

Quantum will: determinism meets quantum mechanics

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Abstract

We present a brief non-technical introduction to the standing discussion on the relation between Quantum Mechanics and Determinism. Quantum Mechanics inherent randomness in the measurement process is sometimes presented as a door to explain free will. We argue against this interpretation. The possibility that Quantum Mechanics provides just an effective description of Nature which is only valid at our low-energy scales is also discussed.

1. The many faces of determinism

Was it written at the time of the Big Bang that you would now be reading these words? Is it already completely fixed the way we shall work, love and die? These questions exemplify the emotional content unavoidably attached to any profound reflection on determinism.

We may envisage a grand picture of the universe where physical laws act in a completely determined way, hence leaving no space for neither randomness, nor free will. We would then not be responsible for our wrong actions, neither for our successes, as both were set to occur before our own existence. It would make no sense to doubt about a subtle decision, given that our final choice was already fixed beforehand by the laws of Physics. At stake are the rightness of justice, the root of morality and the essence of religions. It is also under scrutiny our detailed understanding of Science and the laws that govern the universe. No question that determinism is a subtle and controversial subject, constantly revisited, that should be approached with care, respect and lack of any prejudice. What makes the debate on determinism even more appealing nowadays is the constant and unstoppable progress of Science. Biology, Chemistry and Physics are bringing new elements into the discussion, hereby forcing a new, clean start on the analysis of determinism and free will.

The discussion on determinism in the form of causality is present in the history of humanity

from its very early stages. It is arguable that all ancient cultures looked for a sequence of causal implications that end up with our reality. This chain of causes and effects needed an origin or a cyclic universe, depending on the culture. Both solutions to the initial problem of causes were often presented in poetic and allegoric terms, accepting in a veiled way their unintelligibility. Yet, causality was accepted at intermediate steps. A chain of causes and effects, with the possible inclusion of gods, described why we are hit by a storm, why a drought damages the harvest or why sins will be inexorably punished. Consequences always followed causes, and fate was inexorable and leaved no space for randomness and will.

Popular causality departs from scientific determinism in the sense that some amount of unknown elements are accepted into the game. This subtle play between the ideas of an unavoidable future and some sparse disruptive non-deterministic elements shows at the popular level the very same discussion which is at the heart of scientific progress. Determinism seems real on every experiment we perform on small controled systems, but humans remain reluctant to accept it at a large scale.

For determinism is deeply related to lack of free will. It follows from the strict acceptance of physical determinism that there is no human freedom to alter the course of events. The idea that we make a decision is just an illusion experienced by our brain. The universe proceeds as an extremely complex machine, that has no chance of choosing between options.

It is necessary to realize that the word “determinism” has different meanings depending on authors and context. Often, determinism is qualified as “causal determinism”, “theological determinism”, “biological determinism”, etc. or may turned into lines of thought such as “compatibilism”. Furthermore, determinism is often confused with predictability and the lack of determinism is associated to free will. It is fair to say that determinism offers a rich landscape for theories, beliefs, arguments and refutations for each of them.

It is thus safe to limit the present discussion to debate the implications of Quantum Mechanics on determinism, from a scientific point of view. Many readers may prefer a more philosophical, ethical or even evolutionary approach to the subject of determinism and should resort to the vast existing literature on the subject [1, 2]. On the other hand, some readers may be interested in some of the conceptual developments which are taking place in the real of Quantum Mechanics, in particular when a consistent and critical attitude is taken.

2. Complexity remains deterministic

Complexity conditions our relation to physical phenomena. We experience on a daily basis the apparent impossibility of predicting the outcome of our actions. For instance, we may stir the cream topping a cup of coffee and marvel at the changing black and white figures we have created. It looks out of question that we could predict such a detailed phenomena. Let

alone the problem of weather forecast or the crashing of a tall wave on a beach. The number of particles involved in these phenomena is enormous, so is the number of coupled equations to describe them. Complex phenomena look unpredictable to the human mind.

On the other hand, it should be clear that complexity is not related to lack of determinism. The absence of sufficient computational power to describe complex phenomena limits our capacity to predict in full detail very many macroscopic phenomena. Yet, this is a practical, not an essential obstruction to predictability. It is also an anthropomorphic way of reasoning, since we confuse determinism with human predictability. The Earth will follow a very precise path around the Sun, whether humans compute its trajectory or not. Furthermore, there is no doubt that our predictions are improving as computers get faster since the Newton laws that describe the motion of particles are well understood. It is actually a wonderful fact that the detailed understanding of Newtons deterministic laws opens the possibility for engineering, that is, for the instrumental use of such laws by humans. It is thus possible for us to tame solids and make bridges, cars or clocks. We can build skyscrapers, we can correct our vision with glasses, we can travel to the Moon. We understand the laws and exploit them.

A separate but related problem to computing the evolution of a complex system is that the precise knowledge of the correct differential equations that control a system is not enough to fully describe its evolution. Indeed, to predict how a system evolves it is also necessary to have a perfect knowledge of initial conditions. Any mistake in introducing the initial conditions of all the particles of a system may completely spoil our prediction. As a matter of fact, it is well-known that non-linear differential equations exhibit chaotic behavior. That is, small departures of a given initial condition grow into exponential differences as time evolves. No matter how precise we try to get the initial conditions, we shall always have a finite accuracy and the evolution of the system will be unpredictable at large time scales. Therefore, the evolution of chaotic systems can only be predicted in practice on a short time basis. Weather forecast is a chaotic problem. This is why it is not possible to accurately predict whether it will rain in London in a month time. We may say that chaos means that some systems need much more computational power and observational effort to be predicted than others. But, the profound issue of determinism remains unaltered. Equations are valid, initial conditions are there (whether we know them or not) and the future is completely fixed, even though humans need enormous computational efforts to read it.

The previous discussion about the essence of determinism, as oppose to the apparent stochasticity of our environment was at the heart of the original discussion by Laplace [3]. A thoughtful approach to determinism can be traced back to ancient Greece, as well as other ancient cultures. But it is Laplace the first who noted down the inexorable dictate of differential equations on the flow of events. His poetic words described past and future as present for a powerful mind that would have infinite computational power. He also argued that our

understanding of the motion of stars provides a glimpse for such an idea.

What Laplace understood is often hard to get for many people. The essence of determinism is not about complexity, lack of knowledge of initial conditions, or even the poor understanding of laws of Nature. Determinism means that there are laws that will exactly control the evolution of the universe, to every minute detail. It is irrelevant whether we can compute them or not, whether we can measure the initial conditions, even whether we know the laws at all. Humans play no role.

3. Biology and free will: the meaning of justice

The above discussion has a profound consequence on free will. Taken at face value, strict determinism of the laws of Nature leaves no space to free will. This is indeed shocking. As Einstein, we are ready to think that the moon, quite a macroscopic object, is not deciding whether to rotate around the earth or not. But it is hard to accept that neither humans have any options.

Recent progress in Molecular Biology is producing a large impact on our understanding of decision making. Some experiments show that decisions can be anticipated several seconds ahead by monitoring the chemical activity of the brain. It is then possible to envisage apparent free will as complex workings of our brains. Growing evidence shows that decisions are reduced to flows of ions, whose origin are yet to be fully understood, but might lie on the realm of Chemistry! [4, 5, 6, 7].

This discussion and its consequences have been put forward by Cashmore [8]. The understanding of biological events is currently based on three conditioning elements: Genetics, Environment and Stochasticity (often referred as GES). Note that neither Genetics nor Environment do have any bearing on the core issue of determinism. Both Genetics and Environment may bring complexity, but they follow strict causal laws. On the other hand, Stochasticity, if understood as an inherent element of randomness in Nature, would completely spoil determinism. Before analyzing Stochasticity, let us reflect on the moral debate that follows the possible reduction of free will to pure Chemistry.

Let us accept that decisions are just brain processes which can be monitored using fMRI and, furthermore, can be anticipated given our understand of chemical reactions. This implies that humans have no choices. Each decision is the result of deterministic laws, and the outcome can be anticipated provided we monitor the chemical reactions in our brain. Some subjects will behave in some way, some in others, but the differences can be predicted in advance. We may think of decision making as a magnifying process, whereby small chemical differences get enlarged to macroscopic distinct events. Our behavior, whatever complex it seems, does not involve any genuine randomness at molecular level.

This is indeed an unsettling possibility. Whether a person misbehaves or acts according to accepted moral rules would be pre-fixed. Then, we may ask what is the meaning of punishment? Why do we have prisons? Should justice consider preemptive actions against individuals who are predicted to misbehave? These moral issues have devastating effects on the organization of our society and need profound reflection. We may argue in a pragmatical way that our laws are there to make safer the life of some, given the preconditioned behavior of others. Yet, even this process of creating laws and imposing them would be part of the deterministic global evolution of the universe. Whatever scape we may try, determinism will be there to reassess that the laws of Nature are complex enough to make us feel a false sense of freedom, where there is none.

Free will may well be an illusion, but it may be a very useful one from an evolutionary point of view! This departure of the main line of discussion of free will in Neuroscience and Physics is intriguing and would need a separate discussion for itself [9].

4. Randomness does not imply will

Determinism seems to be eliminated altogether if some randomness is present in the laws of Nature. Indeed, if at any intermediate stage of a physical process there is a random event, there will be no way to determine a priori the outcome of such a process.

Randomness is then often quoted as an ingredient for free will. It should be noted that this is a very weak reasoning. Randomness lacks, by definition, any sense of will. There is no foreseeing of the future, neither intention associated to the drawing of a dice. In contrast, free will implies evaluation of options and foreseeing of the possible outcomes associated to each available choice. Free will is about consciousness, moral stands, and drive. Quite on the contrary, randomness has no will. We shall come back to this point within the realm of Quantum Mechanics later on.

At this level of the discussion it is essential to analyze very critically randomness. There are models in statistical physics that incorporate elements of randomness. But, we should be aware that these models are effective theories that were constructed to describe averages. A trivial example of this point is gambling at a roulette. We are told that a roulette has equal chances to have all possible outcomes. But it is clear that the final output is a consequence of the speed of the ball, trajectory and details of the machinery. It is so clear to the owners of the casino that they perform very strict tests on each roulette before it is used for betting. It is implicitly understood that a very detailed analysis of constituents would supersede any random description of the roulette, though the computational cost of such a step would be gigantic. As a consequence, we should be aware that not all randomness is such. We use the word random to mean that the computation of an outcome is out of our present capabilities.

Quantum Mechanics will introduce an enormous twist in this discussion.

5. Determinism goes elementary

The inevitability imposed by determinism depends on the crucial issue of having no randomness associated to the laws of Nature. This is the stochasticity part of the GES discussion. If the basic laws of Nature do present some intrinsic randomness, then, determinism is no longer ruling the world. This question is outside the realm of Biology and of Chemistry which do not deal with the laws of Nature at the most fundamental level. We need to go deeper into the key axioms of Physics.

At present we have discovered four apparently different types of interactions that control the behavior of the most elementary particles which are observed in our most powerful machines, the elementary particle colliders. These four interactions conform the so-called Standard Model and correspond to Strong interactions (described by Quantum Chromodynamics), Weak and Electromagnetic interactions (described by the Quantum Electroweak theory) and Gravitational interactions (where the best we can do nowadays is to use Einsteins General Relativity). No present experiment seems to suggest the existence of new laws, neither the failure of the Standard Model. There are, though, indications hinting at possible unification schemes of the known interactions at higher energy regimes. For instance, the Standard Model does not predict the masses of each elementary particle, neither why quarks have charges with exact fractions of the electron one. It is likely that we have a partial understanding of the laws of Nature, adequate to the scales we are able to probe. At higher energies, the laws of Physics may merge or be substituted with a more basic scheme.

It is a remarkable fact that all interactions but gravity have been understood as manifestations of the basic scheme provided by Quantum Mechanics. The basic axioms of Quantum Mechanics, namely ideas such as quantum superpositions (that follow from the Hilbert space structure for quantum states) or projection of the wave function (as a projection of the information we have on a system when a measurement is done) are routinely checked when predicting the collisions of elementary particles at large accelerators. The same quantum laws are checked daily on every experiment in many branches of Physics: nuclear physics, condensed matter physics, astrophysics, quantum optics, etc. So far, every single experiment is consistent with Quantum Mechanics. Experiments make constant progress on the understanding of the details of the forces, but do exhibit perfect agreement with the underlying structure provided by Quantum Mechanics.

It is important to emphasize that we understand the basic laws of Nature with great detail and accuracy. For instance, Quantum Electrodynamics – a piece of the Electroweak theory – sustains at large our amazing technological progress. We can master electrons to travel through circuits, jumping over transistors, to create computers, phones, or any of the

many devices that serve to ease our life. We also master photons to travel through optical fibers, coding information. Amazingly, we also master the interaction of single electrons with photons at the level of producing quantum logical gates. All of these technological marvels are originated from our understanding of the interaction between matter and light. Recent progress includes monitoring of entanglement to obtained clock with a precision of one second in the age of the universe. There seems to be no limit in the ways we shall exploit Quantum Mechanics.

6. Effective theories

Along the history of Science, many theories have superseded previous ones. Theories that were considered final were shown to only describe a part of the phenomena they were supposed to govern. A better theory would then emerge, a theory to describe a larger range of phenomena with better accuracy and, often, in a simpler way. As an example, we may recall the Ptolemaic theory describing the motion of planets. It is said that Alfonso X the Wise, King of Castile, responsible of the Alfonsine tables and founder of the Toledo School of Translators, was taught Ptolemaic theory. At his time, the motion of a few bodies was described using over 70 cycles and epicycles. The kings probably apocryphal reaction was to say that, if he were God, the theory would be simpler. As a matter of fact, Copernicus made it simpler by understanding that the natural center to view the orbits of all the planets was the Sun rather than the Earth. Later, Newton created a theory of gravity that would describe with a single equation the falling of bodies and the motion of planets. The theory was more precise, described apparently unrelated phenomena with a same law, and was aesthetically beautiful. The latter twist on gravity corresponds to Einstein's theory of General Relativity. There, a higher symmetry principle describes gravitational phenomena in a range of energies larger than Newtonian laws. We know that Einstein's General Relativity is not the ultimate formulation of gravity, since it does not accommodate quantum phenomena. String Theory is the only serious but incomplete attempt for Quantum Mechanics to encompass gravity.

The lesson to be learned from the improvement of our description of gravitational phenomena is that our knowledge should always be considered as partial and open to improvement. Our theories are just effective theories. That is, we use effective laws that describe all known phenomena within the range of experiments which are available. In the case that new phenomena prove these laws to be of limited validity, scientists would then look for an extension or recreation of a new theory, that should in turn be considered as an effective one.

The summary of the above discussion is simple: as far as we can tell Quantum Mechanics rules Nature, though we should keep our mind open to some better theory. So, there are, at least, three reasonable questions to be asked on the relation of Quantum Mechanics to determinism. First, is Quantum Mechanics deterministic? Second, can Quantum Mechanics explain free will? And third, is it possible that Quantum Mechanics may emerge from a

more fundamental and deterministic theory? We shall discuss these questions along the next sections.

7. Probabilist results of measurements in Quantum Mechanics

Quantum Mechanics establishes that the outcome of a measurement is genuinely probabilistic. Therefore, Quantum Mechanics seems to rule out determinism. To be precise, the postulates of Quantum Mechanics state that observables are related to operators in the theory, that the result of the measurement must be one of the eigenvalues of the operator, and that the actual result which is observed in an experiment will occur with a probability which is computable from the wave function that describes the system. We refer to the quantum postulate of how random outputs are computed from the state of the system as Born rules. This may sound too technical for non-experts, but the key element is that results of measurements are inherently random. To be absolutely clear, the only element which is not fully predetermined takes place at the act of performing a measurement.

It is fair to mention that the present axioms of Quantum Mechanics are not uniquely formulated. Actually, there are alternative ways to set the foundations of Quantum Mechanics which are perfectly consistent ([10]). On the other hand, it is unlikely that any of the reformulations of Quantum Mechanics that we may envisage will ever get rid of its inherent randomness. We may argue that randomness is conserved: either it is there or not. Therefore, the relation of determinism to Quantum Mechanics is at a deeper scale than the discussion made in a particular set of axioms, for the relevant fact is that Quantum Mechanics brings the ingredient of inherent randomness.

Let us emphasize again that Quantum Mechanics only brings an element on randomness when measurements are performed. Between measurements, the evolution of a quantum system is described by the Schrödinger equation, which is a deterministic differential equation for the wave function that contains the information on the system. Furthermore, measurements need an observer, that is, some part of the system is taken apart and acts as observer of the other part. This is certainly an uncomfortable setting, which has been extensively discussed. On one hand, Quantum Mechanics produces fantastic predictions but, on the other hand, our understanding of the role of the observer is distressing.

It is not easy for a scientist to accept randomness in the measurement process. Einstein's dislike for this quantum postulate is well-known. He would argue that God does not play dice in the atomic world (see for instance the wonderful exchange of letters between Einstein and Born [11]). Einstein would not accept the need to resort to a random number generator to describe Nature. Instead, he defended a local element of objective realism which prefixes the results of experiments. The discussion initiated by Einstein is a wonderful history of scientific honesty. It was much later when Bell sorted out the right way to proceed [12]. Bell realized

that local realism can be experimentally verified or disproved. The idea is that local realism can not accommodate correlations among observations at separate sites that are present in the real world. He proposed the so-called Bell inequalities that would tell apart whether our world follows the rules of local realism or those of Quantum Mechanics. Following Popper, Bell showed that classical physics can be falsified in favor of Quantum Mechanics. The first experiments by Aspect [13] showed that our world is quantum, whether we like it or not. At present, Bell inequalities are checked by freshmen students in Physics schools.

There is a recent relevant contribution to randomness in Quantum Mechanics vs. randomness in Classical Physics. The basic idea goes as follows. The question is whether it is possible to distinguish a truly random series from a deterministic series that imitates the former one? For instance, we may open a Casino and buy a random number generator to run a slot machine. Can we be certain that this machine produces a truly random series of numbers? As a matter of fact we cannot. It may happen that the machine we bought has some inner deterministic generators of numbers that simulate a random series. We could check the machine for a few millions outputs and verify that the distributions obey the expected rules of a random generator. But, then, on the opening of the Casino, the next output in the slot will be perfectly determined by the person who wrote the deterministic algorithm. The new development in this discussion is that the lack of distinguishability between true and fake randomness no longer holds in Quantum Mechanics. We can use entangled states and Bell inequalities to generate truly random numbers. This subject is subtle and is fully explained in [14]. There is yet an unsettling premise. Full quantum randomness comes at the price that experimenters must be free to choose instantly the measurement they perform. This initial randomness in the choice of measurements might be very small but not zero for quantum randomness to emerge in full glory. Let us discuss this fact in some more detail.

8. Random choice of experimental settings

Bell inequalities are at the heart of the randomness discussion as we have been arguing previously. Let us briefly recall how a Bell inequality experiment is organized. The typical experiment requires a source of pairs of particles, and each one of them flights to a different observer, usually named Alice and Bob. To analyze the properties of the state, Alice and Bob separately proceed to measure some property of the particle they have separately received. To be more concrete, let us consider the case where two photons are created with correlated polarizations and sent one to Alice, and the other to Bob. Then Alice and Bob may choose to measure the polarization of the light using polarimeters pointing in different directions. The statistics obtained when accumulating the results over very many random directions for the polarimeters turn out to be consistent with Quantum Mechanics but not with classical physics. Indeed, entangled quantum states are much more correlated than any classical state, as proven in the laboratories. These experiments allow us to rule out theories where a local element of realism describes deterministically the output of each experiment. Einstein was

wrong, but his contribution was essential to consider correlations as the figure of merit that discriminates a quantum from a classical world.

Everything seems good and fine for Quantum Mechanics. Yet, there is a small but deep caveat. All along the Bell experiment, both Alice and Bob must take the decision to point their polarimeter in some direction at the very moment they perform their measurement. So we must accept some free will on the side of Alice and Bob! If we could predetermine the polarimeters direction that Alice and bob will use, then it is possible to create a local hidden variable model, consistent with classical physics [15, 16, 17, 18].

The problem of freedom of choice for experimenters is once again showing our poor understanding of the role of the observer in Quantum Mechanics. The observer is responsible for the directions of the polarimeters, for the collapse of the wave function and for the probabilistic outcome of the experiment. In its absence everything would be described as deterministic evolution of the wave function.

9. No Quantum Will

Let us accept for the time being that Quantum Mechanics does bring unquestionable randomness. Then, we can argue that Quantum Mechanics seems to kill determinism (with the caveat that we must attribute some freedom of choice to observers). This is good news for the many people that hate the negation of free will. Nevertheless, it is unclear in which sense the measurement quantum axiom favors free will [19]. We may argue on the contrary in two different ways. First, we may consider that all the physical interactions along a decision process that takes place in our brain are described by a unitary and deterministic evolution, as dictated by the Schrödinger equation. In a decision process, no measurement would ever be made. Thus, Quantum Mechanical evolution of the whole system remains deterministic! A second counterargument of profound consequences says that true randomness is not free will. Outcomes may well follow random rules, so they are not determined, yet there is no choice to be made by any part of the quantum system. Quantum randomness follows no will.

The issue becomes now really subtle, so let us slow down and reconsider the quantum mechanical implications on determinism and free will. So far, we have enumerated a number of key ideas related to the possible absence of determinism, namely complexity and randomness, and we look for some understanding on free will. We argued previously that complexity has no bearing on determinism. Free will does correspond to the moral human appreciation of the whole problem and, as such, is the ultimate big question. Yet, Quantum Mechanics postulates do humbly discuss the role of randomness in the measurement process. Moreover, quantum randomness can only be separate from classical randomness in Bell-type settings. But then, an extra element of randomness must be conceded to observers. Altogether, Quantum Mechanics is about randomness, not free will. We argued above that randomness is

postulated for the result of quantum experiments. This leads to a peculiar conclusion. If free will is eventually emerging from Quantum Mechanics, we are forced to grant such a free will to a distribution of particles and measurements.

This latter idea is the basis for the so-called Free Will Theorem [20], and its evolved version Strong Free Will Theorem. This theorem provocatively uses the word free will for the indeterminism inherent to local quantum degrees of freedom. Based on some basic axioms (FIN, TWINS and MIN), it is proven that the outcome to local observables is not dictated by previous properties of the system. The discussion above shows clearly the delicate use of the word “free will” in the context of Quantum Mechanics. Any honest discussion about the absence of determinism in Quantum Mechanics should also include the point that randomness does not explain free will. A strong form for this comment would be to disregard as erroneous the concept of Quantum Will.

10. Quantum Mechanics as an effective theory

Many people will argue that Quantum Mechanics has opened a window for free will, given the non-deterministic postulate of measurement. Many, on the contrary, will consider that Quantum Mechanics is reinforcing the absence of free will, since evolution is deterministic and measurement is genuinely random. In the extreme case, it is possible to argue that Quantum Mechanics should be applied on the universe as a whole and, then, no observation would ever be made. What we view as an observation in our labs is nothing but a deterministic evolution within the total system. At the grand scale we are finding a familiar situation, the system may be too complex for humans to predict using Schrödinger equation, but we are certain that a unitary and deterministic evolution is taking place.

A more profound and far-reaching discussion is to consider Quantum Mechanics as an effective theory [21]. The idea was already discussed in the context of the Standard Model but now takes a new twist. We may find that the four basic interactions are just an effective way of describing Nature, and that a larger symmetry will encompass these four theories. But we may go much further away. We may find that the quantum structure underlying the Standard Model is effective! That would mean that the quantum axioms that we use are just a good approximation to a deeper organization of concepts. This is the approach to Quantum Mechanics as an effective theory suggested by G. 't Hooft [22].

The theory proposed by 't Hooft is somewhat reminiscent of the old discussion about initial conditions. A deterministic system will be fully predictable given some perfectly known initial conditions. On a twist of the above argument, 't Hooft has argued that the distribution of classical initial conditions of a cellular automata which are consistent with a given output is at the origin of using probabilities in a quantum mechanical way to describe such an automata. That is, Quantum Mechanics probabilities may only reflect the sets of classical

initial conditions which are compatible with our experiments.

The argumentation by 't Hooft links the odd understanding we have of Quantum Mechanics to the also odd understanding we have of Gravity. At present, we do not know how Gravity is realized at very high energies, that is at the Planck scale (10^{19} GeV). At those energies, Gravity must merge with Quantum Mechanics and the output is simply not known. It may happen that space and time are no longer differential manifolds, it may be the case that space and time are emerging structures from more basic ingredients. We really do not have the faintest clue. The proposal by 't Hooft argues that at the Planck scale, Nature is controlled by a deterministic theory such as cellular automata, whose elements have the Planck size. Apparent randomness is just an spurious effective description, only useful at our present low energies.

11. Conclusion

Some of the discussions we have presented can be summarized in short statements. Let us start with clearing the path from complexity:

- Complexity is irrelevant for determinism.
- Predictability or human knowledge of the laws of Nature is irrelevant for determinism.

Determinism is related to the existence of exactly obeyed laws. Whether we know them or we can compute them is not the point.

Then, a human question arises: if Nature follows deterministic evolution, is there room for free will? The answer should be “no”. It is the hands of Chemistry and Biology to clarify this fundamental issue and go ahead with systematic studies of decision making and consciousness at molecular level. It may well be the case that free will reduces to an illusion. Decision making would be a magnification process that could be predicted on a purely chemical basis, whatever complex this process may be.

Yet, are we sure that Nature follows deterministic laws? We know a fact:

- The only possible source for indeterminism in our present understanding of the laws of Nature is the measurement process in Quantum Mechanics.

This measurement process is, sadly enough, the less understood piece of Quantum Mechanics. Whether quantum randomness (Born rules) and the collapse of the wave function will stay as part of the ultimate understanding of Nature is far from obvious. In any case

- Quantum randomness follows no will.

Will implies human concepts as consciousness which are not part of the Born rule. Inherent quantum randomness rules out perfect predictability, but it gives no space for will.

The discussion of randomness in Quantum Mechanics is heavily affected by Bell inequalities and non-locality of correlations. Those are very subtle issues that may be better understood in the future. Furthermore, we should always be aware that

- Quantum Mechanics may well be an effective theory.

It is possible that Quantum Mechanics is no longer the right way to describe Nature at very high scales. If so, some quantum features as randomness could be an emerging effective description, a substitute for a deeper non-random description of Physics. It may be argued that

- Quantum Mechanics will get severely modified when merging with Gravity.

The structure of the would-be unifying theory of Quantum Gravity is simply unknown. We may argue that the ultimate theory will be purely deterministic – a theory of cellular automata – but we may also argue in the opposite direction. It is fair to accept that the hope that the main problems in Physics, namely the emergence of quantum randomness and the quantization of gravity, will be solved simultaneously is probably naive.

We may also wonder what are the coming developments in relation to determinism (it does sound funny to determine the next steps to understand determinism!). It is likely that the relevant near future investigation in the everlasting discussion on free will and determinism will be centered in the understanding of decision making at the chemical level. The systematic study of brain processes will eventually clarify to what extent will is predictable and whether consciousness is also reducible to complex chemical reactions. There is no doubt that progress in the field of Neuroscience will produce a profound reassessing of some controversial intellectual positions about determinism. In a way, we may think of the impact of fMRI experiments on free will as the equivalent of Bell inequalities on local realism. We may have strong opinions, but experiments will decide.

As a separate line of research, it is clear that we need proposing and analyzing theories that would produce Quantum Mechanics as an effective description of our world. This may be considered as too far fetched, since such theories are not likely to be falsifiable. Yet, mathematical consistency has proven an extremely powerful tool to discover the rules of Nature. More realistic progress should come from analyzing in depth the emergence of probabilistic rules in Quantum Mechanics, a subject that relates to decoherence and quantum darwinism [23].

On a personal final note, let me add that I join the group of scientists that argue that the ultimate description of Nature must arise from Arithmetics. But this is an even more profound subject that touches aesthetics and – if possible – absolute truth, for which we have no clues.

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