Strong Parallel Repetition Theorem for Quantum XOR Proof Systems

Richard Cleve*† William Slofstra*
Falk Unger‡ Sarvagya Upadhyay*

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Abstract

We consider a class of two-prover interactive proof systems where each prover returns a single bit to the verifier and the verifier's verdict is a function of the XOR of the two bits received. Such proof systems, called XOR proof systems, have previously been shown to characterize MIP (= NEXP) in the case of classical provers but to reside in EXP in the case of quantum provers (who are allowed to share *a priori* entanglement). We show that, in the quantum case, a *perfect parallel repetition theorem* holds for such proof systems in the following sense. The prover's optimal success probability for simultaneously playing a collection of XOR proof systems is *exactly* the product of the individual optimal success probabilities. This property is remarkable in view of the fact that, *in the classical case, it does not hold.* The theorem is proved by analyzing an XOR operation on XOR proof systems. Using semidefinite programming techniques, we show that this operation satisfies a certain additivity property, which we then relate to parallel repetitions of XOR games.

1 Introduction and summary of results

The theory of interactive proof systems has played an important role in the development of computational complexity and cryptography. Also, the impact of quantum information on the theory of interactive proof systems has been investigated and shown to have interesting consequences [17]. In [5] a variant of the model of interactive proof system was introduced where there are two provers who have unlimited computational power subject to the condition that they cannot communicate between themselves once the execution of the protocol starts. This model is sufficiently powerful to characterize NEXP [1].

Our present focus is on *XOR interactive proof systems*, which are based on *(nondegenerate) XOR games*. For a predicate $f : S \times T \to \{0, 1\}$ and a probability distribution π on $S \times T$, define the XOR game $G = (f, \pi)$ operationally as follows.

*David R. Cheriton School of Computer Science and Institute for Quantum Computing, University of Waterloo. `cleve@cs.uwaterloo.ca`, `weslofst@student.cs.uwaterloo.ca`, `supadhyay@cs.uwaterloo.ca`

†Perimeter Institute for Theoretical Physics.

‡CWI, Amsterdam. `F.Unger@cwi.nl`

- The Verifier selects a pair of questions $(s, t) \in S \times T$ according to distribution π.
- The Verifier sends one question to each prover: s to prover Alice and t to prover Bob (who are forbidden from communicating with each other once the game starts).
- Each prover sends a bit back to the Verifier: a from Alice and b from Bob.
- The Verifier accepts if and only if $a \oplus b = f(s, t)$.

A definition that is essentially equivalent to this[1] appears in [8]. In the classical version, the provers have unlimited computing power, but are restricted to possessing classical information; in the quantum version, the provers may possess qubits whose joint state is entangled. In both versions, the communication between the provers and the verifier is classical.

An *XOR interactive proof system* for a language L associates an XOR game with every input string x, such that, for some constants $0 \leq s < c \leq 1$:

- S_x and T_x consist of strings of length polynomial in $|x|$, π_x can be sampled in time polynomial in $|x|$, and f_x can be computed in time polynomial in $|x|$.
- If $x \in L$ then the maximum acceptance probability over prover's strategies is at least c.
- If $x \notin L$ then the maximum acceptance probability over prover's strategies is at most s.

In [8] it is pointed out that results in [4, 13] imply that, in the case of classical provers, these proof systems have sufficient expressive power to recognize every language in NEXP (with soundness probability $s = 11/16 + \epsilon$ and completeness probability $c = 12/16 - \epsilon$, for arbitrarily small $\epsilon > 0$). Thus, although these proof systems appear restrictive, they can recognize any language that an unrestricted multi-prover interactive proof system can. Moreover, in [9, 18] it is shown that any language recognized by a quantum XOR proof system is in EXP. Thus, assuming EXP $\neq$ NEXP, quantum entanglement strictly weakens the expressive power of XOR proof systems.

Returning to XOR games, quantum physicists have, in a sense, been studying them since the 1960s, when John Bell introduced his celebrated results that are now known as Bell inequality violations [3]. An example is the *CHSH* game, named after the authors of [7]. In this game, $S = T = \{0, 1\}$, π is the unform distribution on $S \times T$, and $f(s, t) = s \wedge t$. It is well known that, for the *CHSH* game, the best possible classical strategy succeeds with probability 3/4, whereas the best possible quantum strategy succeeds with higher probability of $(1 + 1/\sqrt{2})/2 \approx 0.85$ [7, 15].

Following [8], for an XOR game G, define its *classical value* $\omega_c(G)$ as the maximum possible success probability achievable by a classical strategy. Similarly, define its *quantum value* $\omega_q(G)$ as the maximum possible success probability achievable by a quantum strategy. It is convenient to also define the classical and quantum *bias* of an XOR game as $\varepsilon_c(G) = 2\omega_c(G) - 1$ and $\varepsilon_q(G) = 2\omega_q(G) - 1$, respectively.

Our main results are Theorem 1 of Section 2 and Theorem 7 of Section 3.

[1] Except that *degeneracies* are allowed, where for some (s, t) pairs, the Verifier is allowed to accept or reject independently of the value of $a \oplus b$. All results quoted here apply to nondegenerate games.

2 Additivity of XOR games

For any two XOR games $G_1 = (f_1, \pi_1)$ and $G_2 = (f_2, \pi_2)$, define their *sum (modulo two)* as the XOR game

$$G_1 \oplus G_2 = (f_1 \oplus f_2, \pi_1 \times \pi_2). \tag{1}$$

In this game, the verifier chooses questions $((s_1, t_1), (s_2, t_2)) \in (S_1 \times T_1) \times (S_2 \times T_2)$ according to the product distribution $\pi_1 \times \pi_2$, sending (s_1, s_2) to Alice and (t_1, t_2) to Bob. Alice and Bob win if and only if their respective outputs, a and b, satisfy $a \oplus b = f_1(s_1, t_1) \oplus f_2(s_2, t_2)$.

A simple way for Alice and Bob to play $G_1 \oplus G_2$ is to optimally play G_1 and G_2 separately, producing outputs a_1, b_1 for G_1 and a_2, b_2 for G_2, and then to output $a = a_1 \oplus a_2$ and $b = b_1 \oplus b_2$ respectively. It is straightforward to calculate that the above method for playing $G_1 \oplus G_2$ succeeds with probability $\omega_c(G_1)\omega_c(G_2) + (1 - \omega_c(G_1))(1 - \omega_c(G_2))$. Equivalently, the bias of the success probability is $\varepsilon_c(G_1)\varepsilon_c(G_2)$. In this section, we consider the question: Is this the optimal way to play $G_1 \oplus G_2$?

The answer is *no* for *classical* strategies. To see why this is so, note that, using this approach for the XOR game *CHSH*$\oplus$ *CHSH*, produces a success probability of 5/8. A better strategy is for Alice to output $a = s_1 \wedge s_2$ and Bob to output $b = t_1 \wedge t_2$. It is straightforward to verify that this latter strategy succeeds with probability 3/4.

The main result of this section is that the answer is *yes* for *quantum* strategies.

Theorem 1. *For any two XOR games G_1 and G_2 an optimal quantum strategy for playing $G_1 \oplus G_2$ is for Alice and Bob to optimally play G_1 and G_2 separately, producing outputs a_1, b_1 for G_1 and a_2, b_2 for G_2, and then to output $a = a_1 \oplus a_2$ and $b = b_1 \oplus b_2$.*

In this sense, we say that quantum strategies for XOR games are *additive*, whereas classical strategies are not.

The proof of Theorem 1 employs the known characterization of quantum strategies for XOR games in terms of semidefinite programming, and a number of techniques in semidefinite programming.

A quantum strategy for a XOR game consists of a bipartite quantum state $|\psi\rangle$ shared by Alice and Bob, a set of observables X_s ($s \in S$) corresponding to Alice's part of the quantum state, and a set of observables Y_t ($t \in T$) corresponding to Bob's part of the state. We make use of a vector characterization of XOR games due to [16] (also pointed out in [8]), which is a consequence of the following.

Theorem 2. ([16]) *Let S and T be finite sets, and let $|\psi\rangle$ be a pure quantum state with support on a bipartite Hilbert space $\mathcal{H} = \mathcal{A} \otimes \mathcal{B}$ such that $dim(\mathcal{A}) = dim(\mathcal{B}) = n$. For each $s \in S$ and $t \in T$, let X_s and Y_t be observables on $\mathcal{A}$ and $\mathcal{B}$ with eigenvalues ± 1 respectively. Then there exists real unit vectors x_s and y_t in $\mathbb{R}^{2n^2}$ such that*

$$\langle \psi | X_s \otimes Y_t | \psi \rangle = x_s \cdot y_t,$$

for all $s \in S$ and $t \in T$.
Conversely, suppose that S and T are finite sets, and x_s and y_t are unit vectors in $\mathbb{R}^N$ for each $s \in S$ and $t \in T$. Let $\mathcal{A}$ and $\mathcal{B}$ be Hilbert space of dimension $2^{\lceil N/2 \rceil}$, $\mathcal{H} = \mathcal{A} \otimes \mathcal{B}$

and $|\psi\rangle$ be a maximally entangled state on $\mathcal{H}$. Then there exists observables X_s and Y_t with eigenvalues ± 1, on $\mathcal{A}$ and $\mathcal{B}$ respectively, such that

$$\langle\psi|X_s \otimes Y_t|\psi\rangle = x_s \cdot y_t,$$

for all $s \in S$ and $t \in T$.

Using Theorem 2, we can characterize Alice and Bob's strategies by a choice of unit vectors $\{x_s\}_{s\in S}$ and $\{y_t\}_{t\in T}$. Using this characterization, the bias becomes

$$\varepsilon(G) = \max_{\{x_s\},\{y_t\}} \quad \sum_{s,t} \pi(s,t)(-1)^{f(s,t)\oplus 1}\ x_s \cdot y_t. \tag{2}$$

The *cost matrix* for the game is defined as the matrix A with entries $A_{s,t} = \pi(s,t)(-1)^{f(s,t)\oplus 1}$. Note that any matrix A, with the provision that the absolute values of the entries sum to 1, is the cost matrix of an XOR game. If G_1 and G_2 are games with cost matrices A_1 and A_2 respectively, then the cost matrix of $G_1 \oplus G_2$ is $A_1 \otimes A_2$.

The bias of a quantum XOR game may be stated as a semidefinite programming problem (SDP). We refer to Boyd and Vandenberghe [6] for a detailed introduction to semidefinite programming (SDP). The bias is in fact equivalent to the problem

$$\max \ \ \mathrm{Tr}\left(A^T U_1^T U_2\right) \quad : \quad \mathrm{diag}\left(U_1^T U_1\right) = \mathrm{diag}\left(U_2^T U_2\right) = \bar{e}, \tag{3}$$

where $\{x_s\}$ and $\{y_t\}$ appear as the columns of U_1 and U_2 respectively. Here $\mathrm{diag}(M)$ denotes the column vector of diagonal entries of the matrix M, and $\bar{e}$ is the column vector $(1,\ldots,1)^T$. This problem is in turn equivalent to the SDP P_A defined by

$$\max \ \ \mathrm{Tr}\begin{pmatrix} 0 & \frac{1}{2}A \\ \frac{1}{2}A^T & 0 \end{pmatrix} X \quad : \quad \mathrm{diag}(X) = \bar{e}, \quad X \succeq 0.$$

The notation $A \succeq B$ means that the matrix $A - B$ lies in the cone of positive semidefinite matrices. That P_A is equivalent to problem (3) follows from the fact that a semidefinite matrix X can be written as $(U_1\ U_2)^T(U_1\ U_2)$ for some matrices U_1 and U_2.

To show that an optimal solution for P_A exists, we can examine the Lagrange-Slater dual of P_A. The dual, denoted by D_A, is defined to be

$$\min \ \ \bar{e}^T y \quad : \quad \Delta(y) \succeq \begin{pmatrix} 0 & \frac{1}{2}A \\ \frac{1}{2}A^T & 0 \end{pmatrix},$$

where $\Delta(y)$ denotes the diagonal matrix with entries given by the vector y. Both P_A and D_A have Slater points—that is, feasible points in the interior of the semidefinite cone. Explicitly, the identity matrix is a Slater point for P_A, and for large c, $c\bar{e}$ is a Slater point for D_A. The strong duality theorem states that when both the primal and dual problem have Slater points, the optimal values of P_A and D_A are the same and both problems have optimal solutions obtaining this value.

The next proposition illustrates how the SDP formulation may be used. Intuitively, it corresponds to the fact that if Alice and Bob play games G_1 and G_2 optimally, taking the sum of their outputs as the solution to $G_1 \oplus G_2$, they will succeed with bias $\varepsilon(G_1)\varepsilon(G_2)$. Theorem 1 will follow when we show the reverse inequality, that $\varepsilon(G_1 \oplus G_2) \le \varepsilon(G_1)\varepsilon(G_2)$.

Proposition 3. *For two XOR games G_1 and G_2, $\varepsilon(G_1 \oplus G_2) \geq \varepsilon(G_1)\varepsilon(G_2)$.*

Proof. Let game G_i have cost matrix A_i, and let X_i be an optimal solution for P_{A_i}. We may write X_i as $(U_i \ V_i)^T (U_i \ V_i)$. The cost matrix for $G_1 \oplus G_2$ is $A_1 \otimes A_2$. Then $X = (U_1 \otimes U_2 \quad V_1 \otimes V_2)^T (U_1 \otimes U_2 \quad V_1 \otimes V_2)$ is a feasible solution for $P_{A_1 \otimes A_2}$. The optimal value of $P_{A_1 \otimes A_2}$ is greater than the value of this feasible solution, which is

$$\mathrm{Tr}\left(A_1 U_1^T V_1\right) \mathrm{Tr}\left(A_2 U_2^T V_2\right) = \varepsilon(G_1)\varepsilon(G_2).$$

□

We consider two methods, differing from the sum, by which new XOR games may be derived from those on hand. For a game G with cost matrix A, we define G^T to be the game with cost matrix A^T. In other words, Alice and Bob switch places to play G^T. Suppose G_1 and G_2 to be XOR games with cost matrices A_1 and A_2 respectively. For $0 \leq \lambda \leq 1$, we may define the convex combination $\lambda G_1 + (1-\lambda)G_2$ to be the XOR game with cost matrix

$$\begin{pmatrix} 0 & \lambda A_1 \\ (1-\lambda)A_2 & 0 \end{pmatrix}.$$

There is a simple interpretation of this convex combination. If, in G_i, Alice and Bob are posed questions from S_i and T_i respectively, then in $\lambda G_1 + (1-\lambda)G_2$ Alice and Bob are either posed a question from S_1 and T_1 with probability λ, or a question from S_2 and T_2 with probability $1-\lambda$. The next proposition summarizes some simple facts.

Proposition 4.

1. *$\varepsilon(G^T) = \varepsilon(G)$ and $\varepsilon(G_1 \oplus G_2) = \varepsilon(G_2 \oplus G_1)$.*

2. *A limited distributive law holds:*

$$[\lambda G_1 + (1-\lambda) G_2] \oplus H = \lambda G_1 \oplus H + (1-\lambda) G_2 \oplus H$$

for any three games G_1, G_2, and H.

3. *The convex combination of games is additive with respect to ε:*

$$\varepsilon\left(\lambda G_1 + (1-\lambda) G_2\right) = \lambda \varepsilon(G_1) + (1-\lambda)\, \varepsilon(G_2).$$

The next lemma will complete the proof of additivity for the sum of symmetric games. The proof of this lemma requires two properties of positive semidefinite matrices. The first, is that if $A \succeq 0$ and non-singular, then

$$\begin{pmatrix} A & X \\ X^T & M \end{pmatrix} \succeq 0$$

if and only if $M - X^T A^{-1} X \succeq 0$. The matrix $M - X^T A^{-1} X$ is known as Schur complement of the block matrix given above. The second fact, stated as the next proposition, compensates for the fact that $X \succeq W$ and $Y \succeq Z$ does not necessarily imply $X \otimes Y \succeq W \otimes Z$.

Proposition 5. *If $X \succeq W \succeq 0$ and $Y \succeq Z \succeq 0$, then $X \otimes Y \succeq W \otimes Z$.*

Proof. This is a simple consequence of the fact that if $A, B \succeq 0$, then $A \otimes B \succeq 0$. Since $X, W \succeq 0$, thus $X+W \succeq 0$. Thus $(X+W)\otimes(Y-Z) \succeq 0$. Similarly, $(X-W)\otimes(Y+Z) \succeq 0$. Averaging these two inequalities, we get the result. $\square$

Lemma 6. *If G_1 and G_2 are XOR games with symmetric cost matrices, then $\varepsilon(G_1 \oplus G_2) \leq \varepsilon(G_1)\varepsilon(G_2)$.*

Proof. Let A be the cost matrix of a game G. We now consider the dual SDP D_A for this game. A vector $y = (y_1, y_2)$ is feasible in D_A if and only if

$$\begin{pmatrix} \Delta(y_1) & -\frac{1}{2}A \\ -\frac{1}{2}A^T & \Delta(y_2) \end{pmatrix} \succeq 0. \tag{4}$$

For a feasible point y, the diagonal entries of this matrix must be non-negative. If some entry of y_i is zero, then A will have a zero row and a zero column. By removing questions which never arise, we may assume that A has no zero rows or columns, and thus that any feasible point of y has strictly positive entries. We extend this assumption to all cost matrices appearing in this proof.

Now if equation (4) holds, then by rearranging rows and columns we get

$$\begin{pmatrix} \Delta(y_2) & -\frac{1}{2}A^T \\ -\frac{1}{2}A & \Delta(y_1) \end{pmatrix} \succeq 0.$$

Thus when A is symmetric, if $y = (y_1, y_2)$ is optimal, then (y_2, y_1) is optimal. By setting $\bar{y} = \frac{1}{2}(y_1 + y_2)$, we may conclude that D_A has an optimal solution of the form $(\bar{y}, \bar{y})$.

Suppose that y has strictly positive entries. By the Schur complement, equation (4) holds for y if and only if

$$\Delta(y_2) \succeq \frac{1}{4}A^T \Delta(y_1)^{-1} A \succeq 0. \tag{5}$$

Now we consider the two games G_1 and G_2 of the hypothesis. Let A_1 and A_2 be the associated symmetric cost matrices. There is an optimal solution to D_{A_1} of the form $(\bar{x}, \bar{x})$, so that $\varepsilon(G_1) = 2\bar{e_1}^T\bar{x}$. Similarly D_{A_2} has an optimal solution $(\bar{y}, \bar{y})$ so that $\varepsilon(G_2) = 2\bar{e_2}^T\bar{y}$.

Applying equation (5) and Proposition 5 we get that

$$\Delta(\bar{x}) \otimes \Delta(\bar{y}) \succeq \frac{1}{16}(A_1 \otimes A_2)\left(\Delta(\bar{x})^{-1} \otimes \Delta(\bar{y})^{-1}\right)(A_1 \otimes A_2),$$

or in other words that $2(\bar{x} \otimes \bar{y}, \bar{x} \otimes \bar{y})$ satisfies equation (5) for cost matrix $A_1 \otimes A_2$, and is thus a feasible point of $D_{A_1 \otimes A_2}$, the dual problem for $G_1 \otimes G_2$.

The optimal value of $D_{A_1 \otimes A_2}$ is less than the value of $2(\bar{x}\otimes\bar{y}, \bar{x}\otimes\bar{y})$, which is $4\left(\bar{e_1}^T\bar{x}\right)\left(\bar{e_2}^T\bar{y}\right)$ $= \varepsilon(G_1)\varepsilon(G_2)$. Thus $\varepsilon(G_1 \otimes G_2) \leq \varepsilon(G_1)\varepsilon(G_2)$. $\square$

Now we may prove Theorem 1.

Proof of Theorem 1. For a game G, let $\tilde{G}$ denote the convex combination $\frac{1}{2}\left(G + G^T\right)$. Note that $\tilde{G}$ has a symmetric cost matrix, and that $\varepsilon(\tilde{G}) = \varepsilon(G)$.

Now let G_1 and G_2 be two XOR games. Then applying Proposition 4,

$$\begin{aligned}
\varepsilon(\tilde{G}_1 \oplus \tilde{G}_2) &= \frac{1}{4}\left[\varepsilon(G_1 \oplus G_2) + \varepsilon(G_1^T \oplus G_2^T) + \varepsilon(G_1 \oplus G_2^T) + \varepsilon(G_1^T \oplus G_2)\right] \\
&= \frac{1}{2}\left[\varepsilon\left(\widetilde{G_1 \oplus G_2}\right) + \varepsilon\left(\widetilde{G_1 \oplus G_2^T}\right)\right] \\
&= \frac{1}{2}\left[\varepsilon\left(G_1 \oplus G_2\right) + \varepsilon\left(G_1 \oplus G_2^T\right)\right].
\end{aligned}$$

Thus from the lemma,

$$\begin{aligned}
\varepsilon(G_1)\varepsilon(G_2) = \varepsilon\left(\tilde{G}_1\right)\varepsilon\left(\tilde{G}_2\right) &\geq \varepsilon\left(\tilde{G}_1 \oplus \tilde{G}_2\right) \\
&= \frac{1}{2}\left[\varepsilon\left(G_1 \oplus G_2\right) + \varepsilon\left(G_1 \oplus G_2^T\right)\right] \\
&\geq \frac{1}{2}\left[\varepsilon(G_1)\varepsilon(G_2) + \varepsilon(G_1)\varepsilon\left(G_2^T\right)\right] = \varepsilon(G_1)\varepsilon(G_2).
\end{aligned}$$

Equality must hold throughout this calculation, and so $\varepsilon(G_1 \oplus G_2) = \varepsilon(G_1)\varepsilon(G_2)$. $\square$

3 Parallel repetition of XOR games

For any sequence of XOR games $G_1 = (f_1, \pi_1), \ldots, G_n = (f_n, \pi_n)$, define their *conjunction*, denoted by $\wedge_{j=1}^n G_j$, as follows. The verifier chooses questions $((s_1,t_1),\ldots,(s_n,t_n)) \in (S_1 \times T_1)\times\cdots\times(S_n \times T_n)$ according to the product distribution $\pi_1 \times \cdots \times \pi_n$, and sends $(s_1,\ldots,s_n)$ to Alice and $(t_1,\ldots,t_n)$ to Bob. Alice and Bob output bits $a_1,\ldots,a_n$ and $b_1,\ldots,b_n$, respectively, and win if and only if their outputs simultaneously satisfy these n conditions: $a_1 \oplus b_1 = f_1(s_1,t_1),\ldots,a_n \oplus b_n = f_n(s_n,t_n)$. (Note that $\wedge_{j=1}^n G_j$ is not itself an XOR game for $n > 1$.)

A simple way for Alice and Bob to play $\wedge_{j=1}^n G_j$ is to independently play each game optimally. This strategy succeeds with probability $\prod_{j=1}^n \omega(G_j)$. In this section, we consider the question: is this the optimal way to play $\wedge_{j=1}^n G_j$?

The answer is *no* for classical strategies [2], where it is shown[2] that $\omega_c(\mathit{CHSH} \wedge \mathit{CHSH}) = 10/16 > 9/16 = \omega_c(\mathit{CHSH})\omega_c(\mathit{CHSH})$.

Our main result in this section is that the answer is *yes* for quantum strategies.

Theorem 7. *For any XOR games $G_1,\ldots,G_n$, $\omega_q(\wedge_{j=1}^n G_j) = \prod_{j=1}^n \omega_q(G_j)$.*

This is a quantum version of Raz's parallel repetition theorem [14] for the restricted class of XOR games. We call it a *strong* parallel repetition theorem because the probabilities are multiplicative in the exact sense (as opposed to an asymptotic sense, as in [14]).

The proof of Theorem 7 is based on a combination of Theorem 1 and the following probabilistic lemma.

Lemma 8. *For any binary random variables $X_1, X_2, \ldots, X_n$,*

$$\frac{1}{2^n}\sum_{M \subseteq [n]} \mathrm{E}\left[(-1)^{\oplus_{j\in M} X_j}\right] = \Pr[X_1 \ldots X_n = 0 \ldots 0]. \tag{6}$$

[2]After posing this question about $\omega_c(\mathit{CHSH} \wedge \mathit{CHSH})$, the answer was first shown to us by S. Aaronson, who independently discovered the classical protocol and then found the prior result in [2].

Proof.

$$\frac{1}{2^n}\sum_{M\subseteq[n]} \mathrm{E}\left[(-1)^{\oplus_{j\in M}X_j}\right] = \mathrm{E}\left[\frac{1}{2^n}\sum_{M\subseteq[n]}(-1)^{\oplus_{j\in M}X_j}\right] \tag{7}$$

$$= \mathrm{E}\left[\prod_{j=1}^{n}\left(\frac{1+(-1)^{X_j}}{2}\right)\right] \tag{8}$$

$$= \Pr\left[X_1\ldots X_n = 0\ldots 0\right], \tag{9}$$

where the last equality follows from the fact that $\prod_{j=1}^{n}(1+(-1)^{X_j}) \neq 0$ only if $X_1 \ldots X_n = 0 \ldots 0$. $\square$

We introduce the following terminology. For any strategy $\mathcal{S}$ (classical or quantum) for any game G, define $\omega(\mathcal{S}, G)$ as the success probability of strategy $\mathcal{S}$ on game G. Similarly, define the corresponding bias as $\varepsilon(\mathcal{S}, G) = 2\omega(\mathcal{S}, G) - 1$.

Now let $\mathcal{S}$ be any protocol for the game $\wedge_{j=1}^{n} G_j$. For each $M \subseteq [n]$, define the protocol $\mathcal{S}_M$ (for the game $\oplus_{j\in M} G_j$) as follows.

1. Run protocol $\mathcal{S}$, yielding $a_1, \ldots, a_n$ for Alice and $b_1, \ldots, b_n$ for Bob.

2. Alice outputs $\oplus_{j\in M} a_j$ and Bob outputs $\oplus_{j\in M} b_j$.

Lemma 9.

$$\frac{1}{2^n}\sum_{M\subseteq[n]} \varepsilon(\mathcal{S}_M, \oplus_{j\in M} G_j) = \omega(\mathcal{S}, \wedge_{j=1}^{n} G_j). \tag{10}$$

Proof. For all $j \in [n]$, define $X_j = a_j \oplus b_j \oplus f_j(s_j, t_j)$. Then, for all $M \subseteq [n]$, we have $\mathrm{E}[(-1)^{\oplus_{j\in M}X_j}] = \varepsilon(\mathcal{S}_M, \oplus_{j\in M} G_j)$, and $\Pr[X_1 \ldots X_n = 0 \ldots 0] = \omega(\mathcal{S}, \wedge_{j=1}^{n} G_j)$. The result now follows from Lemma 8. $\square$

Corollary 10.

$$\omega_c(\wedge_{j=1}^{n} G_j) \leq \frac{1}{2^n}\sum_{M\subseteq[n]} \varepsilon_c(\oplus_{j\in M} G_j) \tag{11}$$

and

$$\omega_q(\wedge_{j=1}^{n} G_j) \leq \frac{1}{2^n}\sum_{M\subseteq[n]} \varepsilon_q(\oplus_{j\in M} G_j). \tag{12}$$

Now we may prove Theorem 7.

Proof of Theorem 7. By Theorem 1, we have

$$\frac{1}{2^n}\sum_{M\subseteq[n]} \varepsilon_q(\oplus_{j\in M} G_j) = \frac{1}{2^n}\sum_{M\subseteq[n]}\prod_{j\in M}\varepsilon_q(G_j) \tag{13}$$

$$= \prod_{j=1}^{n}\left(\frac{1+\varepsilon_q(G_j)}{2}\right) \tag{14}$$

$$= \prod_{j=1}^{n}\omega_q(G_j). \tag{15}$$

Combining this with Eq. 12, we deduce $\omega_q(\wedge_{j=1}^n G_j) = \prod_{j=1}^n \omega_q(G_j)$. $\square$

We comment that, although Eq. 12 was used to prove a tight upper bound on $\omega_q(\wedge_{j=1}^n G_j)$, Eq. 11 cannot be used to obtain a tight upper bound on $\omega_c(\wedge_{j=1}^n G_j)$ for general XOR games. This is because $\varepsilon_c(CHSH) = \varepsilon_c(CHSH \oplus CHSH) = 1/2$ and it can be shown that $\varepsilon_c(CHSH \oplus CHSH \oplus CHSH) = 5/16$. Therefore, for $G_1 = G_2 = G_3 = CHSH$, we have $\frac{1}{8}\sum_{M\subseteq[3]} \varepsilon_c(\oplus_{j\in M} G_j) = 34.5/64$, whereas $\omega_c(\wedge_{j=1}^3 G_j)$ must be expressible as an integer divided by 64.

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References

[1] L. Babai, L. Fortnow, and C. Lund. Non-deterministic exponential time has two-prover interactive protocols. *Computational Complexity*, 1(1):3–40, 1991.

[2] J. Barrett, D. Collins, L. Hardy, A. Kent, and S. Popescu. Quantum nonlocality, Bell inequalities and the memory loophole. *Physical Review A* 66:042111, 2002.

[3] J. Bell. On the Einstein-Podolsky-Rosen paradox. *Physics*, 1(3):195–200, 1964.

[4] M. Bellare, O. Goldreich, and M. Sudan. Free bits, PCPs, and non-approximability — towards tight results. *SIAM Journal on Computing*, 27(3):804–915, 1998.

[5] M. Ben-Or, S. Goldwasser, J. Kilian, and A. Wigderson. Multi-prover interactive proofs: how to remove intractability assumptions. In *Proceedings of the Twentieth Annual ACM Symposium on Theory of Computing*, pages 113–131, 1988.

[6] S. Boyd and L. Vandenberghe. *Convex Optimization*. Cambridge University Press, 2004.

[7] J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt. Proposed experiment to test local hidden-variable theories. *Physical Review Letters*, 23(15):880–884, 1969.

[8] R. Cleve, P. Høyer, B. Toner, J. Watrous. Consequences and limits of nonlocal strategies. In *Proceedings of the 19th IEEE Conference on Computational Complexity*, pages 236–249, 2004.

[9] R. Cleve, P. Høyer, B. Toner, J. Watrous. Consequences and limits of nonlocal strategies. Presentation given at *19th IEEE Conference on Computational Complexity*, June 2004.

[10] U. Feige. On the success probability of two provers in one-round proof systems. In *Proceedings of the Sixth Annual Conference on Structure in Complexity Theory*, pages 116–123, 1991.

[11] U. Feige and L. Lovász. Two-prover one-round proof systems: their power and their problems. In *Proceedings of the Twenty-Fourth Annual ACM Symposium on Theory of Computing*, pages 733–744, 1992.

[12] L. Fortnow, J. Rompel, and M. Sipser. On the power of multi-prover interactive protocols. *Theoretical Computer Science*, 134:545–557, 1994.

[13] J. Håstad. Some optimal inapproximability results. *Journal of the ACM*, 48(4):798–859, 2001.

[14] R. Raz. A parallel repetition theorem. *SIAM Journal on Computing*, 27(3):763–803, 1998.

[15] B. S. (Tsirelson) Cirel'son. Quantum generalizations of Bell's inequality. *Letters in Mathematical Physics*, 4(2):93–100, 1980.

[16] B. S. (Tsirelson) Tsirel'son. Quantum analogues of the Bell inequalities: The case of two spatially separated domains. *Journal of Soviet Mathematics*, 36:557–570, 1987.

[17] J. Watrous. PSPACE has constant-round quantum interactive proof systems. in *Proceedings of the 40th Annual Symposium on Foundations of Computer Science*, pages 112–119, 1999.

[18] S. Wehner. Entanglement in interactive proof systems with binary answers. In *Proceedings of STACS 2006*, pages 162–171, 2006.