

A data-driven approach to conditional screening of high-dimensional variables

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Marginal screening is a widely applied technique to handily reduce the dimensionality of the data when the number of potential features overwhelms the sample size. Because of the nature of the marginal screening procedures, they are also known for their difficulty in identifying the so-called hidden variables that are jointly important but have weak marginal associations with the response variable. Failing to include a hidden variable in the screening stage has two undesirable consequences: (1) important features are missed out in model selection, and (2) biased inference is likely to occur in the subsequent analysis. Motivated by some recent work in conditional screening, we propose a data-driven conditional screening algorithm, which is computationally efficient, enjoys the sure screening property under weaker assumptions on the model and works robustly in a variety of settings to reduce false negatives of hidden variables. Numerical comparison with alternatives screening procedures is also made to shed light on the relative merit of the proposed method. We illustrate the proposed methodology using a leukaemia microarray data example. Copyright © 2016 John Wiley & Sons, Ltd.

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1 Introduction

1.1 Background

A popular approach for analyzing big data is to first apply a computationally expedient screening procedure to reduce the dimensionality to a moderate size. More sophisticated but often more computationally intensive statistical methods, such as penalized regression, can then be applied in the second stage. This practice has become routine in many fields such as genomics and finance, where the number of available features in the data is often huge compared with the sample size.

Fan & Lv (2008) proposed the sure independence screening (SIS) methodology for linear regression, which screens variables by ranking their marginal correlations with the response variable. Under some regularity conditions, these authors proved that SIS has the ability to keep all the important variables with probability tending to one. This desirable property is often referred to as the sure screening property. The marginal screening procedure has been further developed in a series of recent papers for a variety of settings (Hall & Miller, 2009; Fan & Song, 2010; Bühlmann et al., 2010; Fan et al., 2011; Zhu et al., 2011; Li et al., 2012; Li et al., 2012; Mai & Zou, 2013;

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He et al., 2013; Liu et al., 2014; Shao & Zhang, 2014; among others). A different screening procedure is recently proposed by Wang & Leng (2016), which aims to target joint associations in a covariate space in the dimension of the sample size.

1.2 False negatives in marginal screening

Naturally, the success of any marginal screening procedure depends on how well the marginal utility, correlation coefficient between the response and each individual predictor, captures the importance of the predictors in a joint model. A variable may be retained by the screening procedure when it is marginally important but not jointly important (false positive), or a variable that is jointly important but not marginally important can be screened out, resulting in a false negative.

False negatives have two potentially serious consequences. First, important features may be screened out and will not be reinstated by the second-stage analysis. Second, the false negatives can lead to bias in subsequent inference. The risk of false negatives is widely recognized. An active variable can be hidden when the correlation is estimated marginally. One illustrative example was given by Guyon & Elisseeff (2003, Section 3.3) for a two-class classification problem, where individual variables have no separation power but, jointly, the variables provide good class separation. As another example, we consider the following model from Barut et al. (2016), $Y = b_1X_1 + \dots + b_qX_q - \alpha(b_1 + \dots + b_q)X_{q+1} + e$, where $q \ll p$, $b_1, \dots, b_q$ are nonzero constants and e has a standard normal distribution. The vector of covariates $(X_1, \dots, X_p)^T$ has a multivariate normal distribution, and the covariance matrix of which has an equally correlated structure with the correlation coefficient α . In this case, $\text{cov}(Y, X_{q+1}) = 0$ even if X_{q+1} has a large coefficient. Hence, we expect that marginal screening will give little priority to X_{q+1} .

Existing marginal screening procedures share the simplistic assumption that jointly important variables are also marginally important. This assumption is critical to ensuring the sure screening property because if it is violated, false negatives are likely to arise. To alleviate this problem, Fan & Lv (2008) suggested an iterative procedure (iterative sure independence screening, ISIS) by repeatedly using the residuals from the previous iteration, which was subsequently adopted by many other marginal screening procedures. A generalized linear model version of ISIS is studied in Fan & Song (2010) and Fan et al. (2009). Because of the iterative nature, the computational costs are higher, and the statistical properties of the resulting model are more difficult to analyze. Perhaps more importantly, the performance of the iterative SIS depends a lot on the underlying model. In some settings, particularly when the signal-to-noise ratio is not very high, iterative SIS can underperform SIS, as shown in our empirical comparisons.

Recently, Barut et al. (2016) proposed a conditional screening technique that uses the prior knowledge that a certain set of predictors (denoted by C) are relevant to the response variable. Each remaining variable X_j , where $X_j \notin C$, is evaluated by fitting a regression model using X_j and the predictors in C . The variable X_j is considered important if the magnitude of its coefficient in the aforementioned regression model exceeds a given threshold. They derived the sure screening property and demonstrated that the prior knowledge of a “good” set C can be very helpful for identifying hidden variables. However, the question remains how to select a good set C . Our simulation studies suggest that the performance of such a procedure is sensitive to the choice of C .

Motivated by the work of Barut et al. (2016) and recent developments on sparse principal component analysis, we propose a data-driven algorithm for conditional screening with generalized linear models. Our goal is to reduce false negatives because of marginal screening without relying on a cherry-picked set of C on which the conditional screening is based. To illustrate our proposed methodology, we analyzed the popular leukaemia data (Golub et al., 1999). In this data set, expression levels are measured on 7129 genes for each of the 72 patients. The classification task is to discriminate acute lymphoblastic leukaemia (ALL) from acute myeloid leukaemia (AML). We compare the proposed method with several competing procedures with respect to their abilities to select a small subset of genes to build an interpretable and effective predictive model. This real data example demonstrates that subjective or random choice of

the conditioning set often leads to unstable performance. The proposed data-adaptive method produced meaningful and more reproducible results in the analysis.

2 The proposed three-step method

2.1 Preliminaries

Throughout the paper, we assume that the conditional density of the response variable Y given the vector of predictors $X = x$ belongs to the following exponential family:

$$f(y; x, \theta) = \exp [y\theta(x) - b\{\theta(x)\} + c(x, y)], \quad (1)$$

where $b(\cdot)$ and $c(\cdot, \cdot)$ are known functions and $\theta(x)$ is the canonical parameter. We write $x = (x_1, \dots, x_p)^\top$. The popular generalized linear model assumes that there exists a $(p + 1)$ -vector of parameters $\beta = (\beta_0, \beta_1, \dots, \beta_p)^\top$ such that $E(Y | X = x) = b'\{\theta(x)\} = g^{-1}(\beta_0 + \beta_1 x_1 + \dots + \beta_p x_p)$, where $g(\cdot)$ is the canonical link function. That is, $g = (b')^{-1}$, and $b'(\theta)$ is the first derivative of $b(\theta)$ with respect to θ . In (1), no dispersion parameter is included because we focus on the mean regression. Furthermore, we standardize the covariates so that they have mean zero and standard deviation one. To emphasize the dependence of p on the sample size, we use $p = p_n$ in the remaining of the paper, and let $\beta_* = (\beta_{*0}, \beta_{*1}, \dots, \beta_{*p_n})^\top$ be the vector of true parameter values. Furthermore, assume that β_* is sparse in the sense that the size of the set $M_* = \{j : \beta_{*j} \neq 0, 1 \leq j \leq p_n\}$ is small relative to n even when p_n is large.

In a nutshell, our new algorithm consists of three steps. First, we perform pre-cleaning by standard marginal regression to reduce dimensionality of the problem. Second, we perform sparse principal component analysis on the variables surviving the first step and obtain a set of variables corresponding to those having large loadings on the leading eigenvectors. Finally, using the set of predictors obtained in step 2, we perform conditional marginal screening. Each step of the new algorithm is computationally fast. We will describe the details of the three steps later in this section.

Step 2 of the proposed method relies on the recent work on sparse principal component analysis. Recently, it has been revealed by several authors, including Li (2007), Artemiou & Li (2009, 2013) and Ni (2011), that the response is often highly correlated with the leading principal components of the covariate vector, and hence, principal component analysis is valuable for the purpose of finding a low-dimensional summary of relevant predictors in the regression setting. In Section 3, we demonstrate that, with the assistance of the sparse principal component analysis, the proposed method yields a robust variant of the conditional marginal screening and works well in a variety of settings to reduce false negatives without relying on a pre-selected set of variables with *a priori* information to perform the conditional analysis.

2.2 Step 1: pre-cleaning

In some applications, the number of available predictors can be in the order of tens of thousands or more, but the sample size is limited. To expedite the computation, we first perform a pre-screening step. In this step, the number of predictors we retain is allowed to be larger than the sample size, but usually significantly less than the candidate number of predictors. Although the pre-cleaning is based on the marginal utility as the traditional marginal screening methods, we do not require the assumption that jointly important variables are also marginally important to hold. It is important to note that a variable that is screened out at this stage may still be identified in step 3.

Let $\hat{\beta}_j$ be the maximum likelihood estimator of the coefficient of X_j from fitting a marginal generalized linear model using only the intercept and X_j . Denote $(\hat{\beta}_{0j}, \hat{\beta}_j) = \underset{(\beta_0, \beta_j)}{\operatorname{argmin}} \mathbb{P}_n l(\beta_0 + X_j \beta_j, Y)$, where $l(\theta(x), Y) = -[\theta(x)Y - b\{\theta(x)\}]$,

and for a measurable function g , $\mathbb{P}_n g(X, Y) = n^{-1} \sum_{i=1}^n g(X_i, Y_i)$. We retain the variables whose estimated marginal magnitude is sufficiently large. For a given threshold γ_n , let

$$M_{n1} = \{j : |\hat{\beta}_j| > \gamma_n\}$$

be the index set of the predictors that survive the pre-cleaning.

Define $(\beta_{0j}^*, \beta_j^*) = \arg \min_{(\beta_0, \beta_j)} E\{l(\beta_0 + X_j \beta_j, Y)\}$ as the population version of the marginal regression coefficients. Assume that there exists $A_n \subset \{1, \dots, p_n\}$ such that $\min_{j \in A_n} |\beta_j^*| \geq c_1 n^{-\kappa}$ and $\sup_{j \in A_n^c} |\beta_j^*| \leq c_2 n^{-\kappa-\delta}$, for some $0 < \kappa < 1/2$, $\delta > 0$ and some positive constants c_1 and c_2 . Let $q_n = |A_n|$, where $|A_n|$ denotes the cardinality of A_n . We assume that $q_n \rightarrow \infty$ but $q_n = o(p_n)$.

Proposition 2.1

Assume that conditions 1–5 in the Appendix are satisfied. For $\gamma_n = c_3 n^{-\kappa}$ with $c_3 \leq c_1/2$, there exist positive constants $\xi_i > 0$, $i = 1, 2, 3$, such that $\text{pr}(M_{n1} = A_n) \geq 1 - p_n \{\exp(-\xi_1 n^{1-2\kappa} k_n^{-2} K_n^{-2}) + \exp(-\xi_2 K_n^{\xi_3})\}$, for all n , where K_n and k_n are defined in conditions 2 and 5, respectively.

Remark 1

This result follows from a direct application of the exponential bound for the marginal maximum likelihood estimator in the generalized linear model shown in Fan & Song (2010). Under relatively weak conditions, the aforementioned probability bound converges to 1 as $n \rightarrow \infty$.

2.3 Step 2: sparse principal component analysis

Next, we apply sparse principal component analysis to the variables surviving the pre-cleaning to construct a subset of covariates to condition on. Let X_{A_n} denote the subset of the components of X whose indices are in A_n . Let Σ be the population covariance matrix of X_{A_n} , and consider its spectral decomposition $\Sigma = \sum_{j=1}^{q_n} \lambda_j u_j u_j^T$, where $\lambda_1 \geq \dots \geq \lambda_{q_n}$ are eigenvalues and $u_1, \dots, u_{q_n} \in \mathbb{R}^{q_n}$ constitute an orthonormal basis of the eigenvectors. For a given positive integer $k < q_n$, we consider the principal subspace spanned by the k leading eigenvectors of Σ , that is, the space spanned by $u_1, \dots, u_k$. Our working assumption is that the leading eigenvectors are sparse in the sense that most of their components are zero.

For a vector v , let $\text{supp}(v)$ be the index set corresponding to nonzero entries of v . Then $B_n = \cup_{j=1}^k \text{supp}(u_j)$ represents the collection of the indices of the predictors corresponding to the nonzero components of the first k eigenvectors. In our numerical examples, a small positive integer k , say $k = 1, 2$, is found to work well. The set of predictors X_{B_n} is what we will use in the conditional screening step.

There are a number of different algorithms for sparse principal component analysis; we refer to Jolliffe et al. (2003), Zou et al. (2006), Shen & Huang (2008), Witten et al. (2009), Johnstone & Lu (2009), Ma (2013), Vu & Lei (2013), She (2014) and the references therein. We use the recently developed Fantope projection and selection algorithm of Vu et al. (2013) in our work. Unlike some of the alternatives, Fantope projection and selection algorithm can be applied to correlation matrices and has proved theoretical guarantee for consistently identifying B_n . Let $U = [u_1, \dots, u_k]$. Then the projection matrix associated with the principal subspace is $\Pi = UU^T$. Let S_n be the sample covariance matrix of $X_{M_{n1}}$. Vu et al. (2013) proposed to estimate Π by $\hat{H} = \arg \max \{\langle S_n, H \rangle - \rho \|H\|_{1,1}\}$ subject to the $|M_{n1}| \times |M_{n1}|$ matrix $H \in F^k$, where $F^k = \{H : 0 \leq H \leq I \text{ and } \text{tr}(H) = k\}$, which is called the trace- k Fantope; ρ is a tuning parameter; and $\langle S_n, H \rangle = \text{tr}(S_n^T H)$ is the trace inner product. The matrix $(1,1)$ -pseudonorm $\|H\|_{1,1} = (\|H_{1*}\|_1, \dots, \|H_{k*}\|_1)_1$ with H_{j*} denoting the j th row of H , $j = 1, \dots, k$, that is, $\|H\|_{1,1}$, is the L_1 norm of the vector that consists of row-wise L_1 norms of H . We then estimate B_n by

$$M_{n2} = \text{supp}\{\text{diag}(\hat{H})\},$$

which is the index set corresponding to the nonzero diagonal elements of $\hat{H}$.

Proposition 2.2

Assume that conditions 1–8 in the Appendix are satisfied. Then $\text{pr}(M_{n2} = B_n) \geq (1 - 2q_n^{-2}) \left[1 - p_n \left\{ \exp(-\xi_1 n^{1-2\kappa} K_n^{-2}) + \exp(-\xi_2 K_n^{\xi_3}) \right\} \right]$, for all n .

Remark 2

This result follows directly from Theorem 2 on sparsistency of Lei & Vu (2015). The validity of this result does not depend on any assumption on the joint model. Lei & Vu (2015) also showed that, even without assuming sparsity, Fantope projection and selection method provides a sparse, linear dimension-reducing transformation that is close to the best possible in terms of maximizing the predictive covariance. Vu et al. (2013) recommended to dynamically update ρ after each iteration of their algorithm to keep the primal and dual residual norms within a constant factor of each other.

2.4 Step 3: conditional screening

In the last step, we perform the conditional screening of Barut et al. (2016) by conditioning on $X_{M_{n2}}$. This step allows us to include variables with large additional contributions, which may help recruit predictors that are missed in step 1. More specifically, for each $j \notin M_{n2}$, let $(\hat{\eta}_{0j}, \hat{\eta}_{M_{n2}}, \hat{\eta}_j) = \underset{(\eta_{0j}, \eta_{M_{n2}}, \eta_j)}{\text{argmin}} \mathbb{P}_n l(\eta_0 + X_{M_{n2}}^\top \eta_{M_{n2}} + X_j \eta_j, Y)$.

Conditioning on M_{n2} , we keep the variables in the following set:

$$M_{n3} = \{j : |\hat{\eta}_j| > \gamma_2, j \in M_{n2}^c\}$$

for a given threshold γ_2 . Under weak conditions, it can be shown that M_{n3} enjoys the sure screening property. In practice, the threshold γ_2 may need no prior specification if we choose to retain a fixed number of variables with the largest coefficients $|\hat{\eta}_j|$. At the end of the algorithm, we keep the predictors in the set $\hat{M}_n = M_{n2} \cup M_{n3}$.

Theorem 2.1

(Sure screening property) Assume that conditions 1–11 in the Appendix are satisfied. For the κ' defined in condition 9, let $\gamma_2 = a_1 n^{-\kappa'}$ with $a_1 \leq a_2$, where $a_1 > 0$, $a_2 > 0$ are constants. Then there exist positive constants ξ_i , $i = 4, 5, 6$ such that $\text{pr}(M^* \subset \hat{M}_n) \geq \left[1 - d_n \left\{ \exp(-\xi_4 n^{1-2\kappa} k_n'^{-2} K_n^{-2}) + n \exp(-\xi_5 K_n^{\xi_6}) \right\} \right] (1 - 2q_n^{-2}) \left[1 - p_n \left\{ \exp(-\xi_1 n^{1-2\kappa} K_n^{-2}) + \exp(-\xi_2 K_n^{\xi_3}) \right\} \right]$ for all n , where $d_n = |M^*|$ and k_n' are defined in condition 11.

Remark 3

This result follows from Proposition 2 and Theorem 3 of Barut et al. (2016). For linear and logistic models, the optimal order of K_n is a positive power of $n^{1-2\kappa}$. It is easy to see that the probability in Theorem 1 goes to one even when p_n is allowed to grow exponentially fast.

3 Monte Carlo studies

In the simulation studies, we compare the proposed three-step method (denoted by 3S in Table I) with the following alternatives: (i) SIS of Fan & Lv (2008); (ii) ISIS of Fan et al. (2009); (iii) conditional sure independence screening (CSIS) of Barut et al. (2016) with different choices of the conditioning set C ; and (iv) high-dimensional ordinary least-squares projector of Wang & Leng (2016). SIS and ISIS are both implemented using the R-package SIS on CRAN (version of 0.7-5). We fix $\rho = 0.5$, the tuning parameter in the Fantope projection. In the real analysis, we can determine a value of ρ by cross validation.

Table I. Comparison of true model inclusion and average active viable ratios by different screening methods.

Method		$(p, n) = (1000, 100)$				$(p, n) = (10000, 200)$			
		$R^2 = 50\%$		$R^2 = 90\%$		$R^2 = 50\%$		$R^2 = 90\%$	
		TMR	AAR	TMR	AAR	TMR	AAR	TMR	AAR
Example 1 $(d = 6)$	SIS	0.00	0.60	0.00	0.77	0.00	0.59	0.00	0.80
	ISIS	0.00	0.41	0.98	1.00	0.01	0.49	1.00	1.00
	CSIS with C_1	0.28	0.81	0.80	0.96	0.29	0.82	0.93	0.99
	CSIS with C_2	0.06	0.68	0.46	0.89	0.07	0.68	0.62	0.94
	HOLP	0.06	0.67	0.58	0.91	0.14	0.69	0.77	0.96
	3S	0.08	0.67	0.65	0.93	0.15	0.74	0.82	0.96
Example 2 $(d = 6)$	SIS	0.00	0.48	0.00	0.63	0.00	0.40	0.00	0.64
	ISIS	0.00	0.28	0.01	0.52	0.00	0.29	0.04	0.59
	CSIS with C_1	0.12	0.71	0.32	0.83	0.08	0.70	0.48	0.88
	CSIS with C_2	0.02	0.54	0.14	0.74	0.00	0.46	0.10	0.73
	HOLP	–	–	–	–	–	–	–	–
	3S	0.00	0.55	0.23	0.78	0.03	0.52	0.15	0.76
Example 3 $(d = 2)$	SIS	0.13	0.56	0.22	0.61	0.13	0.56	0.19	0.60
	ISIS	0.06	0.50	0.56	0.78	0.05	0.51	0.79	0.90
	CSIS with C_1	0.24	0.62	0.89	0.94	0.15	0.57	0.95	0.98
	CSIS with C_2	0.14	0.57	0.22	0.61	0.14	0.57	0.21	0.60
	HOLP	0.15	0.57	0.34	0.67	0.13	0.56	0.22	0.61
	3S	0.23	0.62	0.57	0.78	0.13	0.56	0.63	0.82
Example 4 $(d = 12)$	SIS	0.00	0.66	0.07	0.84	0.00	0.69	0.24	0.91
	ISIS	0.00	0.32	0.85	0.96	0.00	0.37	0.98	0.99
	CSIS with C_1	0.01	0.69	0.17	0.87	0.00	0.75	0.40	0.93
	CSIS with C_2	0.00	0.65	0.06	0.83	0.00	0.69	0.24	0.90
	HOLP	0.00	0.64	0.13	0.86	0.02	0.69	0.30	0.92
	3S	0.00	0.65	0.09	0.84	0.02	0.68	0.28	0.91
Example 5 $(d = 4)$	SIS	0.33	0.63	0.51	0.76	0.50	0.73	0.74	0.91
	ISIS	0.00	0.28	0.00	0.44	0.00	0.30	0.00	0.48
	CSIS with C_1	0.56	0.79	1.00	1.00	0.78	0.92	1.00	1.00
	CSIS with C_2	0.15	0.62	0.14	0.66	0.14	0.62	0.20	0.69
	HOLP	0.00	0.25	0.00	0.26	0.02	0.30	0.06	0.48
	3S	0.27	0.65	0.36	0.74	0.30	0.67	0.28	0.65
Example 6 $(d = 3)$		$R^2 = 30\%$		$R^2 = 50\%$	$R^2 = 30\%$		$R^2 = 50\%$		
	SIS	0.71	0.90	0.90	0.97	0.83	0.94	0.97	0.99
	ISIS	0.33	0.70	0.79	0.92	0.37	0.73	0.93	0.94
	CSIS with C_1	0.83	0.94	0.99	0.99	0.83	0.94	1.00	1.00
	CSIS with C_2	0.72	0.90	0.89	0.96	0.70	0.89	0.97	0.99
	HOLP	0.71	0.90	0.89	0.96	0.73	0.91	0.97	0.99
3S	0.72	0.90	0.91	0.97	0.87	0.96	1.00	1.00	

TMR, true model inclusion ratio; AAR, average active variable ratio; SIS, sure independence screening; ISIS, iterative SIS; CSIS, comparative SIS; HOLP, ordinary least-squares projector; 3S, three-step.

We evaluate different screening methods on B simulations runs, where $B = 200$ for $(p, n) = (1000, 100)$ and $B = 100$ for $(p, n) = (10000, 200)$. Across B simulation runs, we compare the different methods according to two criteria: (i) true model inclusion ratio, the proportion of times when the first n variables retained from screening include all the active variables, and (ii) average active variable ratio, the proportion of active variables in the set of n retained variables after screening. Higher values of true model inclusion ratio and average active variable ratio indicate better screening procedures.

In this study, examples 1–4 are adapted or modified from Barut et al. (2016) and Fan & Lv (2008), and example 6 is used in Wang (2009) and Wang & Leng (2016). The random error ϵ follows $N(0, \sigma^2)$ with σ^2 being adjusted to achieve a pre-specified R^2 defined as $\text{var}(X^\top \beta) / \text{var}(Y)$.

Example 1. $Y = X^\top \beta + \epsilon$, where all covariates follow the standard normal distribution with equal correlation 0.5 and $\beta = (3, 3, 3, 3, 3, -7.5, 0, \dots, 0)^\top$. In this setting, X_6 is the hidden active variable because $\text{cov}(X_6, Y) = 0$ although β_6 has a large contribution to the response variable.

Example 2. The conditional distribution of Y given $X = x$ follows the binomial distribution with $\text{pr}(Y = 1 \mid X = x) = \exp(x^\top \beta) / \{1 + \exp(x^\top \beta)\}$, where X and β are the same as in example 1.

Example 3. $Y = X^\top \beta + \epsilon$, where all the covariates except $X_1 - X_7$ follow the independent standard normal distribution and $\beta = (10, 0, \dots, 0, 1)^\top$. The first seven covariates are normal with equi-correlation 0.9.

Example 4. $Y = X^\top \beta + \epsilon$, where $\beta = (1, 1.3, 1, 1.3, 1, 1.3, 1, 1.3, 1, 1.3, 0, \dots, 0)^\top$, $X_j = \epsilon_j$, $\{\epsilon_j\}_{j=1, \dots, [p/3]}$ are independent and identically distributed standard normal variables, $\{\epsilon_j\}_{j=[p/3]+1, \dots, [(2p)/3]}$ are independent and identically distributed double exponential variables with location parameter zero and scale parameter one and $\{\epsilon_j\}_{j=[(2p)/3]+1, \dots, p}$ are independent and identically distributed with a mixture normal distribution with two components $N(-1, 1)$ and $N(1, 0.5)$ of equal mixture proportion, where $[x]$ denotes the integer part of x .

Example 5. $Y = X^\top \beta + \epsilon$, where all the covariates except $X_2 - X_{50}$ are independent standard normal random variables and $\beta = (0.7, 0.2, -0.2, -0.2, 0, \dots, 0)^\top$. The covariates $X_2 - X_{50}$ are normal with equi-correlation 0.9.

Example 6. $Y = X^\top \beta + \epsilon$, where each X_i follows a multivariate normal distribution with mean 0 and $\text{cov}(X_{ij_1}, X_{ij_2}) = 0.3^{|j_1 - j_2|}$ and $\beta = (3, 0, 0, 1.5, 0, 0, 2, 0, \dots, 0)^\top$.

We summarize the simulation results from the aforementioned examples in Table I, but note that the study of Wang & Leng (2016) is not developed for binary responses so is excluded in example 2. The performance of CSIS depends on the prior knowledge of a conditioning set C . We consider the case when such an informative set is available as well as the case where we do not have such knowledge. In example 1, we consider two choices of the conditioning sets, $C_1 = \{1, 2\}$ and $C_2 = \{\text{a random choice of two inactive variables}\}$; in examples 2–6, we consider the choices $C_1 = \{1\}$ and $C_2 = \{\text{a random choice of one inactive variable}\}$. Here, C_1 is a favourable choice, but C_2 is not. For the proposed 3S method, we retain n covariates in the pre-cleaning step. Although the number of predictors kept in this stage can be larger than the sample size, we did not observe significant gains from holding larger sets of covariates such as sizes of $2n$ and $3n$ in the aforementioned examples. To control the effect due to the size of the conditioning set, we let the size of M_{n2} of our proposed procedure be the same as that of the conditioning set used for CSIS. We observe from Table I that

- The ISIS tends to perform well when the signal-to-noise ratio is high (with $R^2 = 0.9$), but it does not always improve over SIS. In a more realistic setting with $R^2 = 0.5$ or lower, the iterative screening often performs worse, and sometimes substantially so (examples 2, 5 and 6).
- The benefit of CSIS is clear when a favourable choice of the conditioning set is given, such as the case with C_1 . However, when the conditioning set is not well chosen, it becomes less robust, and its performance could degenerate easily.

- In all the examples, the proposed method 3S remains highly competitive. Often, it performs significantly better than SIS when the latter has difficulty selecting the hidden active variables (examples 1–3). When compared with CSIS, it is much closer to the behaviour of CSIS under a favourable conditioning set than that without a well-informed choice of the conditioning set.
- High-dimensional ordinary least-squares projector is often a competitive method; however, it has very poor performance in example 5, and it has not been developed for binary regression (example 2).

In summary, for a wide range of settings, the proposed method remains competitive. It can be viewed as a data-adaptive version of the CSIS. Our empirical work demonstrates the potential of the proposed method to reduce the false negatives when hidden variables are present.

4 Real data example

We illustrate the proposed methodology using the widely analyzed leukaemia microarray data set from Golub et al. (1999). The data set contains measurements on specimens from bone marrow or peripheral blood samples taken from 72 patients, who had either ALL or AML. Gene expression levels were measured using Affymetrix high-density oligonucleotide arrays containing $p = 7129$ human genes.

It is important to identify signature genes for distinguishing ALL and AML. We first split the data into 38 training samples (27 ALL and 11 AML) and 34 testing samples (20 ALL and 14 AML) as performed in the original investigation (Golub et al., 1999) and then apply the proposed method to select genes and evaluate the performance of classification power. We standardize the gene expression data so that the arrays have mean 0 and variance 1 across genes, which is a common pre-processing method used in expression data analysis. The predictive performance of the selected genes on the training and testing data is assessed for several competing methods under consideration. They are

- SIS: using top three genes by marginal screening.
- ISIS: using top three genes by iterative screening.
- CSIS-i: the CSIS method conditional on $C_1 = \{X95735, D26156\}$, two genes used in Barut et al. (2016) as good choices.
- CSIS-ii: the CSIS method conditional on $C_2 = \{X95735, M27783\}$, two top genes from marginal screening SIS.
- CSIS-iii: the CSIS method conditional on C_3 , which consists of two randomly chosen genes.
- 3S: the proposed three-step screening method.

The results on the misclassification performance (evaluated on the testing data) are reported in Table II, where the misclassification rates are computed using two different approaches. The first one, $Test\ error^1$, uses the training data to both select the genes and fit the logistic regression model that is then used for classification, while the second one, $Test\ error^2$, uses the training data to select the genes and then use the full data to estimate the logistic model coefficients for classification.

We retain three genes for SIS to compare directly with the results in Barut et al. (2016). For the CSIS-iii, the misclassification rates are averaged over 200 randomly chosen sets of C_3 . For our proposed method 3S, we choose the tuning parameter ρ needed in step 2 (the Fantope projection) by cross validation. The ρ value of 0.45 for the training data set is used.

The proposed data-driven conditional screening method 3S identified genes *D88422* (CYSTATIN A), *X95735* (Zyxin) in step 2 and selected an additional gene *M21624* (TCRD T-cell receptor, delta) in step 3. We observe that the three genes identified by the 3S procedure have satisfactory predictive power. In fact, the misclassification rates ($Test\ error^1 = 2/34$,

Table II. Misclassification rates for the leukaemia data with training and testing samples.			
Method	Train error	Test error ¹	Test error ²
(1) SIS	0/38	5/34	3/34
(2) ISIS	0/38	3/34	3/34
(3) CSIS			
(i) Informative $C_1 = \{X95735, D26156\}$	0/38	2/34	1/34
(ii) Informative $C_2 = \{X95735, M27783\}$	1/38	5/34	3/34
(iii) Non-informative $C_3 = \{\text{two random choices}\}$	$(0.1 \pm 1.14)/38$	$(6.9 \pm 3.42)/34$	$(6.1 \pm 3.93)/34$
(4) Proposed data-driven $C = \{D88422, X95735\}$	0/38	2/34	1/34

SIS, sure independence screening; ISIS, iterative SIS; CSIS, comparative SIS.

Test error² = 1/34) are the same as those for CSIS-i, where a knowledgeable choice of the conditioning set based on information from the medical literature is used (Barut et al., 2016). The original paper of Golub et al. (1999) used 50 genes to build a predictive model but only achieved correct classification on 29 of the 34 cases in the testing data set. In comparison, the proposed 3S method achieve better classification performance with far fewer genes.

It is also informative to see what happens when we apply different methods to the full data. That is, the full data are used to select the genes, fit the model and evaluate the classification performance. When CSIS-i with the same C_1 as in Table II is applied to the full data, it selects an additional gene *HG651–HT4201* and results in a misclassification rate of 4/72. This is clearly not as favourable as the results in Table II and demonstrates that, even though C_1 (subjective choice) gives good performance for the training data, it would lead to less favourable results on the full data. When the proposed method S3 is used, we obtain $C = \{M27891(\text{cystatin C})\}$ for $k = 1$ and $C = \{M27891(\text{cystatin C}), D88422(\text{cystatin A})\}$, for $k = 2$ in step 2 using the Fantope projection tuning parameter $\rho = 0.49$. In step 3, an additional gene *U62136* (putative enterocyte differentiation promoting factor mRNA) is selected conditioning on either $\{M27891, D88422\}$ or $\{M27891\}$. In either case, the method identified a model with no misclassification on the same data. Note that *U62136* is removed in step 1 of the 3S method because of its small marginal utility, but it is retrieved in step 3 by conditioning on the gene(s) selected in step 2. Those three genes by 3S were all identified as important in Golub et al. (1999). Previous studies (Dramiński et al., 2008; Guan & Zhao, 2005) also confirmed *U62136* as one of the top-ranked reference genes for leukaemia.

With SIS, *U62136* is ranked as 63 out of the total number of 7129 genes. Therefore, it can be easily missed by marginal screening when only a small subset of genes are chosen in the final model. It is also missed by CSIS with the subjective choice of C_1 used by Barut et al. (2016). Overall, we conclude that the proposed 3S method with adaptive choice of conditioning set provides reliable results in this example, whether the procedure is applied to the training data alone or to the full data.

Appendix A. Technical conditions

We first introduce some additional notation. Let $\beta_j = (\beta_{0j}, \beta_j)^T$, $\mathbf{X}_j = (1, X_j)^T$, $\boldsymbol{\beta} = (\beta_0, \beta_1, \dots, \beta_{p_n})^T$ and $\mathbf{X} = (1, X_1, \dots, X_{p_n})^T$. Let $\mathbf{X}_{B_n}$ be the subvector of $\mathbf{X}$ consisting of those components in B_n , where B_n is defined in Section 2.3. For $j \notin B_n$, let $\mathbf{X}_{B_{nj}} = (\mathbf{X}_{B_n}^T, X_j)^T$. Let $\boldsymbol{\eta} = (\eta_0, \eta_1, \dots, \eta_{p_n})^T$. For $j \notin B_n$, let $\boldsymbol{\eta}_{B_{nj}} = (\boldsymbol{\eta}_{B_n}^T, \eta_j)^T$ and $\boldsymbol{\eta}_{B_{nj}}^* = \arg \min_{\boldsymbol{\eta}_{B_{nj}}} E(\mathbf{X}_{B_{nj}}^T \boldsymbol{\eta}_{B_{nj}}, Y)$. For a vector $v \in \mathbb{R}^k$, $\|v\|$ denotes the Euclidean norm, and $\|v\|_\infty = \max_{1 \leq i \leq k} |v_i|$. For a matrix $A \in \mathbb{R}^{n \times m}$ and index sets $J_1 \subset \{1, \dots, n\}$ and $J_2 \subset \{1, \dots, m\}$, $A_{J_1 J_2}$ denotes that the submatrix

consists of rows in J_1 and columns in J_2 . For $1 \leq i \leq n$ and $1 \leq j \leq m$, A_{ij} denotes the (i, j) th entry of A . The matrix $(2, \infty)$ -norm $\|A\|_{2, \infty}$ is defined as $\max\{\|A_{1*}\|, \|A_{2*}\|, \dots, \|A_{n*}\|\}$, where A_{i*} denotes the i th row of A , $i = 1, \dots, n$. Let $M_{*B_n} = M_* \cap B_n$. Let $E_L(X_j|\mathbf{X}_{B_n})$ denote the best linear regression fit of X_j regressed on $\mathbf{X}_{B_n}$. Let $\text{cov}_L(Y, X_j|\mathbf{X}_{B_n}) = E(X_j - E_L(X_j|\mathbf{X}_{B_n}))(Y - E_L(Y|\mathbf{X}_{B_n}))$.

- Condition 1. The marginal Fisher information $I_j(\beta_j) = E\{b''(\mathbf{X}_j^\top \beta_j) \mathbf{X}_j \mathbf{X}_j^\top\}$ is finite and positive definite at $\beta_j^* = (\beta_{0j}^*, \beta_j^{*'})^\top$, where $(\beta_{0j}^*, \beta_j^{*'}) = \arg \min_{(\beta_0, \beta_j)} E\{I(\beta_0 + X_j \beta_j, Y)\}$ for $j = 1, \dots, p_n$. Moreover, $\sup_{\beta_j \in \mathbb{B}, \|\mathbf{X}_j\|=1} \|I_j(\beta_j)^{1/2} \mathbf{X}_j\|$ is bounded from earlier, where $\|\cdot\|$ is the Euclidean norm and $\mathbb{B} = \{\beta_j : |\beta_{0j}| \leq B, |\beta_j^{*'}| \leq B\}$ is a sufficiently large set for which β_j^* is an interior point.
- Condition 2. The second derivative of $b(\theta)$ is continuous and positive. There exists an $\epsilon_1 > 0$ such that, for all $j = 1, \dots, p_n$, for some sufficiently large positive constant K_n , $\sup_{\beta_j \in \mathbb{B}, \|\beta_j - \beta_j^*\| \leq \epsilon_1} |Eb(\mathbf{X}_j^\top \beta_j) I(|X_j| > K_n)| = o(n^{-1})$.
- Condition 3. For all $\beta_j \in \mathbb{B}$, we have $E\{I(\mathbf{X}_j^\top \beta_j, Y) - I(\mathbf{X}_j^\top \beta_j^*, Y)\} \geq V \|\beta_j - \beta_j^*\|^2$, for some positive constant V , bounded from the later equation uniformly over $j = 1, \dots, p_n$.
- Condition 4. There exist some positive constants m_0, m_1, s_0, s_1 and α , such that, for sufficiently large t , $P(|X_j| > t) \leq (m_1 - s_1) \exp(-m_0 t^\alpha)$, for $j = 1, \dots, p_n$, and that $E\left[\exp\{b(\mathbf{X}^\top \beta_* + s_0) - b(\mathbf{X}^\top \beta_*)\}\right] + E\left[\exp\{b(\mathbf{X}^\top \beta_* - s_0) - b(\mathbf{X}^\top \beta_*)\}\right] \leq s_1$.
- Condition 5. Let $k_n = b'(K_n B + B) + m_0 K_n^\alpha / s_0$. Assume that $n^{1-2\kappa} / (k_n^2 K_n^2) \rightarrow \infty$.
- Condition 6. The matrix Σ defined in Section 2.3 satisfies the sparse principal subspace condition in Lei & Vu (2015) with some positive integer k and a support set J of size s ; Σ also satisfies the limited correlation condition (LCC) in Lei & Vu (2015) with a constant $\delta \in (0, 1]$. The matrix S_n defined in Section 2.3 satisfies the maximum error bound condition in Lei & Vu (2015) with a scaling constant σ .
- Condition 7. Assume that $s\sqrt{\log q_n/n} \leq \{\delta(\lambda_k - \lambda_{k+1})^2\} / \{4\sigma(8\lambda_1 + \lambda_k - \lambda_{k+1})\}$. The tuning parameter ρ in estimating $\hat{H}$ satisfies $\rho = \sigma\delta^{-1}\sqrt{\log q_n/n}$.
- Condition 8. Either of the following two conditions holds:
(1) $4s\sqrt{\log q_n/n} < \delta(\lambda_k - \lambda_{k+1}) \min_{i \in J} \sqrt{\Pi_{ij}}$, where Π is defined in Section 2.3;
(2) $\text{rank}(\text{sign}(\Sigma_{JJ})) = 1$ and $2\sigma\sqrt{\log q_n/n} < \delta \min_{i \in J, j \in J} \Sigma_{ij}$.
- Condition 9. There exist $c'_1 > 0$ and $0 < k' < 1/2$ such that $\text{cov}_L(Y, X_j|\mathbf{X}_{B_n}) \geq c'_1 n^{-k'}$, $\forall j \in M_{*B_n}$. Let $\phi_j = \{b'(\mathbf{X}_{B_n j}^\top \eta_{B_n j}^*) - b'(\mathbf{X}_{B_n}^\top \eta_{B_n}^*)\} / (\mathbf{X}_{B_n j}^\top \eta_{B_n j}^* - \mathbf{X}_{B_n}^\top \eta_{B_n}^*)$. Assume that $E(\phi_j X_j^2) \leq c'_2$ for some positive constant c_2 , uniformly in $j \in B_n^c$.
- Condition 10. (i) The marginal Fisher information $I_j(\eta_{B_n j}) = E\{b''(\mathbf{X}_{B_n j}^\top \eta_{B_n j}^*) \mathbf{X}_{B_n j} \mathbf{X}_{B_n j}^\top\}$ is bounded. Moreover, $\sup_{\beta_{B_n j} \in \mathbb{B}', \|\mathbf{X}_{B_n j}\|=1} \|I_j(\eta_{B_n j})^{1/2} \mathbf{X}_{B_n j}\|$ is bounded, where $\|\cdot\|$ is the Euclidean norm, $\mathbb{B}' = \{\eta_{B_n j} : |\eta_{B_n j}| \leq B', \forall l \in B_n \cup \{j\}\}$ is a sufficiently large set for which $\eta_{B_n j}^*$ is an interior point, B' is a sufficiently large positive constant and $(\eta_{B_n j})_l$ denotes the l th component of $\eta_{B_n j}$.
(ii) There exists an $\epsilon'_1 > 0$ such that, for all $j \in B_n^c$, for the K_n specified in condition 2, $\sup_{\eta_{B_n j} \in \mathbb{B}', \|\eta_{B_n j} - \eta_{B_n j}^*\| \leq \epsilon'_1} |Eb(\mathbf{X}_{B_n j}^\top \eta_{B_n j}) I(|X_j| > K_n)| = o(n^{-1})$. The function $l(x^\top \beta, y)$ satisfies the Lipschitz condition with positive constant k_n , $|l(x^\top \beta, y) - l(x^\top \beta', y)|_{l_n(x, y)} \leq k_n |x^\top \beta - x^\top \beta'|_{l_n(x, y)}$, for $\beta, \beta' \in B$, a compact, convex parameter set, where $l_n(x, y) = l\{(x, y) \in \Omega_n\}$ and $\Omega_n = \{(x, y) : \|x\|_\infty \leq K_n, |y| \leq K_n^*\}$, for some positive constants K_n and $K_n^* = m_0 K_n^\alpha / s_0$.

(iii) For all $\eta_{B_{nj}} \in \mathbb{B}'$, we have $E\left(l\left(\mathbf{X}_{B_{nj}}^\top \eta_{B_{nj}}, Y\right) - l\left(\mathbf{X}_{B_{nj}}^\top \eta_{B_{nj}}^*, Y\right)\right) \geq V' \|\eta_{B_{nj}}^* - \eta_{B_{nj}}^*\|^2$, for some positive constant V' .

Condition 11. Let $k'_n = b'(K_n B(|B_n| + 1)) + m_0 K_n^\alpha / s_0$. Assume that $n^{1-2\kappa'} / (k_n'^2 K_n^2) \rightarrow \infty$.

Remark 4

Conditions 1–5 are those that appear in Theorem 4 of Fan & Song (2010) for the exponential bound for the marginal maximum likelihood estimator in the generalized linear model. As they have discussed, conditions 1–3 are satisfied by many examples of generalized linear models; condition 4 ensures the tail of Y to be exponentially light; condition 5 is necessary for the exponential inequality of the marginal maximum likelihood estimation. Conditions 6–8 are those that appear in Theorem 2 of Lei & Vu (2015). Conditions 9–11 are those that appear in Theorem 3 of Barut et al. (2016), which are parallel to conditions 1–5 for the unconditional case.

Appendix B. Technical derivations

Proof of Proposition 1.

It is embedded in the proof for Theorem 4(i) of Fan & Song (2010) that, for $\gamma_n = c_3 n^{-\kappa}$ with $c_3 \leq c_1/2$, there exist positive constants $\xi_i > 0$, $i = 1, 2, 3$, such that the marginal likelihood estimator satisfies

$$\text{pr}\left(|\hat{\beta}_j - \beta_j^*| > \gamma_n\right) \leq \exp\left(-\xi_1 n^{1-2\kappa} k_n^{-2} K_n^{-2}\right) + \exp\left(-\xi_2 K_n^{\xi_3}\right), \quad (2)$$

$\forall 1 \leq i \leq p_n$. Consider the event $E_n = \{\max_{1 \leq i \leq p_n} |\hat{\beta}_i - \beta_i^*| \leq \gamma_n\}$. Note that, on this event, we have $M_{n1} = A_n$. Hence, $\text{pr}(M_{n1} = A_n) \geq \text{pr}(E_n) = 1 - \text{pr}(E_n^c)$, and the result follows by an application of (2) and the union bound. $\square$

Proof of Proposition 2.

Note that $\text{pr}(M_{n2} = B_n) \geq \text{pr}(M_{n2} = B_n | M_{n1} = A_n) \text{pr}(M_{n1} = A_n)$. By Theorem 2 of Lei & Vu (2015), $\text{pr}(M_{n2} = B_n | M_{n1} = A_n) \geq 1 - 2q_n^{-2}$. The result then follows by an application of Proposition 1. $\square$

Proof of Theorem 1.

Note that $\text{pr}\left(M^* \subset \hat{M}_n\right) \geq \text{pr}\left(M^* \subset \hat{M}_n | M_{n2} = B_n\right) \text{pr}(M_{n2} = B_n)$. By Theorem 3 of Barut et al. (2016), $\text{pr}(M^* \subset \hat{M}_n | M_{n2} = B_n) \geq \left[1 - d_n \left\{\exp\left(-\xi_4 n^{1-2\kappa} k_n'^{-2} K_n^{-2}\right) + n \exp\left(-\xi_5 K_n^{\xi_6}\right)\right\}\right]$. The result then follows by an application of Proposition 2. $\square$

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