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On the Structure of Learnability beyond $\mathsf{P/poly}$

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Abstract

Motivated by the goal of showing stronger structural results about the complexity of learning, we study the learnability of strong concept classes beyond $\mathsf{P/poly}$, such as $\mathsf{PSPACE/poly}$ and $\mathsf{EXP/poly}$. We show the following:

1. (Unconditional Lower Bounds for Learning) Building on [KKO13], we prove unconditionally that $\mathsf{BPE/poly}$ cannot be weakly learned in polynomial time over the uniform distribution, even with membership and equivalence queries.
2. (Robustness of Learning) For the concept classes $\mathsf{EXP/poly}$ and $\mathsf{PSPACE/poly}$, we unconditionally show that worst-case and average-case learning are equivalent, that PAC-learnability and learnability over the uniform distribution are equivalent, and that membership queries do not help in either case.
3. (Reducing Succinct Search to Decision for Learning) For the decision problems $\mathsf{R_{Kt}}$ and $\mathsf{R_{KS}}$ capturing the complexity of learning $\mathsf{EXP/poly}$ and $\mathsf{PSPACE/poly}$ respectively, we show a *succinct search to decision* reduction: for each of these problems, the problem is in BPP iff there is a probabilistic polynomial-time algorithm computing circuits encoding proofs for positive instances of the problem. This is shown via a more general result giving succinct search to decision results for $\mathsf{PSPACE}, \mathsf{EXP}$ and NEXP, which might be of independent interest.
4. (Implausibility of Oblivious Strongly Black-Box Reductions showing NP-hardness of learning $\mathsf{NP/poly}$) We define a natural notion of hardness of learning with respect to oblivious strongly black-box reductions. We show that learning $\mathsf{PSPACE/poly}$ is PSPACE-hard with respect to oblivious strongly black-box reductions. On the other hand, if learning $\mathsf{NP/poly}$ is NP-hard with respect to oblivious strongly black-box reductions, the Polynomial Hierarchy collapses.

1 Introduction

What is the complexity of learning polynomial-size circuits? Despite extensive research on this question, our knowledge is still fairly sparse. For weak concept classes such as decision trees [LMN93, KM93], DNFs [LMN93, Jac97] or even constant-depth circuits with parity gates [CIKK16], reasonably efficient learning algorithms under the uniform distribution are known for various models of learning. For stronger concept classes, learning is believed to be hard, but the evidence for this is not as strong as one might hope. Cryptographic assumptions such as the existence of one-way functions are known to imply that learning polynomial-size circuits is hard [KV94a, GGM84]. However, we still seem far from showing that PAC-learning polynomial-size circuits is NP-hard - indeed [ABX08] give negative results for certain kinds of black-box reductions to learning.

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In this paper, we adopt a fresh perspective of approaching the learnability question from above, i.e. via circuit classes which are more powerful than $\mathsf{P/poly}$. We consider commonly held beliefs about the complexity of learning, and establish these beliefs unconditionally for strong concept classes such as $\mathsf{PSPACE/poly}$ and $\mathsf{EXP/poly}$. Of course the very learnability of these concept classes has some unlikely implications, eg., that these classes are approximable by efficient Boolean circuits. The point is that this is still consistent with our complexity-theoretic understanding, and we would like to know what current techniques are capable of proving *unconditionally* about learning. Partly this is to understand the limitations of current techniques, and partly this is to understand what structural properties of the stronger concept classes enable us to show unconditional results about them.

We begin by outlining our main results and comparing them with previous work.

1.1 Unconditional Results for Hardness of Learning

Our first set of results deals with unconditional hardness of learning circuit classes. Most complexity theorists believe that learning polynomial-size circuits is unconditionally hard, but of course proving this is at least as hard as the P vs NP problem. We ask: what is the smallest concept class $\mathcal{C}/\mathsf{poly}$[1] for which we can *prove* learning to be hard? Clearly, if we can prove that $\mathcal{C}/\mathsf{poly}$ cannot be approximated by efficient circuits, i.e., there does not even *exist* a good hypothesis for all concepts in the class, then hardness of learning follows. This observation implies for example that learning MAEXP is hard, by using known circuit lower bounds for this class [BFT98].

But can we show hardness of learning unconditionally for some concept class where it is consistent with our current understanding of complexity theory that a good hypothesis exists for every concept in the class? We give an affirmative answer by ruling out PAC-learning with membership and equivalence queries unconditionally for the class $\mathsf{BPE/poly}$.

The notion of PAC-learning $\mathcal{C}/\mathsf{poly}$, for a uniform class $\mathcal{C}$ above P such as EXP or BPE, can have different interpretations. Standard definitions for PAC-learning (cf. [KV94b]) consider the task of learning to be efficient if it is polynomial in the size of the target concept over n inputs (assume that the accuracy ε and confidence δ are both $1/\mathsf{poly}(n)$) and the hypothesis class is $\mathsf{P/poly}$.[2] The standard definition of PAC-learning in $\mathsf{poly}(n)$ time using $\mathsf{P/poly}$ as its hypothesis class naturally extends to the concept class $\mathcal{C}/\mathsf{poly}$ as the size of the target concept is *still* polynomial in the input size n. For the classes $\mathcal{C}$ we consider, PAC-learnability of $\mathcal{C}/\mathsf{poly}$ in $\mathsf{poly}(n)$ time using polynomial-sized hypothesis circuits is still consistent with our current understanding of complexity theory (as we do not have any unconditional average-case lower bounds for $\mathcal{C}$ against $\mathsf{P/poly}$), and therefore worth studying.

We say that a class $\mathcal{C}$ is (ε, δ)-learnable using membership queries over distribution $\mathcal{D}$ in polynomial time, if there exists a probabilistic polynomial time learning algorithm which given oracle access to any $f \in \mathcal{C}$, with probability at least $1 - \delta$, outputs a polynomial-sized hypothesis circuit that approximates f up to an error ε over the target distribution $\mathcal{D}$. This definition also extends

[1]For any uniform complexity class $\mathcal{C}$, define the class $\mathcal{C}/\mathsf{poly}$ as the set of languages L for which there is a language $\mathcal{C}$-machine M and a family of strings $\{a_n\}$, where $a_n \in \{0,1\}^{\mathsf{poly}(n)}$, such that for every $x \in \{0,1\}^n$, $x \in L \iff M$ accepts (x, a_n)

[2]In general, the definition requires the hypothesis class H to be *polynomially evaluatable*, which means that there exists an algorithm that on input any instance $x \in \{0,1\}^n$ and an encoding of the hypothesis $h \in H_n$, outputs the value $h(x)$ in time polynomial in n and the size of the hypothesis encoding. It is well known that $\mathsf{P/poly}$ is polynomially evaluatable.

to the case of (ε, δ)-learning using random examples.

$\mathsf{BPE/poly}$ can equivalently be defined as the class of languages computable by polynomial-sized circuit families with oracle gates to some function in BPE, with the oracle query size restricted to $O(n)$. We prove the unconditional hardness of learning $\mathsf{BPE/poly}$ in polynomial time using membership queries even over the uniform distribution using $\mathsf{P/poly}$ as the hypothesis class. Hardness of exactly learning $\mathsf{BPE/poly}$ with membership and equivalence queries, even using randomized algorithms follows directly from this via [Ang88].

Theorem 1.1. *For every constant $k \in \mathbb{N}$, $\mathsf{BPE/poly}$ cannot be $(1/2 - 1/n^k, 1/n)$-learnt over the uniform distribution using membership queries by randomized learning algorithms running in polynomial time.*

To prove this, we adapt techniques used by [KKO13, OS17] to show that randomized PAC-learning algorithms imply circuit lower bounds. [TV07] show the existence of a PSPACE-Complete function f^* which is in $\mathsf{DSPACE}[n]$, such that f^* is downward self-reducible and self-correctible (see Section 2 for definitions). Using the techniques of [KKO13], along with the fact that f^* belongs to BPE, we see that PSPACE collapses to BPP. Using a padding argument and diagonalizing $\mathsf{DSPACE}[2^{O(n)}]$ against functions which can be approximated by polynomial-sized circuits, we obtain a contradiction to the fact that for every function in $\mathsf{BPE/poly}$, the learner gives a hypothesis circuit which approximates it well.

1.2 Robustness for Hardness of Learning

We believe that polynomial-size circuits are hard to learn in a *robust* sense, i.e., that the precise details of the learning model do not matter. Hardness should hold irrespective of whether we consider PAC-learning or learning over the uniform distribution, worst-case learning or average-case learning over some samplable distribution on concepts, and whether or not the learning model is allowed to use membership queries. We do not know how to show that this robustness holds for $\mathsf{P/poly}$, but we are able to show it unconditionally for $\mathsf{EXP/poly}$ and $\mathsf{PSPACE/poly}$.

We now consider the class $\mathsf{EXP/poly}$, which can be equivalently defined as the circuit class $\mathsf{P^{EXP}/poly}$ i.e. the class of languages that can be computed by a polynomial sized circuit family with EXP oracle gates.

Showing non-trivial derandomization of BPP, i.e. $\mathsf{EXP} \neq \mathsf{BPP}$, is one of the most fundamental questions in complexity theory.[3] We prove that the problem of non-trivial derandomization of BPP is equivalent to the hardness of learning $\mathsf{EXP/poly}$ efficiently in most standard models of PAC-learning. In addition, these results extend to not just showing that $\mathsf{EXP/poly}$ is hard to learn in the worst-case, but also on average with respect to polynomially samplable distributions over $\mathsf{EXP/poly}$.[4] This also gives us an intriguing situation, where hardness of learning $\mathsf{EXP/poly}$ using random examples also implies the hardness of learning $\mathsf{EXP/poly}$ using membership queries.

The following results are stated for hardness of strong learning. However, they also hold for the setting of weak learnability, by standard equivalences between weak learning and strong learning for PAC-learners [FS97].

[3] It is worth mentioning that [IW01] show that $\mathsf{EXP} \neq \mathsf{BPP}$ is equivalent to the fact that BPP can be derandomized on average in deterministic sub-exponential time (over infinitely many input lengths).

[4] In particular, the results hold for polynomially samplable distribution families over $\mathsf{EXP/poly}$, where for each n, there exists a distribution in the family over circuit encodings of n-variate functions in $\mathsf{EXP/poly}$, implicitly defining a distribution on n-variate functions in $\mathsf{EXP/poly}$ (see Remark 2.3 for more details.)

Theorem 1.2 (**Equivalences for hardness of learning** $\mathsf{EXP/poly}$)**.** *The following statements are equivalent.*

(a) ***Non-trivial derandomization of BPP:*** $\mathsf{EXP} \neq \mathsf{BPP}$.

(b) ***Hardness of PAC-learning*** $\mathsf{EXP/poly}$ ***in the worst-case using random examples:*** *There exists $c \geq 0$, such that* $\mathsf{EXP/poly}$ *is not $(1/n^c, 1/20n)$-PAC-learnable in polynomial time using random examples.*

(c) ***Hardness of PAC-learning*** $\mathsf{EXP/poly}$ ***in the worst-case using membership queries:*** *There exists $c \geq 0$, such that* $\mathsf{EXP/poly}$ *is not $(1/n^c, 1/20n)$-PAC-learnable in polynomial time using membership queries.*

(d) ***Hardness of PAC-learning*** $\mathsf{EXP/poly}$ ***on average using random examples:*** *There exists $c \geq 0$, such that* $\mathsf{EXP/poly}$ *is not $(1/n^c, 1/20n)$-PAC-learnable in polynomial time on average using random examples, with respect to polynomially samplable distributions over* $\mathsf{EXP/poly}$.

(e) ***Hardness of PAC-learning*** $\mathsf{EXP/poly}$ ***on average using membership queries:*** *There exists $c \geq 0$, such that* $\mathsf{EXP/poly}$ *is not $(1/n^c, 1/20n)$-PAC-learnable in polynomial time on average using membership queries, with respect to polynomially samplable distributions over* $\mathsf{EXP/poly}$.

A contrasting result to this is the equivalence between the existence of one-way functions (OWFs) and the hardness of learning $\mathsf{P/poly}$ in polynomial time on average with respect to polynomially samplable distributions over $\mathsf{P/poly}$ using random examples [IL90, BFKL93]. Theorem 1.2 not only lends an analogous equivalence between a complexity theoretic assumption that BPP has a non-trivial derandomization and the hardness of learning $\mathsf{EXP/poly}$ in polynomial time on average using random examples, but also extends this equivalence to hardness of learning $\mathsf{EXP/poly}$ efficiently in the worst-case. Note that showing such an equivalence between the existence of OWFs and hardness of learning $\mathsf{P/poly}$ efficiently in the worst-case has been open for decades.[5]

Furthermore, our proof techniques also let us extend all these equivalences to the case where $\mathcal{C} = \mathsf{PSPACE}$.

Corollary 1.3. *The following statements are equivalent.*

1. $\mathsf{PSPACE} \neq \mathsf{BPP}$.
2. *There exists $c \geq 0$, such that* $\mathsf{PSPACE/poly}$ *is not $(1/n^c, 1/20n)$-PAC-learnable in polynomial time using random examples (also using membership queries).*
3. *There exists $c \geq 0$, such that* $\mathsf{PSPACE/poly}$ *is not $(1/n^c, 1/20n)$-PAC-learnable in polynomial time on average using random examples (also using membership queries) with respect to polynomially samplable distributions over* $\mathsf{PSPACE/poly}$.

Essentially, the proof of showing conditional hardness of PAC-learning $\mathsf{EXP/poly}$ uses the fact that strongly learning $\mathsf{EXP/poly}$ using random examples over the *uniform distribution* implies that

[5] In particular, we do not know if hardness of learning $\mathsf{P/poly}$ efficiently using random examples in the worst-case implies OWFs.

$\mathsf{EXP} = \mathsf{BPP}$. This also means that the hardest distribution to learn $\mathsf{EXP}/\mathsf{poly}$ is over the uniform distribution. The same ideas hold for PAC-learning $\mathsf{EXP}/\mathsf{poly}$ using membership queries too.

Our techniques used to show these equivalences are inspired from results on uniform derandomization by [IW01, TV07], which were further used by [FK09, KKO13] to show circuit lower bounds based on the existence of learning algorithms. We use special properties of functions in EXP and PSPACE like downward self-reducibility and self-correctibility to show that learning these functions would imply a collapse for EXP and PSPACE to BPP.

1.3 Reducing Succinct Search to Decision for Learning

Recently, [CIKK16] established an important connection between *natural proofs* and *learning*. They showed that natural proofs of strong lower bounds against a circuit class $\mathcal{C}/\mathsf{poly}$ imply efficient learning algorithms for $\mathcal{C}/\mathsf{poly}$ over the uniform distribution with membership queries, as long as the class $\mathcal{C}/\mathsf{poly}$ satisfies some mild closure properties. One way to interpret their result is as an *approximate search to decision* reduction for learning. The decision version of learning polynomial-size circuits is the language MCSP consisting of truth tables of functions that have small circuits, i.e., for which a good hypothesis exists. The search version is to find a small circuit for a positive instance of MCSP. [CIKK16] show that if MCSP is polynomial-time decidable (which is implied by the existence of natural proofs against P/poly), then the search version of MCSP can be solved approximately, in the sense that we can efficiently compute a polynomially larger sized circuit that approximates the truth table well.

The language R_{Kt} (resp. R_{KS}) of strings with high Kt complexity (resp. high KS complexity) plays an analogous role to MCSP in the theory of learning $\mathsf{EXP}/\mathsf{poly}$ (resp. $\mathsf{PSPACE}/\mathsf{poly}$). We ask if search to decision reductions can be established for these languages as well. However, it is unclear a priori what it would mean to solve search efficiently for a problem that does not have polynomial-size proofs or witnesses. We introduce the notion of *succinct search*. To efficiently solve a search problem succinctly is to efficiently compute for any YES instance of the problem a circuit that encodes a possibly exponential-size proof for the instance. We use the PCP theorem for NEXP [BFL91] and the Easy Witness Lemma [IKW02] to show that for the classes $\mathsf{PSPACE}, \mathsf{EXP}$ and NEXP, efficient decidability of the class is equivalent to efficiently solving succinct search for every language in the class. We then use results from [ABK+06] to argue that for R_{Kt} and R_{KS}, efficient solvability is equivalent to solving succinct search efficiently. Note that this connection is for succinctly solving the search problem *exactly* rather than just for approximate search as in [CIKK16].

Theorem 1.4 (**Equivalence of Succinct Search and Decision for Learning $\mathsf{EXP}/\mathsf{poly}$ and $\mathsf{PSPACE}/\mathsf{poly}$**)**.** *Let L be R_{Kt} or R_{KS}. $L \in \mathsf{BPP}$ iff for each polynomial-time verifier V for L, succinct search is efficiently solvable for L with respect to V.*

1.4 Barriers for Establishing NP-Hardness of Learning

We next look at questions pertaining to hardness of learning classes of the form $\mathcal{C}/\mathsf{poly}$, where $\mathcal{C} \subseteq \mathsf{PH}$. We only focus on the hardness of PAC-learning $\mathcal{C}/\mathsf{poly}$ with random examples. In this section, we consider the limitations of proving the NP-hardness of PAC-learning $\mathsf{NP}/\mathsf{poly}$, i.e. the class of polynomial size non-deterministic circuits, using random examples, via a black-box reduction from deciding SAT.

Informally, a black-box reduction from problem A to B, solves A given access to any oracle solving B. Black-box reductions have been ubiquitously used in complexity theory to prove conditional lower bounds. However, for many fundamental questions in complexity theory, there have been results showing why such reductions are limited in power. Various results have conditionally ruled out special-cases of black-box reductions for showing average-case hardness of NP [FF93, BT06], existence of one-way functions [AGGM06, ABX08, BB15] and the existence of hitting set generators [HW19], from hardness of SAT.

For the case of showing hardness of learnability, a B-adaptive black-box reduction R from some language L to PAC-learning a class $\mathcal{C}$ using random examples is defined by two phases

- The first phase consists of B adaptive rounds of probabilistic polynomial time algorithms, each of which generates queries to the learner oracle. In more detail, each round uses the input z to the reduction, fresh randomness and the hypotheses returned by the $\mathcal{C}$-learner oracle in the previous rounds, and constructs joint distributions (that serve as example oracles for the learner). It then samples a set of independent labeled examples from each of these distributions as queries to the learner oracle.
- In the second phase, a probabilistic polynomial time algorithm takes all the hypotheses from the first phase and decides whether $z \in L$, with high probability.

[ABX08] study the question of the existence of black-box Turing reductions from any language in NP to PAC-learning $\mathsf{P/poly}$ using random examples. They consider a strongly black-box reduction, where a reduction is strongly black-box if it runs correctly given any oracle for the learner, as well as the hypotheses output by the learner. For a special case of such a reduction, where the access to the learner and the hypothesis oracles is additionally non-adaptive, they show that such a reduction from SAT to PAC-learning $\mathsf{P/poly}$ using random examples collapses NP to CoAM (which implies a collapse of PH to the second level). Additionally, they show that if any language L reduces to PAC-learning $\mathsf{P/poly}$ using random examples via an $O(1)$-adaptive black-box reduction, then the hardness of L implies the existence of an auxiliary-input one-way function (which is a major breakthrough in cryptography).[6]

We define a natural special-case of such a reduction, called an *oblivious* strongly black-box reduction, where the obliviousness of a reduction implies that the queries made to the learner do not depend on the input z to the reduction, and try to understand its limitations for showing NP-hardness of PAC-learning $\mathsf{NP/poly}$. At a first glance, ruling out oblivious reductions may seem very restrictive, since ideally, one would like to allow reductions whose queries to the learner can depend on the input to the reduction. However, we observe the proof of Corollary 1.3 which shows hardness of PAC-learning $\mathsf{PSPACE/poly}$ assuming $\mathsf{PSPACE} \neq \mathsf{BPP}$ and reformulate it as an oblivious black-box reduction of the form defined above. In particular, for f^* being the PSPACE-Complete function given by [TV07] which is downward self-reducible and self-correctible, we observe that

Lemma 1.5. *There exists an oblivious, n-adaptive, strongly black-box reduction from deciding f^* to PAC-learning* $\mathsf{PSPACE/poly}$ *using random examples over the uniform distribution.*

On the other hand, for the case of learning $\mathsf{NP/poly}$ using random examples, we show that oblivious strongly black-box reductions from SAT imply a collapse of the polynomial hierarchy. Our main result for the section is

[6] They also show the impossibility of Karp reductions from SAT to PAC-learning $\mathsf{P/poly}$ using random examples, unless NP collapses to SZKA.

Theorem 1.6 (Informal)**.** *If there exists an oblivious,* $\mathsf{poly}(n)$*-adaptive, strongly black-box reduction from deciding* SAT *to learning* NP/poly *using random examples over polynomially samplable distributions, then* PH *collapses to the third level.*[7]

Theorem 1.6 implies that standard techniques used for worst-case to average-case reductions, pseudo-random generator constructions from uniform hardness assumptions and in particular, hardness of efficiently PAC-learning classes like PSPACE/poly, cannot be used to show the NP-hardness of PAC-learning NP/poly using random examples.

Theorem 1.6 compares to some previous results in the following way:

- It shows a conditional impossibility result by ruling out a restricted version of adaptive, strongly black-box reductions to learning P/poly using random examples, in contrast to [ABX08], who only rule out fully non-adaptive, strongly black-box reductions, from a slightly weaker assumption ($\mathsf{NP} \not\subseteq \mathsf{CoAM}$).

- Furthermore, the result by [HW19] which conditionally rules out a non-adaptive black box reduction from deciding SAT to breaking a Hitting Set Generator (HSG), in turn rules out fully non-adaptive, strongly black-box reductions from SAT to learning NP/poly using membership queries over the uniform distribution (by suitably changing the definition of the reduction to the learner).

  Indeed, the ideas of [IW01] can be used to show that hardness of learning NP/poly using membership queries over the uniform distribution, implies the existence of a hitting set generator which hits sufficiently dense circuits. We strengthen this observation by not only extending the reduction to a restricted version of the adaptive case, but also by ruling out a weaker reduction to learning NP/poly with random examples.

- In a similar way, [GV08] conditionally rule out the existence of mildly adaptive (each query length up to n, where n is the length of the input instance, appears in very few levels of adaptivity), strongly black-box reductions from an EXP-Complete problem to learning NP/poly using membership queries (and in fact, learning EXP/poly).

  Our result rules out the restricted cases of mildly adaptive, strongly black-box reductions which show the NP-hardness of learning NP/poly using random examples and hence, is a conceptual strengthening of [GV08], as we rule out a hardness result from a stronger assumption.

- Schapire [Sch90] showed that $\mathsf{NP/poly} \neq \mathsf{P/poly}$ implies the hardness of PAC-learning NP/poly in polynomial time using random examples. Combining this with Yap's [Yap83] variation on the Karp-Lipton theorem, it follows that if PH does not collapse to the third level, then the same result holds.[8] In other words, assuming a statement stronger than $\mathsf{NP} \neq \mathsf{BPP}$ already implies the hardness of efficiently PAC-learning NP/poly using random examples.

  However, it is unclear if these techniques can be extended to prove hardness of learning NP/poly, assuming $\mathsf{NP} \neq \mathsf{BPP}$. Indeed, [Sch90] proved that there exists a $2^{O(n)}$-time algorithm $\mathcal{A}$, that given oracle access to any $f \in \mathsf{NP/poly}$ over n inputs (or even random example oracle

[7] We actually show a stronger result that the existence of such a reduction implies that $\mathsf{NP} \subseteq \mathsf{CoAM}^{\mathsf{poly}}$, where $\mathsf{CoAM}^{\mathsf{poly}}$ is the class of languages recognized by constant-round CoAM protocols with advice, where we require proper acceptance/rejection probabilities only when the advice is correct.

[8] If $\mathsf{NP/poly} \subseteq \mathsf{P/poly}$, then $\mathsf{NP/poly} = \mathsf{CoNP/poly}$. [Yap83] proved that the latter implies that $\Sigma_3^p = \Pi_3^p$.

access with respect to some distribution $\mathcal{D}_n$), as well as a learner for $\mathsf{NP/poly}$ using random examples, outputs a hypothesis of size $\mathsf{poly}(n)$ which is consistent with the entire truth table of f. As such, his result does not prove hardness using a reduction in our sense, but rather only uses the fact that for any $f \in \mathsf{NP/poly}$ over n inputs, we get a polynomial-sized circuit that computes it, even though the algorithm $\mathcal{A}$ that generates this circuit runs in exponential time and moreover, requires oracle access to f.[9]

It is worth noting that our result has no implications for showing the impossibility of adaptive, black-box NP-hardness reductions which imply the average-case hardness for NP [FF93, BT06], existence of one-way functions [AGGM06, ABX08] or the existence of HSGs [GV08, HW19].

Overview of the techniques: The proof of Theorem 1.6 builds on the Feigenbaum-Fortnow [FF93] protocol, which simulates a type of non-adaptive randomized reduction A from SAT to an NP problem $\mathcal{Q}$, by an AM protocol with polynomial-sized advice, and shows that $\mathsf{coNP} \subseteq \mathsf{NP/poly}$.[10]

Suppose that on input x, A makes q non-adaptive queries to $\mathcal{Q}$, sampled independently from certain distribution X. Very briefly, their AM protocol does the following. For K large enough, the verifier first generates K tuples of q non-adaptive queries by running $A(x)$ independently K times. The verifier asks the prover to send a witness to each query which is a YES instance (which it can verify easily). This ensures that the prover cannot cheat if the query is a NO instance and the only way it can cheat is by claiming a YES instance to be a NO instance. Now, if the verifier has the proportion p of YES instances of $\mathcal{Q}$ over the distribution X, then with high probability it knows that the number of YES instances among the Kq queries is concentrated around $q \cdot (pK \pm O(\sqrt{K}))$. The verifier answers with a reject if the number of YES instances is much lesser than pqK.

The honest prover answers each query correctly (with correct witnesses if necessary) and with high probability, the number of YES instances are close to the expectation. Hence, the verifier can pick any of K runs of $A(x)$ using the prover's answers to its queries and the output will be correct with high probability. On the other hand, the cheating prover cannot cheat on more than $O(q\sqrt{K})$ YES instances, with high probability. If we choose $K \gg O(q\sqrt{K})$, then on most of the K independent runs of A, all its queries are answered correctly and the reduction gives the correct answer. Thus, if we pick one of the runs at random and get $A(x)$ by using the prover's answers to its queries, the verifier answers wrongly with low probability.

Consider an oblivious, B-adaptive, strongly black-box reduction R from L to an oracle which learns $\mathsf{NP/poly}$. Suppose we are able to fix $S_1, \ldots, S_t$, which are sets of labeled examples drawn independently from the joint distributions $(X_1, f_1(X_1)), \ldots, (X_t, f_t(X_t))$ where $f_1, \ldots, f_t \in \mathsf{NP/poly}$, as the queries made to the learner. Furthermore, let $h_1, \ldots, h_t$ be a set of fixed hypotheses circuits, some of which are used to generate $S_1, \ldots, S_t$, such that each h_i $(1 - \varepsilon_0)$-approximates f_i over X_i, for some $\varepsilon_0 > 0$. Because R is strongly black-box, each hypothesis is also accessed as an oracle and we see that L is decided by the algorithm M in the second phase, which has access to $h_1, \ldots, h_t$. Now, the t oracles to M can be replaced by a single oracle $\mathcal{O}$ which takes as input $i \in [t]$ and

[9] In more detail, [Sch90] showed that given a polynomial time learner for $\mathsf{NP/poly}$ using random examples, there exists an algorithm $B(m)$ that takes any m labeled samples of a target $f \in \mathsf{NP/poly}$ over n inputs, runs in time $\mathsf{poly}(m, n)$, and with high probability, outputs a hypothesis of size $\mathsf{poly}(n)$ (independent of m) which is consistent with the m labeled samples. Now, the algorithm $\mathcal{A}$ constructs the entire truth table of f, of size 2^n, using oracle access to f, and runs $B(2^n)$ to output a $\mathsf{poly}(n)$-sized hypothesis circuit that is consistent with f on its entire truth table, thus contradicting the assumption $\mathsf{NP/poly} \neq \mathsf{P/poly}$.

[10] Their motivation (and [BT06]) was to rule out certain kinds of non-adaptive, worst-case to average-case black-box reductions for NP.

$y \in \{0,1\}^n$, and outputs $h_i(y)$ ($\mathcal{O}$ can be thought of as a table with t rows and 2^n columns). We then adapt the techniques of [FF93] to design an AM protocol for L with polynomial sized advice, where the verifier expects that the prover answers according to $\mathcal{O}$.

The obliviousness of the reduction helps us in fixing the queries made by R, and implicitly, the corresponding hypotheses output by the oracle. In other words, this helps us fix the proportions of YES instances for each f_i non-uniformly, as the queries generated to the learner do not depend on the input to the reduction. We do this by inductively fixing the queries made by the reduction starting from the first round of adaptivity. Fixing a "good" polynomial-sized random string r^* used by the first phase non-uniformly (using Adleman's trick), we first get the queries to the learner made in the first round.

For any other round $b \geq 2$, assume that the queries to the learner up to round $(b-1)$ and the functionality of the hypothesis oracles used to generate them up to round $(b-2)$ are fixed. Using the fact that r^* is also fixed, we consider the set of all tuples of joint distributions that can be generated in the b^{th} round depending on the answers to the oracle queries of the hypotheses seen so far, and arbitrarily choose one of them. Note that, this implicitly fixes the functionality of the hypothesis oracles for the queries generated in round $b-1$. We continue this process and fix all the queries made to the learner by all the rounds from the first phase.

1.5 Further Discussion

Connections to Karp-Lipton Style Theorems: There is an analogy between our results on implications of learnability and Karp-Lipton style theorems. A Karp-Lipton style theorem for a uniform class $\mathcal{C}$ gives an unlikely uniform implication of the assumption that $\mathcal{C}$ has polynomial-size circuits. The original theorem of Karp and Lipton [KL80] shows such an implication for $\mathcal{C} = \mathsf{NP}$: if $\mathsf{NP} \subseteq \mathsf{P/poly}$, then $\Sigma_2 = \Pi_2$. Karp-Lipton style theorems are now known for many other classes, including $\mathcal{C} = \mathsf{P}^{\#\mathsf{P}}$ [LFKN90], $\mathcal{C} = \mathsf{PSPACE}$ [BFL91] and $\mathcal{C} = \mathsf{EXP}$ [BFL91]. In each of these cases, $\mathcal{C} \subseteq \mathsf{P/poly}$ implies $\mathcal{C} = \mathsf{MA}$, applying techniques from the theory of interactive proofs [LFKN90, BFL91].

Similarly, in some of our results (i.e., Theorem 1.1, Theorem 1.2 and Corollary 1.3), we study implications of learnability for classes $\mathcal{C}/\mathsf{poly}$, where $\mathcal{C} = \mathsf{BPE}, \mathsf{EXP}$ or PSPACE. Since the learner is required to output a polynomial-size Boolean circuit, the learnability assumption already implies that $\mathcal{C}$ is approximated by polynomial-size circuits, where the approximation is over the distribution on the examples. We are interested in establishing strong uniform implications of these assumptions, showing that the assumption is actually false in the case $\mathcal{C} = \mathsf{BPE}$, and that the assumption implies a simulation of $\mathcal{C}$ in BPP in the other cases. What enables us to show stronger implications than in corresponding Karp-Lipton style theorems is that the learner uniformly produces a good hypothesis by our assumption. However, the learner is assumed to have access to random examples or membership queries which cannot be efficiently simulated - this makes our simulation task more challenging, and we therefore exploit various structural properties of complete languages. We also need to deal with the issue of approximation, while standard Karp-Lipton style theorems have as their antecedent an exact simulation by efficient circuits.

Open Questions: One question which stems from our work is to explore the possibility of showing the hardness of PAC-learning $\mathsf{NP/poly}$ efficiently using random examples assuming that $\mathsf{NP} \neq \mathsf{BPP}$. A potential direction is to consider non black-box reductions for the NP-hardness of PAC-learning $\mathsf{NP/poly}$. This viewpoint has lent itself some success in the case of worst-case to average-case reductions [GST07, Hir18, HW19] and in our case, hardness of efficiently PAC-learning $\mathsf{EXP/poly}$. Indeed, the reduction for $\mathsf{EXP/poly}$ only works if the learning algorithm runs in polynomial time, although the reduction still uses the learning algorithm as an oracle.[11] Moreover, [CHO+20] show a non black-box reduction from an approximate version of MCSP to learning $\mathsf{P/poly}$ by sub-exponential-sized circuits (and thus, learning $\mathsf{NP/poly}$). Note that, it is unclear if approximate MCSP is NP-hard and this reduction does not imply the NP-hardness of PAC-learning $\mathsf{NP/poly}$ efficiently.

Another important question is to explore an analogue of the PH collapse for learnability. In other words, does polynomial time learnability of $\mathsf{NP/poly}$ imply polynomial time learnability of $\mathsf{PH/poly}$? Note that, under a strong assumption of the existence of a (possibly adaptive and non-relativizable) worst-case to average-case reduction for NP, we can use the techniques in Lemma 4.2 along with the downward-self-reducibility of SAT to show such a collapse. On the other hand, [Imp11] also shows that there exists an oracle O with respect to which $\mathsf{DistNP}^O \subseteq \mathsf{AvgP}^O$ and $\Sigma_2^O \not\subseteq \mathsf{HeurSIZE}^O[2^{n^\alpha}]$. Essentially, this result negates the existence of any relativizable reductions which show a statement analogous to the PH collapse for average-case algorithms i.e. if NP is easy on average, then Σ_2 is easy on average too. In a similar spirit, can we prove that no relativizable technique can show that if $\mathsf{NP/poly}$ is learnable in polynomial time, then $\Sigma_2\mathsf{/poly}$ is learnable in polynomial time as well?

2 Preliminaries

Let $\mathcal{F} = \{\mathcal{F}_n\}$, where $\mathcal{F}_n$ is set of all Boolean functions over $\{0,1\}^n$, where each $f_n \in \mathcal{F}_n$ is a function $f_n : \{0,1\}^n \to \{0,1\}$. Define $\mathsf{tt}(f)$ as the truth table of a function f_n of length 2^n. On the other hand, given a string $x \in \{0,1\}^{2^n}$, define $\mathsf{fn}(x)$ as the function on n inputs whose truth table is x. For every $n \in \mathbb{N}$, define U_n as the uniform distribution over $\{0,1\}^n$.

2.1 Samplability and Learnability

Let $\mathcal{C} = \{\mathcal{C}_n\}$, where $\mathcal{C}_n \subseteq \mathcal{F}_n$ be a class of functions over $\{0,1\}^n$ and $\mathcal{D} = \{\mathcal{D}_n\}$ be a distribution family over $\{0,1\}^*$, where $\mathcal{D}_n$ is a distribution over $\{0,1\}^n$.

Definition 2.1 (Worst-case PAC-learning using random examples). *For any $0 \le \epsilon, \delta < 1/2$, a class $\mathcal{C}$ is (ϵ,δ)-PAC-learnable in the worst-case using random examples in time $T(n)$, if there exists a randomized algorithm $\mathcal{A}$ such that*

- *For every $n \in N$, for every $f \in \mathcal{C}_n$, for every $\mathcal{D}_n$ over $\{0,1\}^n$, $\mathcal{A}$ takes inputs $1^n, \epsilon, \delta$, a set of $m = m(n)$ labeled samples $(x_1, f(x_1)), \ldots, (x_m, f(x_m))$ where each $x_i \sim \mathcal{D}_n$, and $w \in \{0,1\}^{r(n)}$ as internal randomness. $\mathcal{A}$ then outputs the description of a circuit h such that*

$$\Pr_{w \in \{0,1\}^{r(n)}, x_1, \ldots, x_m \sim \mathcal{D}_n} \left\{ \Pr_{y \in \mathcal{D}_n} \{h(y) = f(y)\} \ge 1 - \varepsilon \right\} \ge 1 - \delta$$

- *$\mathcal{A}$ runs in time at most $T(n)$.*[12]

[11] For EXP to collapse to PSPACE, we need the $\mathsf{EXP/poly}$ learner to be efficient so that it outputs polynomial-sized hypothesis circuits for any language in EXP, and this further implies $\mathsf{EXP} \subseteq \mathsf{P/poly}$.

[12] Note that this immediately implies that $m(n) \le T(n)$

We can also restrict the learnability to a fixed distribution like the uniform distribution U_n, where the learner takes random examples chosen over the uniform distribution and hypothesis error is also measured over the uniform distribution. Unless specified otherwise, we use the class of polynomial-sized Boolean circuits $\mathsf{P/poly}$, as the hypothesis class for our learning algorithms.

Furthermore, we can extend this definition to PAC-learning over membership queries by giving the learner $\mathcal{A}$ oracle access to the function $f \in \mathcal{C}_n$, in addition to the random examples drawn from some fixed distribution $\mathcal{D}_n$ over $\{0,1\}^n$.

To define learnability on average, let $\mathcal{P} = \{\mathcal{P}_n\}$ be a distribution ensemble over $\mathcal{C}$, where $\mathcal{P}_n$ is a fixed distribution over $\mathcal{C}_n$.

Definition 2.2 (**Samplable distributions**). *Let $\mathcal{P}$ be a distribution ensemble over $\mathcal{C}$, where for every $n \in \mathbb{N}$, $\mathcal{P}_n$ is a distribution over the truth tables of $\mathcal{C}_n$. Let $N = 2^n$. For any non-decreasing function $S(N) \geq N$, we say that $\mathcal{P}$ is samplable in time $S(N)$, if there exists a randomized algorithm A such that for every $N = 2^n$, using $m(N)$ bits of randomness (where $m(N) \leq S(N)$), $A(1^N, y)$ is distributed identically to $\mathcal{P}_n$, where the distribution is over the string y picked uniformly at random from $\{0,1\}^{m(N)}$ and A runs in time $S(N)$.*

In other words, if y is picked uniformly at random from $\{0,1\}^{m(N)}$ then $A(1^N, y)$ outputs a truth table from $\mathcal{C}_n$ which is distributed according to $\mathcal{P}_n$. Furthermore, we say that $\mathcal{P}$ is polynomially samplable if $S(N) = \mathsf{poly}(N)$.

Remark 2.3. *For the special case where $\mathcal{C}$ is a class of fixed polynomial sized circuits like $\mathsf{SIZE}[n^k]$ (or $\mathsf{SIZE}^{\mathsf{EXP}}[n^k]$) for any arbitrary fixed k, we define a circuit representation scheme for $\mathcal{C}_n$ given by the set $R_n \subset \{0,1\}^{r(n)}$, where $r(n) = O(n^k \log n)$, such that every $\sigma \in R_n$ is a $\mathcal{C}$-circuit encoding of a function in $\mathcal{C}_n$. Note that this mapping is onto and each function in $\mathcal{C}_n$ has many representations in R_n. We also assume that there exists a uniform circuit sequence in $\mathcal{C}$, which interprets this encoding as a $\mathcal{C}$-circuit and evaluates computations given this encoding.*

Now, we can define a distribution ensemble $\mathcal{P}$ over $\mathcal{C}$, where each $\mathcal{P}_n$ is a distribution over the $\mathcal{C}$-circuit encodings, which implicitly defines a distribution over $\mathcal{C}_n$. We also define $S(r(n))$-samplability of $\mathcal{P}$, if there exists a randomized algorithm A running in time $S(r(n))$ such that for every $n \in \mathbb{N}$, $A(1^{r(n)}, y)$ is distributed identically to $\mathcal{P}_n$, where the distribution is over the random strings $y \in \{0,1\}^{m(n)}$.

Definition 2.4 (**Average-case learnability** [BFKL93]). *Let $\mathcal{C}$ be a class of Boolean functions and $\mathcal{P} = \{\mathcal{P}_n\}$ be a distribution ensemble over $\mathcal{C}$. For any $0 < \epsilon, \delta < 1/2$, we say that $\mathcal{C}$ is (ϵ, δ)-PAC-learnable on average using random examples with respect to $\mathcal{P}$ in time $T(n)$, if there exists a randomized algorithm $\mathcal{A}$ running in time at most $T(n)$ such that*

- *For every large enough n, for any fixed f drawn according to $\mathcal{P}_n$, for every $\mathcal{D}_n$ over $\{0,1\}^n$, $\mathcal{A}$ takes inputs $1^n, \varepsilon, \delta$, a set of $m = m(n)$ labeled samples $(x_1, f(x_1)), \ldots, (x_m, f(x_m))$ where each $x_i \sim \mathcal{D}_n$ and $w \in \{0,1\}^*$ (the internal randomness of $\mathcal{A}$) and outputs the description of a circuit h such that*

$$\Pr_{\substack{f \sim \mathcal{P}_n \\ w \in \{0,1\}^* \\ x_1, \ldots, x_m, y \sim \mathcal{D}_n}} \left\{ \Pr_{y \in \mathcal{D}_n} \{h(y) = f(y)\} \geq 1 - \varepsilon \right\} \geq 1 - \delta$$

- *$\mathcal{A}$ runs in time at most $T(n)$.*

Furthermore, for any $0 < \epsilon, \delta < 1/2$, we say that $\mathcal{C}$ is (ϵ, δ)-PAC-learnable on average with respect to polynomially samplable distributions over $\mathcal{C}$ using random examples in time $T(n)$ if there exists a learning algorithm $\mathcal{A}$ that runs in time $T(n)$ such that for every polynomially samplable distribution ensemble $\mathcal{P}$ over $\mathcal{C}$, we have that for every large enough n, $\mathcal{A}$ (ϵ, δ)-PAC-learns $\mathcal{C}_n$ on average using random examples with respect to $\mathcal{P}_n$.

We can naturally extend this definition to average-case learning $\mathcal{C}$ with respect to $\mathcal{P}$ and a fixed distribution over the examples like U_n, as well as average-case PAC-learning $\mathcal{C}$ with membership queries with respect to $\mathcal{P}$.

2.2 Self-Reducibility

In our reductions, we use the following special properties of a function.

Definition 2.5 (Downward self-reducibility). *A function $f_n : \{0,1\}^n \to \{0,1\}$ is downward-self-reducible if there is a deterministic polynomial time algorithm A such that for all $x \in \{0,1\}^n$, $A^{f_{n-1}}(x) = f_n(x)$.*

Definition 2.6 (Self-Correctibility). *A function $f : \{0,1\}^n \to \{0,1\}$ is said to be self-correctible if there exists a constant $c \geq 0$ and a probabilistic polynomial-time algorithm A such that, for every large enough n, for any function $\mathcal{O} : \{0,1\}^n \to \{0,1\}$ that agrees with f_n with probability $(1 - 1/n^c)$ over the uniform distribution on inputs of length n, we have that $\Pr\{A^{\mathcal{O}}(x) = f_n(x)\} \geq 2/3$ for any $x \in \{0,1\}^n$.*

[BFNW93] show that any function f on n Boolean inputs can be transformed into a function f^* on n inputs from a large enough finite field, such that f^* coincides with f on the subset $\{0,1\}^n$.

Theorem 2.7 ([BFNW93]). *There exists an EXP-Complete problem g^* which is self-correctible.*

Furthermore, Trevisan and Vadhan [TV07] construct a PSPACE-Complete problem which is based on a careful arithmetization and padding of TQBF (using the interactive proof system for PSPACE), which has both these properties.

Theorem 2.8 ([TV07]). *There exists a PSPACE-Complete language $f^* \in \mathsf{DSPACE}[n]$ that is both self-correctible and downward self-reducible (DSR).*

We also use the following results.

Lemma 2.9. *If $\mathsf{EXP} \subseteq \mathsf{P/poly}$, then $\mathsf{EXP} = \mathsf{PSPACE}$. In particular, the function f^* (from Theorem 2.8) is complete for EXP.*

Lemma 2.10 (Hoeffding's inequality). *Let $X_1, \ldots, X_n$ be independent random variables such that $0 \leq X_i \leq 1$ for every $i \in [n]$. Let $X = \sum_{i=1}^{n} X_i$. Then, for any $t > 0$, we have*

$$\Pr\{|X - \boldsymbol{E}[X]| \geq t\} \leq 2\exp(-2t^2/n)$$

2.3 Kolmogorov Complexity

Fix a universal machine U. Levin [Lev84] defined the following notion of time-bounded Kolmogorov complexity: The Kt complexity of a string x is the minimum $\mathsf{Kt}(x)$ over $|p| + \log(t)$ such that $U(p) = x$ in at most t steps. it is known [All01] that $\mathsf{Kt}(x)$ is polynomially related to the size of the smallest EXP-oracle circuit computing the function with truth table x (truncating x to its longest initial segment with length a power of two).

Similarly, $\mathsf{KS}(x)$ is the minimum over $|p| + s$ such that $U(p) = x$ in at most space s. It is known [All01] that $\mathsf{KS}(x)$ is polynomially related to the size of the smallest PSPACE-oracle circuit computing the function with truth table x (truncating x to its longest initial segment with length a power of two).

Let R_{Kt} be the language consisting of strings x such that $\mathsf{Kt}(x) \geq |x|/2$ [ABK+06]. Similarly, let R_{KS} be the language consisting of strings x such that $\mathsf{KS}(x) \geq |x|/2$ [ABK+06].

3 Unconditional Results for Hardness of Learning

Firstly, we show the hardness of learning $\mathsf{BPE/poly}$ over the uniform distribution using non-adaptive membership queries by randomized polynomial time algorithms. The proof of this result uses the following lemma from [KKO13].

Lemma 3.1. *Let $\mathcal{C}$ be any circuit class, $s : \mathbb{N} \to \mathbb{N}$ be a size function and f^* be the* PSPACE-*Complete problem from Theorem 2.8. There exists constant $c \in \mathbb{N}$ such that if $\mathcal{C}[s(n)]$ is learnable up to error n^{-c} in time $T(n)$, then at least one of the following holds :*

- $f^* \notin \mathcal{C}[s(n)]$.
- $f^* \in \mathsf{BPTIME}[\mathsf{poly}(T(n))]$.

We also need the following technical result about the existence of functions which cannot even be approximated by $n^{\log n}$-sized circuits.

Lemma 3.2 (Lemma 4 [OS17])**.** *For any $s(n) \geq n$ and $\delta \in [0, 1/2]$, we have*

$$\Pr_{f \sim \mathcal{F}_n} \{\exists \textit{ circuit of size } \leq s(n) \textit{ computing } f \textit{ on} \geq (1/2 + \delta)\textit{-fraction of the inputs}\}$$
$$\leq \exp(-\delta^2 2^n + 10 s \log s)$$

The proof of Lemma 3.2 follows from an application of the Hoeffding tail bound (Lemma 2.10).

Proof of Theorem 1.1. Towards a contradiction, assume that there exists constants $k, d \geq 1$ and a randomized learning algorithm A which learns $\mathsf{BPE/poly}$ in $O(n^d)$ time over the uniform distribution using membership queries, up to error $1/2 - 1/n^k$ and confidence $1/n$, for every large enough input length n. By non-uniformly fixing a good random string, we ensure that for every function $g \in \mathsf{BPE/poly}$, there exists c such that A always outputs a hypothesis circuit of size $O(n^c)$ which computes g on at least $(1/2 + 1/n^k)$-fraction of n-length inputs. Thus, for every function in $\mathsf{BPE/poly}$, there exists a family of polynomial-sized circuits $\{h_n\}_{n \in \mathbb{N}}$ which $(1/2+1/n^k)$-approximates it, where h_i is the hypothesis output by the learner on input length i.

We next show that the existence of such a learner implies the existence of a function in BPE which cannot be $(1/2 + 1/n^k)$-approximated by polynomial sized circuits. Consider the PSPACE-Complete function f^* from Theorem 2.8 which is computable in time $\mathsf{DSPACE}[n]$. f^* is in $\mathsf{BPE/poly}$ (since f^* can be computed in E) and we use the learning algorithm for $\mathsf{BPE/poly}$ in Lemma 3.1 to see that $\mathsf{PSPACE} \subseteq \mathsf{BPP}$. Using a padding argument we observe that $\mathsf{DSPACE}[2^{O(n)}] \subseteq \mathsf{BPE}$. From Lemma 3.2, we see that there exists a function which cannot be $(1/2 + 1/n^k)$-computed by circuits of size $n^{\log n}$. We can easily construct a Turing Machine which lexicographically searches for the truth table of a function on n inputs which cannot be $(1/2+1/n^k)$-approximated by $n^{\log n}$ sized circuits in $2^{O(n)}$ space and answers according to the first one it finds. From this we have that $\mathsf{DSPACE}[2^{O(n)}]$, and thus $\mathsf{BPE/poly}$ cannot be $(1/2 + 1/n^k)$-approximated by $n^{\log n}$ sized circuits, which leads to a contradiction. □

Remark 3.3. *[OS17] show that if for each c, a circuit class $\mathcal{C}[n^c]$ is $(1/2-1/n^c, 1/n)$-learnable using membership queries over the uniform distribution in $2^n/n^{\omega(1)}$ time, then for each c, there exists $L_c \in \mathsf{BPE}$ such that $L_c \notin \mathcal{C}[n^k]$ (Theorem 12). For any c, the idea of picking $\mathcal{C}[n^c] = \mathsf{SIZE}^{\mathsf{BPE}}[n^c]$, with linear-sized queries to BPE oracles and using the learning algorithm A which learns $\mathsf{BPE/poly}$ in their result to achieve a contradiction (as any function in BPE can be computed by constant sized $\mathsf{SIZE}^{\mathsf{BPE}}$-circuits with linear-sized oracle queries) does not work, as [OS17] crucially uses that $\mathcal{C}[n^c]$ has to be a subset of $\mathsf{SIZE}[n^{c'}]$ for some $c' = O(c)$.*

On the other hand, Theorem 4 in [FK09] shows that if $\mathcal{C}$ is learnable using membership queries over the uniform distribution in polynomial time then $\mathsf{BPE} \not\subseteq \mathcal{C}[\mathsf{poly}(n)]$. Proving Theorem 1.1 by setting $\mathcal{C}$ as $\mathsf{BPE/poly}$ again does not really work, as [FK09]'s result only holds true when $\mathcal{C} = \mathsf{P/poly}$, as it depends on the collapse of EXP to $\mathsf{P/poly}$.

Additionally, we also observe that the class $\mathsf{E/poly}$ cannot be learnt by deterministic learners using membership queries even in $2^n/n$ time up to constant error over the uniform distribution. $\mathsf{E/poly}$ can equivalently be defined as the class of languages which can be computed by polynomial-sized circuit families with oracle access to some function in E, with the constraint that the oracle queries are of size $O(n)$.

We first rule out having deterministic exact learners for $\mathsf{E/poly}$ in Angluin's model of learning [Ang88] i.e. the learners have access to a membership oracle, as well as an equivalence oracle, where the learner presents a hypothesis circuit to the equivalence oracle, receives yes if the hypothesis exactly computes the target concept and receives a counter-example for the hypothesis, otherwise.

Proposition 3.4. *There exists no deterministic exact learners for $\mathsf{E/poly}$ using membership queries and equivalence queries which run in time $O(2^n/n)$.*

Proof Sketch. The proof follows easily from [KKO13]. They show that if there exists a deterministic exact learner that learns any function in a circuit class $\mathcal{C}$ in $2^n/n$ time using membership and equivalence queries, then there exists a function in E which cannot be computed by $\mathcal{C}$-circuits. Using $\mathsf{E/poly}$ for $\mathcal{C}$, we observe that there exists no deterministic exact learners which learn $\mathsf{E/poly}$ using membership queries and equivalence queries in $2^n/n$ time, because, if not, we would end up showing that there exists a function in E which cannot be computed in $\mathsf{E/poly}$, which is trivially false. □

We extend this result to rule out any deterministic learners for $\mathsf{E/poly}$ i.e. even learners which can output an approximate hypothesis.

Proposition 3.5. *For every constant $\delta \in [0, 1/2 - 1/n)$,* E/poly *is hard to learn up to error δ over the uniform distribution using membership queries by deterministic learning algorithms which run in time $2^n/n$.*

Proof. Towards a contradiction assume that there exists a constant $\delta > 0$ and a deterministic learner A running in time $T(n) = 2^n/n$ which learns E/poly using membership queries over the uniform distribution up to an error δ. For every n, let L be the language consisting of only those strings in $\{0,1\}^n$ which are *not* queried by A, when all its queries are answered by 0. Since A runs in time $T(n)$, it is the clear that $L \in \mathsf{E}$ and the size of $L \leq 2^n/n$. However, since A only queries those inputs which are not in L, it cannot distinguish between the all zeros function $\mathbf{0}$ and L. Indeed, if A returns a hypothesis h_1 which is $(1-\delta)$-close to $\mathbf{0}$, then h_1 agrees with L on at most a $\delta + 1/n$ fraction of the inputs. Similarly, if A returns a hypothesis h_2 which is $(1-\delta)$-close to L, then h_2 agrees with $\mathbf{0}$ on at most a $\delta + 1/n$ fraction. In either case, A can learn exactly one of L or $\mathbf{0}$, which contradicts our assumption that A learns every function in E/poly with error at most δ. $\square$

Both propositions can also be extended to show similar results for unconditional hardness of learning $\mathsf{PSPACE}/\mathsf{poly}$ by deterministic polynomial time learners.

4 Robustness of Hardness of Learning

In this section, we establish the equivalences in Theorem 1.2 for hardness of learning $\mathsf{EXP}/\mathsf{poly}$. We first state the following results necessary for its proof.

Lemma 4.1. *Let* $\mathsf{BPP} = \mathsf{EXP}$*. Then, for every $c > 0$,* $\mathsf{EXP}/\mathsf{poly}$ *can be $(1/n^c, 1/20n)$-PAC-learnt using random examples in time polynomial in n.*

Proof. Firstly, we show that if $\mathsf{BPP} = \mathsf{EXP}$, then for every $c > 0$, we can $(1/n^c, 1/20n)$-learn P/poly in the worst-case using random examples over arbitrary distribution $\mathcal{D}$. We consider the following search problem Π. On input $y = \langle 1^n, 1^{s(n)}, (x_1, b_1) \dots (x_m, b_m) \rangle$, where $x_i \in \{0,1\}^n$ and $b_i \in \{0,1\}$, if there exists a circuit C on n inputs of size at most $s(n)$ such that $C(x_i) = b_i$ for all $i \in [m]$, then $\Pi(y)$ outputs an encoding of C. The input length to Π is $t(n) = O(s(n) + n \cdot m(n))$. Π is in EXP as we can exhaustively search through all circuits on n inputs of size $s(n)$ and check if it is consistent with b_i on each $x_1, \dots, x_m$ in time $2^{O(s(n) \log s(n))} \cdot O(m(n) \cdot s(n)) = O\left(2^{t(n)} \mathsf{poly}(t(n))\right)$. Since $\mathsf{EXP} = \mathsf{BPP}$, there exists a randomized algorithm $A(y)$ which runs in time $\mathsf{poly}(t(n))$ which outputs a circuit C_n of size at most $s(n)$ consistent with b_i on each $x_1, \dots, x_m$, if there exists one.

Following this, we use an argument based on Occam's razor [KV94b] to see that for every $\epsilon, \delta > 0$ and $k \geq 0$, $\mathsf{SIZE}[n^k]$ can be (ϵ, δ)-learnt in the worst-case by A using random examples over $\mathcal{D}_n$, for any arbitrary distribution $\mathcal{D}_n$ over $\{0,1\}^n$, if $m = O\left(\frac{1}{\epsilon}(n^k \log n + \log\left(\frac{1}{\delta}\right))\right)$. For any fixed $c > 0$, when $\epsilon = 1/n^c$ and $\delta = 1/20n$, $m(n) = O(n^{c+k+1})$. Thus, for every n, every $k \geq 0$ and every $f \in \mathsf{SIZE}[n^k]$, using $m = O(n^{c+k+1})$ many random examples drawn from U_n and their labels $f(x_1), \dots, f(x_m)$, the randomized algorithm A runs in time $\mathsf{poly}(n)$ and outputs a circuit of size $O(n^k)$ which is $(1-\epsilon)$-close to f, with probability at least $(1-\delta)$.

Finally, observe that if $\mathsf{BPP} = \mathsf{EXP}$, then $\mathsf{EXP} \subseteq \mathsf{P}/\mathsf{poly}$, which in turn implies that $\mathsf{EXP}/\mathsf{poly} \subseteq \mathsf{P}/\mathsf{poly}$. In other words, this means that there exists some constant $k \geq 0$ such that $\mathsf{EXP}/\mathsf{poly} \subseteq \mathsf{SIZE}[n^k]$. This proves the lemma as the learner A can now $(1/n^c, 1/20n)$-learn $\mathsf{EXP}/\mathsf{poly}$ in the worst case using random examples over $\mathcal{D}_n$ in $\mathsf{poly}(n)$ time over any aribitary distribution $\mathcal{D}_n$. $\square$

Lemma 4.2. *Let* $\mathsf{EXP} \neq \mathsf{BPP}$*. Then, there exists* $c \geq 0$ *such that* $\mathsf{EXP/poly}$ *is not* $(1/n^c, 1/20n)$*-learnable in the worst-case using random examples over the uniform distribution in time polynomial in* n*.*

Proof. Towards a contradiction assume that there exists a constant $a > 0$ and an $O(n^a)$-time learner $\mathcal{A}$ that $(1/n^c, 1/20n)$-learns $\mathsf{EXP/poly}$ using random examples over U_n, for every $c \geq 0$. We first show that the existence of the learner $\mathcal{A}$ for $\mathsf{EXP/poly}$ implies that $\mathsf{EXP} \subseteq \mathsf{P/poly}$. Let g^* be an EXP-Complete problem which is self-correctible, whose existence is given by Theorem 2.7, with $c_1 \geq 0$ being the corresponding constant. Use $\mathcal{A}$ to $(1/n^{c_1}, 1/20n)$-learn g^* using random examples over the uniform distribution. Let $\mathcal{A}'$ be the algorithm which takes as input $y \in \{0,1\}^n$ in addition to the inputs of $\mathcal{A}$ and runs the learner $\mathcal{A}$, following which it returns the evaluation of the hypothesis circuit output by $\mathcal{A}$ on the input y. In other words, for every $n \in \mathbb{N}$, we have

$$\Pr_{\substack{w\in\{0,1\}^{r(n)}\\ x_1,\ldots,x_m\sim U_n}} \left\{ \Pr_{y\sim U_n} \{\mathcal{A}'(1^n, w, (x_1, g^*(x_1)), \ldots, (x_m, g^*(x_m), y) = g^*(y)\} \geq 1 - 1/n^{c_1} \right\}$$
$$\geq 1 - 1/20n$$

where both $r(n)$ and $m = m(n) = \mathsf{poly}(n)$.

By amplifying the correctness of $\mathcal{A}'$ using standard techniques, we can then non-uniformly fix the random strings $w, x_1, \ldots, x_m$ and the values of g^* on each x_i to get a polynomial sized circuit C, which takes input $y \in \{0,1\}^n$ and outputs the answer of $\mathcal{A}'$ on the advice string and y. Thus C_n agrees with g^* on at least $(1 - 1/n^{c_1})$-fraction of the inputs. Using C_n with the self-correctibility of g^* (and fixing another "good" random string non-uniformly in the resulting algorithm), we get a polynomial-sized circuit which computes g^* on every input and by the EXP-Completeness of g^*, we see that $\mathsf{EXP} \subseteq \mathsf{P/poly}$.

Since $\mathsf{EXP} \subseteq \mathsf{P/poly}$, we use Lemma 2.9 to observe that f^* given by Theorem 2.8 is now an EXP-Complete problem that is both downward self-reducible and self-correctible. Let c_2 be the constant associated with the self-corrector for f^*. For any integer k, given a procedure B_k which computes f^* on every instance of size k with high probability, we use $\mathcal{A}$ together with the downward self-reduction for f^*, followed by the self-corrector for f^* to obtain a procedure B_{k+1} that computes f^* on any input of size $k+1$. We use this inductively, to compute f^* on n inputs in probabilistic polynomial time.

More precisely, consider the following algorithm B_n which computes f^* on a given input x and does the following. First, it starts with a procedure B_{k_0}, for a constant k_0, which can be computed easily using a look-up table. Assuming that we have the procedure B_k for some input length $k \leq n$, we show how to construct the procedure B_{k+1} inductively. We use the learner $\mathcal{A}$ to learn the function f^*_{k+1} up to error $1/(k+1)^{c_2}$. For every input $f^*(y)$ passed to $\mathcal{A}$, where y is a string randomly picked from $\{0,1\}^{k+1}$, we use B_k with the downward self-reduction of f^* to compute $f^*(y)$. $\mathcal{A}$ outputs a hypothesis h_{k+1} which computes f^*_{k+1} on at least a $(1 - 1/(k+1)^c)$-fraction of the inputs with high probability. We now use the self-corrector for f^* to obtain from h_{k+1} a procedure B_{k+1} which is correct on every input of size $k+1$ with probability $1 - \gamma$ (by using standard error reduction arguments), for some $\gamma > 0$ which we pick later. Repeating this process at most n times, we obtain B_n and output $B_n(x)$.

First, we show that B_n outputs $f^*(x)$ with probability at least $2/3$. Let $d(n)$ be the number of queries made by the DSR to the oracle f^*_{n-1} in computing $f^*(x)$ on any input x of length n. The idea is that at each stage k, the procedure B_k fails only if at least one of $m(n) \cdot d(n)$ queries answered by B_{k-1} is incorrect, with probability at most $m(n)d(n)\gamma \leq 1/20n$ for $\gamma = 1/20nm(n)d(n)$, or if $\mathcal{A}$ fails to output the right hypothesis, with probability at most $1/20n$. Thus, the total failure probability at each stage is at most $1/10n$ and over the n stages, using the union bound, the total failure probability is at most $1/10 + \gamma \leq 1/3$.

We inductively observe that every stage B_k runs in time $\mathsf{poly}(k)$. It is easily seen that B_{k_0} runs in constant time. Assume that B_{k-1} runs in $\mathsf{poly}(k-1)$ time. At stage k, the time taken to compute f^* on $m(k)$ many inputs of length k is $O(m(k) \cdot d(k) \cdot \mathsf{poly}(k-1)) \leq \mathsf{poly}(k)$. After this, $\mathcal{A}$ takes $O(k^d)$ time to output h_k of size at most k^d, which is used by the $\mathsf{poly}(k)$-time self-corrector to compute f^* on all inputs of size k with high probability. Thus, B_k runs in time $\mathsf{poly}(k) = \mathsf{poly}(n)$. Since there at most n stages, the total running time of B_n is $\mathsf{poly}(n)$. This shows that $f^* \in \mathsf{BPP}$ and contradicts the original assumption. $\square$

Using a very similar proof idea, we obtain an analogous statement to Lemma 4.2, but now for worst-case learning $\mathsf{EXP/poly}$ using membership queries.

Lemma 4.3. *Suppose that* $\mathsf{EXP/poly}$ *is* $(1/n^c, 1/20n)$*-learnable in the worst case for every* $c \geq 0$ *over the uniform distribution* U_n *using membership queries in time* $\mathsf{poly}(n)$*. Then,* $\mathsf{EXP} = \mathsf{BPP}$*.*

Proof Sketch. Assume that there exists a $\mathsf{poly}(n)$-time learner $\mathcal{A}$ that $(1/n^c, 1/20n)$-learns $\mathsf{EXP/poly}$ over U_n using membership queries, for every $c > 0$ and for every large enough input length n. We learn the function g^* (given by Theorem 2.7) using $\mathcal{A}$. For every large enough n, let h_n be a circuit of polynomial size output by $\mathcal{A}$ as the hypothesis with probability at least $(1 - 1/20n)$. From the guarantees of the learner, we see that any hypothesis circuit h_n computes g^* on n inputs with error at most $1/n^{c_1}$ (after non-uniformly fixing its randomness). Let h'_n be the polynomial-sized circuit which uses h_n with the self-corrector for g^* (and non-uniformly fixing another random string for the resulting algorithm) and computes g^* on length n. Let $\{h'_n\}_{n\in\mathbb{N}}$ be this sequence of circuits which computes g^* on every large enough n. Since g^* is EXP-Complete, we see that $\mathsf{EXP} \subseteq \mathsf{P/poly}$.

We now use the learner $\mathcal{A}$ to learn the PSPACE-Complete problem f^* given by Theorem 2.8. Using similar ideas as Lemma 4.2, we see that $f^* \in \mathsf{BPP}$. Since EXP has now collapsed to PSPACE we see that $\mathsf{EXP} = \mathsf{BPP}$. $\square$

We next show similar results for learning $\mathsf{EXP/poly}$ on average. In fact, we prove that learning $\mathsf{EXP/poly}$ on average using random examples, with respect to *quasi-polynomially* samplable distributions over $\mathsf{EXP/poly}$, implies that $\mathsf{EXP} = \mathsf{BPP}$. Remark 4.5 provides a natural extension of this result to polynomially samplable distributions over $\mathsf{EXP/poly}$.

Lemma 4.4. *Suppose that* $\mathsf{EXP/poly}$ *is* $(1/n^c, 1/20n)$*-learnable on average for every* $c \geq 0$ *with respect to quasi-polynomially samplable distributions over* $\mathsf{EXP/poly}$ *and the uniform distribution* U_n *using random examples in time* $\mathsf{poly}(n)$*. Then,* $\mathsf{EXP} = \mathsf{BPP}$*.*

Proof Sketch. Again, the proof strategy is very similar to that of Lemma 4.2. Let $\mathcal{A}$ be a polynomial time learner such that for every quasi-polynomially samplable distribution ensemble $\mathcal{P}$ over $\mathsf{EXP/poly}$, for every large enough n, for every $c \geq 0$, $\mathcal{A}$ $(1/n^c, 1/20n)$-learns $\mathsf{EXP/poly}$ with respect to $\mathcal{P}$ and U_n using random examples. Formally, we have for every quasi-polynomially samplable $\mathcal{P}$ over $\mathsf{EXP/poly}$

$$\Pr_{\substack{f\sim\mathcal{P}_n \\ w\in\{0,1\}^* \\ x_1,\ldots,x_m\sim U_n}} \{L(1^n, \epsilon, \delta, w, x_1, f(x_1), \ldots, x_m, f(x_m), w) \text{ is } (1-\epsilon)\text{-close to } f\} \geq 1 - \delta$$

for sufficiently large n.

We first show that the existence of $\mathcal{A}$ implies $\mathsf{EXP} \subseteq \mathsf{P/poly}$. Indeed, consider the quasi-polynomially samplable distribution $\mathcal{P}$ supported only on the function g^* given by Theorem 2.7, defined by the algorithm $S_{\mathcal{P}}$ which takes as inputs 1^N (where $N = 2^n$) and outputs the truth table of g^* on n inputs by running the EXP-machine which computes g^* on every input in $\{0,1\}^n$. Clearly, the running time of the sampler is quasi-polynomial in N. From our assumption in the lemma and since $\mathcal{P}$ is supported only on g^*, $\mathcal{A}$ can be used to output a hypothesis which is $(1 - 1/n^{c_1})$-close to g^* with probability at least $1 - 1/20n$. Using the same idea as Lemma 4.2, we show that $g^* \in \mathsf{P/poly}$.

Following this, we design a similar quasi-polynomially samplable distribution $\mathcal{D}$ supported on the PSPACE-Complete problem f^* given by Theorem 2.8. Since $\mathsf{EXP} \subseteq \mathsf{P/poly}$, we see that f^* is also EXP-Complete. Again, since $\mathcal{D}$ is supported only on f^*, $\mathcal{A}$ can be used to output a hypothesis which approximates f^* with high probability and following from the ideas used in Lemma 4.2, we show that $f^* \in \mathsf{BPP}$ proving that $\mathsf{EXP} = \mathsf{BPP}$. □

Using the proof strategy of Lemma 4.3, we can also show a natural extension of Lemma 4.4 for average-case learning using membership queries as well.

Remark 4.5. *It is easy to extend lemma 4.4 to the case where the samplable distribution is over* $\mathsf{SIZE}^{\mathsf{EXP}}[n^k]$*-circuit encodings in* $R_n \subseteq \{0,1\}^{r(n)}$*, where* $r(n) = O(n^{2k+1})$ *(see Remark 2.3 for more details). In such a case, we only need* $\mathsf{poly}(n)$*-time learnability of* $\mathsf{SIZE}^{\mathsf{EXP}}[n^k]$ *with respect to* ***polynomially samplable*** *distributions over* $\mathsf{SIZE}^{\mathsf{EXP}}[n^k]$ *and* U_n*, to show that* $\mathsf{EXP} = \mathsf{BPP}$*.*

Indeed, for the distribution $\mathcal{P}$ *over* $\mathsf{SIZE}^{\mathsf{EXP}}[n^k]$ *supported only on the function* g^* *(or* f^**) used in the proof, the sampler* $S'_{\mathcal{P}}$ *takes* 1^{n^k} *as input and outputs a* $\mathsf{SIZE}^{\mathsf{EXP}}[n^k]$*-circuit encoding of* g^* *which is just an* EXP*-oracle gate on* n *inputs and this encoding is of size* $O(n^2)$*. The running time of this sampling algorithm is polynomial in the input size.*

We now prove the equivalences for efficiently learning $\mathsf{EXP/poly}$.

Proof of Theorem 1.2. The following implications establish the desired equivalences.

$(b) \implies (a), (c) \implies (a)$: The contrapositives of each of these implications follow from Lemma 4.1. In particular, PAC-learning $\mathsf{EXP/poly}$ with error at most $1/n^c$ for any $c > 0$ using random examples, implies PAC-learnability of $\mathsf{EXP/poly}$ using membership queries, where the queries are just made on the random examples given to the learner.

$(d) \implies (b), (e) \implies (c)$: Follows from the definitions, since PAC-learning $\mathsf{EXP/poly}$ in the worst case in $\mathsf{poly}(n)$ time using random examples implies PAC-learnability for $\mathsf{EXP/poly}$ on average in $\mathsf{poly}(n)$ time using random examples, for any distribution over $\mathsf{EXP/poly}$. A similar implication holds for learning with membership queries too.

$(a) \implies (b)$: For any $c > 0$, suppose $\mathsf{EXP/poly}$ is $(1/n^c, 1/20n)$ PAC-learnable in polynomial time using random examples over every arbitrary distribution. In particular, this means that $\mathsf{EXP/poly}$ can be $(1/n^c, 1/20n)$-learnt in polynomial time using random examples over the uniform distribution. The implication follows from the contrapositive of Lemma 4.2.

$(a) \implies (c)$: Similar to the previous implication, we see that $\mathsf{EXP/poly}$ is $(1/n^c, 1/20n)$-learnable in polynomial time using membership queries over the uniform distribution. The implication holds from the contrapositive of Lemma 4.3.

$(a) \implies (d), (a) \implies (e)$: The implications follow from Lemma 4.4 (along with Remark 4.5) and its corresponding extension to learning on average with membership queries. □

The proof of Corollary 1.3 (equivalences for learning $\mathsf{PSPACE}/\mathsf{poly}$) follows from the same ideas as Theorem 1.2. In more detail, Lemma 4.1 extends easily as the procedure which searches for a polynomial-sized consistent hypothesis also runs in polynomial space. Lemmas 4.2, 4.3 and 4.4 can also be extended, by only using the second step from their proofs, where we compute the downward-self-reducible and self-correctible PSPACE-Complete function f^* (Theorem 2.8) directly using the $\mathsf{PSPACE}/\mathsf{poly}$ learner.

5 Reducing Succinct Search to Decision

The key concepts in this section are verifiability and succinct search. We define verifiers first.

Definition 5.1. *Given language $L \subseteq \{0,1\}^*$ and polynomial-time computable relation $V(\cdot,\cdot)$, we say that V is a verifier for L if for each $x \in \{0,1\}^*$, $x \in L$ iff $\exists y V(x,y)$.*

Given language L, a verifier V for L, and function $f : \mathbb{N} \to \mathbb{N}$, we say that L has $f(n)$-size proofs with respect to V, such that for each $x \in \{0,1\}^*$, $x \in L$ implies $\exists y, |y| \leq f(|x|) : V(x,y)$. We say that L has $f(n)$-size proofs if there is a verifier V for L such that L has $f(n)$-size proofs with respect to V.

Given language L, a verifier V for L and a machine class $\mathcal{D}$, we say that L has $\mathcal{D}$-computable proofs with respect to V if there is a machine $M \in \mathcal{D}$ such that for each $x \in \{0,1\}^*$, $x \in L$ implies $V(x, M(x))$. We say that L has $\mathcal{D}$-computable proofs if there is a verifier V for L such that L has $\mathcal{D}$-computable proofs with respect to V.

Note that NP is the class of languages with polynomial-sized proofs, NEXP is the class of languages with exponential-sized proofs, and for $\mathcal{D} \in \{\mathsf{EXP}, \mathsf{PSPACE}\}$, $\mathcal{D}$ is the class of languages with $\mathcal{D}$-computable proofs (where we abuse notation and use $\mathcal{D}$ to refer both to a machine class and to the class of languages computable by such machines).

Next we define succinct search. We will assume w.l.o.g. that the proof size for any verifier is a power of 2 - this can be ensured by padding the proof if necessary.

Definition 5.2. *Given language L and verifier V for L, we say that **succinct search is easy** for L with respect to V if there is a probabilistic polynomial-time machine N such that for each $x \in L$, there is a V-proof y such that with probability $1 - o(1)$, $\mathsf{tt}(N(x)) = y$, where for Boolean circuit C, $\mathsf{tt}(C)$ denotes the truth table of the function computed by C.*

Thus succinct search is easy for L with respect to a verifier V if there is a probabilistic polynomial-time machine outputting compressed descriptions of V-proofs with high probability for any positive instance of L.

Using the downward self-reducibility of SAT, it is straightforward to see that $\mathsf{NP} \subseteq \mathsf{BPP}$ iff for each $L \in \mathsf{NP}$ and for every verifier V such that L has poly-size proofs with respect to V, succinct search is easy for L with respect to V. We now show analogous results for $\mathsf{PSPACE}, \mathsf{EXP}$ and NEXP. First we show for each of these classes that easiness of the class implies easiness of succinct search. We need the Easy Witness Lemma of Impagliazzo, Kabanets and Wigderson [IKW02].

Lemma 5.3. *[IKW02] If $\mathsf{NEXP} \subseteq \mathsf{P}/\mathsf{poly}$, then for each $L \in \mathsf{NEXP}$ and for each verifier V for L such that L has exponential-size proofs with respect to V, for each $x \in L$, there is a polynomial-size circuit C_x such that $V(x, \mathsf{tt}(C_x))$ holds.*

Lemma 5.4. *The following implications hold:*

1. *Let $\mathcal{D} \in \{\mathsf{PSPACE}, \mathsf{EXP}\}$. If $\mathcal{D} = \mathsf{BPP}$, then for each $L \in \mathcal{D}$ and for each verifier V such that L has $\mathcal{D}$-computable proofs with respect to V, succinct search is easy for L with respect to V.*

2. *If $\mathsf{NEXP} = \mathsf{BPP}$, then for each $L \in \mathsf{NEXP}$ and for each verifier V such that L has exponential-size proofs with respect to V, succinct search is easy for L with respect to V.*

Proof. We establish the first item. Let $\mathcal{D} \in \{\mathsf{PSPACE}, \mathsf{EXP}\}$, and assume $\mathcal{D} = \mathsf{BPP}$. Let $L \in \mathcal{D}$ and V be a verifier for L such that L has $\mathcal{D}$-computable proofs with respect to V. We construct a probabilistic poly-time machine N such that for each input $x \in L$, there is a V-proof y such that with high probability $\mathsf{tt}(N(x)) = y$. Let M be a $\mathcal{D}$-machine outputting V-proofs for positive instances of L.

Consider the language $L' = \{\langle x, i\rangle | i^{\text{th}}$ bit of $M(x)$ is $1\}$. Since M is a $\mathcal{D}$ machine, we have that $L' \in \mathcal{D}$. By assumption, $\mathcal{D} = \mathsf{BPP}$, therefore there is a probabilistic poly-time machine N' deciding L'. Assume w.l.o.g. that N' has error at most $2^{-|y|^2}$ on any input y. Given input x, N operates as follows. It first computes a probabilistic poly-size circuit C' simulating N'. This can be done using the standard efficient conversion of efficient algorithms into small circuits. It then hardwires x into the first part of the input for C', obtaining a circuit C'_x. It then fixes the random input of the circuit C'_x to a uniformly generated random string r to obtain a circuit $D'_{x,r}$, which it outputs.

Since the error of N' is smaller than $2^{-|y|^2}$ on any input y, by a simple union bound, with probability $1 - o(1)$ over the choice of the random string r, $D'_{x,r}$ correctly computes the i'th bit of $M(x)$ for each $i \in [m]$. For $x \in L$, $V(x, M(x))$ holds, and therefore N efficiently solves succinct search for L with respect to V.

We establish the second item. Assume $\mathsf{NEXP} = \mathsf{BPP}$ and let $L \in \mathsf{NEXP}$ and V be a verifier for L such that L has exponential-size proofs with respect to V. Since $\mathsf{NEXP} = \mathsf{BPP}$, we have that $\mathsf{NEXP} \subseteq \mathsf{P/poly}$. By Lemma 5.3, there is a polynomial p such that for each $x \in L$, there is a circuit C_x of size at most $p(|x|)$ such that $V(x, \mathsf{tt}(C_x))$ holds.

Consider the language $L' = \{\langle x, i\rangle |$ There is a circuit C of size $p(|x|)$ such that $V(x, \mathsf{tt}(C))$ is 1, and the i^{th} bit of the lexicographically first such circuit is $1\}$. Clearly $L' \in \mathsf{EXP}$, just by enumerating circuits of size $p(|x|)$ in lexicographic order and finding the first one encoding a V-proof for x, if one exists. Since $\mathsf{EXP} = \mathsf{BPP}$, there is a probabilistic poly-time machine N' deciding L' with error exponentially small. We construct a probabilistic poly-time machine N as follows: on input x, N runs N' on $\{\langle x, i\rangle\}$ for each i at most the description length of a circuit of size $p(|x|)$. It outputs the circuit C whose description has bit i set to 1 iff N' accepts on $\{\langle x, i\rangle\}$. Since N' has error exponentially small, we have that with error exponentially small, N outputs a circuit C encoding a V-proof of x, and therefore N efficiently solves succinct search for L with respect to V. □

For the reverse directions, we use the PCP characterization of NEXP [BFL91, FRS94], where we only require polynomial upper bound on query complexity of the verifier.

Theorem 5.5. *[BFL91, FRS94] Let $L \in \mathsf{NEXP}$. There is a probabilistic poly-time oracle machine V' such that:*

1. *For each $x \in L$, there is y of length exponential in $|x|$ such that $V'(x)$ accepts with probability at least $2/3$ when given oracle access to y.*

2. *For each $x \notin L$ and for all y, $V'(x)$ accepts with probability at most $1/3$ when given oracle access to y.*

We now show that easiness of succinct search implies easiness of decision for any $L \in \mathsf{NEXP}$.

Lemma 5.6. *Let $L \in \mathsf{NEXP}$ and V be a verifier such that L has exponential-size proofs with respect to V. If succinct search is easy for L with respect to V, then $L \in \mathsf{BPP}$.*

Proof. Let $L \in \mathsf{NEXP}$. We show that $L \in \mathsf{BPP}$. By Theorem 5.5, there is a probabilistic poly-time oracle machine V' such that if $x \in L$, there is y of length exponential in $|x|$ for which V' accepts with high probability on x when given oracle access to y, and if $x \notin L$ rejects with high probability irrespective of the oracle.

Now consider a verifier V for L which given input x and proof y, accepts iff $V'(x)$ accepts with oracle y on a majority of its computation paths. Since succinct search is easy for L with respect to V, there is a probabilistic poly-time machine N such that for input $x \in L$, there is a V-proof y for x such that with high probability $\mathsf{tt}(N(x)) = y$. We define a probabilistic poly-time machine W that on input x simulates $V'(x)$ as follows. It first runs $N(x)$ to find a circuit C. It then runs $V(x)$, answering all oracle calls to y by simulating C on input corresponding to the bit of y that is queried. It accepts iff $V(x)$ accepts.

If $x \in L$, by using the assumption that N solves succinct search, $W(x)$ accepts with probability close to $2/3$. If $x \notin L$, $W(x)$ rejects with probability close to $2/3$ since the circuit C output by $N(x)$ corresponds to some purported V'-proof, and every such V'-proof is rejected with high probability by V when given oracle access to the proof. $\square$

Theorem 5.7. *Let $\mathcal{D} \in \{\mathsf{PSPACE}, \mathsf{EXP}\}$. $\mathcal{D} = \mathsf{BPP}$ iff for each $L \in \mathcal{D}$ and for each verifier V for L such that L has $\mathcal{D}$-computable proofs with respect to V, succinct search is easy for L with respect to V.*

$\mathsf{NEXP} = \mathsf{BPP}$ iff for each $L \in \mathsf{NEXP}$ and for each verifier V such that L has exponential-size proofs with respect to V, succinct search is easy for L with respect to V.

Proof. The forward directions of both items follow from Lemma 5.4. The backward direction of the second item follows Lemma 5.6. The backward direction of the first item follows from Lemma 5.6 and the fact that for $\mathcal{D} \in \{\mathsf{PSPACE}, \mathsf{EXP}\}$, if $L \in \mathcal{D}$ and V is a verifer for L such that L has $\mathcal{D}$-computable proofs with respect to V, then $L \in \mathsf{NEXP}$ and L has exponential-size proofs with respect to V. $\square$

We now prove Theorem 1.4. Recall that R_{Kt} as the language consisting of strings x such that $\mathsf{Kt}(x) \geq |x|/2$. Similarly, R_{KS} is the language consisting of strings x such that $\mathsf{KS}(x) \geq |x|/2$ [ABK+06].

Theorem 5.8 (Theorem 1.4 stated formally)**.** *$\mathsf{R}_{\mathsf{Kt}} \in \mathsf{BPP}$ iff for each verifier V for R_{Kt} such that R_{Kt} has EXP-computable proofs with respect to V, succinct search is easy for R_{Kt} with respect to V.*

$\mathsf{R}_{\mathsf{KS}} \in \mathsf{BPP}$ iff for each verifier V for R_{KS} such that R_{KS} has PSPACE-computable proofs with respect to V, succinct search is easy for R_{KS} with respect to V.

Proof. The backward directions of both items follow from Lemma 5.6 and the facts that R_{Kt} and R_{KS} are in NEXP.

For the forward direction of the first item, we use the result shown in [ABK+06] that $\mathsf{R}_{\mathsf{Kt}} \in \mathsf{BPP}$ implies $\mathsf{EXP} = \mathsf{BPP}$. Combining this with the first item of Lemma 5.4 completes the proof.

For the forward direction of the second item, we use the theorem shown in [ABK+06] that $\mathsf{R}_{\mathsf{KS}} \in \mathsf{BPP}$ implies $\mathsf{PSPACE} = \mathsf{BPP}$. Combining this with the first item of Lemma 5.4 completes the proof. $\square$

6 Barriers for Conditional Hardness of Learning

Firstly, we formally define what it means to have a Black-Box Turing reduction from a language L to a PAC-learning algorithm for a class $\mathcal{C}$. Fix the error of the learner to be $\varepsilon = 1/\mathsf{poly}(n)$ (we ignore the confidence parameter, but this only makes our hardness results stronger).

Definition 6.1 (Turing Reduction to Learning $\mathcal{C}$.)**.** *A B-adaptive black-box reduction from deciding L to PAC-learning $\mathcal{C}$ using random examples up to error ε, is a tuple of probabilistic polynomial time algorithms $R = (T_1, \ldots, T_B, M)$ where R is given an input $z \in \{0,1\}^n$ and randomness $w \in \{0,1\}^*$. For each query, R constructs a joint distribution $(X, f(X))$ over $\{0,1\}^r \times \{0,1\}$ for some $r \leq n$ and $f \in \mathcal{C}$, samples a set $S = \{(x_i, y_i)\}_{i \leq \mathsf{poly}(n)}$ of independent labeled examples according to (X, Y) and passes it to the learner. Let $t(n)$ be the query complexity of each round of adaptivity. R decides z by doing the following -*

- *For each $1 \leq j \leq B$, T_j gets input z, fresh random bits from w and all the $(j-1) \cdot t(n)$ hypothesis circuits answered for the queries from the previous rounds (T_1 only has z and randomness w as input), and outputs $t(n)$ new queries $S_{j1}, \ldots, S_{jt}$ for the learner, each of which are sets of labeled examples sampled from joint distributions $(X_{j1}, Y_{j1}), \ldots, (X_{jt}, Y_{jt})$.*
- *R only has oracle access to the learner.*
- *M takes as input z, fresh random bits from w and the $B \cdot t(n)$ hypothesis circuits which are the answers made by the learner for all the queries asked by $T_1, \ldots, T_B$, and outputs the answer.*
- *The reduction guarantees that if for every oracle A that is a $\mathcal{C}$-circuit learner, if every hypothesis circuit returned by the learner is $(1-\varepsilon)$-close with respect to its corresponding query given to the learner by $T_1, \ldots, T_B$, then $M(z) = L(z)$ with high probability over the internal randomness of the reduction R.*

Definition 6.2. *For any B-adaptive black-box reduction $R = (T_1, \ldots, T_B)$ from deciding L to PAC-learning $\mathcal{C}$ using random examples up to error ε, we have*

- *R is called **strongly black-box**, if $T_1, \ldots, T_B, M$ only have oracle access to the hypothesis circuits and M decides L given access to any $(1-\varepsilon)$-close hypothesis circuit answered to each query made by $T_1, \ldots, T_B$.*
- *If $B = 1$, we call the reduction as **non-adaptive**, and if R is strongly black-box and M also makes only non-adaptive queries to the hypotheses circuits, we call the reduction as **fully non-adaptive**.*
- *R is **oblivious**, if $T_1, \ldots, T_B$ output new queries using only fresh randomness from w as input and access to the hypotheses generated during the previous rounds. Furthermore, M accesses each hypothesis using non-adaptively generated, identically distributed queries made from the corresponding distribution over which each hypothesis is guaranteed to be a good approximation. In particular, the obliviousness of the reduction implies the fact that the queries to the learner do not depend on the input z.*

Unless mentioned we think of the query complexity $t(n) = \mathsf{poly}(n)$. It is worth noting that since the algorithms $T_1, \ldots, T_B$ are polynomial time algorithms, each joint distribution (X, Y) must be efficiently samplable.

We first prove Lemma 1.5. This is a reformulation of the proof of Lemma 4.2 used to show hardness of learning $\mathsf{PSPACE/poly}$ from a PSPACE-Complete language, into the framework of a black-box reduction.

Proof of Lemma 1.5. This a readaptation of the proof of Corollary 1.3 (via Lemma 4.2). Consider $R = (T_1, \ldots, T_n, M)$ as an n-adaptive reduction from deciding f^* to learning $\mathsf{PSPACE/poly}$ using random examples over the uniform distribution, where $T_1, \ldots, T_n, M$ are probabilistic polynomial time algorithms which are defined as follows.

For every $k \leq n$, T_k makes exactly one query to the learner which is the set of examples $S_k = \{(x_i, y_i)\}_{i \leq \mathsf{poly}(n)}$ drawn from the joint distribution $(U_k, f^*(U_k))$, where U_k is the uniform distribution over $\{0,1\}^k$. In the k^{th} round of adaptivity, T_k only makes oracle queries to the hypothesis h_{k-1} output in the last round. Indeed, let h'_{k-1} be the oracle circuit which uses h_{k-1} as an oracle in the self-corrector algorithm for f^*, and computes f^* on all $k-1$ length inputs with high probability. It then outputs a set S_k of independent labeled samples (x_i, y_i), where each x_i is sampled uniformly at random from U_k and $y_i = f^*(x_i)$ computed by using the downward self-reducibility of f^* with h'_{k-1}. M takes the final hypothesis h_n output by the learner over n inputs and outputs the value of the self-corrector of f^* with the oracle h_n. The correctness of R and the run-time analyses of $T_1, \ldots, T_n, M$ follow from the proof techniques of Lemma 4.2.

We next show that R has the required properties. As the self-corrector and the downward self-reduction for f^* work for any oracle which satisfy the appropriate constraints, R is correct for any oracle which outputs *any* correct hypothesis for f^* with respect to the uniform distribution (over different input lengths). Further, it makes only oracle queries to the learner, as well as to all the hypothesis circuits $h_1, \ldots, h_n$. This makes the reduction strongly black-box. By the property of the self-corrector, M only makes queries sampled from U_n to h_n, which is the same as the query made to the learner. The obliviousness now follows, since only f^* is learnt in each query, irrespective of the choice of z. $\square$

The main result of the section is the following.

Theorem 6.3. *There exists a universal constant $c > 0$ such that the following holds. For any language L, $\varepsilon_0 = 1/n^c$ and any $B = \mathsf{poly}(n)$, if there exists an oblivious, B-adaptive, strongly black-box reduction from L to PAC-learning $\mathsf{NP/poly}$ using random examples over polynomially samplable distributions up to error ε_0, then $\overline{L} \in \mathsf{AM^{poly}}$.*

Recall that the class $\mathsf{AM^{poly}}$ refers to the class of languages recognized by constant-round interactive protocols with advice, where we require proper acceptance/rejection probabilities only when the advice is correct. [FF93] show that $\mathsf{AM^{poly}} = \mathsf{NP/poly}$. Using Theorem 6.3 with $L = \mathsf{SAT}$, we get

Corollary 6.4. *There exists a universal constant $c > 0$ such that the following holds. For $\varepsilon_0 = 1/n^c$ and any $B = \mathsf{poly}(n)$, if there exists an oblivious, B-adaptive, strongly black-box reduction from deciding SAT to learning $\mathsf{NP/poly}$ using random examples from polynomially samplable distributions up to error ε_0, then $\mathsf{coNP} \subseteq \mathsf{NP/poly}$.*

Corollary 6.4 easily implies Theorem 1.6, since $\mathsf{coNP} \subseteq \mathsf{NP/poly}$ implies that $\Sigma_3^P = \Pi_3^P$ [Yap83].

We now prove Theorem 6.3. For the ease of presentation, we prove it for the case of an oblivious, B-adaptive, strongly black-box reduction $R = (T_1, \ldots, T_B, M)$ from L to learning $\mathsf{NP/poly}$ over the uniform distribution. This means that the queries generated by the reduction to the learner are labeled examples drawn from the uniform distribution. The proof can be easily extended to the case where the reduction makes queries to learn over any polynomially samplable distribution, rather than just the uniform distribution.

Proof of Theorem 6.3. Let $R = (T_1, \ldots, T_B, M)$ be an oblivious, B-adaptive, strongly black-box reduction from L to learning $\mathsf{NP/poly}$ using random examples over the uniform distribution, where $T_1, \ldots, T_B, M$ are probabilistic polynomial time machines.

By using standard techniques (Adleman's trick over R), we non-uniformly fix a random string w_1 to be used by $T_1, \ldots, T_B$ as non-uniform advice to R. This ensures that for every input $z \in \{0,1\}^n$, R decides z correctly with probability at least $1-\gamma$ over M's randomness, for some $0 < \gamma < 1/2$.

By fixing w_1 non-uniformly, we also ensure that the queries made in the first round of adaptivity T_1 get fixed. Let $(X_{11}, Y_{11}), \ldots, (X_{1t}, Y_{1t})$ be the joint distributions constructed by T_1, where for each $i \in [t]$, $X_{1i} = U_{r_{1i}}$, the uniform distribution over r_{1i} bits for $r_{1i} \leq n$ and $Y_{1i} = f_{1i}(U_{r_{1i}})$ for some $f_{1i} \in \mathsf{NP/poly}$. Define $Q_1 = \{(r_{11}, f_{11}), \ldots, (r_{1t}, f_{1t})\}$.

For any b, where $2 \leq b \leq B$, assume that the queries to the learner from the previous rounds have been fixed as Q_{b-1}. T_b takes fresh randomness from w_1 (which has been non-uniformly fixed) as input and has oracle access to the hypotheses, which $(1-\varepsilon_0)$-approximate each corresponding function in Q_{b-1} according to the uniform distribution over their respective input lengths. Let $\mathcal{S}_b$ be the set of all possible tuples of joint distributions queried by T_b to the learner based on the choices it makes after w_1 and the hypothesis oracles for the queries made up to T_{b-2} have been fixed. Arbitrarily pick any such tuple $((U_{r_{b1}}, f_{b1}(U_{r_{b1}}), \ldots, (U_{r_{bt}}, f_{bt}(U_{r_{bt}}))$ and fix $Q_b = Q_{b-1} \cup \{(r_{b1}, f_{b1}), \ldots, (r_{bt}, f_{bt})\}$. In other words, this means that there exists some choice of hypothesis oracles, each of which $(1-\varepsilon_0)$-approximates the functions queried by T_{b-1}, which along with the hypothesis oracles fixed in the previous rounds generate the tuple $((U_{r_{b1}}, f_{b1}(U_{r_{b1}}), \ldots, (U_{r_{bt}}, f_{bt}(U_{r_{bt}}))$.

Let $\ell = Bt$ be the total number of queries made to the learner. For each $i \in [\ell]$, let $\{D_n^i\}_{n \in \mathbb{N}}$ be the corresponding family of non-deterministic circuits which verifies f_i. Let p_i be the probability that f_i accepts a string sampled from U_{r_i} i.e. $|p_i - \Pr_{y \sim U_{r_i}}\{h_i(y) = 1\}| \leq \varepsilon_0$. Finally, let q be the number of *non-adaptive* queries M makes to each hypothesis h_i according to the distribution U_{r_i}.

On input $z \in \{0,1\}^n$, non-uniform advice $D^1_{r_1}, \ldots, D^\ell_{r_\ell}, p_1, \ldots, p_\ell$ and any error parameter $0 < \delta < 1/2$, the Arthur-Merlin protocol for $\overline{L}$ is as follows :

1. **Verifier:** Let $K = \frac{4q^2\ell^2}{\delta^2} \ln\left(\frac{2q\ell}{\delta}\right)$. Run M independently K times. For each $k \in [K]$, let $V^k = (v^k_{11}, \ldots, v^k_{1q}), (v^k_{21}, \ldots, v^k_{2q}), \ldots, (v^k_{\ell 1}, \ldots, v^k_{\ell q})$ be the set of queries made by M in the k^{th} run, where for every $i \in [t]$, $(v^k_{i1}, \ldots, v^k_{iq})$ are the q queries of length r_i made to h_i. Send all the queries $V^1, \ldots, V^K$ to the prover.

2. **Prover:** For each v^k_{ij}, respond by saying if $v^k_{ij} \in f_i$ and if so, provide a certificate that $v^k_{ij} \in f_i$ which can be verified by $D^i_{r_i}$.

3. **Verifier:** Accept if all the conditions hold :

   - All certificates sent by the prover are valid (verified by the circuits $D^1_{r_1}, \ldots, D^t_{r_\ell}$).
   - For every $1 \leq i \leq \ell$, at least $q \cdot \left(p_i K - \varepsilon_0 K - \left(\sqrt{K \ln\left(\frac{2\ell q}{\delta}\right)}\right)\right)$ many queries made to the prover for f_i are answered by the prover as "yes".

- For k picked uniformly at random from $[K]$ and on input z, using the answers given by the prover for the oracle queries on V^k, the output of the k^{th} run of M is "no".

Completeness: Let $\varepsilon = \gamma + 2\delta + 2q\ell\varepsilon_0$. Pick $c > 0$ large enough such that $\varepsilon_0 = 1/n^c$ and thus, $\varepsilon = 1/\mathsf{poly}(n)$. To show completeness, for any input $z \in \overline{L}$, observe that an honest prover would send correct answers for every query and corresponding certificates, if necessary. Furthermore, if all queries are answered correctly, then M decides z correctly with probability at least $1 - \gamma$ on every run. Finally, observe that for each fixed $i \in [\ell], j \in [q]$, the queries $v_{ij}^1, \ldots, v_{ij}^K$ are independent and distributed identically according to X_i, with probability at least $p_i - \varepsilon_0$ of being a yes instance. Using Hoeffding's inequality (Lemma 2.10), with probability at least $\left(1 - \frac{\delta}{q\ell}\right)$, at least $p_i K - \varepsilon_0 K - \left(\sqrt{K \ln(2q\ell/\delta)}\right)$ of these queries are yes instances. By a union bound, with probability at least $(1 - \delta/\ell)$, this is satisfied for all $j \in [q]$ and at least $q \cdot \left(p_i K - \varepsilon_0 K - \left(\sqrt{K \ln(2q\ell/\delta)}\right)\right)$ many queries made to f_i are yes instances. Using a final union bound over all $1 \le i \le \ell$, we see that with probability at least $(1 - \delta)$, the threshold is satisfied for every function f_i. Thus, the verifier accepts z with probability at least $1 - \delta - \gamma \ge 1 - \varepsilon$.

Soundness: For any $z \notin \overline{L}$, note that the cheating prover can only cheat by saying "no" on a query which is a yes instance for any f_i, which is ensured by the first condition. Using Hoeffding's inequality in the same way as above, we see that with probability at least $(1-\delta)$, for every $1 \le i \le \ell$, at most $q\left(p_i K + \varepsilon_0 K + \left(\sqrt{K \ln(2q\ell\delta)}\right)\right)$ many queries made to the prover for f_i are yes instances. In particular, this means that with probability at least $(1-\delta)$, the verifier ensures that the prover can cheat on at most $2q \cdot \left(\sqrt{K \ln(2q\ell/\delta)} + \varepsilon_0 K\right)$ many yes instances for each f_i. Thus, the probability that there exists a run of M which consists of a query to some f_i on which the prover has cheated is at most $2q\ell \cdot \left(\sqrt{\ln(2q\ell/\delta)/K} + \varepsilon_0\right) \le \delta + 2q\ell\varepsilon_0$ for the value of K defined. Thus, the overall probability that the verifier accepts is at most $\delta + \gamma + (\delta + 2q\ell\varepsilon_0) \le \gamma + 2\delta + 2q\ell\varepsilon_0 \le \varepsilon$. □

Remark 6.5. *In addition, we can also extend the proof to the case where M still makes non-adaptive queries but is not constrained distributionally in its access to all the hypotheses, by directly applying the techniques of [BT06] for the simulation of R in $\mathsf{AM}^{\mathsf{poly}}$.*

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