Bioinformatics Algorithms

(Fundamental Algorithms, module 2)

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The q-gram distance

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Motivations for using q-gram distance

1. If two parts of a sequence are exchanged (e.g. two paragraphs, two long substrings, two genes), then one can argue that the resulting strings still have high similarity; however, the edit distance will be big. The q-gram distance can be more appropriate in this case.
2. The edit distance needs quadratic computation time, but this is often too slow. The q-gram distance can be computed in linear time.

What is a q-gram?

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Def.
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Note
q-grams are also called k-mers, w-words, or k-tuples. Typically, q (or k, w, etc.) is small, much smaller than the strings we will want to compare.

We will fix q, and use the number of occurrences of q-grams to compute distances between strings.

Occurrence count

Let s be a string of length $n \geq q$, and u be a q-gram. The occurrence count of u in s is

$$N(s, u) = |\{i \, : \, s_i \ldots s_{i+q-1} = u\}|,$$

the number of times q-gram u occurs in s.

Ex.
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Ex.
Let $s = \texttt{ACAGGGCA}$ and $q = 2$. Then $N(s,\texttt{AC}) = N(s,\texttt{AG}) = N(s,\texttt{GC}) = 1, N(s,\texttt{CA}) = N(s,\texttt{GG}) = 2$, and for all other q-grams u over Σ, $N(s,u) = 0$.

q-gram profile

Fix some enumeration (listing) of Σ^q, i.e. some order in which we want to list all q-grams; e.g. the lexicographic order.

Def.
Let s be a string over Σ, $|s| \geq q$. The q-gram profile of s, $P_q(s)$ is an array of size σ^q, where the ith entry is

$$P_q(s)[i] = N(s, u_i),$$

and u_i is the ith q-gram in the enumeration.

Example:
Let $\Sigma = \{\texttt{A},\texttt{C},\texttt{G},\texttt{T}\}$ and $q = 2$.

Let
$s = \texttt{ACAGGGCA}$,
$t = \texttt{GGGCAACA}$,
$v = \texttt{AAGGACA}$.
Then the q-gram profiles of s, t, v are shown on the right.

Notice that the sum of all entries of $P_q(s) = |s| - q + 1$ = total number of q-gram occurrences in s = number of distinct positions in s where a q-gram starts.

u	$P_q(s)$	$P_q(t)$	$P_q(v)$
AA	0	1	1
AC	1	1	1
AG	1	0	1
AT	0	0	0
CA	2	2	1
CC	0	0	0
CG	0	0	0
CT	0	0	0
GA	0	0	1
GC	1	1	0
GG	2	2	1
GT	0	0	0
TA	0	0	0
TC	0	0	0
TG	0	0	0
TT	0	0	0

q-gram distance

(Introduced by Ukkonen, 1992)

Def.: Given two strings s, t, the q-gram distance of s and t is

$$dist_{q-gram}(s,t) = \sum_{u \in \Sigma^q} |N(s,u) - N(t,u)|.$$

Equivalent def.: Given two strings s, t, the q-gram distance of s and t is

$$dist_{q-gram}(s,t) = \sum_{i=1}^{\sigma^q} |P_q(s)[i] - P_q(t)[i]|,$$

which is the Manhattan distance[1] of the q-gram profiles of s and t.

[1] The Manhattan distance, or L_1-distance, of two vectors $x, y \in \mathbb{R}^n$ is defined as $\sum_{i=1}^{n} |x_i - y_i|$.

q-gram distance

In the previous example ($q = 2$, $s = \texttt{ACAGGGCA}$, $t = \texttt{GGGCAACA}$, and $v = \texttt{AAGGACA}$), we have

$$dist_{2-gram}(s,t) = 2, dist_{2-gram}(s,v) = 5, \text{ and } dist_{2-gram}(t,v) = 5.$$

Note that it is possible to have distinct strings with q-gram distance 0, e.g.

$$\text{for } w = \texttt{AGGGCACA}, \text{ we have } dist_{2-gram}(s,w) = 0.$$

(Don't just believe this, double check it!)

The q-gram distance is a pseudo-metric

Lemma
The q-gram distance is a pseudo-metric, i.e. it is non-negative, symmetric, and obeys the triangle inequality (but it is possible to have $x \neq y$ with $dist_{q-gram}(x,y) = 0$).

Proof:
The three properties follow from the fact that the Manhattan metric is a metric. The example above shows that $dist_{q-gram}(x,y) = 0$ does not imply $x = y$.

Exercise:
Prove the lemma explicitly.

Connection to edit distance

q-gram Lemma

Let $d_{edit}(s,t)$ denote the (unit-cost) edit distance of s and t. Then

$$\frac{dist_{q-gram}(s,t)}{2q} \leq d_{edit}(s,t).$$

Proof

Every edit operation contributes to the q-gram distance at most $2q$: Consider the simplest case, a substitution in position i of s, where character s_i is substituted by character x, and let s' be the resulting string. If $q \leq i \leq |s| - q + 1$, then there are exactly q q-grams of s affected by the substitution: $s_{i-q+1} \ldots s_i$, up to $s_i \ldots s_{i+q-1}$ (otherwise fewer); the counts of all these are decremented by 1, while the counts of the new q-grams $s_{i-1+1} \ldots x$, $s_i \ldots x s_{i+q}$, etc. are incremented by 1. Therefore, $dist_{q-gram}(s,s') \leq 2q$ (it could be less because these q-grams need not be all distinct). For a deletion, the number of q-grams whose count is decremented is at most q, while those whose count is incremented is at most $q-1$; for an insertion the other way around.—The claim follows by induction on the number of edit operations.

Connection to edit distance

Examples

With the earlier examples, we have

1. Exchange of two long substrings: $d_{edit}(s,t) = 6, d_{edit}(s,w) = 4$ (compare to: $dist_{q-gram}(s,t) = 2, dist_{q-gram}(s,w) = 0$, with $q = 2$).
2. The q-gram distance is at most $2q$ times edit distance (q-gram lemma): $d_{edit}(s,v) = 2$ (compare to: $dist_{q-gram}(s,v) = 5 \leq 8 = d_{edit}(s,v) \cdot 2q$, with $q = 2$)

Based on the q-gram lemma and the fact that the q-gram distance can be computed in linear time, we can use the q-gram distance as a filter for edit distance computations.

Computation of the q-gram distance

Basic ideas

- Use a sliding window of size q over s and t
- Use an array d_q of size σ^q
- First slide a window over s, increment respective entry for every q-gram seen
- Then slide over t, decrement respective entry for every q-gram seen
- Now $d_q[r] = N(s,u_r) - N(t,u_r)$.
- Sum up the absolute values of the entries: $dist_{q-gram}(s,t) = \sum_i |d_q[i]|$

We will see: This algorithm runs in linear time.

But: how do we know where to find the entry for the current q-gram?
This is called ranking (coming soon)

Computation of the q-gram distance

Algorithm for computing q-gram distance

input: Strings s,t of length $|s| = n$ and $|t| = m$
output: $dist_{q-gram}(s,t)$

1. initialize $d_q[0 \ldots \sigma^q - 1]$ with 0s
2. for $i = 1, \ldots, n-q+1 : r \leftarrow rank(s_i \ldots s_{i+q-1})$
   $d_q[r] \leftarrow d_q[r] + 1$
3. for $i = 1, \ldots, m-q+1 : r \leftarrow rank(t_i \ldots t_{i+q-1})$
   $d_q[r] \leftarrow d_q[r] - 1$
4. $d \leftarrow 0$
5. for $i = 0 \ldots \sigma^q - 1 : d \leftarrow d + |d_q[i]|$.
6. return d

For an example, see next slide.

Example:

$s = \texttt{ACAGGGCA}$,
$t = \texttt{GGGCAACA}$.

On the right, the array d_q after line 2. of the algo (now d_q equals $P_q(s)$) and after line 3.
Finally, we have $d_2(s,t) = |-1| + 1 = 2$.

r	u_r	d_q after the pass thru s	d_q after the pass thru t
0	AA	0	-1
1	AC	1	0
2	AG	1	1
3	AT	0	0
4	CA	2	0
5	CC	0	0
6	CG	0	0
7	CT	0	0
8	GA	0	0
9	GC	1	0
10	GG	2	0
11	GT	0	0
12	TA	0	0
13	TC	0	0
14	TG	0	0
15	TT	0	0

Goal

Given q-gram u, we want to know which entry of the array u corresponds to.
Ex.: Where is the q-gram CG? In position 6.

Ranking functions

- A ranking function is a bijection $rank : \Sigma^q \to [0 \ldots \sigma^q - 1]$.
- $rank(u)$ gives us the position of u in the enumeration of Σ^q
- needs to be very efficiently computable
- the ranking function we use will give us constant time per q-gram of s

r	u_r	d_q after the pass thru s
0	AA	0
1	AC	1
2	AG	1
3	AT	0
4	CA	2
5	CC	0
6	CG	0
7	CT	0
8	GA	0
9	GC	1
10	GG	2
11	GT	0
12	TA	0
13	TC	0
14	TG	0
15	TT	0

Ranking function

- Basic idea: We will interpret the q-gram itself as a number: a number base σ. In our case: $\sigma = 4$.
- First, we assign numbers $0, \ldots, \sigma - 1$ (here: $0, 1, 2, 3$) to the characters:
$$f : \mathtt{A} \mapsto 0, \mathtt{C} \mapsto 1, \mathtt{G} \mapsto 2, \mathtt{T} \mapsto 3$$
- Second, we extend this to strings: e.g. CG becomes $12_4 = 1 \cdot 4^1 + 2 \cdot 4^0 = 6_{10}$. (i.e. 12 in base 4 equals 6 in base 10.)
- In general, for $u = u_1 \ldots u_q$, the $rank(u)$ is given by:
$$rank(u) = f(u_1) \cdot \sigma^{q-1} + f(u_2) \cdot \sigma^{q-2} + \ldots + f(u_{q-1}) \cdot \sigma^1 + f(u_q) \cdot \sigma^0.$$
- E.g. $rank(\mathtt{CATT}) = 1 \cdot 4^3 + 0 \cdot 4^2 + 3 \cdot 4 + 3 \cdot 1 = 64 + 0 + 12 + 3 = 79.$

Sliding window

Crucial trick

The rank of the q-gram starting in position $i + 1$ can be computed from the rank of the q-gram starting in position i in constant time.

Example

Let $s = \mathtt{GACATTGACGAT}$, and let $q = 4$. Let's compare the rank of CATT and ATTG, two consecutive q-grams:

$$\begin{aligned} rank(\mathtt{CATT}) &= 1 \cdot 4^3 + 0 \cdot 4^2 + 3 \cdot 4^1 + 3 \cdot 4^0 \\ rank(\mathtt{ATTG}) &= \qquad\quad\; 0 \cdot 4^3 + 3 \cdot 4^2 + 3 \cdot 4^1 + 2 \cdot 4^0 \end{aligned}$$

So $1 \cdot 4^3$ has to be subtracted, the rest multiplied by 4, and finally $2 \cdot 4^0 = 2$ added.

Sliding window

In general:

$$\begin{aligned} rank(s_i \ldots s_{i+q-1}) &= f(s_i) \cdot \sigma^{q-1} + f(s_{i+1}) \cdot \sigma^{q-2} + \ldots + f(s_{i+q-1}) \\ rank(s_{i+1} \ldots s_{i+q}) &= \qquad\qquad\quad f(s_{i+1}) \cdot \sigma^{q-1} + \ldots + f(s_{i+q-1}) \cdot \sigma + f(s_{i+q}) \end{aligned}$$

Therefore, if $rank(s_i \ldots s_{i+q-1}) = C$, then

$$rank(s_{i+1} \ldots s_{i+q}) = (C - f(s_i) \cdot \sigma^{q-1}) \cdot \sigma + f(s_{i+q})$$

Ex. $rank(\mathtt{ATTG}) = (rank(\mathtt{CATT}) - 1 \cdot 4^3) \cdot 4 + 2 \cdot 4^0 = (79 - 64) \cdot 4 + 2 = 62.$
Double check: $rank(\mathtt{ATTG}) = 0 \cdot 4^3 + 3 \cdot 4^2 + 3 \cdot 4 + 2 = 48 + 12 + 2 = 62.$

Analysis

- computing the rank of the first q-gram: $O(q)$ time
- computing rank of the $(i + 1)$st q-gram, given the rank of the ith q-gram: constant time ($O(1)$)

Analysis (cont.)

Computing the q-gram distance of two strings s, t of length n resp. m:

- initialize array d_q: $O(\sigma^q)$ time
- slide window of size q over s: there are $n - q + 1$ windows, for each, we have to compute its rank r and then update the entry $d_q(r)$; rank of first window takes $O(q)$ time, for all following windows $O(1)$, while updating entry is always constant time: $O(n)$ time
- slide window of size q over t: similarly, $O(m)$ time
- compute sum of absolute values: $O(\sigma^q)$ time

Analysis (cont.)

Putting it together:

- Total time: $O(n + m + \sigma^q)$
- Total space: $O(\sigma^q)$, for the array d_q
- If we choose
$$q \leq \log_\sigma(n), \log_\sigma(m),$$
then $\sigma^q = O(n + m)$, so we have linear time and space $O(n + m)$.