

Tries and Suffix Trees

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String indexing problem

- **String matching problem.** Given strings T (text) and P (pattern) over an alphabet Σ , report starting positions of all occurrences of P in T .
 - *Finite automaton:* $O(m\Sigma + n)$ time and space
 - *KMP:* $O(m+n)$ time and space
- **String indexing problem.** Given a string S of characters from an alphabet Σ . Preprocess S into a data structure to support
 - $\text{Search}(P)$: Return starting position of all occurrences of P in S .
- **Today:** Data structure using $O(n)$ space and supporting $\text{Search}(P)$ in $O(m)$ time.
- **Applications:**
 - Search engines, e.g. prefix searches.
 - Finding common substrings of many biological strings
 - Finding repeating substructures in biological strings
 - Detecting DNA contamination

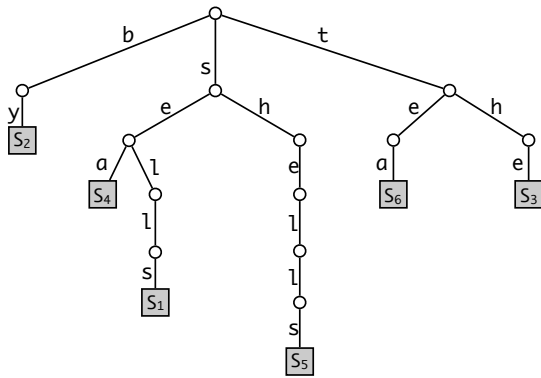
Outline

- Tries
- Compressed tries
- Suffix trees
- Applications of suffix trees

Tries

Tries

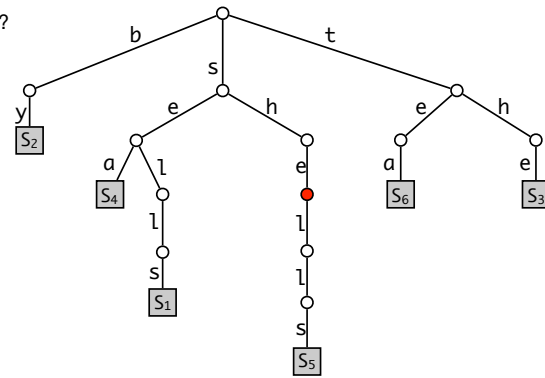
- Text retrieval



- Trie over the strings: sells, by, the, sea, shells, tea.

Tries

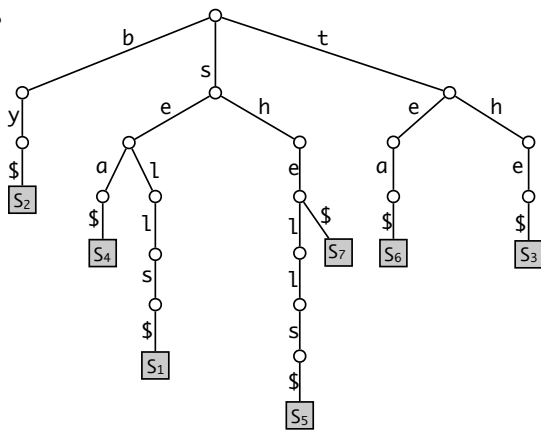
- Text retrieval
- Prefix-free?



- Trie over the strings: sells, by, the, sea, shells, tea, *she*.

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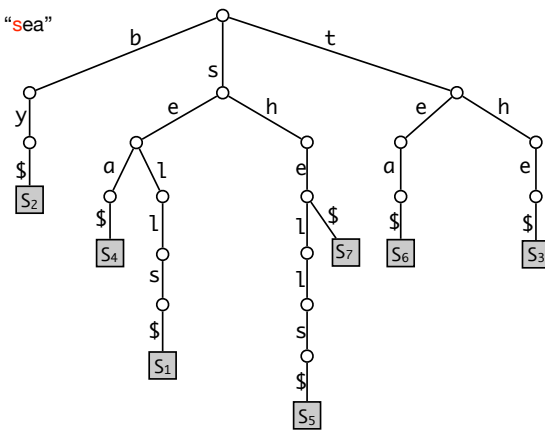
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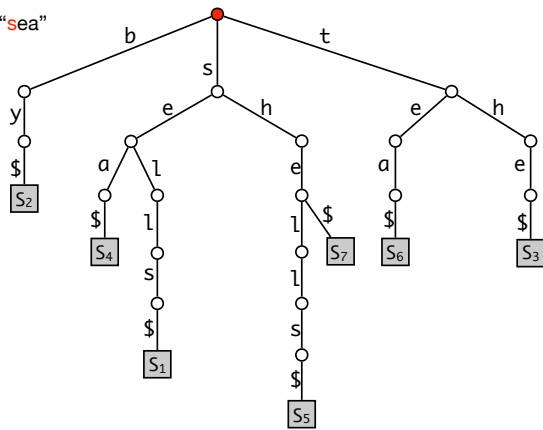
- Text retrieval
- Search for "sea"



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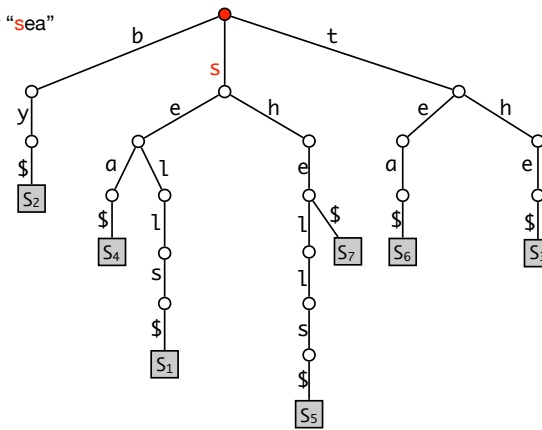
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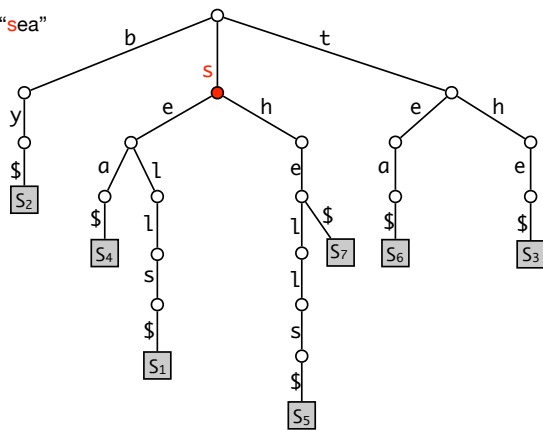
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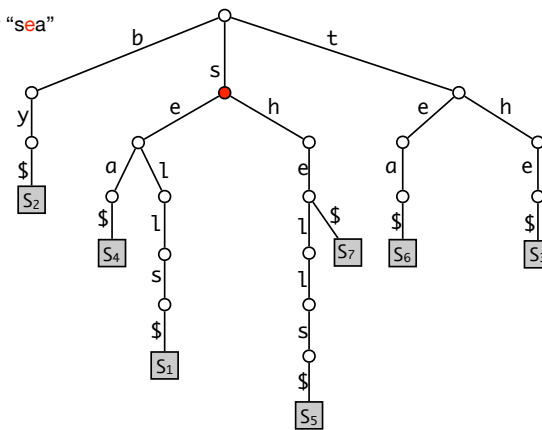
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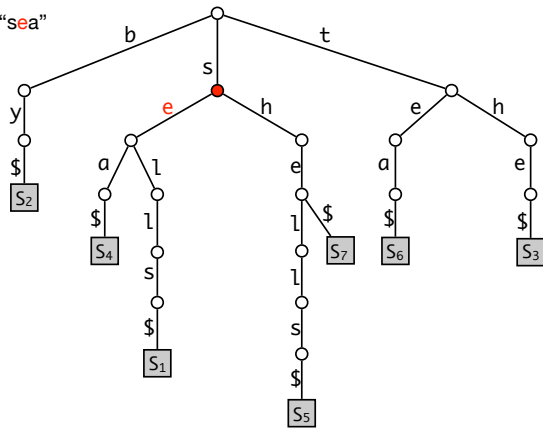
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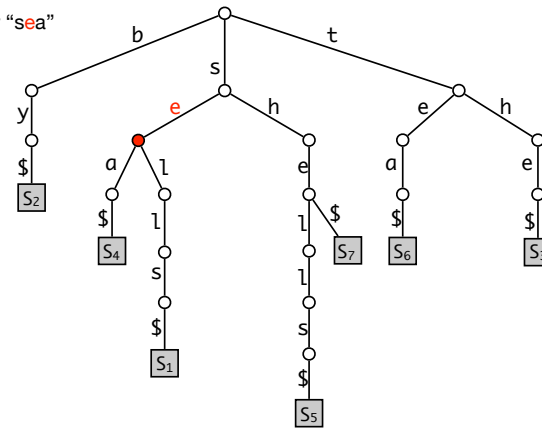
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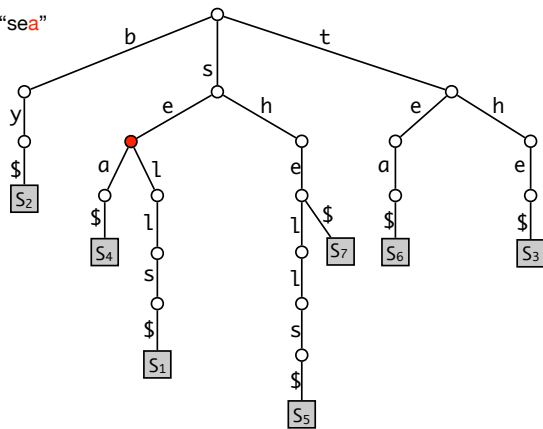
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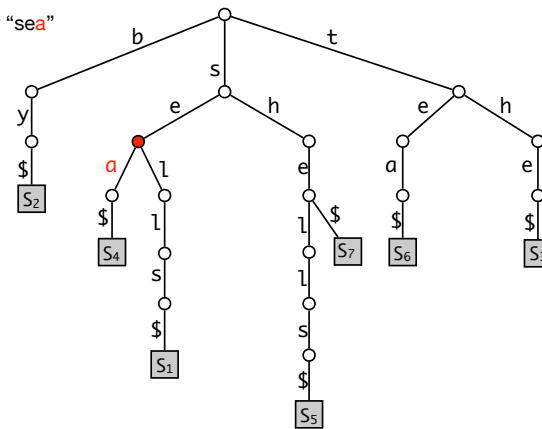
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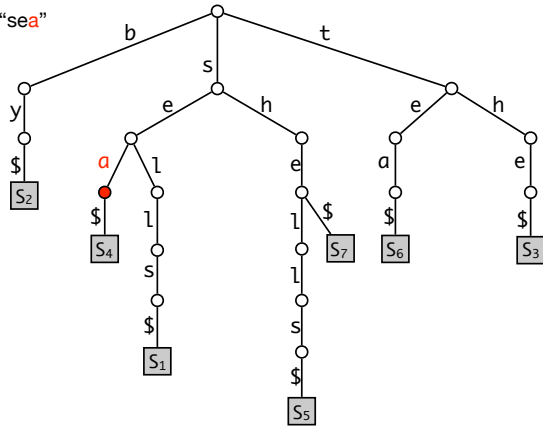
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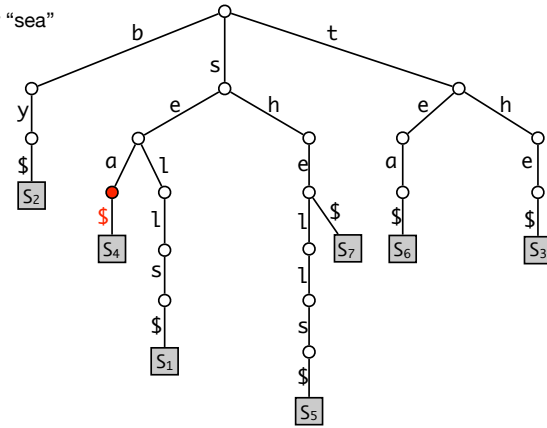
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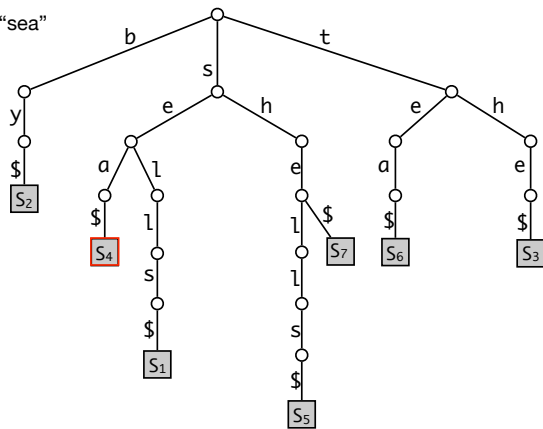
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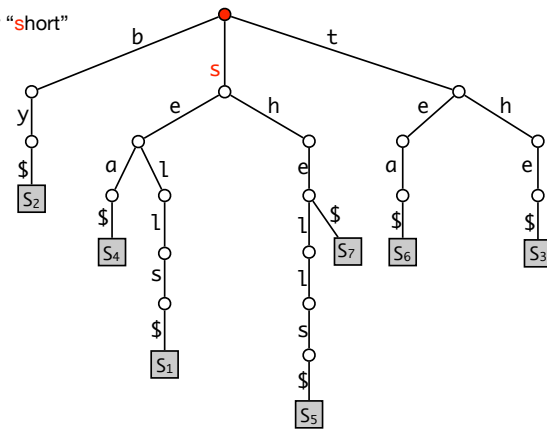
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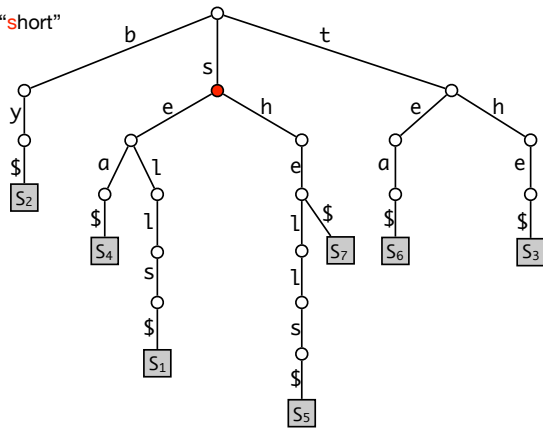
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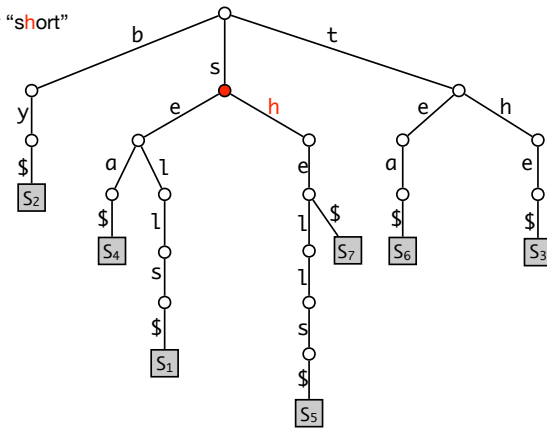
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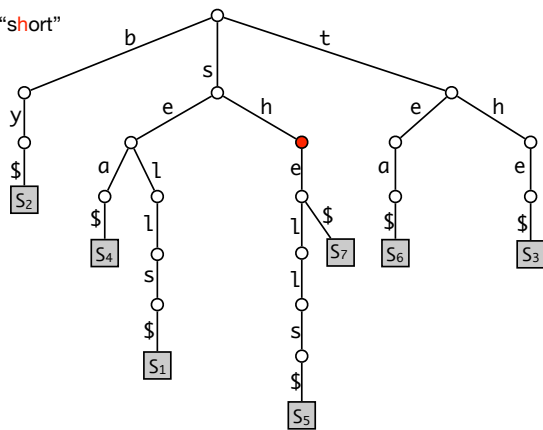
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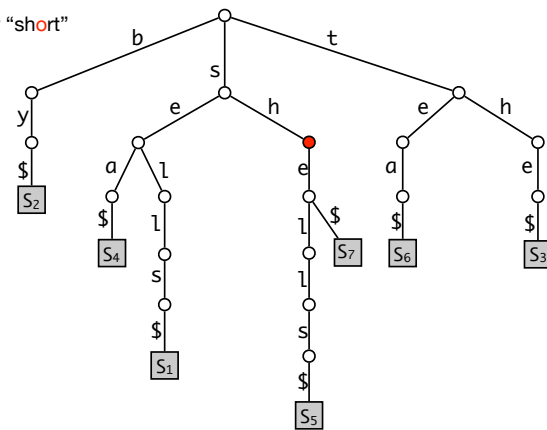
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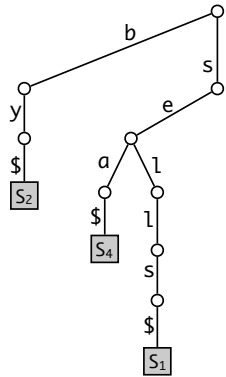
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- Trie over the strings: sells\$, by\$, the\$, sea\$, shells\$, tea\$, she\$.

Tries

- Build a trie over the strings: by\$, sells\$, sea\$.



Trie

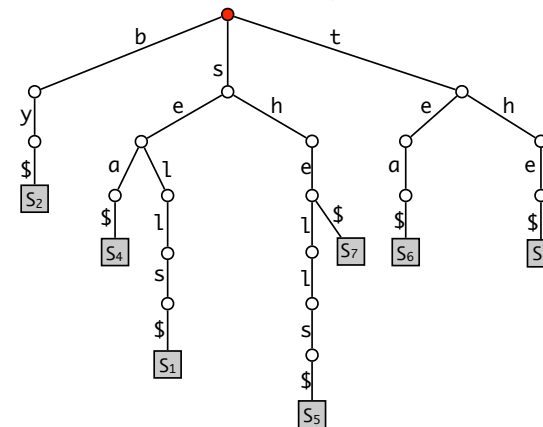
- Properties of the trie.** A trie T storing a collection S of s strings of total length n from an alphabet of size d has the following properties:
 - How many children can a node have?
 - How many leaves does T have?
 - What is the height of T ?
 - What is the number of nodes in T ?

Trie

- Search time:** $O(d)$ in each node $\Rightarrow O(dm)$.
 - $O(m)$ if d constant.
 - d not constant: use dictionary
 - Hashing $O(1)$
 - Balanced BST: $O(\log d)$
- Time and space for a trie (for small/constant d):**
 - $O(m)$ for searching for a string of length m .
 - $O(n)$ space.
 - Preprocessing: $O(n)$

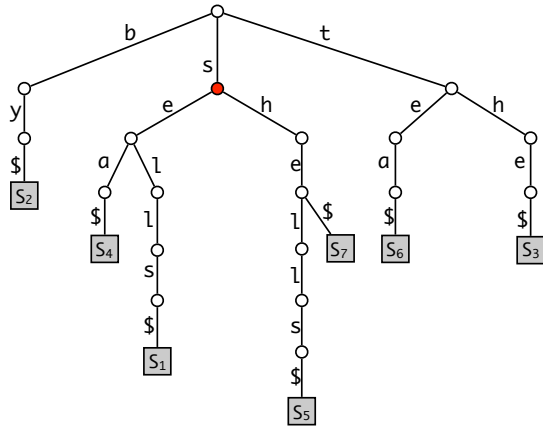
Tries

- Prefix search:** return all words in the trie starting with "se"



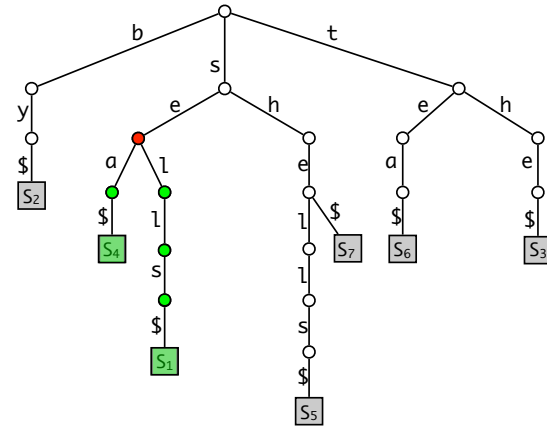
Tries

- Prefix search: return all words in the trie starting with "se"



Tries

- Prefix search: return all words in the trie starting with "se"



Trie

- Time for prefix search: $O(m)$ + time to report all occurrences.

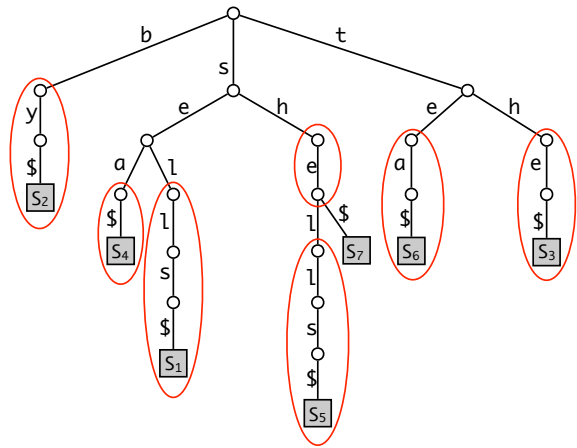
↑
Could be large!!

- Solution: compact tries.

Compact tries

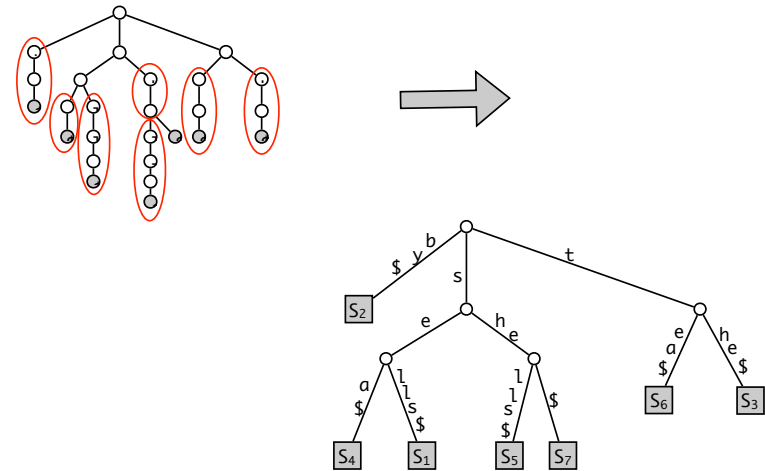
Tries

- Compact trie: Chains of nodes with a single child is merged into a single node.



Tries

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Trie

- **Properties of the compact trie.** A compact trie T storing a collection S of s strings of total length n from an alphabet of size d has the following properties:
 - Every internal node of T has at least 2 and at most d children.
 - T has s leaves
 - The number of nodes in T is $< 2s$.
- **Time and space for a compact trie (constant d):**
 - $O(m)$ for searching for a string of length m .
 - $O(m + occ)$ for prefix search, where $occ = \#occurrences$
 - $O(s)$ space.
 - Preprocessing: $O(n)$

Suffix trees

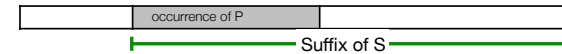
Suffix tree

- **String indexing problem.** Given a string S of characters from an alphabet Σ . Preprocess S into a data structure to support
 - Search(P): Return starting position of all occurrences of P in S.
- Build a compressed trie over all suffixes of S (suffix tree). Label leaves with index of suffix.
- Observation: An occurrence of P is a prefix of a suffix of S.

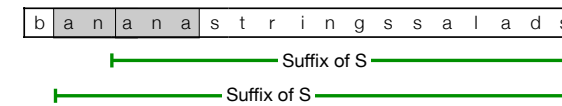


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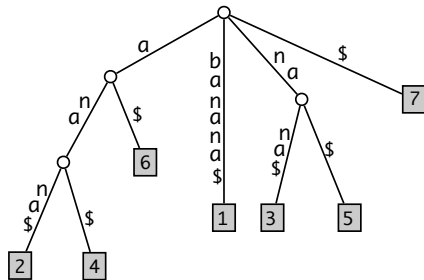


- Example: P = ana.



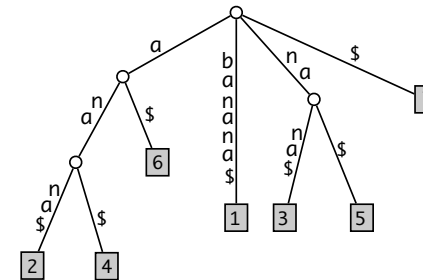
Suffix Tree

- Suffix tree: over the string banana\$



Suffix Tree

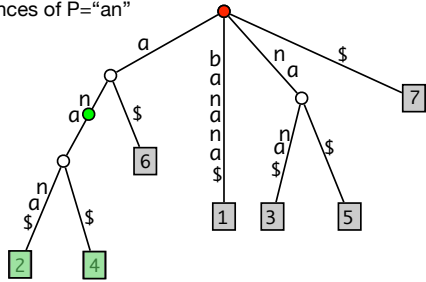
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- Search for P.
- Report labels of all leaves below final node

Suffix Tree

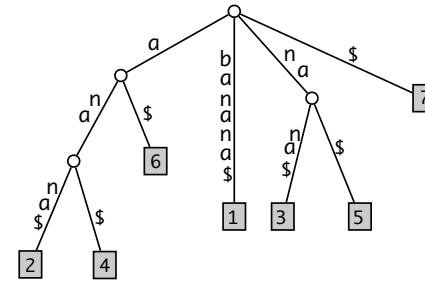
- Suffix tree: over the string banana\$
- Find all occurrences of P="an"



- Search for P.
- Report labels of all leaves below final node

Suffix Tree

- Suffix tree: over the string banana\$

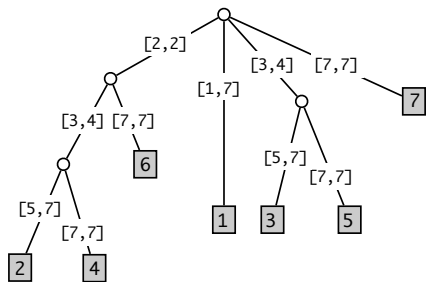


- Store S and store node labels by reference to S.

1 2 3 4 5 6 7
b a n a n a \$

Suffix Tree

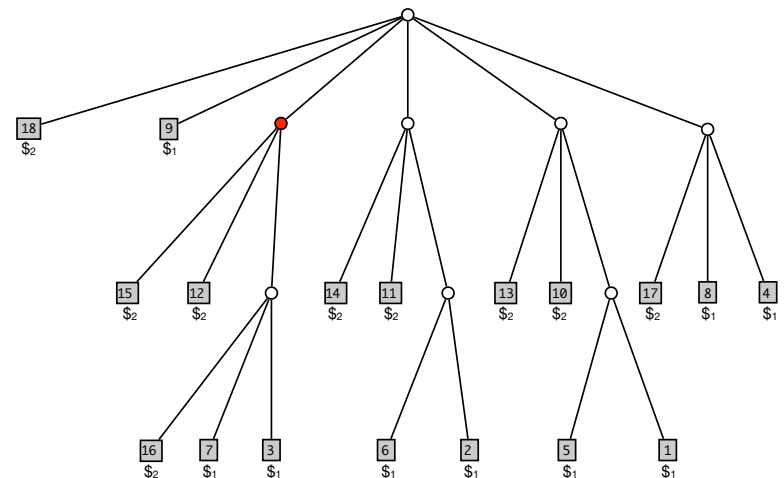
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Suffix trees and common substrings



Suffix tree

- **Suffix tree of a string S:** Compact trie over all suffixes of S.
- Space and time:
 - Space: $O(n)$
 - Search time: $O(m)$ + time to report all occurrences = $O(m+occ)$
 - Preprocessing: Can be done in $O(\text{sort}(n, |\Sigma|))$ time, where $\text{sort}(n, |\Sigma|)$ is the time it takes to sort n characters from an alphabet Σ .
- Suffix trees can be used to solve the **String indexing problem** in:
 - Space: $O(n)$
 - Search time: $O(m+occ)$
 - Preprocessing: $O(\text{sort}(n, |\Sigma|))$ time

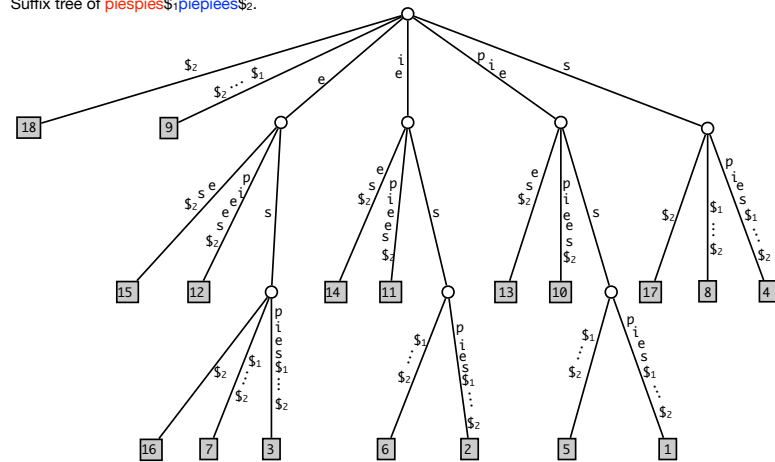
Applications of suffix trees

Longest common substrings

- Find longest common substring of strings S_1 and S_2 .
- Construct the suffix tree over $S_1\$_1S_2\$_2$.
- Example: Find longest common substring of **piespies** and **piepies**:
 - Construct suffix tree of **piespies** $_1$ **piepies** $_2$.

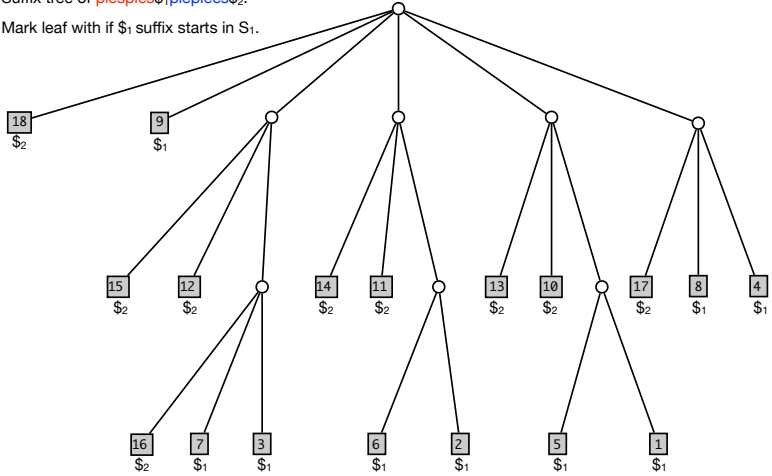
Generalized suffix tree

- Suffix tree of **piespies** $_1$ **piepies** $_2$.



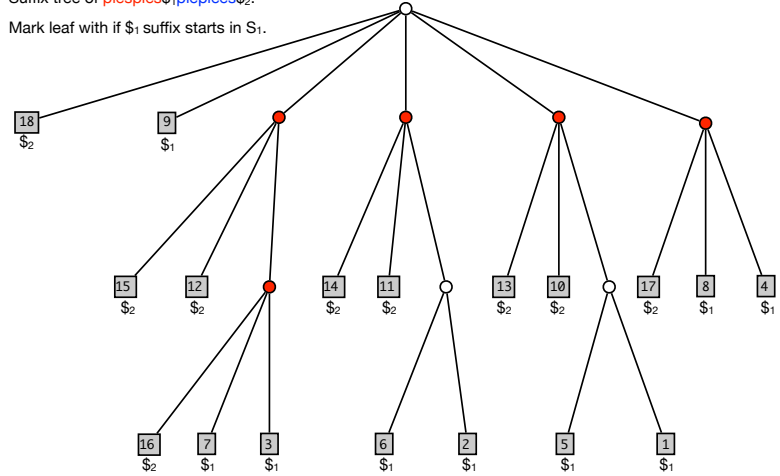
Generalized suffix tree

- Suffix tree of $\text{piespies}\$_1\text{piepies}\$_2$.
- Mark leaf with if $\$_1$ suffix starts in S_1 .



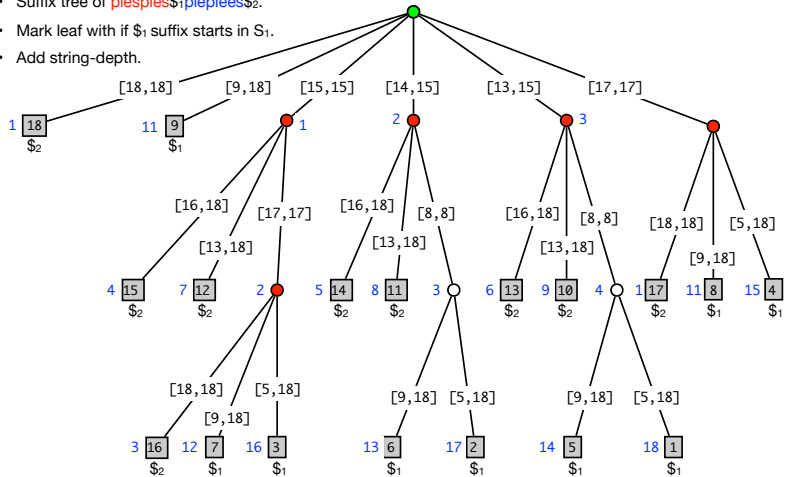
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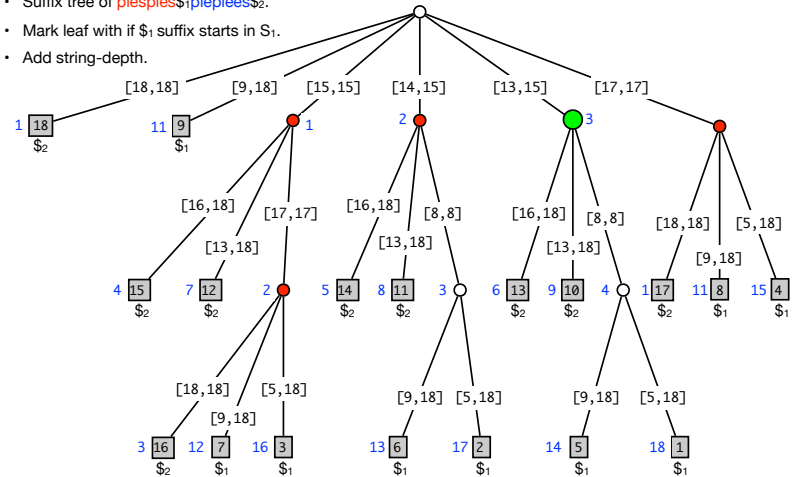
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$S[13, 15] = \text{"pie"}$ is the longest common substring.

Longest common substring

- Using a suffix tree we can solve the longest common substring problem in linear time (for a constant size alphabet).