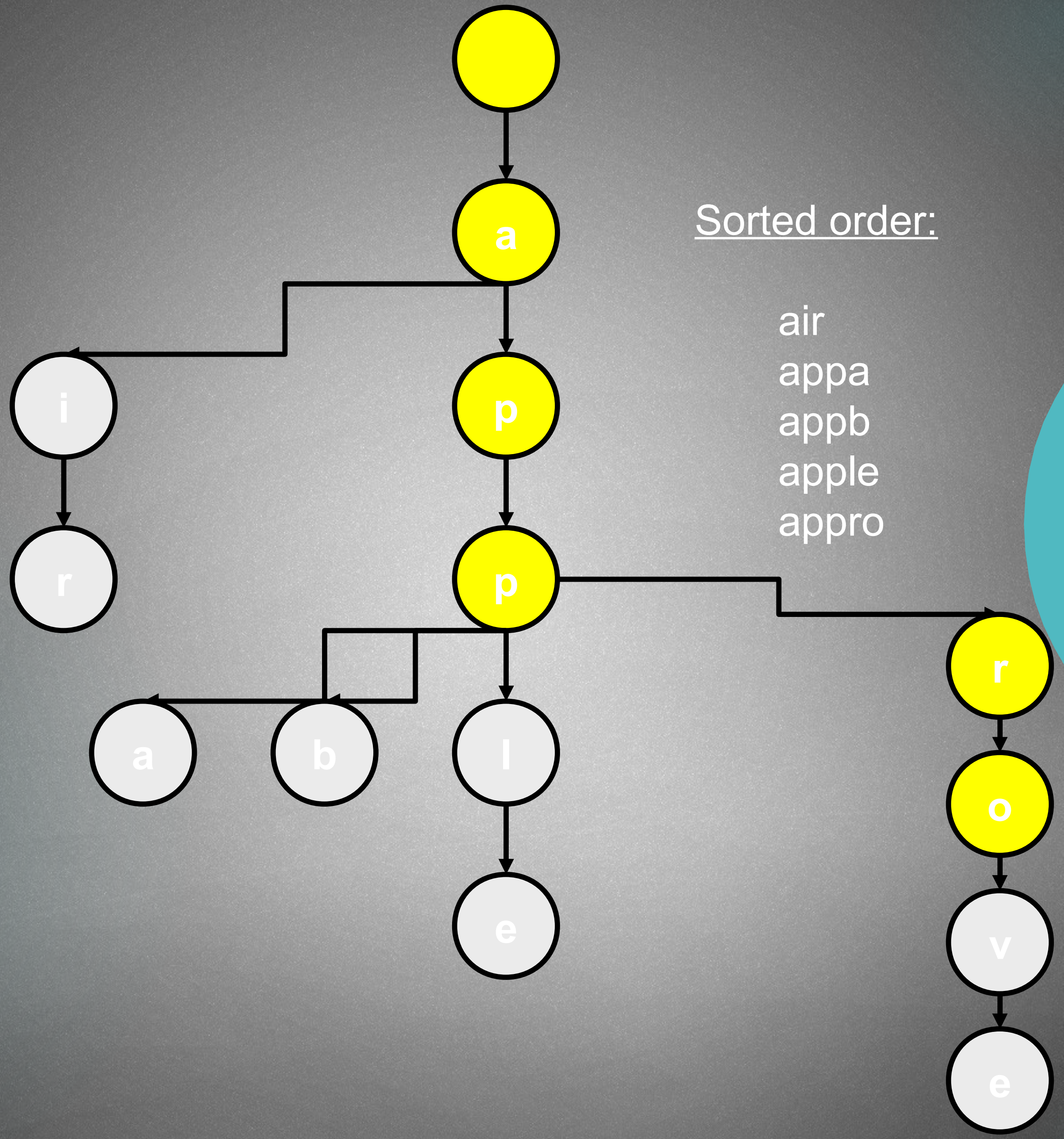

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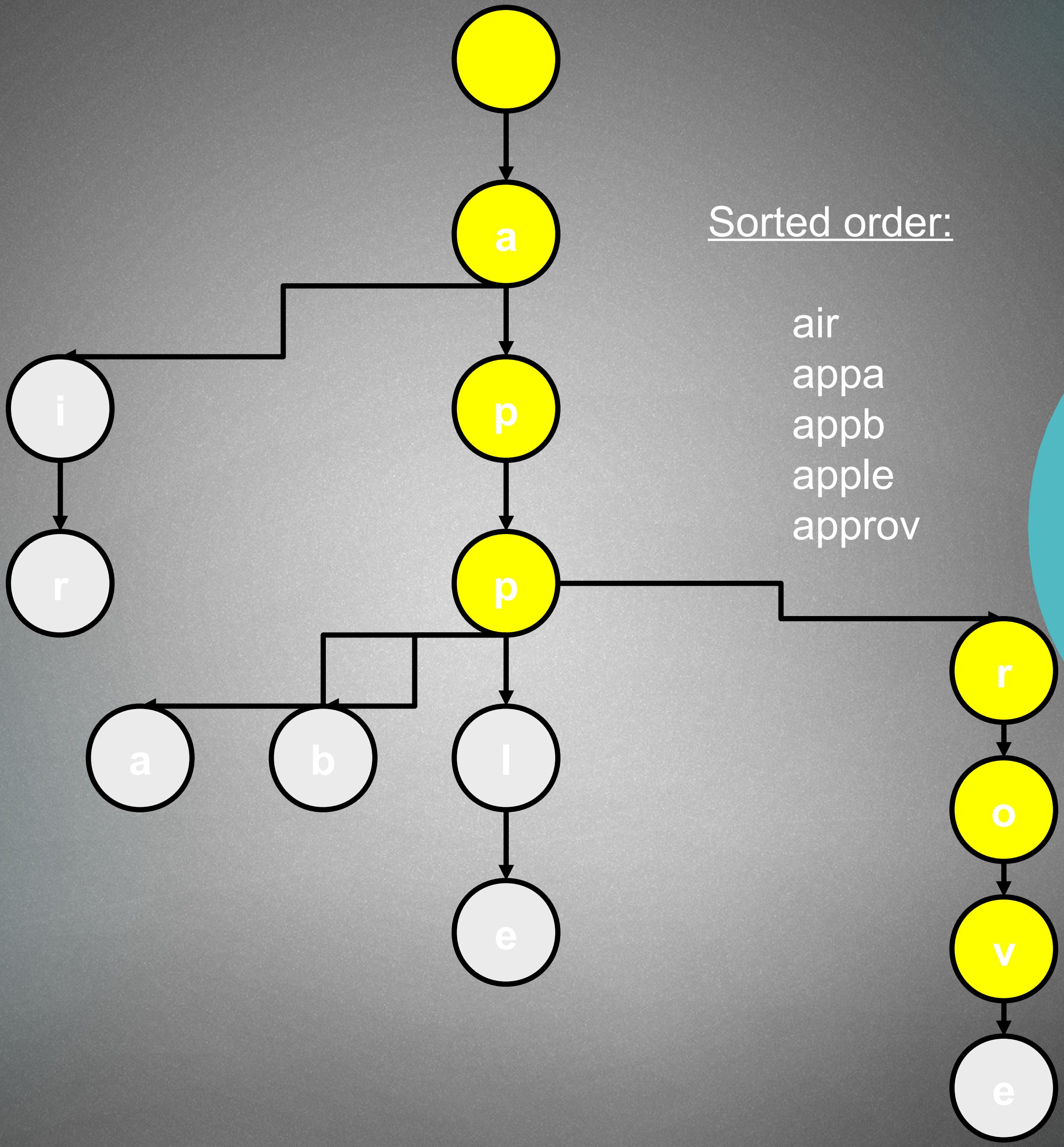

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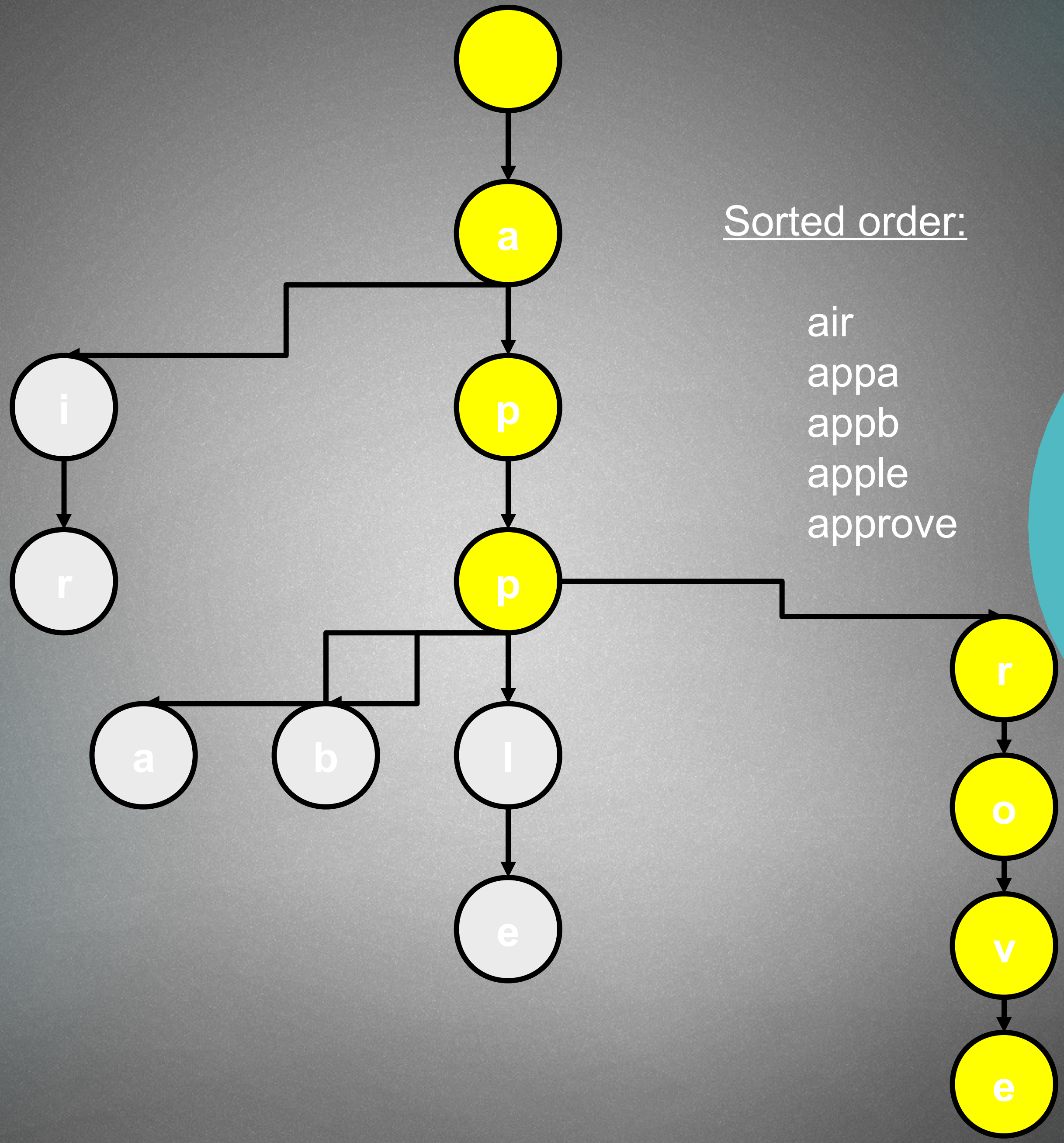

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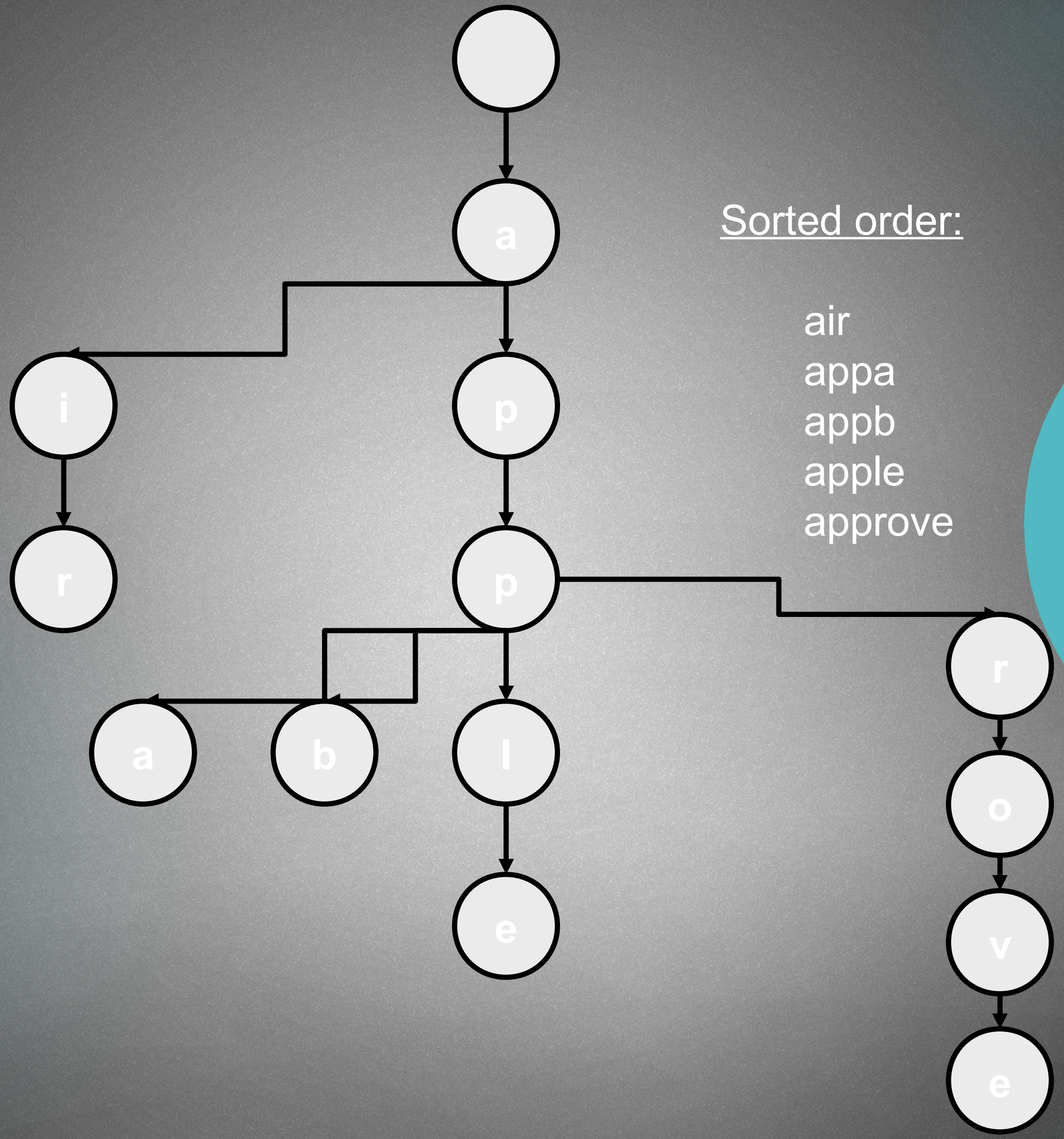

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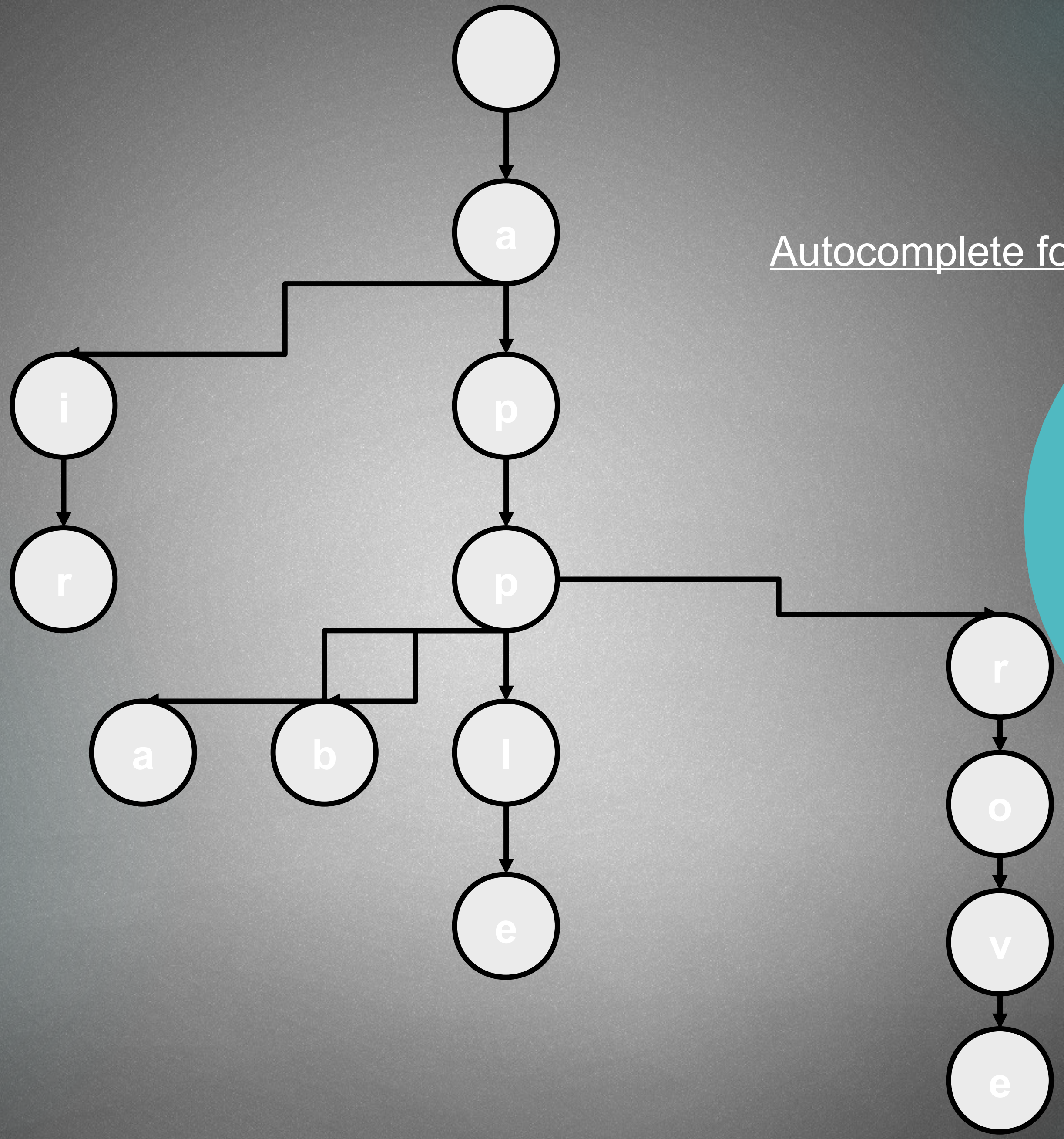
Autocomplete

It is the same as we have seen for the sorting

BUT here we have to look for the prefix first

+ make a depth-first traversal starting with that node



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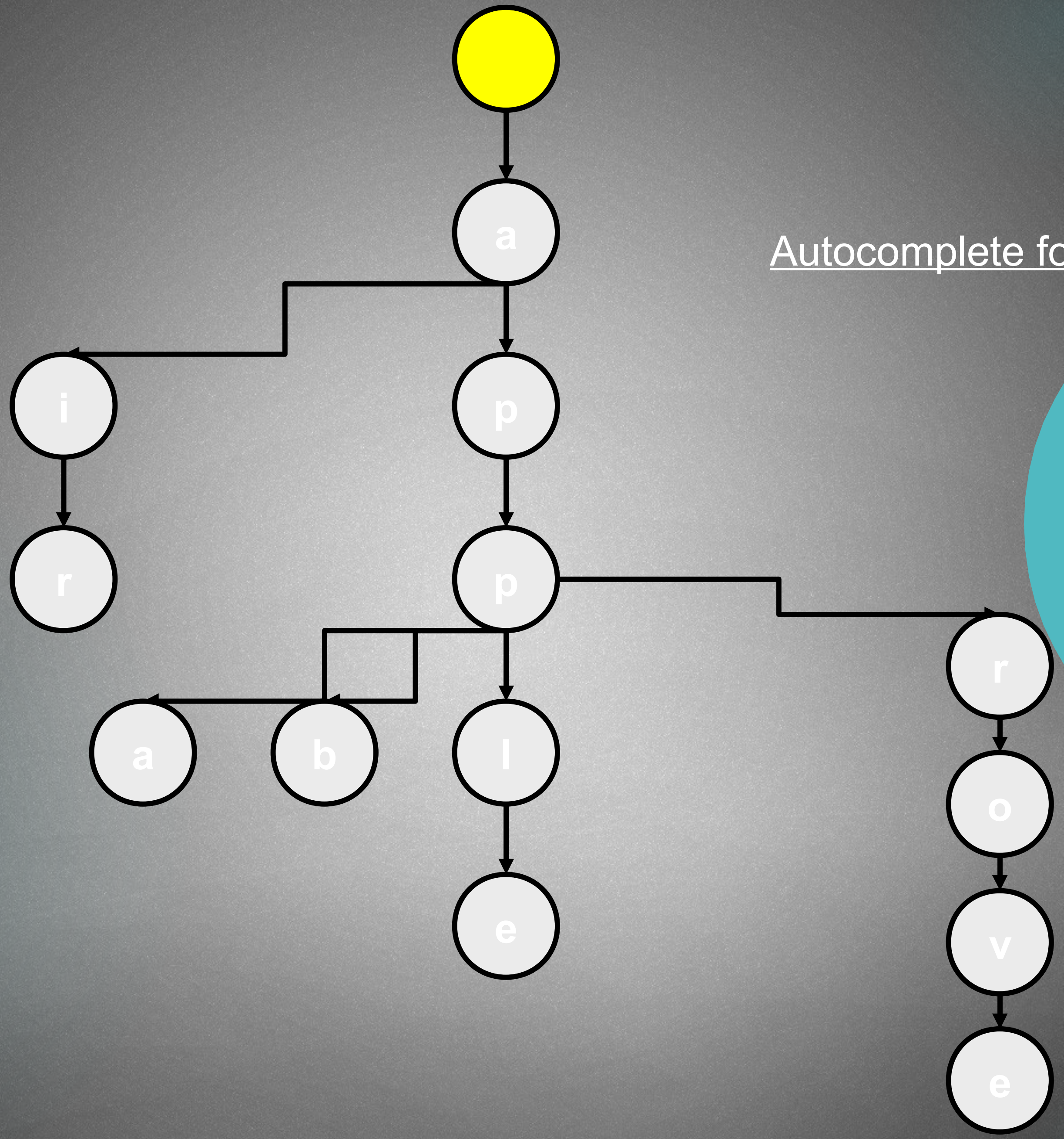

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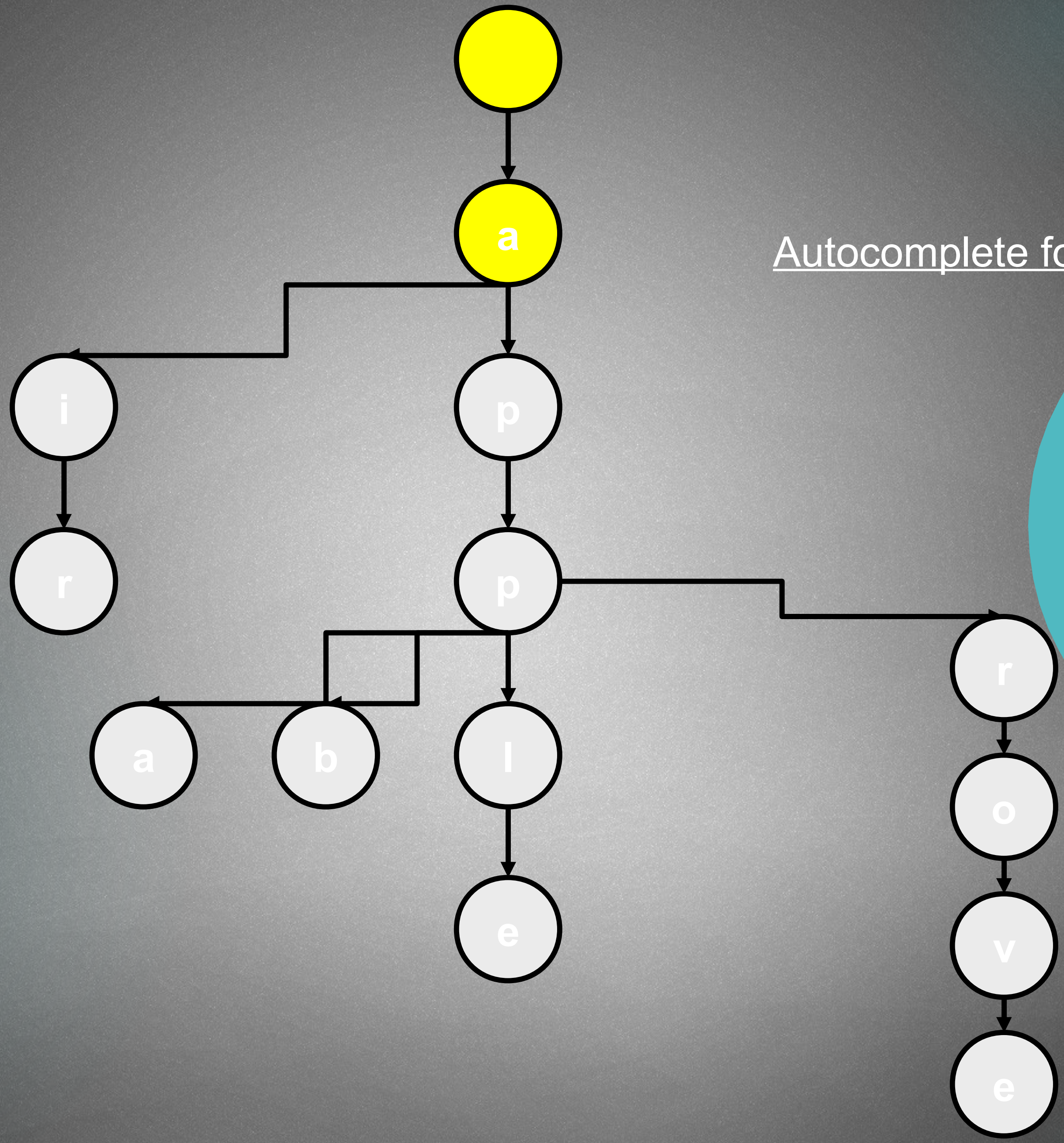

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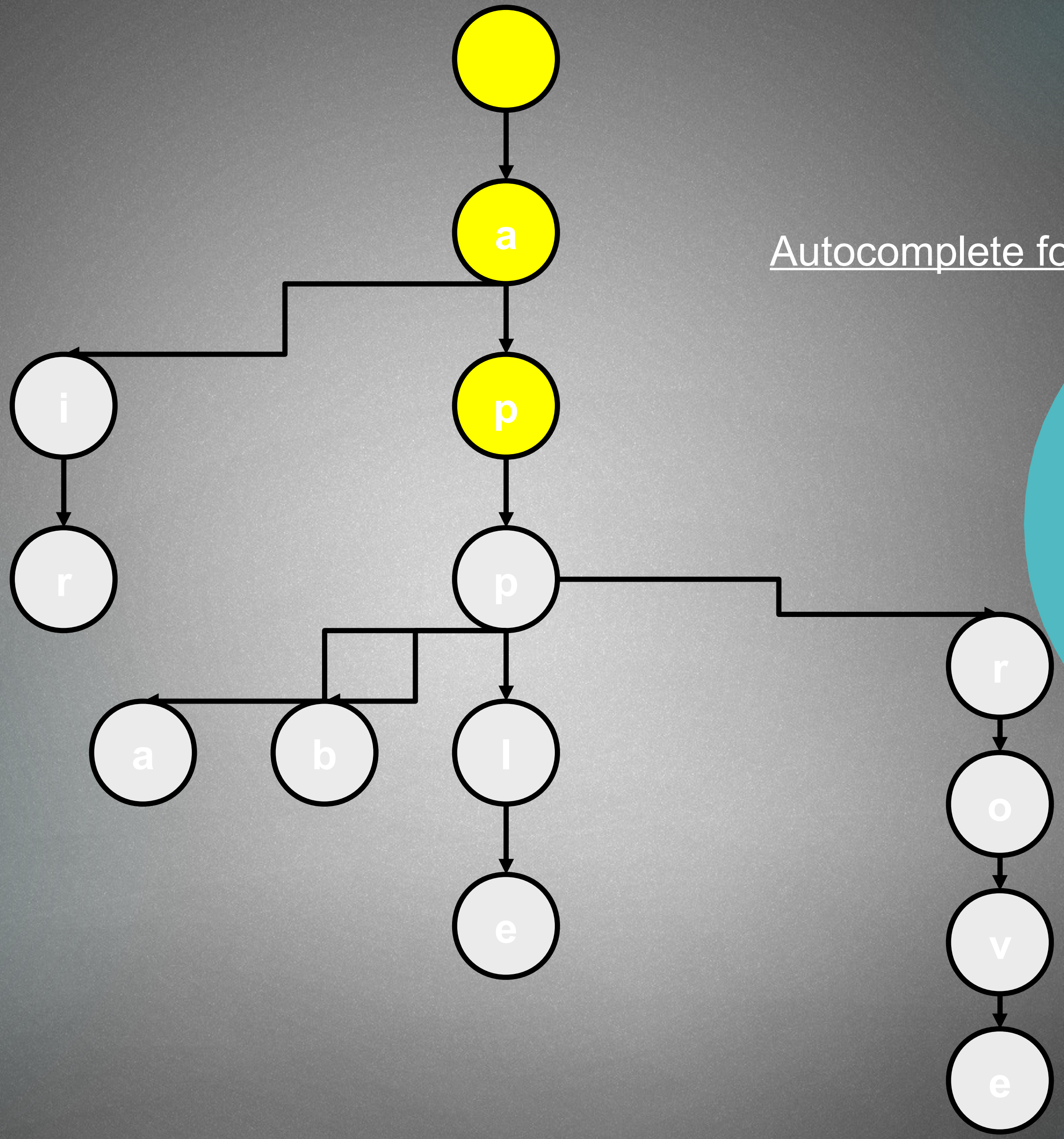

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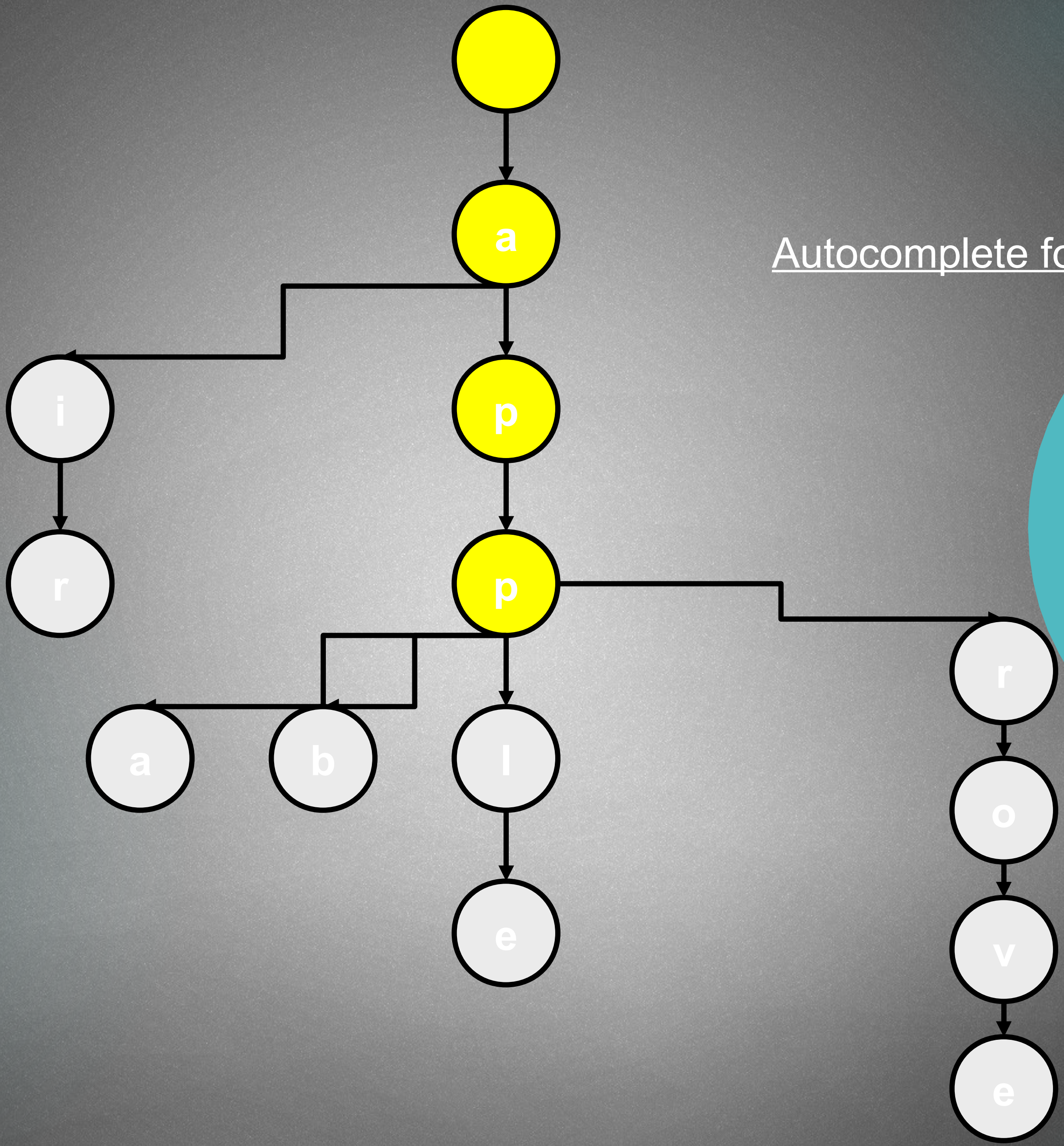

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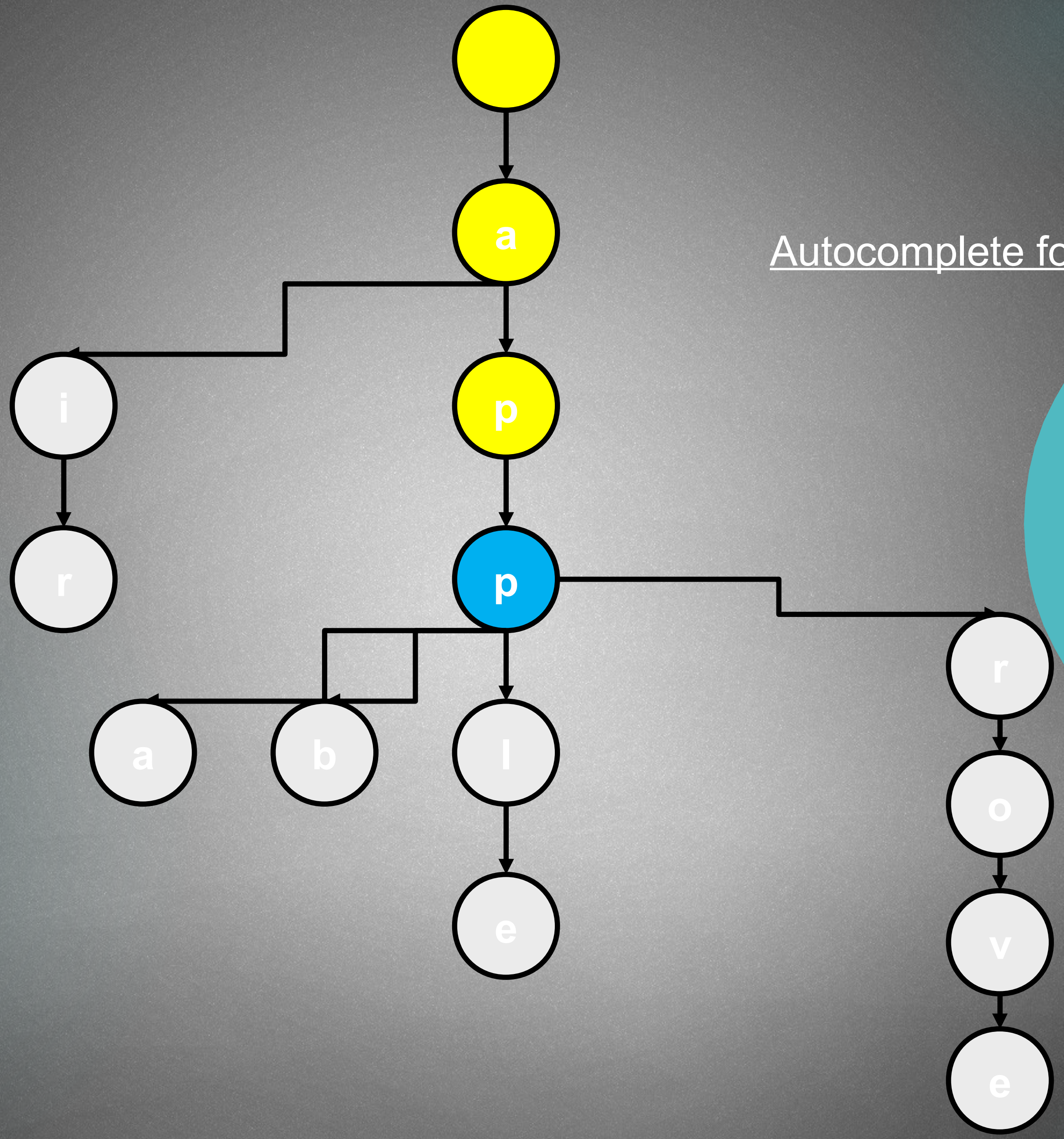

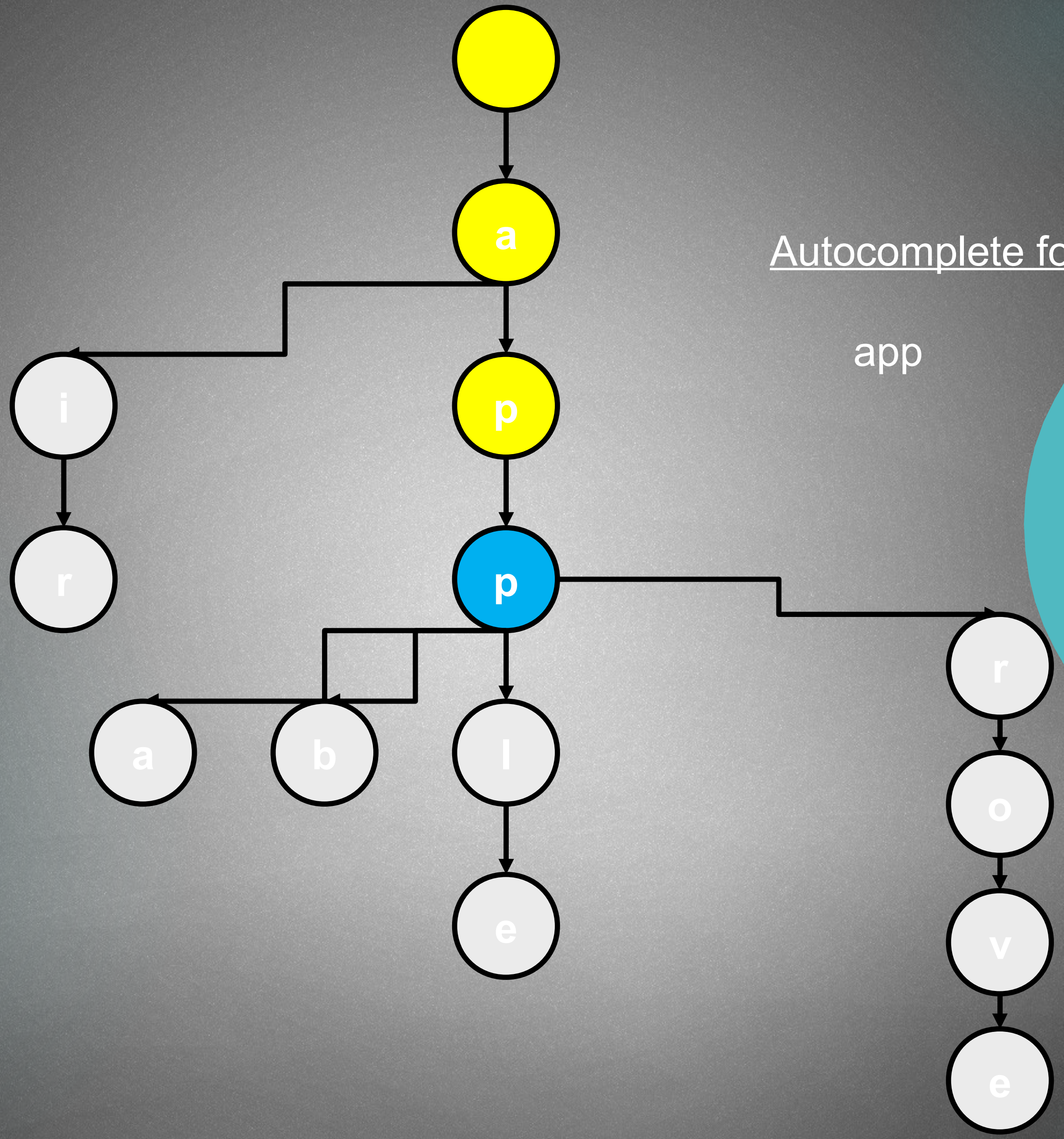

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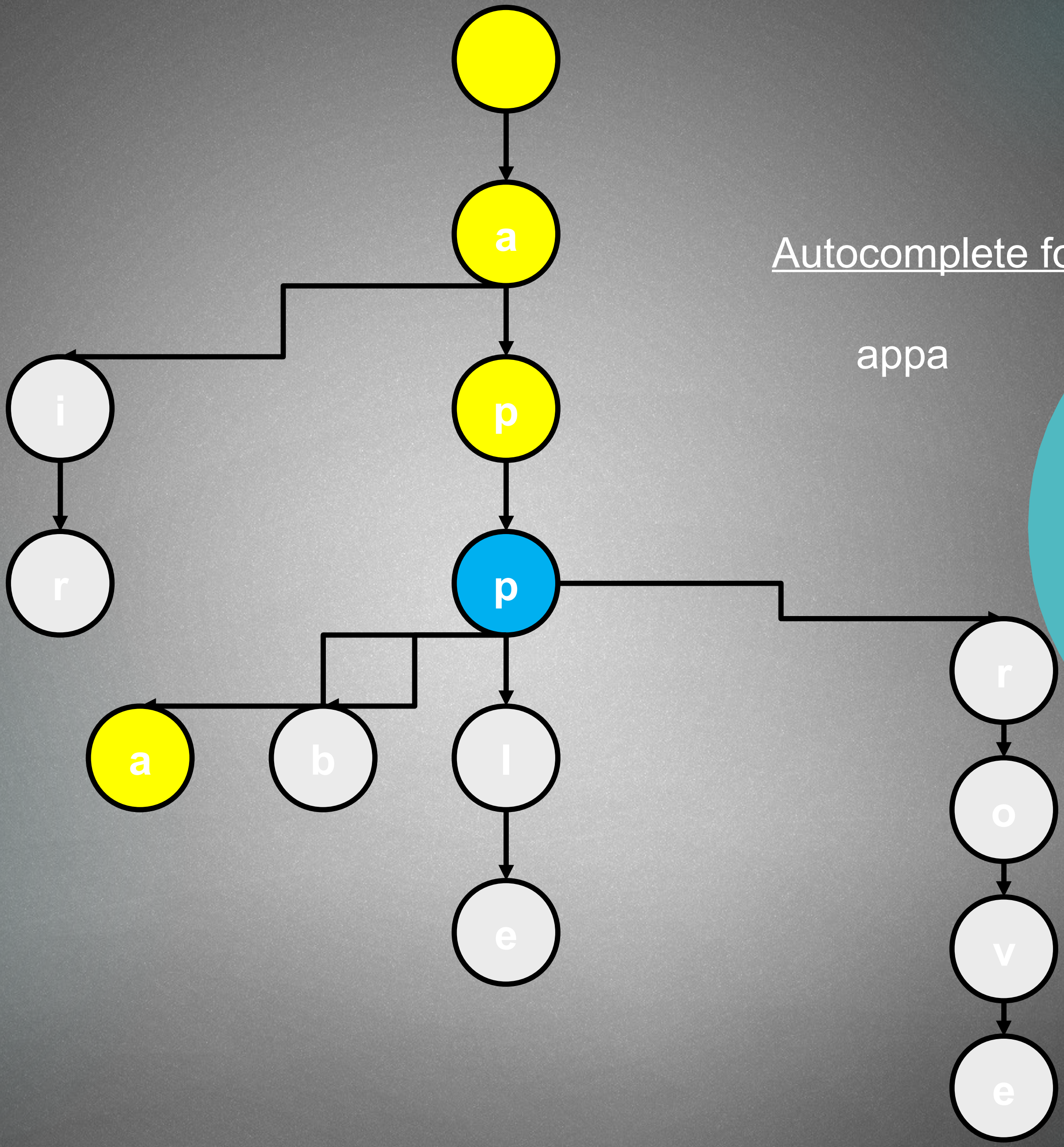

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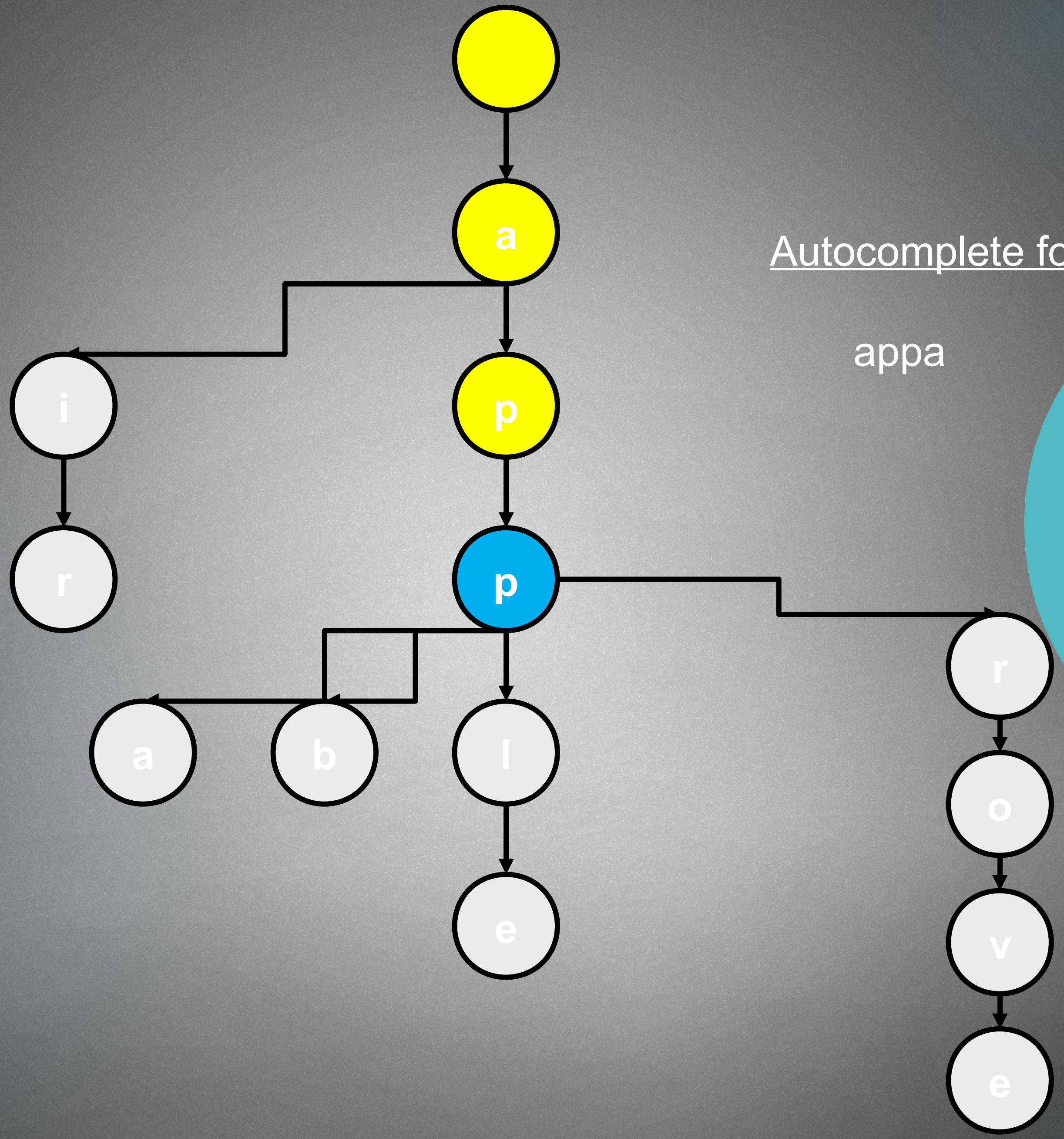

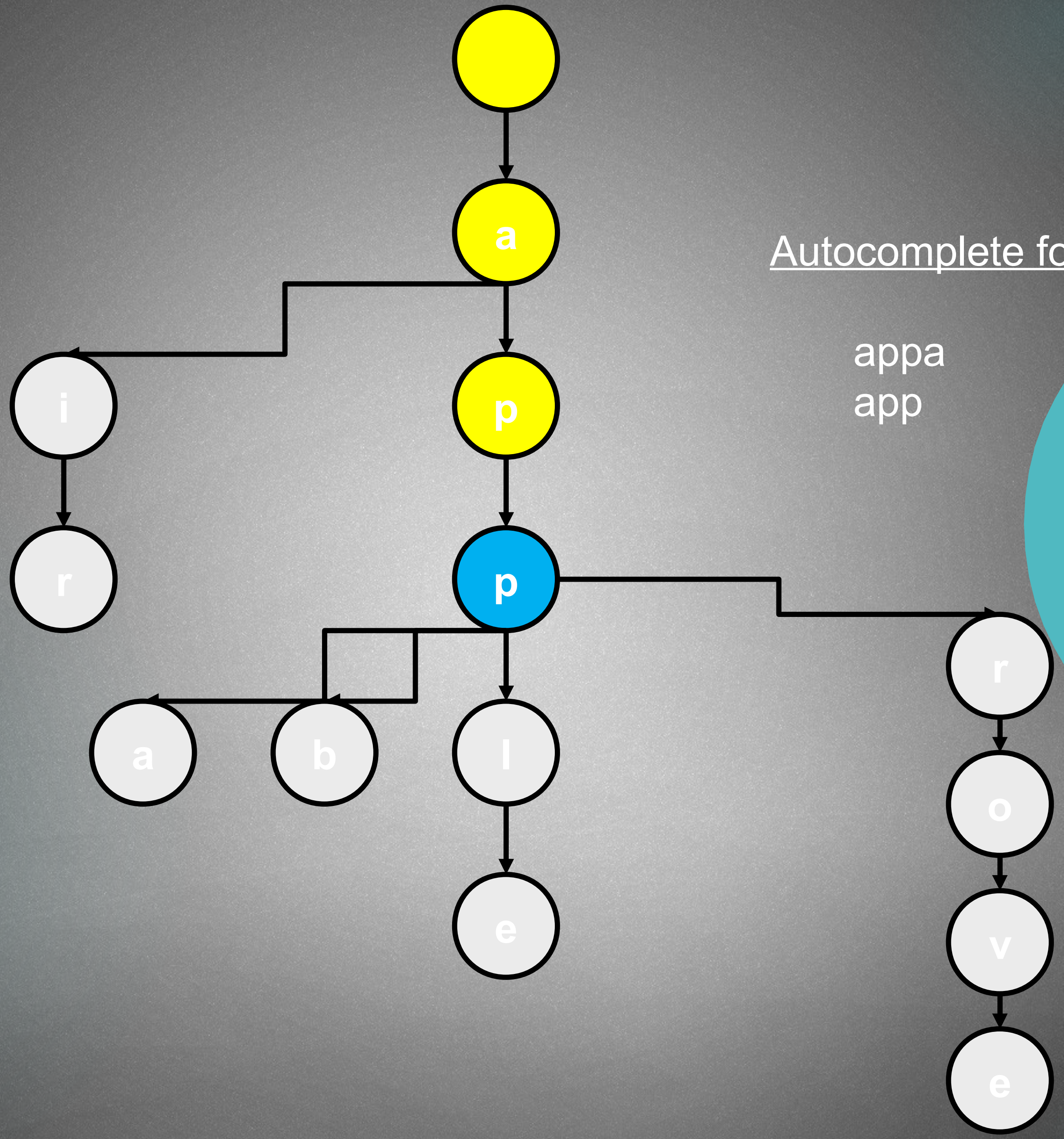

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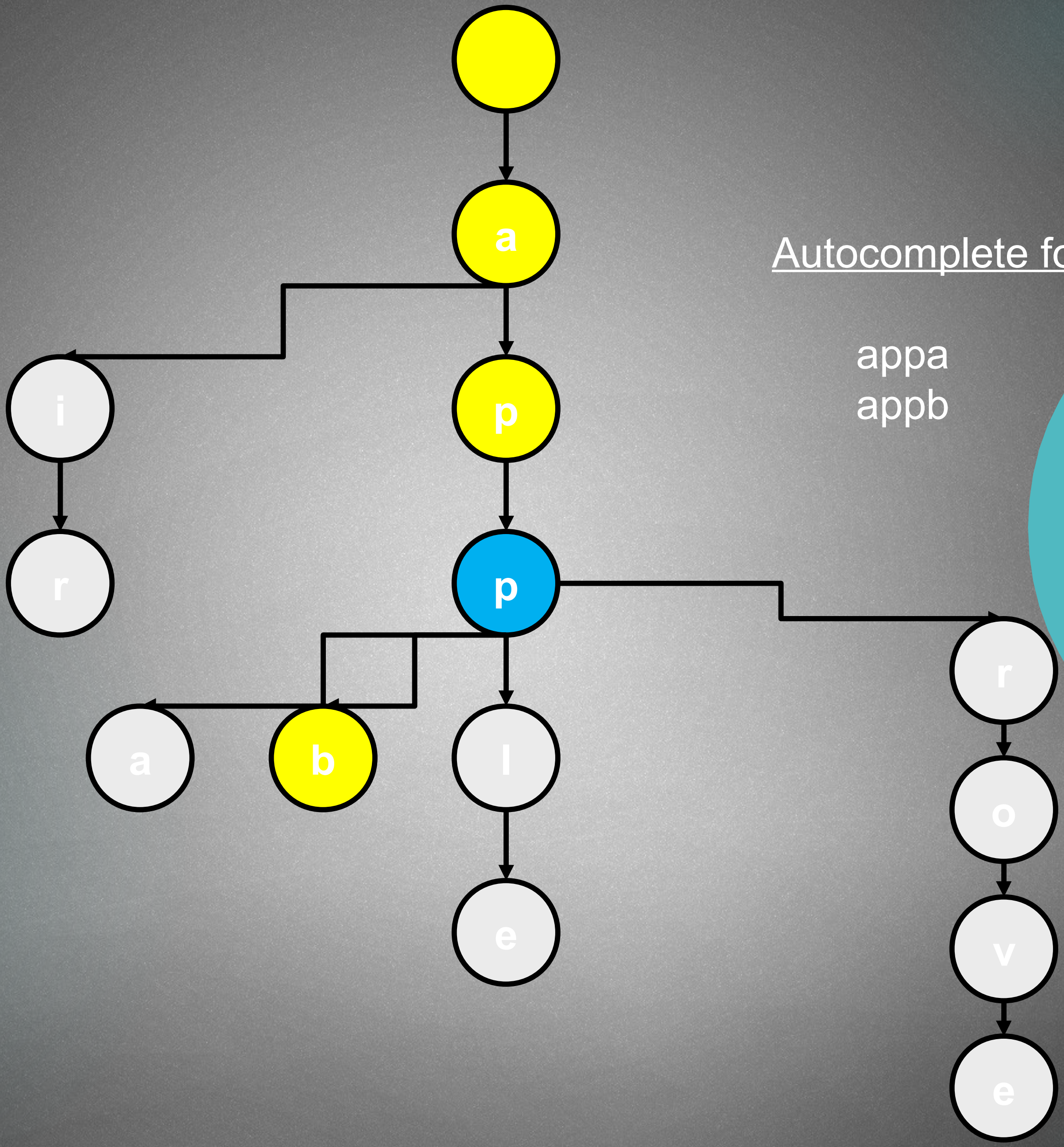

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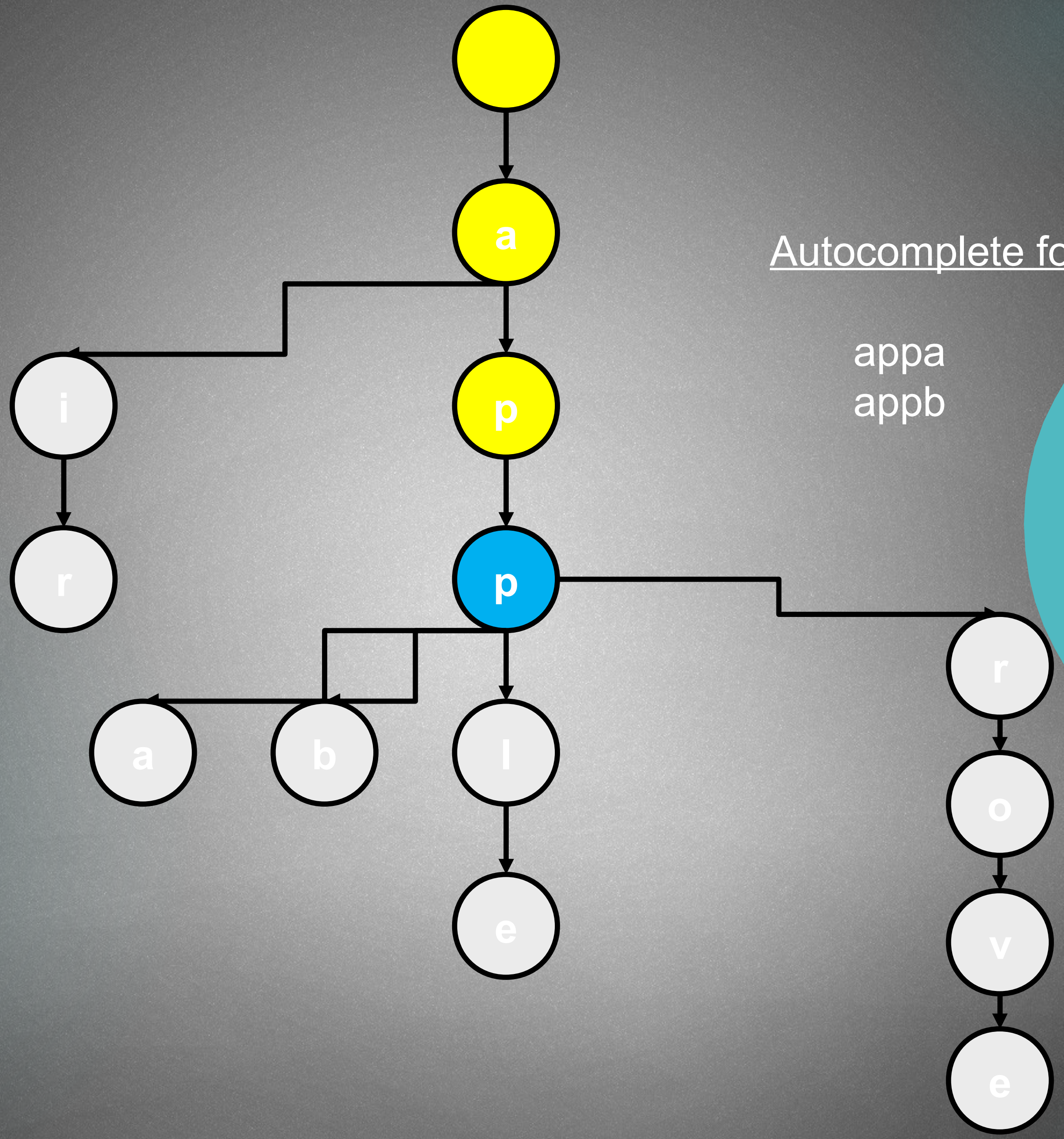

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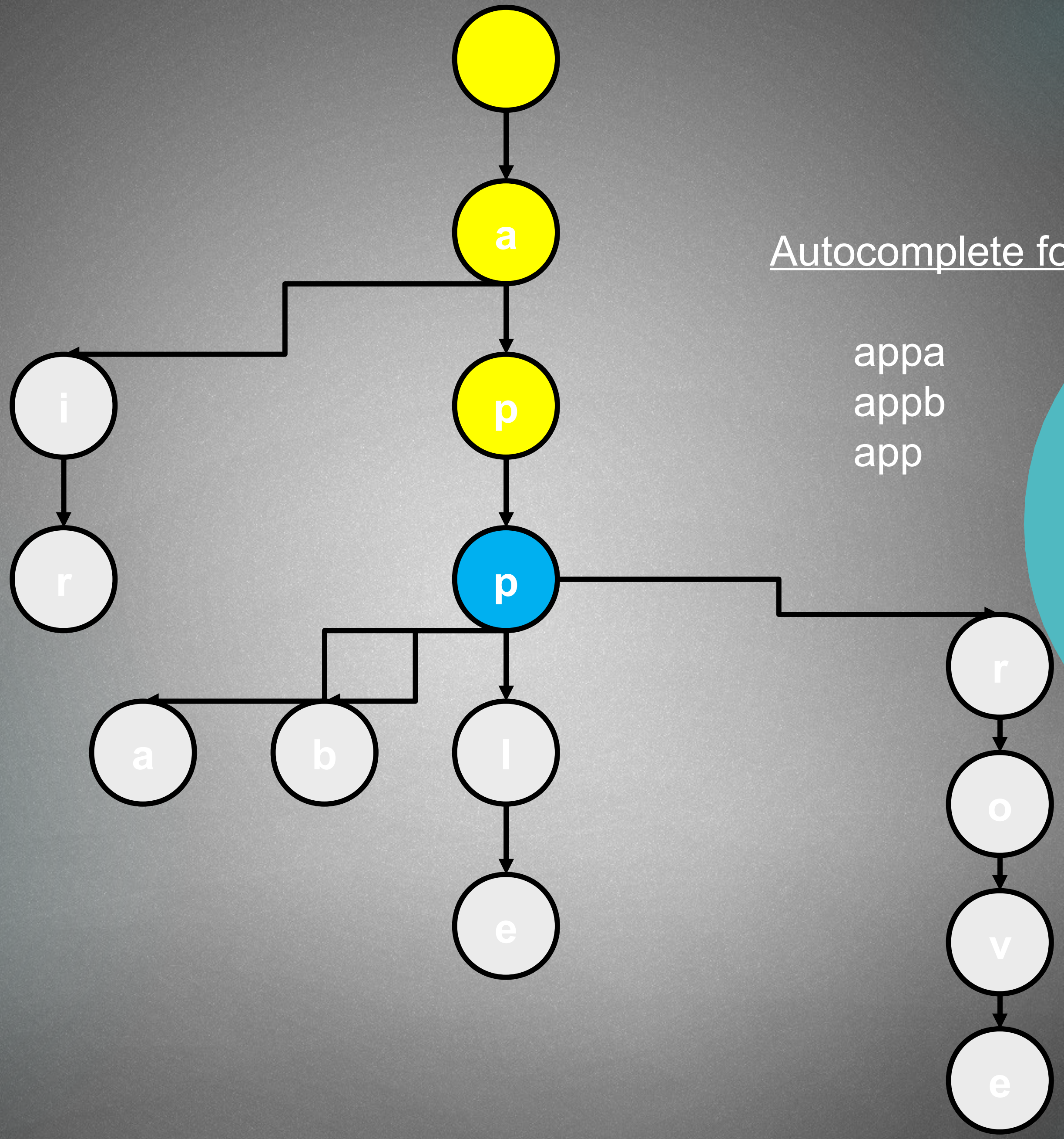

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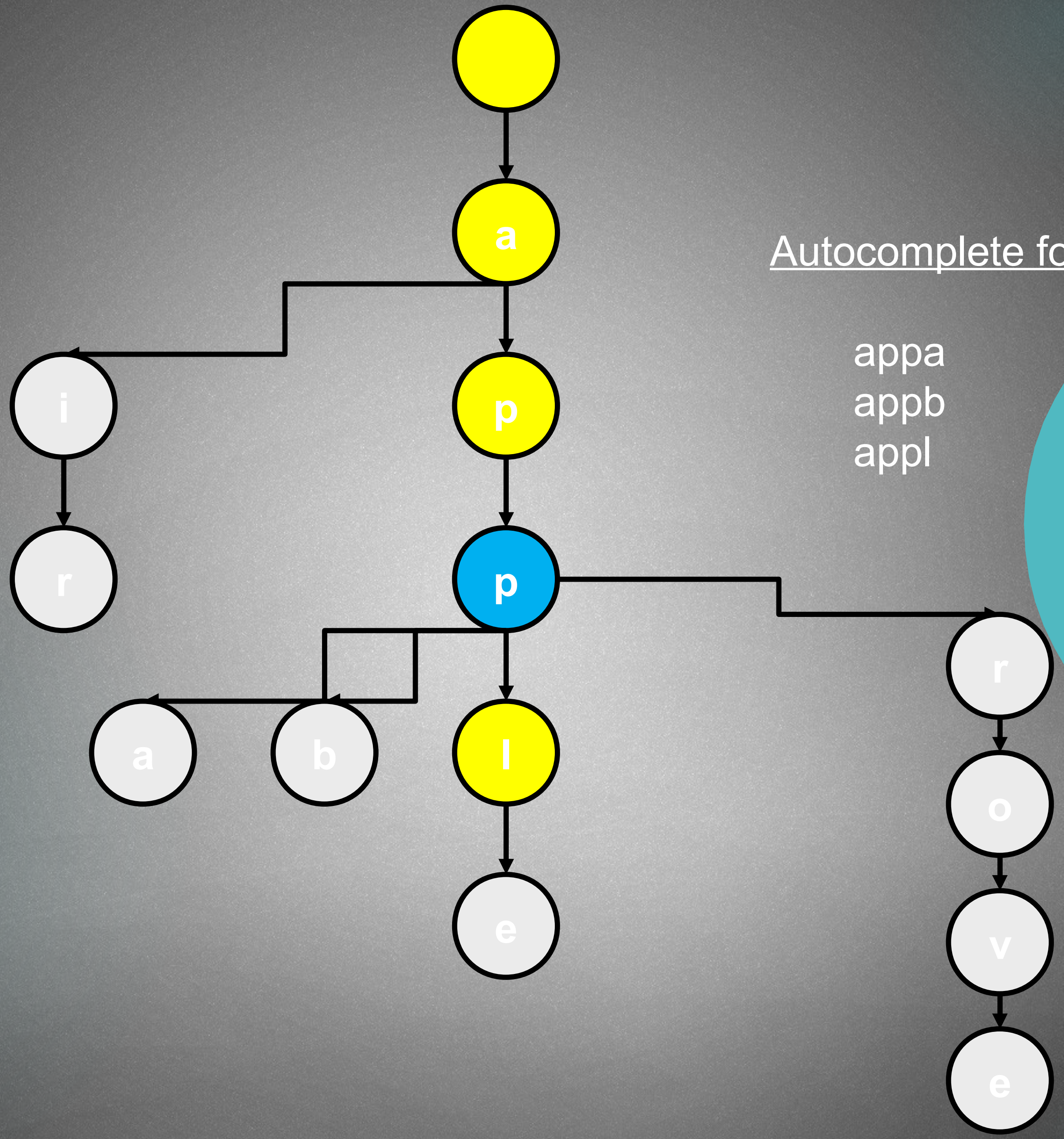

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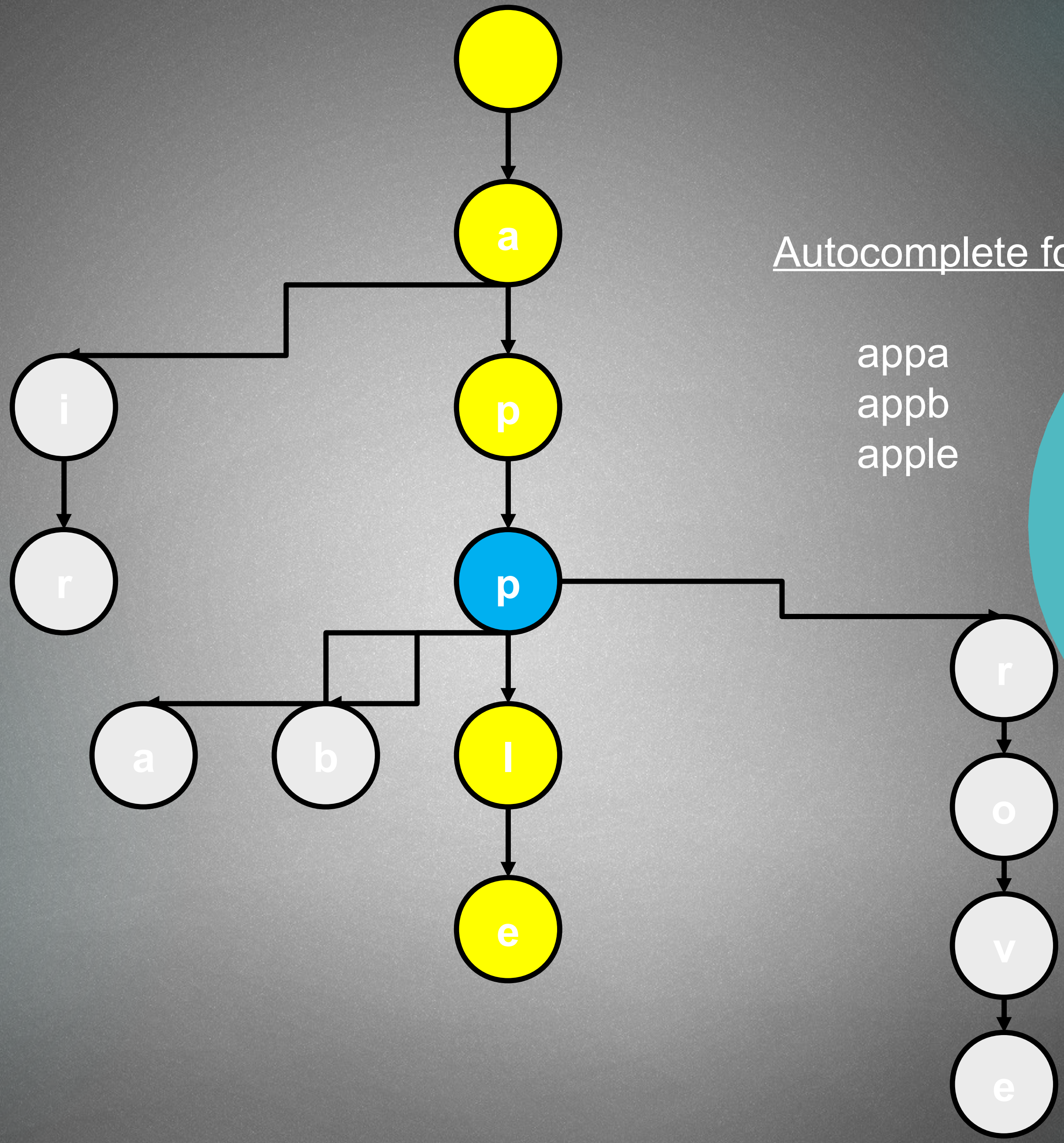

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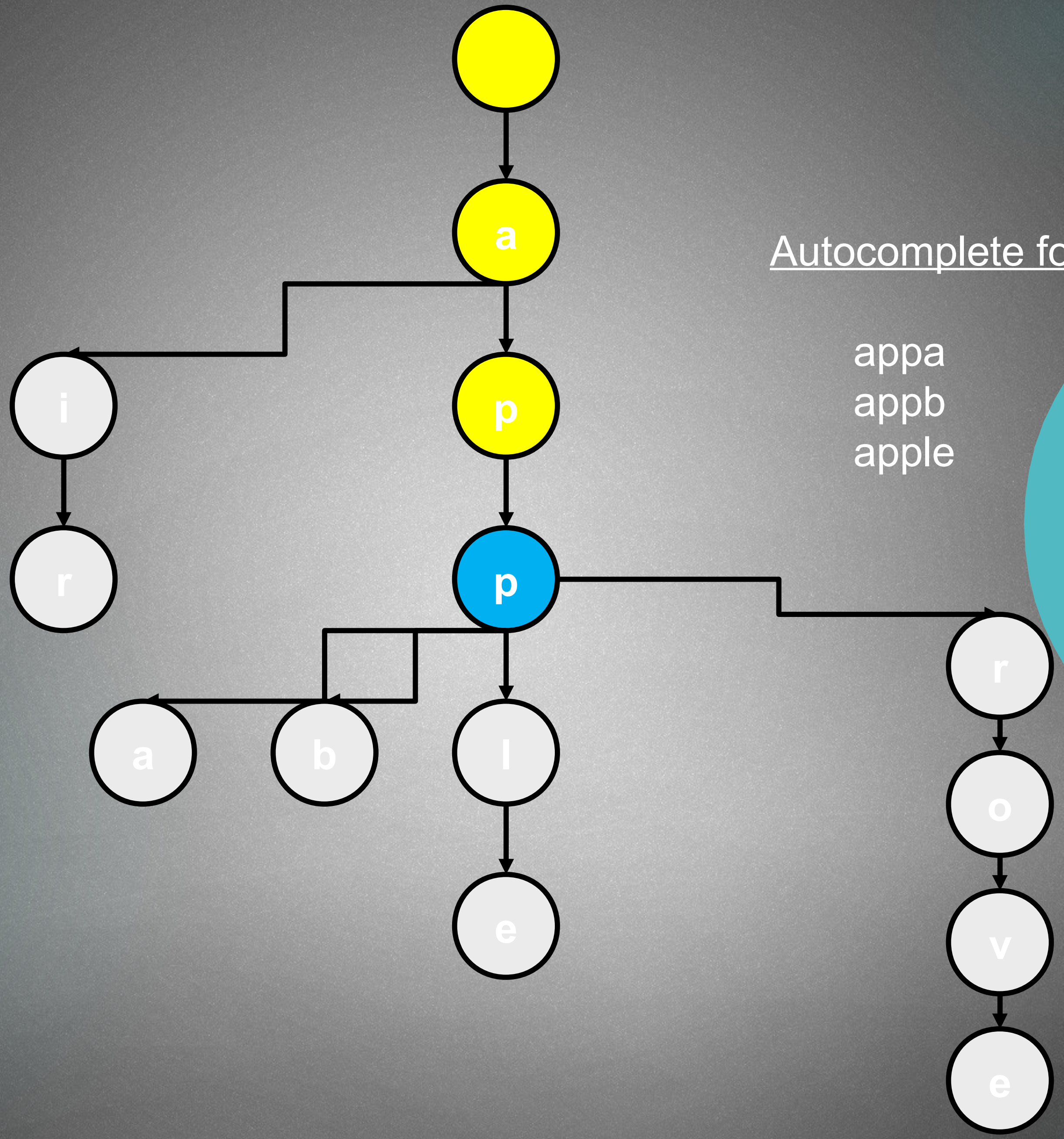

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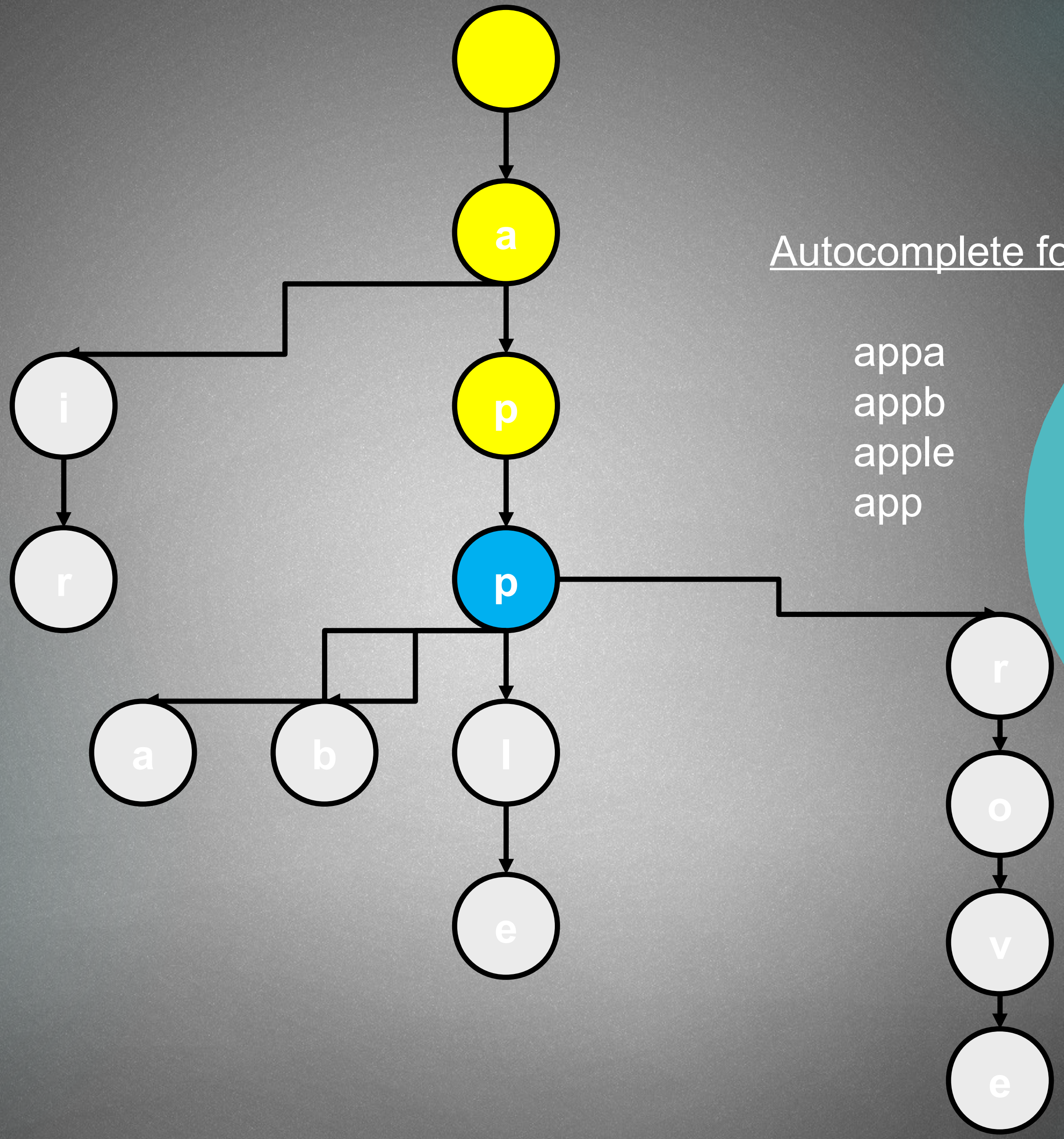

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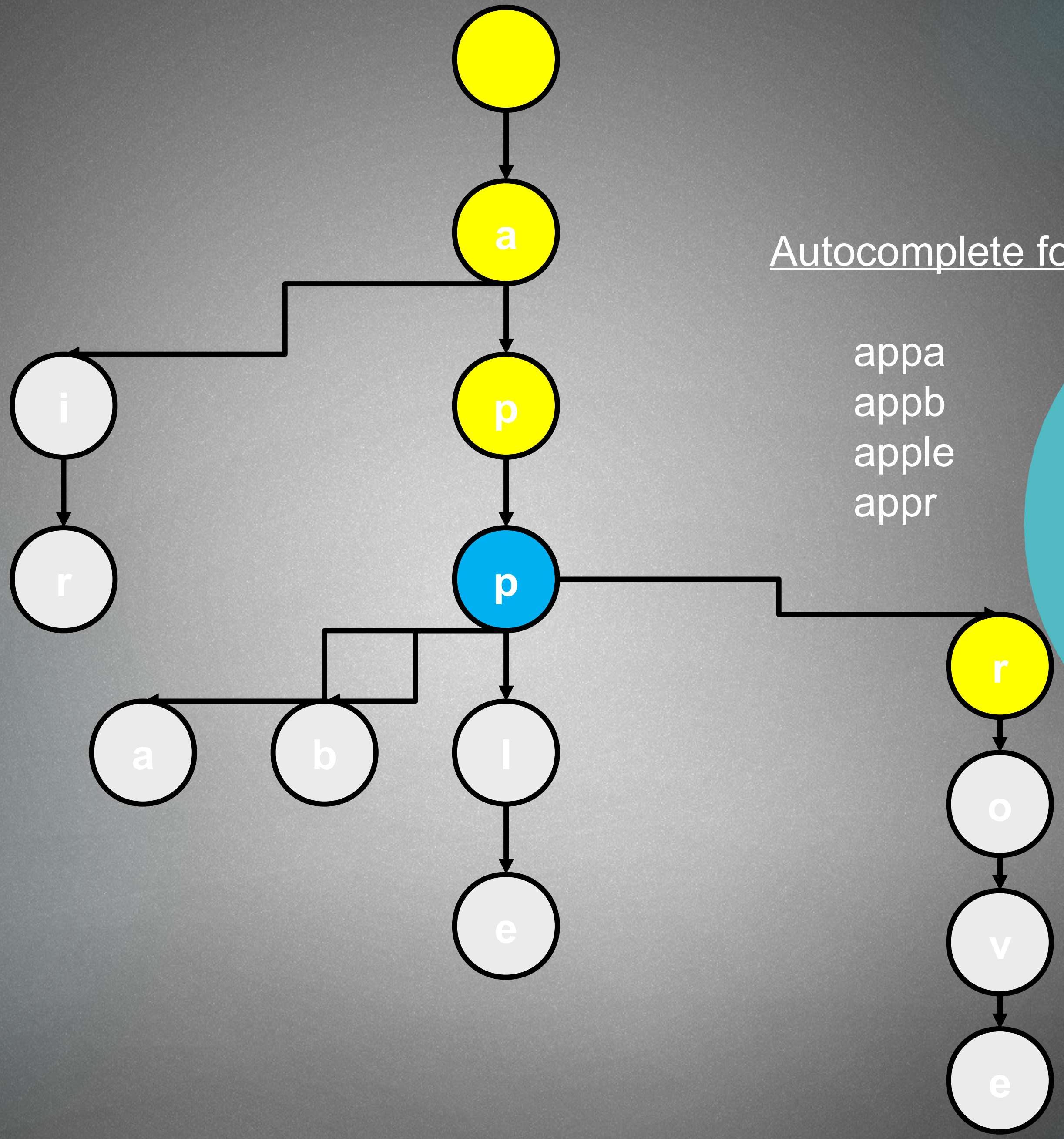

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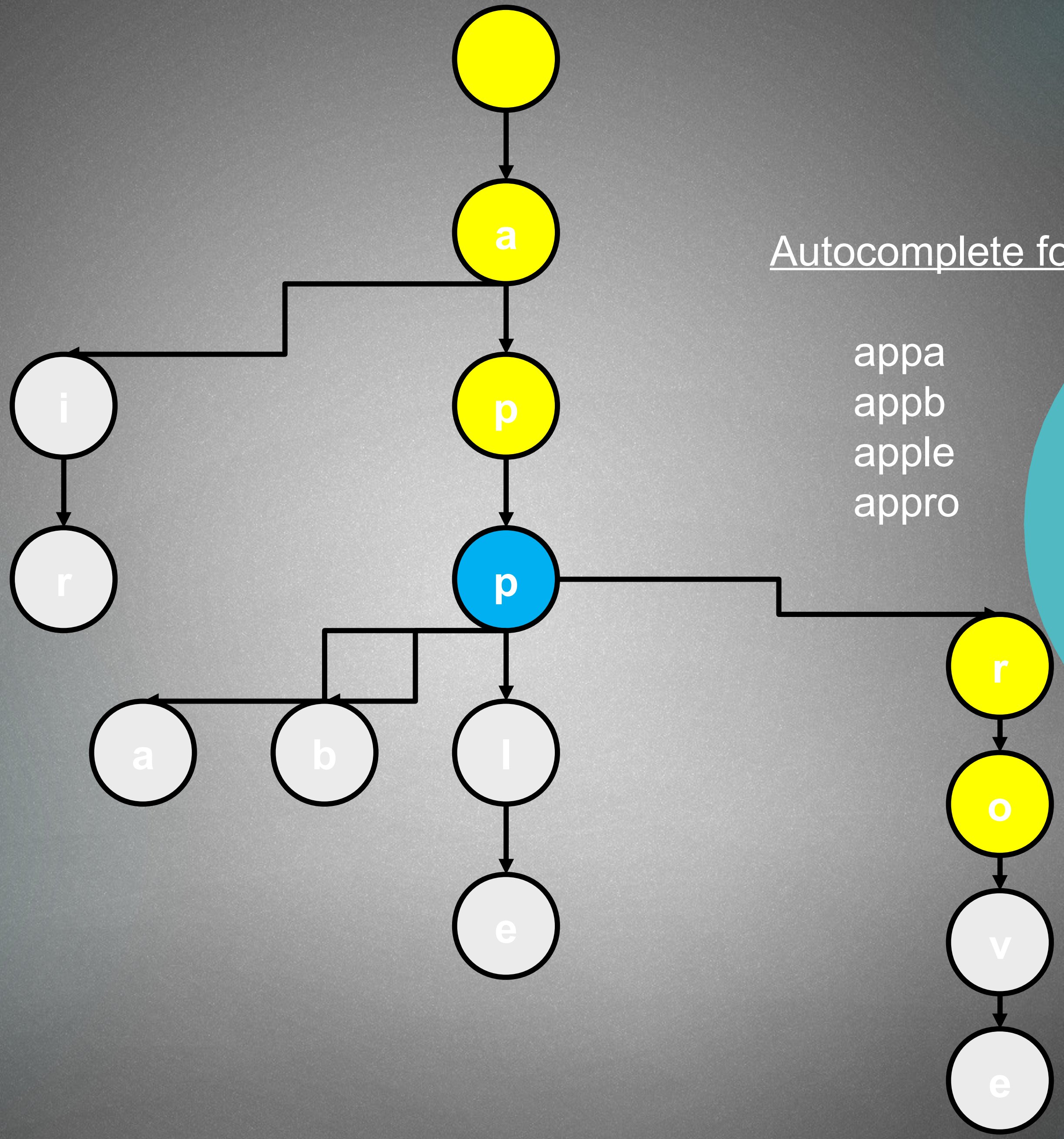

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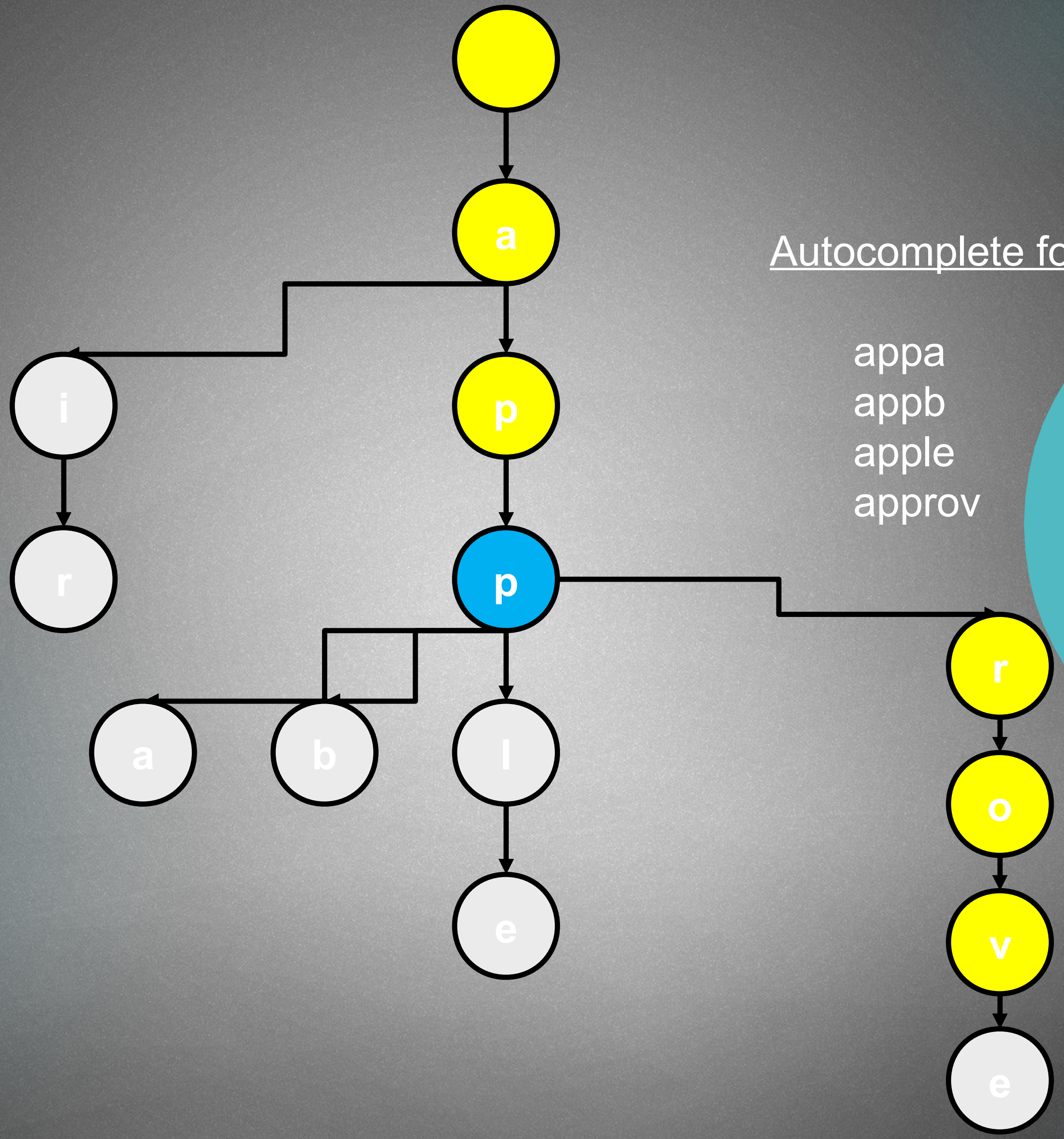

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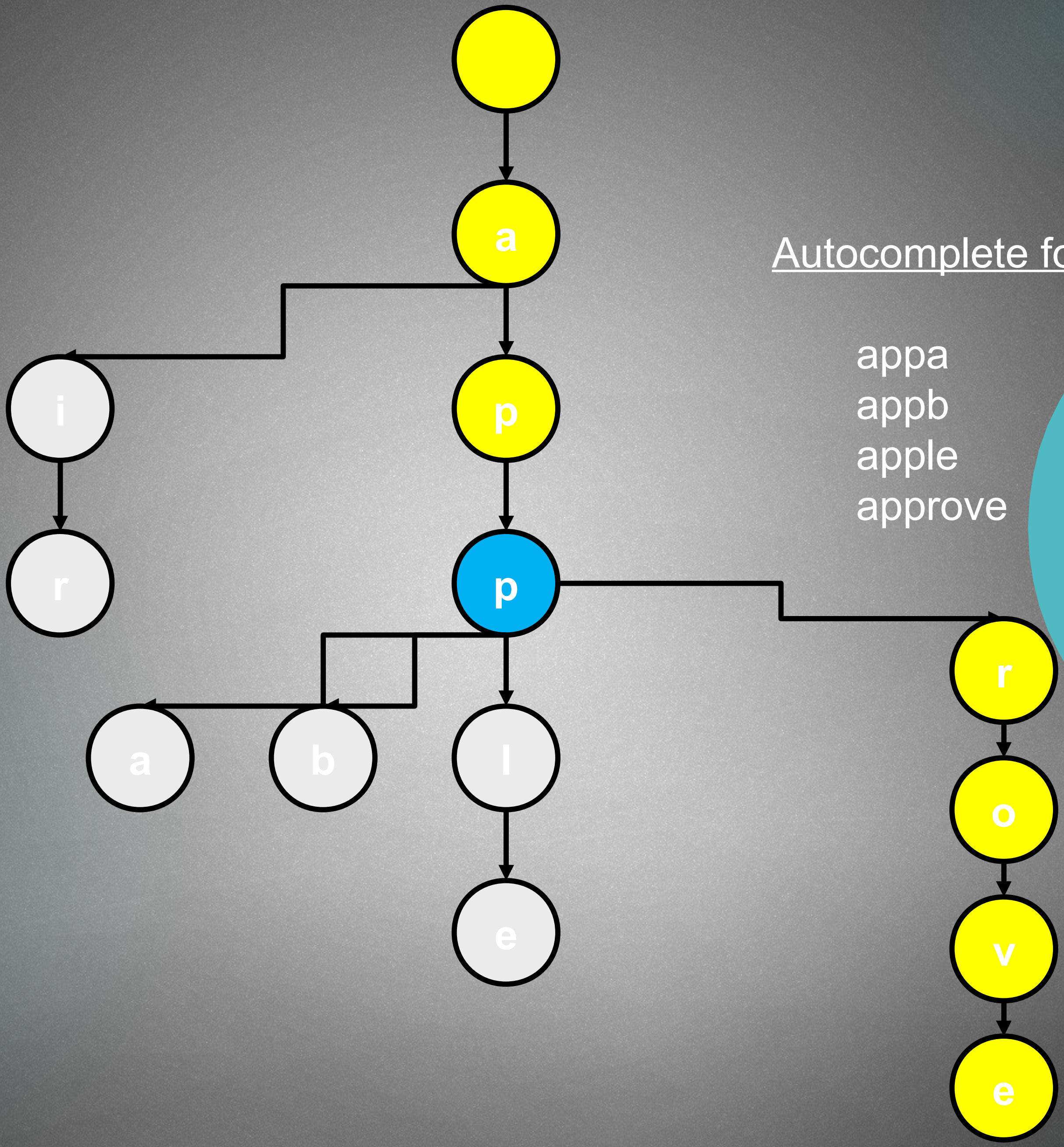

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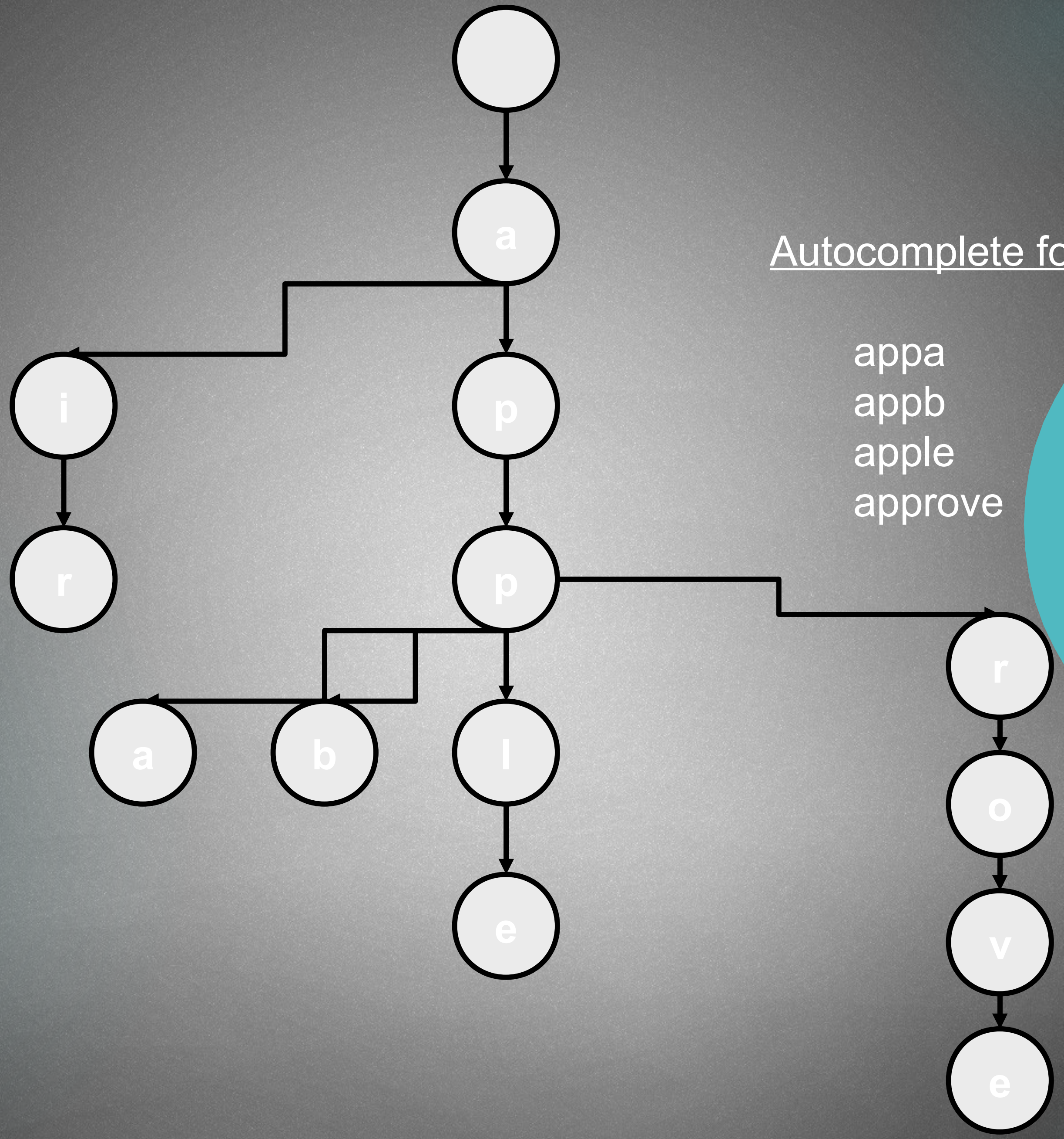

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Trie as a map

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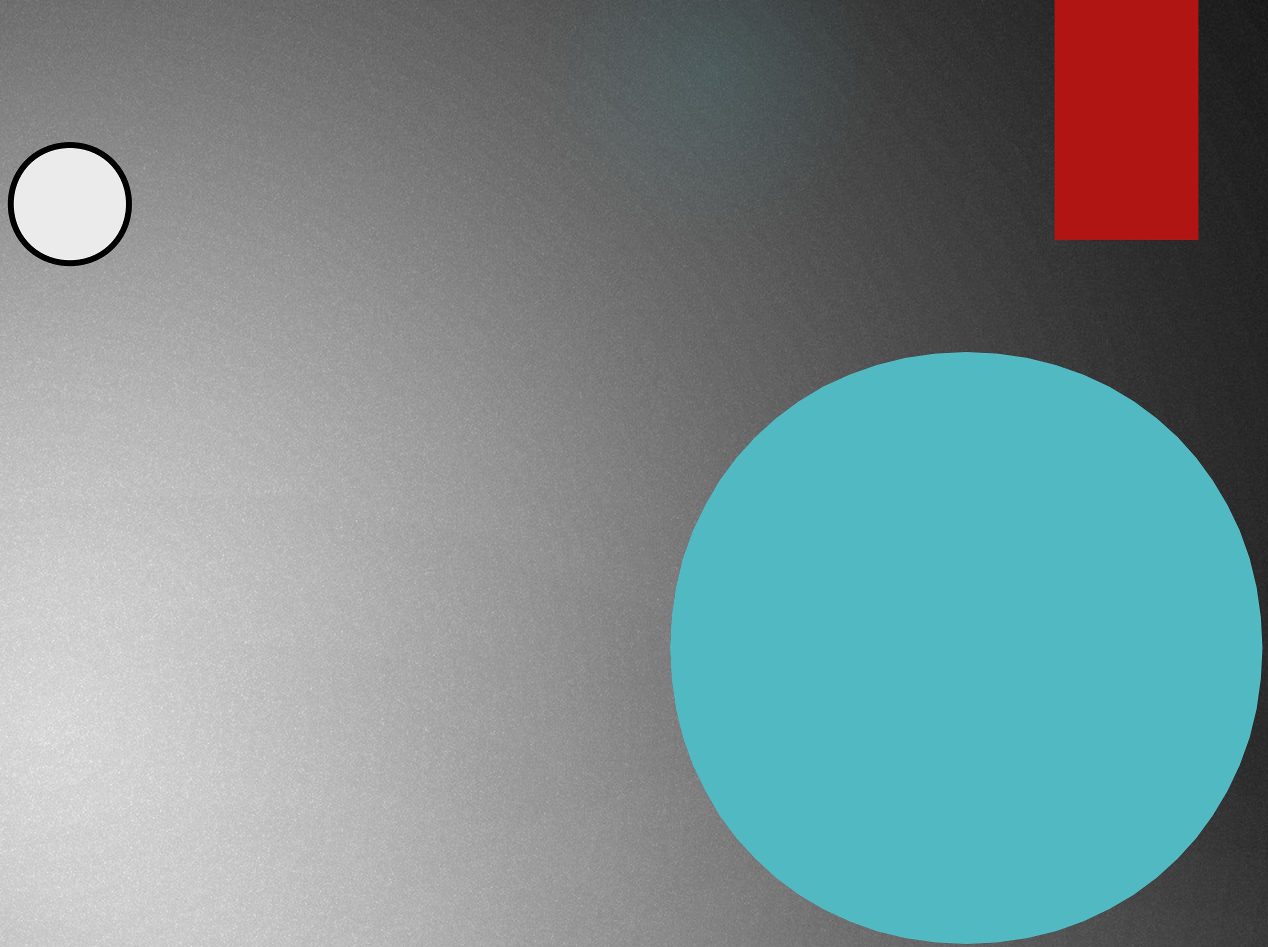

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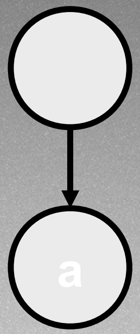

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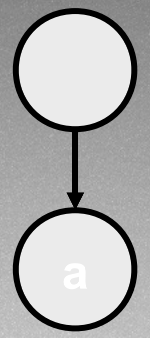

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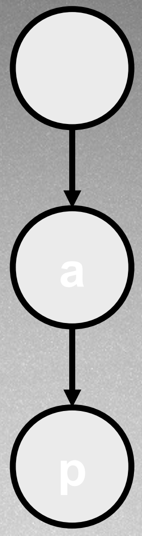

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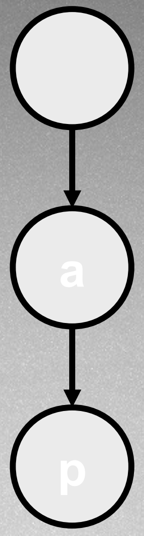

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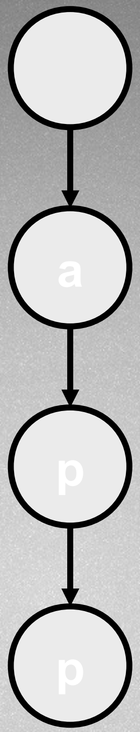

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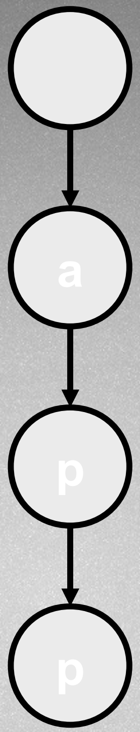

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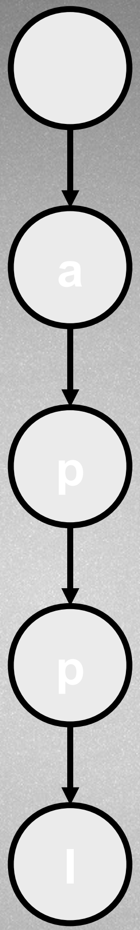

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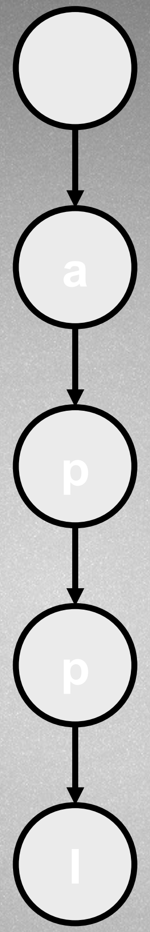

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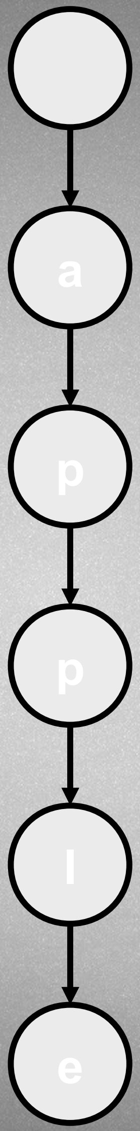

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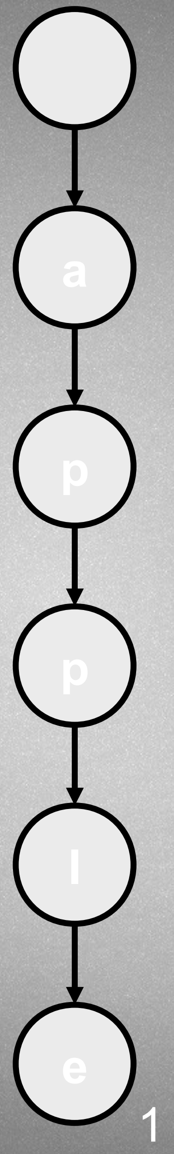

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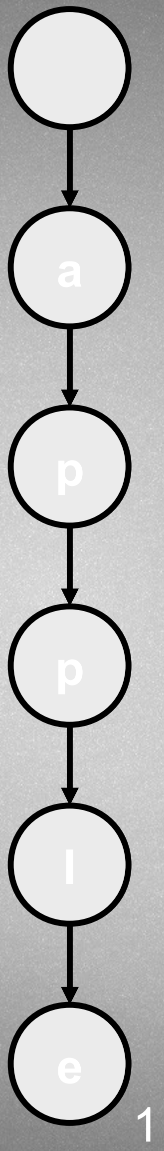

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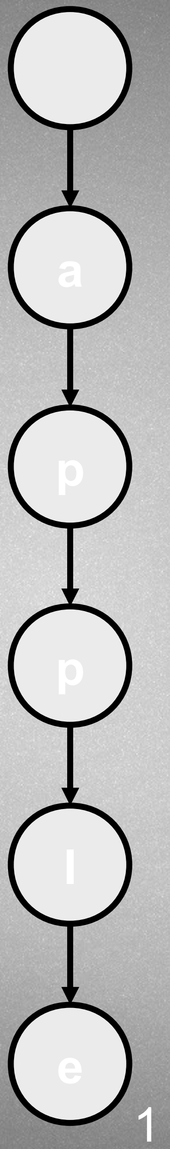

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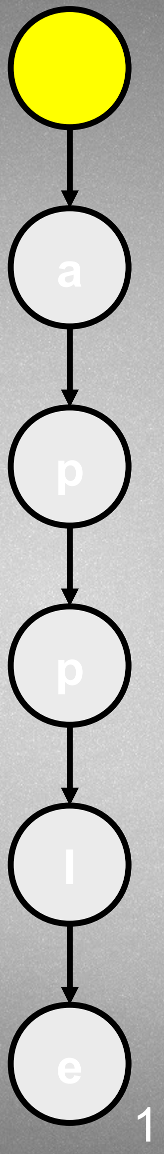

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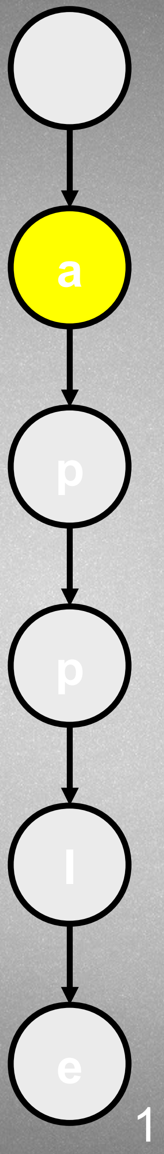

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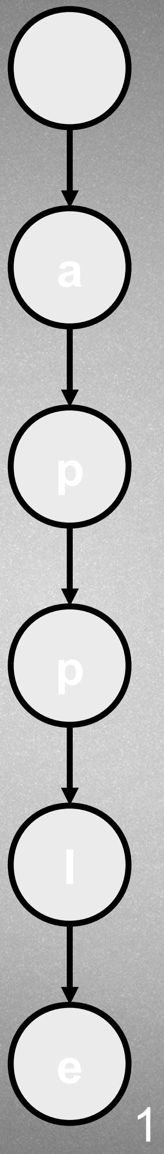

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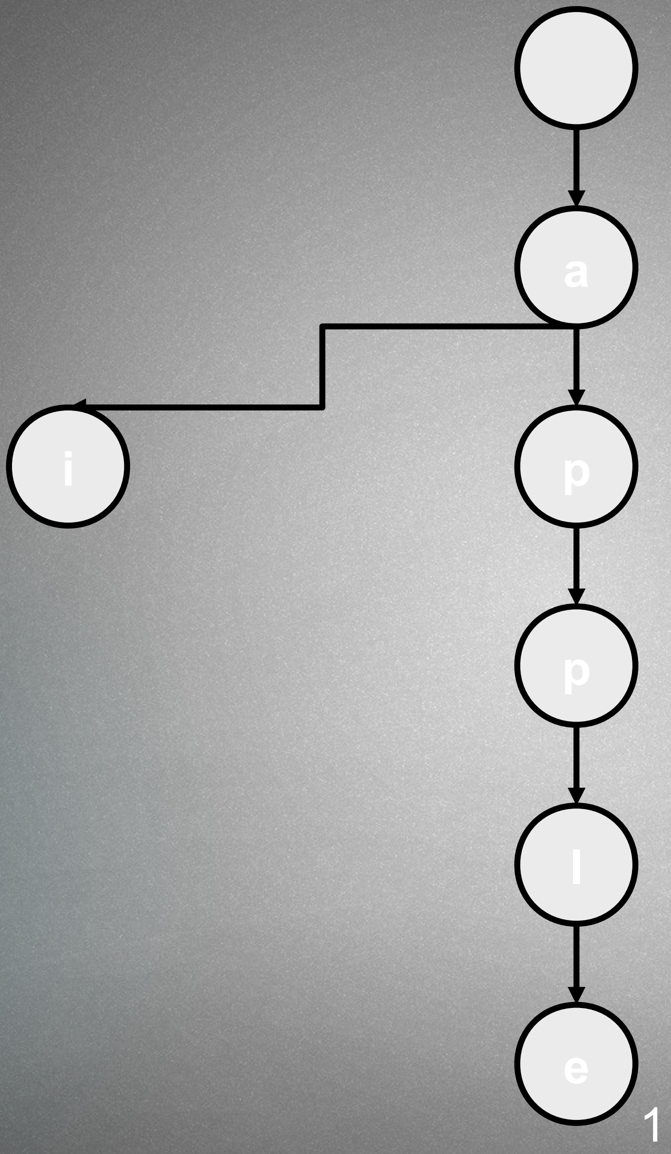

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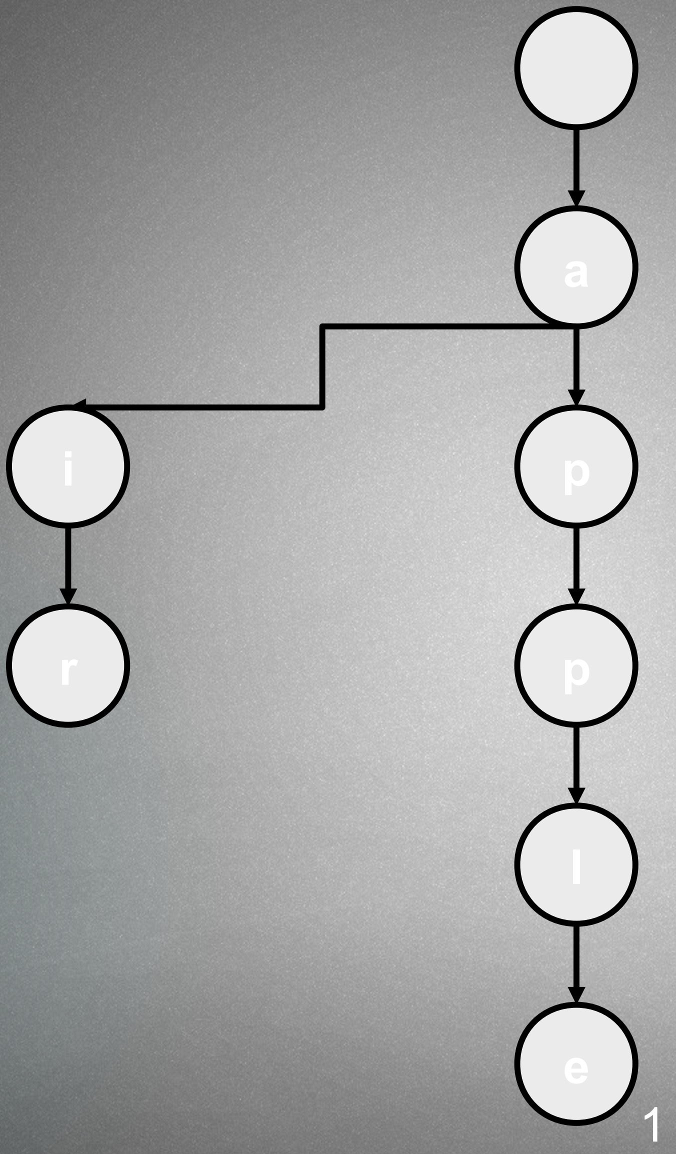
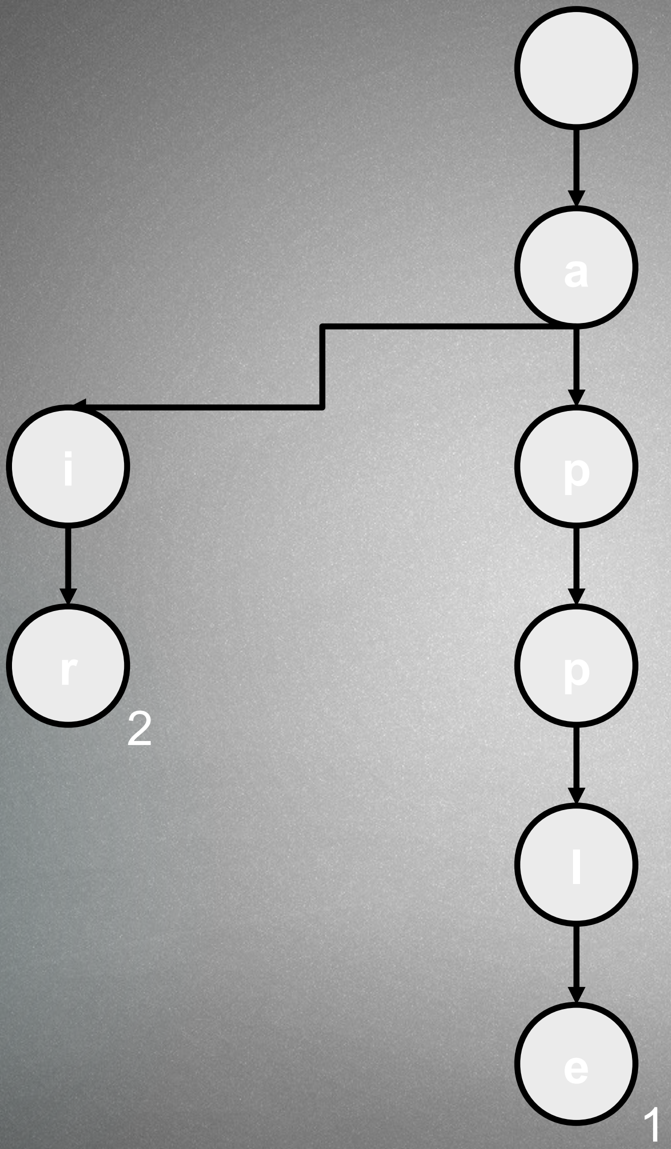


Insertion



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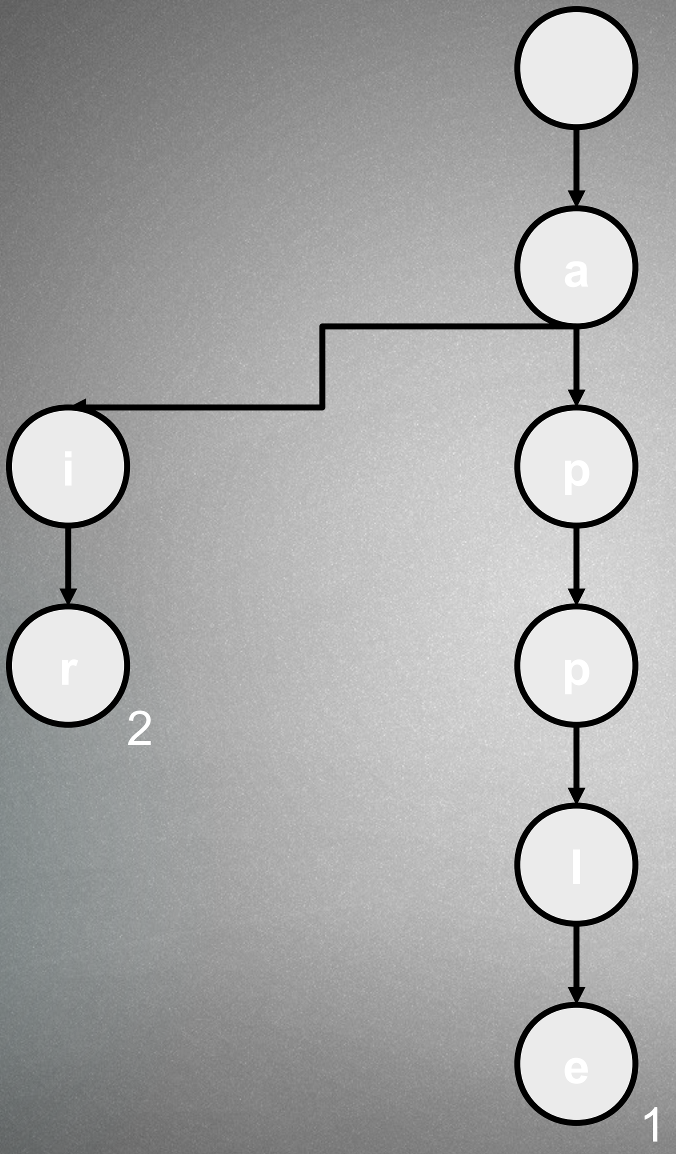

Insertion

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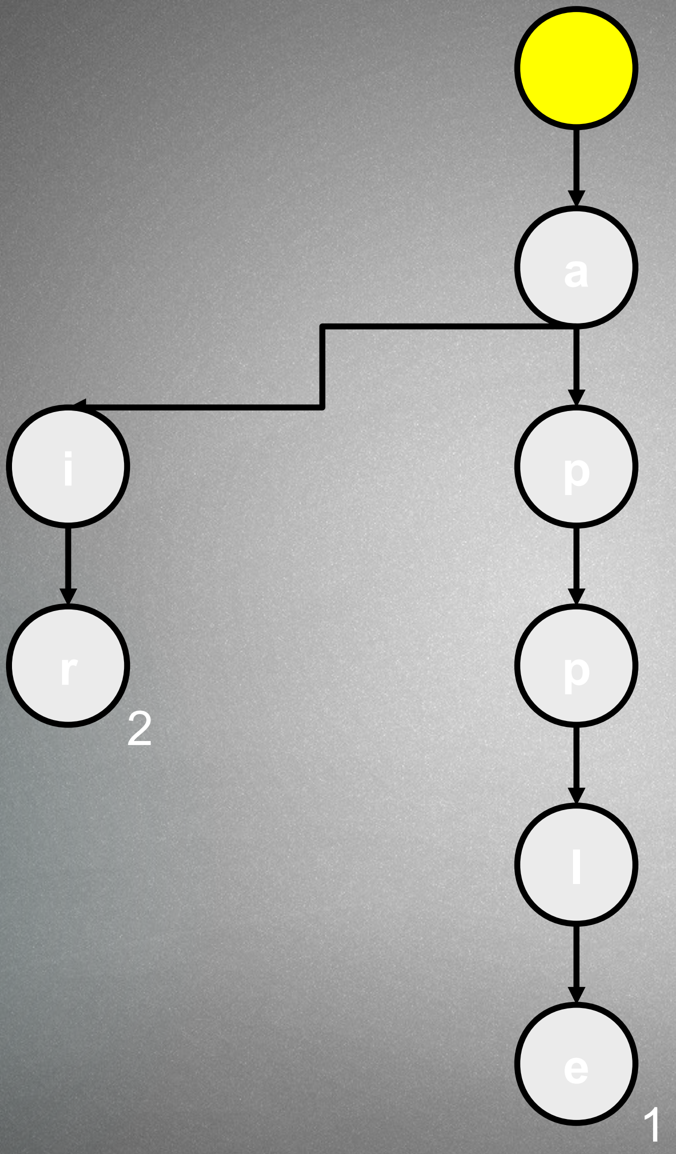

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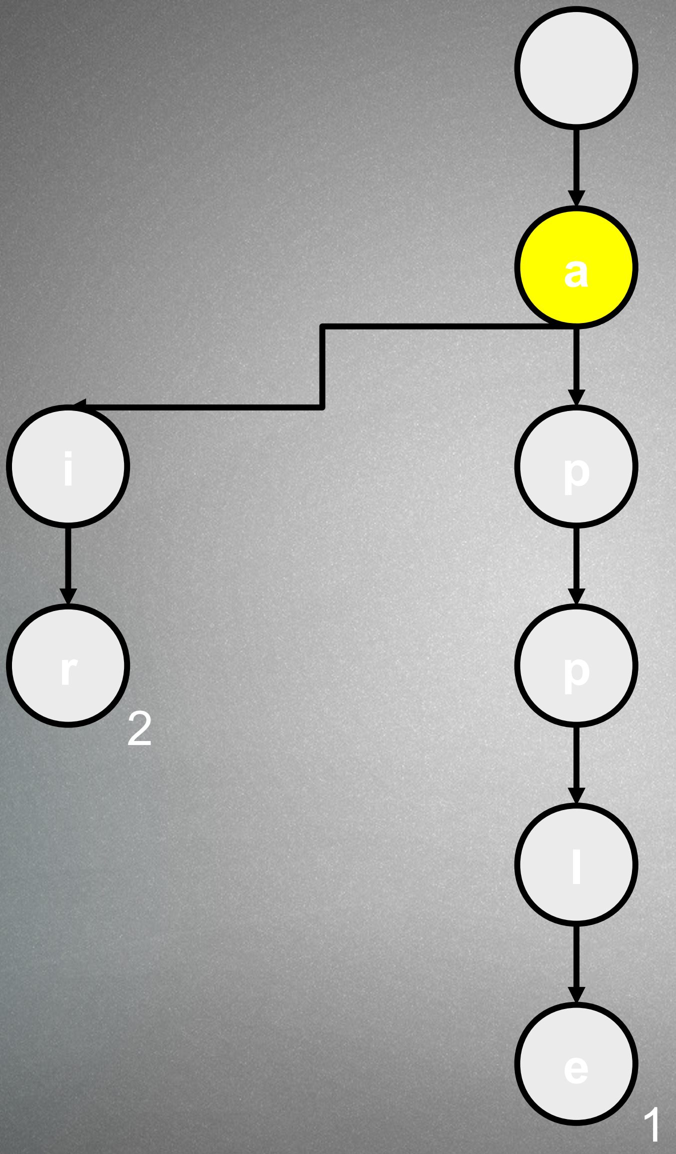

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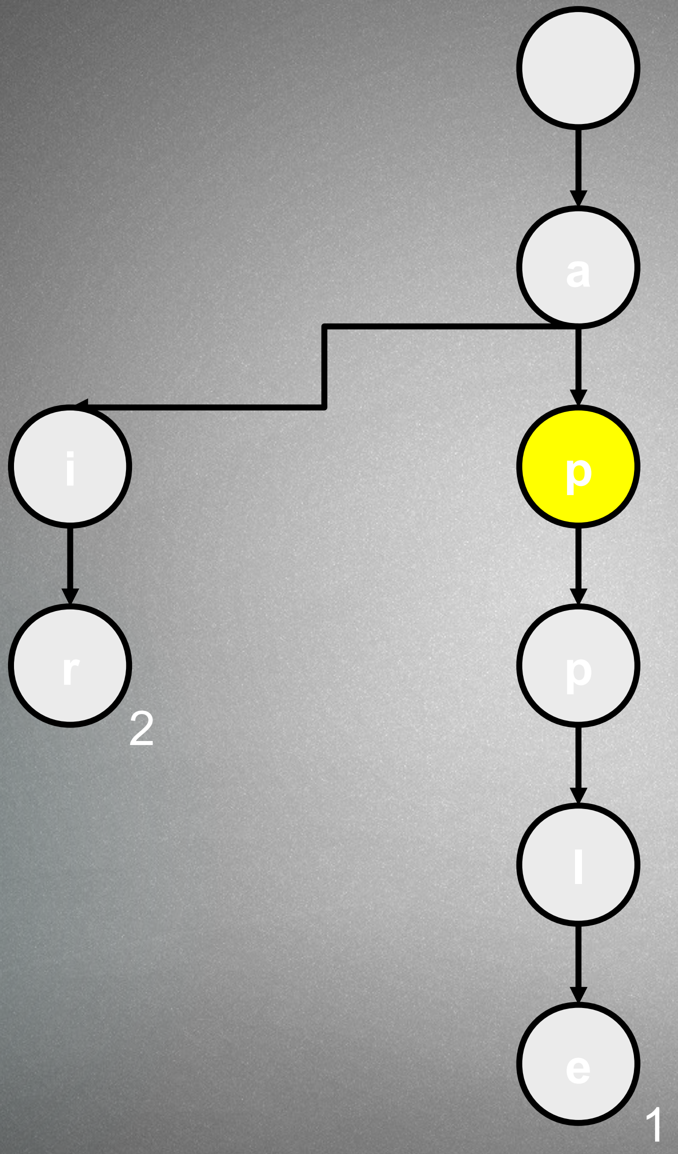

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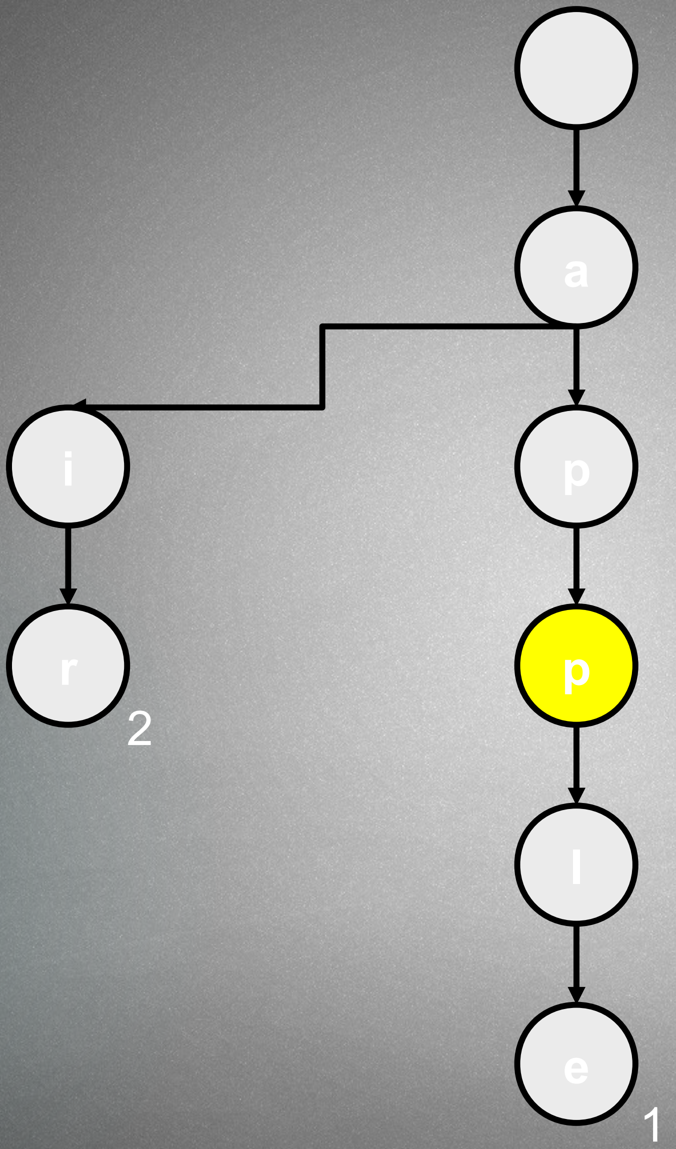

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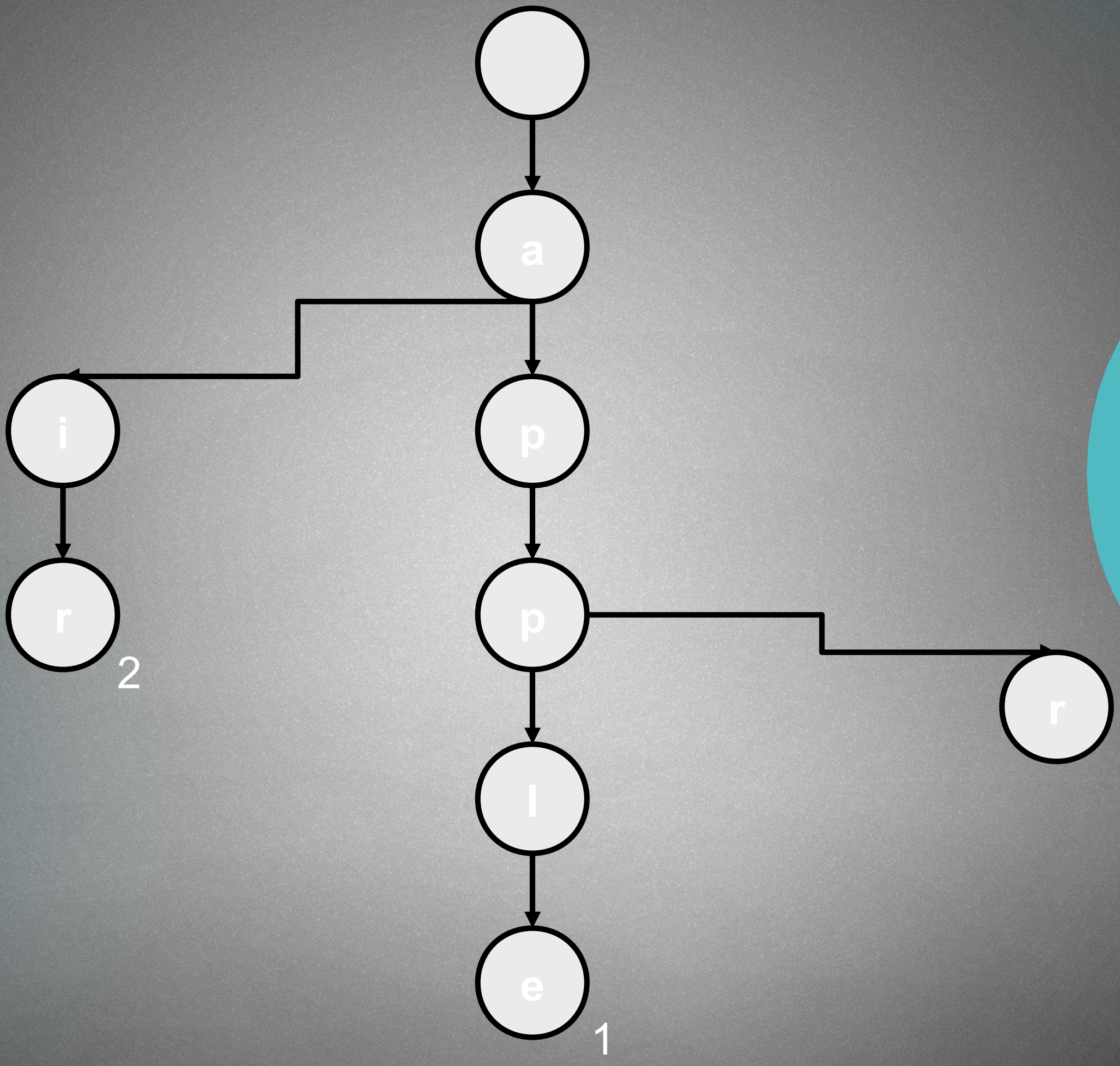

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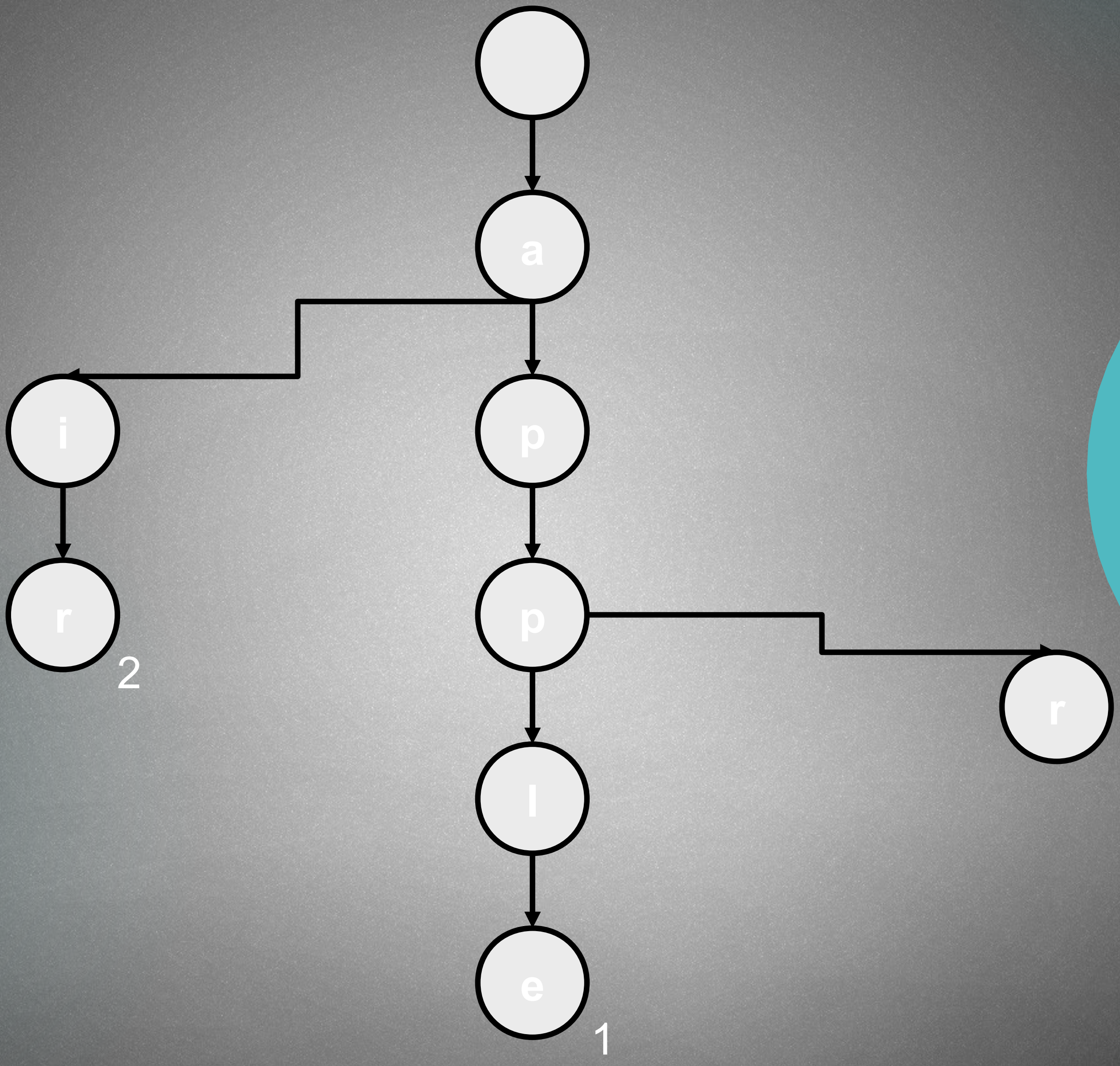

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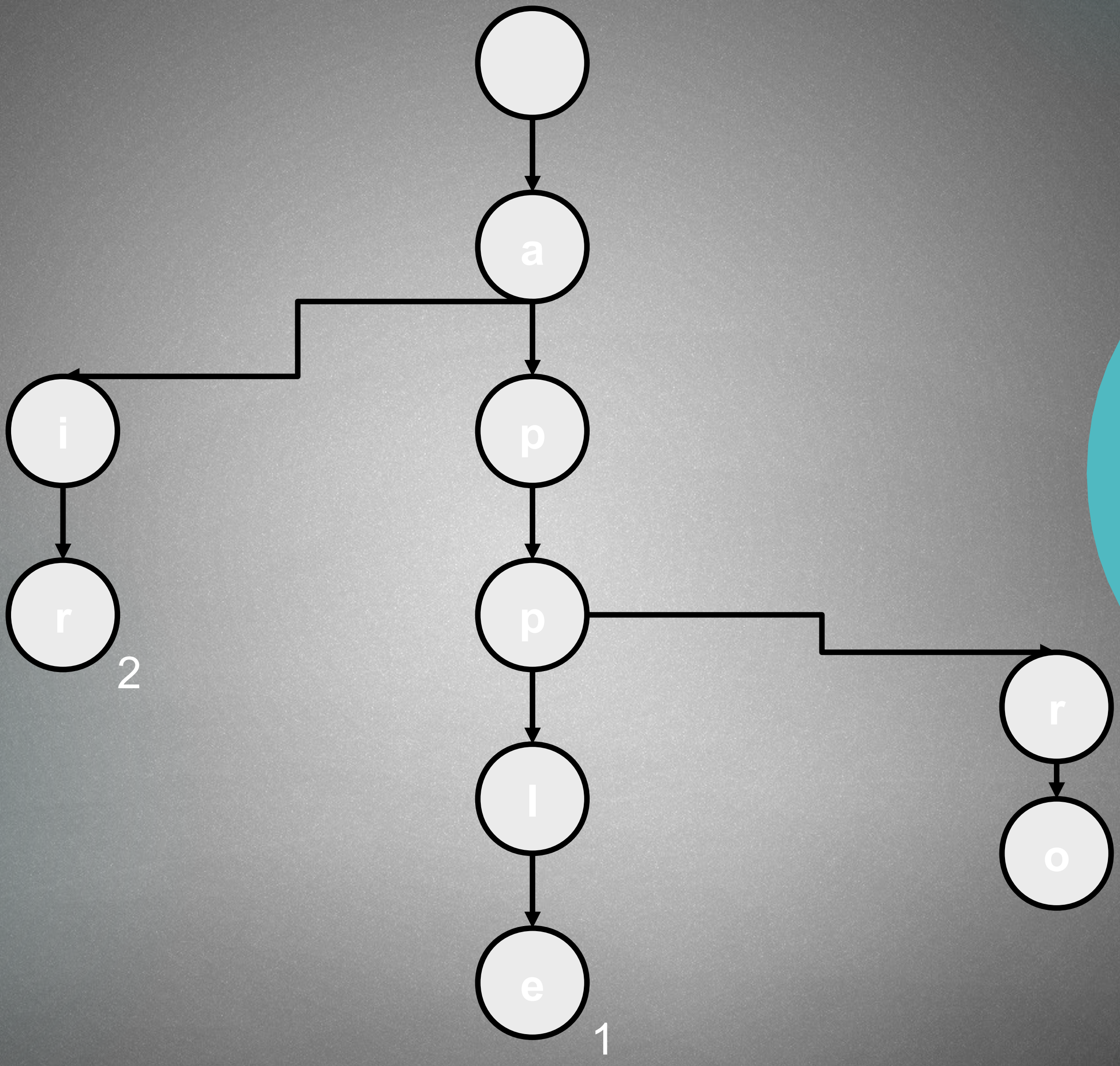

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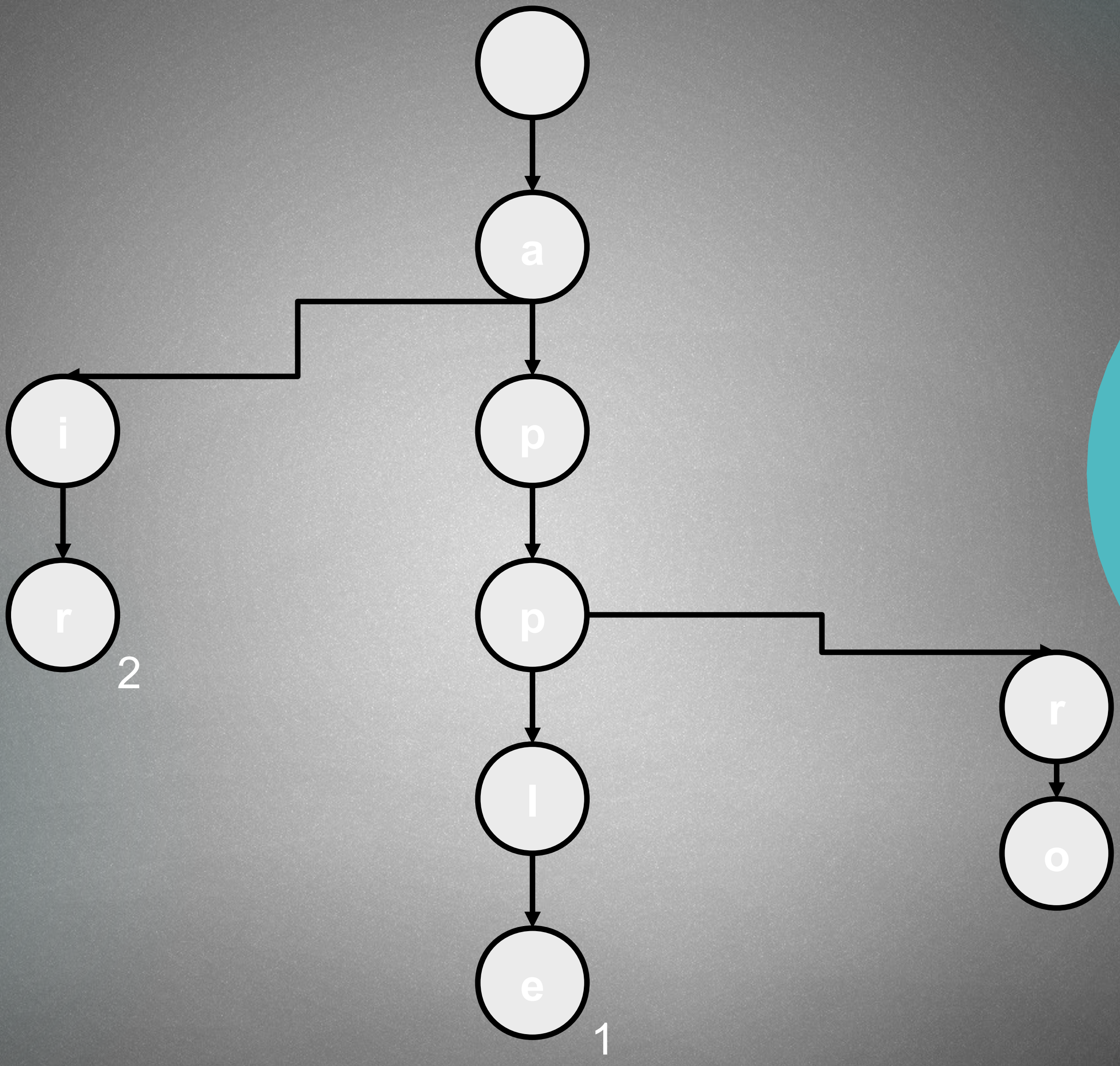

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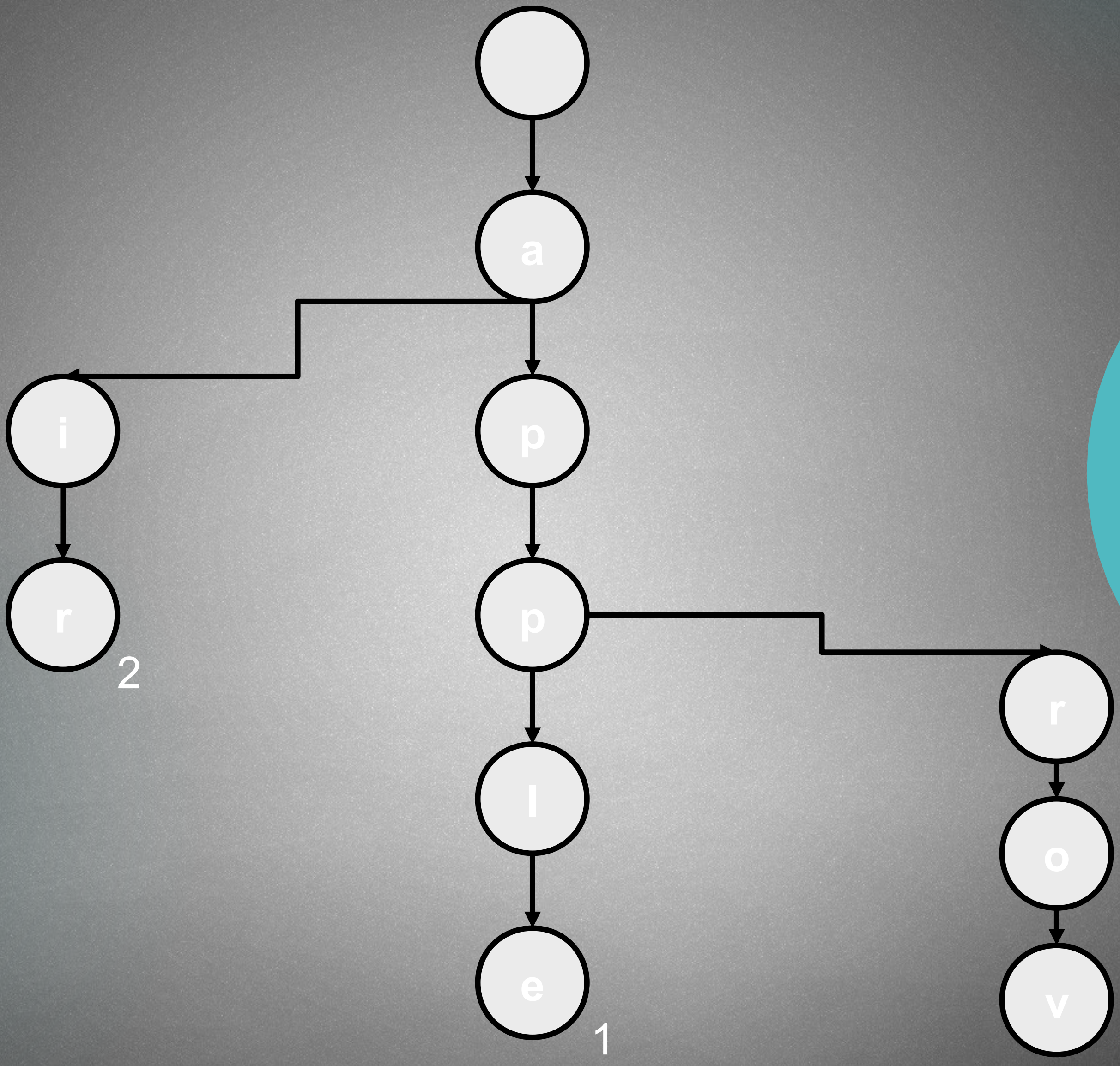

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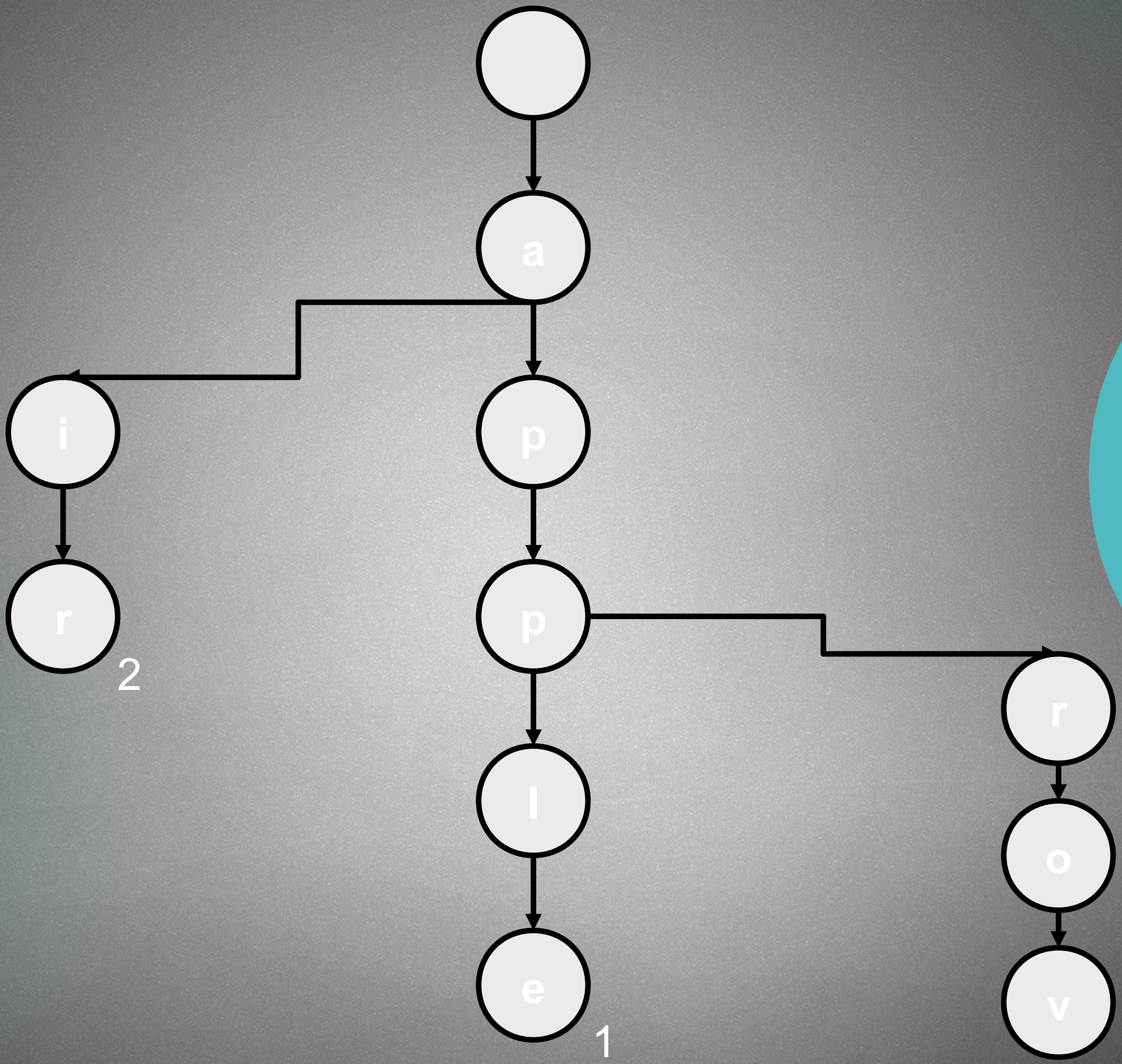
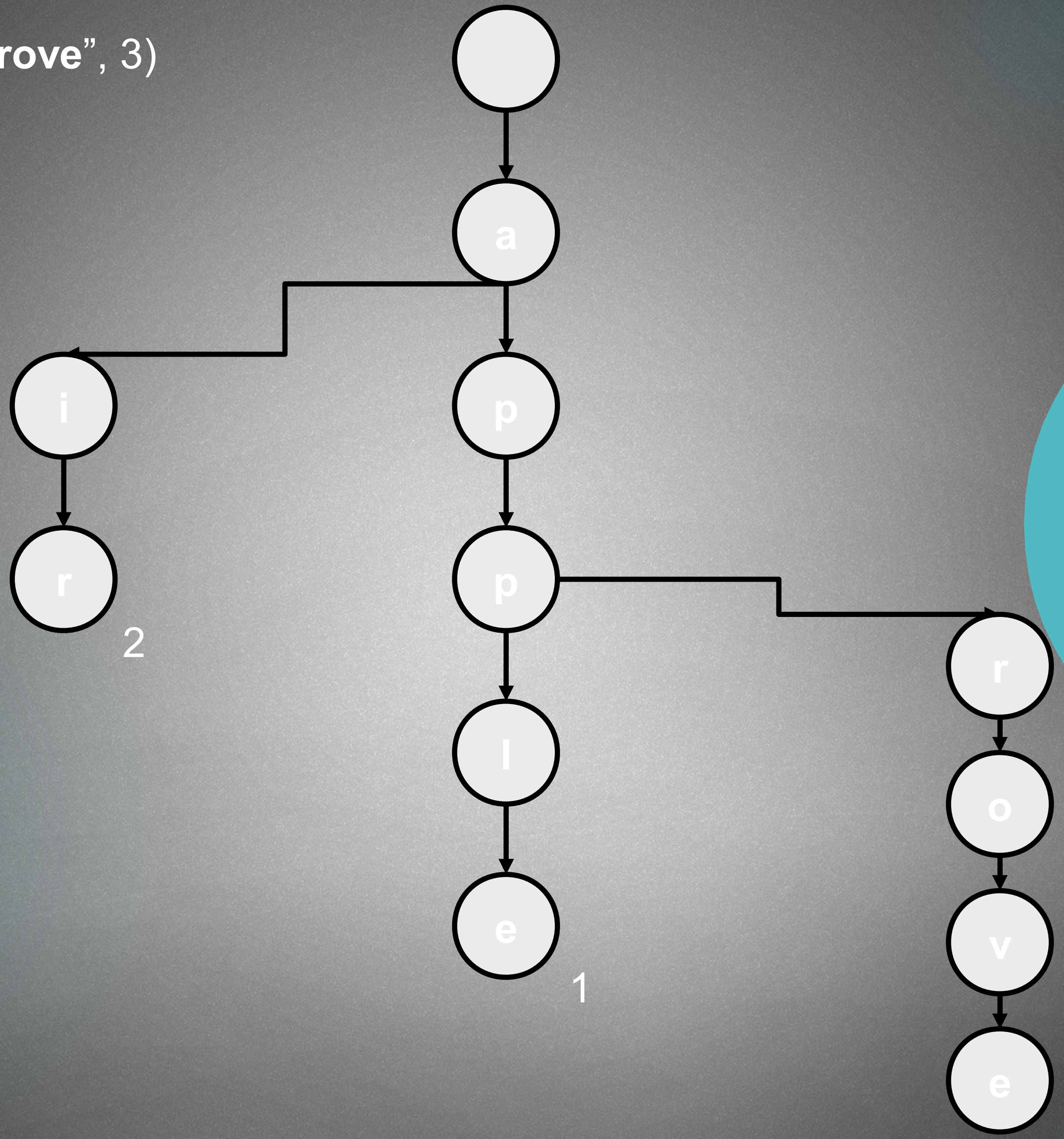
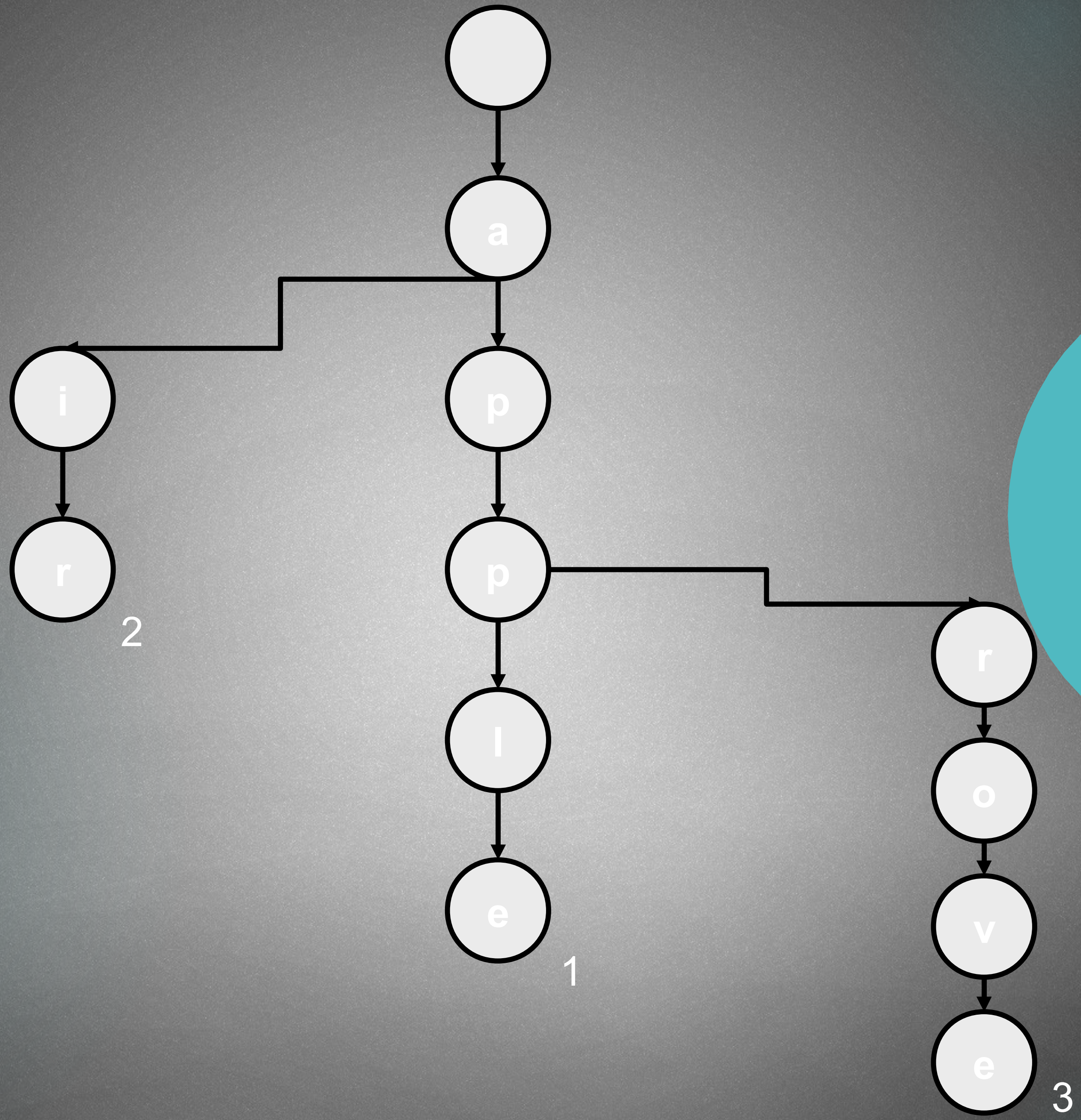


Insertion put(„**approve**”, 3)

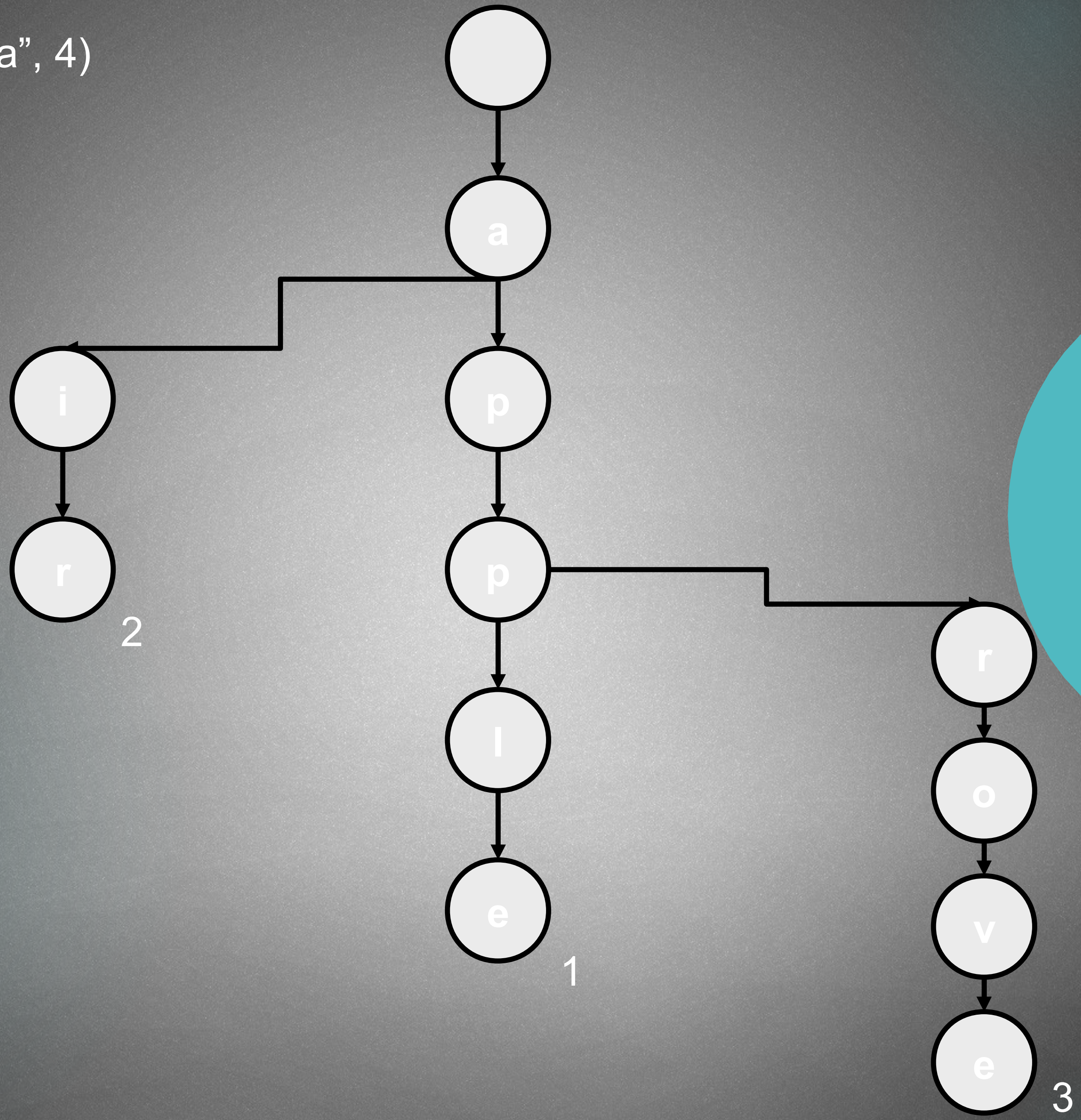


Insertion

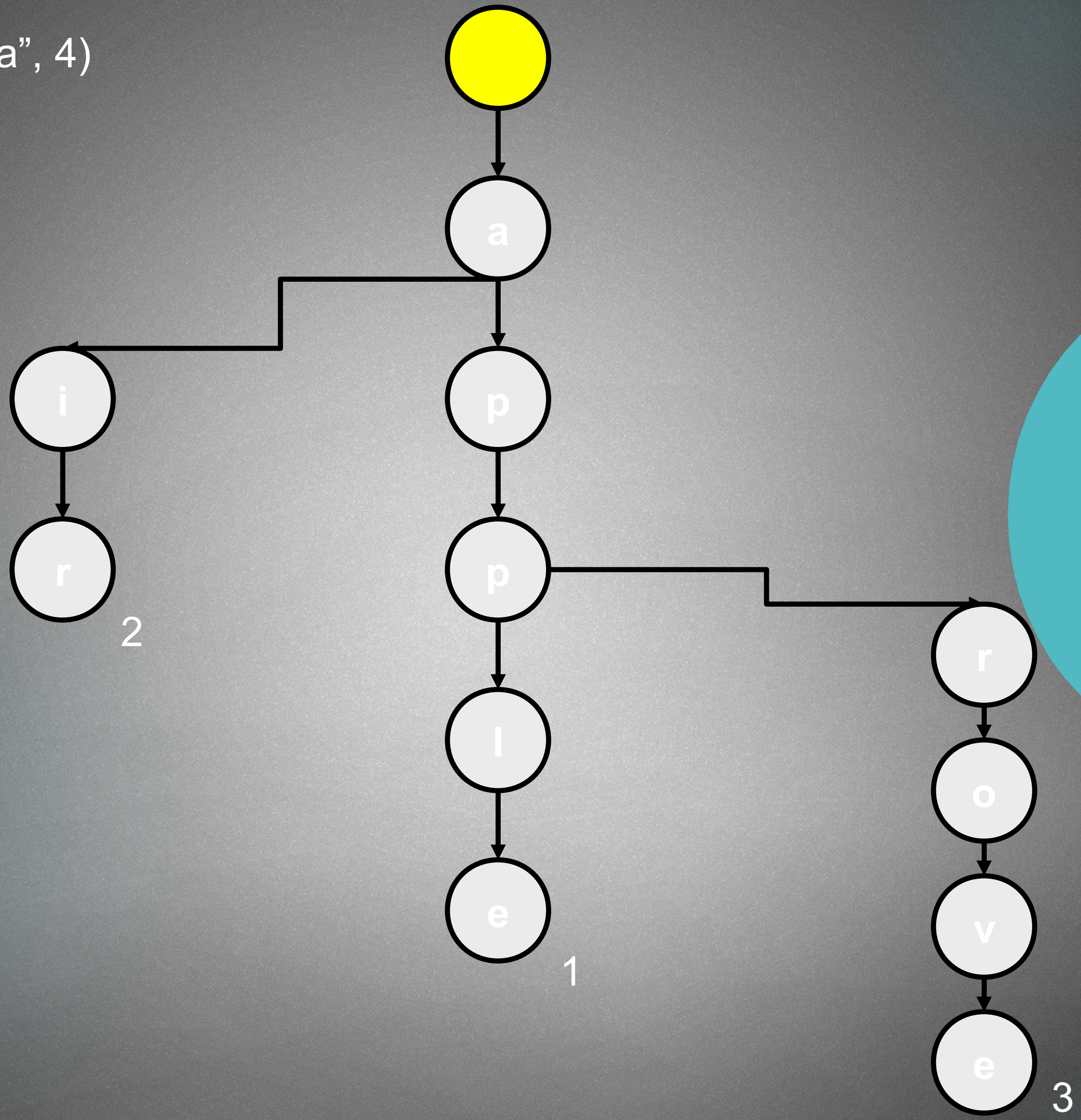


Insertion

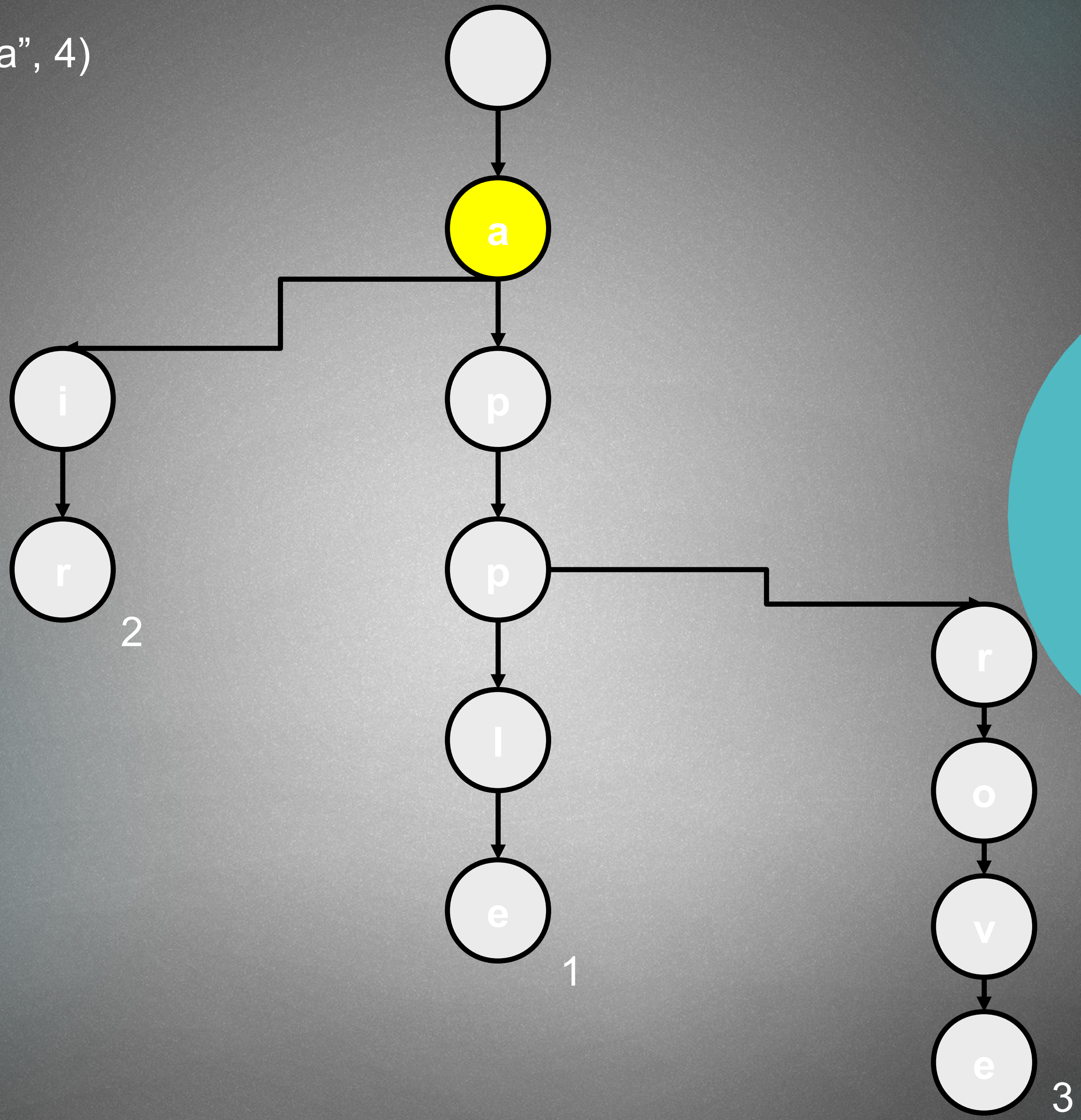
put(„appa", 4)



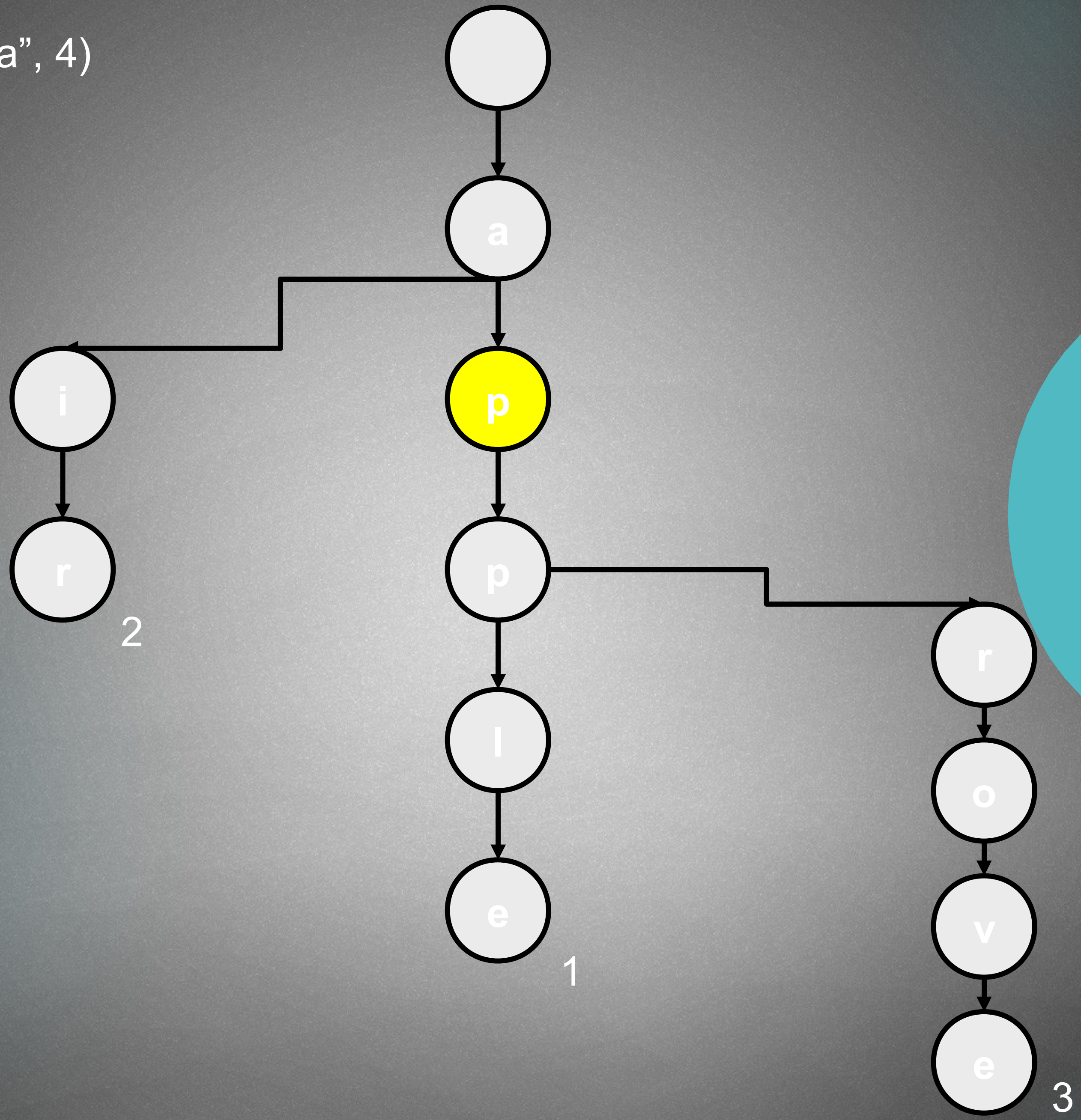
Insertion put(„appa”, 4)



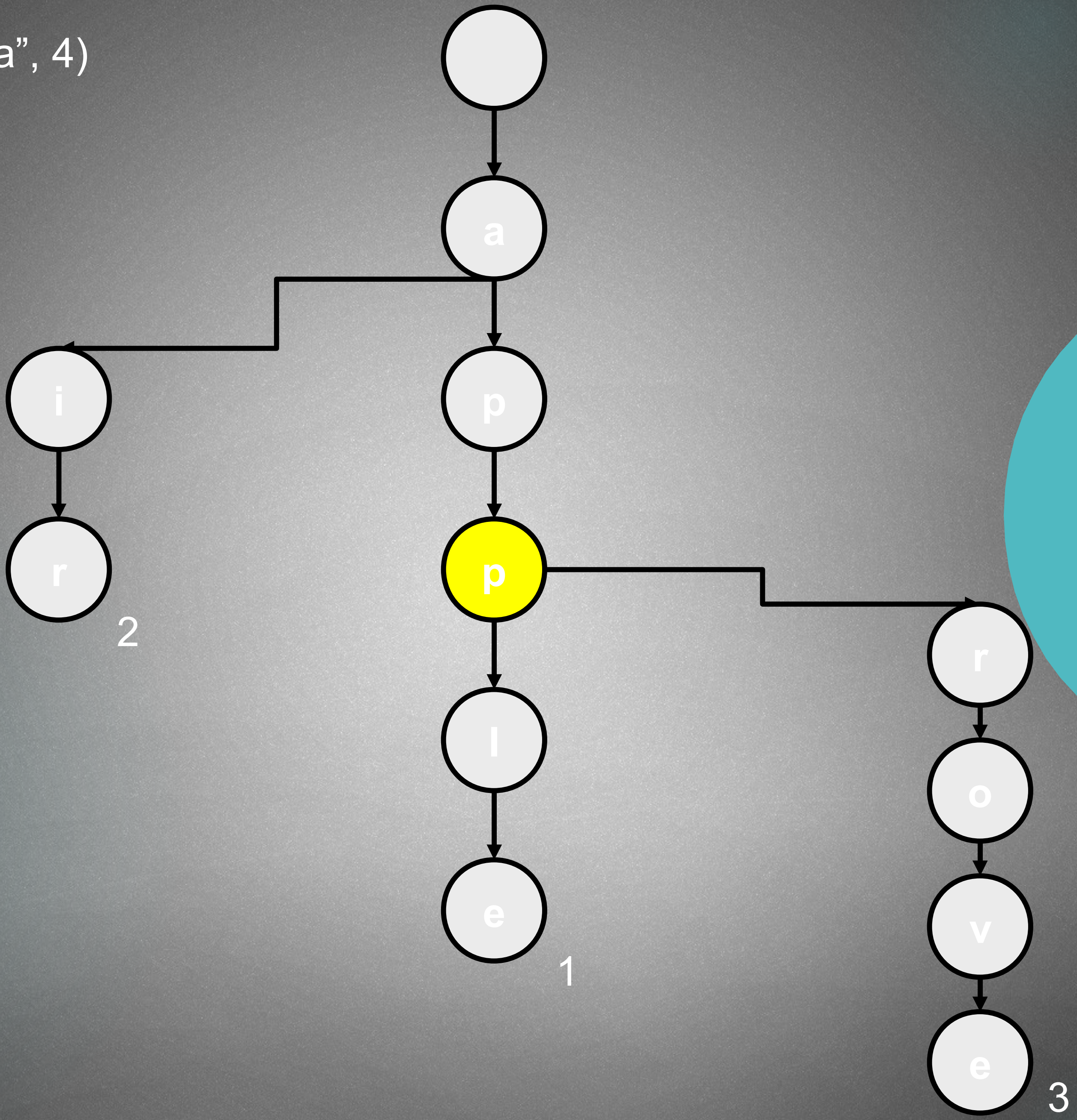
Insertion put(„appa”, 4)



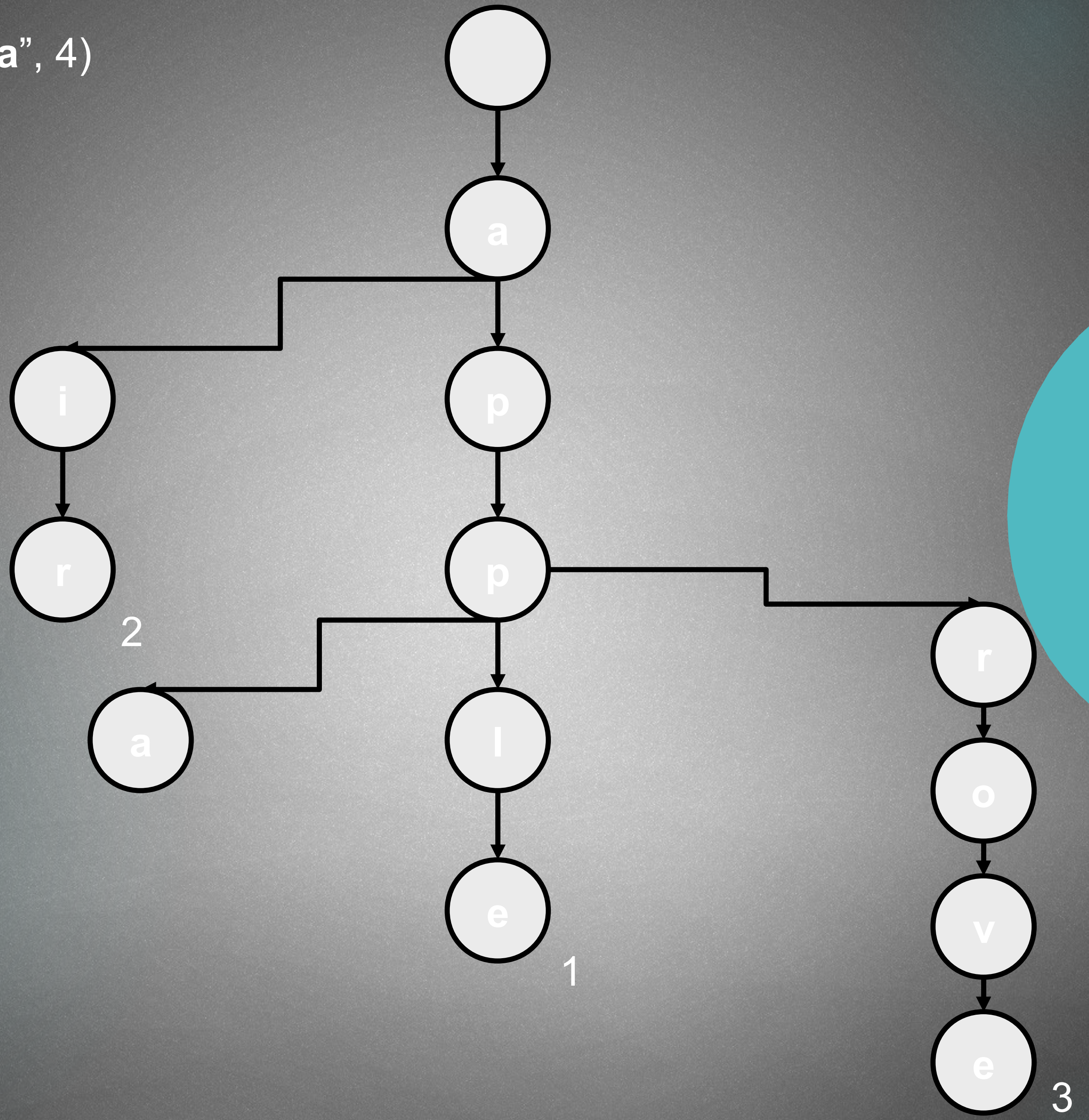
Insertion put(„**ap**pa", 4)



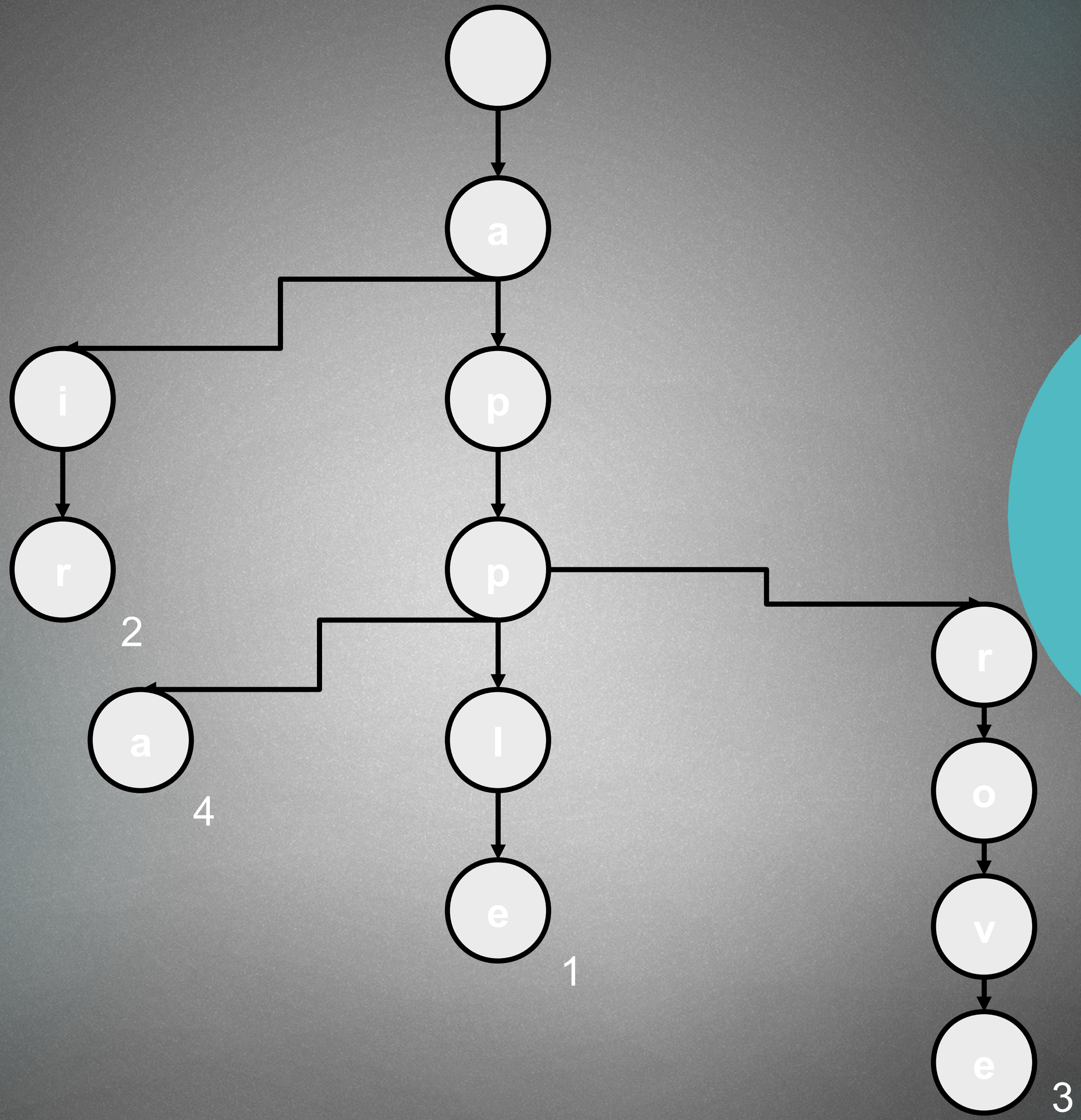
Insertion put(„**appa**", 4)



Insertion put(„**appa**”, 4)

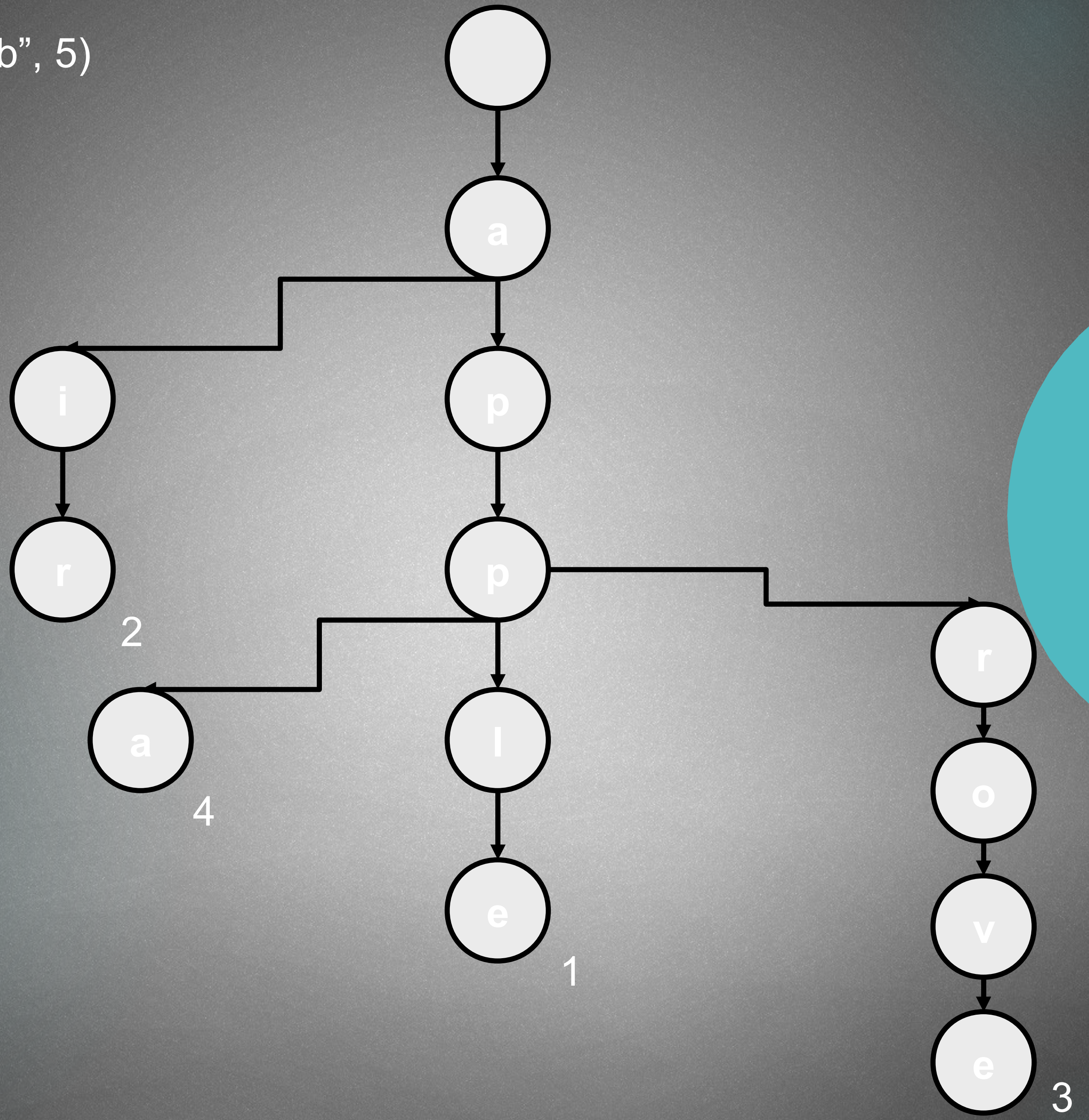


Insertion

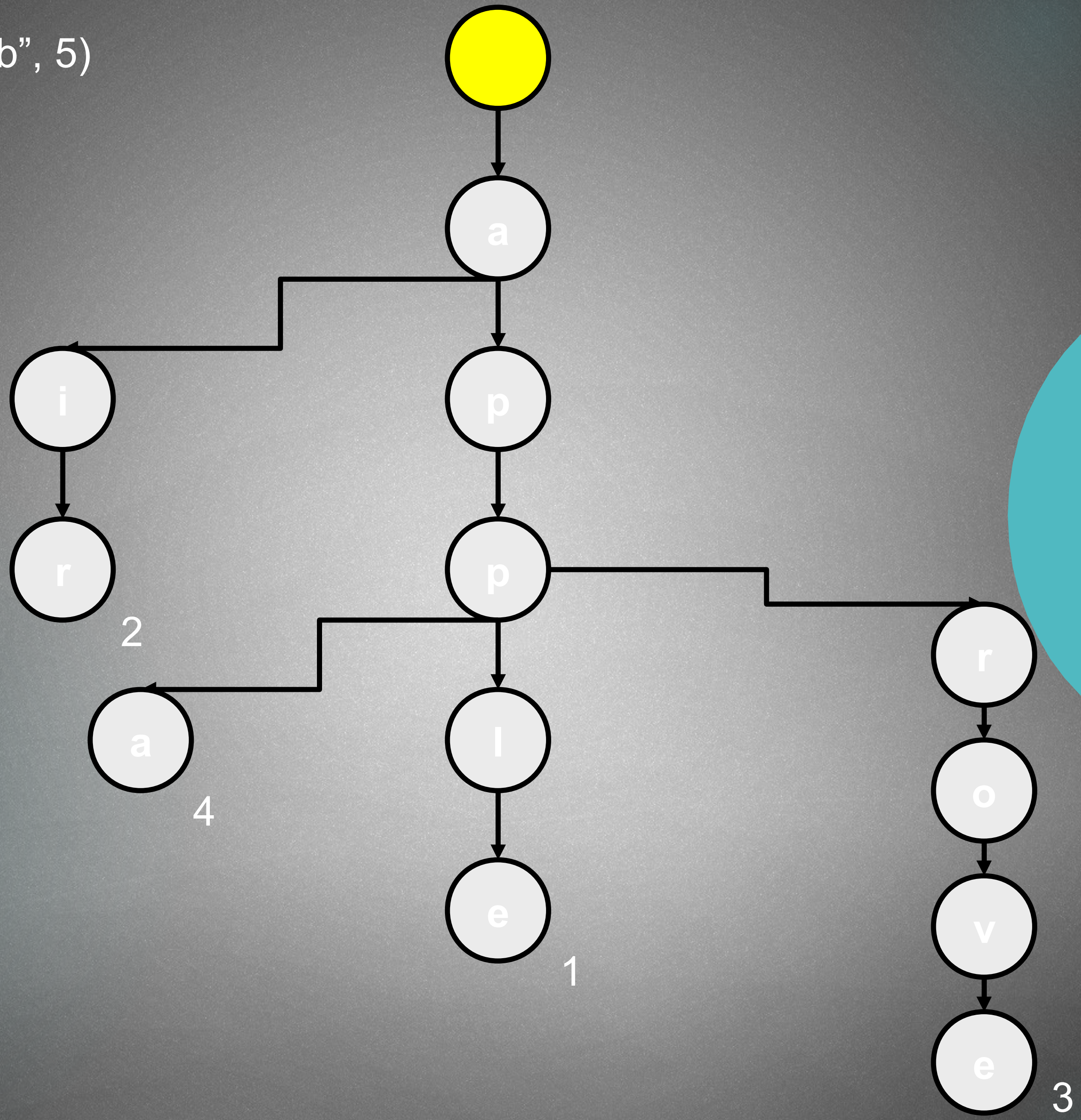


Insertion

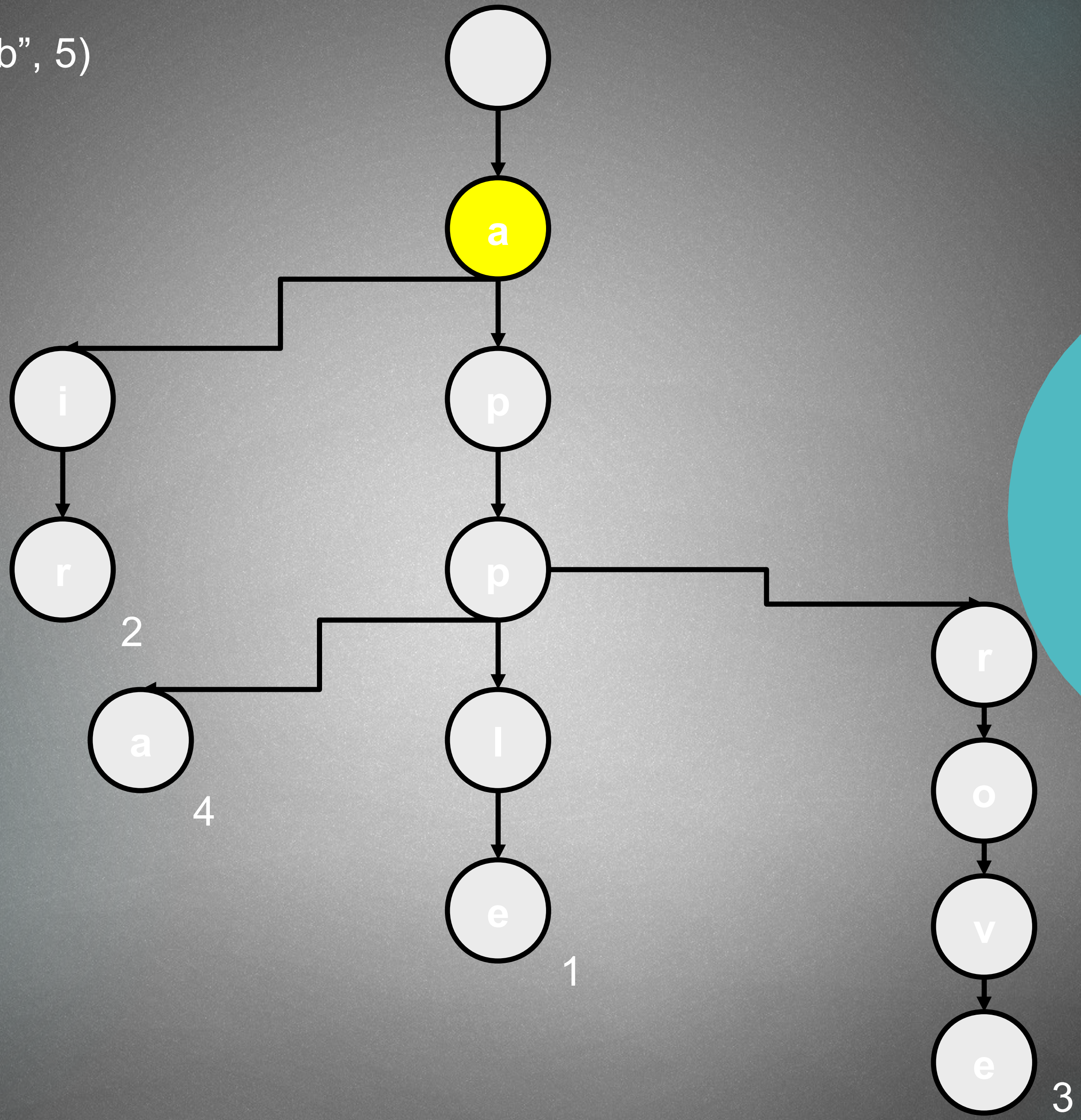
put(„appb”, 5)



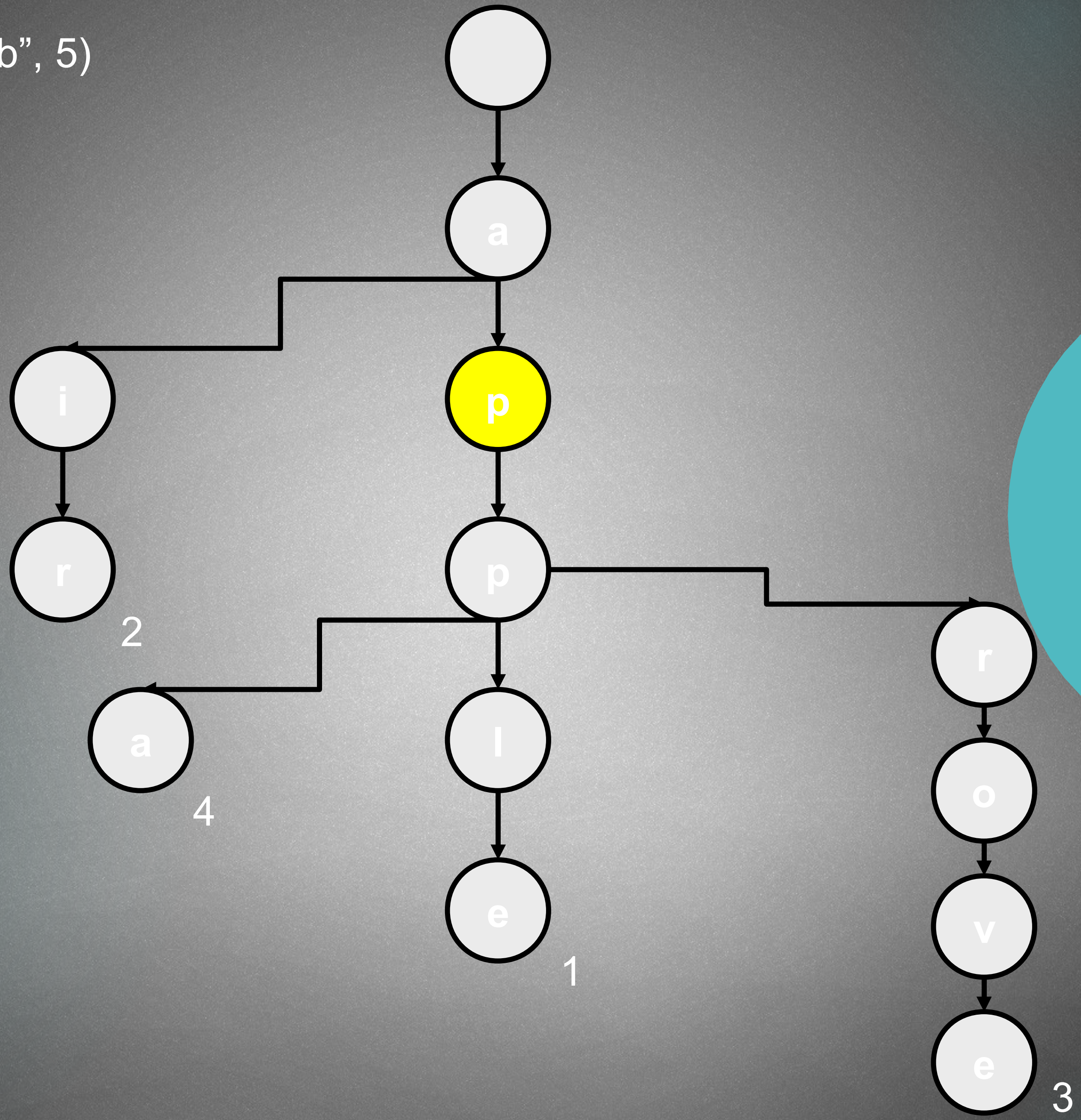
Insertion put(„appb", 5)



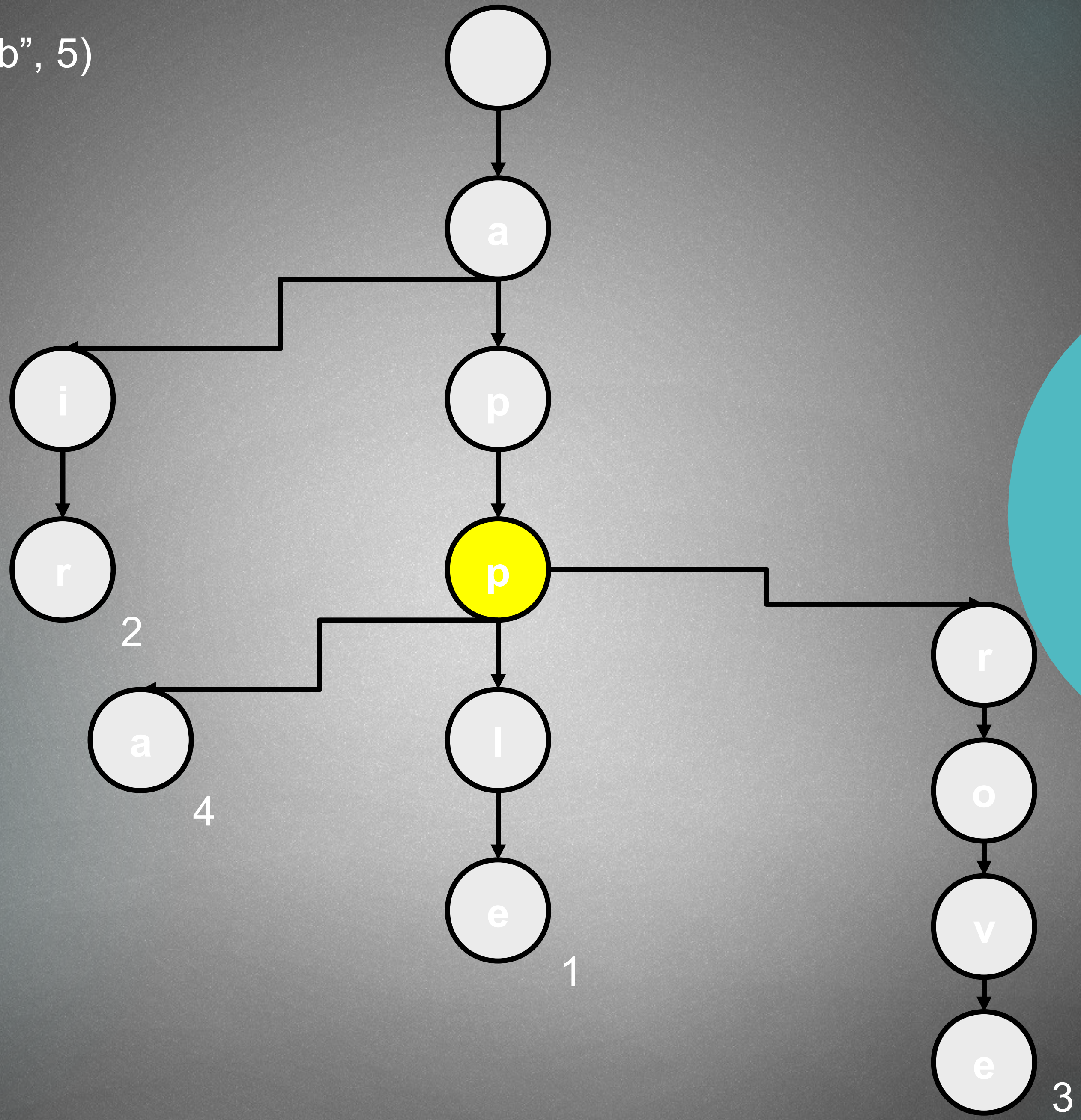
Insertion put(„appb”, 5)



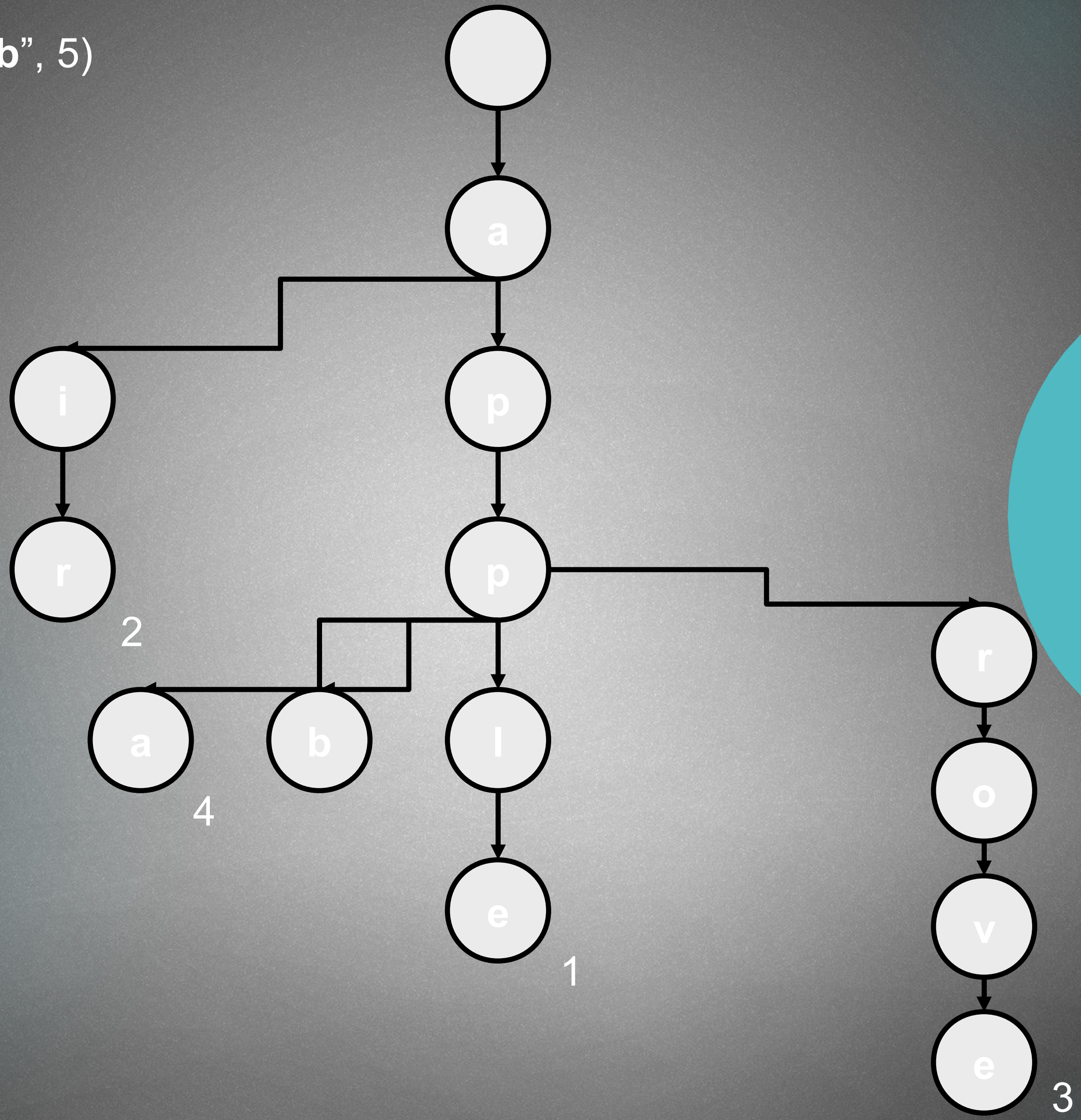
Insertion put(„**ap**pb", 5)

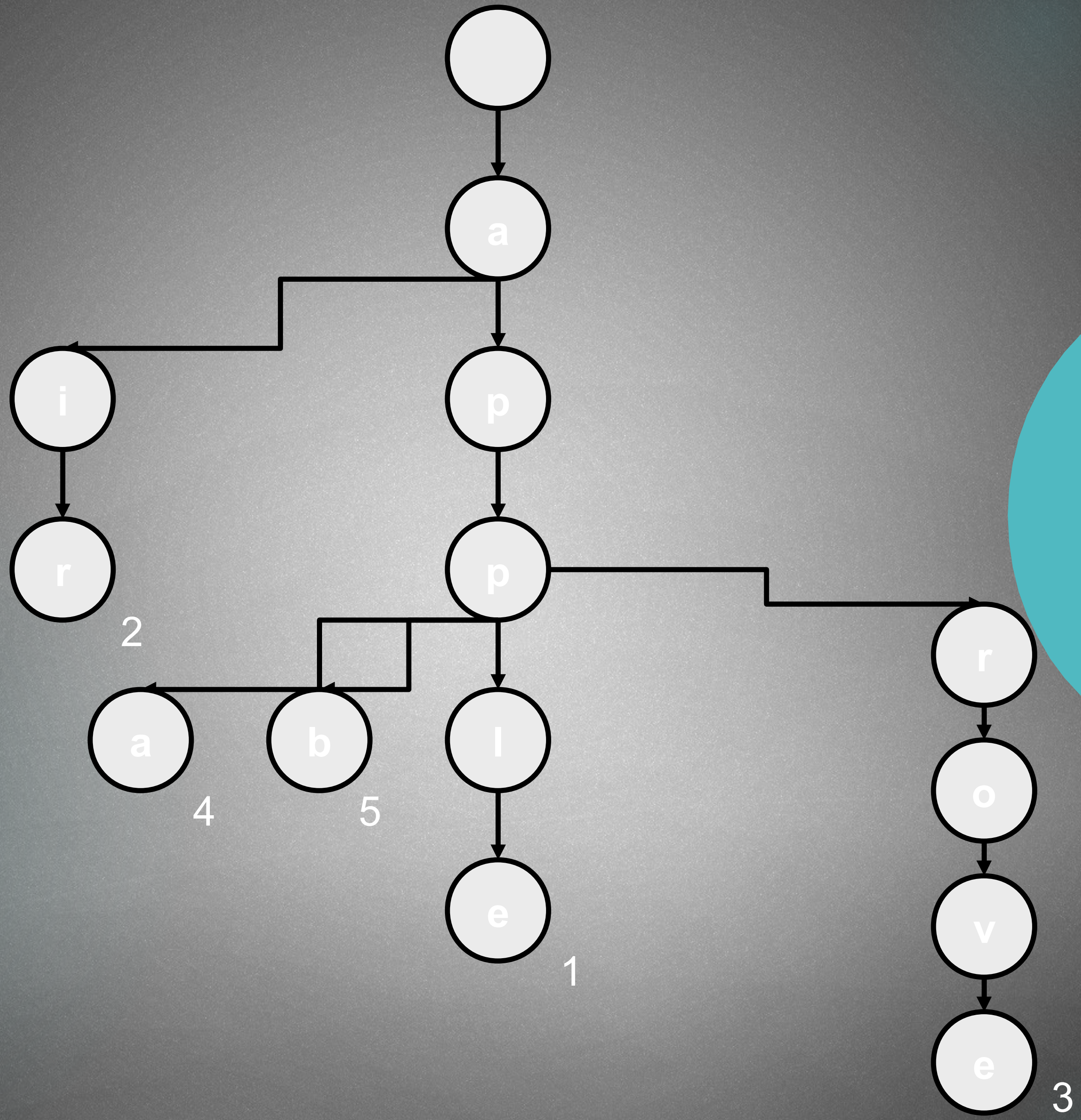


Insertion put(„**app**b", 5)



Insertion put(„**appb**”, 5)

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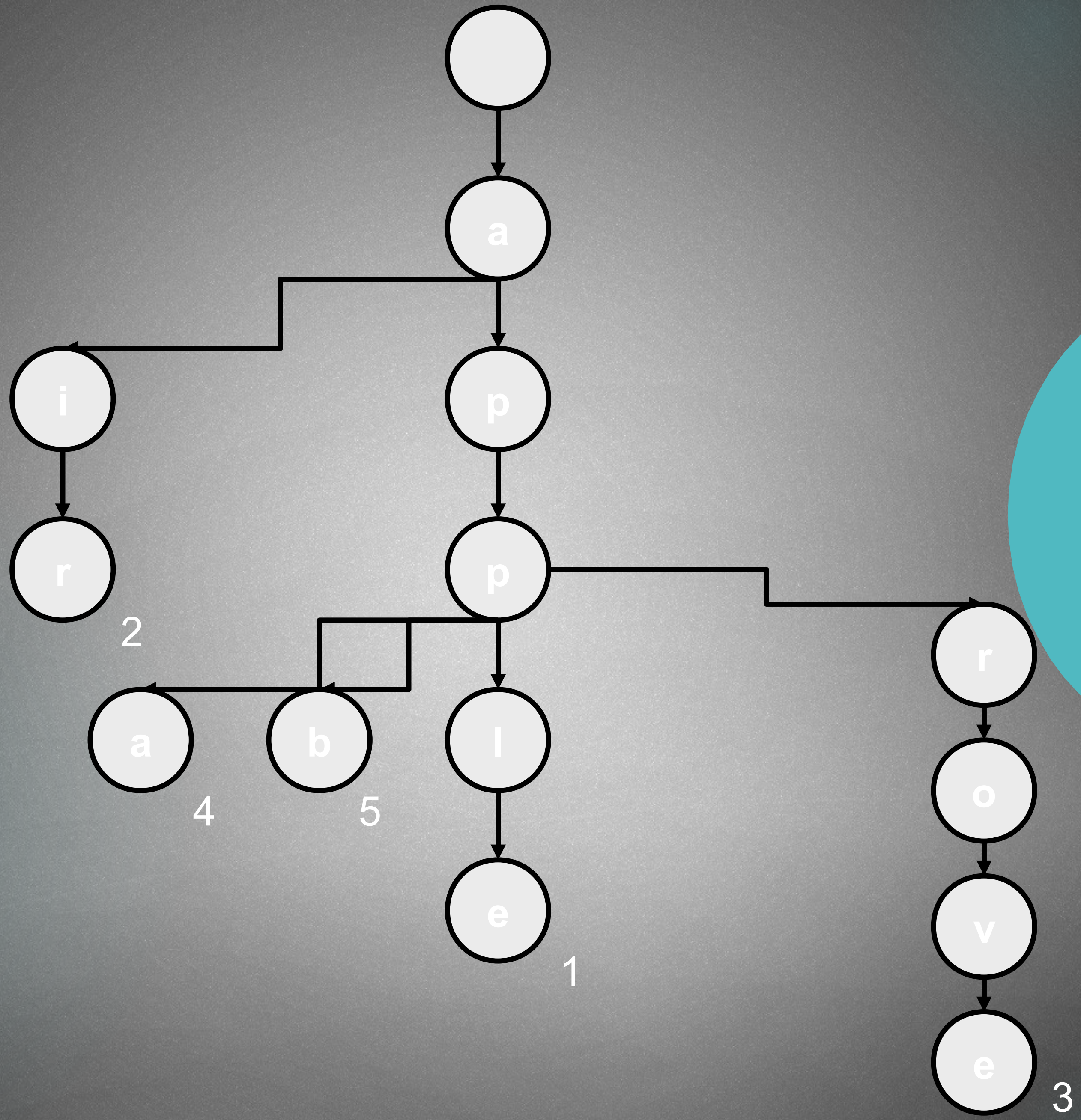
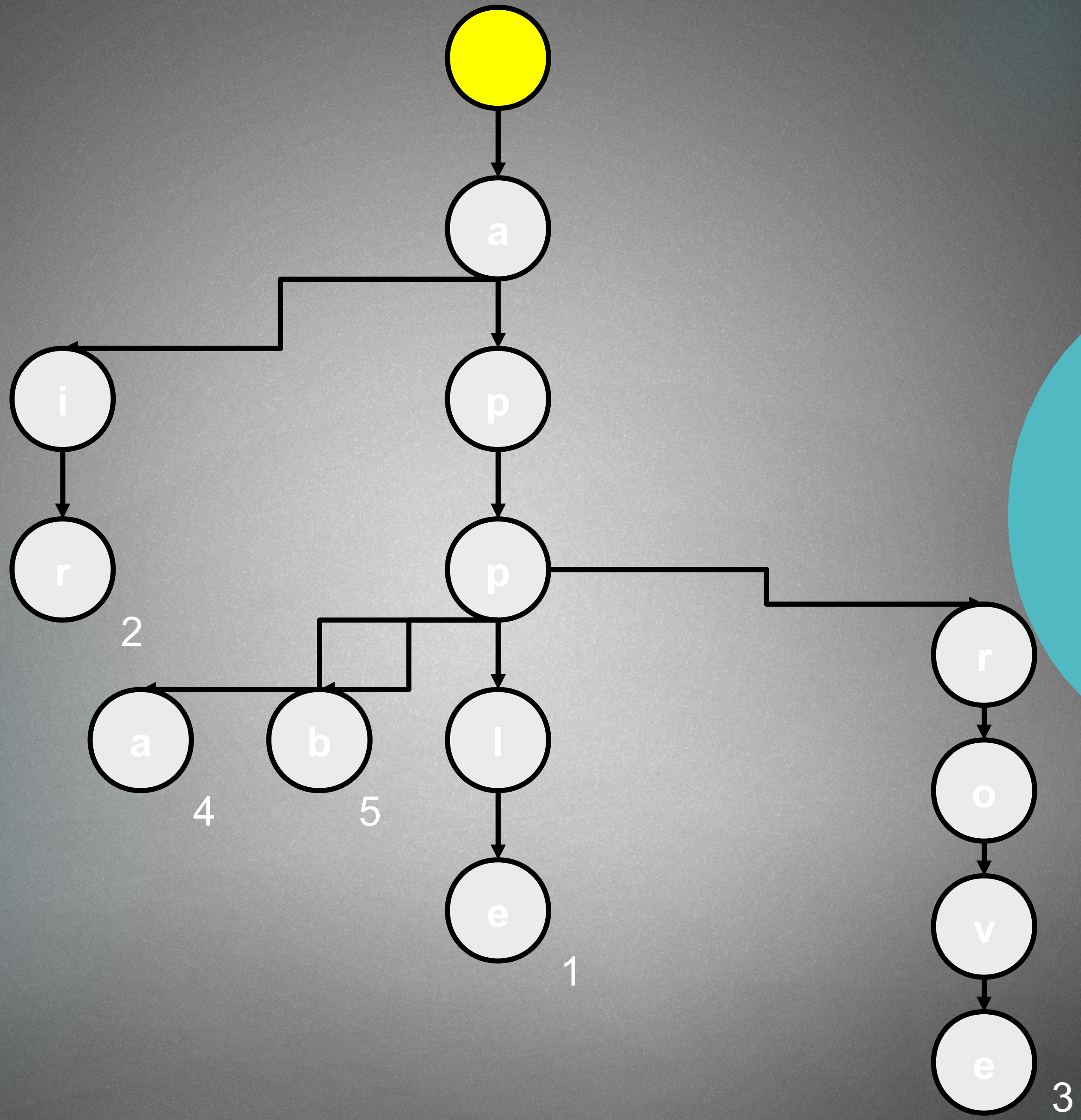
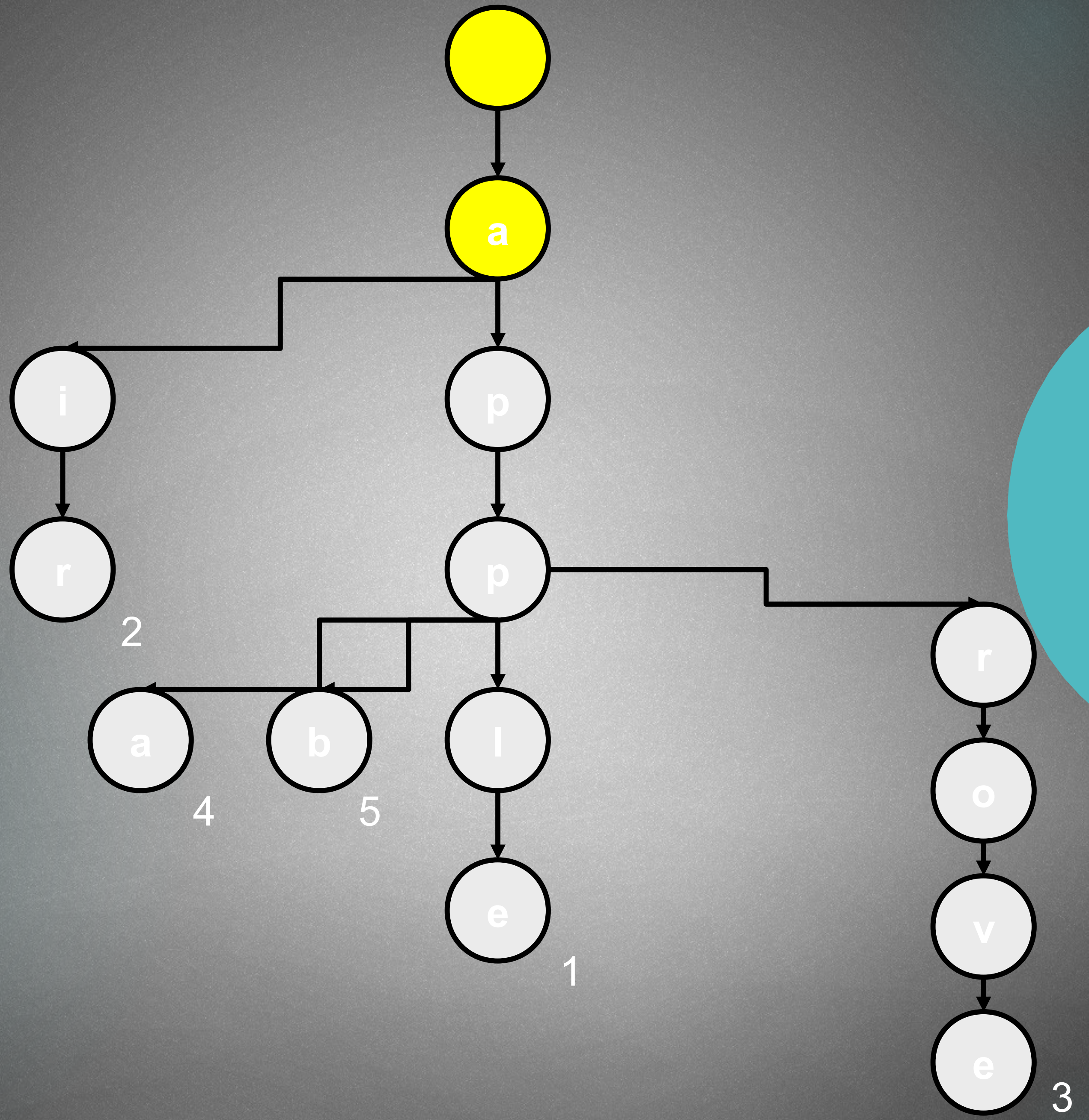
get(„apple")



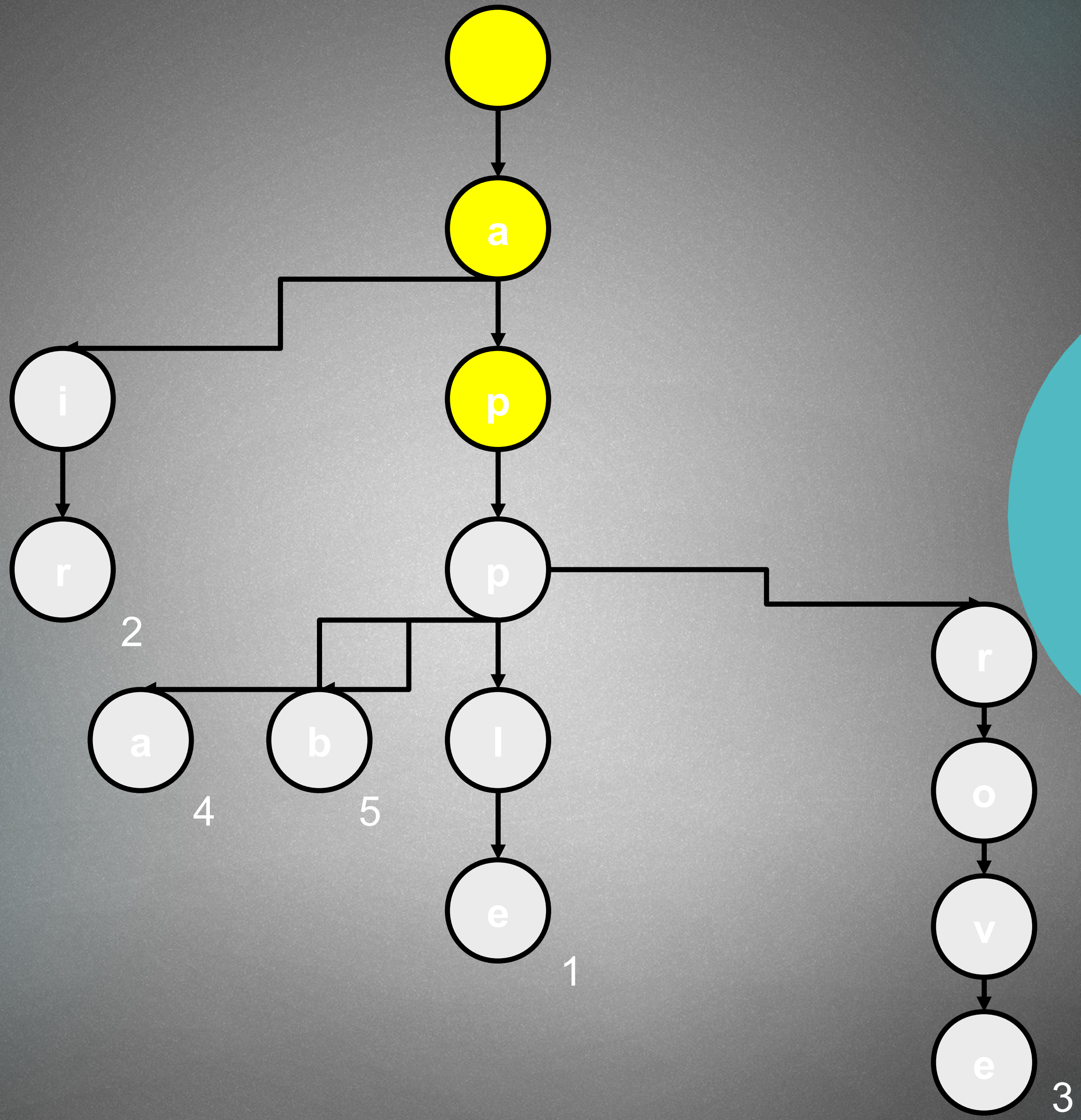
get(„apple”)



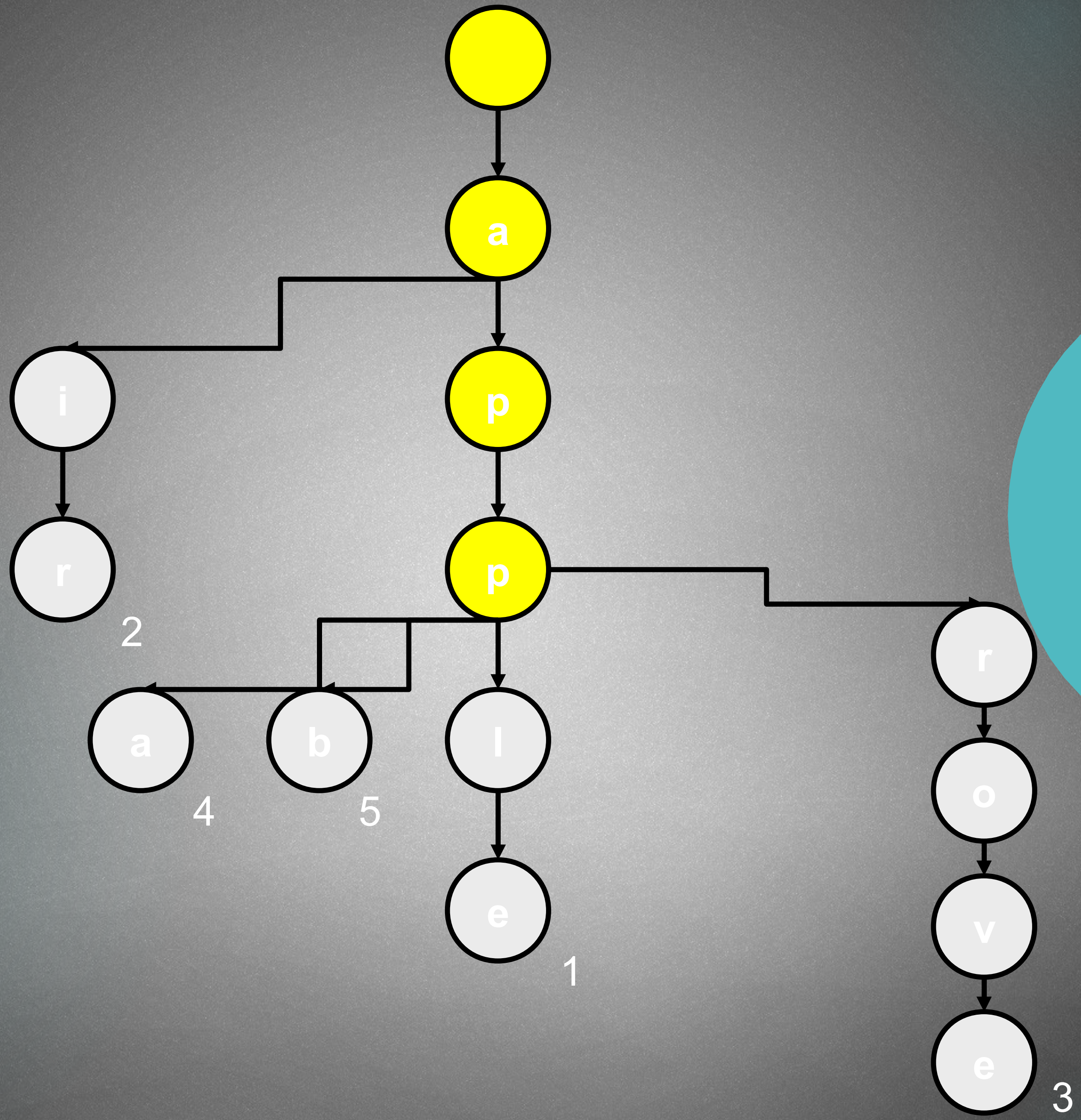
get(„apple”)



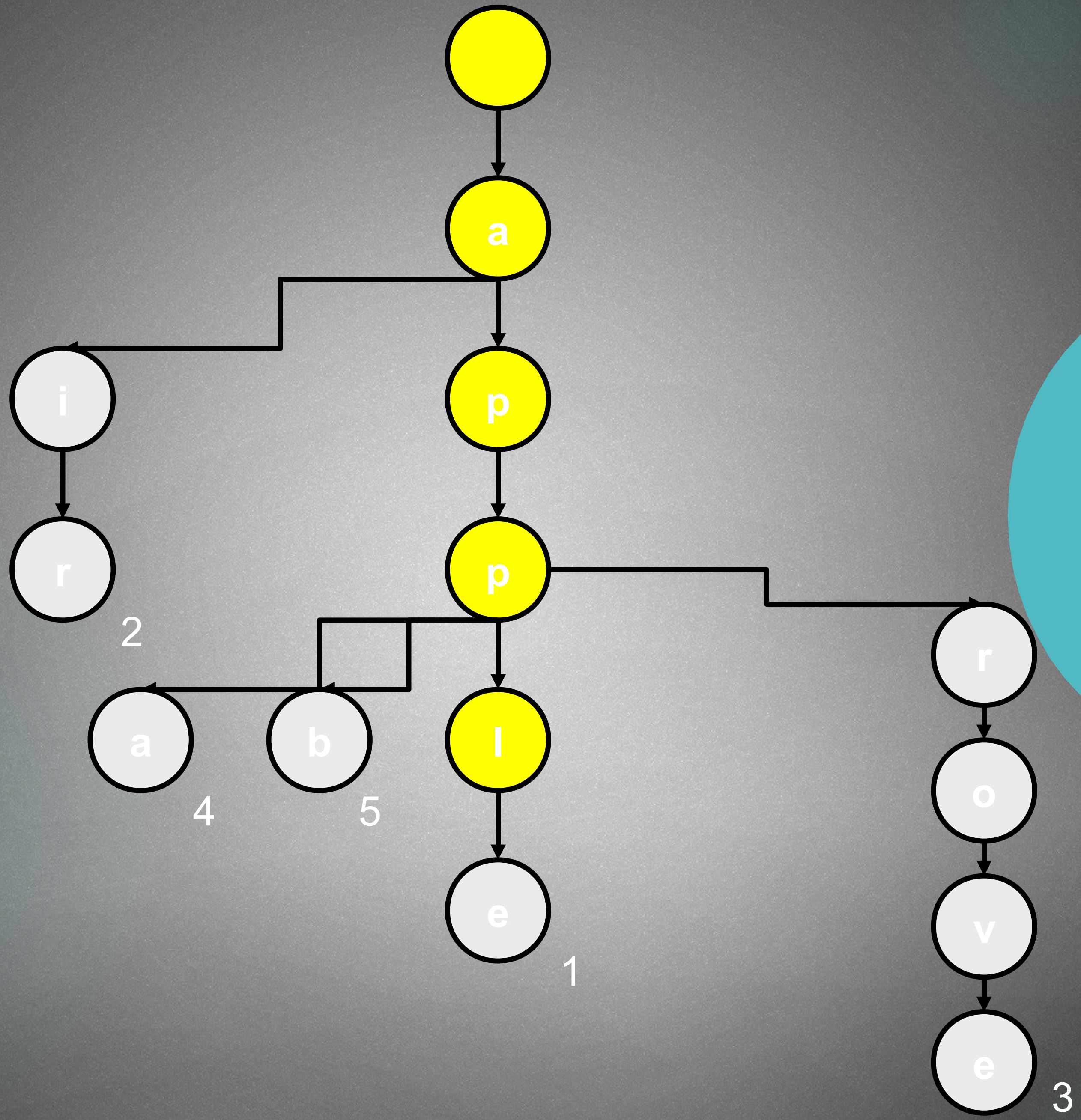
get(„**ap**ple”)



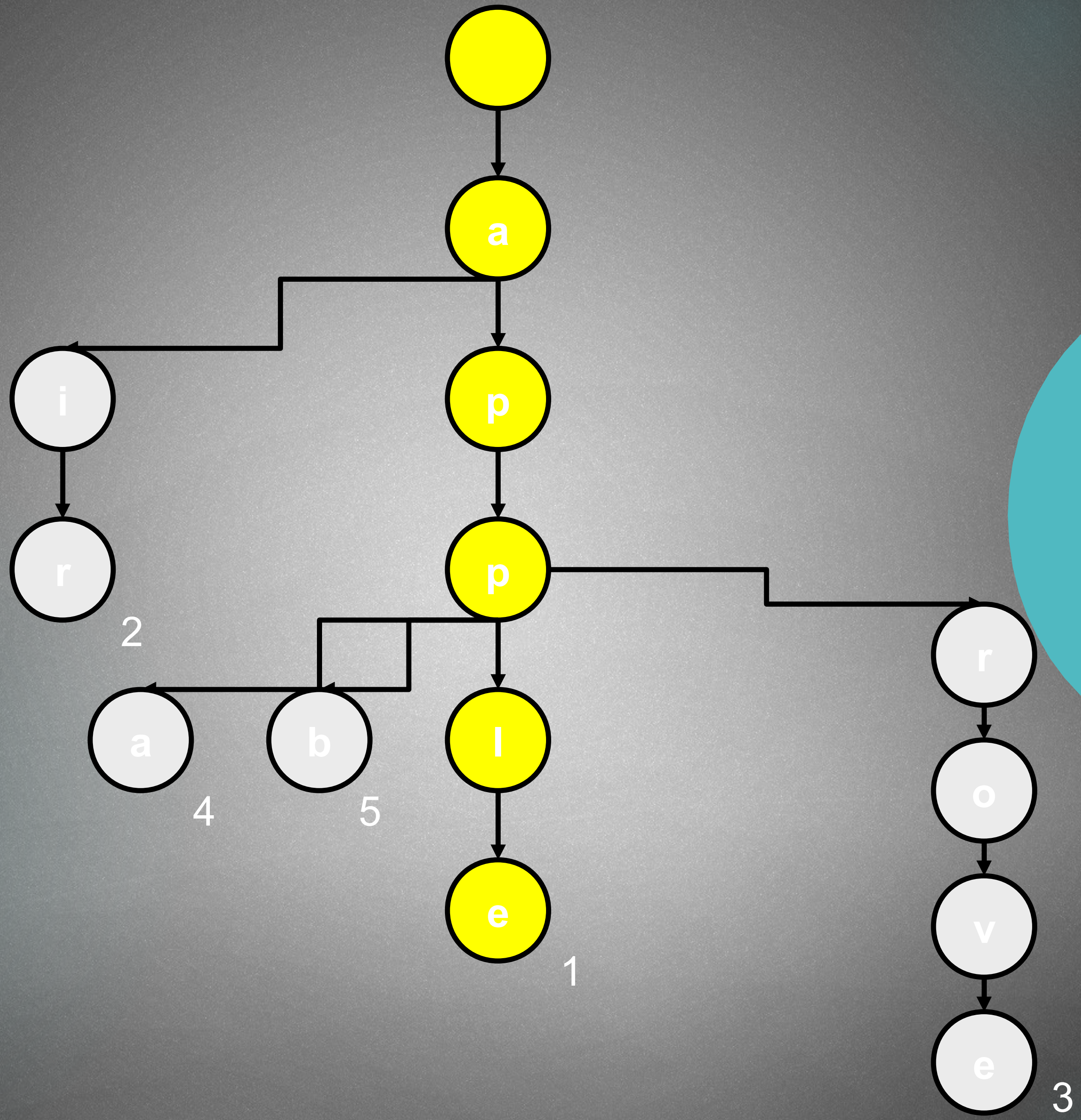
get(„apple”)



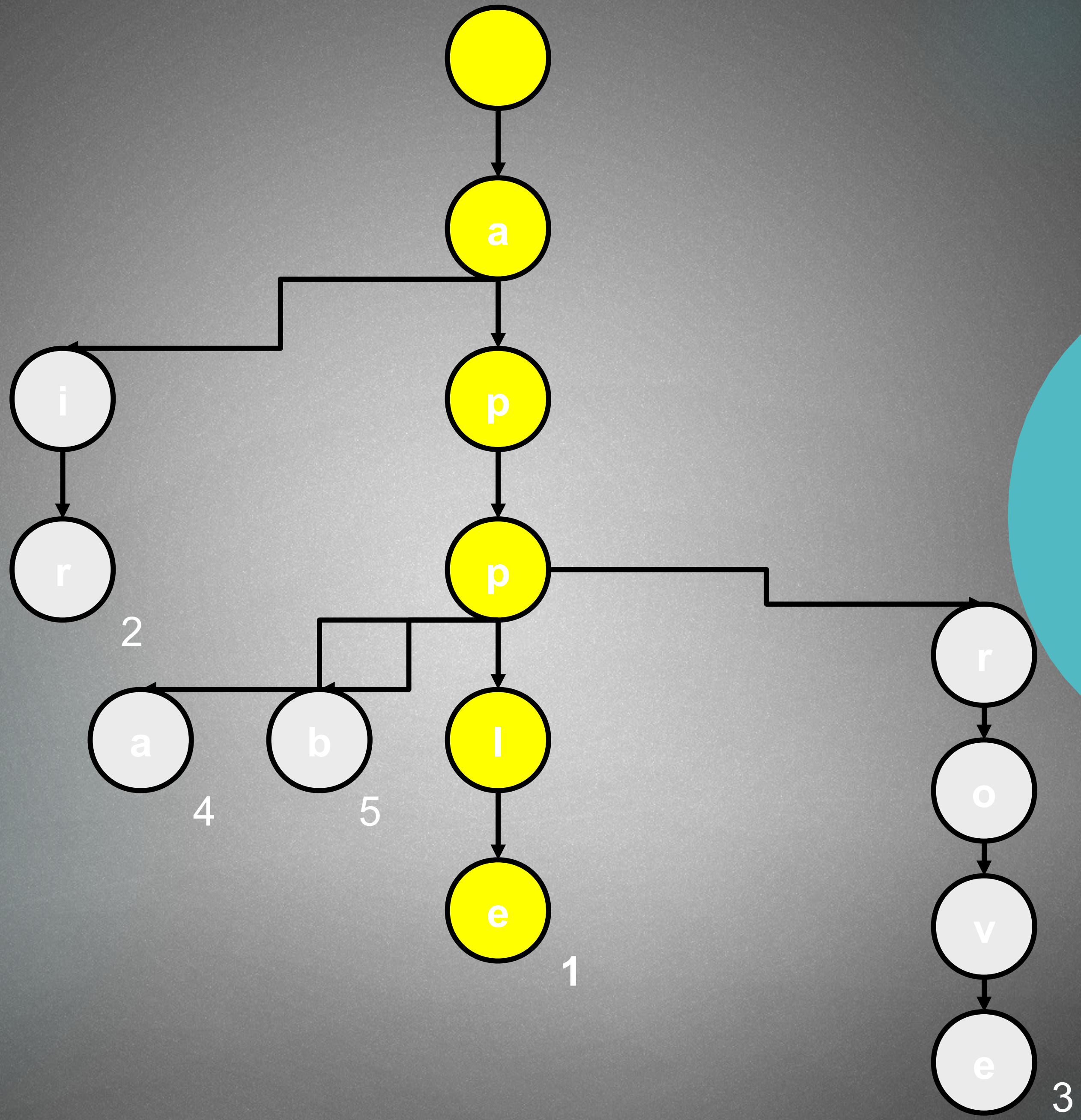
get(„**apple**”)

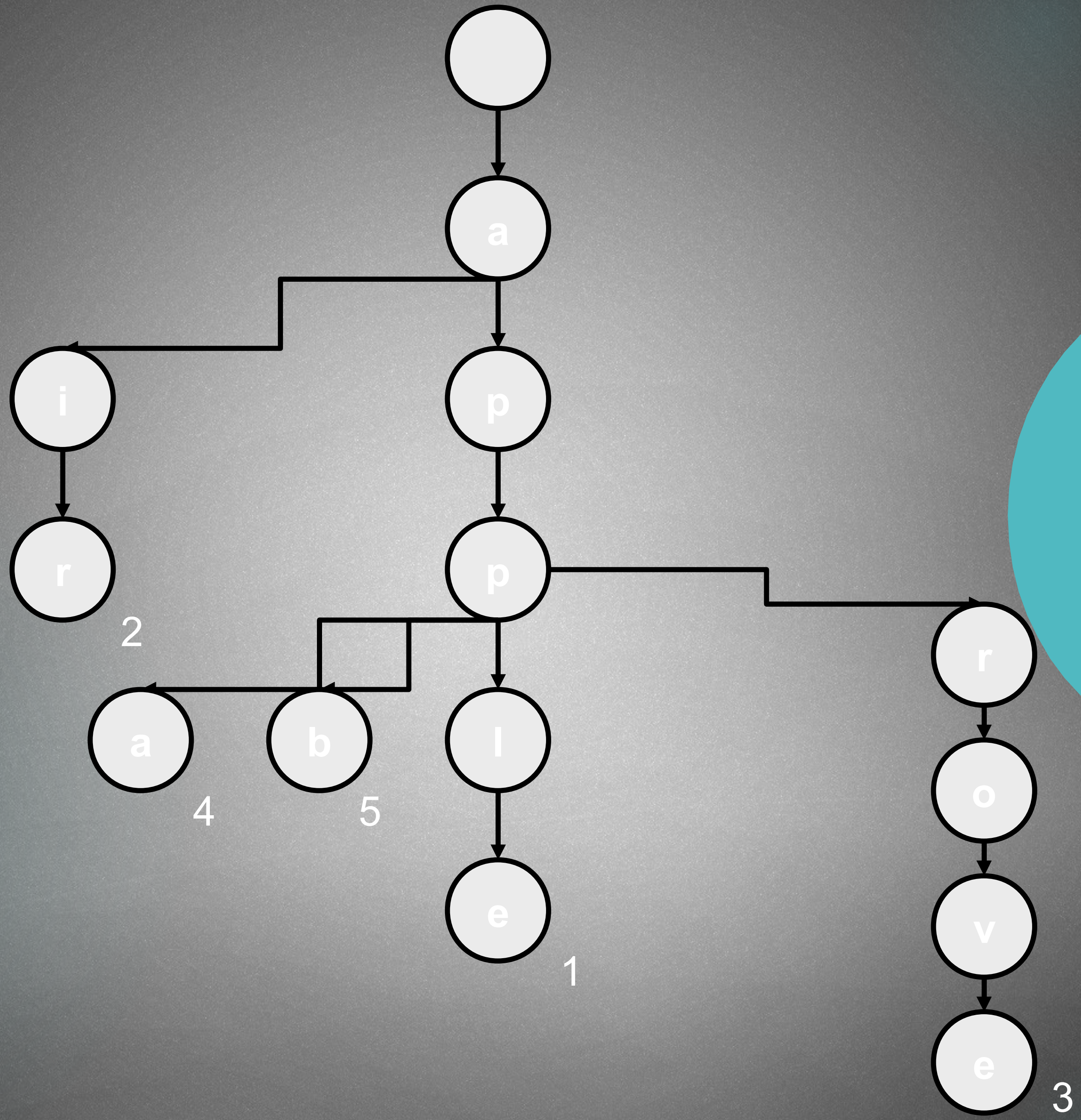


get(„**apple**”)



get(„**apple**")





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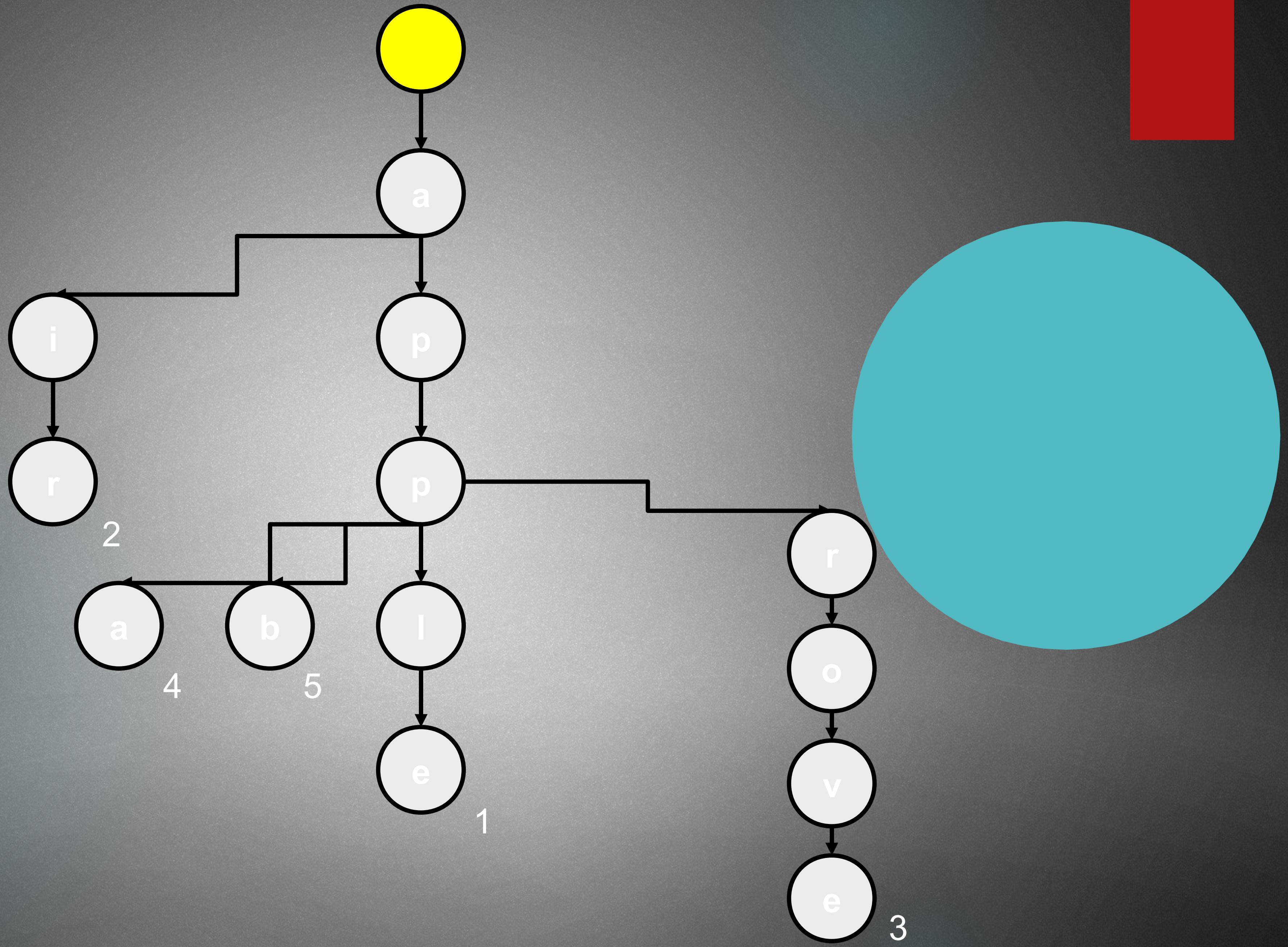
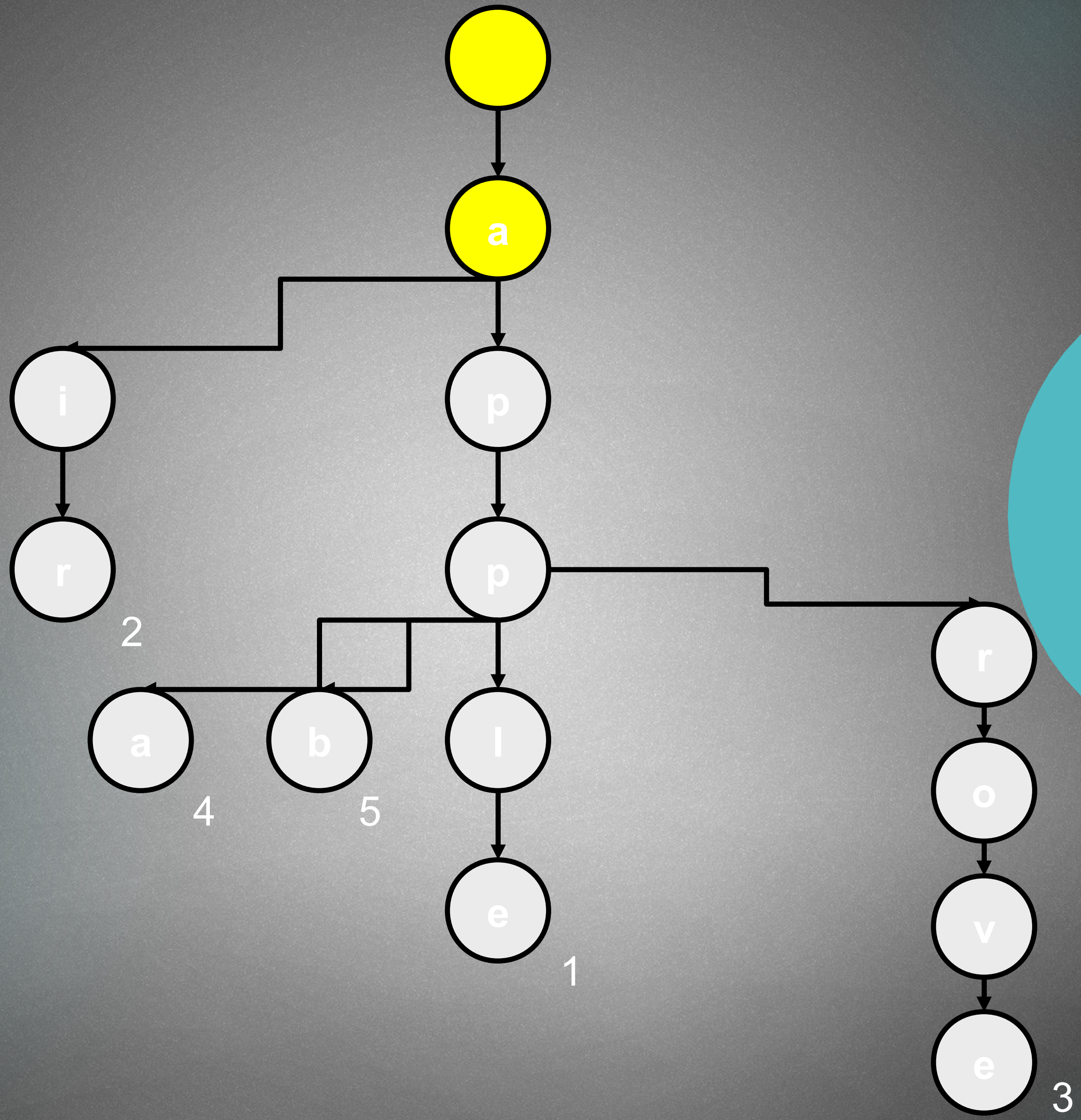
get(„air”)



get(„air”)



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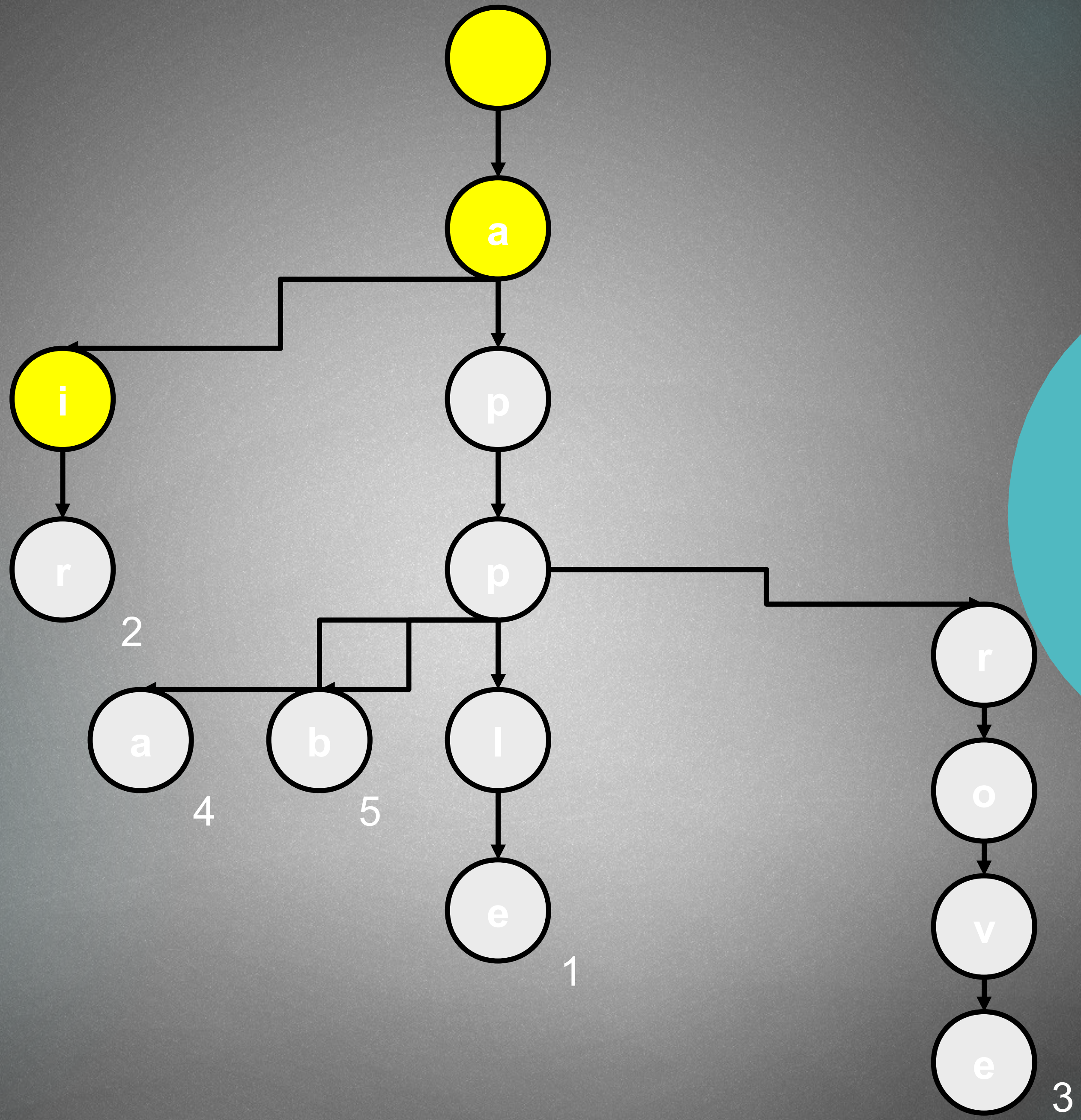
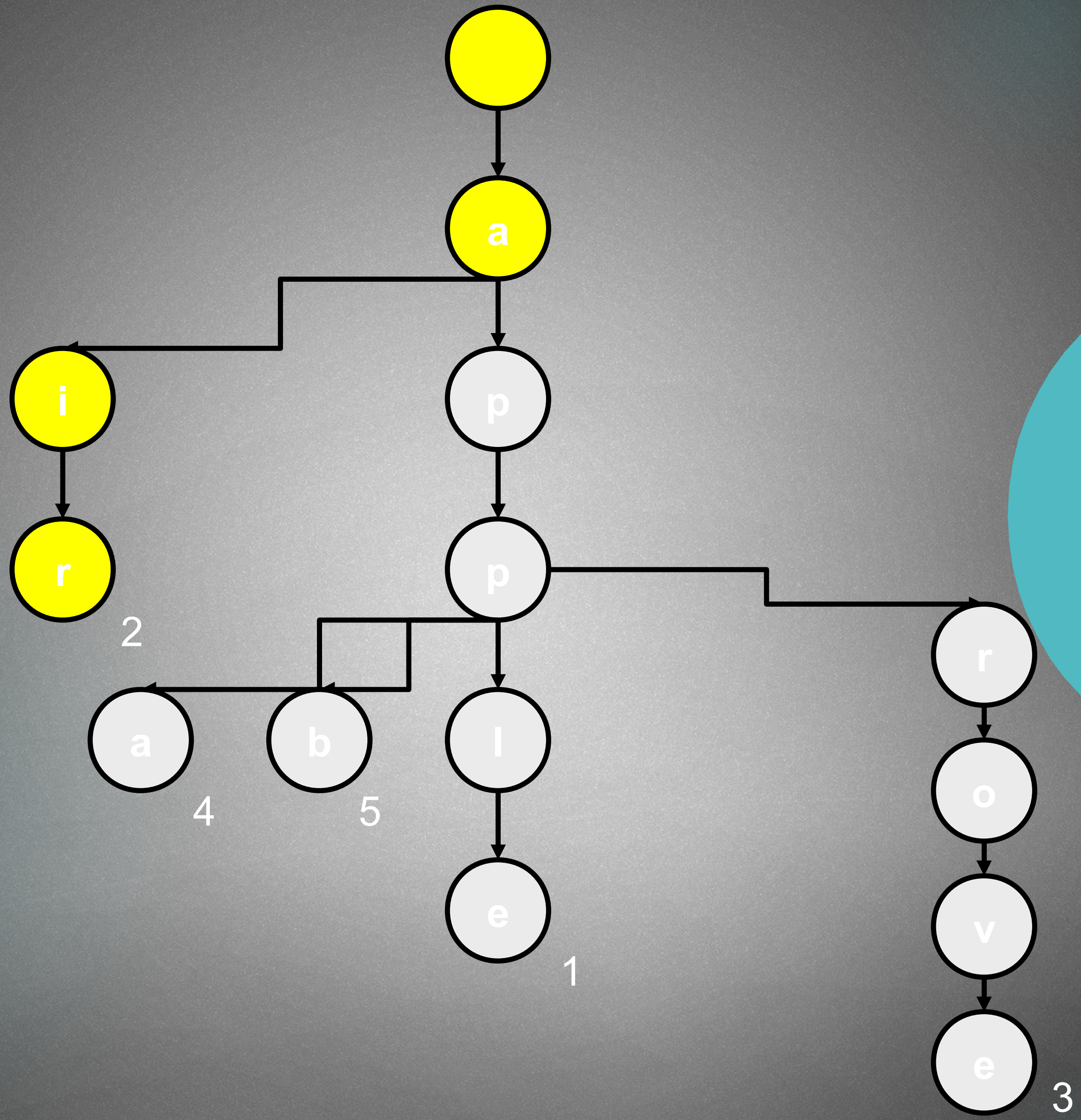
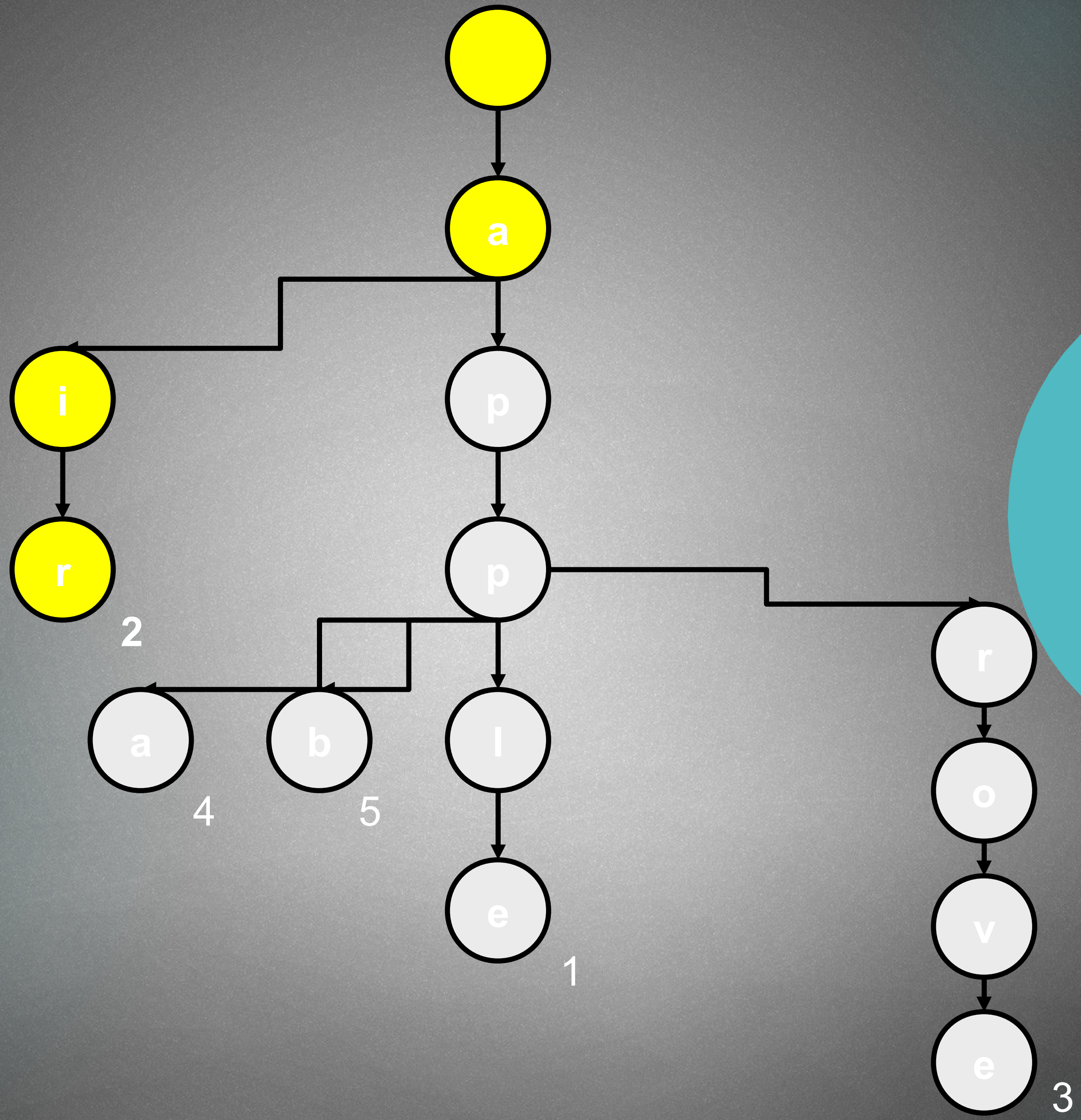


get(„**air**”)



get(„**air**”)



Hashing VS tries

- We can replace hash tables with tries → tries are more effective for search misses

Hashing VS tries

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Hash tables: the key is going to be converted into an array index
with the help of the hash function

For example: key is „apple” → the hash function considers
every single character in the key !!!

Tries: we consider every single character of the key „apple”
BUT we return right when there is a mismatch
// several times we just consider the few first
characters of the key

Hashing VS tries

- We can replace hash tables with tries → tries are more effective for search misses
- So it is faster to use tries in the worst case

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Hash tables: we end up with a linked list, so searching is with **O(N)** running time in this case
N: number of items in the hash table

Tries: worst case is that we have to consider every character of the key → it is **O(m)** complexity
m: length of the key

USUALLY N >> m !!!

Hashing VS tries

- We can replace hash tables with tries → tries are more effective for search misses
- So it is faster to use tries in the worst case
- For tries there are no collisions !!!

Hashing VS tries

- We can replace hash tables with tries → tries are more effective for search misses
- So it is faster to use tries in the worst case
- For tries there are no collisions !!!
- Tries can provide sorting → so alphabetical ordering of the entries by keys !! ~ hash tables does not
- No hash function needed for tries and designing a perfect hash function is a very complex task

Hashing VS tries

- Tries may be slower than hash tables
- Searching on secondary storage (for example HDD hard drive disk)
- Random-access time is high compared to main memory
- Hash tables → we just search by the indexes once when the index is generated by the hash function
- Tries → there is a random-access every time we consider the next character in the key
- Sometimes tries need more memory: a memory chunk is allocated for every single character with tries BUT for hash tables there is just a single chunk of memory !!!

Applications

Predictive text it is sort of an input technology

On smart phones it is quite popular

~ each key press results in a prediction: the predictions come from tries

Autocomplete we start typing – for example - in the browser

and the suggestions are going to be appeared

~ a trie may be the underlying data structure, and the suggestions are the entries with same prefixes !!!

Spell checking a trie data structure can be used as a spell checker

First we have to construct the trie with the words

~ after the construction → we are able to check whether that given string is present in the trie or not

- so we can check whether the given word is spelled correctly or not
- we can even suggest that what may be the correctly spelled word

TERNARY SEARCH TREES

tst

- With the help of tries we can search and sort strings very very efficiently
- The problem is that tries consume a lot of memory, so we should use ternary search trees instead which stores less references and null objects
- TST stores characters or strings in nodes
- Each node has 3 children: less (lower child), equal (middle child) or greater (higher child)
- Can we balance TST-s with rotations? Yes, but it does not worth the trouble
- It can be used instead of hashmap: it is as efficient as hashing
- Hashing need to examine the entire string key ... TST does not

- TST support sorting operation !!!
- So: TST is better than hashing → especially for search misses + flexible than BST (usually there is no perfect hash function)
- Conclusion: TST is faster than hashmap and more flexible than binary search trees

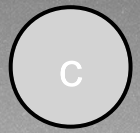
put: with this operation we would like to insert a new element into the ternary search tree with a given key

- if the character is smaller alphabetically: we go to the left
- if the character is equal: we go to the middle
- if the character is greater alphabetically: go right

put: with this operation we would like to insert a new element into the ternary search tree with a given key

put(„cat”,23)

put: with this operation we would like to insert a new element into the ternary search tree with a given key



put(„cat”,23)

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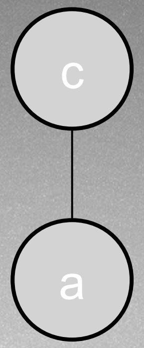

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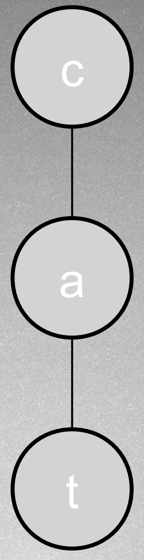
put(„cat”,23)



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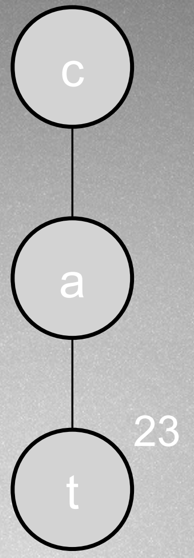
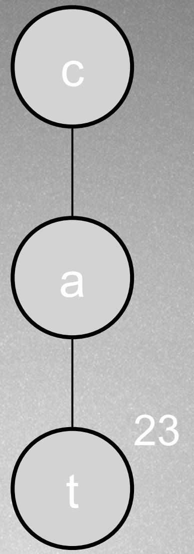


put: with this operation we would like to insert a new element into the ternary search tree with a given key

put(„apple”,46)



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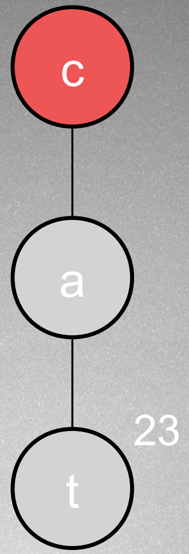
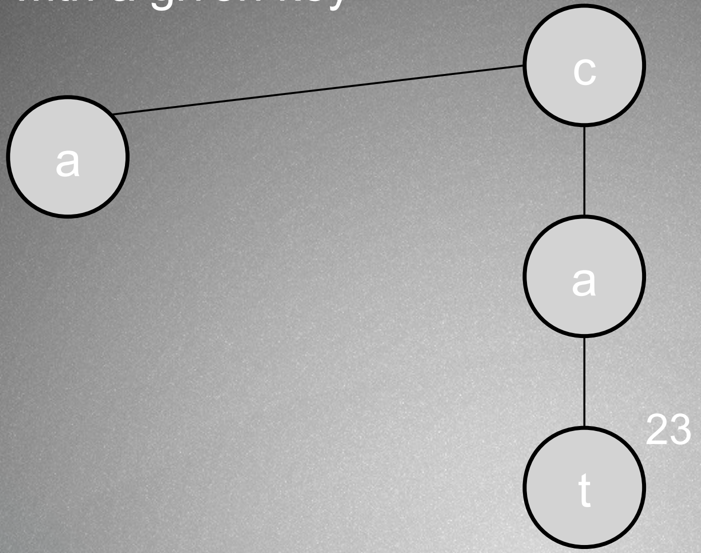


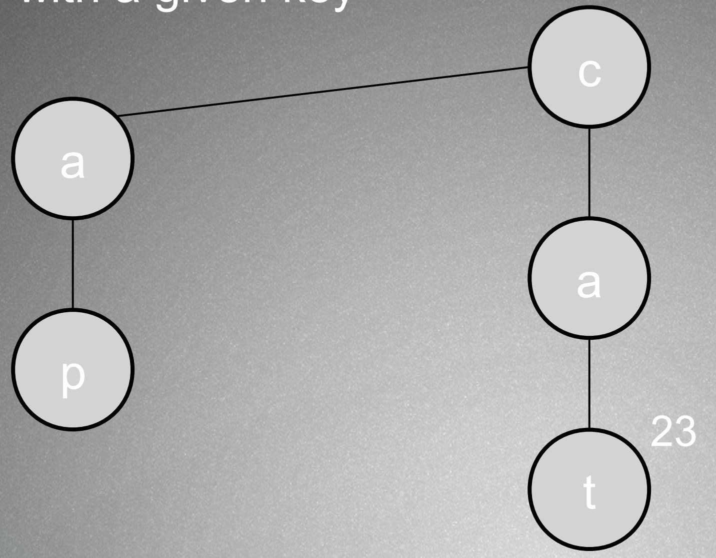
put: with this operation we would like to insert a new element to the ternary search tree with a given key

put(„apple”,46)



put: with this operation we would like to insert a new element to the ternary search tree with a given key

put(„apple”,46)



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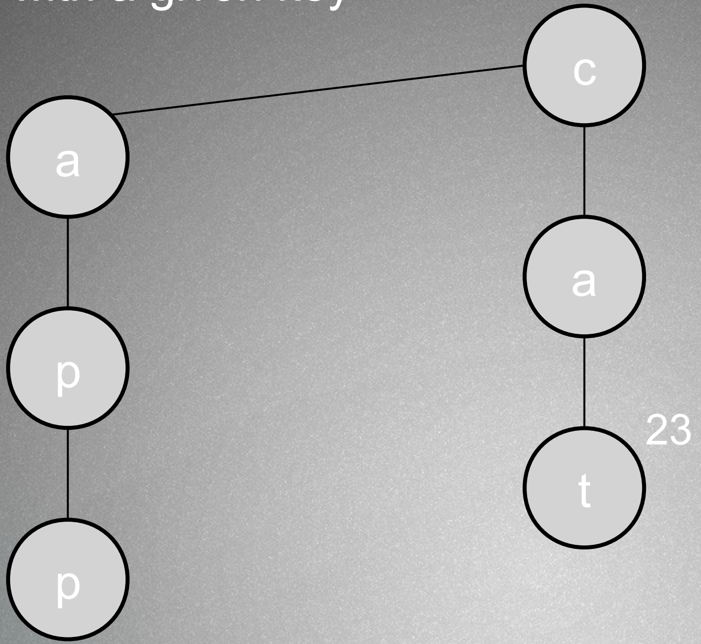
put(„apple”,46)



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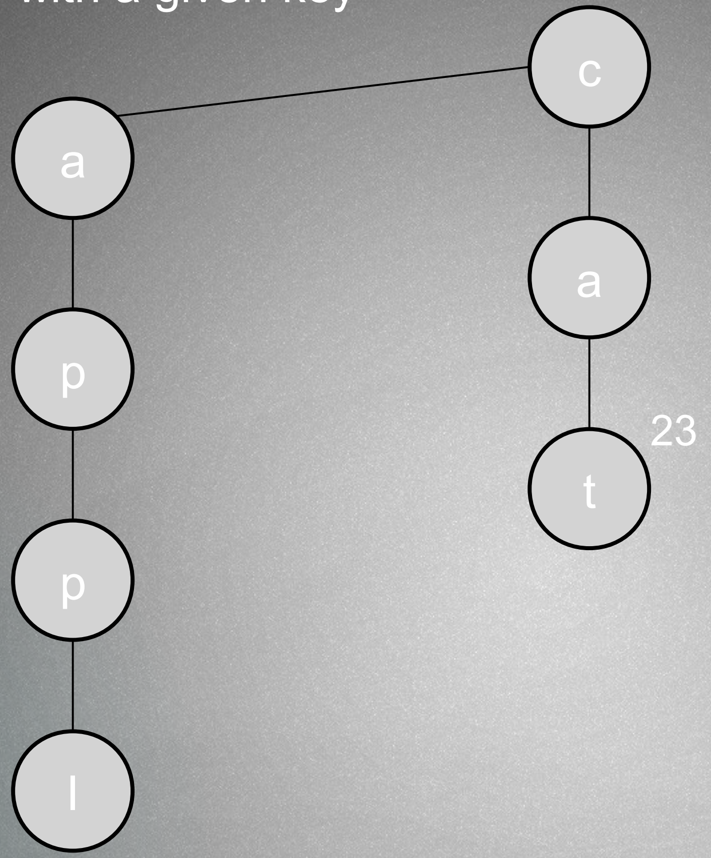
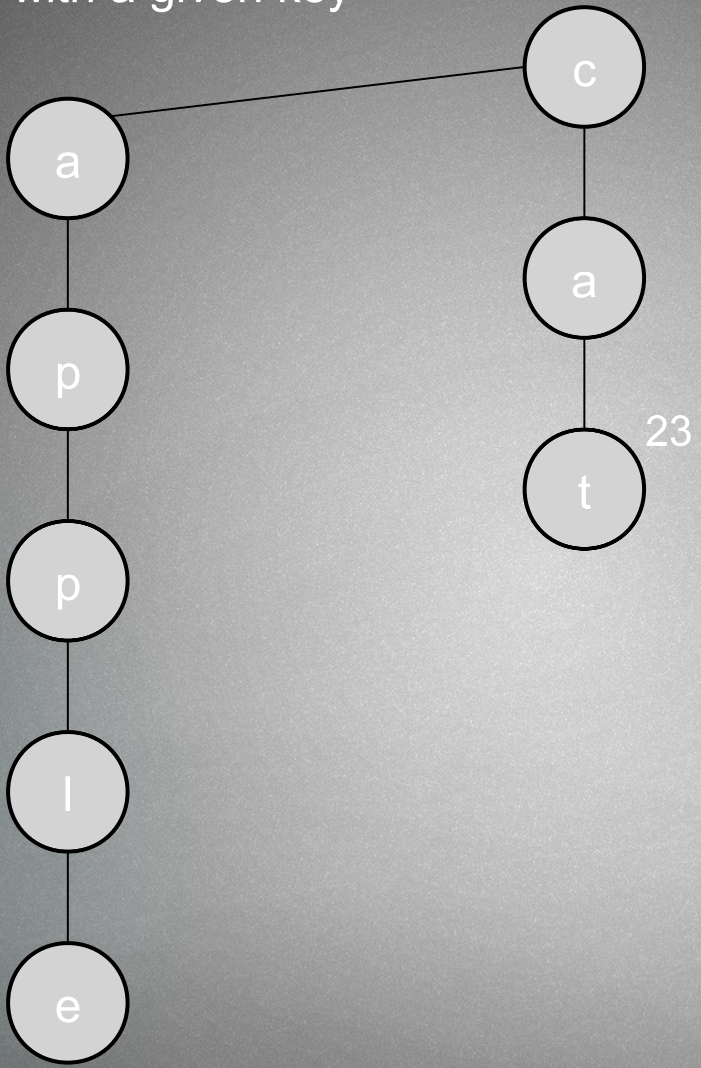
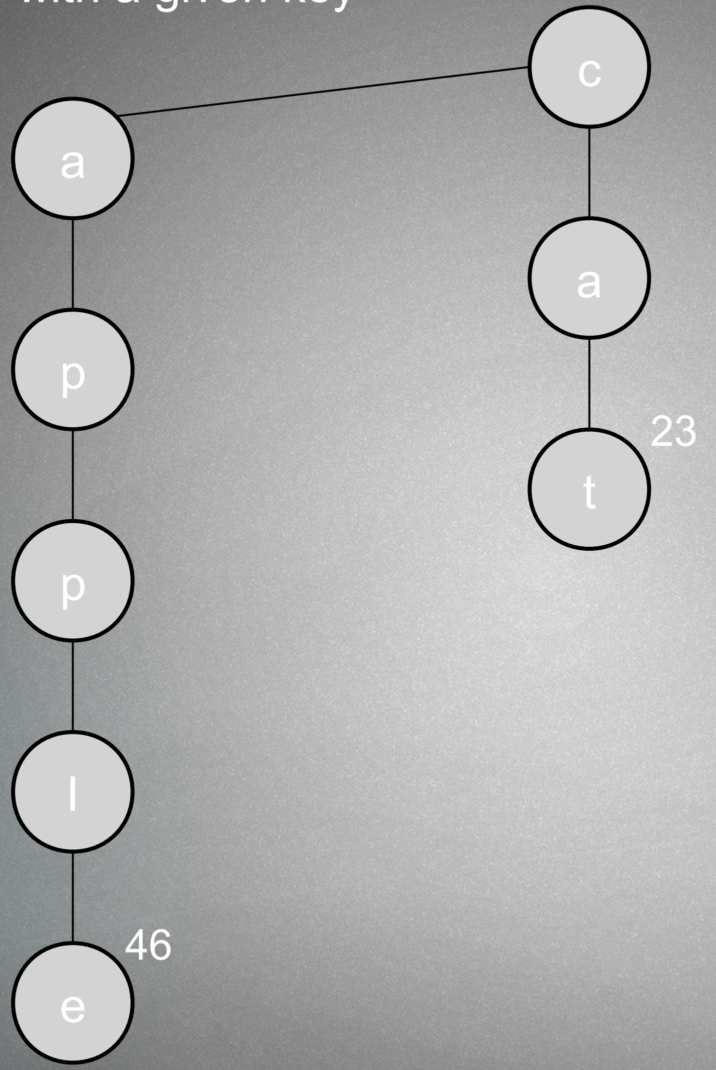


put: with this operation we would like to insert a new element to the ternary search tree with a given key

put(„apple”,46)

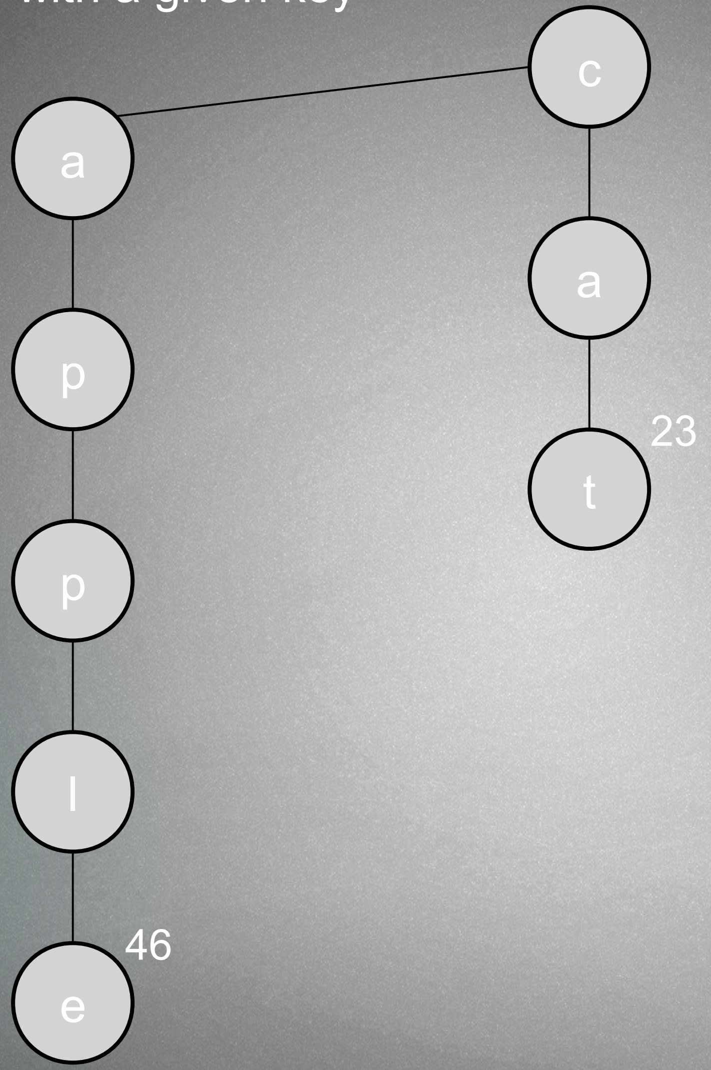


put: with this operation we would like to insert a new element to the ternary search tree with a given key



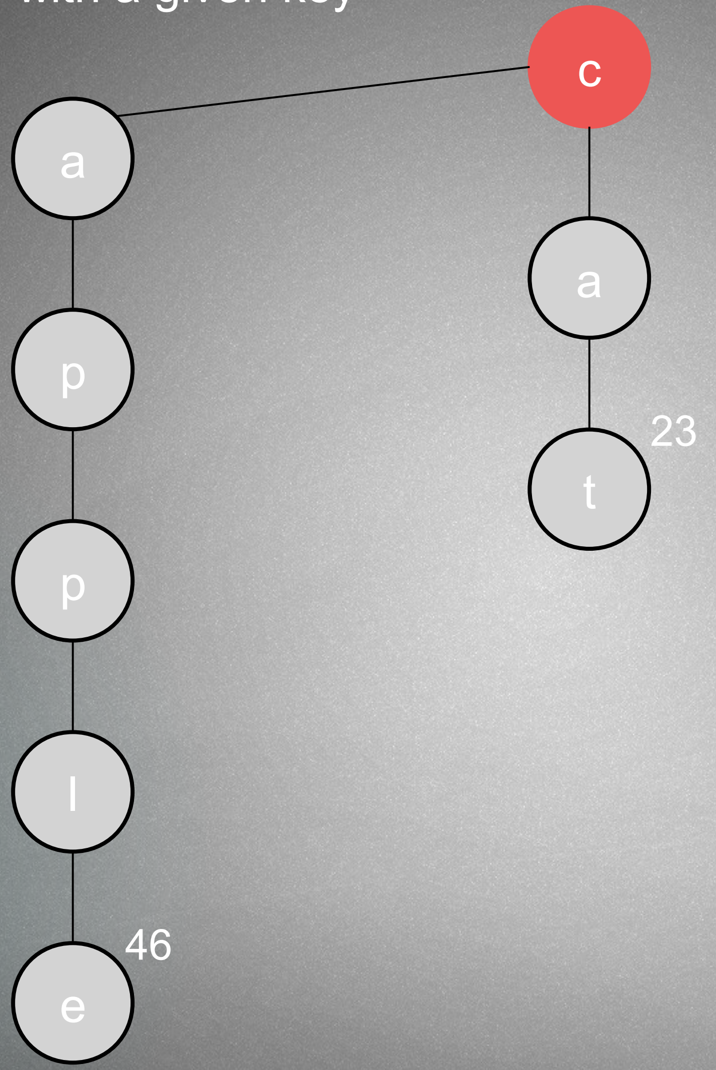
put: with this operation we would like to insert a new element to the ternary search tree with a given key

put(„car”,6)



put: with this operation we would like to insert a new element to the ternary search tree with a given key

put(„**car**”,6)



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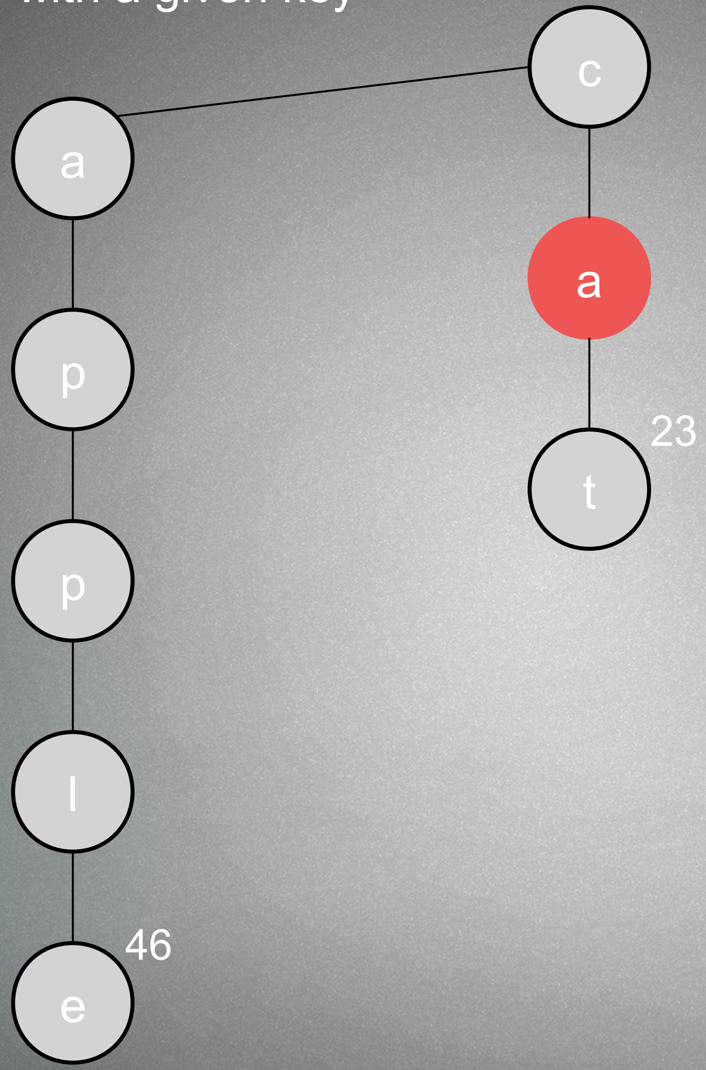

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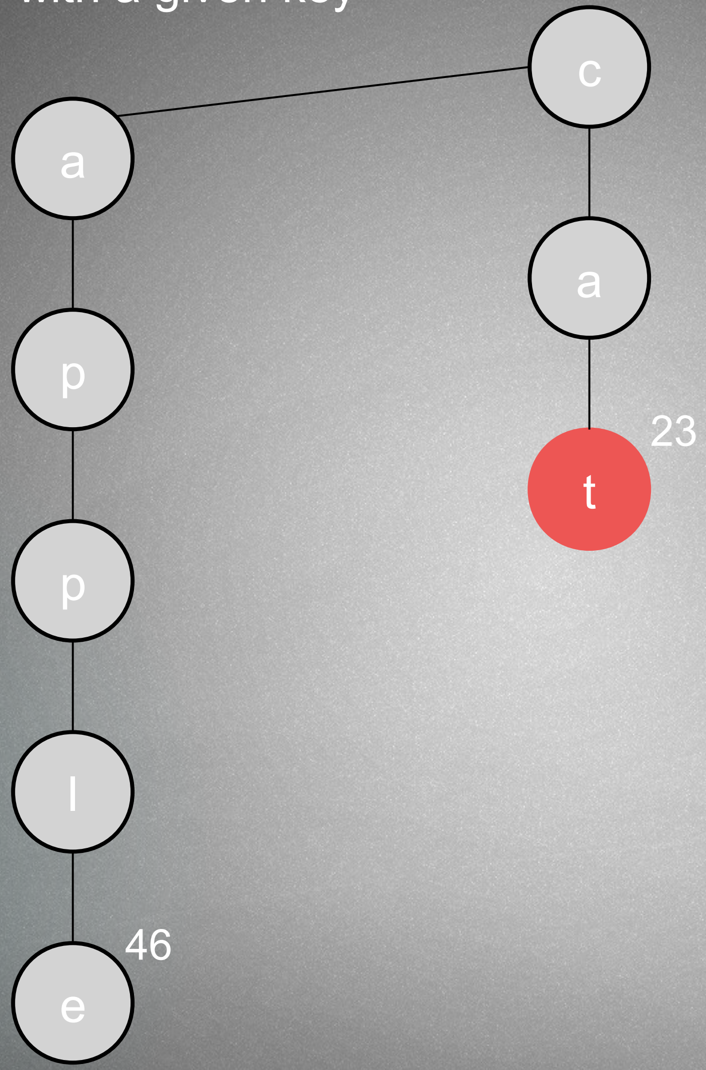

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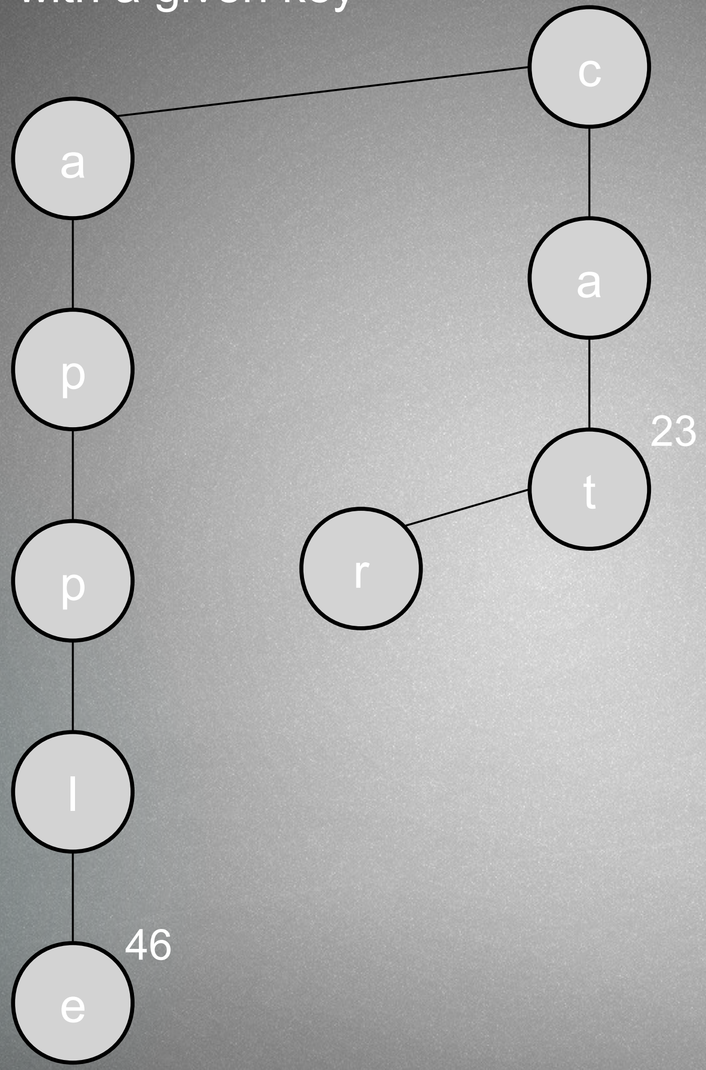

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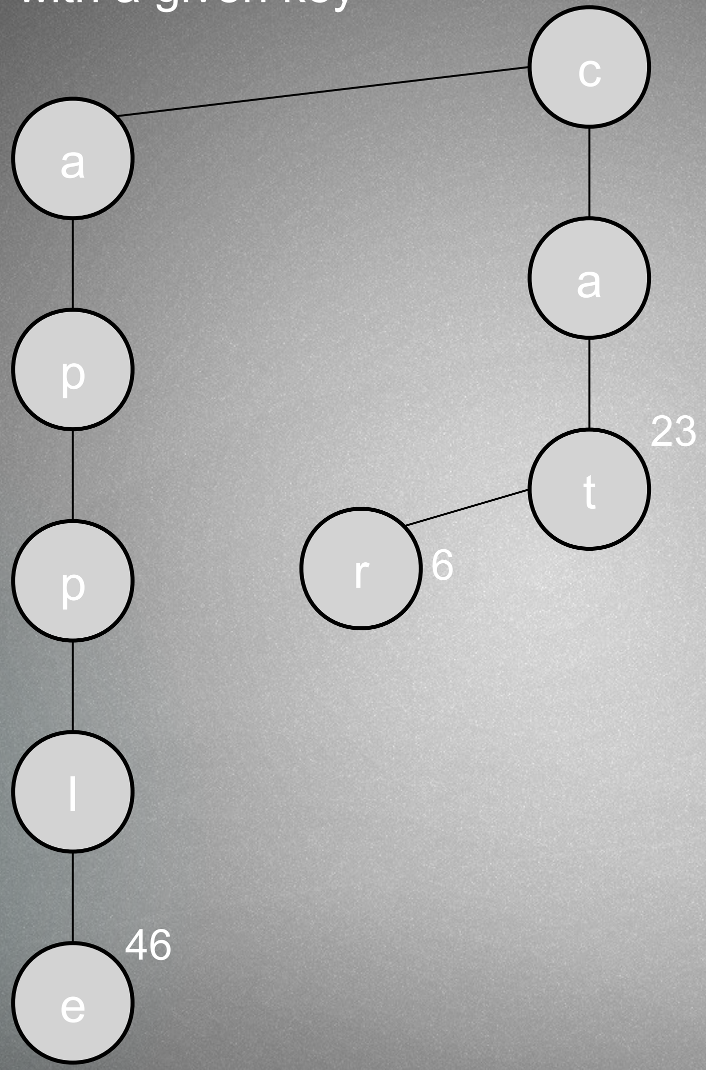

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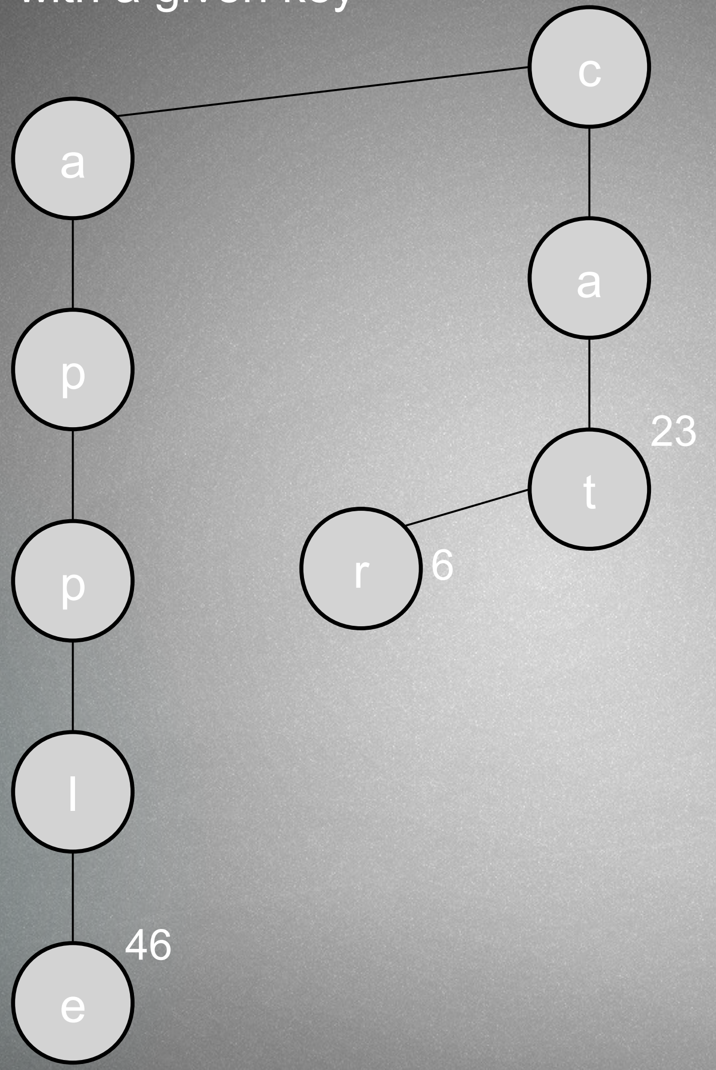
put(„carrot”,68)



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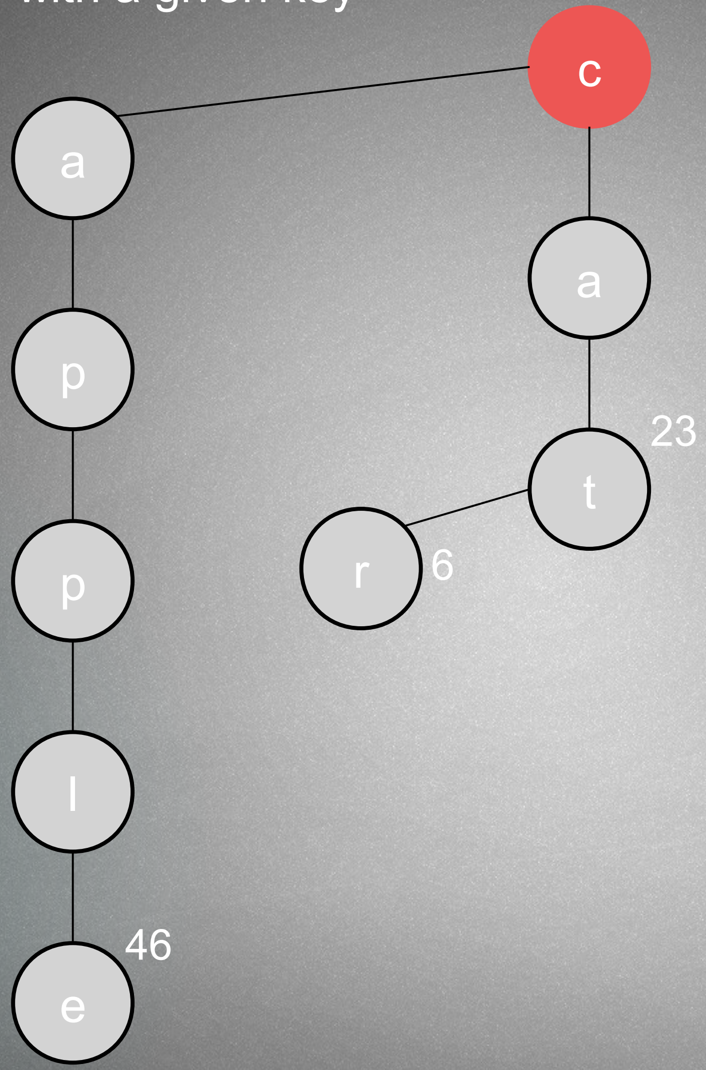
put(„**c**arrot”,68)



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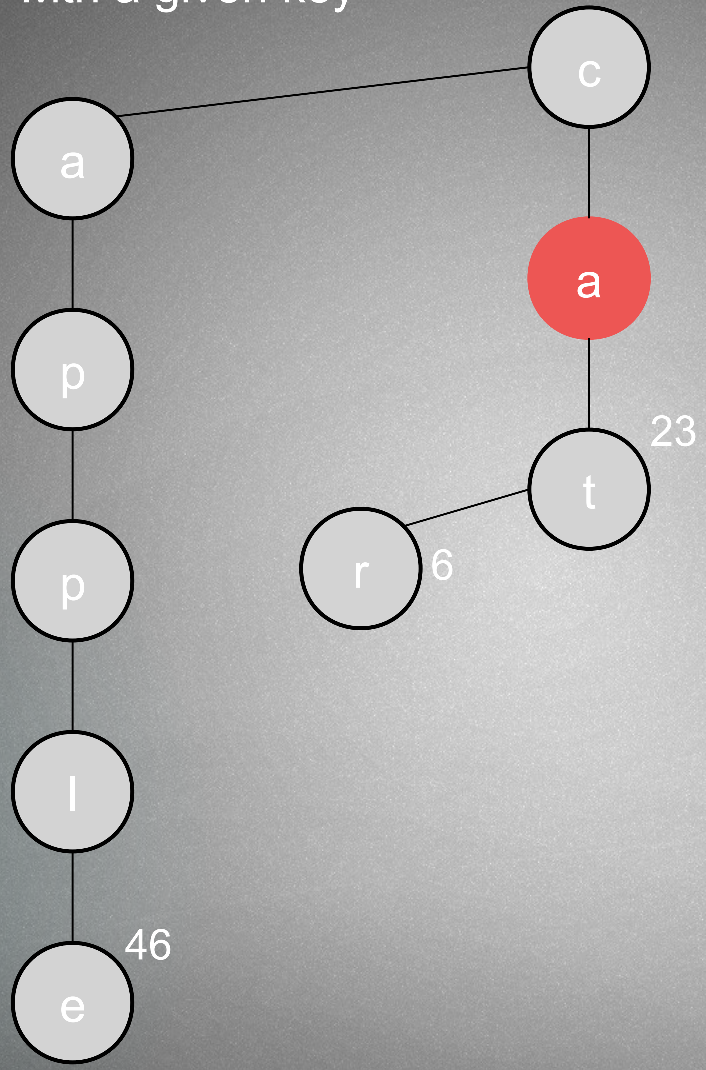

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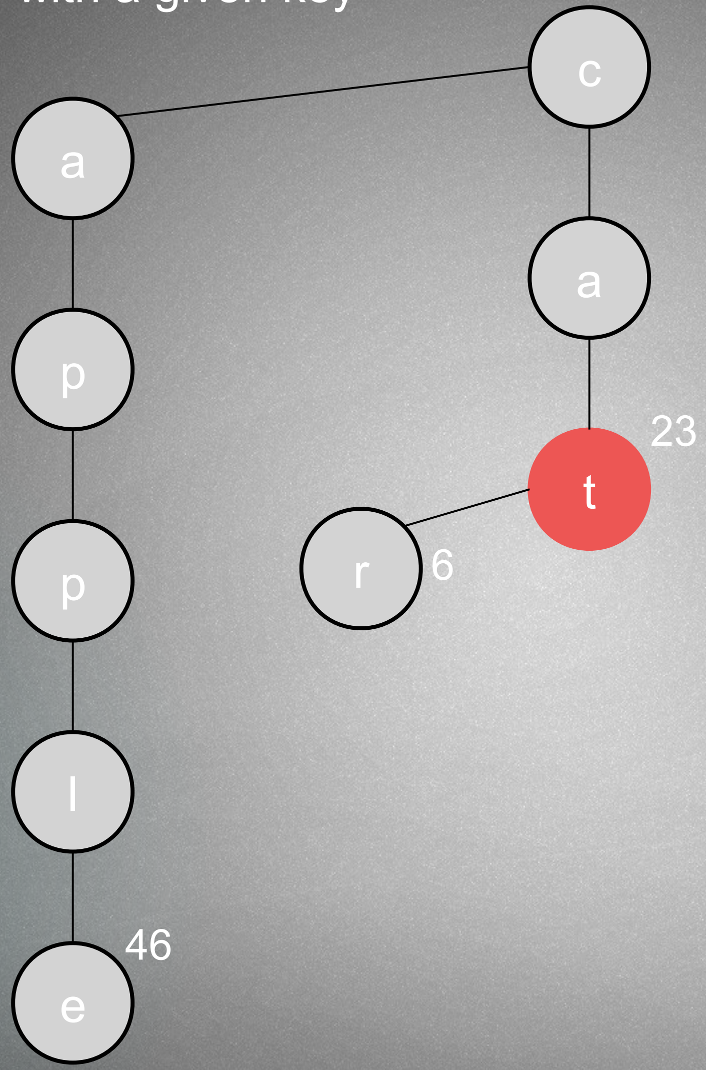

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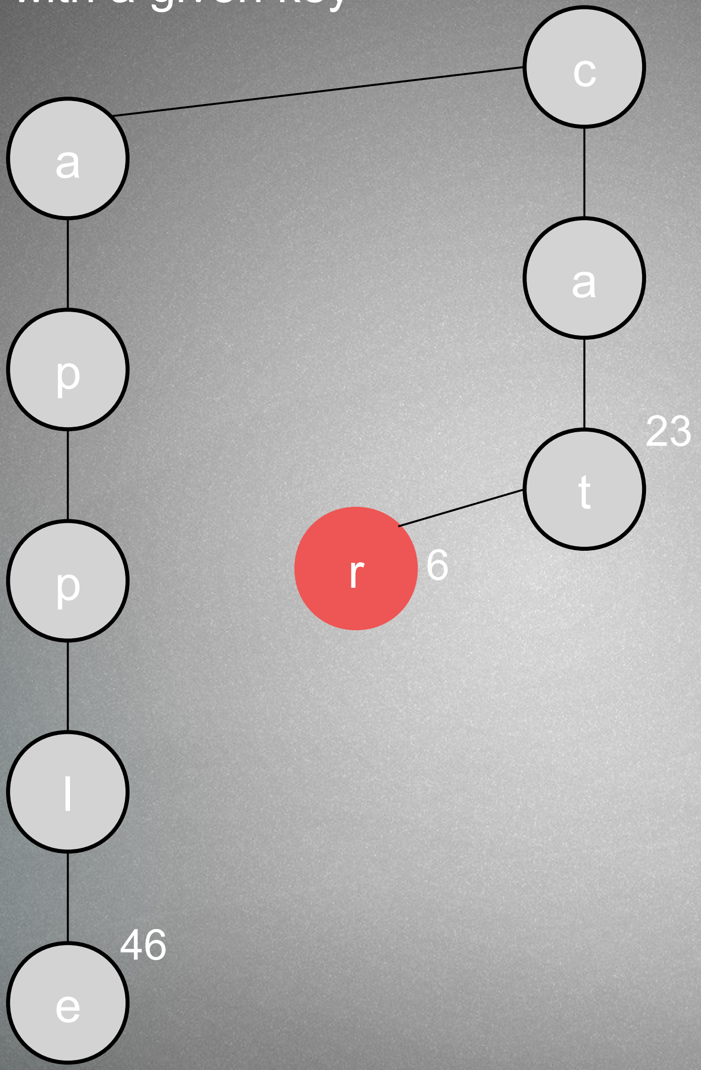

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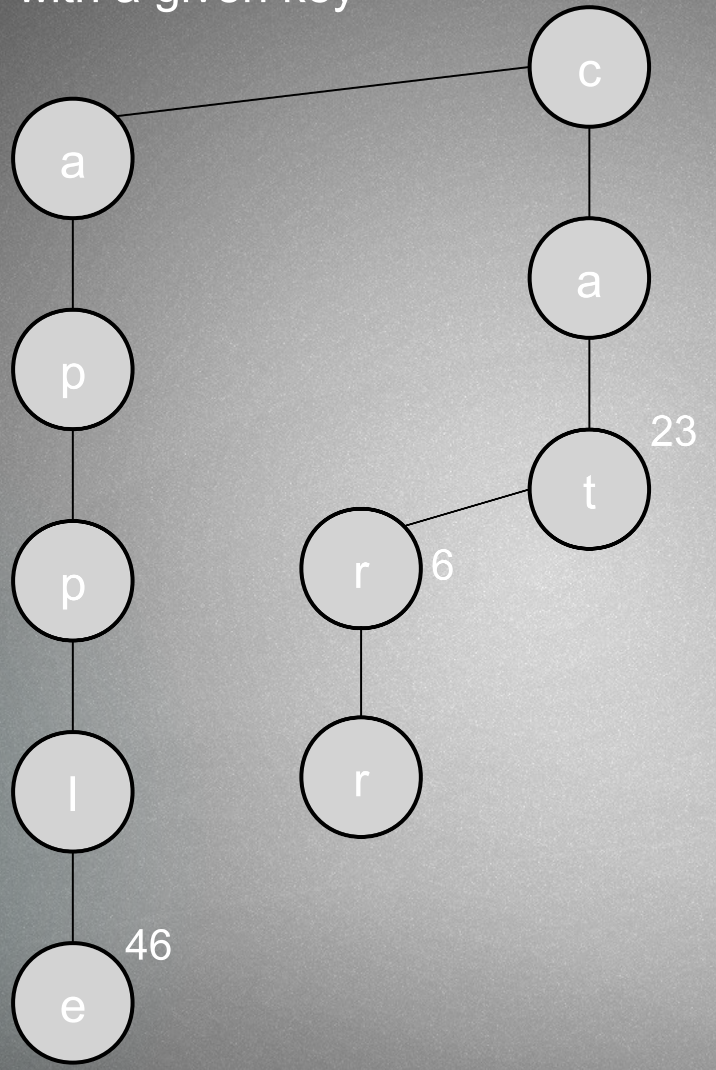

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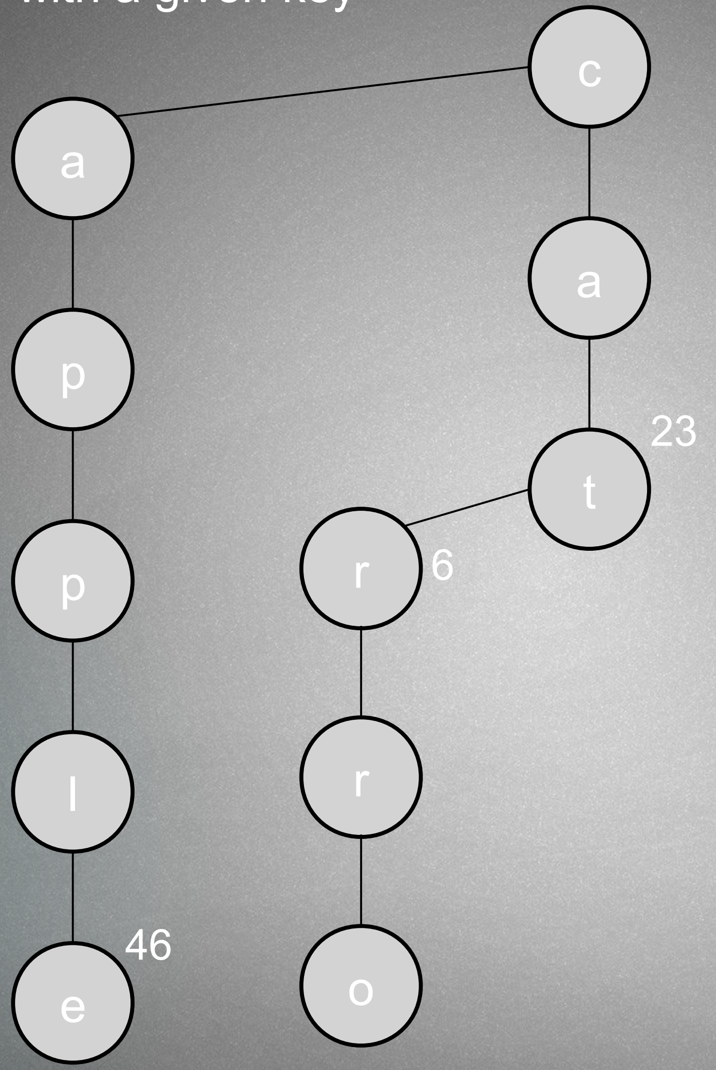

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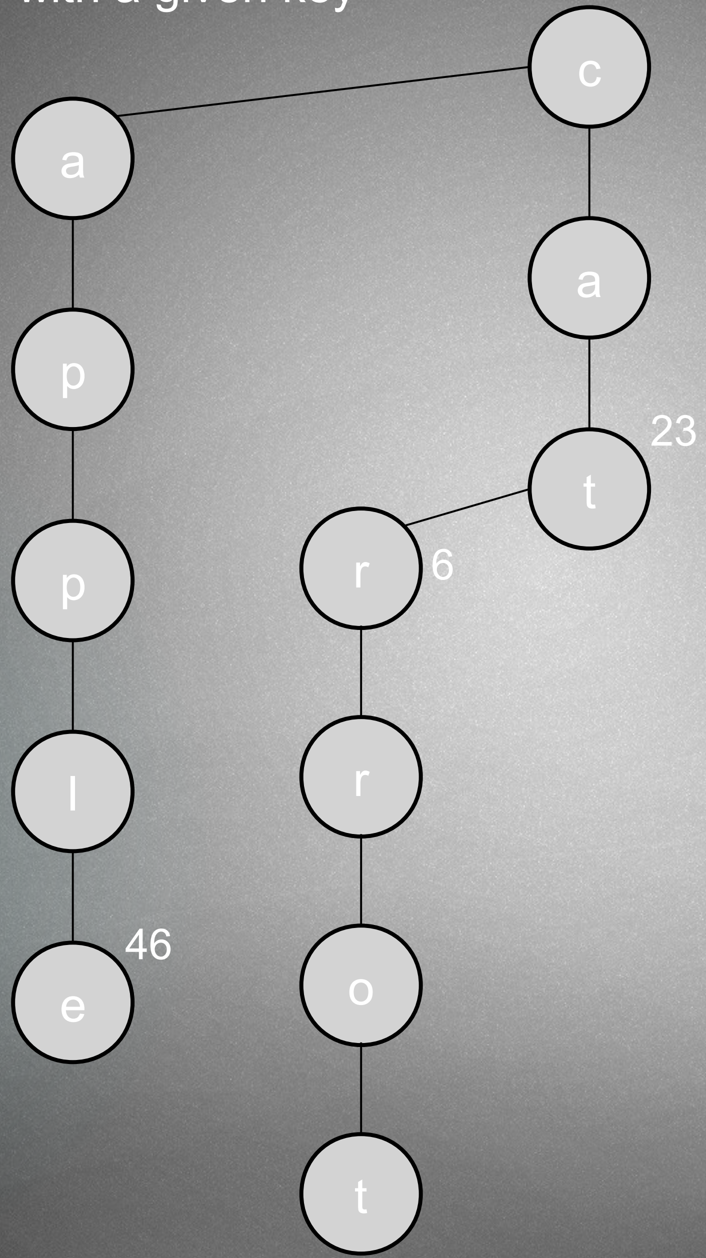

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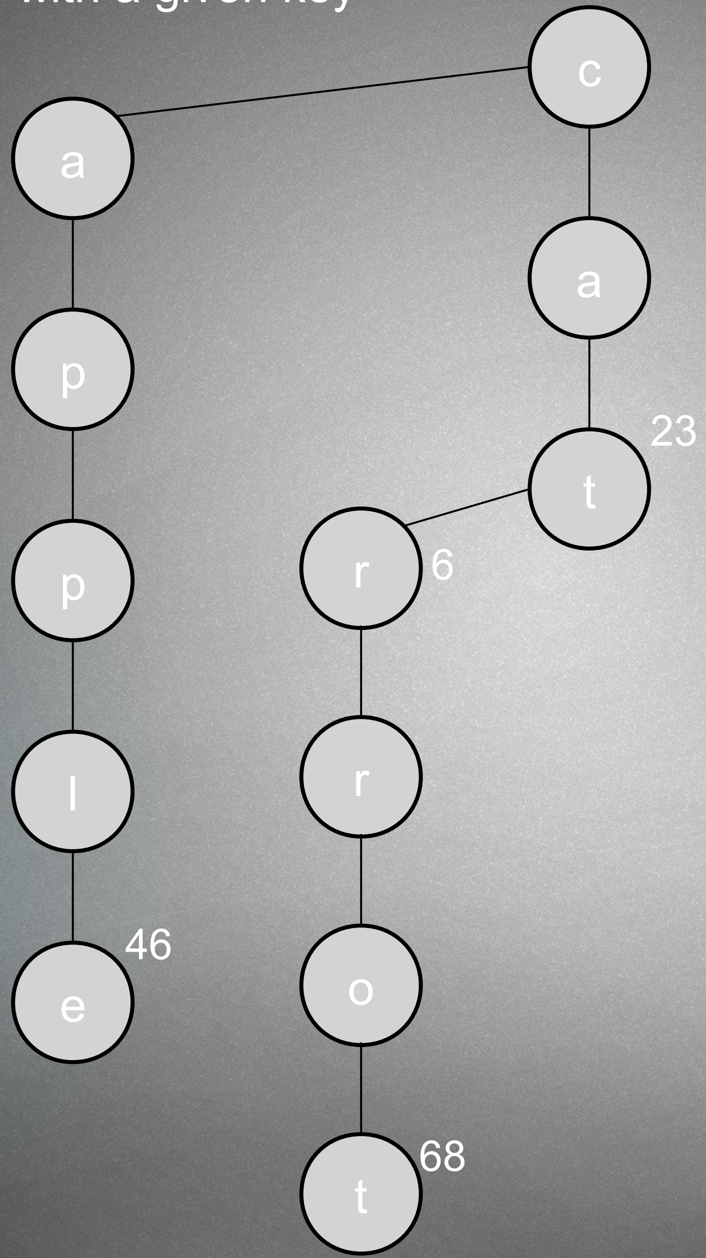
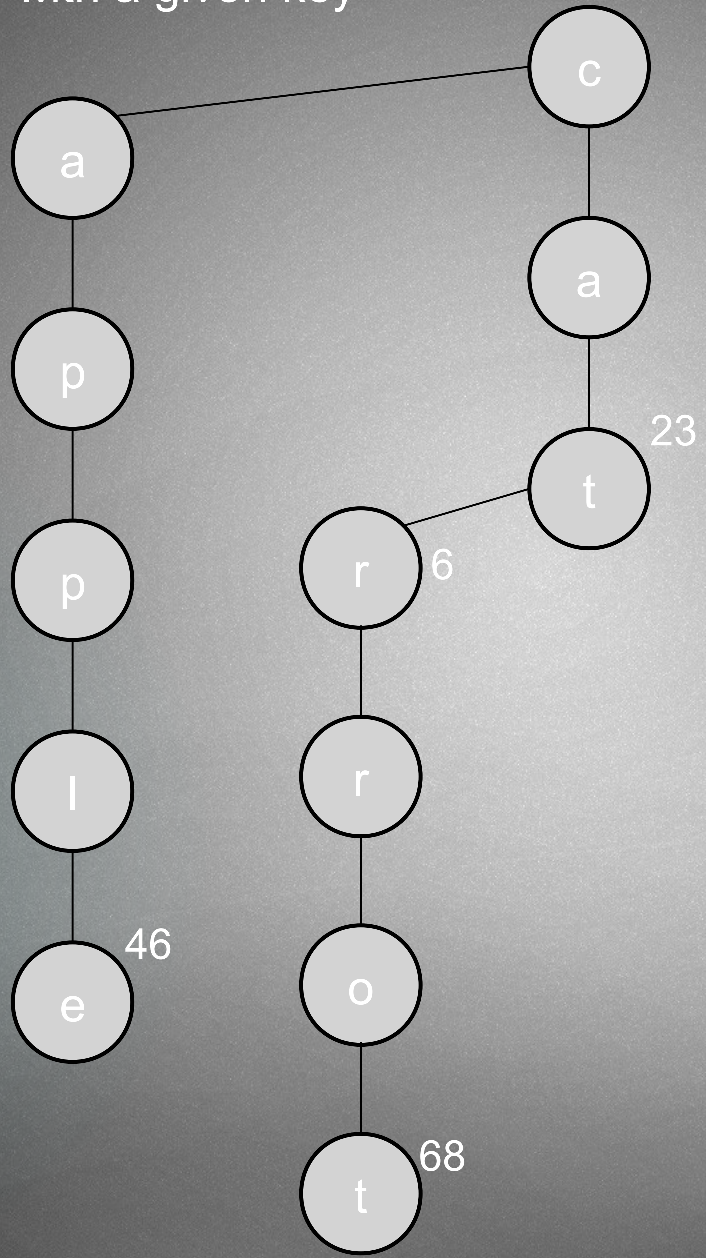


put: with this operation we would like to insert a new element to the ternary search tree with a given key

put(„cow”,112)



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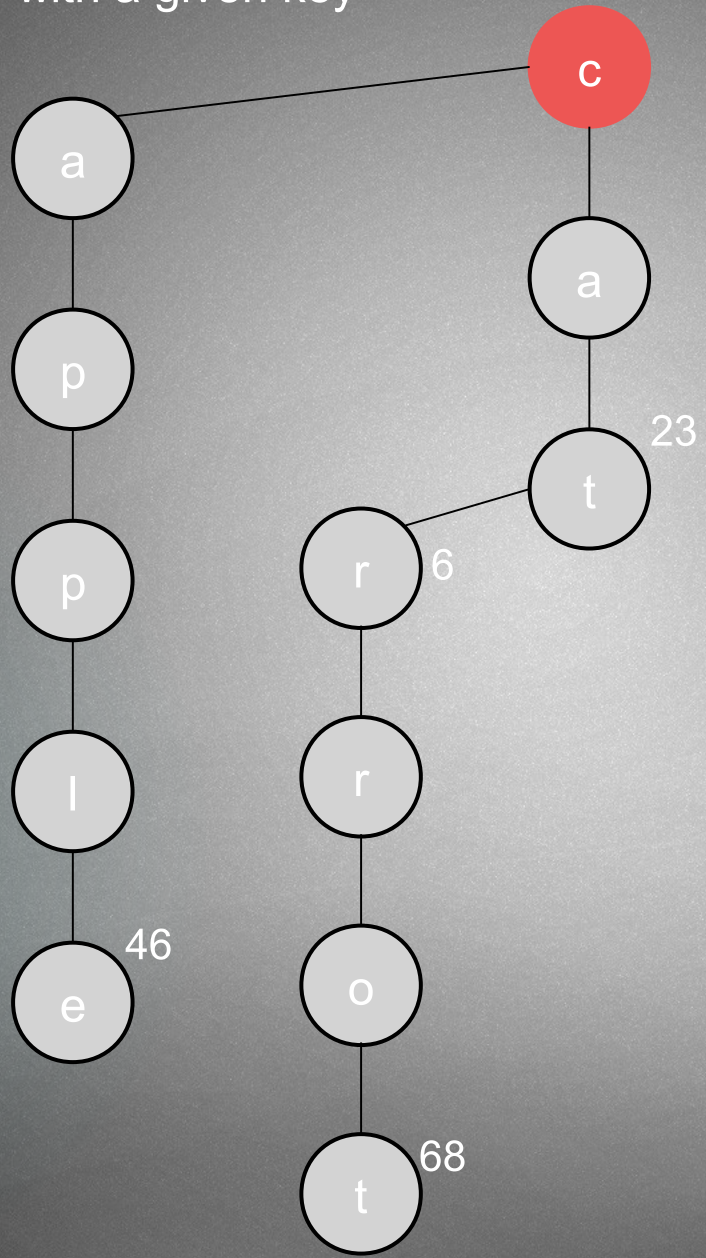

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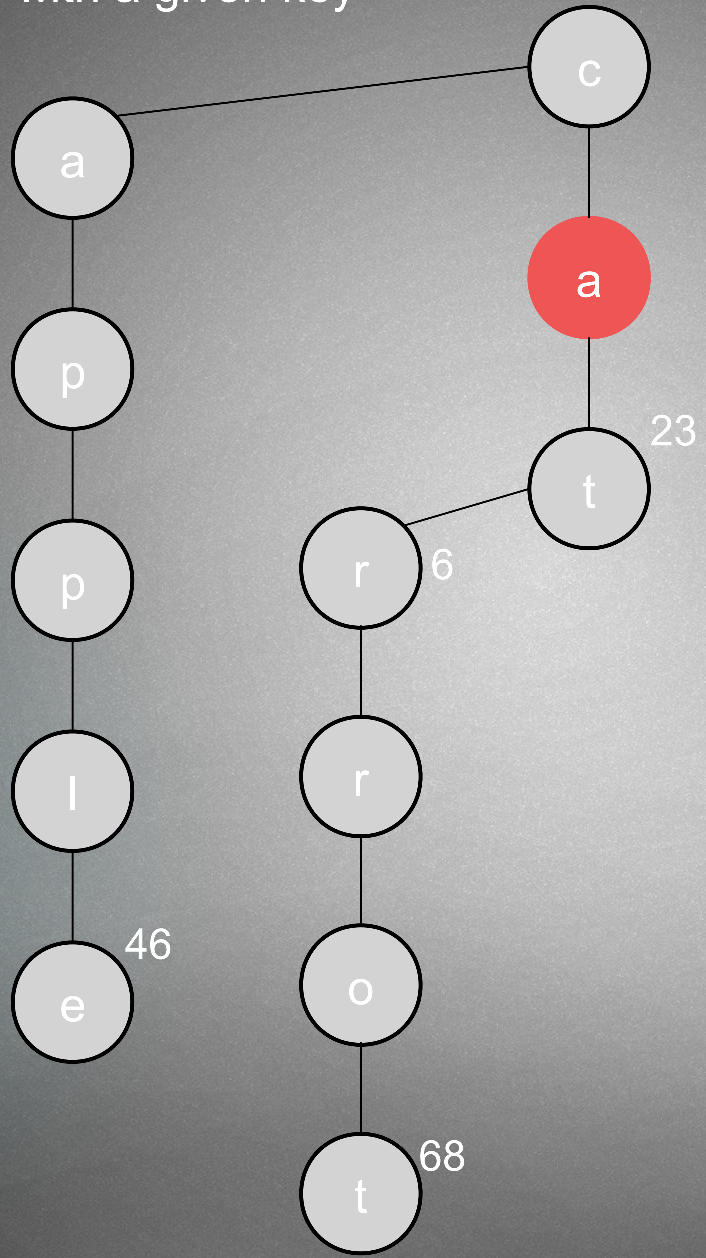
put(„c**o**w”,112)



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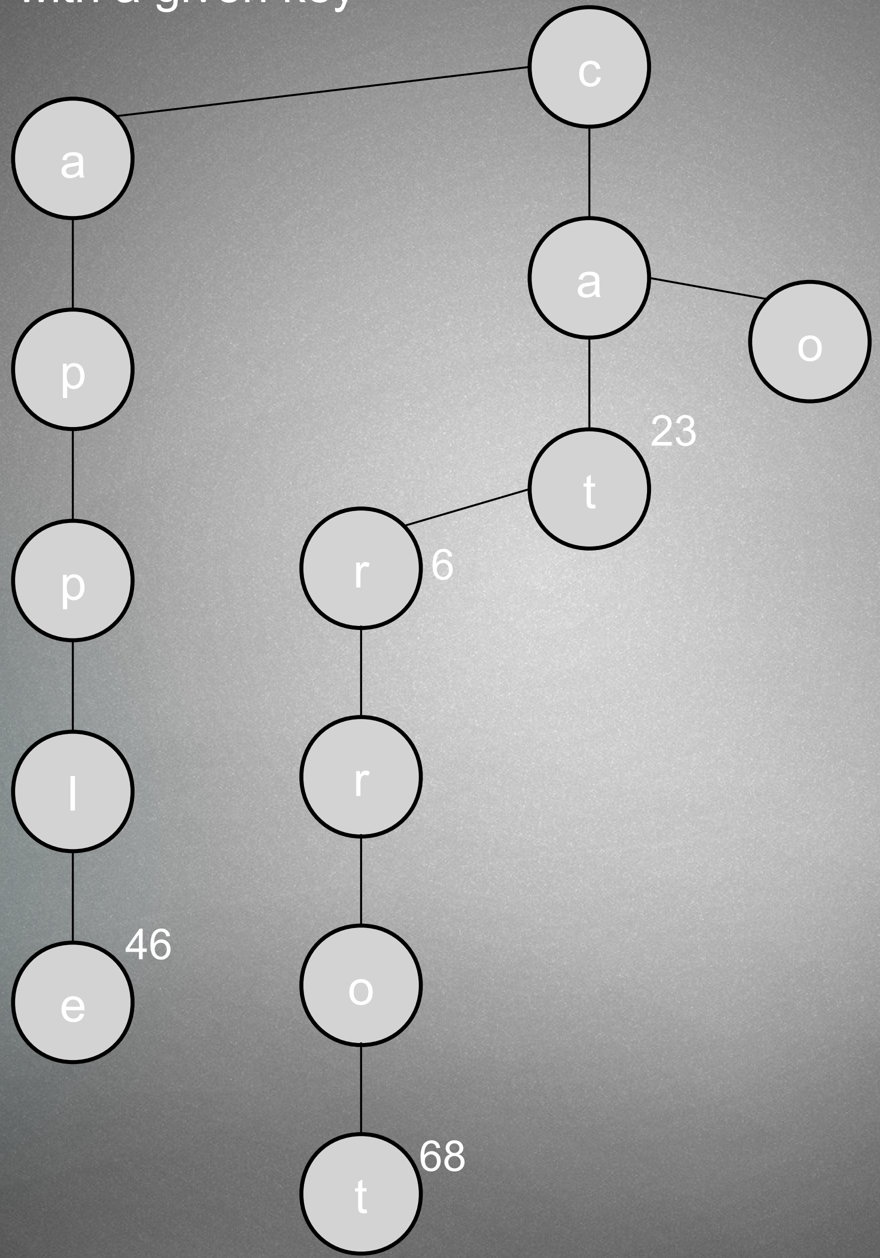

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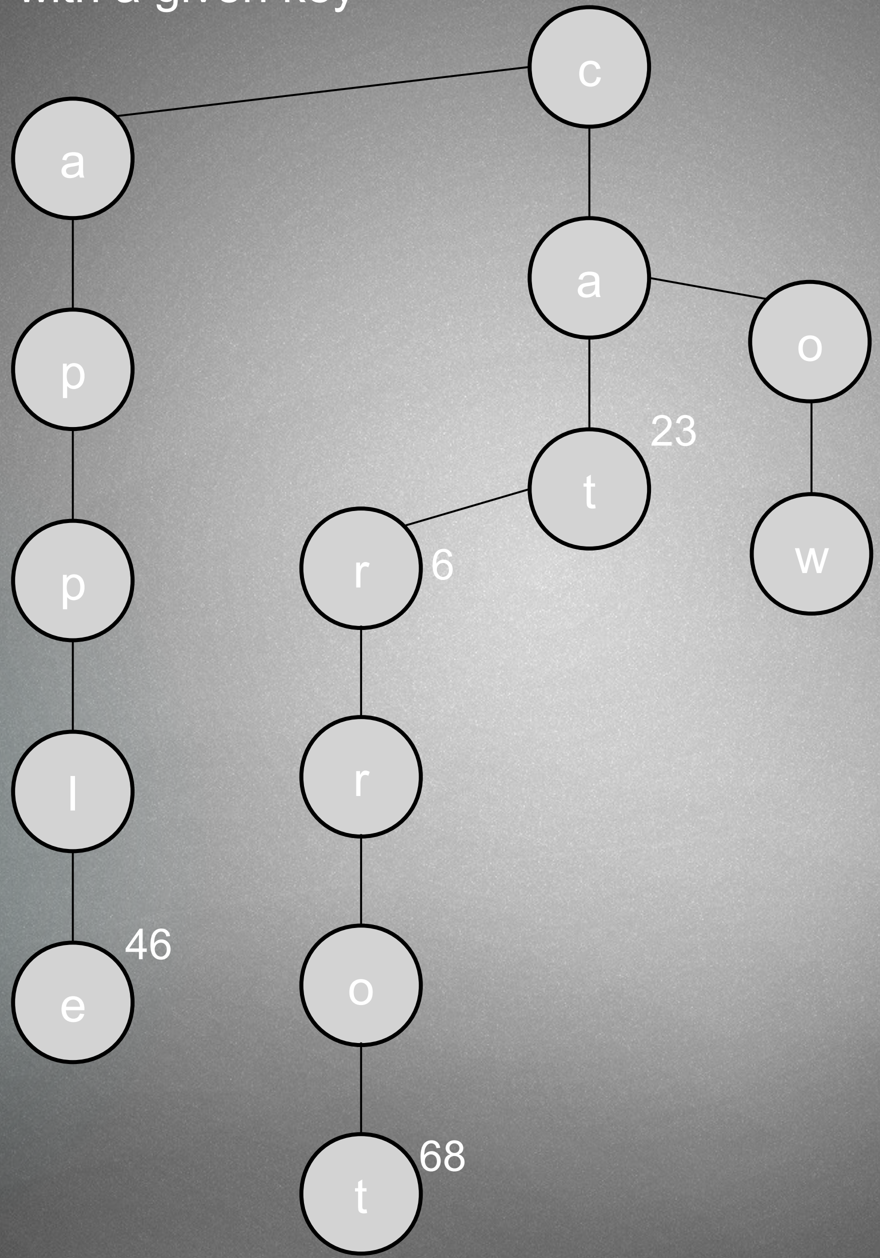

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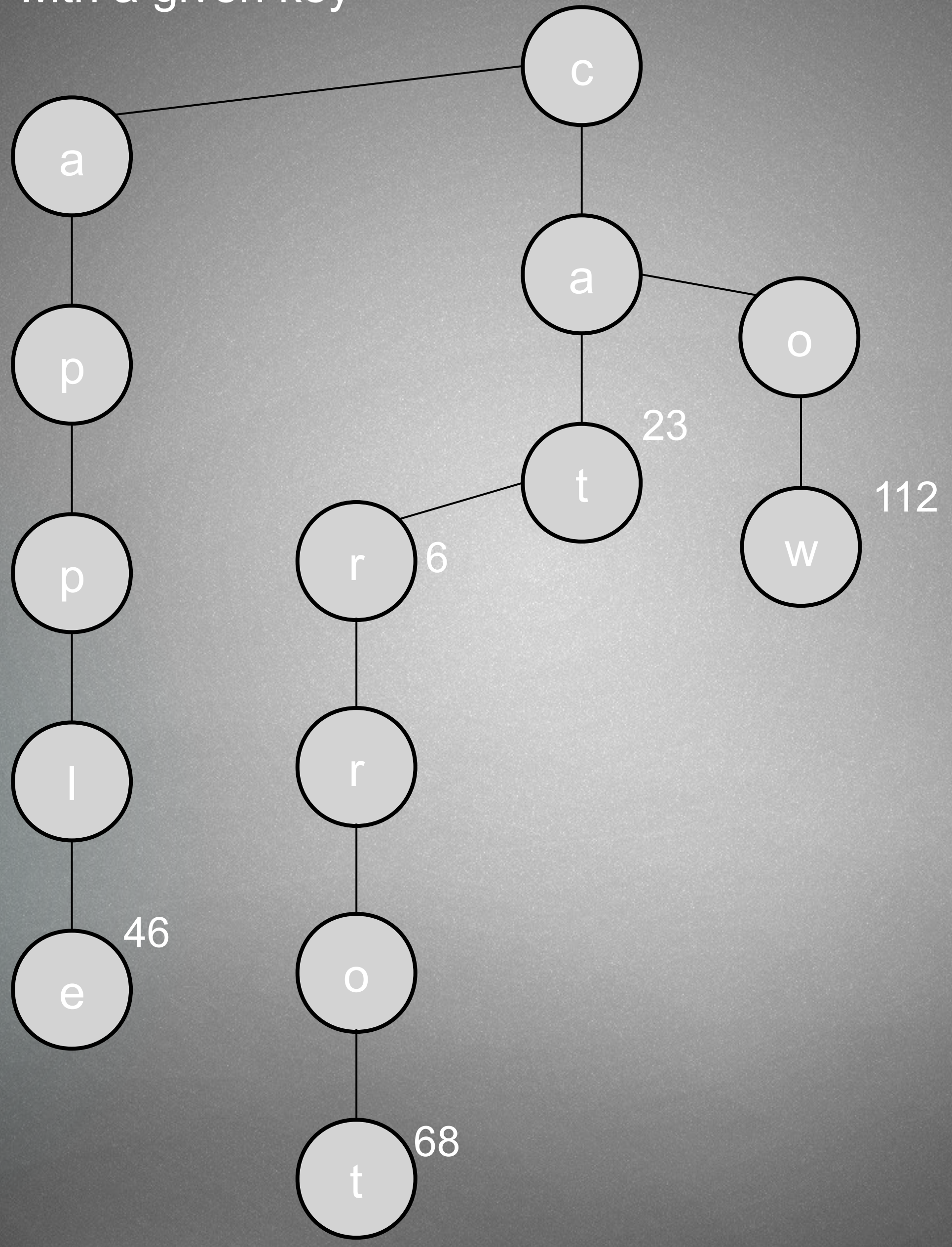


get: with this operation we would like to get an item from the ternary search tree with a given key

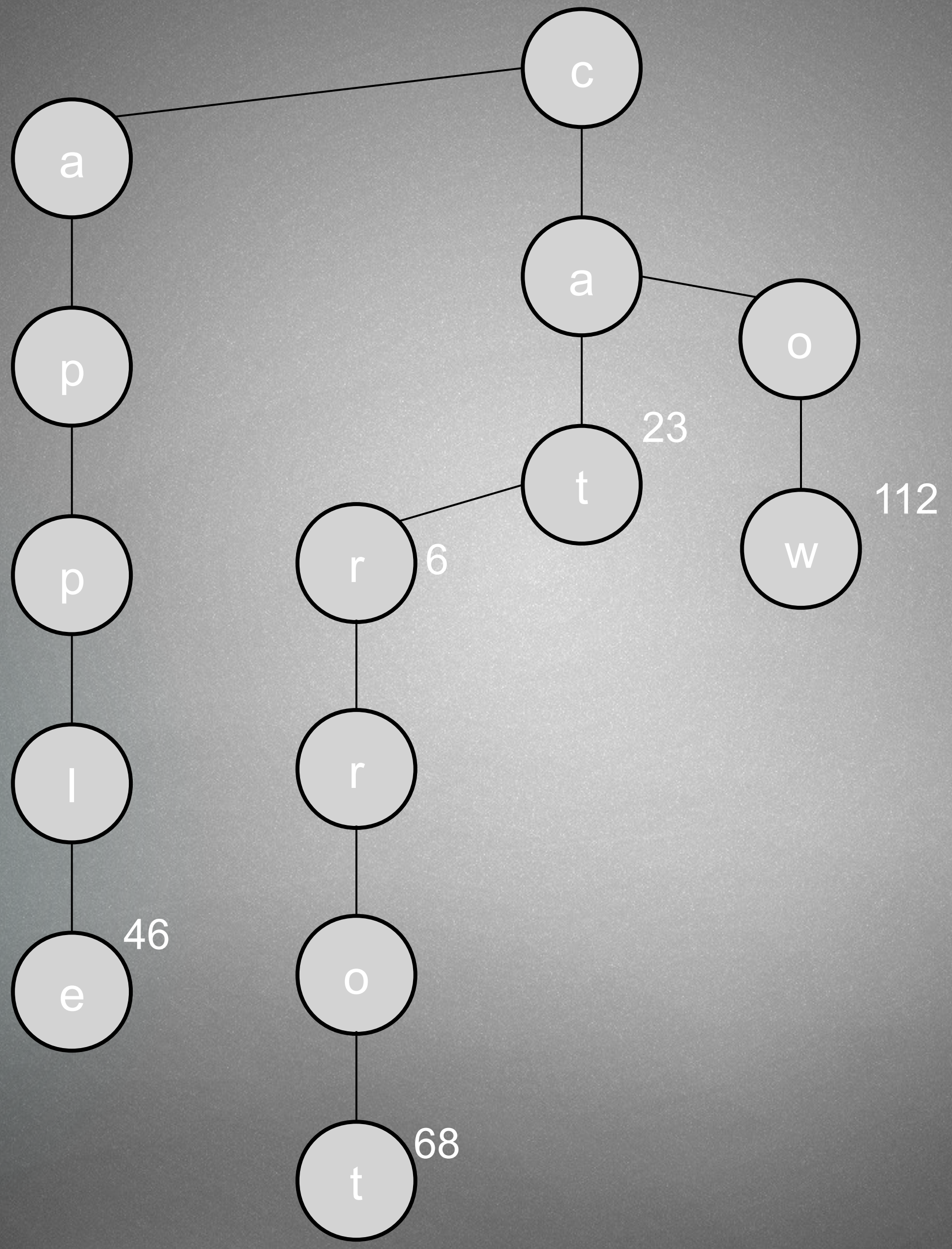
IMPORTANT:

- hashmap: we generate an index from the key with the hashfunction.
  We use every single character of the key

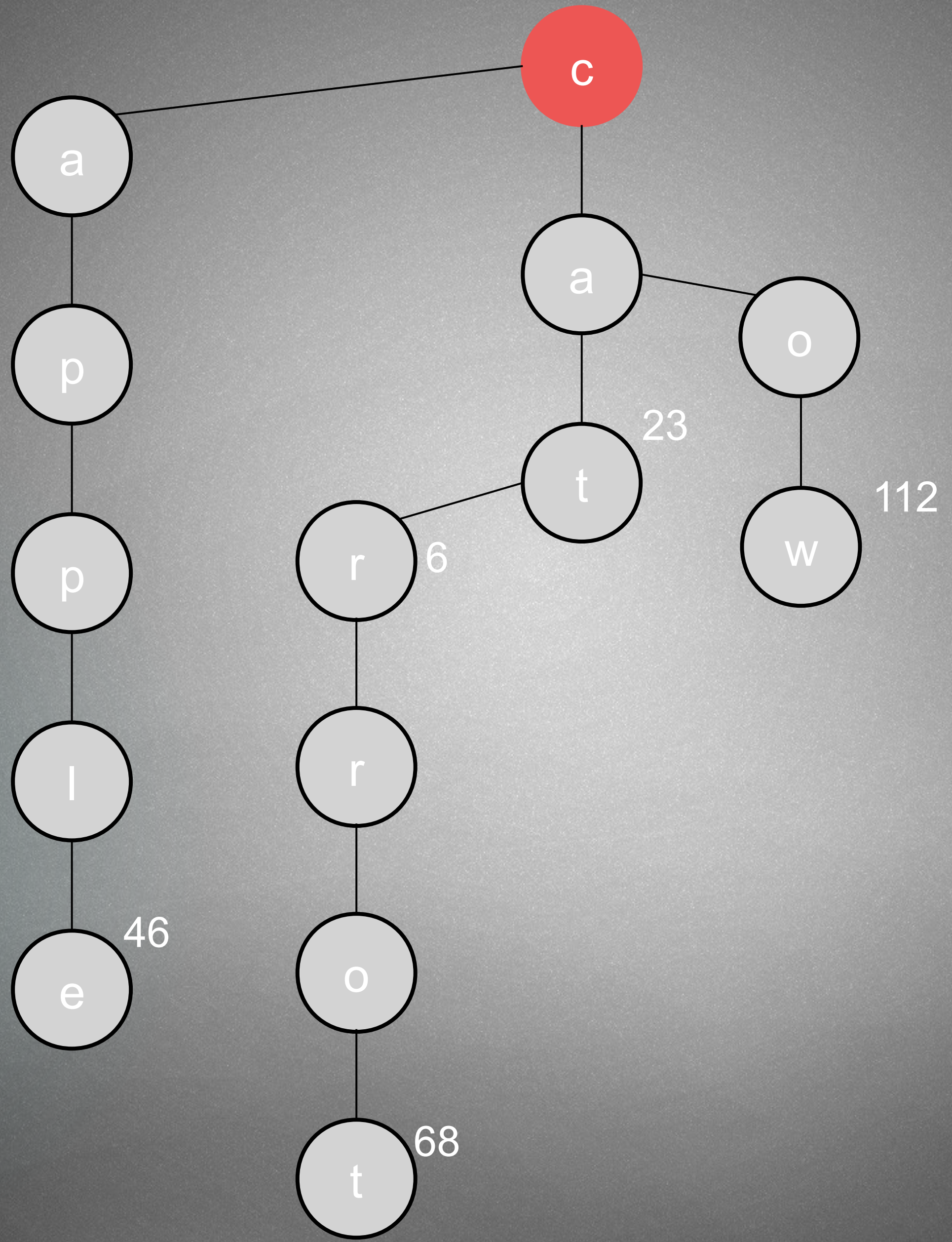
- TST: we may come to the conclusion that there is no value with a given key
  without considering every character
  For example: we may return after the second character

CONCLUSION: for mismatch → TST is faster !!!

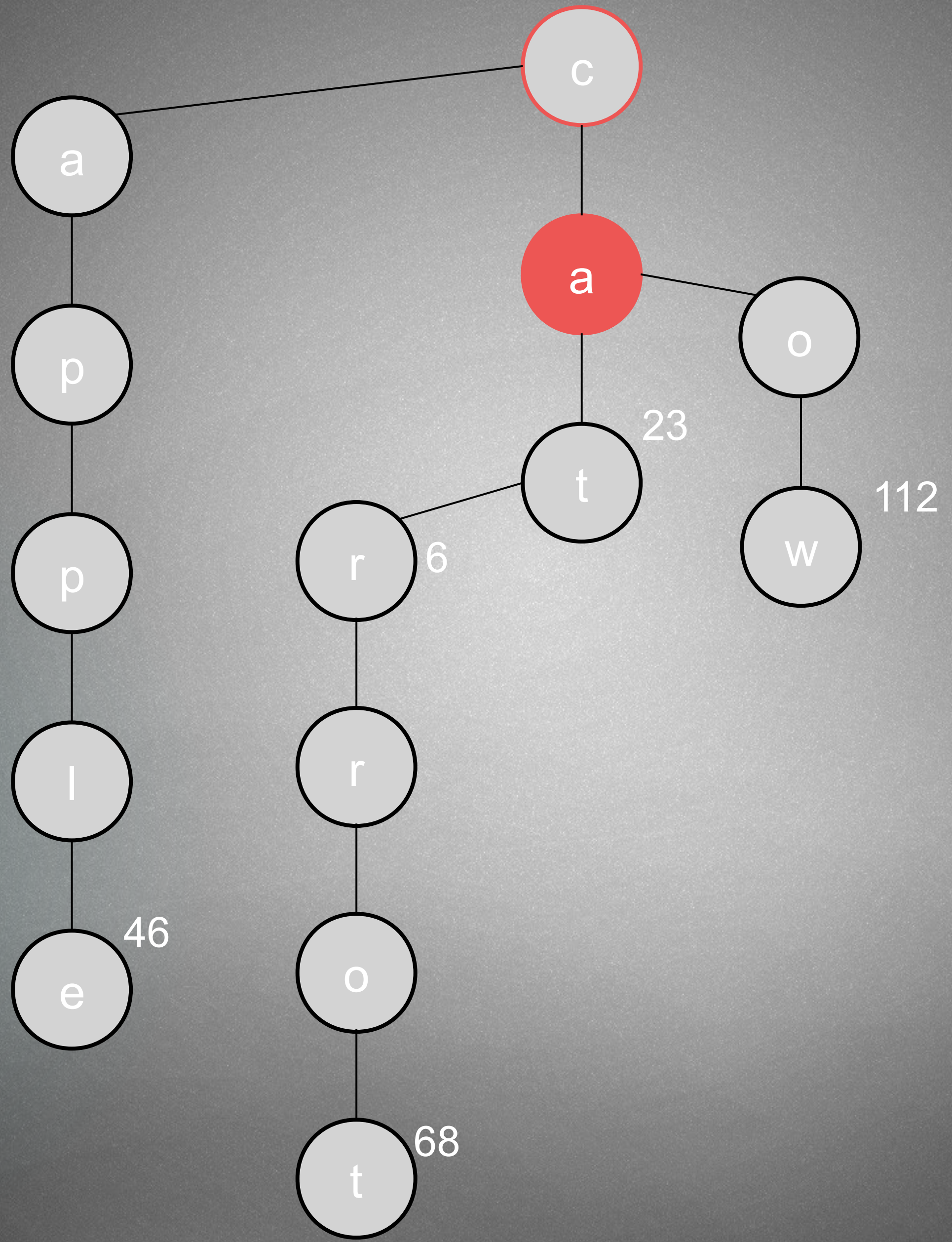
get(„car”)



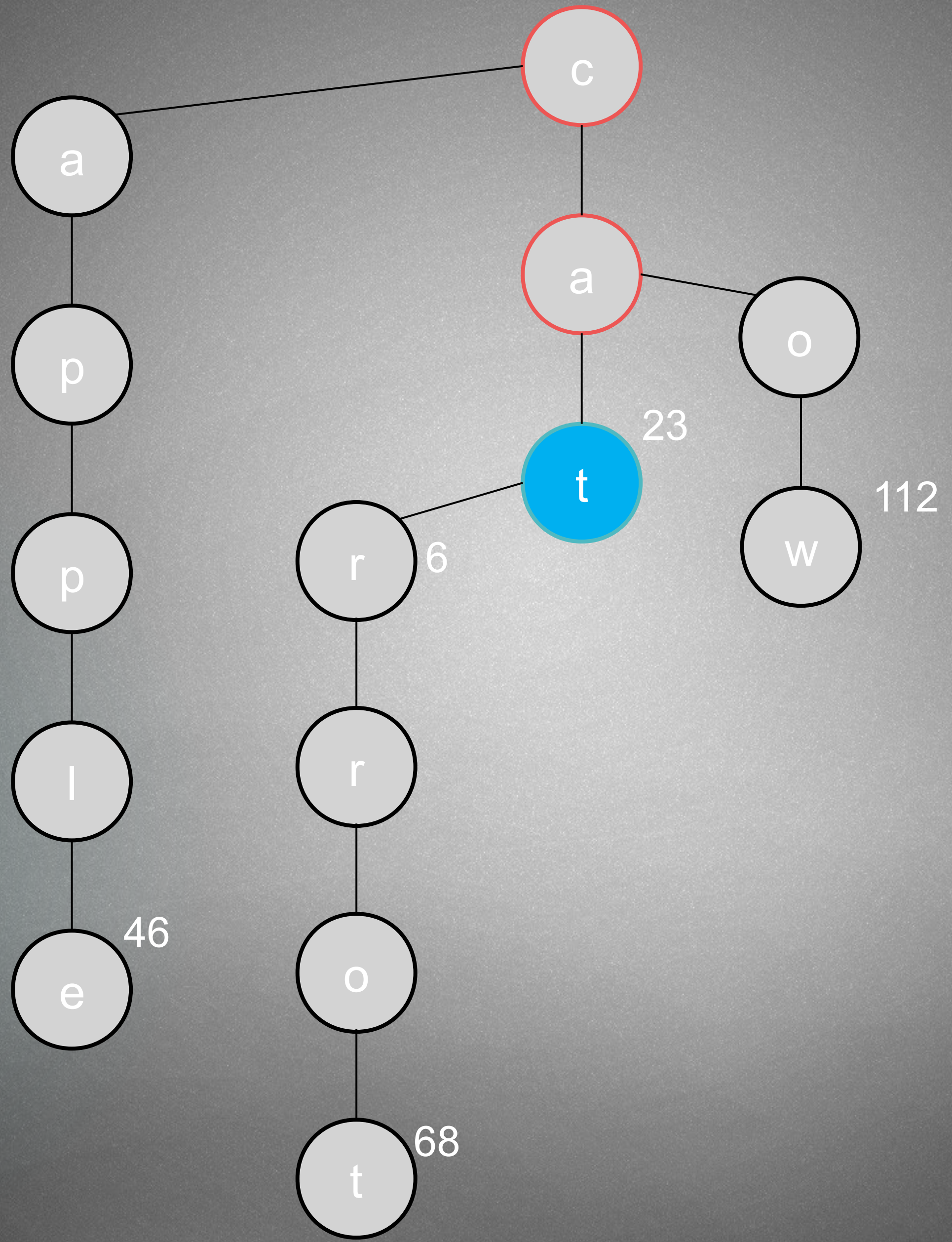
get(„**car**")



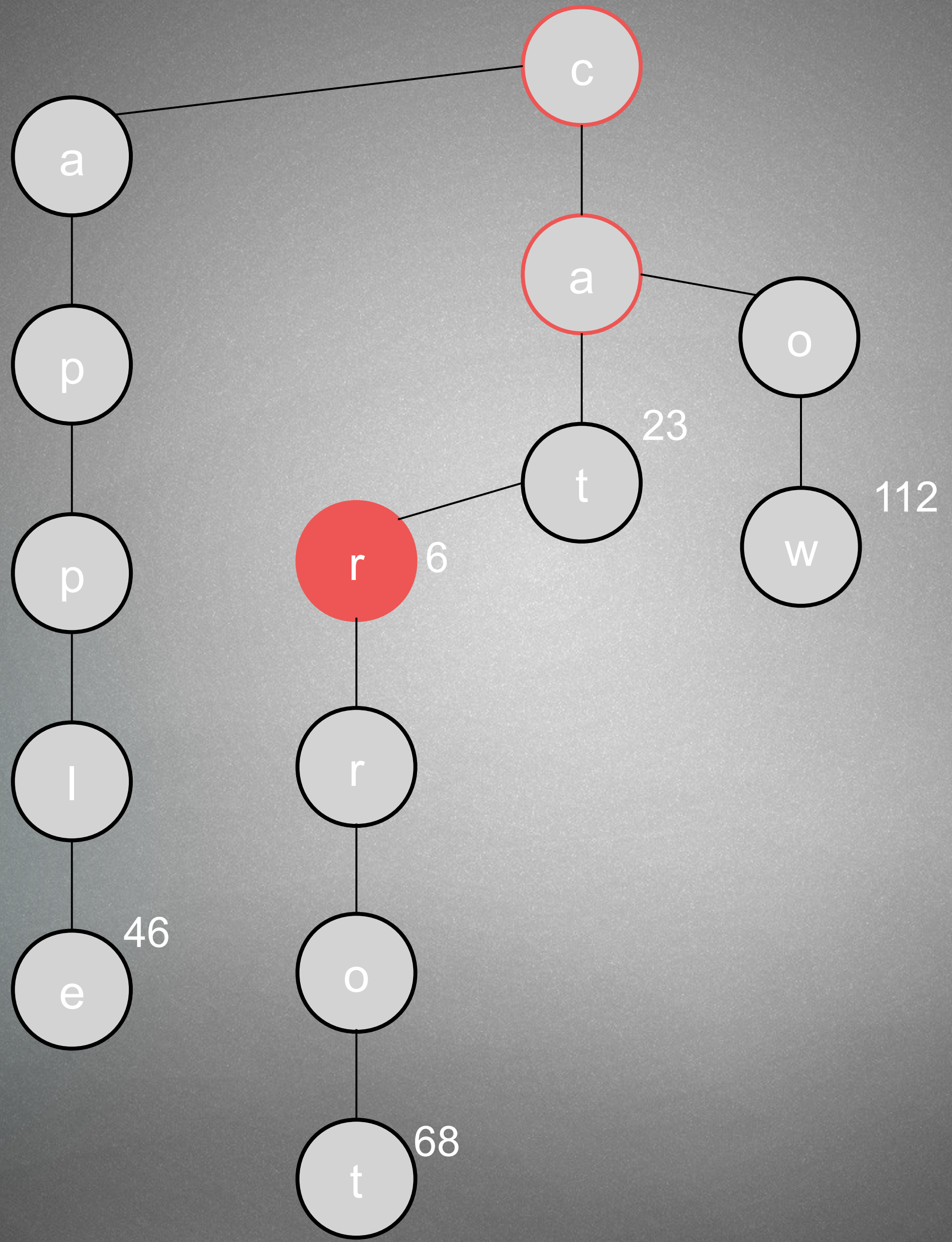
get(„car”)



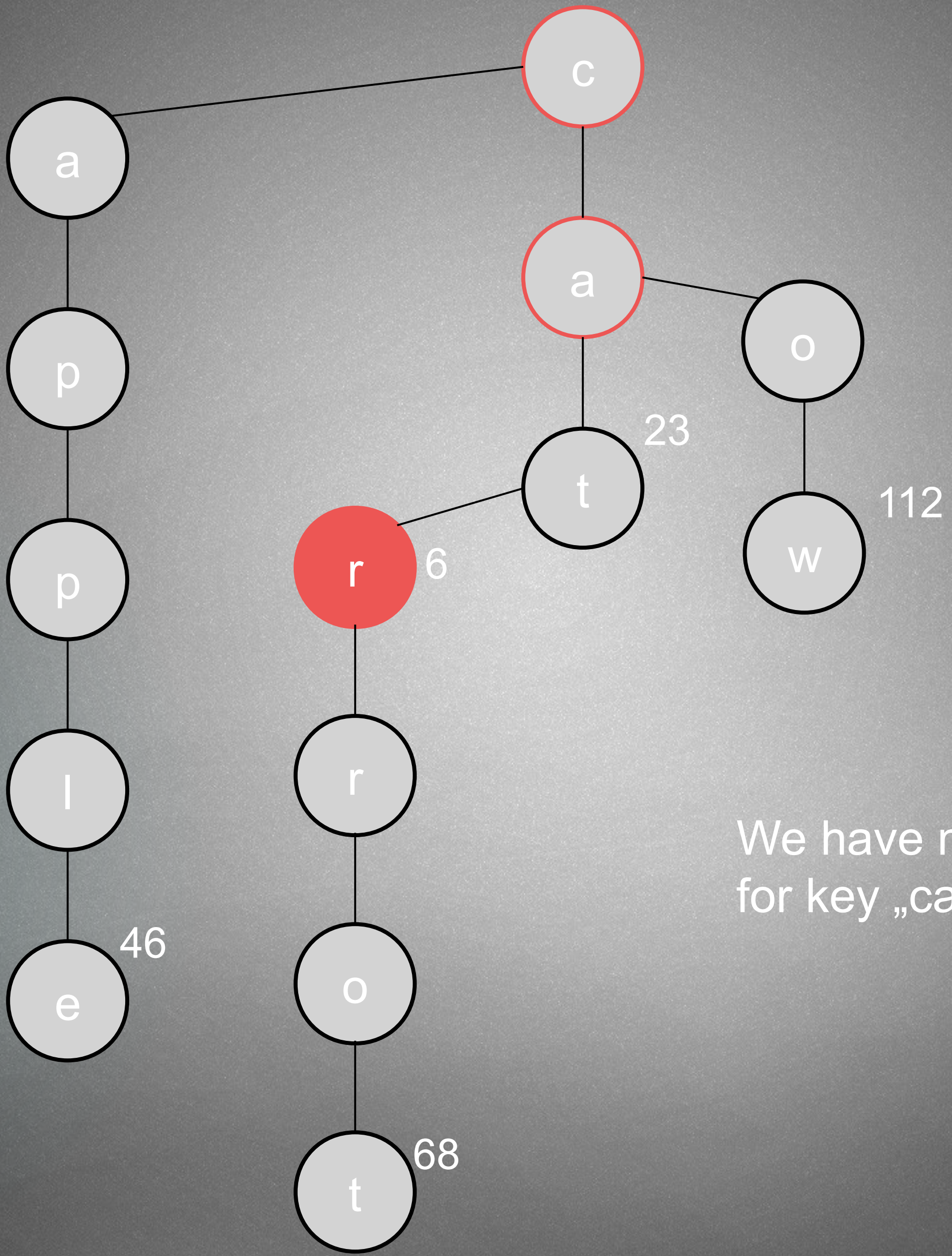
get(„car”)



get(„car”)

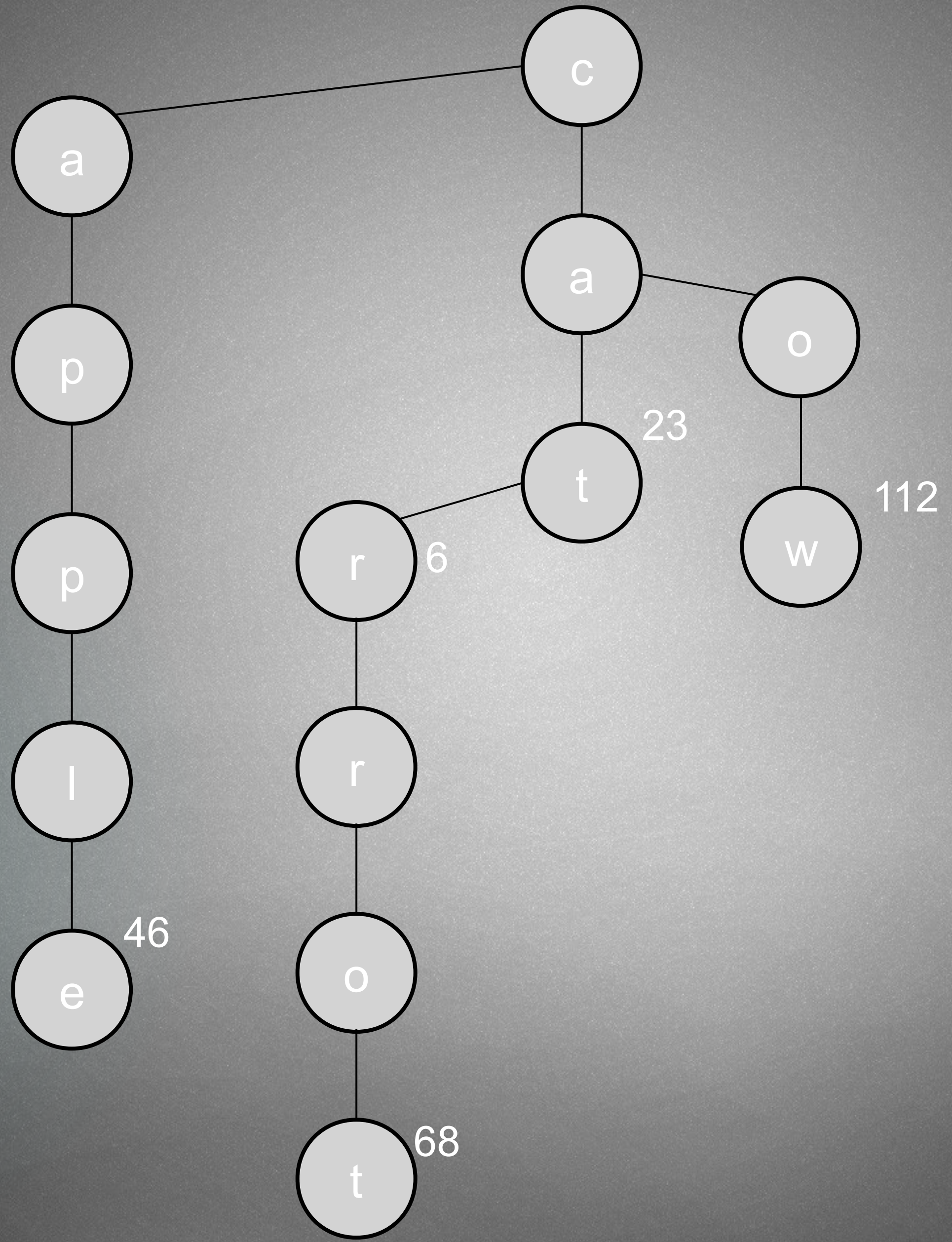


get(„car”)

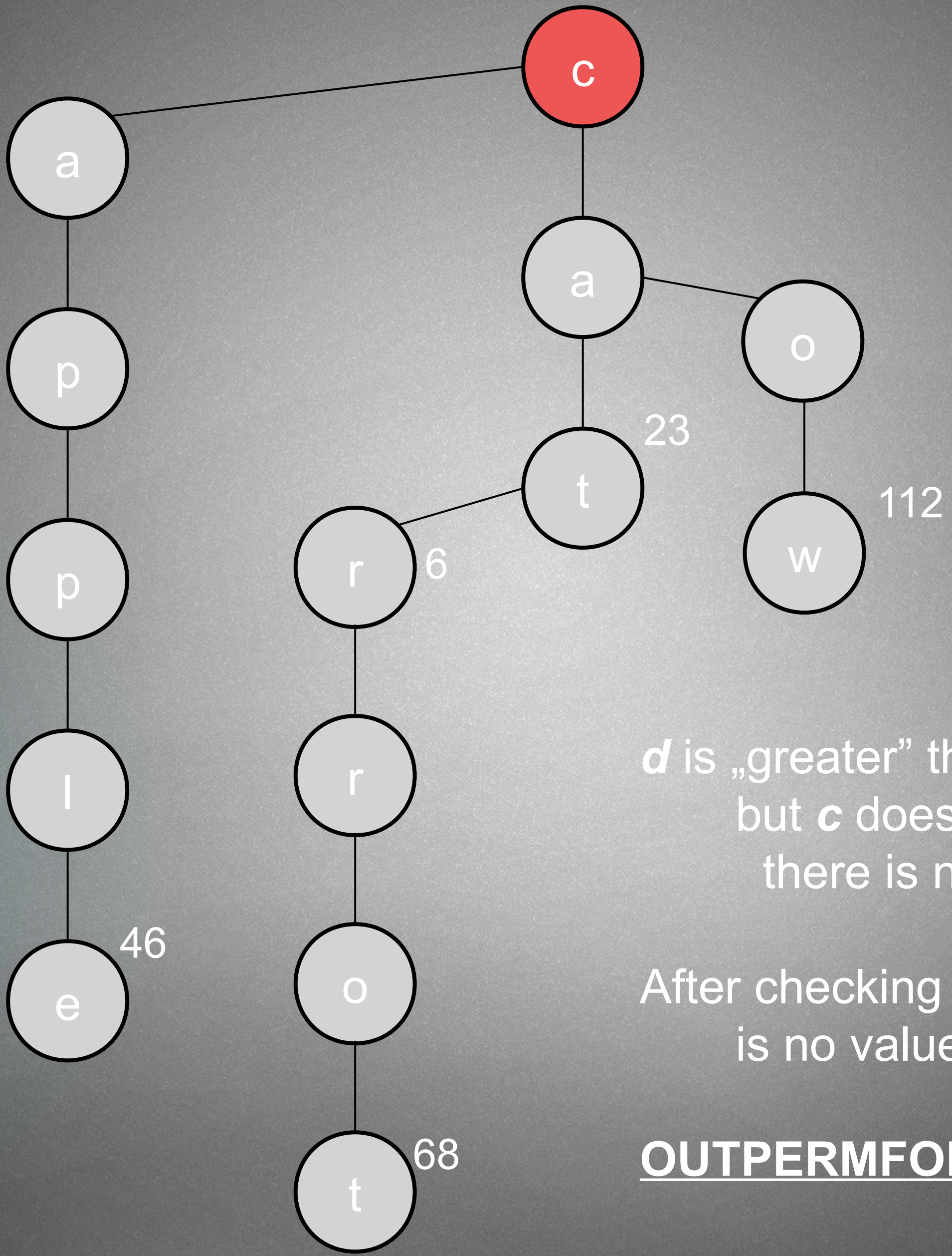


We have managed to find the value 6 for key „car” !!!

get(„dog”)



get(„**dog**”)



d is „greater” than ***c*** in the alphabetical order but ***c*** does not have any right child: it means there is no value with key „dog” in the TST

After checking the first character: we are sure there is no value with this key !!!

__**OUTPERMFORMS HASHMAP**__ !!!

Important notes

- We should combine tries with TST
- At the root: it is a trie with many many children
- At lower levels it becomes a TST with 3 children only
- This combination is quite efficient !!!

TST vs hashing

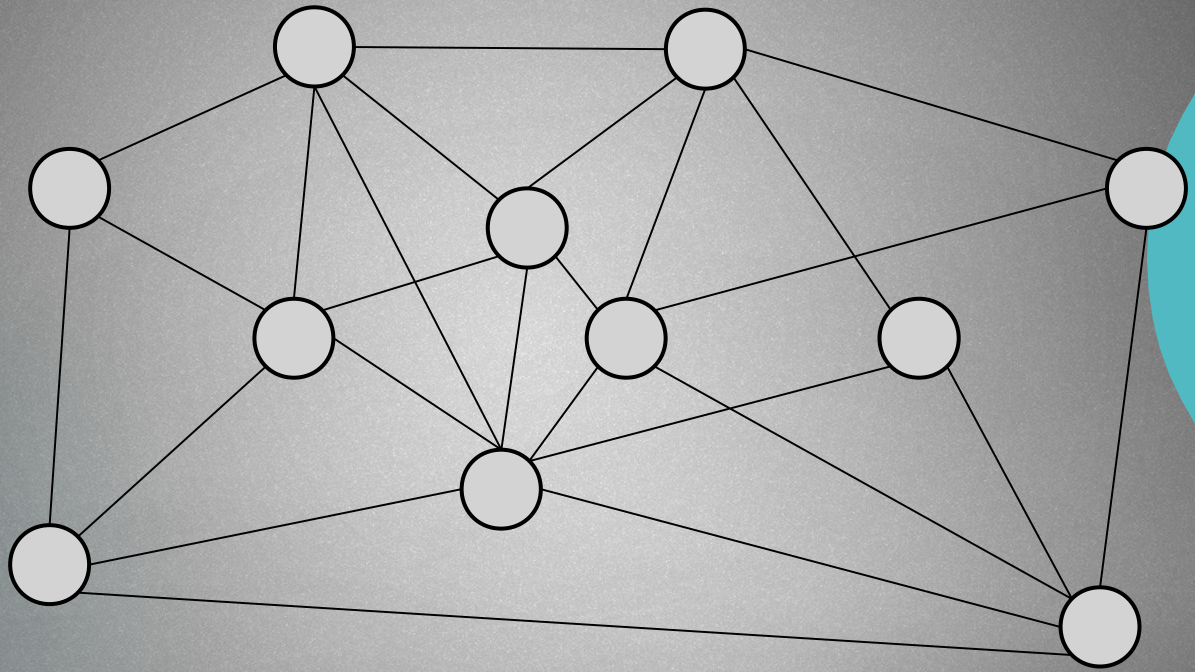
- **Hashing**
  - Need to examine the entire key (because that is the way the hash function works)
  - Search hits and misses cost the same
  - The running time and performance relies heavily on the hashfunction
  - Does not support as much operations than TST (sorting)
- **TST**
  - Works only for strings
  - Only examines just enough key characters
  - Search miss may only involve a few characters
  - Support more operations (sorting)
  - Faster than hashing (for misses especially) and more flexible than BST

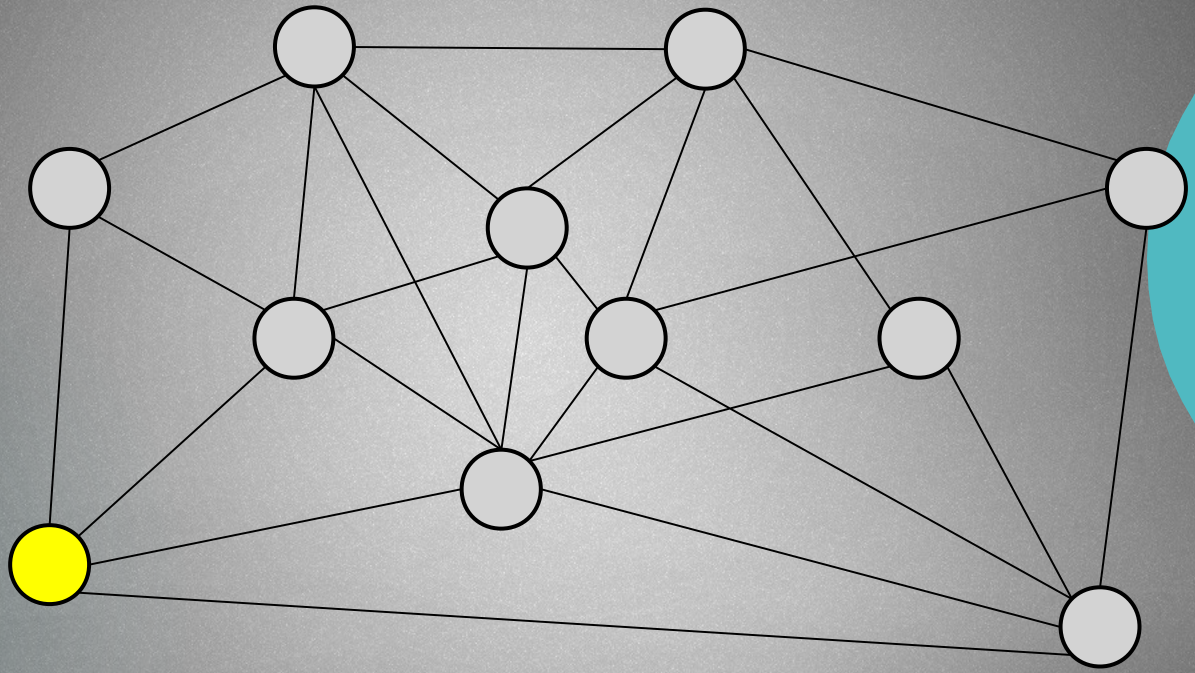
Applications

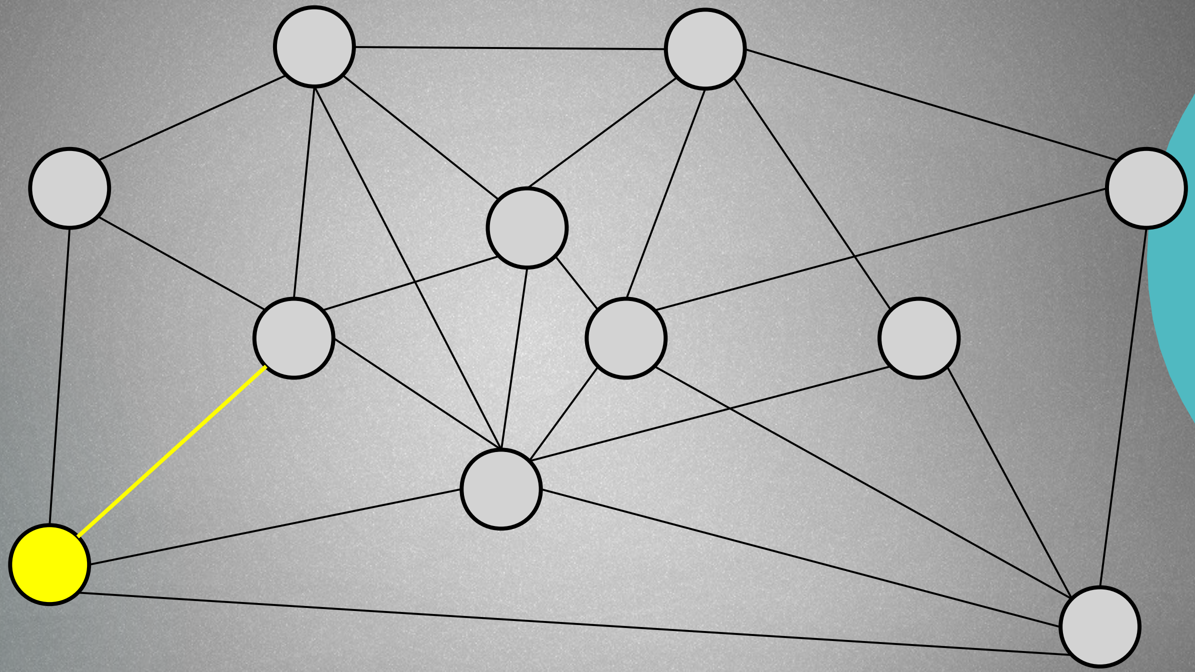
- It can be used to implement the auto-complete feature very very efficiently
- Can be used for spell-checkers
- Near-neighbor searching (of which a spell-check is a special case)
- For databases especially when indexing by several non-key fields is desirable
- Very important in package routing on WWW → the router direct the packages in the direction of the longest prefix. It can be found very quickly with the help of TST-s
- Prefix matching ~ google search
  - We can use DFS instead usually

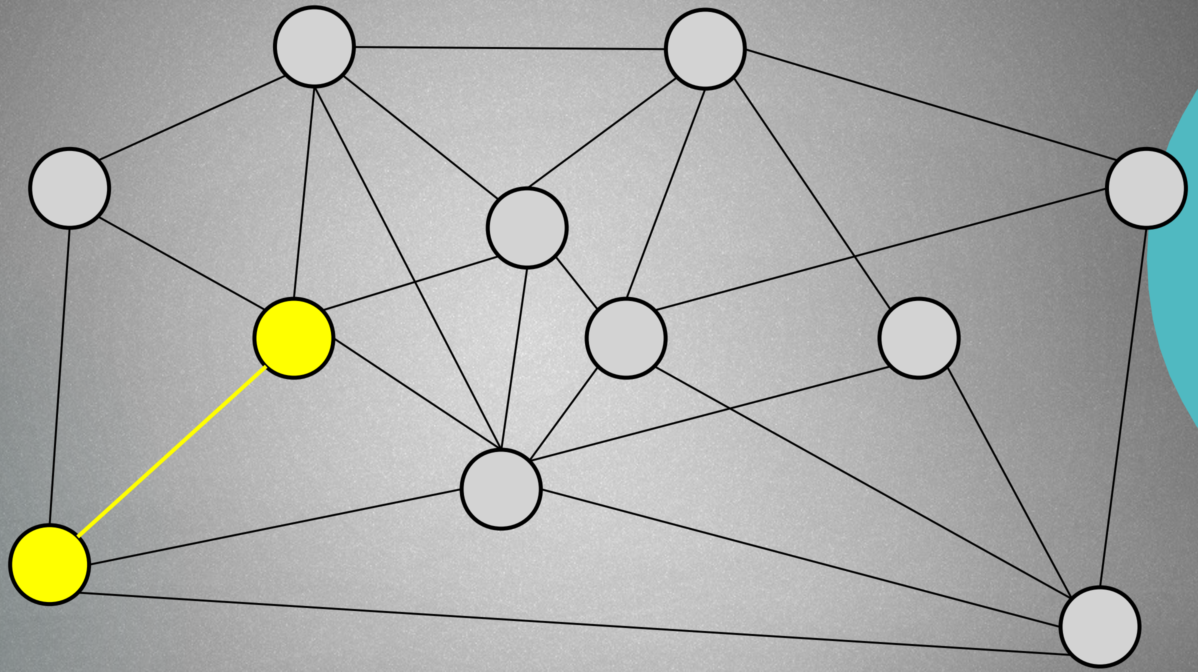
TRIES

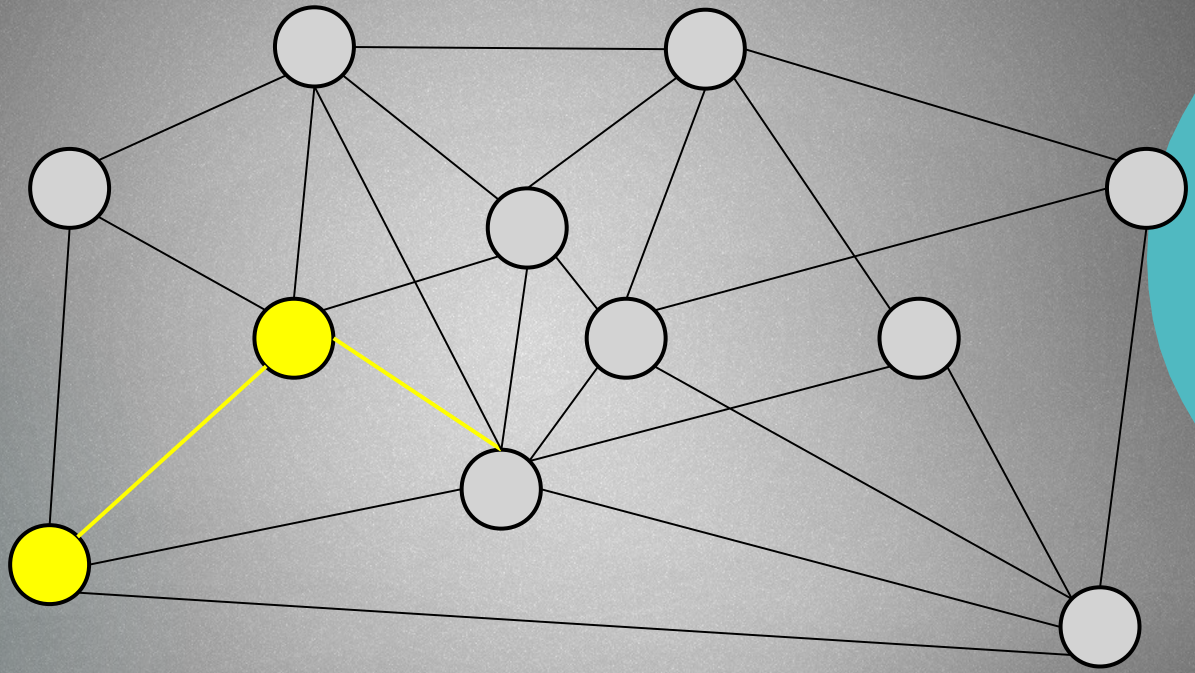
IP routing with trie data structures

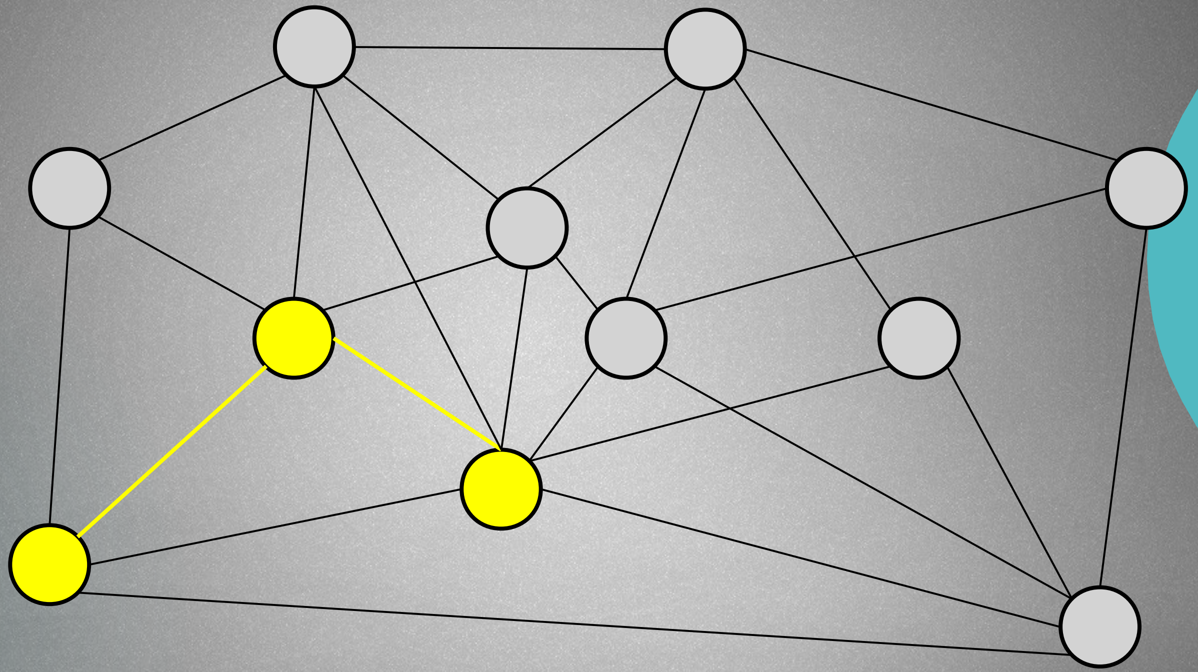


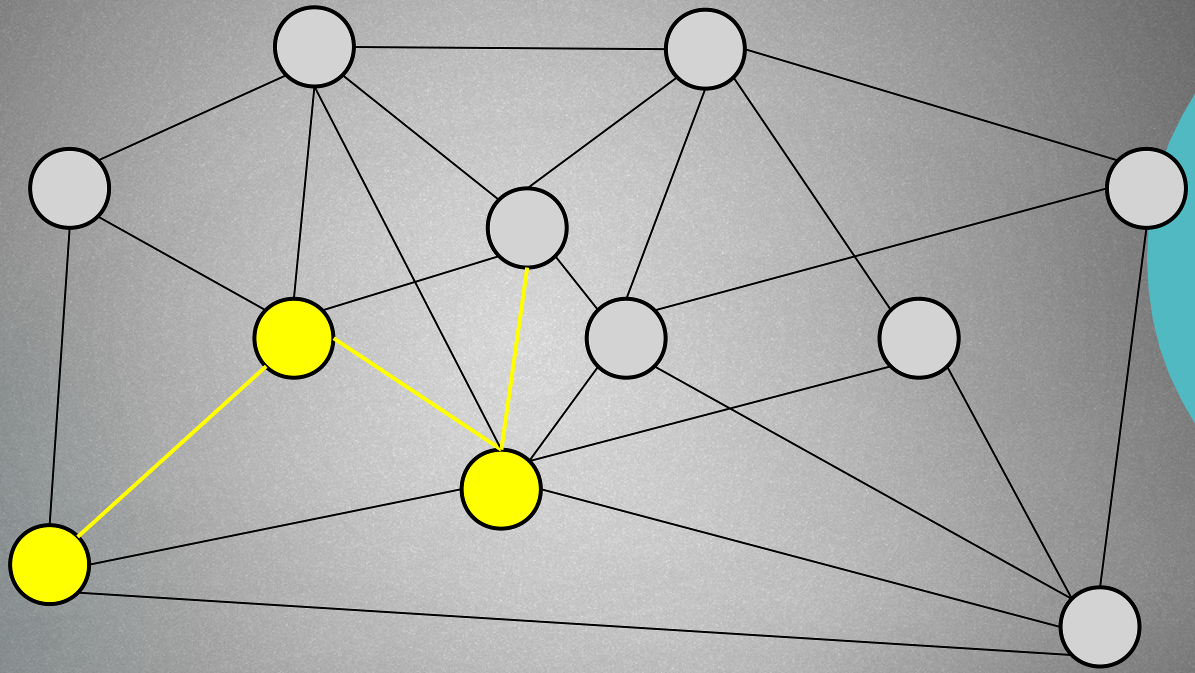


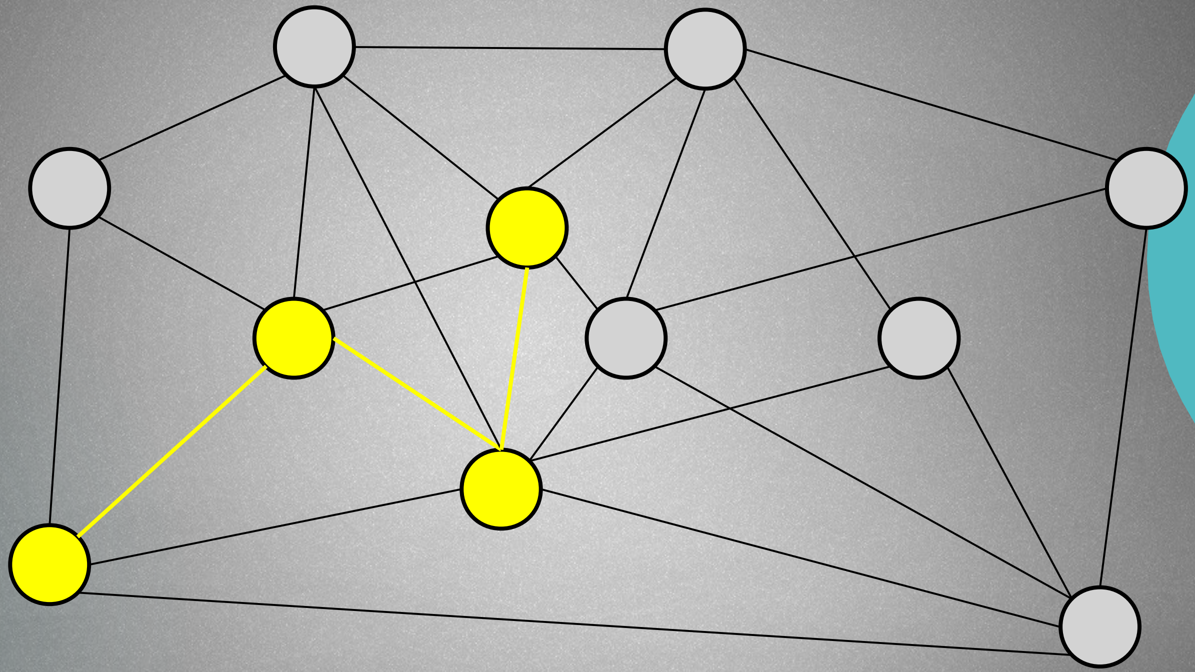


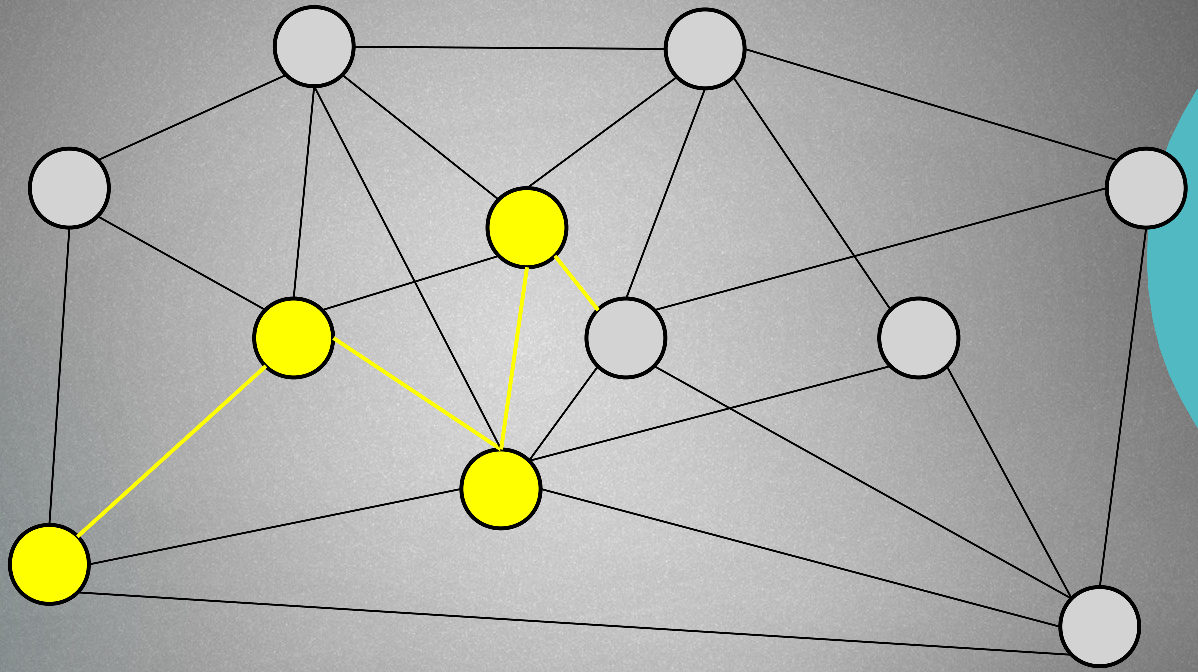


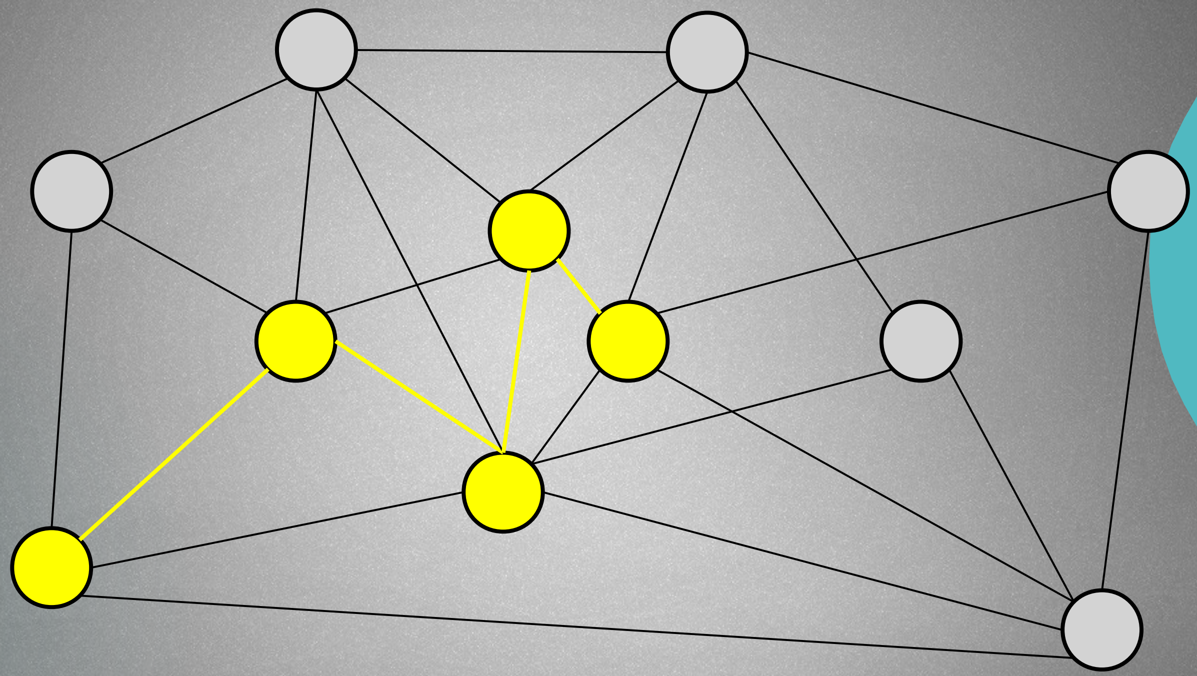


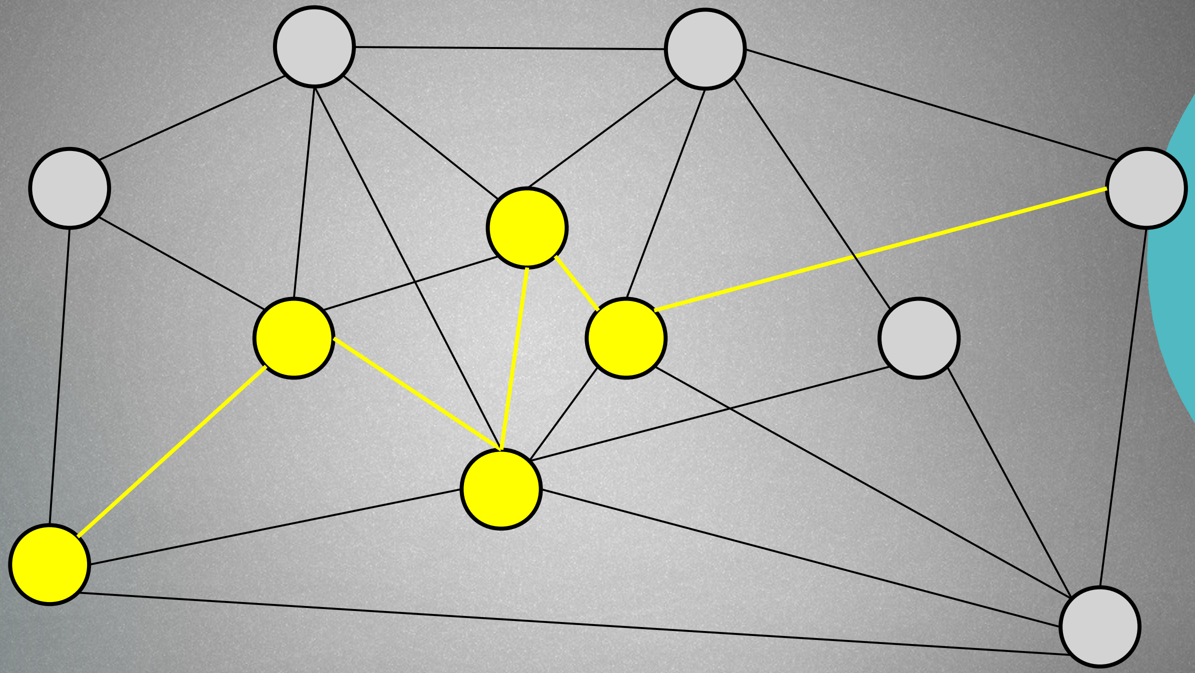


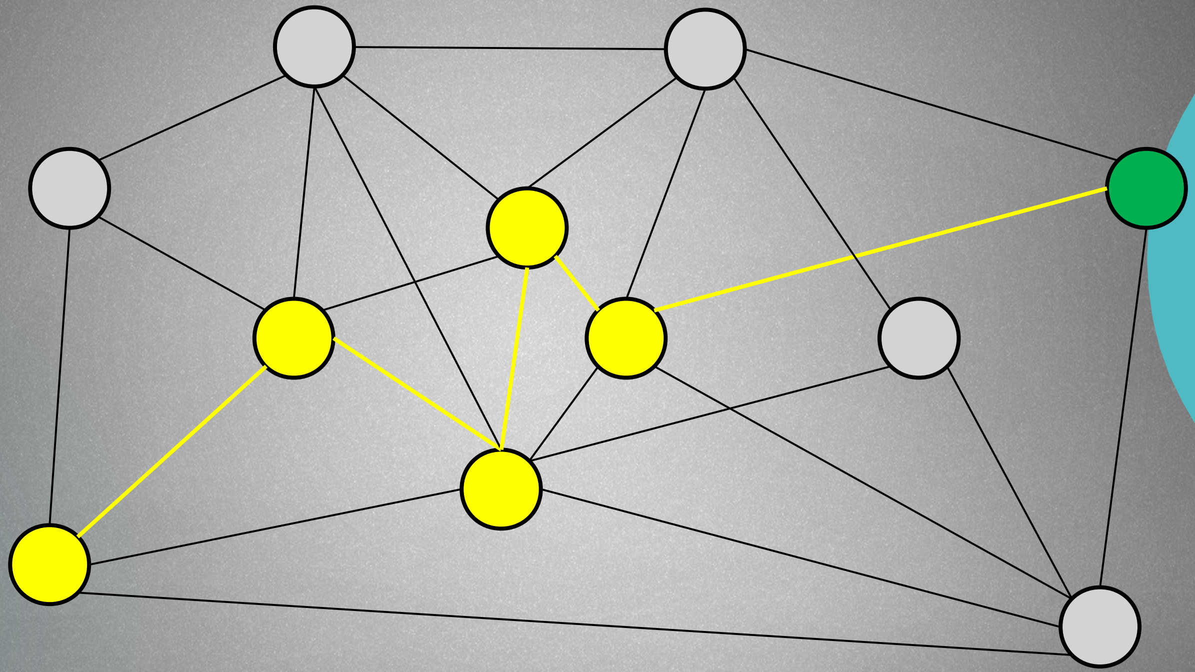












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Routing IP packages on the web relies heavily on graph algorithms and data structures !!!

- the router sends the packages toward the destination IP address
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- just send the packages approximately to the right direction

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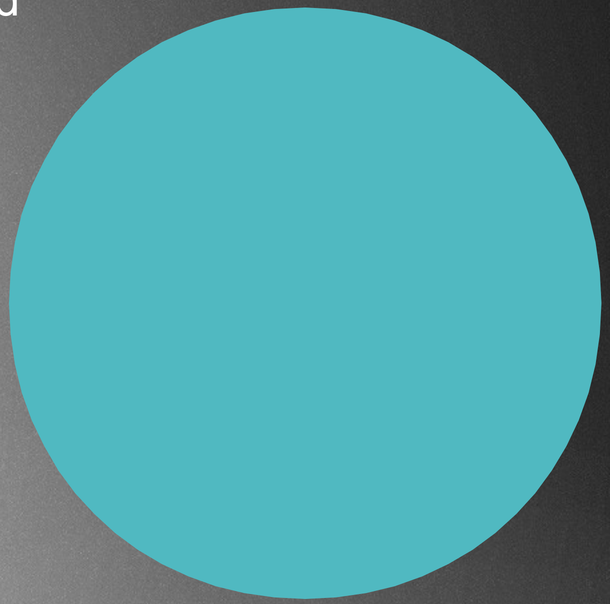
Algorithm

We have to consider the nodes where just a single node is valid
~ so a single node is not null !!!



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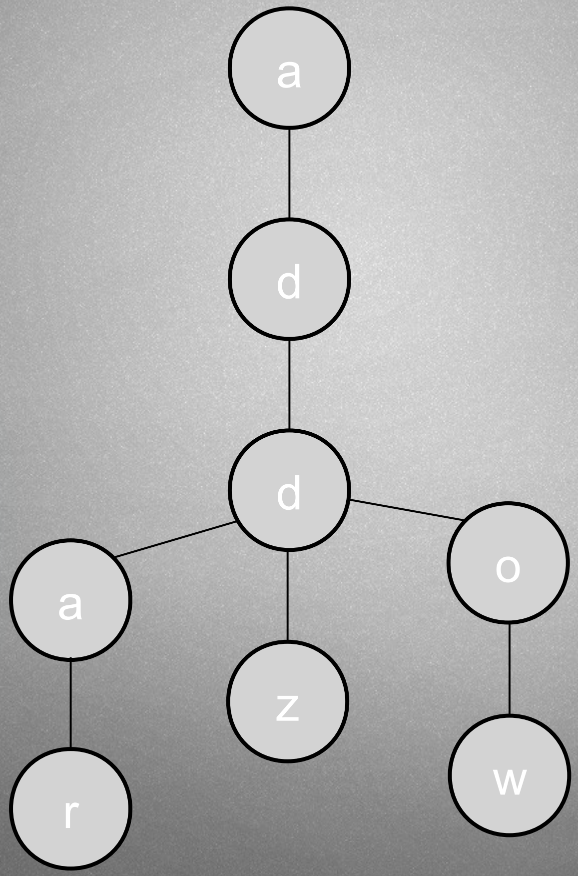

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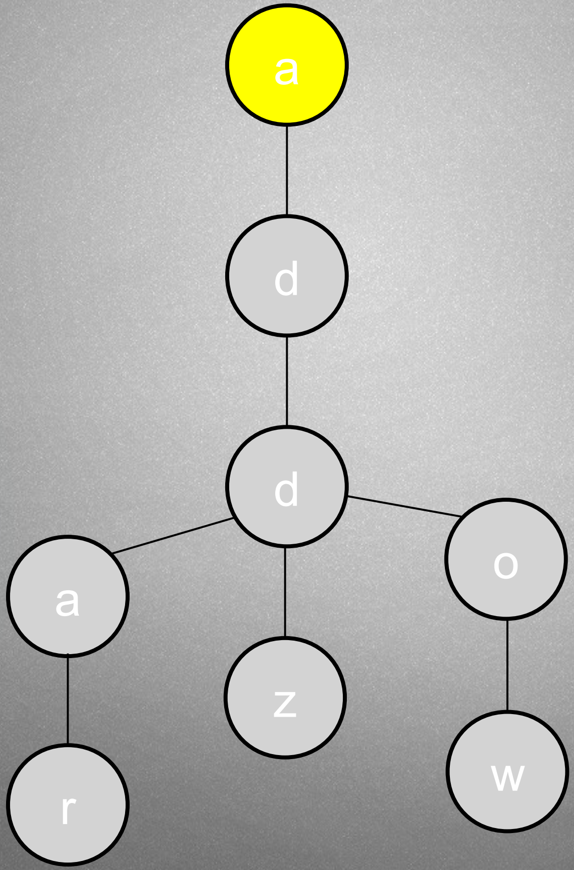

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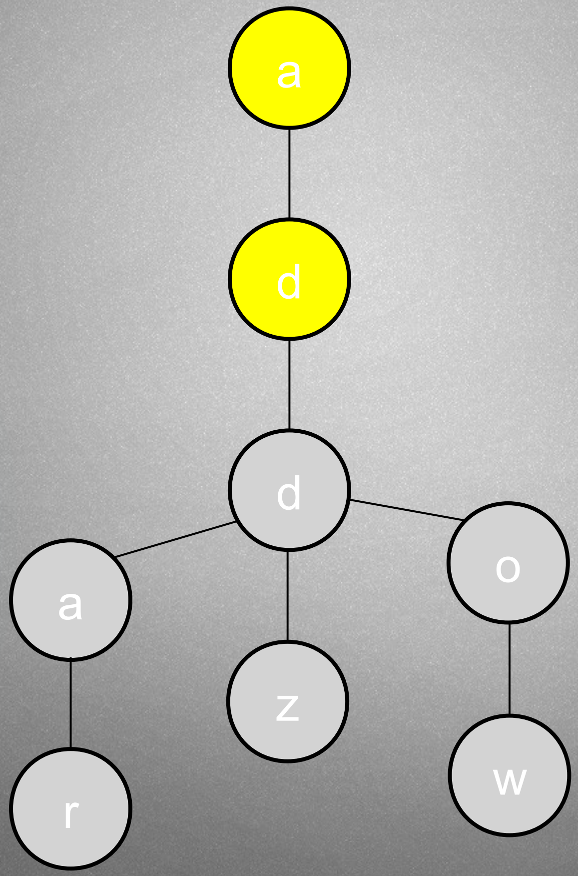

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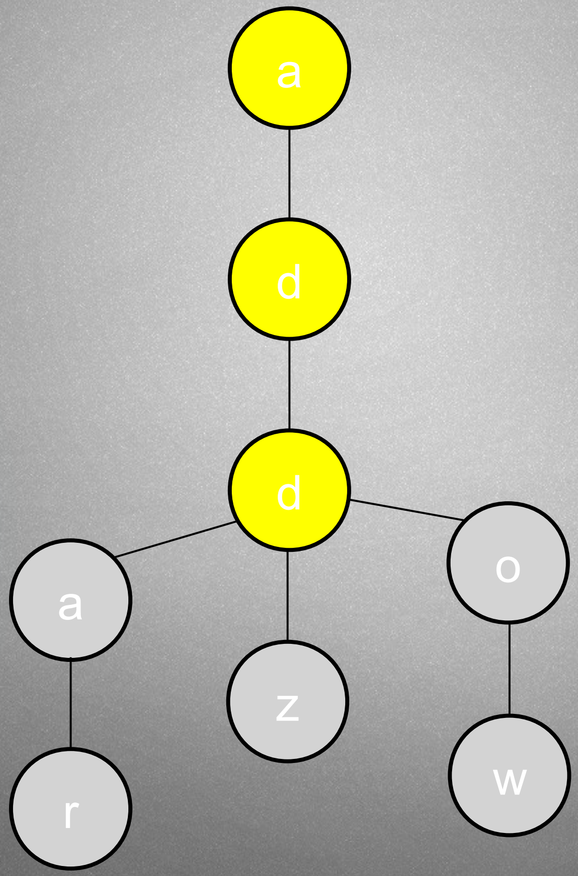

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