

Distributed Learning, Communication Complexity and Privacy

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Abstract

We consider the problem of PAC-learning from distributed data and analyze fundamental communication complexity questions involved. We provide general upper and lower bounds on the amount of communication needed to learn well, showing that in addition to VC-dimension and covering number, quantities such as the teaching-dimension and mistake-bound of a class play an important role. We also present tight results for a number of common concept classes including conjunctions, parity functions, and decision lists. For linear separators, we show that for non-concentrated distributions, we can use a version of the Perceptron algorithm to learn with much less communication than the number of updates given by the usual margin bound. We also show how boosting can be performed in a generic manner in the distributed setting to achieve communication with only logarithmic dependence on $1/\epsilon$ for any concept class, and demonstrate how recent work on agnostic learning from class-conditional queries can be used to achieve low communication in agnostic settings as well. We additionally present an analysis of privacy, considering both differential privacy and a notion of distributional privacy that is especially appealing in this context.

Keywords: Distributed Learning, Communication Complexity, Privacy

1. Introduction

Suppose you have two databases: one with the positive examples and another with the negative examples. How much communication between them is needed to learn a good hypothesis? In this paper we consider this question and its generalizations, as well as

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related issues such as privacy. Broadly, we consider a framework where information is distributed between several locations, and our goal is to learn a low-error hypothesis with respect to the overall distribution of data using as little communication, and as few rounds of communication, as possible. Motivating examples include:

1. Suppose k research groups around the world have collected large scientific datasets, such as genomic sequence data or sky survey data, and we wish to perform learning over the union of all these different datasets without too much communication.
2. Suppose we are a sociologist and want to understand what distinguishes the clientele of two retailers (Macy's vs Walmart). Each retailer has a large database of its own customers and we want to learn a classification rule that distinguishes them. This is an instance of the case of each database corresponding to a different label. It also brings up natural privacy issues.
3. Suppose k hospitals with different distributions of patients want to learn a classifier to identify a common misdiagnosis. Here, in addition to the goal of achieving high accuracy, low communication, and privacy for patients, the hospitals may want to protect their own privacy in some formal way as well.

We note that we are interested in learning a single hypothesis h that performs well overall, rather than separate hypotheses h_i for each database. For instance, in the case that one database has all the positive examples and another has all the negatives, the latter problem becomes trivial. More generally, we are interested in understanding the fundamental communication complexity questions involved in distributed learning, a topic that is becoming increasingly relevant to modern learning problems. These issues, moreover, appear to be quite interesting even for the case of $k = 2$ entities.

1.1. Our Contributions

We consider and analyze fundamental communication questions in PAC-learning from distributed data, providing general upper and lower bounds on the amount of communication needed to learn a given class, as well as broadly-applicable techniques for achieving communication-efficient learning. We also analyze a number of important specific classes, giving efficient learning algorithms with especially good communication performance, as well as in some cases counterintuitive distinctions between proper and non-proper learning.

Our general upper and lower bounds show that in addition to VC-dimension and covering number, quantities such as the teaching-dimension and mistake-bound of a class play an important role in determining communication requirements. We also show how boosting can be performed in a communication-efficient manner, achieving communication depending only logarithmically on $1/\epsilon$ for any class, along with tradeoffs between total communication and number of communication rounds. Further we show that, ignoring computation, agnostic learning can be performed to error $O(\text{opt}(\mathcal{H})) + \epsilon$ with logarithmic dependence on $1/\epsilon$, by adapting results of [Balcan and Hanneke \(2012\)](#).

In terms of specific classes, we present several tight bounds including a $\Theta(d \log d)$ bound on the communication in bits needed for learning the class of decision lists over $\{0, 1\}^d$. For learning linear separators, we show that for non-concentrated distributions, we can

use a version of the Perceptron algorithm to learn using only $O(\sqrt{d \log(d/\epsilon)}/\epsilon^2)$ rounds of communication, each round sending only a single hypothesis vector, much less than the $O(d/\epsilon^2)$ total number of updates performed by the Perceptron algorithm. For parity functions, we give a rather surprising result. For the case of two entities, while proper learning has an $\Omega(d^2)$ lower bound based on classic results in communication complexity, we show that *non-proper* learning can be done efficiently using only $O(d)$ bits of communication. This is a by-product of a general result regarding concepts learnable in the reliable-useful framework of Rivest and Sloan (1988). For a table of results, see Appendix A.

We additionally present an analysis of communication-efficient privacy-preserving learning algorithms, considering both *differential privacy* and a notion of *distributional privacy* that is especially appealing in this context. We show that in many cases we can achieve privacy without incurring any additional communication penalty.

More broadly, in this work we propose and study communication as a fundamental resource for PAC-learning in addition to the usual measures of time and samples. We remark that all our algorithms for specific classes address communication while maintaining efficiency along the other two axes.

1.2. Related Work

Related work in computational learning theory has mainly focused on the topic of learning and parallel computation. Bshouty (1997) shows that many simple classes that can be PAC learned can not be efficiently learned in parallel with a polynomial number of processors. Long and Servedio (2011) show a parallel algorithm for large margin classifiers running in time $O(1/\gamma)$ compared to more naive implementations costing of $\Omega(1/\gamma^2)$, where γ is the margin. They also show an impossibility result regarding boosting, namely that the ability to call the weak learner oracle multiple times in parallel within a single boosting stage does not reduce the overall number of successive stages of boosting that are required. Collins et al. (2002) give an online algorithm that uses a parallel-update method for the logistic loss, and Zinkevich et al. (2010) give a detailed analysis of a parallel stochastic gradient descent in which each machine processes a random subset of the overall data, combining hypotheses at the very end. All of the above results are mainly interested in reducing the time required to perform learning when data can be randomly or algorithmically partitioned among processors; in contrast, our focus is on a setting in which we begin with data arbitrarily partitioned among the entities. Dekel et al. (2011) consider distributed online prediction with arbitrary partitioning of data streams, achieving strong regret bounds; however, in their setting the goal of entities is to perform well on their *own* sequence of data.

In very recent independent work, Daume III et al. (2012a) examine a setting much like that considered here, in which parties each have an arbitrary partition of an overall dataset, and the goal is to achieve low error over the entire distribution. They present communication-efficient learning algorithms for axis-parallel boxes as well as for learning linear separators in R^2 . Daume III et al. (2012b), also independently of our work, extend this to the case of linear separators in R^d , achieving bounds similar to those obtained via our distributed boosting results. Additionally, they consider a range of distributed optimization problems, give connections to streaming algorithms, and present a number of experimental results. Their work overall is largely complementary to ours.

2. Model and Objectives

Our model can be viewed as a distributed version of the PAC model. We have k entities (also called “players”) denoted by K and an instance space X . For each entity $i \in K$ there is a distribution D_i over X that entity i can sample from. These samples are labeled by an unknown target function f . Our goal is to find a hypothesis h which approximates f well on the joint mixture $D(x) = \frac{1}{k} \sum_{i=1}^k D_i(x)$. In the realizable case, we are given a concept class \mathcal{H} such that $f \in \mathcal{H}$; in the agnostic case, our goal is to perform nearly as well as the best $h' \in \mathcal{H}$.

In order to achieve our goal of approximating f well with respect to D , entities can communicate with each other, for example by sending examples or hypotheses. At the end of the process, each entity should have a hypothesis of low error over D . In the *center* version of the model there is also a center, with initially no data of its own, mediating all the interactions. In this case the goal is for the center to obtain a low error hypothesis h . In the *no-center* version, the players simply communicate directly. In most cases, the two models are essentially equivalent; however (as seen in Section 5), the case of parity functions forms a notable exception. We assume the D_i are not known to the center or to any entity $j \neq i$ (in fact, D_i is not known explicitly even by entity i , and can be approximated only via sampling). Finally, let d denote the VC dimension of \mathcal{H} , and ϵ denote our target error rate in the realizable case, or our target gap with respect to $\text{opt}(\mathcal{H})$ in the agnostic case.¹ We will typically think of k as much smaller than d .

Remark: We are assuming all players have the same weight, but all results extend to players with different given weights. We also remark that except for our generic results, all our algorithms for specific classes will be computationally efficient (see Appendix A).

Communication Complexity

Our main focus is on learning methods that minimize the communication needed in order to learn well. There are two critical parameters, the *total communication* (either in terms of bits transmitted or examples or hypotheses transmitted) and *latency* (number of rounds required). Also, in comparison to the baseline algorithm of having each database send all (or a random sample of) its data to a center, we will be looking both at methods that improve over the dependence on ϵ and that improve over the dependence on d in terms of the amount of communication needed (and in some cases we will be able to improve in both parameters). In both cases, we will be interested in the tradeoffs between total communication and the number of communication rounds. The interested reader is referred to [Kushilevitz and Nisan \(1997\)](#) for an excellent exposition of communication complexity.

When defining the exact communication model, it is important to distinguish whether entities can learn information from *not* receiving any data. For the most part we assume an *asynchronous* communication model, where the entities can not deduce any information when they do not receive the data (and there is no assumption about the delay of a message). In a few places we use a much stronger model of *lock-synchronous* communication, where the communication is in time slots (so you can deduce that no one sent a message in a certain time slot) and if multiple entities try to transmit at the same time only one succeeds. Note

1. We will suppress dependence on the confidence parameter δ except in cases where it behaves in a nontrivial manner.

that if we have an algorithm with T time steps and C communication bits in the lock-synchronous model, using an exponential back-off mechanism (Herlihy and Shavit, 2008) and a synchronizer (Peleg, 2000), we can convert it to an asynchronous communication with $O(T \log k)$ rounds and $O((T + C) \log k)$ communication bits.

Privacy

In addition to minimizing communication, it is also natural in this setting to consider issues of privacy, which we examine in Section 10. In particular, we will consider privacy of three forms: *differential privacy for the examples* (the standard form of privacy considered in the literature), *differential privacy for the databases* (viewing each entity as an individual deserving of privacy, which requires k to be large for any interesting statements), and *distributional privacy for the databases* (a weaker form of privacy that we can achieve even for small values of k). See Dwork (2008) for an excellent survey of differential privacy.

3. Baseline approaches and lower bounds

We now describe two baseline methods for distributed learning as well as present general lower bounds.

Supervised Learning: The simplest baseline approach is to just have each database send a random sample of size $O(\frac{1}{k}(\frac{d}{\epsilon} \log \frac{1}{\epsilon}))$ to the center, which then performs the learning. This implies we have a total communication cost of $O(\frac{d}{\epsilon} \log \frac{1}{\epsilon})$ in terms of number of examples transmitted. Note that while the sample received by the center is not precisely drawn from D (in particular, it contains the same number of points from each D_i), the standard double-sample VC-dimension argument still applies, and so with high probability all consistent $h \in \mathcal{H}$ have low error. Similarly, for the agnostic case it suffices to use a total of $O(\frac{d}{\epsilon^2} \log \frac{1}{\epsilon})$ examples. In both cases, there is just one round of communication.

EQ/online algorithms: A second baseline method is to run an Equivalence Query or online Mistake-Bound algorithm at the center. This method is simpler to describe in the lock-synchronization model. In each round the center broadcasts its current hypothesis. If any of the entities has a counter-example, it sends the counter-example to the center. If not, then we are done. The total amount of communication measured in terms of examples and hypotheses transmitted is at most the mistake bound M of the algorithm for learning \mathcal{H} ; in fact, by having each entity run a shadow copy of the algorithm, one needs only to transmit the examples and not the hypotheses. Note that in comparison to the previous baseline, there is now no dependence on ϵ in terms of communication needed; however, the number of rounds may now be as large as the mistake bound M for the class \mathcal{H} . Summarizing,

Theorem 1 *Any class \mathcal{H} can be learned to error ϵ in the realizable case using 1 round and $O(\frac{d}{\epsilon} \log \frac{1}{\epsilon})$ total examples communicated, or M rounds and M total examples communicated, where M is the optimal mistake bound for \mathcal{H} . In the agnostic case, we can learn to error $\text{opt}(\mathcal{H}) + \epsilon$ using 1 round and $O(\frac{d}{\epsilon^2} \log \frac{1}{\epsilon})$ total examples communicated.*

Another baseline approach is for each player to describe an approximation to the joint distribution induced by D_i and f to the center, in cases where that can be done efficiently. See Appendix B.1 for an example.

We now present a general lower bound on communication complexity for learning a class \mathcal{H} . Let $N_{\epsilon,D}(\mathcal{H})$ denote the size of the minimum ϵ -cover of \mathcal{H} with respect to D , and let $N_\epsilon(\mathcal{H}) = \sup_D N_{\epsilon,D}(\mathcal{H})$. Let $d_T(\mathcal{H})$ denote the *teaching dimension* of class \mathcal{H} .²

Theorem 2 *Any class \mathcal{H} requires $\Omega(\log N_{2\epsilon}(\mathcal{H}))$ bits of communication to learn to error ϵ . This implies $\Omega(d)$ bits are required to learn to error $\epsilon \leq 1/8$. For proper learning, $\Omega(\log |\mathcal{H}|)$ bits are required to learn to error $\epsilon < \frac{1}{2d_T(\mathcal{H})}$. These hold even for $k = 2$.*

Proof Consider a distribution D_1 such that $N = N_{2\epsilon,D_1}(\mathcal{H})$ is maximized. Let D_2 be concentrated on a single (arbitrary) point x . In order for player 2 to produce a hypothesis h of error at most ϵ over D , h must have error at most 2ϵ over D_1 . If player 2 receives fewer than $\log_2(N_{2\epsilon}(\mathcal{H})) - 1$ bits from player 1, then (considering also the two possible labels of x) there are less than $N_{2\epsilon}(\mathcal{H})$ possible hypotheses player 2 can output. Thus, there must be some $f \in \mathcal{H}$ that has distance greater than 2ϵ from all such hypotheses with respect to D_1 , and so player 2 cannot learn that function. The $\Omega(d)$ lower bound follows from applying the above argument to the uniform distribution over d points shattered by \mathcal{H} .

For the $\Omega(\log |\mathcal{H}|)$ lower bound, again let D_2 be concentrated on a single (arbitrary) point. If player 2 receives fewer than $\frac{1}{2} \log |\mathcal{H}|$ bits then there must be some $h^* \in \mathcal{H}$ it cannot output. Consider $f = h^*$ and let D_1 be uniform over $d_T(\mathcal{H})$ points uniquely defining f within \mathcal{H} . Since player 2 is a proper learner, it must therefore have error greater than 2ϵ over D_1 , implying error greater than ϵ over D . ■

Note that there is a significant gap between the above upper and lower bounds. For instance, if data lies in $\{0, 1\}^d$, then in terms of d the upper bound in *bits* is $O(d^2)$ but the lower bound is $\Omega(d)$ (or in *examples*, the upper bound is $O(d)$ but the lower bound is $\Omega(1)$). In the following sections, we describe our algorithmic results for improving upon the above baseline methods, as well as stronger communication lower bounds for certain classes. We also show how boosting can be used to generically get only a logarithmic dependence of communication on $1/\epsilon$ for any class, using a logarithmic number of rounds.

4. Intersection-closed classes and version-space algorithms

One simple case where one can perform substantially better than the baseline methods is that of intersection-closed (or union-closed) classes \mathcal{H} , where the functions in \mathcal{H} can themselves be compactly described. For example, the class of conjunctions and the class of intervals on the real line are both intersection-closed. For such classes we have the following.

Theorem 3 *If \mathcal{H} is intersection-closed, then \mathcal{H} can be learned using one round and k hypotheses of total communication.*

Proof Each entity i draws a sample of size $O(\frac{1}{\epsilon}(d \log(\frac{1}{\epsilon}) + \log(k/\delta)))$ and computes the smallest hypothesis $h_i \in \mathcal{H}$ consistent with its sample, sending h_i to the center. The center then computes the smallest hypothesis h such that $h \supseteq h_i$ for all i . With probability at

2. $d_T(\mathcal{H})$ is defined as $\max_{f \in \mathcal{H}} d_T(f)$ where $d_T(f)$ is the smallest number of examples needed to uniquely identify f within \mathcal{H} (Goldman and Kearns, 1991).

least $1 - \delta$, h has error at most ϵ on each D_i and therefore error at most ϵ on D overall. ■

Example (conjunctions over $\{0, 1\}^d$): In this case, the above procedure corresponds to each player sending the bitwise-and of all its positive examples to the center. The center then computes the bitwise-and of the results. The total communication in bits is $O(dk)$. Notice this may be substantially smaller than the $O(d^2)$ bits used by the baseline methods.

Example (boxes in d -Dimensions): In this case, each player can send its smallest consistent hypothesis using $2d$ values. The center examines the minimum and maximum in each coordinate to compute the minimal $h \supseteq h_i$ for all i . Total communication is $O(dk)$ values.

In Appendix B.2 we discuss related algorithms based on version spaces.

5. Reliable-useful learning, parity, and lower bounds

A classic lower bound in communication complexity states that if two entities each have a set of linear equalities over n variables, then $\Omega(n^2)$ bits of communication are needed to determine a feasible solution, based on [JáJá and Prasanna \(1984\)](#). This in turn implies that for *proper* learning of parity functions, $\Omega(n^2)$ bits of communication are required even in the case $k = 2$, matching the baseline upper bound given via Equivalence Query algorithms.

Interestingly, however, if one drops the requirement that learning be proper, then for $k = 2$, parity functions *can* be learned using only $O(n)$ bits of communication. Moreover, the algorithm is efficient. This is in fact a special case of the following result for classes that are learnable in the *reliable-useful* learning model of [Rivest and Sloan \(1988\)](#).

Definition 1 ([Rivest and Sloan, 1988](#)) *An algorithm reliably and usefully learns a class \mathcal{H} if given $\text{poly}(n, 1/\epsilon, 1/\delta)$ time and samples, it produces a hypothesis h that on any given example outputs either a correct prediction or the statement “I don’t know”; moreover, with probability at least $1 - \delta$ the probability mass of examples for which it answers “I don’t know” is at most ϵ .*

Theorem 4 *Suppose \mathcal{H} is properly PAC-learnable and is learnable (not necessarily properly) in the reliable-useful model. Then for $k = 2$, \mathcal{H} can be learned in one round with 2 hypotheses of total communication (or $2b$ bits of communication if each $h \in \mathcal{H}$ can be described in $b = O(\log |\mathcal{H}|)$ bits).*

Proof The algorithm is as follows. First, each player i properly PAC-learns f under D_i to error ϵ , creating hypothesis $h_i \in \mathcal{H}$. It also learns f reliably-usefully to create hypothesis g_i having don’t-know probability mass at most ϵ under D_i . Next, each player i sends h_i to the other player (but not g_i , because g_i may take too many bits to communicate since it is not guaranteed to belong to \mathcal{H}). Finally, each player i produces the overall hypothesis “If my own g_i makes a prediction, then use it; else use the hypothesis h_{3-i} that I received from the other player”. Note that each player i ’s final hypothesis has error at most ϵ under both D_i (because of g_i) and D_{3-i} (because h_{3-i} has error at most ϵ under D_{3-i} and g_i never makes a mistake) and therefore has error at most ϵ under D . ■

Example (parity functions): Parity functions are properly PAC learnable (by an arbitrary consistent solution to the linear equations defined by the sample). They are also learnable

in the reliable-useful model by a (non-proper) algorithm that behaves as follows: if the given test example x lies in the span of the training data, then write x as a sum of training examples and predict the corresponding sum of labels. Else output “I don’t know”. Therefore, for $k = 2$, parity functions are learnable with only $O(n)$ bits of communication.

Interestingly, the above result does *not* apply to the case in which there is a center that must also learn a good hypothesis. The reason is that the output of the reliable-useful learning procedure might have large bit-complexity, for example, in the case of parity it has a complexity of $\Omega(n^2)$. A similar problem arises when there are more than two entities.³

However, we *can* extend the result to the case of a center if the overall distribution D over *unlabeled* data is known to the players. In particular, after running the above protocol to error ϵ/d , each player can then draw $O(d/\epsilon)$ fresh unlabeled points from D , label them using its learned hypothesis, and then perform proper learning over this data to produce a new hypothesis $h' \in \mathcal{H}$ to send to the center.

6. Decision Lists

We now consider the class \mathcal{H} of decision lists over d attributes. The best mistake-bound known for this class is $O(d^2)$, and its VC-dimension is $O(d)$. Therefore, the baseline algorithms give a total communication complexity, in bits, of $\tilde{O}(d^2/\epsilon)$ for batch learning and $O(d^3)$ for the mistake-bound algorithm.⁴ Here, we present an improved algorithm, requiring a total communication complexity of only $O(dk \log d)$ bits. This is a substantial savings over both baseline algorithms, especially when k is small. Note that for constant k and for $\epsilon = o(1/d)$, this bound matches the proper-learning $\Omega(d \log d)$ lower bound of Theorem 2.

Theorem 5 *The class of decision lists can be efficiently learned with a total of at most $O(dk \log d)$ bits of communication and a number of rounds bounded by the number of alternations in the target decision list f .*

Proof The algorithm operates as follows.

1. First, each player i draws a sample S_i of size $O(\frac{1}{\epsilon}(d \log(\frac{1}{\epsilon}) + \log(k/\delta)))$, which is sufficient so that consistency with S_i is sufficient for achieving low error over D_i .
2. Next, each player i computes the set T_i of all triplets (j, b_j, c_j) such that the rule “if $x_j = b_j$ then c_j ” is consistent with all examples in S_i . (For convenience, use $j = 0$ to denote the rule “else c_j ”.) Each player i then sends its set T_i to the center.
3. The center now computes the intersection of all sets T_i received and broadcasts the result $T = \cap_i T_i$ to all players, i.e., the collection of triplets consistent with every S_i .
4. Each player i removes from S_i all examples satisfied by T .

3. It is interesting to note that if we allow communication in the classification phase (and not only during learning) then the center can simply send each test example to all entities, and any entity that classifies it has to be correct.

4. One simple observation is the communication complexity of the mistake-bound algorithm can be reduced to $O(d^2 \log d)$ by having each player, in the event of a mistake, send only the identity of the offending rule rather than the entire example; this requires only $O(\log d)$ bits per mistake. However we will be able to beat this bound substantially.

5. Finally, we repeat steps 2,3,4 but in Step 2 each player only sending to the center any *new* rules that have become consistent since the previous rounds (the center will add them into T_i —note that there is never a need to delete any rule from T_i); similarly in Step 3 the center only sends *new* rules that have entered the intersection T . The process ends once an “else c_j ” rule has entered T . The final hypothesis is the decision list consisting of the rules broadcast by the center, in the order they were broadcast.

To analyze the above procedure, note first that since each player announces any given triplet at most once, and any triplet can be described using $O(\log d)$ bits, the total communication in bits per player is at most $O(d \log d)$, for a total of $O(dk \log d)$ overall. Next, note that the topmost rule in f will be consistent with each S_i , and indeed so will all rules appearing before the first alternation in f . Therefore, these will be present in each T_i and thus contained in T . Thus, each player will remove all examples exiting through any such rule. By induction, after k rounds of the protocol, all players will have removed all examples in their datasets that exit in one of the top k alternations of f , and therefore in the next round all rules in the $k + 1$ st alternation of f that have not been broadcast already will be output by the center. This implies the number of rounds will be bounded by the number of alternations of f . Finally, note that the hypothesis produced will by design be consistent with each S_i since a new rule is added to T only when it is consistent with every S_i . ■

7. Linear Separators

We now consider the case of learning homogeneous linear separators in R^d . For this problem, we will for convenience discuss communication in terms of the number of vectors transmitted, rather than bits. However, for data of margin γ , all vectors transmitted can be given using $O(d \log 1/\gamma)$ bits each.

One simple case is when D is a radially symmetric distribution such as the symmetric Gaussian distribution centered at the origin, or the uniform distribution on the sphere. In that case, it is known that $\mathbf{E}_{x \sim D}[\ell(x)x/||x||]$, is a vector exactly in the direction of the target vector, where $\ell(x)$ is the label of x . Moreover, an average over $O(d/\epsilon^2)$ samples is sufficient to produce an estimate of error at most ϵ with high probability (Servedio, 2002). Thus, so long as each player draws a sufficiently large sample S_i , we can learn to any desired error ϵ with a total communication of only k examples: each database simply computes an average over its own data and sends it to the center, which combines the results.

The above result, however, requires very precise conditions on the overall distribution. In the following we consider several more general scenarios: learning a large-margin separator when data is “well-spread”, learning over non-concentrated distributions, and learning linear separators without any additional assumptions.

7.1. Learning large-margin separators when data is well-spread

We say that data is α -well-spread if for all datapoints x_i and x_j we have $\frac{|x_i \cdot x_j|}{||x_i|| ||x_j||} < \alpha$. In the following we show that if data is indeed α -well-spread for a small value of α , then the Perceptron algorithm can be used to learn with substantially less communication than that given by just using its mistake-bound directly as in Theorem 1.

Theorem 6 *Suppose that data is α -well-spread and furthermore that all points have margin at least γ with the target w^* . Then we can find a consistent hypothesis with a version of the Perceptron algorithm using at most $O(k(1 + \alpha/\gamma^2))$ rounds of communication, each round communicating a single hypothesis.*

Proof We will run the algorithm in meta-rounds. Each meta-round will involve a round robin communication between the players $1, \dots, k$. Starting from initial hypothesis $w_0 = \mathbf{0}$, each player i will in turn run the Perceptron algorithm on its data until it finds a consistent hypothesis $w_{t,i}$ that moreover satisfies $|w_t \cdot x_i| > 1$ for all of its examples x_i . It then sends the hypothesis $w_{t,i}$ produced to player $i + 1$ along with the number of updates it performed, who continues this algorithm on its own data, starting from the most recent hypothesis $w_{t,i}$. When player k sends $w_{t,k}$ to player 1, we start meta-round $t + 1$. At the start of meta-round $t + 1$, player 1 counts the number of updates made in the previous meta-round, and if it is less than $1/\alpha$ we stop and output the current hypothesis.

It is known that this “Margin Perceptron” algorithm makes at most $3/\gamma^2$ updates in total.⁵ Note that if in a meta-round all the players make less than $1/\alpha$ updates in total, then we know the hypothesis will still be consistent with all players’ data. That is because each update can decrease the inner product of the hypothesis with some x_i of another player by at most α . So, if less than $1/\alpha$ updates occur, it implies that every player’s examples are still classified correctly. This implies that the total number of communication meta-rounds until a consistent hypothesis is produced will be at most $1 + 3\alpha/\gamma^2$. In particular, this follows because the total number of updates is at most $3/\gamma^2$, and each round, except the last, makes at least $1/\alpha$ updates. ■

7.2. Learning linear separators over non-concentrated distributions

We now use the analysis of Section 7.1 to achieve good communication bounds for learning linear separators over *non-concentrated* distributions. Specifically, we say a distribution over the d -dimensional unit sphere is non-concentrated if for some constant c , the probability density on any point x is at most c times greater than that of the uniform distribution over the sphere. The key idea is that in a non-concentrated distribution, nearly all pairs of points will be close to orthogonal, and most points will have reasonable margin with respect to the target. (See Appendix C.1.)

Theorem 7 *For any non-concentrated distribution D over R^d we can learn to error $O(\epsilon)$ using only $O(k^2 \sqrt{d \log(dk/\epsilon)}/\epsilon^2)$ rounds of communication, each round communicating a single hypothesis vector.*

Note that in Section 8 we show how boosting can be implemented communication-efficiently so that any class learnable to constant error rate from a sample of size $O(d)$ can be learned to error ϵ with total communication of only $O(d \log 1/\epsilon)$ examples (plus a small number of additional bits). However, as usual with boosting, this requires a distribution-independent weak learner. The “ $1/\epsilon^2$ ” term in the bound of Theorem 7 comes from the

5. Because after update τ we get $\|w_{\tau+1}\|^2 \leq \|w_\tau\|^2 + 2\ell(x_i)(w_\tau \cdot x_i) + 1 \leq \|w_\tau\|^2 + 3$.

margin that is satisfied by a $1 - \epsilon$ fraction of points under a non-concentrated distribution, and so the results of Section 8 do not eliminate it.

7.3. Learning linear separators without any additional assumptions

If we are willing to have a bound that depends on the dimension d , then we can run a mistake-bound algorithm for learning linear separators, using Theorem 1. Specifically, we can use a mistake-bound algorithm based on reducing the volume of the version space of consistent hypotheses (which is a polyhedra). The initial volume is 1 and the final volume is γ^d , where γ is the margin of the sample. In every round, each player checks if it has an example that reduces the volume by half (volume of hypotheses consistent with all examples broadcast so far). If it does, it sends it (we are using here the lock-synchronization model). If no player has such an example, then we are done. The hypothesis we have is for each x to predict with the majority of the consistent hypotheses. This gives a total of $O(d \log 1/\gamma)$ examples communicated. In terms of bits, each example has d dimensions, and we can encode each dimension with $O(\log 1/\gamma)$ bits, thus the total number of bits communicated is $O(d^2 \log^2 1/\gamma)$. Alternatively, we can replace the $\log 1/\gamma$ term with a $\log 1/\epsilon$ term by using a PAC-learning algorithm to learn to constant error rate, and then applying the boosting results of Theorem 10 in Section 8 below.

It is natural to ask whether running the Perceptron algorithm in a round-robin fashion could be used to improve the generic $O(1/\gamma^2)$ communication bound given by the baseline results of Theorem 1, for general distributions of margin γ . However, in Appendix C.2 we present an example where the Perceptron algorithm indeed requires $\Omega(1/\gamma^2)$ rounds.

Theorem 8 *There are inputs for $k = 2$ with margin γ such that the Perceptron algorithm takes $\Omega(1/\gamma^2)$ rounds.*

8. Boosting for Logarithmic Dependence on $1/\epsilon$

We now consider the general question of dependence of communication on $1/\epsilon$, showing how boosting can be used to achieve $O(\log 1/\epsilon)$ total communication in $O(\log 1/\epsilon)$ rounds for any concept class, and more generally a tradeoff between communication and rounds.

Boosting algorithms provide a mechanism to produce an ϵ -error hypothesis given access only to a weak learning oracle, which on any distribution finds a hypothesis of error at most some value $\beta < 1/2$ (i.e., a bias $\gamma = 1/2 - \beta > 0$). Most boosting algorithms are *weight-based*, meaning they assign weights to each example x based solely on the performance of the hypotheses generated so far on x , with probabilities proportional to weights.⁶ We show here that any weight-based boosting algorithm can be applied to achieve strong learning of any class with low overall communication. The key idea is that in each round, players need only send enough data to the center for it to produce a weak hypothesis. Once the weak hypothesis is constructed and broadcast to all the players, the players can use it to separately re-weight their own distributions and send data for the next round. No matter

6. E.g., Schapire (1990); Freund (1990); Freund and Schapire (1997). (For Adaboost, we are considering the version that uses a fixed upper bound β on the error of the weak hypotheses.) Normalization may of course be based on overall performance.

how large or small the weights become, each round only needs a small amount of data to be transmitted. Formally, we show the following (proof in Appendix D):

Lemma 9 *Given any weight-based boosting algorithm that achieves error ϵ by making $r(\epsilon, \beta)$ calls to a β -weak learning oracle for \mathcal{H} , we can construct a distributed learning algorithm achieving error ϵ that uses $O(r(\epsilon, \beta))$ rounds, each involving $O((d/\beta) \log(1/\beta))$ examples and an additional $O(k \log(d/\beta))$ bits of communication per round.*

By adjusting the parameter β , we can trade off between the number of rounds and communication complexity. In particular, using Adaboost (Freund and Schapire, 1997) in Lemma 9 yields the following result (plugging in $\beta = 1/4$ or $\beta = \epsilon^{1/c}$ respectively):

Theorem 10 *Any class \mathcal{H} can be learned to error ϵ in $O(\log \frac{1}{\epsilon})$ rounds and $O(d)$ examples plus $O(k \log d)$ bits of communication per round. For any $c \geq 1$, \mathcal{H} can be learned to error ϵ in $O(c)$ rounds and $O(\frac{d}{\epsilon^{1/c}} \log \frac{1}{\epsilon})$ examples plus $O(k \log \frac{d}{\epsilon})$ bits communicated per round.*

Thus, any class of VC-dimension d can be learned using $O(\log \frac{1}{\epsilon})$ rounds and a total of $O(d \log \frac{1}{\epsilon})$ examples, plus a small number of extra bits of communication.

9. Agnostic Learning

Balcan and Hanneke (2012) show that any class \mathcal{H} can be agnostically learned to error $O(\text{opt}(\mathcal{H})) + \epsilon$ using only $\tilde{O}(d \log 1/\epsilon)$ label requests, in an active learning model where class-conditional queries are allowed. We can use the core of their result to agnostically learn any finite class \mathcal{H} to error $O(\text{opt}(\mathcal{H})) + \epsilon$ in our setting, with a total communication that depends only (poly)logarithmically on $1/\epsilon$. The key idea is that we can simulate their robust generalized halving algorithm using communication proportional only to the number of class-conditional queries their algorithm makes. The proof appears in Appendix E.

Theorem 11 *Any finite class \mathcal{H} can be learned to error $O(\text{opt}(\mathcal{H})) + \epsilon$ with a total communication of $O(k \log(|\mathcal{H}|) \log \log(|\mathcal{H}|) \log(1/\epsilon))$ examples and $O(k \log(|\mathcal{H}|) \log \log(|\mathcal{H}|) \log^2(1/\epsilon))$ additional bits. The latter may be eliminated if shared randomness is available.*

10. Privacy

In the context of distributed learning, it is also natural to consider the question of privacy. We begin by considering the well-studied notion of differential privacy with respect to the examples, showing how this can be achieved in many cases without any increase in communication costs. We then consider the case that one would like to provide additional privacy guarantees for the players themselves. One option is to view each player as a single (large) example, but this requires many players to achieve any nontrivial accuracy guarantees. Thus, we also consider a natural notion of distributional privacy, in which players do not view their distribution D_i as sensitive, but rather only the sample S_i drawn from it. We analyze how large a sample is sufficient so that players can achieve accurate learning while not revealing more information about their sample than is inherent in the distribution it was drawn from. Due to space limitations, we present these results in Appendix F.

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Appendix A. Table of results

Class / Category	Communication	Efficient?
Conjunctions over $\{0, 1\}^n$	$O(nk)$ bits	yes
Parity functions over $\{0, 1\}^n$, $k = 2$	$O(n)$ bits	yes
Decision lists over $\{0, 1\}^n$	$O(nk \log n)$ bits	yes
Linear separators in R^d	$O(d \log(1/\epsilon))$ examples*	yes
under radially-symmetric D	$O(k)$ examples	yes
under α -well-spread D	$O(k(1 + \alpha/\gamma^2))$ hypotheses	yes
under non-concentrated D	$O(k^2 \sqrt{d} \log(dk/\epsilon)/\epsilon^2)$ hyps	yes
General Intersection-Closed	k hypotheses	see Note 1 below
Boosting	$O(d \log 1/\epsilon)$ examples*	see Note 2 below
Agnostic learning	$\tilde{O}(k \log(\mathcal{H}) \log(1/\epsilon))$ exs*	see Note 3 below

*: plus low-order additional bits of communication.

Note 1: Efficient if can compute the smallest consistent hypothesis in \mathcal{H} efficiently, and for any given h_1, \dots, h_k , can efficiently compute the minimum $h \supseteq h_i$ for all i .

Note 2: Efficient if can efficiently weak-learn with $O(d)$ examples.

Note 3: Efficient if can efficiently run robust halving algorithm for \mathcal{H} .

Appendix B. Additional simple cases

B.1. Distribution-based algorithms

An alternative basic approach, in settings where it can be done succinctly, is for each entity i to send to the center a representation of its (approximate) distribution over labeled data. Then, given the descriptions, the center can deduce an approximation of the overall distribution over labeled data and search for a near optimal hypothesis. This example is especially relevant for the agnostic 1-dimensional case, e.g., a union of d intervals over $X = [0, 1]$. Each entity first simply sorts the points, and determines d/ϵ border points defining regions of probability mass (approximately) ϵ/d . For each segment between two border points, the entity reports the fraction of positive versus negative examples. It additionally sends the border points themselves. This communication requires $O(d/\epsilon)$ border points and an additional $O(\log d/\epsilon)$ bits to report the fractions within each such interval, per entity. Given this information, the center can approximate the best union of d intervals with error $O(\epsilon)$. Note that the supervised learning baseline algorithm would have a bound of $\tilde{O}(d/\epsilon^2)$ in terms of the number of points communicated.

Theorem 12 *There is an algorithm for agnostically learning a union of d intervals that uses one round and $O(kd/\epsilon)$ values (each either a datapoint or a $\log d/\epsilon$ bit integer), such that the final hypothesis produced has error $\text{opt}(\mathcal{H}) + \epsilon$.*

B.2. Version space algorithms

Another simple case where one can perform well is when the version space can be compactly described. The version space of \mathcal{H} given a sample S_i is the set of all $h \in \mathcal{H}$ which are consistent with S_i . Denote this set by $VerSp(\mathcal{H}, S_i)$.

Generic Version Space Algorithm: Each entity sends $VerSp(\mathcal{H}, S_i)$ to the center. The center computes $V = \cap_i VerSp(\mathcal{H}, S_i)$. Note that $V = VerSp(\mathcal{H}, \cup_i S_i)$. The center can send either V or some $h \in V$.

Example (linear separators in $[0, 1]^2$): Assume that the points have margin γ . We can cover a convex set in $[0, 1]^2$ using $1/\gamma^2$ rectangles, whose union completely covers the convex set, and is completely covered by the convex set extended by γ . Each entity does this for its positive and negative regions, sending this (approximate) version space to the center. This gives a one-round algorithm with communication cost of $O(1/\gamma^2)$ points.

Appendix C. Linear Separators

C.1. Non-concentrated distributions

Proof (Theorem 7) Note that for any non-concentrated distribution D , the probability that two random examples x, x' from D satisfy $|x \cdot x'| > t/\sqrt{d}$ is $e^{-O(t^2)}$. This implies that in a polynomial-size sample (polynomial in d and $1/\epsilon$), with high probability, any two examples x_i, x_j in the sample satisfy $|x_i \cdot x_j| \leq \sqrt{c' \log(d/\epsilon)/n}$ for some constant c' . Additionally, for any such distribution D there exists another constant c'' such that for any $\epsilon > 0$, there is at most ϵ probability mass of D that lies within margin $\gamma_\epsilon = c''\epsilon/\sqrt{d}$ of the target.

These together imply that using the proof idea of Theorem 6, we can learn to error $O(\epsilon)$ using only $O(k^2 \sqrt{d \log(dk/\epsilon)}/\epsilon^2)$ communication rounds. Specifically, each player acts as follows. If the hypothesis w given to it has error at most ϵ on its own data, then it makes no updates and just passes w along. Otherwise, it makes updates using the margin-perceptron algorithm by choosing random examples x from its own distribution D_i satisfying $\ell(x)(w \cdot x) < 1$ until the fraction of examples x under D_i for which $\ell(x)(w \cdot x) < 1$ is at most ϵ , sending the final hypothesis produced to the next player. Since before each update, the probability mass under D_i of $\{x : \ell(x)(w \cdot x) < 1\}$ is at least ϵ , the probability mass of this region under D is at least $\epsilon/(2k)$. This in turn means there is at least a $1/2$ probability that the example used for updating has margin at least $\frac{1}{2}\gamma_{\epsilon/(2k)} = \Omega(\epsilon/(k\sqrt{d}))$ with respect to the target. Thus, the total number of updates made over the entire algorithm will be only $O(dk^2/\epsilon^2)$. Since the process will halt if all players make fewer than $1/\alpha$ updates in a meta-round, for $\alpha = \sqrt{c' \log(2dk/\epsilon)/n}$, this implies the total number of communication meta-rounds is $O(k^2 \sqrt{d \log(d/\epsilon)}/\epsilon^2)$. ■

C.2. Margin lower bound

Proof (Theorem 8) Suppose we have two players, each with their own set of examples, such that the combined dataset has a linear separator of margin γ . Suppose furthermore we run the perceptron algorithm where each player performs updates on their own dataset until consistent (or at least until low-error) and then passes the hypothesis on to the other player, with the process continuing until one player receives a hypothesis that is already low-error on its own data. How many rounds can this take in the worst case?

Below is an example showing a problematic case where this can indeed result in $\Omega(1/\gamma^2)$ rounds.

In this example, there are 3 dimensions and the target vector is $(0, 1, 0)$. Player 1 has the positive examples, with 49% of its data points at location $(1, \gamma, 3\gamma)$ and 49% of its data points are at location $(1, \gamma, -\gamma)$. The remainder of player 1's points are at location $(1, \gamma, \gamma)$. Player 2 has the negative examples. Half of its data points are at location $(1, -\gamma, -3\gamma)$ and half of its data points are at location $(1, -\gamma, \gamma)$.

The following demonstrates a bad sequence of events that can occur, with the two players essentially fighting over the first coordinate:

player	updates using	producing hypothesis
player 1	$(1, \gamma, \gamma), +$	$(1, \gamma, \gamma)$
player 2	$(1, -\gamma, -3\gamma), -$	$(0, 2\gamma, 4\gamma)$
player 2	$(1, -\gamma, \gamma), -$	$(-1, 3\gamma, 3\gamma)$
player 1	$(1, \gamma, 3\gamma), +$	$(0, 4\gamma, 6\gamma)$
player 1	$(1, \gamma, -\gamma), +$	$(1, 5\gamma, 5\gamma)$
player 2	$(1, -\gamma, -3\gamma), -$	$(0, 6\gamma, 8\gamma)$
player 2	$(1, -\gamma, \gamma), -$	$(-1, 7\gamma, 7\gamma)$
player 1	$(1, \gamma, 3\gamma), +$	$(0, 8\gamma, 10\gamma)$
player 1	$(1, \gamma, -\gamma), +$	$(1, 9\gamma, 9\gamma)$
...		

Notice that when the hypothesis looks like $(-1, k\gamma, k\gamma)$, then the dot-product with the example $(1, \gamma, 3\gamma)$ from player 1 is $-1 + 4k\gamma^2$. So long as this is negative, player 1 will make two updates producing hypothesis $(1, (k + 2)\gamma, (k + 2)\gamma)$. Then, so long as $4(k + 2)\gamma^2 < 1$, player 2 will make two updates producing hypothesis $(-1, (k + 4)\gamma, (k + 4)\gamma)$. Thus, this procedure will continue for $\Omega(1/\gamma^2)$ rounds. ■

Appendix D. Boosting

We present here the proof of Lemma 9, showing how boosting can be implemented in a communication-efficient manner. For convenience we restate the lemma below.

Lemma 9 *Given any weight-based boosting algorithm that achieves error ϵ by making $r(\epsilon, \beta)$ calls to a β -weak learning oracle for \mathcal{H} , we can construct a distributed learning algorithm achieving error ϵ that uses $O(r(\epsilon, \beta))$ rounds, each involving $O((d/\beta) \log(1/\beta))$ examples and an additional $O(k \log(d/\beta))$ bits of communication per round.*

Proof The key property of weight-based boosting algorithms that we will use is that they maintain a current distribution such that the probability mass on any example x is solely a function of the performance of the weak-hypotheses seen so far on x , except for a normalization term that can be communicated efficiently. This will allow us to perform boosting in a distributed fashion. Specifically, we run the boosting algorithm in rounds, as follows.

Initialization: Each player i will have a weight $w_{i,t}$ for round t . We begin with $w_{i,0} = 1$ for all i . Let $W_t = \sum_{i=1}^k w_{i,t}$ so initially $W_0 = k$. These weights will all be known to the center. Each player i will also have a large weighted sample S_i , drawn from D_i ,

known only to itself. S_i will be weighted according to the specific boosting algorithm (and for all standard boosting algorithms, the points in S_i begin with equal weights). We now repeat the following steps for $t = 1, 2, 3, \dots$

1. **Pre-sampling** The center determines the number of samples $n_{i,t}$ to request from each player i by sampling $O(\frac{d}{\beta} \log \frac{1}{\beta})$ times from the multinomial distribution $w_{i,t-1}/W_{t-1}$. It then sends each player i the number $n_{i,t}$, which requires only $O(\log \frac{d}{\beta})$ bits.
2. **Sampling** Each player i samples $n_{i,t}$ examples from its local sample S_i in proportion to its own internal example weights, and sends them to the center.
3. **Weak-learning** The center takes the union of the received examples and uses these $O(\frac{d}{\beta} \log \frac{1}{\beta})$ samples to produce a weak hypothesis h_t of error at most $\beta/2$ over the current weighted distribution, which it then sends to the players.⁷
4. **Updating** Each player i , given h_t , computes the new weight of each example in S_i using the underlying boosting algorithm and sends their sum $w_{i,t}$ to the center. This sum can be sent to sufficient accuracy using $O(\log \frac{1}{\beta})$ bits.

In each round, steps (1) and (2) ensure that the center receives $O((d/\beta) \log(1/\beta))$ examples distributed according to a distribution D' matching that given by the boosting algorithm, except for small rounding error due to the number of bits sent in step (4). Specifically, the variation distance between D' and the distribution given by the boosting algorithm is at most $\beta/2$. Therefore, in step (3), it computes a hypothesis h_t with error at most $\beta/2 + \beta/2 = \beta$ with respect to the current distribution given by the boosting algorithm. In step (4), the examples in all sets S_i then have their weights updated as determined by the boosting algorithm, and the values $w_{i,t}$ transmitted ensure that the normalizations are correct. Therefore, we are simulating the underlying boosting algorithm having access to a β -weak learner, and so the number of rounds is $r(\epsilon, \beta)$. The overall communication per round is $O((d/\beta) \log(1/\beta))$ examples plus $O(k \log(d/\beta))$ bits for communicating the numbers $n_{i,t}$ and $w_{i,t}$, as desired. \blacksquare

Appendix E. Agnostic Learning

We now prove Theorem 11. For convenience we restate the theorem below.

Theorem 11 *Any finite class \mathcal{H} can be learned to error $O(\text{opt}(\mathcal{H})) + \epsilon$ with a total communication of $O(k \log(|\mathcal{H}|) \log \log(|\mathcal{H}|) \log(1/\epsilon))$ examples and $O(k \log(|\mathcal{H}|) \log \log(|\mathcal{H}|) \log^2(1/\epsilon))$ additional bits. The latter may be eliminated if shared randomness is available.*

Proof We prove this result by simulating the robust generalized halving algorithm of Balcan and Hanneke (2012), for the case of finite hypothesis spaces, in a communication-efficient manner.⁸ In particular, the algorithm operates as follows. For this procedure,

7. In fact, because we have a broadcast model, technically the players each can observe all examples sent in step (2) and so can simulate the center in this step.
 8. The algorithm of Balcan and Hanneke (2012) for the case of infinite hypothesis spaces begins by using a large unlabeled sample to determine a small ϵ -cover of \mathcal{H} . This appears to be difficult to simulate communication-efficiently.

$N = O(\log \log |\mathcal{H}|)$ and $s = O(1/(\text{opt}(\mathcal{H}) + \epsilon))$ is such that the probability that the best hypothesis in \mathcal{H} will have some error on a set of s examples is a small constant..

1. We begin by drawing N sets S_1, \dots, S_N of size s from D . This can be implemented communication-efficiently as follows. For $j = 1, \dots, N$, player 1 makes s draws from $\{1, \dots, k\}$ to determine the number n_{ij} of points in S_j that should come from each D_i . Player 1 then sends each player i the list $(n_{i1}, n_{i2}, \dots, n_{iN})$, who draws (but keeps internally and does not send) n_{ij} examples of S_j for each $1 \leq j \leq N$. Total communication: $O(kN \log(s))$ bits. Note that if shared randomness is available, then the computation of n_{ij} can be simulated by each player and so in that case no communication is needed in this step.
2. Next we determine which sets S_j contain an example on which the majority-vote hypothesis over \mathcal{H} , $\text{maj}(\mathcal{H})$, makes a mistake, and identify one such example $(\tilde{x}_j, \tilde{y}_j)$ for each such set. We can implement this communication-efficiently by having each player i evaluate $\text{maj}(\mathcal{H})$ on its own portion of each set S_j and broadcast a mistake for each set on which at least one mistake is made. Total communication: $O(kN)$ examples.
3. If no more than $N/3$ sets S_j contained a mistake for $\text{maj}(\mathcal{H})$ then halt. Else, remove from \mathcal{H} each h that made mistakes on more than $N/9$ of the identified examples $(\tilde{x}_j, \tilde{y}_j)$, and go to (1). This step can be implemented separately by each player without any communication.

Balcan and Hanneke (2012) show that with high probability the above process halts within $O(\log |\mathcal{H}|)$ rounds, does not remove the optimal $h \in \mathcal{H}$, and furthermore that when it halts, $\text{maj}(\mathcal{H})$ has error $O(\text{opt}(\mathcal{H}) + \epsilon)$. The total amount of communication is therefore $O(k \log(|\mathcal{H}|) \log \log(|\mathcal{H}|))$ examples and $O(k \log(|\mathcal{H}|) \log \log(|\mathcal{H}|) \log(1/\epsilon))$ additional bits. The above has been assuming that the value of $\text{opt}(\mathcal{H})$ is known; if not then one can perform binary search, multiplying the above quantities by an additional $O(\log(1/\epsilon))$ term. Thus, we achieve the desired error rate within the desired communication bounds. ■

Appendix F. Privacy

As mentioned in Section 10, We consider here three types of privacy: differential privacy on behalf of the individual examples, differential privacy on behalf of the entities, and a notion of distributional privacy. For each, we examine how it can be achieved and effects on communication.

F.1. Differential privacy with respect to individual examples

In this setting we imagine that each entity i (e.g., a hospital) is responsible for the privacy of each example $x \in S_i$ (e.g., its patients). In particular, suppose σ denotes a sequence of interactions between entity i and the other entities or center, and $\alpha > 0$ is a given privacy parameter. Differential privacy asks that for any S_i and any modification S'_i of S_i in which any one example has been arbitrarily changed, for all σ we have $e^{-\alpha} \leq \Pr_{S_i}(\sigma) / \Pr_{S'_i}(\sigma) \leq$

e^α , where probabilities are over internal randomization of entity i . (See Dwork (2006, 2008, 2009) for a discussion of motivations and properties of differential privacy and a survey of results).

In our case, one natural approach for achieving privacy is to require that all interaction with each entity i be in the form of statistical queries (Kearns, 1998). It is known that statistical queries can be implemented in a privacy-preserving manner (Dwork and Nissim, 2004; Blum et al., 2005; Kasiviswanathan et al., 2008), and in particular that a sample of size $O(\max[\frac{M}{\alpha\tau}, \frac{M}{\tau^2}] \log(M/\delta))$ is sufficient to preserve privacy while answering M statistical queries to tolerance τ with probability $1 - \delta$. For completeness, we present the proof below.

Theorem 13 (Dwork and Nissim, 2004; Blum et al., 2005; Kasiviswanathan et al., 2008) *If \mathcal{H} is learnable using M statistical queries of tolerance τ , then \mathcal{H} is learnable preserving differential privacy with privacy parameter α from a sample S of size $O(\max[\frac{M}{\alpha\tau}, \frac{M}{\tau^2}] \log(M/\delta))$.*

Proof For a single statistical query, privacy with parameter α' can be achieved by adding Laplace noise of width $O(\frac{1}{\alpha'|S|})$ to the empirical answer of the query on S . That is because changing a single entry in S can change the empirical answer by at most $1/|S|$, so by adding such noise we have that for any v , $\Pr_S(v)/\Pr_{S'}(v) \leq e^{\alpha'}$. Note that with probability at least $1 - \delta'$, the amount of noise added to any given answer is at most $O(\frac{1}{\alpha'|S|} \log(1/\delta'))$. Thus, if the overall algorithm requires M queries to be answered to tolerance τ , then setting $\alpha' = \alpha/M, \delta' = \delta/(2M), \tau = O(\frac{1}{\alpha'|S|} \log(1/\delta'))$, privacy can be achieved so long as we have $|S| = O(\max[\frac{M}{\alpha\tau}, \frac{M}{\tau^2}] \log(M/\delta))$, where the second term of the max is the sample size needed to achieve tolerance τ for M queries even without privacy considerations. As described in Dwork et al. (2010), one can achieve a somewhat weaker privacy guarantee using $\alpha' = O(\alpha/\sqrt{M})$. ■

However, this generic approach may involve significant communication overhead over the best non-private method. Instead, in many cases we can achieve privacy without any communication overhead at all by performing statistical queries *internally to the entities*. For example, in the case of intersection-closed classes, we have the following privacy-preserving version of Theorem 3.

Theorem 14 *If \mathcal{H} can be properly learned via statistical queries to D^+ only, then \mathcal{H} can be learned using one round and k hypotheses of total communication while preserving differential privacy.*

Proof Each entity i learns a hypothesis $h_i \in \mathcal{H}$ using privacy-preserving statistical queries to its own D_i^+ , and sends h_i to the center. Note that $h_i \subseteq f$ because the statistical query algorithm must succeed for any possible D^- . Therefore, the center can simply compute the minimal $h \in \mathcal{H}$ such that $h \supseteq h_i$ for all i , which will have error at most ϵ over each D_i and therefore error at most ϵ over D . ■

For instance, the class of conjunctions can be learned via statistical queries to D^+ only by producing the conjunction of all variables x_j such that $\Pr_{D_i^+}[x_j = 0] \leq \frac{\epsilon}{2n} \pm \tau$, for $\tau = \frac{\epsilon}{2n}$. Thus, Theorem 14 implies that conjunctions can be learned in a privacy-preserving manner without any communication overhead.

Indeed, in all the algorithms for specific classes given in this paper, except for parity functions, the interaction between entities and their data can be simulated with statistical queries. For example, the decision list algorithm of Theorem 5 can be implemented by having each entity identify rules to send to the center via statistical queries to D_i . Thus, in these or any other cases where the information required by the protocol can be extracted by each entity using statistical queries to its own data, there is no communication overhead due to preserving privacy.

F.2. Differential privacy with respect to the entities

One could also ask for a stronger privacy guarantee, that each *entity* be able to plausibly claim to be holding any other dataset it wishes; that is, to require $e^{-\alpha} \leq \Pr_{S_i}(\sigma) / \Pr_{S'}(\sigma) \leq e^\alpha$ for all S_i and all (even unrelated) S' . This in fact corresponds precisely to the *local privacy* notion of Kasiviswanathan et al. (2008), where in essence the only privacy-preserving mechanisms possible are via randomized-response.⁹ They show that any statistical query algorithm can be implemented in such a setting; however, because each entity is now viewed as essentially a single datapoint, to achieve any nontrivial accuracy, k must be quite large.

F.3. Distributional privacy

If the number of entities is small, but we still want privacy with respect to the entities themselves, then one type of privacy we *can* achieve is a notion of *distributional privacy*. Here we guarantee that that each player i reveals (essentially) no more information about its own sample S_i than is inherent in D_i itself. That is, we think of S_i as “sensitive” but D_i as “non-sensitive”. Specifically, let us say a probabilistic mechanism A for answering a request q satisfies (α, δ) *distributional privacy* if

$$\Pr_{S, S' \sim D_i} \left[\forall v, e^{-\alpha} \leq \frac{\Pr_A(A(S, q) = v)}{\Pr_A(A(S', q) = v)} \leq e^\alpha \right] \geq 1 - \delta.$$

In other words, with high probability, two random samples S, S' from D_i have nearly the same probability of producing any given answer to request q . Blum et al. (2008) introduce a similar privacy notion,¹⁰ which they show is strictly stronger than differential privacy, but do not provide efficient algorithms. Here, we show how distributional privacy can be implemented efficiently.

Notice that in this context, an ideal privacy preserving mechanism would be for player i to somehow use its sample to reconstruct D_i perfectly and then draw a “fake” sample from D_i to use in its communication protocol. However, since reconstructing D_i perfectly is not in general possible, we instead will work via statistical queries.

Theorem 15 *If \mathcal{H} is learnable using M statistical queries of tolerance τ , then \mathcal{H} is learnable preserving distributional privacy from a sample of size $O(\frac{M^2 \log^3(M/\delta)}{\alpha^2 \tau^2})$.*

9. For example, if an entity is asked a question such as “do you have an example with $x_i = 1$ ”, then it flips a coin and with probability $1/2 + \alpha'$ gives the correct answer and with probability $1/2 - \alpha'$ gives the incorrect answer, for some appropriate α' .

10. In the notion of Blum et al. (2008), D_i is uniform over some domain and sampling is done without replacement.

Proof We will show that we can achieve distributional privacy using statistical queries by adding additional Laplace noise beyond that required solely for differential privacy of the form in Section F.1.

Specifically, for any statistical query q , Hoeffding bounds imply that with probability at least $1 - \delta'$, two random samples of size N will produce answers within $\beta = O(\sqrt{\log(1/\delta')/N})$ of each other (because each will be within $\beta/2$ of the expectation with probability at least $1 - \delta'/2$). This quantity β can now be viewed as the “global sensitivity” of query q for distributional privacy. In particular, it suffices to add Laplace noise of width $O(\beta/\alpha')$ in order to achieve privacy parameter α' for this query q because we have that with probability at least $1 - \delta'$, for two random samples S, S' of size N , for any v , $\Pr(A(S, q) = v)/\Pr(A(S', q) = v) \leq e^{\beta/(\beta/\alpha')} = e^{\alpha'}$. Note that this has the property that with probability at least $1 - \delta'$, the amount of noise added to any given answer is at most $O((\beta/\alpha') \log(1/\delta'))$.

If we have a total of M queries, then it suffices for preserving privacy over the entire sequence to set $\alpha' = \alpha/M$ and $\delta' = \delta/M$. In order to have each query answered with high probability to within $\pm\tau$, it suffices to have $\beta + (\beta/\alpha') \log(1/\delta') \leq c\tau$ for some constant c , where the additional (low-order) β term is just the statistical estimation error without added noise. Solving for N , we find that a sample of size $N = O(\frac{M^2 \log^3(M/\delta)}{\alpha^2 \tau^2})$ is sufficient to maintain distributional privacy while answering each query to tolerance τ , as desired. ■

As in the results of Section F.1, Theorem 15 implies that if each player can run its portion of a desired communication protocol while only interacting with its own data via statistical queries, then so long as $|S_i|$ is sufficiently large, we can implement distributional privacy without any communication penalty by performing internal statistical queries privately as above. For example, combining Theorem 15 with the proof of Theorem 14 we have:

Theorem 16 *If \mathcal{H} can be properly learned via statistical queries to D^+ only, then \mathcal{H} can be learned using one round and k hypotheses of total communication while preserving distributional privacy.*