Received: Added at production | Revised: Added at production | Accepted: Added at production

DOI: xxx/xxxx

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

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	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
G2	Edit distance [37]	The minimum number of edits *(insertions, deletions or substitutions)* 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: $Jac(A,B) = 1 - \frac{\lvert A \cap B \rvert}{\lvert A \cup B \rvert} = 1 - \frac{\lvert A \cap B \rvert}{\lvert A \rvert + \lvert B \rvert - \lvert A \cap B \rvert}$ Sometimes expressed [34] as: $Jac(A,B) = 1 - \frac{A.B}{A.B + \omega(\parallel A \parallel^2 + \parallel B \parallel^2 - 2(A.B))}$ with with $\omega = 1$.	31	62,43,44,10,11,45,63,64,51 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.	19	84,85,86,10,11,13,51 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: $Man(X,Y) = \sum_{i=1}^{n} \lvert x_i - y_i \rvert$	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	Gower-Legendre distance [120]	A variant of the Jaccard Index (G3) where the weight ω is 1/2.	3	51,55,34
G12	Needleman-Wunsch distance [121]	Originally used in bioinformatics to align protein or nucleotide sequences, and can be used to identify similarities between two test cases by encoding them.	3	49,67,51
G13	Crowding distance [122]	A measure of how far a chromosome or an individual is from the rest of the population.	2	123,124

G14	Isolated subTree distance [125]	A variation of tree edit distance (G8), where disjoint subtrees are mapped to similar disjoint subtrees of another set.	2	[114,115]
G15	Jaro-Winkler distance [126]	A variation of the Jaro distance (G26) that adds more weight in strings starting with the exact match characters.	2	[84,44]
G16	L2-test [127]	The distance between a uniform distribution and a sampled distribution by checking if the sampled distribution is ϵ-far from uniformity.	2	[128,129]
G17	Mahalanobis distance [130]	The distance between a point and a distribution.	2	[28,31]
G18	Smith-Waterman distance [131]	The alignment of local sequences for determining similar regions between two strings of nucleic acid sequences or protein sequences.	2	[49,51]
G19	Sokal-Sneath distance [132]	A variant of the Jaccard Index (G3) where the weight ω is 2.	2	[51,34]
G20	Wasserstein distance [133]	The difference between two frequency distributions over a region, which is also known as the earth mover's distance.	2	[134,135]
G21	Anti-Dice [136]	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	[137]
G22	Bilingual Evaluation Understudy [138]	A numerical translation closeness metric of a machine translation to a human translation.	1	[139]
G23	Canberra distance [140]	A weighted version of the Manhattan distance (G5), in which each term in the sum is normalised.	1	[28]
G24	Chebyshev distance [141]	The greatest difference between two points in two vectors along any coordinate dimension.	1	[28]
G25	Fractional distance [142]	A variation of the Euclidean distance (G1) to deal with multi-dimensional space.	1	[143]
G26	Hellinger distance [144]	The difference between two distributions with Hellinger integral [145].	1	[134]
G27	Hill-numbers [146]	A measure originally used in ecology that considers both species richness and species abundances in a sample.	1	[147]
G28	Jaro distance [148]	The number of matching characters and the number of transpositions (i.e. matching characters but not in order) between two strings.	1	[44]
G29	Jeffrey divergence [149]	A derived distribution from the Kullback-Leibler Divergence (G30) that is symmetric and more robust to noises.	1	[28]
G30	Jensen-Shannon distance [150]	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	[134]
G31	Kronecker delta [151]	A discrete function of two variables that is one if they are equal, 0 otherwise.	1	[152]
G32	Kullback-Leibler divergence [153]	The expected value of the logarithmic difference between two probability distributions, but it is not symmetric.	1	[134]

G33	Mean-square-error [154]	The average squared difference between the values predicted from a model and the actual values.	1	155
G34	Modified trigonometric distance [156]	A modified version of the trigonometric distance (G46) with a greater degree of accuracy for points of larger magnitude of values.	1	28
G35	N-gram models [157]	A contiguous sequence of n items from a given sample of text or speech.	1	158
G36	Ochiai coefficient [159]	An approximation of program semantics using passing and failing test cases.	1	139
G37	Proportional distance [160]	The sum of squares of the difference between two vectors over the difference between the maximum and minimum values.	1	34
G38	Shannon's Diversity Index [161]	A measure of diversity used in Ecology to measure the variety and abundance of species in a defined unit of study.	1	27
G39	Singular value decomposition [162]	An estimate of where the evolution is going in search-based approaches, by monitoring the movements of individuals across different generations.	1	163
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 [156]	A normalised distance between two points used in image matching. The distance between two vectors X and Y is $\sum_{i=1}^{n} \sin(\arctan \lvert x_i - y_i \rvert)$	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
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	Basic counting[56]	The overlapping occurrences of method calls between two failing sequences of method calls extracted from execution traces of tests.	2	51,56
S8	Distinguishing mutation adequacy[178]	An assessment of the diversity of mutants' behaviour based on the mutants' killing information.	2	178,179
S9	Extended subTree distance[114]	A variation of isolated subtree distance (G13) with different mapping conditions.	2	114,115
S10	Path distance[180]	The size of the intersection between the two paths of multisets of trees.	2	114,115
S11	[GUI] State similarity[181]	The difference between the values of two GUI states using the widgets of the GUI.	2	181,182
S12	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
S13	[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
S14	Text uniqueness[185]	Text matching between two strings, where a string is unique if no other string matches it.	1	185
S15	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
S16	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
S17	Accuracy-based performance measure[187]	The proportion of correctly predicted test inputs to all the test inputs for a DNN.	1	187
S18	[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
S19	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

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] *CONTeSSi*(*n*)[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 (*MCC*)[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[132]	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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