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

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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 successfull *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]).

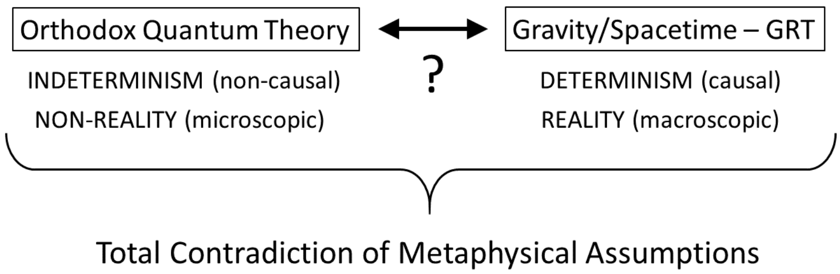

Figure 1. Total contradiction of metaphysical assumptions between orthodox quantum theory and general relativity theory (GRT). *Metaphysical* contradiction implies *physical* contradiction (see Sect. 2.1). How is the reconciliation of metaphysical assumptions possible?

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 decidely *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 reconcilition" – at the *macroscopic* and *microscopic* levels – of any future *physical explanations*. Not suprisingly, 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 decribing 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).

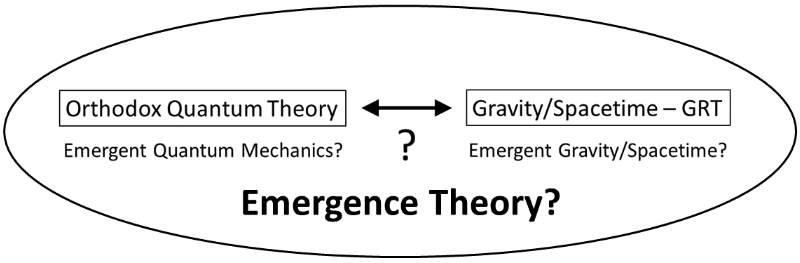

Figure 2. The concept of *emergence* may provide a common *physical* and *metaphysical foundation* in efforts to unify quantum and relativity theories (GRT). A common foundation will be needed for overcoming the deep metaphysical contradictions – in the *orthodox* approach – which have thus far prohibited success in inter-theory unification (compare Fig. 1).

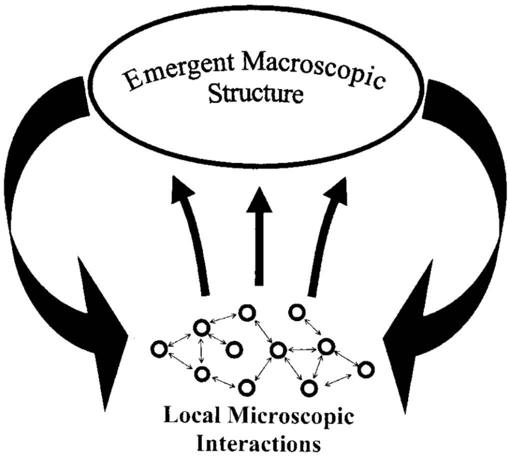

Figure 3. Illustration of self-referential, dynamical interactions across levels of organization – *microscopic* and *macroscopic* (from Walleczek [12]). Both top-down and bottom-up causal flows are indicated in the formation of an *emergent macroscopic structure*. Emergence describes the *spontaneous 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 *uncontrollability*, 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 ψ 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 ψ-ontic and ψ-epistemic approaches to quantum mechanics. In that context, our own recent work showed that *nonlocal quantum information transfers*, which are *inevitably* associated with any ψ-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 ψ. 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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