A Modest Proposal

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Abstract

In the search for a quantum theory of gravity, it is commonly accepted that the universe must be either digital or analog. Here, I wish to suggest a possible third way: that spacetime may be *both* discrete and continuous, in the same sense that light is neither particle nor wave, but occupies a dualistic middle ground. I examine three nascent theories of quantum gravity, and posit that, in each case, a dualistic approach has the potential to resolve open questions or, at least, stimulate fresh thinking on old questions. The conventional approaches may yet be proven to work, but that should not imply that other alternatives may not deserve consideration.

1 Introduction

Ultimately, the grand aim of science is to explain the fundamental characteristics of reality, independent of human experience. Perhaps it is nothing more than the conceit common to every century in history, but it seems that now, more than ever, this grand aim is almost within reach. Specifically, abstract physics has brought us to the point at which we can claim to be making meaningful hypotheses about the nature of reality itself. The great achievements of twentieth century physics were the development of quantum mechanics and the General Theory of Relativity (GTR). Together, they have the capacity to explain the universe on all scales. Ironically, however, the great challenge of the twenty-first century may be to resolve their mutual incompatibility. Each theory represents a different and contradictory picture of the fabric of reality: the smooth continuum of analog GTR, as against the discrete, digitalized world of quantum mechanics. Thus, in order to answer the question of whether reality is analog or digital, it is necessary to examine how current physics attempts to both understand the cosmos and to unite these two great, seemingly contradictory achievements. Here, 'analog' and 'digital' will be taken to correspond to continuous and discrete phenomena, respectively.

The concepts of 'analog' and 'digital' represent a binary split in the ways in which humans tend to envisage the basic character of reality and the universe. Within each term lie foundational assumptions regarding the nature of causality, time, and more concrete physical processes, and each has shown itself to be capable of explaining certain observations. Here, however, I argue that the universe may be neither completely analog nor digital, and that it may make greater philosophical and physical sense to expand upon existing notions of duality. That is, we have often found that the actual universe does not necessarily comply with our assumptions. The idea of a completely analog or digital reality may be intuitively attractive, as our quotidian experience is that phenomena tend to be one or the other (such as analog vs digital sound recording processes.) Nevertheless, we must not forget that there are precedents for departing from 'common sense' and taking observation almost at face value. Both the electromagnetic theory of light and the concept of wave-particle duality represented radical re-evaluations of the central tenets of their respective areas of scientific inquiry. Both times, scientists were forced by the weight of evidence to accept that apparently irreconcilable truths could, in fact, be complementary, rather than contradictory. Whilst a similar approach may not be successful in resolving the quantum gravity dilemma, it is an avenue of investigation that should not be dismissed. String theory itself involves many recognized 'dualities', such as the transformations between the five different versions of the theory. In this review, the 'duality' discussed will only refer to that between digital and analog spacetime. [1] There are many possible forms for such a dualistic physics to take. I envision a greater focus on a mathematical construct that would, perhaps, smooth the interface between the two concepts, rather than prioritising one over the other on all scales.

From the crowded field of candidate quantum gravity theories, two clear front-runners have emerged: string theory and loop quantum gravity (LQG.) Interestingly, as well as moving in different 'directions' (string theory attempts to generalize particle physics, whereas LQG is an attempt at a quantization of GTR), they exemplify contrasting views of the nature of reality. The background dependence of string theory (of which more later) naturally implies an analog spacetime (despite the fact that string theory is itself a quantum theory), as opposed to the unambiguously digital universe of LQG. Accordingly, the respective advances and remaining open questions in each theory provide potential case studies for the effectiveness of a dualistic solution in resolving problems which arise under both fundamental assumptions.

I also examine a third research program: that involving causal sets. Whilst it lacks the pace and size of both the string and loop programs, it has one important quality: that it addresses directly the question of how the apparently completely analog world of GTR can be made to coexist with the digital reality of quantum mechanics. I see it as almost an attempt at dualism (despite some claims to the contrary), albeit in a mathematical context alien to that of the first two theories. As such, it can be used to demonstrate the comparative strengths and weaknesses of one possible dualistic approach. Of course, just as a view of reality as digital does not necessarily imply adherence to LQG, causal sets are not the only way in which dualism could be reasonably explored.

So far, no research program has been able to produce a completely coherent theory of quantum gravity. Of course, this does not mean that existing programs necessarily lack the capacity to do so in the future. However, that the continued efforts of dedicated theorists over several decades have been unable to result in success points to a possible need for a new conceptual approach to the problem. It is my contention that a potential way forward would be to follow in the steps of Copenhagen, and attempt new physics under the assumption that, like waves and particles, digital and analog realities may simply be patterns of behavior exhibited under certain conditions. That is not to say that the project of unification should be abandoned. Rather, the focus could reasonably be shifted to developing ways for a continuous reality to emerge naturally from a discrete one (and *vice versa*), instead of attempting to make either categorization fit for all scenarios. I consider that, in order to judge the success of a scientific theory, two primary qualities must be evaluated: the 'paradigm', or theoretical framework of the hypothesis; and its agreement with experiment and observation. The former guards against the traps of models such as the Ptolemaic epicycles, which were introduced *ad hoc*, without solid theoretical foundation. The latter tethers scientific speculation to its ultimate goal: that of explaining reality as it *is*, rather than as we might imagine or wish it to be. With these two conditions in mind, I shall review the three theories outlined above.

2 History and Precedent

There are several key ways in which the dilemma currently facing quantum gravity theorists is analogous to that confronted by the pioneers the study of electricity and magnetism in the 19th century and, even more strikingly, those scientists in the 20th century investigating the seemingly paradoxical behavior of light. Whilst there are, of course, certain differences in the precise conditions of each of the three situations (the crises in the study of electromagnetism, light, and quantum gravity), they share at least one important feature: a paradigm shift was needed in order to resolve seemingly insurmountable difficulties.

The electromagnetic theory of light grew out of two separate research programs that, at first, did not appear to be linked, namely those investigating magnetism and electricity. It took the chance observation of electromagnetic induction by Oersted in 1820 for the connections between the two, seemingly separate, phenomena to become apparent. Further, it was Maxwell in 1873 who formulated the modern theory of electromagnetism, establishing that electricity and magnetism were, in fact, different aspects of the same fundamental force. Even though two physical processes initially appear to be disconnected, they may be closely related or, in fact, the same.[2]

Whilst the seeds of the Copenhagen interpretation lay in the work of theorists such as Maxwell, as well as in the existing problems with the luminiferous ether model, the crisis in wave-based physics truly began with investigation of blackbody radiation. The details of the story are familiar, so I will sketch them only briefly. When applied to a body that absorbed all incident electromagnetic radiation (hence *black*), adherence to the laws of classical (wave) physics was revealed to result in a 'catastrophe': when at thermal equilibrium, the blackbody would emit radiation with infinite power, clearly violating the laws of conservation (and the evidence of the senses!) Planck and, later, Einstein, contributed to the development of a solution: that light could exist in the form of discrete 'bundles', or photons. [3] Despite the success of this model in agreeing with experiment, it directly conflicted with the results of another, equally successful model: electromagnetic *waves* seemed the only viable way to explain, say, Young's double-slit experiment, in which light was shown to be analogous to waves in any other material.

The solution to the wave/particle dilemma to which most (but, it must be admitted, not all) physicists subscribe is the Copenhagen interpretation. Crucially, this was not an attempt to find a mathematical unification of both theories. Rather, it was a method of describing systems so as to accommodate both complementary facets of their nature: wave and particle. Neither is privileged, nor deemed to be incorrect. Significantly, the wave and particle expressions were not treated as completely separate. Elements of quantum theory are present in the formulation of probability wavefunctions, and it is accepted that measuring instruments, whilst being inherently classical, can measure particle phenomena. Nevertheless, the distinct properties of waves and particles were preserved, in that a given body cannot exhibit the behavior of both at the same time. Despite criticism from Einstein, Podolsky, Rosen and others, the dualistic theory of matter has consistently been confirmed by experiment. [3]

There are obvious parallels, here, with GTR and quantum mechanics. Both theories are internally consistent, founded on a secure mathematical framework, make predictions and agree with experiment, and both theories appear to be mutually incompatible. Physical conclusions cannot be drawn simply on the basis of historical precedent. Nevertheless, such examples can be illustrative of how physicists may escape a seeming impasse by making a radical departure from previous assumptions. In addition, such case studies demonstrate that solutions that do not conform to the principles of human physical intuition may nevertheless be reflective of reality. By 'dualistic solutions', I do not advocate simple acceptance that one kind of physics works for large scales, another for small, and that the two may never be brought into agreement. Rather, I suggest that innovations similar to that of wave packets (a blend of wave and particle), and theoretical developments such as uncertainty principles, and have the potential to engender progress. Henceforth, these will be the possible solutions considered.

3 String Theory

The candidate theory of quantum gravity endowed with the grandest scope and greatest mathematical beauty is commonly accepted to be string theory or, rather, M-theory (the 'meta-theory' in which the five known versions of string theory are seen as distinguished points in eleven-dimensional spacetime.) The essential proposition of string theory is an upward shift in dimensions. That is, particles, instead of being 0-dimensional points, are treated as quantised modes of 1-dimensional oscillating strings. Extending the principles of Feynman diagrams, in which particle interactions are represented by vertices between worldlines, the strings vibrate at different frequencies so as to produce particle properties such as mass, charge and spin.

String theory originated from the dual resonance model, which was an early attempt to explain strong force interactions. In the 1970s, however, it was recognized as being a potential theory of gravity, rather than of hadrons (now understood to be subatomic particles composed of quarks). With the addition of supersymmetry - the theory that, for every boson (subatomic particles that obey Bose-Einstein statistics, including force carrier particles), there exists a supersymmetric, fermionic partner (a particle obeying Fermi-Dirac statistics) - five separate, although related, (super)string theories were formulated. Indeed, these were the *only* consistent theories of this type, implying that supersymmetry is a necessary component of any string theory. [4] It was Edward Witten who posited that these theories were the set of solutions to a broader theory, dubbed M-theory. As an example, one attempt at M-theory is based upon the idea that the universe was comprised of 2-dimensional membranes, or 'branes', oscillating in 11-dimensional spacetime. The original 1-dimensional particle strings can be seen as slices of this higher brane. [5]

Despite its exotic nature, string theory has had some remarkable successes. In particular, string theory can reproduce the Hawking radiation spectrum, including grey body factors, for extremal black holes (those whose charges are equal to their masses). In addition, several versions of the theory are encouragingly compatible with the standard model of particle physics. Nevertheless, there are some crucial problems with the theory that are, as yet, unresolved.

Leaving aside some of the more abstruse mathematical difficulties, I wish to examine the concern that string theory is background dependent, as a case study for whether dualistic, analog-and-digital spacetime has the potential to resolve existing problems in quantum gravity. Strings, and even branes, are seen as objects on a background spacetime, which is not fully treated by the theory. Background dependence is problematic on several levels. Firstly, GTR is background *in*dependent, so any contender quantum gravity theory lacking this feature cannot encompass the full depth of GTR, and cannot therefore be complete. Secondly, even disregarding comparison with GTR, a 'Theory of Everything' which requires a separate spacetime background (not explained by the theory) in order to describe reality, could not really cover 'Everything' after all! [6]

It is possible that a non-perturbative, or background independent, formulation of M-theory (that is, a version of the theory incorporating matter, forces, and spacetime) may resolve the difficulty. Nevertheless, the strings themselves have so far been most satisfactorily explained through perturbation theory, which is an approach to physical calculations in which phenomena are represented in terms of small deviations from a stable state. [7]

Let us assume, for the sake of argument, that (non-perturbative) M-theory may resolve the difficulty. The fundamental proposition of string theory is that particle properties are expressions of modal string vibration. This is an inherently digital system, in that the strings may only take a certain set of allowed frequency values, corresponding to respective particle properties. A background independent string theory would integrate this model of digitally vibrating strings with an analog spacetime. It is possible that either the concept of digital strings or analog spacetime will prove to require modification. However, it is also possible that M-theory may be, at least in some sense, dualistic; that is, a mathematical unification of strings and background into one reality that is simultaneously digital and analog.

4 Loop Quantum Gravity

Loop quantum gravity takes a different approach from that of string theory. Rather than attempting to be a Theory of Everything, LQG is 'simply' a theory of quantum gravity. Unlike string theory, LQG is naturally background independent. This is a direct result of its roots in GTR: it is a theory of spacetime, rather than of particle interactions on a background. Consequently, the natural position of LQG in the debate between digital and analog reality is clear: space is composed of discrete quanta, and can therefore be described as digital. [9] This is a view with a weight of supporting mathematical evidence, based around the the concept of spin foam models. Within these models, motion and space are represented as a system of nodes and lines bestowing area and volume. These nodes and lines form polyhedra, whose evolution in time is a graphical representation of distortions of spacetime. [10] The picture presented by LQG is akin to that of a piece of cloth: when viewed from a distance, the surface is smooth and continuous but, upon closer inspection, it reveals itself to be composed of discontinuous threads.

An examination of the deep mathematics at the heart of the theory, much of which is still being developed, is outside the scope of this article. However, an important open question in LQG is whether it can reproduce continuum physics at the low energy limit. When viewed from afar, do the individual threads really make up a carpet? Here, then, is the heart of the question: in order to reproduce the results of GTR, is it helpful to view continuum physics as an approximation to small-scale, digital reality, or to accept that it is something else, entirely? The former view is well represented in the literature[10], but the latter is also worth examining.

GTR is, by any measure, a very successful theory. In addition to possessing a strong theoretical basis, it has agreed extremely well with even the most rigorous and demanding physical tests (the same can be said of quantum mechanics.) That is not to suggest that it cannot be proven to be incorrect, but rather that declaring GTR to be merely an approximation would require a heavy weight of evidence, in order to validly challenge previous work: the strength of an argument must be equal to the size of its claim. Further, the detailed mathematics of the reproduction of semi-classical limit is not yet clear. [11] That is, classical physics has not yet been shown to emerge from the quantized world of LQG, even as a simple approximation. Perhaps the required transformation may be perfected in the future but, as yet, there is little concrete, physical evidence to suggest that GTR merits significant modification. A dualistic approach would avoid the need for this, by finding a different kind of interface between the classical and quantum worlds, analogous to quantum wavepackets.

The essential feature of GTR is its general spacetime covariance: its symmetry under arbitrary coordinate transformations (diffeomorphisms) in both space *and time*. This means that, say, Galileo's experiments with gravity would give the same results anywhere, and at any time, in the universe (provided, of course, we could replicate the strength of Earth's gravity, the height of the tower, etc.) That is, a ball falling from a certain height under the influence of a certain gravitational field will *always* take the same amount of time to reach the ground, irrespective of location in time or space. The addition of time diffeomorphisms is especially important, and makes the theory particularly difficult to quantize.[8] For example, it implies that GTR obeys the laws of causality, and that the same process, repeated, would have the same result (dropping a ball will lead to it landing on the ground), whereas, in the chaotic quantum world, this is not the case (the ball has a small, but non-negligible, probability of floating). In order to qualify as a successful theory of quantum gravity, LQG must be able to accommodate the spacetime covariance of GTR. In canonical (symmetrical) GTR, this covariance is encoded in the constraint algebra, which relates to conditions placed upon solutions to the equations of the theory. In LQG, the problem arises with the introduction of the Hamiltonian constraint, which places conditions on the total energy of the (quantum) system. Energy transfer is closely related to the behavior of time within a system (via entropy), and as yet there is no rigorously derived Hamiltonian constraint for LQG. The consequence of this seemingly abstract theoretical problem is that LQG cannot yet be made spacetime covariant, and thus lacks one of the most important features of a successful theory of quantum gravity. [12]

An important aspect of this open question is that it cannot be resolved by treating GTR as merely an approximation. A system that does not appear spacetime covariant in the quantum realm has not yet been shown to appear so on large scales. [13] Thus, two available options are: the discovery of an adequate Hamiltonian constraint; or an attempt at a dualistic solution. The former is basically a continuation of the current research program, and may yet prove fruitful. However, the fact that it has not yet yielded an acceptable solution means that alternatives may be helpfully considered. A dualistic solution to the Hamiltonian problem would, admittedly, also be difficult to formulate. However, it would remove the need to develop an entirely new Hamiltonian, and would shift the focus to how to introduce the GTR Hamiltonian into LQG - potentially a simpler problem.

5 Causal Sets

Although most attention is directed towards the two main candidate quantum gravity theories outlined above, there are other research programs that do not deserve to be ignored simply because they are out of the mainstream. One of these is the causal set program, which extends the concept that, if the past can be mapped directly onto the future (i.e. for every event there is one past and one future), then causality will be preserved. Integral to this approach is the assumption of discrete, digital spacetime, in which events are related by a partial order (a formalized, mathematical representation of causality.) Intriguingly, the focus of the causal set approach (CSA) is its emphasis on the fourth dimension: it treats events as, in some ways, being more fundamental than spacetime, which is seen as primarily a vehicle for events to occur. [14]

An interesting aspect of CSA is that it *directly* addresses the question of whether the GTR manifold (the four-dimensional 'shape' that determines the geometry of the universe) should be considered an approximation to digital reality, or taken at face value as an accurate description of spacetime. Thus, in CSA, the point at which the analog and digital interact is given greater attention. Given that the aim of CSA is to embed a causal set into a spacetime manifold, it is important to consider how the analog and digital interact, and which causal sets can be embedded into which manifolds. By "embedding a causal set into a manifold", theorists are essentially discussing the possibility of different 'histories' within the universe, or different ways in which time could have run and developed. An examination of this approach reveals that it is, in fact, inherently dualistic. There is no attempt to 'smooth over' the interface between set and manifold: spacetime itself is seen as digital (a quantised causal set), the background manifold is considered to be continuous, and not as an approximation. Further, the causal set approach is background independent, despite its reliance on a "background manifold". Unlike string theory, the manifold plays a crucial, dynamic role in determining the nature of the history that takes places upon it. [14]

Although causal sets remain on the fringe of quantum gravity research, at least in comparison to string theory and LQG, they provide an example of how dualistic models can be made to work, and can resolve some of the problems faced by other candidate theories. There are, of course, many open questions in causal set theory (such as whether it can be made to reproduce physical spacetime), but its mathematical progress is encouraging.

6 Conclusion

It would be unwise to make premature predictions regarding the characteristics of the theory of quantum gravity, given that it is not yet fully developed. It is true that there have been many advances in recent decades, and that both the major research programs have definite strengths. However, if the approaches to date have not yet succeeded, it may be time to at least consider reasons why this is so. One of those may be that it is the assumptions at the heart of the theories, rather than the particulars of their mathematics, which may be holding them back.

String theory has made undeniable progress, not only in force unification, but also in the explanation of the Standard Model of particle physics, and the expansion of horizons of theoretical physics. Its successful treatment of black holes is remarkable, as is its potential to explain all of physics. However, the crucial problem of background dependence would, perhaps most intuitively, be resolved by integrating the quantized particle methods of string theory with continuous spacetime, thus resulting in a dualistic M-theory.

Two major open problems in LQG are the recovery of classical physics in the low energy limit and the introduction of the Hamiltonian constraint. Both have the possibility to be at least partially resolved by dualistic approaches. The former may be resolved through the abandonment of the assumption that GTR must be modified, or treated as an approximation, in order to be compatible with LQG. Many of the mathematical difficulties found in attempting to produce GTR directly from the digitized equations would be simplified by accepting that the universe may, in fact, be truly analog on some scales, as this would naturally yield the low energy limit. Further, the need to develop a specific Hamiltonian for LQG, which is proving to be extremely difficult, is a direct result of the assumption that space must be completely discrete. It may be possible that the resolution lies in a new, dualistic research program.

This could be considered an unjustified departure from physical orthodoxy. However, the mathematical successes of the dualistic causal set program demonstrate that such an approach is not entirely without theoretical merit or precedent. Physics has shown itself to be almost capable of answering our most fundamental questions about the nature of reality: when conventional methods have not led to success, it may be time to depart from conventional practice. Perhaps reality *is* easy to visualize, and is either analog or digital. Nevertheless, perhaps it is not. It may be far more difficult for us to conceive of because, like light, it is a blend of two, seemingly irreconcilable, concepts.

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