Suffix trees and applications

String Algorithms

Tries

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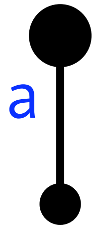

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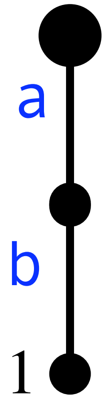

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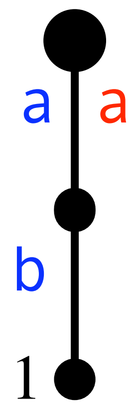

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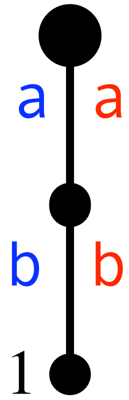

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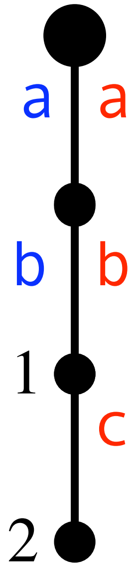

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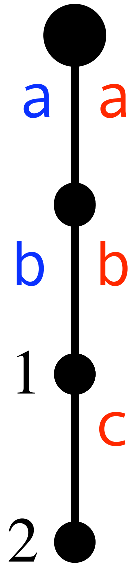

Observations: shared prefixes implies shared initial paths …

Often we want each string to correspond to a unique root-to-leaf path, i.e. make sure that no input-string is a prefix of another. How?

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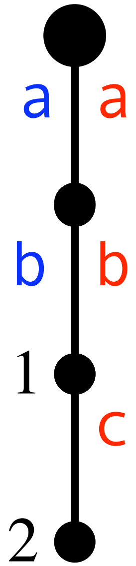

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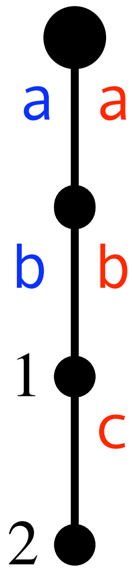

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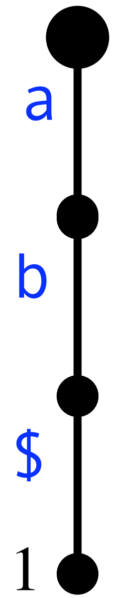

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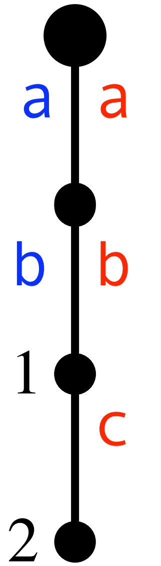

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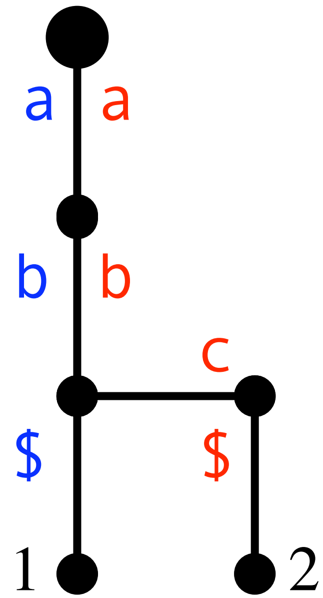

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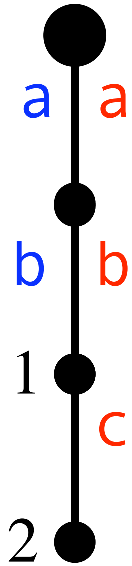

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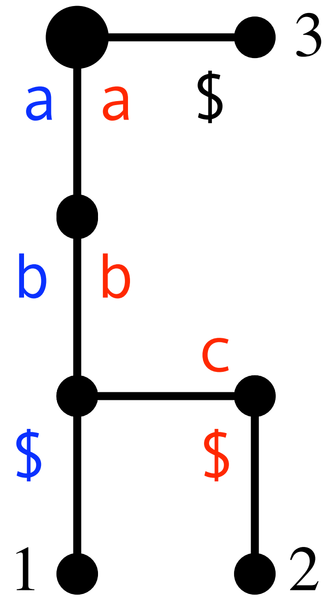

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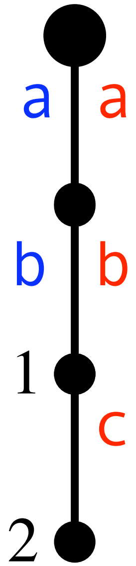

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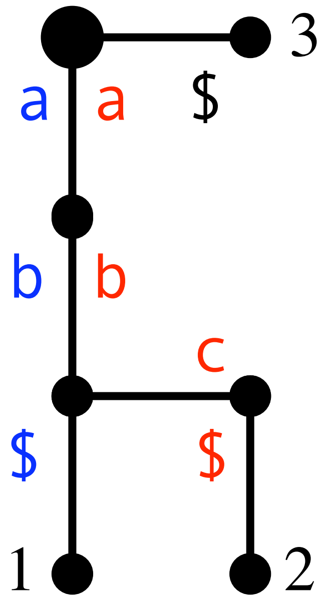

Observations: shared prefixes implies shared initial paths …

Application: Given a query-string $\boldsymbol{y}[1...m]$, we can determine if $\boldsymbol{y}$ equals one of the input-strings (or a prefix of one) in time $O(m)$ ...

Compacted tries

Saving space: Eliminate all internal nodes of degree 2 ...

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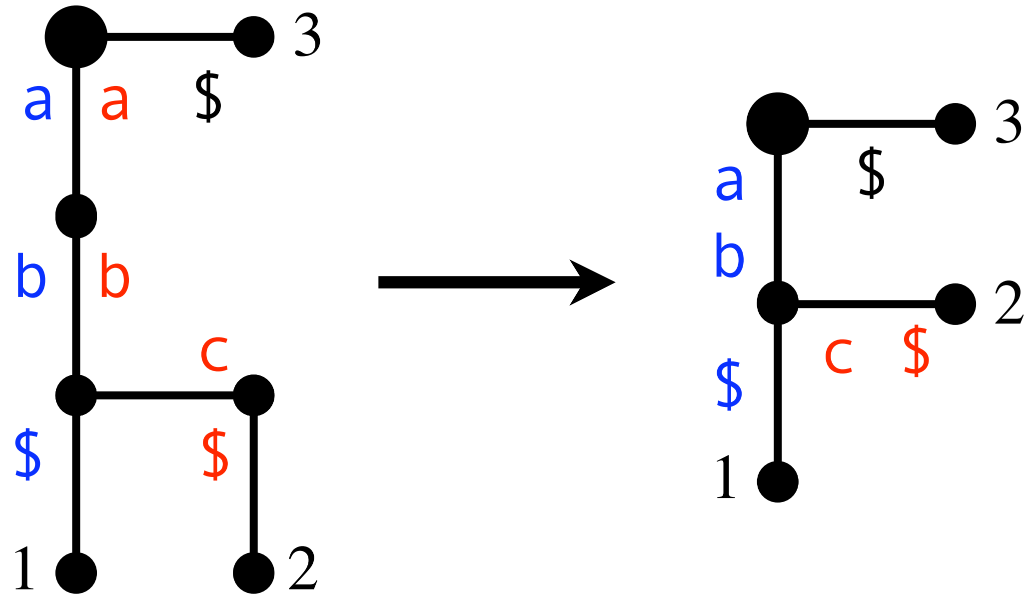

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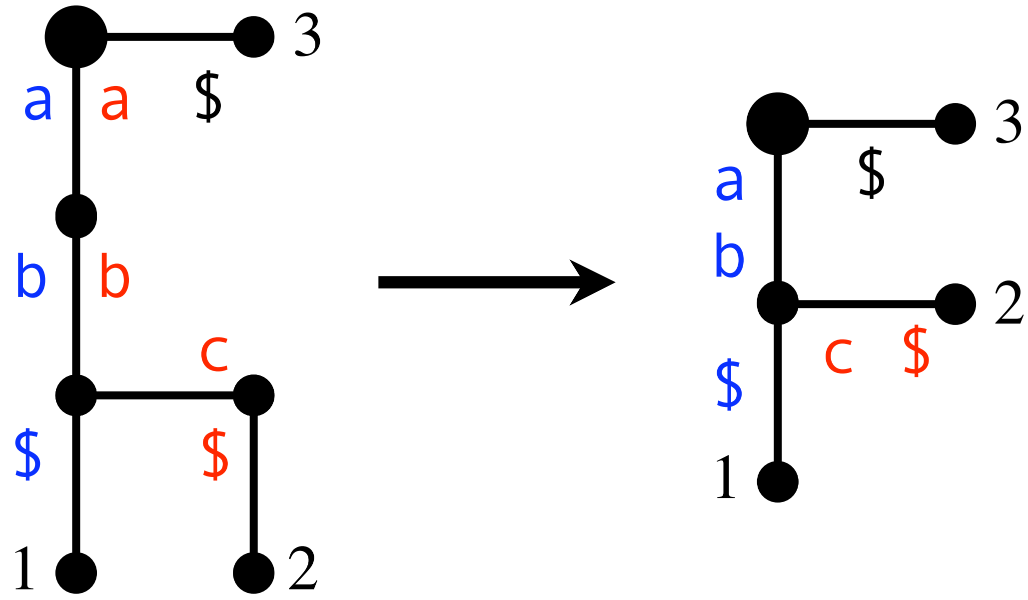

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Labels can be represented in space O(1), i.e. "ab" ⇒ (1,1,2)

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Example for x = `tatat`

```
tatat$
 atat$
  tat$
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    t$
```
ε`$`

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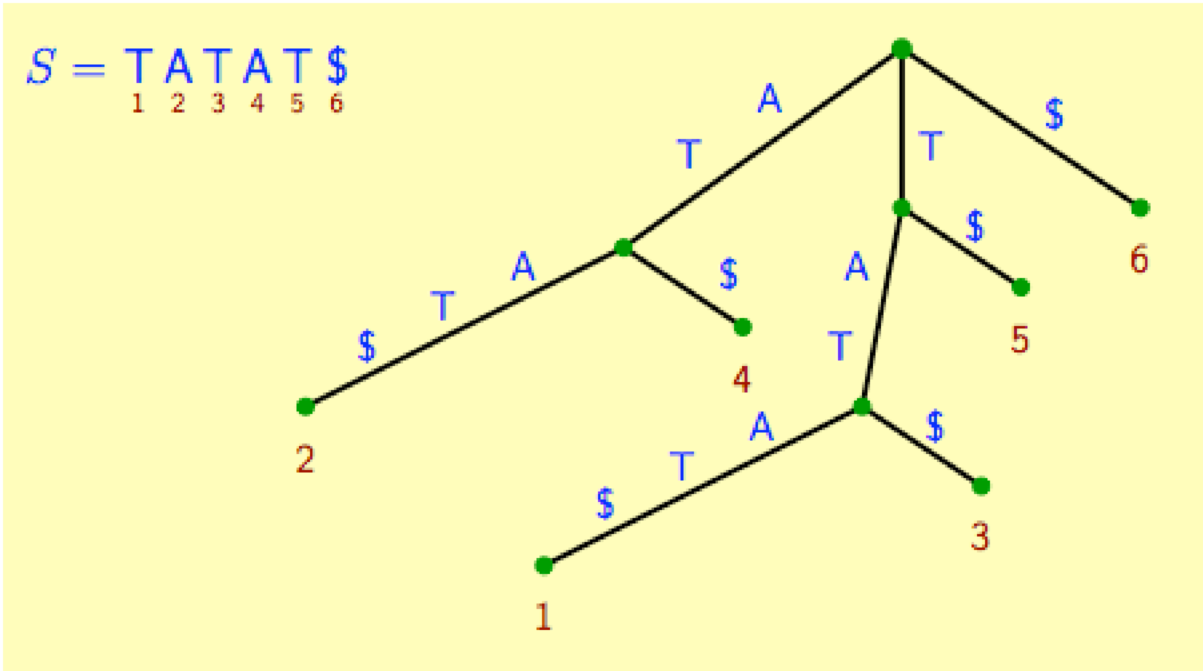

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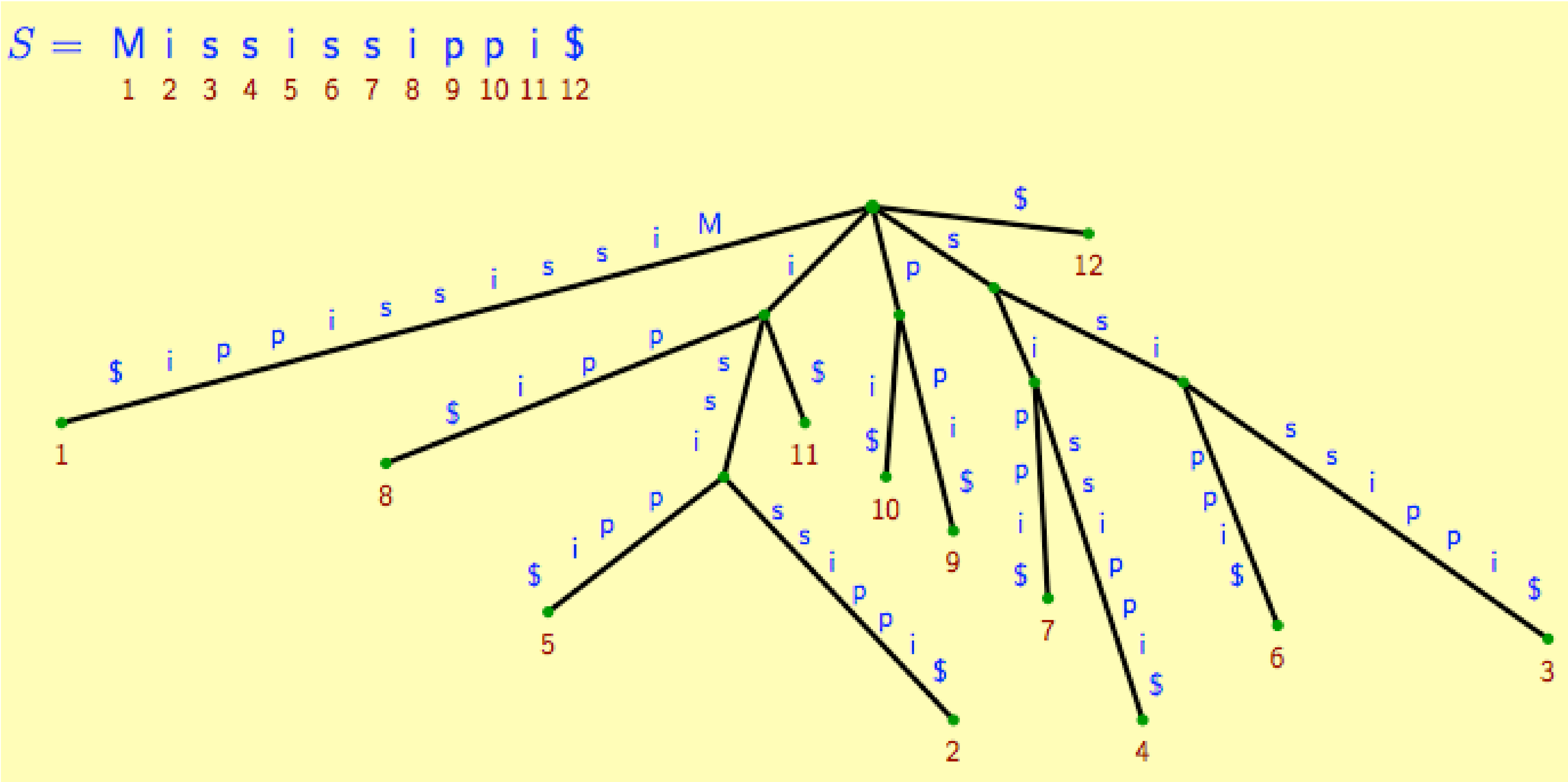

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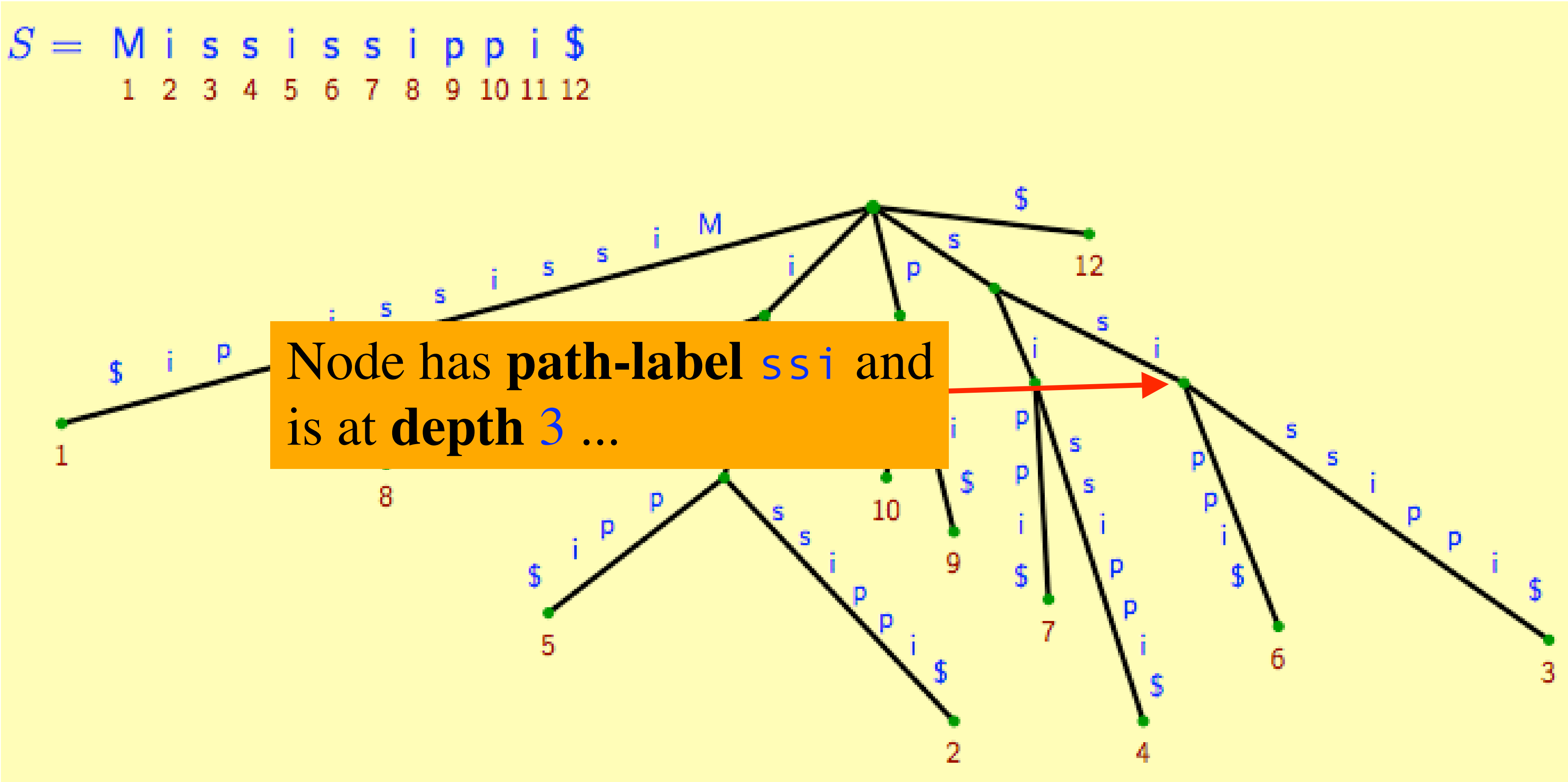

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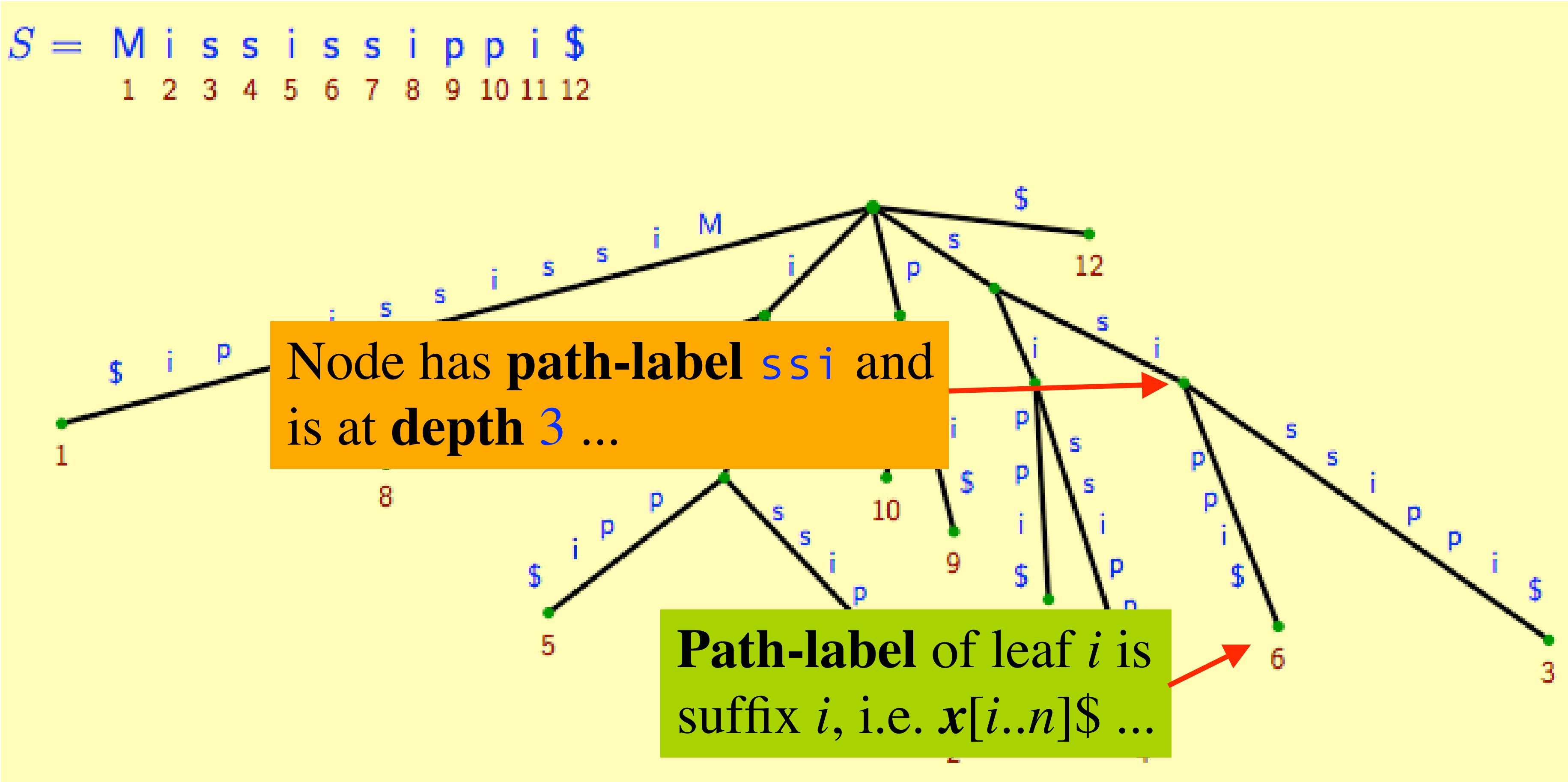

Node has **path-label** `ssi` and is at **depth** 3 ...

Path-label of leaf i is suffix i, i.e. $\boldsymbol{x}[i..n]\$$ ...

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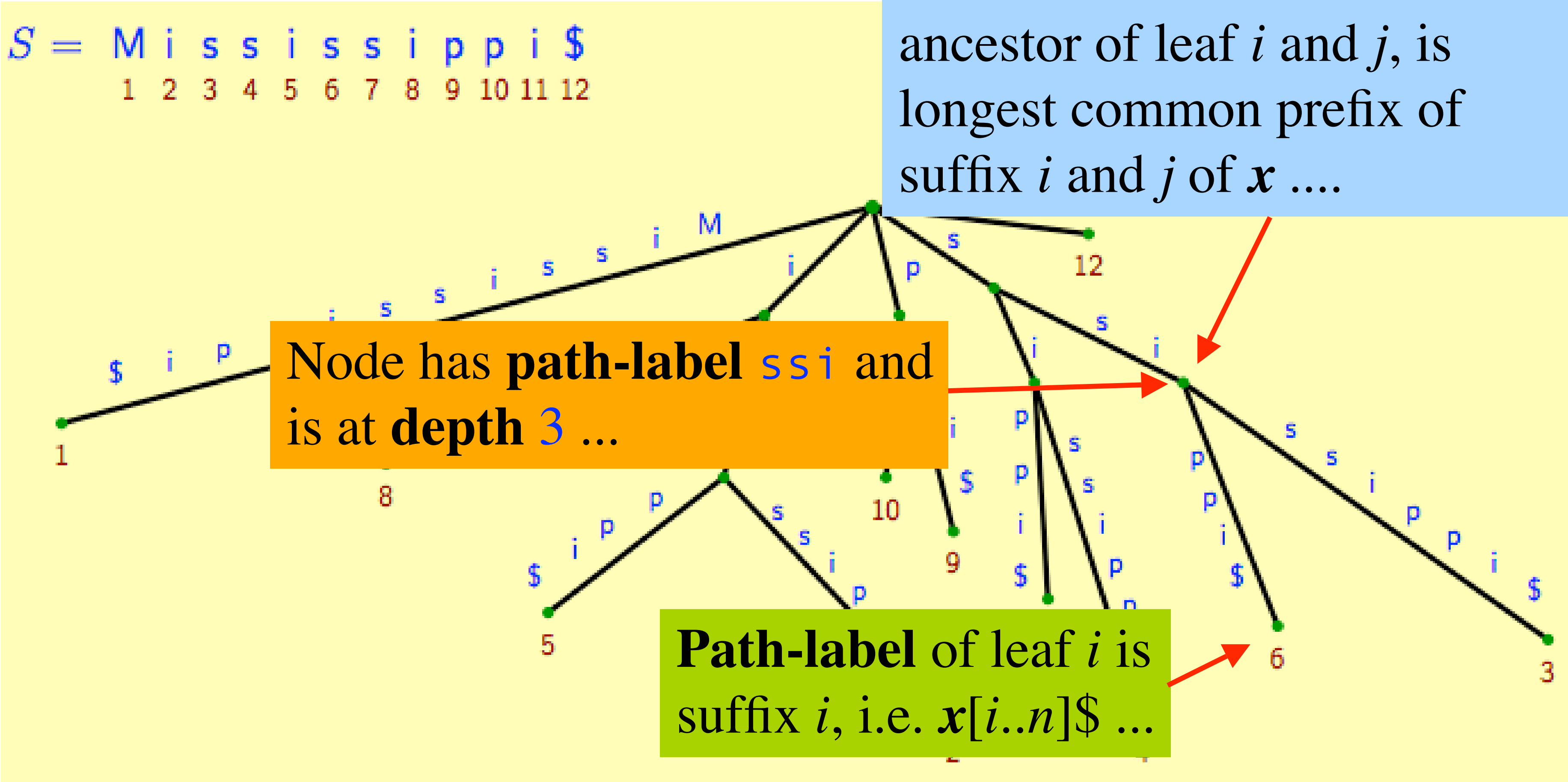


Path-label of lowest common ancestor of leaf *i* and *j*, is longest common prefix of suffix *i* and *j* of ***x*** ....

Node has **path-label** `ssi` and is at **depth** 3 ...

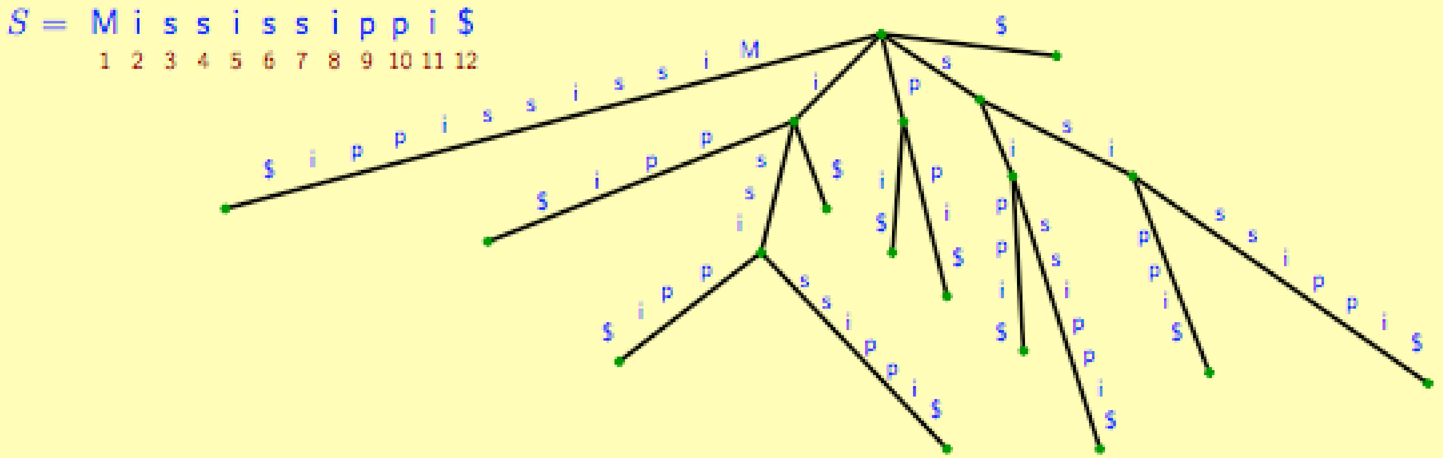
Path-label of leaf *i* is suffix *i*, i.e. ***x***[*i*..*n*]\$ ...

Space consumption

Observation: $T(S)$ requires $\mathcal{O}(n)$ space.

Proof sketch:

1. $T(S)$ has at most n leaves.
2. Each internal node is branching $\Rightarrow$ at most $n-1$ internal nodes.
3. A tree with at most $2n-1$ nodes has at most $2n-2$ edges.
4. Each node requires constant space.
5. Each edge label is a substring of S $\Rightarrow$ pair of pointers (i, j) into S.



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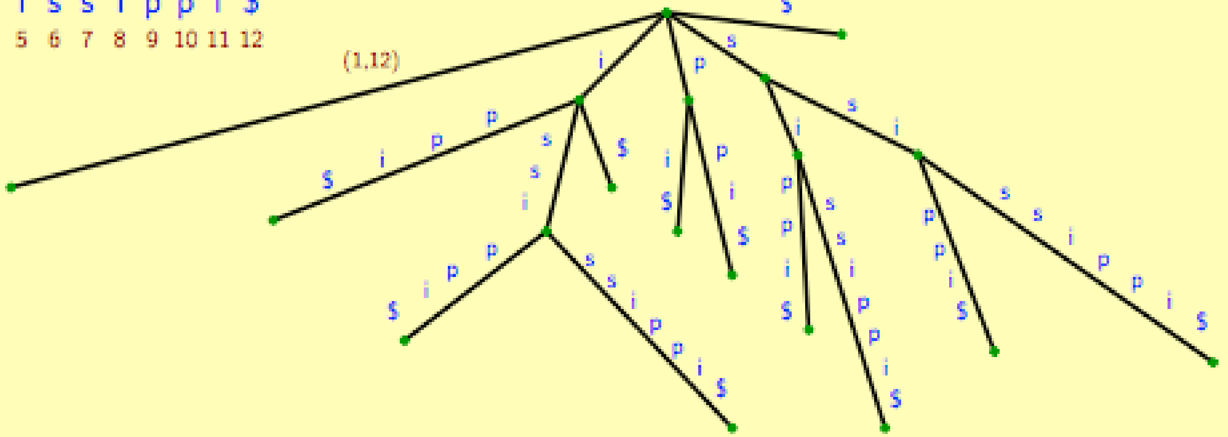
	1	2	3	4	5	6	7	8	9	10	11	12



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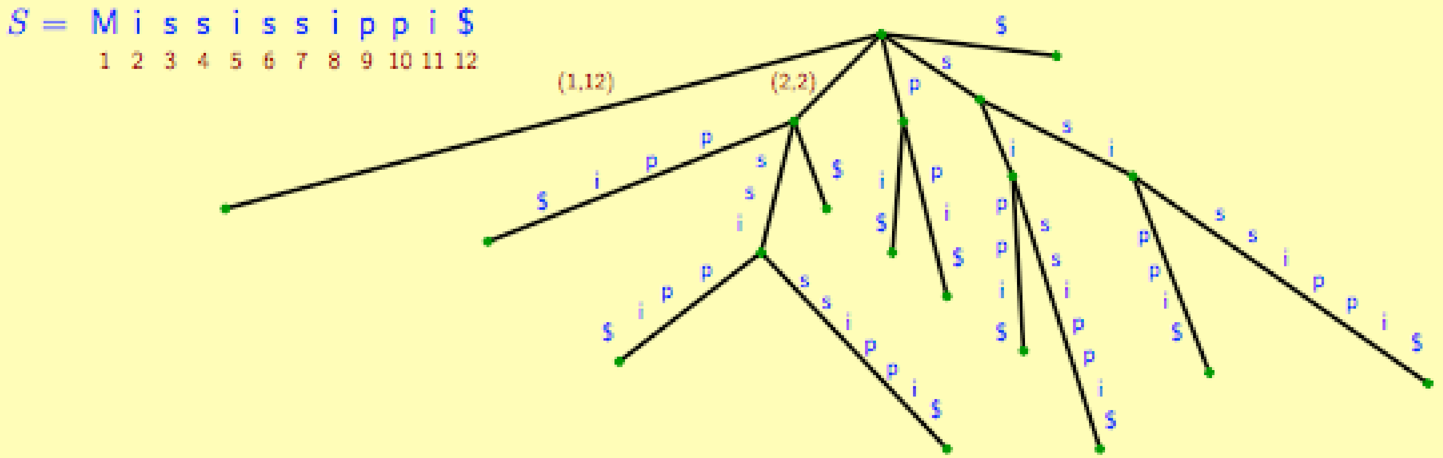

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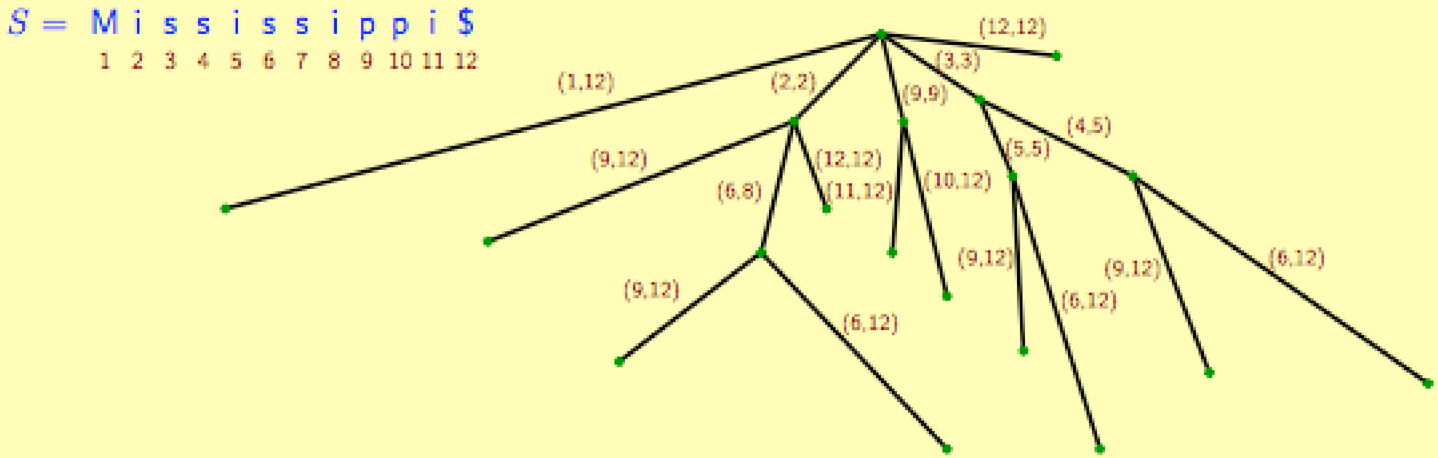

Constructing suffix trees

Constructing $T(\boldsymbol{x})$ by inserting each suffix one by one takes time $O(n^2)$

Can we do better?

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Can we do better?

[Weiner 1973]: $T(\boldsymbol{x})$ can be constructed in time $O(n)$ ...

There are two practical algorithms that construct the suffix tree in linear time: McCreight (1976) and Ukkonen (1993) ...

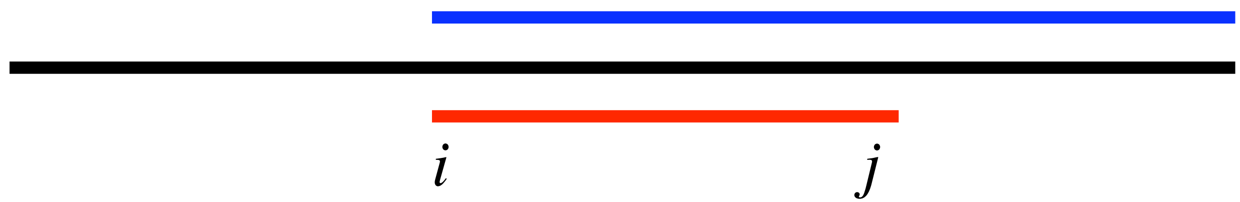
What about applications?

... exact matching, finding repeats, longest common substring ...

Exact matching

Given string $\boldsymbol{x}$ and pattern $\boldsymbol{y}$, report where $\boldsymbol{y}$ occurs in $\boldsymbol{x}$

If $\boldsymbol{y}$ occurs in $\boldsymbol{x}$ at position i, then $\boldsymbol{y}$ is a prefix of suffix i of $\boldsymbol{x}$



$\boldsymbol{y}$ is spelled by an initial part of the path from the root to leaf i in $T(\boldsymbol{x})$

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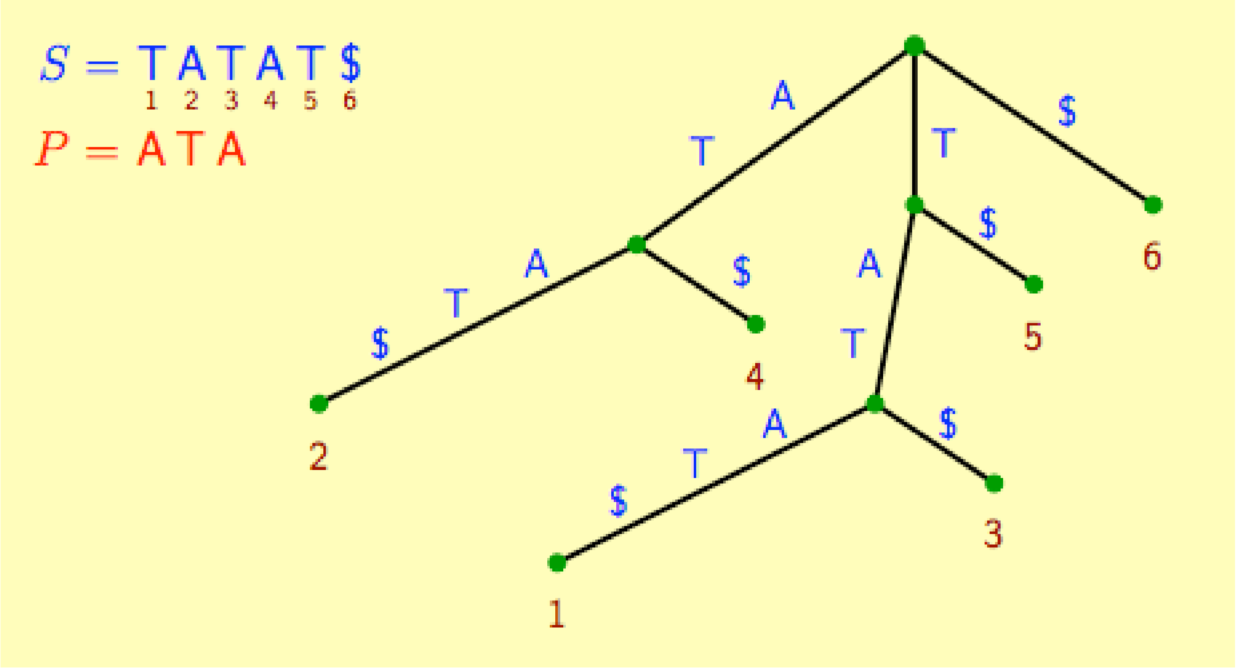

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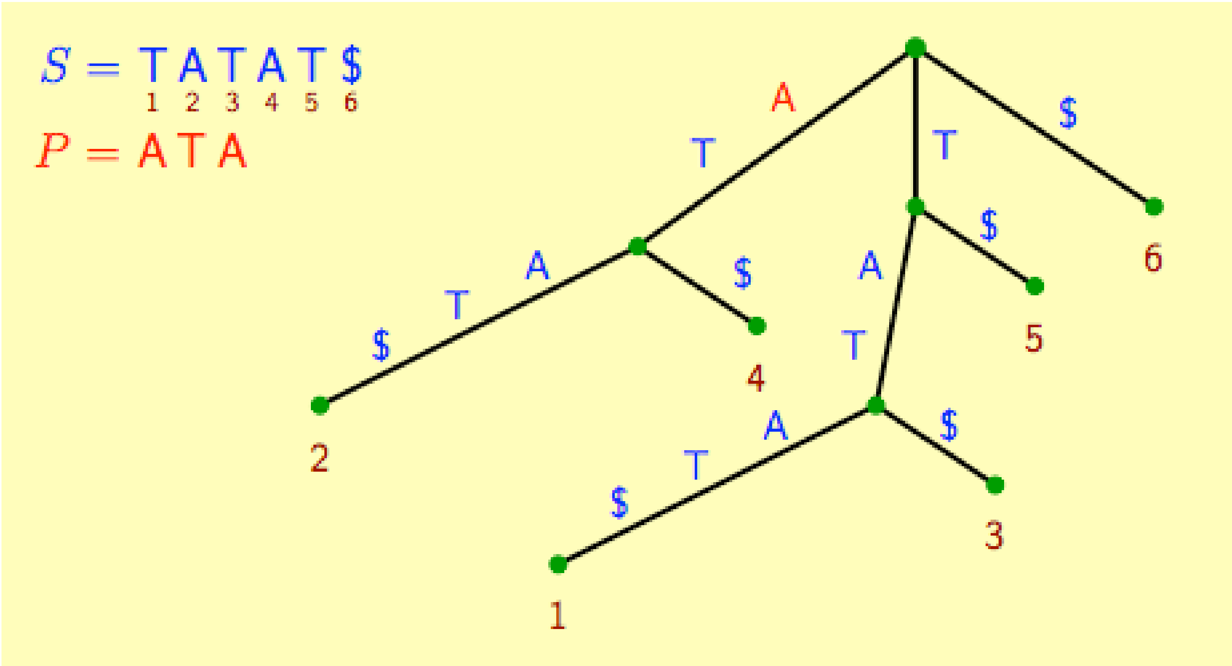

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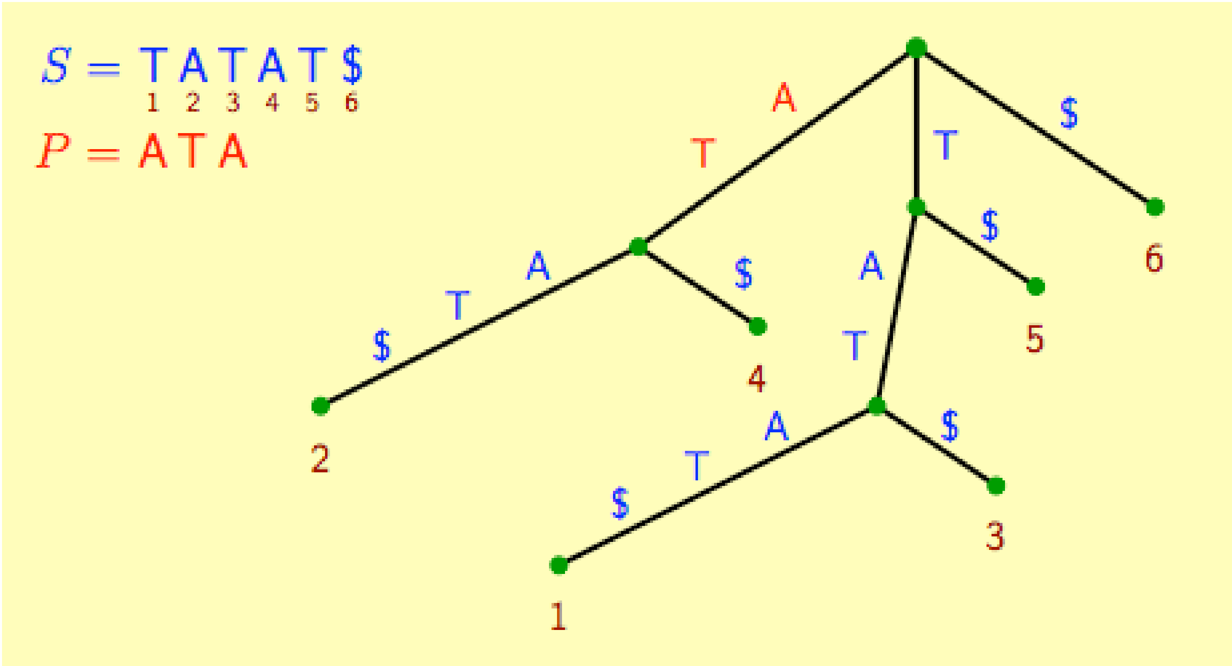

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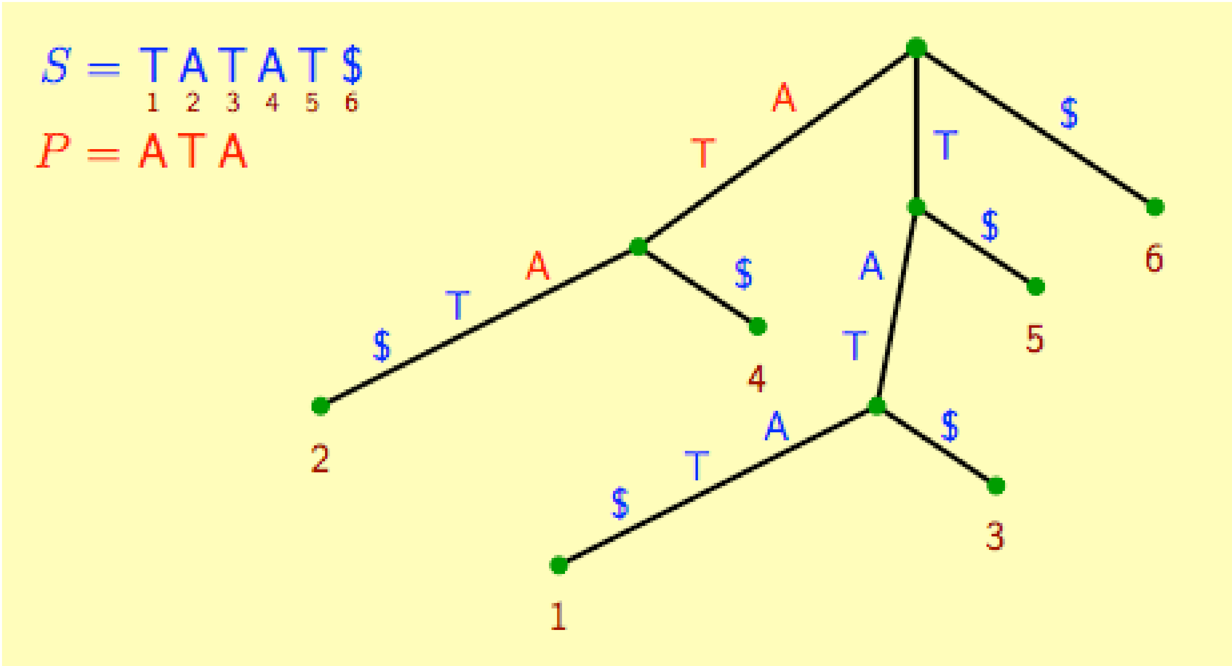

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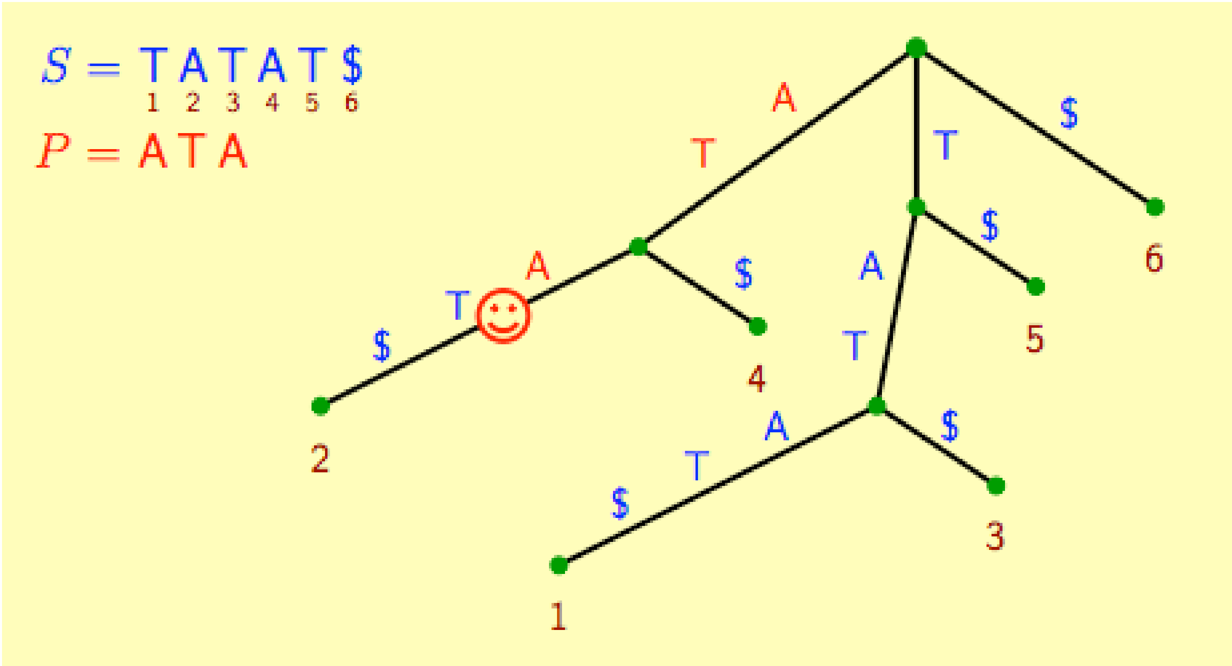

Pattern `ata` occurs at position 2 in `tatat`

Time: O(|*P*|) using the suffix tree *T*(*S*)

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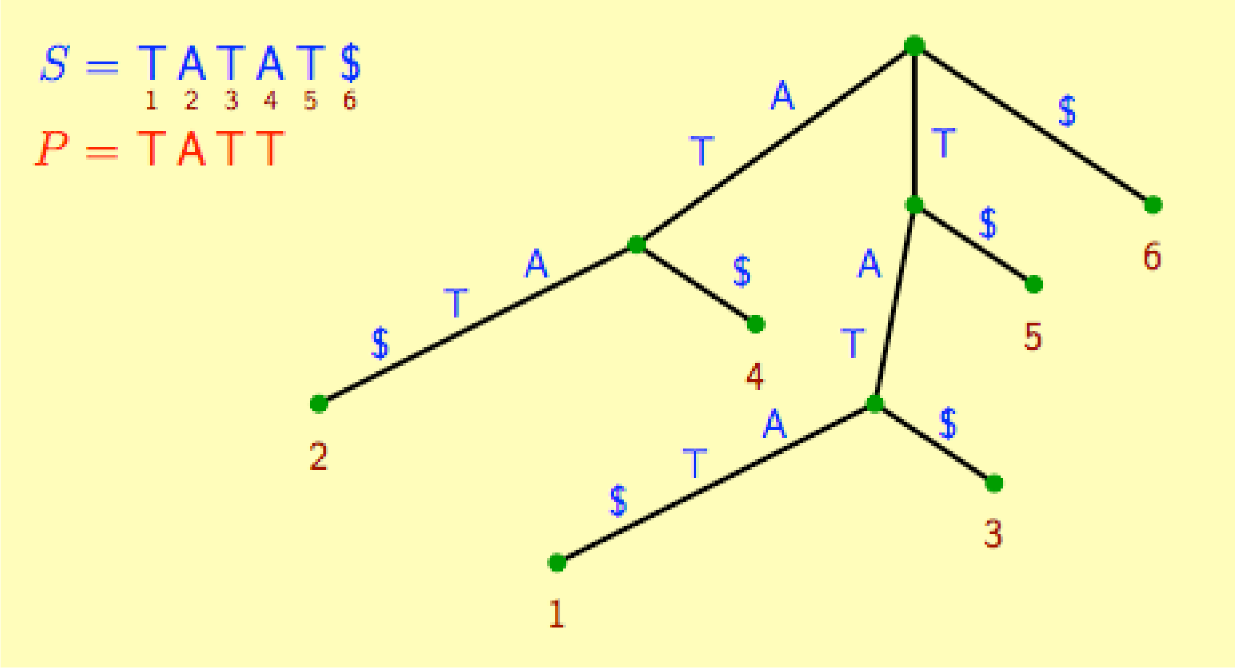

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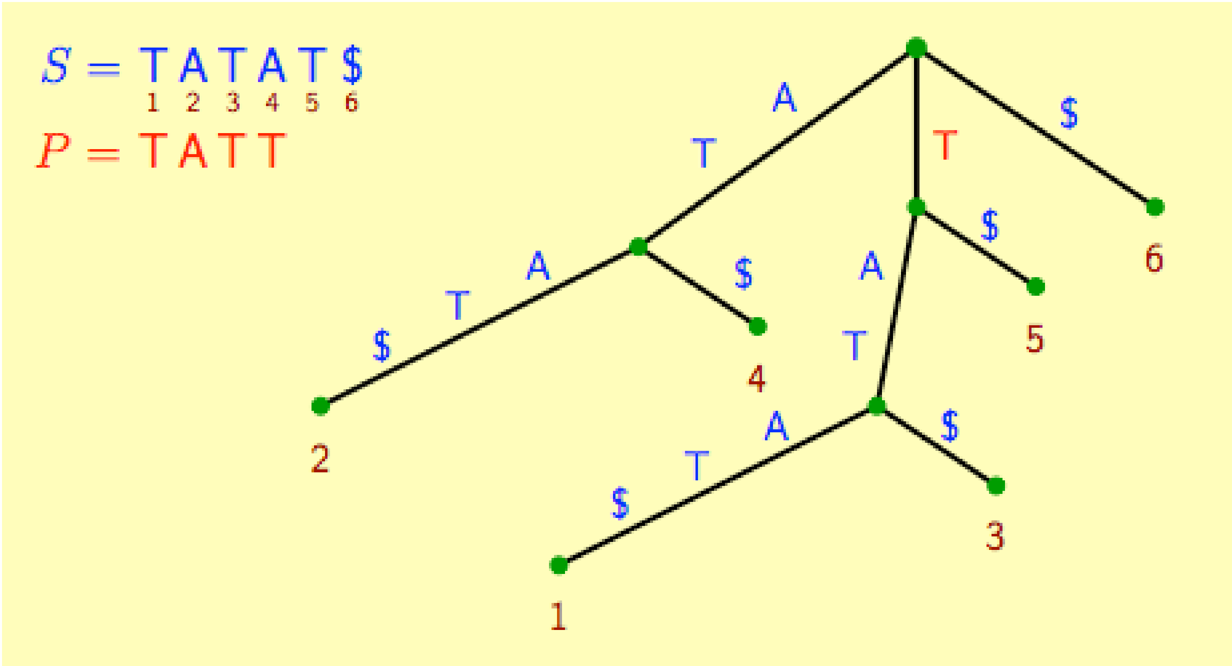

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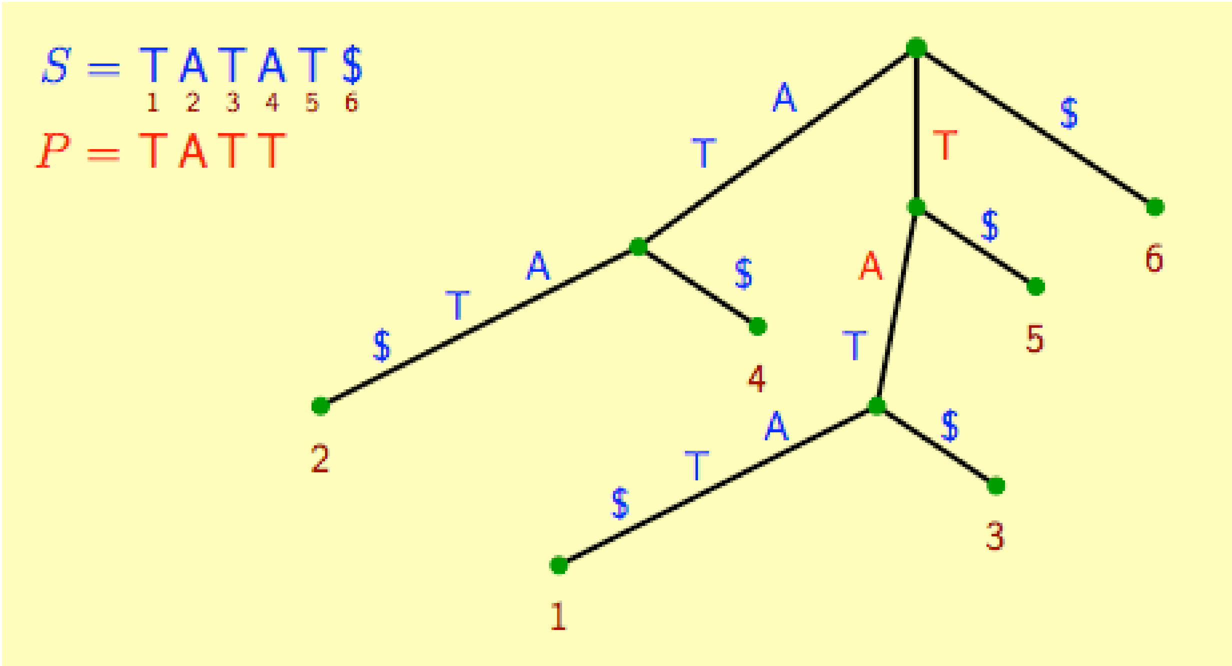

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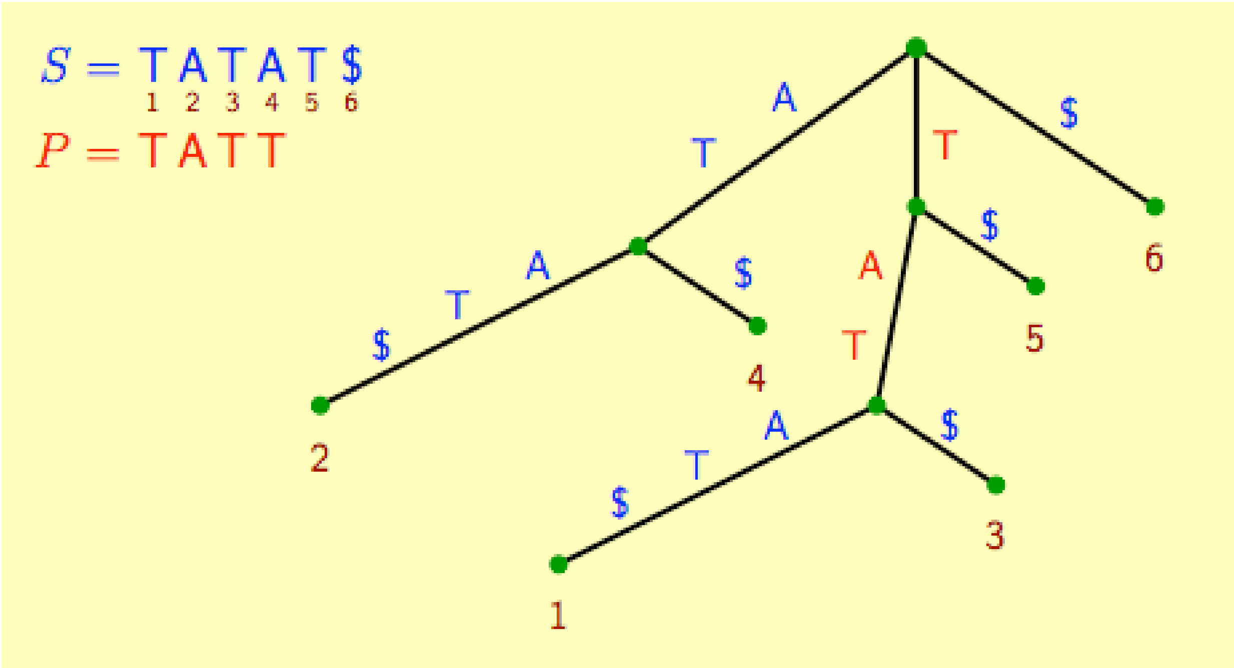

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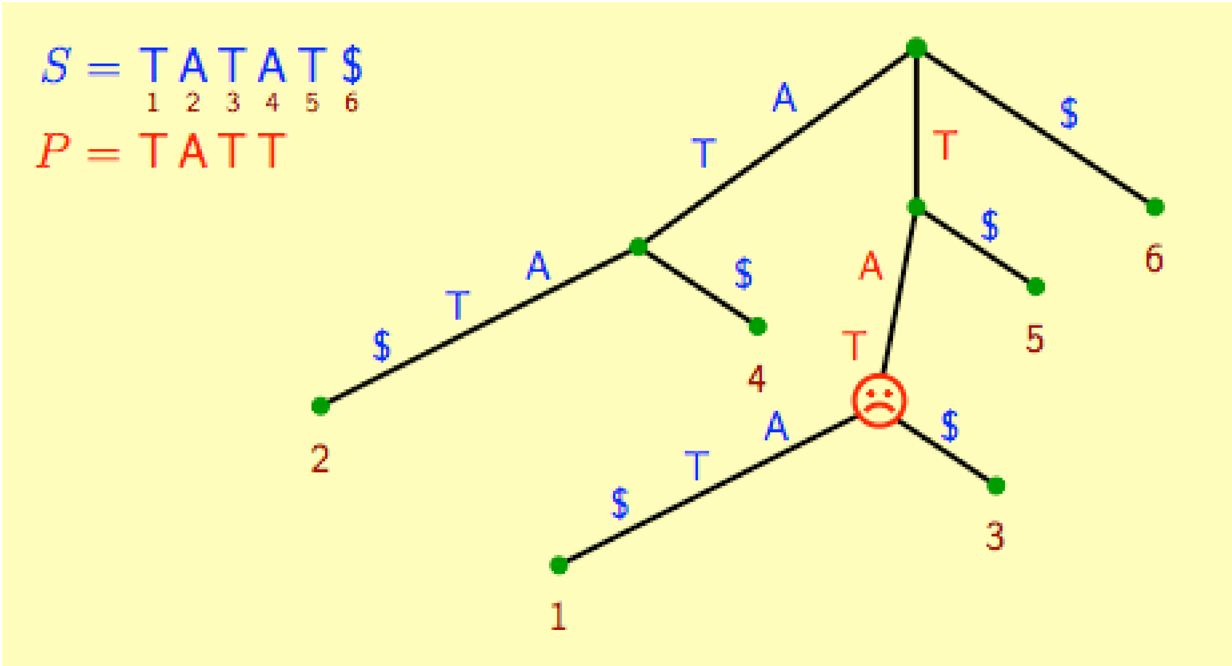

Pattern `tatt` does not occur in `tatat`

Time: O(|*P*|) using the suffix tree *T*(*S*)

Repeats

A pair of substrings R=(S[i_1..j_1], S[i_2..j_2]) is a ...

$\longrightarrow$ *exact* repeat if $S[i_1, j_1] = S[i_2, j_2]$

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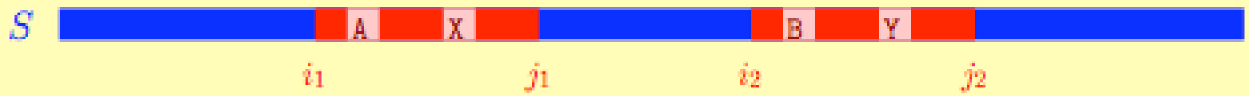

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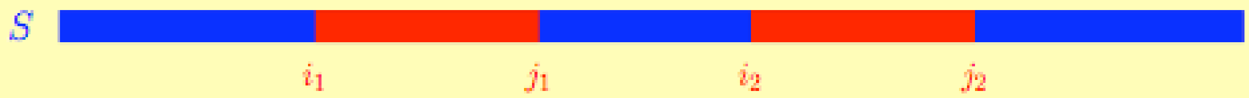
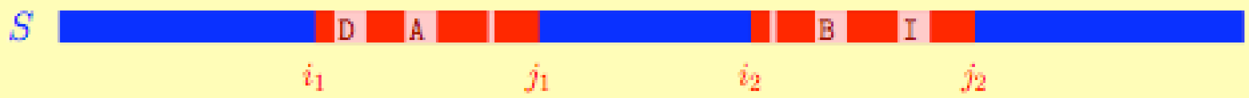


→ *k-mismatch* repeat if there are k mismatches between $S[i_1, j_1]$ and $S[i_2, j_2]$

→ *k-differences* repeat if there are k differences (mismatches, insertions, deletions) between $S[i_1, j_1]$ and $S[i_2, j_2]$



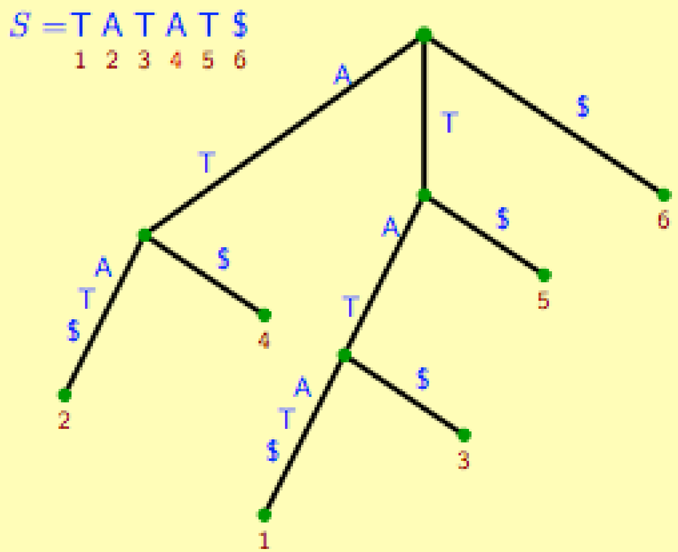
Finding exact repeats

Folklore: (see e.g. Gusfield, 1997)

- It is possible to find all pairs of repeated substrings (repeats) in S in linear time.

Idea:

- consider string S and its suffix tree $T(S)$.
- repeated substrings of S correspond to *internal locations* in $T(S)$.
- leaf numbers tell us positions where substrings occur.



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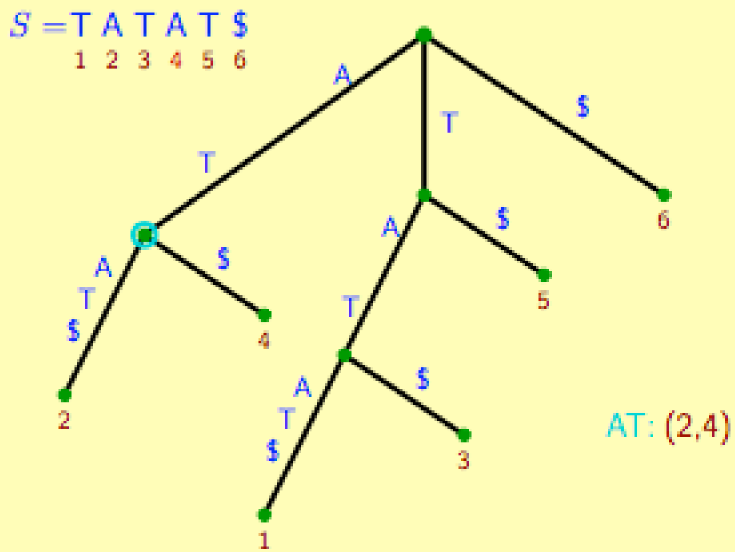

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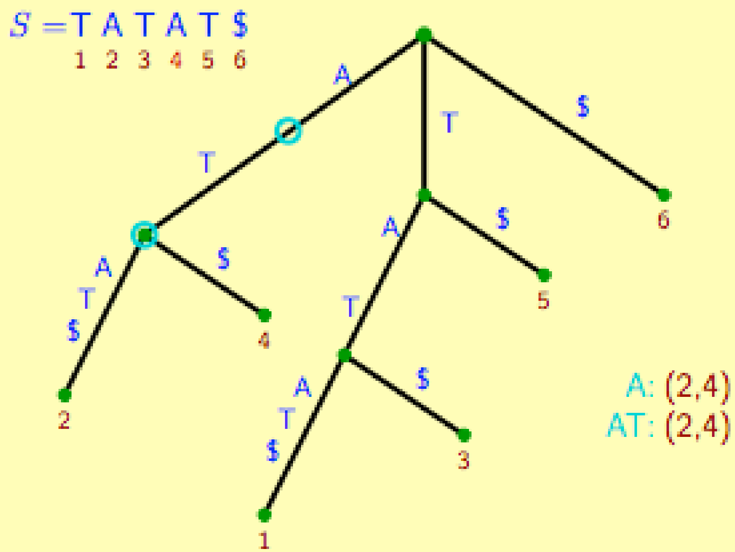

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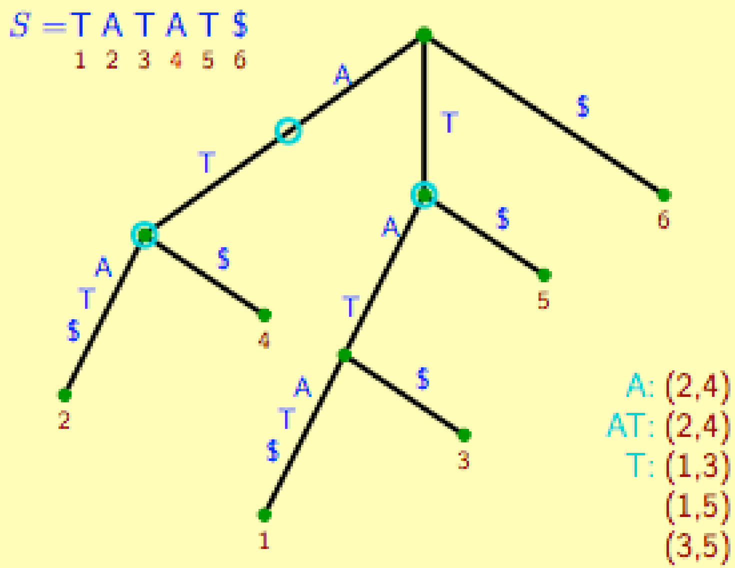
- leaf numbers tell us positions where substrings occur.



Finding exact repeats

Folklore: (see e.g. Gusfield, 1997)

- It is possible to find all pairs of repeated substrings (repeats) in S in linear time.

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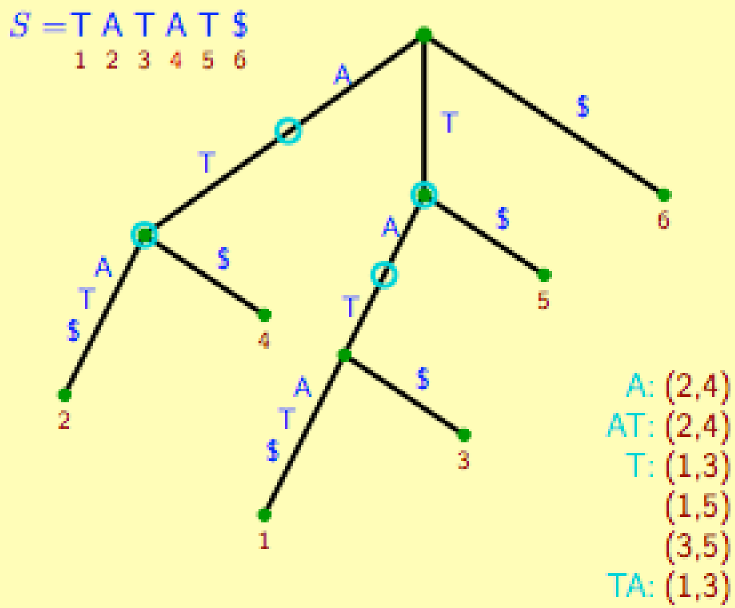

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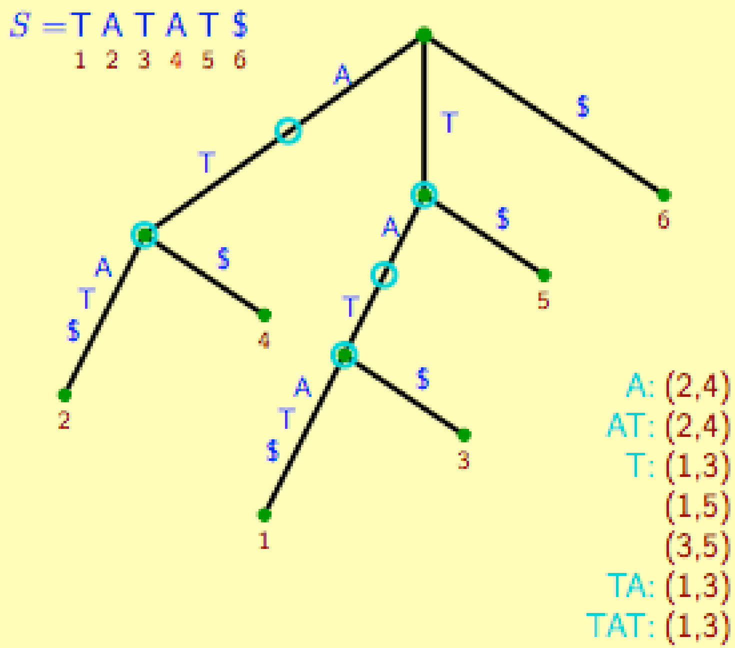

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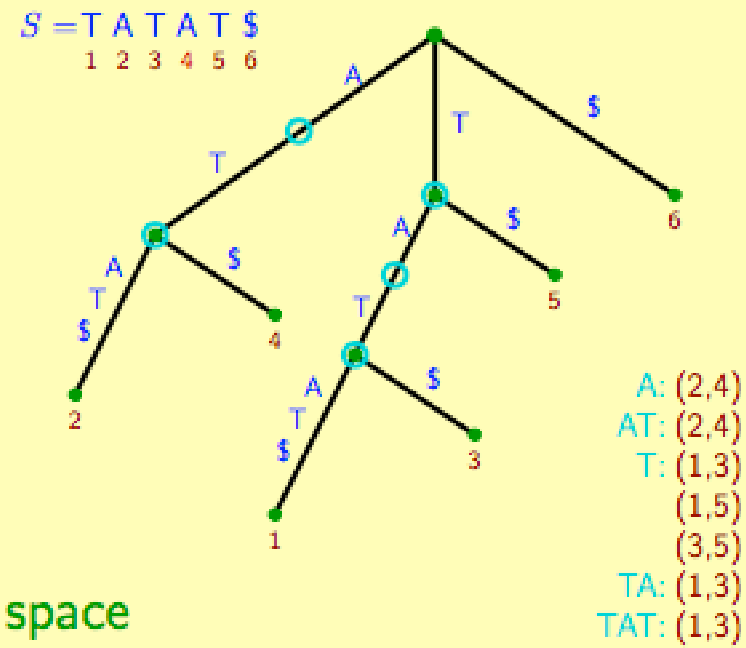
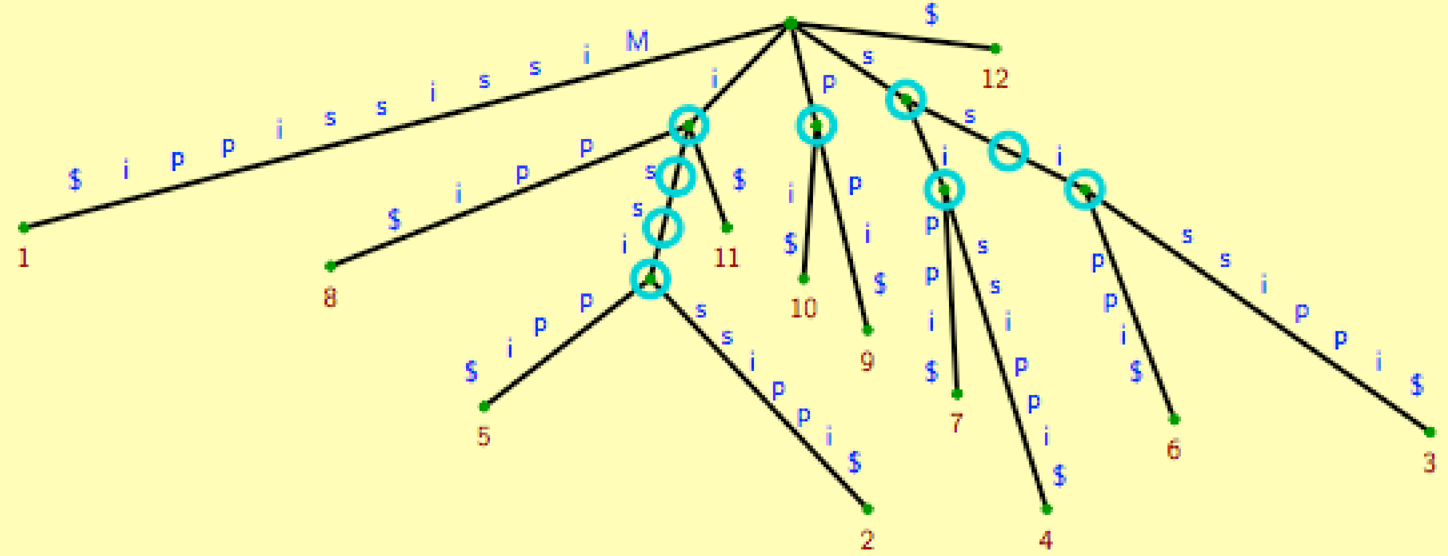


Analysis: $\mathcal{O}(n+z)$ time with $z = |\text{output}|$, $\mathcal{O}(n)$ space

A larger example

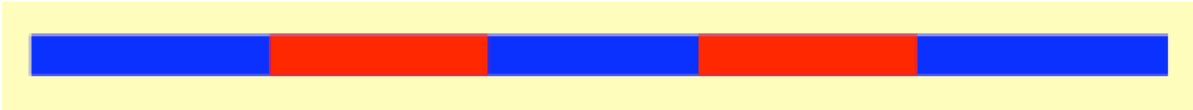
$S =$ M i s s i s s i p p i \$

1 2 3 4 5 6 7 8 9 10 11 12



i: (8,5)	is: (5,2)	p: (10,9)	s: (7,4)	si: (7,4)
(8,2)			(7,6)	
(8,11)	iss: (5,2)		(7,3)	ss: (6,3)
(5,2)			(4,6)	
(5,11)	issi: (5,2)		(4,3)	ssi: (6,3)
(2,11)			(6,3)	

Finding *maximal* exact repeats



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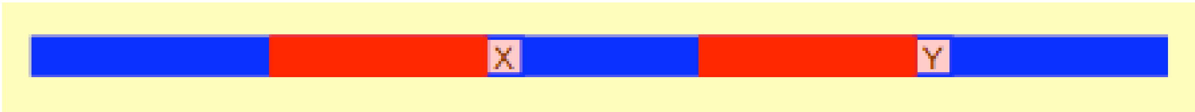
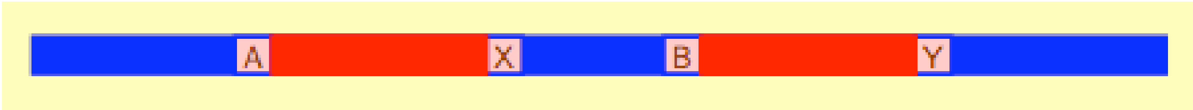


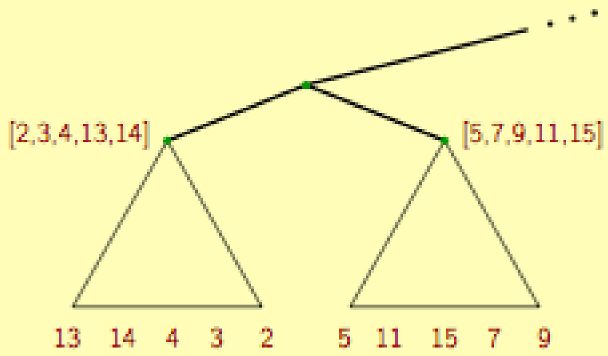
Finding *maximal* exact repeats



Finding *maximal* exact repeats

Idea:

- For right-maximality (X $\neq$ Y)
  - consider only internal nodes of $T(S)$
  - report only pairs of leaves from different subtrees (or from different leaf-lists)



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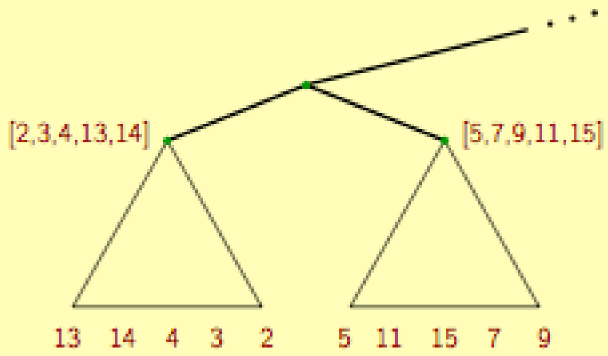
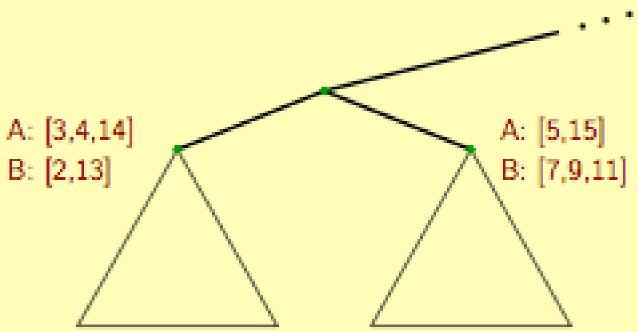


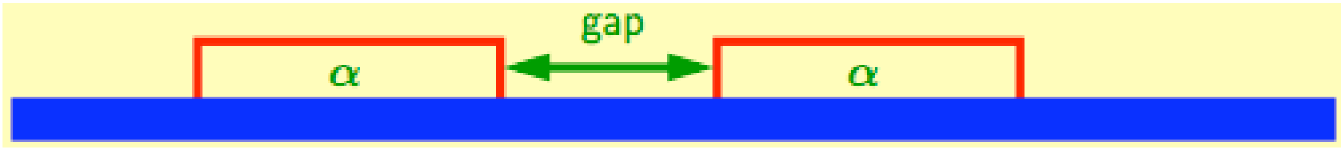
- For left-maximality (A $\neq$ B)
  - keep lists for the different left-characters
  - report only pairs from different lists



Analysis: $\mathcal{O}(n+z)$ time with $z = |\text{output}|$, $\mathcal{O}(n)$ space

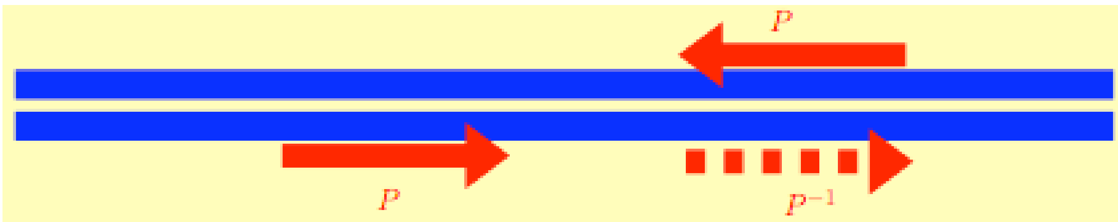
Other repeats

Maximal repeats with bounded gap in time O(n log n + z)



Tandem repeats in time O(n log n + z)

Palindromic repeats in O(n + z)



... all using suffix trees ...

More strings

The ***longest common substring*** of $\boldsymbol{x}[1..n]$ and $\boldsymbol{y}[1..m]$ is the longest string $\boldsymbol{z}$ which occurs in both $\boldsymbol{x}$ and $\boldsymbol{y}$ ...

Can this be found efficiently using a suffix tree?

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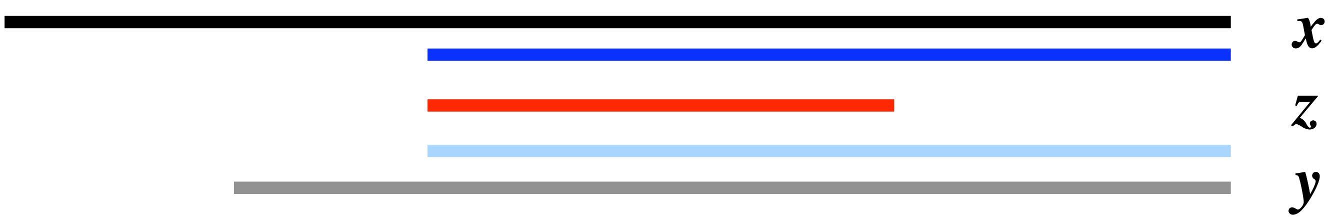
Can this be found efficiently using a suffix tree?

$\boldsymbol{z}$ is the longest common prefix of any pair of suffixes $\boldsymbol{x}[i..n]$ and $\boldsymbol{y}[j..m]$

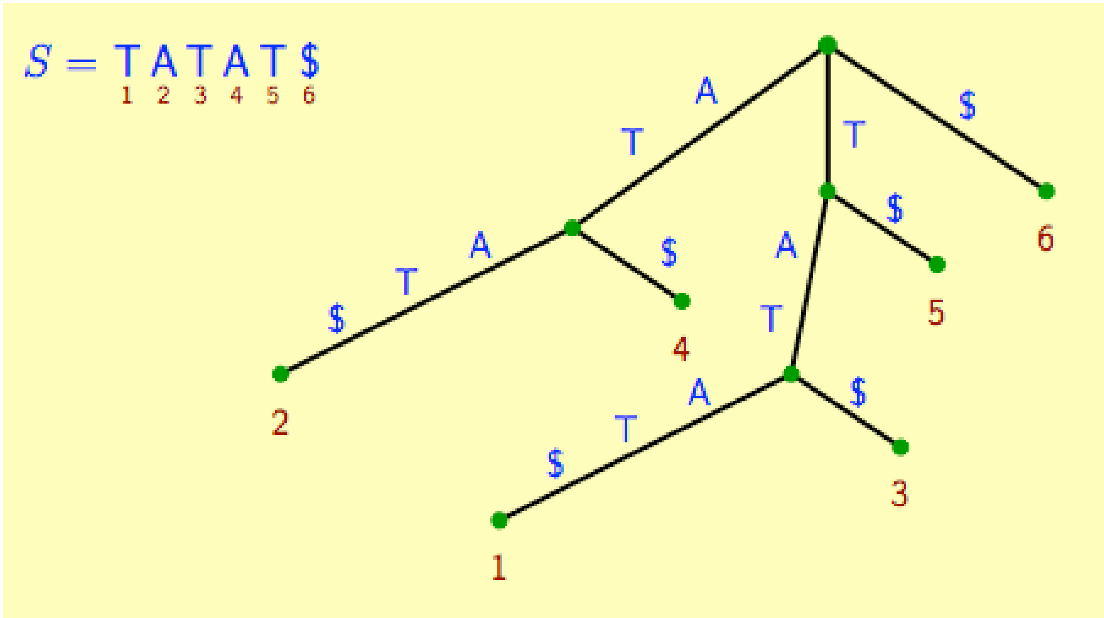


More strings

z is the longest common prefix of any pair of suffixes ***x***[*i*..*n*] and ***y***[*j*..*m*]

Idea: Build a compacted trie of all suffixes of ***x*** and ***y***, such that each suffix of ***x*** and ***y*** corresponds to unique root-to-leaf paths ...

tatat$	aataa#
atat$	ataa#
tat$	taa#
at$	aa#
t$	a#
$\varepsilon$$	ε#



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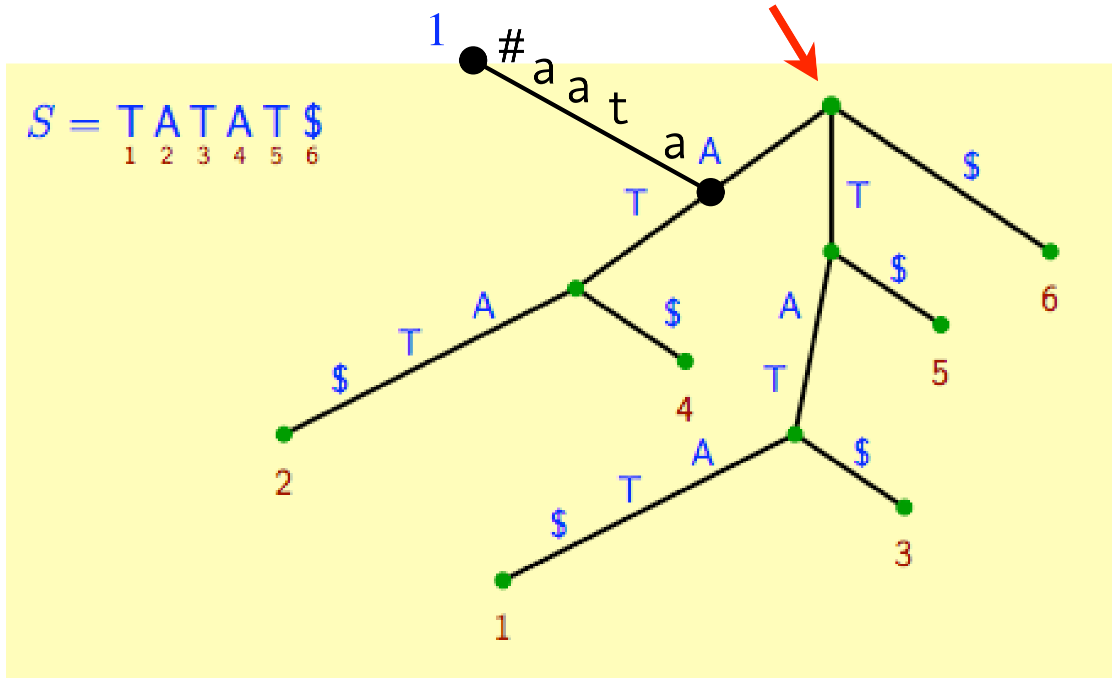

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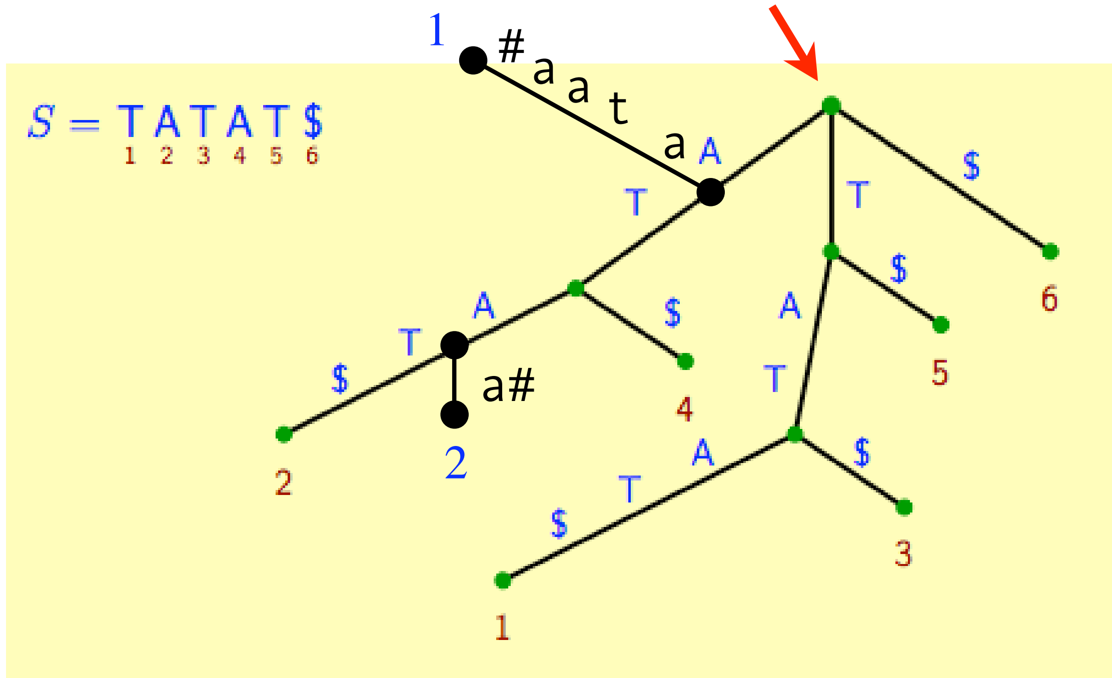

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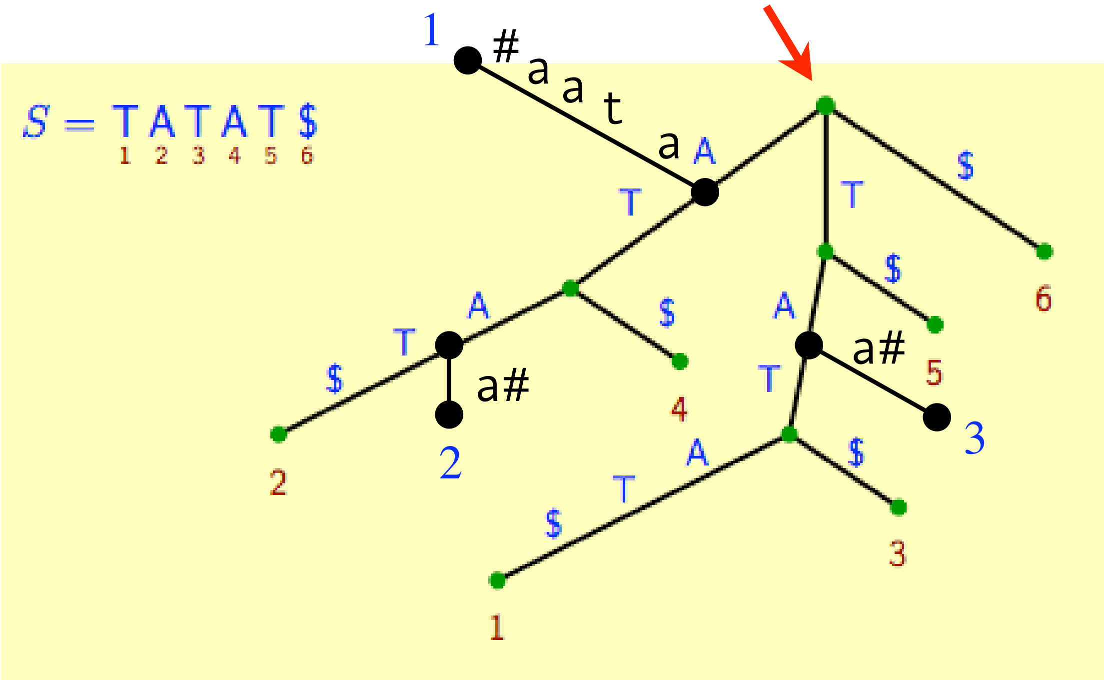

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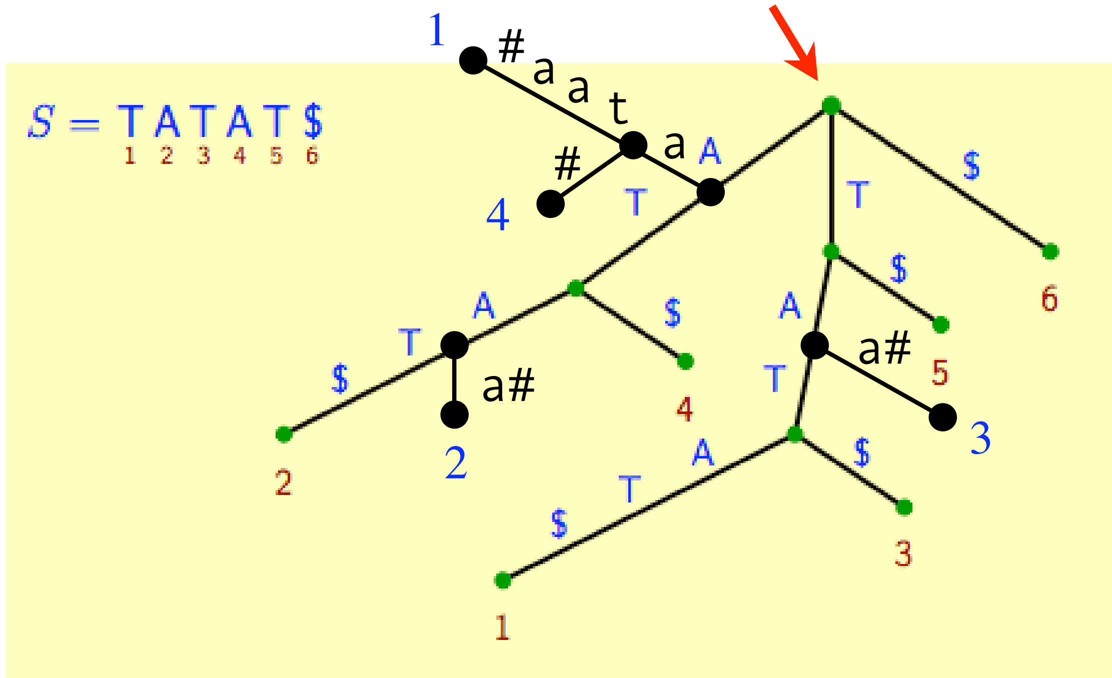

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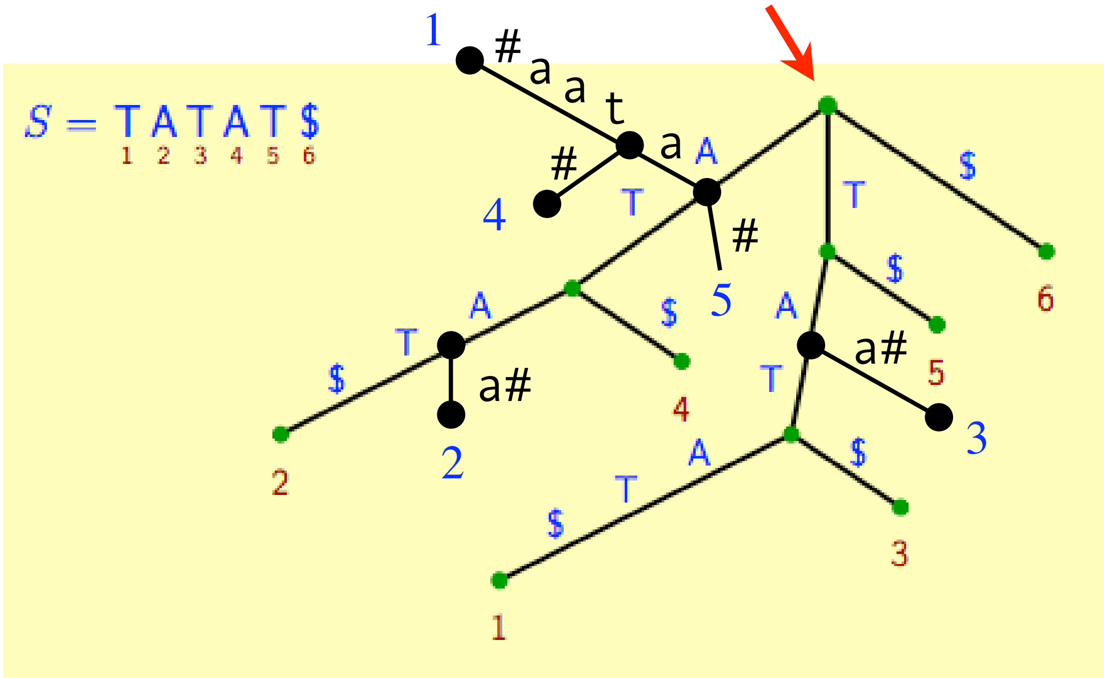

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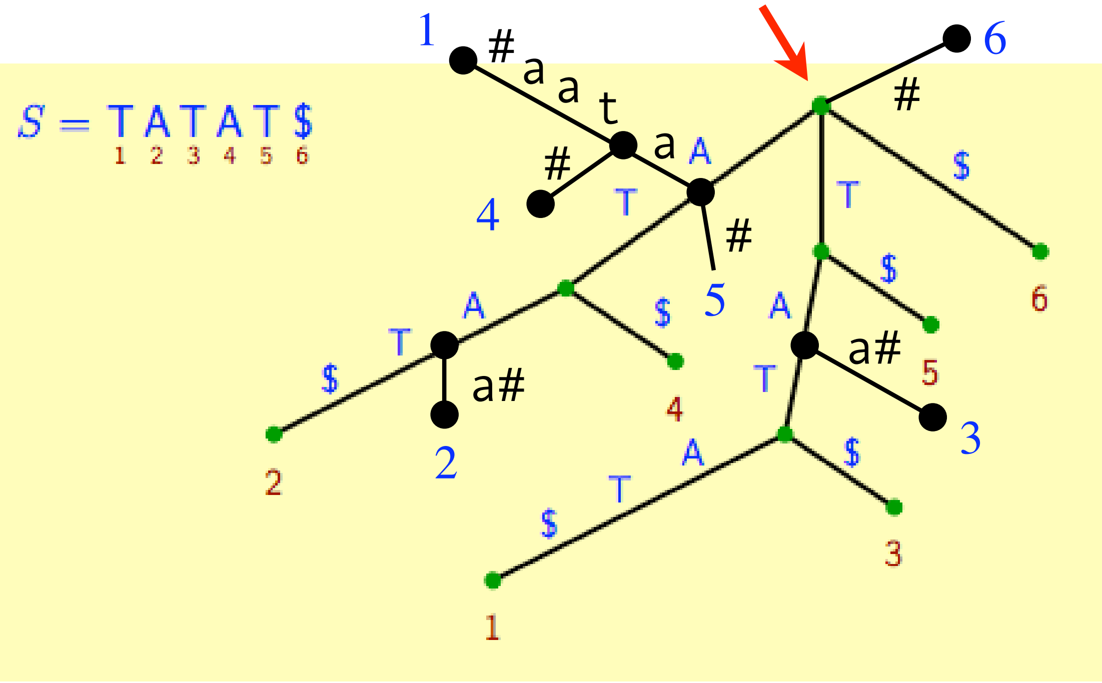
```
tatat$
 atat$
  tat$
   at$
    t$
    ε$
```

```
aataa#
 ataa#
  taa#
   aa#
    a#
    ε#
```



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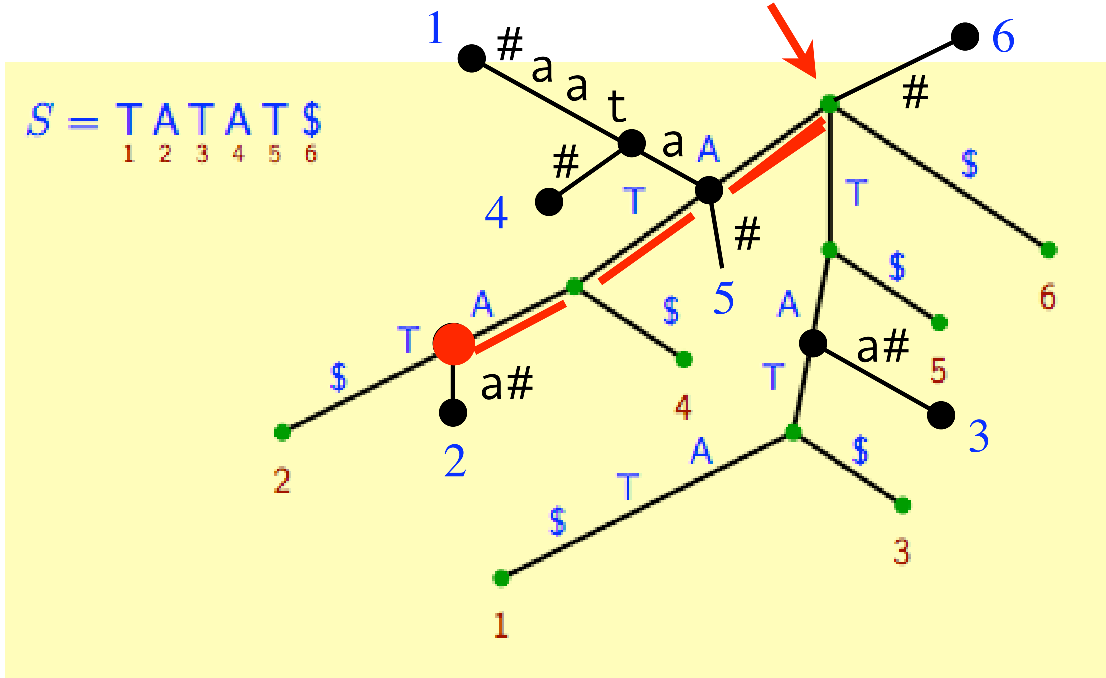

Observe: z is the path-label of the deepest node with suffixes from both $\boldsymbol{x}$ and $\boldsymbol{y}$ as leaves in its sub-tree ...

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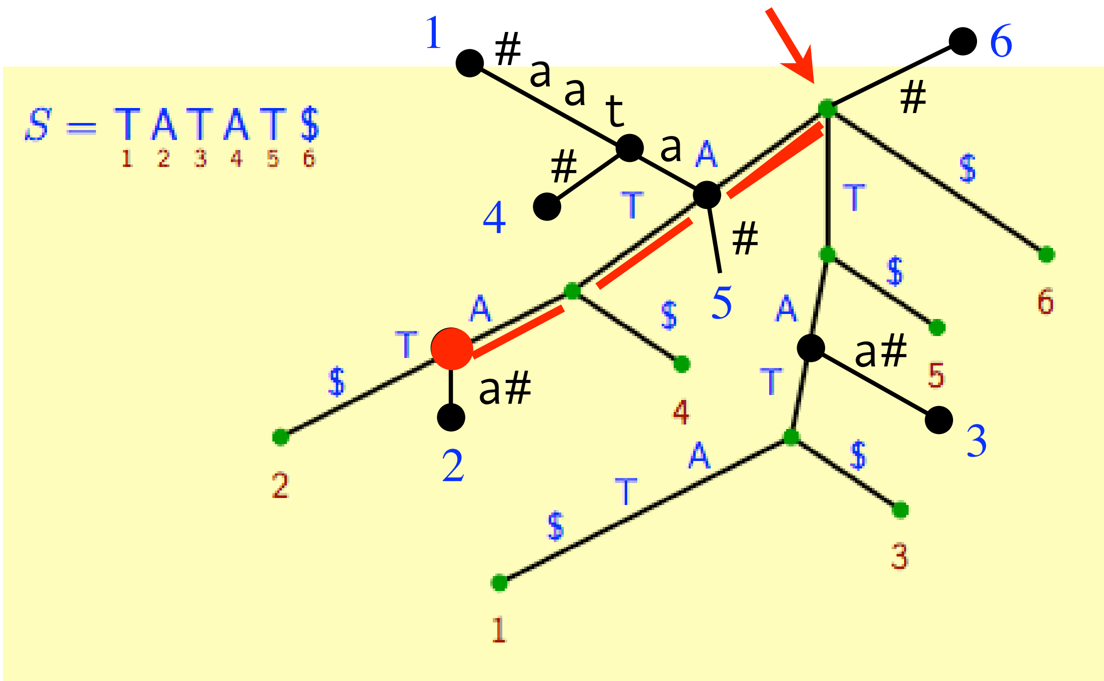
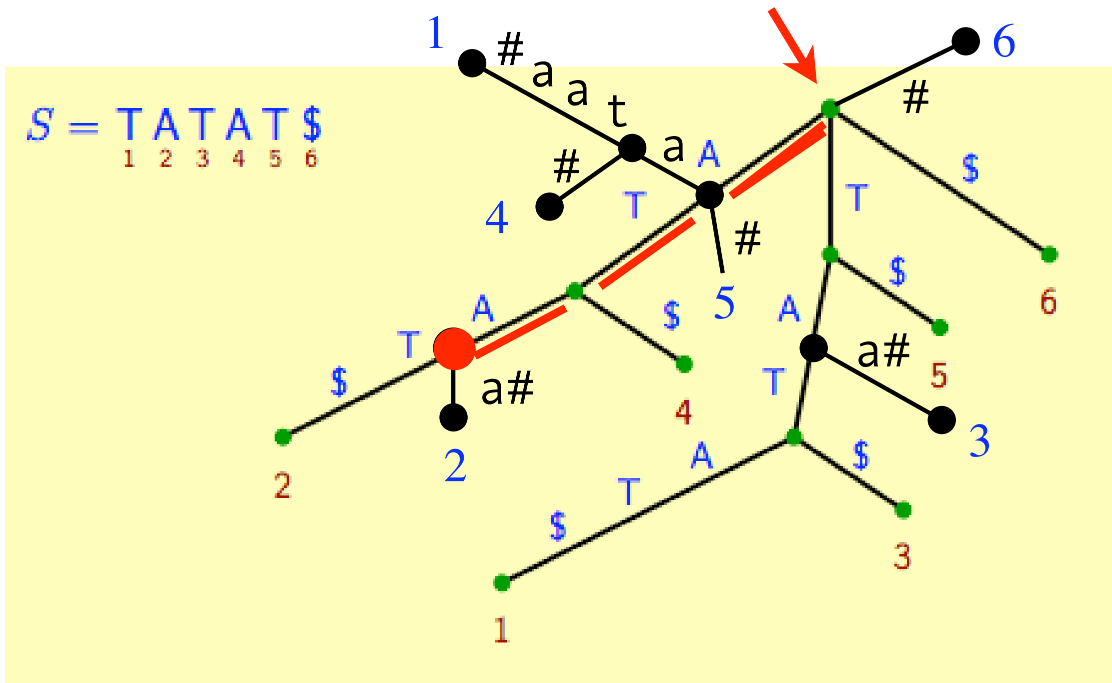


Observe: *z* is the path-label of the deepest node with suffixes from both ***x*** and ***y*** as leaves in its sub-tree ... **Time**: O(n+m)

Generalized suffix tree

This is the **generalized suffix tree** of `tatat` and `aataa`

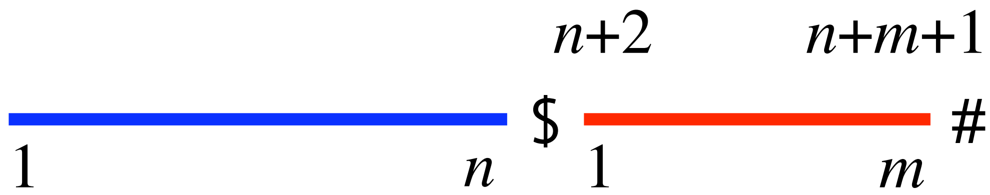
tatat$	aataa#
atat$	ataa#
tat$	taa#
at$	aa#
t$	a#
ε$	ε#



Can be constructed by constructing the suffix tree of ...

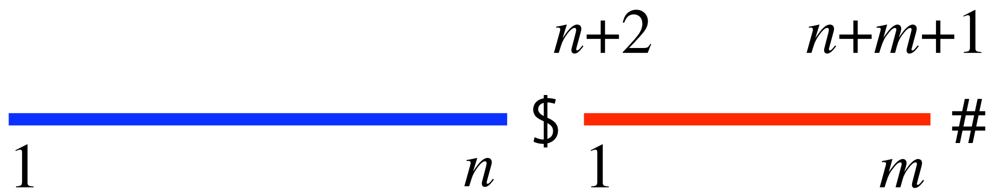
`tatat$aataa#`

Generalized suffix tree

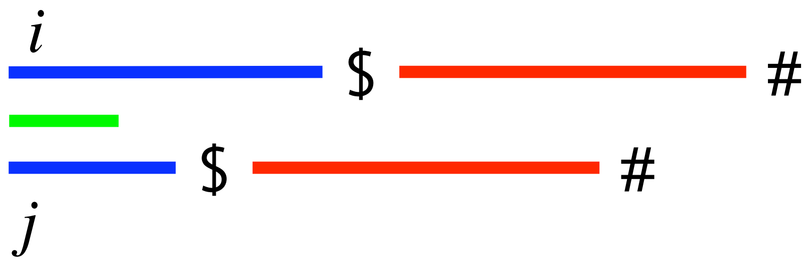


... we must argue that we get the same branching structure ...

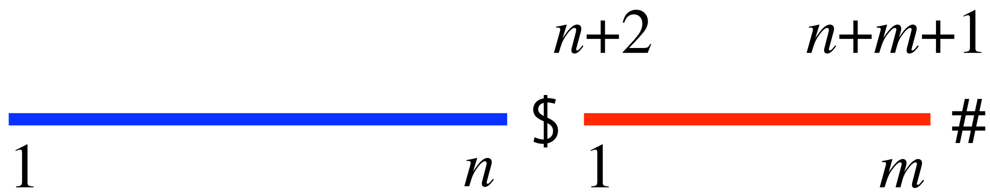
Generalized suffix tree



Case 1:



Generalized suffix tree



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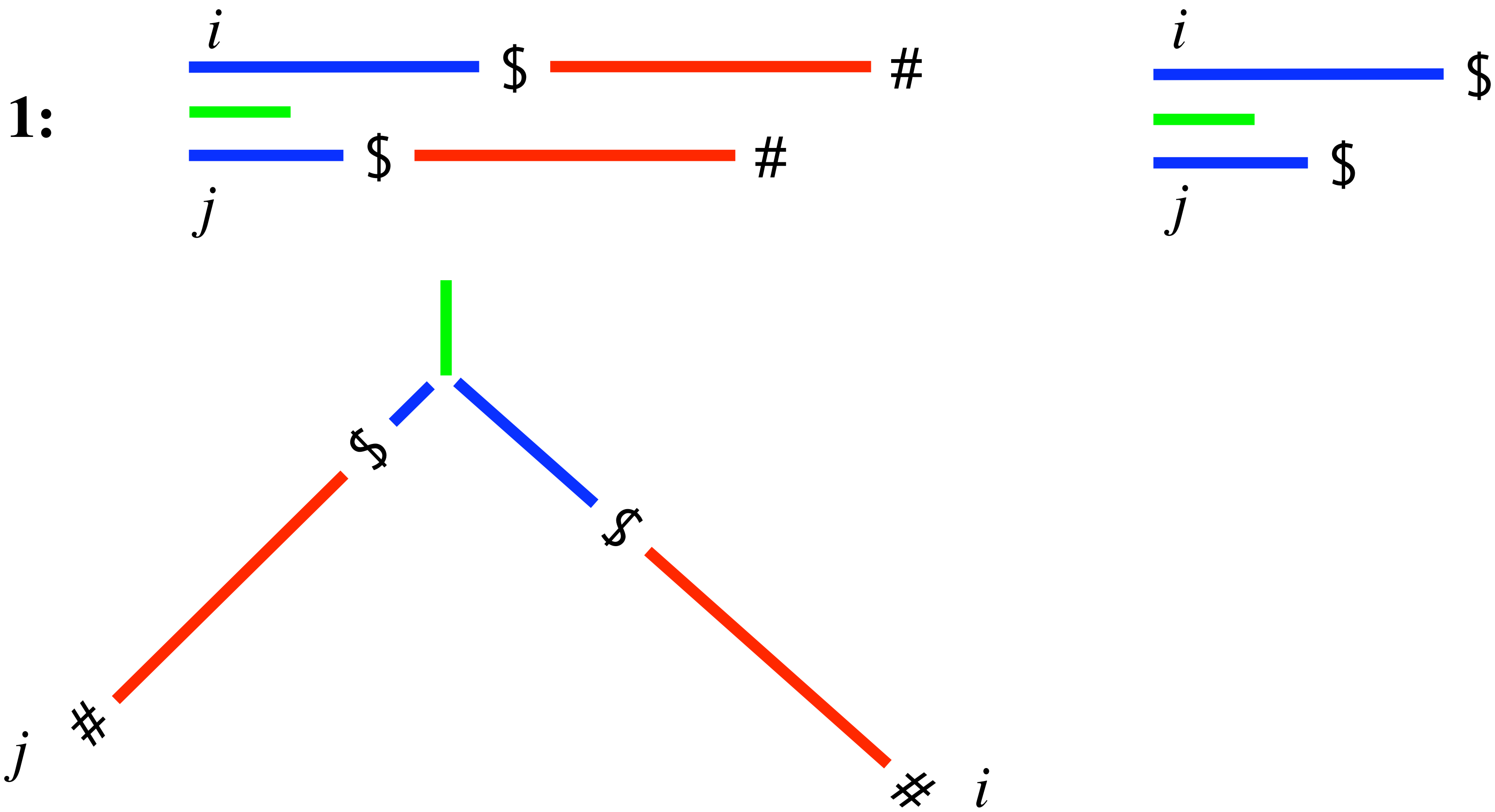
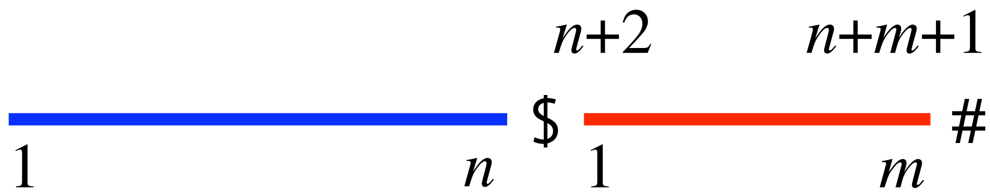


Generalized suffix tree



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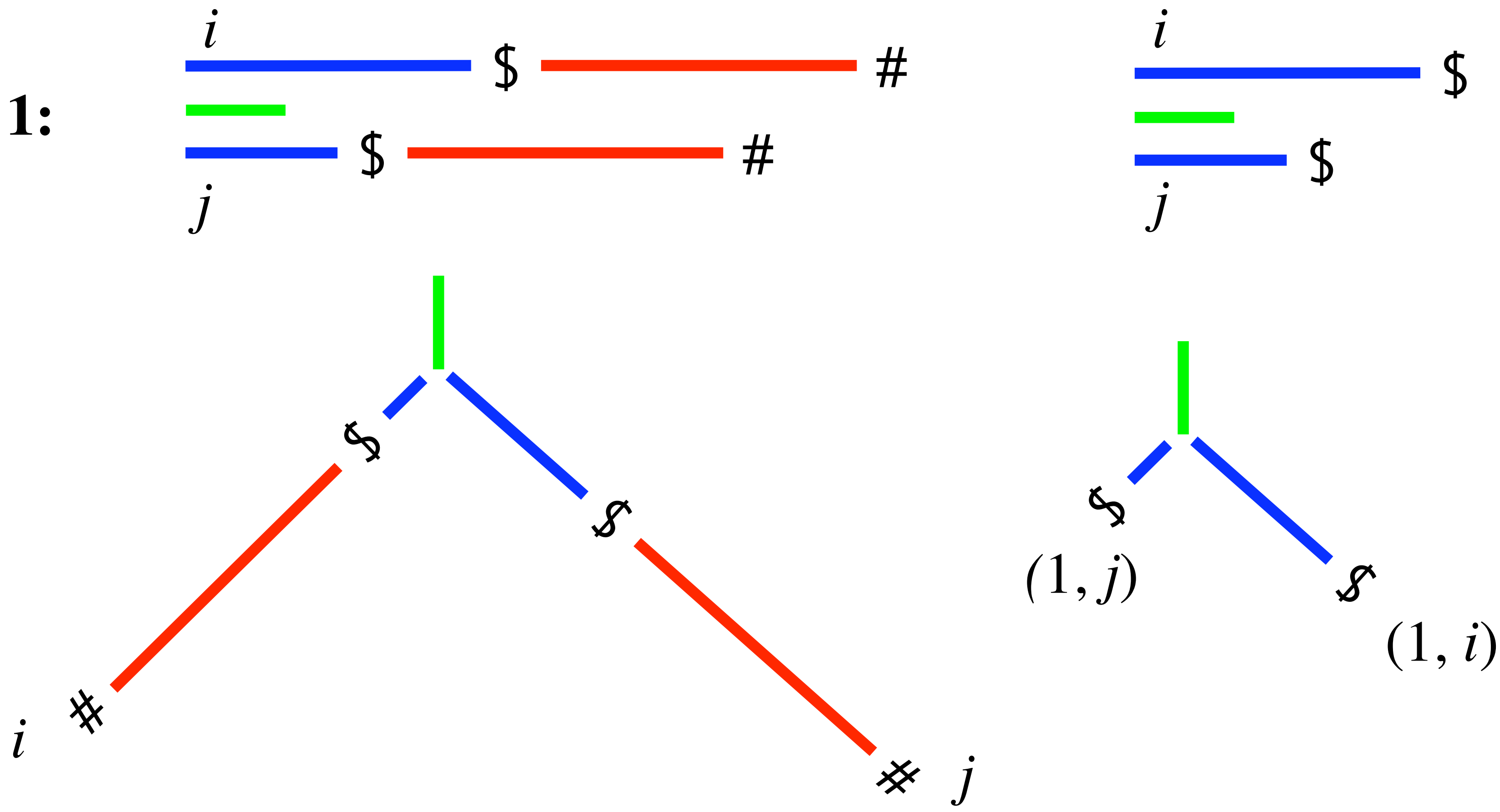
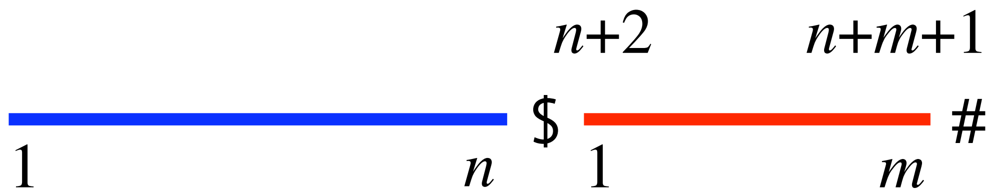
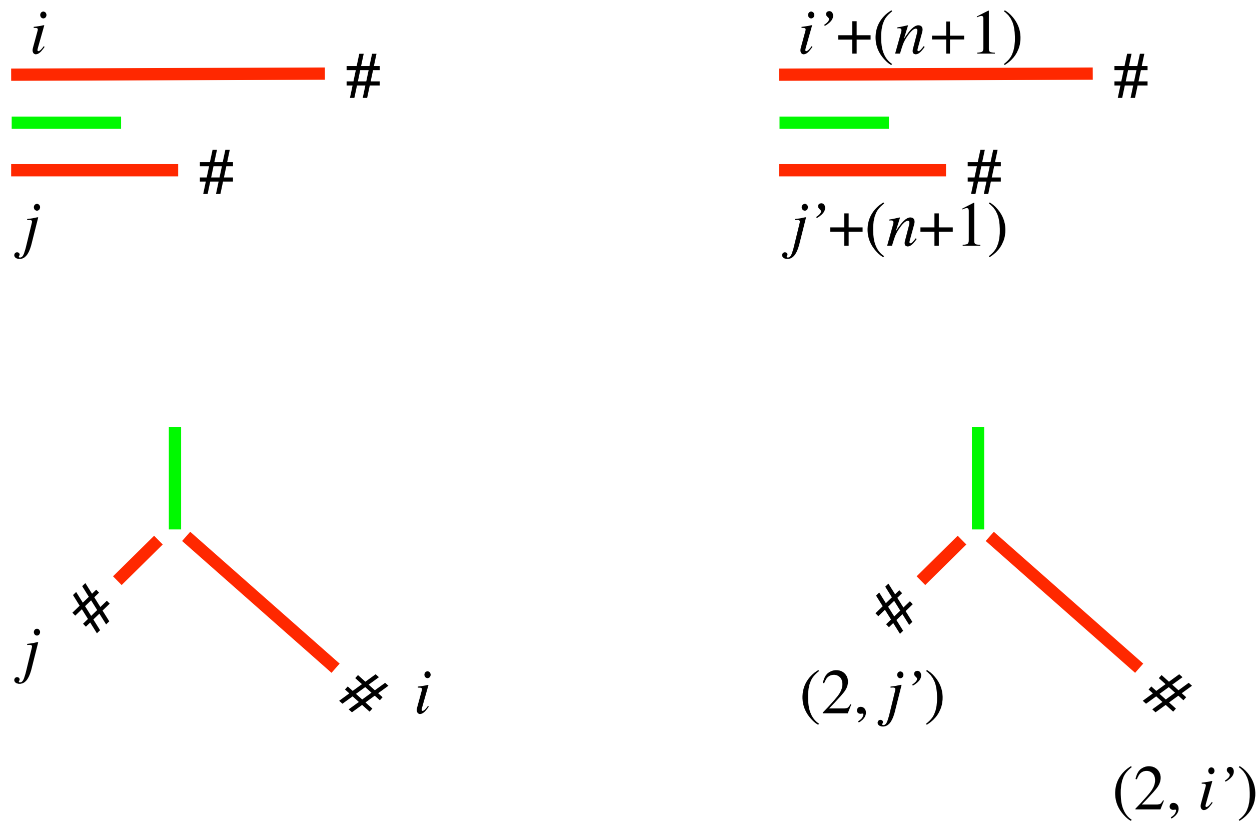


Generalized suffix tree



Case 2:



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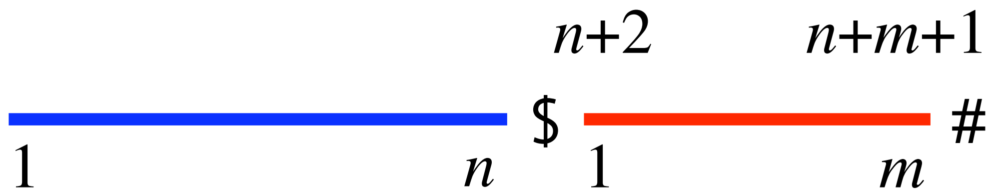
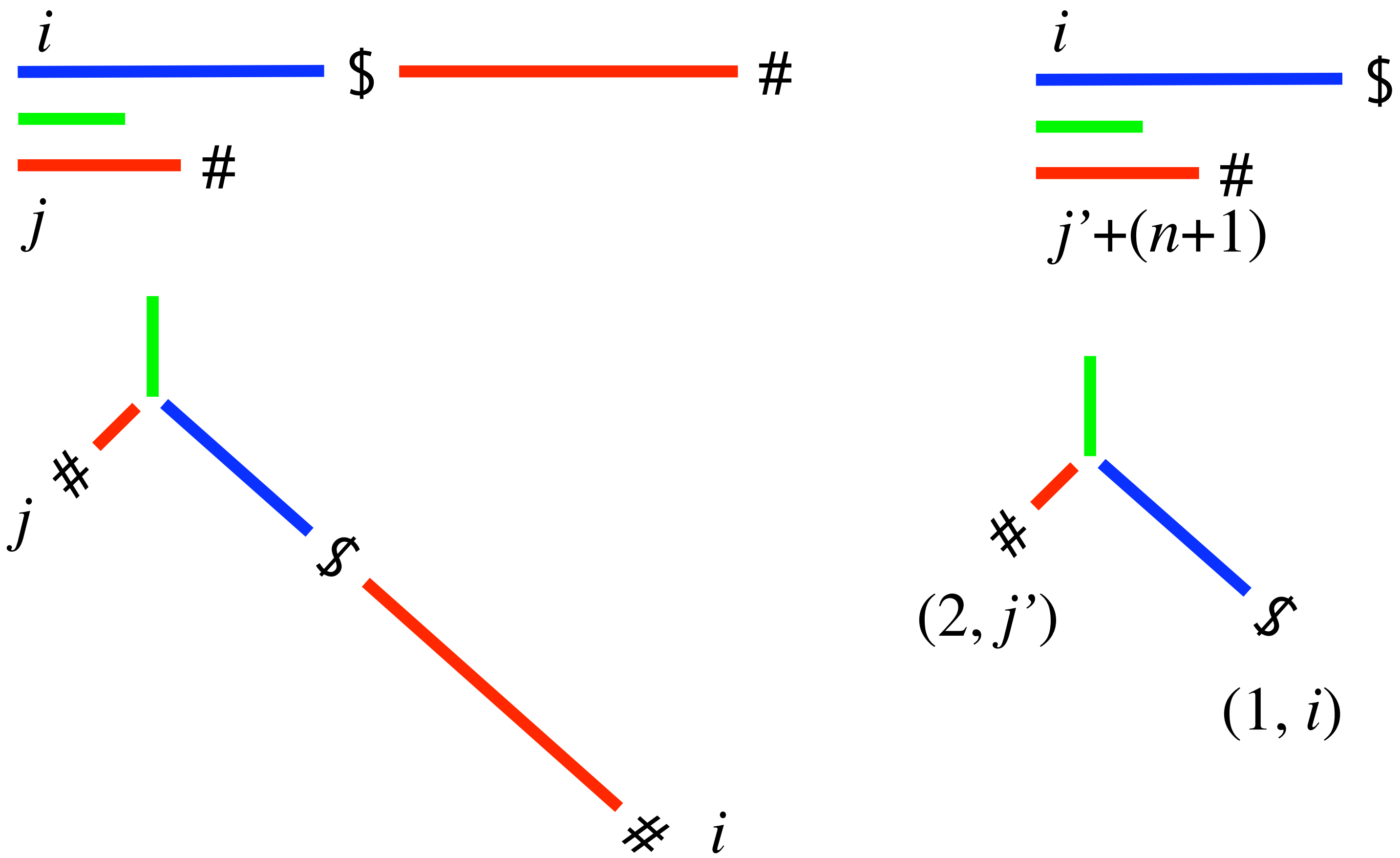


Case 3:

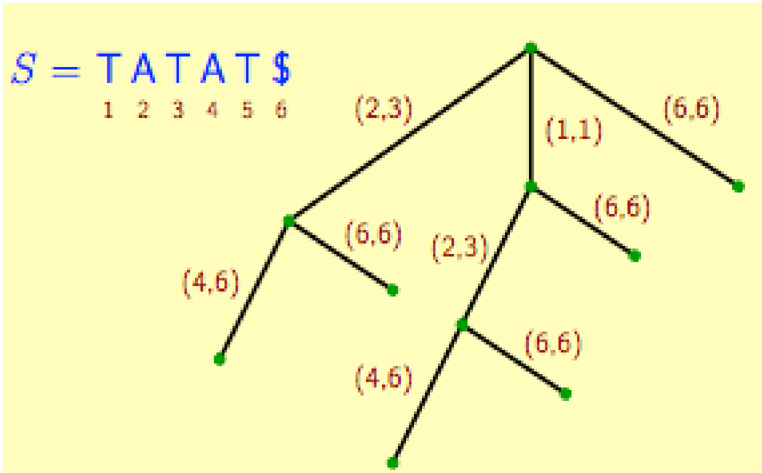


Is everything great?

What are the caveats of suffix trees?

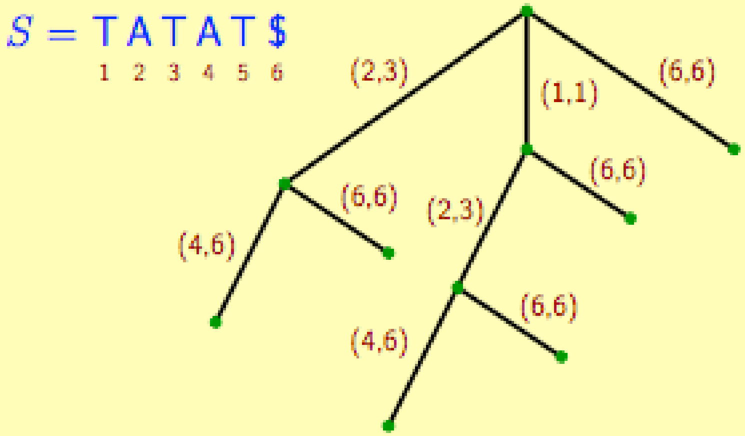
Space consumption

Fact: $T(\boldsymbol{x})$ requires $O(n)$ space, where $n=|\boldsymbol{x}|$



... but how much space does it consume in “practice”?

Representation of suffix trees

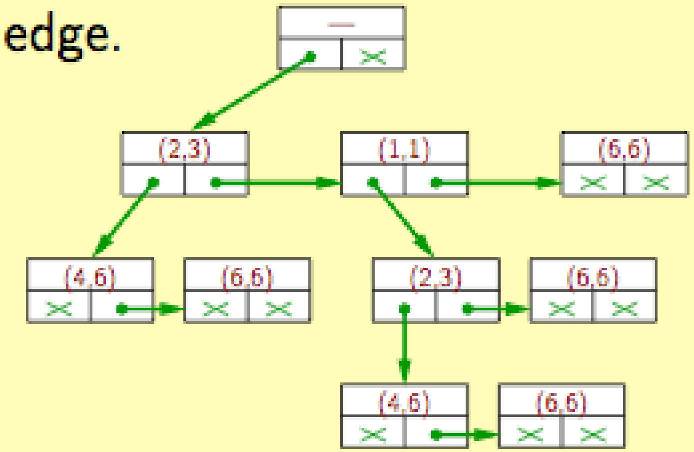


Standard representation of trees:

- Store nodes as records with child and sibling pointer.
- An edge label (i, j) is stored at node below the edge.

$\Rightarrow$ about $32n$ bytes in the worst case

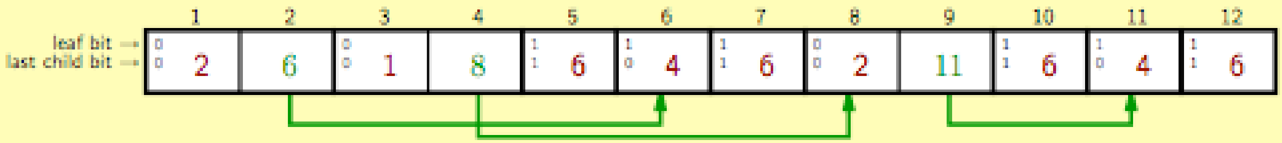
$2n$ nodes $\times$ (2 integers $+$ 2 pointers)



Ideas for more efficient representation:

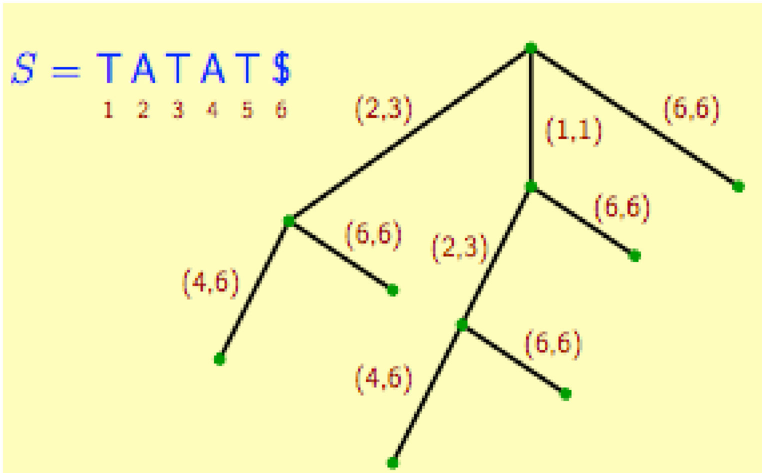
- Do not represent leaves explicitly.
- Avoid sibling pointers by storing all children of the same node in a row.
- Do not represent the right pointer of an edge label.

$\Rightarrow$ below $12n$ bytes in the worst case, $8.5n$ on average



Space consumption

Fact: $T(\boldsymbol{x})$ requires $O(n)$ space, where $n=|\boldsymbol{x}|$, but ....

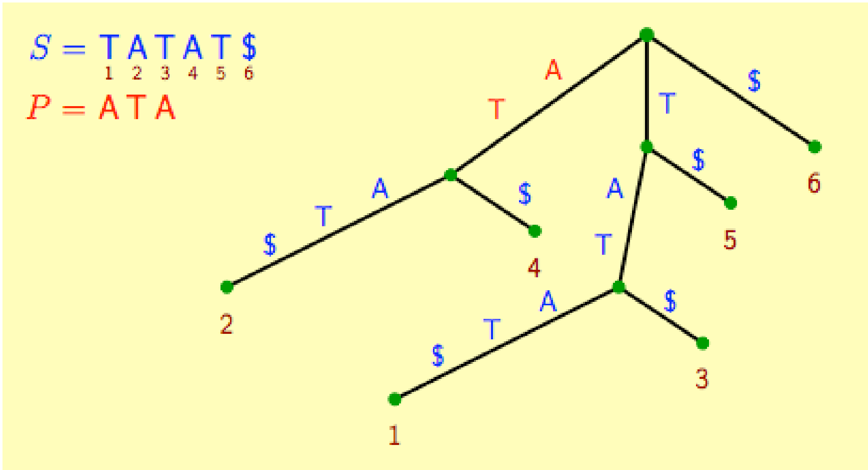


... in practice somewhere between 10 and 40 bytes per letter in $\boldsymbol{x}$ ...

Is this a problem? Depends on n, if ≈500.000.000 then yes...

Alphabet size

How much time does it take to find the proper edge out from a node when searching in a suffix tree?



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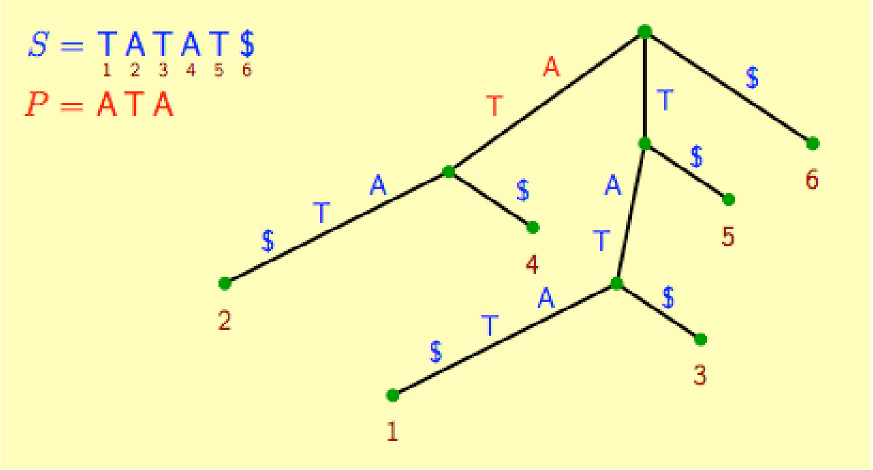

Time proportional to the out-degree of the node ≤ $|A|$ ...

... search time in "pratice" is $O(|A| \cdot |P|)$ ...

If $|A|$ is large, e.g. 256, this matters!!

Alphabet size

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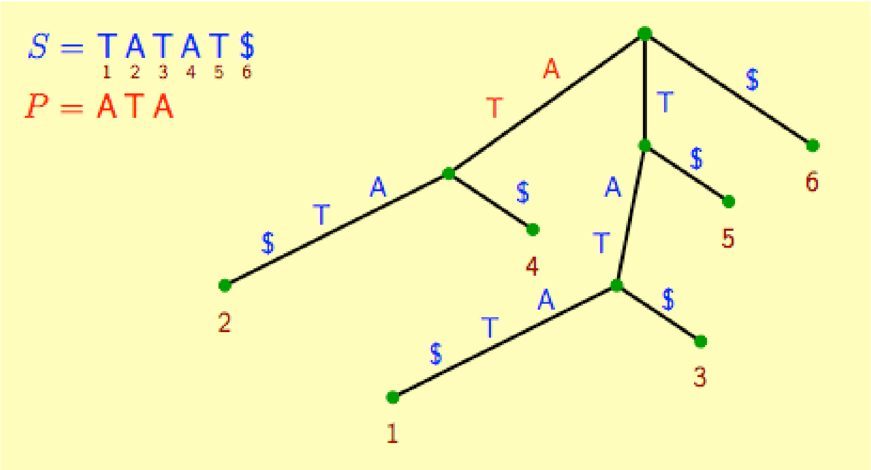
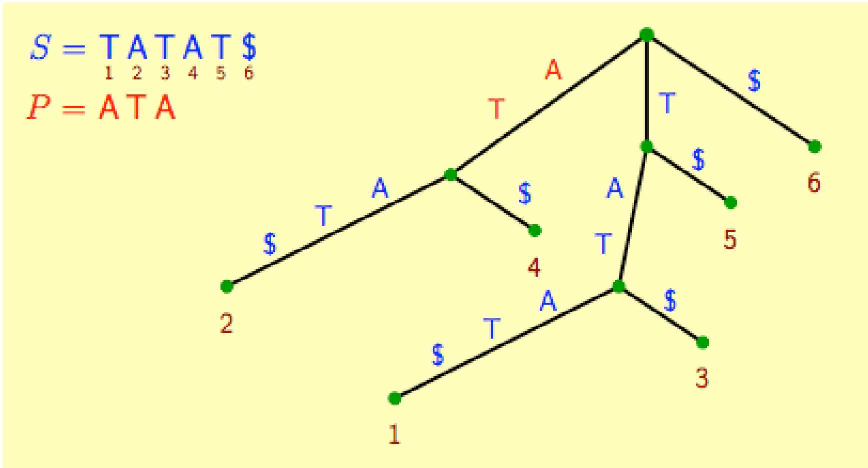


Idea 1: Organized children in a search-tree, reduce search time from |*A*| to O(log |*A*|) ... (requires an ordered alphabet)

Alphabet size

How much time does it take to find the proper edge out from a node when searching in a suffix tree?



Idea 2: Organized children in a vector of size |*A*| indexed by letters, reduce search time from |*A*| to O(1) ... (requires a finite alphabet)

Alphabet size

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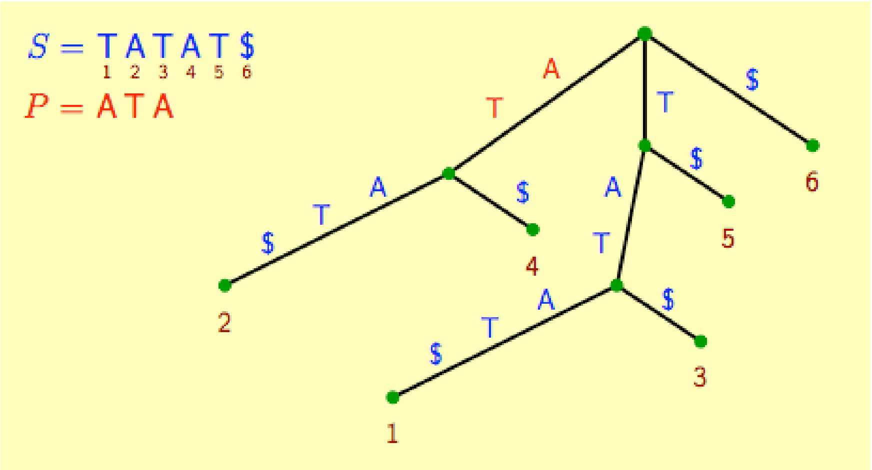

Idea 3: Use some other dictionary for mapping letters to children ...

... the alphabet size matters in practice ...

Next time

Construction of suffix trees in linear time