Robust inference with knockoffs

Rina Foygel Barber∗ Emmanuel J. Candès† Richard J. Samworth‡

January, 2018

Abstract

We consider the variable selection problem, which seeks to identify important variables influencing a response $Y$ out of many candidate features $X_1, \ldots, X_p$. We wish to do so while offering finite-sample guarantees about the fraction of false positives—selected variables $X_j$ that in fact have no effect on $Y$ after the other features are known. When the number of features $p$ is large (perhaps even larger than the sample size $n$), and we have no prior knowledge regarding the type of dependence between $Y$ and $X$, the model-X knockoffs framework nonetheless allows us to select a model with a guaranteed bound on the false discovery rate, as long as the distribution of the feature vector $X$ is exactly known. This model selection procedure operates by constructing “knockoff copies” of each of the $p$ features, which are then used as a control group to ensure that the model selection algorithm is not choosing too many irrelevant features.

In this work, we study the practical setting where the distribution of $X$ could only be estimated, rather than known exactly, and the knockoff copies of the $X_j$’s are therefore constructed somewhat incorrectly. Our results, which are free of any modeling assumption whatsoever, show that the resulting model selection procedure incurs an inflation of the false discovery rate that is proportional to our errors in estimating the distribution of each feature $X_j$ conditional on the remaining features $\{X_k : k \neq j\}$. The model-X knockoffs framework is therefore robust to errors in the underlying assumptions on the distribution of $X$, making it an effective method for many practical applications, such as genome-wide association studies, where the underlying distribution on the features $X_1, \ldots, X_p$ is estimated accurately but not known exactly.

1 Introduction

Our methods of data acquisition are such that we often obtain information on an exhaustive collection of possible explanatory variables. We know a priori that a large proportion of these are irrelevant for our purposes, but in the effort to cover all bases, we gather data on all what we can measure and rely on subsequent analysis to identify the relevant variables. For instance, to achieve a better understanding of biological processes behind a disease, we may evaluate variation across the entire DNA sequence and collect single nucleotide polymorphism (SNP) information, or quantify the expression level of all genes, or consider a large panel of exposures, and so on. We then expect the statistician or the scientist to sort through all these and select those important variables that truly influence a response of interest. For example, we would like the statistician to tell us which of the many genetic variations affect the risk of a specific disease, or which of the many gene expression profiles help determine the severity of a tumor.

This paper is about this variable selection problem. We consider situations where we have observations on a response $Y$ and a large collection of variables $X_1, \ldots, X_p$. With the goal of identifying the important variables, we want to recover the smallest set $S \subseteq \{1, \ldots, p\}$ such that, conditionally on $\{X_j\}_{j \in S}$, the response $Y$ is independent of all the remaining variables $\{X_j\}_{j \notin S}$. In the literature on graphical models, the set $S$ would be called the Markov blanket of $Y$. Effectively, this means that the explanatory variables $X_1, \ldots, X_p$ provide

∗Department of Statistics, University of Chicago
†Departments of Mathematics and of Statistics, Stanford University
‡Statistical Laboratory, University of Cambridge
information about the outcome \( Y \) only through the subset \( \{X_j\}_{j \in S} \). To ensure reproducibility, we are interested in methods that result in the estimation of a set \( \hat{S} \) with false discovery rate (FDR) control \(^1\), in the sense that
\[
\text{FDR} = \mathbb{E} \left[ \frac{\# \{ j : j \in \hat{S} \setminus S \} }{\# \{ j : j \in \hat{S} \} } \right] \leq q,
\]
i.e. a bound on the expected proportion of our discoveries \( \hat{S} \) which are not in the smallest explanatory set \( S \).

(Here \( q \) is some predetermined target error rate, e.g. \( q = 0.1 \).)

In truth, there are not many variable selection methods that would control the FDR with finite-sample guarantees, especially when the number \( p \) of variables far exceeds the sample size \( n \). That said, one solution is provided by the recent model-X knockoffs approach of Candès et al. \(^4\), which is a new read on the earlier knockoff filter of Barber and Candès \(^1\), see also \(^2\). One singular aspect of the method of model-X knockoffs is that it makes assumptions that are substantially different from those commonly encountered in the statistical literature. Most of the model selection literature relies on a specification of the model that links together the response and the covariates, making assumptions on \( P \) the statistical literature. Most of the model selection literature relies on a specification of the model that links together the response and the covariates, making assumptions on \( P \) the statistical literature. Most of the model selection literature relies on a specification of the model that links together the response and the covariates, making assumptions on \( P \) the statistical literature. Most of the model selection literature relies on a specification of the model that links together the response and the covariates, making assumptions on \( P \)

As is standard in the FDR literature, in this expected value we treat \( 0/0 \) as 0, to incur no penalty in the event that no variables are selected, i.e. when \( \hat{S} = \emptyset \).

\(^1\)As is standard in the FDR literature, in this expected value we treat \( 0/0 \) as 0, to incur no penalty in the event that no variables are selected, i.e. when \( \hat{S} = \emptyset \).
Underlying our novel model-X knockoffs theory is a completely new mathematical analysis and understanding of the knockoffs inferential machine. The technical innovation here is essentially twofold. First, with only partial knowledge of the distribution of $X$, we can no longer achieve a perfect exchangeability between the test statistics for the null variables and for their knockoffs. Hence, we need tools that can deal with only a form of approximate exchangeability. Second, our methods to prove FDR control no longer rely on martingale arguments, and rather, involve leave-one-out type of arguments. These new arguments are likely to have applications far outside the scope of the present paper.

2 Robust inference with knockoffs

To begin with, imagine we have data consisting of $n$ i.i.d. draws from a joint distribution on $(X, Y)$, where $X = (X_1, \ldots, X_p) \in \mathbb{R}^p$ is the feature vector while $Y \in \mathbb{R}$ is the response variable. We will gather the $n$ observed data points into a matrix $X \in \mathbb{R}^{n \times p}$ and vector $Y \in \mathbb{R}^n$—that is, the pairs $(X_i, Y_i)$ are i.i.d. copies of the pair $(X, Y)$. The joint distribution of $(X, Y)$ is unknown—specifically, we do not assume any information about the conditional distribution of $Y$ given $X$ as discussed above. We work under the assumption that $P_X$, the marginal distribution of $X$, is known only approximately.

Since the Markov blanket of $Y$ may be ill-defined (e.g. if two features are identical then the choice of the minimal set $S$ may not be unique), we follow [4] and define $X_j$ to be a null variable if $X_j \perp Y \mid X_{-j}$, that is if $X_j$ is independent from the response $Y$ conditionally on all the other variables. (We use the terms “features” and “variables” interchangeably.) Under very mild identifiability conditions, the set of non-nulls is nothing other than the Markov blanket of $Y$. Writing $H_0$ to denote the set of indices corresponding to null variables, we can then reformulate the error we would like to control as $E\left[|\tilde{S} \cap H_0|/|\tilde{S}|\right] \leq q$. 

2.1 Exact model-X knockoffs

Consider first an ideal setting where the distribution $P_X$ is known. The model-X knockoffs method [4] is defined by constructing knockoff features satisfying the following conditions. $\tilde{X}$ is drawn conditional on the feature vector $X$ without looking at the response $Y$ (i.e. $\tilde{X} \perp Y \mid X$), such that the joint distribution of $(X, \tilde{X})$ satisfies a pairwise exchangeability condition,

$$(X, \tilde{X})_{swap(A)} \overset{d}{=} (X, \tilde{X})$$

for any subset $A \subseteq \{1, \ldots, p\}$, where $\overset{d}{=}$ denotes equality in distribution. (In fact, to achieve FDR control, this condition only needs to hold for subsets $A \subseteq H_0$ containing only null variables.) Above, the family $(X, \tilde{X})_{swap(A)}$ is obtained from $(X, \tilde{X})$ by swapping the entries $X_j$ and $\tilde{X}_j$ for each $j \in A$; for example, with $p = 3$ and $A = \{2, 3\}$,

$$(X_1, X_2, X_3, \tilde{X}_1, \tilde{X}_2, \tilde{X}_3)_{swap(\{2, 3\})} = (X_1, \tilde{X}_2, \tilde{X}_3, \tilde{X}_1, X_2, X_3).$$

As a consequence of the pairwise exchangeability property (1), we see that the null knockoff variables $\{\tilde{X}_j\}_{j \in H_0}$ are distributed in exactly the same way as the original nulls $\{X_j\}_{j \in H_0}$ but some dependence is preserved: for instance, for any pair $j \neq k$ where $k$ is a null, we have that $(X_j, \tilde{X}_k) \overset{d}{=} (X_j, X_k)$.

Given knowledge of the true distribution $P_X$ of the features $X$, our first step to implement the method of model-X knockoffs is to construct a distribution for drawing $\tilde{X}$ conditional on $X$ such that the pairwise exchangeability property (1) holds for all subsets of features $A$. We can think of this mechanism as constructing some probability distribution $P_{\tilde{X} \mid X}(\cdot \mid x)$, which is a conditional distribution of $\tilde{X}$ given $X = x$, chosen so that the resulting joint distribution of $(X, \tilde{X})$, which is equal to

$$P_X(x) P_{\tilde{X} \mid X}(\tilde{x} \mid x),$$

is symmetric in the pairs $(x_j, \tilde{x}_j)$, and thus will satisfy the exchangeability property (1). Now, when working with data $(X, Y)$, we will treat each data point $(X_i, Y_i)$ independently. Specifically, after observing the data...
Input: conditional distributions $P_j$, for $j = 1, \ldots, p$

Mechanism for producing knockoff distribution

Output: distribution $P_{\tilde{X}|X}$ for generating knockoffs

Data $(i = 1, 2, \ldots, n)$

Input: features $X_{i,*} \sim P_X$

Distribution $P_{\tilde{X}|X}(\cdot|X_{i,*})$

Output: knockoffs $\tilde{X}_{i,*} \mid X_{i,*} \sim P_{\tilde{X}|X}(\cdot|X_{i,*})$

$(X_{ij}, \tilde{X}_{ij}, X_{i,j}, \tilde{X}_{i,j})$ satisfies exact pairwise exchangeability (2).

Figure 1: Schematic representation of the exact model-X knockoffs construction.

$(X, Y) \in \mathbb{R}^{n \times p} \times \mathbb{R}^n$, the rows $\tilde{X}_{i,*}$ of the knockoff matrix are drawn from $P_{\tilde{X}|X}(\cdot|X_{i,*})$, independently for each $i$ and also independently of $Y$. Figure 1 shows a schematic representation of the exact model-X knockoffs construction.

It is important to point out that mechanisms for producing the pairwise exchangeability property (1) do exist and can be very concrete: Candès et al. \cite{4} develop a general abstract mechanism termed the Sequential Conditional Independent Pairs (SCIP) “algorithm”, which always produces exchangeable knockoff copies and can be applied to any distribution $P_X$. There are also fast algorithms for the case where $X$ follows either a Markov or a hidden Markov model \cite{13}, and simple algorithms for sampling knockoff copies of Gaussian features \cite{4}.

Looking ahead, all of these algorithms can be used in the case where $P_X$ is known only approximately, where the exchangeability property (1) will be required to hold only with reference to the estimated distribution of $X$, discussed in Section 2.2 below.

For assessing a model selection algorithm, the knockoff feature vectors $\tilde{X}_j$ can be used as a “negative control”—a control group for testing the algorithm’s ability to screen out false positives, since $\tilde{X}_j$ is known to have no real effect on $Y$. Although details are given in Section 2.3, it is helpful to build some intuition already at this stage. Imagine for simplicity that we wish to assess the importance of a variable by measuring the strength of the marginal correlation with the response, i.e., we compute $Z_j = |X_j^\top Y|$. Then we can compare $Z_j$ with $\tilde{Z}_j = |\tilde{X}_j^\top Y|$, the marginal correlation for the corresponding knockoff variable. The crucial point is that the pairwise exchangeability property (1) implies that if $j$ is null (recall that this means that $X_j$ and $Y$ are conditionally independent), then

$$(Z_j, \tilde{Z}_j) \overset{d}{=} (\tilde{Z}_j, Z_j).$$

This holds without any assumptions on the form of the relationship $P_Y|X$ between $Y$ and $X$ \cite{4}. In particular, this means that the test statistic $W_j = Z_j - \tilde{Z}_j$ is equally likely to be positive or negative. Thus to reject the null, we would need to observe a large positive value of $W_j$. As we will see in Section 2.3, this way of reasoning extends to any choice of statistic $Z_j$; whatever statistic we choose, knockoff variables obeying (1) offer corresponding values of the statistic which can be used as “negative controls” for calibration purposes.

Throughout this paper, we will pay close attention to the distribution we obtain when swapping only one variable and its knockoff (and do not swap any of the other variables). In this context, we can reformulate the broad exchangeability condition (1) in terms of single variable swaps.

**Proposition 1** (Candès et al. \cite{4} Prop. 3.5)), The pairwise exchangeability property (1) holds for a subset
\[ A \subseteq \{1, \ldots, p\} \text{ if and only if} \]
\[(X_j, \tilde{X}_j, X_{-j}, \tilde{X}_{-j}) \overset{d}{=} (\tilde{X}_j, X_j, X_{-j}, \tilde{X}_{-j}) \quad (2)\]

holds for all \( j \in A \).

In other words, we can restrict our attention to the question of whether a single given feature \( X_j \) and its knockoff \( \tilde{X}_j \) are exchangeable with each other (in the joint distribution that also includes \( X_{-j} \) and \( \tilde{X}_{-j} \)).

### 2.2 Approximate model-X knockoffs and pairwise exchangeability

Now we will work towards constructing a version of this method when the true distribution \( P_X \) of the feature vector \( X \) is not known exactly. Here, we need to relax the pairwise exchangeability assumption, since choosing a useful mechanism \( P_{X|X} \) that satisfies this condition would generally require a very detailed knowledge of \( P_X \), which is typically not available. This section builds towards Definition 1 in two steps.

#### 2.2.1 Exchangeability with respect to an input distribution \( Q_X \)

We are provided with data \( X \) and conditional distributions \( Q_j(\cdot|x_{-j}) \) for each \( j \). We assume that the \( Q_j \)'s are fixed, i.e. do not depend on the data set \((X, Y)\). As a warm-up, assume first that these conditionals are mutually compatible in the sense that there is a joint distribution \( Q_X \) over \( \mathbb{R}^p \) that matches these \( p \) estimated conditionals—we will relax this assumption very soon. Then as shown in Figure 2, we repeat the construction from Figure 1 only with the \( Q_j \)'s as inputs. In words, the algorithm constructs knockoffs, which are samples from \( P_{X|X} \) a conditional distribution whose construction is based on the conditionals \( Q_j \) or, equivalently, the joint distribution \( Q_X \). In place of requiring that pairwise exchangeability of the features \( X_j \) and their knockoffs \( \tilde{X}_j \) holds relative to the true distribution \( P_X \) as in (1) and (2), we instead require that the knockoff construction mechanism satisfy pairwise exchangeability conditions relative to the joint distribution \( Q_X \) that it receives as input:

If \((X, \tilde{X})\) is drawn as \( X \sim Q_X \) and \( \tilde{X} | X \sim P_{\tilde{X}|X}(\cdot|X) \), then
\[(X, \tilde{X})_{\text{swap}(A)} \overset{d}{=} (X, \tilde{X}), \quad \text{for any subset } A \subseteq \{1, \ldots, p\} \quad (3)\]

When only estimated compatible conditionals are available, original and knockoff features are required to be exchangeable with respect to the distribution \( Q_X \), which is provided as input (but not with respect to the true distribution of \( X \), which is unknown). To rephrase, if the distribution of \( X \) were in fact equal to \( Q_X \), then we would have exchangeability.

#### 2.2.2 Exchangeability with respect to potentially incompatible conditionals \( Q_j \)

We wish to provide an extension of (3) to cover the case where the conditionals may not be compatible; that is, when a joint distribution with the \( Q_j \)'s as conditionals may not exist. To understand why this is of interest, imagine we have unlabeled data that we can use to estimate the distribution of \( X \). Then we may construct \( Q_j \) by regressing the \( j \)th feature \( X_j \) onto the \( p-1 \) remaining features \( X_{-j} \). For instance, we may use a regression technique promoting sparsity or some other assumed structure. In such a case, it is easy to imagine that such a strategy may produce incompatible conditionals. It is, therefore, important to develop a framework adapted to this setting. To address this, we shall work throughout the paper with the following definition:

**Definition 1.** \( P_{X|X} \) is pairwise exchangeable with respect to \( Q_j \) if it satisfies the following property:

For any distribution \( D^{(j)} \) on \( \mathbb{R}^p \) with \( j \)th conditional \( Q_j \), if \((X, \tilde{X}) \) is drawn as \( X \sim D^{(j)} \) and \( \tilde{X} | X \sim P_{\tilde{X}|X}(\cdot|X) \), then
\[(X_j, \tilde{X}_j, X_{-j}, \tilde{X}_{-j}) \overset{d}{=} (\tilde{X}_j, X_j, X_{-j}, \tilde{X}_{-j}) \quad (4)\]

Above, \( D^{(j)} \) is the product of an arbitrary marginal distribution for \( X_{-j} \) and of the conditional \( Q_j \).
In words, with estimated conditionals $Q_j$, we choose $P_{\tilde{X}|X}$ to satisfy pairwise exchangeability with respect to these $Q_j$’s, for every $j$. (As before, we remark that this only needs to hold for $j \in H_0$ to ensure FDR control, but since in practice we do not know which features are null, we require (4) to hold for every $j$.)

To see why this is an extension of (3), note that if the $Q_j$’s are mutually compatible, then any algorithm operating such that (4) holds for each $j$, obeys (3) as well. In particular, in the exact model-X framework setting where (1) is satisfied, Proposition 1 implies that the distribution $P_{\tilde{X}|X}$ is pairwise exchangeable with respect to $P_j$, i.e. with respect to the true conditional distribution of $X_j$, for each $j$.

As far as generating knockoff copies obeying (4), imagine we have a mechanism, which, when we input the distribution $P_X$ of $X$, will produce exchangeable knockoffs obeying (1). Supposing that the estimated conditionals $Q_j$ are all compatible with some joint distribution $Q_X$ on $X$, then if we instead provide $Q_X$ as input to this mechanism, it instead produces knockoff copies with the desired property. Hence, if the $Q_j$’s are mutually compatible, then all the mechanisms producing valid knockoffs under exact knowledge of $P_X$—we mentioned a few in the previous section—can be readily used for our purposes. Later in Section 3.3, we will also give an example of a mechanism producing valid knockoffs satisfying (4) under incompatible $Q_j$’s.

From this point on, we will assume without comment that for each $j$, either $X_j$ and $\tilde{X}_j$ are both discrete variables or are both continuous variables, and abusing notation, in these two settings we will use $P_j(\cdot|x_{-j})$ and $Q_j(\cdot|x_{-j})$ to denote the conditional probability mass function or conditional density, respectively, for the true and estimated conditional distribution of $X_j$ given $X_{-j} = x_{-j}$. Furthermore, we assume that $P_j(\cdot|x_{-j})$ and $Q_j(\cdot|x_{-j})$ are supported on the same (discrete or continuous) set for any $x_{-j}$. Our theory can be generalized to the setting of mixed distributions and/or varying supports, but for clarity of the results we do not present these generalizations here.

The construction of the knockoff features as in Figure 2 yields the following approximate pairwise exchangeability result.

**Lemma 1.** Fix any feature index $j$ such that pairwise exchangeability with respect to $Q_j$ (4) is satisfied. If
\( X_j, \tilde{X}_j \) are discrete, then for any \( a, b, \)
\[
\begin{align*}
\mathbb{P}\left\{ X_j = a, \tilde{X}_j = b \mid X_{-j}, \tilde{X}_{-j} \right\} &= \frac{p_j(a|X_{-j})q_j(b|X_{-j})}{q_j(a|X_{-j})p_j(b|X_{-j})}.
\end{align*}
\]

Furthermore, if index \( j \) corresponds to a null feature (i.e. \( X_j \perp Y \mid X_{-j} \)) and we additionally assume that \( \tilde{X} \mid X \) is drawn from \( P_{\tilde{X} \mid X} \) independently of \( Y \), then the same result holds when we also condition on \( Y \):
\[
\begin{align*}
\mathbb{P}\left\{ X_j = a, \tilde{X}_j = b \mid X_{-j}, \tilde{X}_{-j}, Y \right\} &= \frac{p_j(a|X_{-j})q_j(b|X_{-j})}{q_j(a|X_{-j})p_j(b|X_{-j})}.
\end{align*}
\]

The conclusion in the continuous case is identical except with ratios of probabilities replaced with ratios of densities.

This lemma gives a useful formula for computing the ratio between the likelihoods of the two configurations \( (X_j, \tilde{X}_j) = (a, b) \) and \( (X_j, \tilde{X}_j) = (b, a) \) (after conditioning on the remaining data). It is important to observe that if we are working in the exact model-X framework, where \( Q_j = P_j \), in this case the lemma yields
\[
\begin{align*}
\mathbb{P}\left\{ X_j = a, \tilde{X}_j = b \mid X_{-j}, \tilde{X}_{-j}, Y \right\} &= 1
\end{align*}
\]
for each null \( j \); that is, the two configurations are equally likely. This result for the exact model-X setting is proved in Candès et al. \[3\] Lemma 3.2 and is critical for establishing FDR control properties.

To see why this is so, let us return to our marginal correlation example from Section 2.1. In the exact model-X setting, we see from the above display that for a null feature, the variables \( X_j \) and \( \tilde{X}_j \) are exchangeable conditionally on everything else, namely, on \( X_{-j}, \tilde{X}_{-j} \), and \( Y \). Likewise, \( X_j \) and \( \tilde{X}_j \) (the two columns of the data matrix) are also conditionally exchangeable. This implies that \( [X_j^\top, Y] \) and \( [\tilde{X}_j^\top, Y] \) are conditionally exchangeable as well and, therefore, marginally exchangeable as we claimed. When we use estimates \( Q_j \) rather than the true conditionals \( P_j \), however, this property is no longer true, since Lemma 1 shows that the ratio is no longer equal to 1 in general. We can no longer use the knockoff statistics as exact negative controls; only as approximate controls. This is where the major difficulty comes in: if a knockoff statistic is only approximately distributed like its corresponding null, what is the potential inflation of the type-I error that this could cause?

### 2.3 The knockoff filter

After constructing the variables \( \tilde{X}_j \), we apply the knockoff filter to select important variables. We here quickly rehearse the main ingredients of this filter and refer the reader to \[1\] and \[4\] for additional details; our exposition borrows from \[2\]. Suppose that for each variable \( X_j \) (resp. each knockoff variable \( \tilde{X}_j \)), we compute a score statistic \( Z_j \) (resp. \( \tilde{Z}_j \)),
\[
(Z_1, \ldots, Z_p, \tilde{Z}_1, \ldots, \tilde{Z}_p) = z([X, \tilde{X}], Y),
\]
with the idea that \( Z_j \) (resp. \( \tilde{Z}_j \)) measures the importance of \( X_j \) (resp. \( \tilde{X}_j \)) in explaining \( Y \). Assume that the scores are “knockoff agnostic” in the sense that switching a variable with its knockoff simply switches the components of \( Z \) in the same way. This means that
\[
z([X, \tilde{X}_{\text{swap}(A)}], Y) = z([X, \tilde{X}], Y)_{\text{swap}(A)},
\]
\[2\]Formally, this result holds only for \( a, b \) lying in the support of \( P_j(\cdot \mid X_{-j}), \) which is assumed to be equal to the support of \( Q_j(\cdot \mid X_{-j}), \) as otherwise the ratio is 0/0; we ignore this possibility here and throughout the paper since these results will be applied only in settings where \( a, b \) do lie in this support.  

7
i.e. swapping $X_1$ and $\tilde{X}_1$ before calculating $Z$ has the effect of swapping $Z_1$ and $\tilde{Z}_1$, and similarly swapping $X_2$ and $\tilde{X}_2$ swaps $Z_2$ and $\tilde{Z}_2$, and so on. Here, we emphasize that $Z_j$ may be an arbitrarily complicated statistic. For instance, it can be defined as the absolute value of a lasso coefficient, or some random forest feature importance statistic; or, we may fit both a lasso model and a random forest, and choose whichever one has the lowest cross-validated error.

These scores are then combined in a single importance statistic for the variable $X_j$ as

$$W_j = f_j(Z_j, \tilde{Z}_j) = w_j([X, \tilde{X}], Y),$$

where $f_j$ is any anti-symmetric function, meaning that $f_j(v, u) = -f_j(u, v)$. As an example, we may have $W_j = Z_j - \tilde{Z}_j$, where the $Z_j$’s and $\tilde{Z}_j$’s are the magnitudes of regression coefficients estimated by the lasso at a value of the regularization parameter given by cross-validation, say. Again, any choice of anti-symmetric function $f_j$ and score statistic $Z_j$, no matter how complicated, is allowed. By definition, the statistics $W_j$ obey the flip-sign property, which says that swapping the $j$th variable with its knockoff has the effect of changing the sign of $W_j$ (since, by (5) above, if we swap feature vectors $X_j$ and $\tilde{X}_j$ then $Z_j$ and $\tilde{Z}_j$ get swapped):

$$w_j([X, \tilde{X}]_{\text{swap}(A)}, Y) = \begin{cases} w_j([X, \tilde{X}], Y), & j \not\in A, \\ -w_j([X, \tilde{X}], Y), & j \in A. \end{cases} \quad (6)$$

The $W_j$’s are the statistics that the knockoff filter will use. The idea is that large positive values of $W_j$ provide evidence against the hypothesis that the distribution of $Y$ is conditionally independent of $X_j$, while in contrast, if $j \in H_0$, then $W_j$ has a symmetric distribution and, therefore, is equally likely to take on positive or negative values.

In fact, it is equally valid for us to define $W_j = w_j([X, \tilde{X}], Y)$ for any function $w_j$ satisfying the flip-sign property (5), without passing through the intermediate stage of defining $Z_j$’s and $\tilde{Z}_j$’s, and from this point on we do not refer to the feature importance scores $Z_j, \tilde{Z}_j$ in our theoretical results. However, for better understanding of the intuition behind the method, we should continue to think of $W_j$ as comparing the apparent importance of the feature $X_j$ versus its knockoff $\tilde{X}_j$ for modeling the response $Y$.

Now that we have test statistics for each variable, we need a selection rule. For the knockoff filter, we choose a threshold $T_0 > 0$ by setting3

$$T_0 = \min \left\{ t > 0 : \frac{\# \{ j : W_j \leq -t \}}{\# \{ j : W_j \geq t \}} \leq q \right\}, \quad (7)$$

where $q$ is the target FDR level. The output of the procedure is the selected model $\hat{S} = \{ j : W_j \geq T_0 \}$. In (I), it is argued that the ratio appearing in the right-hand side of (7) is an estimate of the false discovery proportion (FDP) if we were to use the threshold $t$—this is true because $\mathbb{P} \{ W_j \geq t \} = \mathbb{P} \{ W_j \leq -t \}$ for any null feature $j \in H_0$, and so we would roughly expect

$$(\# \text{false positives at threshold } t) = \# \{ j \in H_0 : W_j \geq t \} \approx \# \{ j \in H_0 : W_j \leq -t \} \leq \# \{ j : W_j \leq -t \}, \quad (8)$$

that is, the numerator in (7) is an (over)estimate of the number of false positives selected at the threshold $t$.

Hence, the selection rule can be interpreted as a step-up rule stopping the first time our estimate falls below our target level. A slightly more conservative procedure, the knockoff+ filter, is given by incrementing the number of negatives by one, replacing the threshold in (7) with the choice

$$T_+ = \min \left\{ t > 0 : \frac{1 + \# \{ j : W_j \leq -t \}}{\# \{ j : W_j \geq t \}} \leq q \right\}, \quad (9)$$

and setting $\hat{S} = \{ j : W_j \geq T_+ \}$. Formalizing the intuition of our rough calculation (8), the false discovery rate control properties of these two procedures are studied in (1) under an exact pairwise exchangeability setting.

3We want $T_0$ to be positive and the formal definition is that the minimum in (7) is taken over all $t > 0$ taking on values in the set $\{ |W_1|, \ldots, |W_p| \}$.
3 FDR control results

3.1 Measuring errors in the distribution

If the knockoff features are generated using a mechanism designed to mimic the estimated conditionals \( Q_j \) rather than the true conditional distributions \( P_j \), when can we hope for error control? Intuitively, if the conditional distributions \( P_j \) and \( Q_j \) are similar, then we might hope that the knockoff feature \( \tilde{X}_j \) is a reasonably good control group for the original feature \( X_j \).

In order to quantify this, we begin by measuring the discrepancy between the true conditional \( P_j \) and its estimate \( Q_j \). Define the random variable

\[
\hat{KL}_j := \sum_i \log \left( \frac{P_j(X_{ij}|X_{i,-j}) \cdot Q_j(\tilde{X}_{ij}|X_{i,-j})}{Q_j(X_{ij}|X_{i,-j}) \cdot P_j(\tilde{X}_{ij}|X_{i,-j})} \right),
\]

where the notation \( \hat{KL}_j \) suggests the KL divergence. In fact, \( \hat{KL}_j \) is the observed KL divergence between \( (X_j, \tilde{X}_j, X_{-j}, \tilde{X}_{-j}) \) and \( (\tilde{X}_j, X_j, X_{-j}, \tilde{X}_{-j}) \). To prove this, working in the discrete case for simplicity, Lemma 1 tells us that

\[
\sum_i \log \left( \frac{P_j(x_{ij}|x_{i,-j}) \cdot Q_j(\tilde{x}_{ij}|x_{i,-j})}{Q_j(x_{ij}|x_{i,-j}) \cdot P_j(\tilde{x}_{ij}|x_{i,-j})} \right) = \log \left( \frac{P \{ (X_j, \tilde{X}_j, X_{-j}, \tilde{X}_{-j}) = (x_j, \tilde{x}_j, x_{-j}, \tilde{x}_{-j}) \}}{P \{ (\tilde{X}_j, X_j, X_{-j}, \tilde{X}_{-j}) = (x_j, \tilde{x}_j, x_{-j}, \tilde{x}_{-j}) \}} \right)
\]

for any \( x_j, \tilde{x}_j, x_{-j}, \tilde{x}_{-j} \). Therefore, we see that

\[
\mathbb{E} [\hat{KL}_j] = d_{\text{KL}} \left( (X_j, \tilde{X}_j, X_{-j}, \tilde{X}_{-j}) \parallel (\tilde{X}_j, X_j, X_{-j}, \tilde{X}_{-j}) \right),
\]

where \( d_{\text{KL}} \) is the usual KL divergence between distributions.

In the exact model-X setting, where the knockoff construction mechanism \( P_{\tilde{X}|X} \) satisfies the pairwise exchangeability property (1), Proposition 1 immediately implies that \( (X_j, \tilde{X}_j, X_{-j}, \tilde{X}_{-j}) \overset{d}{=} (\tilde{X}_j, X_j, X_{-j}, \tilde{X}_{-j}) \) and, thus, \( \mathbb{E} [\hat{KL}_j] = 0 \). (In fact, since we are using the true conditionals \( P_j \), or in other words \( Q_j = P_j \), we would have \( \hat{KL}_j = 0 \) always.) In the approximate model-X framework, we can interpret \( \hat{KL}_j \) as measuring the extent to which the pairwise exchangeability property (2) is violated for a specific feature \( j \). We will see in our results below that controlling the \( \hat{KL}_j \)'s is sufficient to ensure control of the false discovery rate for the approximate model-X knockoffs method. More precisely, we will be able to bound the false positives coming from those null features which have small \( \hat{KL}_j \).

3.2 FDR control guarantee

We now present our guarantee for robust error control with the model-X knockoffs filter.

Theorem 1. Under the definitions above, for any \( \epsilon \geq 0 \), consider the null variables for which \( \hat{KL}_j \leq \epsilon \). If we use the knockoff+ filter, then the fraction of the rejections that correspond to such nulls obeys

\[
\mathbb{E} \left[ \frac{|\{j: j \in \hat{S} \cap H_0 \text{ and } \hat{KL}_j \leq \epsilon\}|}{|\hat{S}| \lor 1} \right] \leq q \cdot e^\epsilon. \tag{11}
\]

In particular, this implies that the false discovery rate is bounded as

\[
\text{FDR} \leq \min_{\epsilon \geq 0} \left\{ q \cdot e^\epsilon + \mathbb{P} \left( \max_{j \in H_0} \hat{KL}_j > \epsilon \right) \right\}. \tag{12}
\]
Similarly, for the knockoff filter, for any $\epsilon \geq 0$, a slightly modified fraction of the rejections that correspond to nulls with $\hat{KL}_j \leq \epsilon$ obeys
\[
\mathbb{E} \left[ \left\{ j : j \in \hat{S} \cap H_0 \text{ and } \hat{KL}_j \leq \epsilon \right\} \right] \leq q \cdot e^\epsilon, \]
and therefore, we obtain a bound on a modified false discovery rate:
\[
\mathbb{E} \left[ \frac{\hat{S} \cap H_0}{|\hat{S}| + q^{-1}} \right] \leq \min_{\epsilon \geq 0} \left\{ q \cdot e^\epsilon + \mathbb{P} \left( \max_{j \in H_0} \hat{KL}_j > \epsilon \right) \right\}.
\]
In Section 3.3 we will see concrete examples where $\max_{j=1,...,p} \hat{KL}_j$ is small with high probability, yielding a meaningful result on FDR control.

A noteworthy aspect of this result is that it makes no modeling assumption whatsoever. Indeed, our FDR control guarantees hold in any setting—no matter the relationship $P_{Y \mid X}$ between $Y$ and $X$, no matter the distribution $P_X$ of the feature vector $X$, and no matter the test statistics $W$ the data analyst has decided to employ (as long as $W$ obeys the flip-sign condition). What the theorem says is that when we use estimated conditionals $Q_j$, if the $Q_j$’s are close to the true conditionals $P_j$ in the sense that the quantities $\hat{KL}_j$ are small, then the FDR is well under control. In the ideal case where we use the true conditionals, then $\hat{KL}_j = 0$ for all $j \in H_0$, and we automatically recover the FDR-control result from Candès et al. [4]; that is, we get FDR control at the nominal level $q$ since we can take $\epsilon = 0$.

It worth pausing to unpack our main result a little. Clearly, we cannot hope to have error control over all nulls if we have done a poor job in constructing some of their knockoff copies, because our knockoff “negative controls” may be completely off. Having said this, (11) tells us that if we restrict our definition of false positives to only those nulls for which we have a reasonable “negative control” via the knockoff construction, then the FDR is controlled. Since we do not make any assumptions, this type of result is all one can really hope for. In other words, exact model-X knockoffs make the assumption that the knockoff features provide exact controls for each null, thus ensuring control of the false positives; our new result removes this assumption, and provides a bound on the false positives when counting only those nulls for which the corresponding knockoff feature provides an approximate control.

In a similar fashion, imagine running a multiple comparison procedure, e.g. the Benjamini–Hochberg procedure, with $p$-values that are not uniformly distributed under the null. Then in such a situation, we cannot hope to achieve error control over all nulls if some of the null $p$-values follow grossly incorrect distributions. However, we may still hope to achieve reasonable control over those nulls for which the $p$-value is close to uniform.

As we remarked earlier, our FDR bounds apply universally (in a sense, they are worst-case bounds) and it is expected that in any practical scenario, the achieved FDR would be lower than that suggested by our upper bounds. In particular, our theorem applies to any construction of the statistics $W$, including adversarial constructions that might be chosen deliberately to try to detect the differences between the $X_j$’s and the $\tilde{X}_j$’s. In practice, $W$ would instead be chosen to try to identify strong correlations with $Y$, and we would not expect that this type of statistic is worst-case in terms of finding discrepancies between the distributions of $X_j$ and $\tilde{X}_j$. In fact, empirical studies [4,13] have already reported on the robustness of model-X knockoffs vis-à-vis possibly large model misspecifications when $W$ is chosen to identify a strong dependence between $X$ and $Y$.

Finally, we close this section by emphasizing that the proof of Theorem 1 which is presented in Section 4 employs arguments that are completely different from those one finds in the existing literature on knockoffs. We discuss the novelties in our techniques in Section 4.

### 3.3 Bounding $\hat{KL}_j$ to control FDR

To make our FDR control results more concrete, we will consider settings where accurate estimates $Q_j$ of the conditionals $P_j$ ensure that the $\hat{KL}_j$’s are bounded near zero. Examining the definition (10) of $\hat{KL}_j$, we see that $\hat{KL}_j$ is a sum of $n$ i.i.d. terms, and we can therefore expect that large deviation bounds such as Hoeffding’s
inequality can be used to provide an upper bound uniformly across all \( p \) features. Here we give two specific examples.

### 3.3.1 Bounded errors in the likelihood ratio

First, suppose that our estimates \( Q_j \) of the conditional distribution \( P_j \) satisfy a likelihood ratio bound uniformly over any values for the variables:

\[
\log \left( \frac{P_j(x_j \mid x_{-j}) \cdot Q_j(x_j' \mid x_{-j})}{Q_j(x_j \mid x_{-j}) \cdot P_j(x_j' \mid x_{-j})} \right) \leq \delta
\]  

(13)

for all \( j \), all \( x_j, x_j' \), and all \( x_{-j} \). In this setting, the following lemma, proved via Hoeffding’s inequality, gives a bound on the \( \hat{K}L_j \)'s:

**Lemma 2.** If the condition (13) holds uniformly for all \( j \) and all \( x_j, x_j', x_{-j} \), then with probability at least \( 1 - \frac{1}{p} \),

\[
\max_{j=1, \ldots, p} \hat{K}L_j \leq \frac{n\delta^2}{2} + 2\sqrt{n \log(p)} \cdot \delta.
\]

In other words, if \( Q_j \) satisfies (13) for some \( \delta = o\left( \frac{1}{\sqrt{n \log(p)}} \right) \), then with high probability every \( \hat{K}L_j \) will be small. By Theorem[1] then, the FDR for model-X knockoffs in this setting is controlled near the target level \( q \).

### 3.3.2 Gaussian knockoffs

For a second example, suppose that the distribution of the feature vector \( X \) is mean zero and has covariance \( \Theta^{-1} \), where \( \Theta \) is some unknown precision matrix. (We assume zero mean for simplicity, but these results can of course be generalized to an arbitrary mean.) Suppose that we have estimated \( \Theta \) with some approximation \( \tilde{\Theta} \), and let \( \Theta_j \) and \( \tilde{\Theta}_j \) denote the \( j \)th columns of these matrices. Our results below will assume that the error in estimating each column of \( \Theta \) is small, i.e. \( \tilde{\Theta}_j - \Theta_j \) is small for all \( j \).

Following Candès et al. [4] eqn. (3.2)], the Gaussian knockoff construction consists of drawing \( \tilde{X} \) from the distribution

\[
\tilde{X}_{i,*} \mid X_{i,*} \sim \mathcal{N}_p( (I_p - D\tilde{\Theta})X_{i,*}, (2D - D\tilde{\Theta}D) ),
\]  

(14)

independently for each \( i \), where \( D = \text{diag}(d_j) \) is a nonnegative diagonal matrix chosen to satisfy \( 2D - D\tilde{\Theta}D \geq 0 \), or equivalently, \( D \preceq 2\tilde{\Theta}^{-1} \). Another formulation is that the distribution \( P_{\tilde{X} \mid X}(\cdot \mid X) \) for \( \tilde{X} \) conditional on \( X \) is obtained by setting

\[
\tilde{X} \mid X \sim \mathcal{N}_p( (I_p - D\tilde{\Theta})X, 2D - D\tilde{\Theta}D ).
\]  

(15)

If the true precision matrix of \( X \) were given by \( \tilde{\Theta} \) (assumed to be positive definite), then we can calculate that the joint distribution of the pair \( (X, \tilde{X}) \) has first and second moments given by

\[
\mathbb{E}\left(\begin{pmatrix} X \\ \tilde{X} \end{pmatrix}\right) = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \quad \text{Var}\left(\begin{pmatrix} X \\ \tilde{X} \end{pmatrix}\right) = \begin{pmatrix} \tilde{\Theta}^{-1} & \tilde{\Theta}^{-1} - D \\ \tilde{\Theta}^{-1} - D & \tilde{\Theta}^{-1} \end{pmatrix}.
\]

In other words, for every \( j \), \( X_j \) and \( \tilde{X}_j \) are exchangeable if we only look at the first and second moments of the joint distribution.

If the true distribution of \( X \) is in fact Gaussian, again with mean zero and covariance \( \tilde{\Theta}^{-1} \), then a stronger claim follows—the joint distribution of \( (X, \tilde{X}) \) is then multivariate Gaussian and therefore \( (X, \tilde{X})_{\text{swap}(\mathcal{A})} \overset{d}{=} (X, \tilde{X}) \) for every subset \( \mathcal{A} \subseteq [p] \). In other words, the knockoff construction determined by \( P_{\tilde{X} \mid X} \) satisfies pairwise exchangeability, as defined in [3], with respect to the distribution \( Q_X = \mathcal{N}_p(0, \tilde{\Theta}^{-1}) \). To frame this
Then with probability at least $1$ in $(15)$, define $\Theta_{-j,j}$, where the $\Theta_{-j,j}$ is the column $\Theta_j$ with entry $\Theta_{jj}$ removed.

As noted in Section 2.2, we may want to work with estimated precision matrices, which are not positive semidefinite (PSD). The rationale is that if $\Theta$ is fitted by regressing each $X_j$ on the remaining features $X_{-j}$ to produce the $j$th column, $\Theta_j$, then the result will not be PSD in general. If $\Theta$ is not PSD, although there is no corresponding joint distribution, the conditionals $Q_j$, $(16)$ are still well-defined as long as $\Theta_{jj} > 0$ for all $j$; they are just not compatible. (Note that symmetry is a far easier constraint to enforce, e.g. by simply replacing our initial estimate $\Theta$ with $(\Theta + \Theta^\top)/2$, which preserves desirable features such as sparsity that might be present in the initial $\Theta$; in contrast, projecting to the PSD cone while enforcing sparsity constraints may be computationally challenging in high dimensions.)

Our first result verifies that this construction of $P_{\tilde{X}\mid X}$ satisfies pairwise exchangeability with respect to the conditional distributions $Q_j$, given in $(16)$:

**Lemma 3.** Let $\Theta \in \mathbb{R}^{p \times p}$ be a symmetric matrix with a positive diagonal, and let $P_{\tilde{X}\mid X}$ be defined as in $(15)$. Then, for each $j = 1, \ldots, p$, $P_{\tilde{X}\mid X}$ is pairwise exchangeable with respect to the conditional distribution $Q_j$, given in $(16)$—that is, the exchangeability condition $(4)$ is satisfied.

In practice, we would construct Gaussian knockoffs in situations where the distribution of $X$ might be well approximated by a multivariate normal. The lemma below gives a high probability bound on the $\mathbb{K}L_{j, j}$'s in the case where the features are indeed Gaussian but with an unknown covariance matrix $\Theta^{-1}$. Here, Gaussian concentration results can be used to control the $\mathbb{K}L_{j, j}$'s, which then yields FDR control. (We note that recent work by Fan et al. [5] also studies the Gaussian model-X knockoffs procedure with an estimated precision matrix $\tilde{\Theta}$, under a different framework.)

**Lemma 4.** Let $\Theta, \tilde{\Theta} \in \mathbb{R}^{p \times p}$ be any matrices, where $\Theta$ is positive definite and $\tilde{\Theta}$ is symmetric with a positive diagonal. Suppose that $X_{i, s} \sim \mathcal{N}(0, \Theta^{-1})$, while $\tilde{X} \mid X$ is drawn according to the distribution $P_{\tilde{X}\mid X}$ given in $(15)$. Define

$$\delta_{\Theta} = \max_{j=1,\ldots,p} (\Theta_{jj})^{-1/2} \cdot \|\Theta^{-1/2}(\Theta_{j} - \Theta_{j})\|_2.$$ 

Then with probability at least $1 - \frac{1}{p}$,

$$\max_{j=1,\ldots,p} \mathbb{K}L_{j} \leq 4\delta_{\Theta} \sqrt{n \log(p)} \cdot (1 + o(1)),$$

where the $o(1)$ term refers to terms that are vanishing when we assume that $\frac{\log(p)}{n} = o(1)$ and that this upper bound is itself bounded by a constant.

(A formal bound making the $o(1)$ term explicit is provided in the proof.) In particular, comparing to our FDR control result, Theorem 1, we see that as long as the columnwise error in estimating the precision matrix $\Theta$ satisfies $\delta_{\Theta} = o \left( \frac{1}{\sqrt{n \log(p)}} \right)$, the FDR will be controlled near the target level $q$.

### 3.4 A lower bound on FDR

Next, we ask whether it is possible to prove a converse to our FDR control result, Theorem 1. We are interested in knowing whether bounding the $\mathbb{K}L_{j, j}$'s is in fact necessary for FDR control—or is it possible to achieve an FDR control guarantee even when the $\mathbb{K}L_{j, j}$'s are large? Our next result proves that, if there is a feature $j$ for which $\mathbb{K}L_{j, j}$ does not concentrate near zero, then we can construct an honest model selection method that, when...
assuming that the conditional distribution of $X_j \mid X_{-j}$ is given by $Q_j$, fails to control FDR at the desired level if the true conditional distribution is in fact $P_j$. By “honest”, we mean that the model selection method would successfully control FDR at level $q$ if $Q_j$ were the true conditional distribution. Our construction does not run a knockoff filter on the data; it is instead a hypothesis testing based procedure, meaning that the KL$_j$’s govern whether it is possible to control FDR in a general sense. Hence, our converse is information-theoretic in nature and not specific to the knockoff filter.

Theorem 2. Fix any distribution $P_X$, any feature index $j$, and any estimated conditional distribution $Q_j$. Suppose that there exists a knockoff sampling mechanism $P_{X \mid X}$ that is pair-wise exchangeable with respect to $Q_j$, such that

$$P \left\{ \text{KL}_j \geq \epsilon \right\} \geq c$$

for some $\epsilon, c > 0$ when $(X, \tilde{X})$ is drawn from $P_X \times P_{X \mid X}$. Then there exists a conditional distribution $P_{Y \mid X}$, and a testing procedure $\hat{S}$ that maps data $(X, Y) \in \mathbb{R}^{n \times p} \times \mathbb{R}^n$ to a selected set of features $\hat{S}(X, Y) \subseteq \{1, \ldots, p\}$, such that:

- If the data points $(X_{i, *}, Y_i)$ are i.i.d. draws from the distribution $Q_X \times P_{Y \mid X}$, where $Q_X$ is any distribution whose $j$th conditional is $Q_j$ (i.e. our estimated conditional distribution $Q_j$ for feature $X_j$ is correct), then

$$\text{FDR}(\hat{S}) = q.$$

- On the other hand, if the data points $(X_{i, *}, Y_i)$ are i.i.d. draws from the distribution $P_X \times P_{Y \mid X}$ (i.e. our estimated conditional distribution $Q_j$ is not correct, as the true conditional distribution is $P_j$), then

$$\text{FDR}(\hat{S}) \geq q(1 + c(1 - e^{-\epsilon})).$$

For the last case (where $P_X$ is the true distribution), if $c \approx 1$ (i.e. KL$_j \geq \epsilon$ with high probability) then FDR$(\hat{S}) \approx q(2 - e^{-\epsilon})$; when $\epsilon \approx 0$ is small, we have $2 - e^{-\epsilon} \approx 1 + \epsilon \approx e^\epsilon$, thus matching the upper bound in Theorem 1.

4 Proof of Theorem 1

Whereas all proofs of FDR control for the knockoff methods thus far have relied on martingale arguments (see [1, 2, 4]), here we will prove our main theorem using a novel leave-one-out argument. Before we begin, we would like to draw a loose analogy. To prove FDR controlling properties of the Benjamini–Hochberg procedure under independence of the p-values, Storey et al. [15] developed a very elegant martingale argument. Other proof techniques, however, operate by removing or leaving out one hypothesis (or one p-value); see Ferreira and Zwinderman [6] for example. At a very high level, our own methods are partially inspired by the latter approach.

Fix $\epsilon > 0$ and for any threshold $t > 0$, define

$$R_\epsilon(t) := \frac{\sum_{j \in \mathcal{H}_0} \mathbb{I} \{W_j \geq t, \text{KL}_j \leq \epsilon\}}{1 + \sum_{j \in \mathcal{H}_0} \mathbb{I} \{W_j \leq -t\}},$$

Then, for the knockoff+ filter with threshold $T_+$, we can write

$$\frac{|\{j : j \in \hat{S} \cap \mathcal{H}_0 \text{ and } \text{KL}_j \leq \epsilon\}|}{|\hat{S}| \lor 1} = \frac{\sum_{j \in \mathcal{H}_0} \mathbb{I} \{W_j \geq T_+, \text{KL}_j \leq \epsilon\}}{1 + \sum_j \mathbb{I} \{W_j \geq T_+\}} \leq q \cdot R_\epsilon(T_+).$$
where the last step holds by definition of $R_e$ and the construction of the knockoff+ filter. If we instead use the knockoff filter (rather than knockoff+), then we use the threshold $T_0$ and obtain

$$
\frac{|\{j : j \in \hat{S} \cap H_0 \text{ and } \hat{KL}_j \leq \epsilon\}|}{q^{-1} + |\hat{S}|} = 1 + \frac{\sum_j 1 \{W_j \leq -T_0\}}{q^{-1} + \sum_j 1 \{W_j \geq T_0\}} \frac{\sum_{j \in H_0} 1 \{W_j \geq T_0, \hat{KL}_j \leq \epsilon\}}{1 + \sum_j 1 \{W_j \leq -T_0\}} \leq q \cdot R_e(T_0),
$$

where the last step holds by definition of $R_e$ and the construction of the knockoff filter. Either way, then, it is sufficient to prove that $E[R_e(T)] \leq c'$, where $T$ is either $T_+$ or $T_0$.

For each null feature $j$ we will be conditioning on observing $X_{-j}$, $\tilde{X}_{-j}$, $Y$, and on observing the unordered pair $\{X_j, \tilde{X}_j\}$—that is, we observe both the original and knockoff features but do not know which is which. It follows from the flip-sign property that having observed all this, we know all the knockoff statistics $W$ except for the sign of the $j$th component $W_j$. Put differently, $W_{-j}$ and $|W_j|$ are both functions of the variables we are conditioning on, but $\text{sign}(W_j)$ is not. Without loss of generality, label the unordered pair of feature vectors $\{X_j, \tilde{X}_j\}$, as $X_j^{(0)}$ and $X_j^{(1)}$, such that

- if $X_j = X_j^{(0)}$ and $\tilde{X}_j = X_j^{(1)}$, then $W_j \geq 0$;
- if $X_j = X_j^{(1)}$ and $\tilde{X}_j = X_j^{(0)}$, then $W_j \leq 0$.

Next, define

$$
\hat{KL}_j' = \sum_{i=1}^n \log \left( \frac{P_j(X_i^{(0)} \mid X_i^{(0)}, W_j) \cdot Q_j(X_i^{(1)} \mid X_i^{(1)}, W_j)}{Q_j(X_i^{(0)} \mid X_i^{(0)}, W_j) \cdot P_j(X_i^{(1)} \mid X_i^{(1)}, W_j)} \right) = \text{sign}(W_j) \cdot \hat{KL}_j,
$$

where the second equality holds whenever $|W_j| \neq 0$—this follows from the definition of $\hat{KL}_j$ and $(X_j^{(0)}, X_j^{(1)})$. Furthermore, for a threshold rule $T = T(W)$ mapping statistics $W \in \mathbb{R}^p$ to a threshold $T \geq 0$ (i.e. the knockoff or knockoff+ filter threshold), for each index $j = 1, \ldots, p$ we define

$$
T_j = T(W_1, \ldots, W_{j-1}, |W_j|, W_{j+1}, \ldots, W_p) \geq 0,
$$

i.e. the threshold that we would obtain if $\text{sign}(W_j)$ were set to +1. The following lemma establishes a property of the $T_j$’s in the context of the knockoff filter:

**Lemma 5.** Let $T = T(W)$ be the threshold for either the knockoff or the knockoff+. For any $j, k$,

$$
\text{if } W_j \leq -\min\{T_j, T_k\} \text{ and } W_k \leq -\min\{T_j, T_k\}, \text{ then } T_j = T_k.
$$

(17)

(More generally, this result holds for any function $T = T(W)$ that satisfies a “stopping time condition” with respect to the signs of the $W_j$’s, defined as follows: for any $t \geq 0$, the event $1 \{T \leq t\}$ depends on $W$ only through (1) the magnitudes $|W|$, (2) $\text{sign}(W_j)$ for each $j$ with $|W_j| < t$, and (3) $\sum_{j : |W_j| \geq t} \text{sign}(W_j)$.)
Now with $T$ being either the knockoff or knockoff+ thresholding rule, we have

$$
E[R_e(T)] = E \left[ \frac{\sum_{j \in H_0} 1 \{W_j \geq T, \tilde{K}_L j \leq \epsilon\}}{1 + \sum_{j \in H_0} 1 \{W_j \leq -T\}} \right]
$$

$$
= \sum_{j \in H_0} E \left[ \frac{1 \{W_j \geq T, \tilde{K}_L j \leq \epsilon\}}{1 + \sum_{k \in H_0, k \neq j} 1 \{W_k \leq -T\}} \right]
$$

(since $T > 0$ by definition, so if $W_j \geq T$ then $W_j \not\leq -T$)

$$
= \sum_{j \in H_0} E \left[ \frac{1 \{W_j \leq T, \tilde{K}_L j' \leq \epsilon\}}{1 + \sum_{k \in H_0, k \neq j} 1 \{W_k \leq -T\}} \right]
$$

(since if $W_j > 0$ then $T = T_j$ and $\tilde{K}_L j = \tilde{K}_L j'$)  \hspace{1cm} (18)

$$
= \sum_{j \in H_0} E \left[ \frac{1 \{W_j \geq T_j, \tilde{K}_L j \leq \epsilon\}}{1 + \sum_{k \in H_0, k \neq j} 1 \{W_k \leq -T_j\}} \left| X_j^{(0)}, X_j^{(1)}, X_{-j}, \tilde{X}_{-j}, Y \right) \right]
$$

$$
= \sum_{j \in H_0} E \left[ \frac{1 \{W_j > 0 \mid X_j^{(0)}, X_j^{(1)}, X_{-j}, \tilde{X}_{-j}, Y\}}{1 + \sum_{k \in H_0, k \neq j} 1 \{W_k \leq -T_j\}} \left| \left\{W_j \geq T_j, \tilde{K}_L j \leq \epsilon\right\} \right. \right], \hspace{1cm} (19)
$$

where the last step holds since $W_{-j}$ and $|W_j|$ and $\tilde{K}_L j$ are all determined after observing the variables $X_j^{(0)}, X_j^{(1)}, X_{-j}, \tilde{X}_{-j}, Y$; after conditioning on these variables, the only unknown is the sign of $W_j$.

Next, fix any null $j$. Suppose that we observe $X_j^{(0)}, X_j^{(1)}, X_{-j}, \tilde{X}_{-j}, Y$, so that we now know $W_{-j}$ and $|W_j|$ but not sign$(W_j)$. Our goal is now to bound the conditional probability $P \left\{ W_j > 0 \mid X_j^{(0)}, X_j^{(1)}, X_{-j}, \tilde{X}_{-j}, Y \right\}$.

If $|W_j| = 0$ then this probability is zero. If not, then by definition of $X_j^{(0)}, X_j^{(1)}$,

$$
P \left\{ W_j > 0 \mid X_j^{(0)}, X_j^{(1)}, X_{-j}, \tilde{X}_{-j}, Y \right\} = P \left\{ (X_j, \tilde{X}_j) = (X_j^{(0)}, X_j^{(1)}) \mid X_j^{(0)}, X_j^{(1)}, X_{-j}, \tilde{X}_{-j}, Y \right\}
$$

$$
P \left\{ W_j < 0 \mid X_j^{(0)}, X_j^{(1)}, X_{-j}, \tilde{X}_{-j}, Y \right\} = P \left\{ (X_j, \tilde{X}_j) = (X_j^{(1)}, X_j^{(0)}) \mid X_j^{(0)}, X_j^{(1)}, X_{-j}, \tilde{X}_{-j}, Y \right\}.
$$

Since the observations $i = 1, \ldots, n$ are independent, this can be rewritten as

$$
\prod_{i=1}^{n} \frac{P \left\{ (X_{ij}, \tilde{X}_{ij}) = (X_{ij}^{(0)}, X_{ij}^{(1)}) \mid X_{ij}^{(0)}, X_{ij}^{(1)}, X_{i,-j}, \tilde{X}_{i,-j}, Y_i \right\}}{P \left\{ (X_{ij}, \tilde{X}_{ij}) = (X_{ij}^{(1)}, X_{ij}^{(0)}) \mid X_{ij}^{(0)}, X_{ij}^{(1)}, X_{i,-j}, \tilde{X}_{i,-j}, Y_i \right\}}
$$

$$
= \prod_{i=1}^{n} \frac{P_j(X_{ij}^{(0)} \mid X_{i,-j}) \cdot Q_j(X_{ij}^{(1)} \mid X_{i,-j}) \cdot P_j(X_{ij}^{(1)} \mid X_{i,-j})}{Q_j(X_{ij}^{(0)} \mid X_{i,-j}) \cdot P_j(X_{ij}^{(1)} \mid X_{i,-j})} = \exp(\tilde{K}_L j'),
$$

where the first equality holds by Lemma[1]. Rearranging terms, we have

$$
P \left\{ W_j > 0 \mid X_j^{(0)}, X_j^{(1)}, X_{-j}, \tilde{X}_{-j}, Y \right\} = \frac{\exp(\tilde{K}_L j')}{1 + \exp(\tilde{K}_L j')}.
$$

In passing, note that we here recover a key result from the knockoff literature: when $Q_j = P_j$ (i.e. we are using the correct conditionals) then $\tilde{K}_L j' = 0$ and the conditional probability above is equal to 1/2. That is, for nulls, the $W_j$’s are conditionally equally likely to be positive and negative (and also unconditionally).
Returning to the step [19] above, our calculation implies that
\[
\mathbb{E}[R_e(T)] \leq \sum_{j \in H_0} \mathbb{E} \left[ \frac{\exp(\hat{K}L_j) \cdot \mathbb{1}\left\{ |W_j| \geq T_j, \hat{K}L_j \leq \epsilon \right\}}{1 + \sum_{k \in H_0, k \neq j} \mathbb{1}\{ W_k \leq -T_j \}} \right] 
\]
\[
\leq \frac{e^\epsilon}{1 + e^\epsilon} \cdot \sum_{j \in H_0} \mathbb{E} \left[ \frac{\mathbb{1}\{ |W_j| \geq T_j, \hat{K}L_j \leq \epsilon \}}{1 + \sum_{k \in H_0, k \neq j} \mathbb{1}\{ W_k \leq -T_j \}} \right] 
\]
\[
\leq \frac{e^\epsilon}{1 + e^\epsilon} \cdot \left( \sum_{j \in H_0} \mathbb{E} \left[ \frac{\mathbb{1}\{ W_j \geq T_j, \hat{K}L_j \leq \epsilon \}}{1 + \sum_{k \in H_0, k \neq j} \mathbb{1}\{ W_k \leq -T_j \}} \right] + \sum_{j \in H_0} \mathbb{E} \left[ \frac{\mathbb{1}\{ W_j \leq -T_j \}}{1 + \sum_{k \in H_0, k \neq j} \mathbb{1}\{ W_k \leq -T_j \}} \right] \right) 
\]
\[
= \frac{e^\epsilon}{1 + e^\epsilon} \cdot \left( \mathbb{E}[R_e(T)] + \mathbb{E} \left[ \sum_{j \in H_0} \frac{\mathbb{1}\{ W_j \leq -T_j \}}{1 + \sum_{k \in H_0, k \neq j} \mathbb{1}\{ W_k \leq -T_j \}} \right] \right) 
\]

by our earlier calculation [18] for \( R_e \). Finally, the sum in this last expression can be simplified as follows: if for all null \( j, W_j > -T_j \), then the sum is equal to zero, while otherwise, we can write
\[
\sum_{j \in H_0} \frac{\mathbb{1}\{ W_j \leq -T_j \}}{1 + \sum_{k \in H_0, k \neq j} \mathbb{1}\{ W_k \leq -T_j \}} = \sum_{j \in H_0} \frac{\mathbb{1}\{ W_j \leq -T_j \}}{1 + \sum_{k \in H_0, k \neq j} \mathbb{1}\{ W_k \leq -T_k \}} 
= \sum_{j \in H_0} \frac{\mathbb{1}\{ W_j \leq -T_j \}}{\sum_{k \in H_0} \mathbb{1}\{ W_k \leq -T_k \}} = 1, 
\]

where the first step applies Lemma [5] Combining everything, we have shown that
\[
\mathbb{E}[R_e(T)] \leq \frac{e^\epsilon}{1 + e^\epsilon} \cdot (\mathbb{E}[R_e(T)] + 1) . 
\]
Rearranging terms gives \( \mathbb{E}[R_e(T)] \leq e^\epsilon \), which proves the theorem.

5 Discussion

In this paper, we established that the method of model-X knockoffs is robust to errors in the underlying assumptions on the distribution of the feature vector \( X \), making it an effective method for many practical applications, such as genome-wide association studies, where the underlying distribution on the features \( X_1, \ldots, X_p \) can be estimated accurately. One notable aspect is that our theory is free of any modeling assumptions, since our theoretical guarantees hold no matter the data distribution or the statistics that the data analyst wishes to use, even if they are designed to exploit some weakness in the construction of knockoffs. Looking forward, it would be interesting to develop a theory for fixed statistics. For instance, if the researcher commits to using a pre-specified random forest feature importance statistic, or some statistic based on the magnitudes of lasso coefficients (perhaps calculated at a data-dependent value of the regularization parameter), then what can be said about FDR control? In other words, what can we say when the statistics \( W \) only probe the data in certain directions? We leave such interesting questions for further research.

A Additional proofs

A.1 Proof of Lemma [1]

We prove the lemma in the case where all features are discrete; the case where some of the features may be continuous is proved analogously. First, consider any null feature index \( j \). By definition of the nulls, we know
that \( X_j \perp \perp Y \mid X_{-j} \). Furthermore, \( \tilde{X} \perp \perp Y \mid X \) by construction. Therefore, the distribution of \( Y \mid (X, \tilde{X}) \) depends only on \( X_{-j} \), and in particular,

\[
Y \perp \perp (X_j, \tilde{X}_j) \mid (X_{-j}, \tilde{X}_{-j}).
\]

This proves that

\[
\begin{align*}
\mathbb{P} \left\{ X_j = a, \tilde{X}_j = b \ \middle| \ X_{-j}, \tilde{X}_{-j}, Y \right\} &= \mathbb{P} \left\{ X_j = a, \tilde{X}_j = b \ \middle| \ X_{-j}, \tilde{X}_{-j} \right\}, \\
\mathbb{P} \left\{ X_j = b, \tilde{X}_j = a \ \middle| \ X_{-j}, \tilde{X}_{-j}, Y \right\} &= \mathbb{P} \left\{ X_j = b, \tilde{X}_j = a \ \middle| \ X_{-j}, \tilde{X}_{-j} \right\},
\end{align*}
\]

(20)

because the numerator and denominator are each unchanged whether we do or do not condition on \( Y \). Thus, for null features \( j \), it is now sufficient to prove only the first claim of the lemma, namely that the right-hand side above is equal to \( \frac{P_j(a \mid X_{-j})Q_j(b \mid X_{-j})}{Q_j(a \mid X_{-j})P_j(b \mid X_{-j})} \).

From this point on, let \( j \) be any feature (null or non-null). We will now prove the first claim in the lemma. Recalling the assumption that \( P_{\tilde{X} \mid X} \) is pairwise exchangeable with respect to \( Q_j \) (4), we introduce a pair of random variables drawn as follows: first, draw \( X'_{-j} \sim P_{X_{-j}} \), where \( P_{X_{-j}} \) is the distribution of \( X_{-j} \); then draw \( X'_j \mid X'_{-j} \sim Q_j(\cdot \mid X'_{-j}) \); and finally, draw \( X' \mid X' \sim P_{\tilde{X} \mid X} (\cdot \mid X') \). Then by (4),

\[
(X'_{-j}, \tilde{X}_j, X'_{-j}, \tilde{X}_{-j}) \overset{d}{=} (X'_{-j}, X'_j, X'_{-j}, \tilde{X}_{-j}).
\]

(21)

The following schematic compares the distributions of \( (X, \tilde{X}) \) and \( (X', \tilde{X}') \):

We emphasize that \( P_{\tilde{X} \mid X} \) is the same distribution on both sides since it is generated by the same mechanism taking on as inputs the conditionals \( Q_j \)'s (see Figure 3).

The joint distribution of \( (X, \tilde{X}) \) is given by

\[
\mathbb{P} \left\{ X = x, \tilde{X} = \tilde{x} \right\} = P_{X_{-j}}(x_{-j})P_j(x_j \mid x_{-j})P_{\tilde{X} \mid X}(\tilde{x} \mid x)
\]

defined over all pairs \((x, \tilde{x})\) in the support of \((X, \tilde{X})\), and an identical expression holds for the joint distribution of \((X', \tilde{X}')\) except that \( P_j \) is replaced with \( Q_j \). This gives

\[
\begin{align*}
\mathbb{P} \left\{ X_j = a, \tilde{X}_j = b, X_{-j} = x_{-j}, \tilde{X}_{-j} = \tilde{x}_{-j} \right\} &= Q_j(a \mid x_{-j}), \\
\mathbb{P} \left\{ X'_j = a, \tilde{X}'_j = b, X'_{-j} = x_{-j}, \tilde{X}'_{-j} = \tilde{x}_{-j} \right\} &= Q_j(a \mid x_{-j}),
\end{align*}
\]

and of course the analogous statement holds with \( a \) and \( b \) reversed. Therefore,

\[
\begin{align*}
\mathbb{P} \left\{ X_j = a, \tilde{X}_j = b, X_{-j} = x_{-j}, \tilde{X}_{-j} = \tilde{x}_{-j} \right\} &= P_j(a \mid x_{-j}), Q_j(b \mid x_{-j}), \\
\mathbb{P} \left\{ X_j = b, \tilde{X}_j = a, X_{-j} = x_{-j}, \tilde{X}_{-j} = \tilde{x}_{-j} \right\} &= P_j(b \mid x_{-j}), Q_j(a \mid x_{-j}),
\end{align*}
\]

\[
= P_j(a \mid x_{-j}), Q_j(b \mid x_{-j}), P_j(b \mid x_{-j}), Q_j(a \mid x_{-j}), 1,
\]

where the last step holds by the property (21). This proves the lemma.
A.2 Proof of Theorem 2

First, we will show that our statement can be reduced to a binary hypothesis testing problem. We will work under the global null hypothesis where \( Y \perp \perp X \), and our test will be constructed independently of \( Y \). More formally, let \( P_{Y|X} \) be any fixed distribution, e.g. \( \mathcal{N}(0, 1) \). Since all features are null, this means that the false discovery proportion is 1 whenever \( \hat{S}(X, Y) \neq \emptyset \), that is,

\[
\text{FDR}(\hat{S}) = \mathbb{P}\left\{ \hat{S}(X, Y) \neq \emptyset \right\}.
\]

Therefore, in order to prove the theorem, it is sufficient to construct a binary test \( \psi(X) \in \{0, 1\} \) such that

\[
\mathbb{P}_{X_{i,*} \sim P_{X}} \{ \psi(X) = 1 \} \geq q(1 + c(1 - e^{-c})) \quad \text{and} \quad \mathbb{P}_{X_{i,*} \sim Q_{X}} \{ \psi(X) = 1 \} = q, \tag{22}
\]

i.e. a test \( \psi \) that has better-than-random performance for testing whether the conditional distribution of \( X_j \) is given by \( P_j \) or \( Q_j \). Once \( \psi \) is constructed, then this is sufficient for the FDR result, e.g. setting

\[
\hat{S}(X, Y) = \begin{cases} \{j\}, & \psi(X) = 1, \\ \emptyset, & \psi(X) = 0. \end{cases}
\]

Note that the existence of such a test \( \psi \) is essentially equivalent to proving a lower bound on

\[
d_{\text{TV}}(\{P_{X}\}^{\otimes n}, \{Q_{X}\}^{\otimes n})
\]

uniformly over all distributions \( Q_{X} \) whose \( j \)th conditional is \( Q_j \), by the well-known equivalence between total variation distance and hypothesis testing \[9\]. In fact, our \( \psi \) will be given by a randomized procedure (to be fully formal, we can use the independent random \( Y \) values as a source of randomness, if needed). First, we draw \( \tilde{X} \mid X \), independently of \( Y \) and drawn from the rule \( P_{X|Y} \) as specified in the theorem, and independently we also draw \( B \sim \text{Bernoulli}(2q) \) and \( B' \sim \text{Bernoulli}(q) \). Next, defining \( \tilde{K}_{L,j} \) as in \[10\], we let

\[
\psi(\tilde{X}, \tilde{X}, B, B') = \begin{cases} 1 \{ B = 1 \text{ and } \tilde{K}_{L,j} > 0 \} + 1 \{ B' = 1 \text{ and } \tilde{K}_{\bar{L},j} = 0 \}. \end{cases}
\]

Clearly, by definition of \( B \) and \( B' \), we have

\[
\mathbb{P}\left\{ \psi(\tilde{X}, \tilde{X}, B, B') = 1 \right\} = 2q \cdot \mathbb{P}\left\{ \tilde{K}_{L,j} > 0 \right\} + q \cdot \mathbb{P}\left\{ \tilde{K}_{\bar{L},j} = 0 \right\}, \tag{23}
\]

where \( \mathbb{P}\left\{ \tilde{K}_{L,j} > 0 \right\} \) and \( \mathbb{P}\left\{ \tilde{K}_{\bar{L},j} = 0 \right\} \) are taken with respect to the joint distribution of \((\tilde{X}, \tilde{X})\).

Next, we check that the test \( \psi \) satisfies the properties \[22\], as required for the FDR bounds in this theorem. We first prove the second bound in \[22\]. Suppose \( X_{i,*} \overset{\text{iid}}{\sim} Q_{X} \)—that is, \( Q_j \) is indeed the correct conditional distribution for \( X_j \mid X_{-j} \). The knockoff generating mechanism \( P_{X|Y} \) was defined to satisfy pairwise exchangeability with respect to \( Q_j \) \[4\], meaning that \( X_j \) and \( \tilde{X}_j \) are exchangeable conditional on the other variables in this scenario. Examining the form of \( \tilde{K}_{L,j} \), we see that swapping \( X_j \) and \( \tilde{X}_j \) has the effect of changing the sign of \( \tilde{K}_{L,j} \). The exchangeability of the pair \((X_j, \tilde{X}_j)\) implies that the distribution of \( \tilde{K}_{L,j} \) is symmetric around zero, and so under \((X_{i,*}, \tilde{X}_{i,*}) \overset{\text{iid}}{\sim} Q_{X} \times P_{X|Y} \),

\[
\mathbb{P}\left\{ \tilde{K}_{L,j} > 0 \right\} + 0.5 \cdot \mathbb{P}\left\{ \tilde{K}_{L,j} = 0 \right\} = 0.5.
\]

Checking \[23\], this proves that \( \mathbb{P}_{X_{i,*} \sim Q_{X}} \{ \psi(X) = 1 \} = q \), which ensures FDR control for the case that the estimated conditional \( Q_j \) is in fact correct.

Finally we turn to the first part of \[22\], where now we assume that \((X_{i,*}, \tilde{X}_{i,*}) \overset{\text{iid}}{\sim} P_{X} \times P_{X|Y} \). From this point on, we will condition on the observed values of \( X_{-j} \) and \( \tilde{X}_{-j} \). By assumption in the theorem, under
this distribution we have \( \Pr \{ \hat{KL}_j \geq \epsilon \} \geq c. \) As in the proof of Theorem 1, we consider the unordered pair \( \{X_j, \tilde{X}_j\} \)—that is, we see the two vectors \( X_j \) and \( \tilde{X}_j \), but do not know which is which. Note that, with this information, we are able to compute \( |\hat{KL}_j| \) but not \( \text{sign}(\hat{KL}_j) \). Without loss of generality, we can label the unordered pair of feature vectors \( \{X_j, \tilde{X}_j\} \), as \( X_j^{(0)} \) and \( X_j^{(1)} \), such that

- if \( X_j = X_j^{(0)} \) and \( \tilde{X}_j = X_j^{(1)} \), then \( \hat{KL}_j \geq 0 \);
- if \( X_j = X_j^{(1)} \) and \( \tilde{X}_j = X_j^{(0)} \), then \( \hat{KL}_j \leq 0 \).

Define \( C = \text{sign}(\hat{KL}_j) \), so that \( \hat{KL}_j = C \cdot |\hat{KL}_j| \). By definition of the distribution of \( (X, \tilde{X}) \), it follows from Lemma 1 that

\[
\begin{align*}
\Pr \left\{ (X_j, \tilde{X}_j) = (X_j^{(0)}, X_j^{(1)}) \right\} & \Pr \left\{ (X_j, \tilde{X}_j) = (X_j^{(1)}, X_j^{(0)}) \right\} = \prod_i P_j(X_j^{(0)} | X_{i,j}) \prod_i P_j(X_j^{(1)} | X_{i,j}) P_j(X_j^{(1)} | X_{i,j}) = \exp \left\{ |\hat{KL}_j| \right\},
\end{align*}
\]

In other words, if \( |\hat{KL}_j| \neq 0 \), then

\[
\begin{align*}
\Pr \left\{ C = +1 \mid X_j^{(0)}, X_j^{(1)}, X_{i,j}, \tilde{X}_{i,j} \right\} & = \prod_i P_j(X_j^{(0)} | X_{i,j}) Q_j(X_j^{(1)} | X_{i,j}) = \exp \left\{ |\hat{KL}_j| \right\},
\end{align*}
\]

where the last step holds by our choice of which vector to label as \( X_j^{(0)} \) and which to label as \( X_j^{(1)} \).

Therefore, we can write

\[
\begin{align*}
\Pr \{ C = +1 \} & = \Pr \left\{ C = +1 \text{ and } |\hat{KL}_j| \geq \epsilon \right\} \\
& = \Pr \left\{ C = +1 \mid X_j^{(0)}, X_j^{(1)}, X_{i,j}, \tilde{X}_{i,j} \right\} \cdot \Pr \left\{ |\hat{KL}_j| \geq \epsilon \right\} \\
& = \mathbb{E} \left[ \frac{e^{\frac{|\hat{KL}_j|}{1 + e^{\frac{|\hat{KL}_j|}{\epsilon}}}}}{1 + e^{\frac{|\hat{KL}_j|}{\epsilon}}} \cdot \mathbb{I} \left\{ |\hat{KL}_j| \geq \epsilon \right\} \right].
\end{align*}
\]

We can similarly calculate \( \Pr \{ \hat{KL}_j > 0 \} = \mathbb{E} \left[ \frac{e^{\frac{|\hat{KL}_j|}{1 + e^{\frac{|\hat{KL}_j|}{\epsilon}}}}}{1 + e^{\frac{|\hat{KL}_j|}{\epsilon}}} \cdot \mathbb{I} \left\{ |\hat{KL}_j| > 0 \right\} \right]. \) Therefore,

\[
\frac{1}{2} \Pr \{ \hat{KL}_j = 0 \} + \Pr \{ \hat{KL}_j > 0 \} = \mathbb{E} \left[ \frac{e^0}{1 + e^0} \cdot \mathbb{I} \left\{ |\hat{KL}_j| = 0 \right\} \right] + \mathbb{E} \left[ \frac{e^{|\hat{KL}_j|}}{1 + e^{|\hat{KL}_j|}} \cdot \mathbb{I} \left\{ |\hat{KL}_j| > 0 \right\} \right]
\]

To continue, observe that for \( t \geq 0 \), \( e^t/(1 + e^t) \geq 1/2 \). Hence,

\[
\mathbb{E} \left[ \frac{e^{|\hat{KL}_j|}}{1 + e^{|\hat{KL}_j|}} \right] \geq \frac{1}{2} + \mathbb{E} \left[ \frac{e^{|\hat{KL}_j|}}{1 + e^{|\hat{KL}_j|}} - \frac{1}{2} \right] \cdot \mathbb{I} \left\{ |\hat{KL}_j| \geq \epsilon \right\}
\]

\[
\geq \frac{1}{2} + \min_{t \geq \epsilon} \frac{e^t}{1 + e^t} - \frac{1}{2} \cdot \mathbb{E} \left[ \frac{e^{|\hat{KL}_j|}}{1 + e^{|\hat{KL}_j|}} \cdot \mathbb{I} \left\{ |\hat{KL}_j| \geq \epsilon \right\} \right] \geq c \text{ by (24)}
\]

\[
\geq \frac{1}{2} \left( 1 + c(1 - e^{-\epsilon}) \right),
\]
where for the last step we check that the minimum is attained at \( t = \epsilon \). This proves that, when \( \mathbf{X}_{i,*} \overset{iid}{\sim} P_X \), we have \( \psi(\mathbf{X}, \bar{\mathbf{X}}, B, B') = 1 \) with probability at least \( q(1 + c(1 - e^{-\epsilon})) \), and so the first part of (22) is satisfied, as desired.

### A.3 Proof of Lemma 2

We will in fact prove a more general result, which will be useful later on:

**Lemma 6.** Fix any \( \delta \geq 0 \), and define the event

\[
\mathcal{E}_\delta = \left\{ \sum_i \left[ \log \left( \frac{P_j(\mathbf{X}_{ij} \mid \mathbf{X}_{i,-j})}{Q_j(\tilde{\mathbf{X}}_{ij} \mid \mathbf{X}_{i,-j})} \right) \right]^2 \leq n\delta^2 \text{ for all } i, j \right\}.
\]

Then

\[
\mathbb{P} \left\{ \max_{j=1,\ldots,p} \tilde{\KL}_{ij} \leq \frac{n\delta^2}{2} + 2\delta \sqrt{n \log(p)} \right\} \geq 1 - \frac{1}{p} - \mathbb{P} \{ \mathcal{E}_\delta^c \}.
\]

In order to prove Lemma 2 then, we simply observe that if the universal bound (13) holds for the likelihood ratios, then the event \( \mathcal{E}_\delta \) occurs with probability 1.

Now we prove the general result, Lemma 6. Fix any \( j \). Suppose that we condition on \( \mathbf{X}_{-j}, \bar{\mathbf{X}}_{-j} \), and on the unordered pair \( \{ \mathbf{X}_{ij}, \bar{\mathbf{X}}_{ij} \} = \{ a_{ij}, b_{ij} \} \) for each \( i \)—that is, after observing the unlabeled pair, we arbitrarily label them as \( a \) and \( b \). Write \( a_j = (a_{1j}, \ldots, a_{nj}) \) and same for \( b_j \). Let \( C_{ij} = 0 \) if \( a_{ij} = b_{ij} \), and otherwise let

\[
C_{ij} := \begin{cases} +1, & \text{if } (\mathbf{X}_{ij}, \bar{\mathbf{X}}_{ij}) = (a_{ij}, b_{ij}), \\ -1, & \text{if } (\mathbf{X}_{ij}, \bar{\mathbf{X}}_{ij}) = (b_{ij}, a_{ij}). \end{cases}
\]

Then we have

\[
\tilde{\KL}_{ij} = \sum_i \log \left( \frac{P_j(\mathbf{X}_{ij} \mid \mathbf{X}_{i,-j})}{Q_j(\bar{\mathbf{X}}_{ij} \mid \mathbf{X}_{i,-j})} \cdot \frac{Q_j(\tilde{\mathbf{X}}_{ij} \mid \mathbf{X}_{i,-j})}{P_j(\tilde{\mathbf{X}}_{ij} \mid \mathbf{X}_{i,-j})} \right)
\]
\[
= \sum_i C_{ij} \log \left( \frac{P_j(a_{ij} \mid \mathbf{X}_{i,-j}) \cdot Q_j(b_{ij} \mid \mathbf{X}_{i,-j})}{Q_j(a_{ij} \mid \mathbf{X}_{i,-j}) \cdot P_j(b_{ij} \mid \mathbf{X}_{i,-j})} \right) =: \sum_i C_{ij} \tilde{\KL}_{ij}.
\]

By Lemma 1 for each \( i \) with \( a_{ij} \neq b_{ij} \) we have

\[
\mathbb{P} \{ C_{ij} = +1 \mid a_j, b_j, \mathbf{X}_{-j}, \bar{\mathbf{X}}_{-j} \} = \mathbb{P} \{ (\mathbf{X}_{ij}, \bar{\mathbf{X}}_{ij}) = (a_{ij}, b_{ij}) \mid a_j, b_j, \mathbf{X}_{-j}, \bar{\mathbf{X}}_{-j} \}
\]
\[
= \frac{P_j(a_{ij} \mid \mathbf{X}_{i,-j}) Q_j(b_{ij} \mid \mathbf{X}_{i,-j})}{Q_j(a_{ij} \mid \mathbf{X}_{i,-j}) P_j(b_{ij} \mid \mathbf{X}_{i,-j})} = e^{\tilde{\KL}_{ij}}. \tag{25}
\]

Note that this binary outcome is independent for each \( i \). From this point on we treat \( \mathbf{X}_{-j}, \bar{\mathbf{X}}_{-j}, a_j, b_j \) as fixed (where \( a_j = (a_{1j}, \ldots, a_{nj}) \) and same for \( b_j \), and only the \( C_{ij} \)'s as random. Since \( \tilde{\KL}_{ij} \) depends only on \( \mathbf{X}_{-j}, \bar{\mathbf{X}}_{-j}, a_j, b_j \) (i.e. on the variables that we are conditioning on), and is therefore treated as fixed, while \( |C_{ij}| \leq 1 \) by definition, we see that

\[
\mathbb{P} \left\{ \tilde{\KL}_{ij} - E [\tilde{\KL}_{ij} \mid \mathbf{X}_{-j}, \bar{\mathbf{X}}_{-j}, a_j, b_j] \geq 2 \sqrt{\log(p)} \sqrt{\sum_i (\tilde{\KL}_{ij})^2} \mid \mathbf{X}_{-j}, \bar{\mathbf{X}}_{-j}, a_j, b_j \right\} \leq \frac{1}{p^2}
\]
by Hoeffding’s inequality. Next we work with the conditional expectation of \( \tilde{KL}_j \). For any \( i \) with \( a_{ij} \neq b_{ij} \), we use (25) to calculate

\[
\left| \mathbb{E} \left[ C_{ij} \mid X_{-j}, \tilde{X}_{-j}, a_j, b_j \right] \right| = \left| \frac{e^{\tilde{KL}_{ij}} - 1}{e^{\tilde{KL}_{ij}} + 1} \right| \leq \frac{|\tilde{KL}_{ij}|}{2}.
\]

Then

\[
\left| \mathbb{E} \left[ \tilde{KL} \mid X_{-j}, \tilde{X}_{-j}, a_j, b_j \right] \right| = \sum_i \mathbb{E} \left[ C_{ij} \mid X_{-j}, \tilde{X}_{-j}, a_j, b_j \right] \cdot \tilde{KL}_{ij} \leq \frac{1}{2} \sum_i (\tilde{KL}_{ij})^2.
\]

Therefore, combining everything,

\[
\mathbb{P} \left\{ \tilde{KL}_j \geq \frac{1}{2} \sum_i (\tilde{KL}_{ij})^2 + 2\sqrt{\log(p)} \sqrt{\sum_i (\tilde{KL}_{ij})^2} \mid X_{-j}, \tilde{X}_{-j}, a_j, b_j \right\} \leq \frac{1}{p^2}.
\]

Now, under the event \( \mathcal{E}_\delta \) we must have \( \sum_i (\tilde{KL}_{ij})^2 \leq n\delta^2 \), and so we can write

\[
\mathbb{P} \left\{ \tilde{KL}_j \cdot 1 \{ \mathcal{E}_\delta \} \geq \frac{n\delta^2}{2} + 2\delta \sqrt{n \log(p)} \mid X_{-j}, \tilde{X}_{-j}, a_j, b_j \right\} \leq \frac{1}{p^2}.
\]

Marginalizing over all the conditioned variables, and taking a union bound over all \( j \), we have proved that

\[
\mathbb{P} \left\{ \max_{j=1,\ldots,p} \tilde{KL}_j \cdot 1 \{ \mathcal{E}_\delta \} \geq \frac{n\delta^2}{2} + 2\delta \sqrt{n \log(p)} \right\} \leq \frac{1}{p}.
\]

This proves the lemma.

### A.4 Proof of Lemma 3

Fix any feature index \( j \), and consider any distribution \( D^{(j)} \) on \( \mathbb{R}^p \) with \( j \)-th conditional equal to \( Q_j \), as defined in (16). For simplicity, from this point on, we will perform calculations treating \( D^{(j)} \) as a joint density, but the result is valid without this assumption. Drawing \( X \sim D^{(j)} \) and \( \tilde{X} \mid X \sim P_{\tilde{X} \mid X}(\cdot \mid X) \), then the joint density of \( (X, \tilde{X}) \) is given by

\[
D^{(j)}(x) \cdot P_{\tilde{X} \mid X}(\tilde{x} \mid x) = D^{(j)}(x_{-j}) \cdot \left( \underbrace{Q_j(x_j \mid x_{-j}) \cdot \exp \left\{ -\frac{1}{2} x^\top \Theta x \right\}}_{\text{Term 1}} \right) \cdot \left( \underbrace{P_{\tilde{X} \mid X}(\tilde{x} \mid x) \cdot \exp \left\{ -\frac{1}{2} x^\top \tilde{\Theta} x \right\}}_{\text{Term 2}} \right),
\]

where \( D^{(j)} \) is the marginal distribution of \( X_{-j} \) under the joint distribution \( X \sim D^{(j)} \). In order to check that (4) holds, i.e. that \( (X_j, \tilde{X}_j, X_{-j}, \tilde{X}_{-j}) \overset{d}{=} (\tilde{X}_j, X_j, X_{-j}, \tilde{X}_{-j}) \) under this distribution, we therefore need to check that this joint density is exchangeable in the variables \( x_j \) and \( \tilde{x}_j \); that is, swapping \( x_j \) and \( \tilde{x}_j \) does not change the value of the joint density \( D^{(j)}(x) \cdot P_{\tilde{X} \mid X}(\tilde{x} \mid x) \). We check this by considering each of the three terms separately. Term 1 clearly does not depend on either \( x_j \) or \( \tilde{x}_j \). Next, using the calculation of \( Q_j \) in (16), we can simplify Term 2 to obtain

\[
\text{Term 2} \propto \exp \left\{ -\frac{1}{2} \Theta_{jj} \left( x_j + x_{-j} \tilde{\Theta}_{-j,j} \tilde{\Theta}_{j,j} \right)^2 + \frac{1}{2} x^\top \tilde{\Theta} x \right\} = \exp \left\{ \frac{1}{2} x_{-j} \left( \tilde{\Theta}_{-j,-j} - \frac{\tilde{\Theta}_{-j,j} \tilde{\Theta}_{j,j}^\top}{\Theta_{jj}} \right) x_{-j} \right\},
\]

21
which also does not depend on either \(x_j\) or \(\bar{x}_j\). Finally, Term 3 is exchangeable in the pair \(x_j, \bar{x}_j\) by the construction of the knockoff distribution \(P_{X_k|X}\). More concretely, using the definition of \(P_{X_k|X}\) given in (15), we can calculate

\[
\text{Term 3} \propto \exp \left\{ -\frac{1}{2} (\bar{x} - (I - D\Theta)x)^\top (2D - D\Theta D)^{-1} (\bar{x} - (I - D\Theta)x) - \frac{1}{2} x^\top \Theta x \right\}
\]

\[
= \exp \left\{ -\frac{1}{2} (x + \bar{x})^\top (2D - D\Theta D)^{-1} (x + \bar{x}) + x^\top D^{-1}x \right\},
\]

which is clearly exchangeable in the pair \(x_j, \bar{x}_j\) (note that the exchangeability of \(x_j, \bar{x}_j\) in the term \(x^\top D^{-1}x\) follows from the fact that \(D\) is a diagonal matrix).

### A.5 Proof of Lemma 4

We will apply Lemma 6 to prove this result. We first recall the conditional distributions \(P_j\) for the joint distribution \(P_X = \mathcal{N}_p((0, \Theta)^{-1}\), which can be computed as

\[
P_j(x_{-j}) = \mathcal{N}(x_{-j} (-\Theta_{-j,j}/\Theta_{jj}), 1/\Theta_{jj}),
\]

and the conditionals \(Q_j\), calculated earlier in (16) as

\[
Q_j(x_{-j}) = \mathcal{N}(x_{-j} (-\Theta_{-j,j}/\Theta_{jj}), 1/\Theta_{jj}).
\]

Then we can calculate

\[
\sum_i \left[ \log \left( \frac{P_j(X_{ij} | X_{i,-j})Q_j(\bar{X}_{ij} | X_{i,-j})}{Q_j(X_{ij} | X_{i,-j})P_j(\bar{X}_{ij} | X_{i,-j})} \right) \right]^2
\]

\[
= \sum_i \left[ \frac{-(X_{ij} - \bar{X}_{ij}) \cdot (\Theta_{ij} - \Theta_{jj}) + X_{i}^\top (\bar{\Theta}_j - \Theta_j)}{2} \right] \cdot \left[ X_{ij} - \bar{X}_{ij} \right]^2
\]

\[
\leq \frac{1}{2} \sum_i \left[ \frac{-(X_{ij} - \bar{X}_{ij}) \cdot (\Theta_{ij} - \Theta_{jj}) + X_{i}^\top (\bar{\Theta}_j - \Theta_j)}{2} \right]^4 + \frac{1}{2} \sum_i \left[ X_{ij} - \bar{X}_{ij} \right]^4.
\]

Using standard tail bounds on Gaussian and \(\chi^2\) random variables, and computing the variances \(v_j^2\) and \(w_j^2\), after some calculations we can show that the quantity above is bounded as

\[
\sum_i \left[ \log \left( \frac{P_j(X_{ij} | X_{i,-j})Q_j(\bar{X}_{ij} | X_{i,-j})}{Q_j(X_{ij} | X_{i,-j})P_j(\bar{X}_{ij} | X_{i,-j})} \right) \right]^2 \leq 4 \left[ \left( \frac{\delta_{\theta}}{1 - \delta_{\theta}} \right)^2 + \left( \frac{\delta_{\theta}}{1 - \delta_{\theta}} \right)^4 \right] \cdot \left( \sqrt{n} + 2\sqrt{\log(p)} \right)^2,
\]

with probability at least \(1 - \frac{1}{p}\), and therefore, \(\mathbb{P} \{ \mathcal{E}_3 \} \geq 1 - \frac{1}{p}\). When we take

\[
\delta = 2 \sqrt{\left( \frac{\delta_{\theta}}{1 - \delta_{\theta}} \right)^2 + \left( \frac{\delta_{\theta}}{1 - \delta_{\theta}} \right)^4} \cdot \left( 1 + 2\sqrt{\frac{\log(p)}{n}} \right) = 2\delta_{\theta} \cdot (1 + o(1)),
\]

where the last step holds as long as \(\frac{\log(p)}{n} = o(1)\) and \(\delta_{\theta} = o(1)\). Applying Lemma 6 then proves that

\[
\mathbb{P} \left\{ \max_{j=1,\ldots,p} \hat{\mathcal{KL}}_j \leq \frac{\sqrt{\hat{\delta}_2}}{\sqrt{n}} + 2\delta_{\theta} \sqrt{n \log(p)} \right\} \geq 1 - \frac{2}{p}.
\]

Assuming this upper bound on the \(\hat{\mathcal{KL}}_j\)'s is bounded by a constant, the dominant term is therefore \(2\delta_{\theta} \sqrt{n \log(p)}\), which proves the lemma.
A.6 Proof of Lemma

First, recall that \( T = T(W) \) is defined as follows:

\[
T = \min \left\{ t \geq \epsilon(W) : \frac{\sum_{\ell=1}^p 1 \{ W_{\ell} \geq t \}}{c + \sum_{\ell=1}^p 1 \{ W_{\ell} \leq -t \}} \leq q \right\},
\]

where \( \epsilon(W) > 0 \) is chosen to be the smallest magnitude of the \( W \) statistics, i.e. \( \epsilon(W) = \min \{ |W_{\ell}| : |W_{\ell}| > 0 \} \), and where \( c = 0 \) for knockoff or \( c = 1 \) for knockoff+. Next, define

\[
W^j := (W_1, \ldots, W_{j-1}, |W_j|, W_{j+1}, \ldots, W_p) \quad \text{and} \quad W^k := (W_1, \ldots, W_{k-1}, |W_k|, W_{k+1}, \ldots, W_p),
\]

so that \( T_j = T(W^j) \) and \( T_k = T(W^k) \). Note that \( |W^j| = |W^k| = |W| \), and so \( \epsilon(W^j) = \epsilon(W^k) = \epsilon(W) \) since \( \epsilon(W) \) depends on \( W \) only through \( |W| \).

Without loss of generality, assume \( T_j \leq T_k \), so that by assumption we have \( W_j \leq -T_j \) and \( W_k \leq -T_j \). Then we have

\[
f(W^k, T_j) = \frac{\sum_{\ell=1}^p 1 \{ W^k_{\ell} \geq T_j \}}{c + \sum_{\ell=1}^p 1 \{ W^k_{\ell} \leq -T_j \}}.
\]

which can be written as

\[
\frac{\sum_{\ell=1}^p 1 \{ W^j_{\ell} \geq T_j \} + (1 \{ W^k_{\ell} \geq T_j \} - 1 \{ W^j_{\ell} \geq T_j \}) + (1 \{ W^k_{\ell} \geq T_j \} - 1 \{ W^k_{\ell} \geq T_j \})}{c + \sum_{\ell=1}^p 1 \{ W^j_{\ell} \leq -T_j \} + (1 \{ W^k_{\ell} \leq -T_j \} - 1 \{ W^j_{\ell} \leq -T_j \}) + (1 \{ W^k_{\ell} \leq -T_j \} - 1 \{ W^k_{\ell} \leq -T_j \})},
\]

since \( W^j \) and \( W^k \) differ only on entries \( j, k \). Next, we know from our assumptions and definitions that \( W^k_j = W_j \leq -T_j \); \( W^j_j = |W_j| \geq T_j \); \( W^k_k = |W_k| \geq T_j \); and \( W^j_k = W_k \leq -T_j \). Therefore,

\[
(1 \{ W^j_j \geq T_j \} - 1 \{ W^j_j \geq T_j \}) + (1 \{ W^k_k \geq T_j \} - 1 \{ W^k_k \geq T_j \}) = 0 - 1 + 1 - 0 = 0
\]

and

\[
(1 \{ W^k_k \leq -T_j \} - 1 \{ W^k_k \leq -T_j \}) + (1 \{ W^j_k \leq -T_j \} - 1 \{ W^j_k \leq -T_j \}) = 1 - 0 + 0 - 1 = 0.
\]

Returning to our expression for \( f(W^k, T_j) \) above, then,

\[
f(W^k, T_j) = \frac{\sum_{\ell=1}^p 1 \{ W^k_{\ell} \geq T_j \} + 0}{c + \sum_{\ell=1}^p 1 \{ W^k_{\ell} \leq -T_j \} + 0} = f(W^j, T_j) \leq q,
\]

where the last step holds by definition of \( T_j \). Therefore, since \( T_j \geq \epsilon(W^j) = \epsilon(W^k) \), we see from the definition of \( T_k \) that we must have \( T_k \leq T_j \). This proves that \( T_j = T_k \), as desired.

Acknowledgements

R. F. B. was partially supported by the National Science Foundation via grant DMS 1654076, and by an Alfred P. Sloan fellowship. E. C. was partially supported by the Office of Naval Research under grant N00014-16-1-2712, by the National Science Foundation via DMS 1712800, by the Math + X Award from the Simons Foundation and by a generous gift from TwoSigma. E. C. would like to thank Chiara Sabatti for useful conversations related to this project. R. J. S. was partially supported by Engineering and Physical Sciences Research Council Fellowships EP/J017213/1 and EP/P031447/1, and by grant RG81761 from the Leverhulme Trust.
References


