The Multiverse, the Initial Conditions, the Laws and, Mathematics

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Often we physicists speak liberally of reality as a common knowledge concept that we all share and agree with. This is not so. Of course each one of us has a grasp of what reality is about. Yet we hold different views on what reality means. Views that are becoming more divergent with the progress made in artificial intelligence. Thoughts on the structure of reality and a possible convergence of views quietly and persistently nag in our minds. The reason is simple: we have chosen to spend our lives in mapping reality by accumulating knowledge about nature through scientific discoveries.

The open debate Fqxi has initiated through these essays on the structure of reality and the place mathematics occupies in it, is very timely. For the first time this decade, we are in a position where the possibility of a vaster and complex cosmos - the multiverse - has not only moved firmly into the realm of scientific exploration, but can potentially be detected in our sky. Naturally the next question in line in this exploration of nature becomes: 'is the multiverse all there is to reality?'. To me (and I expect many other colleagues), the obvious answer is: 'of course not! .

In this essay, with a good dose of humility, I present my thoughts on the layers of reality, and the arguments that led me to this way of thinking. The arguments create more questions than answers. The views presented here are meant to be provocative rather than conclusive.

Thus I should start by positing what reality means to me. My understanding of reality is the state of all things and their evolution. In Plato's language: 'the being' and the 'becoming'. I understand nature and reality to mean the same thing. And I take it for granted that there is a reality out there existing independently of human observation. However, this manner of definition is too elusive. A more useful description relies on categories or layers of reality.

If I were writing this essay a decade ago I would have speculated that nature is made up of four levels, stacked one on top of the other as follows: the multiverse as the most tangible and basic bottom layer of reality; the next level above it being the set or theory of initial conditions; the realm of laws of nature above that, on the third level; and above the third level, the set of mathematical structures, axioms, relations and objects – with all of its three branches - as the ultimate layer. I suspect Galileo would have been pleased with this hierarchy. For reasons I explain below, unlike laws and mathematics which are space and time independent, the most distinct feature of the multiverse would be to have space and time as its building blocks, and all there is embedded in these spacetimes.

More recently, my views on these categories have been modified. I now think of nature as made up of two levels: the multiverse and the laws…, and perhaps a third. I find myself at a loss when trying to decipher the speculative third level, and will here try to confuse you as much as I have confused myself thinking about it.

The Multiverse

The multiverse contains all the universes, domains, matter and particles, energy and vacua, and any other object you can think of embedded in its spacetimes. In this one sentence, I have used three difficult and controversial topics that need elaboration: the multiverse; a plurality of spacetimes; and, time. Let's briefly go over these concepts [1,2].

Does the multiverse exist? I have argued for a decade that it must [1,2,3]. How else can we meaningfully ask how the initial conditions of our universe were selected from an underlying theory, if that theory does not provide an ensemble of possible initial conditions to choose from? Indeed, candidates for an underlying theory such as string theory, seem to point that way.

Hugh Everett moved the study of the multiverse from philosophy to science more than fifty years ago with the many worlds interpretation of quantum mechanics. D. Zeh and W. Zurek, through decoherence, helped us understand how to obtain classical universes from the many quantum worlds. But the truly large scale scientific investigation of the existence of a multiverse and its structure only began, aggressively, in the last decade. The first baby steps in the field have already been taken. Perhaps I am an optimist, but I do expect breakthroughs in this direction will continue and accelerate. Simply because, its time has come. Scientific progress is incremental and at this time we have reached the stage of investigation into fundamental aspects of spacetime. Three highly regarded theories of modern physics – quantum mechanics, cosmic inflation, and string theory - independently of each other, lead to the conclusion of more worlds than one, although they were neither created nor driven to do so. It is hard to accept this as a coincidence.

Clever arguments do not make the existence of the multiverse come true. As scientists, besides a good idea, we also need to test and falsify our theories. My own work on the origins of the universe from the landscape multiverse [3] and the derivation of a series of testable predictions from this theory [4], (such as the cold spot, the power asymmetry, the suppression of sigma_8 and of temperature autocorrelations), has convinced me that collecting observational evidence to infer a vaster and more complex world beyond our own universe, is within reach of current observation. This means that theories of the multiverse are part of the mainstream scientific enterprise because they can be tested. The Planck satellite experiment[6] has already detected the series of signatures I listed above to an appreciable statistical level. They are known as the anomalies in the cosmic microwave background. The upcoming new Planck data will confirm them or rule them out.

If there is a multiverse, what does it look like? Is it all part of one spacetime or, does it contain a set of many spacetimes with varying dimensions? It is too early into our collective scientific enquiry of the multiverse to provide a dichotomy of the multiverse. In its absence, a variety of spacetimes with different dimensions cannot be ruled out. In an attempt to understand this question, in [1] I proposed that we apply two principles to the multiverse :

i) the principle *of 'Domains Correlations'* as a criterion for determining the background spacetime in which the multiverse is embedded; and,

ii) the principle of *'No Perpetual Motion'* as a criterion for the parameter of time.

The first principle, 'Domains Correlations', simply states that all the domains, universes and objects in the multiverse which are correlated with our universe, must be part of the same spacetime into which our universe is embedded. The reasoning behind this statement relies on the fact that the only way we can observe the existence of other parts of the multiverse is by measuring their correlations to us. In this case, observations ensure that they share their spacetime with ours. The principle is not exhaustive. There may be domains in the multiverse that are not correlated with us but are connected to our spacetime. For this case, we will not be able to observe those parts and therefore cannot meaningfully make any statements about them. We can also consider that there may be uncorrelated sectors of the multiverse which live in their own spacetimes and are completely disconnected from ours. Thus, until we find a criterion that forbids the existence of more than one spacetime, we have to allow for a plurality of spacetimes. On the other hand, with a certain amount of confidence, we can state for the correlated domains of the multiverse, that they are embedded in the same spacetime as ours, since we can probe them via their correlation to us.

The second principle, 'No Perpetual Motion', is designed to help with the definition in the multiverse of a notoriously more difficult and delicate issue: the nature of time and its arrow. There is a problem here though: in addressing time all the way to the initial state of the universe and perhaps before, we go through the process of reverse engineering, which many examples in physics have taught us is an ill-defined procedure. A perfect case for illustrating the problem of reverse engineering is the attempt to map our present classical universe to its quantum self at infancy. Since there is no one-to-one mapping of quantum to classical solutions, then our present universe could have arisen from a variety of infant universes [7] instead of a unique origin. The latter difficulty underlines the long history of the human struggles with the nature of time and time's arrows.

I cannot do justice to a question of this magnitude in a brief essay. Those interested in more details can find them in [1, 2]. In my thinking the nature of time is closely related to the nature of information. I take the view that the parameter of time has to exist in the multiverse in a fundamental way, or else any statements about *initial conditions* or *spacetimes* would be meaningless. This parameter is different from our perception of time. I coined the parameter of time in the multiverse *'fundamental time'* in [1,2] in order to distinguish it from the locally emerging arrow of time in our universe. Then the principle of 'No perpetual motion' motion guarantees, (from a loosely speaking, global energy conservation), that the multiverse and the laws of nature are time symmetric. Based on [3,4] our universe (and many others) emerges locally from the multiverse and goes through the standard inflationary growth. The very event of the Big bang distinguishes a before and after, thus breaks the time symmetry of the multiverse only in the neighborhood of our initial state. But not globally. It follows that locally within our domain we find ourselves with an arrow of time, despite that the laws of nature transferred onto us from the multiversal origins, remain time symmetric. Due to the time symmetry of the multiverse, questions about a time ordered sequence of events are meaningless. A sequence of events is meaningful only if there is a time direction. The latter can be found within the universes emerging from the multiverse as they break the time symmetry locally. Unlike fundamental time, space and a local time's arrow emerge with the creation of the universe.

The Set of Initial Conditions

A factor that differentiates universes emerging from the multiverse, from each other, are the initial conditions they were born into. Their initial conditions together with the respective constants of nature, become the unique 'DNAs' of universes.

Normally one may think that initial conditions of the world cannot be part of the world that emerged from them at the beginning, since the initial conditions were there before the respective spacetime of the universe in question emerged from them. I will not go on through the many subtleties of this argument and its inspiration from the goal of a 'unified theory'. A beautiful description can be found in P. Davies's book 'The Mind of God' [5]. Hence this basic reasoning suffices to justify the plausibility that the theory of initial conditions could be an independent layer 'ruling over' the multiverse and deciding which universe would emerge and what characteristics it would have.

Through a counterexample taken from my theory of the origins of the universe from the landscape multiverse [3, 4], I would now like to argue that such beliefs of an independent realm of initial conditions may not be correct. In [3] I proposed to place the wavefunction of the universe on the N-vacua landscape and, through quantum cosmology, *derive the answer to the question*: 'which vacua on the landscape is the more likely initial state from which our universe arose ?' . Normally the wavefunction would operate on a mini-superspace defined by the 3-geometries and the collective variables labelling the landscape vacua – the string moduli. With my collaborator R. Holman, we took decoherence into account in this proposal. Decoherence was triggered by an environment made up of an infinite number of quantum fluctuations. The (not so) mini-superspace, which included fluctuations, became of infinite dimension. The backreaction of fluctuations onto the system resulted in a Master Equation [3] operating on an infinite midi-superspace, which replaced the Wheeler De Witt equation operating on a finite minisuperspace. Existence of solutions for the wavefunctional of the universe obtained from the Master Equation, were determined by an interplay of the strength of fluctuations – which can be viewed as a collection of massive particles - relative to the energy of the landscape vacua which became the energy of the Big Bang. Wavefunctions that (Anderson) localized on high energy vacua on the landscape, were able to survive the backreaction of 'matter' and continue to grow and give rise to a classical universe. Wavefunctions localized on low energy vacua became terminal and a classical universe could not be obtained from them.

Through this work, we learned: firstly that only high energy initial state can give rise to a universe; and secondly, that the selection of the initial state for the 'survivor' universes is not a priori given, neither is it based on unknown symmetries of nature. In this theory, the selection criterion of initial states emerged dynamically from the quantum dynamics of gravity (energy of vacua) versus matter (massive fluctuations). Here is an example where postulating an independent level for the set of initial conditions is not necessary. It illustrates how the dynamically emerging initial conditions are part of the fabric of the multiverse instead of being postulated over it.

Laws

Wherever the realm of initial conditions resides, it does not and cannot address the question of *how* a universe emerges and *why*. This honor is reserved for the laws of nature. I include axiomatic and empirical laws in the set of laws of nature.

And where do laws reside? For the sake of argument, suppose the set of laws of nature is part of the basic layer - the multiverse. In this case we could think of the multiverse itself as a stupendous Turing machine since it is able to perform operations. If laws were part of the multiversal realm, then according to Frege's logic inference and Gödel's incompleteness theorem we may never be able to prove their validity. Because this type of structure would either be incomplete or it would be inconsistent. By definition if a law is false then it cannot be a law. Besides, we would run the risk that the 'stupendous Turing machine' would itself crash while inferring the validity of an axiom in it. Gödel's incompleteness theorem thus places us in an impossible situation where, there is no way to distinguish a true law from a fake and the whole structure of reality built this way could not be simultaneously complete and consistent. Not an appealing notion.

Thanks to the powerful implications of Frege, Gödel and Turing's work, I am strongly inclined to think that laws of nature occupy a realm of their own, above the basic level taken by the multiverse and initial conditions. Space and time are not part of this layer.

So far, I have argued that the previous three levels, can be reduced to only two: the realm of spacetimes with all it embeds, a.k.a the multiverse, and the level for the set of laws of nature.

Mathematics

What about the role of mathematics? We admittedly are in awe of the level of rigour and razor sharp logic that mathematics introduces to all of science. We are intrinsically conditioned to think of laws of nature written in a mathematical language. Practising science without mathematics is inconceivable to us. Mathematics gives a set of abstract symbols and relations, which when combined, produce an infinity of objects. We are familiar with some of these objects. We can imagine some other objects. Yet there may be an infinite number of objects which we have neither imagined nor are familiar with so far.

Our collective experience and the infinite set of objects mathematics contains, led me to believe, like many others in the community, that mathematics is the ultimate level of reality.

But, subtleties already lurking in the above paragraphs, and the work of Cantor, challenged this view and triggered my change of mind. The features that changed my view of mathematics as the ultimate building block of reality are: the problem of infinities, and the role of mathematics as a language in which laws are written.

An analogous case can be found in the role language plays on the human mind. Questions such as: 'can the human mind operate without a language?', seem to already be settled with the reply: 'yes'. There still exist tribes in our planet whose members communicate with each other without language.

Let us then ask a similar question where laws and mathematics are concerned, namely: '*can nature contain laws and axioms that cannot be written in a mathematical language, yet still exist?*' The existence of a law that cannot be written in mathematics, (if such a law does exist), could be settled by other means, for example empirically by observation even if it were impossible to write it down as an equation or subject it to logical inference. Consider an axiom of the kind 'consciousness exists'. Empirically we know this to be true in at least our universe, and therefore in nature. But we cannot infer it from mathematical logic or write it down as an equation yet. The day science is far advanced to address why consciousness exists, will be the day we learn if it can written in a mathematical language. At present, a 'yes' and a 'no' seem equally likely.

I don't have a definite answer for this question. But I believe hints of the answer are related to the second feature*, infinities* in mathematics. Cantor aimed to compare and categorize the class of infinities, which by itself is an infinite set. Yet, definitely not due to a lack of talent, he struggled with questions like: is there an infinity which is larger than the infinity of whole numbers, but smaller than the infinite set of real numbers?' He had equally excellent proofs for both answers: 'yes' and 'no'. And the real answer is indeed: 'yes' and 'no'. How can this be given the rigour of mathematical proof? Well, the reason why both answers are correct, reveals a crucial fact about mathematics: it is limited! While we have no reason to believe that the set of laws must be limited, *thanks to Cantor we know the set of mathematical objects, although infinite, is limited.* We do not know if the set of laws is a larger infinity than the set of mathematical objects. Yet we can probe this issue by raising questions of the kind: can we have laws that are not written in a mathematical language? The puzzle that bothered Cantor all his life and that ultimately demonstrated math is limited, and, the problems of incompleteness and inconsistency presented by Gödel, make it feasible that the set of laws is a larger infinity than the set of mathematical objects.

This line of reasoning would make me willing to consider math as a subset in the realm of laws, rather than place it on a realm above that of laws. In this case, within the realm of laws, math would be the language that binds the laws and their distribution into a coherent map. Were this the case, then it becomes unlikely that virtual reality could compete with reality, and that artificial intelligence could substitute human mind. Ultimately machines would run into problems similar to Cantor's continuum hypothesis and test their own limit. Nature would not.

We are now left with only two levels, the multiverse and the laws.

I have briefly talked about how universes emerge out of the multiverse and how their initial state is selected dynamically [3,4]. We also expect on general grounds that the realm of laws and mathematics is highly complex. We are familiar with chaos, critical phenomena and phase transitions, that in (random or organized) highly complex systems can potentially have a new phase arise spontaneously. Can phenomena such as spontaneous phase transitions arise out of complexity in the set of laws? If yes, what does this new phase contain and what does it look like? At this stage I am at a complete loss of words and further speculation. But if there is such a process occurring and a new phase, a new level of organization arises spontaneously out of the complexity of the realm of laws, then I am tempted to reserve a third level for this completely unidentified and unexplored meta structure.

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