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Article

Randomness, Quantum Uncertainty, and Emergence: A Suggestion for Testing the Seemingly Untestable

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Abstract

The functioning of complex natural structures, such as living systems, still lacks a generally accepted theoretical basis with respective empirical experimental verification for decades. We propose a class of experiments to test whether such systems could be subject to an unknown ordering principle that cannot be captured by known physical laws. We hypothesise that the quantum mechanical uncertainty principle enables ordering phenomena in nearly chaotic systems in the sense of a strong emergence principle, which would not be expected when they are modelled conventionally, as several authors have already formulated in various forms. To account for the harsh conditions prevailing in living systems that may preclude fragile macroscopic quantum coherence, our hypothesis does not require such coherence at all, contrary to earlier related proposals. To test this hypothesis, two virtually identical and sufficiently complex experimental setups should be compared. One setup will operate with deterministic pseudo-random number generators at key sensitive points, while the other one will use quantum-based physical random-number generators, the two setups being otherwise identical. Existing artificial neural networks are proposed as possible test objects, and their performance under identical training conditions can be used as a quantitative benchmark. As this working hypothesis extends far beyond artificial networks, a successful outcome of such an experiment could have significant implications for many other branches of science.

Keywords: complex systems; neural networks; emergence; uncertainty principle; randomness

1. Introduction

In the exact sciences, which include disciplines related to mathematics and the natural sciences, a hypothesis put forward can be proven or refuted either by comprehensible logic or by reproducible experiments. This practice has been and continues to be extremely successful, but it is not applicable to all branches of science, or only to a limited extent. Direct counterparts to statements made by the exact sciences can be found, for example, in theological dogmas of many religions, which explicitly, and probably rightly, avoid such scrutiny altogether. However, there is also a grey area between these two extremes. This is where attempts are made to contextualize scientific results within a broader philosophical or even religious framework (for a critical reading, see Ladyman et al. (2007)). Prime examples are interpretations of cosmological findings on a metaphysical level, for example in relation to the creation and the meaning of the universe, or the discussion of the relevance of known physical laws for the occurrence of life or the nature of human intelligence (read, for example, Davies (1992, 2006)). Unfortunately, most corresponding scenarios that are circulating seem to be completely beyond the possibility of experimental verification.

In this article we would like to revisit a question that has been raised by many authors before, namely whether quantum mechanics can be used to shed light on the fundamental principles of certain yet poorly understood phenomena in complex structures that exhibit chaotic or nearly chaotic behaviour. For example, the much-discussed 'principle of emergence', according to which a kind of order can emerge from a multitude of individual building blocks which cannot be readily deduced from the properties of the individual parts (for an overview about principles of emergence, see

Chalmers (2006)), has often been cited in this context (e.g., in Bishop et al. (2022)). While for comparatively simple, non-chaotic systems in condensed matter, with phenomena ranging from crystallization, magnetism, superfluidity and superconductivity, such a presumed emergence (Anderson, 1972; Drossel, 2021) can perhaps be derived from the known equations of quantum mechanics with some effort, other, more complex ordering phenomena, such as those occurring in living systems, have so far defied a conclusive description by any known law of nature. So-called 'downward causation', which could be seen as supporting the idea of emergent principles at work, has been brought into play for biological systems, e.g., by Campbell (1974), Davies (2008), Noble (2011), Walker (2012), Laland et al. (2013), and even for digital computers by Ellis & Drossel (2019), with or without the need to invoke quantum mechanical principles. However, this topic is highly contentious (Kim, 1992; Hulswit, 2005; Craver & Bechtel, 2007; Haddad, 2025). Within this context, many attempts have been made to discuss quantum theory or chaos in relation to life in general, to the functioning of the human brain in particular, and to the controversial terms 'consciousness' and 'free will'. These physical and related mathematical concepts have sometimes even been suggested as potential causal factors (see, e.g., Jordan, 1945; Beck & Eccles, 1992; Garson, 1995; Wildman & Russell, 1995; Chalmers, 1996; Kane, 1996, 2014; Hu & Wu, 2004; Bishop, 2011; Gisin, 2013, 2021; Hameroff, 2014; Jedlicka, 2014; Fisher, 2015; Stapp, 2017; D'Ariano & Faggin, 2022; Faggin, 2023; Liu et al., 2024; Bishop, 2025, and others).

Unfortunately, the vast majority of these works are purely argumentative, and their conclusions generally do not lead to concrete proposals for experiments that could be verified with the rigour of a scientific proof. Only a very few publications are referring to actual or proposed experiments that could help to clarify these or related fundamental questions, such as those of Libet (1994), Davies (2004), Fisher (2015), Gamez (2018, 2021), Andrews et al. (2025), and of the Cogitate Consortium (2025). However, any scientific situation that is unclear ultimately requires a scientific clarification. Based on a particular hypothesis to be examined, a specific experiment should be designed to provide the most meaningful result possible regarding the validity of the underlying hypothesis. In the following, we formulate such a narrowly defined hypothesis and outline an experiment, the results of which could either prove the hypothesis, or can serve as a counterargument against it.

2. The Hypothesis

The working hypothesis that we propose to test assumes that in every natural chaotic or just sufficiently complex physical system near chaotic behaviour, defined, for example, according to the classification by Langton (1990), there is a hitherto unknown natural principle at work that is largely robust to environmental influences such as noise or temperature, provided that these influences do not destroy the integrity and functionality of the system entirely. On the one hand, this principle must obey the known laws of physics, but on the other, it can allow for subtle changes that are still physically allowed by the uncertainty principle of quantum mechanics. Over time, however, such small changes in complex dynamical systems can have major effects (for an overview, see Gleick (1987)), and may lead to a course of events that seems to run counter to purely statistical considerations. Scenarios invoking quantum uncertainty are not at all new and have been formulated by a number of scientists and philosophers, without (Heisenberg, 1969; Kane, 1996, 2014; Jedlicka, 2014; Youvan, 2024; and others) or with a metaphysical or even theological context (Polkinghorne, 1995; Tracy, 2000; Russell et al., 2001; Polkinghorne, 2009; Russell, 2018; and others). Although they may seem a little hackneyed today, their justification as part of our working hypothesis lies in the simple fact that, despite decades of very intensive research, many phenomena occurring in complex natural dynamical structures have not found any satisfactory explanation within known physical laws, and therefore the introduction of unconventional ideas should at least be considered. While our proposal is still based on the concept of indeterminism according to the view of the Copenhagen interpretation of quantum mechanics (see, e.g., Faye, 2024), it explicitly adds an additional ingredient, which can be interpreted as a yet unknown physical law or as an additional ordering principle of nature in the sense of the strong emergence principle (for a definition, see Chalmers (2006)), according

to which it cannot be derived from the already known laws describing the constituents of the complex system and their microscopic mutual interactions. Ultimately, the hypothesis also implies abandoning the requirement for macroscopic quantum coherence, which has been argued to be extremely unstable in biological systems under the environmental conditions prevailing in the biosphere. We consider it necessary to include such an assumption in our working hypothesis, however, in order to specifically address the legitimate objections regarding the role of quantum coherence in natural extended complex dynamical systems at room temperature (Tegmark, 2000; Davies, 2004; Koch & Hepp, 2006), while deliberately leaving open the possibility that quantum phenomena could nevertheless play a decisive role. Whether such an additional law or principle can ultimately be captured theoretically and mathematically, or whether it represents an ordering phenomenon toward higher-order organization that fundamentally eludes such analysis altogether, is a very important question in itself, but is left open here as it is not decisive for the present proposal.

In a related experiment, we need to be able to distinguish between the behaviour over time of a complex system that is subject to quantum uncertainty, and another virtually identical system that is not. A potentially different behaviour must then be verifiable and quantifiable. The evaluation could include checking whether one of the systems performs certain tasks better than the other in a reproducible way, for example, in terms of speed or accuracy, thereby defining a certain quantitative benchmark.

3. The Experiment

3.1. An Implementation Using Current Technology

A corresponding preliminary experiment could be carried out in a variant of existing computer-based neural networks, which are routinely used to find patterns in huge amounts of data and to generate predictions deduced from these data. Inspired by the internal structure of natural neuronal networks and the brain, whose functioning has incidentally often been suggested to be on the verge of chaotic behaviour (Hansel & Sompolinsky, 1992; Korn & Faure, 2003; Kitzbichler et al., 2009; Chialvo, 2010; O'Byrne & Jerbi, 2022; Wang et al., 2023), simulated neuron-like entities are virtually connected, and mathematical parameters such as weights and biases, which determine the strength of connections between the simulated neurons and influence their activation, are adjusted during a learning process (Rosenblatt, 1962; Tappert, 2019). Introducing random noise at various stages of the learning process, as it has also been proposed to be relevant in biological systems (Brown et al., 2019), turned out to be very beneficial to approach an optimum learning performance (Holmstrom & Koistinen, 1992; Welling & Teh, 2011), but randomness is mostly simulated by software-based deterministic pseudo-random number generators (PRNGs). The role of this randomness is usually interpreted as preventing the process from overfitting or getting stuck in so-called local minima, and driving it to seek better solutions (for a review, see Ghaith Altarabichi et al. (2024)). However, such purely software-based architectures, which operate on computer platforms with finite computational precision, are inherently deterministic and predictable, since identical initial conditions must lead to identical results as even pseudo-random number generators are ultimately based on deterministic algorithms.

The key idea is to replace these PRNGs with quantum-random number generators (for a corresponding review, see Herrero-Collantes & Garcia-Escartin (2017)), making a sufficiently complex network intrinsically unpredictable, while those network components that are expected to obey more or less classical physical laws could initially remain unchanged. Quantum-random number generators (QRNGs) have indeed been demonstrated to be incomputable (Calude et al., 2010). Genuine QRNGs could be based, for example, on the use of entangled photons (Bierhorst et al., 2018), or on radioactive decay (Isida & Ikeda, 1956; Schmidt, 1970). To apply the benchmark test, the overall performance of such a network should then be compared in a control experiment with an identical network using software-based PRNGs, with the same learning input and operating at the same clock-cycle rate equivalent, i.e., under otherwise identical conditions. If a fundamental

difference in their properties were observed in favour of the QRNG version, this could be a first indication. Special care must be taken here to ensure that the accuracy during the simulation of the temporal behaviour of the complex system is not compromised by the digital discretization (Boghosian et al., 2019; Klöwer et al., 2023) or other numeric artifacts. Quantum-based random-number generators inherently have the potential to generate infinitely precise random numbers, whereas corresponding computer-generated random numbers always have finite precision. A general statement as to where exactly QRNGs should be placed in any given complex network cannot be made here, however, as this depends on the specific architecture of the used network. Quantum uncertainty should naturally be introduced where the network is most sensitive to small changes in relation to a possible transition from non-chaotic to chaotic behaviour.

For the time being, experiments with existing memristor-based networks may already provide a certain clue, as they have been reported to outperform software-based networks in terms of accuracy (Dalgaty et al., 2021) and speed (Lin et al., 2025). These advantages, which go hand in hand with significantly reduced energy consumption (Zhao et al., 2025), stem partly from the fact that these devices can perform analog computations directly within the memory array (see, for example, Dalgaty et al. (2021) and the references cited therein). Memristor crossbar arrays inherently support highly parallel operations, mimicking the parallel processing nature of the brain (Liu et al., 2020; Chen et al. 2021). Interestingly, memristors also produce physical randomness, arising from their intrinsic stochastic variability (Chen, 2014; Balatti et al., 2015), which has been exploited to considerably enhance the learning performance of the in-memory computing hardware (Lin et al., 2025). Although it is clear that the electrons involved ultimately obey the laws of quantum mechanics, it remains to be seen whether the random behaviour of the many-body electronic system in memristors is equivalent to that realised in genuine QRNGs. Examining the performance of such existing networks according to the above benchmark test would nevertheless be of the utmost interest, as it appears to be sufficiently simple to implement with current technology.

3.2. *Proposals for More Tailored Versions of the Experiment*

While current neural-network architectures are designed to perform rather specific tasks, other more open architectures, perhaps not yet implemented, may be more appropriate to test the current proposal. Existing versions of artificial neural networks are usually designed to first learn and then produce an output based on that training process, but only in response to an external query. These systems are often colloquially referred to as exhibiting a kind of 'artificial intelligence', perhaps because of the impressive results they sometimes obtain. An additional property that is usually ascribed to the term 'intelligence' is the ability not only to react, but also to reason in the absence of an external request. Many would agree that this can sometimes lead to the spontaneous generation of new, even revolutionary and disruptive ideas not directly related to recent learning activities. In our context, it is therefore particularly relevant that the behaviour of the network continues to be influenced by random processes even after training. As far as we know, the ability to freely reflect without any related external prompting is not routinely implemented in current models, but should (and certainly will) be considered as a challenge for future software architectures. It may be that this would be the ultimate way to reveal a clear distinction between deterministic and quantum-random systems and to provide either an ultimate evidence, or indication of the contrary.

As the proposed experiment may seem challenging to implement, and in order to quickly test our proposal, it may not at all be necessary to use very large-scale brain-like systems and thus to limit oneself to digital neural architectures, since many primitive yet living systems do not have neurons at all. At the very least, we would only need a sufficiently complex dynamical structure with a close connection to the 'physical' world to allow some kind of interaction with it, whose behaviour can be influenced at key points by natural physical random processes at the quantum level, and whose response to external stimuli can be compared with corresponding mathematical software simulations based on already known physical laws. In principle, any highly complex chaotic or near-chaotic

physical system can be considered, provided that its unpredictability can ultimately be traced back to quantum uncertainty, which can include biological but also even purely mechanical systems.

3.3. A Thermodynamic Consideration

Let us assume that we had implemented such a complex network with QRNGs whose performance outperformed that of its PRNG-based counterpart. If we were to statistically analyse the random-number streams generated in both cases during a single experiment, we would probably not find any significant difference between them, as their statistics would still conform to the statistical expectations for a single experiment according to the laws of known physics. However, over a longer period of time, certain differences or even patterns should emerge that deviate from these expectations, suggesting some kind of ordering phenomenon in the QRNGs network. This argument could, of course, be used to argue that the proposed experiment is doomed to failure from the outset because it seems to contradict the second law of thermodynamics. According to this law, the statistically most probable states must be assumed in the long term, which seems to be at odds with any principle of emerging order. However, this objection can be easily countered by the fact that local ordering phenomena, such as the formation of complex life forms, are permitted as long as the total entropy of the universe does not decrease. Since artificial complex networks do not emit any material metabolic products that enter their entropy balance, such an order would necessarily have to be accompanied by additional irreversible heat dissipation to the environment and thus increased energy consumption, which might even be measurable, and should ultimately lead to an increase of the total entropy.

3.4. Quantum Coherence

As stated in our working hypothesis, our proposal does not require a state of macroscopic quantum coherence. If we really want to clearly establish a difference between the use of PRNGs and QRNGs beyond any doubt and without adding any further complications within that hypothesis, we should design the experiment in such a way that the formation of a stable, macroscopically entangled coherent quantum-mechanical state involving the quantum nature of the QRNGs can at first be ruled out. The formation of such a state and its consequences would in themselves be highly attractive topics for another experiment, but it would not only be extremely challenging to realize it on a large scale and at ambient temperature. For now, it also conflicts with our assumption of robustness of the proposed ordering principle, because entangled states are inherently fragile and susceptible to external disturbances. The existence of possible extended coherent states of quantum-mechanical origin has indeed been postulated to explain certain capabilities of the human brain, for example by Penrose and Hameroff (Penrose, 1989; Hameroff, 1994; Hameroff & Penrose, 1996; Penrose et al., 1997) or in Hu & Wu (2004), Fisher (2015), D'Ariano & Faggin (2022), Faggin (2023), and Liu et al. (2024), but it has also been widely and rightly questioned because of the problem of decoherence under the conditions prevailing in a living body at ambient temperature (Tegmark, 2000; Davies, 2004; Koch & Hepp, 2006). Similar arguments can be put forward for the present proposal. Although the concept described here relies heavily on consequences of the laws of quantum mechanics, it does not at all need a macroscopic quantum-mechanically coherent state. In our proposal we only require local quantum uncertainty but at many, possibly very distant key points in a complex structure. By using, for example, normal-conducting wires for the electrical interconnections in a dedicated electrical circuit, long-range quantum coherence over several of such points can be safely ruled out on the time scales and at the temperatures at which this structure is operating - a situation that is probably equivalent to that in living systems. The statistical behaviour due to local quantum uncertainty could then at first be simulated separately for each of the key points using suitable distribution functions in combination with conventional PRNGs. As there is *a priori* no reason to assume that simply replacing the PRNGs with their quantum cousins would make any difference under these circumstances, a positive result in favour of a QRNG-based system would strongly suggest an unexpected natural tendency towards some kind of order.

3.5. Cloning and the Freedom of Choice

A hypothetical clone of a complex but deterministic system - that is, an exactly identical copy containing all the information stored within it - must react to subsequent external stimuli in exactly the same way as the original. This is a direct consequence of the assumption of determinism. By contrast, clones of systems based on quantum randomness such as those that we have discussed here, have the potential to evolve independently of their originals and behave differently, even under identical external conditions. Within the constraints of their physical construction and the previous learning input, they should, like their originals, have complete freedom of choice for future actions (see Shushi (2025) for a discussion of the possibility of 'freedom of choice' in quantum systems). As outlined in the introduction to this article, many authors have previously invoked quantum uncertainty as a means of explaining the 'free will' of living beings. While our concept is in line with these proposals, there is a subtle difference to those scenarios that are based on the existence of a macroscopically coherent quantum state. Since our working hypothesis does not assume a such a state in the original system as we have described it above, cloning would be physically permissible and would not violate the 'no-cloning theorem' introduced by Wootters & Zurek (1982).

4. Concluding Remarks

We have proposed that the quantum-mechanical uncertainty principle enables a previously undiscovered principle of order in chaotic or nearly chaotic systems which cannot be explained by the known physical laws. The novel aspect of the present proposal is predicated on the assumption that it is sufficient for quantum uncertainty to be relevant at potentially well-separated localized key points, so that the existence of an extended macroscopic quantum state is not required. The specific mechanism by which this principle should operate has deliberately not been specified here, however, as it would currently only possible to make speculative statements about it. We have proposed a corresponding experiment based on current technology, in which two artificial neural networks are compared. One of them uses quantum-based random-number generators for specific tasks, while the other one relies on deterministic software-based random-number generators. A superior performance of the quantum-based version would provide substantial support for our hypothesis.

Any proposal for an experiment always involves the possibility of failure, however, which could then be regarded as a counterargument to the hypothesis put forward. Nevertheless, an experimental examination of our suggestion has the potential to provide new insights into previously unexplained properties of complex natural systems, and we have demonstrated that such testing is indeed within the reach of current technology.

At this point, it should be allowed to speculate about the consequences of a successful experiment. If no other explanations for a positive outcome could be found, an unknown law of nature or principle of order must be brought into play. According to this, only 'natural' intrinsically indeterministic complex physical systems subject to true randomness can exhibit certain ordering phenomena, while corresponding deterministic replicas cannot. Whether or not this would prove to be the manifestation of a principle of 'strong emergence', or at least a form of quantum- (Davies, 2008) or classical-randomness (Del Santo & Gisin, 2019) enabled downward causation, should then be seriously considered, as such a qualification seems appropriate. It would then be conceivable that the same principle of order that we have postulated here also applies to living organisms. However, if life were in fact driven by, or even the result of such a process in its origins, it would most probably not be possible to draw any further teleological conclusions, and questions such as whether life has a predetermined purpose for its existence would remain unanswered. Perhaps it would simply like to be part of natural systems and try to survive in them. These and related ethical considerations could remain safely sheltered in the realm of philosophy, individual faith, and religion.

At the very least, conducting experiments on this or related topics in any form, whether successful or not, can help to shed some light on an ongoing unsatisfactory situation and, in the best-case scenario, help to free the principle of emergence from its niche, where it is sometimes considered a placeholder for our ignorance and a way to avoid the hard work of finding a detailed physical clarification (Teller, 1992).

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