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, has been awaiting a generally accepted theoretical basis and respective empirical verification for decades, partly due to a lack of meaningful experiments. We therefore propose a class of experiments designed to test whether an unknown principle of order is at work in natural dynamical systems that cannot be captured by known physical laws. The working hypothesis is that the quantum mechanical uncertainty principle allows for ordering phenomena in chaotic or nearly chaotic physical systems, in the sense of a strong emergence principle, which would not be expected when systems are modelled conventionally, as several authors have already formulated in various forms. In order to account for the harsh conditions prevailing in living systems which appear to preclude fragile macroscopic quantum coherence, our hypothesis does not require such coherence at all, contrary to earlier proposals that included coherent quantum mechanical states. The key idea behind testing this bold hypothesis is to compare two virtually identical, sufficiently complex experimental setups. One setup operates with deterministic pseudo-random number generators at key sensitive points, while the other uses quantum-based physical random-number generators, the two setups being otherwise identical. Existing artificial neural networks are proposed as possible test objects for this purpose, and their overall performance under identical training conditions could 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.

Key words: 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, attempt to 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 attempts to interpret 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). Unfortunately, most corresponding scenarios that are circulating seem to be completely beyond the possibility of experimental verification.

In this short 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 such a presumed emergence can be derived with some effort from the known equations of quantum mechanics in comparatively simple, non-chaotic systems in condensed matter, with phenomena ranging from cystallization, magnetism, superfluidity and superconductivity (Anderson 1972), 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; Noble 2011; Laland et al. 2013) and even for digital computers (by Ellis and Drossel 2019), without the need to invoke quantum mechanical principles. However, this topic is highly contentious (Kim 1992; Hulswit 2005; Craver and Bechtel

2007; Haddad 2025). Many attempts have been made to discuss quantum theory and 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 mathematical concepts have sometimes even been identified as causal factors (see, e.g., Jordan 1945; Garson 1995; Beck and Eccles 1992; Hameroff 2014; Kane 2014; Bishop 2011, 2025; Jedlicka 2014; Wildman and Russell 1995; Chalmers 1996; D'Ariano and Faggin 2022; Faggin 2023). However, serious critical objections have been raised against the latter claims (Tegmark 2000; Davies 2004; Koch and Hepp 2006).

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; 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 is based on the assumption that in every natural chaotic or just sufficiently complex physical system near chaotic behaviour (defined, for example, based on 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, unnoticed 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 2014; Jedlicka 2014; Youvan 2024) or with (Polkinghorne 1995, 2009; Tracy 2000; Russell 2018; Russell et al. 2002) a metaphysical or even theological context. 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 interpeted 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 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 and Hepp 2006), while deliberately leaving open the possibility that quantum phenomena could nevertheless play a decisive role. Whether this additional law or principle can ultimately be captured theoretically and mathematically, or whether it fundamentally eludes such analysis altogether, 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 based on these data. Inspired by the internal structure of the brain, whose functioning has incidentally often been suggested to be on the verge of chaotic behaviour (Kitzbichler et al. 2009; Chialvo 2010; O'Byrne and 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 and Koistinen 1992; Welling and Teh 2011), but randomness is mostly simulated by software-based deterministic pesudo-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 are inherently deterministic and predictable, since identical initial conditions must lead to identical results, and because even pseudo-random number generators are ultimately based on deterministic algorithms.

The key idea is to replace these PRNGs with quantum-random number generators (QRNGs) (for a corresponding review, see Herrero-Collantes and 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 can remain unchanged. Such QRNGs could be based, for example, on the use of entangled photons (Bierhorst et al. 2018), or on radioactive decay (Isida and 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). 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.

For the time being, experiments with existing memristor-based networks may already provide a certain clue, as they have been reported to have the potential 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 reduced energy consumption, 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 (Herrero-Collantes and Garcia-Escartin 2017). 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. In our context, it is particularly relevant that the behaviour of the network continues to be influenced by stochastic processes even after training, for instance when generating a response to an enquiry. 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. As far as we know, the ability to freely reflect without a related external query 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 challenging as the proposed experiment may seem to implement, it may not at all be necessary to use very large-scale, close-to-brain systems for rapid testing of our proposal, since many primitive but living systems have no 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. It is therefore also not at all necessary to limit oneself to digital neural architectures. In principle, every highly complex chaotic or near-chaotic physical system could be considered, provided that its unpredictability can ultimately be traced back to quantum uncertainty.

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

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 our working 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 an entangled state and its consequences would in themselves be very 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 working hypothesis of robustness, 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 Hemroff (Penrose 1989; Penrose et al. 1997; Hameroff 1994; Hameroff and Penrose 1996) or D'Ariano and Faggin 2022; Faggin 2023, 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 and 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 simply keeping the distance between these points large enough, and using normal-conducting wires for the electrical interconnections between them, long-range quantum coherence over several of such points can be ruled out on the smallest time scales and at the temperature 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 therefore strongly suggest an unexpected natural tendency towards some kind of order.

4 Concluding remarks

At this point, it should be allowed to take the thread further and speculate about the consequences of a successful experiment (an unsuccessful experiment could, of course, be used as a counterargument against our working hypothesis). If no other explanations for a positive outcome could be found, an unknown law of nature or principle of order should be brought into play. According to this, only 'natural' intrinsically indeterministic complex physical systems subject to quantum uncertainty can exhibit certain ordering phenomenona, while corresponding deterministic replicas cannot. Whether or not this would prove to be the manifestation of a principle of 'strong emergence' should then be seriously considered, as such a qualification seems appropriate. As a by-product of our hypothesis, it also immediately follows that a clone of a complex but deterministic system - that is, an identical copy of the system, including all the information stored within it - will react to an external stimulus exactly like the original. 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. Since our working hypothesis does not assume the existence of a coherent quantum state in the original system, such cloning would be physically permissible and would not violate the “no-cloning theorem” introduced by Wootters and Zurek 1982.

Finally, it is conceivable that the same principle of order that we have postulated here would also apply to natural 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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