

# Algorithms and Datastructures

## Levenshtein distance, Dynamic programming

Prof. Dr. Rolf Backofen

Bioinformatics Group / Department of Computer Science

Algorithms and Datastructures, February 2018

# Structure

Introduction

Edit distance

# Introduction

## **Edit distance:**

- ▶ Measurement for similarity of two words / strings
- ▶ Algorithm for efficient calculation
- ▶ General principle: dynamic programming

# Introduction

Motivation: Error tolerant string comparison

## BioInfSearch



Ulrich Latzenhofer; CC BY-SA 2.0

|                          |
|--------------------------|
| ejafjatlajökuk           |
| eyjafjallajökull         |
| eyjafjallajökull movie   |
| eyjafjallajälull trailer |

Search!

Wikipedia.org:

"Der Eyjafjallajökull ([ˈeɪjaˌfjatlaˌjœːkʏtʃ])[3], auf Deutsch Eyjafjöll-Gletscher, ist der sechstgrößte Gletscher Islands.

Er liegt an der äußersten Südküste, westlich des Gletschers Mýrdalsjökull in der Gemeinde Rangárþing eystra, die größte Höhe beträgt 1651 m. Unter dem Gletscher befindet sich der Vulkan Eyjafjöll mit eigener Magmakammer, der seit der Besiedelung von Island in den Jahren 920, 1612 (oder 1613), 1821 bis 1823 und zuletzt im Jahr 2010 aktiv war."

# Introduction

## Motivation

### **A lot of applications where similar string are searched:**

- ▶ Duplicates in databases:

Hein Blöd     27568 Bremerhaven

Hein Bloed    27568 Bremerhafen

Hein Doof     27478 Cuxhaven

- ▶ Product search:

memory stik

- ▶ Websearch:

eyjaföllajaküll

uniwersität verien 2017

- ▶ Bioinformatics: Similarity of DNA-sequences

# Introduction

Example: Bioinformatics DNA-matching

## Search of similar proteins:

- ▶ BLAST (**B**asic **L**ocal **A**lignment **S**earch **T**ool)
- ▶ Alignment  $\hat{=}$  Edit distance
- ▶ Changed life-science completely
- ▶ Cited 63437 times on Google Scholar (Sep. 2017)

# Edit distance

## Definition of edit distance: (*Levenshtein-distance*)

- ▶ Let  $x$ ,  $y$  be two strings
- ▶ Edit distance  $ED(x, y)$  of  $x$  and  $y$ :  
The minimal number of operations to transform  $x$  into  $y$ 
  - ▶ Insert a character
  - ▶ Replace a character with another
  - ▶ Delete a character

# Edit distance

## Example

|   |               |
|---|---------------|
| 1 2 3 4 5   |               |
| DOOF  |               |
| ↓   | replace(1, B) |
| BOOF  |               |
| ↓   | replace(2, L) |
| BLOF  |               |
| ↓   | insert(4, E)  |
| BLOEF   |               |
| ↓   | replace(5, D) |
| BLOED   |               |
|  |               |
| ED=4  |               |

|  |               |
|--|---------------|
| 1 2 3 4 5  |               |
| B LOED   |               |
| ↓  | replace(5, F) |
| B LOEF   |               |
| ↓  | delete(4)     |
| B LOF  |               |
| ↓  | replace(2, O) |
| B OOF  |               |
| ↓  | replace(1, D) |
| DOOF   |               |
|  |               |
| ED=4   |               |



# Edit distance

## Notation:

- ▶  $\varepsilon$  is the empty string
- ▶  $|x|$  is the length of the string  $x$  (number of characters)
- ▶  $x[i..j]$  is the slice of  $x$  from  $i$  to  $j$  where  $1 \leq i \leq j \leq |x|$



# Edit distance

## Trivial facts:

- ▶  $ED(x, y) = ED(y, x)$
- ▶  $ED(x, \epsilon) = |x|$
- ▶  $ED(x, y) \geq \text{abs}(|x| - |y|)$
- ▶  $ED(x, y) \leq ED(x[1..n-1], y[1..m-1]) + 1$   $n = |x|, m = |y|$

$$\text{abs}(x) = \begin{cases} x & \text{if } x \geq 0 \\ -x & \text{else} \end{cases}$$

# Edit distance

## Solving examples

### Solutions based on examples:

- ▶ From VERIEN to FERIEEN?
- ▶ From MEXIKO to AMERIKA?
- ▶ From AAEBEAAABEAREEEAEBA to RBEAAEEBAAAEBBAEAE?
- ▶ Searching biggest substrings can yield the solution but doesn't have to

### Recursive approach:

- ▶ Dividing in two halves? Not a good idea:

$$\text{ED}(\text{GRAU}, \text{RAUM}) = 2 \quad \text{but} \\ \text{ED}(\text{GR}, \text{RA}) + \text{ED}(\text{AU}, \text{UM}) = 4$$

- ▶ Finding “smaller” sub problems?  
Let's try it!

# Edit distance

## Terminology:

- ▶ Let  $x, y$  be two strings
- ▶ Let  $\sigma_1, \dots, \sigma_k$  be a sequence of  $k$  operations where  $k = \text{ED}(x, y)$  for  $x \rightarrow y$  (transform  $x$  into  $y$ )  
(We do not know this sequence but we assume it exists)

# Edit distance

## Terminology:

- ▶ We only consider **monotonous** sequences:

The position of  $\sigma_{i+1}$  is  $\geq$  the position of  $\sigma_i$  where we only allow the positions to be equal on a delete operation

1 2 3 4 5

DOOF



replace(1, B)

BOOF



replace(2, L)

BLOF



insert(4, E)

BLOEF



replace(5, D)

BLOED

1 2 3 4 5 6 7

SAUDOOOF



delete(1)

AUDOOOF



delete(1)

UDOOOF



delete(1)

DOOF



insert(4, 0)

DOOOOF

# Edit distance

## Terminology:

- ▶ **Lemma:** For any  $x$  and  $y$  with  $k = \text{ED}(x, y)$  exists a **monotonous** sequence of  $k$  operations for  $x \rightarrow y$
- ▶ **Intuition:** The order of our sequence is not relevant  
(Therefore we can also sort them monotonously)

|   |   |   |   |   |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| D | O | O | F |   |

|   |   |   |   |   |
|---|---|---|---|---|
| B | L | O | E | D |
|---|---|---|---|---|

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| S | A | U | D | O | O | F |

|   |   |   |   |   |
|---|---|---|---|---|
| D | O | O | O | F |
|---|---|---|---|---|

# Edit distance

## Recursive approach

### Consider the last operation:

- Solve **blue** part recursively

DOOF

↓↓↓↓↓

BLOE

↓ insert

BLOED

Figure: Case 1a

DOOF

↓↓↓↓↓↓↓

BLOEDF

↓ delete

BLOED

Figure: Case 1b

DOOF

↓↓↓↓↓↓↓

BLOEF

↓ replace

BLOED

Figure: Case 1c

# Edit distance

## Recursive approach

### Consider the last operation:

- Solve **blue** part recursively

W I N T E R  
↓ ↓ ↓ ↓ ↓ ↓  
S O M M E R  
          ↓ nothing  
S O M M E R

Figure: Case 2

### Display of solution:

- Alignment
- Example:

|   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|
| - | - | - | B | L | O | E | D |
| S | A | U | B | L | O | E | D |



# Edit distance

## Dynamic programming

### Dynamic programming:

- ▶ Instances of Bellman's principle of optimality:
  - ▶ Shortest paths
  - ▶ Edit distance



Figure: Richard Bellman  
(1920 - 1984)

- ▶ Optimal solutions consist of optimal partial solutions
  - ▶ Shortest paths: Each partial path has to be optimal
  - ▶ Edit distance: Each partial alignment has to be optimal

|   |   |   |   |  |   |   |   |   |   |   |
|---|---|---|---|--|---|---|---|---|---|---|
| - | - | - | B |  | L | O | E | D | E | R |
| S | A | U | B |  | L | O | E | D | - | - |

- ▶ Always solvable through dynamic programming  
(Caching of optimal partial solutions)

# Edit distance

## Case analysis:

- ▶ We consider the last operation  $\sigma_k$ 
  - ▶  $\sigma_1, \dots, \sigma_{k-1}: x \rightarrow z$  and  $\sigma_k: z \rightarrow y$

Example:

$x = \text{DOOF}, z = \text{SAUBLOEF}, y = \text{SAUBLOED}$

- ▶ Let  $n = |x|$ ,  $m = |y|$ ,  $m' = |z|$
- ▶ We note  $m' \in \{m-1, m, m+1\}$       why?

# Edit distance

## Case analysis:

- ▶ Case 1:  $\sigma_k$  does something at the outer end:
  - ▶ Case 1a:  $\sigma_k = \text{insert}(m' + 1, y[m])$  [then  $m' = m - 1$ ]
  - ▶ Case 1b:  $\sigma_k = \text{delete}(m')$  [then  $m' = m + 1$ ]
  - ▶ Case 1c:  $\sigma_k = \text{replace}(m', y[m])$  [then  $m' = m$ ]
- ▶ Case 2:  $\sigma_k$  does nothing at the outer end:
  - ▶ Then  $z[m'] = y[m]$  and  $x[n'] = z[m']$  and with that  
 $\sigma_1, \dots, \sigma_{k-1}: x[1..n-1] \rightarrow y[1..m-1]$  and  $x[n] = y[m]$

# Edit distance

## Case analysis:

- ▶ Case 1a (insert):  $\sigma_1, \dots, \sigma_{k-1}: x \rightarrow y[1..m-1]$
- ▶ Case 1b (delete):  $\sigma_1, \dots, \sigma_{k-1}: x[1..n-1] \rightarrow y$
- ▶ Case 1c (replace):  $\sigma_1, \dots, \sigma_{k-1}: x[1..n-1] \rightarrow y[1..m-1]$
- ▶ Case 2 (nothing):  $\sigma_1, \dots, \sigma_k: x[1..n-1] \rightarrow y[1..m-1]$

## This results in the recursive formula:

- ▶ For  $|x| > 0$  and  $|y| > 0$  is  $ED(x, y)$  the minimum of
  - ▶  $ED(x, y[1..m-1]) + 1$  and
  - ▶  $ED(x[1..n-1], y) + 1$  and
  - ▶  $ED(x[1..n-1], y[1..m-1]) + 1$  if  $x[n] \neq y[m]$
  - ▶  $ED(x[1..n-1], y[1..m-1]) + 0$  if  $x[n] = y[m]$
- ▶ For  $|x| = 0$  is  $ED(x, y) = |y|$
- ▶ For  $|y| = 0$  is  $ED(x, y) = |x|$

# Edit distance

## Implementation - Python

```
def edit_distance(x, y):  
    if len(x) == 0:  
        return len(y)  
    if len(y) == 0:  
        return len(x)  
  
    ed1 = edit_distance(x, y[:-1]) + 1  
    ed2 = edit_distance(x[:-1], y) + 1  
    ed3 = edit_distance(x[:-1], y[:-1])  
    if x[-1] != y[-1]:  
        ed3 += 1  
  
    return min(ed1, ed2, ed3)
```

# Edit distance

## Runtime analysis

### Recursive program:

- ▶ The algorithm results in the following recursive formular:

$$\begin{aligned}T(n, m) &= T(n-1, m) + T(n, m-1) + T(n-1, m-1) + 1 \\&\geq T(n-1, m-1) + T(n-1, m-1) + T(n-1, m-1) \\&= 3 \cdot T(n-1, m-1)\end{aligned}$$

- ▶ This results in  $T(n, n) \geq 3^n$
- ⇒ The runtime is at least exponential

# Edit distance

## Dynamic programming:

- ▶ We create a table with all possible combination of substrings and save calculated entries
- ▶ This results in a runtime and space consumption of  $O(n \cdot m)$

## Visualization on the next slide:

- ▶ Operations always refer to the last position (indices are omitted)
- ▶ We also display the replaced character on a replace operation to visualize operations without costs  
 $\Rightarrow \text{repl}(\text{A}, \text{A})$

# Edit Distance





# Edit distance

## Fast algorithm

### **Fast algorithm:**

We can determine the **edit distance** for all combination of partial strings from the top left to bottom right.

# Edit Distance

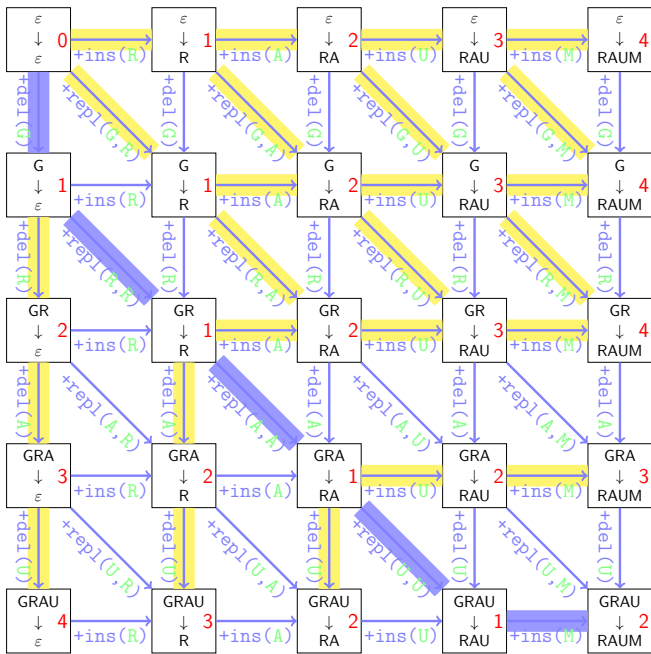


# Edit distance

## How to get the sequence of operations?

- ▶ We save at each recursion the most efficient previous entry (the highlighted arrows in our image)
- ▶ There can be more than one arrows to the three previous entries
- ▶ If we follow the highlighted path from  $(n, m)$  to  $(1, 1)$  we get the optimum operations to transform  $x$  into  $y$ 
  - ▶ If we can follow more than one path there exist more than one ideal sequence

# Edit Distance



# Edit distance

## General principle:

- ▶ Recursive computation of ...
  - ... the same reoccurring partial problems
  - ... a limited number of partial problems
- ▶ Computation of the solutions for all partial problems
- ▶ In a order that unsolved partial problems consist of already solved partial problems
- ▶ The “path” to our solution normally gets computed while searching the best solution
- ▶ Dijkstra algorithm is basically dynamic programming!

# Edit distance

## Additional applications (I)

### Additional applications:

- ▶ *Edit distance*: global alignment with  $O(n^2)$  space and time consumption
- ▶ But: Model for deletion unrealistic
  - ▶ In evolution larger pieces are more likely
  - ▶ delete operation: first gap expensive (e.g. 2), remaining are cheaper (e.g. 0.5)

|   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|
| - | - | - | B | L | O | E | D |
| S | A | U | B | L | O | E | D |

- ▶ Solution in  $O(n^3)$  time or  $O(n^2)$  affine

# Edit distance

## Additional applications (II)

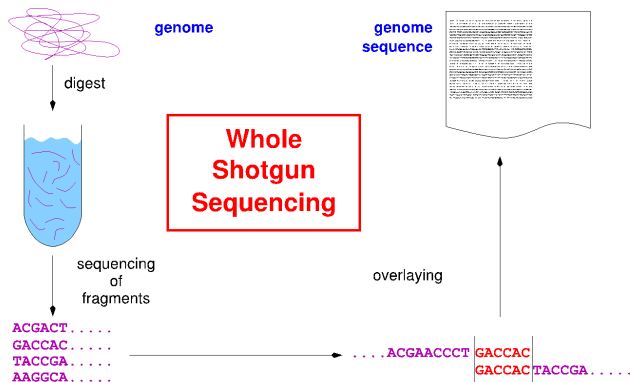
$O(n^2)$  space consumption might be problematic:

### **Hirschberg algorithm:**

- ▶ Divide-and-conquer approach
- ▶  $O(n)$  space and  $O(n^2)$  time consumption

# Edit distance

## Additional applications (III)



- ▶ Sequencing:  $O(n^2)$  is too much
- ▶ Index: suffixtree, suffixarray, burrow-wheeler-transform



# Further Literature

## ► General

[CRL01] Thomas H. Cormen, Ronald L. Rivest, and Charles E. Leiserson.

*Introduction to Algorithms.*

MIT Press, Cambridge, Mass, 2001.

[MS08] Kurt Mehlhorn and Peter Sanders.

Algorithms and data structures, 2008.

<https://people.mpi-inf.mpg.de/~mehlhorn/ftp/Mehlhorn-Sanders-Toolbox.pdf>.

# Further Literature

- ▶ **Dynamic programming**

[Wik] [Dynamic programming](#)

https:

[//en.wikipedia.org/wiki/Dynamic\\_programming](https://en.wikipedia.org/wiki/Dynamic_programming)

- ▶ **Edit distance**

[Wik] [Levenshtein distance](#)

https:

[//en.wikipedia.org/wiki/Levenshtein\\_distance](https://en.wikipedia.org/wiki/Levenshtein_distance)