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Necessary and Sufficient Conditions for an Extended Noncontextuality in a Broad Class of Quantum Mechanical Systems

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The notion of (non)contextuality pertains to sets of properties measured under a set (context) at a time. We extend this notion to include so-called inconsistently connected systems, in which the measurements of a given property in different contexts may have different distributions, due to contextual biases in experimental design or physical interactions (signaling): a system of measurements has a maximally noncontextual description if they can be imposed a joint distribution on in which the measurements of any one property in different contexts are equal with probability 1. If no such description exists we say that the system is contextual. Note that the existence of a joint distribution of several random variables is equivalent to the possibility of presenting them as functions of a single, “hidden” variable $\lambda$ [2,8–11].

This formulation applies to systems in which the random variables $R_{q1}, R_{q2}, \ldots$ representing a given physical quantity in different contexts always have the same distribution. We call such systems consistently connected, because we call the set of all such variables $R_{q1}, R_{q2}, \ldots$ for a given $q$ a connection. If the properties forming any given context are space-time separated, consistent connectedness coincides with the no-signaling condition [12].

Earlier treatments.—In the Kochen-Specker theorem [1] or its variants [24,25], contexts are chosen so that each property enters in more than one context, and in each context, according to QM, one and only one of the measurements has a nonzero value. The proof of contextuality, using our language, consists of showing that the variables $R_q$ cannot be jointly assigned values consistent with this constraint so that all the variables representing the same property $q$ are assigned the same value. An experimental test of contextuality here consists of simply showing that the observables it specifies can be measured in the contexts it specifies, and that the QM constraint in question is satisfied.
There has been recent work translating the value assignment proofs into probabilistic inequalities (sometimes called Kochen-Specker inequalities), giving necessary conditions for noncontextuality [2,26]. Inequalities that do not use value-assignment restrictions but only the assumption of noncontextuality are known as noncontextuality inequalities [14,27,28]. Bell inequalities [9,20,21,29,30] and LG inequalities [8,17] are also established through noncontextuality [31], motivated by specific physical considerations (locality and noninvasive measurement, respectively).

An extension of the notion of (non)contextuality that allows for inconsistent connectedness was suggested in Refs. [2,32]. However, the error probability proposed in those papers as a measure of context-dependent change in a random variable cannot be measured experimentally. The suggestion in both Refs. [2,32] is to estimate the accuracy of the measurement and from that argue for a particular value of the error probability. For example, Ref. [32] uses the quantum description of the system for the estimate (quantum tomography), but there is no clear reason why or how the quantum error model would be related to that of the proposed noncontextual description. A noncontextuality test should not mix the two descriptions, as it attempts to show their fundamental differences.

In this Letter we generalize the definition of contextuality in a different manner, to allow for inconsistent connectedness while only using directly measurable quantities. We derive a criterion of (non)contextuality for a broad class of systems that includes as special cases the systems recently studied in the recent literature on contextuality: KCBS, EPR-Bell, and LG systems [14,33,34], with their inconsistently connected versions [35,36].

Basic concepts and definitions.—We begin by formalizing the notation and terminology. Consider a finite set of distinct physical properties \( Q = \{q_1, \ldots, q_n\} \). These properties are measured in subsets of \( Q \) called contexts, \( c_1, \ldots, c_m \). Let \( C \) denote the set of all contexts, and \( C_q \) the set of all contexts containing a given property \( q \).

The result of measuring property \( q \) in context \( c \) is a random variable \( R_q^c \). The result of jointly measuring all properties within a given context \( c \in C \) is a set of jointly distributed random variables \( R^c = \{R_q^c: q \in c\} \).

No two random variables in different contexts, \( R_q^c, R_q'^{c'} \), \( c \neq c' \), are jointly distributed, they are stochastically unrelated [6,7]. The set of random variables representing the same property \( q \) in different contexts is called a connection (for \( q \)). So the elements of a connection \( \{R_q^c: c \in C_q\} \) are pairwise stochastically unrelated. If all random variables within each connection are identically distributed, the system is called consistently connected; if it is not necessarily so, it is inconsistently connected. Consistent connectedness is also known in QM as the Gleason property [37], outside physics as marginal selectivity [6], and Ref. [38] lists some dozen names for the same notion; a recent addition to the list is the no-disturbance principle [39,40].

The set \( Q \) of all properties together with the set \( C \) of all contexts and the set \( \{R^c: c \in C\} \) of all sets of random variables representing contexts is referred to as a system. In the systems we consider here the set of properties \( q \) is finite (whence the set of contexts \( c \) is finite too), and each random variable has a finite number of possible values (e.g., spin measurement outcomes).

We introduce next the notion of a (probabilistic) coupling of all the random variables \( R_q^c \) in our system [41]. Intuitively, this is simply a joint distribution imposed, or “forced” on all of them (recall that they include stochastically unrelated variables from different contexts). Formally, a coupling of \( \{R_q^c: q \in c \in C\} \) is any jointly distributed set of random variables \( S = \{S_q^c: q \in c \in C\} \) such that, for every \( c \in C \), \( \{S_q^c: q \in c\} \sim \{R_q^c: q \in c\} \), where \( \sim \) stands for “has the same (joint) distribution as.” One can also speak of a coupling for any subset of the random variables \( R_q^c \). Thus, fixing a property \( q \), a coupling of a connection \( \{R_q^c: c \in C_q\} \) is any jointly distributed \( \{X_q^c: c \in C_q\} \) such that \( X_q^c \sim R_q^c \) for all contexts \( c \in C_q \). Note that if \( S \) is a coupling of all \( R_q^c \), then every marginal (jointly distributed subset) \( \{S_q^c: c \in C_q\} \) of \( S \) is a coupling of the corresponding connection \( \{R_q^c: c \in C_q\} \).

Expressed in this language, the traditional approach is to consider a system noncontextual if there is a coupling \( S \) of the random variables \( R_q^c \) such that for every property \( q \) the random variables in \( \{S_q^c: c \in C_q\} \) are equal to each other with probability 1. That is, for every possible coupling \( S \) of the random variables \( R_q^c \) and every property \( q \) we consider the marginal \( \{S_q^c: c \in C_q\} \) corresponding to a connection \( \{R_q^c: c \in C_q\} \), and we compute

\[
\text{Pr}[S_q^{c_1} = \cdots = S_q^{c_{n_q}}] = \{c_{q_1}, \ldots, c_{q_{n_q}}\} = C_q.
\]

If there exists a coupling \( S \) for which this probability equals 1 for all \( q \), this \( S \) provides a noncontextual description for our system. Otherwise, if in every possible coupling \( S \) the probability in question is less than 1 for some properties \( q \), the system is considered contextual.

This understanding, however, only involves consistently connected systems. As mentioned in the introduction, a system may be inconsistently connected due to systematic biases or interactions (such as signaling in time in LG systems). If for some \( q \) and some contexts \( c, c' \in C_q \), the distribution of \( R_q^c \) and \( R_q^{c'} \) are not the same, then \( \text{Pr}[S_q^c = S_q^{c'}] \) cannot equal 1 in any coupling \( S \). There would be nothing wrong if one chose to say that any such inconsistently connected system is therefore contextual, but contextuality due to systematic measurement errors or signaling is clearly a special, trivial kind of contextuality. One should be interested in whether the system exhibits any contextuality that is not reducible to (or explainable by) the factors that make distributions of random variables within a connection different. For systems in general, therefore, we propose a different definition.
Definition 1.—A system has a maximally noncontextual description if there is a coupling $S$ of the random variables $R^q_i$ such that for any $q$ the random variables $\{X^q_i; c \in C_q\}$ in $S$ are equal to each other with the maximum probability allowed by the individual distributions of $R^q_i$.

To explain, consider a connection $\{R^q_i; c \in C_q\}$ in isolation, and let $\{X^q_i; c \in C_q\}$ be its coupling. Among all such couplings there must be maximal ones, those in which the probability that all variables in $\{X^q_i; c \in C_q\}$ are equal to each other is maximal possible, given the distributions of $X^q_i \sim R^q_i$. If a connection consists of two dichotomic $(\pm 1)$ variables $R^1_q$ and $R^2_q$, and $\{X^1_q, X^2_q\}$ is its coupling (i.e., $X^1_q, X^2_q$ are jointly distributed with $\langle X^1_q = (R^1_q), \langle X^2_q = (R^2_q) \rangle$), then by Lemma 3 in the Supplemental Material [42], the maximal possible expectation $\langle X^1_q X^2_q \rangle$ is $1 - |\langle R^1_q \rangle - \langle R^2_q \rangle|$. A coupling $\{X^1_q, X^2_q\}$ with this expectation is maximal. Now take every possible coupling $S$ of all our random variables $R^q_i$, consider the marginals $\{S^q_i; c \in C_q\}$ corresponding to connections $\{R^q_i; c \in C_q\}$, and for each of these marginals compute the probability (1).

If there is a coupling $S$ in which this probability equals its maximal possible value for every $q$, this $S$ provides a maximally noncontextual description for our system. For consistently connected systems Definition 1 reduces to the traditional understanding: the maximal probability with which all variables in $\{X^q_i; c \in C_q\}$ can be equal to each other is 1 if all these variables are identically distributed.

Cyclic systems of dichotomic random variables.—We focus now on systems in which (S1) each context consists of precisely two distinct properties; (S2) each property belongs to precisely two distinct contexts; and (S3) each random variable representing a property is dichotomic $(\pm 1)$.

As shown in Lemma A1 (Supplemental Material [42]), a set of properties satisfying S1–S2 can be arranged into one or more distinct cycles $q_1 \rightarrow q_2 \rightarrow \cdots \rightarrow q_n \rightarrow q_1$, in which any two successive properties form a context. Without loss of generality we will assume that we deal with a single-cycle arrangement $q_1 \rightarrow q_2 \rightarrow \cdots \rightarrow q_n \rightarrow q_1$ of all the properties $\{q_1, \ldots, q_n\}$. The number $n$ is referred to as the rank of the system.

A schematic representation of a cyclic system is shown in Fig. 1. The LG paradigm exemplifies a cyclic system of rank $n = 3$, on labeling the observables $q_1$, $q_2$, $q_3$ measured chronologically. The contexts $\{q_1, q_2\}$, $\{q_2, q_3\}$, $\{q_3, q_1\}$ here are represented by, respectively, pairs $(R^1_q, R^2_q)$, $(R^2_q, R^3_q)$, $(R^3_q, R^1_q)$ with observed joint distributions, whereas $(R^1_q, R^3_q)$, $(R^2_q, R^3_q)$, $(R^3_q, R^1_q)$ are connections for $q_1$, $q_2$, $q_3$, respectively. The EPR-Bell paradigm exemplifies a cyclic system of rank $n = 4$, on labeling the observables $q_1$, $q_3$ for Alice and $q_2$, $q_4$ for Bob. Cyclic systems of rank $n = 5$ are exemplified by the KCBS paradigm, on labeling the vertices of the KCBS pentagram by $q_1 \rightarrow q_2 \rightarrow q_3 \rightarrow q_4 \rightarrow q_5$.

(Non)contextuality criterion.—For any $n$, and any $x_1, \ldots, x_n \in \mathbb{R}$, we define the function

$$s_1(x_1, \ldots, x_n) = \max_{t_1, \ldots, t_n \in (-1, 1)} \sum_{k=1}^{n} t_k x_k.$$ (2)

The maximum is taken over all combinations of $\pm 1$ coefficients $t_1, \ldots, t_n$ containing odd numbers of $-1$’s. The following is our main theorem.

Theorem 1.—A cyclic system of rank $n > 1$ with dichotomic random variables (see Fig. 1) has a maximally noncontextual description if and only if

$$s_1(|\langle R^i_q \rangle - \langle R^i_{q(-1)} \rangle|; i = 1, \ldots, n) \leq 2n - 2$$ (3)

($s_1$ here having $2n$ arguments, each entry being taken with $i = 1, \ldots, n$).

See the Supplemental Material [42] for the proof. In Eq. (3), $\langle R^i_q | R^i_{q(-1)} \rangle$ are the quantum correlations observed within contexts, whereas $1 - |\langle R^i_q \rangle - \langle R^i_{q(-1)} \rangle|$ are the maximal values for the unobservable correlations within the couplings of connections. If the system is consistently connected, i.e., $\langle R^i_q \rangle = \langle R^i_{q(-1)} \rangle$, then these maximal values equal 1. By Corollary A10 [42], the criterion (3) then reduces to the formula

$$s_1(|\langle R^i_q \rangle - \langle R^i_{q(-1)} \rangle|; i = 1, \ldots, n) \leq n - 2,$$ (4)

well known for $n = 3$ (the LG inequality in the form derived in Ref. [8]) and for $n = 4$ (CHSH inequalities [29]). For $n = 5$, Eq. (4) contains the KCBS inequality (which by Corollary A11 [42] is not only necessary but also sufficient for the existence of a maximally noncontextual description). Finally, for any even $n \geq 4$, inequality (4) contains the

![FIG. 1 (color online). A schematic representation of a cyclic (single-cycle) system of rank $n > 1$. The properties $q_1, \ldots, q_n, q_1$ form a circle, any two successive properties $(q_i, q_{i+1})$ form a context, denoted $c_i$ ($\oplus$ is clockwise shift $1 \rightarrow 2 \rightarrow \cdots \rightarrow n \rightarrow 1$). In a given context $c_i$, the random variable representing $q_i$ is denoted $R^i$, and the one representing $q_{i+1}$ is denoted $R^{i+1}$. Each property $q_i$, therefore, is represented by two random variables: $R^i$ (when $q_i$ is measured in context $c_i$) and $R^{i+1}$ (when $q_i$ is measured in context $c_{i+1}$). The pair $(R^{i+1}, R^i)$ is the connection for $q_i$, and the pair $(R^i, R^{i+1})$ represents the context $c_i$.](150401-3)
chained Bell inequalities studied in Refs. [43,44]. It is known that for \(n > 4\) the chained Bell inequalities are not criteria, the latter requiring many more inequalities [45–48].

Generally, some of the terms \(R_i^n \sim R_i^{G_1}\) in Eq. (3) may be nonzero. Thus, in an LG system \((n = 3)\), if inconsistency is due to signaling in time [18,19], these may include \(R_2^n \sim R_3^n\) and \(R_3^n \sim R_2^n\) but not \(R_1^n \sim R_2^n\), because \(q_1\) cannot be influenced by later events. However, \(R_1^n \sim R_2^n\) may be nonzero due to contextual biases in design, if something in the procedure of measuring \(q_1\) is different depending on whether the next measurement is going to be of \(q_2\) or \(q_3\).

An application to experimental data.—To illustrate the applicability of our theory to real experiments, consider the data from the KCBS experiment of Ref. [13]. The experiment uses a single photon in a quantum overlap of three optical modes (paths) as an indivisible quantum system. Readout is performed through single-photon detectors that terminate the three paths. Context is chosen through “activation” of transformations, by rotating a wave plate that precedes each beam splitter to change the behavior of two out of three paths. Each transformation leaves one path untouched, which serves as justification for consistent connectedness of the corresponding measurements, \(R_i^n = R_i^{G_1}\), so that the target inequality is Eq. (4) for \(n = 5\).

\(R_1^n\) and \(R_2^n\) are recorded in different experimental setups with zero or four polarizing beam splitters “activated.” These outputs have significantly different distributions: from the standard taking them as means and standard errors of 20 replications, \(\langle R_1^n \rangle\) and \(\langle R_2^n \rangle\) but not \(\langle R_1^n \rangle \sim \langle R_2^n \rangle\), because \(q_1\) cannot be influenced by later events. However, \(\langle R_1^n \rangle \sim \langle R_2^n \rangle\) may be nonzero due to contextual biases in design, if something in the procedure of measuring \(q_1\) is different depending on whether the next measurement is going to be of \(q_2\) or \(q_3\).

\[S_1(\langle R_i^n R_i^{G_1} \rangle: i = 1, \ldots, n) - \sum_{i=1}^{n} |\langle R_i^n \rangle - \langle R_i^{G_1} \rangle| \leq n - 2.\]  

(5)

which, by Corollary A9 [42], follows from the criterion (3) [49]. One way of using it is to construct a conservative 100\((1 - \alpha/10)\)% confidence intervals for each of the approximately normally distributed terms \(\langle R_i^n R_i^{G_1} \rangle\) and \(\langle R_i^n \rangle - \langle R_i^{G_1} \rangle\) \((i = 1, \ldots, 5)\), with respective error terms read or computed from Table 1 of Ref. [13], and then determine the range of Eq. (5). Treating each estimated term as the mean of 20 observations, we have \(t_{n-1}(19) < 14\), and so a conservative confidence interval for each term is given by ±14 \times standard error. Using these intervals, we can calculate the conservative 100\((1 - 10^{-10})\)% confidence interval for Eq. (5) as

\[\begin{align*}
-805.028 & \sim -804.042 \sim -709.042 \sim -810.028 \sim 766.028
\end{align*}\]

\[S_1\left(\langle R_1^n R_1^{G_1} \rangle, \langle R_2^n R_1^{G_1} \rangle, \langle R_3^n R_1^{G_1} \rangle, \langle R_1^n R_2^{G_1} \rangle, \langle R_1^n R_3^{G_1} \rangle\right) \sim 0.036 \pm 0.10 \sim 0.004 \pm 0.10 \sim 0.006 \pm 0.126 \sim 0.020 \pm 0.08 \sim 0.006 \pm 0.080.
\]

The system is contextual. The conclusion is the same as in Ref. [13], but we arrive at it by a shorter and more robust route.

Conclusion.—We have derived a criterion of (non)contextuality applicable to cyclic systems of arbitrary ranks. Even for consistently connected systems this criterion has not been previously known for ranks \(n \geq 5\) (KCBS and higher-rank systems). However, it is the inclusion of inconsistently connected systems that is of special interest, because it makes the theory applicable to real experiments. A “system” is not just a system of properties being measured, but also a system of measurement procedures being used, with possible contextual biases and unaccounted-for interactions. Our analysis opens the possibility of studying contextuality without attempting to eliminate these first, whether by statistical analysis or by improved experimental procedure.

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