The non-local nature of a measurement

by
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Abstract: This short paper identifies that the concept of a local measurement is always violated by a necessary metrological process - calibration. J. S. Bell's formal development of the same violation demonstrates that the EPR paradox and related discontinuities may be resolved by including the calibration process in a measurement process, as formalized in Measurement, February 2018 "Relative Measurement Theory."

In February 2018, Measurement published "Relative Measurement Theory: the unification of experimental and theoretical measurements" (RMT).[1] RMT formally develops and proves that all experimental and theoretical measurement results must be correlated to a reference interval. RMT proposed that a formal calibration process determines the variation between each interval of a measuring apparatus and a defined reference interval. As example, a calibration process determines the variation of each metre interval marked on one measuring rod relative to a definition of the metre length (reference interval).

A *measurement result* occurs when the calibrated measuring apparatus intervals are projected on the observable and the resulting set of calibrated intervals is summed. When intervals are defined as equal (even if infinitesimal) and counted rather than summed, this is a *measure*. As an experimental expedient calibration may refer to corrections of an average interval value. In RMT formal calibration is the correction of the variation of each interval of a measurement result. It is experimentally recognized, [2] and formally developed in RMT, that the variation of each interval or a sum of intervals cannot be reduced to zero. Theoretical measurements based upon the currently accepted representational measure theory[3] assume that the variation of any interval or sum of intervals can be reduced to zero.

Representational measure theory counts a magnitude of projected equal intervals (states) which is a local measure. This treats calibration as an artifact of the experimental measuring apparatus and does not consider a reference. In an experimental measuring apparatus, the interval variation due to calibration does not cancel when summed over a number of intervals, e.g., calibrating each metre interval of a measuring rod to a reference metre usually adjusts each metre interval by a similar amount. Then this variation of each calibrated metre interval sums in a measurement. Two independent measurements, each correlated to the same reference interval, or simply correlated to each other, by a calibration process, become relative to each other.

J. S. Bell identified that the EPR paradox[4] occurs due to the definition of a local measurement: "the result of a measurement on one system [is] unaffected by operations on a distant system with which it has interacted in the past".[5] Interval calibration is an interaction which creates a non-local relationship between a reference interval (a distant system) and the measurement intervals of a local system. As RMT develops, each measured interval cannot be exactly equal to the other intervals in a quantized (discrete) vector space. When a measurement includes the effect of interval calibration, there is no Bell inequality, instantaneous effect or EPR paradox.

The difference between local measure and QM experimental results is shown in experiments using an entangled pair of spin one-half particles.[6] Each entangled particle is passed through a polarizer and moves to remote space or time locations where the spin of each particle is detected by independent counters. The correlation (*P*) of the spin of the two particles, no matter how far apart in space or time, tracks the angle (θ) between the polarizers as shown in Figure 1. below, even when unknown initially.

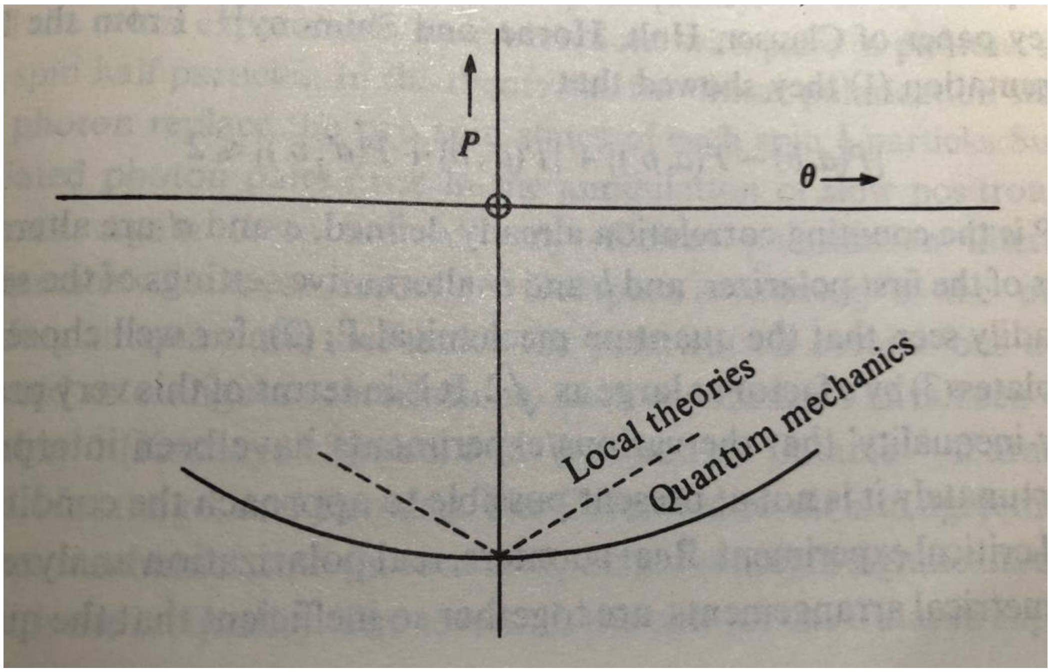

Figure 1, Correlation between local and QM theories near *P = -1* on the vertical line.[7]

The dashed line in Fig. 1 links the four possible measurement states (--, +-, ++, -+). Perfect correlation (-- or ++) occurs when θ is 0° or 180° (*P = -1 or +1*) and no correlation (+-, -+, not shown in Fig. 1) occurs when θ is 90° or 270°. This short paper proposes that adjusting the relative angle θ between the polarizers, is a continuous calibration process and not a discrete measurement process which produces one of the four states. The curved line (QM) properly represents the correlation *P* created by this calibration process. When the experiment is recognized as a calibration process, the dashed line becomes a normal cosine distribution equal to the solid curve.

Due to the effect of each calibration process on a series of measurements of the same observable, the standard deviation of the Gaussian distribution of measurement results spreads as the number of intervals summed increases. This spread, which is zero when all the intervals summed are equal, is the difference (Bell's inequality) between local measure and QM measurement theory shown in Fig. 1.

Measure theory, which does not include calibration, explains the dashed line in Figure 1. The effect of calibration is not considered in measure theory. This is because the calibration effect is insignificant when a measuring apparatus has been properly calibrated. However, in Fig. 1 the dashed line does not include calibration, while the QM measurement (solid curve) includes calibration. In an experimental measurement, calibration may occur before or after the actual measurement process so long as the effect of calibration is included in the final measurement result. Including calibration the two curves are the same and the appearance of an instantaneous correlation between remote counters resolves into the calibration of the polarizers.

In these particle spin experiments the relative angle of each polarizer to the other is determined when the polarizers are calibrated to each other. After passing through the calibrated polarizers, the entangled particles just remain entangled. There is no instantaneous effect, only the appearance of such when the different angles between the two polarizers are considered a series of separate measurements rather than a series of relative calibrations.

In these experiments with two opposite intervals (i.e., + or – spin), the counters identify two distributions of + or – spin intervals, not measurement results. Measurement results are a sum of calibrated intervals and opposite calibrated intervals sum to near zero. This subtle difference between detecting calibrated intervals and measurement results is verified in experiments which identify the + and - spin distributions as two separate distributions.[8] The opposite spin distributions would appear as one distribution if this distribution represented one set of measurement results.

Opposite interval experiments have been performed at both quantum and classical scales. At all scales a calibration process produces the correlation seen when the intervals of different particles are detected separately in space or time. The Bell (space) and Leggett-Garg[9] (time) inequalities identify that calibration preclude the concept of a local measurement.

In RMT, the digital voltmeter example of a classical measurement (Krechmer Section 3) is shown to produce a Gaussian distribution when calibration and resolution effects are considered in a classical measurement, not a linear distribution consistent with a local measurement.

Other explanations of the apparent discontinuities (uncertainty, disturbance, collapse and entanglement) between quantum and classical measurements are found in RMT. All experimental measurement results are calibrated relative to a reference. This makes a local measurement, as formalized by J. S. Bell, impossible. When a local measurement is not possible, there is no EPR paradox.

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[1] K. Krechmer, Relative Measurement Theory, The unification of experimental and theoretical measurements, *Measurement*, Volume 116, February 2018, Pages 77-82. https://www.sciencedirect.com/science/article/pii/S0263224117306887

[2] A. E. Fridman, *The Quality of Measurements*, Springer, 2012, page 23. "It is in principle impossible to find the true value of a quantity."

[3] D. H. Krantz, R. D. Luce, P. Suppes, A. Tversky, *Foundations of Measurement*, Academic Press, New York, 1971, Vol. 1, page 32, Section 1.5 Roles of Theories of Measurement in the Sciences. This three volume work is the foundational text on representational measure. "The construction and calibration of measuring devices is a major activity, but it lies rather far from the sorts of qualitative theories we examine here."

[4] A. Einstein, B. Podolsky, N. Rosen, Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?, *Physical Review*, Vol. 47, 15 May 1935. This paper is often referred to as the EPR paper.

[5] J. S. Bell, *Speakable and unspeakable in quantum mechanics*, Cambridge University Press, Cambridge, GB, 1989, Chapter 2, On the Einstein-Podolsky-Rosen paradox.

[6] A. Aspect, P. Grangier, and G. Roger, Experimental Realization of Einstein-Podolsky-Rosen-Bohm Gedankenexperiment: A New Violation of Bell's Inequalities, *Physical Review Letters*, Vol. 49, #2, 12 July 1982.

[7] J. S. Bell, Chapter 10, Einstein-Podolsky-Rosen experiments, Fig. 2, page 85.

[8] J. S. Bell, Chapter 16, Bertlmann's socks and the nature of reality, Fig. 5, page 141.

[9] C. Emary, N. Lambert, F.Nori, Leggett-Garg Inequalities, *Rep. Prog. Phys.* 77, 016001 (2014).