

Neither Contextuality nor Nonlocality Admits Catalysts

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We show that the resource theory of contextuality does not admit catalysts, i.e., there are no correlations that can enable an otherwise impossible resource conversion and still be recovered afterward. As a corollary, we observe that the same holds for nonlocality. As entanglement allows for catalysts, this adds a further example to the list of “anomalies of entanglement,” showing that nonlocality and entanglement behave differently as resources. We also show that catalysis remains impossible even if, instead of classical randomness, we allow some more powerful behaviors to be used freely in the free transformations of the resource theory.

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Introduction.—Contextuality [1,2] and nonlocality [3,4] play a prominent role in a wide variety of applications of quantum mechanics, with nonlocality being used, for example, in quantum key distribution [5], certified randomness [6], and randomness expansion [7]. Similarly, contextuality powers quantum computation in some computational models [8–13] and even increases expressive power in quantum machine learning [14]. Consequently, it is vital to understand how nonlocality and contextuality behave as resources.

In this Letter, we show that neither contextuality nor nonlocality admits catalysts, that is, there are no correlations that can be used to enable an otherwise impossible conversion between correlations and still be recovered afterward. Slightly more precisely, let us write d, e, f, \dots for various correlations (whether classical or not), $d \otimes e$ for having independent instances of d and e , and $d \rightsquigarrow e$ (read as “ d simulates e ”) for the existence of a conversion $d \rightarrow e$. Then our results state that, in suitably formalized resource theories of contextuality and nonlocality, whenever $d \otimes e \rightsquigarrow d \otimes f$, then $e \rightsquigarrow f$ already. This gives a strong indication that contextuality (and nonlocality) are resources that *get spent* when you use them: there is no way of using a correlation d to achieve a task you could not do otherwise while keeping d intact. As entanglement theory famously allows for catalysts [15], this can be seen as yet another “anomaly of nonlocality” [16] and thus further testament to the fact that nonlocality and entanglement are different resources.

We prove our results by working in precisely defined resource theories of contextuality and nonlocality. These are not strictly speaking quantum resource theories [17] but resource theories in a more general sense [18,19], as we allow resources such as Popescu-Rohrlich boxes (PR boxes) [20] that are not quantum realizable. The kinds of conversions between correlations we have in mind capture the intuitive idea of using one system to *simulate* another one and have been studied in earlier literature [21–29].

These roughly correspond to the local operations and shared randomness paradigm (LOSR) or to wirings and prior-to-input classical communication, depending on the precise definitions of these terms. However, existing formalizations of these in the literature are often limited to the bipartite or tripartite settings and at times overlook some technical issues resulting in nonconvex sets of transformations [30, Appendix].

More importantly, existing formalizations of the resource theory of nonlocality tend to focus on the case where each party has a discrete set of measurements of which they can perform at most one. However, this is false even in relatively simple situations: for instance, if Alice shares one PR box with Bob and one with Charlie, then she has four measurements available but is not restricted to only one measurement as she can choose a measurement for each of her boxes. In particular, she might first measure one of the boxes and use the outcome (and possible auxiliary randomness) to choose what to measure next.

To overcome such issues, we work in the general approach to contextuality initiated in [31] and later extended in [32] to capture building some correlations from others using such *probabilistic* and *adaptive* means, resulting in a resource theory for contextuality. We then obtain the resource theory of nonlocality from this via a general mathematical construction used in [33] that builds a resource theory of n -partite resources from a given resource theory. Working with such generality clarifies the relationship between resource theories of contextuality and nonlocality and captures the kinds of interconversions studied in earlier literature in the exact, single-shot regime [34] in a precise yet tractable manner.

We believe that our result could be phrased and proved in terms of other approaches to contextuality [36–40] as long as one formalizes such adaptive measurement protocols and transformations between correlations within them. However, the current proof strategy no longer applies if one works with

axiomatically defined transformations as in [41], i.e., with abstract functions between sets of correlations satisfying properties such as preservation of locality and of convex combinations. This is because such abstract functions might not arise from operationally defined protocols that one might implement physically. Indeed, operational transformations form a proper subset of axiomatically defined ones for the resource theories of entanglement [42] and magic [43]. For contextuality and nonlocality, it is not known if the axiomatic and operational resource theories agree, although a characterization of those functions arising from (nonadaptive) operational transformations is given in [44] Theorem 44.

One possible explanation for anomalies of nonlocality, put forward in [45], is that they stem from using LOSR transformations with nonlocality and local operations and classical communication (LOCC) with entanglement. Indeed, [45] shows that many of the anomalies disappear when working with LOSR entanglement. In particular, they show, for bipartite pure states, that there are no catalysts for LOSR entanglement. We conjecture that there are no catalysts in general for LOSR entanglement, in which case this anomaly is fully explained by entanglement and nonlocality being measured with LOCC and LOSR transformations, respectively. For a contrasting viewpoint, see [46], which argues that both entanglement and nonlocality should be measured in terms of LOCC transformations.

No catalysis for contextuality.—We begin by briefly reviewing the resource theory of contextuality as defined in [32]. To start, we formalize the idea of a “measurement scenario” S : we imagine a situation where there is a finite set X_S of measurements available, each measurement $x \in X_S$ giving rise to outcomes in some finite set $O_{S,x}$. However, only some measurements might be feasible to perform together—other combinations may be ruled out by practical limitations or excluded by physical theory. We collect all jointly compatible measurements into a single set Σ_S , which we expect to satisfy two natural properties: (1) any measurement $x \in X_S$ induces a compatible set $\{x\} \in \Sigma_S$, and (2) any subset of a compatible set of measurements is compatible. Collecting all this data together results in the measurement scenario $S = \langle X_S, \Sigma_S, O_S \rangle$.

Given two scenarios S and T , we let $S \otimes T$ denote the scenario that represents having access to S and T in parallel, so that a joint measurement is possible precisely if its components in S and T are possible.

An *empirical model* over a scenario S is given by specifying for each compatible $\sigma \in \Sigma_S$ a joint probability distribution e_σ for measurements in σ . We only consider empirical models for which the behavior of a joint measurement does not depend on what is measured with it, if anything. Thus, whenever $\tau \subset \sigma \in \Sigma_S$, the distribution e_τ over τ can be obtained by marginalizing e_σ to τ . We express this generalization of the usual no-signaling conditions as $e_\sigma|_\tau = e_\tau$, so that more generally for a joint distribution d over outcomes of $Y \subset X_S$ and $Z \subset Y$, the expression $d|_Z$ denotes the marginal distribution on outcomes of Z .

If the impossibility of measuring everything together is only a practical limitation, one can contemplate the distribution d that would arise when measuring X_S . If d explained the model e we have at hand, we would expect it to satisfy $d|_\sigma = e_\sigma$ for every $\sigma \in \Sigma_S$. If such a distribution exists, we call e “noncontextual.” If no such distribution exists, we call e “contextual,” as we have reason to believe that it is infeasible in principle to measure everything together unless one accepts that the observed joint distribution for a subset $Y \subset X$ depends on what it is measured with, i.e., its context.

A simple example of scenario and a contextual empirical model on it, discussed in [47], is given by three measurements, any two of which are compatible but not all three together. Each measurement takes outcomes in $\{0, 1\}$, and whenever two measurements are performed one observes (0,1) and (1,0) with equal probability, with the probability distributions for singletons fixed by this and resulting in observing the two outcomes with equal probability. To see that this is contextual, note that there is no joint outcome for all three measurements that is consistent with the observed marginals.

More examples can be obtained from scenarios studied in nonlocality, where one typically specifies a scenario by giving the number of parties, the number of measurements available to each of them, and the size of the outcome sets, where it is then understood that maximal compatible measurements are given by a choice of a single measurement by each party. This includes for instance the famous Clauser, Home, Shimony, and Holt model [48] and the PR box [20] which goes beyond what is allowed in quantum mechanics, both models arising in the scenario with two parties having access to two dichotomic measurements.

We now move on to transformations between scenarios and empirical models. We will build up to “wirings” that in full generality capture the idea of “simulating” an empirical model from another adaptively with the help of non-contextual randomness. These will be the free transformations of our resource theory, but we begin by considering the problem of building one scenario from another. A particularly simple way of building T from S is by declaring that for each measurement $x \in X_T$ of T some measurement $\pi(x) \in X_S$ of S is to be performed instead. Moreover, each outcome o of $\pi(x)$ is to be interpreted as the outcome $\alpha_x(o)$ instead. If for each compatible $\sigma \in \Sigma_S$ the corresponding measurement $\pi(\sigma)$ is jointly compatible in S , the pair $\langle \pi, \alpha = (\alpha_x)_{x \in X} \rangle$ describes a way of building T from S , and we will denote this by writing $\langle \pi, \alpha \rangle: S \rightarrow T$.

Given such $\langle \pi, \alpha \rangle: S \rightarrow T$, any empirical model $e: S$ induces a model on T that describes the statistics one would see if one was to observe the statistics given by e and then transform them according to $\langle \pi, \alpha \rangle$. We then denote by $\langle \pi, \alpha \rangle_*$ the function that pushes empirical models on S forward to empirical models on T , so that for $e: S$ the

induced model on T is denoted by $\langle \pi, \alpha \rangle_*(e)$. The pair $\langle \pi, \alpha \rangle$ is defined to be a “deterministic simulation” of $e : T$ from $d : S$, denoted by $\langle \pi, \alpha \rangle : d \rightarrow e$, precisely when $\langle \pi, \alpha \rangle$ transforms d to e , i.e., if $\langle \pi, \alpha \rangle_*(d) = e$. Such a simulation is depicted in Fig. 1.

There are two ways in which these deterministic simulations are weaker than one would want in a general resource theory of contextuality: first, one might want to allow the usage of auxiliary (noncontextual) randomness so that the dependence of measurements and their outcomes of T on those of S is stochastic. The usage of auxiliary randomness is captured in [49] and discussed further in [50] and, in our terms, could be defined by allowing probabilistic mixtures of transformations. However, this viewpoint leaves out another important generalization: namely the possibility that a single measurement in T can depend on a joint measurement of S as in [51] or more generally on a measurement protocol on S that chooses which joint measurement to perform *adaptively*. The most general formulation of this idea would allow a measurement x in T to be simulated by a probabilistic and *adaptive* procedure that first measures (depending on some classical randomness) something in S and then, based on the outcome (and possibly further classical randomness), chooses what to measure next (if anything) and so on. This idea is formalized carefully in [32] in two stages, the first one adding adaptivity and the second adding randomness.

To model adaptivity, one builds from a scenario S a new scenario $\text{MP}(S)$ of (deterministic) “measurement protocols” over S . A measurement protocol is a procedure that, at any stage, either stops and reports all of the measurement results obtained so far, or, based on previously seen outcomes, performs a measurement in S that is compatible with the previous measurements. The measurements of $\text{MP}(S)$ are given by such protocols over S , and a set of measurement protocols is compatible if they can be performed jointly without having to query measurements outside of Σ_S . Then one can define adaptive (but still deterministic) transformations $S \rightarrow T$ between scenarios as deterministic transformations $\text{MP}(S) \rightarrow T$ as in Fig. 2. In [32], we show that the assignment $S \mapsto \text{MP}(S)$ defines a comonad on the category of scenarios: this abstract language is not needed here but can be thought of as guaranteeing that one has a well-behaved way of composing $\text{MP}(S) \rightarrow T$ with $\text{MP}(T) \rightarrow U$ to obtain a map $\text{MP}(S) \rightarrow U$. Intuitively, the composite is obtained by first interpreting each measurement in U as a measurement protocol over T , and each measurement in that measurement protocol as an measurement protocol over S , and then “flattening” the resulting measurement protocol of measurement protocols {i.e., a measurement of $\text{MP}[\text{MP}[(S)]]$ } into a measurement protocol over S .

To model (noncontextual) randomness, one then defines a simulation $d \rightarrow e$ to be a deterministic simulation $\text{MP}(d \otimes c) \rightarrow e$ for some noncontextual model c as in

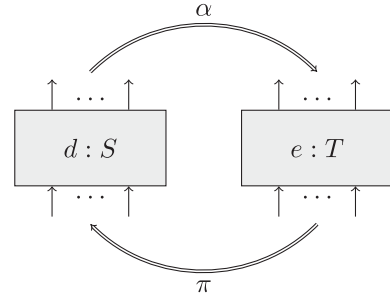


FIG. 1. Depiction of a deterministic simulation $d \rightarrow e$, with π transforming inputs of T to those of S and α transforming outputs of S to outputs of T .

Fig. 3. Again, such simulations compose in a well-behaved manner, i.e. they form a category [52].

We will denote the existence of such a simulation $d \rightarrow e$ by $d \rightsquigarrow e$, read as “ d simulates e .” Simulations thus defined interact well with contextuality. For instance, [[32] Theorem 21] states that the noncontextual fraction, studied in [13], is a monotone, that is, if $d \rightsquigarrow e$, then $\text{NCF}(d) \leq \text{NCF}(e)$; and [[51] Theorem 4.1] implies that an empirical model is noncontextual if and only if it can be simulated from the trivial model on the empty scenario. In fact, the notions of logical and strong contextuality can be captured along similar lines [44] by relaxing the equality of probability distributions in the definition of simulation by equality (or inclusion) of supports of these distributions.

We now state our main result for this resource theory of contextuality.

Theorem 1. If $d \otimes e \rightsquigarrow d \otimes f$ in the resource theory of contextuality, then $e \rightsquigarrow f$.

The key ideas of the proof are simple, even if the full details get technical: if d can catalyze a transformation $e \rightarrow f$ once, it can do so arbitrarily many times. Choosing a big enough number of copies of e to transform to copies of f , using the pigeonhole principle, we can show that one only needs a compatible subset of S_d (or rather, a compatible set of measurement protocols). Making this precise requires formalizing our framework more carefully, and we do this in the Supplemental Material [53]. Our result subsumes [[32], Theorem 22], as setting $d = f$ and letting e be the trivial model on the empty scenario implies that if $d \rightsquigarrow d \otimes d$, the model d must be noncontextual.

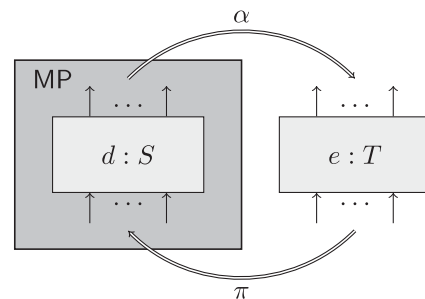


FIG. 2. Depiction of an adaptive simulation $d \rightarrow e$.

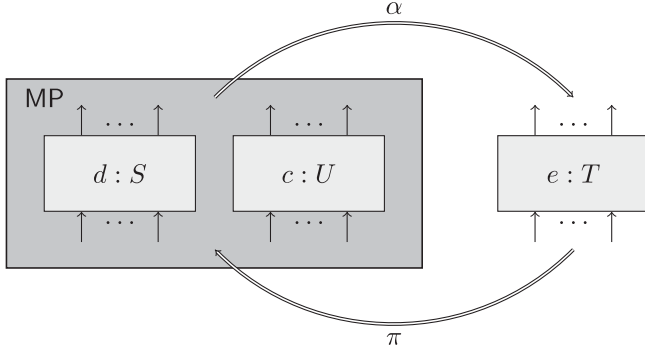


FIG. 3. General simulation $d \rightarrow e$, where we require c to be noncontextual.

No catalysis for nonlocality.—We know explain how to interpret nonlocality within this framework. At the level of scenarios and models on them, nonlocality can be seen as a special case of contextuality: for nonlocality, the measurement scenario typically arises by considering n parties, with the i th party choosing one measurement from a set X_i of measurements available to them, with a measurement $x \in X_i$ giving outcomes in some outcome set $O_{i,x}$. Often one restricts the situation even further and assumes that each party has the same number of measurements available and each measurement takes outcomes in a set of the same size, so that the scenario is specified (up to isomorphism) by three numbers: the number of parties, the number of measurements available to each of them, and the size of the outcome sets. Whether or not one imposes this further restriction, such scenarios are of the form $S = \otimes_{i=1}^n S_i$, where each S_i is just a discrete set of measurements (so only singleton measurements are possible in each S_i). In particular, a maximal measurement corresponds to a choice (x_1, \dots, x_n) of a measurement at each site, and a set of correlations can be given as a family $p(o_1, \dots, o_n | x_1, \dots, x_n)$ of conditional probabilities for each such measurement. If the family p is (fully) no-signaling, it corresponds to a unique empirical model $e: S$ (where the probabilities over nonmaximal measurements are obtained by marginalization), and p is local if and only if e is noncontextual.

However, if we allow parties to share different nonlocal resources, we move away from the situation where each party chooses one measurement from a set of mutually exclusive measurements. For instance, if Bob shares one box with Alice and one with Charlie, Bob is not limited to a single measurement: he can choose one for each box. As quantum theory allows for arbitrary joint measurability graphs in the case of projection-valued measurements [54] and arbitrary simplicial complexes in the case of positive-operator valued measurements [55], we impose no restrictions on the measurement scenarios available at each site. However, if we are thinking about a n -partite scenario, it is reasonable to expect that measurement choices done at one site do not affect the measurements available at another

one. Thus, we model an n -partite scenario as a tuple $(S_i)_{i=1}^n$ of scenarios, thought of as representing the n parties sharing the scenario $\otimes_{i=1}^n S_i$.

At the level of transformations between models and scenarios, nonlocality is no longer a special case of contextuality, as observed for example in [30] [Appendix A.1]. This is because our wirings are slightly too general as they allow the i th party to wire some of their measurements to measurements belonging to other parties, whereas operationally speaking it is reasonable to require each party to have access only to measurements available to them (and shared randomness). Nevertheless, the resource theories are very closely related, as one can obtain the resource theory for n -partite nonlocality from that of contextuality via a general construction, used in the context of cryptography in [33], that builds a resource theory of n -partite resources from a given resource theory.

In our setting, this amounts to defining the resource theory of n -partite nonlocality as follows: an n -partite scenario is an n -tuple $(S_i)_{i=1}^n$ of scenarios (some of which may be empty), and an n -partite empirical model $e: (S_i)_{i=1}^n$ is an empirical model on $\otimes_{i=1}^n S_i$. The parallel composite \boxtimes of scenarios is defined pointwise, i.e., by setting $(S_i)_{i=1}^n \boxtimes (T_i)_{i=1}^n = (S_i \otimes T_i)_{i=1}^n$. To define \boxtimes for two n -partite models $e: (S_i)_{i=1}^n$ and $d: (T_i)_{i=1}^n$, note that the scenarios $(\otimes_{i=1}^n S_i) \otimes (\otimes_{i=1}^n T_i)$ and $\otimes_{i=1}^n (S_i \otimes T_i)$ are canonically isomorphic so that the model $e \otimes d: (\otimes_{i=1}^n S_i) \otimes (\otimes_{i=1}^n T_i)$ induces a model $e \boxtimes d$ on $\otimes_{i=1}^n (S_i \otimes T_i)$ via this isomorphism. Finally, an n -partite simulation $d \rightarrow e$ is defined as an n tuple of simulations $[\text{MP}(T_i \otimes P_i \rightarrow S_i)]$ that, when taken together, transform $d \boxtimes c$ to e where c is some noncontextual shared correlation. In this manner, the resource theory of n -partite nonlocality is derived from that of contextuality by keeping track of the n -partite nature of scenarios and transformations between them.

Our proof of Theorem 1 readily implies that nonlocality admits no catalysts.

Theorem 2. If $d \boxtimes e \rightsquigarrow d \boxtimes f$ in the resource theory of n -partite nonlocality, then $e \rightsquigarrow f$.

Quantum-assisted transformations and beyond.—We briefly discuss a further generalization of our main result. One could consider resource theories with even more expressive simulations than the ones defined above. In the above, we define simulations as deterministic simulations assisted by noncontextual randomness. As suggested in [32], one could allow more general correlations to be used in transformations and study, e.g., quantum-assisted simulations. More specifically, one could define quantum-assisted simulations $e \rightarrow f$ as deterministic simulations $\text{MP}(e \otimes q) \rightarrow f$, where q is a quantum-realizable empirical model. More generally, for any class \mathcal{X} of empirical models that is closed under \otimes , one gets a well-defined notion of \mathcal{X} -assisted simulations, and we will write $d \rightsquigarrow_{\mathcal{X}} e$ to denote the existence of an \mathcal{X} -assisted simulation from d to e . If the class \mathcal{X} contains all nonlocal

correlations, the resulting resource theory has no catalysts. A similar result holds for \mathcal{X} -assisted n -partite transformations between n -partite correlations, but we restrict ourselves to stating the theorem for contextuality.

Theorem 3. Let \mathcal{X} be a class of empirical models that is closed under \otimes and contains all classical correlations. Then $d \otimes e \rightsquigarrow_{\mathcal{X}} d \otimes f$ implies $e \rightsquigarrow_{\mathcal{X}} f$.

For instance, if we take \mathcal{X} to be the class of quantum-realizable empirical models, this result implies that, if by some miracle we got access to a single PR box, we could not use it to catalyze a quantum-assisted transformation that was hitherto impossible. Put another way, no matter what class of correlations we can use freely, the only way to get mileage out of a box that goes beyond our powers is to spend it—so we must choose wisely.

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