

PH = PSPACE

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Abstract. We show that \mathbb{PSPACE} is equal to 4th level in the polynomial hierarchy.

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1 Introduction

In computational complexity theory, \mathbb{NP} is one of the most fundamental complexity classes. The complexity class \mathbb{NP} is associated with computational problems having solutions that, once given, can be efficiently tested for validity. It is customary to define \mathbb{NP} as the class of languages which can be recognized by a non-deterministic polynomial-time machine.

A decision problem is a member of $\text{co-}\mathbb{NP}$ if and only if its complement (the complement of a decision problem is the decision problem resulting from reversing the "yes" and "no" answers) is in the complexity class \mathbb{NP} . In simple terms, $\text{co-}\mathbb{NP}$ is the class of problems for which efficiently verifiable proofs of "no" instances, sometimes called counterexamples, exist. Equivalently, $\text{co-}\mathbb{NP}$ is the set of decision problems where the "no" instances can be accepted in polynomial time by a non-deterministic Turing machine.

On the other hand, \mathbb{PSPACE} is the set of all decision problems that can be solved by a Turing machine using a polynomial amount of space.

An oracle machine is an abstract machine used to study decision problems. It can be visualized as a Turing machine with a black box, called an oracle, which is able to solve certain decision problems in a single operation. We use notation $\mathbb{L}^{\mathbb{O}}$, where \mathbb{O} is the oracle.

On the contemporary state-of-the-art, the interested reader is referred to [1] and references therein.

Our result resolves some of unsolved problems in Computer Science.

The essential idea of the proof is to show that for any (fully) quantified Boolean formula ϕ we can obtain a formula ϕ' which is in the fourth level of the polynomial hierarchy, no more than polynomial in the size of a given ϕ , such that the truth of ϕ can be determined from the truth of ϕ' . The idea is to skolemize, and then use additional formulas from the second level of the polynomial hierarchy inside the skolemized prefix to enforce that the skolem variables indeed depend only on the universally quantified variables they are supposed to. However, some dependence is lost when the quantification is reversed. It is called "XOR issue" in the paper because the functional dependence can be expressed by means of an XOR formula. Thus, it is needed to locate these XORs. The last can be done locally, when all arguments are specified (keep in mind the algebraic normal form (ANF)), i.e. as a polynomial subroutine.

The paper is organized as follows. Chapters 2-4 refresh basic definitions. Chapter 5 contains the proof.

2 Quantified Boolean formula

The Boolean Satisfiability Problem (abbreviated as SAT) is the problem of determining if there exists an interpretation that satisfies a given Boolean formula. In other words, it asks whether the variables of a given Boolean formula can be consistently replaced by the values true or false in such a way that the formula evaluates to true. SAT was the first known \mathbb{NP} -complete problem, as proved by Stephen Cook [2] and independently by Leonid Levin [3].

One simple example of a $\text{co-}\mathbb{NP}$ -complete problem is tautology, the problem of determining whether a given Boolean formula is a tautology; that is, whether every possible assignment of true/false values to variables yields a true statement.

For a Boolean formula $\phi(x_1, \dots, x_n)$, we can think of its satisfiability as determining the true of the statement

$$\exists x_1 \in \{0, 1\} \exists x_2 \in \{0, 1\} \dots \exists x_n \in \{0, 1\} \phi(x_1, \dots, x_n).$$

The SAT problem becomes more difficult if both "for all" (\forall) and "there exists" (\exists) quantifiers are allowed. It is known as the quantified Boolean formula problem or QSAT. QSAT is the canonical complete problem for \mathbb{PSPACE} [1].

3 The Polynomial Hierarchy

We have seen the classes NP and co-NP , which are defined as follows [1]:

$L \in \text{NP}$ if there is a deterministic Turing machine M running in time polynomial in its first input, such that $x \in L \Leftrightarrow \exists w M(x; w) = 1$, w has length polynomial in x .

$L \in \text{co-NP}$ if there is a deterministic Turing machine M running in time polynomial in its first input, such that $x \in L \Leftrightarrow \forall w M(x; w) = 1$, w has length polynomial in x .

It is natural to generalize the above [1][4].

Let i be a positive integer. $L \in \Sigma_i$ if there is a deterministic Turing machine M running in time polynomial in its first input, such that

$$x \in L \Leftrightarrow \underbrace{\exists w_1 \forall w_2 \dots Q_i w_i}_{i \text{ times}} M(x; w_1; \dots; w_i) = 1,$$

where $Q_i = \forall$ if i is even, and $Q_i = \exists$ if i is odd.

Let i be a positive integer. $L \in \Pi_i$ if there is a deterministic Turing machine M running in time polynomial in its first input, such that

$$x \in L \Leftrightarrow \underbrace{\forall w_1 \exists w_2 \dots Q_i w_i}_{i \text{ times}} M(x; w_1; \dots; w_i) = 1,$$

where $Q_i = \forall$ if i is odd, and $Q_i = \exists$ if i is even.

As in the cases of NP , co-NP , we require that w_i each have length polynomial in x .

The polynomial hierarchy PH consists of all those languages of the form defined above. Note also the similarity to QSAT . The crucial difference is that QSAT allows an unbounded number of alternating quantifiers, whereas Σ_i , Π_i each allow (at most) i quantifiers. From here, $\text{PH} \subseteq \text{PSPACE}$.

4 Alternating Turing machine

An alternating Turing machine (ATM) is a non-deterministic Turing machine (NTM) with a rule for accepting computations that generalizes the rules used in the definition of the complexity classes NP and co-NP . The concept of an ATM was set forth by Ashok Chandra, Larry Stockmeyer and Dexter Kozen [5].

The definition of NP uses the existential mode of computation: if any choice leads to an accepting state, then the whole computation accepts. The definition of co-NP uses the universal mode of computation: only if all choices lead to an accepting state, then the whole computation accepts. An alternating Turing machine (or to be more precise, the definition of acceptance for such a machine) alternates between these modes.

An alternating Turing machine with k alternations is an alternating Turing machine which switches from an existential to a universal state or vice versa no more than $k - 1$ times. The complexity class PH is a special case of hierarchy of bounded alternating Turing machine [5].

$\text{AP} = \text{PSPACE}$, where AP is the class of problems alternating machines can solve in polynomial time [5].

5 Main result

Next theorem shows that QBF is indeed a **generalisation** of the Boolean Satisfiability Problem, where determining of interpretation that satisfies a given Boolean formula is replaced by existence of Boolean functions that makes a given QBF to be tautology. Such functions are called the **Skolem functions**.

Theorem 1. *The quantified Boolean formula*

$$\Omega_1 x_1 \in \{0, 1\} \Omega_2 x_2 \in \{0, 1\} \dots \Omega_n x_n \in \{0, 1\} \phi(x_1, \dots, x_n),$$

where $\phi(x_1, \dots, x_n)$ is a Boolean formula, Ω_s , $s = i_1, \dots, i_j$, is the quantifier \exists and Ω_t , $t \neq i_1, \dots, i_j$, is the quantifier \forall , j is the number of variables with the quantifier \exists , is a true quantified Boolean formula if and only if there are Boolean functions y_q , where y_q depends only on variables with the quantifier \forall and indexes less i_q , $q = 1, \dots, j$, that after substituting $x_{i_q} := y_q$ the given quantified Boolean formula becomes tautology.

Proof. It follows from a simple recursive algorithm for determining whether a QBF is true. We take off the first quantifier and check both possible values for the first variable:

$$A = \Omega_2 x_2 \in \{0, 1\} \dots \Omega_n x_n \in \{0, 1\} \phi(0, \dots, x_n),$$

$$B = \Omega_2 x_2 \in \{0, 1\} \dots \Omega_n x_n \in \{0, 1\} \phi(1, \dots, x_n).$$

If $\Omega_1 = \exists$, then return A disjunction B (that's it, A or B is true; to avoid unambiguous, if A and B is true, take A for determining the function, so the value depends only on values of previous variables). If $\Omega_1 = \forall$, then return A conjunction B (A and B is true).

Notice that a Boolean function determines the truth table (one-to-one correspondence).

Example 1. Let only the quantifier for x_k , $k \geq 1$, be existential, then y_1 is some function of variables x_1, \dots, x_{k-1} , as QBF means in that case that for any possible values of x_1, \dots, x_{k-1} there exists value of x_k that for all possible values of $x_{i>k}$ the given formula is true. It is indeed the truth table, where values of x_1, \dots, x_{k-1} determine the value x_k .

Example 2. $\forall x_1 \exists z_1 \forall x_2 \exists z_2 \forall x_3 \exists z_3 \phi(x_1, z_1, x_2, z_2, x_3, z_3)$ is a true QBF if and only if there exist such Boolean functions $y_1 : \{0, 1\} \rightarrow \{0, 1\}$, $y_2 : \{0, 1\}^2 \rightarrow \{0, 1\}$, $y_3 : \{0, 1\}^3 \rightarrow \{0, 1\}$ that

$$\phi(x_1, y_1(x_1), x_2, y_2(x_1, x_2), x_3, y_3(x_1, x_2, x_3)) \text{ is tautology.}$$

Theorem 2.

$$\prod_4 = (co\text{-NP})^{\text{NP}(co\text{-NP})^{\text{NP}}} = \text{PSPACE}$$

Proof. From [1][6] we know that without loss of generality we can assume a quantified Boolean formula to be in form (prenex normal form), where existential and universal quantifiers alternate. We assume it, for simplicity.

We **wish** that a quantified Boolean formula

$$\forall x_1 \in \{0, 1\} \exists y_1 \in \{0, 1\} \forall x_2 \in \{0, 1\} \exists y_2 \in \{0, 1\} \dots \forall x_n \in \{0, 1\} \exists y_n \in \{0, 1\}$$

$$\phi(x_1, y_1, \dots, x_n, y_n)$$

would be equivalent (equisatisfiable, more correctly) to

$$\forall(x_1, x_2, \dots, x_n) \exists(y_1, \dots, y_n) \{$$

$$\phi(x_1, y_1, x_2, y_2, \dots, x_n, y_n) \wedge$$

$$\wedge \forall(\hat{x}_n) \exists(z_n) \phi(x_1, y_1, x_2, y_2, \dots, x_{n-1}, y_{n-1}, \hat{x}_n, z_n) \wedge$$

$$\wedge \forall(\hat{x}_{n-1}, \hat{x}_n) \exists(z_{n-1}, z_n) \phi(x_1, y_1, x_2, y_2, \dots, x_{n-2}, y_{n-2}, \hat{x}_{n-1}, z_{n-1}, \hat{x}_n, z_n) \wedge \dots$$

$$\dots \wedge \forall(\hat{x}_2, \dots, \hat{x}_n) \exists(z_2, \dots, z_n) \phi(x_1, y_1, \hat{x}_2, z_2, \dots, \hat{x}_{n-2}, z_{n-2}, \hat{x}_{n-1}, z_{n-1}, \hat{x}_n, z_n)$$

}

Namely, iterations of $\forall x \exists y$ reduce to conjunctions of separated $\forall \hat{x} \exists z$, as in the beginning we fix values of $\{y_q, q = 1, \dots, n\}$ and conjunctions jointly check that for predetermined $\{y_l, l < q\}$ suitable continuation $\{y_l, l \geq q\}$ can be found. In each conjunction we consider $\{y_l, l < q\}$ as functions dependent on all $\{x_i, i < q\}$ and $\{z_l, l \geq q\}$ as functions dependent on every $\{x_i, i = 1, \dots, n\}$ (if $\forall x_1 F(x_1, 0) = F(x_1, 1)$, then variable x_2 is dummy variable for Boolean formula $F(x_1, x_2)$). From here, if it is a true quantified Boolean formula, the above confirms it. However, another implication is not always true. Let's exam when two parts are different, allowing ϕ to have also odd number of variables with preserving alternations for quantifiers for foregoing induction.

m = 1: for a Boolean formula of one variable the equivalence obviously holds.

m = 2: inconsistency can possibly happen only with $\exists y \forall x \phi(y, x)$; we have 16 different Boolean formulas of two variables and the equivalence is violated only for $XOR : (y \oplus x), \neg(y \oplus x)$.

Example 3. $\exists y \forall x x \cdot y$ is FALSE as well as $\forall x \exists y x \cdot y$

Example 4. $\exists y \forall x x + y$ is TRUE as well as $\forall x \exists y x + y$

Example 5. $\exists y \forall x x \oplus y$ is FALSE, but $\forall x \exists y x \oplus y$ is TRUE

$\mathbf{m} \geq \mathbf{3}$: taking off the first quantifier and checking both possible values for the first variable in way we did in Theorem 1, we come to the $\mathbf{m} - \mathbf{1}$ case. Indeed, for example, considering $\mathbf{m} = \mathbf{3}$, we have

$$\begin{aligned} \forall z \exists y \forall x \phi(z, y, x) &\equiv \exists y \forall x \phi(0, y, x) \text{ AND } \exists y \forall x \phi(1, y, x), \\ \exists t \forall x \exists y \phi(t, x, y) &\equiv \forall x \exists y \phi(0, x, y) \text{ OR } \forall x \exists y \phi(1, x, y), \end{aligned}$$

where the second expression can be viewed as negation of the first expression. Consequently, it is enough to inspect only the first expression due to double negation.

If $\exists y \forall x \phi(0, y, x) \equiv \forall x \exists y \phi(0, y, x)$ and $\exists y \forall x \phi(1, y, x) \equiv \forall x \exists y \phi(1, y, x)$, then $\forall z \exists y \forall x \phi(z, y, x) \equiv \forall z \forall x \exists y \phi(z, y, x) \equiv \forall z \exists \xi \forall x \exists y \phi(z, y, x)$. Otherwise, the equivalence is false due to XOR issue from $\mathbf{m} = \mathbf{2}$. Then $\exists y \forall x \phi(0, y, x)$ or $\exists y \forall x \phi(1, y, x)$ is false. Therefore, $\forall z \exists y \forall x \phi(z, y, x)$ is false.

Thus, using mathematical induction we have shown that XOR issue from $\mathbf{m} = \mathbf{2}$ appears whenever the equivalence we want doesn't work and the emergence means that the real value is false, but the displayed formula says that it is true (there is no need to locate all chains with XORs: any chain includes a XOR of only two variables). The algebraic normal form (ANF, Zhegalkin normal form) is used here, i.e. the fact that any Boolean formula can be rewritten using only conjunctions and XORs.

Indeed, as we have $2n$ variables, XOR issue from $\mathbf{m} = \mathbf{2}$ appears not only lonely, it can be some polynomial from ANF representation, i.e.,

$$(x_1 \text{ AND } \dots \text{ AND } x_s \text{ AND } x) \text{ XOR } (y_1 \text{ AND } \dots \text{ AND } y_t \text{ AND } y) \text{ XOR } \dots,$$

which is needed to be detected. However, despite the exponential number of such polynomials, the AND allows to examine them as a polynomial subroutine.

So, for

$$\begin{aligned} \forall(x_1, x_2, \dots, x_n) \exists(y_1, \dots, y_n) \forall(\hat{x}_1, \dots, \hat{x}_n) \exists(z_1, \dots, z_n) \\ \phi(x_1, y_1, x_2, y_2, \dots, \hat{x}_i, z_i, \dots, \hat{x}_{n-1}, z_{n-1}, \hat{x}_n, z_n) \end{aligned}$$

we additionally need to verify that for specific x_1, \dots, x_{i-1} and $\hat{x}_i, \dots, \hat{x}_n$ and found y_1, \dots, y_{i-1} and z_i, \dots, z_n the given formula ϕ with the above fixed arguments except any variable with universal quantifier and any variable with existential quantifier is not equivalent to $\exists y \forall x (x \oplus y)$ or $\exists y \forall x \neg(x \oplus y)$ (there are n^2 formulas to examine in total).

The idea is the following: if something1 XOR something2 XOR ... causes unequiasatisfiability, then for certain values of variables the expression something1 XOR something2 XOR ... must become $\exists y \forall x (x \oplus y)$ or $\exists y \forall x \neg(x \oplus y)$. And, otherwise, if something1 XOR something2 XOR ... does not cause unequiasatisfiability, then there are not values of variables such that the expression something1 XOR something2 XOR ... becomes to be in the form $\exists y \forall x (x \oplus y)$ or $\exists y \forall x \neg(x \oplus y)$. This finds some analogy with Full (Perfect) Disjunctive Normal Form.

To conclude, definition of alternating Turing machine shows that $(\text{co-NP})^{\text{NP}(\text{co-NP})^{\text{NP}}}$ is enough and this way we solve complete problem for PSPACE.

Remark 1. PSPACE = P? PSPACE = NP? PSPACE = P^{NP}? PSPACE = NP^{NP}? PSPACE = NP^{NP^{NP}}?

Remark 2. Maximal Satisfying Assignment_{odd}, the problem of indicating, that the lexicographical maximum $x_1, \dots, x_n \in \{0, 1\}^n$, that satisfies a given Boolean formula, is odd (is x_1 odd?), is complete for P^{NP}.

BQP (bounded-error quantum polynomial time) is the class of decision problems solvable by a quantum computer in polynomial time, with an error probability of at most 1/3 for all instances, see [1][6].

Corollary 1. The polynomial hierarchy collapses and BQP \subseteq PH.

Proof. See Chapter 3 and Theorem 2. It is known that BQP \subseteq PSPACE.

Remark 3. The relationship between BQP and PH has been an open problem since the earliest days of quantum computing [7].

Remark 4. The polynomial hierarchy is infinite relative to a random oracle with probability 1 and there exists an oracle separation of PH and PSPACE, see, for example, [8]. However, note that an oracle separation does not necessarily imply the ordinary separation. There is no contradiction.

The proof of Theorem 2 relies strongly on Boolean algebra (the exchange is possible due to finite possibilities for arguments) and that defeats **the relativization**. Moreover, one useful reformulation is that PH = PSPACE if and only if second-order logic over finite structures gains no additional power from the addition of a transitive closure operator.

\mathbb{BPP} (bounded-error probabilistic polynomial time) is the class of decision problems solvable by a probabilistic Turing machine in polynomial time with an error probability bounded away from $1/3$ for all instances, see [1]. If the access to randomness is removed from the definition of \mathbb{BPP} , we get the complexity class \mathbb{P} .

Corollary 2. *If $\mathbb{P} = \mathbb{NP}$, then $\mathbb{P} = \mathbb{PSPACE}$. If $\mathbb{BPP} = \mathbb{NP}$, then $\mathbb{BPP} = \mathbb{PSPACE}$.*

Proof. If $\mathbb{P} = \mathbb{NP}$, then $\mathbb{NP} = \text{co-}\mathbb{NP}$, since $\mathbb{P} = \text{co-}\mathbb{P}$. Moreover, a \mathbb{P} machine with the power to solve \mathbb{P} problems instantly (a \mathbb{P} oracle machine) is not any more powerful than the machine without this extra power. Thus, we obtain that $\mathbb{P} = \mathbb{PH}$.

\mathbb{BPP} can be treated in the same manner, as it is known that \mathbb{BPP} is closed under complement and low for itself, meaning that $\mathbb{BPP}^{\mathbb{BPP}} = \mathbb{BPP}$.

Corollary 3. *If $\mathbb{NP} = \text{co-}\mathbb{NP}$, then $\mathbb{NP} = \mathbb{PSPACE}$.*

Proof. It is known that if $\mathbb{NP} = \text{co-}\mathbb{NP}$, then $\mathbb{NP} = \mathbb{PH}$.

\mathbb{PP} is the class of decision problems solvable by a probabilistic Turing machine in polynomial time, with an error probability of less than $1/2$ for all instances, see [1][9]. \mathbb{PP} has natural complete problems, for example, MAJSAT. It is a decision problem, in which one is given a Boolean formula ϕ . The answer must be "yes" if more than half of all assignments make ϕ true and "no" otherwise.

Corollary 4. $\mathbb{P}^{\mathbb{PP}} = \mathbb{PSPACE}$.

Proof. By Toda's theorem $\mathbb{PH} \subseteq \mathbb{P}^{\mathbb{PP}}$ [1][10]. Further, $\mathbb{P}^{\mathbb{PP}} \subseteq \mathbb{P}^{\mathbb{PSPACE}} = \mathbb{P}^{\mathbb{PH}} = \mathbb{PH}$.

Remark 5. By adding postselection to \mathbb{BQP} ($\mathbb{BQP} \subseteq \mathbb{PP}$), a larger class is obtained [11]. It is known that it is equal to \mathbb{PP} [11]. Is it true that $\mathbb{BQP} \neq \mathbb{PP}$?

Corollary 5. *If $\mathbb{NP} \subseteq \mathbb{BQP}$, then $\mathbb{BQP} = \mathbb{PSPACE}$.*

Proof. \mathbb{BQP} is low for itself, which means $\mathbb{BQP}^{\mathbb{BQP}} = \mathbb{BQP}$ [12]; $\mathbb{BQP} \subseteq \mathbb{PSPACE}$.

Remark 6. Dependency quantified Boolean formulas (DQBFs) are a generalization of ordinary quantified Boolean formulas [13]. While the latter is restricted to linear dependencies of existential variables in the quantifier prefix, DQBFs allow arbitrary dependencies, which are explicitly specified in the formula. This makes decision problem with a DQBF to be \mathbb{NEXP} -complete [14].

Theorem 2 is not applicable to the case of DQBFs directly as the looping is possible (**the linear order** is used in Theorem 2). Is it within reach to generalise Theorem 2 for it? Notice that $\mathbb{NEXP} \subseteq \mathbb{EXP}^{\mathbb{NP}}$.

Remark 7. Theorem 2 opens the road for comprehensive pursuing of all exponential complexity classes and their relationships with probabilistic Turing machines and the polynomial hierarchy. The beginning of such kind of research can be found in [15][16][17][18][19].

Corollary 6. $\mathbb{PSPACE} \neq \mathbb{EXP}$.

Proof. $\mathbb{EXP} \neq \mathbb{EXP}^{\mathbb{EXP}}$ by the time hierarchy theorems, but $\mathbb{PSPACE}^{\mathbb{PSPACE}} = \mathbb{PH}^{\mathbb{PH}} = \mathbb{PH}$ due to Theorem 2.

Remark 8. The complexity of the ATL (Alternating-time Temporal Logic) satisfiability problem was proven to be \mathbb{EXP} -complete by van Drimmlen [20] for a fixed number of agents (notice that even with an unbounded supply of agents it is true [18] and that gives another insight about collapsing of the polynomial hierarchy).

There is fixed point representation of ATL via QBF encoding, i.e., Unbounded Model Checking, see [21]. Hence, there exists a translation of ATL formulas into propositional formulas.

According to Remark 6 and Corollary 6 decision problem with a certain type DQBF is \mathbb{EXP} -complete. What could possibly be in-between these extremes? Notice that $\mathbb{EXP} \neq \mathbb{NEXP}$ if and only if $\mathbb{P} \neq \mathbb{NP}$.

Multiset $\{\mathbb{P}, \mathbb{NP}, \mathbb{NP}^{\mathbb{NP}}, \mathbb{NP}^{\mathbb{NP}^{\mathbb{NP}}}, \mathbb{NP}^{\mathbb{NP}^{\mathbb{NP}^{\mathbb{NP}}}}\}$ shows that there is always a key.

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