

# Tries and Suffix Trees

# String Data Structures

- Our next topic for the quarter is the wonderful world of string data structures.
- Why are they worth studying?
  - ***They're practical.*** These data structures were developed to meet practical needs in data processing. Lots of important data can be encoded as strings.
  - ***They're different.*** The questions typically asked about strings involve properties of sequences, not individual elements, in a way that you don't normally otherwise see.
  - ***They're algorithmically interesting.*** The techniques that power these data structures involve some truly beautiful connections and observations.

# Where We're Going

- Today, we'll cover *tries* and *suffix trees*, two powerful data structures for exposing shared structures in strings.
- On Tuesday, we'll see the *suffix array* and *LCP array*, which are a more space-efficient way of encoding suffix trees.

## Part I: *Tries and Patricia Tries*

# A Motivating Problem



what is the cutest ani|



what is the cutest animal in the world

what is the cutest animal

what is the cutest animal on earth

what is the cutest animal ever

what is the cutest animal in the whole entire world

what is the cutest animal in the whole world

what is the cutest animal alive

what is the cutest animal on the planet

what is the cutest animal in australia

what is the cutest animal in the sea

Google Search

I'm Feeling Lucky

*Report inappropriate predictions*

***How is this done so quickly?***

# The Autocomplete Problem

- We have a series of text strings  $T_1, T_2, \dots, T_k$  of total length  $m$ . ( $|T_1| + \dots + |T_k| = m$ )
- We have a pattern string  $P$  of length  $n$ . ( $|P| = n$ ).
- **Goal:** Find all text strings that start with  $P$ .
- If we just do a single query, then we can solve this pretty easily.
  - Just scan over all the strings and see which ones start with  $P$ .
- **Question:** If we have a set of fixed text strings and varying patterns, can we speed this up?

# A Naive Solution



a n t



a n t e



a n t e a t e r



a n t e l o p e



a n t i q u e

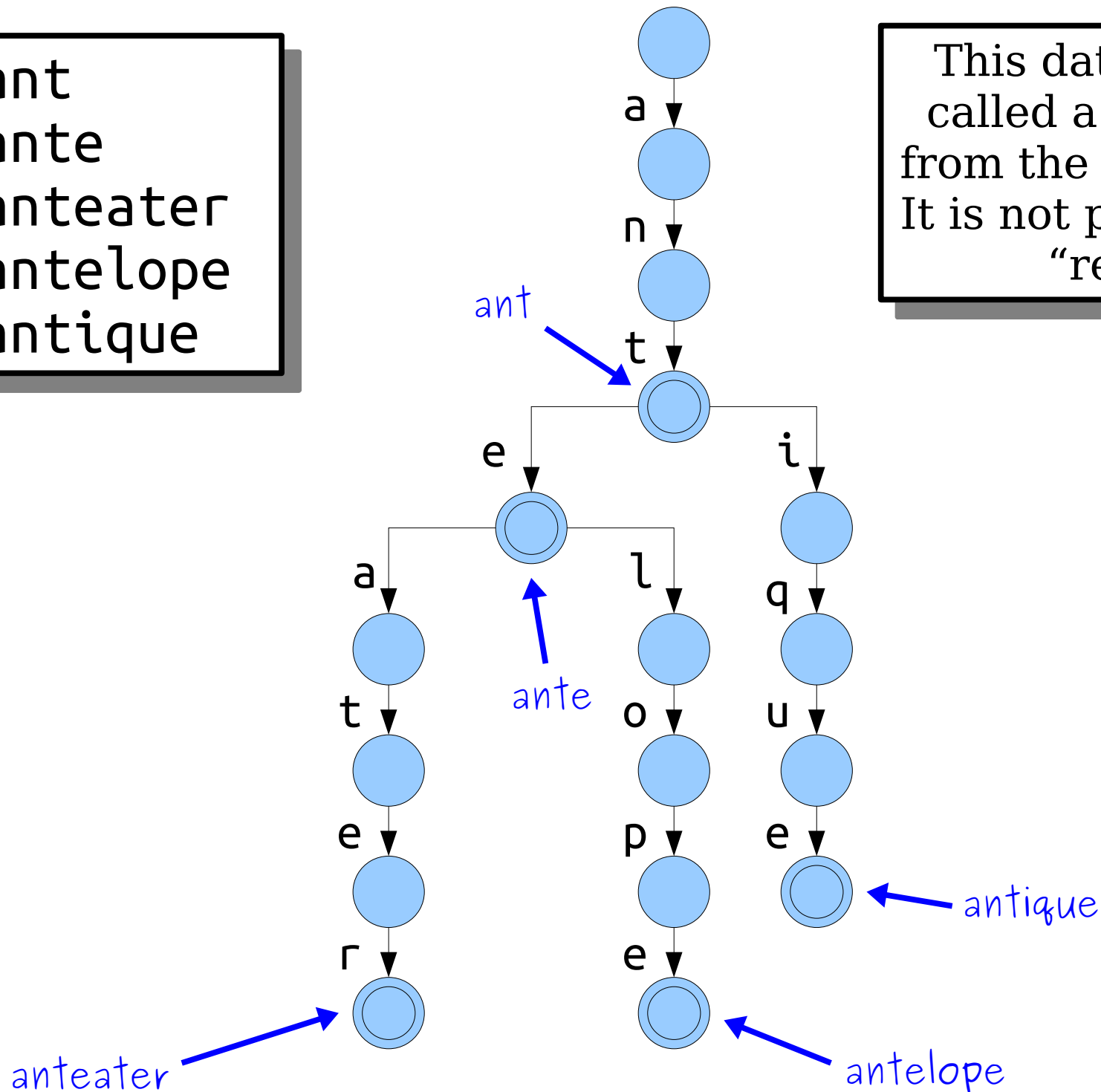


a n t e

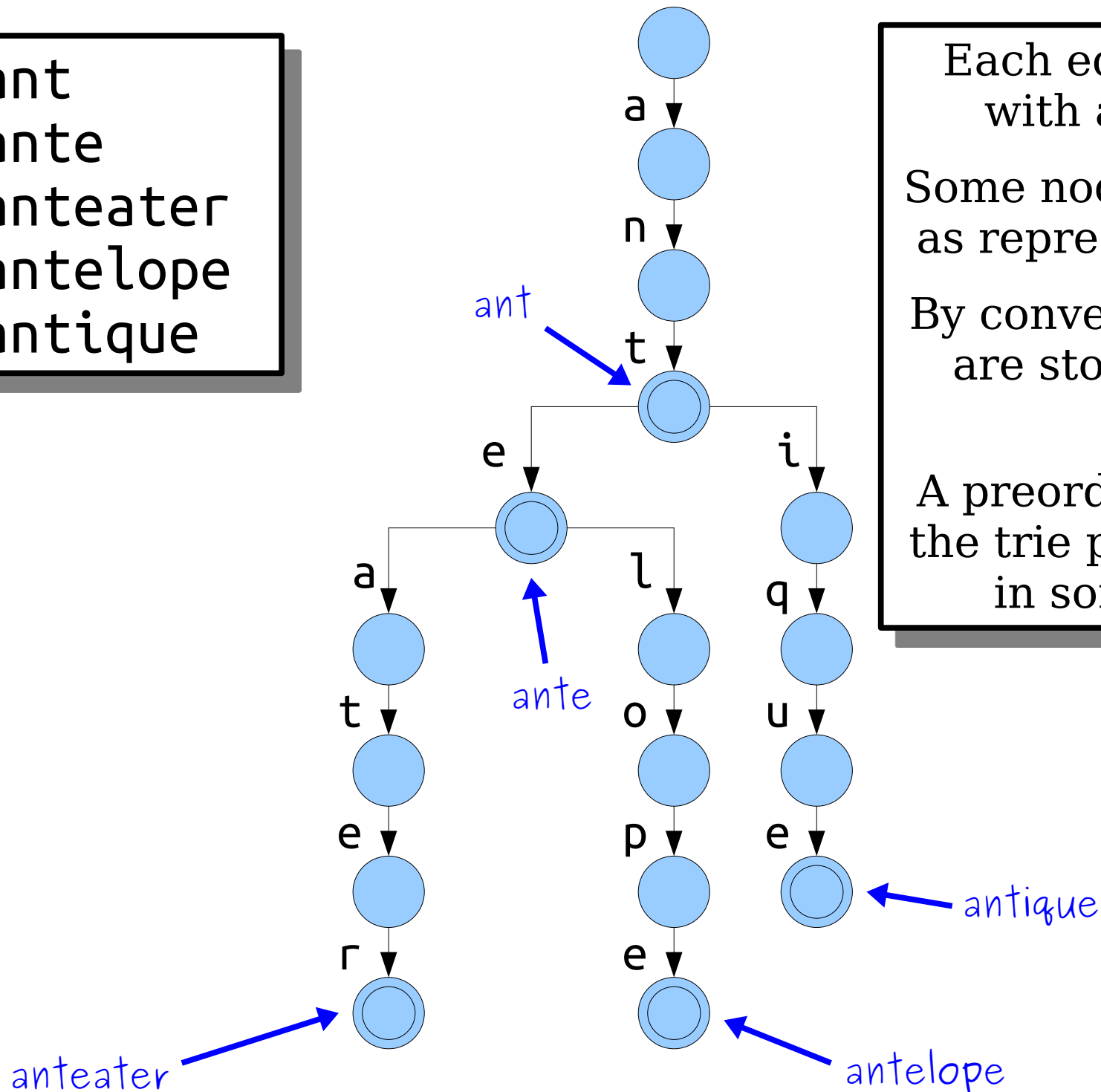
We're spending a lot of time scanning shared prefixes. Is there a way to avoid this?

ant  
ante  
anteater  
antelope  
antique

This data structure is called a **trie**. It comes from the word re**trie**val. It is not pronounced like "retrieval."



ant  
ante  
anteater  
antelope  
antique



Each edge is labeled with a character.

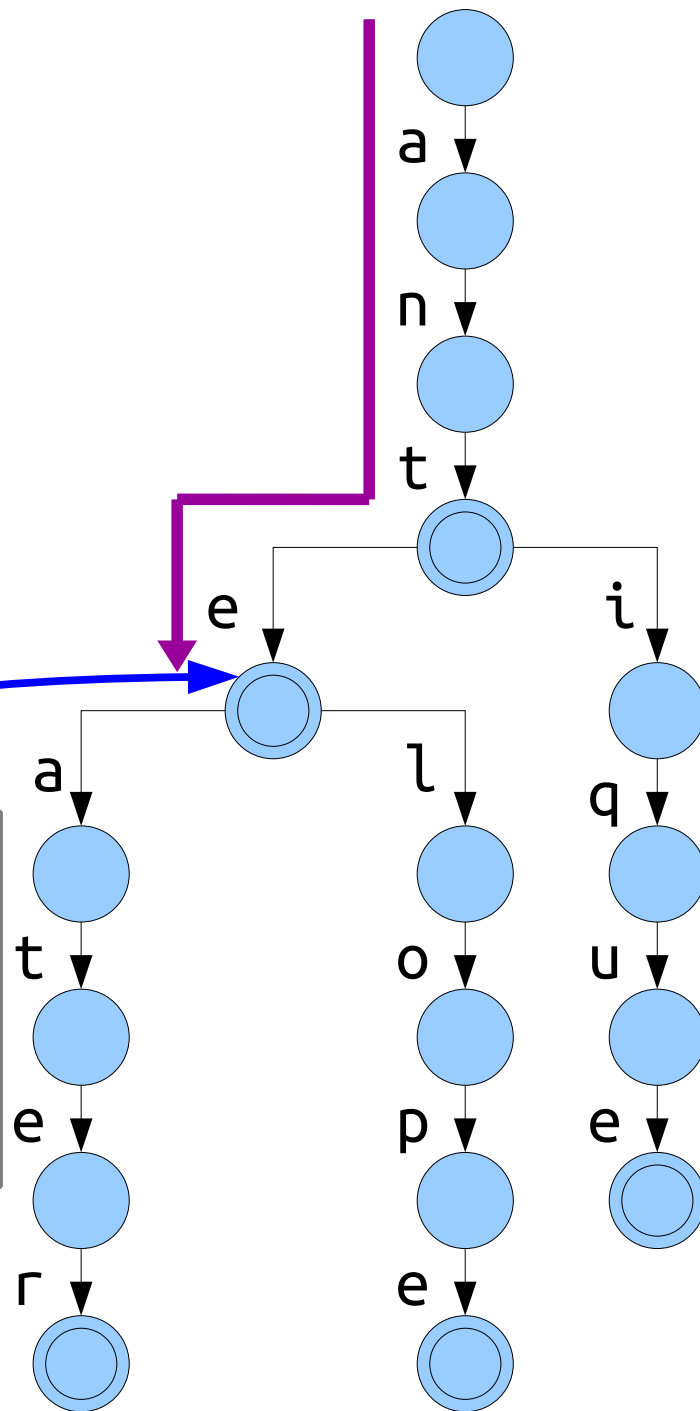
Some nodes are marked as representing words.

By convention, children are stored in sorted order.

A preorder traversal of the trie prints all words in sorted order.

ant  
ante  
anteater  
antelope  
antique

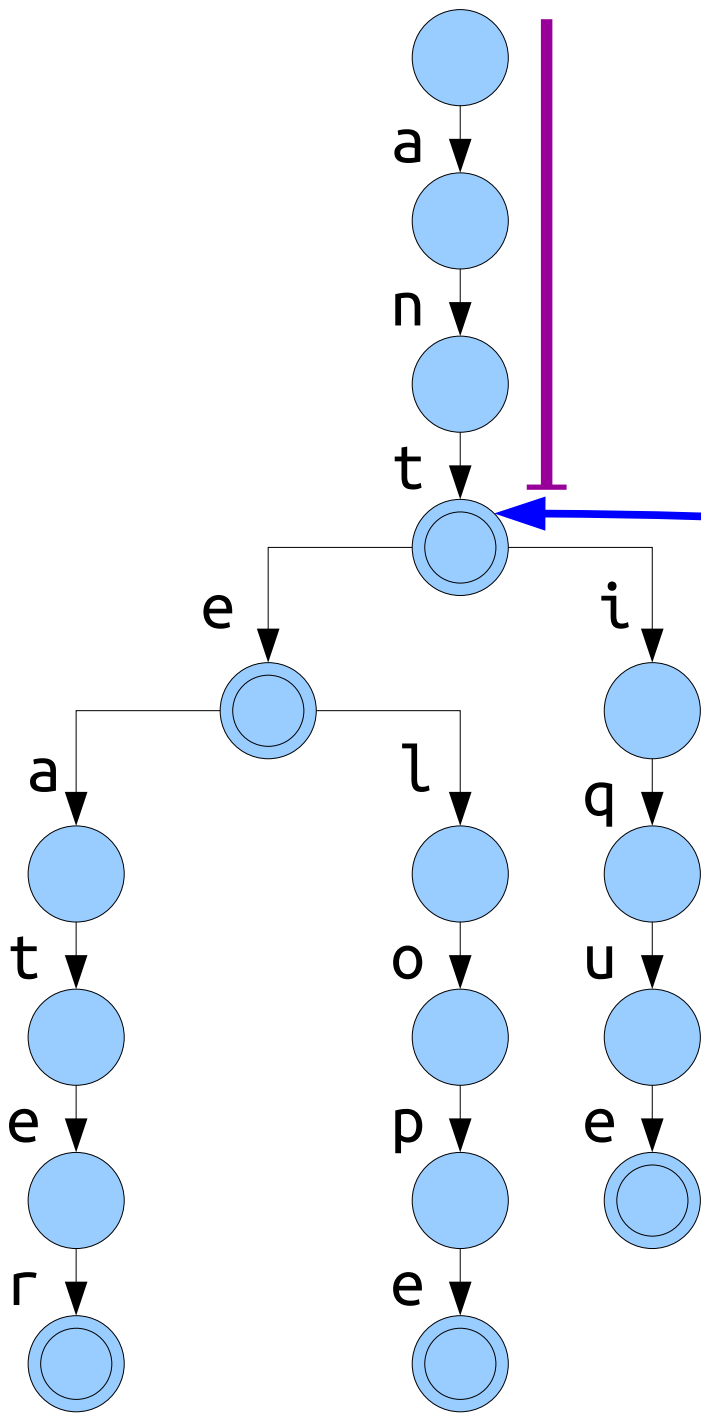
Now, do a DFS to find all words rooted here.



|   |   |   |   |
|---|---|---|---|
| a | n | t | e |
|---|---|---|---|

ant  
ante  
anteater  
antelope  
antique

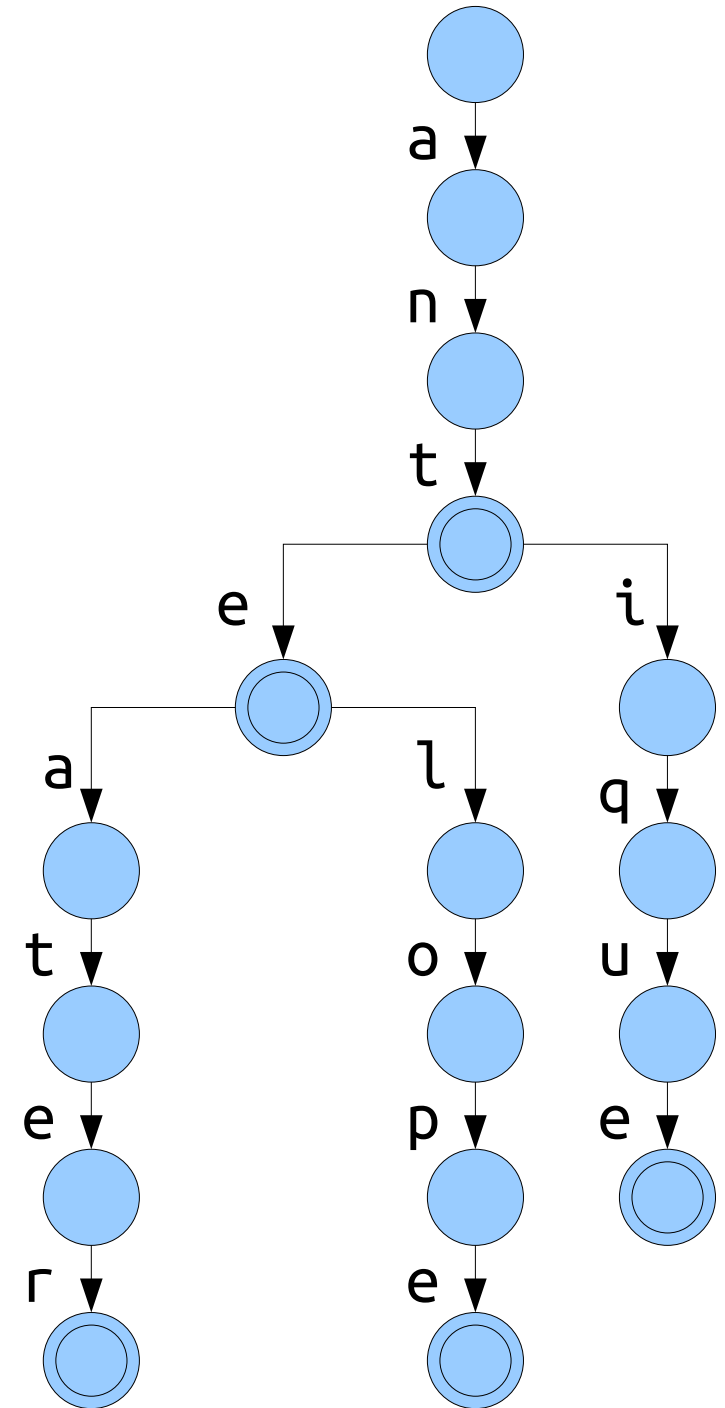
|   |   |   |   |
|---|---|---|---|
| a | n | t | w |
|---|---|---|---|



We fell off  
the trie.  
There are no  
matches!

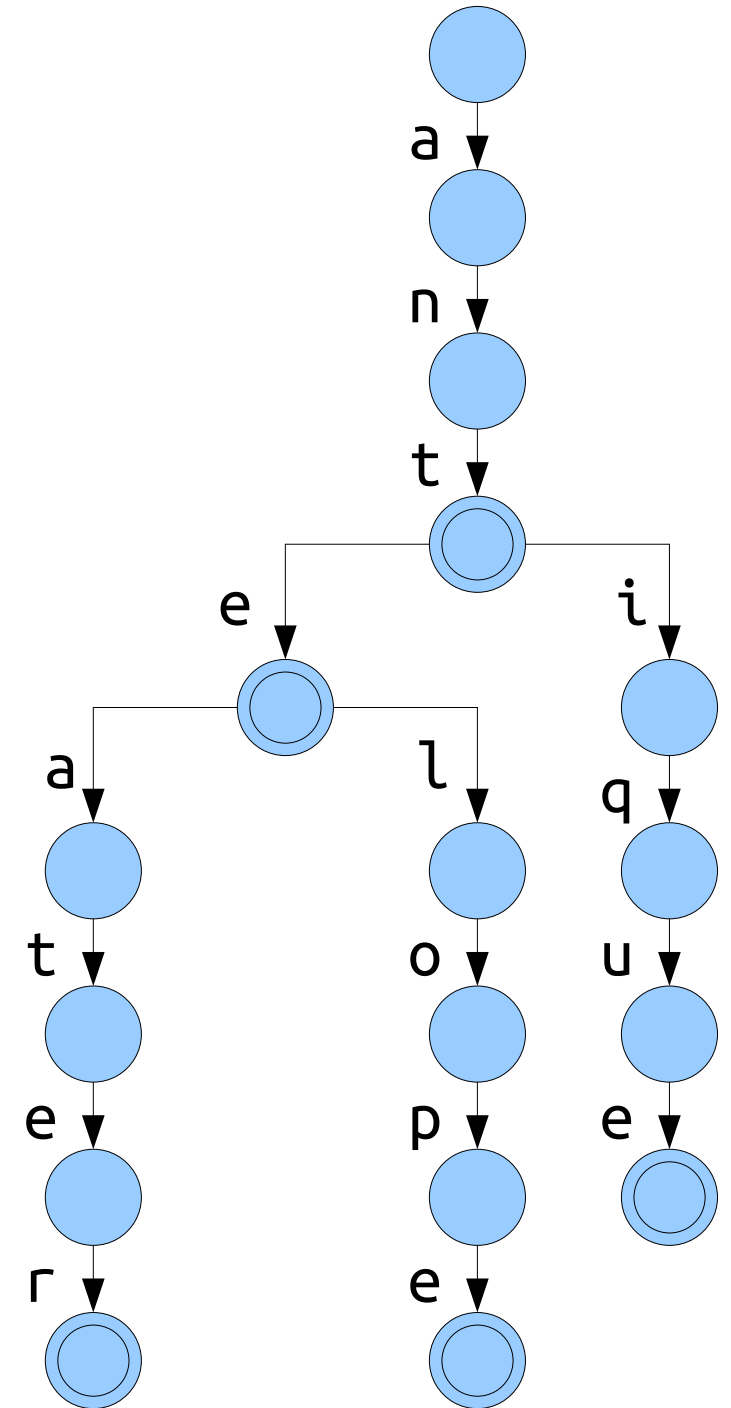
# Tries

- **Recall:** The total length of our text strings is  $m$ , and the length of our pattern string is  $n$ .
- How long does it take to build our trie?
- **Claim:** Ignoring the size of the alphabet, the runtime is  $O(m)$ .



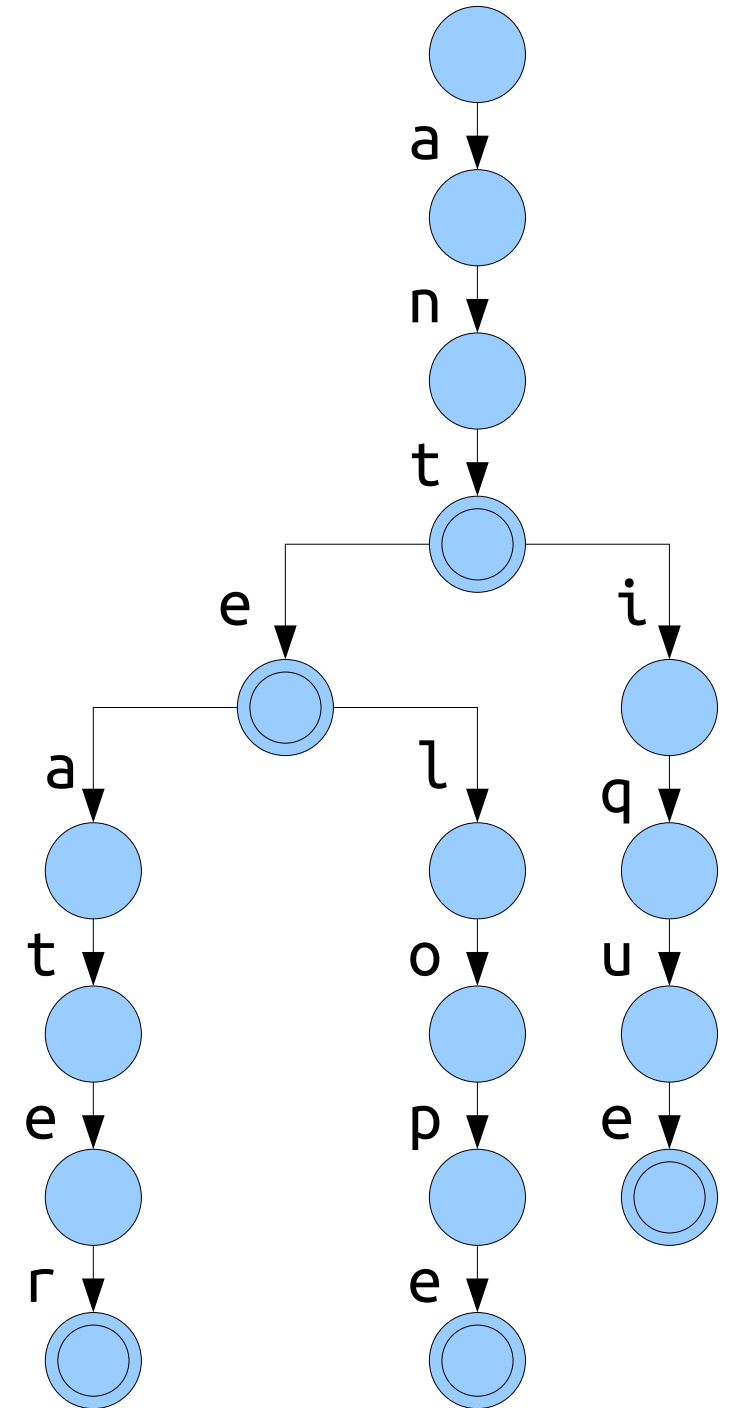
# Tries

- **Recall:** The total length of our text strings is ***m***, and the length of our pattern string is ***n***.
- How long does it take to check if the pattern is a prefix of any string?
- **Claim:** Ignoring the size of the alphabet, the runtime is  $O(n)$ .



# Tries

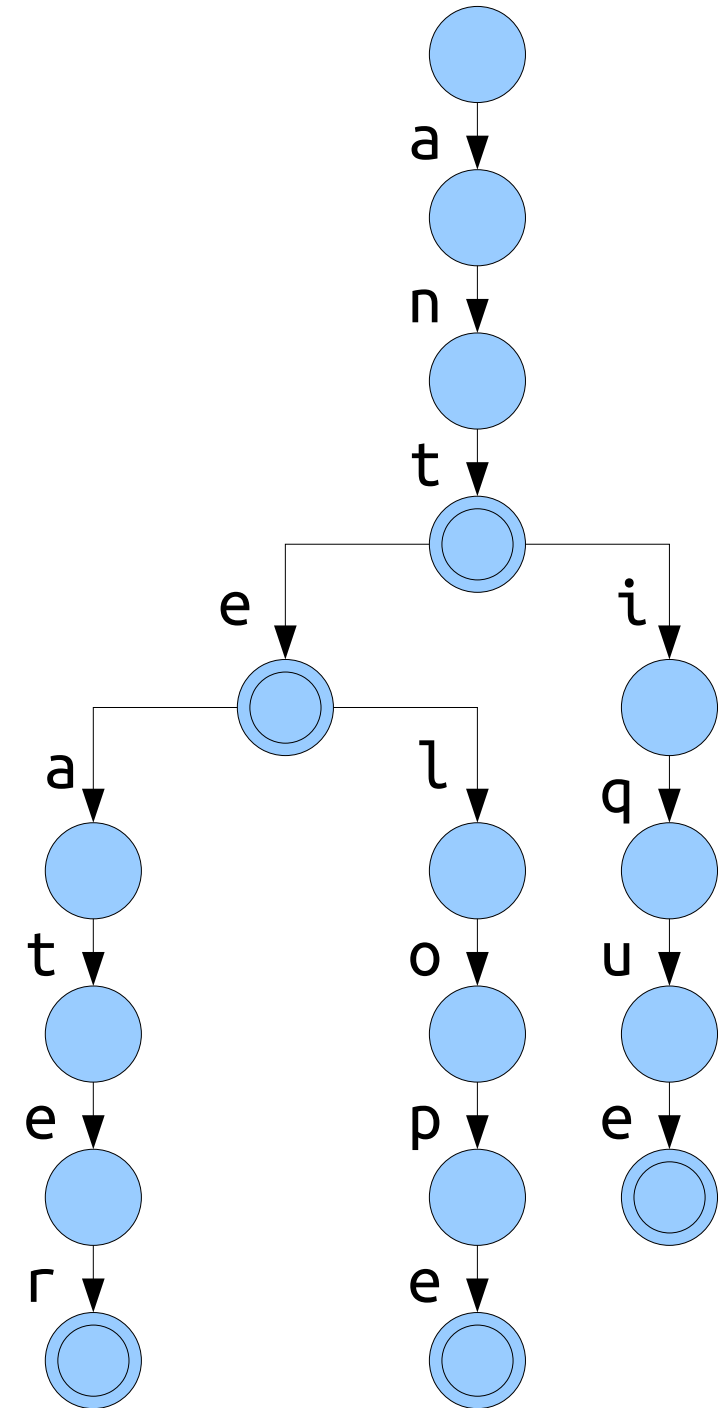
- **Recall:** The total length of our text strings is ***m***, and the length of our pattern string is ***n***.
- How long does it take to find all text strings that start with the pattern?
- That's a trickier question.





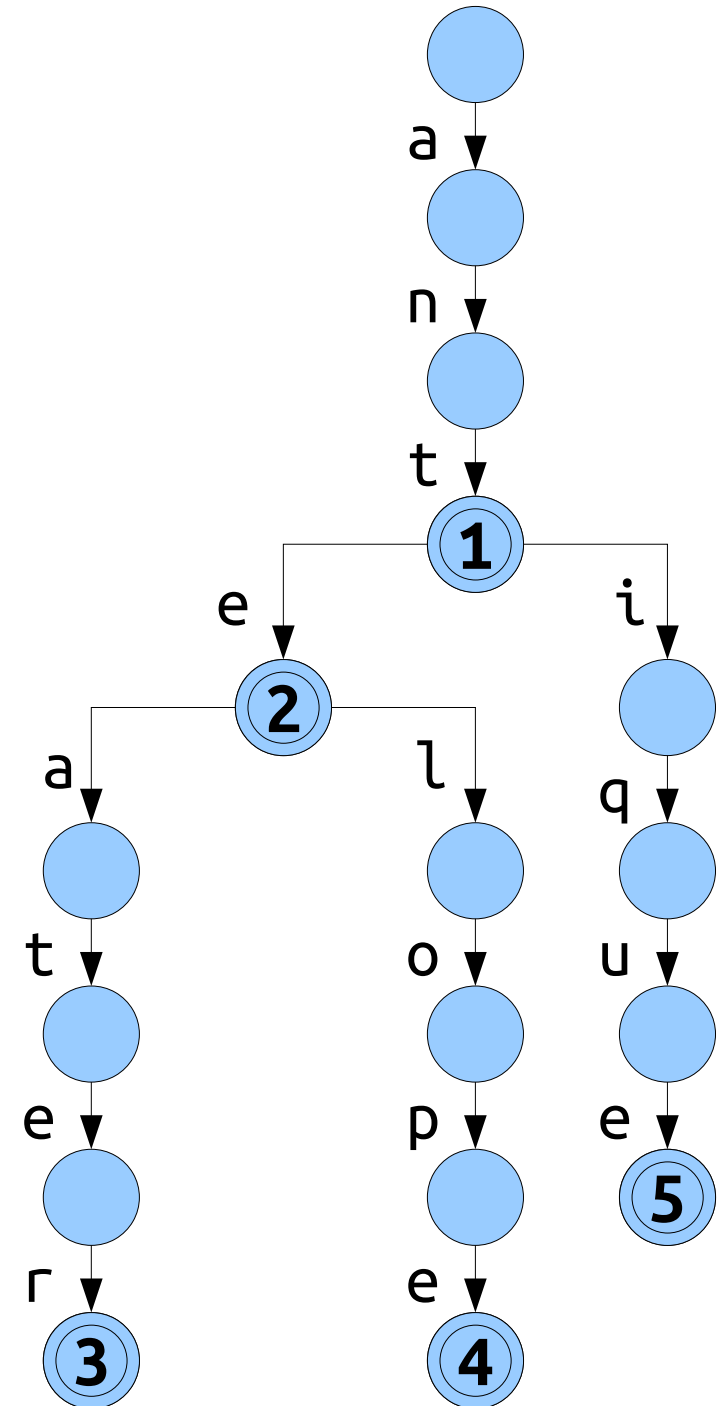
# Tries

- **Question:** In what format do we want our matches?
- **Option 1:** Just print out all the matches.
  - Search for the prefix as usual.
  - Do a DFS, recording the letters seen on each branch, to rebuild all the words.
- We can upper-bound runtime at  $O(m + n)$ , but it's hard to say much more than that.
  - (We could upper-bound this expression at  $O(m)$  if we'd like, but I like showing both costs here.)

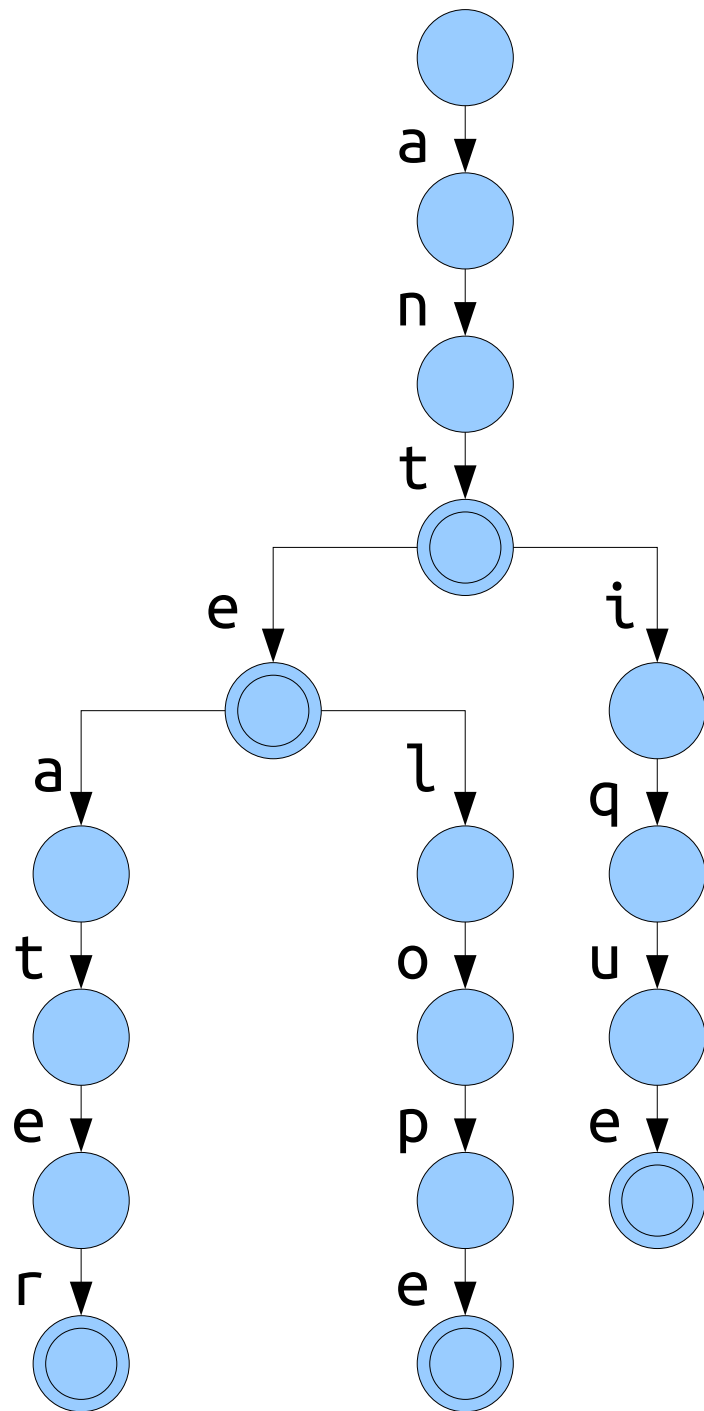


# Tries

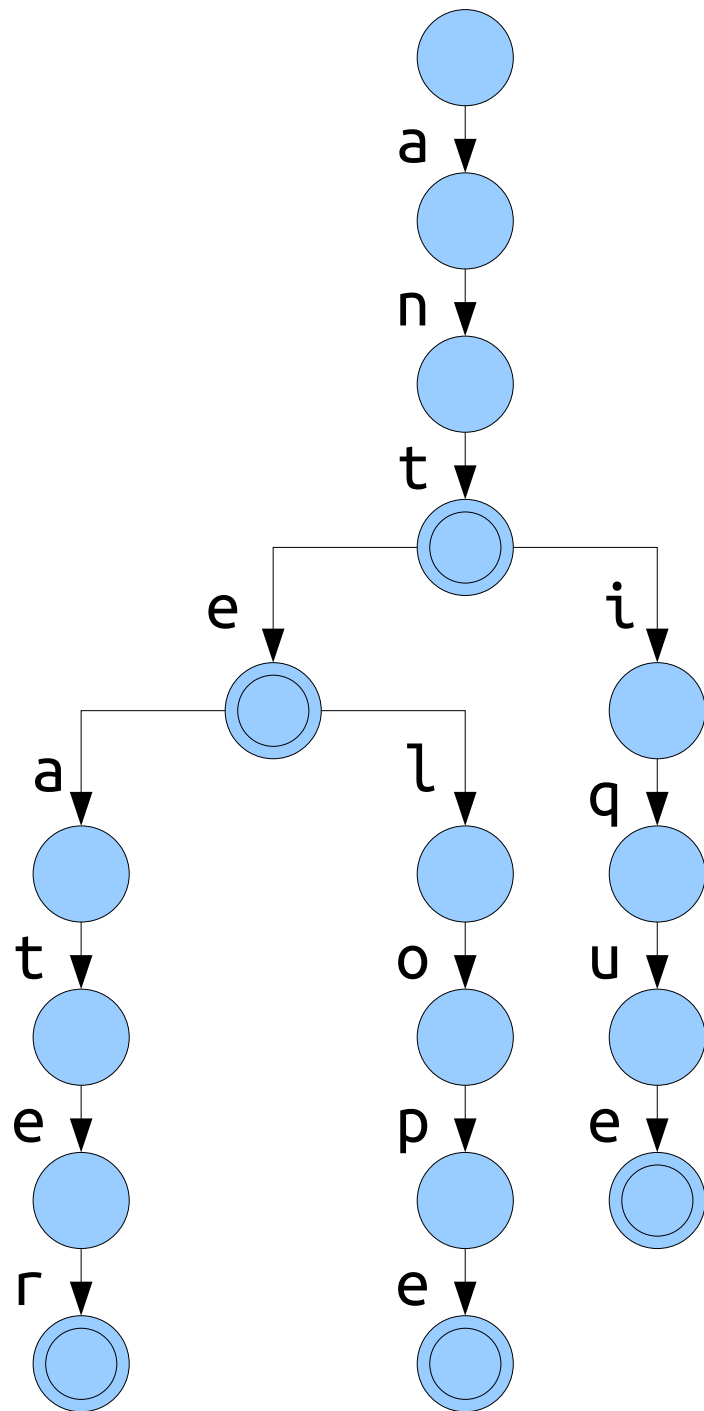
- **Question:** In what format do we want our matches?
- **Option 2:** Assume each text string has some numeric ID, and we want all matching IDs.
- Ideally, we'd like a time complexity of something like  $O(n + z)$ , where  $z$  is the number of matches.
- Our current DFS can't achieve this; the lengths of the strings matter.
- Can we do better?



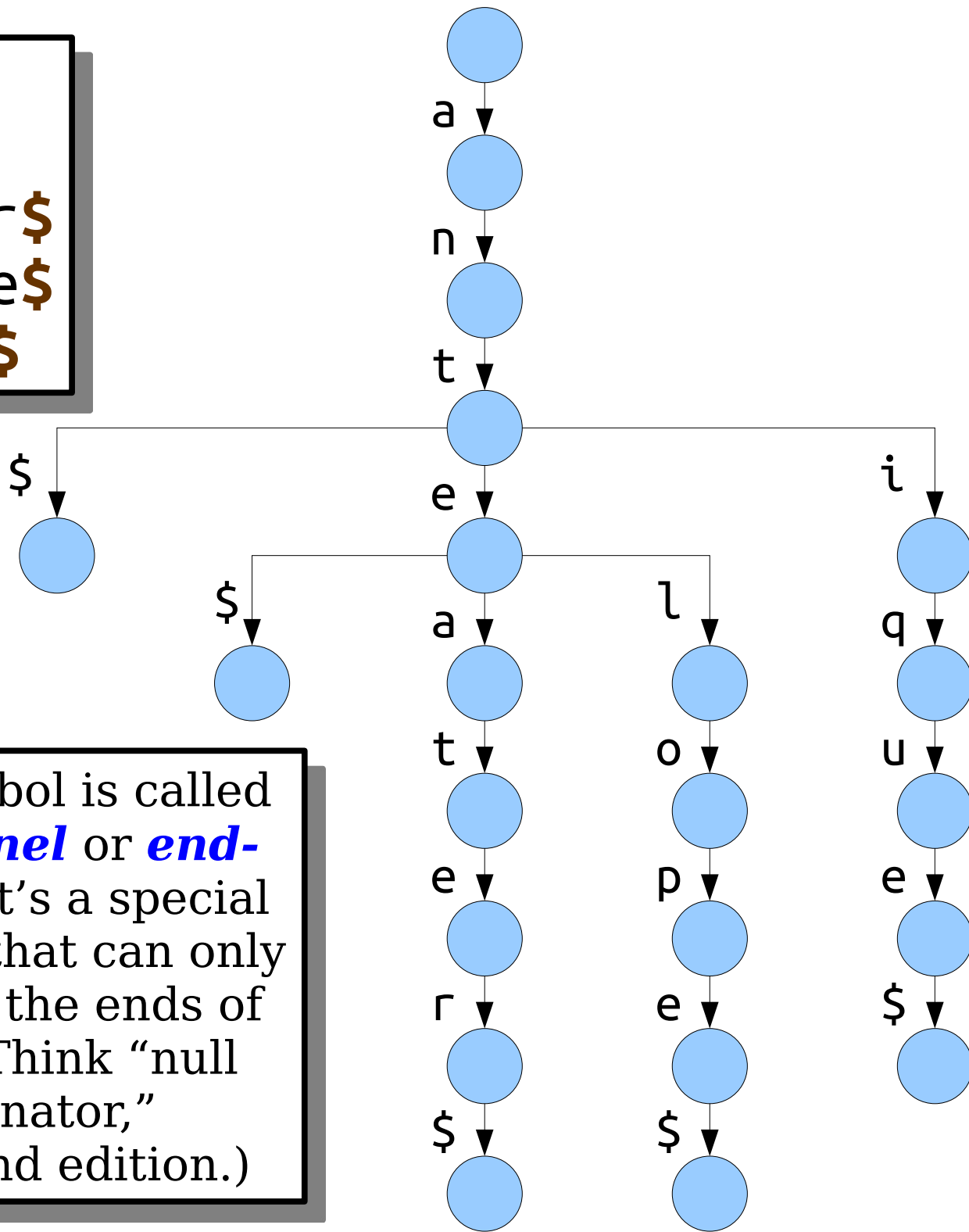
ant  
ante  
anteater  
antelope  
antique



ant\$  
ante\$  
anteater\$  
antelope\$  
antique\$

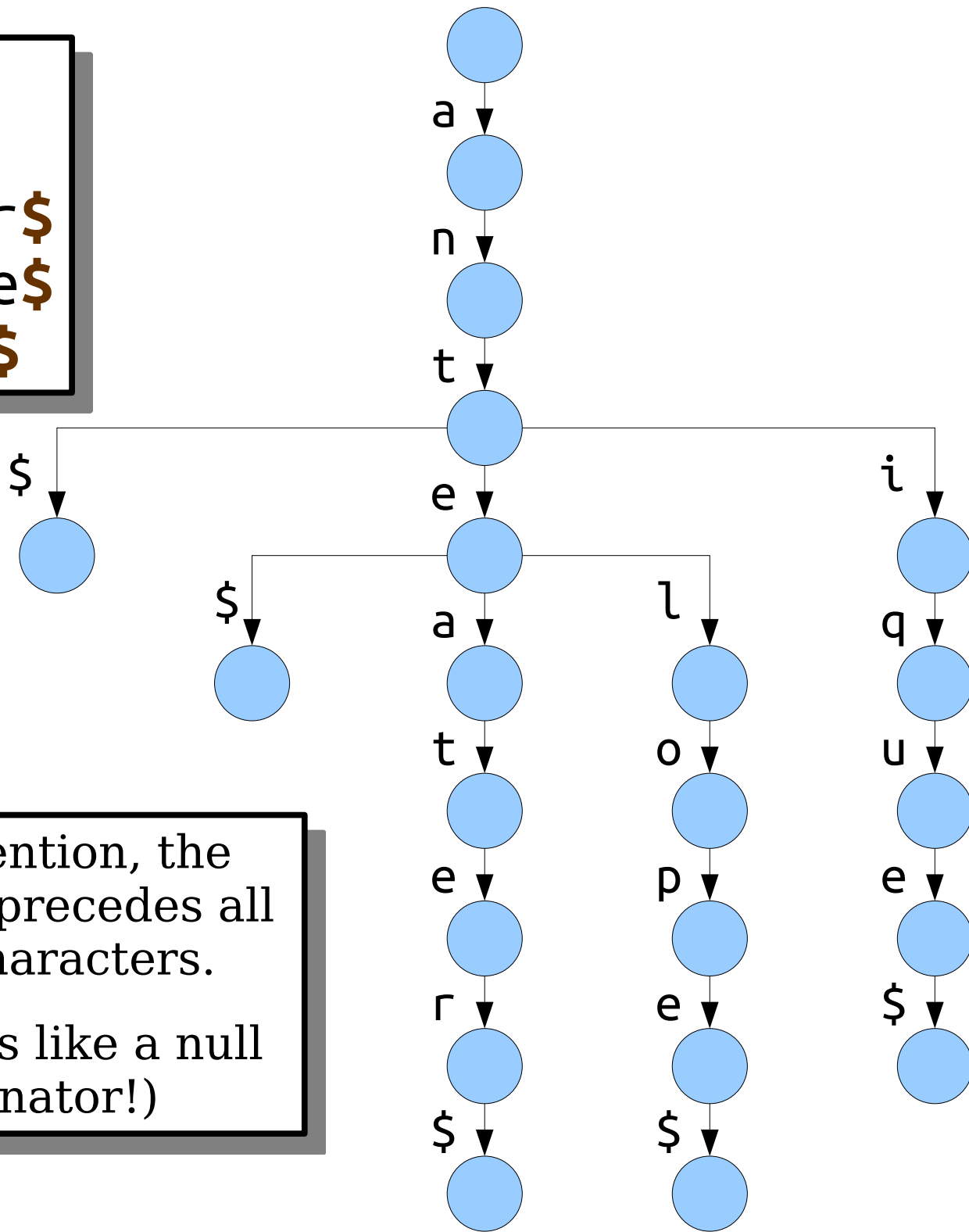


ant\$  
ante\$  
anteater\$  
antelope\$  
antique\$



The \$ symbol is called the ***sentinel*** or ***end-marker***. It's a special character that can only appear at the ends of words. (Think "null terminator," Theoryland edition.)

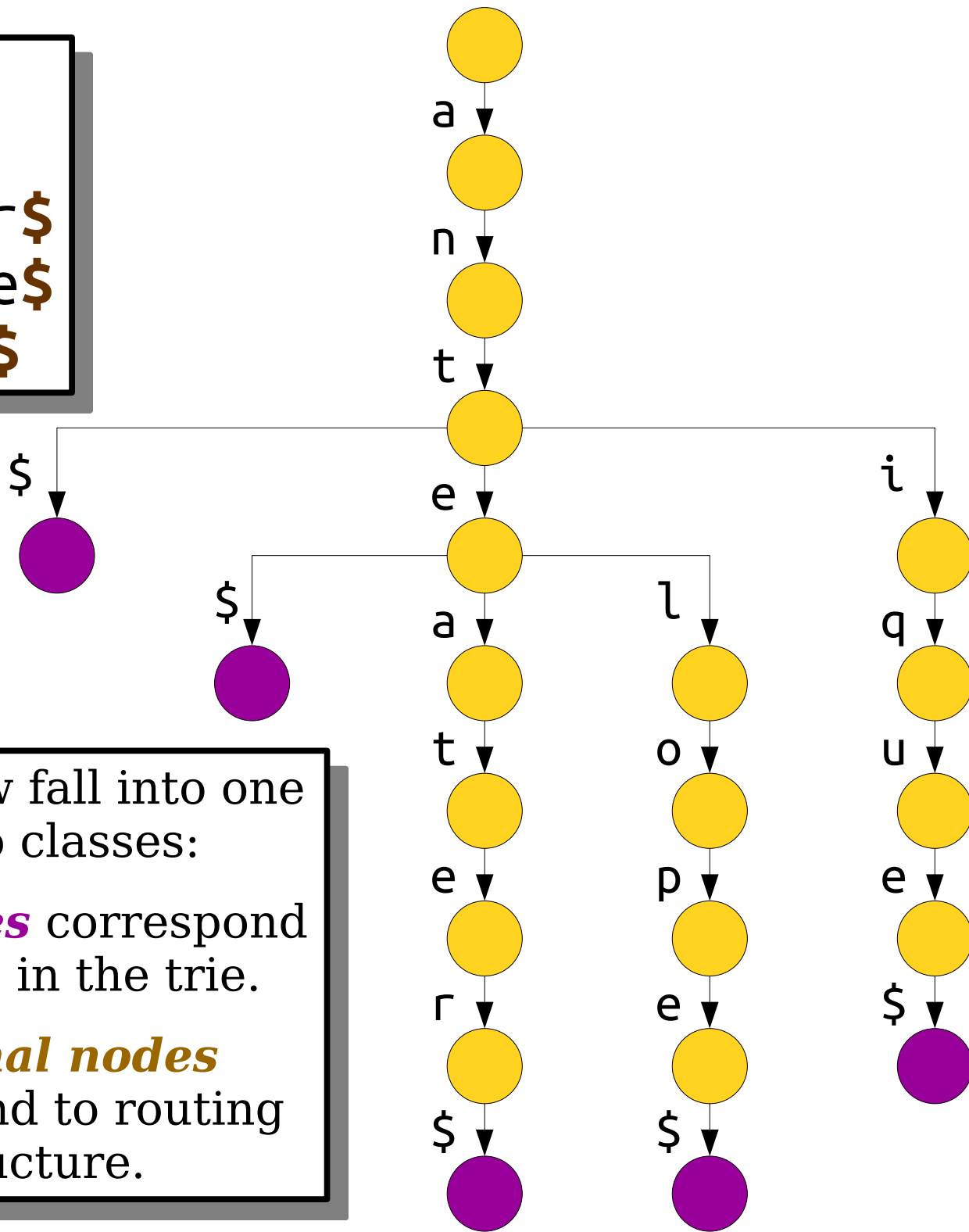
ant\$  
ante\$  
anteater\$  
antelope\$  
antique\$



By convention, the  
sentinel \$ precedes all  
other characters.

(It really is like a null  
terminator!)

ant\$  
ante\$  
anteater\$  
antelope\$  
antique\$

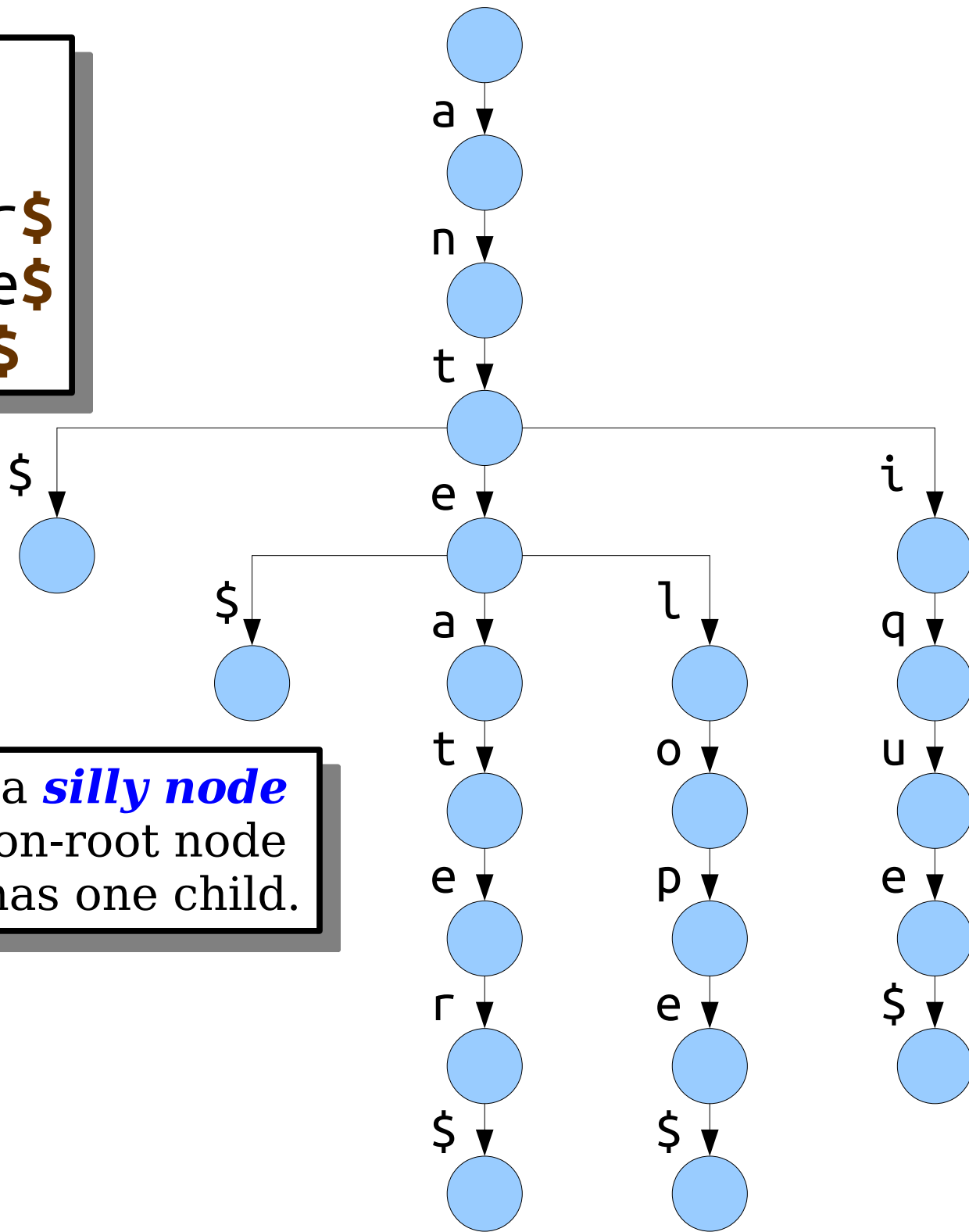


Nodes now fall into one of two classes:

**Leaf nodes** correspond to words in the trie.

**Internal nodes** correspond to routing structure.

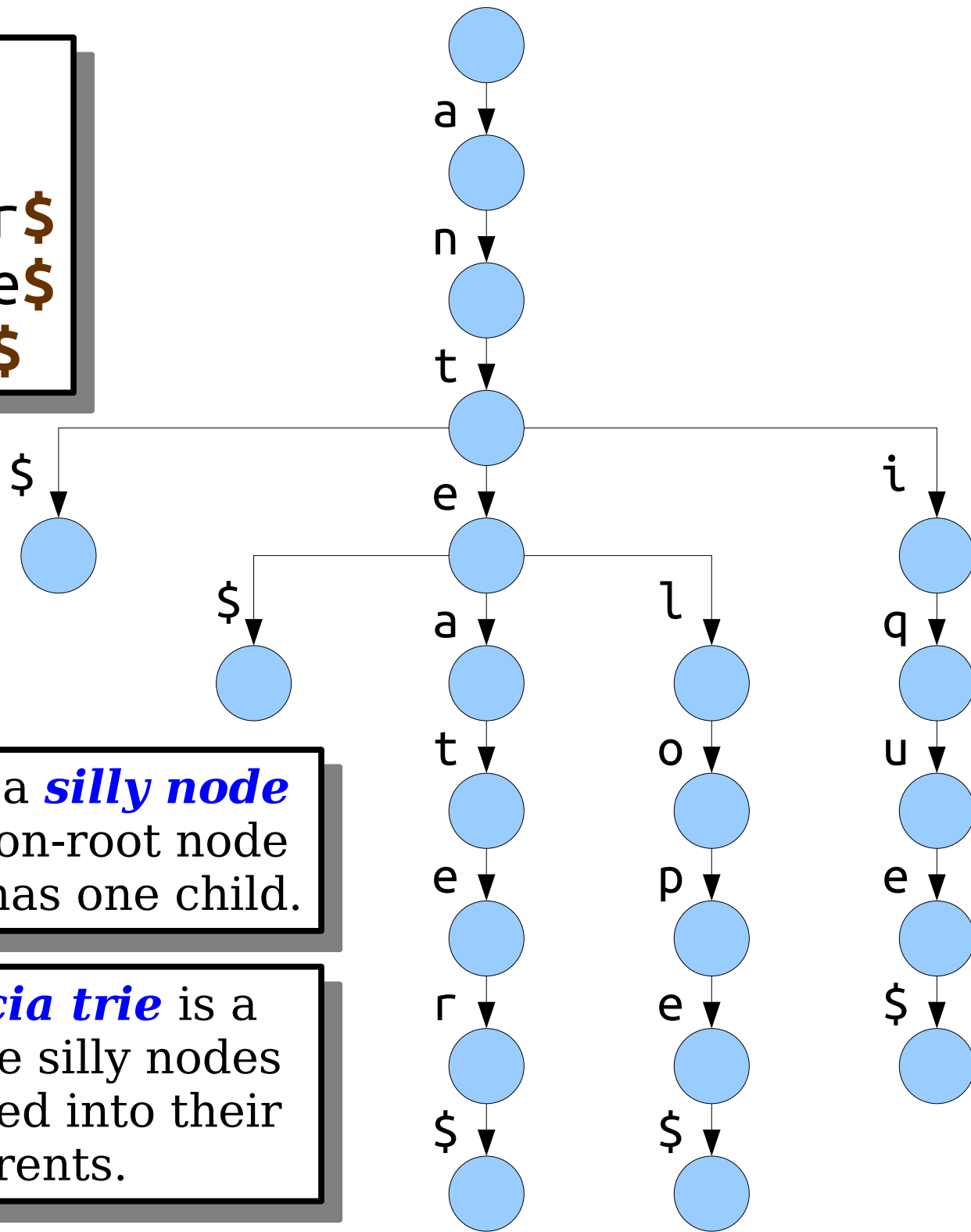
ant\$  
ante\$  
anteater\$  
antelope\$  
antique\$



A node is a ***silly node***  
if it is a non-root node  
that only has one child.



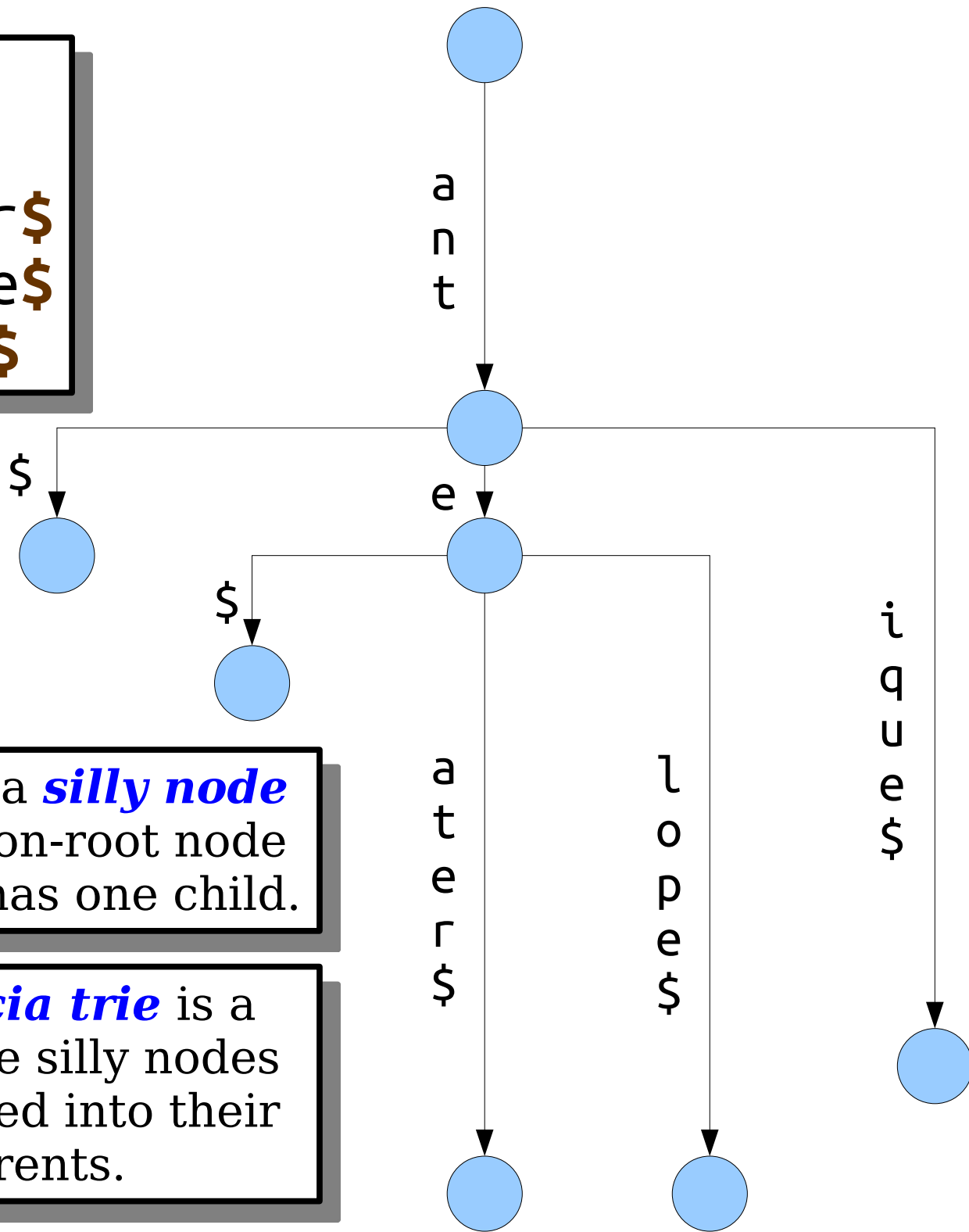
ant\$  
ante\$  
anteater\$  
antelope\$  
antique\$



A node is a ***silly node*** if it is a non-root node that only has one child.

A ***Patricia trie*** is a trie where silly nodes are merged into their parents.

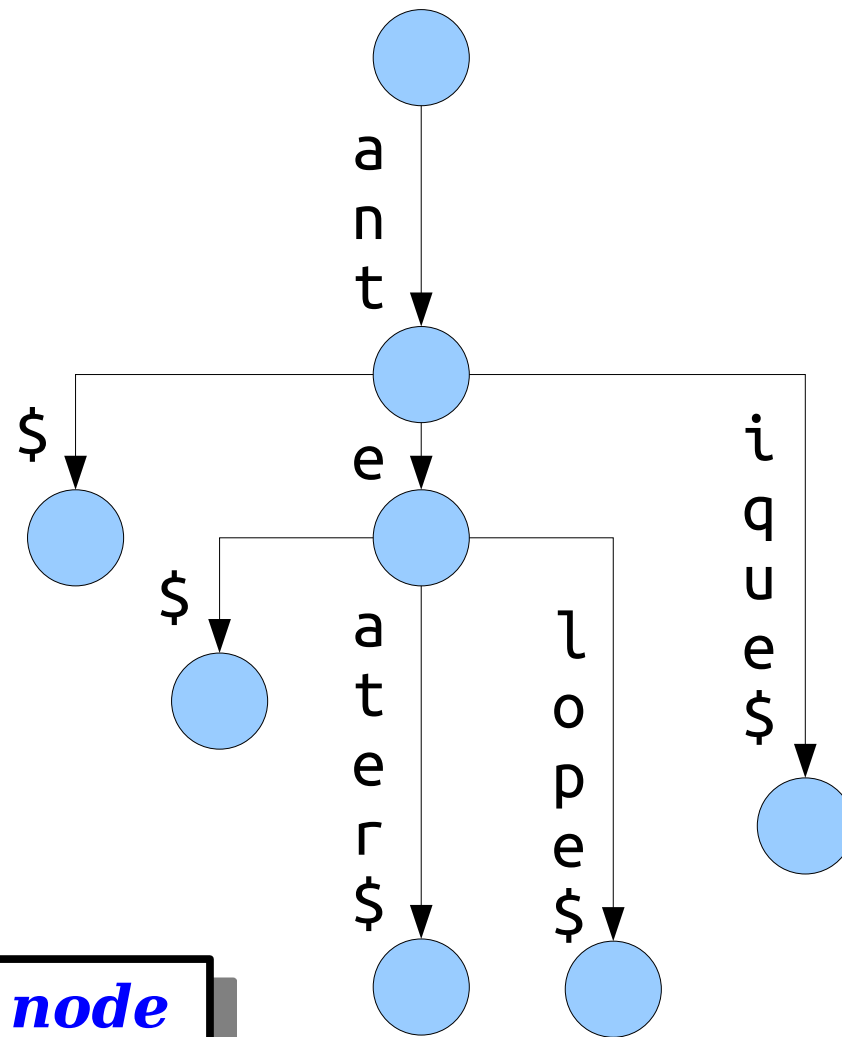
ant\$  
ante\$  
anteater\$  
antelope\$  
antique\$



A node is a ***silly node*** if it is a non-root node that only has one child.

A ***Patricia trie*** is a trie where silly nodes are merged into their parents.

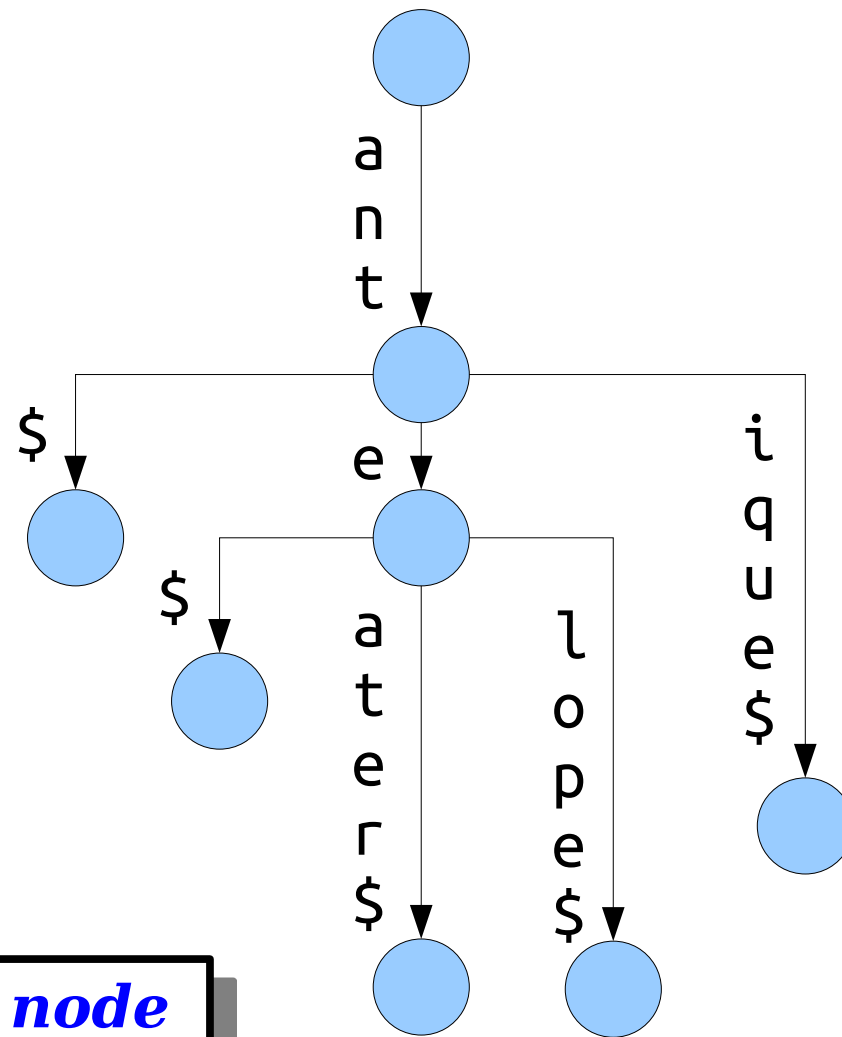
ant\$  
ante\$  
anteater\$  
antelope\$  
antique\$



A node is a ***silly node*** if it is a non-root node that only has one child.

A ***Patricia trie*** is a trie where silly nodes are merged into their parents.

ant\$  
ante\$  
anteater\$  
antelope\$  
antique\$

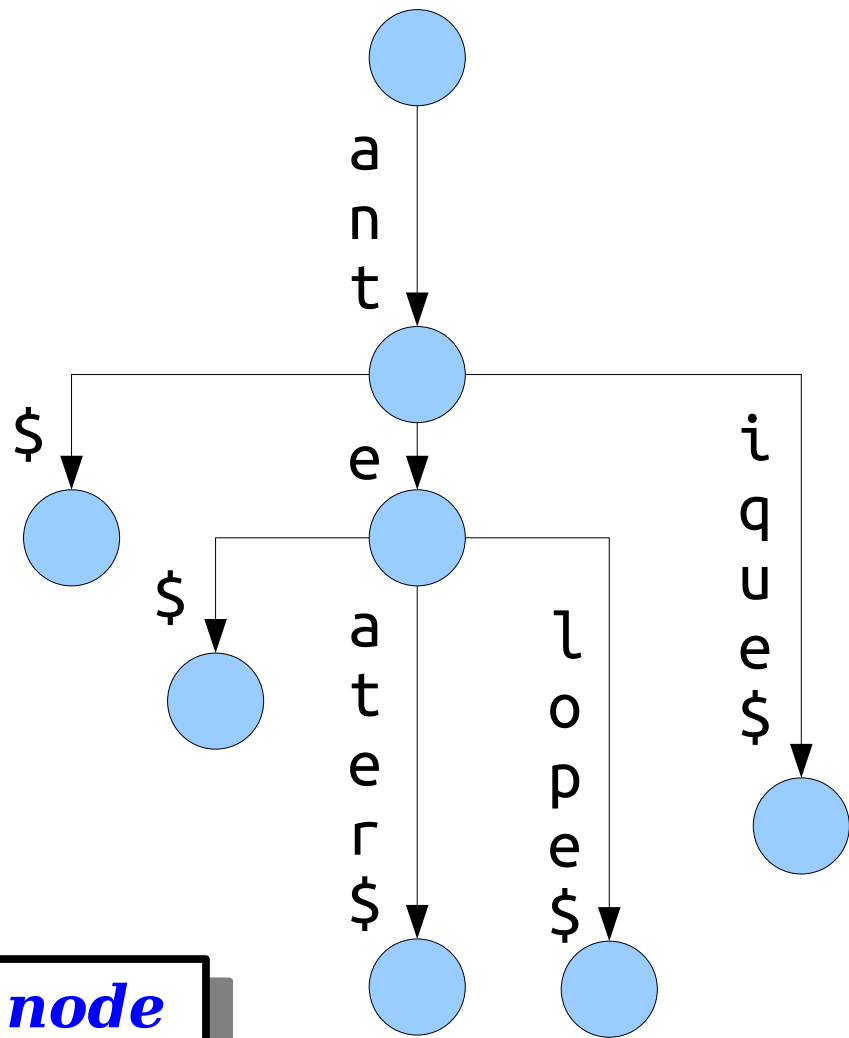


A node is a ***silly node*** if it is a non-root node that only has one child.

A *Patricia trie* is a trie where silly nodes are merged into their parents.

**Observation 1:** Every internal node in a Patricia trie (except possibly the root) has two or more children.

ant\$  
ante\$  
anteater\$  
antelope\$  
antique\$



A node is a ***silly node*** if it is a non-root node that only has one child.

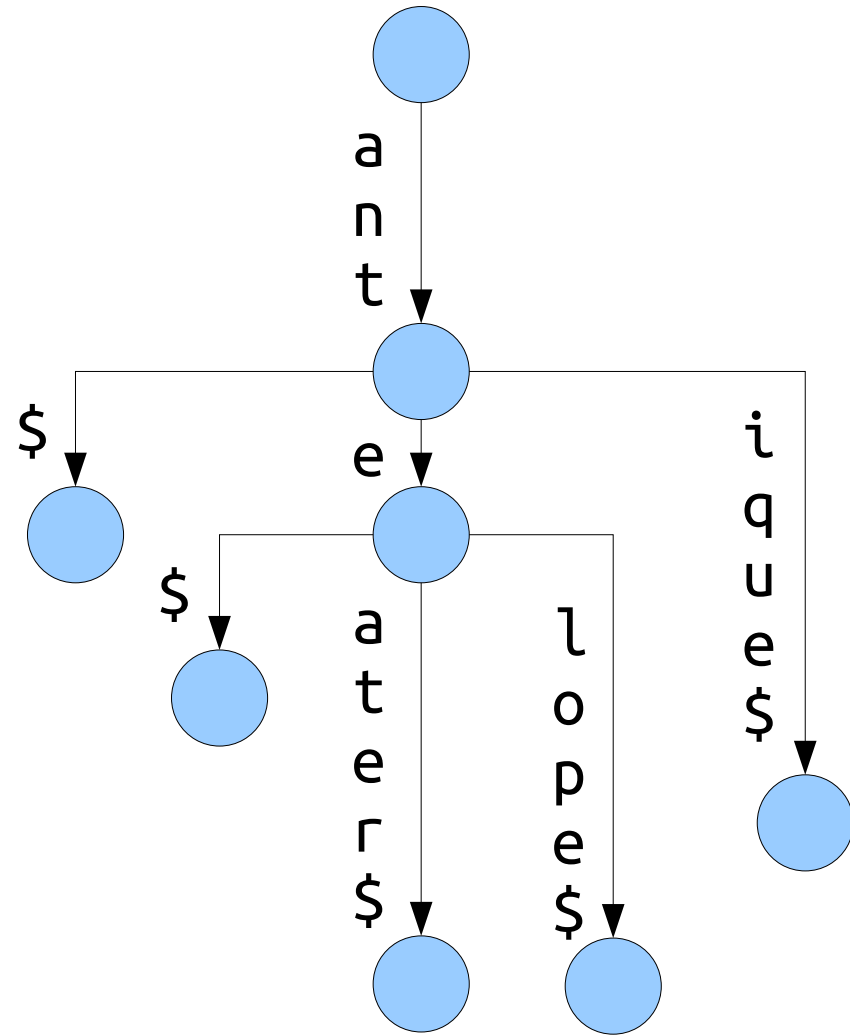
A *Patricia trie* is a trie where silly nodes are merged into their parents.

***Observation 2:***  
Leaves correspond to words; internal nodes are there for routing purposes.

***Observation 2:***  
Leaves correspond to words; internal nodes are there for routing purposes.

# Patricia Tries

- **Theorem:** The number of nodes in a Patricia trie with  $k$  words is always  $O(k)$ , regardless of what those words are.



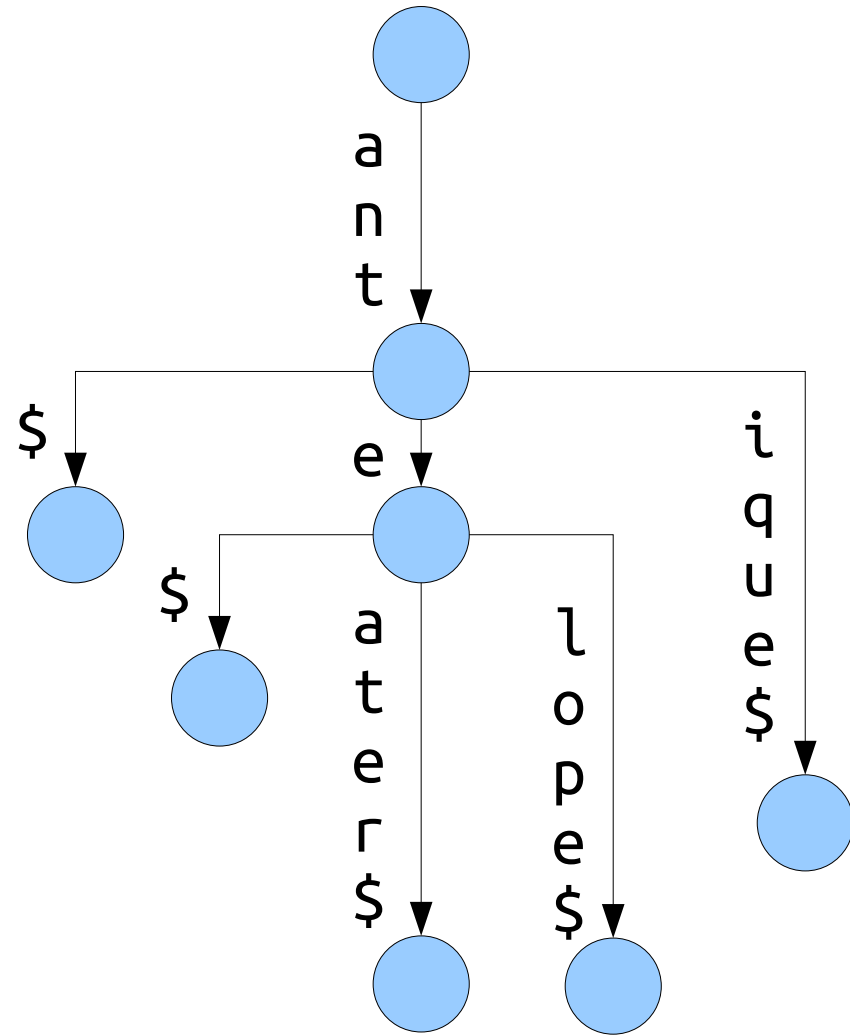
# Patricia Tries

- **Theorem:** The number of nodes in a Patricia trie with  $k$  words is always  $O(k)$ , regardless of what those words are.

Why?

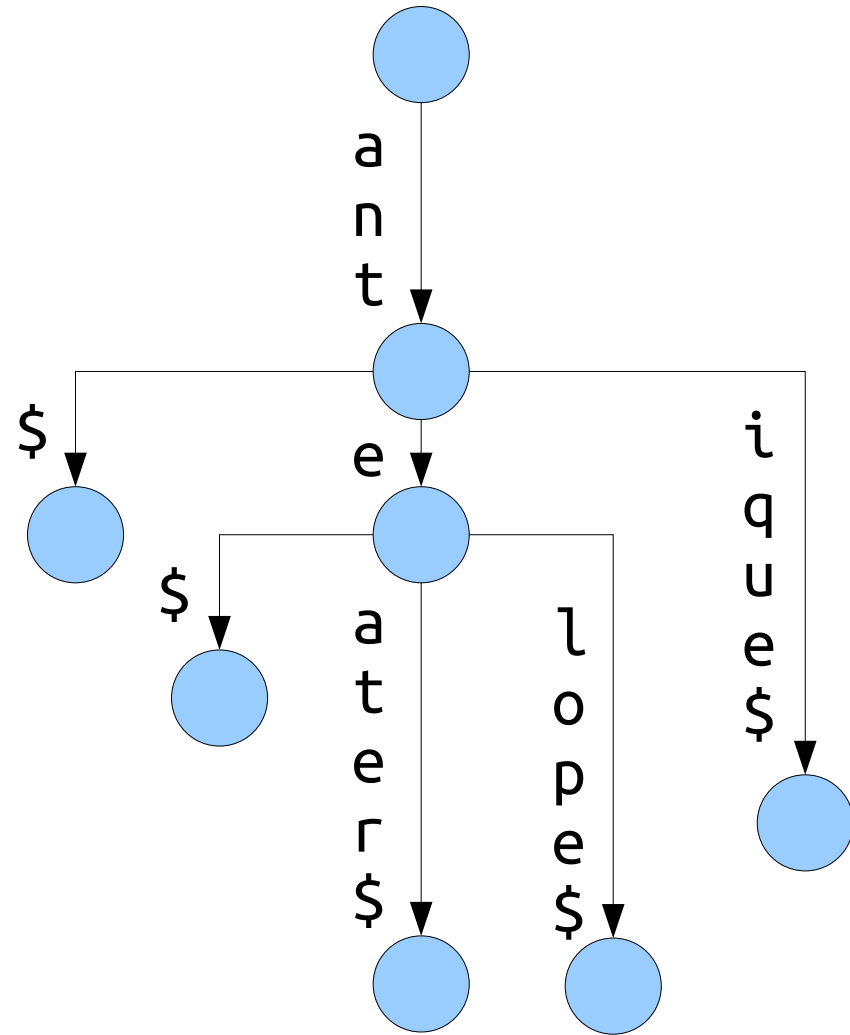
Answer at

<https://cs166.stanford.edu/pollev>



# Patricia Tries

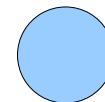
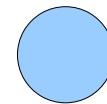
- **Theorem:** The number of nodes in a Patricia trie with  $k$  words is always  $O(k)$ , regardless of what those words are.



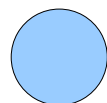
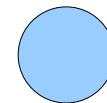
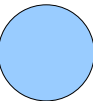


# Patricia Tries

- **Theorem:** The number of nodes in a Patricia trie with  $k$  words is always  $O(k)$ , regardless of what those words are.

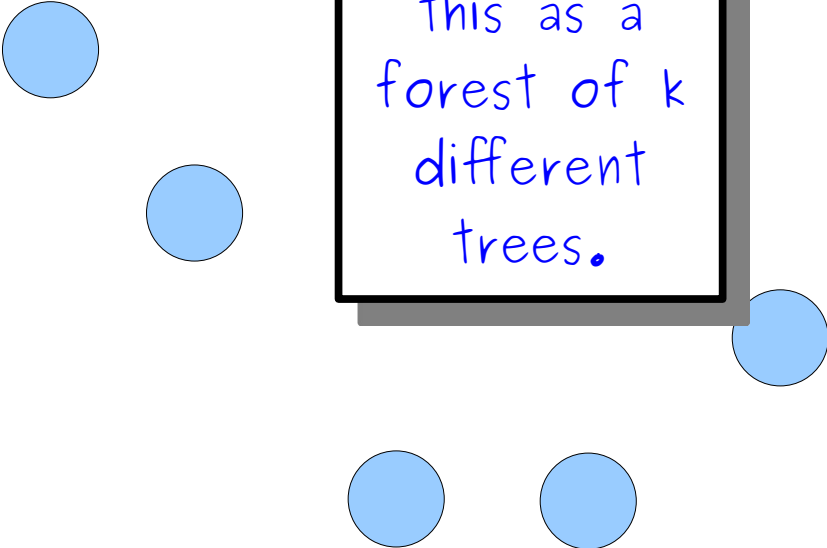


There are  $k$   
leaves, one  
per word in  
the trie.



# Patricia Tries

- **Theorem:** The number of nodes in a Patricia trie with  $k$  words is always  $O(k)$ , regardless of what those words are.



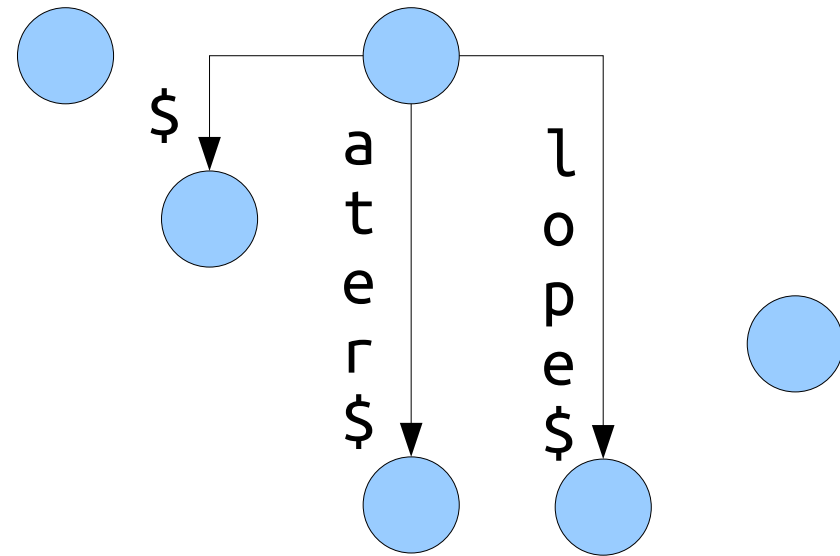
Think of this as a forest of  $k$  different trees.

The diagram illustrates a Patricia trie structure. It consists of five light blue circular nodes. One node is at the top left, another is to its right and slightly lower. Below the right node is another node. At the bottom, there are two nodes side-by-side. A rectangular box with a black border and a grey drop shadow is positioned to the right of the middle node, containing the text 'Think of this as a forest of k different trees.'

# Patricia Tries

- **Theorem:** The number of nodes in a Patricia trie with  $k$  words is always  $O(k)$ , regardless of what those words are.

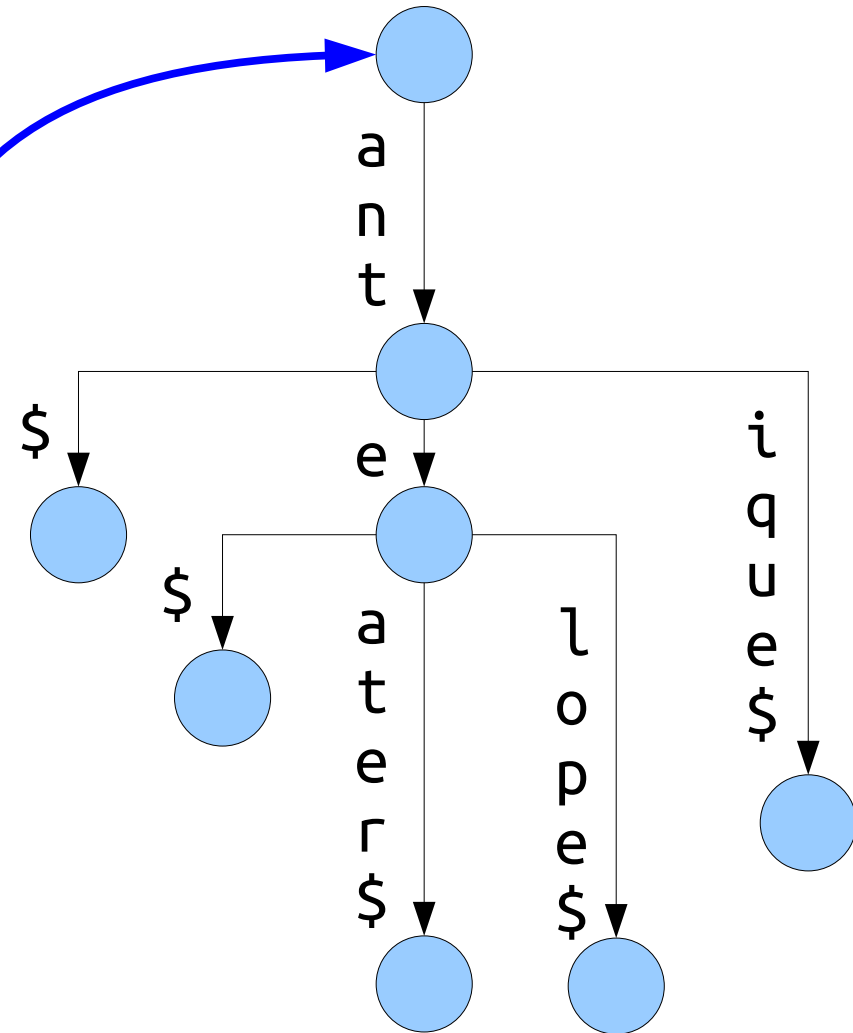
Adding an internal node merges two or more trees together, decreasing the number of trees by at least one.



# Patricia Tries

- **Theorem:** The number of nodes in a Patricia trie with  $k$  words is always  $O(k)$ , regardless of what those words are.

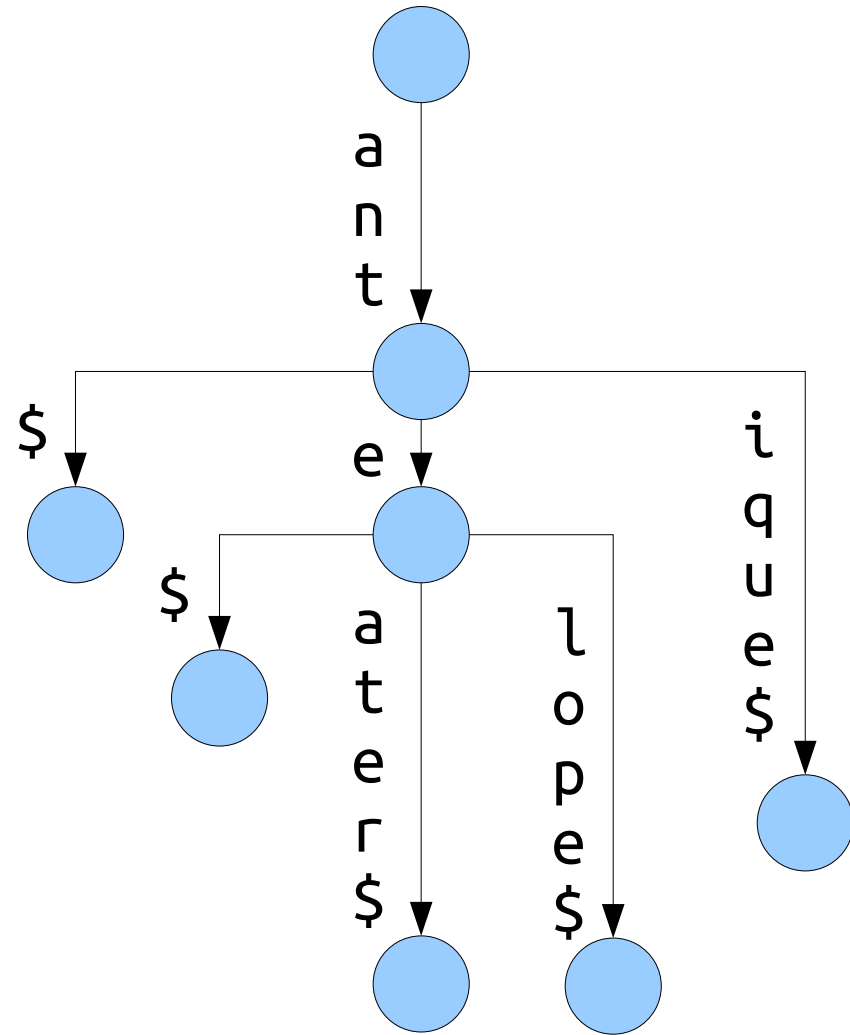
Adding the root might not decrease the number of trees, but there's only one root.



# Patricia Tries

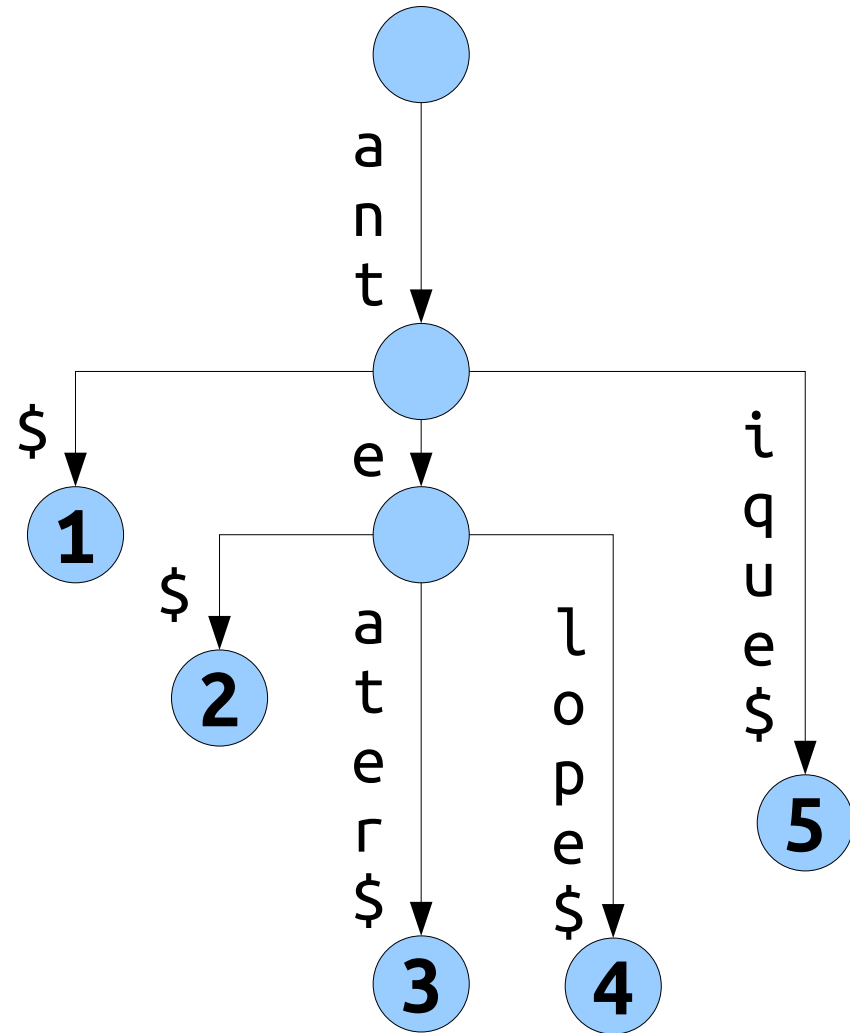
- **Theorem:** The number of nodes in a Patricia trie with  $k$  words is always  $O(k)$ , regardless of what those words are.
- **Proof Sketch:** There are  $k$  leaves, one per word. Remove all internal nodes, leaving a forest of  $k$  trees.

Add the internal nodes back one at a time. Each addition (except possibly root) decreases the number of trees in the forest by at least one, since each (non-root) internal node has at least two children. This means there are at most  $k$  internal nodes, for a total of  $O(k)$  nodes. ■



# Patricia Tries

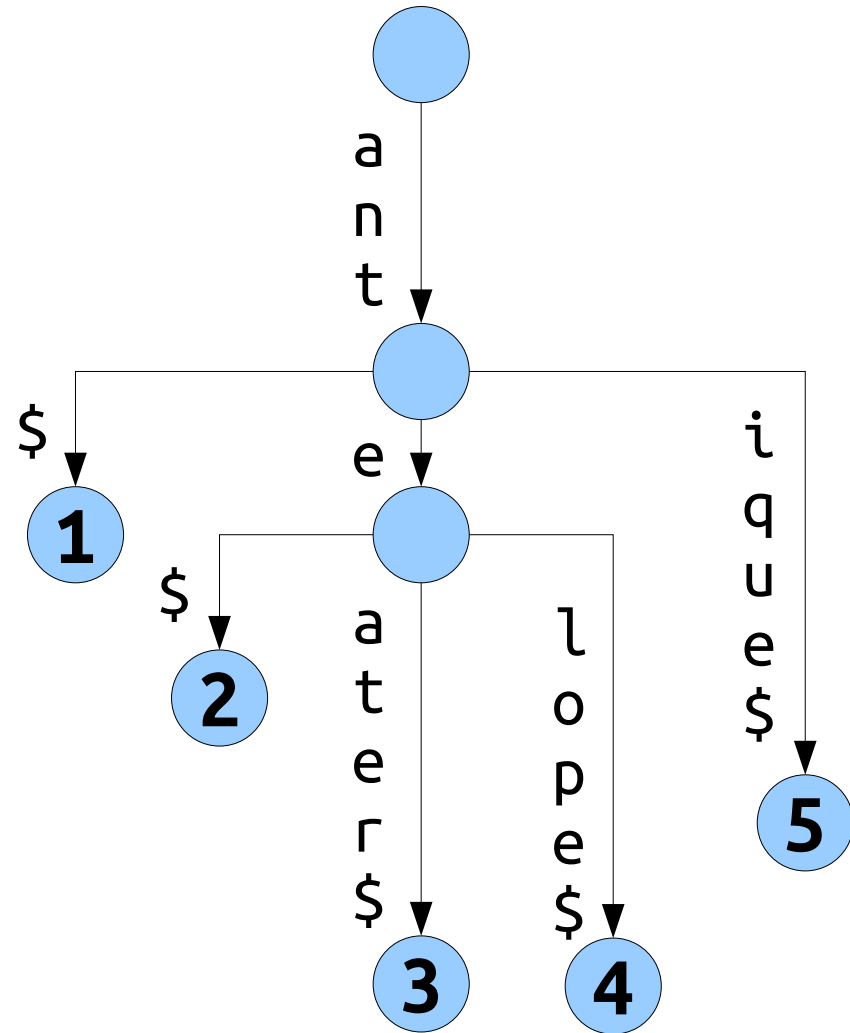
- **Claim:** If each leaf in a Patricia trie is annotated with the index of the word it comes from, the indices of strings starting with a given prefix can be found in time  $O(n + z)$ , where  $n$  is the length of that prefix and  $z$  is the number of matches.
- **Question:** How is this possible?



Answer at  
<https://cs166.stanford.edu/pollev>

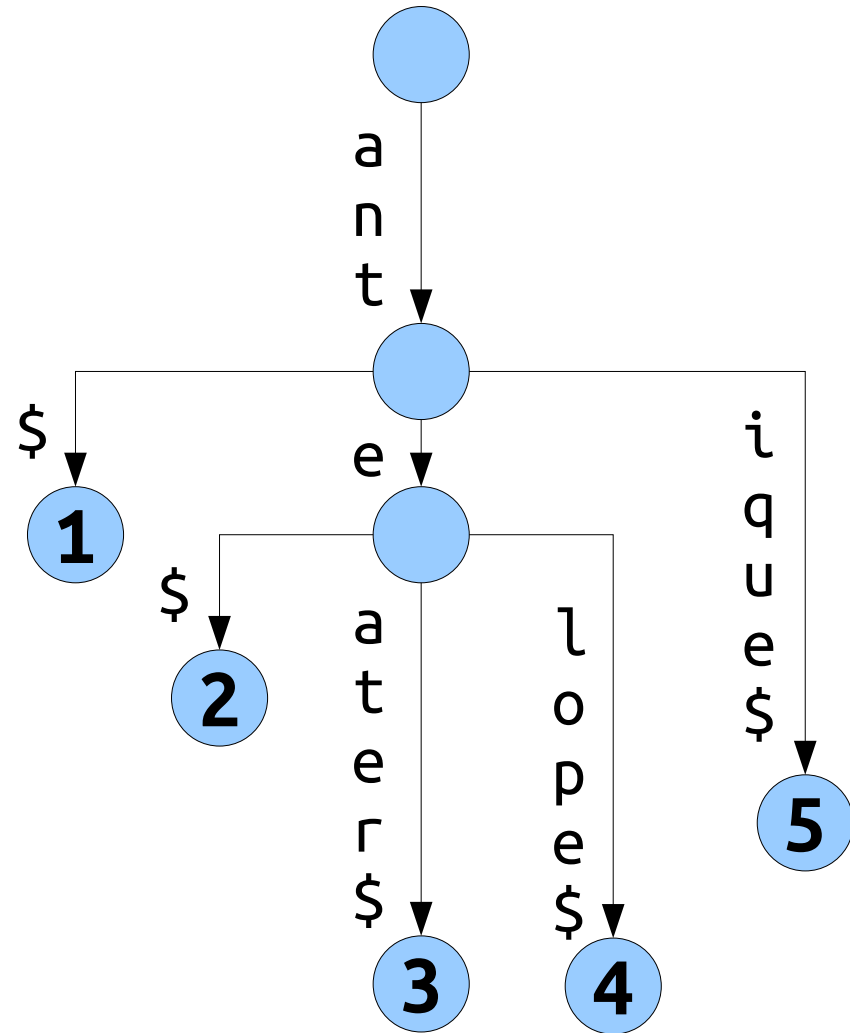
# Patricia Tries

- Use a two-phase search algorithm!
- **(Character-aware)** Read the prefix to search for, matching characters as you walk down the Patricia trie.
  - Time required:  $O(n)$ , since we have to read all the characters of the prefix.
- **(Character-blind)** If you didn't walk off the trie, do a DFS below your current point to find all leaves, ignoring the strings on the edges.
  - Time required:  $O(z)$ . If there are  $z$  matches, there are  $z$  leaves to explore. As we saw earlier, in a Patricia trie, a subtree with  $z$  leaves has  $O(z)$  total nodes.



# The Story So Far

- Adopting our notation from RMQ, a Patricia trie gives an  $\langle O(\textcolor{blue}{m}), O(\textcolor{violet}{n} + \textcolor{brown}{z}) \rangle$  solution to prefix matching.
- Those runtimes hide the effect of the alphabet size; take some time to evaluate those tradeoffs!





## Part II: *Suffix Trees*

# Two Motivating Problems



The *United States Statutes at Large* contains all  
legislation ever passed in the United States.  
Make it searchable.



Cancers often have repeated copies the same gene.

Given a cancer genome (length  $\sim 3,000,000,000$ ),  
find the longest repeated DNA sequence.

Patricia tries are great tools for finding *prefixes*.

These problems involve looking for *substrings*.

Can we use what we've developed so far?

# A Fundamental Theorem

- The ***fundamental theorem of stringology*** says that, given two strings  $w$  and  $x$ , that

**$w$  is a substring of  $x$**   
*if and only if*  
 **$w$  is a prefix of a suffix of  $x$**

|   |   |
|---|---|
| b | e |
|---|---|

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| f | l | i | b | b | e | r | t | i | g | i | b | b | e | t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

# A Fundamental Theorem

- The ***fundamental theorem of stringology*** says that, given two strings  $w$  and  $x$ , that

**$w$  is a substring of  $x$**   
*if and only if*  
 **$w$  is a prefix of a suffix of  $x$**

|   |   |
|---|---|
| b | e |
|---|---|

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| f | l | i | b | b | e | r | t | i | g | i | b | b | e | t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

# A Fundamental Theorem

- The ***fundamental theorem of stringology*** says that, given two strings  $w$  and  $x$ , that

**$w$  is a substring of  $x$**   
*if and only if*  
 **$w$  is a prefix of a suffix of  $x$**

|   |   |
|---|---|
| b | e |
|---|---|

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| f | l | i | b | b | e | r | t | i | g | i | b | b | e | t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|



# A Fundamental Theorem

- The ***fundamental theorem of stringology*** says that, given two strings  $w$  and  $x$ , that

**$w$  is a substring of  $x$**   
*if and only if*  
 **$w$  is a prefix of a suffix of  $x$**

|   |   |
|---|---|
| b | e |
|---|---|

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| f | l | i | b | b | e | r | t | i | g | i | b | b | e | t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

# A Fundamental Theorem

- The ***fundamental theorem of stringology*** says that, given two strings  $w$  and  $x$ , that

**$w$  is a substring of  $x$**   
*if and only if*  
 **$w$  is a prefix of a suffix of  $x$**



# A Fundamental Theorem

- The ***fundamental theorem of stringology*** says that, given two strings  $w$  and  $x$ , that

**$w$  is a substring of  $x$**   
*if and only if*  
 **$w$  is a prefix of a suffix of  $x$**

|   |   |
|---|---|
| b | e |
|---|---|

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| f | l | i | b | b | e | r | t | i | g | i | b | b | e | t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

# A Fundamental Theorem

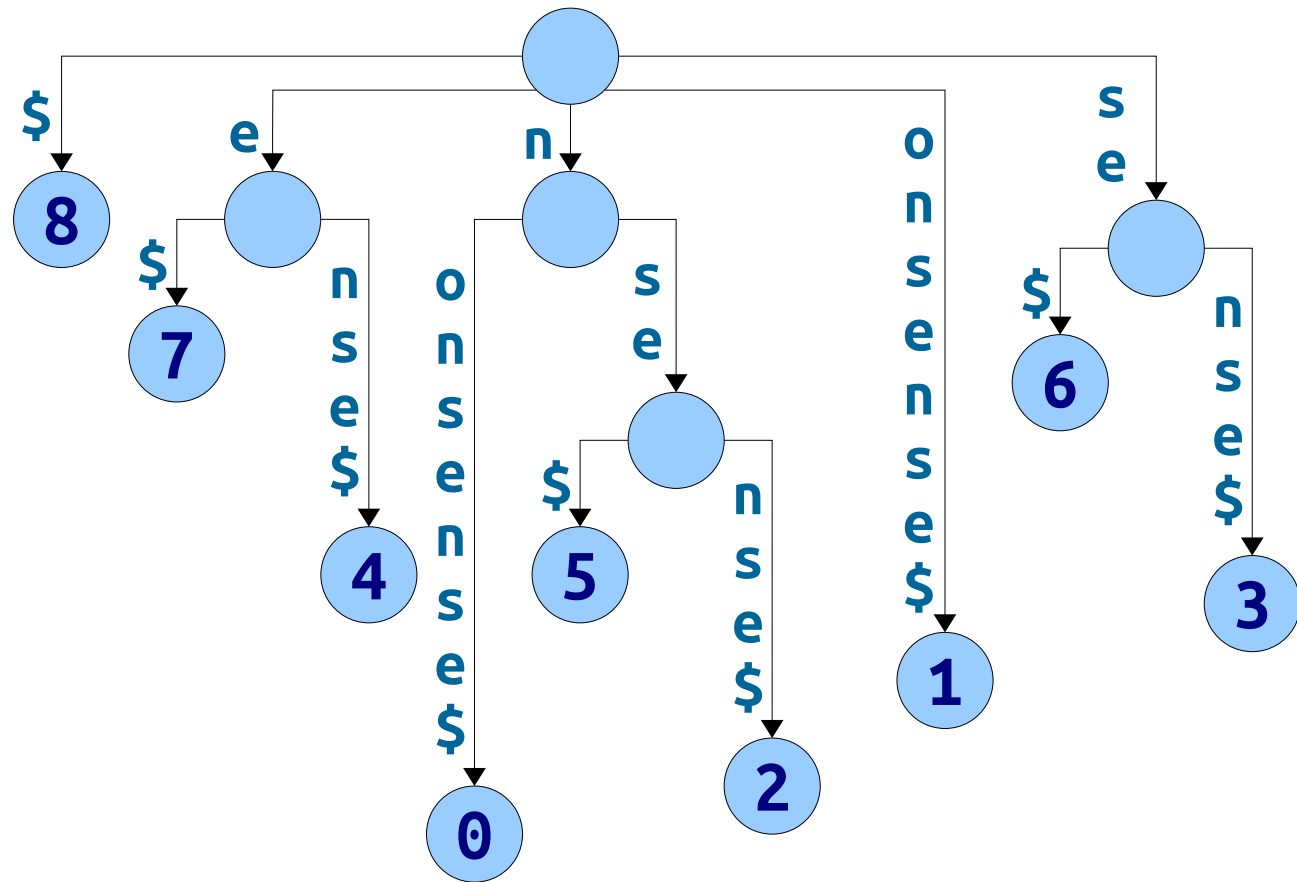
- The ***fundamental theorem of stringology*** says that, given two strings  $w$  and  $x$ , that

**$w$  is a substring of  $x$**   
*if and only if*

**$w$  is a prefix of a suffix of  $x$**

- To find all matches of  $w$  in  $x$ , we just need to find all suffixes of  $x$  that start with  $w$ .

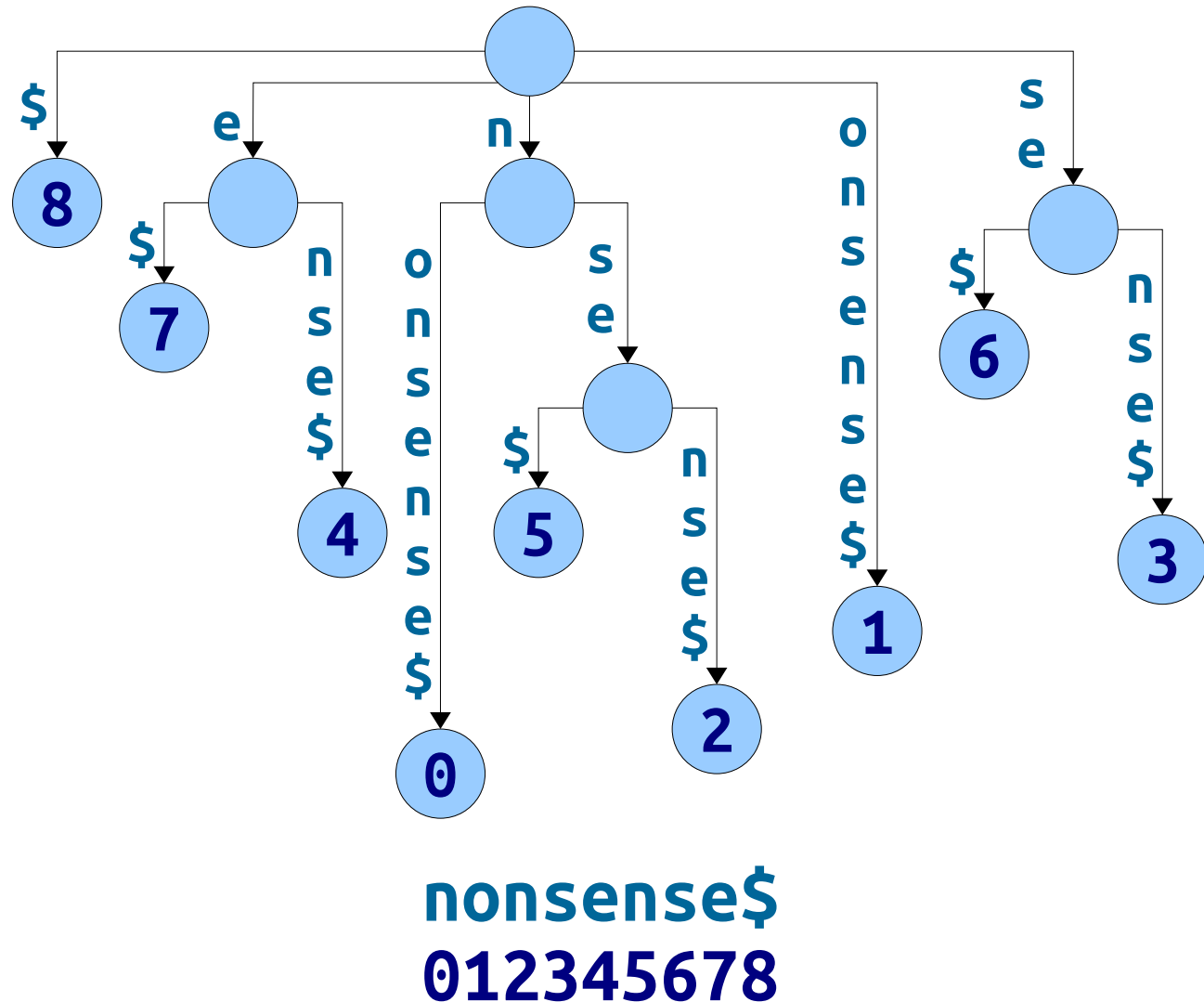
nonsense\$  
 onsense\$  
 nsense\$  
 sense\$  
 ense\$  
 nse\$  
 se\$  
 e\$  
 \$



nonsense\$  
 012345678

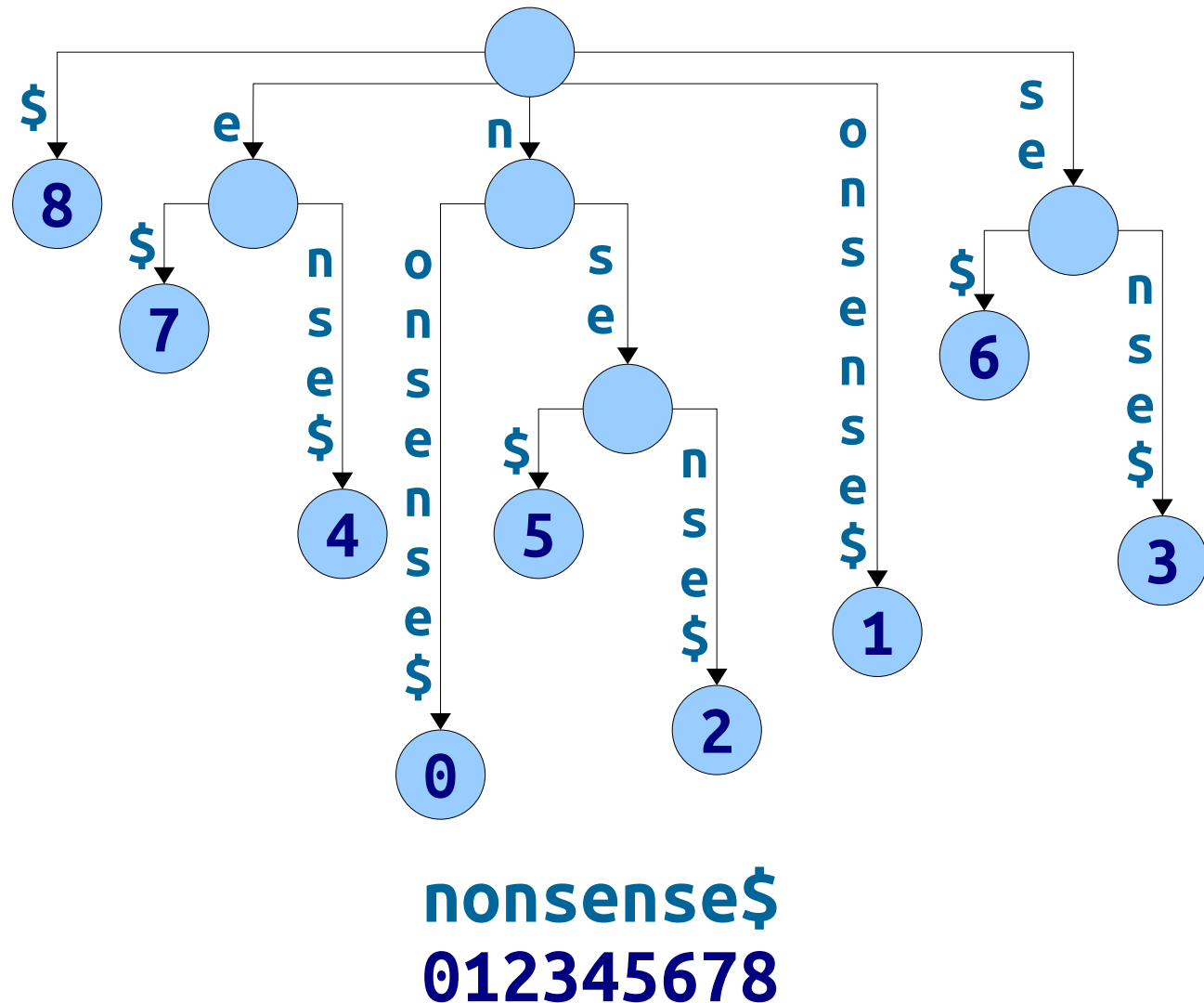
# Suffix Trees

- A **suffix tree** for a string  $T$  is a Patricia trie of all suffixes of  $T$ .
- Each leaf is labeled with the starting index of that suffix.
- Two facts:
  - It's possible to build a suffix tree from a string of length  $m$  in time  $O(m)$ . (Yes, really!)
  - It's possible to store a suffix tree for a string of length  $m$  using  $O(m)$  words of memory. (Yes, really!)



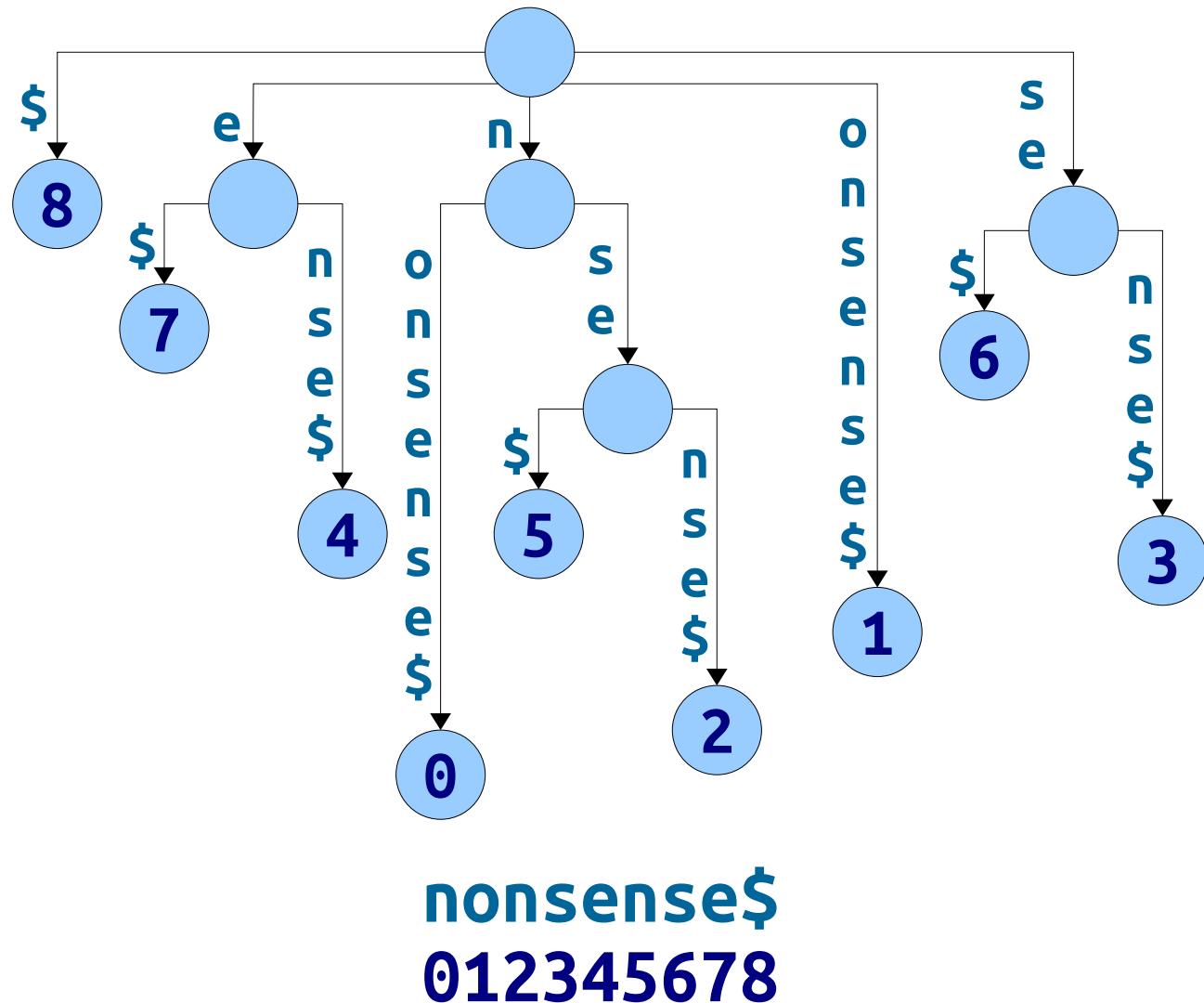
# Substring Search

- **Claim:** Once we have a suffix tree for a string  $T$ , we can find all matches of a pattern  $P$  of length  $n$  in time  $O(n + z)$ , where  $z$  is the number of matches.
- **Idea:** Use the standard Patricia trie search from before!



# Substring Search

- Look up the pattern in the suffix tree, then use a DFS to find all matches.
- Looking up the pattern takes time  $O(\textcolor{violet}{n})$ .
- Finding all matches takes time  $O(\textcolor{brown}{z})$ .





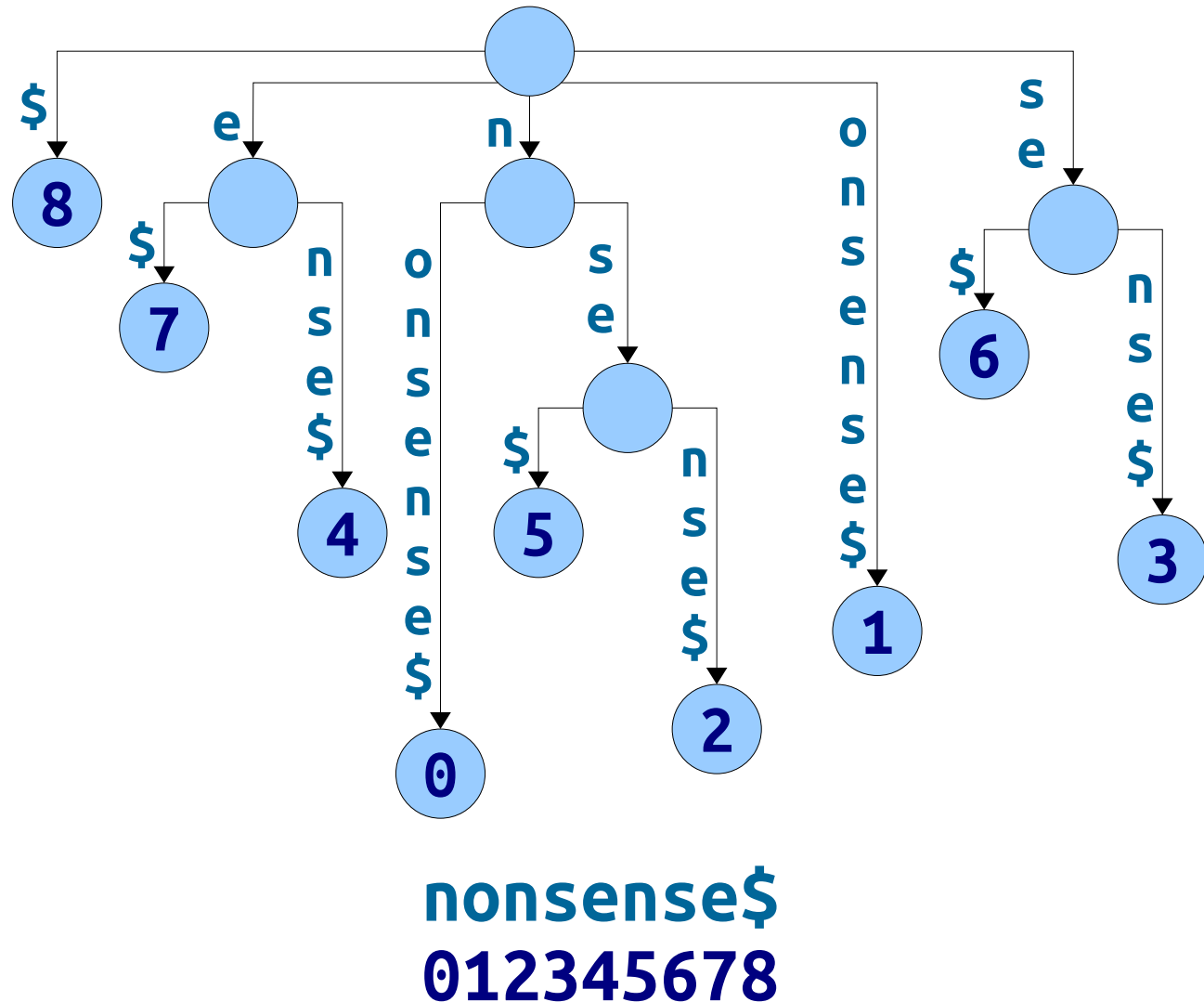


Cancers often have repeated copies the same gene.

Given a cancer genome (length  $\sim 3,000,000,000$ ),  
find the longest repeated DNA sequence.

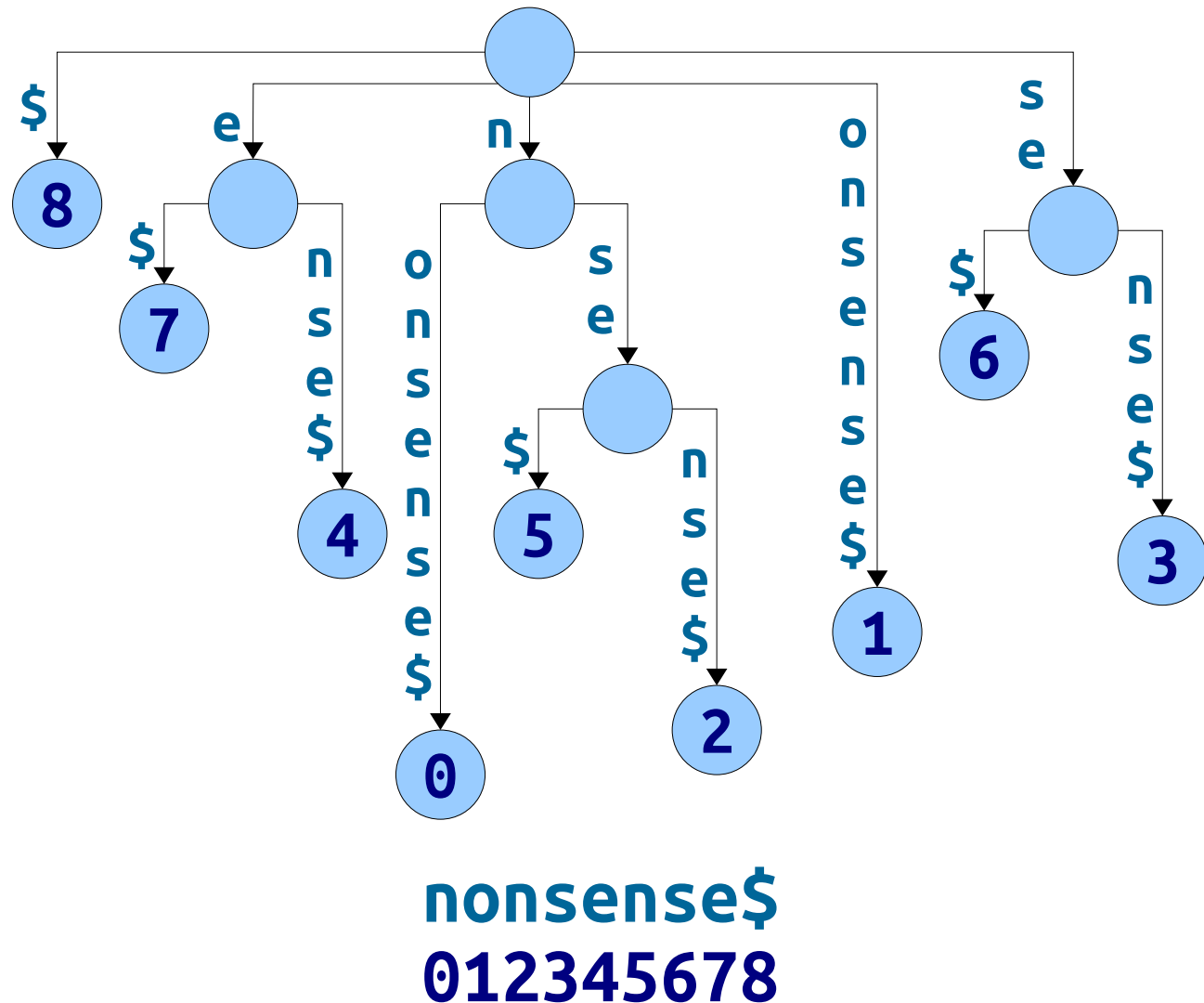
# The Anatomy of a Suffix Tree

- Think back to Cartesian trees. We can describe them in two ways.
  - Mechanically:** Hoist the minimum element up to the root, then recursively process the two subarrays.
  - Operationally:** It's a min-heap whose inorder traversal gives the original array.
- We now have a **mechanical** definition of a suffix tree. Can we get an **operational** one?



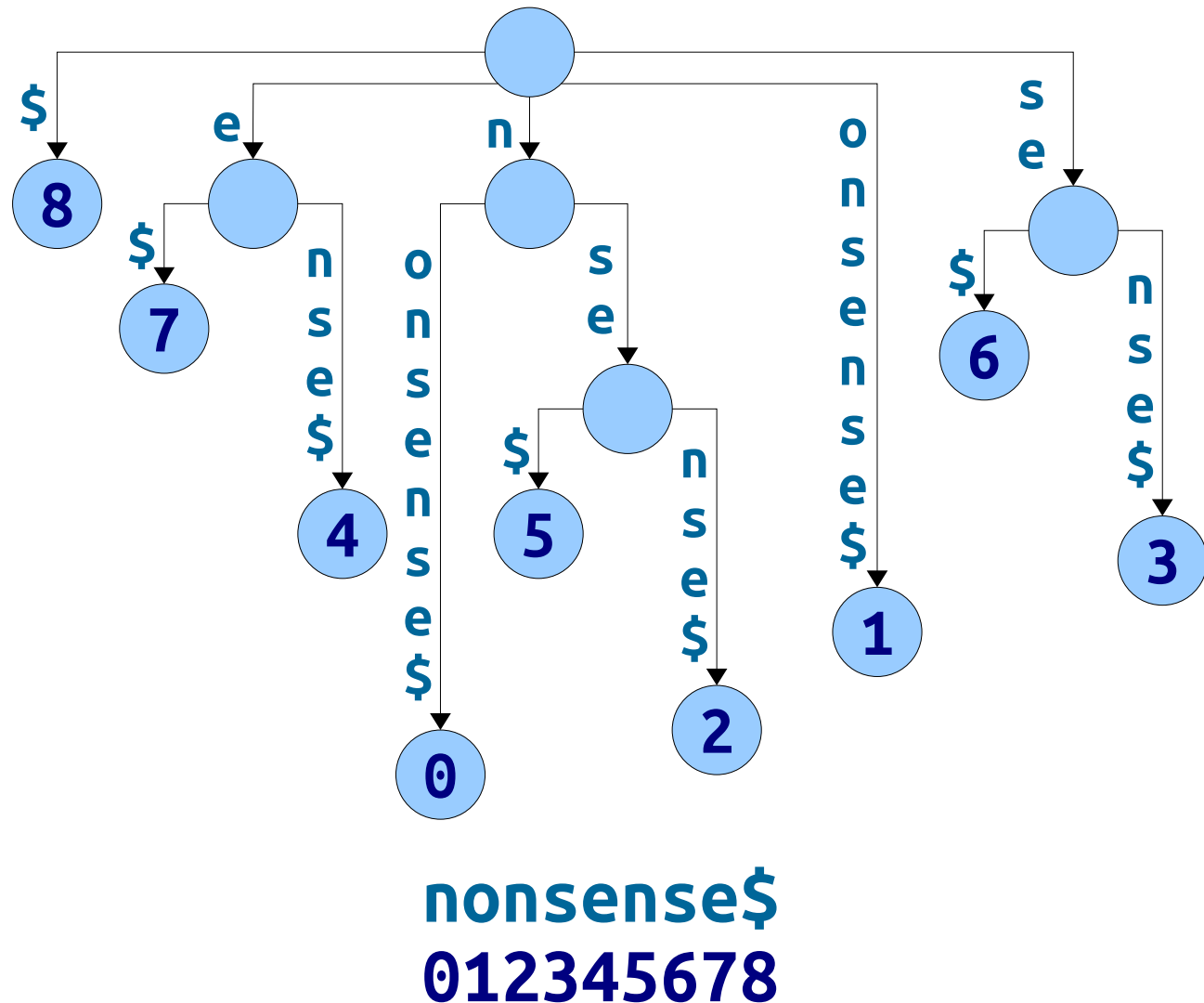
# The Anatomy of a Suffix Tree

- The leaves of a suffix tree correspond to the suffixes of the text string  $T$ .
- **Question:** What do the *internal* nodes of the suffix tree correspond to?



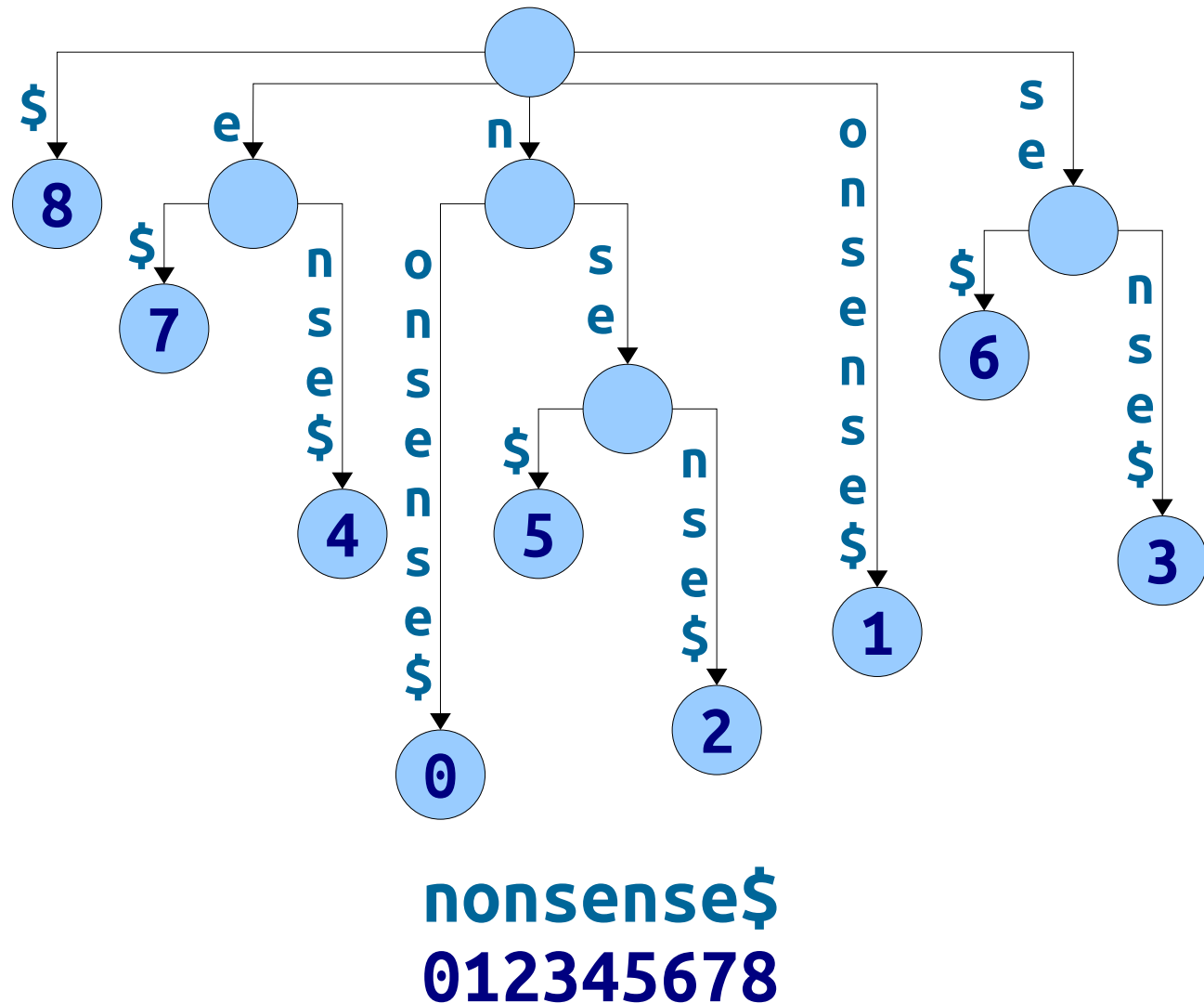
# The Anatomy of a Suffix Tree

- In this suffix tree, there are internal nodes for the substrings **e**, **n**, **nse**, and **se**.
- All these substrings appear at least twice in the original string!
- More generally: if there is an internal node for a substring  $\alpha$ , then  $\alpha$  appears at least twice in the original text.



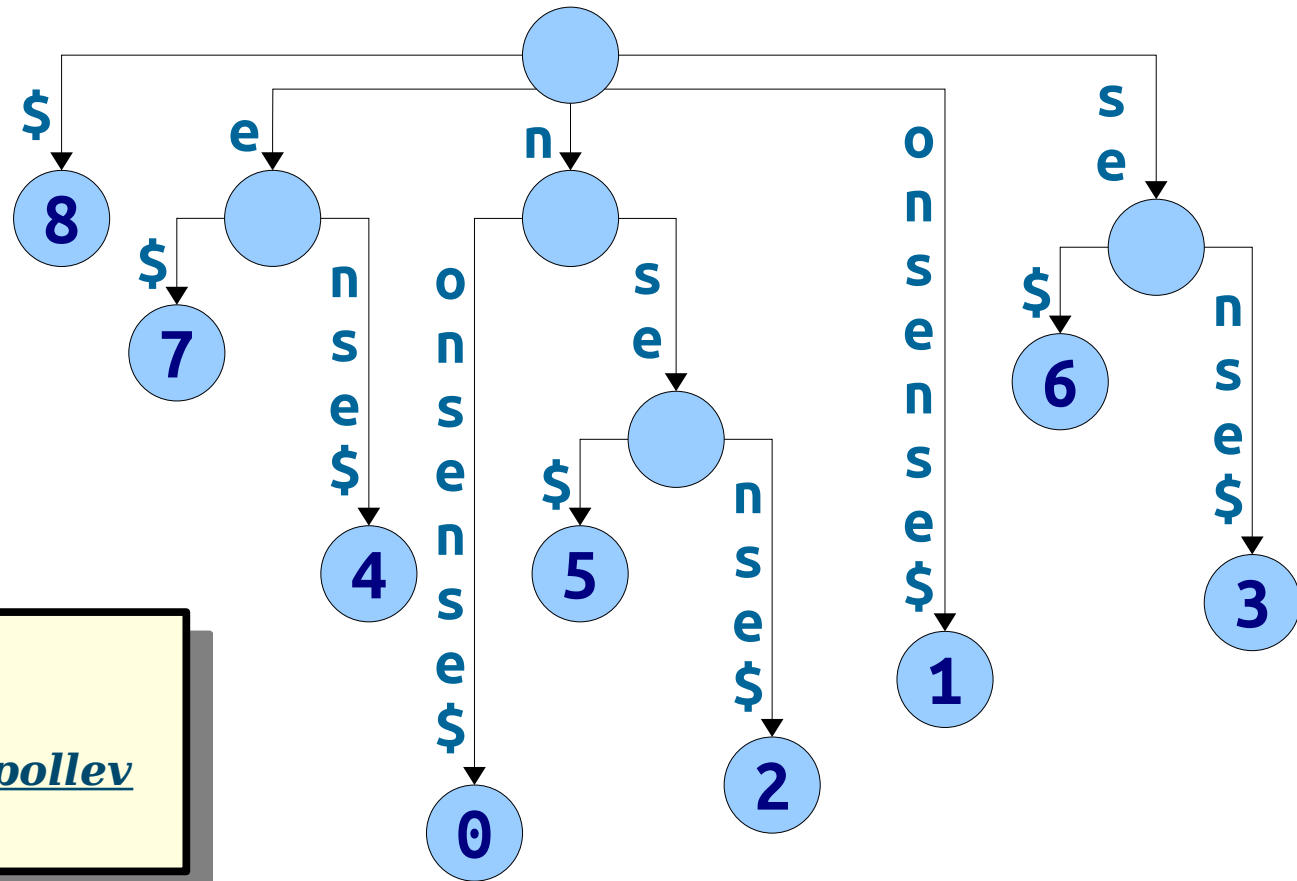
# The Anatomy of a Suffix Tree

- **Question:** why is there an internal node for the substring **n**, but *isn't* there an internal node for the substring **ns**?



# The Anatomy of a Suffix Tree

- Question:** why is there an internal node for the substring **n**, but *isn't* there an internal node for the substring **ns**?



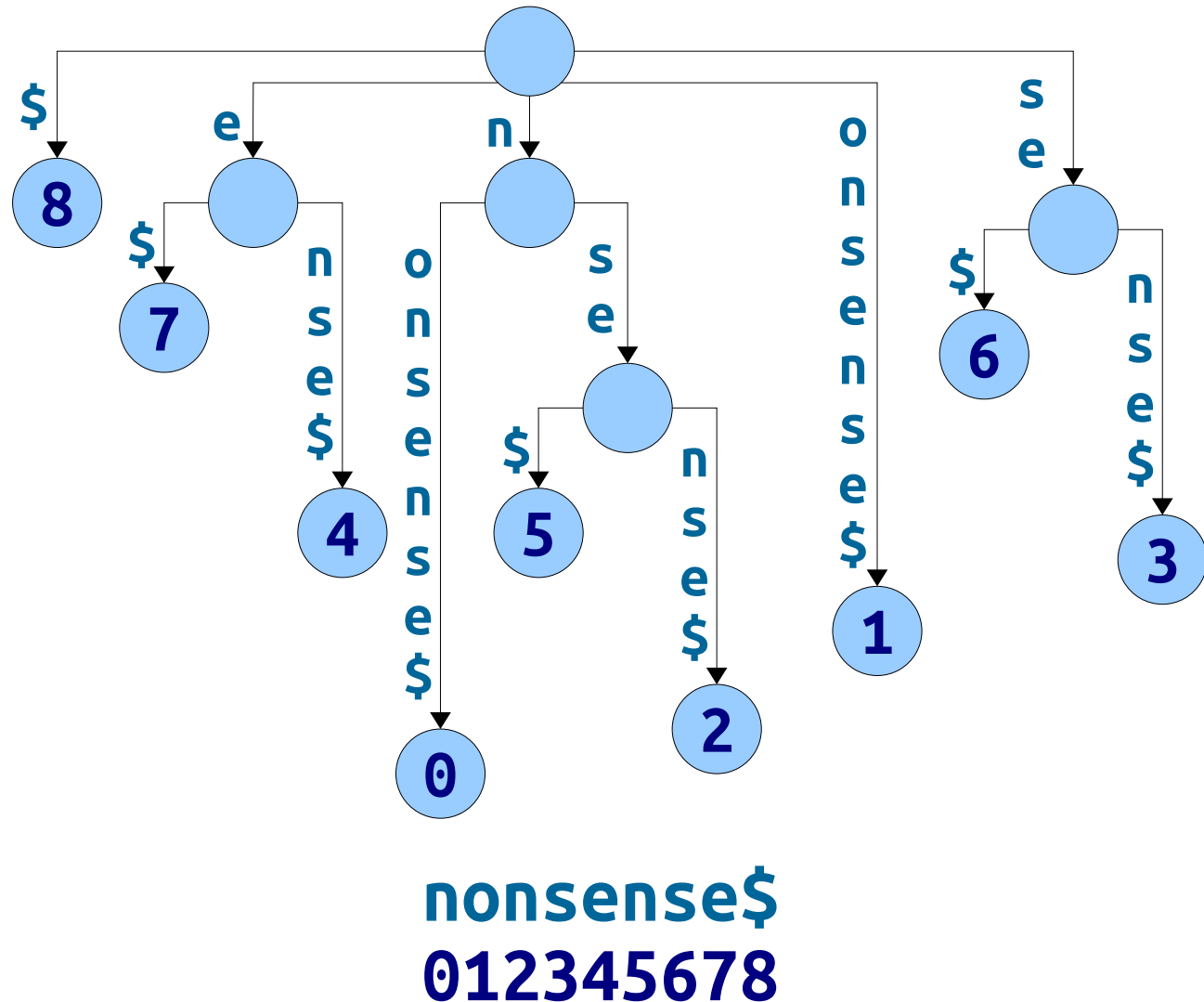
nonsense\$  
012345678

Answer at

<https://cs166.stanford.edu/pollev>

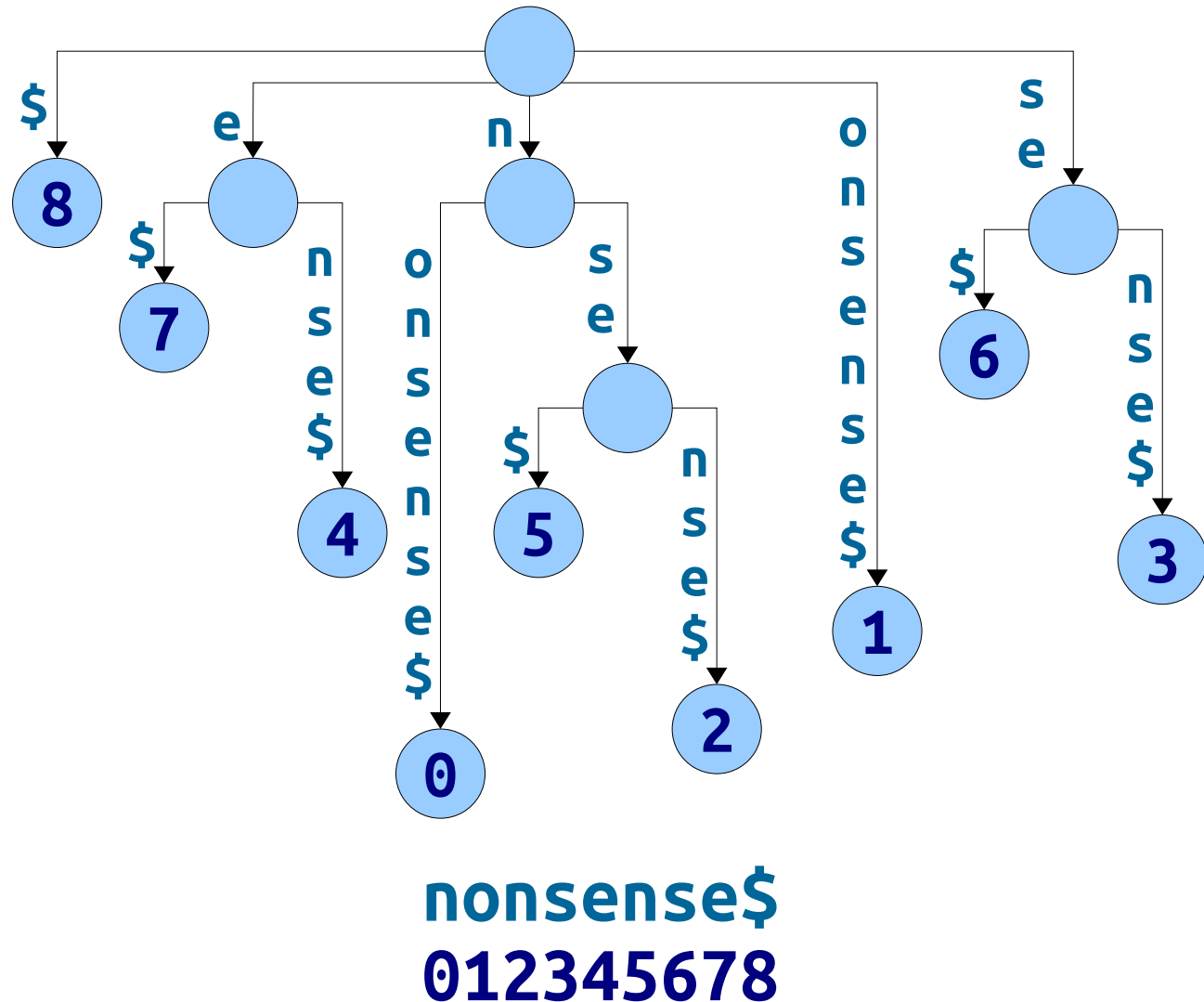
# The Anatomy of a Suffix Tree

- **Question:** why is there an internal node for the substring **n**, but *isn't* there an internal node for the substring **ns**?
- Every occurrence of **ns** can be extended by appending the same character (**e**).
- Not all occurrences of **n** can be extended by appending the same character.



# The Anatomy of a Suffix Tree

- A **branching word** in  $T\$$  is a string  $\omega$  such that there are characters  $a \neq b$  where  $\omega a$  and  $\omega b$  are substrings of  $T\$$ .
  - Edge case: the empty string is always considered branching.
- **Theorem:** The suffix tree for a string  $T$  has an internal node for a string  $\omega$  if and only if  $\omega$  is a branching word in  $T\$$ .



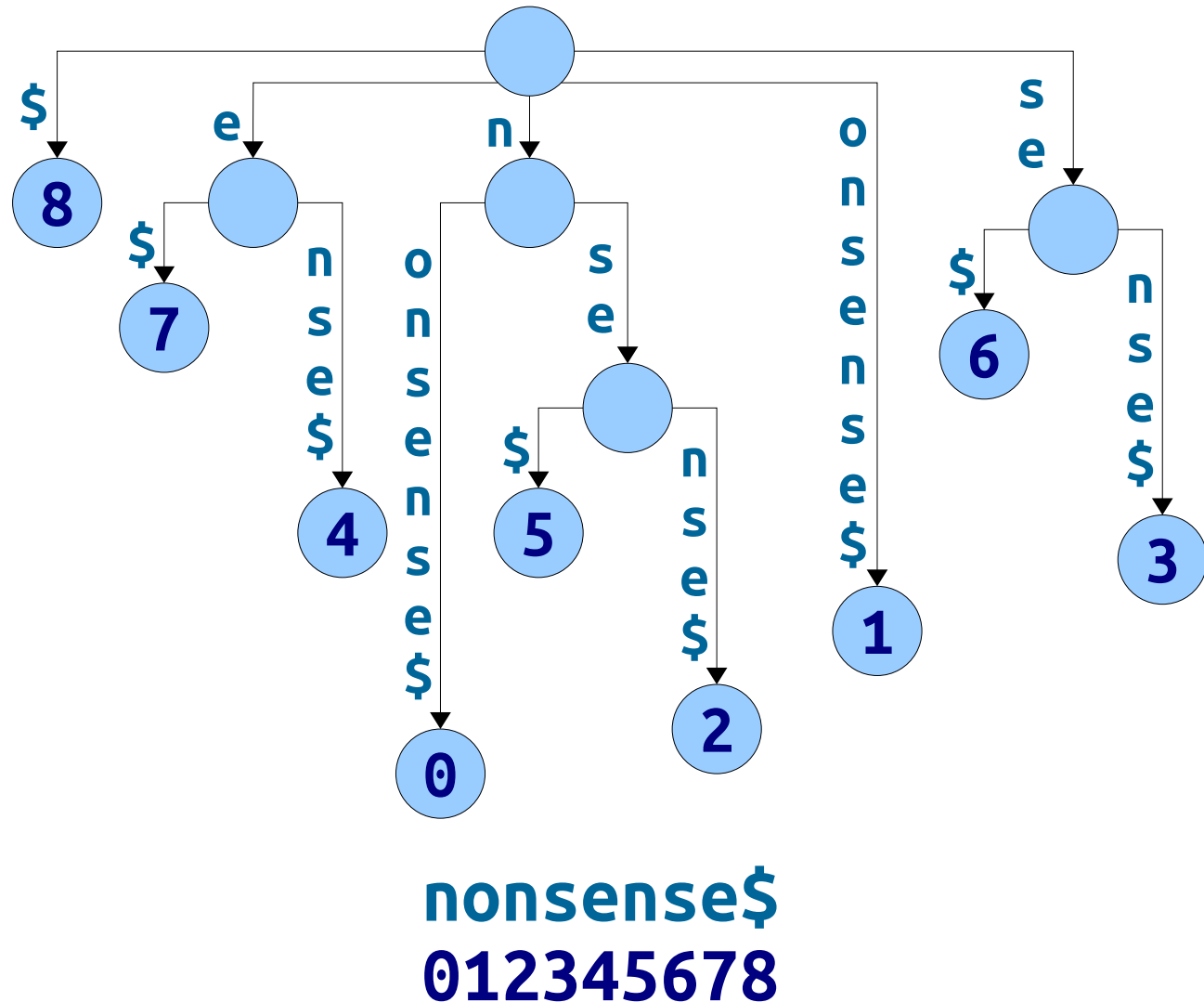


# The Anatomy of a Suffix Tree

- Combining our previous points together, we can give a (partial) operational definition of a suffix tree:

**The leaves of a suffix tree for  $T$  correspond to suffixes of  $T\$$ , and the internal nodes of a suffix tree for  $T$  correspond to branching words of  $T\$$ .**

- We'll make extensive use of this fact going forward.



# Longest Repeated Substrings

- **Theorem:** The longest repeated substring of a string  $T$  must be a branching word in  $T\$$ .
- **Proof idea:** If  $\omega$  isn't branching, it can't be the longest repeated substring.

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| f | l | i | b | b | e | r | t | i | g | i | b | b | e | t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

# Longest Repeated Substrings

- **Theorem:** The longest repeated substring of a string  $T$  must be a branching word in  $T\$$ .
- **Proof idea:** If  $\omega$  isn't branching, it can't be the longest repeated substring.

The substring `berti` isn't repeated.

It therefore can't be the longest repeated substring.

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| f | l | i | b | b | e | r | t | i | g | i | b | b | e | t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

# Longest Repeated Substrings

- **Theorem:** The longest repeated substring of a string  $T$  must be a branching word in  $T\$$ .
- **Proof idea:** If  $\omega$  isn't branching, it can't be the longest repeated substring.

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| f | l | i | b | b | e | r | t | i | g | i | b | b | e | t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

# Longest Repeated Substrings

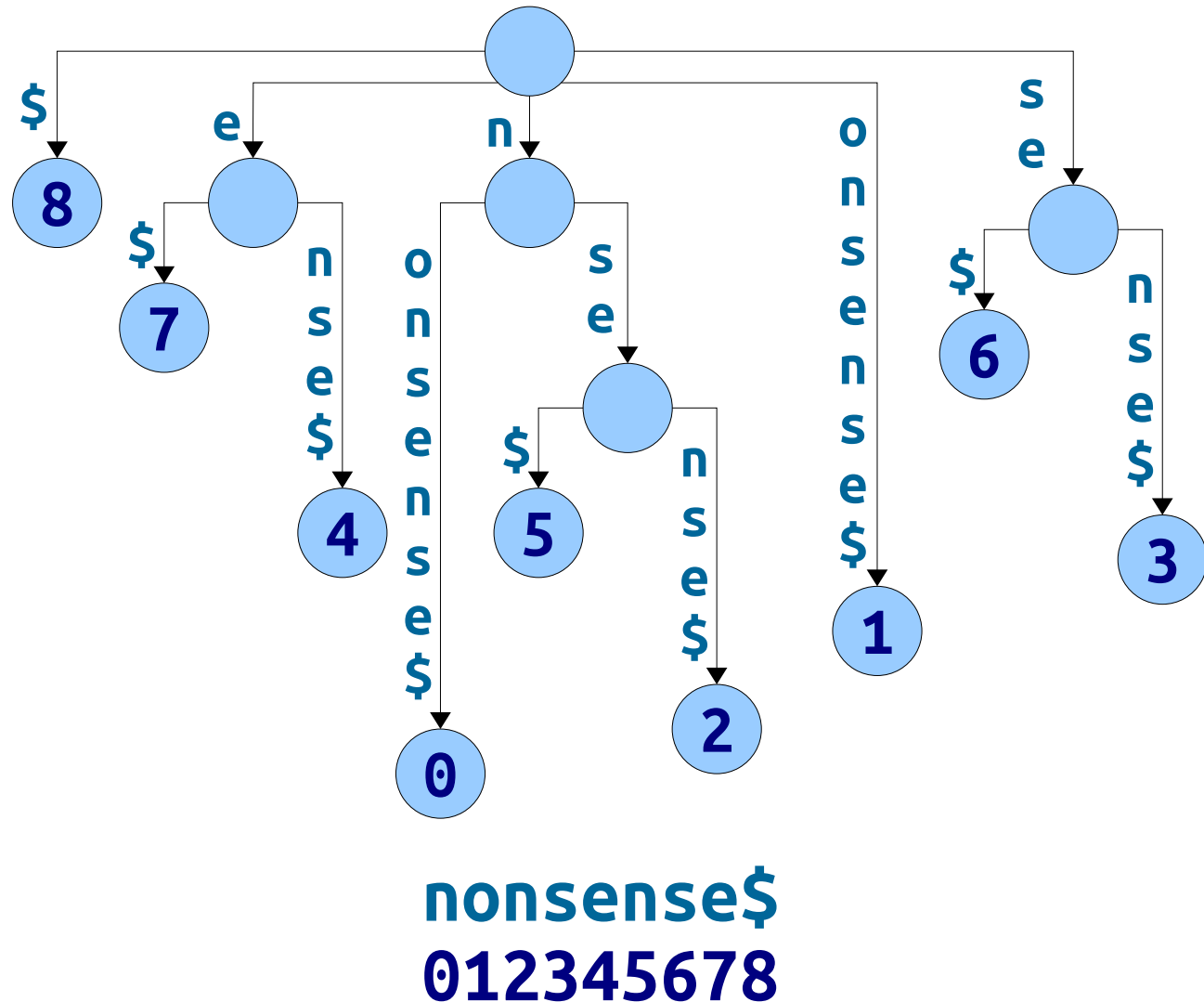
- **Theorem:** The longest repeated substring of a string  $T$  must be a branching word in  $T\$$ .
- **Proof idea:** If  $\omega$  isn't branching, it can't be the longest repeated substring.

Every instance of bb  
can be extended to bbe.  
It therefore can't be the  
longest repeated  
substring.

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| f | l | i | b | b | e | r | t | i | g | i | b | b | e | t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

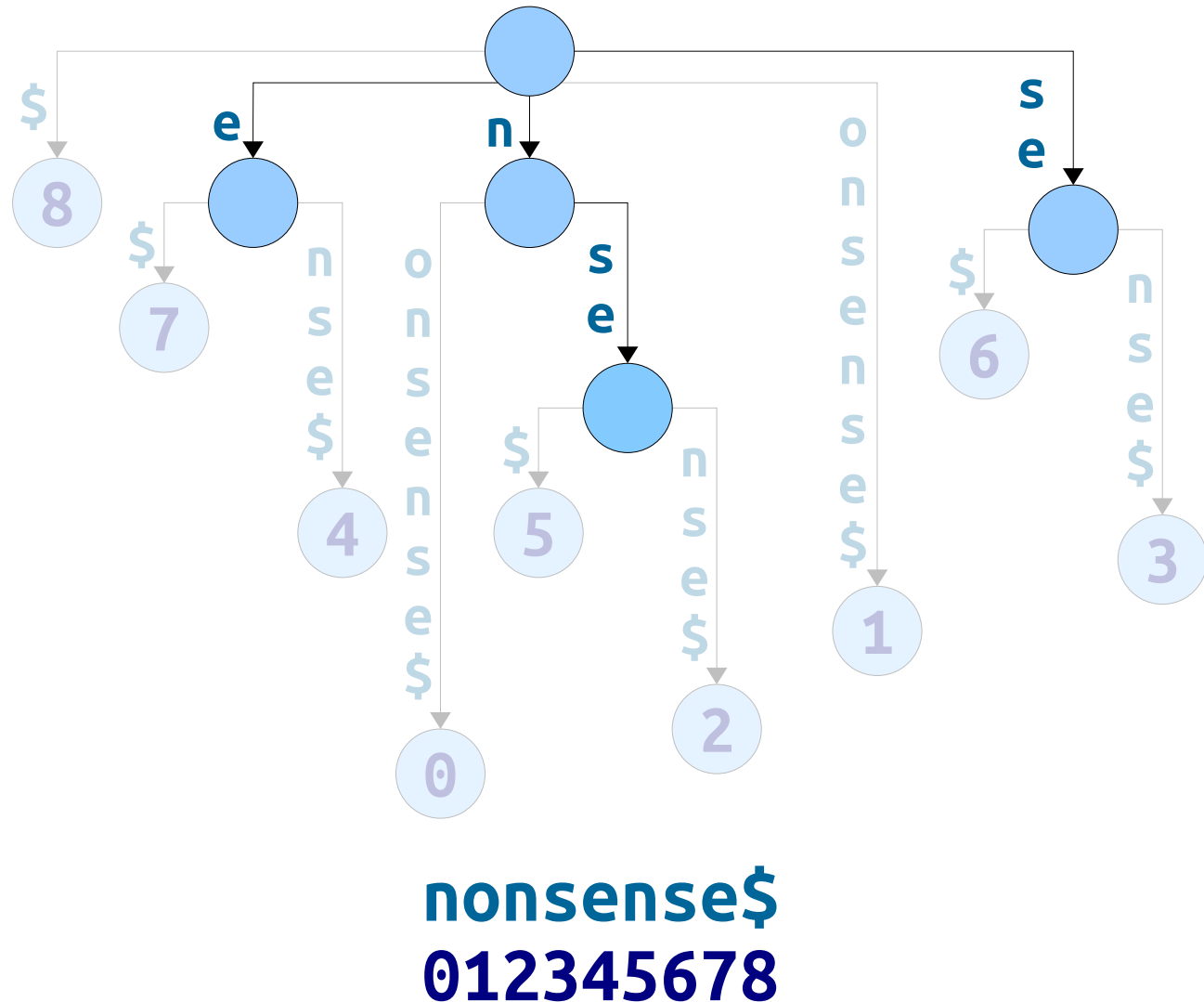
# Longest Repeated Substrings

- **Theorem:** The longest repeated substring of  $T$  is a branching word in  $T\$$ .
- To find the longest repeated substring of a string  $T$ , we just need to find the internal node with the longest label!



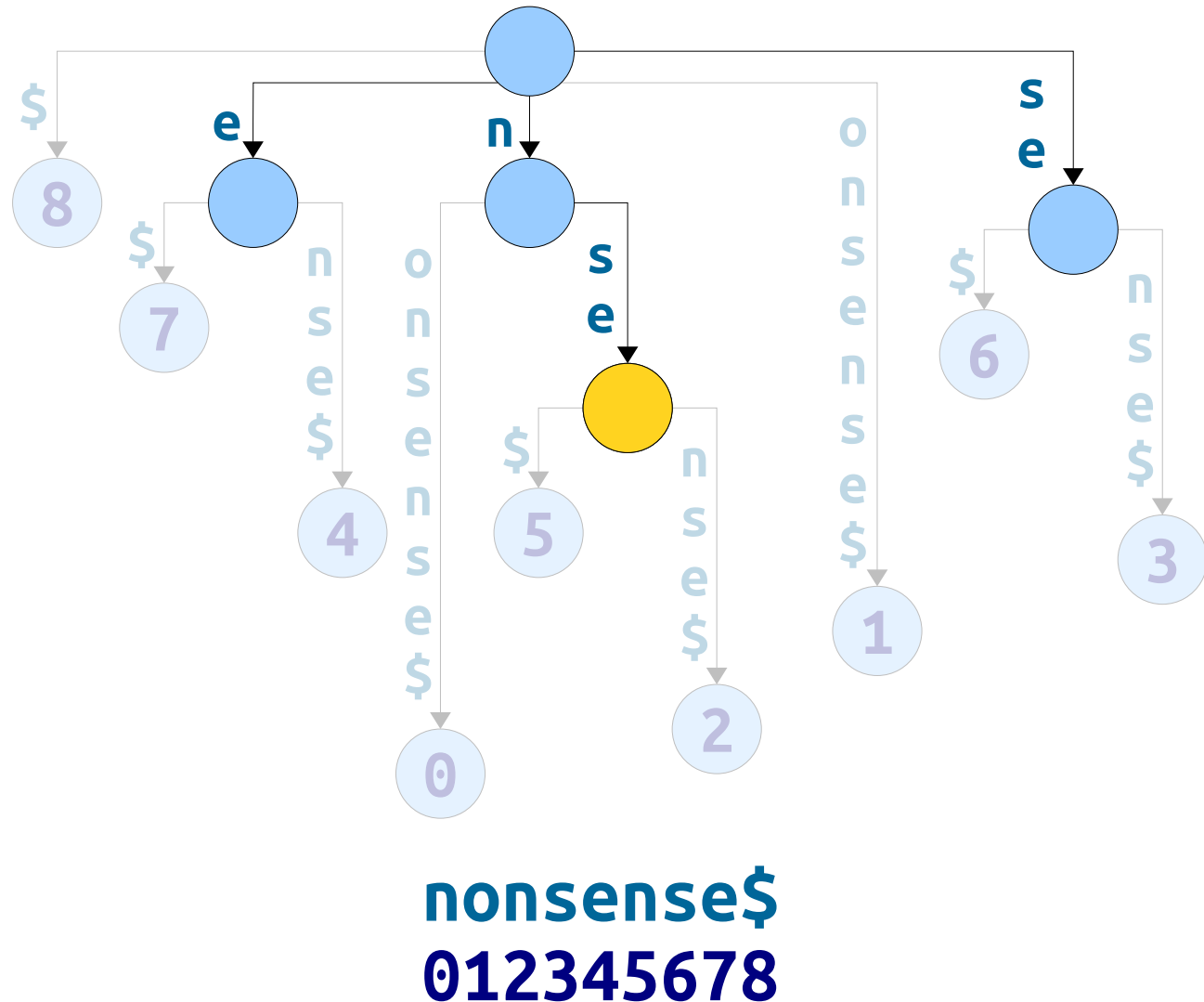
# Longest Repeated Substrings

- Given a suffix tree for a string  $T$  of length  $m$ , there is an  $O(m)$ -time algorithm for finding the longest repeated substring of  $T$ .
- Basic idea:** Run a DFS over the tree and find the internal node with the longest string on its path from the root.
- There are some subtle details required to get this to run in time  $O(m)$ . Think this over! See what you find.



# Longest Repeated Substrings

- Given a suffix tree for a string  $T$  of length  $m$ , there is an  $O(m)$ -time algorithm for finding the longest repeated substring of  $T$ .
- Basic idea:** Run a DFS over the tree and find the internal node with the longest string on its path from the root.
- There are some subtle details required to get this to run in time  $O(m)$ . Think this over! See what you find.





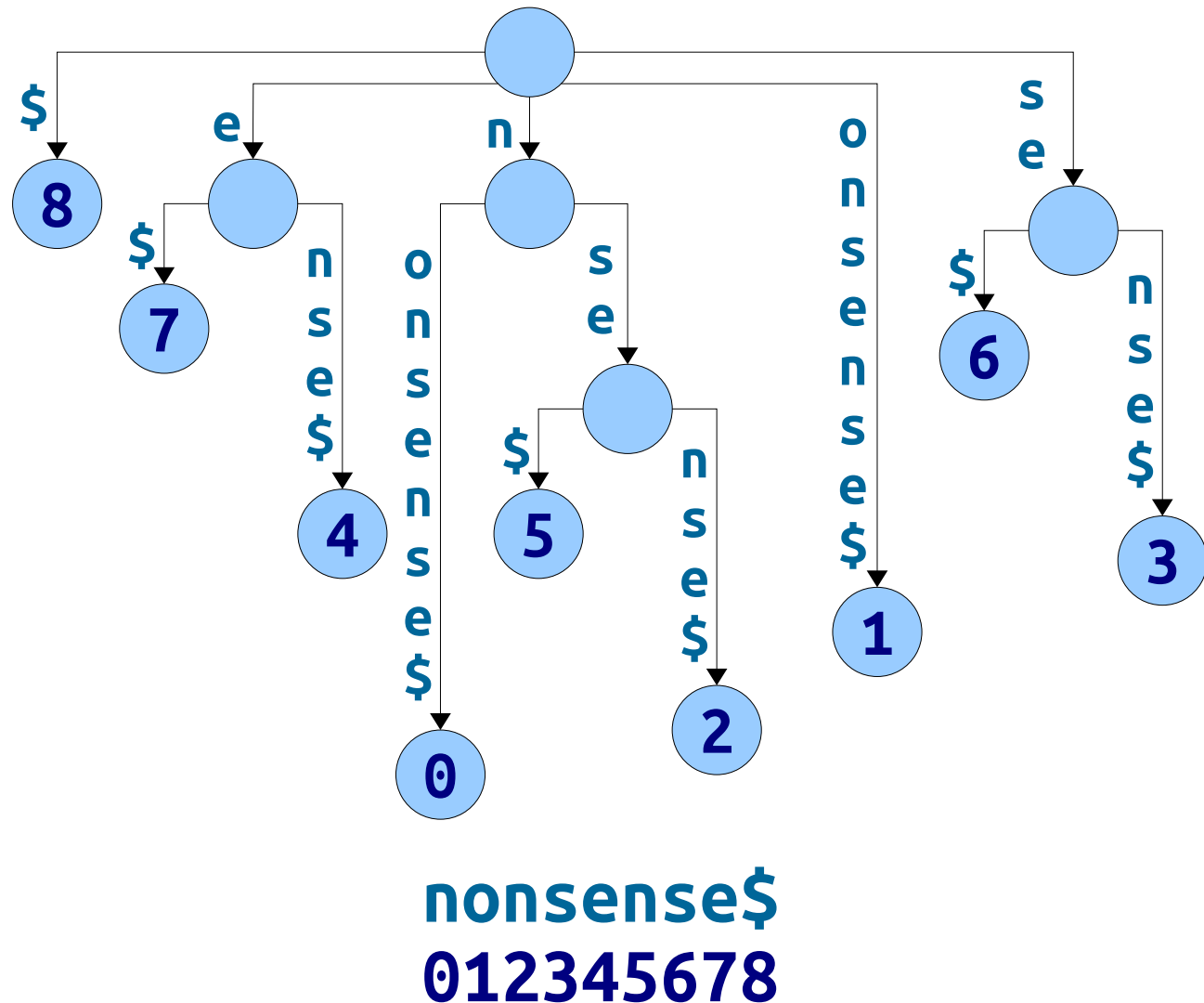
# More to Explore

- We've barely scratched the surface of suffix trees. They can be used for tons of other problems.
- A sampling:
  - **Generalized suffix trees**: Solves fast substring searching over multiple text strings, not just a single text string.
  - **Approximate string matching**: Given a text string  $T$  and a pattern  $P$ , see the closest match to  $P$  in  $T$ .
  - **Fast matrix multiplication**: The matrix multiplications needed in computing word embeddings can, amazingly, be optimized using suffix trees.
- This is a rich space to explore – and I encourage you to do so!

# Representing Suffix Trees

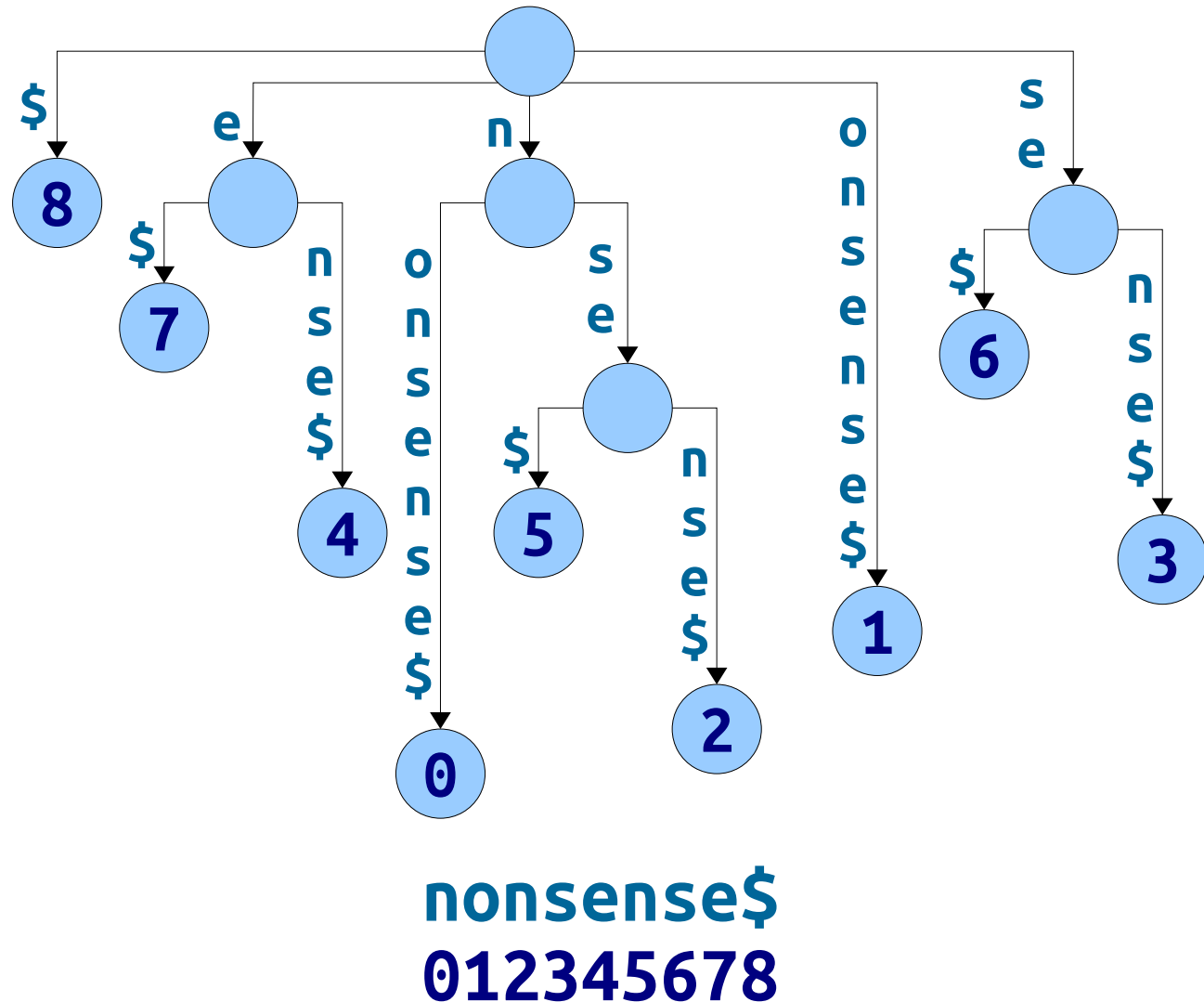
# Representing a Suffix Tree

- 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  $O(m)$ ?



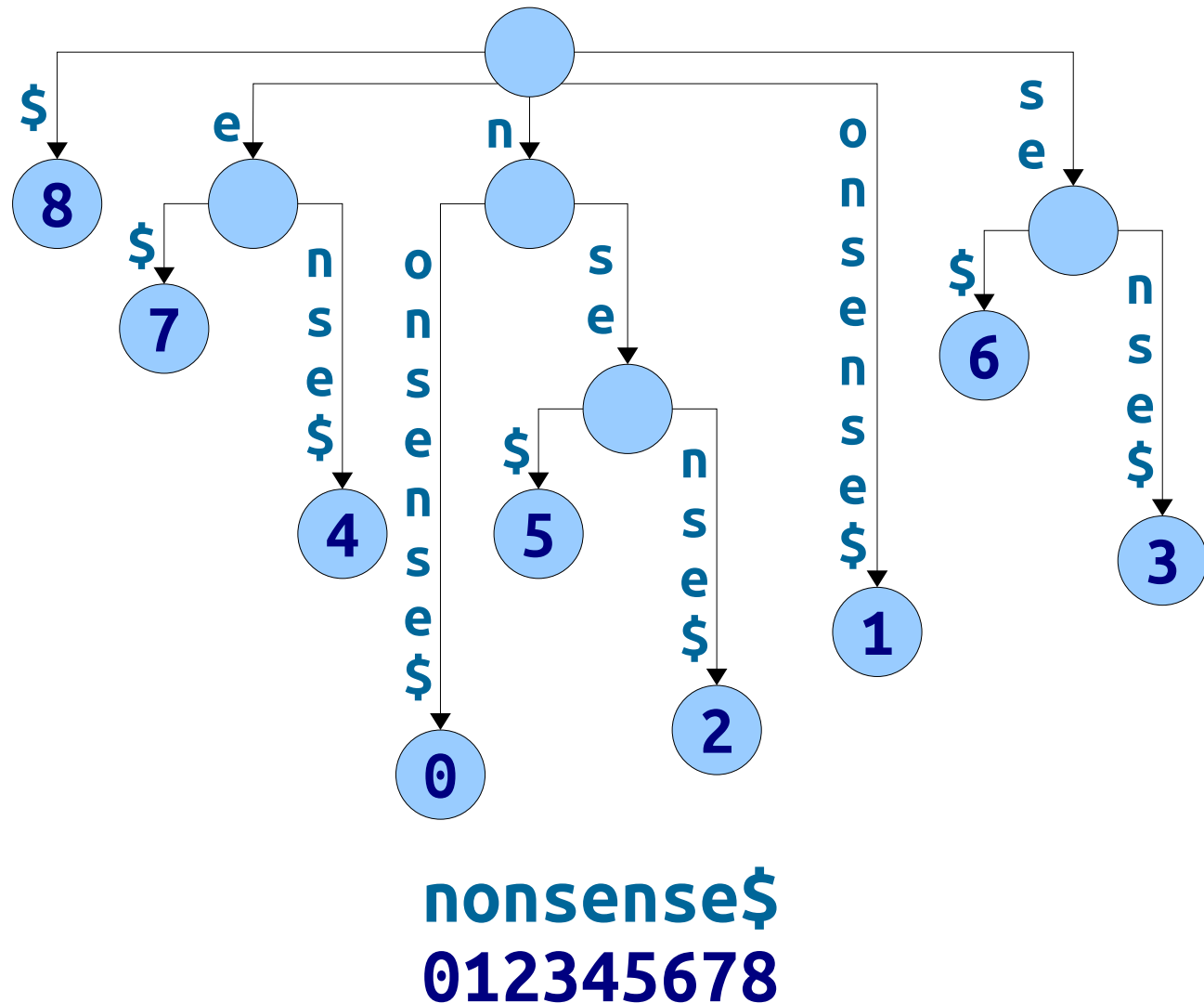
# Representing a Suffix Tree

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

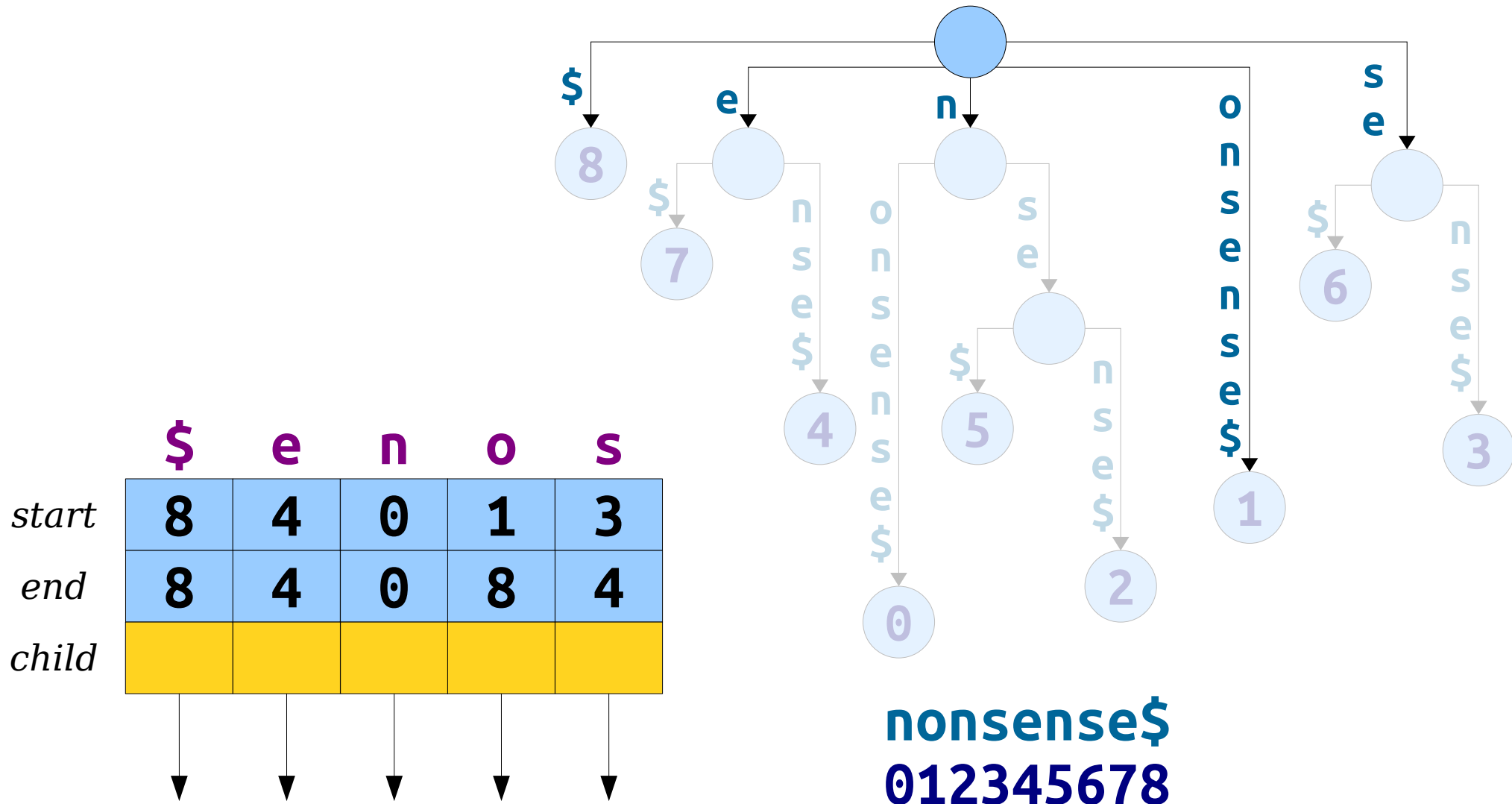


# Representing a Suffix Tree

- 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!

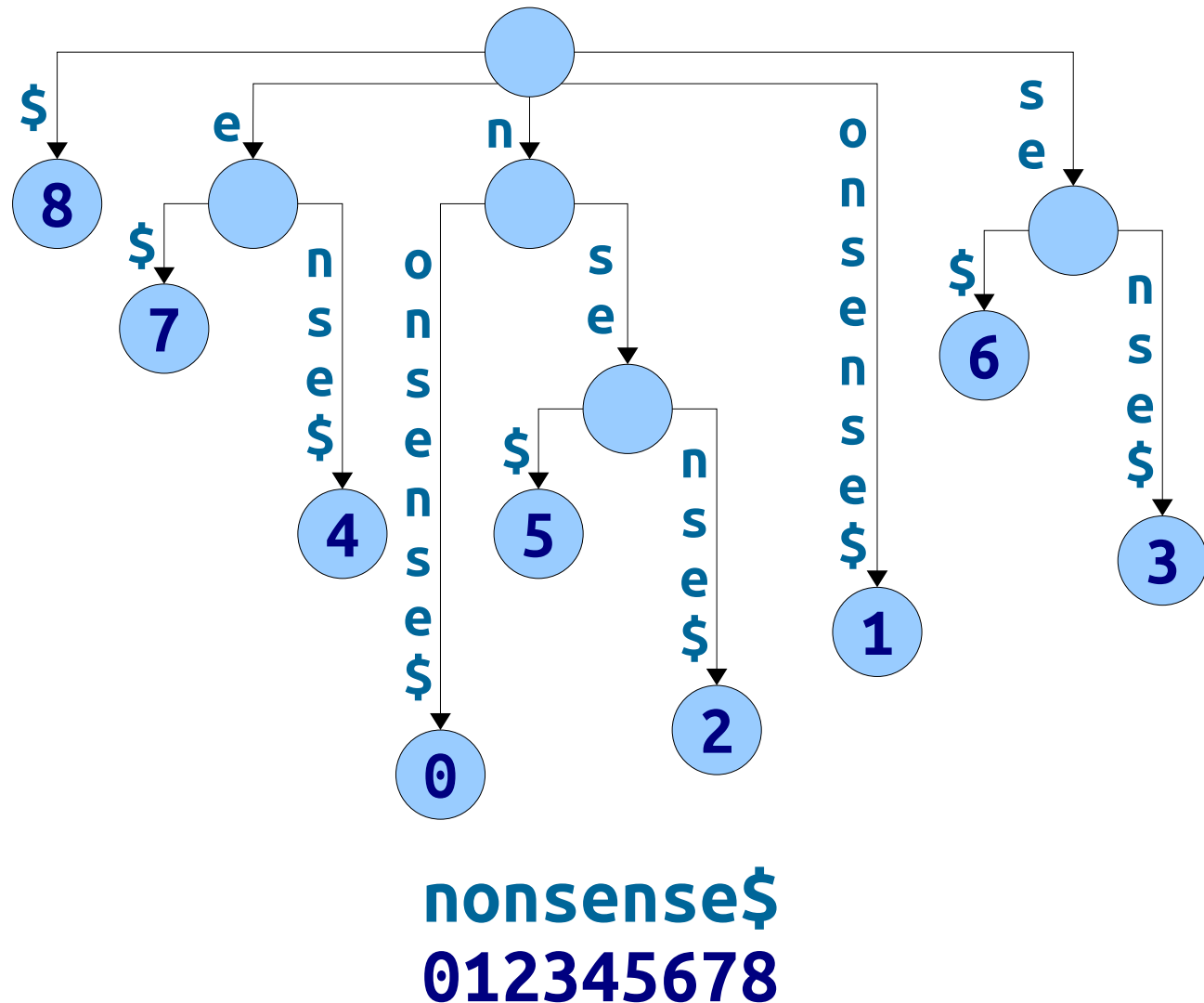


# Representing a Suffix Tree



# 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:  $O(m)$ .



# 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!



# Next Time

- ***Suffix Arrays***
  - A space-efficient alternative to suffix trees.
- ***LCP Arrays***
  - Implicitly capturing suffix tree structure.