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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 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 or other influences. In this paper, we derive necessary and sufficient conditions for the existence of such a description in a broad class of systems including Klyachko-Can-Binicioğlu-Shumovsky-type (KCBS) systems. Because these conditions allow for inconsistent connectedness, they are applicable to real experiments. We illustrate this by analyzing an experiment by Lapkiewicz and colleagues aimed at testing contextuality in a KCBS-type system.

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The notion of (non)contextuality in quantum mechanics (QM) relates to the measurement of a physical property $q$ to the choice of properties $q', q''$, etc. co-measured with $q$ [1]. The set of co-measured properties $q, q', q''$, etc. forms a measurement context for each of its members. The traditional understanding of a contextual QM system is that if the measurement of each property in different contexts are equal to each other with the maximal probability allowed by their different distributions. We derive necessary and sufficient conditions for the existence of such a description in a broad class of systems including Klyachko-Can-Binicioğlu-Shumovsky-type (KCBS), EPR-Bell-type, and Leggett-Garg-type systems. Because these conditions allow for inconsistent connectedness, they are applicable to real experiments. We illustrate this by analyzing an experiment by Lapkiewicz and colleagues aimed at testing contextuality in a KCBS-type system.

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 $R_q^c$ 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 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.

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We introduce next the notion of a (probabilistic) coupling of all the random variables \( R^c_q \) of 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 \( \{ R^c_q \colon q \in C \} \) is any jointly distributed set of random variables \( S = \{ S^c_q \colon q \in C \} \) such that, for every \( c \in C \), \( \{ S^c_q \colon q \in c \} \sim \{ R^c_q \colon q \in c \} \), where \( \sim \) stands for “has the same (joint) distribution as.”

One can also speak of a coupling for any subset of the random variables \( R^c_q \). Thus, fixing a property \( q \), a coupling of a connection \( \{ R^c_q \colon c \in C \} \) is any jointly distributed \( \{ X^c_q \colon c \in C \} \) such that \( X^c_q \sim R^c_q \) for all contexts \( c \in C \). Note that if \( S \) is a coupling of all \( R^c_q \), then every marginal (jointly distributed subset) \( \{ S^c_q \colon c \in C \} \) of \( S \) is a coupling of the corresponding connection \( \{ R^c_q \colon c \in C \} \).

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

\[
\Pr \left[ \{ S^c_q \} \sim \ldots \sim S^{c_{m_q}} \right] \quad \{ c_1, \ldots, c_{m_q} \} = C_q. \quad (1)
\]

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 \( R^c_q \) and \( R^{c'}_q \) are not the same, then \( \Pr[S^c_q = S^{c'}_q] \) 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 $R_i^q$, such that for any $q$ the random variables $\{S_i^q : c \in C_q\}$ in $S$ are equal to each other with the maximum probability allowed by the individual distributions of $R_i^q$.

To explain, consider a connection $\{R_i^q : c \in C_q\}$ in isolation, and let $\{X_i^q : c \in C_q\}$ be its coupling. Among all such couplings there must be maximal ones, those in which the probability that all variables in $\{X_i^q : c \in C_q\}$ are equal to each other is maximal possible, given the distributions of $X_i^q \sim R_i^q$. If a connection consists of two dichotomic ($\pm1$) variables $R_i^q$ and $R_i^q$, and $\{X_i^q, X_i^q\}$ is its coupling (i.e., $X_i^q, X_i^q$ are jointly distributed), then by Lemma A3 in the Supplemental Material [42], the maximal possible expectation $\mathbb{E}[X^q_i X^q_i]$ is taken over all combinations of $\pm1$ 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

$$s_1(\{R_i^q : q \in \{0, 1\}\} : i = 1, \ldots, n) \leq n - 2$$

(S1 here having $2n$ arguments, each entry being taken with $i = 1, \ldots, n$).

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

$$s_1(\{R_i^q R_i^{q'} \} : i = 1, \ldots, n) \leq n - 2,$$

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 A.11 [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

[Diagram of a cyclic system with labels $R_i^q$, $R_i^{q'}$, $q_1, q_2, \ldots, q_n$, and cycles connecting them, illustrating the noncontextuality criterion.]
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 \( \langle R_{\text{i}}^1 \rangle - \langle R_{\text{i}}^{(2)} \rangle \) 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 \( \langle R_{\text{2}}^2 \rangle - \langle R_{\text{3}}^2 \rangle \) and \( \langle R_{\text{3}}^3 \rangle - \langle R_{\text{2}}^3 \rangle \) but not \( \langle R_{\text{i}}^1 \rangle - \langle R_{\text{i}}^{(2)} \rangle \), because \( q_{1} \) cannot be influenced by later events. However, \( \langle R_{\text{i}}^1 \rangle - \langle R_{\text{i}}^{(2)} \rangle \) 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 \( q_{3} \).

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, \( \langle R_{\text{i}}^1 \rangle = \langle R_{\text{i}}^{(1)} \rangle \), so that the target inequality is Eq. (4) for \( n = 5 \).

\( R_{\text{i}}^1 \) and \( R_{\text{i}}^2 \) 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, it is measured by blocking two paths early in the setup. 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, \( \langle R_{\text{i}}^1 \rangle = \langle R_{\text{i}}^{(1)} \rangle \), so that the target inequality is Eq. (4) for \( n = 5 \).

\( R_{\text{i}}^1 \) and \( R_{\text{i}}^2 \) are recorded in different experimental setups with zero or four polarizing beam splitters “activated.” These outputs have significantly different distributions: from Ref. [13] Table 1, \( \langle R_{\text{i}}^1 \rangle = 0.136(6) \), \( \langle R_{\text{i}}^2 \rangle = 0.172(4) \), and taking them as means and standard errors of 20 replications, the standard \( t \) test with \( df = 19 \) is significant at 0.1%. Lapkiewicz et al. deal with this by introducing in Eq. (4) a correction term involving \( \langle R_{\text{i}}^1 R_{\text{i}}^2 \rangle \). They estimate \( \langle R_{\text{i}}^1 R_{\text{i}}^2 \rangle \) by identifying \( R_{\text{i}}^1 \) with \( R_{\text{i}}^1 \), an output measured in a separate context and in a special manner: instead of photon detections it is measured by blocking two paths early in the setup. While this results in a well-motivated experimental test, the identification of \( R_{\text{i}}^1 \) with \( R_{\text{i}}^1 \) involves additional assumptions [15,16]. Furthermore, Lapkiewicz et al. have to discount the fact that the assumption \( \langle R_{\text{i}}^1 \rangle = \langle R_{\text{i}}^{(1)} \rangle \) can also be challenged for \( i = 4 \); the same \( t \) test as above for \( \langle R_{\text{4}}^4 \rangle = 0.122(4) \) and \( \langle R_{\text{3}}^3 \rangle = 0.142(4) \) is significant at 1%. We see that the traditional approach adopted in Ref. [13] encounters considerable experimental and analytic difficulties due to the necessity of avoiding inconsistent connectedness.

Our theory allows one to analyze the data directly as found in the measurement record. It is convenient to do this by using the inequality

\[
S_{1}(\langle R_{\text{i}}^1 R_{\text{i}}^{(1)} \rangle : i = 1, \ldots, n) - n - 2 \leq \sum_{i=1}^{n} |\langle R_{\text{i}}^1 \rangle - \langle R_{\text{i}}^{(1)} \rangle| \leq n - 2,
\]

which, by Corollary A9 [42], follows from the criterion (3) [49]. One way of using it is to construct a conservative 100(1 − \( \alpha \))% confidence interval with, say, \( \alpha = 10^{-10} \) for the left-hand side of Eq. (5) with \( n = 5 \) and show that its lower endpoint exceeds \( n - 2 = 3 \). One can, e.g., construct 10 Bonferroni 100(1 − \( 1/10 \))% confidence intervals for each of the approximately normally distributed terms \( \langle R_{\text{i}}^1 R_{\text{i}}^{(2)} \rangle \) and \( \langle R_{\text{i}}^1 \rangle - \langle R_{\text{i}}^{(1)} \rangle \) (i = 1, ..., 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 \( t_{1-\alpha/10}(19) < 14 \), and so a conservative confidence interval for each term is given by \( \pm 14 \times \) standard error. Using these intervals, we can calculate the conservative 100(1−10^{-10})% confidence interval for Eq. (5) as

\[
0.57 \pm 0.028 - 0.57 \pm 0.028 - 0.57 \pm 0.028 - 0.57 \pm 0.028 - 0.57 \pm 0.028
\]

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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[57] This formula is in fact equivalent to Eq. (3), as conjectured in Ref. [36] and proved in Ref. [50].