Nonparametric Methods III

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OVERVIEW

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For basis expansion, functions are represented as expansions in basis functions, $x \in \mathbb{R}^p$:

$$f(x) = \sum_{j=1}^{M} \beta_j b\left(x; \gamma_j\right)$$

In single-hidden-layer neural networks

- $b(x; \gamma) = \sigma\left(\gamma_0 + \gamma_1^\top x\right)$, where $\sigma(t) = 1/\left(1 + e^{-t}\right)$ (with $M = 1$) is the sigmoid function (logistic function)
- γ parameterizes a linear combination of the predictors.

Radial basis expansion generalize these ideas, by treating the kernel functions $K_\lambda(\xi, x)$ as basis functions. This leads to the model

$$
\begin{aligned}
f(x) &= \sum_{j=1}^{M} K_{\lambda_j}\left(\xi_j, x\right)\beta_j \\
&= \sum_{j=1}^{M} \bar{K}\left(\frac{\|x-\xi_j\|}{\lambda_j}\right)\beta_j
\end{aligned}
$$

where each basis element is indexed by

- location or prototype parameter ξ_j
- a scale parameter λ_j.

RBF network

To estimate $\{\lambda_j, \xi_j, \beta_j\}, j = 1, \ldots, M$, optimize the sum-of-squares with respect to all the parameters:

$$\min_{\beta_0, (\lambda_j, \xi_j, \beta_j)_{j=1}^M} \sum_{i=1}^n \left(y_i - \beta_0 - \sum_{j=1}^M \beta_j \exp\Big(- \frac{(x_i - \xi_j)^\top (x_i - \xi_j)}{\lambda_j^2} \Big) \right)^2$$

Often, $\bar{K}$ is replaced by the *renormalized radial basis functions*:

$$h_j(x) = \frac{\bar{K}\left(\|x - \xi_j\| / \lambda\right)}{\sum_{k=1}^{M} \bar{K}\left(\|x - \xi_k\| / \lambda\right)}$$

The Nadaraya-Watson kernel regression estimator in $\mathbb{R}^p$ can be viewed as an expansion in renormalized radial basis functions,

$$\begin{aligned} \hat{f}\left(x_0\right) &= \sum_{i=1}^{n} y_i \frac{K_\lambda\left(x_0, x_i\right)}{\sum_{j=1}^{n} K_\lambda\left(x_0, x_j\right)} \\ &= \sum_{i=1}^{n} y_i h_i\left(x_0\right) \end{aligned}$$

- a basis function h_i located at every observation and coefficients y_i
  - $\xi_i = x_i, \hat{\beta}_i = y_i, i = 1, \ldots, n.$

Nonparametric classification

knn classifier

For any given $X = x_0$, we find the K closest neighbors to $X = x_0$ in the training data, and examine their corresponding Y.

$$P(Y = j \mid X = x_0) = \frac{1}{K} \sum_{i \in N_K(x_0)} I(y_i = j)$$

Estimate the conditional probability for group j by the proportion out of the k neighbors that are in group j.

Kernel density classification

Suppose for a J class problem, we fit nonparametric density estimates $\hat{f}_j(X), j = 1, \ldots, J$ separately in each of the classes, and we also have estimates of the class priors $\hat{\pi}_j$ (usually the sample proportions).

$$\hat{\Pr}(Y = j \mid X = x_0) = \frac{\hat{\pi}_j \hat{f}_j(x_0)}{\sum_{k=1}^{J} \hat{\pi}_k \hat{f}_k(x_0)}$$

Nonparametric logistic regression

Let $Y \in \{0, 1\}$.

$$f(x) = \log\left(\frac{Pr(Y = 1 \mid X = x)}{Pr(Y = 0 \mid X = x)}\right)$$

Therefore, $p(x) = Pr(Y = 1|x) = \frac{e^{f(x)}}{1+e^{f(x)}}$.

Logistic (cubic) smoothing spline estimate is defined by

$$\min_f -\ell(f) = \min_f \sum_{i=1}^{n} \left(-y_i f\left(x_i\right) + \log\left(1 + e^{-f(x_i)}\right)\right) + \frac{\lambda}{2} \int \left(f^{(2)}(x)\right)^2 dx$$

- $N_1, \ldots, N_n$: the natural cubic spline basis
- the basis matrix: $\mathbf{N} \in \mathbb{R}^{n \times n}$
- penalty matrix: $\Omega \in \mathbb{R}^{n \times n}$

$f(x) = \sum_{j=1}^{n} N_j(x)\theta_j$.

$\mathbf{p}$ is the n-vector with elements $p(x_i;\theta)$, $\mathbf{W}$ is a diagonal matrix of weights $p(x_i;\theta)(1-p(x_i;\theta))$

$$\begin{aligned}
\frac{\partial(-\ell(\theta))}{\partial\theta} &= -\mathbf{N}^\top(\mathbf{y}-\mathbf{p})+\lambda\boldsymbol{\Omega}\theta \\
\frac{\partial^2(-\ell(\theta))}{\partial\theta\partial\theta^\top} &= \mathbf{N}^\top\mathbf{W}\mathbf{N}+\lambda\boldsymbol{\Omega}
\end{aligned}$$

The gradient descent update and the Newton's update are respecitively

$$\theta^{(k+1)} = \theta^{(k)} + \alpha \times \left(\mathbf{N}^\top(\mathbf{y}-\mathbf{p}^{(k)}) - \lambda\boldsymbol{\Omega}\theta^{(k)}\right)$$

$$\begin{aligned}
\theta^{(k+1)} &= \theta^{(k)} + \left(\mathbf{N}^\top\mathbf{W}^{(k)}\mathbf{N}+\lambda\boldsymbol{\Omega}\right)^{-1}\left(\mathbf{N}^\top(\mathbf{y}-\mathbf{p}^{(k)}) - \lambda\boldsymbol{\Omega}\theta^{(k)}\right) \\
&= \left(\mathbf{N}^\top\mathbf{W}^{(k)}\mathbf{N}+\lambda\boldsymbol{\Omega}\right)^{-1}\mathbf{N}^\top\mathbf{W}^{(k)}\left(\mathbf{N}\theta^{(k)} + {\mathbf{W}^{(k)}}^{-1}(\mathbf{y}-\mathbf{p}^{(k)})\right) \\
&= \left(\mathbf{N}^\top\mathbf{W}^{(k)}\mathbf{N}+\lambda\boldsymbol{\Omega}\right)^{-1}\mathbf{N}^\top\mathbf{W}^{(k)}\mathbf{z}^{(k)}
\end{aligned}$$

iteratively reweighted (penalized) LS

Newton's update $\quad \theta^{(k+1)} = \left(\mathbf{N}^\top \mathbf{W}^{(k)} \mathbf{N} + \lambda \boldsymbol{\Omega}\right)^{-1} \mathbf{N}^\top \mathbf{W}^{(k)} \mathbf{z}^{(k)}$

$$
\begin{aligned}
\mathbf{f}^{(k+1)} &= \mathbf{N} \left(\mathbf{N}^\top \mathbf{W}^{(k)} \mathbf{N} + \lambda \boldsymbol{\Omega}\right)^{-1} \mathbf{N}^\top \mathbf{W}^{(k)} \left(\mathbf{f}^{(k)} + {\mathbf{W}^{(k)}}^{-1} (\mathbf{y} - \mathbf{p}^{(k)})\right) \\
&= \mathbf{S}_{\lambda,\mathbf{W}}^{(k)} \mathbf{z}^{(k)}
\end{aligned}
$$

The Newton's update fits a weighted smoothing spline to the adjusted response z:

$$
\min_f \mathrm{RSS}(f, \lambda) = \sum_{i=1}^{n} w_i \big(z_i - f(x_i)\big)^2 + \lambda \int \left(f^{(2)}(x)\right)^2 dx
$$

Nonparametric additive models

In the regression setting, a generalized additive model has the form

$$\mathrm{E}\left(Y \mid X_1, X_2, \ldots, X_p\right)=\alpha+f_1\left(X_1\right)+f_2\left(X_2\right)+\cdots+f_p\left(X_p\right)$$

Let $\mu(X)=E(Y|X)$. The generalized additive models:

$$g(\mu(X))=\alpha+\sum_{j=1}^p f_j\left(X_j\right)$$

- $g(\mu)=\mu$: additive model for Gaussian response data.
- $g(\mu)=\operatorname{logit}(\mu)$ or $g(\mu)=\operatorname{probit}(\mu)$: logistic / probit additive models for binary response data.
- $g(\mu)=\log(\mu)$: log-additive model for Poisson count data.

Fitting additive models

$$Y = \alpha + \sum_{j=1}^{p} f_j\left(X_j\right) + \varepsilon$$

Penalized sum of squares:

$$\sum_{i=1}^{n} \left\{ y_i - \alpha - \sum_{j=1}^{p} f_j\left(x_{ij}\right) \right\}^2 + \sum_{j=1}^{p} \lambda_j \int \left(f_j^{(2)}\left(t_j\right) \right)^2 dt_j$$

where $\lambda_j \geq 0$ are tuning parameters.

The minimizer is an additive cubic spline model; each of the functions f_j is a cubic spline.

- α is not identified.
    - assume $\sum_{i=1}^{n} f_j\left(x_{ij}\right) = 0$ for any j (thus $\hat{\alpha} = \bar{y}$).

Back-fitting algorithm

For any j, $\mathrm{E}(Y-\alpha-\sum_{k\neq j} f_k(X_k)|X_j) = f_j(X_j)$.

Suppose our univariate smoothing algorithm smooth(z, y) has been chosen (smooth$(z, y) = \hat{E}(Y = y|Z = z)$).

We initialize $\hat{f}_1, \ldots, \hat{f}_p$ (say, to all to zero), let $\hat{\alpha} = \bar{y}$:

cycle over the following steps for $j = 1, \ldots, p, 1, \ldots, p, \ldots$

- define the response $r_i = y_i - \hat{\alpha} - \sum_{k\neq j} \hat{f}_k\left(x_{ik}\right), i = 1, \ldots, n$
- smooth $\hat{f}_j \leftarrow$ fitted smooth$\left(\mathbf{x}_j, r\right)$, where $\mathbf{x}_j = \left(x_{11}, \ldots, x_{nj}\right), r = \left(r_1, \ldots, r_n\right)$.
- center $\hat{f}_j \leftarrow \hat{f}_j - \frac{1}{n}\sum_{i=1}^{n} \hat{f}_j\left(x_{ij}\right)$

Generalized additive logistic regression

$$\log \frac{\Pr(Y=1 \mid X)}{\Pr(Y=0 \mid X)} = \eta(x) = \alpha + f_1(X_1) + \cdots + f_p(X_p)$$

smoothing splines solution:

$$\hat{f} = \underset{f_1,\ldots,f_p}{\operatorname{argmin}} \sum_{i=1}^{n} \left(-y_i \eta(x_i) + \log\left(1 + e^{-\eta(x_i)}\right)\right) + \frac{\lambda}{2} \sum_{j=1}^{p} \int \left(f_j^{(2)}(t_j)\right)^2 dt_j$$

Algorithm: IRLS (iteratively reweighted least squares) + weighted backfitting

- update adjusted response $\{z_i\}$ and weights $\{w_i\}$ (IRLS loop)
  - update components $\{\hat{f}_j\}$ (backfitting loop)

Inference

Let $\text{logit}(Pr(Y = 1|X)) = \theta_0 + \sum_{j=1}^{p} f_j(X_j)$,
$f_j(x_j) = \sum_{k=1}^{M_j} \theta_{jk} h_{jk}(x_j)$

- $\{\theta_{jk} : k = 1, \ldots, M_j\}$
- $h_j = \{h_{jk} : k = 1, \ldots, M_j\}$
- $\theta = (\theta_0, \theta_1^\top, \ldots, \theta_p^\top)^\top$
- $\mathbf{H}$ be the $n \times (1 + M)$ hat matrix ($M = \sum_{j=1}^{M} M_j$).

We have

$$cov(\hat{\theta}) = \hat{\Sigma} = (\mathbf{H}^\top \mathbf{W} \mathbf{H})^{-1}$$

For $\hat{f}_j(x_j) = h_j^\top(x_j)\hat{\theta}_j$,

- variance $var(\hat{f}_j(x_j)) = h_j^\top(x_j)\hat{\Sigma}_{j,j} h_j(x_j)$.
- pointwise confidence interval (biased): $\hat{f}_j(x_j) \pm z_{\alpha/2}\sqrt{var(\hat{f}_j(x_j))}$.

Alleviation of the Curse of Dimensionality

If the true function is indeed additive, and each component function is s-times differentiable, then the optimal MSE rate achievable becomes $pn^{-2s/(2s+1)}$.

- p does not appear in the exponent in the rate
- p times univariate optimal rate!

See later on *deep* neural network, the curse of dimensionality can be circumvented if f has composition and sparse structure.

Variable selection in nonparametric regression

Variable selection in nonparametric regression

$$f(x) = \beta_0 + \sum_{j=1}^{p} f_j(x_j)$$

Claim X_j as unimportant if the function $f_j = 0$

Two-way interaction model

$$f(x) = \beta_0 + \sum_{j=1}^{p} f_j(x_j) + \sum_{j<k} f_{jk}(x_j, x_k)$$

The interaction effect between X_j and X_k is unimportant if $f_{jk} = 0$.

- Multivariate Adaptive Regression Splines (MARS) (Friedman 1991)
- Classification and Regression Tree (CART, Brieman 1985) (not quite do the job)
- Group-LASSO Methods (Huang et al. 2010)
- Sparse Additive Models (Ravikuma et al. 2009)
    - Sparse logistic additive models