

13

Text Indexing – Searching entire genomes

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Learning Outcomes

Unit 13: *Text Indexing*

1. Know and understand methods for text indexing: *inverted indices, suffix trees, (enhanced) suffix arrays*
2. Know and understand *generalized suffix trees*
3. Know properties, in particular *performance characteristics*, and limitations of the above data structures.
4. Design (simple) *algorithms based on suffix trees*.
5. Understand *construction algorithms* for suffix arrays and LCP arrays.

13 Text Indexing

13.1 Motivation

13.2 Suffix Trees

13.3 Applications

13.4 Longest Common Extensions

13.5 Suffix Arrays

13.6 Linear-time suffix sorting: Induced sorting and merging

13.7 Linear-Time Suffix Sorting: The DC3 Algorithm

13.8 The LCP Array

13.9 LCP Array Construction

13.1 Motivation

Text indexing

- ▶ *Text indexing* (also: *offline text search*):

- ▶ case of string matching: find $P[0..m]$ in $T[0..n]$

- ▶ but with *fixed* text \rightsquigarrow preprocess T (instead of P)

- \rightsquigarrow expect many queries P , answer them without looking at all of T

- \rightsquigarrow essentially a data structuring problem: “building an *index* of T ”

Latin: “one who points out”

- ▶ application areas

- ▶ web search engines

- ▶ online dictionaries

- ▶ online encyclopedia

- ▶ DNA/RNA data bases

- ▶ ... searching in any collection of text documents (that grows only moderately)

Inverted indices

- ▶ original indices ^{same as "indexes"} in books: list of (key) words \mapsto page numbers where they occur
 - ▶ assumption: searches are only for **whole** (key) **words**
- \rightsquigarrow often reasonable for natural language text

Inverted index:

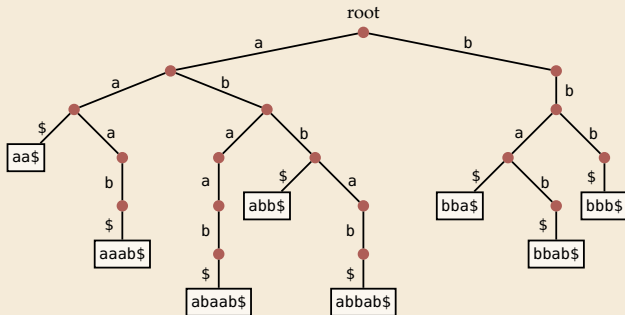
- ▶ collect all words in T
 - ▶ can be as simple as splitting T at whitespace
 - ▶ actual implementations typically support *stemming* of words
goes \rightarrow go, cats \rightarrow cat
- ▶ store mapping from words to a list of occurrences \rightsquigarrow *how?*

Tries

- ▶ efficient dictionary data structure for strings
- ▶ name from retrieval, but pronounced “try”
- ▶ tree based on symbol comparisons
- ▶ **Assumption:** stored strings are *prefix-free* (no string is a prefix of another)
 - ▶ strings of same length ✓
 - ▶ strings have “end-of-string” marker \$ ✓

▶ **Example:**

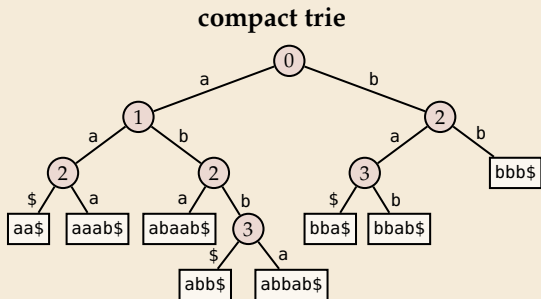
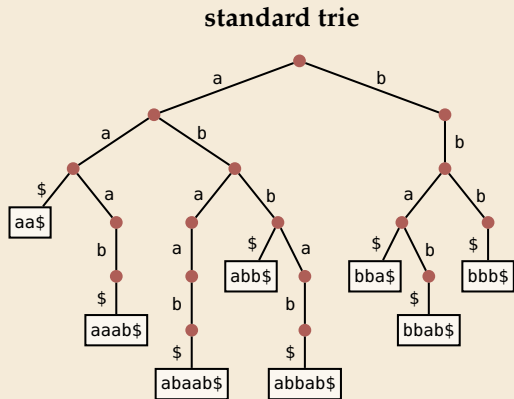
{aa\$, aaab\$, abaab\$, abb\$,
abbab\$, bba\$, bbab\$, bbb\$}



Compact tries

- compress paths of unary nodes into single edge
- nodes store *index* of next character to check

=1 child



↪ searching slightly trickier, but same time complexity as in trie

- all nodes ≥ 2 children ↪ $\#nodes \leq \#leaves = \#strings$ ↪ linear space

Tries as inverted index

👍 simple

👍 fast lookup

👎 cannot handle more general queries:

- ▶ search part of a word
- ▶ search phrase (sequence of words)

👎 what if the 'text' does not even have words to begin with?!

- ▶ biological sequences

```
ACAAGATGCCATTGTCCCCGGCCTCCTGCTGCTGCTCTCCGGGGCCACGGCCACCGCTGCCCTGCCCTGGAGGGTGGCCCCACCGGC  
CGAGACAGCGAGCATATGCAGGAAGCGGCAGGAATAAGGAAAAGCAGCCTCCTGACTTTCCTCGCTTGGTGGTTTGAGTGGACCTCCAGGC  
CAGTGCCGGGCCCCCATAGGAGAGGAAGCTCGGGAGGTGGCCAGGCGGCAGGAAGGCGCACCCCCAGCAATCCGCGCGCCGGGACAGAA  
TGCCCTGCAGGAACCTTCTCTGGAAGACCTTCTCTCCTGCAAATAAAACCTCACCCATGAATGCTCACGCAAGTTTAATTACAGACCTGAA
```

- ▶ binary streams

```
0000001010100111101011100000111110001111011111001101101000011100010011011110000010001101010  
0110110000110101101000000010000000011101011000001000011110101110110010001100101101111111  
110001010001011001010000001110101010011000000001101100001100111110000101 0101011101111000011  
10101110010010101010100000111110100110000001111001101010000000100100100000101100011000110111
```

~> need new ideas

13.2 Suffix Trees

Suffix trees – A ‘magic’ data structure

Appetizer: Longest common substring problem

► Given: strings S_1, \dots, S_k

Example: $S_1 = \text{superiorcalifornialives}$, $S_2 = \text{sealiver}$

► Goal: find the longest substring that occurs in all k strings

↪ alive



Can we do this in time $O(|S_1| + \dots + |S_k|)$? How??

Enter: *suffix trees*

- versatile data structure for index with full-text search
- linear time (for construction) and linear space
- allows efficient solutions for many advanced string problems



“Although the longest common substring problem looks trivial now, given our knowledge of suffix trees, it is very interesting to note that in 1970 Don Knuth conjectured that a linear-time algorithm for this problem would be impossible.”

[Gusfield: Algorithms on Strings, Trees, and Sequences (1997)]

Suffix trees – Definition

- ▶ suffix tree \mathcal{T} for text $T = T[0..n)$ = compact trie of all suffixes of $T\$$ (set $T[n] := \$$)
- ▶ except: in leaves, store *start index* (instead of copy of actual string)

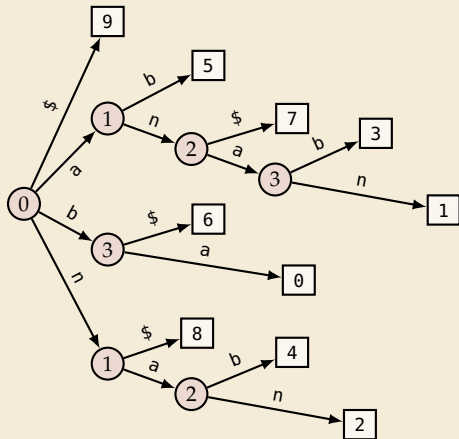
Example:

$T = \text{bananaban\$}$

suffixes: { $\text{bananaban\$}$, $\text{ananaban\$}$, $\text{nanaban\$}$,
 $\text{anaban\$}$, $\text{naban\$}$, $\text{aban\$}$, $\text{ban\$}$, $\text{an\$}$, $\text{n\$}$, $\text{\$}$ }

0	1	2	3	4	5	6	7	8	9
b	a	n	a	n	a	b	a	n	\$

- ▶ also: edge labels like in compact trie
- ▶ (more readable form on slides to explain algorithms)



Suffix trees – Construction

- ▶ $T[0..n]$ has $n + 1$ suffixes (starting at character $i \in [0..n]$)
- ▶ We can build the suffix tree by inserting each suffix of T into a compressed trie. But that takes time $\Theta(n^2)$. \rightsquigarrow not interesting!



same order of growth as reading the text!

Amazing result: Can construct the suffix tree of T in $\Theta(n)$ time!

- ▶ algorithms are a bit tricky to understand
- ▶ but were a theoretical breakthrough
- ▶ and they are efficient in practice (and heavily used)!

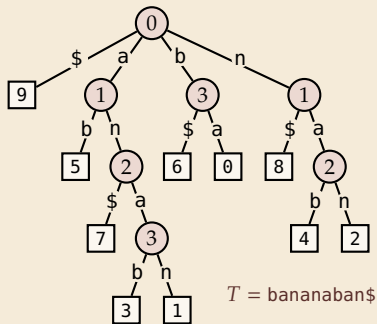
\rightsquigarrow for now, take linear-time construction for granted. What can we do with them?

13.3 Applications

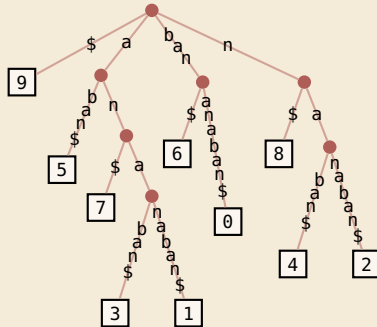
Applications of suffix trees

- In this section, always assume suffix tree \mathcal{T} for T given.

Recall: \mathcal{T} stored like this:



but think about this:



- Moreover: assume internal nodes store pointer to *leftmost leaf in subtree*.
- Notation: $T_i = T[i..n]$ (including \$)

Application 1: Text Indexing / String Matching

► P occurs in $T \iff P$ is a prefix of a suffix of T

► we have all suffixes in T !

↪ (try to) follow path with label P , until

1. we get stuck

at internal node (no node with next character of P)

or inside edge (mismatch of next characters)

↪ P does not occur in T

2. we run out of pattern

reach end of P at internal node v or inside edge towards v

↪ P occurs at all leaves in subtree of v

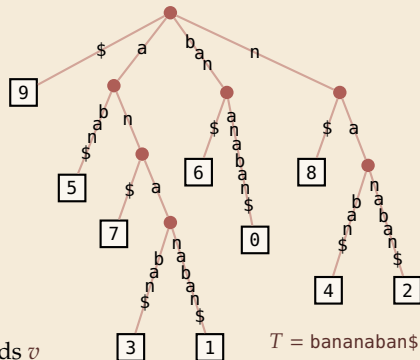
3. we run out of tree

reach a leaf ℓ with part of P left ↪ compare P to ℓ .



This cannot happen when testing edge labels since $\$ \notin \Sigma$, but needs check(s) in compact trie implementation!

► Finding first match (or NO_MATCH) takes $O(|P|)$ time!



Examples:

- $P = \text{ann}$
- $P = \text{baa}$
- $P = \text{ana}$
- $P = \text{ba}$
- $P = \text{briar}$

Application 2: Longest repeated substrng

- **Goal:** Find longest substring $T[i..i + \ell)$ that occurs also at $j \neq i$: $T[j..j + \ell) = T[i..i + \ell)$.



How can we efficiently check *all possible substrings*?



Repeated substrngs = shared paths in *suffix tree*



e. g. for compression \rightsquigarrow Unit 7

- $T_5 = \text{aban\$}$ and $T_7 = \text{an\$}$ have *longest common prefix* 'a'

$\rightsquigarrow \exists$ internal node with path label 'a'

here single edge, can be longer path

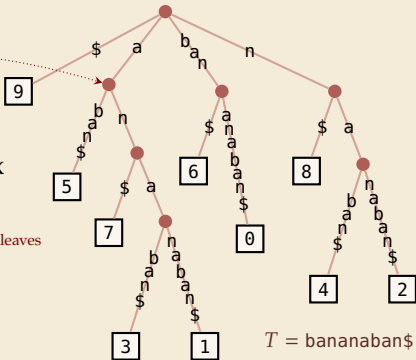
\rightsquigarrow longest repeated substrng = longest common prefix (LCP) of two suffixes

actually: adjacent leaves

- **Algorithm:**

1. Compute *string depth* (=length of path label) of nodes
2. Find internal nodes with maximal string depth

- Both can be done in depth-first traversal $\rightsquigarrow \Theta(n)$ time



Generalized suffix trees

- ▶ longest *repeated* substring (of one string) feels very similar to longest *common* substring of several strings $T^{(1)}, \dots, T^{(k)}$ with $T^{(j)} \in \Sigma^{n_j}$
 - ▶ can we solve that in the same way?
 - ▶ could build the suffix tree for each $T^{(j)}$... but doesn't seem to help
- \rightsquigarrow need a *single/joint* suffix tree for *several* texts

Enter: *generalized suffix tree*

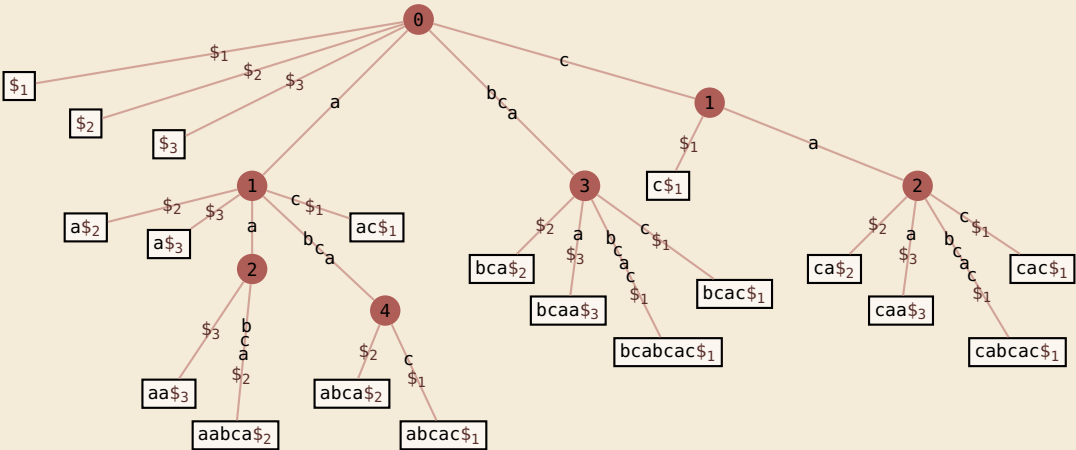
- ▶ Define $T := T^{(1)}\$_1 T^{(2)}\$_2 \dots T^{(k)}\$_k$ for k new end-of-word symbols
- ▶ Construct suffix tree \mathcal{T} for T

\rightsquigarrow $\$_j$ -edges always leads to leaves $\rightsquigarrow \exists$ leaf (j, i) for each suffix $T_i^{(j)} = T^{(j)}[i..n_j]$



Generalized Suffix Tree – Example

$T^{(1)} = bcabcac, \quad T^{(2)} = aabca, \quad T^{(3)} = bcaa$



Application 3: Longest common substring

- ▶ With that new idea, we can find longest common substrings:
 1. Compute generalized suffix tree \mathcal{T} .
 2. Store with each node the *subset of strings* that contain its path label:
 - 2.1. Traverse \mathcal{T} bottom-up.
 - 2.2. For a leaf (j, i) , the subset is $\{j\}$.
 - 2.3. For an internal node, the subset is the union of its children.
 3. In top-down traversal, compute *string depths* of nodes. (as above)
 4. Report deepest node (by string depth) whose subset is $\{1, \dots, k\}$.

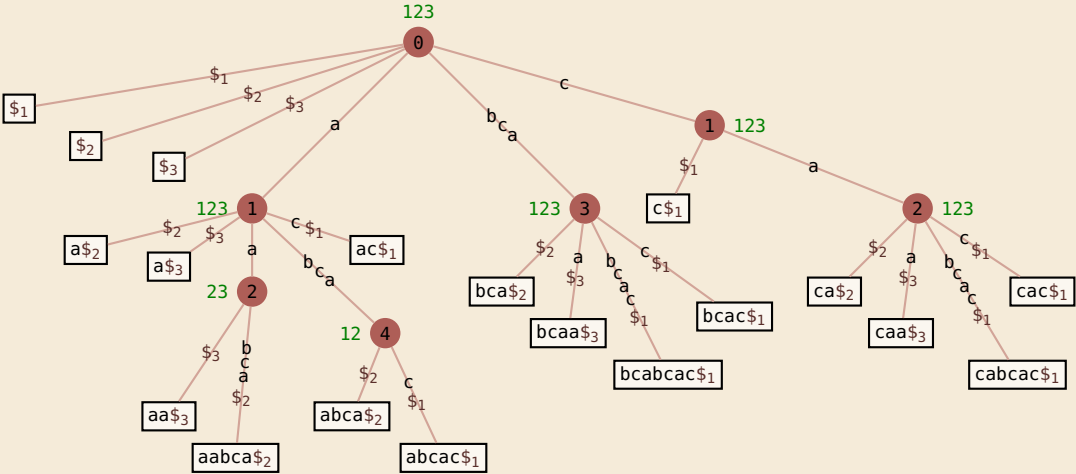
- ▶ Each step takes time $\Theta(n)$ for $n = n_1 + \dots + n_k$ the total length of all texts.

“Although the longest common substring problem looks trivial now, given our knowledge of suffix trees, it is very interesting to note that in 1970 Don Knuth conjectured that a linear-time algorithm for this problem would be impossible.”

[Gusfield: Algorithms on Strings, Trees, and Sequences (1997)]

Longest common substring – Example

$T^{(1)} = \text{bcabcac}, \quad T^{(2)} = \text{aabca}, \quad T^{(3)} = \text{bcaa}$



13.4 Longest Common Extensions

Application 4: Longest Common Extensions

- We implicitly used a special case of a more general, versatile idea:

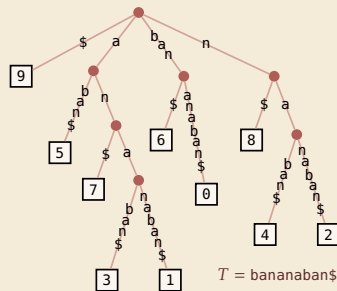
The *longest common extension (LCE)* data structure:

- **Given:** String $T[0..n)$
- **Goal:** Answer LCE queries, i. e.,
given positions i, j in T ,
how far can we read the same text from there?
formally: $\text{LCE}(i, j) = \max\{\ell : T[i..i + \ell) = T[j..j + \ell)\}$

↪ use suffix tree of T !

- In \mathcal{T} : $\text{LCE}(i, j) = \text{LCP}(T_i, T_j) \rightsquigarrow$ same thing, different name!
= string depth of
lowest common ancestor (LCA) of
leaves \boxed{i} and \boxed{j}

- in short: $\text{LCE}(i, j) = \text{LCP}(T_i, T_j) = \text{stringDepth}(\text{LCA}(\boxed{i}, \boxed{j}))$



Efficient LCA

How to find lowest common ancestors?

- ▶ Could walk up the tree to find LCA $\rightsquigarrow \Theta(n)$ worst case 🙄
- ▶ Could store all LCAs in big table $\rightsquigarrow \Theta(n^2)$ space and preprocessing 🙄



Amazing result: Can compute data structure in $\Theta(n)$ time and space that finds any LCA in **constant(!) time**.

- ▶ a bit tricky to understand
- ▶ but a theoretical breakthrough
- ▶ and useful in practice

and suffix tree construction inside ...



\rightsquigarrow for now, use $O(1)$ LCA as black box.

\rightsquigarrow After linear preprocessing (time & space), we can find LCEs in $O(1)$ time.

Application 5: Approximate matching

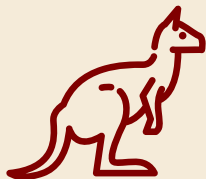
k -mismatch matching:

- ▶ **Input:** text $T[0..n)$, pattern $P[0..m)$, $k \in [0..m)$
- ▶ **Output:** “Hamming distance $\leq k$ ”
 - ▶ smallest i so that $T[i..i+m)$ are P differ in at most k characters
 - ▶ or NO_MATCH if there is no such i

\rightsquigarrow searching with typos

- ▶ Adapted brute-force algorithm $\rightsquigarrow O(n \cdot m)$
- ▶ Assume longest common extensions in $T\$_1P\$_2$ can be found in $O(1)$
 - \rightsquigarrow generalized suffix tree \mathcal{T} has been built
 - \rightsquigarrow string depths of all internal nodes have been computed
 - \rightsquigarrow constant-time LCA data structure for \mathcal{T} has been built

Kangaroo Algorithm for approximate matching



```
1 procedure kMismatch( $T[0..n - 1]$ ,  $P[0..m - 1]$ ):  
2   // build LCE data structure  
3   for  $i := 0, \dots, n - m - 1$  do  
4     mismatches := 0;  $t := i$ ;  $p := 0$   
5     while mismatches  $\leq k \wedge p < m$  do  
6        $\ell := \text{LCE}(t, p)$  // jump over matching part  
7        $t := t + \ell + 1$ ;  $p := p + \ell + 1$   
8       mismatches := mismatches + 1  
9     if  $p == m$  then  
10      return  $i$ 
```

► **Analysis:** $\Theta(n + m)$ preprocessing + $O(n \cdot k)$ matching

\rightsquigarrow very efficient for small k

► State of the art

- $O\left(n \frac{k^2 \log k}{m}\right)$ possible with complicated algorithms
- extensions for edit distance $\leq k$ possible

Application 6: Matching with wildcards

- ▶ Allow a wildcard character in pattern
stands for arbitrary (single) character
- ▶ similar algorithm as for k -mismatch $\rightsquigarrow O(n \cdot k + m)$ when P has k wildcards

unit*	P
in_unit5_we_will	T

* * *

Many more applications, in particular for problems on biological sequences

20+ described in Gusfield, *Algorithms on strings, trees, and sequences* (1999)

Suffix trees – Discussion

- ▶ Suffix trees were a threshold invention



linear time and space



suddenly many questions efficiently solvable in theory



construction of suffix trees:
linear time, but significant overhead



construction methods fairly complicated



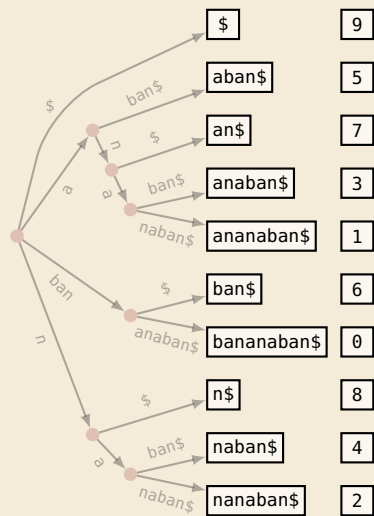
many pointers in tree incur large space overhead



13.5 Suffix Arrays

Putting suffix trees on a diet

$L[0..n]$



► **Observation:** order of leaves in suffix tree
= suffixes lexicographically *sorted*

- Idea: only store list of leaves $L[0..n]$
- Sufficient to do efficient string matching!
 1. Use binary search for pattern P
 2. check if P is prefix of suffix after position found

► **Example:** $P = \text{ana}$

~ $L[0..n]$ is called *suffix array*:

$L[r] = (\text{start index of } r\text{th suffix in sorted order})$

- using L , can do string matching with
 $\leq (\lg n + 2) \cdot m$ character comparisons

Digression: Recall BWT

Burrows-Wheeler Transform

1. Take all cyclic shifts of S
2. Sort cyclic shifts
3. Extract last column

$S = \text{alf_eats_alfalfa\$}$

$B = \text{asff\$f_e_lllaaata}$

alf_eats_alfalfa\$
lf_eats_alfalfa\$
f_eats_alfalfa\$
_eats_alfalfa\$
eats_alfalfa\$
ats_alfalfa\$
ts_alfalfa\$
s_alfalfa\$
_alfalfa\$
alfalfa\$
lfalfa\$
falffa\$
alfa\$
lfa\$
fa\$
a\$
\$alf_eats_alfalfa

sort

\$alf_eats_alfalf**a**
_alfalfa\$alf_eat**s**
_eats_alfalfa\$alf**f**
a\$alf_eats_alfalf**f**
alf_eats_alfalfa\$**f**
alfalfa\$alf_eats_alf**f**
alfalfa\$alf_eats_**e**
ats_alfalfa\$alf_**t**
eats_alfalfa\$alf_**t**
f_eats_alfalfa\$a**l**
fa\$alf_eats_alfalf**a**
falffa\$alf_eats_alf**a**
lf_eats_alfalfa\$a**a**
lfa\$alf_eats_alf**a**
lfalfa\$alf_eats_**a**
s_alfalfa\$alf_eat**t**
ts_alfalfa\$alf_ea**a**

BWT
↓

Digression: Computing the BWT

How can we compute the BWT of a text efficiently?

- ▶ cyclic shifts $S \hat{=}$ suffixes of S
 - ▶ comparing cyclic shifts stops at first \$
 - ▶ for comparisons, anything after \$ irrelevant!
- ▶ BWT is essentially suffix sorting!
 - ▶ $B[i] = S[L[i] - 1]$
 - ▶ where $L[i] = 0, B[i] = \$$

\rightsquigarrow Can compute B in $O(n)$ time from L

	r		$\downarrow L[r]$
alf_eats_alfalfa\$	0	\$alf_eats_alfalf a	16
lf_eats_alfalfa\$	1	_alfalfa\$alf_eat s	8
f_eats_alfalfa\$	2	_eats_alfalfa\$alf f	3
_eats_alfalfa\$	3	a\$alf_eats_alfalf f	15
eats_alfalfa\$	4	alf_eats_alfalfa\$ f	0
ats_alfalfa\$	5	alfa\$alf_eats_alf f	12
ts_alfalfa\$	6	alfalfa\$alf_eats_ _	9
s_alfalfa\$	7	ats_alfalfa\$alf_ e	5
_alfalfa\$	8	eats_alfalfa\$alf_ _	4
alfalfa\$	9	f_eats_alfalfa\$alf l	2
lfalfa\$	10	fa\$alf_eats_alfalf l	14
falfa\$	11	falfa\$alf_eats_alf l	11
alfa\$	12	lf_eats_alfalfa\$ a	1
lfa\$	13	lfa\$alf_eats_alf a	13
fa\$	14	lfalfa\$alf_eats_ a	10
a\$	15	s_alfalfa\$alf_eat t	7
\$	16	ts_alfalfa\$alf_ e	6

Suffix arrays – Construction

How to compute $L[0..n]$?

- ▶ from suffix tree
 - ▶ possible with traversal . . .
 - 👎 but we are trying to avoid constructing suffix trees!
- ▶ sorting the suffixes of T using general purpose sorting method
 - 👍 trivial to code!
 - ▶ but: comparing two suffixes can take $\Theta(n)$ character comparisons
 - 👎 $\Theta(n^2 \log n)$ time in worst case
- ▶ We can do better!

Fat-pivot radix quicksort – Example

she	by	are					
sells	are	by					
seashells	she	sells	sells	seashells	seashells	seashells	sea
by	sells	seashells	seashells	sea	sea\$	seashells	seashells
the	seashells	sea	sea	sells	seashells	sells	seashells
sea	sea	sells	sells	sells	sells	sells	sells
shore	shore	seashells	seashells	sells	sells	sells	sells
the	shells	she	she\$	she	she	shells	
shells	she	shore	shells	shells	shells		
she	sells	shells	she\$				
sells	surely	she	shore				
are	seashells	surely					
surely	the	the	the	the			
seashells	the	the	the	the			


Fat-pivot radix quicksort

details in §5.1 of Sedgewick, Wayne *Algorithms 4th ed.* (2011), Pearson

- ▶ **partition** based on d th character only (initially $d = 0$)
 - ↪ 3 segments: smaller, equal, or larger than d th symbol of pivot
- ▶ recurse on smaller and large with same d , on equal with $d + 1$
 - ↪ never compare equal prefixes twice

↪ can show: $\sim 2 \ln(2) \cdot n \lg n \approx 1.39n \lg n$ character comparisons on average ↖ for random strings

 simple to code

 efficient for sorting many lists of strings

- ▶ fat-pivot radix quicksort finds suffix array in $O(n \log n)$ expected time ↖ random string

*but we can do $O(n)$ time **worst case!***

13.6 Linear-time suffix sorting: Induced sorting and merging

Inverse suffix array: going left & right

► to understand the fastest algorithm, it is helpful to define the *inverse suffix array*:

- $R[i] = r \iff L[r] = i$ $L = \text{leaf array}$
 - \iff there are r suffixes that come before T_i in sorted order
 - $\iff T_i$ has (0-based) **rank** $r \rightsquigarrow$ call $R[0..n]$ the **rank array**

i	$R[i]$	T_i		r	$L[r]$	$T_{L[r]}$
0	6 th	bananaban\$		0	9	\$
1	4 th	ananaban\$		1	5	aban\$
2	9 th	nanaban\$		2	7	an\$
3	3 th	anaban\$		3	3	anaban\$
4	8 th	naban\$		4	1	ananaban\$
5	1 th	aban\$		5	6	ban\$
6	5 th	ban\$		6	0	bananaban\$
7	2 th	an\$		7	8	n\$
8	7 th	n\$		8	4	naban\$
9	0 th	\$		9	2	nanaban\$

Diagram illustrating the relationship between the suffix array R and the leaf array L . The suffix array R maps indices i to ranks r . The leaf array L maps ranks r back to indices i . The diagram shows the mapping from $R[0] = 6$ to $L[6] = 0$ and from $R[8] = 7$ to $L[7] = 8$. A large arrow at the bottom indicates the process of sorting suffixes.

Linear-time suffix sorting

DC3 / Skew algorithm

not a multiple of 3

1. Compute rank array $R_{1,2}$ for suffixes T_i starting at $i \not\equiv 0 \pmod{3}$ recursively.
2. Induce rank array R_3 for suffixes $T_0, T_3, T_6, T_9, \dots$ from $R_{1,2}$.
3. Merge $R_{1,2}$ and R_0 using $R_{1,2}$.
 \rightsquigarrow rank array R for entire input

► We will show that steps 2. and 3. take $\Theta(n)$ time

\rightsquigarrow Total complexity is $n + \frac{2}{3}n + \left(\frac{2}{3}\right)^2 n + \left(\frac{2}{3}\right)^3 n + \dots \leq n \cdot \sum_{i \geq 0} \left(\frac{2}{3}\right)^i = 3n = \Theta(n)$

► **Note:** L can easily be computed from R in one pass, and vice versa.

\rightsquigarrow Can use whichever is more convenient.

DC3 / Skew algorithm – Step 2: Inducing ranks

- ▶ **Assume:** rank array $R_{1,2}$ known:

$$\text{▶ } R_{1,2}[i] = \begin{cases} \text{rank of } T_i \text{ among } T_1, T_2, T_4, T_5, T_7, T_8, \dots & \text{for } i = 1, 2, 4, 5, 7, 8, \dots \\ \text{undefined} & \text{for } i = 0, 3, 6, 9, \dots \end{cases}$$

- ▶ **Task:** sort the suffixes $T_0, T_3, T_6, T_9, \dots$ in linear time (!)

- ▶ Suppose we want to compare T_0 and T_3 .

- ▶ Characterwise comparisons too expensive
- ▶ but: after removing first character, we obtain T_1 and T_4
- ▶ these two can be compared in *constant time* by comparing $R_{1,2}[1]$ and $R_{1,2}[4]$!

⇒ T_0 comes before T_3 in lexicographic order
iff pair $(T[0], R_{1,2}[1])$ comes before pair $(T[3], R_{1,2}[4])$ in lexicographic order

DC3 / Skew algorithm – Inducing ranks example

$T = \text{hannahbansbananasman}\$ \$ \$$

(append 3 \$ markers)

T_0 hannahbansbananasman\$\$\$
 T_3 nahbansbananasman\$\$\$
 T_6 bansbananasman\$\$\$
 T_9 sbanasman\$\$\$
 T_{12} nanasman\$\$\$
 T_{15} asman\$\$\$
 T_{18} an\$\$\$
 T_{21} \$\$

$\text{smans} = T_{16}$

T_0 h05
 T_3 n02
 T_6 b06
 T_9 s07
 T_{12} n04
 T_{15} a14
 T_{18} a10
 T_{21} \$00

$R_{1,2}[16] = 14$

T_1	annahbansbananasman\$\$\$	$R_{1,2}[22] = 0$	T_{22}	\$
T_2	nahbansbananasman\$\$\$	$R_{1,2}[20] = 1$	T_{20}	\$\$\$
T_4	ahbansbananasman\$\$\$	$R_{1,2}[4] = 2$	T_4	ahbansbananasman\$\$\$
T_5	hbansbananasman\$\$\$	$R_{1,2}[11] = 3$	T_{11}	anasman\$\$\$
T_7	ansbananasman\$\$\$	$R_{1,2}[13] = 4$	T_{13}	anasman\$\$\$
T_8	nsbananasman\$\$\$	$R_{1,2}[1] = 5$	T_1	annahbansbananasman\$\$\$
T_{10}	bananasman\$\$\$	$R_{1,2}[7] = 6$	T_7	ansbananasman\$\$\$
T_{11}	anasman\$\$\$	$R_{1,2}[10] = 7$	T_{10}	bananasman\$\$\$
T_{13}	anasman\$\$\$	$R_{1,2}[5] = 8$	T_5	hbansbananasman\$\$\$
T_{14}	nasman\$\$\$	$R_{1,2}[17] = 9$	T_{17}	man\$\$\$
T_{16}	smans	$R_{1,2}[19] = 10$	T_{19}	n\$\$\$
T_{17}	man\$\$\$	$R_{1,2}[14] = 11$	T_{14}	nasman\$\$\$
T_{19}	n\$\$\$	$R_{1,2}[2] = 12$	T_2	nahbansbananasman\$\$\$
T_{20}	\$\$\$	$R_{1,2}[8] = 13$	T_8	nsbananasman\$\$\$
T_{22}	\$	$R_{1,2}[16] = 14$	T_{16}	smans

$R_{1,2}$ (known)

radix sort

T_{21}	\$00	\rightsquigarrow	$R_0[21] = 0$
T_{18}	a10	\rightsquigarrow	$R_0[18] = 1$
T_{15}	a14	\rightsquigarrow	$R_0[15] = 2$
T_6	b06	\rightsquigarrow	$R_0[6] = 3$
T_0	h05	\rightsquigarrow	$R_0[0] = 4$
T_3	n02	\rightsquigarrow	$R_0[3] = 5$
T_{12}	n04	\rightsquigarrow	$R_0[12] = 6$
T_9	s07	\rightsquigarrow	$R_0[9] = 7$

R_0

► sorting of pairs doable in $O(n)$ time by 2 iterations of counting sort

\rightsquigarrow Obtain R_0 in $O(n)$ time

DC3 / Skew algorithm – Step 3: Merging

T_{21} \$\$
 T_{18} an\$\$\$
 T_{15} asman\$\$\$
 T_6 bansbananasman\$\$\$
 T_0 hannahbansbananasman\$\$\$
 T_3 nahbansbananasman\$\$\$
 T_{12} nanasman\$\$\$
 T_9 sbanasman\$\$\$

T_{22} \$
 T_{20} \$\$\$
 T_4 ahbansbananasman\$\$\$
 T_{11} ananasman\$\$\$
 T_{13} anasman\$\$\$
 T_1 annahbansbananasman\$\$\$
 T_7 ansbananasman\$\$\$
 T_{10} bananasman\$\$\$
 T_5 hbansbananasman\$\$\$
 T_{17} man\$\$\$
 T_{19} n\$\$\$
 T_{14} nasman\$\$\$
 T_2 nnahbansbananasman\$\$\$
 T_8 nsbananasman\$\$\$
 T_{16} sman\$\$\$

T_{22} \$
 T_{21} \$\$
 T_{20} \$\$\$
 T_4 ahbansbananasman\$\$\$
 T_{18} an\$\$\$

► Have:

- sorted 1,2-list:

$T_1, T_2, T_4, T_5, T_7, T_8, T_{10}, T_{11}, \dots$

- sorted 0-list:

$T_0, T_3, T_6, T_9, \dots$

► Task: Merge them!

- use standard merging method from Mergesort
- but speed up comparisons using $R_{1,2}$

$\rightsquigarrow O(n)$ time for merge

Compare T_{15} to T_{11}

Idea: try same trick as before

$T_{15} = \text{asman}$$$
 $= \text{asman}$$$ can't compare T_{16}
 $= aT_{16}$ and T_{12} either!
 $T_{11} = \text{ananasman}$$$
 $= \text{ananasman}$$$
 $= aT_{12}$$$$$

\rightsquigarrow Compare T_{16} to T_{12}

$T_{16} = \text{sman}$$$
 $= \text{sman}$$$ always at most 2 steps
 $= sT_{17}$ then can use $R_{1,2}$!
 $T_{12} = \text{nanasman}$$$
 $= \text{aanasman}$$$
 $= aT_{13}$$$$$

13.7 Linear-Time Suffix Sorting: The DC3 Algorithm

DC3 / Skew algorithm – Fix recursive call

- ▶ both step 2. and 3. doable in $O(n)$ time!
 - ▶ But: we cheated in 1. step! “compute rank array $R_{1,2}$ recursively”
 - ▶ Taking a *subset* of suffixes is *not* an instance of the same problem!
- ↪ Need a single *string* T' to recurse on, from which we can deduce $R_{1,2}$.



How can we make T' “skip” some suffixes?



redefine alphabet to be *triples of characters* \boxed{abc}

↪ suffixes of $T^\square \iff T_0, T_3, T_6, T_9, \dots$

▶ $T' = T[1..n]^\square \boxed{\text{\$}\text{\$}\text{\$}} T[2..n]^\square \boxed{\text{\$}\text{\$}\text{\$}} \iff T_i$ with $i \not\equiv 0 \pmod{3}$.

↪ Can call suffix sorting recursively on T' and map result to $R_{1,2}$

$T = \text{bananaban}\text{\$}\text{\$}\text{\$}$
↪ $T^\square = \boxed{\text{ban}}\boxed{\text{ana}}\boxed{\text{ban}}\boxed{\text{\$}\text{\$}\text{\$}}$
 $\boxed{\text{ana}}\boxed{\text{ban}}\boxed{\text{\$}\text{\$}\text{\$}}$
 $\boxed{\text{ban}}\boxed{\text{\$}\text{\$}\text{\$}}$
 $\boxed{\text{\$}\text{\$}\text{\$}}$

DC3 / Skew algorithm – Fix alphabet explosion

► Still does not quite work!

► Each recursive step *cubes* σ by using triples!

↪ (Eventually) cannot use linear-time sorting anymore!

► But: Have at most $\frac{2}{3}n$ different triples \boxed{abc} in T' !

↪ Before recursion:

1. Sort all occurring triples. (using counting sort in $O(n)$)

2. Replace them by their *rank* (in Σ).

↪ Maintains $\sigma \leq n$ without affecting order of suffixes.

DC3 / Skew algorithm – Step 3. Example

$$T' = T[1..n) \square \square \square T[2..n) \square \square \square$$

► $T = \text{hannahbansbananasman\$}$ $T_2 = \text{nnahbansbananasman\$}$
 $T' = \text{annahbansbananasman\$} \square \square \square \text{nnaahbansbananasman\$}$

► Occurring triples:
 $\text{annahbansbananasman\$} \square \square \square \text{nnaahbansbananasman\$}$

► Sorted triples with ranks:

Rank	00	01	02	03	04	05	06	07	08	09	10	11	12
Triple	$\square \square \square$	ahb	ana	ann	ans	ban	hba	man	n\$\$	nas	nna	nsb	sma

► $T' = \text{annahbansbananasman\$} \square \square \square \text{nnaahbansbananasman\$}$
 $T'' = \text{03 01 04 05 02 12 08 00 10 06 11 02 09 07 00}$

Suffix array – Discussion

- 👍 sleek data structure compared to suffix tree
- 👍 simple and fast $O(n \log n)$ construction
- 👍 more involved but optimal $O(n)$ construction
- 👍 supports efficient string matching
- 👎 string matching takes $O(m \log n)$, not optimal $O(m)$
- 👎 Cannot use more advanced suffix tree features
e. g., for longest repeated substrings



13.8 The LCP Array

String depths of internal nodes

- Recall algorithm for longest repeated substring in **suffix tree**

1. Compute *string depth* of nodes
2. Find *path label* to node with maximal string depth

- Can we do this using **suffix arrays**?

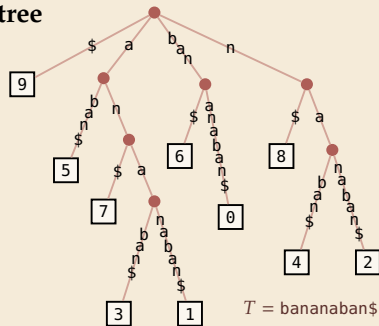
- Yes, by **enhancing** the suffix array with the **LCP array**!

$\text{LCP}[1..n]$

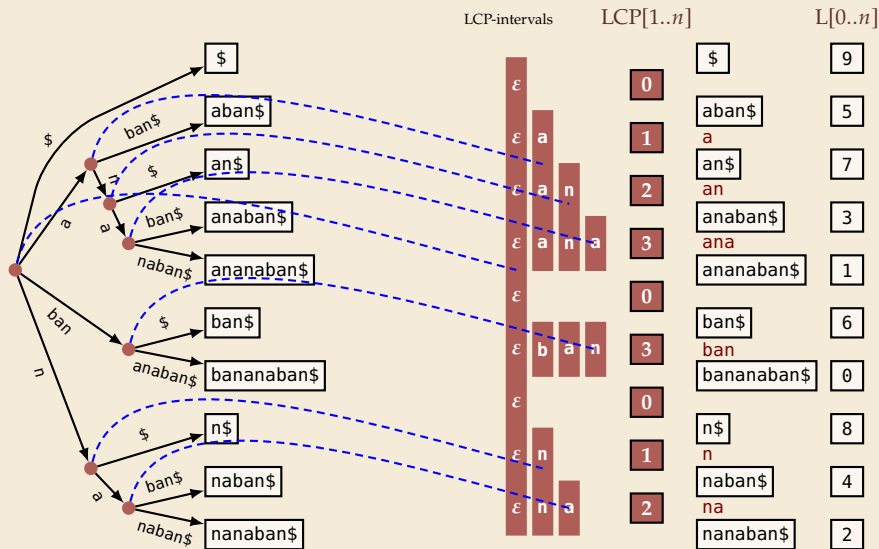
$\text{LCP}[r] = \text{LCP}(T_{L[r]}, T_{L[r-1]})$

length of longest common prefix of suffixes of rank r and $r - 1$

\rightsquigarrow longest repeated substring = find maximum in $\text{LCP}[1..n]$



LCP array and internal nodes



↪ Leaf array $L[0..n]$ plus LCP array $LCP[1..n]$ encode full tree!

13.9 LCP Array Construction

LCP array construction

- ▶ computing $\text{LCP}[1..n]$ naively too expensive

- ▶ each value could take $\Theta(n)$ time

- 👉 $\Theta(n^2)$ in total

- ▶ but: seeing one large (= costly) LCP value \rightsquigarrow can find another large one!

- ▶ Example: $T = \text{Buffalo_buffalo_buffalo_buffalo\$}$

- ▶ first few suffixes in sorted order:

$T_{L[0]} = \$$

$T_{L[1]} = \text{alo_buffalo\$}$

$T_{L[2]} = \text{alo_buffalo_buffalo\$}$

alo_buffalo_buffalo $\rightsquigarrow \text{LCP}[3] = 19$

$T_{L[3]} = \text{alo_buffalo_buffalo_buffalo\$}$

\rightsquigarrow **Removing first character** from $T_{L[2]}$ and $T_{L[3]}$ gives two new suffixes:

$T_{L[?]} = \text{lo_buffalo_buffalo\$}$

lo_buffalo_buffalo $\rightsquigarrow \text{LCP}[?] = 18$

$T_{L[?]} = \text{lo_buffalo_buffalo_buffalo\$}$

\uparrow
unclear where...



Shortened suffixes might *not* be *adjacent* in sorted order!

\rightsquigarrow no LCP entry for them!

Kasai's algorithm – Example

- ▶ Kasai et al. used above observation systematically
- ▶ Key idea: *compute* LCP values in *text order*
- ▶ Dropping first character of adjacent suffixes might not lead to *adjacent* shorter suffixes, but LCP entry can only be *longer*.

i	$R[i]$	T_i	r	$L[r]$	$T_{L[r]}$	LCP[r]
0	6 th	bananaban\$	0	9	\$	–
1	4 th	ananaban\$	1	5	aban\$	0
2	9 th	nanaban\$	2	7	an\$	1
3	3 th	anaban\$	3	3	anaban\$	2
4	8 th	naban\$	4	1	ananaban\$	3
5	1 th	aban\$	5	6	ban\$	0
6	5 th	ban\$	6	0	bananaban\$	3
7	2 th	an\$	7	8	n\$	0
8	7 th	n\$	8	4	naban\$	1
9	0 th	\$	9	2	nanaban\$	2

Kasai's algorithm – Code

```
1 procedure computeLCP( $T[0..n]$ ,  $L[0..n]$ ,  $R[0..n]$ ):  
2   // Assume  $T[n] = \$$ ,  $L$  and  $R$  are suffix array and inverse  
3    $\ell := 0$   
4   for  $i := 0, \dots, n - 1$  // Consider  $T_i$  now  
5      $r := R[i]$   
6     // compute  $\text{LCP}[r]$ ; note that  $r > 0$  since  $R[n] = 0$   
7      $i_{-1} := L[r - 1]$   
8     while  $T[i + \ell] == T[i_{-1} + \ell]$  do  
9        $\ell := \ell + 1$   
10     $\text{LCP}[r] := \ell$   
11     $\ell := \max\{\ell - 1, 0\}$   
12  return  $\text{LCP}[1..n]$ 
```

- ▶ remember length ℓ of induced common prefix
- ▶ use L to get start index of suffixes

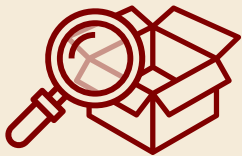
Analysis:

- ▶ dominant operation:
character comparisons
- ▶ separately count those with
outcomes “=” resp. “≠”
- ▶ each “≠” ends iteration of for-loop
 $\rightsquigarrow \leq n$ cmps
- ▶ each “=” implies increment of ℓ ,
but $\ell \leq n$ and
decremented $\leq n$ times
 $\rightsquigarrow \leq 2n$ cmps

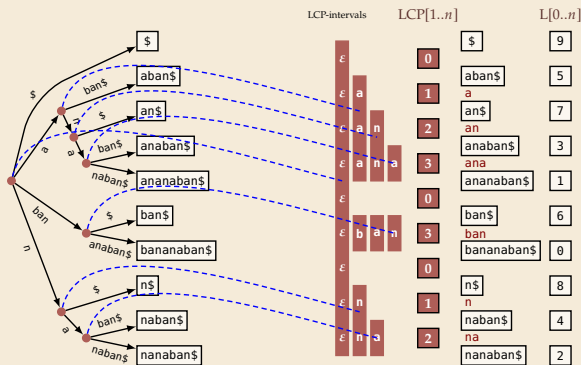
$\rightsquigarrow \Theta(n)$ overall time

Back to suffix trees

We can finally look into the black box of linear-time suffix-array construction!





1. Compute suffix array for T .
2. Compute LCP array for T .
3. Construct \mathcal{T} from suffix array and LCP array.





Conclusion

- ▶ (Enhanced) Suffix Arrays are the modern version of suffix trees
 - ▶ directly simulate suffix tree operations on L and LCP arrays

 can be harder to reason about

 can support same algorithms as suffix trees

 but use much less space

 simpler linear-time construction

Outlook:

- ▶ enhanced suffix arrays still need original text T to work
- ▶ a *self-index* avoids that
 - ▶ can store T in *compressed* form **and** support operations like string matching

↪ *Advanced Data Structures*