

8 Strings

Notation:

- Σ is an *alphabet* – a finite set of *characters*.
- Σ^* is the set of all *strings* (finite sequences) over Σ .
- We will use Greek letters for string variables, Latin letters for character and numeric variables, and **typewriter** letters for concrete characters. We will make no difference between a character and a single-character string.
- $|\alpha|$ is the *length* of the string α .
- ε is the *empty string* — the only string of length 0.
- $\alpha\beta$ is the *concatenation* of strings α and β ; we have $\alpha\varepsilon = \varepsilon\alpha = \alpha$ for all α .
- $\alpha[i]$ is the *i*-th character of the string α ; characters are indexed starting with 0.
- $\alpha[i : j]$ is the *substring* $\alpha[i]\alpha[i+1] \dots \alpha[j-1]$; note that $\alpha[j]$ is the first character *behind* the substring, so we have $|\alpha[i : j]| = j - i$. If $i \geq j$, the substring is empty. Either i or j can be omitted, the beginning or the end of α is used instead.
- $\alpha[:j]$ is the *prefix* of α formed by the first j characters. A word of length n has $n+1$ prefixes, one of them being the empty string.
- $\alpha[i:]$ is the *suffix* of α from character number i to the end. A word of length n has $n+1$ suffixes, one of them being the empty string.
- $\alpha[:] = \alpha$.
- $\alpha \leq \beta$ denotes *lexicographic order* of strings: $\alpha \leq \beta$ if α is a prefix of β or if there exists k such that $\alpha[k] < \beta[k]$ and $\alpha[:k] = \beta[:k]$.

8.1 Suffix arrays

Definition: The *suffix array* for a string α of length n is a permutation S of the set $\{0, \dots, n\}$ such that $\alpha[S[i]:] < \alpha[S[i+1]:]$ for all $0 \leq i < n$.

Claim: The suffix array can be constructed in time $\mathcal{O}(n)$.

Once we have the suffix array for a string α , we can easily locate all occurrences of a given substring β in α . Each occurrence corresponds to a suffix of α whose prefix is β . In the lexicographic order of all suffixes, these suffixes form a range. We can easily find the start and end of this range using binary search on the suffix array. We need $\mathcal{O}(\log |\alpha|)$ steps, each step involves string comparison with α , which takes $\mathcal{O}(|\beta|)$ time in the worst case. This makes $\mathcal{O}(|\beta| \log |\alpha|)$ total.

i	$S[i]$	$R[i]$	$L[i]$	$suffix$
0	14	3	0	ε
1	8	11	3	ananas
2	10	10	2	anas
3	0	7	2	annbansbananas
4	4	4	1	ansbananas
5	12	12	0	as
6	7	14	3	bananas
7	3	6	0	bansbananas
8	9	1	2	nanas
9	11	8	1	nas
10	2	2	1	nbansbananas
11	1	9	1	nnbansbananas
12	5	5	0	nsbananas
13	13	13	1	s
14	6	0	0	sbananas

Figure 8.1: Suffixes of annbansbananas and the arrays S , R , and L

Corrolary: Using the suffix array for α , we can enumerate all occurrences of a substring β in time $\mathcal{O}(|\beta| \log |\alpha| + p)$, where p is the number of occurrences reported. Only counting the occurrences costs $\mathcal{O}(|\beta| \log |\alpha|)$ time.

Note: With further precomputation, time complexity of searching can be improved to $\mathcal{O}(|\beta| + \log |\alpha|)$.

Definition: The *rank array* $R[0 \dots n]$ is the inverse permutation of S . That is, $R[i]$ tells how many suffixes of α are lexicographically smaller than $\alpha[i :]$.

Note: The rank array can be trivially computed from the suffix array in time $\mathcal{O}(n)$.

Definition: The *LCP array* $L[0 \dots n - 1]$ stores the length of the *longest common prefix* of each suffix and its lexicographic successor. That is, $L[i] = \text{LCP}(\alpha[S[i] :], \alpha[S[i + 1] :])$, where $\text{LCP}(\gamma, \delta)$ is the maximum k such that $\gamma[: k] = \delta[: k]$.

Claim: Given the suffix array, the LCP array can be constructed in time $\mathcal{O}(n)$.

Observation: The LCP array can be easily used to find the longest common prefix of any two suffixes $\alpha[i :]$ and $\alpha[j :]$. We use the rank array to locate them in the lexicographic order of all suffixes: they lie at positions $i' = R[i]$ and $j' = R[j]$ (w.l.o.g. $i' < j'$). Then we compute $k = \min(L[i'], L[i' + 1], \dots, L[j' - 1])$. We claim that $\text{LCP}(\alpha[i :], \alpha[j :])$ is exactly k .

First, each pair of adjacent suffixes in the range $[i', j']$ has a common prefix of length at least k , so our LCP is at least k . However, it cannot be more: we have $k = L[\ell]$ for some $\ell \in [i', j' - 1]$, so the ℓ -th and $(\ell + 1)$ -th suffix differ at position $k + 1$ (or one of the suffixes ends at position k , but we can simply imagine a padding character at the end, ordered before all ordinary characters.) Since all suffixes in the range share the first k characters, their $(k + 1)$ -th characters must be non-decreasing. This means that the $(k + 1)$ -th character of the first and the last suffix in the range must differ, too.

This suggests building a *Range Minimum Query* (RMQ) data structure for the array L : it is a static data structure, which can answer queries for the position of the minimum element in a given range of indices. One example of a RMQ structure is the 1-dimensional range tree from section ??: it can be built in time $\mathcal{O}(n)$ and it answers queries in time $\mathcal{O}(\log n)$. There exists a better structure with build time $\mathcal{O}(n)$ and query time $\mathcal{O}(1)$.

Examples: The arrays we have defined can be used to solve the following problems in linear time:

- *Histogram of k -grams*: we want to count occurrences of every substring of length k . Occurrences of every k -gram correspond to ranges of suffixes in their lexicographic order. These ranges can be easily identified, because we have $L[\dots] < k$ at their boundaries. We only have to be careful about suffixes shorter than k , which contain no k -gram.
- *The longest repeating substring of a string α* : Consider two positions i and j in α . The length of the longest common substring starting at these positions is equal to the LCP of the suffixes $\alpha[i :]$ and $\alpha[j :]$, which is a minimum over some range in L . So it is always equal to some value in L . It is therefore sufficient to consider only pairs of suffixes adjacent in the lexicographic order, that is to find the maximum value in L .
- *The longest common substring of two strings α and β* : We build a suffix array and LCP array for the string $\alpha\#\beta$, using a separator $\#$ which occurs in neither α nor β . We observe that each suffix of $\alpha\#\beta$ corresponds to a suffix of either α or β . Like in the previous problem, we want to find a pair of positions i and j such that the LCP of the i -th and j -th suffix is maximized. We however need one i and j to come from α and the other from β . Therefore we find the maximum $L[k]$ such that $S[k]$ comes from α and $S[k + 1]$ from β or vice versa.

Construction of the LCP array: Kasai's algorithm

We show an algorithm which constructs the LCP array L in linear time, given the suffix array S and the rank array R . We will use α_i to denote the i -th suffix of α in lexicographic order, that is $\alpha[S[i] :]$.

We can easily compute all $L[i]$ explicitly: for each i , we compare the suffixes α_i and α_{i+1} character-by-character from the start and stop at the first difference. This is obviously correct, but slow. We will however show that most of these comparisons are redundant.

Consider two suffixes α_i and α_{i+1} adjacent in lexicographic order. Suppose that their LCP $k = L[i]$ is non-zero. Then $\alpha_i[1:]$ and $\alpha_{i+1}[1:]$ are also suffixes of α , equal to $\alpha_{i'}$ and $\alpha_{j'}$ for some $i' < j'$. Obviously, $\text{LCP}(\alpha_{i'}, \alpha_{j'}) = \text{LCP}(\alpha_i, \alpha_{i+1}) - 1 = k - 1$. However, this LCP is a minimum of the range $[i', j']$ in the array L , so we must have $L[i'] \geq k - 1$.

This allows us to process suffixes of α from the longest to the shortest one, always obtaining the next suffix by cutting off the first character of the previous suffix. We calculate the L of the next suffix by starting with L of the previous suffix minus one and comparing characters from that position on:

Algorithm BUILDLCP

Input: A string α of length n , its suffix array S and rank array R

1. $k \leftarrow 0$ \triangleleft The LCP computed in previous step
2. For $p = 0, \dots, n - 1$: \triangleleft Start of the current suffix in α
3. $k \leftarrow \max(k - 1, 0)$ \triangleleft The next LCP is at least previous $- 1$
4. $i \leftarrow R[p]$ \triangleleft Index of current suffix in sorted order
5. $q \leftarrow S[i + 1]$ \triangleleft Start of the lexicographically next suffix in α
6. While $(p + k < n) \wedge (q + k < n) \wedge (\alpha[p + k] = \alpha[q + k])$:
7. $k \leftarrow k + 1$ \triangleleft Increase k while characters match
8. $L[i] = k$ \triangleleft Record LCP in the array L

Output: LCP array L

Lemma: The algorithm BUILDLCP runs in time $\mathcal{O}(n)$.

Proof: All operations outside the while loop take $\mathcal{O}(n)$ trivially. We will amortize time spent in the while loop using k as a potential. The value of k always lies in $[0, n]$ and it starts at 0. It always changes by 1: it can be decreased only in step 3 and increased only in step 7. Since there are at most n decreases, there can be at most $2n$ increases before k exceeds n . So the total time spent in the while loops is also $\mathcal{O}(n)$. \square

Construction of the suffix array by doubling

There is a simple algorithm which builds the suffix array in $\mathcal{O}(n \log n)$ time. As before, α will denote the input string and n its length. Suffixes will be represented by their starting position: α_i denotes the suffix $\alpha[i:]$.

The algorithm works in $\mathcal{O}(\log n)$ passes, which sort suffixes by their first k characters, where $k = 2^0, 2^1, 2^2, \dots$. For simplicity, we will index passes by k .

Definition: For any two strings γ and δ , we define comparison of prefixes of length k : $\gamma =_k \delta$ if $\gamma[: k] = \delta[: k]$, $\gamma \leq_k \delta$ if $\gamma[: k] \leq \delta[: k]$.

The k -th pass will produce a permutation S_k on suffix positions, which sorts suffixes by \leq_k . We can easily compute the corresponding ranking array R_k , but this time we have to be careful to assign the same rank to suffixes which are equal by $=_k$. Formally, $R_k[i]$ is the number of suffixes α_j such that $\alpha_j <_k \alpha_i$.

In the first pass, we sort suffixes by their first character. Since the alphabet can be arbitrarily large, this might require a general-purpose sorting algorithm, so we reserve $\mathcal{O}(n \log n)$ time for this step. The same time obviously suffices for construction of the ranking array.

In the $2k$ -th pass, we get suffixes ordered by \leq_k and we want to sort them by \leq_{2k} . For any two suffixes α_i and α_j , the following holds by definition of lexicographic order:

$$\alpha_i \leq_{2k} \alpha_j \iff (\alpha_i <_k \alpha_j) \vee (\alpha_i =_k \alpha_j) \wedge (\alpha_{i+k} \leq_k \alpha_{j+k}).$$

Using the ranking function R_k , we can write this as lexicographic comparison of pairs $(R_k[i], R_k[i+k])$ and $(R_k[j], R_k[j+k])$. We can therefore assign one such pair to each suffix and sort suffixes by these pairs. Since any two pairs can be compared in constant time, a general-purpose sorting algorithm sorts them in $\mathcal{O}(n \log n)$ time. Afterwards, the ranking array can be constructed in linear time by scanning the sorted order.

Overall, we have $\mathcal{O}(\log n)$ passes, each taking $\mathcal{O}(n \log n)$ time. The whole algorithm therefore runs in $\mathcal{O}(n \log^2 n)$ time. In each pass, we need to store only the input string α , the ranking array from the previous step, the suffix array of the current step, and the encoded pairs. All this fits in $\mathcal{O}(n)$ space.

We can improve time complexity by using Bucketsort to sort the pairs. As the pairs contain only numbers between 0 and n , we can sort in two passes with n buckets. This takes $\mathcal{O}(n)$ time, so the whole algorithm runs in $\mathcal{O}(n \log n)$ time. Please note that the first pass still remains $\mathcal{O}(n \log n)$, unless we can assume that the alphabet is small enough to index buckets. Space complexity stays linear.