A Multiobjective Genetic Programming-Based Ensemble for Simultaneous Feature Selection and Classification

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***Abstract*—We present an integrated algorithm for simultaneous feature selection (FS) and designing of diverse classifiers using a steady state multiobjective genetic programming (GP), which minimizes three objectives: 1) false positives (FPs); 2) false negatives (FNs); and 3) the number of leaf nodes in the tree. Our method divides a *c*-class problem into *c* binary classification problems. It evolves *c* sets of genetic programs to create *c* ensembles. During mutation operation, our method exploits the fitness as well as unfitness of features, which dynamically change with generations with a view to using a set of highly relevant features with low redundancy. The classifiers of *i*th class determine the net belongingness of an unknown data point to the *i*th class using a weighted voting scheme, which makes use of the FP and FN mistakes made on the training data. We test our method on eight microarray and 11 text data sets with diverse number of classes (from 2 to 44), large number of features (from 2000 to 49 151), and high feature-to-sample ratio (from 1.03 to 273.1). We compare our method with a bi-objective GP scheme that does not use any FS and rule size reduction strategy. It depicts the effectiveness of the proposed FS and rule size reduction schemes. Furthermore, we compare our method with four classification methods in conjunction with six features selection algorithms and full feature set. Our scheme performs the best for 380 out of 474 combinations of data sets, algorithm and FS method.**

***Index Terms*—Classification, ensemble, feature selection (FS), genetic programming (GP).**

I. Introduction

CLASSIFICATION is one of the most important and frequently encountered problems in data mining and machine learning. A wide range of real world problems of different domains can be restated as classification problems. This includes diagnosis from microarray data, text categorization, medical diagnosis, software quality assurance, and many more. The objective of classification is to take an input vector $\boldsymbol{x} = (x_1, \ldots, x_d)^T$ and to assign it to one of the K classes $\boldsymbol{C_k}$, where $k = 1, \ldots, K$. A model, called classifier, is used to solve this problem. The classifier encodes a set of criteria. Depending upon some features of the data point, these criteria assign the data point to a particular class [1]. Sometimes, ensembles of weak classifiers are used to obtain better classification accuracy. High dimensionality, high feature-to-sample ratio, and redundant and/or noisy features are some common sources of difficulties associated with classification.

Feature selection (FS) is a process to select a small but useful subset of features from the set of available features which is adequate for solving the problem in an efficient manner. Some available features may be redundant, not useful, and may cause confusion during the learning phase. These unwanted features needlessly increase the size and complexity of the feature space. It increases the computation cost for learning, and may sometimes be responsible for finding suboptimal solutions of the problem. This makes FS techniques important for the analysis of high dimensional data sets, especially when feature-to-sample ratio is extremely high.

The microarray technology has made it possible to diagnose different types of cancers directly using the microarray data sets. One of the main difficulties we face to do this is the high feature-to-sample ratio of microarray data sets, which makes FS an important step. Finding keywords as well as contexts from text data is essential to detect (without human intervention) the context of web pages, emails, or questions/answers, etc. A large set of distinct words in large texts (high number of features) and many categories of texts (high number of classes) are the two complicated challenges that we face in this task.

Genetic programming (GP) [2]–[5] is a biological-evolution inspired methodology where each solution is a program or an equation that evolves with one or more objective functions to perform specific tasks. References [6]–[12] used GP to design classifiers or to generate rules for binary classification problems. Some researchers have also attempted to solve multiclass problems [13]–[17]. GP has also been used for simultaneous FS and classification [18]. Liu and Xu [19] used GP to create ensembles of classifiers (genetic programs). They have used these ensembles to classify microarray data sets. Though GP is a powerful tool, it has a drawback: without special care each genetic program (equation) becomes huge. As an effect, they do not learn the patterns in the training data. Rather, memorizes them. It also makes genetic programs to be difficult to comprehend. Besides, though ensembles can

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perform better than individual classifiers [20], to obtain better performance, each ensemble should be diverse and each member of the ensemble should be accurate [20]–[22]. Without special care, due to lack of explicit diversity preservation mechanism, the solutions of single objective GP may lose diversity.

The objective of this paper is to find an embedded methodology of simultaneous FS and classification employing GP as a tool. Some of the novel contributions of our schemes are as follows. We have introduced a new multiobjective GP (MOGP), called archive-based steady state micro GP (ASMiGP). It is enriched by several new operators. The mating selection judicially uses Roulette wheel selection, instead of two tire multiobjective selection scheme (where domination is preferred over diversity). The crossover is new and uses male–female differentiation so that the off-spring is more likely to be close to the female parent in the genotypic space. The mutation is restrictive and performs less exploration in the hypothesis space. Thus, it reduces disruption. For feature nodes, instead of fitness, mutation uses unfitness to select the mutation point. Altering the fitness and unfitness of the features in different stages of learning, we change the objective of searching in the corresponding stages. We use ASMiGP to learn c diverse sets of classifiers (equations) minimizing three objectives: 1) false positive (FP); 2) false negative (FN); and 3) number of leaf nodes of a tree to restrict the rule size. Throughout the learning process, implicit FS is performed using MOGP, whereas several filter-based approaches are used in different stages of the procedure. In this way, we obtain concise rules that involve only simple arithmetic operations. A weighted negative voting is then used among the rules of each ensemble. These weights are determined on the basis of the performance of the binary classifiers on the training data set. A new measure of weighted negative voting, called net belongingness, is also introduced.

The proposed method has been tested on eight multiclass microarray data sets having large number of features, varying from 2000 to 49 151, and high feature-to-sample ratio, varying from 32.26 to 273.06. It has also been tested on eleven high dimensional (varying from 3182 to 26 832) text data sets, where the number of classes (categories) vary from 6 to 44. Experimental results reveal that our method can generate ensembles of classifiers with concise rules that can do a good job of classification with a small subset of features.

II. Background and Related Works

This section provides a background to GP, GP-based online FS and classification, ensembles, voting schemes, and concise rule finding. This section also includes some related works on these topics.

A. Concise Introduction to GP

GP [2]–[5] is an approach to find programs that can solve a given problem. GP uses Darwinian principle of "survival of the fittest." It evolves the programs using biologically inspired genetic operations like reproduction, crossover, and mutation in the search space to find such programs which would be able to solve the given problem [15], [23], [24]. The overall search process of traditional single objective GP is quite similar to traditional population-based genetic algorithm. The main difference among them is in the representation of solutions. The usual steps of traditional single objective GP can be found in [2], [15], and [24].

There exist several ways to encode a program. Probably, the most popular one is to use a tree structure [25]–[27] which we use. In tree-based GP, a program is represented by a tree where the internal nodes are from a set of functions $\mathcal{F}$, and the leaf nodes are from a set of terminals $\mathcal{T}$. The subtrees of a function node are the arguments of that function. The sets $\mathcal{F}$ and $\mathcal{T}$ must satisfy the closure and sufficiency properties [2], [15]. To satisfy the closure property, $\mathcal{F}$ must be well defined and closed for any combination of probable arguments that it may encounter [15]. Again, to satisfy the sufficiency property, $\mathcal{F}$ and $\mathcal{T}$ must be able to represent any possible valid solution of the problem.

B. FS: Why Embedded?

FS methods are generally divided into two main groups: 1) filter method and 2) wrapper method [28]. A filter method does not use any feedback from the classifier or any mining algorithm. It relies on the general characteristics of data. On the contrary, to measure the goodness of features, a wrapper method uses a predetermined classifier or mining algorithm, which will finally use the selected features. Consequently, a wrapper method exploits interactions among the subset of features on which it is tested. But, to find an optimal set of features, a wrapper method needs to measure performances on all possible subsets of features. This becomes infeasible for high dimensional data sets. To overcome this problem, wrapper methods typically use a heuristic-based forward or backward selection mechanism [28], which does not evaluate all possible subsets. So, in this paper, we consider embedded methods, where FS and designing of the classification system are done together. Embedded methods do not need to evaluate all possible subsets. Moreover, they can account for interaction between features and the classifier that is used to solve the problem [29]. Usually, embedded methods attain comparable accuracy to wrapper methods as well as comparable efficiency to filter methods. Though for every classification tool it may not be easy to define such an integrated mechanism, several attempts of FS using embedded methods have already been made. These attempts include using single objective GP [18], neural networks [30], [31], and support vector machines [32].

C. GP in Classification and FS

Many researchers have used GP as a tool for classification and FS. Some literature on this topic can be found in [1] and [33]. It has been used in both filter [34]–[37] and wrapper [38]–[41] approaches. GP has also been used for extracting decision trees [42]–[47]. Among these in [45] and [46], MOGP has been used. GP has also been adopted for learning rule-based systems [7]–[9], [48]–[51]. Both binary classification [6], [7], [10]–[12], [48] and multiclass [8], [9], [13]–[17], [49]–[51] classification problems have been addressed by GP-based (rule-based) systems. Even, researchers have applied GP-based (rule-based) system for binary classification of imbalanced data [52], [53]. Discriminant functions (DFs)-based GP for online FS and classification has been adopted in [18] to solve multiclass problems. It is noteworthy that GP has also been used in feature extraction for edge detection [54].

Since, in this paper, we have used MOGP for learning DFs, we discuss some relevant GP-based systems. In DFs-based GP, each program is a mathematical equation, where the variables are features of the data. Usually every program is associated with a class. For every input data point, the program converts it to a single output value. If this output value is more than a predefined threshold (usually zero), the point belongs to the class to which the program is associated with. Thus, a single equation is enough for binary classification problems. For c-class problems, there are two common ways. The first and more frequently used approach is to consider a c-class problem as c binary classification problems [1]. Thus, c number of DFs are used to discriminate c classes. The second and less popular approach is to use a single DF with $(c - 1)$ threshold values to create c intervals. Each of these intervals is then assigned to a particular class. For both categories, a common practice is to evolve a population where each individual encodes either one (for binary classification problems having single threshold, or for multiclass problems having multiple thresholds) or multiple DFs each of which uses a single threshold. Such encoding schemes have been used in [15] and [18]. In another practice, each solution encodes multiple DFs having a single threshold. The final output value in this case may be obtained using a (weighted) voting scheme among the output values of each function of the same individual. An example of this scheme can be found in [19].

In the recent years, researchers have made some notable attempts to solve classification problems using MOGP. Wang *et al.* [55] proposed a MOGP to obtain a group of nondominated classifiers, with which the maximum receiver operating characteristic convex hull (ROCCH) can be obtained. To achieve this, they have adopted four different multiobjective frameworks into GP. For further improvement of each individual GPs performance, they have defined two local search strategies that have been especially designed for classification problems. The experimental results in [55] have demonstrated the efficacy of the proposed memetic scheme in their MOGP framework. Another convex hull-based MOGP, called CH-MOGP, can be found in [56]. Wang *et al.* [56] showed the differences between the conventional multiobjective optimization problem and ROCCH maximization problem. Wang *et al.* introduced a convex hull-based sorting without redundancy and a new selection procedure which are suitable for ROCCH maximization problem. Again, Bhowan *et al.* [22] proposed a MOGP-based approach that is especially designed for unbalanced data sets. This approach [22] evolves diverse and accurate ensembles of GP classifiers with good performance on both the majority and the minority classes. The individual members of the evolved ensembles, that are composed of nondominated solutions, vote on class membership.

D. GP, Bloating, and Concise Rules

During evolution of GP, variable length genomes gradually start to increase its length without significant improvement in fitness. This incident, called bloating [57], is a well known phenomenon in GP. Bloating causes genetic programs: 1) to keep reducible genome structures and 2) to memorize training data points, rather than recognizing patterns hidden in them. To find rules which are to some extent human interpretable and can be analyzed, each of the genetic programs must be concise. A plausible way to achieve this target is to control bloating. A popular way to handle bloating is to take into account the program size [2], [58]–[61]. Some other methods include spatially-structured populations [62], [63], island-based models to introduce spatial structure to the population [62], [63], intron deletion [64], and dynamic population sizing [65], [66]. Song *et al.* [67] attempted to understand the GP evolved solutions; while Luna *et al.* [68] attempted to find comprehensible rules in subgroup discovery.

E. Ensemble Classifier

In classification, the basic task is to search through a hypothesis space to find a suitable hypothesis that will be able to classify the data points in a better way. An ensemble combines multiple hypotheses to form a better one [19], [21], [22], [53], [69], [70]. Empirically, an ensemble performs better when each of the classifiers is highly accurate (strong learner) and the members of the ensemble are significantly diverse. The explanation behind the better performance of ensemble classifiers than a single classifier has been described in [20]. Normally, to decide the class label of a data point, the member classifiers of an ensemble use (weighted) voting. Ensembles are often used in bio-informatics [71].

III. Proposed Work

A. Representation of Classifiers or Solutions

In this paper, we evolve c-populations of genetic programs. Each individual of these populations is a binary classifier. Each binary classifier is represented by a single tree. When a data point is passed through an individual of the ith population, if the output value is positive, the individual says that the passed data point belongs to the ith class; otherwise it says that the point does not belong to that class. The internal (nonleaf) nodes of these trees are functions $\mathcal{F}$. The terminal nodes must be either a feature or a constant from the set $\mathcal{C}$. We have imposed some constraint on the minimum size (architecture) of the trees. In each tree there must be at least one function node and two terminal nodes (with at least one feature node). Though, a single feature (terminal) node might be enough to determine the class label, this would rarely happen in practice. The above restrictions make the trees more useful without any loss of generalization capability. Again, after generation of any tree throughout the learning phase (using mutation, crossover, or random initialization), the largest subtree consisting of only constants as its leaf nodes is replaced by a constant leaf node having the equivalent constant value.

B. MOGP for Learning

Larger genetic programs may memorize the training patterns which, in turn, may increase the training accuracy and reduce the understandability of the rules. Therefore, we aim to find smaller but accurate classifiers. Again, when c is high enough, even a balanced c-class data set may get converted to c number of highly imbalanced bi-classification data sets. Instead of minimization of classification error, simultaneous minimization of FP and FN would be more appropriate in this regard. Suppose a classifier makes some mistakes $m = m_p + m_n$ on a given training data set, where m_p and m_n are, respectively, the number of FPs and FNs. Consider two classifiers, each making the same number of mistakes m on a given data set. Let for the first classifier $m_p = m_n$ and for the second classifier $m_p \gg m_n$ or $m_p \ll m_n$. If the cost of an FP is the same as that of a FN, we would prefer the first classifier. Consequently, minimization of both FP and FN would be a better strategy than minimization of the total number of misclassification, particularly for imbalanced data sets. Thus, we have three objectives, i.e., minimizations of: 1) FP; 2) FN; and 3) rule size. Moreover, when different classes are overlapped, minimization of FP is usually in conflict with the minimization of FN and vice versa. Multiobjective optimization is more suitable when we need to optimize more than one conflicting objective. Therefore, during the learning of each binary classifier, we minimize three objectives using an MOGP: 1) FP; 2) FN; and 3) number of leaf nodes in the tree. The third objective is used to reduce the size of the tree which enhances the understandability and reduces the pattern memorization capability. The algorithm, proposed in this paper, is called ASMiGP, which is presented in Algorithm 1.

In an evolutionary search, it is desired to have as many generations as possible and steady state nature of an algorithm maximizes the number of generations when the number of function evaluations is fixed [72]. Due to maximization of generations, a steady state evolutionary search is more exploitative to enhance the searching in a region which is more likely to have or closer to the Pareto front and avoiding exploration in regions that are less likely to improve the solutions. It causes faster convergence. In other words, independent of the fitness evaluation process, steady state selection is more performant than discrete generational selection [73]. Therefore, we have used a steady state algorithm instead of a generational one.

Algorithm 1: ASMiGP

```
Initialize population using ramped-half-and-half method.
Initialize the archive solutions using initial solutions.
while $Evaluations^{Current} \leq Evaluations^{Maximum}$ do
    repeat
        operator = Select crossover or mutation.
        if $operator == crossover$ then
            Select male and female parents (mating
            selection).
            Perform crossover.
        end
        else
            Select an individual (mating selection).
            Mutate the individual.
        end
    until the infix equation of off-spring is distinct from
    infix equation of any individual of the archive
    Evaluate the new off-spring.
    $Evaluations^{Current} = Evaluations^{Current} + 1$
    Update the archive using new offspring
    (multi-objective environmental selection).
end
$\mathcal{F}ronts$ = Perform fast-non-dominated-sort.
return first front of $\mathcal{F}ronts$.
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C. FS

In this paper, we have used the embedded model of FS. Explicit FS is performed during population initialization and mutation. Implicit FS is performed during crossover. Filtering is also performed at three different stages of the learning process; in particular, at the beginning and after 50% and after 75% of evaluations as described next in this subsection.

To facilitate the FS, following [74], we define an index that assesses the discriminating ability of a feature. Consider a two-class problem. Note that for a multiclass problem, the one-versus-all case can also be viewed as a two-class problem. Let there be n_p number of training points and the class label for the jth data point be $+1$ if it belongs to class 1 and -1 if it belongs to class 2. Let the value of the fth feature for the ith data point be f_i; $i = 1, \ldots, n_p$. If the fth feature is a good discriminatory feature then for all data points from class 1, it should have high values and for all points from class 2, it should have low values or vice-versa. Hence for a good discriminatory feature, we can define an ideal feature vector with values 1, if the data point is from class 1 and 0 otherwise; or the feature value is 0, if it is from class 1, otherwise, it is 0. Let $\mathbf{S}_f$ be the vector containing the ideal feature values for feature f and s_{fi} be the ideal feature value of the fth feature for the ith sample. Note that, there could other important features that are not linearly related to the class structure. We are not considering them in this preliminary filtering step. As in [74], we compute the Pearson's correlation (or any other measure of similarity) between f and s as a measure of feature relevance

$$C_f = \sum_{j=1}^{n_p}(s_{ji} - \bar{s})(f_j - \bar{f}) \Bigg/ \sqrt{\sum_{j=1}^{n_p}(s_{ji} - \bar{s})^2 \sum_{j=1}^{n_p}(f_j - \bar{f})^2}. \tag{1}$$

A higher value of $|C_f|$ indicates a stronger discriminative power of feature f. For a multiclass problem, using the one-versus-all strategy, for the ith binary classification problem (class i versus the rest), the correlation for the fth feature is denoted by C_f^i.

Now, we describe the FS procedure. Let the set of all features be $\mathcal{F}_{\text{all}}$. We intend to incorporate only those features from $\mathcal{F}_{\text{all}}$ which are more likely to help the classifiers to decide the class label. We assign different fitness and unfitness measures to the features during the learning phase. To remove a feature node from any tree (during mutation), we select it using Roulette wheel selection on the unfitness values of the features which are present in that tree. Similarly, when a new feature is inserted in the tree, it is selected using Roulette wheel selection on the fitness values. During the first 50% evaluations, the fitness and unfitness features are defined as

$$F^{0\%,i}_{\text{fitness}}(f,i) = \begin{cases} \left(\dfrac{C^i_f}{C^i_{\max}}\right)^2, & \text{if } \dfrac{\left|C^i_f\right|}{C^i_{\max}} > 0.3 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

$$F^{0\%,i}_{\text{unfitness}}(f,i) = 1.0 - F^{0\%,i}_{\text{fitness}} \tag{3}$$

where $C^i_{\max} = \max_{f \in \mathcal{F}_{\text{all}}} |C^i_f|$. Equation (2) sets the fitness of very poor (poor with respect to its discriminating power) to zero to eliminate their impact during the initial evolution. Let $\mathcal{F}_{\text{eval}=0\%,i} \subseteq \mathcal{F}_{\text{all}}$ be the features with nonzero fitness values. Basically, at this stage we are using a filter on the feature set $\mathcal{F}_{\text{all}}$ to obtain a smaller feature set.

After completion of 50% evaluations for each population, we find the features used in that population. Let the feature set be $\mathcal{F}_{\text{eval}=50\%,i}$. Then we make the fitness of all features in $\mathcal{F}_{\text{all}} - \mathcal{F}_{\text{eval}=50\%,i}$ to zero. This is done with the assumption that after 50% evaluations useful features have been used by the collection of decision trees. Now, the fitness and unfitness values of all features in $\mathcal{F}_{\text{eval}=50\%,i}$ are modified according to (4) and (5), respectively

$$F^{50\%,i}_{\text{fitness}}(f,i) = \begin{cases} \dfrac{|C^i_f|}{\sum\limits_{\substack{f \neq g \\ g \in \mathcal{F}_{50\%,i}}} |\rho_{fg}|}, & \text{if } f \in \mathcal{F}_{\text{eval}=50\%,i} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

$$F^{50\%,i}_{\text{unfitness}}(f,i) = e^{-\frac{F^{50\%,i}_{\text{fitness}}(f,i) - \min_f\left\{F^{50\%,i}_{\text{fitness}}\right\}}{\max_f\left\{F^{50\%,i}_{\text{fitness}}\right\} - \min_f\left\{F^{50\%,i}_{\text{fitness}}\right\}}} \tag{5}$$

where ρ_{fg} is the Pearson's correlation between fth and gth features. Here, we try to select features with higher relevance but reducing the redundancy in the set of selected features. The fitness, defined in (4), increases when the feature is highly correlated with class label. Similarly, it reduces when it is more correlated with other existent features. This is done to achieve maximum relevance minimum redundancy.

After 75% function evaluations, again we take another snapshot of the population. Let the existent features for the population be $\mathcal{F}_{\text{eval}=75\%,i} \subseteq \mathcal{F}_{\text{eval}=50\%,i}$. Then, the fitness and unfitness values of the features in $\mathcal{F}_{\text{eval}=75\%,i}$ are defined in (6) and (7), respectively

$$F^{75\%,i}_{\text{fitness}}(f,i) = \begin{cases} F^{0\%}_{\text{fitness}}(f,i), & \text{if } f \in \mathcal{F}_{\text{eval}=75\%,i} \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

$$F^{75\%,i}_{\text{unfitness}}(f,i) = 1.0 - F^{75\%,i}_{\text{fitness}}(f,i). \tag{7}$$

D. Population and Archive Initialization

We initialize each population using ramped-half-and-half method. While constructing the random trees, selection of terminal nodes has been made with a probability p_{var}. To insert a terminal node in a tree, a random number r_n is drawn in [0, 1]. If $r_n < p_{\text{var}}$ then a feature node is added, otherwise a constant node is added. The function nodes are chosen from the set $\mathcal{F}$, with equal probability of inclusion for all functions. The feature nodes are selected using Roulette wheel selection on fitness $F^{0\%}_{\text{fitness}}$, defined in (2).

To initialize the archive from the initial population, we have used the multiobjective archive initialization scheme present in [72] and [75]. It requires two parameters: 1) maximum archive size ($N_{\max}$) and 2) minimum archive size ($N_{\min}$).

E. Selection of Crossover or Mutation

Since ASMiGP is a steady state MOGP, in each generation we generate only one offspring. We use either crossover or mutation to do that. A random number r_c is drawn in [0, 1]. if $r_c < p_c$ then crossover operator is selected otherwise the mutation operator is selected for that generation.

F. Mating Selection

ASMiGP uses crossover with male and female differentiation which needs one male and female parent. We perform Roulette wheel selection using classification accuracy of the binary classifiers as fitness to select the female parent. Then the male parent is selected randomly from the remaining archive. The only condition to be satisfied is that the male and female parents must be distinct. For mutation, we need only one individual and it is selected in the same way as done for the female parent in case of crossover operator.

A choice of mating selection could have been the use of some bi-level selection operator, where Pareto dominance is preferred over diversity. In that case, solutions along the whole Pareto optimal solution set with good diversity would have been selected as the primary (female) parents. Note that, we have used crossover with male–female differentiation that tries to generate an off-spring near the primary parent in the hypothesis space. Consequently, this might cause generation of Pareto optimal binary classifiers along the whole Pareto optimal solution set. Though they are Pareto optimal, these binary classifiers may have poor accuracies. This is because of the implicit imbalance nature of the binary classification problems (due to conversion from multiclass classification problems) and different classifier sizes. An ensemble classifier, however, performs better when individual members of the ensemble are more accurate. Therefore, we use classification accuracy-based mating selection. It guides the search to generate more accurate binary classifiers.

G. Crossover

In this paper, we have used crossover operation with male and female differentiation. We want the off-spring to be near the female (acceptor) parent in the hypothesis space. The male (donor) parent is used to make the off-spring diverse from its mother. To do this, two random points (nodes) are selected from each of the parents. The probabilities of selection of terminal nodes and function nodes as a crossover point (node) are, respectively, p_t^c and $(1 - p_t^c)$. Then, the subtree rooted at the selected node of the mother tree is replaced with a similarly selected subtree from the father tree. If the off-spring is identical to any of its parents, the whole procedure is repeated (before evaluation/learning of the off-spring).

H. Mutation

In most of the GP-based systems, for mutation a subtree rooted at a randomly selected node is replaced by a new randomly generated subtree. Though this kind of mutation explores more in the hypothesis space, it may be too disruptive in nature. Therefore, we intend to use less exploration by keeping the tree structure unaltered. During mutation we perform the following operations on a tree.

1) Each constant of the tree is replaced by another random constant with probability p_c^m.
2) Each function node of the tree is replaced by anther random function node with probability p_f^m.
3) Only one feature node of the tree is replaced by another feature node.

For feature nodes, to select the mutation point Roulette wheel selection is performed on the unfitness of the features which are present in the tree. Similarly, to insert a new feature at the mutation point, we select a feature using Roulette wheel selection based on the fitness values (probability proportional to fitness) of the features.

This restricted mutation scheme ensures that the tree structure of an equation remains the same. It also ensures that the variables in an equation do not change drastically—changing more than one variable would shift the solution (equation) in the hypothesis space by a larger amount.

I. Environmental Selection

ASMiGP uses the archive truncation strategy used in [72] and [75]. This multiobjective archive truncation strategy uses Pareto-based fitness function, i.e., fitness is Pareto dominance rank. This scheme maintains an archive (ensemble) which has an adaptive and dynamic size. It does not allow the archive to fall below a minimum size ensuring diversity in the genotypic space. Moreover, the environmental selection diminishes the exploration in areas of objective space that are less likely to yield improved solutions [72], ensuring diversity in phenotypic space. Furthermore, we have made the following difference in the environmental selection. ASMiGP ensures that the infix expression of every off-spring (after mutation or crossover) is distinct from every member of the archive. To achieve this, before evaluating the offspring, ASMiGP converts it to its infix expression and then compares the expression with that of each individual of the archive. Only if the expression is unique, the off-spring is evaluated and added to the archive. Otherwise it is discarded and a new off-spring is generated. Another noticeable difference is that here the number of objectives is three. Note that the diversity maintenance in each ensemble both in phenotypic space and in genotypic space finds a diverse set of trees (bi-classifiers). Trees, being diverse, enhance the performance of the corresponding ensemble. In this context, it is worth mentioning that the archive, along with the archive truncation strategy, helps to realize a good Pareto front by explicitly maintaining diversity among the fit (according to rank) solutions. However, the archive alone is not sufficient to evolve a good Pareto front along all the objectives.

J. Decision Making

To determine the class label, we find the net belongingness of a point to each class. The net belongingness lies in [0, 1]. A higher value indicates more net belongingness to that class. A data point is assigned to that class for which it has the highest net belongingness.

After the learning, we obtain a set of c archives, $\mathcal{A} = \{\mathcal{A}_1, \mathcal{A}_2, \ldots, \mathcal{A}_c\}$; $\forall i,\, 1 \leq |\mathcal{A}_i| \leq N_{\max}$, where c is the number of classes, and $\mathcal{A}_i$ is the set of all binary classifiers for the ith class. To determine the net belongingness of a data point $\mathbf{p}$ to class m, $\mathcal{B}_m^{\text{net}}(\mathbf{p})$, it is passed through all genetic programs of set $\mathcal{A}_m$. The net belongingness, $\mathcal{B}_m^{\text{net}}(\mathbf{p})$, of the point $\mathbf{p}$ for class m is computed using

$$\mathcal{B}_m^{\text{net}}(\mathbf{p}) = \frac{1}{2}\left(\frac{1}{|\mathcal{A}_m|}\sum_{i=1}^{|\mathcal{A}_m|}\mathcal{B}_m^i(\mathbf{p}) + 1.0\right) \tag{8}$$

where $\mathcal{B}_m^i$ is defined as

$$\mathcal{B}_m^i(\mathbf{p}) = \begin{cases} +\left(1.0 - \dfrac{\text{FP}_m^i}{\text{FP}_m^{\max}}\right), & \text{if } \mathcal{A}_m^i(\mathbf{p}) > 0 \\ -\left(1.0 - \dfrac{\text{FN}_m^i}{\text{FN}_m^{\max}}\right), & \text{otherwise.} \end{cases} \tag{9}$$

In (9), FP_m^i and FN_m^i, respectively, represent the number of FPs and FNs made by the ith individual in set $\mathcal{A}_m$ on the training data. $\text{FP}_m^{\max}$ and $\text{FN}_m^{\max}$ are, respectively, the maximum possible FP and the maximum possible FN for the mth class; and $\mathcal{A}_m^i(\mathbf{p})$ is the output from ith individual of $\mathcal{A}_m$ for input data point $\mathbf{p}$. Finally, $\mathbf{p}$ is assigned the class k, when $\mathcal{B}_k^{\text{net}} = \max_{m=1}^{c}\{\mathcal{B}_m^{\text{net}}\}$. Note that $\text{FP}_m^{\max}$ and $\text{FP}_m^{\min}$ are determined by the training data.

The concept of net belongingness is inspired by the concept of negative voting. Negative voting has been widely used in diverse applications [76]–[78]. It is more effective when circumstances unfavorable to the preferences invoke stronger electoral responses than the similar favorable responses, as well as the behaviors of the voters are well defined [79]. In our scheme, the learners for the ith class learn to vote yes for the points of the ith class and no for the points which do not belong to the ith class. For multiclass problems, it is more likely that a binary classifier learns to say no than to say yes for a much higher number of points. Therefore, we found negative voting to be more suitable in this context. However, we have used a weighted negative voting scheme. The accuracies for the responses yes and no of the ith binary classifier of mth class are, respectively, $\left(1.0 - \text{FP}_m^i/\text{FP}_m^{\max}\right)$ and $\left(1.0 - \text{FN}_m^i/\text{FN}_m^{\max}\right)$. These values have been used as corresponding weights for the responses yes and no of the ith binary classifier of the mth class. We have used the positive

TABLE I
PARAMETER SETTINGS FOR THE PROPOSED METHOD

Parameter	Value
Set of functions ($\mathcal{F}$)	$\{+, -, \times, \div\}$
Range of initial values of constants ($\mathcal{C}$)	[0, 2]
Maximum depth of tree during initialization	6
Maximum allowable depth of tree	10
Maximum archive size (N_{max})	50
Minimum archive size (N_{min})	30
Initial Probability of feature nodes (p_{var})	0.8
Probability of crossover (p_c)	0.8
Probability of crossover for terminal nodes (p_t^c)	0.2
Probability of mutation for constants (p_c^m)	0.3
Probability of mutation for function nodes (p_f^m)	0.1
Function evaluations for each binary classifier	400000

TABLE II
SUMMARY OF MICROARRAY DATA SETS

	Data Set	Features (F)	Samples (S)	Classes (C)	$\left(\frac{F}{S}\right)$
1	Colon	2000	62	2	32.26
2	TOX-171	5748	171	4	33.61
3	Leukemia 1	7129	34	2	209.68
4	Leukemia 2	7129	38	2	187.61
5	CLL-SUB-111	11340	111	3	102.16
6	GCM	16063	144	14	111.55
7	SMK-CAN-187	19993	187	2	106.91
8	GLA-BRA-180	49151	180	4	273.06

TABLE III
SUMMARY OF TEXT DATA SETS

	Data Set	Features (F)	Samples (S)	Classes (C)	$\left(\frac{F}{S}\right)$
1	oh0.wc	3182	1003	10	3.17
2	oh10.wc	3238	1050	10	3.08
3	tr12.wc	5804	313	8	18.54
4	tr23.wc	5832	204	6	28.59
5	tr11.wc	6429	414	9	15.53
6	tr21.wc	7902	336	6	23.52
7	wap.wc	8460	1560	20	5.42
8	ohscal.wc	11465	11162	10	1.03
9	la2s.wc	12432	3075	6	4.04
10	la1s.wc	13195	3204	6	4.12
11	new3s.wc	26832	9558	44	2.81

and the negative signs to indicate acceptance and rejection of the data point for the *m*th class, respectively.

IV. EXPERIMENTATION

A. Experimental Settings

We have repeated tenfold cross validation of the proposed method for ten times. Table I shows the parameter settings that we have used for this purpose. The training data is Z-score normalized. Furthermore, based on the means and the standard deviations of the features of the training data, the test data was Z-score normalized. Note that except $N_{\max}$ and $N_{\min}$, all parameters are standard parameters used in any GP simulations, while $N_{\max}$ and $N_{\min}$ are needed for archive maintenance. Although all the parameters can be chosen using a cross validation mechanism, because of huge computational overhead, we could not do that. Based on a few experiments we selected these parameters. These choices are not optimal. However, since the same set of values are used for widely different types of data sets, it demonstrates the effectiveness of the proposed scheme. The proposed method has been implemented in Java with the help of jMetal [80], [81].

We have used eight microarray and eleven text data sets which are summarized in Tables II and III, respectively.

B. Importance of FS and Rule Size Reduction

To demonstrate the importance of the proposed FS and rule size reduction scheme, we have compared our method with GP without FS and no restriction to equation size. To do that, we have made the following changes in the proposed method.

1) No explicit FS as described in Section III-C is done.
2) There are only two objectives, FP and FN.

All other parts of the algorithm and the parameter values remain unchanged. Similar to the proposed scheme, we have also executed tenfold cross validation for ten times for all the data sets. Along with results (mean values of the corresponding ten runs) obtained using the proposed method, the results obtained using this scheme for microarray and for text data sets are, respectively, summarized in Tables IV and V. From these two tables, we observe the following.

1) In all cases, the test accuracy is much higher for the proposed method. Especially, for GCM having 14 classes, the difference between the test accuracies are remarkably high.
2) The tree size increases significantly when the third objective, i.e., the restriction on rule size, is not used.
3) For most of the data sets the proposed method selects smaller number of distinct features per tree as well as for per classifier.

These observations clearly demonstrate the importance of the FS as well as constraining the rule size. Since our FS scheme discards features with poor relevance and uses features with good discriminating power yet avoiding use of redundant features, it not only makes the discovery of useful rules easier but also implicitly constrains the rule length. Thus, FS plays a very important role having two positive impacts: it makes identification of useful rules easier and it promotes the minimization of the third objective.

C. Comparing With Other Methods

To compare the performance of the proposed method we have used the experimental results reported in [82] (see [82, Tables IV–VII]). Song *et al.* [82] used four different types of classification algorithms: 1) probability-based naive Bayes (NB); 2) tree based C4.5; 3) instance-based lazy learning algorithm IB1; and 4) rule-based RIPPER both before and after FS. Along with the full feature set, they have used six FS algorithms in their experiment.

1) FAST [82].
2) FCBF [83], [84].
3) CFS [85].
4) ReliefF [86].
5) Consist [87].
6) FOCUS-SF [88].

TABLE IV
EXPERIMENTAL RESULTS ON MICROARRAY DATA SETS (MEAN VALUES OF TEN RUNS OF TENFOLD CROSS VALIDATION)

Data Set	%TA[a]		FS[b]		TS[c]		$(F/T)^d$		%F[e]		$(\%F/T)^f$	
	PM[g]	$W^h_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$
Colon	85.12 (2.07)	71.93 (4.12)	195.0	182.5	6.76	123.60	3.11	8.56	9.75	9.13	0.16	0.43
TOX-171	81.07 (3.42)	58.52 (4.57)	407.6	540.9	8.83	148.44	3.53	11.97	7.09	9.41	0.06	0.21
Leukemia1	93.50 (2.85)	74.08 (6.42)	188.6	276.6	3.01	76.09	2.00	6.52	2.65	3.88	0.03	0.09
Leukemia2	91.58 (3.67)	77.33 (6.84)	147.8	229.0	3.50	74.16	2.02	5.72	2.07	3.21	0.03	0.08
CLL-SUB-111	80.52 (2.60)	54.51 (3.51)	335.3	465.3	7.29	134.28	3.20	10.75	2.96	4.10	0.03	0.09
GCM	69.35 (1.96)	33.97 (2.60)	854.3	1086.0	4.70	105.42	1.91	6.22	5.32	6.76	0.01	0.04
SMK-CAN-187	68.68 (1.18)	62.12 (2.30)	319.9	435.8	22.23	135.88	6.41	15.33	1.60	2.18	0.03	0.08
GLA-BRA-180	68.22 (2.25)	58.89 (2.75)	784.4	569.9	11.30	150.81	4.33	11.40	1.60	1.16	0.01	0.02

[a] Test Accuracy (standard deviation is provided within parenthesis), [b] Number of Features Selected per Classifier, [c] Tree Size, [d] Number of Features per Tree, [e] Percentage of Features Selected, [f] Percentage of Features Selected per Tree, [g] Proposed Method, [h] GP without FS and Rule Size Reduction

TABLE V
EXPERIMENTAL RESULTS ON TEXT DATA SETS (MEAN VALUES OF TEN RUNS OF TENFOLD CROSS VALIDATION)

Data Set	%TA[a]		FS[b]		TS[c]		$(F/T)^d$		%F[e]		$(\%F/T)^f$	
	PM[g]	$W^h_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$
oh0.wc	87.75 (0.51)	70.53 (1.17)	484.1	2080.7	17.06	145.38	6.46	25.90	15.21	65.39	0.20	0.81
oh10.wc	81.06 (0.61)	66.11 (1.52)	439.6	2166.8	24.11	140.67	7.12	26.03	13.58	66.92	0.22	0.80
tr12.wc	87.86 (1.50)	60.55 (2.36)	603.7	1697.3	8.67	123.91	4.17	17.22	10.40	29.24	0.07	0.30
tr23.wc	93.95 (1.19)	64.90 (2.14)	396.5	1154.2	6.10	117.15	3.09	14.81	6.80	19.79	0.05	0.25
tr11.wc	86.08 (0.72)	64.63 (2.56)	631.6	1785.8	8.82	128.57	4.03	17.03	9.82	27.78	0.06	0.26
tr21.wc	89.64 (1.14)	71.46 (2.62)	362.0	1219.2	9.51	114.51	4.17	15.00	4.58	15.43	0.05	0.19
wap.wc	79.60 (0.60)	58.96 (1.64)	1199.8	4377.5	17.38	125.53	6.07	21.02	14.18	51.74	0.07	0.25
ohscal.wc	73.45 (0.23)	62.59 (1.21)	232.9	3853.8	63.48	111.52	7.78	24.87	2.03	33.61	0.07	0.22
la2s.wc	83.95 (0.62)	67.32 (0.99)	354.6	2369.1	53.17	133.76	11.41	28.65	2.85	19.06	0.09	0.23
la1s.wc	83.06 (0.36)	65.62 (1.05)	380.6	2372.0	56.40	133.21	12.30	28.35	2.88	17.98	0.09	0.21
new3s.wc	81.32 (0.27)	58.96 (1.64)	1674.2	4377.5	33.93	125.53	7.10	21.02	6.24	16.31	0.03	0.08

[a] Test Accuracy (standard deviation is provided within parenthesis), [b] Number of Features Selected per Classifier, [c] Tree Size, [d] Number of Features per Tree, [e] Percentage of Features Selected, [f] Percentage of Features Selected per Tree, [g] Proposed Method, [h] GP without FS and Rule Size Reduction

Use of all features can be viewed as the seventh FS algorithm. To make this paper comprehensive, we are not discussing the experimental settings used in [82]. Note that accuracies for few data sets for few pairs of FS schemes are not available in [82].

1) Results With Microarray Data Sets: Table IV presents the results of the proposed method on microarray data sets. We have already stated that for each classifier, Song *et al.* [82] used seven FS schemes (six FS method as well as the set of all features). For each FS method five repetitions of the tenfold cross validation experiment were done in [82]. And then, for each FS method, the average accuracy over the five repetitions is reported. We compare this average accuracy with the average accuracy that we have obtained by our method over the ten repetitions of the tenfold cross validation experiments. In particular, we count the number of cases (each case refers to one FS scheme) in which our algorithm outperforms. Note that, for some combination of data set and classifier, the total number of cases is less than seven as for those combinations some results are not available. Table VI reports these counts. To elaborate Table VI, consider the entry corresponding to column IB1 and row CLL-SUB-111. For the data set CLL-SUB-111, in [82, Table VI], Song *et al.* reported the performance of the algorithm IB1 for six different FS algorithms. Our algorithm is found to perform better than five of the six FS algorithms and hence the entry for row CLL-SUB-111 and column IB1 is 5/6. Note that, for this data set, Song *et al.* [82] did not report performance of IB1 using all features. All but the entries in the last column of Table VI are generated in the same manner. The last column of Table VI, which reports the row total, reveals that our method performs the best for 61.40% (132 out of 215) test cases.

TABLE VI
COMPARISON WITH NB, C4.5, IB1, AND RIPPER
ON MICROARRAY DATA SETS

Data Set	NB	C4.5	IB1	RIPPER	Total
Colon	4/7	2/7	4/7	6/7	16/28
TOX-171	4/7	7/7	3/7	7/7	21/28
Leukemia1	2/7	2/7	2/7	2/7	8/28
Leukemia2	5/7	6/7	6/7	5/7	22/28
CLL-SUB-111	4/7	6/7	5/6	4/7	19/27
GCM	4/7	7/7	6/7	7/7	24/28
SMK-CAN-187	2/6	2/6	2/6	2/6	8/24
GLA-BRA-180	3/6	5/6	1/6	5/6	14/24
Total	28/54	37/54	29/53	38/54	132/215

If we compute the percentage of features selected by the ensembles, it may not be very small for some data sets, like Colon. But, if we consider the number of features selected per binary classifier (tree), we find that this number is quite small, e.g., the maximum value is 0.16% for Colon. We assume that binary classifiers (binary trees) having less than twenty nodes are concise enough. We need to remember that we are talking about raw rules (equations) directly obtained from GP which are most likely affected by bloating. Simplification of these rules may lead to reduction in their sizes. Based on this, in all but one data set we could find easy to analyze rules. For SMK-CAN-187 the extracted rules are more complex possibly because of complex structure of the data.

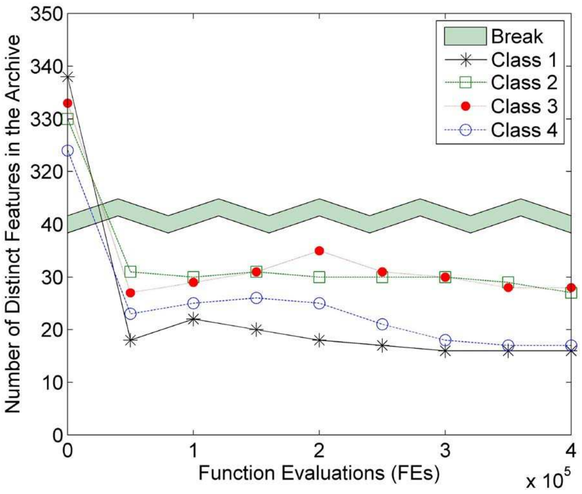

Fig. 1. Showing the number of distinct features present in the archive with respect to function evaluations for GLA-BRA-180 data set.

TABLE VII
COMPARISON WITH NB, C4.5, IB1, AND RIPPER ON TEXT DATA SETS

Data Set	NB	C4.5	IB1	RIPPER	Total
oh0.wc	7/7	7/7	7/7	6/6	27/27
oh10.wc	7/7	7/7	7/7	6/6	27/27
tr12.wc	7/7	7/7	7/7	7/7	28/28
tr23.wc	7/7	5/7	7/7	4/7	23/28
tr11.wc	7/7	7/7	7/7	6/6	27/27
tr21.wc	6/7	6/7	6/7	3/6	21/27
wap.wc	7/7	6/6	6/6	6/6	25/25
ohscal.wc	4/4	4/4	4/4	4/4	16/16
la2s.wc	6/6	5/5	5/5	5/5	21/21
la1s.wc	6/6	5/5	5/5	5/5	21/21
new3s.wc	3/3	3/3	3/3	3/3	12/12
Total	67/68	62/65	64/65	55/61	248/259

In Table S-I (see supplementary materials), we present the best rules (or binary classifiers or GPs) we found for each class of each microarray data set. These GPs have the highest training accuracy among the GPs obtained from the first fold of the first ten fold cross validation. If there are more than one rule having the same maximum training accuracy, the rule with the smallest length has been reported. The features in the equations are indexed starting from “0.” From Table S-I, we can observe that for several classes the proposed method could find substantially small rules. Noticeably, for four, six, eight, and three classes, the proposed method could find the best binary classifier having only 1–4 distinct variables, respectively. So, 21 out of 33 (i.e., 63.64%) cases, we could find considerably small (and hence easy to interpret) rules. For some classes, the rules having the highest training accuracy were not very comprehensible because the length of the rule was not very small. If we think that $(2.0 \times x_i)$ is more easy to understand than $(x_i + x_i)$, though both equations have the same size, we observe that for 21 out of 33 (i.e., 63.64%) cases the proposed method could find rules having highest accuracy, which are not at all affected by bloating and are comprehensible without simplification.

To investigate how the number of distinct features changes in the archive, we have executed our algorithm with 400 000 function evaluations using the entire GLA-BRA-180 data set. In Fig. 1, we have plotted the number of distinct features after initial and after each 12.5% of maximum function evaluations. For all four classes of GLA-BRA-180 data set, the number of distinct features in the archive initially falls drastically depicting the impact of FS. After some generations, it becomes almost constant. Moreover, the number of final distinct features for each class is quite small. This indeed reveals a desirable behavior of the our scheme.

To show how the individual binary classifiers’ accuracies change with function evolutions, we have plotted each individuals’ FPs and FNs for all four classes of GLA-BRA-180 data set in Figs. S-1 and S-2 (see supplementary materials). For this part of the experiment also, we have used the entire data set for training. From the figures, it is observed that with the increase in number of evolutions, the average accuracy of the solutions tends to increase. However, for class four, some solutions having lower level of accuracies (having higher FPs and FNs) are there even after 400 000 function evaluations. This is because, even after such high number of function evaluations, the algorithm was still searching for more concise solutions, and could find some trees of comparatively smaller size.

2) Results With Text Data Sets: Similar to Table VI with microarray data sets, we present the same result (number of test cases for which our algorithm provides the best results for each classifier and data set pair) with text data sets in Table VII. Table VII reveals that for text data sets the proposed scheme performs the best for 95.75% (248 out of 259) cases.

If we consider the same criteria that binary classifiers (trees) having less than twenty nodes are concise enough, then our method could not find interpretable rules for 5 (oh10.wc, ohoscal.wc, la2s.wc, la1s.wc, and new3s.wc) out of the 11 text data sets. The number of selected features is not at all small for most of the text data sets. Some reasons behind this may be that the number of classes is high for the text data sets and the existence of more complex class structure, which is defined by the keywords and relation of keywords to the imposed classes is usually not as straightforward as genes have to cancers. However, the percentage of features selected per binary classifiers (trees) is quite small. Noticeably, the accuracy obtained for new3s.wc (having 44 classes), is much higher than that of the other methods (for accuracies of other methods, see [82]). We can also observe that for data sets having more than or equal to ten classes, our methods performs comparatively better than other methods.

D. Statistical Significance Testing

To compare the proposed method with existing FS and classification methods, we consider four classification and six FS methods as well as with the full feature set. Thus we compare our algorithm with 28 FS and classification algorithm pairs. We have performed Wilcoxon signed ranks test to show that the performance of the proposed algorithm is significantly different over 28 pairs of FS and classification algorithm. For this, we have considered both the microarray and the text data sets together and have used the average test

TABLE VIII
WILCOXON SIGNED RANKS TEST (ONE-TAILED) FOR PAIRWISE COMPARISONS WITH THE PROPOSED METHOD AT $\alpha = 0.05$

	NB	C4.5	IB1	RIPPER
FAST	A	R	R	R
FCBF	R	R	R	R
CFS	R	R	R	R
ReliefF	R	R	R	R
Consist	R	R	R	R
FOCUS-SF	R	R	R	R
Full Set	R	R	R	R

A: H_0 Accepted, R: H_0 Rejected.

accuracies achieved with different algorithms on these data sets. Moreover, we have removed the cases for which accuracies are not known (see [82, Tables IV–VII]). Table VIII shows that out of the 28 cases, only in one case the null hypothesis H_0 was accepted. Here the null hypothesis is that there is no significant difference in performance between our algorithm and a comparing algorithm. We have also used Friedman test [89], [90] to check if all the 29 (28 existing and our proposed) algorithms perform similarly over seven data sets: Colon, TOX-171, Leukemia1, Leukemia2, GCM, tr12.wc, and tr23.wc (see [82, Tables IV–VII], some accuracies for other data sets are not available). The obtained Friedman statistics is 60.13, which is significant at $\alpha = 0.001$, as the corresponding statistic χ^2 with 28 degrees of freedom is 56.90. Thus, Friedman test suggests existence of significant difference among the algorithms.

V. CONCLUSION

In this paper, we have used a MOGP, called ASMiGP, to evolve diverse sets of binary classifiers to solve multiclass classification problems. Simultaneous FS and rule extraction are performed during the genetic evolution. An important objective of this paper is to find simple classification rules that may be human understandable, which in the given context translates to rules with simple operations and short length. The proposed method is found to achieve its goal.

Ensembles perform better when weighted voting is used, the members of the ensembles are diverse enough, and the classifiers are accurate [21]. Here, we have created c sets of diverse ensembles. Unlike other ensemble-based method, here each ensemble represents diverse classifiers for just one class. The number of features used by the ensembles is high with respect to the number of features selected per (binary classifier) tree. This suggests that the binary classifiers are diverse enough. In our algorithm, we evolve c distinct species in parallel, which try to learn distinct patterns and no interspecies gene exchange is ever allowed. This property makes each species different from the other species and the system becomes less vulnerable, especially when each species has successfully learnt its designated patterns.

Our method has been tested on nineteen (eight microarray and eleven text) data sets. The experimental results show that we could find easy-to-understand rules for overall 63.2% (87.5% for microarray and 54.5% for text) data sets. We compared our method with four classification methods in conjunction with seven FS methods including use of the all-feature set. For 80.17% (61.40% for microarray and 95.75% for text) cases our method outperforms others. The improvement in performance is shown statistically significant compared to the others.

The overall performance of the proposed method is better on text data sets compared to that of microarray data sets. Two important differences between these two groups of data sets are that: 1) microarray data sets have comparatively large feature-to-sample ratios and may not have enough number of points in each class for MOGP to learn the structure of the data sets and 2) the text data sets have comparatively large number of classes as well as instances. Our limited experiments suggest that when there are enough points in each class so that each species can successfully learn its target pattern, the proposed method works better. We found that for text data our method performs noticeably better than the other methods particularly when number of classes is high (ten or more than that).

We have shown that our method is very effective when the dimension of the data sets are as high as 49 151. But in all our data sets, number of samples were not very big. If we apply the proposed method on a data set with a really large number samples, it may require a significant amount of time. The method may also take a substantial amount of time when the number of classes is high and we have limited parallel processing capability. With the today's high performance computing technologies, however, these are not really crucial shortcomings. Yet, we have not applied it to truly big data. This paper can be adapted to deal with big data, especially using Hadoop.

Our future research interest is to use MOGP to classify multiclass text data, where each text may belong to more than one category (class) and to use net belongingness as a fuzzy membership of the documents to the corresponding category. We also intend to modify the proposed learning method to stepwise learning, so that we can use it for big text data.

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A Multiobjective Genetic Programming-Based Ensemble for Simultaneous Feature Selection and Classification

Kaustuv Nag and Nikhil R. Pal, *Fellow, IEEE*

***Abstract*—We present an integrated algorithm for simultaneous feature selection (FS) and designing of diverse classifiers using a steady state multiobjective genetic programming (GP), which minimizes three objectives: 1) false positives (FPs); 2) false negatives (FNs); and 3) the number of leaf nodes in the tree. Our method divides a *c*-class problem into *c* binary classification problems. It evolves *c* sets of genetic programs to create *c* ensembles. During mutation operation, our method exploits the fitness as well as unfitness of features, which dynamically change with generations with a view to using a set of highly relevant features with low redundancy. The classifiers of *i*th class determine the net belongingness of an unknown data point to the *i*th class using a weighted voting scheme, which makes use of the FP and FN mistakes made on the training data. We test our method on eight microarray and 11 text data sets with diverse number of classes (from 2 to 44), large number of features (from 2000 to 49 151), and high feature-to-sample ratio (from 1.03 to 273.1). We compare our method with a bi-objective GP scheme that does not use any FS and rule size reduction strategy. It depicts the effectiveness of the proposed FS and rule size reduction schemes. Furthermore, we compare our method with four classification methods in conjunction with six features selection algorithms and full feature set. Our scheme performs the best for 380 out of 474 combinations of data sets, algorithm and FS method.**

***Index Terms*—Classification, ensemble, feature selection (FS), genetic programming (GP).**

I. Introduction

CLASSIFICATION is one of the most important and frequently encountered problems in data mining and machine learning. A wide range of real world problems of different domains can be restated as classification problems. This includes diagnosis from microarray data, text categorization, medical diagnosis, software quality assurance, and many more. The objective of classification is to take an input vector $\boldsymbol{x} = (x_1, \ldots, x_d)^T$ and to assign it to one of the K classes $\boldsymbol{C_k}$, where $k = 1, \ldots, K$. A model, called classifier, is used to solve this problem. The classifier encodes a set of criteria. Depending upon some features of the data point, these criteria assign the data point to a particular class [1]. Sometimes, ensembles of weak classifiers are used to obtain better classification accuracy. High dimensionality, high feature-to-sample ratio, and redundant and/or noisy features are some common sources of difficulties associated with classification.

Feature selection (FS) is a process to select a small but useful subset of features from the set of available features which is adequate for solving the problem in an efficient manner. Some available features may be redundant, not useful, and may cause confusion during the learning phase. These unwanted features needlessly increase the size and complexity of the feature space. It increases the computation cost for learning, and may sometimes be responsible for finding suboptimal solutions of the problem. This makes FS techniques important for the analysis of high dimensional data sets, especially when feature-to-sample ratio is extremely high.

The microarray technology has made it possible to diagnose different types of cancers directly using the microarray data sets. One of the main difficulties we face to do this is the high feature-to-sample ratio of microarray data sets, which makes FS an important step. Finding keywords as well as contexts from text data is essential to detect (without human intervention) the context of web pages, emails, or questions/answers, etc. A large set of distinct words in large texts (high number of features) and many categories of texts (high number of classes) are the two complicated challenges that we face in this task.

Genetic programming (GP) [2]–[5] is a biological-evolution inspired methodology where each solution is a program or an equation that evolves with one or more objective functions to perform specific tasks. References [6]–[12] used GP to design classifiers or to generate rules for binary classification problems. Some researchers have also attempted to solve multiclass problems [13]–[17]. GP has also been used for simultaneous FS and classification [18]. Liu and Xu [19] used GP to create ensembles of classifiers (genetic programs). They have used these ensembles to classify microarray data sets. Though GP is a powerful tool, it has a drawback: without special care each genetic program (equation) becomes huge. As an effect, they do not learn the patterns in the training data. Rather, memorizes them. It also makes genetic programs to be difficult to comprehend. Besides, though ensembles can

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perform better than individual classifiers [20], to obtain better performance, each ensemble should be diverse and each member of the ensemble should be accurate [20]–[22]. Without special care, due to lack of explicit diversity preservation AQ2 mechanism, the solutions of single objective GP may lose diversity.

The objective of this paper is to find an embedded methodology of simultaneous FS and classification employing GP as a tool. Some of the novel contributions of our schemes are as follows. We have introduced a new multiobjective GP (MOGP), called archive-based steady state micro GP (ASMiGP). It is enriched by several new operators. The mating selection judicially uses Roulette wheel selection, instead of two tire multiobjective selection scheme (where domination is preferred over diversity). The crossover is new and uses male– AQ3 female differentiation so that the off-spring is more likely to be close to the female parent in the genotypic space. The mutation is restrictive and performs less exploration in the hypothesis space. Thus, it reduces disruption. For feature nodes, instead of fitness, mutation uses unfitness to select the mutation point. Altering the fitness and unfitness of the features in different stages of learning, we change the objective of searching in the corresponding stages. We use ASMiGP to learn c diverse sets of classifiers (equations) minimizing three objectives: 1) false positive (FP); 2) false negative (FN); and 3) number of leaf nodes of a tree to restrict the rule size. Throughout the learning process, implicit FS is performed using MOGP, whereas several filter-based approaches are used in different stages of the procedure. In this way, we obtain concise rules that involve only simple arithmetic operations. A weighted negative voting is then used among the rules of each ensemble. These weights are determined on the basis of the performance of the binary classifiers on the training data set. A new measure of weighted negative voting, called net belongingness, is also introduced.

The proposed method has been tested on eight multiclass microarray data sets having large number of features, varying from 2000 to 49 151, and high feature-to-sample ratio, varying from 32.26 to 273.06. It has also been tested on eleven high dimensional (varying from 3182 to 26 832) text data sets, where the number of classes (categories) vary from 6 to 44. Experimental results reveal that our method can generate ensembles of classifiers with concise rules that can do a good job of classification with a small subset of features.

II. Background and Related Works

This section provides a background to GP, GP-based online FS and classification, ensembles, voting schemes, and concise rule finding. This section also includes some related works on these topics.

A. Concise Introduction to GP

GP [2]–[5] is an approach to find programs that can solve a given problem. GP uses Darwinian principle of "survival of the fittest." It evolves the programs using biologically inspired genetic operations like reproduction, crossover, and mutation in the search space to find such programs which would be able to solve the given problem [15], [23], [24]. The overall search process of traditional single objective GP is quite similar to traditional population-based genetic algorithm. The main difference among them is in the representation of solutions. The usual steps of traditional single objective GP can be found in [2], [15], and [24].

There exist several ways to encode a program. Probably, the most popular one is to use a tree structure [25]–[27] which we use. In tree-based GP, a program is represented by a tree where the internal nodes are from a set of functions $\mathcal{F}$, and the leaf nodes are from a set of terminals $\mathcal{T}$. The subtrees of a function node are the arguments of that function. The sets $\mathcal{F}$ and $\mathcal{T}$ must satisfy the closure and sufficiency properties [2], [15]. To satisfy the closure property, $\mathcal{F}$ must be well defined and closed for any combination of probable arguments that it may encounter [15]. Again, to satisfy the sufficiency property, $\mathcal{F}$ and $\mathcal{T}$ must be able to represent any possible valid solution of the problem.

B. FS: Why Embedded?

FS methods are generally divided into two main groups: 1) filter method and 2) wrapper method [28]. A filter method does not use any feedback from the classifier or any mining algorithm. It relies on the general characteristics of data. On the contrary, to measure the goodness of features, a wrapper method uses a predetermined classifier or mining algorithm, which will finally use the selected features. Consequently, a wrapper method exploits interactions among the subset of features on which it is tested. But, to find an optimal set of features, a wrapper method needs to measure performances on all possible subsets of features. This becomes infeasible for high dimensional data sets. To overcome this problem, wrapper methods typically use a heuristic-based forward or backward selection mechanism [28], which does not evaluate all possible subsets. So, in this paper, we consider embedded methods, where FS and designing of the classification system are done together. Embedded methods do not need to evaluate all possible subsets. Moreover, they can account for interaction between features and the classifier that is used to solve the problem [29]. Usually, embedded methods attain comparable accuracy to wrapper methods as well as comparable efficiency to filter methods. Though for every classification tool it may not be easy to define such an integrated mechanism, several attempts of FS using embedded methods have already been made. These attempts include using single objective GP [18], neural networks [30], [31], and support vector machines [32].

C. GP in Classification and FS

Many researchers have used GP as a tool for classification and FS. Some literature on this topic can be found in [1] and [33]. It has been used in both filter [34]–[37] and wrapper [38]–[41] approaches. GP has also been used for extracting decision trees [42]–[47]. Among these in [45] and [46], MOGP has been used. GP has also been adopted for learning rule-based systems [7]–[9], [48]–[51]. Both binary classification [6], [7], [10]–[12], [48] and multiclass [8], [9], [13]–[17], [49]–[51] classification problems have been addressed by GP-based (rule-based) systems. Even, researchers have applied GP-based (rule-based) system for binary classification of imbalanced data [52], [53]. Discriminant functions (DFs)-based GP for online FS and classification has been adopted in [18] to solve multiclass problems. It is noteworthy that GP has also been used in feature extraction for edge detection [54].

Since, in this paper, we have used MOGP for learning DFs, we discuss some relevant GP-based systems. In DFs-based GP, each program is a mathematical equation, where the variables are features of the data. Usually every program is associated with a class. For every input data point, the program converts it to a single output value. If this output value is more than a predefined threshold (usually zero), the point belongs to the class to which the program is associated with. Thus, a single equation is enough for binary classification problems. For c-class problems, there are two common ways. The first and more frequently used approach is to consider a c-class problem as c binary classification problems [1]. Thus, c number of DFs are used to discriminate c classes. The second and less popular approach is to use a single DF with $(c - 1)$ threshold values to create c intervals. Each of these intervals is then assigned to a particular class. For both categories, a common practice is to evolve a population where each individual encodes either one (for binary classification problems having single threshold, or for multiclass problems having multiple thresholds) or multiple DFs each of which uses a single threshold. Such encoding schemes have been used in [15] and [18]. In another practice, each solution encodes multiple DFs having a single threshold. The final output value in this case may be obtained using a (weighted) voting scheme among the output values of each function of the same individual. An example of this scheme can be found in [19].

In the recent years, researchers have made some notable attempts to solve classification problems using MOGP. Wang *et al.* [55] proposed a MOGP to obtain a group of nondominated classifiers, with which the maximum receiver operating characteristic convex hull (ROCCH) can be obtained. To achieve this, they have adopted four different multiobjective frameworks into GP. For further improvement of each individual GPs performance, they have defined two local search strategies that have been especially designed for classification problems. The experimental results in [55] have demonstrated the efficacy of the proposed memetic scheme in their MOGP framework. Another convex hull-based MOGP, called CH-MOGP, can be found in [56]. Wang *et al.* [56] showed the differences between the conventional multiobjective optimization problem and ROCCH maximization problem. Wang *et al.* introduced a convex hull-based sorting without redundancy and a new selection procedure which are suitable for ROCCH maximization problem. Again, Bhowan *et al.* [22] proposed a MOGP-based approach that is especially designed for unbalanced data sets. This approach [22] evolves diverse and accurate ensembles of GP classifiers with good performance on both the majority and the minority classes. The individual members of the evolved ensembles, that are composed of nondominated solutions, vote on class membership.

D. GP, Bloating, and Concise Rules

During evolution of GP, variable length genomes gradually start to increase its length without significant improvement in fitness. This incident, called bloating [57], is a well known phenomenon in GP. Bloating causes genetic programs: 1) to keep reducible genome structures and 2) to memorize training data points, rather than recognizing patterns hidden in them. To find rules which are to some extent human interpretable and can be analyzed, each of the genetic programs must be concise. A plausible way to achieve this target is to control bloating. A popular way to handle bloating is to take into account the program size [2], [58]–[61]. Some other methods include spatially-structured populations [62], [63], island-based models to introduce spatial structure to the population [62], [63], intron deletion [64], and dynamic population sizing [65], [66]. Song *et al.* [67] attempted to understand the GP evolved solutions; while Luna *et al.* [68] attempted to find comprehensible rules in subgroup discovery.

E. Ensemble Classifier

In classification, the basic task is to search through a hypothesis space to find a suitable hypothesis that will be able to classify the data points in a better way. An ensemble combines multiple hypotheses to form a better one [19], [21], [22], [53], [69], [70]. Empirically, an ensemble performs better when each of the classifiers is highly accurate (strong learner) and the members of the ensemble are significantly diverse. The explanation behind the better performance of ensemble classifiers than a single classifier has been described in [20]. Normally, to decide the class label of a data point, the member classifiers of an ensemble use (weighted) voting. Ensembles are often used in bio-informatics [71].

III. Proposed Work

A. Representation of Classifiers or Solutions

In this paper, we evolve c-populations of genetic programs. Each individual of these populations is a binary classifier. Each binary classifier is represented by a single tree. When a data point is passed through an individual of the ith population, if the output value is positive, the individual says that the passed data point belongs to the ith class; otherwise it says that the point does not belong to that class. The internal (nonleaf) nodes of these trees are functions $\mathcal{F}$. The terminal nodes must be either a feature or a constant from the set $\mathcal{C}$. We have imposed some constraint on the minimum size (architecture) of the trees. In each tree there must be at least one function node and two terminal nodes (with at least one feature node). Though, a single feature (terminal) node might be enough to determine the class label, this would rarely happen in practice. The above restrictions make the trees more useful without any loss of generalization capability. Again, after generation of any tree throughout the learning phase (using mutation, crossover, or random initialization), the largest subtree consisting of only constants as its leaf nodes is replaced by a constant leaf node having the equivalent constant value.

B. MOGP for Learning

Larger genetic programs may memorize the training patterns which, in turn, may increase the training accuracy and reduce the understandability of the rules. Therefore, we aim to find smaller but accurate classifiers. Again, when c is high enough, even a balanced c-class data set may get converted to c number of highly imbalanced bi-classification data sets. Instead of minimization of classification error, simultaneous minimization of FP and FN would be more appropriate in this regard. Suppose a classifier makes some mistakes $m = m_p + m_n$ on a given training data set, where m_p and m_n are, respectively, the number of FPs and FNs. Consider two classifiers, each making the same number of mistakes m on a given data set. Let for the first classifier $m_p = m_n$ and for the second classifier $m_p \gg m_n$ or $m_p \ll m_n$. If the cost of an FP is the same as that of a FN, we would prefer the first classifier. Consequently, minimization of both FP and FN would be a better strategy than minimization of the total number of misclassification, particularly for imbalanced data sets. Thus, we have three objectives, i.e., minimizations of: 1) FP; 2) FN; and 3) rule size. Moreover, when different classes are overlapped, minimization of FP is usually in conflict with the minimization of FN and vice versa. Multiobjective optimization is more suitable when we need to optimize more than one conflicting objective. Therefore, during the learning of each binary classifier, we minimize three objectives using an MOGP: 1) FP; 2) FN; and 3) number of leaf nodes in the tree. The third objective is used to reduce the size of the tree which enhances the understandability and reduces the pattern memorization capability. The algorithm, proposed in this paper, is called ASMiGP, which is presented in Algorithm 1.

Algorithm 1: ASMiGP

```
Initialize population using ramped-half-and-half method.
Initialize the archive solutions using initial solutions.
while $Evaluations^{Current} \leq Evaluations^{Maximum}$ do
    repeat
        operator = Select crossover or mutation.
        if $operator == crossover$ then
            Select male and female parents (mating
            selection).
            Perform crossover.
        end
        else
            Select an individual (mating selection).
            Mutate the individual.
        end
    until the infix equation of off-spring is distinct from
    infix equation of any individual of the archive
    Evaluate the new off-spring.
    $Evaluations^{Current} = Evaluations^{Current} + 1$
    Update the archive using new offspring
    (multi-objective environmental selection).
end
$\mathcal{F}ronts$ = Perform fast-non-dominated-sort.
return first front of $\mathcal{F}ronts$.
```

In an evolutionary search, it is desired to have as many generations as possible and steady state nature of an algorithm maximizes the number of generations when the number of function evaluations is fixed [72]. Due to maximization of generations, a steady state evolutionary search is more exploitative to enhance the searching in a region which is more likely to have or closer to the Pareto front and avoiding exploration in regions that are less likely to improve the solutions. It causes faster convergence. In other words, independent of the fitness evaluation process, steady state selection is more performant than discrete generational selection [73]. Therefore, we have used a steady state algorithm instead of a generational one.

C. FS

In this paper, we have used the embedded model of FS. Explicit FS is performed during population initialization and mutation. Implicit FS is performed during crossover. Filtering is also performed at three different stages of the learning process; in particular, at the beginning and after 50% and after 75% of evaluations as described next in this subsection.

To facilitate the FS, following [74], we define an index that assesses the discriminating ability of a feature. Consider a two-class problem. Note that for a multiclass problem, the one-versus-all case can also be viewed as a two-class problem. Let there be n_p number of training points and the class label for the jth data point be $+1$ if it belongs to class 1 and -1 if it belongs to class 2. Let the value of the fth feature for the ith data point be f_i; $i = 1, \ldots, n_p$. If the fth feature is a good discriminatory feature then for all data points from class 1, it should have high values and for all points from class 2, it should have low values or vice-versa. Hence for a good discriminatory feature, we can define an ideal feature vector with values 1, if the data point is from class 1 and 0 otherwise; or the feature value is 0, if it is from class 1, otherwise, it is 0. Let $\mathbf{S}_f$ be the vector containing the ideal feature values for feature f and s_{fi} be the ideal feature value of the fth feature for the ith sample. Note that, there could other important features that are not linearly related to the class structure. We are not considering them in this preliminary filtering step. As in [74], we compute the Pearson's correlation (or any other measure of similarity) between f and s as a measure of feature relevance

$$C_f = \sum_{j=1}^{n_p}\left(s_{ji} - \bar{s}\right)\left(f_j - \bar{f}\right) \Bigg/ \sqrt{\sum_{j=1}^{n_p}\left(s_{ji} - \bar{s}\right)^2 \sum_{j=1}^{n_p}\left(f_j - \bar{f}\right)^2}. \tag{1}$$

A higher value of $|C_f|$ indicates a stronger discriminative power of feature f. For a multiclass problem, using the one-versus-all strategy, for the ith binary classification problem (class i versus the rest), the correlation for the fth feature is denoted by C_f^i.

Now, we describe the FS procedure. Let the set of all features be $\mathcal{F}_{\text{all}}$. We intend to incorporate only those features from $\mathcal{F}_{\text{all}}$ which are more likely to help the classifiers to decide the class label. We assign different fitness and unfitness measures to the features during the learning phase. To remove a feature node from any tree (during mutation), we select it using Roulette wheel selection on the unfitness values of the features which are present in that tree. Similarly, when a new feature is inserted in the tree, it is selected using Roulette wheel selection on the fitness values. During the first 50% evaluations, the fitness and unfitness features are defined as

$$F^{0\%,i}_{\text{fitness}}(f,i) = \begin{cases} \left(\dfrac{C^i_f}{C^i_{\max}}\right)^2, & \text{if } \dfrac{\left|C^i_f\right|}{C^i_{\max}} > 0.3 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

$$F^{0\%,i}_{\text{unfitness}}(f,i) = 1.0 - F^{0\%,i}_{\text{fitness}} \tag{3}$$

where $C^i_{\max} = \max_{f \in \mathcal{F}_{\text{all}}} |C^i_f|$. Equation (2) sets the fitness of very poor (poor with respect to its discriminating power) to zero to eliminate their impact during the initial evolution. Let $\mathcal{F}_{\text{eval}=0\%,i} \subseteq \mathcal{F}_{\text{all}}$ be the features with nonzero fitness values. Basically, at this stage we are using a filter on the feature set $\mathcal{F}_{\text{all}}$ to obtain a smaller feature set.

After completion of 50% evaluations for each population, we find the features used in that population. Let the feature set be $\mathcal{F}_{\text{eval}=50\%,i}$. Then we make the fitness of all features in $\mathcal{F}_{\text{all}} - \mathcal{F}_{\text{eval}=50\%,i}$ to zero. This is done with the assumption that after 50% evaluations useful features have been used by the collection of decision trees. Now, the fitness and unfitness values of all features in $\mathcal{F}_{\text{eval}=50\%,i}$ are modified according to (4) and (5), respectively

$$F^{50\%,i}_{\text{fitness}}(f,i) = \begin{cases} \dfrac{|C^i_f|}{\sum\limits_{\substack{f \neq g \\ g \in \mathcal{F}_{50\%,i}}} |\rho_{fg}|}, & \text{if } f \in \mathcal{F}_{\text{eval}=50\%,i} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

$$F^{50\%,i}_{\text{unfitness}}(f,i) = e^{-\frac{F^{50\%,i}_{\text{fitness}}(f,i) - \min_f\left\{F^{50\%,i}_{\text{fitness}}\right\}}{\max_f\left\{F^{50\%,i}_{\text{fitness}}\right\} - \min_f\left\{F^{50\%,i}_{\text{fitness}}\right\}}} \tag{5}$$

where ρ_{fg} is the Pearson's correlation between fth and gth features. Here, we try to select features with higher relevance but reducing the redundancy in the set of selected features. The fitness, defined in (4), increases when the feature is highly correlated with class label. Similarly, it reduces when it is more correlated with other existent features. This is done to achieve maximum relevance minimum redundancy.

After 75% function evaluations, again we take another snapshot of the population. Let the existent features for the population be $\mathcal{F}_{\text{eval}=75\%,i} \subseteq \mathcal{F}_{\text{eval}=50\%,i}$. Then, the fitness and unfitness values of the features in $\mathcal{F}_{\text{eval}=75\%,i}$ are defined in (6) and (7), respectively

$$F^{75\%,i}_{\text{fitness}}(f,i) = \begin{cases} F^{0\%}_{\text{fitness}}(f,i), & \text{if } f \in \mathcal{F}_{\text{eval}=75\%,i} \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

$$F^{75\%,i}_{\text{unfitness}}(f,i) = 1.0 - F^{75\%,i}_{\text{fitness}}(f,i). \tag{7}$$

D. Population and Archive Initialization

We initialize each population using ramped-half-and-half method. While constructing the random trees, selection of terminal nodes has been made with a probability p_{var}. To insert a terminal node in a tree, a random number r_n is drawn in [0, 1]. If $r_n < p_{\text{var}}$ then a feature node is added, otherwise a constant node is added. The function nodes are chosen from the set $\mathcal{F}$, with equal probability of inclusion for all functions. The feature nodes are selected using Roulette wheel selection on fitness $F^{0\%}_{\text{fitness}}$, defined in (2).

To initialize the archive from the initial population, we have used the multiobjective archive initialization scheme present in [72] and [75]. It requires two parameters: 1) maximum archive size ($N_{\max}$) and 2) minimum archive size ($N_{\min}$).

E. Selection of Crossover or Mutation

Since ASMiGP is a steady state MOGP, in each generation we generate only one offspring. We use either crossover or mutation to do that. A random number r_c is drawn in [0, 1]. if $r_c < p_c$ then crossover operator is selected otherwise the mutation operator is selected for that generation.

F. Mating Selection

ASMiGP uses crossover with male and female differentiation which needs one male and female parent. We perform Roulette wheel selection using classification accuracy of the binary classifiers as fitness to select the female parent. Then the male parent is selected randomly from the remaining archive. The only condition to be satisfied is that the male and female parents must be distinct. For mutation, we need only one individual and it is selected in the same way as done for the female parent in case of crossover operator.

A choice of mating selection could have been the use of some bi-level selection operator, where Pareto dominance is preferred over diversity. In that case, solutions along the whole Pareto optimal solution set with good diversity would have been selected as the primary (female) parents. Note that, we have used crossover with male–female differentiation that tries to generate an off-spring near the primary parent in the hypothesis space. Consequently, this might cause generation of Pareto optimal binary classifiers along the whole Pareto optimal solution set. Though they are Pareto optimal, these binary classifiers may have poor accuracies. This is because of the implicit imbalance nature of the binary classification problems (due to conversion from multiclass classification problems) and different classifier sizes. An ensemble classifier, however, performs better when individual members of the ensemble are more accurate. Therefore, we use classification accuracy-based mating selection. It guides the search to generate more accurate binary classifiers.

G. Crossover

In this paper, we have used crossover operation with male and female differentiation. We want the off-spring to be near the female (acceptor) parent in the hypothesis space. The male (donor) parent is used to make the off-spring diverse from its mother. To do this, two random points (nodes) are selected from each of the parents. The probabilities of selection of terminal nodes and function nodes as a crossover point (node) are, respectively, p_t^c and $(1 - p_t^c)$. Then, the subtree rooted at the selected node of the mother tree is replaced with a similarly selected subtree from the father tree. If the off-spring is identical to any of its parents, the whole procedure is repeated (before evaluation/learning of the off-spring).

H. Mutation

In most of the GP-based systems, for mutation a subtree rooted at a randomly selected node is replaced by a new randomly generated subtree. Though this kind of mutation explores more in the hypothesis space, it may be too disruptive in nature. Therefore, we intend to use less exploration by keeping the tree structure unaltered. During mutation we perform the following operations on a tree.

1) Each constant of the tree is replaced by another random constant with probability p_c^m.
2) Each function node of the tree is replaced by anther random function node with probability p_f^m.
3) Only one feature node of the tree is replaced by another feature node.

For feature nodes, to select the mutation point Roulette wheel selection is performed on the unfitness of the features which are present in the tree. Similarly, to insert a new feature at the mutation point, we select a feature using Roulette wheel selection based on the fitness values (probability proportional to fitness) of the features.

This restricted mutation scheme ensures that the tree structure of an equation remains the same. It also ensures that the variables in an equation do not change drastically—changing more than one variable would shift the solution (equation) in the hypothesis space by a larger amount.

I. Environmental Selection

ASMiGP uses the archive truncation strategy used in [72] and [75]. This multiobjective archive truncation strategy uses Pareto-based fitness function, i.e., fitness is Pareto dominance rank. This scheme maintains an archive (ensemble) which has an adaptive and dynamic size. It does not allow the archive to fall below a minimum size ensuring diversity in the genotypic space. Moreover, the environmental selection diminishes the exploration in areas of objective space that are less likely to yield improved solutions [72], ensuring diversity in phenotypic space. Furthermore, we have made the following difference in the environmental selection. ASMiGP ensures that the infix expression of every off-spring (after mutation or crossover) is distinct from every member of the archive. To achieve this, before evaluating the offspring, ASMiGP converts it to its infix expression and then compares the expression with that of each individual of the archive. Only if the expression is unique, the off-spring is evaluated and added to the archive. Otherwise it is discarded and a new off-spring is generated. Another noticeable difference is that here the number of objectives is three. Note that the diversity maintenance in each ensemble both in phenotypic space and in genotypic space finds a diverse set of trees (bi-classifiers). Trees, being diverse, enhance the performance of the corresponding ensemble. In this context, it is worth mentioning that the archive, along with the archive truncation strategy, helps to realize a good Pareto front by explicitly maintaining diversity among the fit (according to rank) solutions. However, the archive alone is not sufficient to evolve a good Pareto front along all the objectives.

J. Decision Making

To determine the class label, we find the net belongingness of a point to each class. The net belongingness lies in [0, 1]. A higher value indicates more net belongingness to that class. A data point is assigned to that class for which it has the highest net belongingness.

After the learning, we obtain a set of c archives, $\mathcal{A} = \{\mathcal{A}_1, \mathcal{A}_2, \ldots, \mathcal{A}_c\}$; $\forall i, 1 \leq |\mathcal{A}_i| \leq N_{\max}$, where c is the number of classes, and $\mathcal{A}_i$ is the set of all binary classifiers for the ith class. To determine the net belongingness of a data point $\mathbf{p}$ to class m, $\mathcal{B}_m^{\text{net}}(\mathbf{p})$, it is passed through all genetic programs of set $\mathcal{A}_m$. The net belongingness, $\mathcal{B}_m^{\text{net}}(\mathbf{p})$, of the point $\mathbf{p}$ for class m is computed using

$$\mathcal{B}_m^{\text{net}}(\mathbf{p}) = \frac{1}{2}\left(\frac{1}{|\mathcal{A}_m|}\sum_{i=1}^{|\mathcal{A}_m|}\mathcal{B}_m^i(\mathbf{p}) + 1.0\right) \tag{8}$$

where $\mathcal{B}_m^i$ is defined as

$$\mathcal{B}_m^i(\mathbf{p}) = \begin{cases} +\left(1.0 - \dfrac{\text{FP}_m^i}{\text{FP}_m^{\max}}\right), & \text{if } \mathcal{A}_m^i(\mathbf{p}) > 0 \\ -\left(1.0 - \dfrac{\text{FN}_m^i}{\text{FN}_m^{\max}}\right), & \text{otherwise.} \end{cases} \tag{9}$$

In (9), FP_m^i and FN_m^i, respectively, represent the number of FPs and FNs made by the ith individual in set $\mathcal{A}_m$ on the training data. $\text{FP}_m^{\max}$ and $\text{FN}_m^{\max}$ are, respectively, the maximum possible FP and the maximum possible FN for the mth class; and $\mathcal{A}_m^i(\mathbf{p})$ is the output from ith individual of $\mathcal{A}_m$ for input data point $\mathbf{p}$. Finally, $\mathbf{p}$ is assigned the class k, when $\mathcal{B}_k^{\text{net}} = \max_{m=1}^{c}\{\mathcal{B}_m^{\text{net}}\}$. Note that $\text{FP}_m^{\max}$ and $\text{FP}_m^{\min}$ are determined by the training data.

The concept of net belongingness is inspired by the concept of negative voting. Negative voting has been widely used in diverse applications [76]–[78]. It is more effective when circumstances unfavorable to the preferences invoke stronger electoral responses than the similar favorable responses, as well as the behaviors of the voters are well defined [79]. In our scheme, the learners for the ith class learn to vote yes for the points of the ith class and no for the points which do not belong to the ith class. For multiclass problems, it is more likely that a binary classifier learns to say no than to say yes for a much higher number of points. Therefore, we found negative voting to be more suitable in this context. However, we have used a weighted negative voting scheme. The accuracies for the responses yes and no of the ith binary classifier of mth class are, respectively, $\left(1.0 - \text{FP}_m^i/\text{FP}_m^{\max}\right)$ and $\left(1.0 - \text{FN}_m^i/\text{FN}_m^{\max}\right)$. These values have been used as corresponding weights for the responses yes and no of the ith binary classifier of the mth class. We have used the positive

TABLE I
PARAMETER SETTINGS FOR THE PROPOSED METHOD

Parameter	Value
Set of functions ($\mathcal{F}$)	$\{+, -, \times, \div\}$
Range of initial values of constants ($\mathcal{C}$)	[0, 2]
Maximum depth of tree during initialization	6
Maximum allowable depth of tree	10
Maximum archive size (N_{max})	50
Minimum archive size (N_{min})	30
Initial Probability of feature nodes (p_{var})	0.8
Probability of crossover (p_c)	0.8
Probability of crossover for terminal nodes (p_t^c)	0.2
Probability of mutation for constants (p_c^m)	0.3
Probability of mutation for function nodes (p_f^m)	0.1
Function evaluations for each binary classifier	400000

TABLE II
SUMMARY OF MICROARRAY DATA SETS

	Data Set	Features (F)	Samples (S)	Classes (C)	$\left(\frac{F}{S}\right)$
1	Colon	2000	62	2	32.26
2	TOX-171	5748	171	4	33.61
3	Leukemia 1	7129	34	2	209.68
4	Leukemia 2	7129	38	2	187.61
5	CLL-SUB-111	11340	111	3	102.16
6	GCM	16063	144	14	111.55
7	SMK-CAN-187	19993	187	2	106.91
8	GLA-BRA-180	49151	180	4	273.06

and the negative signs to indicate acceptance and rejection of the data point for the *m*th class, respectively.

IV. EXPERIMENTATION

A. Experimental Settings

We have repeated tenfold cross validation of the proposed method for ten times. Table I shows the parameter settings that we have used for this purpose. The training data is Z-score normalized. Furthermore, based on the means and the standard deviations of the features of the training data, the test data was Z-score normalized. Note that except $N_{\max}$ and $N_{\min}$, all parameters are standard parameters used in any GP simulations, while $N_{\max}$ and $N_{\min}$ are needed for archive maintenance. Although all the parameters can be chosen using a cross validation mechanism, because of huge computational overhead, we could not do that. Based on a few experiments we selected these parameters. These choices are not optimal. However, since the same set of values are used for widely different types of data sets, it demonstrates the effectiveness of the proposed scheme. The proposed method has been implemented in Java with the help of jMetal [80], [81].

We have used eight microarray and eleven text data sets which are summarized in Tables II and III, respectively.

B. Importance of FS and Rule Size Reduction

To demonstrate the importance of the proposed FS and rule size reduction scheme, we have compared our method with GP without FS and no restriction to equation size. To do that, we have made the following changes in the proposed method.

1) No explicit FS as described in Section III-C is done.
2) There are only two objectives, FP and FN.

TABLE III
SUMMARY OF TEXT DATA SETS

	Data Set	Features (F)	Samples (S)	Classes (C)	$\left(\frac{F}{S}\right)$
1	oh0.wc	3182	1003	10	3.17
2	oh10.wc	3238	1050	10	3.08
3	tr12.wc	5804	313	8	18.54
4	tr23.wc	5832	204	6	28.59
5	tr11.wc	6429	414	9	15.53
6	tr21.wc	7902	336	6	23.52
7	wap.wc	8460	1560	20	5.42
8	ohscal.wc	11465	11162	10	1.03
9	la2s.wc	12432	3075	6	4.04
10	la1s.wc	13195	3204	6	4.12
11	new3s.wc	26832	9558	44	2.81

All other parts of the algorithm and the parameter values remain unchanged. Similar to the proposed scheme, we have also executed tenfold cross validation for ten times for all the data sets. Along with results (mean values of the corresponding ten runs) obtained using the proposed method, the results obtained using this scheme for microarray and for text data sets are, respectively, summarized in Tables IV and V. From these two tables, we observe the following.

1) In all cases, the test accuracy is much higher for the proposed method. Especially, for GCM having 14 classes, the difference between the test accuracies are remarkably high.
2) The tree size increases significantly when the third objective, i.e., the restriction on rule size, is not used.
3) For most of the data sets the proposed method selects smaller number of distinct features per tree as well as for per classifier.

These observations clearly demonstrate the importance of the FS as well as constraining the rule size. Since our FS scheme discards features with poor relevance and uses features with good discriminating power yet avoiding use of redundant features, it not only makes the discovery of useful rules easier but also implicitly constrains the rule length. Thus, FS plays a very important role having two positive impacts: it makes identification of useful rules easier and it promotes the minimization of the third objective.

C. Comparing With Other Methods

To compare the performance of the proposed method we have used the experimental results reported in [82] (see [82, Tables IV–VII]). Song *et al.* [82] used four different types of classification algorithms: 1) probability-based naive Bayes (NB); 2) tree based C4.5; 3) instance-based lazy learning algorithm IB1; and 4) rule-based RIPPER both before and after FS. Along with the full feature set, they have used six FS algorithms in their experiment.

1) FAST [82].
2) FCBF [83], [84].
3) CFS [85].
4) ReliefF [86].
5) Consist [87].
6) FOCUS-SF [88].

TABLE IV
EXPERIMENTAL RESULTS ON MICROARRAY DATA SETS (MEAN VALUES OF TEN RUNS OF TENFOLD CROSS VALIDATION)

Data Set	%TA[a]		FS[b]		TS[c]		$(F/T)^d$		%F[e]		$(\%F/T)^f$	
	PM[g]	$W^h_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$
Colon	85.12 (2.07)	71.93 (4.12)	195.0	182.5	6.76	123.60	3.11	8.56	9.75	9.13	0.16	0.43
TOX-171	81.07 (3.42)	58.52 (4.57)	407.6	540.9	8.83	148.44	3.53	11.97	7.09	9.41	0.06	0.21
Leukemia1	93.50 (2.85)	74.08 (6.42)	188.6	276.6	3.01	76.09	2.00	6.52	2.65	3.88	0.03	0.09
Leukemia2	91.58 (3.67)	77.33 (6.84)	147.8	229.0	3.50	74.16	2.02	5.72	2.07	3.21	0.03	0.08
CLL-SUB-111	80.52 (2.60)	54.51 (3.51)	335.3	465.3	7.29	134.28	3.20	10.75	2.96	4.10	0.03	0.09
GCM	69.35 (1.96)	33.97 (2.60)	854.3	1086.0	4.70	105.42	1.91	6.22	5.32	6.76	0.01	0.04
SMK-CAN-187	68.68 (1.18)	62.12 (2.30)	319.9	435.8	22.23	135.88	6.41	15.33	1.60	2.18	0.03	0.08
GLA-BRA-180	68.22 (2.25)	58.89 (2.75)	784.4	569.9	11.30	150.81	4.33	11.40	1.60	1.16	0.01	0.02

[a] Test Accuracy (standard deviation is provided within parenthesis), [b] Number of Features Selected per Classifier, [c] Tree Size, [d] Number of Features per Tree, [e] Percentage of Features Selected, [f] Percentage of Features Selected per Tree, [g] Proposed Method, [h] GP without FS and Rule Size Reduction

TABLE V
EXPERIMENTAL RESULTS ON TEXT DATA SETS (MEAN VALUES OF TEN RUNS OF TENFOLD CROSS VALIDATION)

Data Set	%TA[a]		FS[b]		TS[c]		$(F/T)^d$		%F[e]		$(\%F/T)^f$	
	PM[g]	$W^h_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$	PM	$W_{F\&R}$
oh0.wc	87.75 (0.51)	70.53 (1.17)	484.1	2080.7	17.06	145.38	6.46	25.90	15.21	65.39	0.20	0.81
oh10.wc	81.06 (0.61)	66.11 (1.52)	439.6	2166.8	24.11	140.67	7.12	26.03	13.58	66.92	0.22	0.80
tr12.wc	87.86 (1.50)	60.55 (2.36)	603.7	1697.3	8.67	123.91	4.17	17.22	10.40	29.24	0.07	0.30
tr23.wc	93.95 (1.19)	64.90 (2.14)	396.5	1154.2	6.10	117.15	3.09	14.81	6.80	19.79	0.05	0.25
tr11.wc	86.08 (0.72)	64.63 (2.56)	631.6	1785.8	8.82	128.57	4.03	17.03	9.82	27.78	0.06	0.26
tr21.wc	89.64 (1.14)	71.46 (2.62)	362.0	1219.2	9.51	114.51	4.17	15.00	4.58	15.43	0.05	0.19
wap.wc	79.60 (0.60)	58.96 (1.64)	1199.8	4377.5	17.38	125.53	6.07	21.02	14.18	51.74	0.07	0.25
ohscal.wc	73.45 (0.23)	62.59 (1.21)	232.9	3853.8	63.48	111.52	7.78	24.87	2.03	33.61	0.07	0.22
la2s.wc	83.95 (0.62)	67.32 (0.99)	354.6	2369.1	53.17	133.76	11.41	28.65	2.85	19.06	0.09	0.23
la1s.wc	83.06 (0.36)	65.62 (1.05)	380.6	2372.0	56.40	133.21	12.30	28.35	2.88	17.98	0.09	0.21
new3s.wc	81.32 (0.27)	58.96 (1.64)	1674.2	4377.5	33.93	125.53	7.10	21.02	6.24	16.31	0.03	0.08

[a] Test Accuracy (standard deviation is provided within parenthesis), [b] Number of Features Selected per Classifier, [c] Tree Size, [d] Number of Features per Tree, [e] Percentage of Features Selected, [f] Percentage of Features Selected per Tree, [g] Proposed Method, [h] GP without FS and Rule Size Reduction

Use of all features can be viewed as the seventh FS algorithm. To make this paper comprehensive, we are not discussing the experimental settings used in [82]. Note that accuracies for few data sets for few pairs of FS schemes are not available in [82].

1) Results With Microarray Data Sets: Table IV presents the results of the proposed method on microarray data sets. We have already stated that for each classifier, Song *et al.* [82] used seven FS schemes (six FS method as well as the set of all features). For each FS method five repetitions of the tenfold cross validation experiment were done in [82]. And then, for each FS method, the average accuracy over the five repetitions is reported. We compare this average accuracy with the average accuracy that we have obtained by our method over the ten repetitions of the tenfold cross validation experiments. In particular, we count the number of cases (each case refers to one FS scheme) in which our algorithm outperforms. Note that, for some combination of data set and classifier, the total number of cases is less than seven as for those combinations some results are not available. Table VI reports these counts. To elaborate Table VI, consider the entry corresponding to column IB1 and row CLL-SUB-111. For the data set CLL-SUB-111, in [82, Table VI], Song *et al.* reported the performance of the algorithm IB1 for six different FS algorithms. Our algorithm is found to perform better than five of the six FS algorithms and hence the entry for row CLL-SUB-111 and column IB1 is 5/6. Note that, for this data set, Song *et al.* [82] did not report performance of IB1 using all features. All but the entries in the last column of Table VI are generated in the same manner. The last column of Table VI, which reports the row total, reveals that our method performs the best for 61.40% (132 out of 215) test cases.

TABLE VI
COMPARISON WITH NB, C4.5, IB1, AND RIPPER
ON MICROARRAY DATA SETS

Data Set	NB	C4.5	IB1	RIPPER	Total
Colon	4/7	2/7	4/7	6/7	16/28
TOX-171	4/7	7/7	3/7	7/7	21/28
Leukemia1	2/7	2/7	2/7	2/7	8/28
Leukemia2	5/7	6/7	6/7	5/7	22/28
CLL-SUB-111	4/7	6/7	5/6	4/7	19/27
GCM	4/7	7/7	6/7	7/7	24/28
SMK-CAN-187	2/6	2/6	2/6	2/6	8/24
GLA-BRA-180	3/6	5/6	1/6	5/6	14/24
Total	28/54	37/54	29/53	38/54	132/215

If we compute the percentage of features selected by the ensembles, it may not be very small for some data sets, like Colon. But, if we consider the number of features selected per binary classifier (tree), we find that this number is quite small, e.g., the maximum value is 0.16% for Colon. We assume that binary classifiers (binary trees) having less than twenty nodes are concise enough. We need to remember that we are talking about raw rules (equations) directly obtained from GP which are most likely affected by bloating. Simplification of these rules may lead to reduction in their sizes. Based on this, in all but one data set we could find easy to analyze rules. For SMK-CAN-187 the extracted rules are more complex possibly because of complex structure of the data.

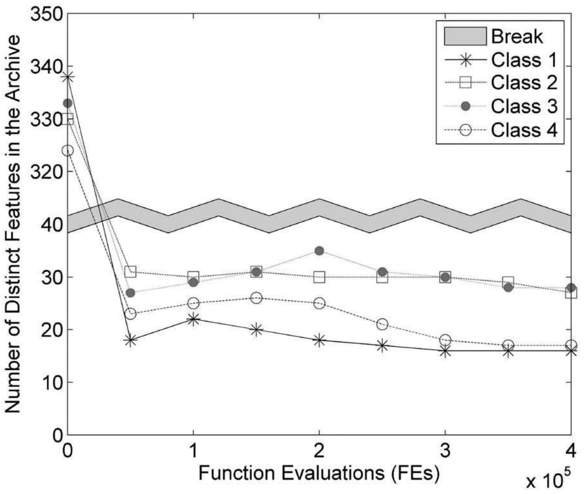

Fig. 1. Showing the number of distinct features present in the archive with respect to function evaluations for GLA-BRA-180 data set.

In Table S-I (see supplementary materials), we present the best rules (or binary classifiers or GPs) we found for each class of each microarray data set. These GPs have the highest training accuracy among the GPs obtained from the first fold of the first ten fold cross validation. If there are more than one rule having the same maximum training accuracy, the rule with the smallest length has been reported. The features in the equations are indexed starting from "0." From Table S-I, we can observe that for several classes the proposed method could find substantially small rules. Noticeably, for four, six, eight, and three classes, the proposed method could find the best binary classifier having only 1–4 distinct variables, respectively. So, 21 out of 33 (i.e., 63.64%) cases, we could find considerably small (and hence easy to interpret) rules. For some classes, the rules having the highest training accuracy were not very comprehensible because the length of the rule was not very small. If we think that $(2.0 \times x_i)$ is more easy to understand than $(x_i + x_i)$, though both equations have the same size, we observe that for 21 out of 33 (i.e., 63.64%) cases the proposed method could find rules having highest accuracy, which are not at all affected by bloating and are comprehensible without simplification.

To investigate how the number of distinct features changes in the archive, we have executed our algorithm with 400 000 function evaluations using the entire GLA-BRA-180 data set. In Fig. 1, we have plotted the number of distinct features after initial and after each 12.5% of maximum function evaluations. For all four classes of GLA-BRA-180 data set, the number of distinct features in the archive initially falls drastically depicting the impact of FS. After some generations, it becomes almost constant. Moreover, the number of final distinct features for each class is quite small. This indeed reveals a desirable behavior of the our scheme.

To show how the individual binary classifiers' accuracies change with function evolutions, we have plotted each individuals' FPs and FNs for all four classes of GLA-BRA-180 data set in Figs. S-1 and S-2 (see supplementary materials). For this part of the experiment also, we have used the entire data set for training. From the figures, it is observed that with the increase in number of evolutions, the average accuracy of the solutions tends to increase. However, for class four, some solutions having lower level of accuracies (having higher FPs and FNs) are there even after 400 000 function evaluations. This is because, even after such high number of function evaluations, the algorithm was still searching for more concise solutions, and could find some trees of comparatively smaller size.

TABLE VII
COMPARISON WITH NB, C4.5, IB1, AND RIPPER ON TEXT DATA SETS

Data Set	NB	C4.5	IB1	RIPPER	Total
oh0.wc	7/7	7/7	7/7	6/6	27/27
oh10.wc	7/7	7/7	7/7	6/6	27/27
tr12.wc	7/7	7/7	7/7	7/7	28/28
tr23.wc	7/7	5/7	7/7	4/7	23/28
tr11.wc	7/7	7/7	7/7	6/6	27/27
tr21.wc	6/7	6/7	6/7	3/6	21/27
wap.wc	7/7	6/6	6/6	6/6	25/25
ohscal.wc	4/4	4/4	4/4	4/4	16/16
la2s.wc	6/6	5/5	5/5	5/5	21/21
la1s.wc	6/6	5/5	5/5	5/5	21/21
new3s.wc	3/3	3/3	3/3	3/3	12/12
Total	67/68	62/65	64/65	55/61	248/259

2) Results With Text Data Sets: Similar to Table VI with microarray data sets, we present the same result (number of test cases for which our algorithm provides the best results for each classifier and data set pair) with text data sets in Table VII. Table VII reveals that for text data sets the proposed scheme performs the best for 95.75% (248 out of 259) cases.

If we consider the same criteria that binary classifiers (trees) having less than twenty nodes are concise enough, then our method could not find interpretable rules for 5 (oh10.wc, ohoscal.wc, la2s.wc, la1s.wc, and new3s.wc) out of the 11 text data sets. The number of selected features is not at all small for most of the text data sets. Some reasons behind this may be that the number of classes is high for the text data sets and the existence of more complex class structure, which is defined by the keywords and relation of keywords to the imposed classes is usually not as straightforward as genes have to cancers. However, the percentage of features selected per binary classifiers (trees) is quite small. Noticeably, the accuracy obtained for new3s.wc (having 44 classes), is much higher than that of the other methods (for accuracies of other methods, see [82]). We can also observe that for data sets having more than or equal to ten classes, our methods performs comparatively better than other methods.

D. Statistical Significance Testing

To compare the proposed method with existing FS and classification methods, we consider four classification and six FS methods as well as with the full feature set. Thus we compare our algorithm with 28 FS and classification algorithm pairs. We have performed Wilcoxon signed ranks test to show that the performance of the proposed algorithm is significantly different over 28 pairs of FS and classification algorithm. For this, we have considered both the microarray and the text data sets together and have used the average test

TABLE VIII
WILCOXON SIGNED RANKS TEST (ONE-TAILED) FOR PAIRWISE COMPARISONS WITH THE PROPOSED METHOD AT $\alpha = 0.05$

	NB	C4.5	IB1	RIPPER
FAST	A	R	R	R
FCBF	R	R	R	R
CFS	R	R	R	R
ReliefF	R	R	R	R
Consist	R	R	R	R
FOCUS-SF	R	R	R	R
Full Set	R	R	R	R

A: H_0 Accepted, R: H_0 Rejected.

accuracies achieved with different algorithms on these data sets. Moreover, we have removed the cases for which accuracies are not known (see [82, Tables IV–VII]). Table VIII shows that out of the 28 cases, only in one case the null hypothesis H_0 was accepted. Here the null hypothesis is that there is no significant difference in performance between our algorithm and a comparing algorithm. We have also used Friedman test [89], [90] to check if all the 29 (28 existing and our proposed) algorithms perform similarly over seven data sets: Colon, TOX-171, Leukemia1, Leukemia2, GCM, tr12.wc, and tr23.wc (see [82, Tables IV–VII], some accuracies for other data sets are not available). The obtained Friedman statistics is 60.13, which is significant at $\alpha = 0.001$, as the corresponding statistic χ^2 with 28 degrees of freedom is 56.90. Thus, Friedman test suggests existence of significant difference among the algorithms.

V. CONCLUSION

In this paper, we have used a MOGP, called ASMiGP, to evolve diverse sets of binary classifiers to solve multiclass classification problems. Simultaneous FS and rule extraction are performed during the genetic evolution. An important objective of this paper is to find simple classification rules that may be human understandable, which in the given context translates to rules with simple operations and short length. The proposed method is found to achieve its goal.

Ensembles perform better when weighted voting is used, the members of the ensembles are diverse enough, and the classifiers are accurate [21]. Here, we have created c sets of diverse ensembles. Unlike other ensemble-based method, here each ensemble represents diverse classifiers for just one class. The number of features used by the ensembles is high with respect to the number of features selected per (binary classifier) tree. This suggests that the binary classifiers are diverse enough. In our algorithm, we evolve c distinct species in parallel, which try to learn distinct patterns and no interspecies gene exchange is ever allowed. This property makes each species different from the other species and the system becomes less vulnerable, especially when each species has successfully learnt its designated patterns.

Our method has been tested on nineteen (eight microarray and eleven text) data sets. The experimental results show that we could find easy-to-understand rules for overall 63.2% (87.5% for microarray and 54.5% for text) data sets. We compared our method with four classification methods in conjunction with seven FS methods including use of the all-feature set. For 80.17% (61.40% for microarray and 95.75% for text) cases our method outperforms others. The improvement in performance is shown statistically significant compared to the others.

The overall performance of the proposed method is better on text data sets compared to that of microarray data sets. Two important differences between these two groups of data sets are that: 1) microarray data sets have comparatively large feature-to-sample ratios and may not have enough number of points in each class for MOGP to learn the structure of the data sets and 2) the text data sets have comparatively large number of classes as well as instances. Our limited experiments suggest that when there are enough points in each class so that each species can successfully learn its target pattern, the proposed method works better. We found that for text data our method performs noticeably better than the other methods particularly when number of classes is high (ten or more than that).

We have shown that our method is very effective when the dimension of the data sets are as high as 49 151. But in all our data sets, number of samples were not very big. If we apply the proposed method on a data set with a really large number samples, it may require a significant amount of time. The method may also take a substantial amount of time when the number of classes is high and we have limited parallel processing capability. With the today's high performance computing technologies, however, these are not really crucial shortcomings. Yet, we have not applied it to truly big data. This paper can be adapted to deal with big data, especially using Hadoop.

Our future research interest is to use MOGP to classify multiclass text data, where each text may belong to more than one category (class) and to use net belongingness as a fuzzy membership of the documents to the corresponding category. We also intend to modify the proposed learning method to stepwise learning, so that we can use it for big text data.

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