
More data speeds up training time in learning halfspaces over sparse vectors

Amit Daniely
Department of Mathematics
The Hebrew University
Jerusalem, Israel

Nati Linial
School of CS and Eng.
The Hebrew University
Jerusalem, Israel

Shai Shalev-Shwartz
School of CS and Eng.
The Hebrew University
Jerusalem, Israel

Abstract

The increased availability of data in recent years has led several authors to ask whether it is possible to use data as a *computational* resource. That is, if more data is available, beyond the sample complexity limit, is it possible to use the extra examples to speed up the computation time required to perform the learning task?

We give the first positive answer to this question for a *natural supervised learning problem* — we consider agnostic PAC learning of halfspaces over 3-sparse vectors in $\{-1, 1, 0\}^n$. This class is inefficiently learnable using $O(n/\epsilon^2)$ examples. Our main contribution is a novel, non-cryptographic, methodology for establishing computational-statistical gaps, which allows us to show that, under a widely believed assumption that refuting random 3CNF formulas is hard, it is impossible to efficiently learn this class using only $O(n/\epsilon^2)$ examples. We further show that under stronger hardness assumptions, even $O(n^{1.499}/\epsilon^2)$ examples do not suffice. On the other hand, we show a new algorithm that learns this class efficiently using $\tilde{\Omega}(n^2/\epsilon^2)$ examples. This formally establishes the tradeoff between sample and computational complexity for a natural supervised learning problem.

1 Introduction

In the modern digital period, we are facing a rapid growth of available datasets in science and technology. In most computing tasks (e.g. storing and searching in such datasets), large datasets are a burden and require more computation. However, for learning tasks the situation is radically different. A simple observation is that more data can never hinder you from performing a task. If you have more data than you need, just ignore it!

A basic question is how to learn from “big data”. The statistical learning literature classically studies questions like “how much data is needed to perform a learning task?” or “how does accuracy improve as the amount of data grows?” etc. In the modern, “data revolution era”, it is often the case that the amount of data available far exceeds the information theoretic requirements. We can wonder whether this, seemingly redundant data, can be used for other purposes. An intriguing question in this vein, studied recently by several researchers ([Decatur et al., 1998, Servedio., 2000, Shalev-Shwartz et al., 2012, Berthet and Rigollet, 2013, Chandrasekaran and Jordan, 2013]), is the following

Question 1: Are there any learning tasks in which more data, *beyond the information theoretic barrier*, can *provably* be leveraged to speed up computation time?

The main contributions of this work are:

- Conditioning on the hardness of refuting random 3CNF formulas, we give the first example of a *natural supervised learning problem* for which the answer to Question 1 is positive.
- To prove this, we present a novel technique to establish computational-statistical tradeoffs in supervised learning problems. To the best of our knowledge, this is the first such a result that is not based on cryptographic primitives.

Additional contributions are non trivial efficient algorithms for learning halfspaces over 2-sparse and 3-sparse vectors using $\tilde{O}\left(\frac{n}{\epsilon^2}\right)$ and $\tilde{O}\left(\frac{n^2}{\epsilon^2}\right)$ examples respectively.

The natural learning problem we consider is the task of learning the class of *halfspaces over k -sparse vectors*. Here, the instance space is the *space of k -sparse vectors*,

$$C_{n,k} = \{x \in \{-1, 1, 0\}^n \mid |\{i \mid x_i \neq 0\}| \leq k\},$$

and the hypothesis class is *halfspaces over k -sparse vectors*, namely

$$\mathcal{H}_{n,k} = \{h_{w,b} : C_{n,k} \rightarrow \{\pm 1\} \mid h_{w,b}(x) = \text{sign}(\langle w, x \rangle + b), w \in \mathbb{R}^n, b \in \mathbb{R}\},$$

where $\langle \cdot, \cdot \rangle$ denotes the standard inner product in \mathbb{R}^n .

We consider the standard setting of agnostic PAC learning, which models the realistic scenario where the labels are not necessarily fully determined by some hypothesis from $\mathcal{H}_{n,k}$. Note that in the realizable case, i.e. when some hypothesis from $\mathcal{H}_{n,k}$ has zero error, the problem of learning halfspaces is easy even over \mathbb{R}^n .

In addition, we allow improper learning (a.k.a. representation independent learning), namely, the learning algorithm is not restricted to output a hypothesis from $\mathcal{H}_{n,k}$, but only should output a hypothesis whose error is not much larger than the error of the best hypothesis in $\mathcal{H}_{n,k}$. This gives the learner a lot of flexibility in choosing an appropriate representation of the problem. This additional freedom to the learner makes it much harder to prove lower bounds in this model. Concretely, it is not clear how to use standard reductions from NP hard problems in order to establish lower bounds for improper learning (moreover, Applebaum et al. [2008] give evidence that such simple reductions do not exist).

The classes $\mathcal{H}_{n,k}$ and similar classes have been studied by several authors (e.g. Long. and Servedio [2013]). They naturally arise in learning scenarios in which the set of all possible features is very large, but each example has only a small number of active features. For example:

- *Predicting an advertisement based on a search query*: Here, the possible features of each instance are all English words, whereas the active features are only the set of words given in the query.
- *Learning Preferences [Hazan et al., 2012]*: Here, we have n players. A *ranking* of the players is a permutation $\sigma : [n] \rightarrow [n]$ (think of $\sigma(i)$ as the rank of the i 'th player). Each ranking induces a *preference* h_σ over the ordered pairs, such that $h_\sigma(i, j) = 1$ iff i is ranked higher than j . Namely,

$$h_\sigma(i, j) = \begin{cases} 1 & \sigma(i) > \sigma(j) \\ -1 & \sigma(i) < \sigma(j) \end{cases}$$

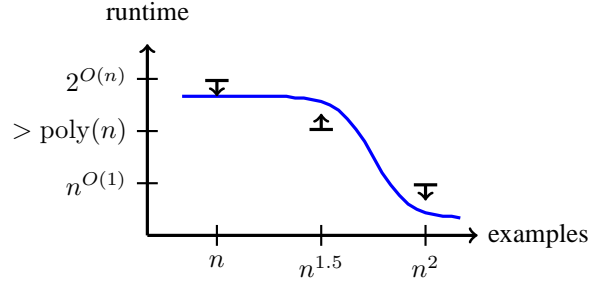
The objective here is to learn the class, \mathcal{P}_n , of all possible preferences. The problem of learning preferences is related to the problem of learning $\mathcal{H}_{n,2}$: if we associate each pair (i, j) with the vector in $C_{n,2}$ whose i 'th coordinate is 1 and whose j 'th coordinate is -1 , it is not hard to see that $\mathcal{P}_n \subset \mathcal{H}_{n,2}$: for every σ , $h_\sigma = h_{w,0}$ for the vector $w \in \mathbb{R}^n$, given by $w_i = \sigma(i)$. Therefore, every upper bound for $\mathcal{H}_{n,2}$ implies an upper bound for \mathcal{P}_n , while every lower bound for \mathcal{P}_n implies a lower bound for $\mathcal{H}_{n,2}$. Since $\text{VC}(\mathcal{P}_n) = n$ and $\text{VC}(\mathcal{H}_{n,2}) = n + 1$, the information theoretic barrier to learn these classes is $\Theta\left(\frac{n}{\epsilon^2}\right)$. In Hazan et al. [2012] it was shown that \mathcal{P}_n can be *efficiently* learnt using $O\left(\frac{n \log^3(n)}{\epsilon^2}\right)$ examples. In section 4, we extend this result to $\mathcal{H}_{n,2}$.

We will show a positive answer to Question 1 for the class $\mathcal{H}_{n,3}$. To do so, we show¹ the following:

¹In fact, similar results hold for every constant $k \geq 3$. Indeed, since $\mathcal{H}_{n,3} \subset \mathcal{H}_{n,k}$ for every $k \geq 3$, it is trivial that item 3 below holds for every $k \geq 3$. The upper bound given in item 1 holds for every k . For item 2,

1. Ignoring computational issues, it is possible to learn the class $\mathcal{H}_{n,3}$ using $O\left(\frac{n}{\epsilon^2}\right)$ examples.
2. It is also possible to *efficiently* learn $\mathcal{H}_{n,3}$ if we are provided with a larger training set (of size $\tilde{\Omega}\left(\frac{n^2}{\epsilon^2}\right)$). This is formalized in Theorem 3.1.
3. It is impossible to *efficiently* learn $\mathcal{H}_{n,3}$, if we are only provided with a training set of size $O\left(\frac{n}{\epsilon^2}\right)$ under Feige’s assumption regarding the hardness of refuting random 3CNF formulas [Feige, 2002]. Furthermore, for every $\alpha \in [0, 0.5)$, it is impossible to learn efficiently with a training set of size $O\left(\frac{n^{1+\alpha}}{\epsilon^2}\right)$ under a stronger hardness assumption. This is formalized in Theorem 4.1.

A graphical illustration of our main results is given below:



The proof of item 1 above is easy – simply note that $\mathcal{H}_{n,3}$ has VC dimension $n + 1$.

Item 2 is proved in section 4, relying on the results of Hazan et al. [2012]. We note, however, that a weaker result, that still suffices for answering Question 1 in the affirmative, can be proven using a naive improper learning algorithm. In particular, we show below how to learn $\mathcal{H}_{n,3}$ efficiently with a sample of $\Omega\left(\frac{n^3}{\epsilon^2}\right)$ examples. The idea is to replace the class $\mathcal{H}_{n,3}$ with the class $\{\pm 1\}^{C_{n,3}}$ containing *all* functions from $C_{n,3}$ to $\{\pm 1\}$. Clearly, this class contains $\mathcal{H}_{n,3}$. In addition, we can efficiently find a function f that minimizes the empirical training error over a training set S as follows: For every $x \in C_{n,k}$, if x does not appear at all in the training set we will set $f(x)$ arbitrarily to 1. Otherwise, we will set $f(x)$ to be the majority of the labels in the training set that correspond to x . Finally, note that the VC dimension of $\{\pm 1\}^{C_{n,3}}$ is smaller than n^3 (since $|C_{n,3}| < n^3$). Hence, standard generalization results (e.g. Vapnik [1995]) implies that a training set size of $\Omega\left(\frac{n^3}{\epsilon^2}\right)$ suffices for learning this class.

Item 3 is shown in section 3 by presenting a novel technique for establishing statistical-computational tradeoffs.

The class $\mathcal{H}_{n,2}$. Our main result gives a positive answer to Question 1 for the task of improperly learning $\mathcal{H}_{n,k}$ for $k \geq 3$. A natural question is what happens for $k = 2$ and $k = 1$. Since $\text{VC}(\mathcal{H}_{n,1}) = \text{VC}(\mathcal{H}_{n,2}) = n + 1$, the information theoretic barrier for learning these classes is $\Theta\left(\frac{n}{\epsilon^2}\right)$. In section 4, we prove that $\mathcal{H}_{n,2}$ (and, consequently, $\mathcal{H}_{n,1} \subset \mathcal{H}_{n,2}$) can be learnt using $O\left(\frac{n \log^3(n)}{\epsilon^2}\right)$ examples, indicating that significant computational-statistical tradeoffs start to manifest themselves only for $k \geq 3$.

1.1 Previous approaches, difficulties, and our techniques

[Decatur et al., 1998] and [Servedio., 2000] gave positive answers to Question 1 in the realizable PAC learning model. Under cryptographic assumptions, they showed that there exist binary learning problems, in which more data can provably be used to speed up training time. [Shalev-Shwartz et al., 2012] showed a similar result for the agnostic PAC learning model. In all of these papers, the main idea is to construct a hypothesis class based on a one-way function. However, the constructed

it is not hard to show that $\mathcal{H}_{n,k}$ can be learnt using a sample of $\Omega\left(\frac{n^k}{\epsilon^2}\right)$ examples by a naive improper learning algorithm, similar to the algorithm we describe in this section for $k = 3$.

classes are of a very synthetic nature, and are of almost no practical interest. This is mainly due to the construction technique which is based on one way functions. In this work, instead of using cryptographic assumptions, we rely on the hardness of refuting random 3CNF formulas. The simplicity and flexibility of 3CNF formulas enable us to derive lower bounds for natural classes such as halfspaces.

Recently, [Berthet and Rigollet, 2013] gave a positive answer to Question 1 in the context of unsupervised learning. Concretely, they studied the problem of sparse PCA, namely, finding a *sparse* vector that maximizes the variance of an unsupervised data. Conditioning on the hardness of the planted clique problem, they gave a positive answer to Question 1 for sparse PCA. Our work, as well as the previous work of Decatur et al. [1998], Servedio. [2000], Shalev-Shwartz et al. [2012], studies Question 1 in the supervised learning setup. We emphasize that unsupervised learning problems are radically different than supervised learning problems in the context of deriving lower bounds. The main reason for the difference is that in supervised learning problems, the learner is allowed to employ improper learning, which gives it a lot of power in choosing an adequate representation of the data. For example, the upper bound we have derived for the class of sparse halfspaces switched from representing hypotheses as halfspaces to representation of hypotheses as tables over $C_{n,3}$, which made the learning problem easy from the computational perspective. The crux of the difficulty in constructing lower bounds is due to this freedom of the learner in choosing a convenient representation. This difficulty does not arise in the problem of sparse PCA detection, since there the learner must output a good sparse vector. Therefore, it is not clear whether the approach given in [Berthet and Rigollet, 2013] can be used to establish computational-statistical gaps in supervised learning problems.

2 Background and notation

For hypothesis class $\mathcal{H} \subset \{\pm 1\}^X$ and a set $Y \subset X$, we define the *restriction of \mathcal{H} to Y* by $\mathcal{H}|_Y = \{h|_Y \mid h \in \mathcal{H}\}$. We denote by $J = J_n$ the all-ones $n \times n$ matrix. We denote the j 'th vector in the standard basis of \mathbb{R}^n by e_j .

2.1 Learning Algorithms

For $h : C_{n,3} \rightarrow \{\pm 1\}$ and a distribution \mathcal{D} on $C_{n,3} \times \{\pm 1\}$ we denote the *error of h w.r.t. \mathcal{D}* by $\text{Err}_{\mathcal{D}}(h) = \Pr_{(x,y) \sim \mathcal{D}}(h(x) \neq y)$. For $\mathcal{H} \subset \{\pm 1\}^{C_{n,3}}$ we denote the *error of \mathcal{H} w.r.t. \mathcal{D}* by $\text{Err}_{\mathcal{D}}(\mathcal{H}) = \min_{h \in \mathcal{H}} \text{Err}_{\mathcal{D}}(h)$. For a sample $S \in (C_{n,3} \times \{\pm 1\})^m$ we denote by $\text{Err}_S(h)$ (resp. $\text{Err}_S(\mathcal{H})$) the error of h (resp. \mathcal{H}) w.r.t. the empirical distribution induces by the sample S .

A *learning algorithm*, L , receives a sample $S \in (C_{n,3} \times \{\pm 1\})^m$ and return a hypothesis $L(S) : C_{n,3} \rightarrow \{\pm 1\}$. We say that L *learns $\mathcal{H}_{n,3}$ using $m(n, \epsilon)$ examples* if,² for every distribution \mathcal{D} on $C_{n,3} \times \{\pm 1\}$ and a sample S of more than $m(n, \epsilon)$ i.i.d. examples drawn from \mathcal{D} ,

$$\Pr_S(\text{Err}_{\mathcal{D}}(L(S)) > \text{Err}_{\mathcal{D}}(\mathcal{H}_{3,n}) + \epsilon) < \frac{1}{10}$$

The algorithm L is *efficient* if it runs in polynomial time in the sample size and returns a hypothesis that can be evaluated in polynomial time.

2.2 Refuting random 3SAT formulas

We frequently view a boolean assignment to variables x_1, \dots, x_n as a vector in \mathbb{R}^n . It is convenient, therefore, to assume that boolean variables take values in $\{\pm 1\}$ and to denote negation by “ $-$ ” (instead of the usual “ \neg ”). An n -variables 3CNF clause is a boolean formula of the form

$$C(x) = (-1)^{j_1} x_{i_1} \vee (-1)^{j_2} x_{i_2} \vee (-1)^{j_3} x_{i_3}, \quad x \in \{\pm 1\}^n$$

An n -variables 3CNF formula is a boolean formula of the form

$$\phi(x) = \bigwedge_{i=1}^m C_i(x),$$

²For simplicity, we require the algorithm to succeed with probability of at least 9/10. This can be easily amplified to probability of at least $1 - \delta$, as in the usual definition of agnostic PAC learning, while increasing the sample complexity by a factor of $\log(1/\delta)$.

where every C_i is a 3CNF clause. Define the *value*, $\text{Val}(\phi)$, of ϕ as the maximal fraction of clauses that can be simultaneously satisfied. If $\text{Val}(\phi) = 1$, we say the ϕ is *satisfiable*. By $3\text{CNF}_{n,m}$ we denote the set of 3CNF formulas with n variables and m clauses.

Refuting random 3CNF formulas has been studied extensively (see e.g. a special issue of TCS Dubios et al. [2001]). It is known that for large enough Δ ($\Delta = 6$ will suffice) a random formula in $3\text{CNF}_{n,\Delta n}$ is not satisfiable with probability $1 - o(1)$. Moreover, for every $0 \leq \epsilon < \frac{1}{4}$, and a large enough $\Delta = \Delta(\epsilon)$, the value of a random formula $3\text{CNF}_{n,\Delta n}$ is $\leq 1 - \epsilon$ with probability $1 - o(1)$.

The problem of refuting random 3CNF concerns efficient algorithms that provide a proof that a random 3CNF is not satisfiable, or far from being satisfiable. This can be thought of as a game between an adversary and an algorithm. The adversary should produce a 3CNF-formula. It can either produce a satisfiable formula, or, produce a formula uniformly at random. The algorithm should identify whether the produced formula is random or satisfiable.

Formally, let $\Delta : \mathbb{N} \rightarrow \mathbb{N}$ and $0 \leq \epsilon < \frac{1}{4}$. We say that an efficient algorithm, A , ϵ -refutes random 3CNF with ratio Δ if its input is $\phi \in 3\text{CNF}_{n,n\Delta(n)}$, its output is either “typical” or “exceptional” and it satisfies:

- *Soundness*: If $\text{Val}(\phi) \geq 1 - \epsilon$, then

$$\Pr_{\text{Rand. coins of } A} (A(\phi) = \text{“exceptional”}) \geq \frac{3}{4}$$

- *Completeness*: For every n ,

$$\Pr_{\text{Rand. coins of } A, \phi \sim \text{Uni}(3\text{CNF}_{n,n\Delta(n)})} (A(\phi) = \text{“typical”}) \geq 1 - o(1)$$

By a standard repetition argument, the probability of $\frac{3}{4}$ can be amplified to $1 - 2^{-n}$, while efficiency is preserved. Thus, given such an (amplified) algorithm, if $A(\phi) = \text{“typical”}$, then with confidence of $1 - 2^{-n}$ we know that $\text{Val}(\phi) < 1 - \epsilon$. Since for random $\phi \in 3\text{CNF}_{n,n\Delta(n)}$, $A(\phi) = \text{“typical”}$ with probability $1 - o(1)$, such an algorithm provides, for most 3CNF formulas a proof that their value is less than $1 - \epsilon$.

Note that an algorithm that ϵ -refutes random 3CNF with ratio Δ also ϵ' -refutes random 3CNF with ratio Δ for every $0 \leq \epsilon' \leq \epsilon$. Thus, the task of refuting random 3CNF’s gets easier as ϵ gets smaller. Most of the research concerns the case $\epsilon = 0$. Here, it is not hard to see that the task is getting easier as Δ grows. The best known algorithm [Feige and Ofek, 2007] 0-refutes random 3CNF with ratio $\Delta(n) = \Omega(\sqrt{n})$. In Feige [2002] it was conjectured that for constant Δ no efficient algorithm can provide a proof that a random 3CNF is not satisfiable:

Conjecture 2.1 (R3SAT hardness assumption – [Feige, 2002]). *For every $\epsilon > 0$ and for every large enough integer $\Delta > \Delta_0(\epsilon)$ there exists no efficient algorithm that ϵ -refutes random 3CNF formulas with ratio Δ .*

In fact, for all we know, the following conjecture may be true for every $0 \leq \mu \leq 0.5$.

Conjecture 2.2 (μ -R3SAT hardness assumption). *For every $\epsilon > 0$ and for every integer $\Delta > \Delta_0(\epsilon)$ there exists no efficient algorithm that ϵ -refutes random 3CNF with ratio $\Delta \cdot n^\mu$.*

Note that Feige’s conjecture is equivalent to the 0-R3SAT hardness assumption.

3 Lower bounds for learning $\mathcal{H}_{n,3}$

Theorem 3.1 (main). *Let $0 \leq \mu \leq 0.5$. If the μ -R3SAT hardness assumption (conjecture 2.2) is true, then there exists no efficient learning algorithm that learns the class $\mathcal{H}_{n,3}$ using $O\left(\frac{n^{1+\mu}}{\epsilon^2}\right)$ examples.*

In the proof of Theorem 3.1 we rely on the validity of a conjecture, similar to conjecture 2.2 for 3-variables majority formulas. Following an argument from [Feige, 2002] (Theorem 3.2) the validity of the conjecture on which we rely for majority formulas follows the validity of conjecture 2.2.

Define

$$\forall(x_1, x_2, x_3) \in \{\pm 1\}^3, \text{MAJ}(x_1, x_2, x_3) := \text{sign}(x_1 + x_2 + x_3)$$

An n -variables 3MAJ clause is a boolean formula of the form

$$C(x) = \text{MAJ}((-1)^{j_1}x_{i_1}, (-1)^{j_2}x_{i_2}, (-1)^{j_3}x_{i_3}), \quad x \in \{\pm 1\}^n$$

An n -variables 3MAJ formula is a boolean formula of the form

$$\phi(x) = \bigwedge_{i=1}^m C_i(x)$$

where the C_i 's are 3MAJ clauses. By $3\text{MAJ}_{n,m}$ we denote the set of 3MAJ formulas with n variables and m clauses.

Theorem 3.2 ([Feige, 2002]). *Let $0 \leq \mu \leq 0.5$. If the μ -R3SAT hardness assumption is true, then for every $\epsilon > 0$ and for every large enough integer $\Delta > \Delta_0(\epsilon)$ there exists no efficient algorithm with the following properties.*

- Its input is $\phi \in 3\text{MAJ}_{n,\Delta n^{1+\mu}}$, and its output is either “typical” or “exceptional”.
- If $\text{Val}(\phi) \geq \frac{3}{4} - \epsilon$, then

$$\Pr_{\text{Rand. coins of } A} (A(\phi) = \text{“exceptional”}) \geq \frac{3}{4}$$

- For every n ,

$$\Pr_{\text{Rand. coins of } A, \phi \sim \text{Uni}(3\text{MAJ}_{n,\Delta n^{1+\mu}})} (A(\phi) = \text{“typical”}) \geq 1 - o(1)$$

Next, we prove Theorem 3.1. In fact, we will prove a slightly stronger result. Namely, define the subclass $\mathcal{H}_{n,3}^d \subset \mathcal{H}_{n,3}$, of homogenous halfspaces with binary weights, given by $\mathcal{H}_{n,3}^d = \{h_{w,0} \mid w \in \{\pm 1\}^n\}$. As we show, under the μ -R3SAT hardness assumption, it is impossible to efficiently learn this subclass using only $O\left(\frac{n^{1+\mu}}{\epsilon^2}\right)$ examples.

Proof idea: We will reduce the task of refuting random 3MAJ formulas with linear number of clauses to the task of (improperly) learning $\mathcal{H}_{n,3}^d$ with linear number of samples. The first step will be to construct a transformation that associates every 3MAJ clause with two examples in $C_{n,3} \times \{\pm 1\}$, and every assignment with a hypothesis in $\mathcal{H}_{n,3}^d$. As we will show, the hypothesis corresponding to an assignment ψ is correct on the two examples corresponding to a clause C if and only if ψ satisfies C . With that interpretation at hand, every 3MAJ formula ϕ can be thought of as a distribution \mathcal{D}_ϕ on $C_{n,3} \times \{\pm 1\}$, which is the empirical distribution induced by ψ 's clauses. It holds furthermore that $\text{Err}_{\mathcal{D}_\phi}(\mathcal{H}_{n,3}^d) = 1 - \text{Val}(\phi)$.

Suppose now that we are given an efficient learning algorithm for $\mathcal{H}_{n,3}^d$, that uses $\kappa \frac{n}{\epsilon^2}$ examples, for some $\kappa > 0$. To construct an efficient algorithm for refuting 3MAJ-formulas, we simply feed the learning algorithm with $\kappa \frac{n}{0.01^2}$ examples drawn from \mathcal{D}_ϕ and answer “exceptional” if the error of the hypothesis returned by the algorithm is small. If ϕ is (almost) satisfiable, the algorithm is guaranteed to return a hypothesis with a small error. On the other hand, if ϕ is far from being satisfiable, $\text{Err}_{\mathcal{D}_\phi}(\mathcal{H}_{n,3}^d)$ is large. If the learning algorithm is proper, then it must return a hypothesis from $\mathcal{H}_{n,3}^d$ and therefore it would necessarily return a hypothesis with a large error. This argument can be used to show that, unless $NP = RP$, learning $\mathcal{H}_{n,3}^d$ with a *proper* efficient algorithm is impossible. However, here we want to rule out *improper* algorithms as well.

The crux of the construction is that if ϕ is random, *no algorithm* (even improper and even inefficient) can return a hypothesis with a small error. The reason for that is that since the sample provided to the algorithm consists of only $\kappa \frac{n}{0.01^2}$ samples, the algorithm won't see most of ψ 's clauses, and, consequently, the produced hypothesis h will be *independent of them*. Since these clauses are random, h is likely to err on about half of them, so that $\text{Err}_{\mathcal{D}_\phi}(h)$ will be close to half!

To summarize we constructed an efficient algorithm with the following properties: if ϕ is almost satisfiable, the algorithm will return a hypothesis with a small error, and then we will declare “exceptional”, while for random ϕ , the algorithm will return a hypothesis with a large error, and we will declare “typical”.

Our construction crucially relies on the restriction to learning algorithm with a small sample complexity. Indeed, if the learning algorithm obtains more than $n^{1+\mu}$ examples, then it will see most of ψ 's clauses, and therefore it might succeed in “learning” even when the source of the formula is random. Therefore, we will declare “exceptional” even when the source is random.

Proof. (of theorem 3.1) Assume by way of contradiction that the μ -R3SAT hardness assumption is true and yet there exists an efficient learning algorithm that learns the class $\mathcal{H}_{n,3}$ using $O\left(\frac{n^{1+\mu}}{\epsilon^2}\right)$ examples. Setting $\epsilon = \frac{1}{100}$, we conclude that there exists an efficient algorithm L and a constant $\kappa > 0$ such that given a sample S of more than $\kappa \cdot n^{1+\mu}$ examples drawn from a distribution \mathcal{D} on $C_{n,3} \times \{\pm 1\}$, returns a classifier $L(S) : C_{n,3} \rightarrow \{\pm 1\}$ such that

- $L(S)$ can be evaluated efficiently.
- W.p. $\geq \frac{3}{4}$ over the choice of S , $\text{Err}_{\mathcal{D}}(L(S)) \leq \text{Err}_{\mathcal{D}}(\mathcal{H}_{n,3}) + \frac{1}{100}$.

Fix Δ large enough such that $\Delta > 100\kappa$ and the conclusion of Theorem 3.2 holds with $\epsilon = \frac{1}{100}$. We will construct an algorithm, A , contradicting Theorem 3.2. On input $\phi \in 3\text{MAJ}_{n,\Delta n^{1+\mu}}$ consisting of the 3MAJ clauses $C_1, \dots, C_{\Delta n^{1+\mu}}$, the algorithm A proceeds as follows

1. Generate a sample S consisting of $\Delta n^{1+\mu}$ examples as follows. For every clause, $C_k = \text{MAJ}((-1)^{j_1} x_{i_1}, (-1)^{j_2} x_{i_2}, (-1)^{j_3} x_{i_3})$, generate an example $(x_k, y_k) \in C_{n,3} \times \{\pm 1\}$ by choosing $b \in \{\pm 1\}$ at random and letting

$$(x_k, y_k) = b \cdot \left(\sum_{l=1}^3 (-1)^{j_l} e_{i_l}, 1 \right) \in C_{n,3} \times \{\pm 1\}.$$

For example, if $n = 6$, the clause is $\text{MAJ}(-x_2, x_3, x_6)$ and $b = -1$, we generate the example

$$((0, 1, -1, 0, 0, -1), -1)$$

2. Choose a sample S_1 consisting of $\frac{\Delta n^{1+\mu}}{100} \geq \kappa \cdot n^{1+\mu}$ examples by choosing at random (with repetitions) examples from S .
3. Let $h = L(S_1)$. If $\text{Err}_S(h) \leq \frac{3}{8}$, return “exceptional”. Otherwise, return “typical”.

We claim that A contradicts Theorem 3.2. Clearly, A runs in polynomial time. It remains to show that

- If $\text{Val}(\phi) \geq \frac{3}{4} - \frac{1}{100}$, then

$$\Pr_{\text{Rand. coins of } A} (A(\phi) = \text{“exceptional”}) \geq \frac{3}{4}$$

- For every n ,

$$\Pr_{\text{Rand. coins of } A, \phi \sim \text{Uni}(3\text{MAJ}_{n,\Delta n^{1+\mu}})} (A(\phi) = \text{“typical”}) \geq 1 - o(1)$$

Assume first that $\phi \in 3\text{MAJ}_{n,\Delta n^{1+\mu}}$ is chosen at random. Given the sample S_1 , the sample $S_2 := S \setminus S_1$ is a sample of $|S_2|$ i.i.d. examples which are independent from the sample S_1 , and hence also from $h = L(S_1)$. Moreover, for every example $(x_k, y_k) \in S_2$, y_k is a Bernoulli random variable with parameter $\frac{1}{2}$ which is independent of x_k . To see that, note that an example whose instance is x_k can be generated by exactly two clauses – one corresponds to $y_k = 1$, while the other corresponds to $y_k = -1$ (e.g., the instance $(1, -1, 0, 1)$ can be generated from the clause $\text{MAJ}(x_1, -x_2, x_4)$ and $b = 1$ or the clause $\text{MAJ}(-x_1, x_2, -x_4)$ and $b = -1$). Thus, given the instance x_k , the probability that $y_k = 1$ is $\frac{1}{2}$, independent of x_k .

It follows that $\text{Err}_{S_2}(h)$ is an average of at least $(1 - \frac{1}{100}) \Delta n^{1+\mu}$ independent Bernoulli random variable. By Chernoff's bound, with probability $\geq 1 - o(1)$, $\text{Err}_{S_2}(h) > \frac{1}{2} - \frac{1}{100}$. Thus,

$$\text{Err}_S(h) \geq \left(1 - \frac{1}{100}\right) \text{Err}_{S_2}(h) \geq \left(1 - \frac{1}{100}\right) \cdot \left(\frac{1}{2} - \frac{1}{100}\right) > \frac{3}{8}$$

And the algorithm will output “typical”.

Assume now that $\text{Val}(\phi) \geq \frac{3}{4} - \frac{1}{100}$ and let $\psi \in \{\pm 1\}^n$ be an assignment that indicates that. Let $\Psi \in \mathcal{H}_{n,3}$ be the hypothesis $\Psi(x) = \text{sign}(\langle \psi, x \rangle)$. It can be easily checked that $\Psi(x_k) = y_k$ if and only if ψ satisfies C_k . Since $\text{Val}(\phi) \geq \frac{3}{4} - \frac{1}{100}$, it follows that

$$\text{Err}_S(\Psi) \leq \frac{1}{4} + \frac{1}{100}.$$

Thus,

$$\text{Err}_S(\mathcal{H}_{n,3}) \leq \frac{1}{4} + \frac{1}{100}.$$

By the choice of L , with probability $\geq 1 - \frac{1}{4} = \frac{3}{4}$,

$$\text{Err}_S(h) \leq \frac{1}{4} + \frac{1}{100} + \frac{1}{100} < \frac{3}{8}$$

and the algorithm will return “exceptional”. \square

4 Upper bounds for learning $\mathcal{H}_{n,2}$ and $\mathcal{H}_{n,3}$

The following theorem derives upper bounds for learning $\mathcal{H}_{n,2}$ and $\mathcal{H}_{n,3}$. Its proof relies on results from Hazan et al. [2012] about learning β -decomposable matrices, and due to the lack of space is given in the appendix.

Theorem 4.1.

- *There exists an efficient algorithm that learns $\mathcal{H}_{n,2}$ using $O\left(\frac{n \log^3(n)}{\epsilon^2}\right)$ examples*
- *There exists an efficient algorithm that learns $\mathcal{H}_{n,3}$ using $O\left(\frac{n^2 \log^3(n)}{\epsilon^2}\right)$ examples*

5 Discussion

We formally established a computational-sample complexity tradeoff for the task of (agnostically and improperly) PAC learning of halfspaces over 3-sparse vectors. Our proof of the lower bound relies on a novel, non cryptographic, technique for establishing such tradeoffs. We also derive a new non-trivial upper bound for this task.

Open questions. An obvious open question is to close the gap between the lower and upper bounds. We conjecture that $\mathcal{H}_{n,3}$ can be learnt efficiently using a sample of $\tilde{O}\left(\frac{n^{1.5}}{\epsilon^2}\right)$ examples. Also, we believe that our new proof technique can be used for establishing computational-sample complexity tradeoffs for other natural learning problems.

Acknowledgements: Amit Daniely is a recipient of the Google Europe Fellowship in Learning Theory, and this research is supported in part by this Google Fellowship. Nati Linial is supported by grants from ISF, BSF and I-Core. Shai Shalev-Shwartz is supported by the Israeli Science Foundation grant number 590-10.

References

Benny Applebaum, Boaz Barak, and David Xiao. On basing lower-bounds for learning on worst-case assumptions. In *Foundations of Computer Science, 2008. FOCS'08. IEEE 49th Annual IEEE Symposium on*, pages 211–220. IEEE, 2008.

- Quentin Berthet and Philippe Rigollet. Complexity theoretic lower bounds for sparse principal component detection. In *COLT*, 2013.
- Nicolo Cesa-Bianchi, Alex Conconi, and Claudio Gentile. On the generalization ability of on-line learning algorithms. *IEEE Transactions on Information Theory*, 50:2050–2057, 2001.
- Venkat Chandrasekaran and Michael I. Jordan. Computational and statistical tradeoffs via convex relaxation. *Proceedings of the National Academy of Sciences*, 2013.
- S. Decatur, O. Goldreich, and D. Ron. Computational sample complexity. *SIAM Journal on Computing*, 29, 1998.
- O. Dubios, R. Monasson, B. Selma, and R. Zecchina (Guest Editors). *Phase Transitions in Combinatorial Problems*. Theoretical Computer Science, Volume 265, Numbers 1-2, 2001.
- U. Feige. Relations between average case complexity and approximation complexity. In *STOC*, pages 534–543, 2002.
- Uriel Feige and Eran Ofek. Easily refutable subformulas of large random 3cnf formulas. *Theory of Computing*, 3(1):25–43, 2007.
- E. Hazan, S. Kale, and S. Shalev-Shwartz. Near-optimal algorithms for online matrix prediction. In *COLT*, 2012.
- P. Long. and R. Servedio. Low-weight halfspaces for sparse boolean vectors. In *ITCS*, 2013.
- R. Servedio. Computational sample complexity and attribute-efficient learning. *J. of Comput. Syst. Sci.*, 60(1):161–178, 2000.
- Shai Shalev-Shwartz, Ohad Shamir, and Eran Tromer. Using more data to speed-up training time. In *AISTATS*, 2012.
- V.N. Vapnik. *The Nature of Statistical Learning Theory*. Springer, 1995.

A Proof of Theorem 4.1

The proof of the theorem relies on results from Hazan et al. [2012] about learning β -decomposable matrices. Let W be an $n \times m$ matrix. We define the *symmetrization* of W to be the $(n+m) \times (n+m)$ matrix

$$\text{sym}(W) = \begin{bmatrix} 0 & W \\ W^T & 0 \end{bmatrix}$$

We say that W is β -decomposable if there exist positive semi-definite matrices P, N for which

$$\begin{aligned} \text{sym}(W) &= P - N \\ \forall i, P_{ii}, N_{ii} &\leq \beta \end{aligned}$$

Each matrix in $\{\pm 1\}^{n \times m}$ can be naturally interpreted as a hypothesis on $[n] \times [m]$.

We say that a learning algorithm L learns a class $\mathcal{H}_n \subset \{\pm 1\}^{X_n}$ using $m(n, \epsilon, \delta)$ examples if, for every distribution \mathcal{D} on $X_n \times \{\pm 1\}$ and a sample S of more than $m(n, \epsilon, \delta)$ i.i.d. examples drawn from \mathcal{D} ,

$$\Pr_S (\text{Err}_{\mathcal{D}}(L(S)) > \text{Err}_{\mathcal{D}}(\mathcal{H}_n) + \epsilon) < \delta$$

Hazan et al. [2012] have proved³ that

Theorem A.1. *Hazan et al. [2012] The hypothesis class of β -decomposable $n \times m$ matrices with ± 1 entries can be efficiently learnt using a sample of $O\left(\frac{\beta^2(n+m)\log(n+m)+\log(1/\delta)}{\epsilon^2}\right)$ examples.*

We start with a generic reduction from a problem of learning a class \mathcal{G}_n over an instance space $X_n \subset \{-1, 1, 0\}^n$ to the problem of learning $\beta(n)$ -decomposable matrices. We say that \mathcal{G}_n is *realized* by $m_n \times m_n$ matrices that are $\beta(n)$ -decomposable if there exists a mapping $\psi_n : X_n \rightarrow [m_n] \times [m_n]$ such that for every $h \in \mathcal{G}_n$ there exists a $\beta(n)$ -decomposable $m_n \times m_n$ matrix W for which $\forall x \in X_n, h(x) = W_{\psi_n(x)}$. The mapping ψ_n is called a *realization* of \mathcal{G}_n . In the case that the mapping ψ_n can be computed in time polynomial in n , we say that \mathcal{G}_n is *efficiently realized* and ψ_n is an *efficient realization*. It follows from Theorem A.1 that:

Corollary A.2. *If \mathcal{G}_n is efficiently realized by $m_n \times m_n$ matrices that are $\beta(n)$ -decomposable then \mathcal{G}_n can be efficiently learnt using a sample of $O\left(\frac{\beta(n)^2 m_n \log(m_n) + \log(1/\delta)}{\epsilon^2}\right)$ examples.*

We now turn to the proof of Theorem 4.1. We start with the first assertion, about learning $\mathcal{H}_{n,2}$. The idea will be to partition the instance space into a disjoint union of subsets and show that the restriction of the hypothesis class to each subset can be efficiently realized by $\beta(n)$ -decomposable. Concretely, we decompose $C_{n,2}$ into a disjoint union of five sets

$$C_{n,2} = \cup_{r=-2}^2 A_n^r$$

where

$$A_n^r = \left\{ x \in C_{n,2} \mid \sum_{i=1}^n x_i = r \right\}.$$

In section A.1 we will prove that

Lemma A.3. *For every $-2 \leq r \leq 2$, $\mathcal{H}_{n,2}|_{A_n^r}$ can be efficiently realized by $n \times n$ matrices that are $O(\log(n))$ -decomposable.*

To glue together the five restrictions, we will rely on the following Lemma, whose proof is given in section A.1.

Lemma A.4. *Let X_1, \dots, X_k be partition of a domain X and let H be a hypothesis class over X . Define $H_i = H|_{X_i}$. Suppose the for every H_i there exist a learning algorithm that learns H_i using $\leq C(d + \log(1/\delta))/\epsilon^2$ examples, for some constant $C \geq 8$. Consider the algorithm A which*

³The result of Hazan et al. [2012] is more general than what is stated here. Also, Hazan et al. [2012] considered the online scenario. The result for the statistical scenario, as stated here, can be derived by applying standard online-to-batch conversions (see for example Cesa-Bianchi et al. [2001]).

receives an i.i.d. training set S of m examples from $X \times \{0, 1\}$ and applies the learning algorithm for each H_i on the examples in S that belongs to X_i . Then, A learns H using at most

$$\frac{2Ck(d + \log(2k/\delta))}{\epsilon^2}$$

examples.

The first part of Theorem 4.1 is therefore follows from Lemma A.3, Lemma A.4 and Corollary A.2.

Having the first part of Theorem 4.1 and Lemma A.4 at hand, it is not hard to prove the second part of Theorem 4.1:

For $1 \leq i \leq n - 2$ and $b \in \{\pm 1\}$ define

$$D_{n,i,b} = \{x \in C_{n,3} \mid x_i = b \text{ and } \forall j < i, x_j = 0\}$$

Let $\psi_n : C_{n,3} \rightarrow C_{n,2}$ be the mapping that zeros the first non zero coordinate. It is not hard to see that $\mathcal{H}_{n,3}|_{D_{n,i,b}} = \{h \circ \psi_n|_{D_{n,i,b}} \mid h \in \mathcal{H}_{n,2}\}$. Therefore $\mathcal{H}_{n,3}|_{D_{n,i,b}}$ can be identified with $\mathcal{H}_{n,2}$ using the mapping ψ_n , and therefore can efficiently learnt using $O\left(\frac{n \log^3(n) + \log(1/\delta)}{\epsilon^2}\right)$ examples (the dependency on δ does not appear in the statement, but can be easily inferred from the proof). The second part of Theorem 4.1 is therefore follows from the first part of the Theorem and Lemma A.4.

A.1 Proofs of Lemma A.3 and Lemma A.4

In the proof, we will rely on the following facts. The *tensor product* of two matrices $A \in M_{n \times m}$ and $B \in M_{k \times l}$ is defined as the $(n \cdot k) \times (m \cdot l)$ matrix

$$A \otimes B = \begin{bmatrix} A_{1,1} \cdot B & \cdots & A_{1,m} \cdot B \\ \vdots & \ddots & \vdots \\ A_{n,1} \cdot B & \cdots & A_{n,m} \cdot B \end{bmatrix}$$

Proposition A.5. *Let W be a β -decomposable matrix and let A be a PSD matrix whose diagonal entries are upper bounded by α . Then $W \otimes A$ is $(\alpha \cdot \beta)$ -decomposable.*

Proof. It is not hard to see that for every matrix W and a symmetric matrix A ,

$$\text{sym}(W) \otimes A = \text{sym}(W \otimes A)$$

Moreover, since the tensor product of two PSD matrices is PSD, if $\text{sym}(W) = P - N$ is a β -decomposition of W , then

$$\text{sym}(W \otimes A) = P \otimes A - N \otimes A$$

is a $(\alpha \cdot \beta)$ -decomposition of $W \otimes A$. \square

Proposition A.6. *If W is a β -decomposable matrix, then so is every matrix obtained from W by iteratively deleting rows and columns.*

Proof. It is enough to show that deleting one row or column leaves W β -decomposable. Suppose that W' is obtained from $W \in M_{n \times m}$ by deleting the i 'th row (the proof for deleting columns is similar). It is not hard to see that $\text{sym}(W')$ is the i 'th principal minor of $\text{sym}(W)$. Therefore, since principal minors of PSD matrices are PSD matrices as well, if $\text{sym}(W) = P - N$ is β -decomposition of W then $\text{sym}(W') = [P]_{i,i} - [N]_{i,i}$ is a β -decomposition of W' . \square

Proposition A.7. *Hazan et al. [2012] Let T_n be the upper triangular matrix whose all entries in the diagonal and above are 1, and whose all entries beneath the diagonal are -1 . Then T_n is $O(\log(n))$ -decomposable.*

Lastly, we will also need the following generalization of proposition A.7

Proposition A.8. *Let W be an $n \times n$ ± 1 matrix. Assume that there exists a sequence $0 \leq j(1), \dots, j(n) \leq n$ such that*

$$W_{ij} = \begin{cases} -1 & j \leq j(i) \\ 1 & j > j(i) \end{cases}$$

Then, W is $O(\log(n))$ -decomposable.

Proof. Since switching rows of a β -decomposable matrix leaves a β -decomposable matrix, we can assume without loss of generality that $j(1) \leq j(2) \leq \dots \leq j(n)$. Let J be the $n \times n$ all ones matrix. It is not hard to see that W can be obtained from $T_n \otimes J$ by iteratively deleting rows and columns. Combining propositions A.5, A.6 and A.7, we conclude that W is $O(\log(n))$ -decomposable, as required. \square

We are now ready to prove Lemma A.3

Proof. (of Lemma A.3) Denote $\mathcal{A}_n^r = \mathcal{H}_{n,2}|_{A_n^r}$. We split into cases.

Case 1, $r=0$: Note that $A_n^0 = \{e_i - e_j \mid i, j \in [n]\}$. Define $\psi_n : A_n^0 \rightarrow [n] \times [n]$ by $\psi_n(e_i - e_j) = (i, j)$. We claim that ψ_n is an efficient realization of \mathcal{A}_n^0 by $n \times n$ matrices that are $O(\log(n))$ decomposable. Indeed, let $h = h_{w,b} \in \mathcal{A}_n^0$, and let W be the $n \times n$ matrix $W_{ij} = W_{\psi_n(e_i - e_j)} = h(e_i - e_j)$. It is enough to show that W is $O(\log(n))$ -decomposable.

We can rename the coordinates so that

$$w_1 \geq w_2 \geq \dots \geq w_n \tag{1}$$

From equation (1), it is not hard to see that there exist numbers

$$0 \leq j(1) \leq j(2) \leq \dots \leq j(n) \leq n$$

for which

$$W_{ij} = \begin{cases} -1 & j \leq j(i) \\ 1 & j > j(i) \end{cases}$$

The conclusion follows from Proposition A.8

Case 2, $r=2$ and $r=-2$: We confine ourselves to the case $r = 2$. The case $r = -2$ is similar. Note that $A_n^2 = \{e_i + e_j \mid i \neq j \in [n]\}$. Define $\psi_n : A_n^2 \rightarrow [n] \times [n]$ by $\psi_n(e_i + e_j) = (i, j)$. We claim that ψ_n is an efficient realization of \mathcal{A}_n^2 by $n \times n$ matrices that are $O(\log(n))$ decomposable. Indeed, let $h = h_{w,b} \in \mathcal{A}_n^2$, and let W be the $n \times n$ matrix $W_{ij} = W_{\psi_n(e_i + e_j)} = h(e_i + e_j)$. It is enough to show that W is $O(\log(n))$ -decomposable.

We can rename the coordinates so that

$$w_1 \leq w_2 \leq \dots \leq w_n \tag{2}$$

From equation (2), it is not hard to see that there exist numbers

$$n \geq j(1) \geq j(2) \geq \dots \geq j(n) \geq 0$$

for which

$$W_{ij} = \begin{cases} -1 & j \leq j(i) \\ 1 & j > j(i) \end{cases}$$

The conclusion follows from Proposition A.8

Case 3, $r=1$ and $r=-1$: We confine ourselves to the case $r = 1$. The case $r = -1$ is similar. Note that $A_n^1 = \{e_i \mid i \in [n]\}$. Define $\psi_n : A_n^1 \rightarrow [n] \times [n]$ by $\psi_n(e_i) = (i, i)$. We claim that ψ_n is an efficient realization of \mathcal{A}_n^1 by $n \times n$ matrices that are 3-decomposable (let alone, $\log(n)$ -decomposable). Indeed, let $h = h_{w,b} \in \mathcal{A}_n^1$, and let W be the $n \times n$ matrix with $W_{ii} = W_{\psi_n(e_i)} = h(e_i)$ and -1 outside the diagonal. It is enough to show that W is 3-decomposable. Since J is 1-decomposable, it is enough to show that $W + J$ is 2-decomposable. However, it is not hard to see that every diagonal matrix D is $(\max_i |D_{ii}|)$ -decomposable. \square

Proof. (of Lemma A.4) Let $S = (x_1, y_1), \dots, (x_m, y_m)$ be a training set and let \hat{m}_i be the number of examples in S that belong to X_i . Given that the values of the random variables $\hat{m}_1, \dots, \hat{m}_i$ is determined, we have that w.p. of at least $1 - \delta$,

$$\forall i, \text{Err}_{D_i}(h_i) - \text{Err}_{D_i}(h^*) \leq \sqrt{\frac{C(d + \log(k/\delta))}{\hat{m}_i}},$$

where D_i is the induced distribution over X_i , h_i is the output of the i 'th algorithm, and h^* is the optimal hypothesis w.r.t. the original distribution D . Define,

$$m_i = \max\{C(d + \log(k/\delta)), \hat{m}_i\}.$$

It follows from the above that we also have, w.p. at least $1 - \delta$, for every i ,

$$\text{Err}_{D_i}(h_i) - \text{Err}_{D_i}(h^*) \leq \sqrt{\frac{C(d + \log(k/\delta))}{m_i}} =: \epsilon_i.$$

Let $\alpha_i = D\{(x, y) : x \in X_i\}$, and note that $\sum_i \alpha_i = 1$. Therefore,

$$\begin{aligned} \text{Err}_D(h_S) - \text{Err}_D(h^*) &\leq \sum_i \alpha_i \epsilon_i = \sum_i \sqrt{\alpha_i} \sqrt{\alpha_i \epsilon_i^2} \\ &\leq \sqrt{\sum_i \alpha_i} \sqrt{\sum_i \alpha_i \epsilon_i^2} = \sqrt{\sum_i \alpha_i \epsilon_i^2} \\ &= \sqrt{\frac{C(d + \log(k/\delta))}{m}} \sqrt{\sum_i \frac{\alpha_i m}{m_i}}. \end{aligned}$$

Next note that if $\alpha_i m < C(d + \log(k/\delta))$ then $\alpha_i m / m_i \leq 1$. Otherwise, using Chernoff's inequality, for every i we have

$$\Pr[m_i < 0.5\alpha_i m] \leq e^{-\alpha_i m/8} \leq e^{-(d + \log(k/\delta))} = e^{-d} \frac{\delta}{k} \leq \frac{\delta}{k}.$$

Therefore, by the union bound,

$$\Pr[\exists i : m_i < 0.5\alpha_i m] \leq \delta.$$

It follows that with probability of at least $1 - \delta$,

$$\sqrt{\sum_i \frac{\alpha_i m}{m_i}} \leq \sqrt{2k}.$$

All in all, we have shown that with probability of at least $1 - 2\delta$ it holds that

$$\text{Err}_D(h_S) - \text{Err}_D(h^*) \leq \sqrt{\frac{2Ck(d + \log(k/\delta))}{m}}.$$

Therefore, the the algorithm learns \mathcal{H} using

$$\leq \frac{2Ck(d + \log(2k/\delta))}{\epsilon^2}$$

examples. □