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The number of spaced-word matches between two *DNA* sequences as a function of the underlying pattern weight

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January 22, 2019

Abstract

We study the number N_k of (spaced) word matches between pairs of evolutionarily related DNA sequences depending on the word length or pattern weight k, respectively. We show that, under the *Jukes-Cantor* model, the number of substitutions per site that occurred since two sequences evolved from their last common ancestor, can be estimated from the slope of a certain function of N_k. Based on these considerations, we implemented a software program for alignment-free sequence comparison called *Slope-SpaM*. Test runs on simulated sequence data show that *Slope-SpaM* can estimate phylogenetic distances with high accuracy for up to around 0.5 substitutions per positions. The statistical stability of our results is improved if spaced words are used instead of contiguous k-mers. Unlike previous methods that are based on the number of (spaced) word matches, our approach can deal with sequences that share only local homologies.

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1 Introduction

Phylogeny reconstruction is a fundamental task in computational biology [12]. Here, a basic step is to estimate pairwise evolutionary distances between protein or nucleic-acid sequences. Under the *Jukes-Cantor* model of evolution [20], the distance between two evolutionarily related *DNA* sequences can be defined as the (estimated) number of nucleotide substitutions per site that have occurred since the two sequences have evolved from their last common ancestor. Traditionally, phylogenetic distances are inferred from pairwise or multiple sequence alignments. For the huge amounts of sequence data that are now available, however, sequence alignment has become far too slow. Therefore, considerable efforts have been made in recent years, to develop fast *alignment-free* approaches that can estimate phylogenetic distances without the need to calculate full alignments of the input sequences, see [15, 36, 42, 3] for recent review articles. Alignment-free approaches are not only used in phylogeny reconstruction, but are also important in metagenomics [9, 31, 25] and in medical applications, for example to identify drug-resistant bacteria [4] or to classify viruses [41, 2]. In all these applications, it is crucial to rapidly estimate the degree of similarity or dissimilarity between large sets of sequence data.

Some alignment-free approaches are based on word frequencies [32, 35] or on the length of common substrings [38, 21, 18]. Other methods use variants of the D_2 distance that is defined based on the number of shared k-mers [33, 39, 37, 2]; a review focusing on these methods is given in [34]. *kWIP* [29] is a further development of this concept that uses information-theoretical weighting. Most of these approaches calculate heuristic measures of sequence (dis-)similarity that may not be easy to interpret. At the same time, alignment-free methods have been proposed that can accurately estimate phylogenetic distances between sequences based on stochastic models of DNA or protein evolution, using the length of common substrings [17, 27] or so-called *micro alignments* [40, 16, 23, 22].

Several authors have proposed to estimate phylogenetic distances from the number of k-mer matches between two sequences. The tools *Cnidaria* [1] and *AAF* [11] use the *Jaccard index* between sets of k-mers from two genomes to estimate the distance between them. In *Mash* [31], the *MinHash* [5] technique is used to reduce the input sequences to small 'sketches' which can be used to rapidly approximate the *Jaccard index*. In a previous article, we proposed another way to infer evolutionary distances between DNA sequences

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from the number of word matches between them, and we generalized this to so-called *spaced-word* matches [28]. A *spaced-word match* is a pair of words from two sequences that are identical at certain positions, specified by a predefined binary pattern of *match* and *don't-care* positions. Theoretically, this previous approach is based on a simple model of molecular evolution without insertions or deletions. In particular, we assumed that the compared sequences are homologous to each other over their entire length. In practice, the derived distance values are still reasonably accurate if a limited number of insertions and deletions is allowed, and phylogenetic trees could be obtained from these distance values that are similar to trees obtained with more traditional approaches. Like other methods that are based on the number of common k-mers, however, our previous approach cannot produce accurate results for sequences that share only local regions of homology.

Recently, Bromberg *et al.* published an interesting new approach to alignment-free protein sequence comparison that they called *Slope Tree* [6]. They defined a distance measure using the decay of the number of k-mer matches between two sequences, as a function of k. Trees reconstructed with this distance measure were in accordance to known phylogenetic trees for various sets of prokaryotes. *Slope Tree* can also correct for horizontal gene transfer and can deal with composition variation and low complexity sequences. From a theoretical point-of-view, however, it is not clear if the distance measure used in *Slope Tree* is an accurate estimator of evolutionary distances.

In the present paper, we study the number N_k of word and spaced-word matches between two DNA sequences, where k is the word length or the number of *match positions* of the underlying pattern for spaced words, respectively. Inspired by Bromberg's *Slope Tree* approach, we study the decay of N_k as a function of k. More precisely, we define a function $F(k)$ that depends on N_k and that can be approximated, under a simple probabilistic model of DNA evolution, by an affine-linear function of k. The number of substitutions per site can be estimated from the slope of F.

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2 The number of k-mer matches as a function of k

We are using standard notation from stringology as used, for example, in [13]. For a string or sequence S over some alphabet $\mathcal{A}$, $|S|$ denotes the length of S, and $S(i)$ is the i-th character of S, $1 \leq i \leq |S|$. $S[i..j]$ is the (contiguous) substring of S from i to j. We consider a pair of DNA sequences S_1 and S_2 that have evolved under the *Jukes-Cantor* substitution model [20] from some unknown ancestral sequence. That is, we assume that substitution rates are equal for all nucleotides and sequence positions, and that substitution events at different positions are independent of each other. For simplicity, we first assume that there are no insertions and deletions (indels). We call a pair of positions or k-mers from S_1 and S_2, respectively, *homologous* if they go back to the same position or k-mer in the ancestral sequence. In our model, we have a nucleotide match probability p for homologous positions and a background match probability q for non-homologous nucleotides; the probability of two homologous k-mers to match exactly is p^k.

In our indel-free model, S_1 and S_2 must have the same length $L = |S_1| = |S_2|$, and positions i_1 and i_2 in S_1 and S_2, respectively, are homologous if and only if $i_1 = i_2$. Note that, under this model, a pair of k-mers from S_1 and S_2 is either homologous or completely non-homologous, in the sense that *none* of the corresponding pairs of positions is homologous, and for a pair of non-homologous k-mers from S_1 and S_2, the probability of an exact match is q^k. Let the random variable X_k be defined as the number of k-mer matches between S_1 and S_2. More precisely, X_k is defined as the number of pairs (i_1, i_2) for which

$$S_1[i_1..i_1 + k - 1] = S_2[i_2..i_2 + k - 1]$$

holds. There are $(L - k + 1)$ possible homologous and $(L - k + 1) \cdot (L - k)$ possible background k-mer matches, so the expected total number of k-mer matches is

$$E(X_k) = (L - k + 1) \cdot p^k + (L - k + 1) \cdot (L - k) \cdot q^k \tag{1}$$

In [28], we used this expression directly to estimate the match probability p for two observed sequences using a *moment-based* approach, by replacing the expected number $E(X_k)$ by the empirical number N_k of word matches or spaced-word matches, respectively. Although in equation (1), an indel-free

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model is assumed, we could show that this approach gives still reasonable estimates of p for sequences with insertions and deletions, as long as the sequences are globally related, *i.e.* as long as the insertions and deletions are small compared to the length of the sequences. It is not possible, however, to estimate p from N_k in this way in the presence of large insertions and deletions, *i.e.* if sequences are only locally related.

Here, we propose a different approach to estimate evolutionary distances from the number N_k of k-mer or spaced-word matches with weight k, by considering the *decay* of N_k if k increases. For simplicity, we first consider an indel-free model as above, and we study exact k-mer matches with $k \leq k_{\max}$ for some maximal word length $k_{\max}$. Also, to simplify the following equations, we first restrict ourselves to word matches starting in both sequences at positions $\leq L - k_{\max} + 1$. From equation (1), we obtain

$$\ln p \cdot k + \ln(L - k_{\max} + 1) = \ln\left(E(X_k) - (L - k_{\max} + 1) \cdot (L - k_{\max}) \cdot q^k\right) \quad (2)$$

which is an affine-linear function of k with slope $\ln p$. Substituting the expected value $E(X_k)$ in the right-hand side of (2) with the corresponding *empirical* number N_k of k-mer matches for two observed sequences, we define

$$F(k) = \ln\left(N_k - (L - k_{\max} + 1) \cdot (L - k_{\max}) \cdot q^k\right)$$

We can now simply estimate p as the exponential of the slope of F.

The above considerations can be generalized to a model of *DNA* evolution with insertions and deletions. Let us consider two *DNA* sequences S_1 and S_2 of different lengths L_1 and L_2, respectively, that have evolved from a common ancestor under the *Jukes-Cantor* model, this time with insertions and deletions. Note that, unlike with the indel-free model, it is now possible that a k-mer match involves homologous as well as background nucleotide matches. Instead of deriving exact equations like (1) and (2), we therefore make some simplifications and approximations.

We can decompose S_1 and S_2 into indel-free pairs of 'homologous' substrings that are separated by non-homologous segments of the sequences. Let L_H be the total length of the homologous substring pairs in each sequence. As above, we define the random variable X_k as the number of k-mer matches between the two sequences, and p and q are, again, the homologous and background nucleotide match probabilities. We then use

$$E(X_k) \approx L_H \cdot p^k + L_1 \cdot L_2 \cdot q^k \quad (3)$$

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as a rough approximation, and we obtain

$$\ln p \cdot k + \ln L_H \approx \ln \left(E(X_k) - L_1 \cdot L_2 \cdot q^k \right) \tag{4}$$

Similar as in the indel-free case, we define

$$F(k) = \ln \left(N_k - L_1 \cdot L_2 \cdot q^k \right) \tag{5}$$

where N_k is, again, the empirical number of k-mer matches. As above, we can estimate p as the exponential of the slope of F. Note that this estimation can still be applied if L_H is small compared to L_2 and L_2, since L_H appears only in an additive constant on the left-hand side of (4). Thus, while the absolute values $F(k)$ do depend on the extent L_H of the homology between S_1 and S_2, the *slope* of F only depends on p, q, L_1 and L_2, but not on L_H.

3 The number of spaced-word matches

In many fields of biological sequence analysis, k-mers and k-mer matches have been replaced by *spaced words* or *spaced-word matches*, respectively. Let us consider a fixed word P over $\{0, 1\}$ representing *match positions* ('1') and *don't-care* positions ('0'). We call such a word a *pattern*; the number of *match positions* in P is called its *weight*. In most applications, the first and the last symbol of a pattern P are assumed to be match positions. A *spaced word* with respect to P is defined as a string W over the alphabet $\{A, C, G, T, *\}$ of the same length as P with $W(i) = *$ if and only if $P(i) = 0$, i.e. if and only if i is a *don't-care position* of P. Here, '*' is interpreted as a *wildcard* symbol. We say that a spaced word W w.r.t P occurs in a sequence S at some position i if $W(m) = S(i + m - 1)$ for all match positions m of P.

We say that there is a *spaced-word match* between sequences S_1 and S_2 at (i, j) if the same spaced word occurs at position i in S_1 and at position j in S_2, see Fig. 1 for an example. A spaced-word match can therefore be seen as a gap-free alignment of length $|P|$ with matching characters at the *match positions* and possible mismatches a the *don't-care positions*. *Spaced-word matches* or *spaced seeds* have been introduced in database searching as an alternative to exact k-mer matches [7, 26, 24]. The main advantage of spaced words compared to contiguous k-mers is the fact that results based on spaced words are statistically more stable than results based on k-mers [19, 10, 9, 8, 28, 30].

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S_1 :		T	T	A	T	G	A	C	C	A	C	T	C
S_2 :	A	C	T	A	C	G	A	T	C	G	A		
P :			1	1	0	0	1	0	1				

Figure 1: Spaced-word match between two DNA sequences S_1 and S_2 at (2,3) with respect to a pattern $P = 1100101$ representing *match positions* ('1') and *don't-care positions* ('0'). The same spaced word $TA**A*C$ occurs at position 2 in S_1 and at position 3 in S_2.

Quite obviously, approximations (3) and (4) remain valid if we define X_k to be the number of spaced-word matches for a given pattern P of weight k, and we can generalize the definition of $F(k)$ accordingly: if we consider a maximum pattern weight $k_{\max}$ and a given set of patterns $\{P_k, 1 \leq k \leq k_{\max}\}$ where k is the weight of pattern P_k, then we can define N_k as the empirical number of spaced-word matches with respect to pattern P_k between two observed DNA sequences. $F(k)$ can then be defined exactly as in (5), and we can estimate the nucleotide match probability p as the exponential of the slope of F.

4 Implementation

It is well known that the set of all k-mer matches between two sequences can be calculated efficiently by lexicographically *sorting* the list of all k-mers from both sequences, such that identical k-mers appear as contiguous *blocks* in this list. Note that, to find k-mer matches for all $k \leq k_{\max}$, it is sufficient to sort the list of $k_{\max}$-mers since this sorted list also contains the sorted lists of k-mers for $k < k_{\max}$.

This standard procedure can be directly generalized to spaced-word matches. In order to calculate the numbers N_k efficiently, we start by generating a suitable set of patterns $\{P_k, 1 \leq k \leq k_{\max}\}$. We first specify a pattern $P = P_{k_{\max}}$ of weight $k_{\max}$, for example by using the tool *rasbhari* [14]. As usual, we require the first and the last position of P to be match positions, i.e. we have $P(1) = P(k_{\max}) = 1$. Let ℓ_k be the k-th *match position* in the pattern P. We then define the k-th pattern as

$$P_k = P[1..\ell_k]$$

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In other words, for $k < k_{\max}$, the pattern P_k is obtained by cutting off P after the k-th match position, so each pattern P_k has a weight of k. To find all spaced-word matches with respect to all patterns $P_k, 1 \leq i \leq k_{\max}$, it suffices to lexicographically sort the set of spaced words with respect to P in S_1 and S_2.

To estimate the slope of F, one has to take into account that the values $F(k)$ are statistically stable only for a certain range of k. If k is too small, N_k and $F(k)$ are dominated by the number of background (spaced) word matches. If k is too large, on the other hand, the number of homologous (spaced) word matches becomes small, and for $N_k < L_1 \cdot L_2 \cdot q^k$, the value $F(k)$ is not even defined. For two input sequences, we therefore need to identify a range $k_1, \ldots, k_2$ in which F is approximately affine linear. To this end, we consider the differences

$$\delta_k = (F(k) - F(k-1))$$

and we choose a maximal range $k_1 \ldots k_2$ where the difference $|\delta_k - \delta_{k-1}|$ is smaller than some threshold T for all k with $k_1 < k \leq k_2$. In our implementation, we used a value of $T = 0.2$. We then estimate the slope of F as the *average* value of δ_k in this range, so we estimate the match probability as

$$\hat{p} = \exp\left(\frac{F(k_2) - F(k_1)}{k_2 - k_1}\right) \tag{6}$$

Finally, we apply the usual *Jukes-Cantor* correction to estimate the *Jukes-Cantor* distance between the sequences, e.g. the number of substitutions per position that have occurred since they diverged from their last common ancestor. Examples are given in Fig. 2, 3 and 4.

5 Test results

We first simulated pairs of *DNA* sequences of length $L = 10,000$ without indels, and with different phylogenetic distances. As a first example, we generated a pair of sequences with a *Jukes-Cantor* distance of 0.2, i.e with 0.2 substitutions per position. According to the *Jukes-Cantor* correction formula, this corresponds to a match probability of $p = 0.82$. In Fig. 2 (top), $F(k)$ is plotted against k for these sequences based on exact k-mer matches; the difference $F(k) - F(k-1)$ is stable for $k_1 = 5 < k \leq k_2 = 20$. With (6),

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we therefore estimate the slope of F from the numbers N_k of k-mer matches as

$$\frac{F(k_2) - F(k_1)}{k_2 - k_1} = \frac{5.24 - 8.12}{20 - 5} = -0.19$$

This way, we obtain an estimated match probability of $\hat{p} = e^{-0.19} = 0.827$ which is rather close to the correct value $p = 0.82$. A similar value was obtained when we used spaced-word matches instead of contiguous k-mer matches (Fig. 2, bottom). Results for indel-free sequences of the same length, with a *Jukes-Cantor* distance of 0.5 are shown in Fig. 3. Here, the slope of F was 0.449 when k-mer matches were used an 0.446 with spaced-word matches, leading to an estimated match probability of $\hat{p} = 0.638$ which corresponds to a *Jukes-Cantor* distance of 0.494, again very close to the true value.

Fig. 4 shows the corresponding results for a pair of simulated sequences with insertions and deletions and with only local sequence homology. In a region of length $L_H = 10,000$, the sequences are homologous to each other, with a *Jukes-Cantor* distance of 0.2 substitutions per position, as in our first example (Fig. 2) – but this time, we included 20 insertions and deletions of length 50 each at random positions. In addition, the homology region was flanked on both sides and in both sequences by non-related random sequences of length 10,000 each. So both sequences had a length of around 30,000 where one third of the sequences were homologous to each other. Here, *Slope-SpaM* estimated a nucleotide match frequency of $\hat{p} = 0.838$ corresponding to a *Jukes-Cantor* distance of 0.18, somewhat smaller than the true value of 0.2.

For a more systematic evaluation, we simulated pairs of *DNA* sequences with *Jukes-Cantor* distances d between 0.05 and 1.0. For each value of d, we generated 20,000 sequence pairs of length 10,000 each and with distance d, and we estimated the distances with *Slope-SpaM*. In Fig. 5, the average estimated distances are plotted against the real distances. Our estimates are fairly accurate for distances up to around 0.5 substitutions per site, but become statistically less stable for larger distances.

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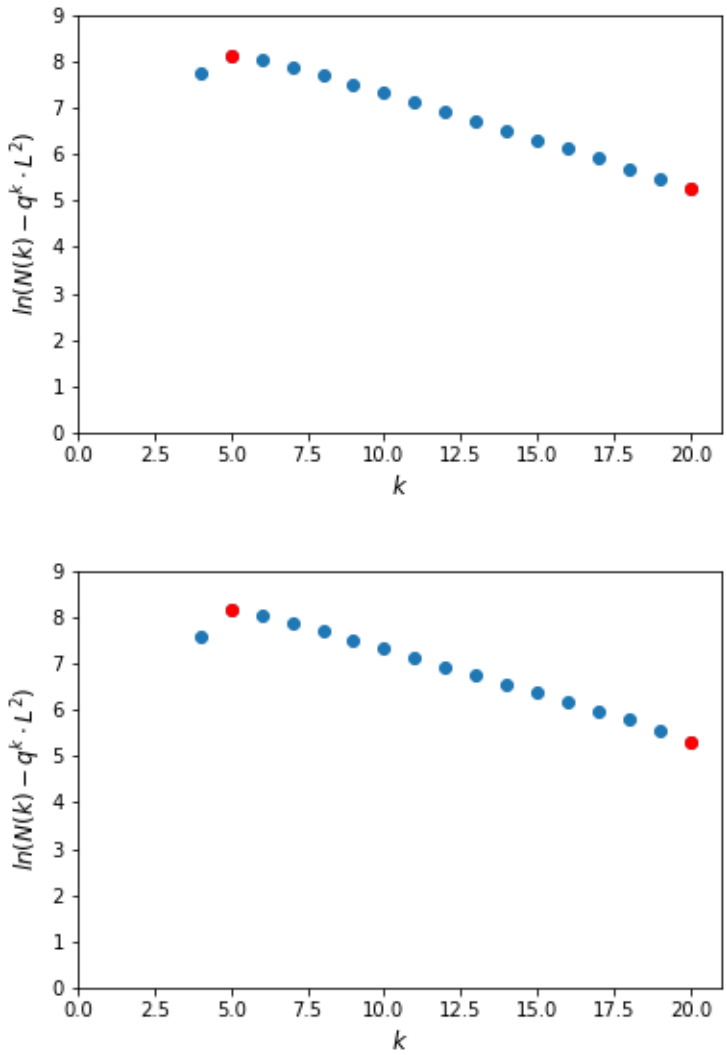

Figure 2: Test runs on simulated indel-free *DNA* sequences of length $L = 10,000$, with a *Jukes-Cantor* distance of 0.2. *Top:* $F(k) = \ln\left(N_k - L^2 \cdot q^k\right)$ plotted against k, where N_k is the number of k-mer matches. *Bottom:* for $P_{20} = 11001110111001110111000101011011$, patterns P_k were generated for $k = 1, \ldots, 19$ as explained in section 4. $F(k)$ is plotted against k, based on the number N_k of spaced-word matches with respect to P_k. In both cases, $\delta_k = F(k) - F(k-1)$ is stable for $k_1 = 5 < k \leq k_2 = 20$ (red dots).

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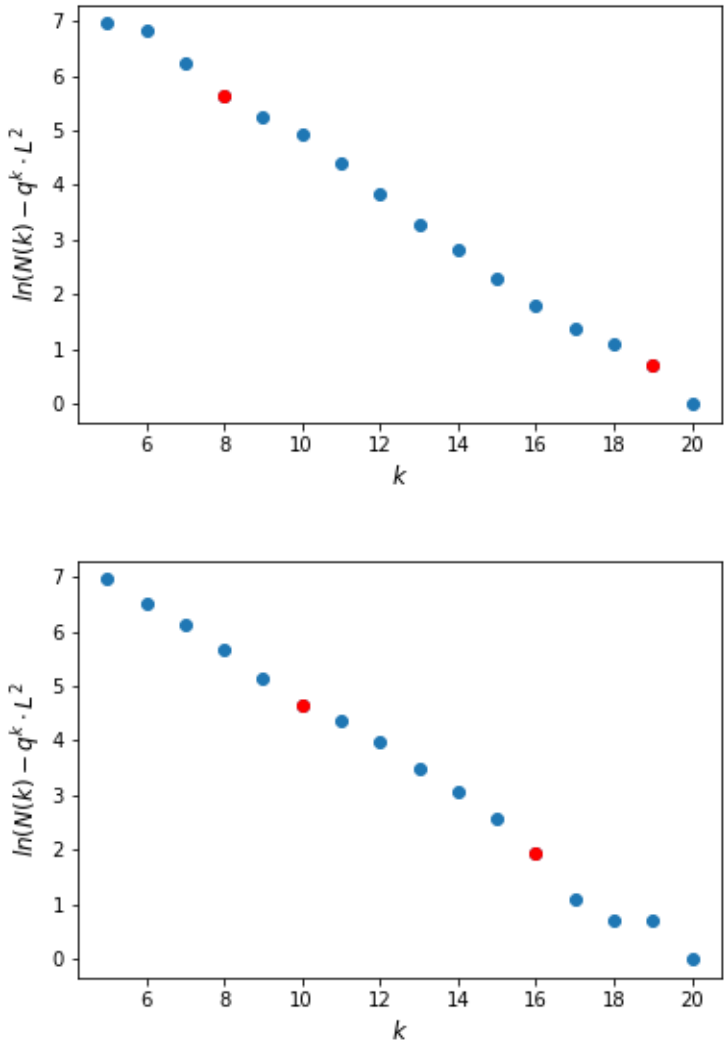

Figure 3: $F(k)$ plotted against k as in Fig. 2 and for simulated indel-free *DNA* sequences of length $L = 10,000$ with a *Jukes-Cantor* distance of 0.5 for contiguous k-mers (top) and for spaced-word matches (bottom).

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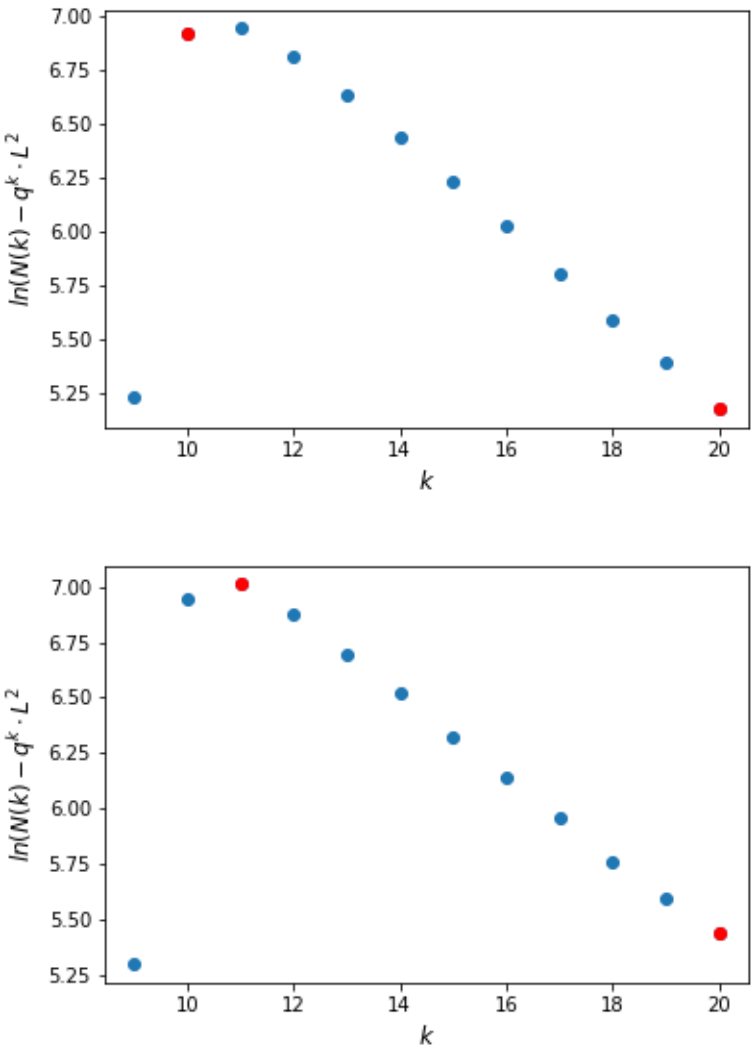

Figure 4: $F(k)$ plotted against k as in Fig. 2 and 3, for simulated indel-free *DNA* sequences of length $L = 30,000$. In a region of length $L_H = 10,000$, the two sequences are related to each other with a *Jukes-Cantor* distance of 0.2; this region contains around 20 indels at random positions. The 'homologous' region is flanked on both sides and in both sequences by unrelated random sequences of length 10,000 each. $F(k)$ is plotted for contiguous k-mers (top) and for spaced-word matches (bottom).

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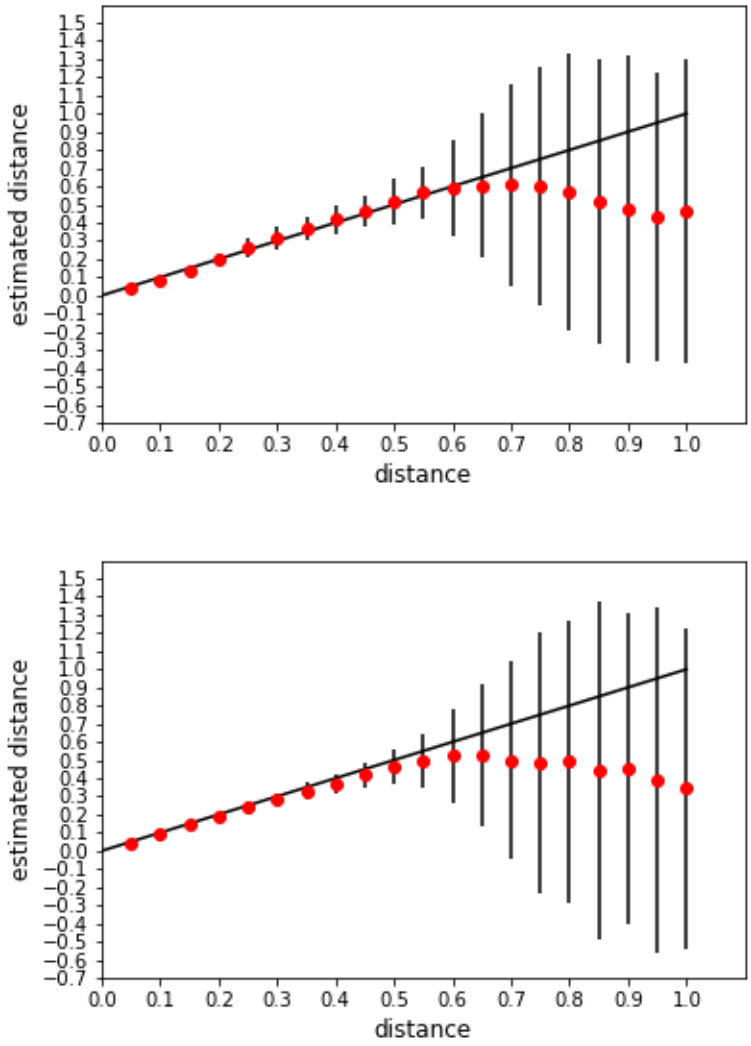

Figure 5: For *Jukes-Cantor* distances d between 0.05 and 1.0, we generated pairs of simulated *DNA* sequences of length $L = 10,000$; for each value of d, 20,000 sequences pairs with a distance of d were generated. For each pair, we estimated the distance d with *Slope-SpaM*, using *exact* k-mers (top) and spaced-word matches (bottom). Average estimated distances are plotted against the real distances; standard deviations are shown as error bars.

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6 Discussion

A number of alignment-free methods have been proposed in the literature to estimate the nucleotide match probability p for a pair of DNA sequences from the number N_k or D_2 of k-mer matches for a fixed value of k. This can be done by setting N_k in relation to the total number of k-mers in the compared sequences [31] or to the length of the sequences [27]. A certain draw-back of these approaches is that, in order to accurately estimate the match probability p, not only N_k and the sequence lengths (or total number of k-mers, respectively), but also the extent of the homology between the compared sequences must be known.

Indeed, if two sequences share only short, local homologies with each other, an observed number N_k of k-er matches could indicate a high match probability p within the homologous regions – while the same value of N_k would correspond to a lower p if the homology would extend over the entire length of the sequences. Since it is, in general, not known which proportion of the input sequences is homologous to each other, the above methods assume, for simplicity, that the compared sequences are homologous over their entire length. Obviously, this assumption affects the accuracy of these approaches since genome sequences often share only local homologies.

In this paper, we introduced *Slope-SpaM*, another approach to estimate the match probability p between two DNA sequences – and thereby their *Jukes-Cantor* distance – from the number N_k of word matches; we generalized this approach to *spaced-word matches*, based on patterns with k match positions. The main difference between *Slope-SpaM* and previous methods is that, instead of using only one single word length or pattern weight k, our program calculates N_k, together with an expression $F(k)$ that depends on N_k, for a whole range of values of k. The nucleotide match probability p in an alignment of the input sequences is then estimated from the slope of F. From the definition of $F(k)$, it is easy to see that the slope of F and our estimate of p depend on the values of N_k, but not on the extent of the homology between the compared sequences.

Test results on simulated sequences show that our distance estimates are accurate for distances up to around 0.5 substitutions per sequence position. Our experimental results also confirm that *Slope-SpaM* still produces accurate distance estimates if sequences contain only local regions of homology. In Fig. 2 and Fig. 4, sequence pairs with a *Jukes-Cantor* distance of 0.2 were used. While the sequences in Fig. 2 are similar to each other over their

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entire length, in Fig. 4 a local region of sequence 'homology' is embedded in non-related random sequences twice the length of the homology region. Nevertheless, the slope of the function F is almost the same in both figure, leading to similar estimates of the match probability p. In fact, with the values shown in Fig. 4 (top), we would have obtained the same correct estimate for p that we obtained with the data from Fig. 2, if our program had chosen a minimum value $k_1 = 11$ for the word length k, instead of $k_1 = 10$. Alternatively, a sufficiently large maximal value k_2 would have led to a more accurate estimate of p. A better way of selecting these parameters may further improve the accuracy of *Slope-SpaM*.

Given the good performance of our approach on simulated sequences, we expect that *Slope-SpaM* will also be useful to calculate phylogenetic trees for real-world sequences.

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