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CLASSIFICATION ALGORITHMS USING ADAPTIVE PARTITIONING¹

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Algorithms for binary classification based on adaptive tree partitioning are formulated and analyzed for both their risk performance and their friendliness to numerical implementation. The algorithms can be viewed as generating a set approximation to the Bayes set and thus fall into the general category of *set estimators*. In contrast with the most studied tree-based algorithms, which utilize piecewise constant approximation on the generated partition [*IEEE Trans. Inform. Theory* **52** (2006) 1335–1353; *Mach. Learn.* **66** (2007) 209–242], we consider decorated trees, which allow us to derive higher order methods. Convergence rates for these methods are derived in terms of the parameter α of margin conditions and a rate s of best approximation of the Bayes set by decorated adaptive partitions. They can also be expressed in terms of the Besov smoothness β of the regression function that governs its approximability by piecewise polynomials on adaptive partition. The execution of the algorithms does not require knowledge of the smoothness or margin conditions. Besov smoothness conditions are weaker than the commonly used Hölder conditions, which govern approximation by nonadaptive partitions, and therefore for a given regression function can result in a higher rate of convergence. This in turn mitigates the compatibility conflict between smoothness and margin parameters.

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1. Introduction. A large variety of methods has been developed for classification of randomly drawn data. Most of these fall into one of two basic categories: *set estimators* or *plug-in estimators*. Both of these families are based on some underlying form of approximation. In the case of set estimators, one directly approximates the *Bayes set*, using elements from a given family of sets. For plug-in estimators, one approximates the underlying *regression function* and builds the classifier as a level set of this approximation.

The purpose of this paper is to introduce a family of classification algorithms using tree-based adaptive partitioning and to analyze their risk performance as well as their friendliness to numerical implementation. These algorithms fall into the category of set estimators. Tree-based classification algorithms have been well studied since their introduction in [8], and their convergence properties have been discussed both in terms of oracle inequalities and minimax convergence estimates; see, for example, [14] and [6]. Among the specific features of the approach followed in our paper are (i) the use of decorated trees which allow us to derive faster rates for certain classes of distributions than obtained when using standard trees and (ii) a convergence analysis based on nonlinear approximation theory which allows us to significantly weaken the usual assumptions that are made to establish a given convergence rate. More detailed comparisons with existing methods and results are described later.

We place ourselves in the following setting of binary classification. Let $X \subset \mathbb{R}^d$, $Y = \{-1, 1\}$ and $Z = X \times Y$. We assume that $\rho = \rho_X(x) \cdot \rho(y|x)$ is a probability measure defined on Z . We denote by $p(x)$ the probability that $y = 1$ given x and by $\eta(x)$ the regression function

$$(1.1) \quad \eta(x) := \mathbb{E}(y|x) = p(x) - (1 - p(x)) = 2p(x) - 1,$$

where \mathbb{E} denotes expectation. For any set S , we use the notation

$$(1.2) \quad \rho_S := \rho_X(S) = \int_S d\rho_X \quad \text{and} \quad \eta_S := \int_S \eta d\rho_X.$$

A classifier returns the value $y = 1$ if x is in some set $\Omega \subset X$ and $y = -1$ otherwise. Therefore, the classifier is given by a function $T_\Omega = \chi_\Omega - \chi_{\Omega^c}$ where Ω is some ρ_X measurable set, and Ω^c is its complement. With a slight abuse of notation, we sometimes refer to the set Ω itself as the classifier. We denote by $R(\Omega) := \mathbb{P}\{T_\Omega(x) \neq y\}$ the risk (probability of misclassification) of this classifier, and by $\Omega^* := \{x : \eta(x) \geq 0\}$ the Bayes classifier which minimizes this risk $R(\Omega)$, or equivalently, maximizes the quantity η_Ω among all possible sets Ω .

We measure the performance of a classifier Ω by the *excess risk*

$$(1.3) \quad R(\Omega) - R(\Omega^*) = \int_{\Omega \Delta \Omega^*} |\eta| d\rho_X,$$

with $A \triangle B := (A - B) \cup (B - A)$ the symmetric difference between A and B .

Given the data $\mathbf{z} = (z_i)_{i=1}^n$, $z_i = (x_i, y_i)$, $i = 1, \dots, n$, drawn independently according to ρ , a classification algorithm uses the draw to find a set $\widehat{\Omega} = \widehat{\Omega}(\mathbf{z})$ to be used as a classifier. Obtaining a concrete estimate of the decay of the excess risk for a given classification algorithm as n grows requires assumptions on the underlying measure ρ . These conditions are usually spelled out by assuming that ρ is in a *model class* \mathcal{M} . Model classes are traditionally formed by two ingredients: (i) assumptions on the behavior of ρ near the boundary of the Bayes set Ω^* and (ii) assumptions on the smoothness of the regression function η .

Conditions that clarify (i) are called margin conditions and are an item of many recent papers; see, for example, [13, 15]. One formulation (sometimes referred to as the Tsybakov condition) requires that

$$(1.4) \quad \rho_X \{x \in X : |\eta(x)| \leq t\} \leq C_\alpha t^\alpha, \quad 0 < t \leq 1,$$

for some constant $C_\alpha > 0$ and $\alpha \geq 0$. This condition becomes more stringent as α tends to $+\infty$. The limiting case $\alpha = \infty$, known as Massart condition, means that for some $A > 0$, we have $|\eta| > A$ almost everywhere. A common choice for (ii) in the classification literature (see, e.g., [2]) is that η belongs to the Hölder space C^β . This space can be defined for any $\beta > 0$ as the set of functions f such that

$$(1.5) \quad \|\Delta_h^m f\|_{L_\infty} \leq C|h|^\beta, \quad h \in \mathbb{R}^d,$$

where Δ_h^m is the m th power of the finite difference operator defined by $\Delta_h f = f(\cdot + h) - f$, with m being the smallest integer such that $m \geq \beta$. The Hölder class may be viewed intuitively as the set of functions whose derivatives of fractional order β belong to L_∞ .

An important observation is that there is a conflict between margin and smoothness assumptions, in the sense that raising the smoothness β limits the range of α in the margin condition. For example, when ρ_X is the Lebesgue measure on X , it is easily checked that the constraint $\alpha\beta \leq 1$ must hold as soon as the Bayes boundary $\partial\Omega^*$ has nonzero $(d - 1)$ -dimensional Hausdorff measure.

An instance of a convergence result exploiting (i) and (ii), Theorem 4.3 in [2], is that under the assumption that the density of ρ_X with respect to the Lebesgue measure is uniformly bounded, certain classifiers based on plug-in rules achieve in expectation the rate

$$(1.6) \quad \mathbb{E}(R(\widehat{\Omega}) - R(\Omega^*)) \leq Cn^{-((1+\alpha)\beta)/((2+\alpha)\beta+d)}$$

if the margin assumption holds with parameter α , and if η belongs to the Hölder class C^β .

The classification algorithms that we study in this paper have natural links with the process of approximating the regression function using piecewise constant or piecewise polynomials on adaptive partitions, which is an instance of *nonlinear approximation*. It is well known in approximation theory that, when using nonlinear methods, the smoothness condition needed to attain a specified rate can be dramatically weakened. This state of affairs is reflected in the convergence results for our algorithms that are given in Theorems 6.1 and 6.3. These results say that with high probability (larger than $1 - Cn^{-r}$ where $r > 0$ can be chosen arbitrarily large), our classifiers achieve the rate

$$(1.7) \quad R(\widehat{\Omega}) - R(\Omega^*) \leq C \left(\frac{n}{\log n} \right)^{-((1+\alpha)\beta)/((2+\alpha)\beta+d)}$$

if the margin assumption holds with parameter α and if η belongs to the Besov space $B_\infty^\beta(L_p)$ with $p > 0$ such that $\beta p > d$. This Besov space is defined by the condition

$$(1.8) \quad \|\Delta_h^m f\|_{L_p} \leq C|h|^\beta, \quad h \in \mathbb{R}^d,$$

with m being an integer such that $m > \beta$ and may be viewed as the set of function whose derivatives of fractional order β belong to L_p . Notice that the constraint $\beta p > d$ ensures that $B_\infty^\beta(L_p)$ is compactly embedded in L_∞ . Therefore our algorithm achieves the same rate as (1.6), save for the logarithm, however, with a significant weakening on the smoothness condition imposed on the regression function because of the use of adaptive partitioning. In particular, an individual regression function may have significantly higher smoothness β in this scale of Besov spaces than in the scale of Hölder spaces, resulting in a better rate when using our classifier.

In addition, the weaker smoothness requirement for a given convergence rate allows us to alleviate the conflict between smoothness and margin conditions in the sense that the constraint $\alpha\beta \leq 1$ can be relaxed when using the space $B_\infty^\beta(L_p)$; see (6.12). Let us also observe that our risk bound in (1.7) holds in the stronger sense of high probability, rather than expectation, and that no particular assumption (such as equivalence with Lebesgue measure) is made on the density of ρ_X . Finally, let us stress that our algorithms are numerically implementable and do not require the a priori knowledge of the parameters α and β .

The distinction between Theorems 6.1 and 6.3 is the range of β for which they apply. Theorem 6.1 only applies to the range $\beta \leq 1$ and can be seen as the analog of using piecewise constant approximation on adaptive partition for plug-in estimators. On the other hand, Theorem 6.3 applies for any $\beta \leq 2$. The gain in the range of β results from the fact that the algorithm uses decorated trees. This corresponds to piecewise affine approximation for

plug-in methods. In principle, one can extend the values of β arbitrarily by using higher polynomial order decorated trees. However, the numerical implementation of such techniques becomes more problematic and is therefore not considered in this paper. In the regression context, piecewise polynomial estimators on adaptive partitions have been considered in [1, 3].

Set estimators aim at approximating the Bayes set Ω^* by elements S from a family of sets \mathcal{S} in the sense of the distance defined by the excess risk. Our approach to deriving the risk bounds in Theorems 6.1 and 6.3 is by splitting this risk into

$$(1.9) \quad R(\widehat{\Omega}) - R(\Omega^*) = (R(\widehat{\Omega}) - R(\Omega_{\mathcal{S}})) + (R(\Omega_{\mathcal{S}}) - R(\Omega^*)),$$

where $\Omega_{\mathcal{S}} := \operatorname{argmin}_{S \in \mathcal{S}} R(S) = \operatorname{argmax}_{S \in \mathcal{S}} \eta_S$. The two terms are positive, and are, respectively, referred to as the estimation error and approximation error. We bound in Section 2 the estimation error by introducing a certain modulus, which is defined utilizing any available uniform estimate between the quantity $\eta_S - \eta_{\Omega_S}$ and its empirical counterpart computed from the draw. For set estimators based on empirical risk minimization, we show in Section 3 how margin conditions can be used to bound this modulus, and therefore the estimation error term.

In Section 4, we turn to estimates for the approximation term. This analysis is based on the smoothness of η and the margin condition. A typical setting when building set classifiers is a nested sequence $(\mathcal{S}_m)_{m \geq 1}$ of families of sets, that is, $\mathcal{S}_m \subset \mathcal{S}_{m+1}$, where m describes the complexity of \mathcal{S}_m in the sense of VC dimension. The value of m achieving between the optimal balance between the estimation and approximation terms depends on the parameters α and β , which are unknown. A standard model selection procedure is discussed in Section 5 that reaches this balance for a variety of model classes $\mathcal{M} = \mathcal{M}(\alpha, \beta)$ over a range of α and β .

Many ingredients of our analysis of general classification methods appear in earlier works; see, for example, [7, 11]. However, in our view, the organization of the material in these sections helps clarify various issues concerning the roles of approximation and estimation error bounds.

In Section 6, we turn to our proposed classification methods based on adaptive partitioning. We analyze their performance using the results from the previous sections and obtain the aforementioned Theorems 6.1 and 6.3. The implementation and complexity of these algorithms are discussed in Section 7.

2. A general bound for the estimation error in set estimators. In view of $\Omega^* = \operatorname{argmax}_{\Omega \subset X} \eta_{\Omega}$, if $\hat{\eta}_S$ is any empirical estimator for η_S , a natural way to select a classifier within \mathcal{S} is by

$$(2.1) \quad \widehat{\Omega} := \widehat{\Omega}_{\mathcal{S}} := \operatorname{argmax}_{S \in \mathcal{S}} \hat{\eta}_S.$$

One of the most common strategies for building $\hat{\eta}_S$ is by introducing the empirical counterparts to (1.2),

$$(2.2) \quad \bar{\rho}_S := \frac{1}{n} \sum_{i=1}^n \chi_S(x_i) \quad \text{and} \quad \bar{\eta}_S = \frac{1}{n} \sum_{i=1}^n y_i \chi_S(x_i).$$

The choice $\hat{\eta}_S = \bar{\eta}_S$ is equivalent to minimizing the empirical risk over the family \mathcal{S} , namely choosing

$$(2.3) \quad \hat{\Omega}_S = \bar{\Omega}_S := \operatorname{argmin}_{S \in \mathcal{S}} \bar{R}(S), \quad \bar{R}(S) := \frac{1}{n} \#\{i : T_S(x_i) \neq y_i\}.$$

However, other choices of $\hat{\eta}_S$ are conceivable, leading to other classifiers.

We give in this section a general method for bounding the estimation error, whenever we have an empirical estimator $\hat{\eta}_S$ for η_S , with a bound of the form

$$(2.4) \quad |\eta_S - \eta_{\Omega_S} - (\hat{\eta}_S - \hat{\eta}_{\Omega_S})| \leq e_n(S),$$

for each set $S \in \mathcal{S}$. In the case where we use for $\hat{\eta}_S$ the set estimators $\bar{\eta}_S$ defined in (2.2), we have the following bound.

THEOREM 2.1. *For any sufficiently large constant $A > 0$, the following holds. If \mathcal{S} is a collection of ρ_X measurable sets $S \subset X$ with finite VC dimension $V := V_S$, and if*

$$(2.5) \quad e_n(S) := \sqrt{\rho_{S \Delta \Omega_S} \varepsilon_n} + \varepsilon_n, \quad \varepsilon_n := A \max\{r + 1, V\} \frac{\log n}{n},$$

where $r > 0$ is arbitrary, then there is an absolute constant C_0 such that for any $n \geq 2$, with probability at least $1 - C_0 n^{-r}$ on the draw $\mathbf{z} \in Z^n$, we have

$$(2.6) \quad |\eta_S - \eta_{\Omega_S} - (\bar{\eta}_S - \bar{\eta}_{\Omega_S})| \leq e_n(S), \quad S \in \mathcal{S}.$$

The techniques for proving this result are well known in classification, but we cannot find any reference that give the bounds in this theorem in the above form, and therefore we give its proof in the supplementary material [4].

REMARK 2.2. The above theorem covers, in particular, the case where \mathcal{S} is a *finite* collection of sets, since then trivially $V_S \leq \#\mathcal{S}$. Alternatively, in this case, a straightforward argument using Bernstein's inequality yields the same result with the explicit expression $\varepsilon_n := \frac{10(\log(\#\mathcal{S}) + r \log n)}{3n}$ and probability at least $1 - 2n^{-r}$.

To analyze the estimation error in classifiers, we define the following modulus:

$$(2.7) \quad \omega(\rho, e_n) := \sup \left\{ \int_{S \Delta \Omega_S} |\eta| : S \in \mathcal{S} \text{ and } \int_{S \Delta \Omega_S} |\eta| \leq 3e_n(S) \right\}.$$

Notice that the second argument e_n is not a number but rather a set function. In the next section, we discuss this modulus in some detail and bring out its relation to other ideas used in classification, such as margin conditions. For now, we use it to prove the following theorem.

THEOREM 2.3. *Suppose that for each $S \in \mathcal{S}$, we have that (2.4) holds with probability $1 - \delta$. Then with this same probability, we have*

$$(2.8) \quad R(\widehat{\Omega}_{\mathcal{S}}) - R(\Omega_{\mathcal{S}}) \leq \max\{\omega(\rho, e_n), a(\Omega^*, \mathcal{S})\}$$

with $a(\Omega^*, \mathcal{S}) := R(\Omega_{\mathcal{S}}) - R(\Omega^*)$ being the approximation error from (1.9).

PROOF. We consider any data \mathbf{z} such that (2.4) holds and prove that (2.8) holds for such \mathbf{z} . Let $S_0 := \Omega_{\mathcal{S}} \setminus \widehat{\Omega}_{\mathcal{S}}$ and $S_1 := \widehat{\Omega}_{\mathcal{S}} \setminus \Omega_{\mathcal{S}}$ so that $S_0 \cup S_1 = \widehat{\Omega}_{\mathcal{S}} \triangle \Omega_{\mathcal{S}}$. Notice that, in contrast to $\Omega_{\mathcal{S}}$ and $\widehat{\Omega}_{\mathcal{S}}$, the sets S_0, S_1 are generally not in \mathcal{S} . We start from the equality

$$(2.9) \quad R(\widehat{\Omega}_{\mathcal{S}}) - R(\Omega_{\mathcal{S}}) = \eta_{\Omega_{\mathcal{S}}} - \eta_{\widehat{\Omega}_{\mathcal{S}}} = \eta_{S_0} - \eta_{S_1}.$$

We can assume that $\eta_{S_0} - \eta_{S_1} > 0$, since otherwise we have nothing to prove. From the definition of $\widehat{\Omega}_{\mathcal{S}}$, we know that $\hat{\eta}_{\Omega_{\mathcal{S}}} - \hat{\eta}_{\widehat{\Omega}_{\mathcal{S}}} \leq 0$. Using this in conjunction with (2.4), we obtain

$$(2.10) \quad \eta_{S_0} - \eta_{S_1} = \eta_{\Omega_{\mathcal{S}}} - \eta_{\widehat{\Omega}_{\mathcal{S}}} \leq e_n(\widehat{\Omega}_{\mathcal{S}}).$$

In going further, we introduce the following notation. Given a set $S \subset X$, we denote by $S^+ := S \cap \Omega^*$ and $S^- := S \cap (\Omega^*)^c$. Thus $\eta \geq 0$ on S^+ and $\eta < 0$ on S^- . Also $S = S^+ \cup S^-$ and $S^+ \cap S^- = \emptyset$. Hence we can write $\eta_{S_0} - \eta_{S_1} = A - B$, where $A := \eta_{S_0^+} - \eta_{S_1^-} \geq 0$ and $B := \eta_{S_1^+} - \eta_{S_0^-} \geq 0$. Note that $A, B \geq 0$. We consider two cases.

Case 1. If $A \leq 2B$, then

$$(2.11) \quad R(\widehat{\Omega}_{\mathcal{S}}) - R(\Omega_{\mathcal{S}}) = A - B \leq B \leq a(\Omega^*, \mathcal{S}),$$

where we have used the fact that $S_1^+ \subset \Omega^* \setminus \Omega_{\mathcal{S}}$ and $S_0^- \subset \Omega_{\mathcal{S}} \setminus \Omega^*$.

Case 2. If $A > 2B$, then, by (2.10),

$$(2.12) \quad \int_{\widehat{\Omega}_{\mathcal{S}} \triangle \Omega_{\mathcal{S}}} |\eta| = A + B \leq 3A/2 \leq 3(A - B) = 3(\eta_{S_0} - \eta_{S_1}) \leq 3e_n(\widehat{\Omega}_{\mathcal{S}}).$$

This means that $\widehat{\Omega}_{\mathcal{S}}$ is one of the sets appearing in the definition of $\omega(\rho, e_n)$, and (2.8) follows in this case from the fact that

$$\eta_{S_0} - \eta_{S_1} = A - B \leq \int_{\widehat{\Omega}_{\mathcal{S}} \triangle \Omega_{\mathcal{S}}} |\eta| \leq \omega(\rho, e_n). \quad \square$$

From Theorem 2.3, we immediately obtain the following corollary.

COROLLARY 2.4. *Suppose that for each $S \in \mathcal{S}$, (2.4) holds with probability $1 - \delta$. Then with this same probability we have*

$$(2.13) \quad R(\widehat{\Omega}_{\mathcal{S}}) - R(\Omega^*) \leq \omega(\rho, e_n) + 2a(\Omega^*, \mathcal{S}).$$

REMARK 2.5. The corollary does not impose any particular assumption on ρ and \mathcal{S} , apart from finite VC dimension. For later comparisons with existing results, we briefly mention how $e_n(S)$ can be sharpened under additional assumptions on ρ_X . Assume that ρ_X is (or is equivalent to) the Lebesgue measure, and for any arbitrary integer $l \geq 1$, consider a uniform partition \mathcal{Q} of $X = [0, 1]^d$ into $m = l^d$ cubes of side length l^{-1} , providing the collection \mathcal{S} of all sets S that are unions of cubes from \mathcal{Q} . Then, defining

$$(2.14) \quad e_n(S) := \rho_{S \Delta \Omega_S} \sqrt{\varepsilon_n} \quad \text{where } \varepsilon_n := \frac{8(r+1)m(1+\log n)}{3n},$$

application of a union bound on Bernstein's inequality to the random variable $y\chi_{\Omega_S}(x) - y\chi_S(x)$ gives

$$(2.15) \quad \mathbb{P}\{|\eta_S - \bar{\eta}_S - (\eta_{\Omega_S} - \bar{\eta}_{\Omega_S})| \leq e_n(S) : S \in \mathcal{S}\} \geq 1 - Cn^{-r},$$

where C is an absolute constant depending on r .

REMARK 2.6. Theorem 2.3 can be applied to any classification method that is based on an estimation $\hat{\eta}_S$ of η_S , once the bounds for $|\eta_S - \eta_{\Omega_S} - (\hat{\eta}_S - \hat{\eta}_{\Omega_S})|$ in terms of $e_n(S)$ have been established for all $S \in \mathcal{S}$. This determines $\omega(\rho, e_n)$ and thereby gives a bound for the estimation error.

REMARK 2.7. The usual approach to obtaining bounds on the performance of classifiers is to assume at the outset that the underlying measure ρ satisfies a margin condition. Our approach is motivated by the desire to obtain bounds with no assumptions on ρ . This is accomplished by introducing the modulus ω . As we discuss in the following section, a margin assumption allows one to obtain an improved bound on ω and thereby recover existing results in the literature. Another point about our result is that we do not assume that the Bayes classifier Ω^* lies in \mathcal{S} . In some approaches, as discussed in the survey [7], one first bounds the estimation error under this assumption, and then later removes this assumption with additional arguments that employ margin conditions.

3. Margin conditions. The modulus ω introduced in the previous section is not transparent and, of course, depends on the set function $e_n(S)$. However, as we now show, for the types of e_n that naturally occur, the modulus is intimately connected with margin conditions. Margin assumptions are one

of the primary ingredients in obtaining estimates on the performance of empirical classifiers. The margin condition (1.4) recalled in the [Introduction](#) has the following equivalent formulation: for any measurable set S , we have

$$(3.1) \quad \rho_S \leq C_\gamma \left(\int_S |\eta| \right)^\gamma, \quad \gamma := \frac{\alpha}{1+\alpha} \in [0, 1]$$

for some constant $C_\gamma > 0$ and $\gamma \in [0, 1]$. This condition is void when $\gamma = 0$ and becomes more stringent as γ tends to 1. The case $\gamma = 1$ gives Massart's condition.

In going further, we define \mathcal{M}^α as the set of all measures ρ such that ρ_X satisfies (1.4) or equivalently (3.1), and we define

$$(3.2) \quad |\rho|_{\mathcal{M}^\alpha} := \sup_{0 < t \leq 1} t^{-\alpha} \rho_X \{x \in X : |\eta(x)| \leq t\}.$$

We want to bring out the connection between the modulus ω and the condition (3.1). In the definition of ω and its application to bounds on the estimation error, we assume that we have an empirical estimator for which (2.4) holds with probability $1 - \delta$. Notice that this is only assumed to hold for sets $S \in \mathcal{S}$ which is a distinction with (3.1). We shall make our comparison first when e_n is of the form $e_n(S) = \sqrt{\varepsilon_n \rho_S} + \varepsilon_n$ as appears for set estimators in Theorem 2.1.

We introduce the function

$$(3.3) \quad \phi(\rho, t) := \sup_{\int_S |\eta| \leq 3(t + \sqrt{t\rho_S})} \int_S |\eta|, \quad 0 < t \leq 1,$$

where now in this definition, we allow arbitrary measurable sets S (not necessarily from \mathcal{S}). Under our assumption on the form of e_n , we have $\omega(\rho, e_n) \leq \phi(\rho, \varepsilon_n)$, and so the decay of ϕ gives us a bound on the decay of ω . We say that ρ satisfies the ϕ -condition of order $s > 0$ if

$$(3.4) \quad \phi(\rho, t) \leq C_0 t^s, \quad 0 < t \leq 1$$

for some constants C_0 and $s > 0$.

LEMMA 3.1. *Suppose that ρ is a measure that satisfies (1.4) for a given value of $0 \leq \alpha \leq \infty$. Then ρ satisfies the ϕ -condition (3.4) for $s = \frac{1+\alpha}{2+\alpha}$ with C_0 depending only on C_α and α . Conversely, if ρ satisfies the ϕ -condition with $s = \frac{1+\alpha}{2+\alpha}$ and a constant $C_0 > 0$, then it satisfies (1.4) for the value α with the constant C_α depending only on s and C_0 .*

PROOF. Suppose that ρ satisfies (1.4) for α and constant C_α , which equivalently means that it satisfies (3.1) for $\gamma := \frac{\alpha}{1+\alpha}$ and a constant C_γ . To check that the ϕ -condition is satisfied for $s = \frac{1+\alpha}{2+\alpha} = \frac{1}{2-\gamma}$, we let $t \in (0, 1]$ be

fixed and let S be such that $\int_S |\eta| \leq 3(\sqrt{t\rho_S} + t)$. From (3.1),

$$(3.5) \quad \rho_S \leq C_\gamma \left(\int_S |\eta| \right)^\gamma \leq C_\gamma 3^\gamma (\sqrt{t\rho_S} + t)^\gamma.$$

From this, one easily derives

$$(3.6) \quad \rho_S \leq Mt^{\gamma/(2-\gamma)},$$

with a constant M depending only on C_γ and γ . To see this, suppose to the contrary that for some (arbitrarily large) constant M

$$(3.7) \quad \rho_S > Mt^{\gamma/(2-\gamma)}.$$

Rewriting (3.5) as

$$\rho_S^{(2-\gamma)/(2\gamma)} \leq C_\gamma^{1/\gamma} 3(t^{1/2} + t\rho_S^{-1/2}),$$

and using (3.7) to estimate ρ_S on both sides from below, we obtain

$$M^{(2-\gamma)/(2\gamma)} t^{1/2} \leq C_\gamma^{1/\gamma} 3(t^{1/2} + M^{-1/2} t^{(4-3\gamma)/(4-2\gamma)}).$$

Since $0 < \gamma \leq 1$, we have $\frac{4-3\gamma}{4-2\gamma} \geq \frac{1}{2}$, which yields

$$t^{1/2} \leq M^{-(2-\gamma)/(2\gamma)} C_\gamma^{1/\gamma} 3(1 + M^{-1/2}) t^{1/2}.$$

When M is chosen large enough, we have $M^{-(2-\gamma)/(2\gamma)} C_\gamma^{1/\gamma} 3(1 + M^{-1/2}) < 1$ which is a contradiction thereby proving (3.6).

It follows from (3.5) and (3.6) that

$$(3.8) \quad \int_S |\eta| \leq 3(t + \sqrt{t\rho_S}) \leq 3(t + Mt^{1/(2-\gamma)}) \leq C_0 t^{1/(2-\gamma)},$$

where C_0 depends on C_γ and γ . Taking now a supremum over all such sets S gives

$$(3.9) \quad \phi(\rho, t) \leq C_0 t^s, \quad s = \frac{1}{2-\gamma},$$

which is the desired inequality.

We now prove the converse. Suppose that ρ satisfies the ϕ -condition of order $s = \frac{1+\alpha}{2+\alpha}$ with constant C_0 . We want to show that

$$(3.10) \quad \rho_X \{x : |\eta(x)| \leq h\} \leq C_\alpha h^\alpha, \quad 0 \leq h \leq 1,$$

with C_α depending only on s and C_0 . As we noted before, this is equivalent to condition (3.1) of order $\gamma = \frac{\alpha}{\alpha+1}$. To prove (3.10), it is enough to prove

$$(3.11) \quad \rho_X \{x : h/2 \leq |\eta(x)| \leq h\} \leq C'_\alpha h^\alpha, \quad 0 < h \leq 1,$$

since then (3.10) follows easily by a summation argument. We fix h and define $S := \{x : h/2 \leq |\eta(x)| \leq h\}$ and $t := h^2 \rho_S \in (0, 1]$. Then we have

$$(3.12) \quad \int_S |\eta| \leq h \rho_S = \sqrt{t \rho_S}.$$

This means that S is an admissible set in the definition of $\phi(\rho, t)$ in (3.3). Hence from the ϕ -condition (3.4), we know

$$(3.13) \quad h \rho_S / 2 \leq \int_S |\eta| \leq \phi(\rho, t) \leq C_0 t^s = C_0 (h^2 \rho_S)^s.$$

In other words, we have

$$(3.14) \quad \rho_S \leq (2C_0)^{1/(1-s)} h^{(2s-1)/(1-s)} = (2C_0)^{1/(1-s)} h^\alpha,$$

which completes the proof. \square

REMARK 3.2. The purpose of this section is to show the connection of the modulus $\omega(\rho, e_n)$ with the existing and well-studied margin conditions. However, the estimates for performance given in (2.13) can be applied without any specific assumption such as a margin condition, which corresponds to the case $\gamma = 0$. One could also examine other types of bounds for $\phi(\rho, t)$ than the power bound (3.4) and obtain similar results.

4. Bounds for the approximation error $a(\Omega^*, \mathcal{F})$. The approximation error $a(\Omega^*, \mathcal{S})$ depends on ρ and the richness of the collection \mathcal{S} . A typical setting starts with a nested sequence $(\mathcal{S}_m)_{m \geq 1}$ of families of sets, that is such that $\mathcal{S}_m \subset \mathcal{S}_{m+1}$ for all $m \geq 1$. The particular value of m and the collection \mathcal{S}_m that is used for a given draw of the data depends on n and properties of ρ (such as the smoothness of η and margin conditions) and is usually chosen through some form of model selection as discussed further. In order to analyze the performance of such classification algorithms, we would like to know conditions on ρ that govern the behavior of the approximation error as $m \rightarrow \infty$. We study results of this type in this section.

The error

$$(4.1) \quad a_m(\rho) := a(\Omega^*, \mathcal{S}_m), \quad m \geq 1,$$

is monotonically decreasing. We define the approximation class $\mathcal{A}^s = \mathcal{A}^s((\mathcal{S}_m)_{m \geq 1})$ as the set of all ρ for which

$$(4.2) \quad |\rho|_{\mathcal{A}^s} := \sup_{m \geq 1} m^s a_m(\rho)$$

is finite. Our goal is to understand what properties of ρ guarantee membership in \mathcal{A}^s . In this section, we give sufficient conditions for ρ to be in

an approximation classes \mathcal{A}^s for both set estimators and plug-in estimators. These conditions involve the smoothness (or approximability) of η and margin conditions.

Given a measure ρ , it determines the regression function η and the Bayes set $\Omega^* := \{x : \eta(x) > 0\}$. We fix such a ρ , and for each $t \in \mathbb{R}$, we define the level set $\Omega(t) := \{x : \eta(x) \geq t\}$. Notice that $\Omega(t) \subset \Omega(t')$ if $t \geq t'$. Also,

$$(4.3) \quad \{x : |\eta(x)| < t\} \subset \Omega(-t) \setminus \Omega(t) \subset \{x : |\eta(x)| \leq t\}.$$

For each $m = 1, 2, \dots$, we define

$$(4.4) \quad t_m := t_m(\rho, \mathcal{S}_m) := \inf\{t > 0 : \exists S \in \mathcal{S}_m \text{ s.t. } \Omega(t) \subset S \subset \Omega(-t)\}.$$

For convenience, we assume that there is always an $S_m^* \in \mathcal{S}_m$ such that $\Omega(t_m) \subset S_m^* \subset \Omega(-t_m)$. [If no such set exists then one replaces t_m by $t_m + \varepsilon$ with $\varepsilon > 0$ arbitrarily small and arrives at the same conclusion (4.6) given below.] It follows that

$$(4.5) \quad \Omega^* \Delta S_m^* \subset \Omega(-t_m) \setminus \Omega(t_m).$$

If ρ satisfies the margin condition (1.4), then

$$(4.6) \quad a_m(\rho) \leq \int_{\Omega^* \Delta S_m^*} |\eta| d\rho_X \leq C_\alpha t_m \cdot t_m^\alpha = C_\alpha t_m^{\alpha+1}.$$

Thus a sufficient condition for ρ to be in \mathcal{A}^s is that $t_m^{\alpha+1} \leq Cm^{-s}$.

The following example illustrates how the margin condition (1.4) combined with Hölder smoothness of the regression function implies that ρ belongs to the approximation class \mathcal{A}^s where s depends on the margin and smoothness parameters. To be specific, let $X = [0, 1]^d$. Let \mathcal{D} be the collection of dyadic cubes Q contained in X , that is, cubes $Q \subset X$ of the form $Q = 2^{-j}(k + [0, 1]^d)$ with $k \in \mathbb{Z}^d$ and $j \in \mathbb{Z}$. Let \mathcal{D}_j , $j = 0, 1, \dots$, be the collection of dyadic cubes of sidelength 2^{-j} . Let $\mathcal{S}_{2^{dj}}$ be the collection of all sets of the form $S_\Lambda = \bigcup_{Q \in \Lambda} Q$, where $\Lambda \subset \mathcal{D}_j$. This corresponds to the family \mathcal{S} considered in Remark 2.5 for $m = 2^{jd}$. In fact, $\#(\mathcal{D}_j) = 2^{jd}$ and $\#(\mathcal{S}_{2^{dj}}) = 2^{2^{jd}}$. We complete the family $(\mathcal{S}_m)_{m \geq 1}$ by setting $\mathcal{S}_m = \mathcal{S}_{2^{dj}}$ when $2^{dj} \leq m < 2^{d(j+1)}$.

PROPOSITION 4.1. *We assume that ρ has the two following properties:*

(i) *the regression function η is in the Lipschitz (or Hölder) space C^β for some $0 < \beta \leq 1$, that is,*

$$|\eta|_{C^\beta} := \sup\{|\eta(x) - \eta(\tilde{x})| : |x - \tilde{x}|^{-\beta} : x, \tilde{x} \in X\} < \infty;$$

(ii) *ρ satisfies the margin condition (1.4).*

Then one has

$$(4.7) \quad \rho \in \mathcal{A}^s = \mathcal{A}^s((\mathcal{S}_m)_{m \geq 1}) \quad \text{with } s := \frac{\beta(\alpha + 1)}{d}.$$

PROOF. We claim that

$$(4.8) \quad a_{2^{dj}}(\rho) \leq (M2^{-j\beta})^{\alpha+1}, \quad j \geq 0,$$

with $M := 2^{-\beta}d^{\beta/2}|\eta|_{C^\beta}$. To this end, we first note that when $Q \in \mathcal{D}_j$, and ξ_Q is the center of Q , then

$$(4.9) \quad |\eta(x) - \eta(\xi_Q)| \leq M2^{-j\beta}.$$

We define $S_j \in \mathcal{S}_{2^{dj}}$ as the union of all $Q \in \mathcal{D}_j$ for which $\eta(\xi_Q) \geq 0$. If $t := M2^{-j\beta}$, then we claim that

$$(4.10) \quad \Omega(t) \subset S_j \subset \Omega(-t), \quad j \geq 0.$$

For example, if $x \in \Omega(t)$, then $\eta(x) \geq t$. So, if $x \in Q$, then $\eta(\xi_Q) \geq 0$ and hence $Q \subset S_j$. Similarly, if $x \in Q \subset S_j$, then $\eta(\xi_Q) \geq 0$ and hence $\eta(x) \geq -t$ for all $x \in Q$, and this implies the right containment in (4.10). \square

It is well known that margin and smoothness conditions are coupled, in the sense that higher values of α force the regression function to have a sharper transition near the Bayes boundary, therefore putting restrictions on its smoothness. As an example, assume that ρ_X is bounded from below by the Lebesgue measure, that is, there exists a constant $c > 0$ such that for any $S \in \mathcal{S}$,

$$\rho_X(S) \geq c|S| = c \int_S dx.$$

In the most typical setting, the Bayes boundary $\partial\Omega^*$ is a $(d-1)$ -dimensional surface of nonzero \mathcal{H}^{d-1} Hausdorff measure. If $\eta \in C^\beta$ with $0 \leq \beta \leq 1$, then $|\eta(x)|$ is smaller than t at any point x which is at distance less than $|\eta|_{C^\beta}^{1/\beta} t^{1/\beta}$ from this boundary. It follows that

$$\rho_X\{x \in X : |\eta(x)| \leq t\} \geq c_0 t^{1/\beta},$$

where c_0 depends on $\mathcal{H}^{d-1}(\partial\Omega^*)$ and $|\eta|_{C^\beta}$, showing that $\alpha\beta \leq 1$. In such a case the approximation rate is therefore limited by $s \leq \frac{1+\beta}{d}$.

As observed in [2] one can break this constraint either by considering pathological examples, such as regression functions that satisfy $\mathcal{H}^{d-1}(\partial\Omega^*) = 0$, or by considering marginal measures ρ_X that vanish in the vicinity of the Bayes boundary. We show in Section 6 that this constraint can also be broken when the Hölder spaces C^β are replaced by the Besov spaces $B_\infty^\beta(L_p)$, defined by (1.8), that govern the approximation rate when $\mathcal{S}_{2^{dj}}$ is replaced by a collection of adaptive partitions.

5. Risk performance and model selection. In this section, we combine our previous bounds for approximation and estimation errors in order to obtain an estimate for risk performance of classification schemes.

Let us assume that we have a sequence $(\mathcal{S}_m)_{m \geq 1}$ of families \mathcal{S}_m of sets that are used to develop a binary classification algorithm. We suppose that for some constant C_0 ,

$$(5.1) \quad VC(\mathcal{S}_m) \leq C_0 m, \quad m \geq 1,$$

and we denote by $\bar{\Omega}_m$ the empirical risk minimization classifier picked in \mathcal{S}_m according to (2.1) with $\hat{\eta}_S = \bar{\eta}_S$. Theorem 2.1 gives that such an estimator provides a bound (2.6) with

$$e_n(S) = \sqrt{\rho_S \Delta \Omega_S \varepsilon_n} + \varepsilon_n, \quad \varepsilon_n = C \frac{m \log n}{n}$$

and C depending only on r and C_0 . If $\rho \in \mathcal{A}^s((\mathcal{S}_m)_{m \geq 1})$, for some $s > 0$, then according to Corollary 2.4, for any $m \geq 1$, we have with probability $1 - n^{-r}$,

$$(5.2) \quad R(\bar{\Omega}_m) - R(\Omega^*) \leq \omega(\rho, e_n) + 2|\rho|_{\mathcal{A}^s} m^{-s}.$$

If in addition ρ satisfies the margin condition (1.4) of order $\alpha > 0$, then using Lemma 3.1 and the fact that $\omega(\rho, e_n) \leq C\phi(\rho, \varepsilon_n) \leq C\varepsilon_n^{(1+\alpha)/(2+\alpha)}$, we obtain

$$(5.3) \quad R(\bar{\Omega}_m) - R(\Omega^*) \leq C \left(\frac{m \log n}{n} \right)^{(1+\alpha)/(2+\alpha)} + 2|\rho|_{\mathcal{A}^s} m^{-s},$$

where C depends on $|\rho|_{\mathcal{M}^\alpha}$. If we balance the two terms appearing on the right in (5.3) by taking $m = \left(\frac{n}{\log n} \right)^{(1+\alpha)/((2+\alpha)s+1+\alpha)}$, we obtain that, with probability at least $1 - n^{-r}$,

$$(5.4) \quad R(\bar{\Omega}_m) - R(\Omega^*) \leq C \left(\frac{\log n}{n} \right)^{((1+\alpha)s)/((2+\alpha)s+1+\alpha)},$$

where C depends on $|\rho|_{\mathcal{M}^\alpha}$ and $|\rho|_{\mathcal{A}^s}$. The best rates that one can obtain from the above estimate correspond to $\alpha = \infty$ (Massart's condition) and $s \rightarrow \infty$ (the regression function η has arbitrarily high smoothness), and are limited by the so-called fast rate $\mathcal{O}\left(\frac{\log n}{n}\right)$.

To obtain the bound (5.4), we need to know both s and α in order to make the optimal choice of m and \mathcal{S}_m . Of course, these values are not known to us, and to circumvent this we employ a standard model selection technique based on an independant validation sample.

Model selection. Let $(\mathcal{S}_m)_{m \geq 1}$ be any collection of set estimators. For notational convenience, we assume that n is even, that is, $n = 2\bar{n}$. Given the draw \mathbf{z} , we divide \mathbf{z} into two independent sets \mathbf{z}' and \mathbf{z}'' of equal size \bar{n} .

Step 1. For each $1 \leq m \leq \bar{n}$, we let $\bar{\Omega}_m$ be defined by (2.1) with $\mathcal{S} = \mathcal{S}_m$ and \mathbf{z} replaced by \mathbf{z}' .

Step 2. We now let $\bar{\mathcal{S}} := \{\bar{\Omega}_1, \dots, \bar{\Omega}_{\bar{n}}\}$ and let $\hat{\Omega} := \bar{\Omega}_{m^*}$ be the set chosen from $\bar{\mathcal{S}}$ by (2.1) when using \mathbf{z}'' .

The set $\hat{\Omega}$ is our empirical approximation of Ω^* obtained by this model selection procedure. To see how well it performs, let us now assume that $\rho \in \mathcal{A}^s$ and that ρ also satisfies the margin condition (1.4) for α . In step 1, we know that for each m , $\bar{\Omega}_m$ satisfies (5.3) with n replaced by \bar{n} with probability at least $1 - \bar{n}^{-r}$. Thus, with probability $1 - c\bar{n}^{-r+1}$, we have

$$(5.5) \quad R(\bar{\Omega}_m) - R(\Omega^*) \leq C \left(m^{-s} + \left(\frac{m \log n}{n} \right)^{(1+\alpha)/(2+\alpha)} \right),$$

$m = 1, \dots, \bar{n}.$

It follows that for $\bar{\mathcal{S}}$ of step 2, we have

$$a(\Omega^*, \bar{\mathcal{S}}) = \min_{1 \leq m \leq \bar{n}} \int_{\bar{\Omega}_m \triangle \Omega^*} |\eta| d\rho_X \leq C \min_{1 \leq m \leq \bar{n}} \left\{ m^{-s} + \left(\frac{m \log n}{n} \right)^{(1+\alpha)/(2+\alpha)} \right\}.$$

Since $\#(\bar{\mathcal{S}}) = \bar{n} = n/2$, we can take $\varepsilon_n \leq C \frac{\log n}{n}$ in Remark 2.2 and a suitable constant C when bounding performance on $\bar{\mathcal{S}}$. Hence, from Corollary 2.4, we have for the set $\hat{\Omega}$ given by step 2,

$$\begin{aligned} R(\hat{\Omega}) - R(\Omega^*) &\leq 2a(\Omega^*, \bar{\mathcal{S}}) + C \left(\frac{\log n}{n} \right)^{(1+\alpha)/(2+\alpha)} \\ &\leq C \min_{1 \leq m \leq \bar{n}} \left\{ m^{-s} + \left(\frac{m \log n}{n} \right)^{(1+\alpha)/(2+\alpha)} \right\} \\ &\quad + C \left(\frac{\log n}{n} \right)^{(1+\alpha)/(2+\alpha)}. \end{aligned}$$

In estimating the minimum, we choose m that balances the two terms and obtain

$$(5.6) \quad R(\hat{\Omega}) - R(\Omega^*) \leq C \left(\frac{\log n}{n} \right)^{((1+\alpha)s)/((2+\alpha)s+1+\alpha)}.$$

Thus, the set $\hat{\Omega}$, while not knowing α and s gives the same estimate we obtained earlier when assuming we knew α and s .

REMARK 5.1. Note that we have done our model selection without using a penalty term. The use of a penalty term would have forced us to know the value of α in (3.1). A discussion of why penalty approaches may still be of interest in practice can be found in [5].

A simple application of (5.6) and Proposition 4.1 gives an estimate in the general case. In the case of Remark 2.5 one has $\omega(\rho, e_n) \leq C\varepsilon_n^{(\alpha+1)/2}$ and can balance the terms in the estimate corresponding to (5.6) by taking $m := (\frac{n}{(\log n)^{1/(2+d)}})^{d/(2\beta+d)}$. These give the following result.

COROLLARY 5.2. *Let $(\mathcal{S}_m)_{m \geq 1}$ be the sequence of family of sets built from uniform partitions as are used in Proposition 4.1.*

(i) *Assume that ρ satisfies the margin condition (1.4) of order α and that η is Hölder continuous of order β . Then the classifier resulting from the above model selection satisfies*

$$(5.7) \quad \text{Prob} \left\{ R(\bar{\Omega}_{m^*}) - R(\Omega^*) \leq C \left(\frac{\log n}{n} \right)^{((1+\alpha)\beta)/((2+\alpha)\beta+d)} \right\} \geq 1 - Cn^{-r},$$

where C depends on $r, |\rho|_{\mathcal{M}^\alpha}, |\eta|_{C^\beta}$.

(ii) *If one assumes in addition that ρ_X is equivalent to the Lebesgue measure, one obtains*

$$(5.8) \quad \text{Prob} \left\{ R(\bar{\Omega}_{m^*}) - R(\Omega^*) \leq C \left(\frac{(\log n)^{1/(2+d)}}{n} \right)^{((1+\alpha)\beta)/((2+\alpha)\beta)} \right\} \geq 1 - Cn^{-r}.$$

Case (ii) illustrates the improvement of the rates that results from constraining the marginal ρ_X . In view of our earlier comments on the conflict between margin and Hölder smoothness conditions of high order, the main deficiency of both results is the underlying strong assumption of Hölder smoothness. The sequence $(\mathcal{S}_m)_{m \geq 1}$ is based on uniform partitions and does not allow us to exploit weaker Besov-smoothness conditions. In what follows, we remedy this defect by turning to classification algorithms based on *adaptive* partitioning. In doing so, we avoid any a priori constraints on ρ_X and hence use the set function e_n given by (2.5).

6. Classification using tree based adaptive partitioning. One of the most natural ways to try to capture Ω^* is through adaptive partitioning. Indeed, such partitioning methods have the flexibility to give fine scale approximation near the boundary of Ω^* but remain coarse away from the boundary. We now give two examples. The first is based on simple dyadic tree partitioning,

while the second adds wedge ornatation on the leaves of the tree to enhance risk performance. For simplicity of presentation, we only consider dyadic partitioning on the specific domain $X = [0, 1]^d$, even though our analysis covers far greater generality.

Algorithm I: Dyadic tree partitioning. We recall the dyadic cubes \mathcal{D} introduced in Section 4. These cubes organize themselves into a tree with root X . Each $Q \in \mathcal{D}_j$ has 2^d children which are its dyadic subcubes from \mathcal{D}_{j+1} . A finite subtree \mathcal{T} of \mathcal{D} is a finite collection of cubes with the property that the root X is in \mathcal{T} , and whenever $Q \in \mathcal{T}$ its parent is also in \mathcal{T} . We say a tree is *complete* if, whenever Q is in \mathcal{T} , then all of its siblings are also in \mathcal{T} . The set $\mathcal{L}(\mathcal{T})$ of leaves of such a tree \mathcal{T} consists of all the cubes $Q \in \mathcal{T}$ such that no child of Q is in \mathcal{T} . The set of all such leaves of a complete tree forms a partition of X .

Any finite complete tree is the result of a finite number of successive cube refinements. We denote by \mathfrak{T}_m the collection of all complete trees \mathcal{T} that can be obtained using m refinements. Any such tree $\mathcal{T} \in \mathfrak{T}_m$ has $(2^d - 1)m + 1$ leaves. We can bound the number of trees in \mathfrak{T}_m by assigning a bitstream that encodes, that is, precisely determines, \mathcal{T} as follows. Let $\mathcal{T} \in \mathfrak{T}_m$. We order the children of X lexicographically and assign a one to every child which is refined in \mathcal{T} and a zero otherwise. We now consider the next generation of cubes (i.e., the grandchildren of X) in \mathcal{T} . We know these grandchildren from the bits already assigned. We arrange the grandchildren lexicographically and again assign them a one if they are refined in \mathcal{T} and a zero otherwise. We continue in this way and receive a bitstream which exactly determines \mathcal{T} . Since \mathcal{T} has exactly $2^d m + 1$ cubes, every such bitstream has length $2^d m$ and has a one in exactly $m - 1$ positions. Hence we have

$$(6.1) \quad \#(\mathfrak{T}_m) \leq \binom{2^d m}{m-1} \leq \frac{(2^d m)^m}{(m-1)!} \leq e^m 2^{dm}.$$

For each $\mathcal{T} \in \mathfrak{T}_m$ and any $\Lambda \subset \mathcal{L}(\mathcal{T})$, we define $S = S_\Lambda := \bigcup_{Q \in \Lambda} Q$. We denote by \mathcal{S}_m the collection of all such sets S that can be obtained from a $\mathcal{T} \in \mathfrak{T}_m$ and some choice of Λ . Once \mathcal{T} is chosen, there are $2^{\#\mathcal{L}(\mathcal{T})} \leq 2^{2^d m}$ choices for Λ . Hence

$$(6.2) \quad \#(\mathcal{S}_m) \leq a^m$$

with $a := e2^{d+2^d}$.

Given our draw \mathbf{z} , we use the set estimator and model selection over $(\mathcal{S}_m)_{m \geq 1}$ as described in the previous section. We discuss the numerical implementation of this algorithm in Section 7. This results in a set $\overline{\Omega}(\mathbf{z})$, and we have the following theorem for its performance.

THEOREM 6.1. (i) *For any $r > 0$, there is a constant $c > 0$ such that the following holds. If $\rho \in \mathcal{A}^s$, $s > 0$ and ρ satisfy the margin condition (1.4), then with probability greater than $1 - cn^{-r+1}$, we have*

$$(6.3) \quad R(\overline{\Omega}(\mathbf{z})) - R(\Omega^*) \leq C \left(\frac{\log n}{n} \right)^{((1+\alpha)s)/((2+\alpha)s+1+\alpha)}$$

with C depending only on d, r , $|\rho|_{\mathcal{A}^s}$ and the constant in (1.4).

(ii) *If $\eta \in B_\infty^\beta(L_p(X))$ with $0 < \beta \leq 1$ and $p > d/\beta$ and if ρ satisfies the margin condition (1.4), then with probability greater than $1 - cn^{-r+1}$, we have*

$$(6.4) \quad R(\overline{\Omega}(\mathbf{z})) - R(\Omega^*) \leq C \left(\frac{\log n}{n} \right)^{((1+\alpha)\beta)/((2+\alpha)\beta+d)},$$

with C depending only on d, r , $|\eta|_{B_\infty^\beta(L_p(X))}$ and the constant in (1.4).

PROOF. Since $\log(\#(\mathcal{S}_m)) \leq C_0 m$ where C_0 depends only on d , we have that $R(\Omega(\mathbf{z})) - R(\Omega^*)$ is bounded by the right-hand side of (5.6) which proves (i). We can derive (ii) from (i) if we prove that the assumptions on ρ in (ii) imply that $\rho \in \mathcal{A}^s$, $s = \frac{(\alpha+1)\beta}{d}$. To see that this is the case, we consider the approximation of η by piecewise constants subordinate to partitions $\mathcal{L}(\mathcal{T})$, $\mathcal{T} \in \mathfrak{T}_m$. It is known (see [10]) that the Besov space assumption on η implies that there is a tree \mathcal{T}_m and piecewise constant η_m on $\mathcal{L}(\mathcal{T}_m)$ that satisfies $\|\eta - \eta_m\|_{L_\infty} \leq \delta_m = C_1 |\eta|_{B_\infty^\beta(L_p)} m^{-\beta/d}$ with C_1 depending on p, β and d . Let $\Lambda := \{Q \in \mathcal{L}(\mathcal{T}_m) : \eta_m(x) > 0, x \in Q\}$ and $\Omega_m := \bigcup_{Q \in \Lambda_m} Q$. Then $\Omega_m \in \mathcal{S}_m$ and $\Omega_m \triangle \Omega^* \subset \{x : |\eta(x)| \leq \delta_m\}$, and so

$$(6.5) \quad a_m(\rho) \leq \int_{\Omega_m \triangle \Omega^*} |\eta| d\rho_X \leq C_\alpha \delta_m^{\alpha+1} \leq C_\alpha (C_1 |\eta|_{B_\infty^\beta(L_p)})^{\alpha+1} m^{-s},$$

as desired. \square

Algorithm II: Higher order methods via decorated trees. We want to remove the restriction $\beta \leq 1$ that appears in Theorem 6.1 by enhancing the family of sets \mathcal{S}_m of the previous section. This enhancement can be accomplished by choosing, for each $Q \in \mathcal{L}(\mathcal{T})$, a subcell of Q obtained by a hyperplane cut (henceforth called an *H-cell*) and then taking a union of such subcells. To describe this, we note that, given a dyadic cube Q , any $(d-1)$ -dimensional hyperplane H partitions Q into at most two disjoint sets Q_0^H and Q_1^H which are the intersections of Q with the two open half spaces generated by the hyperplane cut. By convention we include $Q \cap H$ in Q_0^H . Given a tree $\mathcal{T} \in \mathfrak{T}_m$, we denote by $\zeta_{\mathcal{T}}$ any mapping that assigns to

each $Q \in \mathcal{L}(\mathcal{T})$ an H-cell $\zeta_{\mathcal{T}}(Q)$. Given such a collection $\{\zeta_{\mathcal{T}}(Q)\}_{Q \in \mathcal{L}(\mathcal{T})}$, we define

$$S := S(\mathcal{T}, \zeta) := \bigcup_{Q \in \mathcal{L}(\mathcal{T})} \zeta_{\mathcal{T}}(Q).$$

For any given tree \mathcal{T} , we let $\mathcal{S}_{\mathcal{T}}$ be the collection of all such sets that result from arbitrary choices of ζ . For any $m \geq 1$, we define

$$(6.6) \quad \mathcal{S}_m := \bigcup_{\mathcal{T} \in \mathfrak{T}_m} \mathcal{S}_{\mathcal{T}}.$$

Thus any such $S \in \mathcal{S}_m$ is the union of H-cells of the $Q \in \mathcal{L}(\mathcal{T})$, with one H-cell chosen for each $Q \in \mathcal{L}(\mathcal{T})$. Clearly \mathcal{S}_m is infinite, however, the following lemma shows that \mathcal{S}_m has finite VC dimension.

LEMMA 6.2. *If $\Gamma_1, \dots, \Gamma_N$ are each collections of sets from X with VC dimension $\leq k$, then the collection $\Gamma := \bigcup_{i=1}^N \Gamma_i$ has VC dimension not greater than $\max\{8 \log N, 4k\}$.*

PROOF. We follow the notation of Section 9.4 in [12]. Let us consider any set of points p_1, \dots, p_L from X . Then from Theorem 9.2 in [12], the shattering number of Γ for this set of point satisfies

$$s(\Gamma, \{p_1, \dots, p_L\}) \leq \sum_{i=0}^k \binom{L}{i} =: \Phi(k, L)$$

and therefore

$$s(\Gamma, \{p_1, \dots, p_L\}) \leq N\Phi(k, L).$$

By Hoeffding's inequality, if $k \leq L/2$, we have $2^{-L}\Phi(k, L) \leq \exp(-2L\delta^2)$ with $\delta := \frac{1}{2} - \frac{k}{L}$. It follows that if $L > \max\{8 \log N, 4k\}$, we have

$$s(\Gamma, \{p_1, \dots, p_L\}) < 2^L N \exp(-L/8) < 2^L,$$

which shows that $\text{VC}(\Gamma) \leq \max\{8 \log N, 4k\}$. \square

We apply Lemma 6.2 with the role of the Γ_j being played by the collection $\mathcal{S}_{\mathcal{T}}$, $\mathcal{T} \in \mathfrak{T}_m$. As shown in (6.1), we have $N = \#\{\mathfrak{T}_m\} \leq e^m 2^{dm}$. We note next that the VC dimension of each $\mathcal{S}_{\mathcal{T}}$ is given by

$$(6.7) \quad \text{VC}(\mathcal{S}_{\mathcal{T}}) = (d+1)\#\{\mathcal{L}(\mathcal{T})\} \leq (d+1)2^d m.$$

In fact, given \mathcal{T} placing $d+1$ points in every $Q \in \mathcal{L}(\mathcal{T})$ shows that $(d+1)\#\{\mathcal{L}(\mathcal{T})\}$ points can be shattered since $d+1$ points can be shattered by hyperplanes in \mathbb{R}^d . No matter how one distributes more than $(d+1)\#\{\mathcal{L}(\mathcal{T})\}$ points in X , at least one $Q \in \mathcal{L}(\mathcal{T})$ contains more than $d+1$ points. These

points can no longer be shattered by a hyperplane which confirms (6.7). Lemma 6.2 now says that

$$(6.8) \quad \text{VC}(\mathcal{S}_m) \leq \max\{8(d+2)m, 4(d+1)2^d m\} = C_d m,$$

where $C_d := \max\{8(d+2), 4(d+1)2^d\}$.

Given our draw \mathbf{z} , we use the set estimator and model selection as described in Section 5 with \mathcal{S}_m now given by (6.6). This results in a set $\bar{\Omega}(\mathbf{z})$, and we have the following theorem for the performance of this estimator.

THEOREM 6.3. (i) *For any $r > 0$, there is a constant $c > 0$ such that the following holds. If $\rho \in \mathcal{A}^s$, $s > 0$ and ρ satisfy margin condition (1.4), then with probability greater than $1 - cn^{-r+1}$, we have*

$$(6.9) \quad R(\bar{\Omega}(\mathbf{z})) - R(\Omega^*) \leq C \left(\frac{\log n}{n} \right)^{((1+\alpha)s)/((2+\alpha)s+1+\alpha)}$$

with C depending only on $d, r, |\rho|_{\mathcal{A}^s}$ and the constant in (1.4).

(ii) *If $\eta \in B_\infty^\beta(L_p(X))$ with $0 < \beta \leq 2$ and $p > d/\beta$ and if ρ satisfies the margin condition (3.1), then with probability greater than $1 - cn^{-r+1}$, we have*

$$(6.10) \quad R(\bar{\Omega}(\mathbf{z})) - R(\Omega^*) \leq C \left(\frac{\log n}{n} \right)^{((1+\alpha)\beta)/((2+\alpha)\beta+d)},$$

with C depending only on $d, r, |\eta|_{B_\infty^\beta(L_p(X))}$ and the constant in (1.4).

PROOF. In view of (6.8) we can invoke Theorem 2.1 with $\varepsilon_n = Cm \log n/n$, where C depends on d and r , to conclude that $e_n(S) = \sqrt{\rho_S \Delta \Omega_{S_m} \varepsilon_n} + \varepsilon_n$ satisfies (2.6) and hence is an admissible set function for the modulus (2.7). Now (i) follows from (5.6).

To derive (ii) from (i), we prove that the assumptions on ρ in (ii) imply that $\rho \in \mathcal{A}^s$, $s = \frac{(\alpha+1)\beta}{d}$, for $\beta \in (0, 2]$. To see that this is the case, we consider the approximation of η by piecewise linear functions subordinate to partitions $\mathcal{L}(\mathcal{T})$, $\mathcal{T} \in \mathfrak{T}_m$. It is known (see [9]) that the Besov space assumption on η implies that there is a tree \mathcal{T}_m and a piecewise linear function η_m on $\mathcal{L}(\mathcal{T}_m)$ that satisfies $\|\eta - \eta_m\|_{L_\infty} \leq \delta_m = C_1 |\eta|_{B_\infty^\beta(L_p(X))} m^{-\beta/d}$. Now for any cube Q consider the H-cell mapping $\zeta_{\mathcal{T}}(Q) := \{x \in Q : \eta_m(x) \geq 0\}$. Then

$$\Omega_m := \bigcup_{Q \in \mathcal{L}(\mathcal{T})} \zeta_{\mathcal{T}}(Q)$$

is in \mathcal{S}_m and $\Omega_m \Delta \Omega^* \subset \{x : |\eta(x)| \leq \delta_m\}$ so that

$$(6.11) \quad a_m(\rho) \leq \int_{\Omega_m \Delta \Omega^*} |\eta| d\rho_X \leq C_\alpha \delta_m^{\alpha+1} \leq C_\alpha (C_1 |\eta|_{B_\infty^\beta(L_p)})^{\alpha+1} m^{-s},$$

as desired. \square

REMARK 6.4. It is, in theory, possible to further extend the range of β by considering more general decorated trees, where for each considered cube Q , we use an algebraic surface A of degree $k > 1$ instead of a hyperplane H that corresponds to the case $k = 1$. The resulting families \mathcal{S}_m consist of level sets of piecewise polynomials of degree k on adaptive partitions obtained by m splits. From this one easily shows that the corresponding VC dimension is again controlled by m (with multiplicative constants now depending both on d and k) and that (6.10) now holds for all $0 < \beta \leq k + 1$. However, the practical implementation of such higher order classifiers appears to be difficult.

We have seen in Section 5 that the approximation rate for nonadaptive partitioning is also given by $s = \frac{\beta(\alpha+1)}{d}$, but with β denoting the smoothness of η in the sense of the Hölder space C^β . The results established in this section show that the same approximation rate is obtained under the weaker constraint that $\eta \in B_\infty^\beta(L_p)$ with $p > d/\beta$ if we use adaptive partitioning.

We also observed in Section 5 that the Hölder smoothness β and the parameter α in the margin condition are coupled, for example, by the restriction $\alpha\beta \leq 1$ when ρ_X is bounded from below by the Lebesgue measure. Replacing the Hölder space C^β by a Besov space $B_\infty^\beta(L_p)$ with $p > d/\beta$ allows us to relax the above constraint. As a simple example consider the case where ρ_X is the Lebesgue measure and

$$\eta(x) = \eta(x_1, \dots, x_d) = \text{sign}(x_1 - 1/2)|x_1 - 1/2|^\delta,$$

for some $0 < \delta \leq 1$, so that $\Omega^* = \{x \in X : x_1 > 1/2\}$, and margin condition (1.4) holds with α up to $1/\delta$. Then one checks that $\eta \in B_\infty^\beta(L_p)$ for β and p such that $\beta \leq \delta + 1/p$. The constraint $1/p < \beta/d$ may then be rewritten as $\beta(1 - 1/d) < \delta$ or equivalently

$$(6.12) \quad \alpha\beta(1 - 1/d) < 1,$$

which is an improvement over $\alpha\beta \leq 1$.

7. Numerical implementation. The results we have presented thus far on adaptive partitioning do not constitute a numerical algorithm since we have not discussed how one would find the sets $\bar{\Omega}_m \in \mathcal{S}_m$ required by (2.1) and used in the model selection. We discuss this issue next.

Given the draw \mathbf{z} , we consider the collection of all dyadic cubes in $\mathcal{D}_0 \cup \dots \cup \mathcal{D}_{\bar{n}}$ with $\bar{n} = n/2$ which contain an x_i , $i = 1, \dots, \bar{n}$. These cubes form a tree $\mathcal{T}'(\mathbf{z})$ which we call the *occupancy tree*. Adding to all such cubes their siblings, we obtain a complete tree $\mathcal{T}(\mathbf{z})$ whose leaves form a partition of X .

Let us first discuss the implementation of Algorithm I. For each complete subtree $\mathcal{T} \subset \mathcal{T}(\mathbf{z})$ we define

$$(7.1) \quad \gamma_{\mathcal{T}} := \sum_{Q \in \mathcal{L}(\mathcal{T})} \max(\bar{\eta}_Q, 0),$$

which we call the *energy* in \mathcal{T} . The set estimator $\bar{\Omega}_m$ corresponds to a complete tree $\bar{\mathcal{T}}_m \in \mathfrak{T}_m$ which maximizes the above energy. Note that several different trees may attain the maximum. Since only the values $m = 1, \dots, \bar{n}$ are considered in the model selection procedure, and since there is no gain in subdividing a nonoccupied cube, a maximizing tree is always a subtree of $\mathcal{T}(\mathbf{z})$.

Further, for each cube $Q \in \mathcal{T}(\mathbf{z})$, we denote by $\mathfrak{T}_m(Q)$ the collection of all complete trees \mathcal{T} with root Q obtained using at most m subdivisions and being contained in $\mathcal{T}(\mathbf{z})$. We then define

$$(7.2) \quad \gamma_{Q,m} = \max_{\mathcal{T} \in \mathfrak{T}_m(Q)} \gamma_{\mathcal{T}}.$$

Again, this maximum may be attained by several trees in $\mathfrak{T}_m(Q)$. In fact, if, for instance, for a maximizer $\mathcal{T} \in \mathfrak{T}_m(Q)$, $\bar{\eta}_R > 0$ holds for all $R \in \mathcal{C}(R') \subset \mathcal{L}(\mathcal{T})$, the children of some parent node $R' \in \mathcal{T}$, then the subtree $\tilde{\mathcal{T}}$ of \mathcal{T} obtained by removing $\mathcal{C}(R')$ from \mathcal{T} , has the same energy. We denote by $\mathcal{T}(Q, m)$ any tree in $\mathfrak{T}_m(Q)$ that attains the maximum $\gamma_{Q,m}$. By convention, we set

$$(7.3) \quad \mathcal{T}(Q, m) = \emptyset,$$

when Q is not occupied. With this notation, we define

$$(7.4) \quad \bar{\mathcal{T}}_m := \mathcal{T}(X, m) \quad \text{and} \quad \bar{\Omega}_m := \bigcup_{Q \in \mathcal{L}(\bar{\mathcal{T}}_m)} \{Q : \bar{\eta}_Q > 0\}$$

to be used in the model selection discussed earlier.

We now describe how to implement the maximization that gives $\bar{\mathcal{T}}_m$ and therefore $\bar{\Omega}_m$. Notice that $\bar{\eta}_Q = \gamma_{Q,m} = 0$ and $\mathcal{T}(Q, m)$ is empty when Q is not occupied, and therefore these values are available to us for free. Thus the computational work in this implementation is solely determined by the occupied cubes that form $\mathcal{T}'(\mathbf{z})$. For $l = 0, \dots, \bar{n}$, we define

$$(7.5) \quad \mathcal{U}_l := \mathcal{T}'(\mathbf{z}) \cap \mathcal{D}_{\bar{n}-l},$$

the set of occupied cubes of resolution level $\bar{n} - l$. Notice that $\mathcal{U}_0 = \mathcal{L}(\mathcal{T}'(\mathbf{z}))$. We work from the leaves of $\mathcal{T}'(\mathbf{z})$ toward the root, in a manner similar to CART optimal pruning (see [8]), according to the following steps:

- $l = 0$: we compute for each $Q \in \mathcal{U}_0$ the quantities $\bar{\eta}_Q$ and define $\gamma_{Q,0} := \max\{0, \bar{\eta}_Q\}$, $\mathcal{T}(Q, 0) := \{Q\}$. This requires at most \bar{n} arithmetic operations.

- For $l = 1, \dots, \bar{n}$: suppose we have already determined the quantities $\gamma_{Q,j}$ and $\bar{\eta}_Q$, as well as the trees $\mathcal{T}(Q, j)$, for all $Q \in \mathcal{U}_{l-1}$ and $0 \leq j \leq l-1$. Recall that $\mathcal{T}(Q, j)$ is a complete subtree. Now for all $0 \leq j \leq l$ and all cubes $Q \in \mathcal{U}_l$, we compute

$$(7.6) \quad (\ell_j^*(R))_{R \in \mathcal{C}'(Q)} := \operatorname{argmax} \left\{ \sum_{R \in \mathcal{C}'(Q)} \gamma_{R, \ell'(R)} : \sum_{R \in \mathcal{C}'(Q)} \ell'(R) = j \right\},$$

where $\mathcal{C}'(Q) := \mathcal{C}(Q) \cap \mathcal{T}'(\mathbf{z})$ denotes the set of occupied children of Q . Notice that the above argmax may not be unique, in which case we can pick any maximizer. We obviously have for each $Q \in \mathcal{U}_l$ and any $1 \leq j \leq l$,

$$(7.7) \quad \gamma_{Q,j} = \sum_{R \in \mathcal{C}'(Q)} \gamma_{R, \ell_{j-1}^*(R)},$$

with

$$\mathcal{T}(Q, j) = \{Q\} \cup \left(\bigcup_{R \in \mathcal{C}'(Q)} \mathcal{T}(R, \ell_{j-1}^*(R)) \right) \cup (\mathcal{C}(Q) \setminus \mathcal{C}'(Q)).$$

For $j = 0$, we compute the $\bar{\eta}_Q$ for all $Q \in \mathcal{U}_l$ by summing the $\bar{\eta}_R$ for $R \in \mathcal{C}'(Q)$ and define $\gamma_{Q,0} = \max\{0, \bar{\eta}_Q\}$ and $\mathcal{T}(Q, 0) = \{Q\}$.

- At the final step $l = \bar{n}$, the set $\mathcal{U}_{\bar{n}}$ consists only of the root X , and we have computed $\mathcal{T}(X, m)$ for $m = 0, \dots, \bar{n}$. This provides the estimators $\bar{\Omega}_m$ for $m = 0, \dots, \bar{n}$.

To estimate the complexity of the algorithm, we need to bound for each $l \in \{1, \dots, \bar{n}\}$ the number of computations required by (7.6) and (7.7). With proper organization, the argmax in (7.6) can be found using at most $\mathcal{O}(\#\mathcal{C}'(Q)l^2)$ operations. We can execute (7.7) with the same order of computation. The total complexity over all levels is therefore at most $\mathcal{O}(n^4)$ [a finer analysis can reduce it to $\mathcal{O}(n^3)$]. Also each optimal tree $\mathcal{T}(Q, m)$ can be recorded with at most dm bits. It should be noted that the complexity with respect to the data size n is independent of the spatial dimension d which only enters when encoding the optimal trees $\mathcal{T}(X, m)$.

We turn now to the implementation of Algorithm II. We denote by \mathcal{H} the set of all $(d-1)$ -dimensional hyperplanes. Using the notation therein, for any subtree \mathcal{T} of $\mathcal{T}(\mathbf{z})$ and any $Q \in \mathcal{L}(\mathcal{T})$, the energy is now defined as

$$(7.8) \quad \gamma_{\mathcal{T}} := \sum_{Q \in \mathcal{L}(\mathcal{T})} \max_{H \in \mathcal{H}, i=0,1} \max\{0, \bar{\eta}_{Q_i^H}\}.$$

The set estimator $\bar{\Omega}_m$ corresponds to a tree $\bar{\mathcal{T}}_m \in \mathfrak{T}_m$ which maximizes the above energy. Similarly to the previous discussion, we define

$$(7.9) \quad \gamma_{Q,0} := \max_{H \in \mathcal{H}, i=0,1} \max\{0, \bar{\eta}_{Q_i^H}\}$$

and define as before $\gamma_{Q,m}$ and $\mathcal{T}(Q,m)$ by (7.2) and (7.4).

The procedure of determining the trees $\mathcal{T}(X,m)$ for $m = 0, \dots, k$ is then, in principle, the same as above, however with a significant distinction due to the search for a “best” hyperplane $H = H_Q$ that attains the maximum in (7.9). Since a cube Q contains a finite number n_Q of data, the search can be reduced to $\binom{n_Q}{d}$ hyperplanes and the cost of computing $\gamma_{Q,0}$ is therefore bounded by n_Q^d . In addition, the search of H_Q needs to be performed on *every* cube $Q \in \mathcal{T}(\mathbf{z})$, so that a crude global bound for this cost is given by n^{d+2} . This additional cost is affordable for small d but becomes prohibitive in high dimension. An alternate strategy is to rely on more affordable classifiers to produce an affine (or even higher order algebraic) decision boundary on each Q . Examples are plug-in classifiers that are based on least-square estimation of η on Q by a polynomial.

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SUPPLEMENTARY MATERIAL

Proof of Theorem 2.1 (DOI: [10.1214/14-AOS1234SUPP](https://doi.org/10.1214/14-AOS1234SUPP); .pdf). This supplement contains the detailed proof of Theorem 2.1 [4].

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