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Is the World Local or Nonlocal? Towards an Emergent Quantum Mechanics in the 21st Century

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Abstract. What defines an emergent quantum mechanics (EmQM)? Can new insight be advanced into the nature of quantum nonlocality by seeking new links between quantum and emergent phenomena as described by self-organization, complexity, or emergence theory? Could the development of a future EmQM lead to a unified, relational image of the cosmos? One key motivation for adopting the concept of emergence in relation to quantum theory concerns the persistent failure in standard physics to unify the two pillars in the foundations of physics: quantum theory and general relativity theory (GRT). The total contradiction in the foundational, metaphysical assumptions that define orthodox quantum theory versus GRT might render inter-theoretic unification impossible. On the one hand, indeterminism and non-causality define orthodox quantum mechanics, and, on the other hand, GRT is governed by causality and determinism. How could these two metaphysically-contradictory theories ever be reconciled? The present work argues that metaphysical contradiction necessarily implies physical contradiction. The contradictions are essentially responsible also for the measurement problem in quantum mechanics. A common foundation may be needed for overcoming the contradictions between the two foundational theories. The concept of emergence, and the development of an EmQM, might help advance a common foundation – physical and metaphysical – as required for successful inter-theory unification.

1. Introduction

The question “Is the world local or non-local?” has long guided work in quantum foundations. At the latest, this started with the introduction, by Einstein, Podolsky, and Rosen (EPR), of the first precise metaphysical definitions in relation to nonlocality as a concept (Einstein et al. [1]). 80 years on, that question – rather surprisingly – remains unanswered still. On the one hand, there is no doubt any longer that EPR-type nonlocal correlations can be observed in quantum experiments by observers who are separated at space-like distances. On the other hand, the ontological question remains wholly undecided of whether these nonlocal observations might imply the actual existence of a “nonlocal reality” – not merely in terms of an operational metaphor as in orthodox quantum theory. The prospect of fundamentally “real nonlocality” was proposed, for example, by de Broglie–Bohm theory (Bohm [2,3]). Inspired by both Bohm’s proposal (Bohm [2,3]) and the EPR argument (Einstein et al. [1]), John Bell succeeded in proving that no quantum theory based on the joint assumptions of reality and locality could successfully reproduce the predictions that are yielded by orthodox, i.e., operationalist quantum mechanics (Bell [4]).
Total Contradiction of Metaphysical Assumptions

Figure 1. Total contradiction of metaphysical assumptions between orthodox quantum theory and general relativity theory (GRT). Metaphysical contradiction implies physical contradiction (see Sect. 2.1). How is the reconciliation of metaphysical assumptions possible?

The seminal proof of Bell’s theorem left open, however, the extraordinary possibility that reality might be – ontologically-speaking – nonlocal in nature. That possibility, which necessarily reaches beyond operationalist quantum theory, is pursued by what has become known as the ontological, realist, approach to quantum mechanics (e.g., Bohm and Hiley [5]). The project of developing an ‘emergent quantum mechanics’ (EmQM) is usually placed in the context of realist approaches to quantum mechanics.

The implications of an EmQM are startling, however, when viewed through the lens of the orthodox perspective: instead of finding – at reality’s deepest levels – absolute “quantum randomness”, a future EmQM, including also de Broglie–Bohm theory, would find “quantum interconnectedness”, e.g., possibly in the form of instantaneous nonlocal influences across the universe. For example, when John Bell was asked what the meaning was of nonlocality, he answered that nonlocality “… means that what you do here has immediate consequences in remote places” (Mann and Crease [6]). What might the phenomenon of ‘emergence’ offer towards a new understanding of nonlocality in the deeper sense of Bell’s “immediate consequences” – beyond the standard operationalism of orthodox theory?

2. Why ‘emergence’ in quantum mechanics?

One key motivation for adopting the concept of (irreducible) emergence in relation to quantum theory concerns the much-debated failure to unify the two pillars in the foundations of physics: quantum theory and general relativity theory (GRT). Therefore, the long-term project of inter-theory unification might be injected with fresh thinking via the introduction into quantum mechanics of the concept of emergence. Why might that be so?

On the one hand, orthodox quantum theory, as we understand it today, is an entirely indeterministic and non-causal theory, which presumes the complete absence of any fundamental, ontological reality at the level of the quantum. “There is no quantum world.” Niels Bohr’s explained, “There is only abstract quantum-mechanical description” (Petersen [7]). On the other hand, relativity theory (GRT) represents an ontological theory of space-time reality, in a decidedly causal and deterministic manner. Fig. 1 illustrates the fact that the metaphysical assumptions associated with the theories contradict each other: “indeterminism” versus “determinism”, and “non-reality” versus “reality”. These contradictions are responsible also, of course, for the so-called measurement problem in quantum mechanics.

2.1. Why ‘metaphysics’ in quantum physics?

Why is there this emphasis on metaphysical assumptions? It is helpful to remember that in the EPR argument already, which called for the incompleteness of orthodox quantum mechanics (Einstein et al. [1]), it was the exact derivation and definition of metaphysical assumptions which
allowed the EPR argument to have relevance to concrete problems facing quantum physics: Is the world local or nonlocal? It was only through the consideration of metaphysical notions like “locality”, “nonlocality”, “causality”, and “reality”, that the breakthrough of Bell’s theorem was possible (Bell [4]). What is often lost in this picture is the following: metaphysical assumptions essentially constrain the application of any mathematical theory to concrete physical situations. Importantly, “metaphysical” is neither “mystical” nor “irrational”. A metaphysical analysis refers to the first principles and the foundational physical assumptions which inevitably underpin any scientific or mathematical analysis of nature. Often, foundational assumptions represent the preferred world view of the working scientist, including preconceived notions of what may, or may not, be possible in reality. Thus, by adopting a new metaphysical position, a new vista might open up towards the solution of a previously intractable scientific problem.

It appears likely that not any amount of mathematical or technical sophistication will reconcile the two theories – quantum and relativity, unless the problem of their immediate metaphysical opposition could be resolved also (compare Fig. 1). Similarly, any resolution of the measurement problem is likely to depend on the “metaphysical reconciliation” – at the macroscopic and microscopic levels – of any future physical explanations. Not surprisingly, it was John Bell [8] again who suggested “... that a real synthesis of quantum and relativity theories requires not just technical developments but radical conceptual renewal.”

3. Towards an emergent quantum mechanics

The research project of an EmQM follows the spirit of John Bell’s call for “radical conceptual renewal” (Bell [8]), a call consistent with his well-documented realist expectations about the future of quantum mechanics (e.g., Bell [9]). EmQM research seeks a common foundation upon which might rest both quantum theory and GRT. Presently, the availability of a common foundation is disputed or, at least, entirely unconfirmed. However, the concept of ‘emergence’ from self-organization, chaos, or complexity, theory – once properly adapted – might offer a universal framework, both physically and metaphysically, for finally promoting “... a real synthesis of quantum and relativity theories...” (Bell [8]).

For some time now, the concept of emergence has found use already in gravitational theory and in understanding the nature of space and time. Both the puzzles and the possibilities of notions such as ‘emergent gravity’ and ‘emergent space-time’ have been well summarized, for example, by David Gross [10]: “Many of us are convinced that space is an emergent, not fundamental concept. We have many examples of interesting quantum mechanical states, for which we can think of some (or all) of the spatial dimensions as emergent. Together with emergent space, we have the emergent dynamics of space and thus emergent gravity. But it is hard to imagine how time could be emergent? How would we formulate quantum mechanics without time as a primary concept? Were time to be emergent, our understanding of quantum mechanics would have to change.” See Fig. 2 for a sketch illustrating the proposal that new understanding of quantum mechanics, based on emergence, could lessen, or even lift, the inter-theoretic contradiction shown before in Fig. 1.

The key point is the following: once space-time and gravity are recast in terms of fundamentally emergent states or dynamics, this invites the new view of the quantum nature of reality in terms of emergent dynamics as well. Thus, a common conceptual foundation might be developed – based on emergence as a guiding principle – capable of bridging the vast chasm between quantum and relativity theories. Maybe, then, there could be a new way to look at the problem of inter-theory unification. In the future, there might be theories describing some kind of “emergent quantum gravity” as a result. For example, pioneering work based upon a locally-deterministic form of an “emergent quantum mechanics” was carried out by ’t Hooft [11] (2007).
Figure 2. The concept of emergence may provide a common physical and metaphysical foundation in efforts to unify quantum and relativity theories (GRT). A common foundation will be needed for overcoming the deep metaphysical contradictions – in the orthodox approach – which have thus far prohibited success in inter-theory unification (compare Fig. 1).

Figure 3. Illustration of self-referential, dynamical interactions across levels of organization – microscopic and macroscopic (from Walleczek [12]). Both top-down and bottom-up causal flows are indicated in the formation of an emergent macroscopic structure. Emergence describes the spontaneous synchronization of individual random motions into a unified collective motion. Emergence accounts for the rise of global macroscopic order from local microscopic randomness. An example is the emergent formation of spatio-temporal, long-range coherence.

4. What is emergence?
In a more general context, what is emergence? The concept of emergence is present under the guise of many different names and theories: complexity theory, chaos theory, self-organization theory, non-linear dynamical systems theory, synergetics, cybernetics, fractal sets, cellular automata, and so on. Emergent events are characterized by sensitive dependencies on initial conditions in combination with evolving boundary conditions. Generally, emergence accounts for the rise of global macroscopic order from local microscopic randomness. Both, top-down and bottom-up causal flows are implicated in the formation of an emergent macroscopic structure (Fig. 3). These causal flows are considered to be relational because vastly different levels in the hierarchy of organization are actively interconnecting without exclusive priority of one level over another (see legend to Fig. 3).
4.1. Determination without pre-determination: “effective indeterminism”
An important dimension in the development of an EmQM, i.e., for any theory which connects (classical) emergence theory with quantum mechanics, is the question of the inherently probabilistic nature of quantum phenomena. Crucially, in-principle unpredictability, as well as uncontrol lability, of individual microscopic (quantum) events must be ensured by any kind of non-orthodox theory which claims success in reproducing the predictions that are yielded by orthodox quantum mechanics. Otherwise, for example, the non-signalling theorem of quantum mechanics would be instantly violated as we have discussed before at great length (Walleczek and Grössing [13, 14]). Critical in this context is that emergent phenomena are subject to unpredictability as a consequence of the intrinsically self-referential nature of the governing dynamics as illustrated in Fig. 3 (e.g., compare also the halting problem in computational theory). A well-known example is the phenomenon of deterministic chaos, which provides a vivid image of determination without predetermination, i.e., “effective indeterminism”. Future work in EmQM foundations needs to clearly establish the limits and conditions under which such scenarios apply in alternative models for quantum phenomena, including for quantum nonlocality.

5. Outlook: new approaches in realist quantum mechanics
What are the prospects for an ‘Emergent Quantum Mechanics’? It is possible – in principle – that the universe is deterministic, e.g., nonlocally causal in light of EPR-type nonlocal correlations. Yet – at the same time – even a deterministic universe can have an open future in the context of emergence theory, i.e., a future where both the free-choice performances of an observer/agent, and other physical processes in the cosmos, are not pre-determined by past events. As was explained in Sect. 4, emergent dynamical processes are well-known for being governed by entirely deterministic relations, and yet these very same processes can be without pre-determined outcomes in the future. As a consequence of the intrinsically self-referential nature of emergent phenomena, the in-principle unpredictability of individual microscopic events is granted. Whether such concepts might apply productively in a future quantum mechanics remains for now a promising vision. However, the resurgence of interest in ontological approaches to quantum mechanics, including those pioneered and envisioned by David Bohm [2,3] and John Bell [8,9,15,16] may further increase interest in the project of an EmQM (e.g., see also Bohm and Hiley [5]; Holland [17]).

In conclusion, a new wave of work has drawn attention to ontological, realist questions in quantum mechanics: Does the concept of ‘nonlocality’ reflect the true nature of reality? Is the quantum state real? Is the wave function \( \psi \) a reality? On the theoretical side, especially work by Harrigan and Spekkens [18] has renewed interest in ontological theory, including de Broglie–Bohm theory, by presenting the productive distinction between \( \psi \)-ontic and \( \psi \)-epistemic approaches to quantum mechanics. In that context, our own recent work showed that nonlocal quantum information transfers, which are inevitably associated with any \( \psi \)-ontic quantum theory, including Bohm’s theory, need not violate the non-signalling theorem (Walleczek and Grössing [14]). On the experimental side, the important work by Kocsis et al. [19], Ringbauer et al. [20], and Mahler et al. [21], has advanced fresh insight into the non-orthodox option of nonlocality as a reality, e.g., the reality of the wave function \( \psi \). Finally, the most recent available findings provide a “compelling visualization” – as the authors put it – “of the nonlocality inherent in any realistic interpretation of quantum mechanics” (Mahler et al. [21]).

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References
[1] Einstein A, Podolsky B and Rosen N 1935 Can quantum-mechanical description of physical reality be considered complete? *Phys. Rev.* **47**(10) 777–780
[2] Bohm D 1952 A suggested interpretation of the quantum theory in terms of "hidden" variables. I *Phys. Rev.* **85**(2) 166–179
[3] Bohm D 1952 A suggested interpretation of the quantum theory in terms of "hidden" variables. II *Phys. Rev.* **85**(2) 180–193
[4] Bell J S 1964 On the Einstein Podolsky Rosen paradox *Physics* **1**(3) 195–200
[5] Bohm D and Hiley B J 1993 *The Undivided Universe: An Ontological Interpretation of Quantum Theory* (London, UK: Routledge) ISBN 0-415-06588-7
[6] Mann C and Crease R 1988 Interview: John Bell, particle physicist *Omni* **10**(8) 84–92
[7] Petersen A 1963 The philosophy of Niels Bohr *Bulletin of the Atomic Scientists* **19**(7) 8–14
[8] Bell J S 1987 Speakable and unspeakable in quantum mechanics, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge, UK: Cambridge University Press) pp 169–172
[9] Bell J S 2004 La nouvelle cuisine, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge, UK: Cambridge University Press) pp 232–248 revised ed ISBN 978-0-511-81567-6
[10] Gross D 2014 A century of quantum mechanics, ed Struppa D C and Tollaksen J M *Quantum Theory: A Two-Time Success Story* (Milano: Springer) pp 3–8 ISBN 978-88-470-5216-1
[11] 't Hooft G 2007 Emergent quantum mechanics and emergent symmetries *AIP Conf. Proc.* **957**(1) 154–163 (*Preprint* arXiv:0707.4568)
[12] Walleczech J (ed) 2000 *Self-Organized Biological Dynamics and Nonlinear Control* (Cambridge, UK: Cambridge University Press) ISBN 0-521-62436-3
[13] Walleczech J and Grössing G 2014 The non-signalling theorem in generalizations of Bell’s theorem *J. Phys.: Conf. Ser.* **504** 012001 (*Preprint* arXiv:1403.3588 [quant-ph])
[14] Walleczech J and Grössing G 2016 Nonlocal quantum information transfer without superluminal signalling and communication *Found. Phys.* in press. (*Preprint* arXiv:1501.07177 [quant-ph])
[15] Bell J S 1976 The theory of local beables *Epistemol. Lett.* **9**(3)(March) repr. in *Dialectica* **39** (1985) 85-96.
[16] Bell J S 1977 Free variables and local causality *Epistemol. Lett.* **15**(2)(February) repr. in *Dialectica* **39** (1985) 103-106.
[17] Holland P R 1993 *The Quantum Theory of Motion* (Cambridge, UK: Cambridge University Press) ISBN 0-521-35404-8
[18] Harrigan N and Spekkens R W 2010 Einstein, incompleteness, and the epistemic view of quantum states *Found. Phys.* **40**(2) 125–157
[19] Koéls S, Braverman B, Ravets S, Stevens M J, Mirin R P, Shalm L K and Steinberg A M 2011 Observing the average trajectories of single photons in a two-slit interferometer *Science* **332**(6034) 1170–1173
[20] Ringbauer M, Duffus B, Branciard C, Cavalcanti E G, White A G and Fedrizzi A 2015 Measurements on the reality of the wavefunction *Nature Phys.* **11**(3) 249–254 (*Preprint* arXiv:1412.6213 [quant-ph])
[21] Mahler D H, Rozema L, Fisher K, Vermeulen L, Resch K J, Wiseman H M and Steinberg A 2016 Experimental nonlocal and surreal Bohmian trajectories *Science Advances* **2**(2) e1501466