APPENDIX

TABLE 1: **The detailed description of the Metamorphic Relations used in the subjects**

Subject	Input	Output	Metamorphic Relation	Origination
Schedule	Three priority job-lists: P_1, P_2 and P_3, with priorities: $P_3 > P_2 > P_1$. One blocked job list PB. A set of operations on jobs.	The execution order of the jobs.	1. If the size of the a job-list is 1, then the operation that moving the job at the top of this list to the end will not affect the output. 2. Two different sets of operations: The first is adding one job at the end of the P_3, while the second is adding one job at the end of P_2 and then moving it to P_3. They will output the same.	[1]
Determinant1 (From the library of flanagan).	A matrix A.	The determinant of this matrix, i.e., det(A).	1. Transposition: det(A) = det(A^T) 2. Row Multiplied with Scalar: β*det($(a_1,...,a_{k-1},a_k,a_{k+1},...,a_n)^\intercal$) = det($(a_1,...,a_{k-1},\beta^* a_k,a_{k+1},...,a_n)^\intercal$) for $k \in \{1,\ldots,n\}$	[2]
JAMA (From the library of JAMA).	A matrix A.	The determinant of this matrix, i.e., det(A).	1. Transposition: det(A) = det(A^T) 2. Row Multiplied with Scalar: β*det($(a_1,...,a_{k-1},a_k,a_{k+1},...,a_n)^\intercal$) = det($(a_1,...,a_{k-1},\beta^* a_k,a_{k+1},...,a_n)^\intercal$) for $k \in \{1,\ldots,n\}$	[2]
ClosestPair	A set of points with x-y Cartesian coordinates in a plane.	The distance of two closest points.	1. Adding one point to this plane, the distance should not be larger than before.	Newly identified
Printtoken	A sequence of strings from a file.	All the tokens and their categories in order.	1. Changing all the characters from lower case to upper case, the keyword will disappear. 2. Deleting the comments, the output should not change. 3. Adding the comments, the output should not change.	[1]
Printtokens2	A sequence of strings from a file.	All the tokens and their categories in order.	1. Changing all the characters from lower case to upper case, the keyword will disappear. 2. Deleting the comments, the output should not change. 3. Adding the comments, the output should not change.	[1]
TCAS	12 integers (the parameters of the controlled aircraft and the intruder aircraft).	Output 0, or 1, or 2 (indicating the controlled aircraft to climb, descend, or remain the current trajectory).	1. If the relation of the 4th parameter and 6th parameter is not changed, meanwhile other parameter values are not changed too, then the outputs of the TCAS should be the same. 2. Given that the intruder aircraft does not have the TCAS system, if we change the state that the intruder aircraft has an intention or not, the output should not change. 3. Given that the intruder aircraft does not have the TCAS system, if we change the state that the report describing the presence of any intruder is valid or not, the output should not change. 4. Given that the intruder aircraft does not have any intention, and the report describing the presence of any intruder is valid, if we change the state that the intruder aircraft has the TCAS system or not, the output should not change.	[1], [3]
Multi-MAXSUM	An array with integers, a number m.	Find m contiguous mutex subarray with the largest sum, and output the sum.	1. Adding one number at the end of the array, then the output should be the same as or larger than the original one.	Newly identified
SurroundedRegion	Given a 2D board (matrix) containing 'X's and 'O's.	Capture all regions surrounded by 'X', and then flip all 'O's into 'X's in these regions.	1. Adding one row with all 'O's to the end of the matrix, then the output should be increased by one row with all 'O's. 2. Adding one column with all 'O's to the end of the matrix, then the output should be increased by one column with all 'O's.	Newly identified

MaxRectangle	A binary matrix filled with 0s and 1s.	Find the largest rectangle containing all 1s and output its area.	1. Adding one row, the output should be the same as or larger than the original one. 2. Adding one column, the output should be the same as or larger than the original one.	Newly identified
InterleavingString	Given three strings A, B and C.	Check whether C is the interleaving of A and B.	1. Adding one same character to the end of A and C, the result will be the same.	Newly identified
QuickSort	An array with integers.	Return an array sorted in ascending or descending order.	1. Shuffling the elements in the input array, the output will be the same. 2. Adding a constant K to each element in the input array, then each element of the output array will be larger by K than the element at the same location of the original output array. 3. Multiplying -1 to each element in the input array, then if we multiply -1 to each element of the output array, it should be the same as the original output array, but in reverse order.	Newly identified
Bsearch1	Given an array of integers in ascending order (can be duplicated), and a searching number.	Output the starting position and ending position of the searching number. If this searching number is not in this array, output (-1, -1).	1. Increasing the searching number by 1, if the original searching number and this new number are both in the array, then the starting position of the new number should be larger by 1 than the ending position of the original number. 2. Adding one small number to the head of the array, then the index of the searching number should also be increased by 1 (both the starting and ending positions) if it is contained in the array.	[4]
Spwiki	Given an undirected graph with positive edge weights, a source vertex, and a destination vertex.	Find the shortest path between these two vertices.	1. Reversing the source and destination vertices, the length of the shortest path should be the same. 2. Doubling the weight of each edge, the length of the shortest path should also be doubled.	[5]
DistinctSubsequence	Two strings A and B.	Count the number of unique ways in sequence A, to form a subsequence that is identical to the sequence B.	1. Adding one character to the end of A, the number of unique ways should be the same or larger.	Newly identified
Editingdistance	Two strings A and B.	Count the minimum number of operations (Insertion, Deletion, and Substitution) required to transform one string A into the other B.	1. Adding one character to the end of A, the number should be the same or larger.	Newly identified
FirstMissingPositive	An array with integers.	Find the first missing positive integer.	1. Adding one integer to this array, which is identical to one element of the original array, the output should be the same. 2. Shuffling the elements in the input array, the output will be the same.	Newly identified
HeapSort	An array with integers.	Return an array sorted in ascending or descending order.	1. Shuffling the elements in the input array, the output will be the same. 2. Adding a constant K to each element in the input array, then each element of the output array will be larger by K than the element at the same location of the original output array. 3. Multiplying -1 to each element in the input array, then if we multiply -1 to each element of the output array, it should be the same as the original output array, but in reverse order.	Newly identified
Schedule2	Three priority job-lists: P_1, P_2 and P_3, with priorities: $P_3 > P_2 > P_1$. One blocked job list PB. A set of operations on jobs.	The execution order of the jobs.	1.Two different sets of operations: The first is moving one job to the end of one job-list. The second is putting the job on the PB at first and then taking it out and putting it at the end of that job-list. They will output the same. 2. Two different sets of operations: The first is adding one job at the end of the P_3, while the second is adding one job at the end of P_2 and then moving it to P_3. They will output the same.	[1]

Maxsub	An array with integers.	Find the subarray with the largest sum, and output the sum.	1. Reversing this array, the output should be the same.	Newly identified
Jodatime	Year, month, day, hour, minute, second, millisecond, increment_week, increment_day, increment_second.	Output the Year, month, day, hour, minute, second, millisecond, after adding the increment_week, increment_day, increment_second.	1. When the year, month, day, hour, minute, second, millisecond are equal, and the sum of increment_week, increment_day, increment_second (all of them are transformed into seconds) are equal for two inputs, then their outputs are the same.	Newly identified
Klp	Given a set K of keys that can collectively open a set L of locks. The relations between the keys and locks are recorded in an $K * L$ Matrix M. $M[i, j]$ = 1 indicates that the ith key can open the jth lock, and 0 otherwise.	Find a set of keys in K of smallest size that can open all locks in L.	1. Adding a useless key row (all 0s, these keys cannot open any lock) to the end of the matrix M, then the output will not change. 2. Adding a column with all 1s (the added lock can be open by any key) to the matrix M, then the output will not change.	[6]
Trisquarej	Three integers: a, b, and c.	The type and square of a triangle	a, b, c is the first triangle, and a', b' c' is the second triangle. 1. (a, b, c) = (b', a', c'), the output will not change. 2. (a, b, c) = (a', c', b'), the output will not change. 3. (a, b, c) = (c', b', a'), the output will not change. 4. (a, b, c) = (2a', 2b', 2c'), then the type will not change, but the area of the first triangle is four times the second triangle.	[7]
Boyer	A source text, a pattern string.	Returns the index of the first occurrence of the specified pattern within the text.	1. If the pattern occurred in the original text, when adding one character to the end of the source text, the output should be the same. 2. If the pattern occurred in the original text, when deleting one character from the end of the pattern, the output should be the same as or less than the original output.	Newly identified
Lucene	A text, a search query.	Each item is given a relevance score, and they are sorted accordingly.	1. Swapping the terms of a OR or AND operator in the query should not affect the results. 2. Inserting an OR term in the query that does not exist in the text should not affect the results. 3. Excluding term in the query that does not exist in the text should not affect the results.	[8]
Superstring	An array of strings.	Find a shortest string, which contains each string in the array.	1. Adding one string A to the array, and A must be contained in the original array, then the output should be the same.	Newly identified
Bsearch2	Given an array of integers and a searching number.	Output 1 if the searching number is in this array, otherwise 0.	1. Multiplying all the numbers (including the numbers in the array and the searching number), then the output should be the same.	Newly identified
RSA	Two prime numbers p and q, an integer e, which is coprime to (p-1)*(q-1), and a plaintext m.	Output the ciphertext of m.	1. Keeping p, q, and e the same (e = 1), and giving a new plaintext which is equals to $m + p*q$, then, the ciphertext is the same.	Newly identified.
Shortest-path	Given a graph with positive edge weights, a source vertex, and a destination vertex, an algorithm (e.g., Dijkstra, Floyd-Warshall).	Return the shortest path between these two vertices.	1. Given the same graph, the same source and destination vertices, but with different algorithms, the output should be the same.	Newly identified
Rotate	Given an image, a rotating degree.	Return an image after rotating the original image by the specific degree.	1. Rotating the same image by N degree and $N + 360$ degree will output the same result.	Newly identified
Foneway	Three samples a, b, and c.	The p-value of these samples.	1. Changing the order of the samples, the result should not change.	Newly identified

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