

Penalized feature selection and classification in bioinformatics

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Abstract

In bioinformatics studies, supervised classification with high-dimensional input variables is frequently encountered. Examples routinely arise in genomic, epigenetic and proteomic studies. Feature selection can be employed along with classifier construction to avoid over-fitting, to generate more reliable classifier and to provide more insights into the underlying causal relationships. In this article, we provide a review of several recently developed penalized feature selection and classification techniques—which belong to the family of embedded feature selection methods—for bioinformatics studies with high-dimensional input. Classification objective functions, penalty functions and computational algorithms are discussed. Our goal is to make interested researchers aware of these feature selection and classification methods that are applicable to high-dimensional bioinformatics data.

Keywords: *bioinformatics application; feature selection; penalization*

INTRODUCTION

In the past decade, we have witnessed a period of unparalleled development in the field of bioinformatics [1, 2]. Among the many encountered problems, classification is one that has attracted extensive attentions. In general, classification can be defined as unsupervised or supervised, depending on if there is an observed class label. Although both are of great importance, we focus on supervised classification in this article. Supervised classification in bioinformatics is challenging partly because of the high dimensionality of the input variables. Several examples of supervised classification with high-dimensional inputs are described in ‘Examples of supervised classification in bioinformatics’ section.

When the dimension of the input variables is high compared with the number of subjects (sample size), dimension reduction or feature selection is usually needed along with classifier construction. Dimension reduction or feature selection can help to (i) provide more insights into the underlying causal relationships

by focusing on a smaller number of features; (ii) generate more reliable estimates by excluding noises and (iii) provide faster and more efficient models for future studies ([3–5] and references therein).

Dimension reduction techniques, such as principal component analysis and partial least squares, construct ‘super variables’—usually linear combinations of original input variables—and use them in classification [3, 6, 7]. Although they may also lead to satisfactory classification, biomedical implications of the classifiers are usually not obvious, since all input variables are used in construction of the super variables and hence classification.

Feature selection methods can be classified into three categories, depending on their integration into the classification method [4, 5, 8]. Filter approach separates feature selection from classifier construction. Wrapper approach evaluates classification performance of selected features and keeps searching until certain accuracy criterion is satisfied. Embedded approach embeds feature selection within classifier construction.

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Among feature selection methods, ‘embedded methods have the advantage that they include the interaction with the classification model, while at the same time being far less computationally intensive than wrapper methods’ [5]. In this article, we review several penalization methods, which have attracted special attentions in statistics literature in the past decade. Penalization methods belong to the family of embedded methods. They have well-defined classification objective functions, penalty terms and deterministic computational algorithms. Statistical properties of penalization methods can be easier to establish than other methods.

The goal of this article is to provide a review of several recently proposed penalized feature selection and classification methods for data with high-dimensional inputs, with special emphasis on applications of these methods in bioinformatics. This article differs from published ones in the following aspects. First, compared with review articles such as Saeys *et al.* [5], this article focuses only on penalization methods. We are hence able to provide a much more detailed review of such methods. Second, compared with methodological publications such as Ghosh and Chinnaiyan [9], Zhang *et al.* [10] and Liu *et al.* [11], this article does not try to propose any new methodology. Instead, it attempts to establish a unified framework which includes many published methodologies as special cases. Third, compared with statistical publications, this article focuses more on bioinformatics practice, such as real-life applications and computational aspects.

In ‘Examples of supervised classification in bioinformatics’ section, we describe a few bioinformatics examples that involve supervised classification with high-dimensional input variables. In ‘Feature selection’ section, we provide general discussions of feature selection methods and some insights into where the penalization methods fit in the big picture. Penalized feature selection and classification methods are introduced in ‘Penalized feature selection and supervised classification’ section. Classification objective functions, penalty functions and computational algorithms are discussed in details. A small showcase example of cancer classification using microarray is provided in ‘Empirical performance and application’ section. Several related issues are addressed in ‘Discussions’ section. Concluding remarks are given in ‘Concluding remarks’ section.

EXAMPLES OF SUPERVISED CLASSIFICATION IN BIOINFORMATICS

Genomics: cancer classification using microarray

Cancer is a genetic disease, which can be caused by mutations or defects of genes. Microarray technology makes it possible to survey the genome on a global scale. Microarray gene expression experiments have been conducted to identify biomarkers in cancers, including colon, prostate, breast, head and neck, skin, lymphoma and many others. It has been shown that up- or down-regulations of a subset of genes are associated with cancer development. Many cancer microarray studies have categorical phenotypes of interest—such as cancer occurrence, stages or subtypes—which naturally leads to supervised classification. We refer to Golub *et al.* [12] and West *et al.* [13] for representative examples.

Epigenetics: cancer classification using epigenetic measurements

In addition to having genetic causes, cancer can also be considered an epigenetic disease. Regulation by genetics involves a change in the DNA sequence, whereas epigenetic regulation involves alteration in chromatin structure and methylation of promoter region. Epigenetic measurements, such as DNA methylation patterns, have been used for cancer classification. Examples include Zukiel *et al.* [14], Piyathilake and Johannig [15] and references therein.

Proteomics: cancer classification using mass spectrometry

Mass spectrometry is an analytical technique that measures the mass-to-charge ratio of ions. It is generally used to find the composition of a physical sample. Some cancers affect the concentration of certain molecules in the blood, which allows early diagnosis by analyzing the blood mass spectrum. Features measured with mass spectra—often summary statistics of the peaks (for example, the peak probability contrasts in Tibshirani *et al.* [16])—can be used to discriminate between individuals with different cancer phenotypes. Researchers have used mass spectra for the detection of prostate, ovarian, breast, bladder, pancreatic, kidney, liver and colon cancers. See Yang *et al.* [17] and Diamandis and van der Merwe [18] for examples.

Proteomics: protein marker identification and classification

Protein is encoded by genes, and represented by sequence of amino acids. One of the central problems in bioinformatics is the classification of protein sequences into functional and structural families based on sequence homology. It is usually easy to sequence protein, but difficult to obtain structure. An analytic solution is to use statistical techniques and classify protein sequence data into families and super-families defined by structure/function relationships [19–21].

Proteomics: protein localization

Subcellular location of a protein is one of the key functional characters as proteins must be localized correctly at the subcellular level to have normal biological functions. Automated imaging of subcellular locations and structures can provide the ability to detect abnormalities and associate them with specific proteins. Prediction of protein subcellular localization is an important component of bioinformatics-based prediction of protein function and genome annotation, and it can aid identification of drug targets [22–24].

Remarks

Although examples described above differ significantly in techniques and application areas, their data structures share the following similarities. First, there is a categorical phenotype of interest, which may be cancer status, protein family or super-family

membership, or protein location. Second, high-dimensional input variables are available for supervised classification. The input variables can be microarray gene expressions, methylation patterns, mass spectra or protein sequences. Third, such studies usually have the number of input variables much larger than the sample sizes. Thus, there is a critical demand for dimension reduction or feature selection.

FEATURE SELECTION

We show in Figure 1 a taxonomy of feature selection and dimension reduction. A similar one has been presented as Table 1 of Saeys *et al.* [5].

Statistical methodologies that can reduce the dimensionality of input variables can be categorized depending on the relationships between original input variables and new input variables. (i) Dimension reduction methods construct new input variables using linear combinations of *all* original input variables. Examples include partial least squares and principal component analysis among others. (ii) Feature selection methods, which select a subset of original input variables. (iii) Hybrid methods. Most recently, researchers propose methods that combine dimension reduction and feature selection. One example is the sparse principal component analysis [25]. The hybrid methods have not been extensively used in bioinformatics yet.

Compared with dimension reduction, feature selection techniques have the potential benefits of (i) facilitating data visualization and data

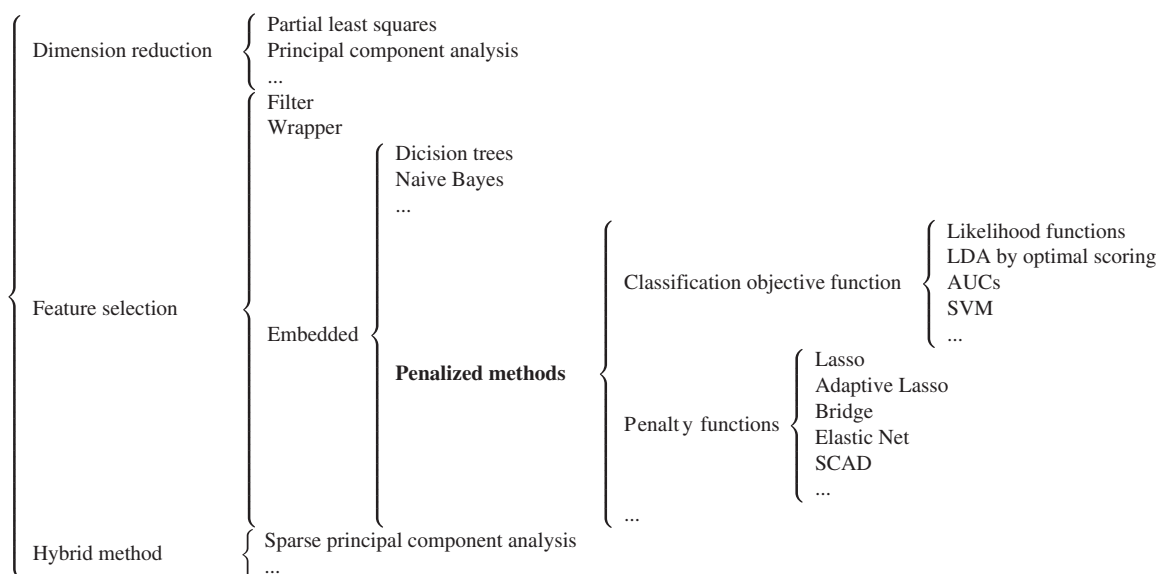


Figure 1: A taxonomy of feature selection and dimension reduction.

Table I: Published articles that use penalized classification methods for microarray data (incomplete list)

Author	Objective function	Penalty	Numerical study
Ghosh and Chinnaiyan [9]	LDA	Lasso	Simulation; microarray data
Zhang <i>et al.</i> [10]	SVM	SCAD	Simulation; microarray data; metabolism data
Liu <i>et al.</i> [11]	Likelihood	Elastic net/bridge	Simulation; methylation data; microarray data
Ma and Huang [32]	ROC	Lasso	Microarray data
Pan <i>et al.</i> [50]	Likelihood	Adaptive Lasso	Simulation; microarray data
Roth [43]	Likelihood	Lasso	Microarray data
Segal <i>et al.</i> [45]	Likelihood	Lasso	Microarray data
	SVM	Ridge	Microarray data
Shen and Tan [28]	Likelihood	Ridge	Microarray data
Zhu and Hastie [27]	Likelihood	Ridge	Microarray data
Zou and Hastie [54]	Likelihood	Elastic net	Microarray data

understanding; (ii) reducing measurement and storage requirements and (iii) reducing training and utilization times. Those properties are especially desirable for bioinformatics where a typical study measures 10^{3-5} features on 10^{1-3} subjects.

Feature selection methods can be further classified as filter, wrapper or embedded. We refer to table 1 of Saeys *et al.* [5] and the ‘Introduction’ section for related discussions. Embedded methods integrate feature selection with classifier construction (we note that this has been deemed as a drawback by some researchers). They have less computational complexity than wrapper methods. Compared with filter methods, embedded methods can better account for correlations among input variables.

Penalization methods are a subset of embedded methods, as can be seen from Figure 1. Penalization methods can be further categorized based on the classification objective functions and penalty terms, which will be discussed in details in next section.

PENALIZED FEATURE SELECTION AND SUPERVISED CLASSIFICATION

Data

For simplicity of notations, we consider binary classification only. Extensions to multi-class classification will be discussed in ‘Classification objective function’ section. Denote $Y = \{0, 1\}$ as the binary phenotype of interest. For example, subjects with $Y = 1$ may be referred to as diseased and $Y = 0$ may be referred to as healthy. Let X be the length- p input variable. Suppose there are n i.i.d. copies of $(X, Y) : (x_1, y_1), \dots, (x_n, y_n)$. Without loss of generality, we only consider the case that classification of Y can be based on a linear combination of the X variables, denoted as $X^T\beta$, where X^T is the

transpose of X , and β is the unknown, length- p regression coefficient. Nonlinear terms and interactions can be included in X as new variables.

Penalized feature selection and classification

With penalization methods, feature selection and classifier construction are achieved *simultaneously* by computing $\hat{\beta}$, estimate of β that minimizes a penalized objective function. Classification rule can be defined as $Y = 1$ if $X^T\hat{\beta} > c$ for a cutoff c . With properly tuned penalties, estimated β can have components exactly equal to zero. Feature selection is thus achieved, since only variables with nonzero coefficients will be used in the classifier.

Specifically, we define $\hat{\beta}$ as

$$\hat{\beta} = \operatorname{argmin}_{\beta} \{m(\beta; D) + \lambda \times \operatorname{pen}(\beta)\}, \quad (1)$$

where D represents the dataset consisting of $(x_1, y_1), \dots, (x_n, y_n)$.

In [1], m is referred to as the ‘classification objective function’. We introduce different forms of m in ‘Classification objective function’ section. The penalty $\operatorname{pen}(\beta)$ in (1) controls the complexity of the model. With the penalty functions described in ‘Penalty function’ section and properly chosen λ , some components of $\hat{\beta}$ are exactly zero. This leads to sparse classifiers and feature selection. The tuning parameter $\lambda > 0$ balances the goodness-of-fit and complexity of the model. When $\lambda \rightarrow 0$, the model has better goodness-of-fit. However, since the classifier is too complex, it may have unsatisfactory prediction and be less interpretable. When $\lambda \rightarrow \infty$, the classifier has fewer input variables in it. The case of $\lambda = \infty$ corresponds to the simplest classifier where no input variable is used for classification. When λ is properly tuned using cross-validation, the classifier

can have satisfactory classification/prediction performance and is interpretable.

Classification objective function

In this section, we describe five extensively used classification objective functions.

Likelihood function for parametric model

Parametric classification models assume that $P(Y=1|X) = \phi(X^T\beta)$, where ϕ is the *known* link function [26]. Commonly assumed link functions include the logistic, logit, identity and probit functions. When a parametric model is assumed, m can be chosen as the negative log-likelihood function. For example, if a logistic regression model is assumed, i.e. $Pr(Y=1|X) = \exp(\beta_0 + X^T\beta)/(1 + \exp(\beta_0 + X^T\beta))$, then

$$m = -\frac{1}{n} \sum_i y_i \log\left(\frac{\exp(\beta_0 + x_i^T\beta)}{1 + \exp(\beta_0 + x_i^T\beta)}\right) + (1 - y_i) \log\left(\frac{1}{1 + \exp(\beta_0 + x_i^T\beta)}\right). \quad (2)$$

Parametric models for binary classification can be easily extended to multiclass cases [26]. Examples of using likelihood functions for classification in bioinformatics include Liu *et al.* [11], Zhu and Hastie [27], Shen and Tan [28], Shevade and Keerthi [29], and many others.

Linear discriminant function by optimal scoring

Linear discriminant analysis (LDA) has been used in microarray studies [9, 30]. Typically, LDA can be calculated using matrix algebra techniques. An effective alternative is to use the optimal scoring, where the problem of classification is re-expressed as a regression problem based on quantities known as optimal scores.

Let $\theta(Y) = (\theta(y_1), \dots, \theta(y_n))^T$ be the $n \times 1$ vector of quantitative scores assigned to (y_1, \dots, y_n) . The optimal scoring problem involves finding the vector of coefficients β and the scoring map $\theta: \{0, 1\} \rightarrow R$ that minimize the average squared residual:

$$m = \frac{1}{n} \sum_i (\theta(y_i) - x_i^T\beta)^2. \quad (3)$$

The optimal scoring approach can be easily modified to incorporate multiclass cases [30].

Area under curve with receiver operating characteristics

Under the receiver operating characteristics (ROC) framework, it is assumed that $P(Y=1|X) = G(X^T\beta)$. Here G is an increasing link function. Its functional

form does not need to be assumed. We refer to Pepe [31] for more details. With the ROC, classification accuracy is evaluated using the true and false positive rates (TPR and FPR), which can be defined as $TPR = P(X^T\beta \geq c|Y=1)$, $FPR = P(X^T\beta \geq c|Y=0)$, for a cutoff c . The ROC curve is a 2D plot of $\{(FPR(c), TPR(c)) : -\infty < c < \infty\}$. Denote \mathbb{D} and \mathbb{H} as the index sets for subjects with $Y=1$ and $Y=0$, with sizes n_D and n_H , respectively. Let X^D denote the input variables of a diseased subject and X^H the input variables of a healthy subject. The overall performance of a classifier can be measured by the area under curve (AUC), with larger AUC indicating better performance.

As a function of β , the empirical AUC is $AUC_e(\beta) = \frac{1}{n_D n_H} \sum_{i \in \mathbb{D}; j \in \mathbb{H}} I(x_i^T\beta - x_j^T\beta \geq 0)$, where I is the indicator function. AUC_e is not continuous and hence difficult to optimize.

Ma and Huang [32] proposes AUC_s , a smooth approximation of the AUC_e :

$$m = -AUC_s(\beta) = -\frac{1}{n_D n_H} \sum_{i \in \mathbb{D}; j \in \mathbb{H}} S((x_i^T\beta - x_j^T\beta)/\sigma_n), \quad (4)$$

where $S(u) = 1/(1 + \exp(-u))$, and σ_n is the tuning parameter satisfying $\sigma_n = o(n^{-1/2})$ as $n \rightarrow \infty$.

An alternative to the empirical AUC is the bi-normal AUC [31, 33]. Assume that X^D and X^H have normal distributions $X^D \sim N(\mu^D, \Sigma^D)$ and $X^H \sim N(\mu^H, \Sigma^H)$, respectively. Then the AUC can be computed as

$$AUC_n(\beta) = \Phi\left(\frac{(\mu^D - \mu^H)^T\beta}{(\beta^T(\Sigma^D + \Sigma^H)\beta)^{1/2}}\right),$$

where Φ is the normal distribution function. For a sample with n subjects, the (negative) bi-normal AUC can be estimated by

$$m = -\widehat{AUC}_n(\beta) = -\Phi\left(\frac{(\hat{\mu}^D - \hat{\mu}^H)^T\beta}{(\beta^T(\hat{\Sigma}^D + \hat{\Sigma}^H)\beta)^{1/2}}\right), \quad (5)$$

where $\hat{\mu}$ and $\hat{\Sigma}$ denote the sample mean and variance-covariance matrix, respectively.

Classification using the ROC can also be extended to multiclass problems. We refer to Mossman [34] for the volume under surface (VUS) and Provost and Domingos [35] for the one-versus-rest approaches, respectively.

Support vector machine

Under the support vector machine (SVM) framework, the binary outcome variable is recoded as

$\tilde{Y} = 2Y - 1$, i.e. $\tilde{Y} \in \{-1, 1\}$. SVM is a large margin classifier which separates two classes by maximizing the margin between them. The SVM can be formulated as a penalized optimization problem with an L_2 penalty

$$\min_{\beta_0, \beta} \frac{1}{n} \sum_i [1 - \tilde{y}_i(\beta_0 + x_i^T \beta)]_+ + \tau \|\beta\|_2^2 \quad (6)$$

where β_0 is the intercept term, β is the directional vector, $a_+ = |a|I(a > 0)$, $\|\beta\|_2^2 = \sum_{j=1}^p \beta_j^2$, and τ is a tuning parameter.

Usually with SVM, nonlinear kernels are needed. We refer to Cristianini and Shawe-Taylor [36] for detailed discussions. However, Zhang *et al.* [10] suggests that ‘when $p \gg n$, under mild assumptions for data distribution . . . linear classifiers then become natural choices to discriminate two simplices’. In addition, with nonlinear kernels, once the kernels are defined, they can be treated as new input variables, and the above linear formulation is applicable. We thus provide formulation with linear kernels only.

When using with other penalties, such as L_1 or SCAD, the SVM objective function in [6] can be simplified by setting $\tau = 0$. With convex penalties such as the L_1 and L_2 , there exist efficient computational algorithms to minimize the penalized SVM function. To utilize the SVM loss function with penalties such as the SCAD, which is not convex, Zhang *et al.* [10] and references therein propose to approximate SVM(β) with $\tau = 0$ by

$$m = - \sum_i \frac{\tilde{y}_i(\beta_0 + x_i^T \beta)}{2n} - \frac{1}{2n} \sum_i \frac{\tilde{y}_i(\beta_0 + x_i^T \beta)}{|\tilde{y}_i - (b_0 + x_i^T b)|} + \frac{1}{4n} \sum_i \frac{(\beta_0 + x_i^T \beta)^2}{|\tilde{y}_i - (b_0 + x_i^T b)|}, \quad (7)$$

where (b_0, b) is an initial estimate of (β_0, β) .

Application of SVM to cancer classification using gene-expression data and protein localization prediction can be found in Guyon *et al.* [37] and Hua and Sun [38]. We refer to Noble [39] for a review of SVM in bioinformatics.

Remarks

All the aforementioned classification objective functions have been extensively used for binary classification in bioinformatics.

When a model can be explicitly assumed, likelihood is the most straightforward choice. It has the following properties: (i) when the underlying model is correctly assumed, likelihood based classification is optimal; (ii) with a newly observed X , likelihood

approach cannot only predict the class label, but also the corresponding probability; (iii) on a negative side, likelihood-based classification relies on strong assumptions and may suffer from model misspecification.

The LDA approach maximizes class separability. The classification objective function [3] has a simple least squares form and is easy to compute—only simple matrix operations are involved. However, the LDA approach implicitly assumes that mean is the discriminating factor (not variance), and data is normally distributed. Such assumptions may be violated and limit the applicability of LDA.

The ROC approach uses AUCs as classification objective functions. The AUC is a direct measurement of classification accuracy [31]. Classification rule obtained by maximizing the AUC is hence optimal in terms of having the largest AUC. The empirical AUC relies on much weaker assumptions compared with likelihood and LDA approaches. However, an approximation has to be used, which demands an extra tuning. The bi-normal AUC is easy to compute. However, its validity depends on the normal distribution assumption, which may be violated.

The SVM classification objective function maximizes the geometric margin between different classes. There is no explicit distribution assumption associated with SVM. With certain penalty functions, there exist efficient computational algorithms. Otherwise, an approximation may have to be introduced. In addition, SVM has no supporting incremental learning and can be sensitive to noises and outliers, which are frequently encountered in bioinformatics [40].

There is unlikely to be an objective function that is dominantly better under all scenarios. In practice, researchers may need to try different objective functions and select the proper one based on criteria such as prediction accuracy.

Penalty function

Lasso: the L_1 penalty

The Lasso penalty is proposed by Tibshirani [41] and defined as

$$\text{pen}(\beta) = \sum_{j=1}^p |\beta_j|, \quad (8)$$

i.e. the L_1 norm of the regression coefficient. An important property of the L_1 penalty is that it can

generate exact zero estimated coefficients [42]. Therefore, it can be used for feature selection.

Applications of the Lasso penalty in bioinformatics include Ghosh and Chinnaiyan [9], Shevade and Keerthi [29], Roth [43], Wei and Pan [44], Segal *et al.* [45] and many others. Those studies have shown that with the Lasso penalty, a small number of representative features can be selected and satisfactory classification can be achieved.

Adaptive Lasso: the weighted L_1 penalty

The Lasso is in general not variable selection consistent in the sense that the whole Lasso path may not contain the true model [46]. Selection consistency of the Lasso requires an irrepresentable condition, which may not be satisfied in practice [47].

To improve the selection performance of the Lasso, Zou [48] proposes the adaptive Lasso method, which uses a weighted L_1 penalty:

$$\text{pen}(\beta) = \sum_{j=1}^p \frac{1}{|b_j|} |\beta_j|, \quad (9)$$

where b_j is the weighted adjustment for each coefficient [48]. For linear models with $n \gg p$, it has been proved that if b_j is a \sqrt{n} consistent estimate of β_j , then the adaptive Lasso estimate is feature selection consistent under very general conditions. Also for linear models but $p \gg n$, Huang *et al.* [49] shows that the adaptive Lasso can still be feature selection consistent if certain orthogonality conditions are satisfied. For classification problems, Pan *et al.* [50] and several other articles show that the adaptive Lasso has satisfactory classification/prediction and feature selection properties with high-dimensional input.

Bridge: the L_γ penalty

The L_1 Lasso penalty is a special case of the bridge penalty [42, 51, 52], which is defined as

$$\text{pen}(\beta) = \sum_j |\beta_j|^\gamma, \quad 0 < \gamma \leq 1. \quad (10)$$

For linear models with $n \gg p$ and $\gamma < 1$, the bridge penalty is feature selection consistent, even when the Lasso is not [53]. For linear models with high-dimensional input, i.e. $n \ll p$ and $\gamma < 1$, Huang *et al.* [53] shows that the bridge can still be feature selection consistent, if the features associated with the phenotype and those not associated with the phenotype are only weakly correlated.

Numerically, Liu *et al.* [11] adopts a mixture penalty, which has a bridge term, in binary classification using microarray data.

Elastic net: a mixture penalty

Zou and Hastie [54] shows for linear models, when there exist highly correlated input variables, the Lasso tends to select only one of the correlated variables. With bioinformatics data, it is common that a few input features are highly correlated. One penalty that can effectively deal with high correlations is the elastic net penalty:

$$\text{pen}(\beta) = \sum_j |\beta_j|^\gamma + \left(\sum_j \beta_j^2 \right)^\eta, \quad (11)$$

with $0 < \gamma \leq 1$ and $\eta \geq 1$. That is, the elastic net is a mixture of bridge type penalties. Zou and Hastie [54] proposes $\gamma = 1$ and $\eta = 1$. In Liu *et al.* [11], it is extended to $\gamma < 1$ and $\eta = 1$. Applications of the elastic net in bioinformatics classification are considered in Liu *et al.* [11].

SCAD penalty

The above penalties share the same property that they increase as $|\beta_j|$ increases, which may cause biases in estimating large coefficients. One solution is the SCAD penalty [55]:

$$\begin{aligned} \text{pen}(\beta) &= |\beta| && \text{if } |\beta| \leq \lambda \\ &= -\frac{|\beta|^2 - 2a\lambda|\beta| + \lambda^2}{2\lambda(a-1)} && \text{if } \lambda < |\beta| \leq a\lambda \\ &= (a+1)\lambda/2 && \text{if } |\beta| > a\lambda, \end{aligned} \quad (12)$$

where a is a tuning parameter and Fan and Li [55] suggests using $a = 3.7$. Estimation and feature selection consistency of the SCAD penalty have been established for many distinct models with $n \gg p$. In bioinformatics, Zhang *et al.* [10] and Wang *et al.* [56] adopt it in microarray studies and show its satisfactory performance.

Remarks

Although aforementioned penalty functions differ in their format, they all have the capability of feature selection. This can be explained by the singularity of derivatives of the penalties at zero [55].

The main advantage of Lasso is that, computationally, it is a convex optimization problem. Although it is in general not feature selection consistent, its low computational cost may compensate this drawback. In addition, multiple published

articles have shown satisfactory classification performance of Lasso with high-dimensional input.

For linear models, the adaptive Lasso may fix the inconsistent feature selection problem, while still sharing the simplicity of Lasso. We expect similar properties to hold for classification models. With high-dimensional classification, selection of weights is yet to be solved. There have been published articles proposing *ad hoc* weights selection and showing improvement of classification using adaptive Lasso (over Lasso) with high-dimensional input. More extensive numerical studies need be conducted to draw an affirmative conclusion.

The bridge does not require any weights selection. However, there is still no satisfactory computational algorithm and an approximation may be needed (see ‘Computational algorithms’ section for more details).

The elastic net is the only penalty capable of handling ‘grouping effects’, i.e. highly correlated input variables. Such a property is especially desirable for bioinformatics studies. However, it may share the same inconsistency as the Lasso if $\gamma = 1$, or the computational difficulty as the bridge if $\gamma < 1$.

The SCAD has been very popular with statisticians in recent years because of its satisfactory theoretical properties. Zhang *et al.* [10] and Wang *et al.* [21] show its superior performance with high-dimensional classification. However, it can be computationally much harder than alternatives such as the Lasso. In addition, it involves an extra tuning parameter, which may be hard to choose objectively.

Computational algorithms

The singularity of the penalties at zero makes commonly used maximization algorithms, such as the Newton–Raphson or gradient searching, invalid. Computational algorithms for individual penalties have been proposed in early publications and summarized subsequently. A unified approach, called ‘herding lambdas’, is proposed by Friedman [57] and described.

Lasso and adaptive Lasso

The adaptive Lasso can be computed using the same algorithms as the Lasso. In early studies, the Lasso is computed with the quadratic programming (QP) or general nonlinear programming, which can be computationally intensive. For linear models, Efron *et al.* [58] proposes the efficient LARS approach,

which is later extended to generalized linear models [59].

With high-dimensional data, an alternative approach based on boosting has been proposed by Kim and Kim [60] and later used in microarray data analysis by Ma and Huang [61]. Computational cost of the boosting approach is relatively independent of the dimensionality of input variables, which makes it especially suitable for high-dimensional data. However, the boosting approach only provides an approximation solution.

Bridge and elastic net

The elastic net penalty is the sum of the bridge and ridge penalties. The ridge penalty term is differentiable. So for the elastic net, we only need to be concerned with the bridge penalty. With $\gamma = 1$, algorithms for computing the Lasso and the augmentation algorithm in Zou and Hastie [54] are applicable for computing the elastic net estimate.

For the bridge and elastic net with $\gamma < 1$, Huang *et al.* [53] proposes to approximate the derivative of $|\beta_j|^\gamma$ with $\text{sgn}(\beta_j)/(|\beta_j|^{1-\gamma} + \epsilon)$, where $\text{sgn}(\beta_j)$ is the sign of β_j and ϵ is a small positive number. In Liu *et al.* [11], $|\beta_j|^\gamma$ is approximated with $(\beta_j^2 + \epsilon)^{\gamma/2}$, with a small positive ϵ . Then a gradient searching type algorithm can be employed. β_j s smaller than a chosen cutoff are set to be zero. When $\epsilon \sim 0$, estimation with the approximated penalties is close to the exact solution.

SCAD

In Fan and Li [55] and Zhang *et al.* [10], a quadratic approximation to the SCAD penalty is proposed. The iterative successive quadratic algorithm (SQA) can then be employed. Denote β^k as the estimate of β at Step k . Then $\text{pen}(\beta) = \sum_j \text{pen}(\beta_j)$, where $\text{pen}(\beta_j) = \text{pen}(\beta_j^k) + 0.5(\text{pen}'(\beta_j^k)/|\beta_j^k|) \times (\beta_j^2 - \beta_j^{k2})$. After the iteration is terminated, $\hat{\beta}_j$ s smaller than a cutoff are set to be zero. We refer to Zhang *et al.* [10] for more details on this approximation.

Herding lambdas: a unified computational algorithm

We now describe a stagewise incremental approach, which can be applied to optimize objective functions with any of the above penalties, or their approximations.

Denote $g(\beta) = -\partial m(\beta)/\partial \beta$ and its j th component as $g_j(\beta)$. Denote $p(\beta) = -\partial \text{pen}(\beta)/\partial \beta$ and its j th component as $p_j(\beta)$. Denote ϵ as the fixed, small,

positive increment. The ‘herding lambdas’ is an iterative approach. Denote $\beta(k)$ as the estimate of β after iteration k . The algorithm can be summarized as follows:

- (1) Initialize $k=0$ and $\beta(0) = \operatorname{argmin}\{m(\beta) + \infty \times \operatorname{pen}(\beta)\}$.
- (2) If $\max_j |g_j(\beta)| = 0$, then stop iteration.
- (3) Compute $\lambda_j(k) = \frac{g_j(\beta(k))}{p_j(\beta(k))}$.
- (4) Denote the active set $S = \{j : \lambda_j(k) < 0\}$. If S is empty, then $l = \operatorname{argmax}_j |\lambda_j(k)|$. Otherwise $l = \operatorname{argmax}_{j \in S} |\lambda_j(k)|$.
- (5) $\Delta = \epsilon |g_l(\beta(k))|$.
- (6) Update $\beta(k) = \beta(k) + \Delta \operatorname{sgn}(g_l(\beta(k))) 1(l)$, where $1(l)$ is the length p vector with its l th component 1 and the rest 0.
- (7) Repeat Steps 2–7 until a cross-validated criterion is satisfied.

As Friedman [57] points out that this algorithm ‘... does *not* always generate exactly the same path as defined by (1), it is usually close enough to maintain similar statistical properties.’ Numerical studies in Friedman [57] support this argument. The affordable computational cost and great applicability compensate the negligible loss of accuracy. Another advantage is that it can generate the complete parameter path from $\lambda = \infty$ to $\lambda = 0$, which is important when λ needs to be determined by cross-validation.

EMPIRICAL PERFORMANCE AND APPLICATION

A showcase example

Breast cancer is the second leading cause of deaths from cancer among women in the United States. Despite major progresses in breast cancer treatment, the ability to predict the metastatic behavior of tumor remains limited. The Breast Cancer study was first reported in van’t Veer *et al.* [62]. A total of 97 lymph node-negative breast cancer patients aged 55 years old or younger participated in this study. Among them, 46 developed distant metastases within 5 years (metastatic outcome coded as 1) and 51 remained metastases free for at least 5 years (metastatic outcome coded as 0). Expression levels for 24481 gene probes were collected using microarray. We refer to van’t Veer *et al.* [62] for more details on experimental setup. The goal of this study is to build a statistical model that can accurately predict the risk of distant recurrence

of breast cancer in a 5-year post-surgery period. The dataset is publicly available at <http://www.rii.com/publications/2002/vantveer.html>.

We first preprocess gene-expression data as follows: (i) Remove genes with more than 30% missing measurements. (ii) Fill in missing gene-expression measurements with median values across samples. (iii) Normalize gene expressions to have zero means and unit variances. (iv) Compute the simple correlation coefficients of gene expressions with the binary outcome. (v) Select the 500 genes with the largest absolute values of correlation coefficients.

We analyze the breast cancer data using several penalized approaches. Tuning parameters are selected using the 5-fold cross-validation. Since independent validation data is not present, we use the leave one out cross-validation (LOOCV) to evaluate the predictive power. Especially, we first remove one subject. The reduced data, with sample size $n-1$, is then analyzed using penalized approaches. We note that the preprocessing and optimal tuning selection need to be conducted for each reduced data. With the statistical model generated with the reduced data, we can make prediction for the removed subject. This process is repeated over all subjects. An overall prediction error can then be computed. With different approaches, we are interested in the sets of genes identified, and LOOCV prediction error.

- (1) Logistic + Lasso. We assume the logistic regression model and use the negative log-likelihood function as the objective function. The Lasso is used for penalized gene selection. A total of 42 genes are selected. With the LOOCV, 14 subjects are misclassified.
- (2) Logistic + adaptive Lasso. Under the logistic regression model, we use the adaptive Lasso for penalized gene selection. We use the Lasso estimate as weight in the adaptive Lasso. A total of 22 genes are selected, and 14 subjects are misclassified.
- (3) Logistic + bridge. Under the logistic regression model, we use the bridge penalty with $\gamma = 1/2$ for penalized gene selection. A total of 19 genes are selected. With the LOOCV, 21 subjects cannot be properly predicted.
- (4) Logistic + elastic net. Under the logistic regression model, we also consider the elastic net penalty with $\gamma = 1/2$ and $\eta = 2$. A total of 19

genes are identified. With the LOOCV, 21 subjects cannot be properly predicted.

- (5) SVM+SCAD. We adopt the approach and software in Zhang *et al.* [10]. Especially, approximations are considered for both the SVM objective function and the SCAD penalty. With the 5-fold cross-validation, $\lambda = 0.003$ is selected as the optimal tuning. A total of 236 genes are selected. It is believed that the large number of identified genes is partly caused by the V-fold cross-validation. The LOOCV misclassifies 12 subjects.

Due to limited availability of software, we only consider five different combinations of objective functions and penalties, whereas there are many more possibilities. The lists of genes identified using the above five approaches are available upon request from the authors.

With different approaches, different sets of genes can be identified. Since we use the Lasso estimate as weight for the adaptive Lasso, the set of genes identified using the adaptive Lasso is a subset of those using the Lasso. For this specific dataset, the bridge and elastic net identify the same set of 19 genes, although in general this is not true. The cross-validation selects very small penalty for the SVM+SCAD. Thus a large set of genes are identified. Although the sets of identified genes can vary, all five approaches considered here have reasonably good prediction performance.

We expect performance of different approaches to be data specific. Thus, conclusions drawn from this study may not be extended to general scenarios.

General remark

The goal of this article is to provide a review of penalized methodologies that are useful in supervised bioinformatics classification studies. We provide a partial list of published articles that use penalized classification methods microarray data in Table 1. We suggest interested researchers to read those articles regarding the numerical performance of penalization methods, comparisons with alternatives, and applications. Extensive numerical studies will be needed to draw conclusions on the relative performance of penalized methods in high-dimensional classification. Such a study is of great interest, but beyond scope of this article.

DISCUSSIONS

Other forms of penalties

The ridge penalty has been used for microarray classification in Zhu and Hastie [27]. Although it is computationally simpler than the penalties discussed in ‘Penalty function’ section, it does not have a ‘built-in’ feature selection mechanism. Feature selection needs to be conducted after classifier construction. There exist other penalties that have properties similar to ridge. Although they may have satisfactory classification performance, we do not further pursue them due to their lack of feature selection capability.

Related issues

Supervised classification and feature selection with high-dimensional input are related to the following subjects: (i) prescreening, which carries out a rough screening to remove input variables unlikely to be important [63]; (ii) tuning parameter selection. The penalized approaches involve the unknown tuning parameters that should be chosen using cross-validation; (iii) classifier comparison and evaluation. Cross-validated classification accuracy, such as classification error, and number of selected features need to be compared to select the optimal classifier.

Although these issues are of great importance, they are not the focus of this article. We refer to other published papers for more detailed discussions.

Modeling of other bioinformatics data

In this article, we only consider data with categorical outcomes and classification problems. Other outcomes, such as linear or censored survival, are also commonly encountered in bioinformatics studies. Apparently, models and objective functions different from those in ‘Classification objective function’ section need to be considered. However, the general framework of penalization in section ‘Penalized feature selection and classification’ and the penalty functions in ‘Penalty function’ section are still applicable.

CONCLUDING REMARKS

Penalization methods are a family of embedded feature selection methods and have been used in bioinformatics studies with high-dimensional input. In this article, we provide a review of such methods, so that interested researchers can use them more in future bioinformatics studies. We describe five

different classification objective functions and five different penalties. Corresponding computational algorithms are also discussed. A combination of any classification objective functions described in 'Classification objective function' section and any penalties in section 'Penalty function' can potentially be used for feature selection and classification. Computational and statistical aspects of several combinations, such as logistic likelihood + Lasso, logistic likelihood + elastic net, AUC + Lasso, and SVM + SCAD, have been studied in the literature cited in this article. The rest need to be studied in the future.

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