

String edit distance

Data Structures and Algorithms for Computational Linguistics III
(ISCL-BA-07)

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Edit distance

- In many applications, we want to know how similar (or different) two strings are
 - Comparing two files (e.g., source code)
 - Comparing two DNA sequences
 - Spell checking
 - Approximate string matching
 - Determining similarity of two languages
 - Machine translation
- The solution is typically formulated as the (inverse) cost of obtaining one of the strings from the other through a number of *edit operations*
- Once we obtain the optimal edit operations, we may (depending on the edit operations) also be able to determine the optimal alignment between the strings

Hamming distance

a simple distance metric between two sequences

- The Hamming distance measures number of different symbols in the corresponding positions

| | | | | | | |
|---|---|---|---|---|---|---|
| h | y | g | i | e | n | e |
| h | i | g | i | e | n | e |

$$0 + 1 + 0 + 0 + 0 + 0 + 0 = 1$$

| | | | | | | |
|---|---|---|---|---|---|---|
| h | y | g | i | e | n | e |
| h | i | y | g | e | i | n |

$$0 + 1 + 1 + 1 + 0 + 1 + 1 = 5$$

- Very easy/efficient calculation
- But cannot handle sequences of different lengths (consider *hygene* – *hiygeine*)

A family of edit distance problems

- The same overall idea applies to a number of well-known problems/solutions that differ in the type of operations allowed
 - *Hamming distance*: only replacements
 - *Longest common subsequence*: (LCS) insertions and deletions
 - *Levenshtein distance* insertions, deletions and substitutions
 - *Levenshtein-Damerau distance* insertions, deletions and substitutions and transpositions (swap) of adjacent symbols
- Naive solutions to all (except Hamming distance) have exponential time complexity
- Polynomial-time solution can be obtained using *dynamic programming*

Longest common subsequence (LCS)

Problem definition

- A subsequence is an order-preserving (but not necessarily continuous) sequence of symbols from a string (a version of the sequence where zero or more elements are removed)
 - *hyg, gn, yene, hen, gene* are subsequences of *hygiene*
- Note that a subsequence does not have to be a substring (substrings are continuous)
 - *hyg, giene, ene* are substrings of *hygiene*
- The LCS of two strings is the longest string that is a subsequence of both strings
 - $\text{LCS}(\text{hygiene}, \text{hiygien}) = \text{hygien}$
 - $\text{LCS}(\text{hygiene}, \text{hygeine}) = \text{hygine} / \text{hygene}$
- LCS is exactly the problem solved by the UNIX diff utility
- It has wide-ranging applications from source-code comparison to bioinformatics (e.g., DNA sequencing)

LCS: a naive solution

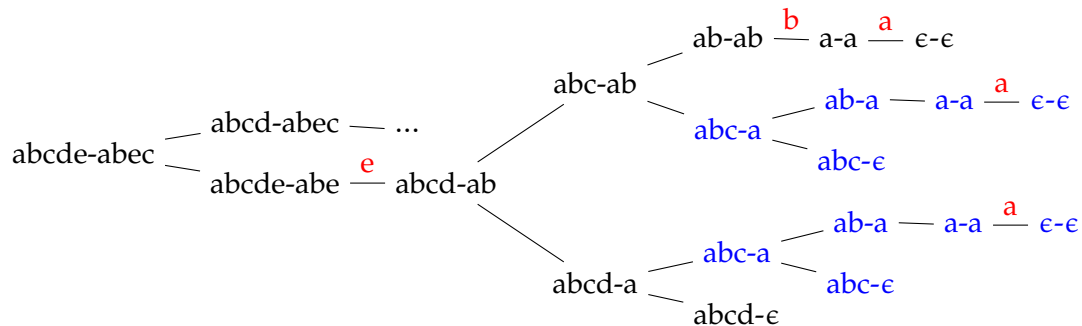
- A simple solution is:
 1. Enumerate all subsequences of the first string
 2. Check if it is also a subsequence of the second string
- There are exponential number of subsequences of a string
 - the string *abc* has 8 subsequences:
 - *abc*: nothing removed
 - *ab*, *ac*, *bc*: individual elements are removed
 - *a*, *b*, *c*: length-2 subsequences are removed
 - ϵ (empty string): *abc* removed
 - For *abcd*, we have subsequences of *abc* once with, and once without *d*
 - Each additional symbol doubles the number of subsequences
- For strings of size *n* and *m*, the complexity of the brute-force algorithm is $O(2^n m)$

LCS: recursive definition

- Consider two strings Xx , Yy and their LCS Zz (X , Y , Z are possibly empty strings, x , y , z are characters)
- If $x = y$, then this character has to be part of the LCS, $x = y = z$, and Z must be the LCS of X and Y
- If $x \neq y$, there are three cases
 - $x \neq y \neq z$: Zz is also the LCS of X and Y
 - $x = z$: Zz is also the LCS of Xx and Y
 - $y = z$: Zz is also the LCS of X and Yy
- This leads to following recursive definition:

$$\text{LCS}(Xx, Yy) = \begin{cases} \text{LCS}(X, Y)x & \text{if } x = y \\ \text{longer of } \text{LCS}(Xx, Y) \text{ and } \text{LCS}(X, Yy) & \text{otherwise} \end{cases}$$

LCS: divide-and-conquer



- Note the **repeated computation**

LCS: dynamic programming

general sketch

- To calculate $\text{LCS}(X_{:i}, Y_{:j})$, the LCS of string X up to index i , and the LCS of string Y up to index j , we (may) need
 - $\text{LCS}(X_{:i-1}, Y_{:j-1})$
 - $\text{LCS}(X_{:i-1}, Y_{:j})$
 - $\text{LCS}(X_{:i}, Y_{:j-1})$
- If we store the above three values, we need only $i \times j$ operations
- In the standard dynamic programming algorithm, we store the length of the LCS, in a matrix ℓ , where $\ell_{i,j}$ the length of the $\text{LCS}(X_{:i}, Y_{:j})$
- Once we fill in the matrix, the $\ell_{n,m}$ is the length of the LCS
- We can trace back and recover the LCS using the dynamic programming matrix

LCS with dynamic programming

demonstration

| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ε | h | i | y | g | e | i | n | e |
| 0 | ε | | | | | | | | | |
| 1 | h | | | | | | | | | |
| 2 | y | | | | | | | | | |
| 3 | g | | | | | | | | | |
| 4 | i | | | | | | | | | |
| 5 | e | | | | | | | | | |
| 6 | n | | | | | | | | | |
| 7 | e | | | | | | | | | |

LCS with dynamic programming

demonstration

| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ε | h | i | y | g | e | i | n | e |
| 0 | ε | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | h | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | y | 0 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3 | g | 0 | 1 | 1 | 2 | 3 | 3 | 3 | 3 | 3 |
| 4 | i | 0 | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 4 |
| 5 | e | 0 | 1 | 2 | 2 | 3 | 4 | 4 | 4 | 5 |
| 6 | n | 0 | 1 | 2 | 2 | 3 | 4 | 4 | 5 | 5 |
| 7 | e | 0 | 1 | 2 | 2 | 3 | 4 | 4 | 5 | 6 |

Complexity of filling the LCS matrix

```
l = np.zeros(shape=(n+1,m+1))
for i in range(1, n):
    for j in range(1, m):
        if X[i] == Y[j]:
            l[i, j] = l[i - 1, j - 1] + 1
        else:
            l[i, j] = max(l[i-1, j], l[i, j-1])
```

- Two loops up to n and m , the time complexity is $O(nm)$
- Similarly, the space complexity is also $O(nm)$

Recovering the LCS from the matrix

| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ε | h | i | y | g | e | i | n | e |
| 0 | ε | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | h | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | y | 0 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3 | g | 0 | 1 | 1 | 2 | 3 | 3 | 3 | 3 | 3 |
| 4 | i | 0 | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 4 |
| 5 | e | 0 | 1 | 2 | 2 | 3 | 4 | 4 | 4 | 5 |
| 6 | n | 0 | 1 | 2 | 2 | 3 | 4 | 4 | 5 | 5 |
| 7 | e | 0 | 1 | 2 | 2 | 3 | 4 | 4 | 5 | 6 |

Transforming one string to another

- The table (back arrows) also gives a set of edit operations to transform one string to another
- For LCS, operations are:
 - *copy* (diagonal arrows in the demonstration)
 - *insert* (left arrows in the demo – assuming original string is the vertical one)
 - *delete* (up arrows in the demo)
- These also form an alignment between two strings
- Different set of edit operations recovered will yield the same LCS, but different alignments

LCS alignments

| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ε | h | i | y | g | e | i | n | e |
| 0 | ε | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | h | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | y | 0 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3 | g | 0 | 1 | 1 | 2 | 3 | 3 | 3 | 3 | 3 |
| 4 | i | 0 | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 4 |
| 5 | e | 0 | 1 | 2 | 2 | 3 | 4 | 4 | 4 | 5 |
| 6 | n | 0 | 1 | 2 | 2 | 3 | 4 | 4 | 5 | 5 |
| 7 | e | 0 | 1 | 2 | 2 | 3 | 4 | 4 | 5 | 6 |

Alignments:

h-yg-iene

ciccicdccc

hiygei-ne

h-ygie-ne

ciccdicc

hiyg-eine

LCS – some remarks

- We formulated the algorithm as maximizing the LCS
- Alternatively, we can minimize the costs associated with each operation:
 - copy = 0
 - delete = 1
 - insert = 1
- The cost settings above are the typical, e.g., as in `diff`
- In some applications we may want to have different costs for delete and insert (e.g., mapping lemmas to inflected forms of words)
- Similarly, we may want to assign different costs for different characters (e.g., higher cost to delete consonants in historical linguistics)

Levenshtein distance

definition

- Levenshtein difference between two strings is the total cost of *insertions*, *deletions* and *substitutions*
- With cost of 1 for all operations

$$\text{lev}(Xx, Yy) = \begin{cases} \text{len}(X) & \text{if } \text{len}(Yy) = 0 \\ \text{len}(Y) & \text{if } \text{len}(Xx) = 0 \\ \text{lev}(X, Y) & \text{if } x = y \\ 1 + \min \begin{cases} \text{lev}(X, Yy) \\ \text{lev}(Xx, Y) \\ \text{lev}(X, Y) \end{cases} & \text{otherwise} \end{cases}$$

- Naive recursion (as defined above), again, is intractable
- But, the same dynamic programming method works

Levenshtein distance

demonstration

| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ε | h | i | y | g | e | i | n | e |
| 0 | ε | | | | | | | | | |
| 1 | h | | | | | | | | | |
| 2 | y | | | | | | | | | |
| 3 | g | | | | | | | | | |
| 4 | i | | | | | | | | | |
| 5 | e | | | | | | | | | |
| 6 | n | | | | | | | | | |
| 7 | e | | | | | | | | | |

Levenshtein distance

demonstration

| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ε | h | i | y | g | e | i | n | e |
| 0 | ε | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | h | 1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 2 | y | 2 | 1 | 1 | 1 | 2 | 3 | 4 | 5 | 6 |
| 3 | g | 3 | 2 | 2 | 2 | 1 | 2 | 3 | 4 | 5 |
| 4 | i | 4 | 3 | 2 | 3 | 2 | 2 | 2 | 3 | 4 |
| 5 | e | 5 | 4 | 3 | 3 | 3 | 2 | 3 | 3 | 3 |
| 6 | n | 6 | 5 | 4 | 4 | 4 | 3 | 3 | 3 | 4 |
| 7 | e | 7 | 6 | 5 | 5 | 5 | 4 | 4 | 4 | 3 |

Levenshtein distance

edits and alignments

| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ε | h | i | y | g | e | i | n | e |
| 0 | ε | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | h | 1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 2 | y | 2 | 1 | 1 | 1 | 2 | 3 | 4 | 5 | 6 |
| 3 | g | 3 | 2 | 2 | 2 | 1 | 2 | 3 | 4 | 5 |
| 4 | i | 4 | 3 | 2 | 3 | 2 | 2 | 2 | 3 | 4 |
| 5 | e | 5 | 4 | 3 | 3 | 3 | 2 | 3 | 3 | 3 |
| 6 | n | 6 | 5 | 4 | 4 | 4 | 3 | 3 | 3 | 4 |
| 7 | e | 7 | 6 | 5 | 5 | 5 | 4 | 4 | 4 | 3 |

Edit distance: extensions and variations

- Another possible operation we did not cover is *swap* (or transpose), which is useful for applications like spell checking
- In some applications (e.g., machine translation, OCR correction) we may want to have one-to-many or many-to-one alignments
- Additional requirements often introduce additional complexity
- It is sometimes useful to learn costs from data



Summary

- Edit distance is an important problem in many fields including computational linguistics
- A number of related problems can be efficiently solved by dynamic programming
- Edit distance is also important for approximate string matching and alignment
- Reading suggestion: Goodrich, Tamassia, and Goldwasser (2013, chapter 13), Jurafsky and Martin (2009, section 3.11, or 2.5 in online draft)

Next:

- Algorithms on strings: tries
- Reading: Goodrich, Tamassia, and Goldwasser (2013, chapter 13),

Acknowledgments, credits, references

-  Goodrich, Michael T., Roberto Tamassia, and Michael H. Goldwasser (2013). *Data Structures and Algorithms in Python*. John Wiley & Sons, Incorporated. ISBN: 9781118476734.
-  Jurafsky, Daniel and James H. Martin (2009). *Speech and Language Processing: An Introduction to Natural Language Processing, Computational Linguistics, and Speech Recognition*. second edition. Pearson Prentice Hall. ISBN: 978-0-13-504196-3.

