Econometrics **June 17, 2023**

Topic 17: False Discovery Rate (FDR) and Knockoffs

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Key points: Constructing knockoff variables to control FDR when estimating regression coefficients.

Disclaimer: *The note is built on Prof. Jinchi Lv's lectures of the course at USC, DSO 607, High-Dimensional Statistics and Big Data Problems.*

17.1 Motivation

Consider the classical linear regression setting

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\epsilon}$$

where $\boldsymbol{\beta} \in \mathbb{R}^p$ is the unknown vector of coefficients and $\boldsymbol{\epsilon} \sim \mathcal{N}(\mathbf{0}, \sigma^2\mathbf{I})$. In a high-dimensional problem, we would like to just select a subset of all variables $\hat{S} \subset \{1, \cdots, p\}$ s.t. conditional on $\{\mathbf{X}_j\}_{j\in\hat{S}}$, $\mathbf{y}$ is **independent** of all other variables, we can define the **False Discovery Rate** **(FDR)** in can be defined as

Definition 17.1.1: False Discovery Rate (FDR)

$$\mathrm{FDR} = \mathbb{E}(\mathrm{FDP}) = \mathbb{E}\left[\frac{|\hat{\mathcal{S}} \cap \mathcal{H}_0|}{|\hat{\mathcal{S}}|} = \frac{\#\{j : j \in \hat{\mathcal{S}} \setminus \mathcal{S}\}}{\#\{j : j \in \hat{\mathcal{S}}\}}\right]$$

where $\mathcal{H}_0 \subset \{1, \cdots, p\}$ is the set of **null** variables: $\mathbf{X}_j$ is **null** iff $\mathbf{Y}$ is independent of $\mathbf{X}_j$ conditional on the other variables $\mathbf{X}_{-j} = \{\mathbf{X}_1, \cdots, \mathbf{X}_p\} \setminus \{\mathbf{X}_j\}$.

In this note, we consider a series of knockoff-based methods to control FDR. They all follow a common procedure:

- **Step 1**: Construct Knockoffs
- **Step 2**: Calculate test statistics for both original and knockoff variables
- **Step 3**: Calculate a threshold for the test statistics, controling for a desired FDR level
- **Step 4**: Select variables that pass the threshold

17.2 Barber and Candes (2015)

Constructing the knockoffs Barber and Candes (2015) construct the knockoffs by the following procedure

- Calculate the Gram matrix $\boldsymbol{\Sigma} = \mathbf{X}'\mathbf{X}$ for the normalized original variables, where $\Sigma_{jj} = \|\mathbf{X}_j\|_2^2 = 1$

- Construct the knockoffs $\tilde{\mathbf{X}}$ s.t.

$$\tilde{\mathbf{X}}'\tilde{\mathbf{X}} = \mathbf{\Sigma} \qquad\qquad \mathbf{X}'\tilde{\mathbf{X}} = \mathbf{\Sigma} - \text{diag}\{\mathbf{s}\}$$

  where $\mathbf{s} \in \mathbb{R}_+^p$ is a p-dimensional non-negative vector (larger s_j indicates higher power) and

  - $\tilde{\mathbf{X}}$ exhibits the **same** covariance structrue as the original design $\mathbf{X}$
  - The correlation between distinct original variables and knockoffs are the same as between the originals:

$$\mathbf{X}_j'\tilde{\mathbf{X}}_k = \mathbf{X}_j'\mathbf{X}_k,\ \forall j \neq k$$

  - The correlation between the original variables and their own knockoffs is **less than 1**

$$\mathbf{X}_j'\tilde{\mathbf{X}}_j = \Sigma_{jj} - s_j = 1 - s_j$$

  To construct such knockoffs,

  - Given a proper $\mathbf{s}$, if $n \geq 2p$, then

$$\tilde{\mathbf{X}} = \mathbf{X}(\mathbf{I} - \mathbf{\Sigma}^{-1}\text{diag}\{\mathbf{s}\}) + \tilde{\mathbf{U}}\mathbf{C}$$

    where $\tilde{\mathbf{U}} \in \mathbb{R}^{n\times p}$ is an **orthonormal** matrix s.t. $\tilde{\mathbf{U}}'\mathbf{X} = \mathbf{0}$ and $\mathbf{C}'\mathbf{C} = 2\text{diag}\{\mathbf{s}\} - \text{diag}\{\mathbf{s}\}\,\mathbf{\Sigma}^{-1}\text{diag}\{\mathbf{s}\} \geq \mathbf{0}$
  - A sufficient and necessary condition for $\tilde{\mathbf{X}}$ to exist: $\text{diag}\{\mathbf{s}\} \leq 2\mathbf{\Sigma}$

  2 types of knockoffs can be constructed, following these procedures

  T1 **Equi-correlated** knockoffs: set $s_j = 2\lambda_{\min}(\mathbf{\Sigma}) \wedge 1$ for all j, then $\langle \mathbf{X}_j, \tilde{\mathbf{X}}_j\rangle = 1 - 2\lambda_{\min}(\mathbf{\Sigma}) \wedge 1$ for all j. This is essentially minimizing $\left|\langle \mathbf{X}_j, \tilde{\mathbf{X}}_j\rangle\right|$

  T2 **SDP** knockoffs: solve the convex problem

$$\arg\min_{\mathbf{x}} \sum_j (1 - s_j) \qquad\qquad s.t. 0 \leq s_j \leq 1, \text{diag}\{\mathbf{s}\} \leq 2\mathbf{\Sigma}$$

  which is essentially minimizing the average of $\langle \mathbf{X}_j, \tilde{\mathbf{X}}_j\rangle$

Calculate test statistics Define and calculate test statistics W_j for each $\beta_j \in \{1, \cdots, p\}$ using $\begin{bmatrix}\mathbf{X} & \tilde{\mathbf{X}}\end{bmatrix}$:

- the test statistic W_j should be constructed s.t. large positive values are evidence against the null hypothesis $\beta_j = 0$, for example, consider a Lasso on $\begin{bmatrix}\mathbf{X} & \tilde{\mathbf{X}}\end{bmatrix}$

$$\hat{\beta}(\lambda) = \arg\min_{\mathbf{b}} \left\{\frac{1}{2}\left\|\mathbf{y} - \begin{bmatrix}\mathbf{X} & \tilde{\mathbf{X}}\end{bmatrix}\mathbf{b}\right\|_2^2 + \lambda\left\|\mathbf{b}\right\|\right\}_1$$

  where λ is the point on the Lasso path at which the feature enters the model as

$$Z_j = \sup\left\{\lambda : \hat{\beta}_j(\lambda) \neq 0\right\}$$

  and set $W_j = (Z_j \vee \tilde{Z}_j) \cdot \begin{cases} +1, & Z_j > \tilde{Z}_j \\ -1, & Z_j < \tilde{Z}_j \end{cases}$ [1]

- In general, the statistics W should satisfy the **sufficient** property and **anti-symmetry** property:

[1]Other choices of W_j are $W_j = \left|\mathbf{X}_j'\mathbf{y}\right| - \left|\tilde{\mathbf{X}}_j'\mathbf{y}\right|$, or $\left|\hat{\beta}_j^{\text{LS}}\right| - \left|\hat{\beta}_{j+p}^{\text{LS}}\right|$

Definition 17.2.1: Property of Test Statistics W_j

The test statistic W_j is said to obey

– the **sufficient**

References

Rina Foygel Barber and Emmanuel J. Candes. Controlling the false discovery rate via knockoffs. *Annals of Statistics*, 43(5):2055–2085, 2015.