

ARTICLE TYPE

Appendix

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Abstract

A more detailed similarity metrics and explanation of the search operationalization.

1 | INTRODUCTION

This appendix contains detailed information about the exact search strings used in every search engine and all the similarity metrics reported in our study.

2 | RQ2: SIMILARITY METRICS

What similarity metrics have been used in the literature? Which ones have been used the most, and why?

All studies that apply diversity in their approaches use some metric to measure the level of similarity or diversity. The similarity can be calculated for inputs, outputs, or any other testing artefacts.

There are many similarity metrics used in the literature, and we found 79 metrics in the collected papers. Some of these metrics are well-known, like Euclidean distance, Hamming distance, and so on, while others are more specific to certain types of subject domains or new metrics. We categorized the similarity metrics into two groups. The first group consists of the generic similarity metrics that originated from other fields. The second group are specialised metrics in Software Engineering to measure similarity based on information acquired from software programs, or metrics proposed to solve a Software Engineering problem. Figure ?? shows the distribution of similarity metrics used in DBT papers.

Table 1 presents the generic similarity metrics, while Table 2 lists the specialised similarity metrics in software engineering. For both tables, records are ordered by usage popularity in the literature and then by alphabetical order. For each similarity metric, we provide a citation for more details, a short description, how many papers used that metric, and all papers using the metric in our collection. The citation after the specialised similarity metric in Table 2 is the paper that introduced the specialised metric.

The three most popular similarity metrics are Euclidean distance, Edit distance, and Jaccard distance used in 35, 31, and 30 papers, respectively. Numeric programs are used by many researchers to evaluate their techniques and Euclidean distance is a natural choice for such programs. Also, with string data, the Edit distance is very popular to use. Furthermore, Jaccard distance is widely used when the testing artefacts can be represented as sets, with an example being software product lines in which a product can be seen as being a set of features.

TABLE 1: A list of the generic similarity metrics citing the source, a brief description, the number of papers using them and citations

| ID | Metric & Source | Description | Total | Papers |
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| | | | | 2,3,4,5,6,7,8 9,10,11,12,13,14,15 16,17,18,19,20,21,22 23,24,25,26,27,28,29 30,31,32,33,34,35,36 |
| G1 | Euclidean distance ¹ | The square root of the sum of the squared differences between the vectors X and Y . The formula is: $Euc(X, Y) = \sqrt{\sum_{i=1}^n (x_i - y_i)^2}$ | 35 | |
| G2 | Edit distance ³⁷ | The minimum number of edits (<i>insertions, deletions or substitutions</i>) required to change one string into the other. It takes into consideration that parts of the strings can be similar even if not in corresponding places, and can work with strings of different sizes. | 31 | 38,39,40,41,42,43,10,11 44,45,13,46,47,16,48 49,50,51,52,21,53,54,55 56,26,32,57,58,59,60 |
| G3 | Jaccard distance ⁶¹ | The ratio of intersection over union between two sets A and B of values. The formula is: $Jac(A, B) = 1 - \frac{ A \cap B }{ A \cup B } = 1 - \frac{ A \cap B }{ A + B - A \cap B }$ Sometimes expressed ³⁴ as: $Jac(A, B) = 1 - \frac{A.B}{A.B + \omega(\ A\ ^2 + \ B\ ^2 - 2(A.B))}$ with $\omega = 1$. | 30 | 62,43,44,10,11,45,63,64 65,16,66,49,67,68,69 52,70,71,72,54,73,74 75,76,77,34,78,79,80,81 |
| G4 | Hamming distance ⁸² | The number of times when the corresponding characters in two strings are different. Some ⁸³ refer to this as “Overlap” distance. | 18 | 84,85,86,10,11,13 87,49,83,21,70,55 56,32,88,89,90,91 |
| G5 | Manhattan distance ⁹² | The sum of the absolute differences between two vectors X and Y . The formula is: $Man(X, Y) = \sum_{i=1}^n x_i - y_i $ | 18 | 42,85,93,94,13,16 66,18,21,95,71,72 22,28,31,32,96,97 |
| G6 | Normalised compression distance ⁹⁸ | An approximation of the Kolmogorov complexity using real-world compressors. | 15 | 99,100,101,45,102,103,13 104,105,106,16,66,52,27,31 |
| G7 | Cosine similarity ¹⁰⁷ | The cosine of the angle of two vectors X and Y . The formula is: $Cosine(X, Y) = \frac{\sum_{i=1}^n x_i \times y_i}{\sqrt{\sum_{i=1}^n x_i^2} \times \sqrt{\sum_{i=1}^n y_i^2}}$ | 13 | 108,109,10,11,101,52,110 22,111,32,112,77,34 |
| G8 | Tree edit distance ¹¹³ | The minimum number of edit operations required to change one tree into the other. | 4 | 73,114,115,116 |
| G9 | Locality-sensitive hashing ¹¹⁷ | A technique that maps similar strings or inputs to the same hash code with high probability to get a fast estimation of the dissimilarity between two subjects. | 3 | 66,75,32 |
| G10 | Geometric diversity ¹¹⁸ | The measurement of feature similarity between two feature vectors given an input sample. | 3 | 99,100,119 |
| G11 | Crowding distance ¹²⁰ | A measure of how far a chromosome or an individual is from the rest of the population. | 2 | 121,122 |
| G12 | Gower-Legendre distance ¹²³ | A variant of the Jaccard Index (G3) where the weight ω is 1/2. | 2 | 55,34 |
| G13 | Isolated subTree distance ¹²⁴ | A variation of tree edit distance (G8), where disjoint subtrees are mapped to similar disjoint subtrees of another set. | 2 | 114,115 |

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| G14 | Jaro-Winkler distance ¹²⁵ | A variation of the Jaro distance (G26) that adds more weight in strings starting with the exact match characters. | 2 | 84,44 |
| G15 | L2-test ¹²⁶ | The distance between a uniform distribution and a sampled distribution by checking if the sampled distribution is ϵ -far from uniformity. | 2 | 127,128 |
| G16 | Mahalanobis distance ¹²⁹ | The distance between a point and a distribution. | 2 | 28,31 |
| G17 | Needleman-Wunsch distance ¹³⁰ | Originally used in bioinformatics to align protein or nucleotide sequences, and can be used to identify similarities between two test cases by encoding them. | 2 | 49,67 |
| G18 | Wasserstein distance ¹³¹ | The difference between two frequency distributions over a region, which is also known as the earth mover's distance. | 2 | 132,133 |
| G19 | Anti-Dice ¹³⁴ | It is a variation of the Jaccard distance, that measure the similarity between two sets where the denominator is the sum of the lengths of the two sets rather than the union. | 1 | 135 |
| G20 | Bilingual Evaluation Understudy ¹³⁶ | A numerical translation closeness metric of a machine translation to a human translation. | 1 | 137 |
| G21 | Canberra distance ¹³⁸ | A weighted version of the Manhattan distance (G5), in which each term in the sum is normalised. | 1 | 28 |
| G22 | Chebyshev distance ¹³⁹ | The greatest difference between two points in two vectors along any coordinate dimension. | 1 | 28 |
| G23 | Fractional distance ¹⁴⁰ | A variation of the Euclidean distance (G1) to deal with multi-dimensional space. | 1 | 141 |
| G24 | Hellinger distance ¹⁴² | The difference between two distributions with Hellinger integral ¹⁴³ . | 1 | 132 |
| G25 | Hill-numbers ¹⁴⁴ | A measure originally used in ecology that considers both species richness and species abundances in a sample. | 1 | 145 |
| G26 | Jaro distance ¹⁴⁶ | The number of matching characters and the number of transpositions (i.e. matching characters but not in order) between two strings. | 1 | 44 |
| G27 | Jeffrey divergence ¹⁴⁷ | A derived distribution from the Kullback-Leibler Divergence (G30) that is symmetric and more robust to noises. | 1 | 28 |
| G28 | Jensen-Shannon distance ¹⁴⁸ | An improved version of Kullback-Leibler Divergence (G30) to measure the similarity of two probability distributions. The metric is symmetric and always has a finite value. | 1 | 132 |
| G29 | Kronecker delta ¹⁴⁹ | A discrete function of two variables that is one if they are equal, 0 otherwise. | 1 | 150 |
| G30 | Kullback-Leibler divergence ¹⁵¹ | The expected value of the logarithmic difference between two probability distributions, but it is not symmetric. | 1 | 132 |
| G31 | Mean-square-error ¹⁵² | The average squared difference between the values predicted from a model and the actual values. | 1 | 153 |

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| G32 | Modified trigonometric distance ¹⁵⁴ | A modified version of the trigonometric distance (G46) with a greater degree of accuracy for points of larger magnitude of values. | 1 | 28 |
| G33 | N-gram models ¹⁵⁵ | A contiguous sequence of n items from a given sample of text or speech. | 1 | 156 |
| G34 | Ochiai coefficient ¹⁵⁷ | An approximation of program semantics using passing and failing test cases. | 1 | 137 |
| G35 | Proportional distance ¹⁵⁸ | The sum of squares of the difference between two vectors over the difference between the maximum and minimum values. | 1 | 34 |
| G36 | Shannon's Diversity Index ¹⁵⁹ | A measure of diversity used in Ecology to measure the variety and abundance of species in a defined unit of study. | 1 | 27 |
| G37 | Singular value decomposition ¹⁶⁰ | An estimate of where the evolution is going in search-based approaches, by monitoring the movements of individuals across different generations. | 1 | 161 |
| G38 | Smith-Waterman distance ¹⁶² | The alignment of local sequences for determining similar regions between two strings of nucleic acid sequences or protein sequences. | 1 | 49 |
| G39 | Sokal-Sneath distance ¹⁶³ | A variant of the Jaccard Index (G3) where the weight ω is 2. | 1 | 34 |
| G40 | Statistic value X^2 ¹⁶⁴ | A distance function that emphasizes large absolute difference existing between the feature values. | 1 | 28 |
| G41 | String-Kernels ¹⁶⁵ | The inner product between two strings by counting the occurrences of common substrings in the two strings. | 1 | 34 |
| G42 | Sellers algorithm ¹⁶⁶ | A variation of the edit distance (G2) to find a substring in another string with at most k edit operations. | 1 | 44 |
| G43 | Tree Bottom-Up ¹⁶⁷ | A similarity measure for tree structured data based on the bottom-up maximum common subtree isomorphism algorithm. | 1 | 116 |
| G44 | Tree Kernels ¹⁶⁸ | A similarity measure for tree structured data by summing the contribution of fragments (e.g. whole subtree, or subsets of a tree) to the overall similarity by the tree. | 1 | 169 |
| G45 | Tree Top-Down ¹⁶⁷ | A similarity measure for tree structured data based on the top-down maximum common subtree isomorphism algorithm. | 1 | 116 |
| G46 | Trigonometric distance ¹⁵⁴ | A normalised distance between two points used in image matching. The distance between two vectors X and Y is $\sum_{i=1}^n \sin(\arctan x_i - y_i)$ | 1 | 28 |
| G47 | Word mover's distance ¹⁷⁰ | The minimum amount of distance that the embedded words of one document need to be moved to reach the embedded words of another document. | 1 | 77 |

TABLE 2: A list of the specialised Software Engineering similarity metrics.

| ID | Metric & Source | Description | Total | Papers |
|----|-----------------|-------------|-------|--------|
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| S1 | Identical transition distance ¹⁷¹ | The number of identical transitions between two finite state machines divided by the average length of paths. | 6 | 171,172,48,49,50,51 |
| S2 | Test set diameter (TSDm) ¹⁰⁵ | An extension of the pairwise normalised compression distance (G6) to multisets. | 6 | 105,66,17,114,115,101 |
| S3 | Identical state distance ⁴⁸ | The number of identical states between two paths of finite state machines divided by their average number of states. | 3 | 48,50,51 |
| S4 | Trigger-based distance ⁴⁸ | An extension of identical transition similarity (S1) to account for triggers in the transitions. | 3 | 48,50,51 |
| S5 | Average population diameter ¹⁷³ | The average distance between all vectors in a population, where the distance between two vectors is the difference of their lengths. | 2 | 173,174 |
| S6 | Approach level ¹⁷⁵ | The number of mismatched branch predicates to reach the target branch. | 2 | 176,177 |
| S7 | Distinguishing mutation adequacy ¹⁷⁸ | An assessment of the diversity of mutants' behaviour based on the mutants' killing information. | 2 | 178,179 |
| S8 | Extended subTree distance ¹¹⁴ | A variation of isolated subtree distance (G13) with different mapping conditions. | 2 | 114,115 |
| S9 | Path distance ¹⁸⁰ | The size of the intersection between the two paths of multisets of trees. | 2 | 114,115 |
| S10 | [GUI] State similarity ¹⁸¹ | The difference between the values of two GUI states using the widgets of the GUI. | 2 | 181,182 |
| S11 | Test diversity ¹⁸³ | A hybrid measure calculating the difference between two test cases in terms of branches covered, variation of the data inputs, and standard deviation between conditions covered. | 2 | 183,184 |
| S12 | [Graph model diversity] Symmetric distance ¹¹¹ | The difference between two models in a domain-specific language, where it is calculated as the number of "shapes" contained exclusively in one of the models but not both. | 1 | 111 |
| S13 | Text uniqueness ¹⁸⁵ | Text matching between two strings, where a string is unique if no other string matches it. | 1 | 185 |
| S14 | Tree Combined ¹¹⁶ | A similarity measure for tree structured data that combines bottom-up (G43) and top-down (G45) common subtree isomorphism algorithms. | 1 | 116 |
| S15 | Achieved coverage of pools ¹⁸⁶ | The number of items selected from a pool of values for a program's variables over the time spent using that pool of values. | 1 | 186 |
| S16 | Accuracy-based performance measure ¹⁸⁷ | The proportion of correctly predicted test inputs to all the test inputs for a DNN. | 1 | 187 |
| S17 | [Test behavioural similarity] Accuracy (acc) ¹⁸⁸ | The percentage of tests that fail or pass together, calculated as the number of correct predictions divided by the total number of predictions in a confusion matrix. | 1 | 102 |
| S18 | Average cyclomatic complexity per method (ACCM) ¹⁸⁹ | Cyclomatic complexity is the number of independent paths in a program or method. ACCM is calculated by computing the number of independent paths within each method and then taking the sum, over all methods, of these values. | 1 | 190 |

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| S19 | Basic counting ⁵⁶ | The overlapping occurrences of method calls between two failing sequences of method calls extracted from execution traces of tests. | 1 | 56 |
| S20 | Code complexity (cm) ³ | Consists of three types of information (Lines of code, Nested Block Depth, and Cyclomatic Complexity) derived from the source code to measure similarity. | 1 | 3 |
| S21 | [GUI similarity] <i>CONTeSSi(n)</i> ¹⁰⁹ | The differences of the frequencies between the past n executed events of one test suite to another test suite. | 1 | 109 |
| S22 | Distance entropy ¹⁹¹ | The distribution of tests in a set represented in a graph using the minimum weight set (i.e. the set of vertices or edges in a weighted graph that collectively has the smallest sum of weights). | 1 | 191 |
| S23 | Diversification distance ¹⁹² | A measure in Output Diversified Sampling strategy ¹⁹² that measures the distance between iteration output and the original output. | 1 | 193 |
| S24 | Enhanced Jaro-Winkler ⁸⁴ | A hybrid metric between Jaro-Winkler (G14) and Hamming Distance (G4) that considers the deselected features from Hamming distance combined into the Jaro distance equation. | 1 | 84 |
| S25 | Graph edit distance ¹⁹⁴ | The minimum number of edit operations required to make two graphs identical. | 1 | 76 |
| S26 | Matthew's correlation coefficient (<i>MCC</i>) ¹⁹⁵ | A more accurate measure of tests behavioural similarity than accuracy (S17) that accounts for both true positives and true negatives. | 1 | 102 |
| S27 | Probabilistic type tree ¹⁹⁶ | A tree structure to represent a probability distribution over the types. | 1 | 196 |
| S28 | Response for class (RFC) ¹⁸⁹ | The sum of the number of methods inside the class and the number of external methods used by the class. | 1 | 190 |
| S29 | Syntax-tree similarity ¹⁹⁷ | The structural similarity between two sentences represented as "syntax trees" by comparing the tree topologies, node positions, and the types of grammatical relationships. | 1 | 197 |
| S30 | Traces ¹⁶³ | The difference between two execution paths, that takes into account the branches covered and the number of times these branches were covered. | 1 | 198 |
| S31 | Weighted distance function ¹⁹⁹ | The number of statements covered by one test case but not the other, and the difference of the execution times between the two test cases. | 1 | 199 |
| S32 | Extensible access control markup language (XACML) Similarity ²⁰⁰ | The distance between the requests attributes' values of two XACML test cases and the difference between their policies. | 1 | 200 |

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