

## 1.1 Introduction

### 1.1.1 Motivation

This work has been motivated by recent advances of molecular genetics. The human genome has been sequenced in 2001. Also mouse, drosophila, etc. Nowadays # reference model genomes are available in genbank.

Next-generation sequencing has been the second revolution. NGS produces billions of reads for 1000\$ dollars. Why should one re-sequence a known genome? Resequencing applications include variant calling, etc. So NGS impacts biomedicine.

Given a set of reads, two approaches are possible: assembly and mapping.

Assembly methods are based on overlaps, de brujin graphs, or...

Read mapping methods work on a previously assembled reference genome.

The typical SNPs analysis pipeline ?? consists of...

In this work we focus on read mapping, although many core algorithms considered are also applicable to assembly, as well as to later pipeline stages.

*Figure 1.1: NGS pipeline.*

### 1.1.2 Fundamentals

#### Fundamental definitions

Let us start by defining primitive objects of stringology: alphabets and strings. An alphabet is a finite set of symbols (or characters); a string (or word) over an alphabet is a finite sequence of symbols from that alphabet. We denote the length of a string  $s$  by  $|s|$ , and by  $\epsilon$  the empty string s.t.  $|\epsilon| = 0$ . Given an alphabet  $\Sigma$ , we define  $\Sigma^0 = \{\epsilon\}$  as the set containing the empty string,  $\Sigma^n$  as the set of all strings over  $\Sigma$  of length  $n$ , and  $\Sigma^* = \cup_{n=0}^{\infty} \Sigma^n$  as the set of all strings over  $\Sigma$ . Finally, we call any subset of  $\Sigma^*$  a language over  $\Sigma$ .

We now define concatenation, the most fundamental operation on strings. The concatenation operator of two strings is denoted with  $\cdot$  and defined as  $\cdot : \Sigma^* \times \Sigma^* \rightarrow \Sigma^*$ . Given two strings,  $x \in \Sigma^n$  with  $x = \alpha_1\alpha_2 \dots \alpha_n$ , and  $y \in \Sigma^m$  with  $y = \beta_1\beta_2 \dots \beta_m$ , their concatenation  $x \cdot y$  (or simply denoted  $xy$ ) is the string  $z \in \Sigma^{n+m}$  consisting of the symbols  $\alpha_1\alpha_2 \dots \alpha_n\beta_1\beta_2 \dots \beta_m$ .

From concatenation we can derive the notion of prefix, suffix, and substring. A string  $x$  is a prefix of  $y$  iff there is some string  $z$  s.t.  $y = x \cdot z$ . Analogously,  $x$  is a suffix of  $y$  iff there is some string  $z$  s.t.  $y = z \cdot x$ . Similarly,  $x$  is a substring of  $y$  iff there is some string  $w, z$  s.t.  $y = w \cdot x \cdot z$ . Moreover, if  $x$  is a substring of  $y$ , then we say that  $x$  occurs within  $y$  at position  $|w|$ .

For example, let us consider the alphabet  $\Sigma$  consisting of DNA bases:  $\Sigma = \{A, C, G, T\}$ . Examples of strings over  $\Sigma$  are  $x = A$ ,  $y = AGGTAC$ ,  $z = TA$ . For instance,  $y \in \Sigma^6$  and  $|y| = 6$ . An example of concatenation is  $x \cdot z = ATA$ . The string  $x$  is a prefix of  $y$ . The string  $z$  is a substring of  $y$ , occurring at position 4 in  $y$ .

## Fundamental problems

We now define exact string matching, the most fundamental problem in stringology. Given a string  $p$  called the pattern and a longer string  $t$  called the text, the exact string matching problem is to find all occurrences, if any, of pattern  $p$  into text  $t$  [?].

This problem can be generalized in various ways. For instance, the definition of distance between strings yields approximate string matching.

Define distance between two strings. Let  $d$  be a distance function over words, defined as  $d : (\Sigma^*, \Sigma^*) \rightarrow \mathcal{N}$ . Common distance metrics are the Hamming and Levenshtein or edit distance.

$$d_H =$$

$$d_E =$$

Define alignment between two strings.

Define occurrence. We say that a word  $p$  of length  $m$  occurs in another word  $t$  at position  $e$  if  $t_{e-m,e} = p$ . The notion of occurrence can be generalized to metric distances...

Define approximate string matching. Given two words  $t$  and  $p$  such that  $t \gg p$ , respectively called text and pattern. Given a distance threshold  $k \in \mathcal{N}$ . The approximate string matching problem is to find all occurrences of  $p$  into  $t$  within the error threshold  $k$ .

These definitions allow us to model basic biological.

## 1.2 Overview of existing methods

Existing methods can be classified in three categories: online, indexed and filtering. Online and filtering in [?]. Indexed in [?].

### 1.2.1 Online methods

#### Dynamic Programming

The edit distance between two strings can be efficiently computed via dynamic programming.

The recurrence relation is as follows:  $D[i, j] = \dots$

Answering the question whether the distance  $d(x, y) \leq k$  is an easier problem: a band of size  $k + 1$  is sufficient.

Finding all occurrences of a pattern  $p$  in a text  $t$ ...

Change initialization.

Change traceback to start from all  $j : D[m, j] \leq k$ .

## **DP Bit-parallelism**

### **Automata**

### **NFA**

## **1.2.2 Indexed methods**

### **Suffix tree**

### **Backtracking**

## **1.2.3 Filtering methods**

### **Why filtering**

### **Pigeonhole principle**

### **$q$ -Gram lemma**

## **1.3 Related problems**

### **1.3.1 Local similarity search**

Define score and scoring scheme.

Define local similarity.

### **Online methods**

Give dynamic programming solution.

### **Indexed methods**

Backtracking over substring index. BWT-SW.

### **Filtering methods**

SWIFT/Stellar is based on the  $q$ -gram lemma. Lastz resembles a suffix filter.

## **1.3.2 Dictionary search**

Define problem.

**Trie**

**Backtracking**

### **1.3.3 Overlaps computation**

Define problem.

DP solution.

Indexed solution, exact and approximate.

**2.1 Myers' bit-vector algorithm**

**2.2 Banded Myers' bit-vector algorithm**

**2.3 Increased bit-parallelism using SIMD instructions**



## **3.1 Classic Full-Text Indices**

### **3.1.1 Trie**

### **3.1.2 Suffix trie and suffix tree**

### **3.1.3 Suffix array**

### **3.1.4 $q$ -Gram index**

## **3.2 Compressed Full-Text Indices**

### **3.2.1 Burrows-Wheeler transform**

### **3.2.2 FM-index**

### **3.2.3 Rank dictionaries**

## **3.3 Backtracking**

### **3.3.1 Pruning methods**

### **3.3.2 Multiple backtracking**





**4.1  $q$ -Gram filters**

**4.1.1 Exact seeds**

**4.1.2 Gapped seeds**

**4.2 Factor filters**

**4.2.1 Exact seeds**

**4.2.2 Approximate seeds**

**4.3 Suffix filters**



**5.1 Related work**

**5.1.1 Best mappers**

**5.1.2 All mappers**

**5.2 The Masai mapper**

**5.2.1 Single-end mapping**

**5.2.2 Paired-end mapping**

**5.3 The Masai 2 mapper**

**5.3.1 Single-end mapping**

**5.3.2 Paired-end mapping**

**5.3.3 Parallelization**

**5.3.4 Hardware acceleration**

**5.4 Experimental results**

**5.4.1 Comparison of filtration strategies**

**5.4.2 Rabema benchmark results**

**5.4.3 Variant detection results**

**5.4.4 Runtime results**

**5.5 Discussion**



**6.1 The competition**

**6.2 Our method**

**6.2.1 Implementation**

**6.2.2 Parallelization**

**6.3 Related methods**

**6.4 Experimental results**

**6.4.1 Search**

**6.4.2 Join**

**6.5 Discussion**