SPACE, TIME, AND (how they) MATTER: A Discussion of Some Metaphysical Insights about the Nature of Space and Time Provided by Our Best Fundamental Physical Theories

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Abstract

This paper is a brief (and hopelessly incomplete) non-standard introduction to the philosophy of space and time. It is an introduction because I plan to give an overview of what I consider some of the main questions about space and time: Is space a substance over and above matter? How many dimensions does it have? Is space-time fundamental or emergent? Does time have a direction? Does time even exist? Nonetheless, this introduction is not standard because I conclude the discussion by presenting the material with an original spin, guided by a particular understanding of fundamental physical theories, the so-called primitive ontology approach.

1. Introduction

Scientific realists believe that our best scientific theories could be used as reliable guides to understand what the world is like. First, they tell us about the nature of matter: for instance, matter can be made of particles, or two-dimensional strings, or continuous fields. In addition, whatever matter fundamentally is, it seems there is matter *in* space, which moves *in* time. The topic of this paper is what our best physical theories tell us about the nature of space and time.

I will start in the next section with the traditional debate concerning the question of whether space is itself a substance or not. Section 3 is focused instead on the question of the dimensionality of space in light of string theory and quantum mechanics. I will then continue in Section 4 explaining how quantum gravity may suggest that space and time are not fundamental but emergent. In section 5, I discuss whether physical theories successfully suggest the passage of time is illusory, and whether change does not exist. I conclude the discussion illustrating how the primitive ontology approach to fundamental physical theory can shed some new light on to the issues discussed.

2. Is Space a Substance?

Material things seems to be arranged in space, but is that true? There are two positions: either there is space, and objects are arranged within it; or there is no space over and above the spatial relations between the objects. The first position, known as substantivalism, was first suggested by Newton and was heavily criticized by Leibniz. According to Leibniz, there is no absolute 'here' or 'there,' 'now' or 'then;' rather there are just spatial and temporal relations between material objects. This view is known as relationism: all motion is relative motion.

2.1. Arguments for Substantivalism

Newton's suggestion is that space and time are absolute, immutable quantities which provide the fundamental arena in which matter can exist and evolve. This view has been developed in the framework of classical (or Newtonian) mechanics but can also be generalized to other theories. Newton provided an argument, the bucket argument, to show that only substantivalism is able to account for certain observations. Consider a bucket of water hanged with a winded up rope. When the rope is let go and the bucket starts to rotate, the water's surface becomes concave. Why? The substantivalist's response is that it is accelerating with respect to absolute space. Instead, on the relationist view there has to be a body with respect to which the water will rotate, and the problem is that there is no such body: it cannot be the bucket itself (the water and the bucket are at rest with one another at the end when the water is concave, but also at the beginning when the water was not concave; the water was in motion relative to the bucket in the intermediate state, yet the water was not concave); it cannot be motion with respect of the walls of the room ("put the walls on wheels and spin them around a bucket of water, and the water will not go concave" [Dasgupta 2015]).

2.2. Arguments against Substantivalism

Leibniz argued against substantivalism, suggesting that it is fundamentally problematic. Leibniz observes that a 'shifted' world, a world just like ours except that all matter is shifted in another place in absolute space without any change in the relations of one object to another, will count as a different world for the substantivalist, even if the two worlds do not differ in their fundamental properties. The same is true for a 'boosted' world, a world just like ours except that all matter is drifting through space at uniform velocity. Leibniz concludes that this is absurd because it violates either the principle of sufficient reason or the principle of identity of indiscernibles, namely that God had a reason to create the world exactly as it is, and that indiscernible possibilities are identical.

One can easily resist these arguments denying such principles are true, but there is a stronger argument against substantivalism based on symmetries that generalizes to theories other than Newtonian mechanics, as we will see. Translations and rotations are symmetry of shape: they are transformations that leave the shape of an object the same. Similarly, it is argued that symmetries of a law are transformations that preserve that law. In classical mechanics, shifts and boosts are symmetries: if w_1 is a classical world, then a world w_2 shifted 5 feet to the left will also be classical; likewise, a boosted world w_3. By definition, F is an invariant feature of a law if any two worlds related by a symmetry of the law agree on the values of F [Dasgupta 2015]. In classical mechanics, only relative (as opposed to absolute) distances and velocities are invariant: w_1, w_2 and w_3 are governed by the same laws, regardless of their absolute position and absolute velocity. This suggests that (all things being equal) invariant features are the only ones we should think of as real: if F is not preserved in symmetries, then there are systematic ways to alter its values and yet preserve the law. Tus, they 'do not make any difference' in the law, they are redundant or irrelevant [North 2009], [Baker 2010]. In addition (or alternatively), non-invariant features are by definition undetectable, and thus we do not have any reason to believe they exist [Dasgupta 2015]. In both cases, substantivalism is in trouble since according to her absolute position and velocity are real, even if they are not invariant.

There is consensus among substantivalists that the symmetry argument against absolute velocity is compelling. Thus they endorse Galilean substantivalism, in which absolute acceleration is defined without reference to absolute velocity. Like in Newtonian substantivalism, bodies traveling in straight lines have no acceleration, but differently from it, there is no fact of the matter about absolute velocities: a vertical straight trajectory in space-time or a tilted one will not be different. A body is accelerating only if it has a curved trajectory in space-time. The majority of substantivalists think that the symmetry argument against absolute position instead does not work. 'Sophisticated' substantivalists (see e.g. [Butterfield 1989]) argue that they are not committed to maintain that the shifted and the actual worlds are different, as claimed by the relationists (see [Dasgupta 2015]).

The situation does not change much when we consider relativistic physics, in which we move from space and time to space-time, combined into a unique manifold. Therefore, space substantivalism arguably transforms into space-time (or manifold) substantivalism, the doctrine that the manifold of events in space-time is a substance. The basic idea of general relativity is that matter changes the geometry of space-time, curving it. Therefore, a crucial element is the metric, which captures all the geometric structure of space-time. The most famous (symmetry) argument against substantivalism in this framework is the 'hole' argument [Stachel 1989], [Earman-Norton 1987]. Since there is no privileged coordinate system (the so-called general covariance of general relativity), we can 'spread' metric and matter in space-time in different ways without changing invariant properties. For instance, we can have a 'regular' translation of matter and metric, or we could have a 'hole' transformation: smoothly joined, we leave matter and metric unchanged outside the hole, and we spread them differently inside. Since the two distributions agree on all invariant features (i.e. on coordinate-independent properties such as the distance along spatial curves), they arguably describe the same physical situation. The problem is that according to manifold substantivalism they instead depict two distinct physical situations, characterized by undetectable non-invariant properties.

The most popular response to the 'hole' argument is again sophisticated substantivalism: one can regard these distributions as representing the same physical possibility (see [Pooley 2013]). Another response is 'metric essentialism:' contrarily to manifold substantivalism, points in space-time possess their relations essentially. That is, the metric is, so to speak, part of the container [Maudlin 1990].

3. How Many Dimensions Does Space Have?

Another interesting question is what dimensions space (or space-time) has. In Newtonian mechanics and relativity theory, matter is represented respectively by three-dimensional entities evolving in time, or by four-dimensional 'worms' in space-time so it seems obvious that space has three dimensions, and space-time four. The situation changes in the framework of string theory and non-relativistic quantum mechanics.

3.1. Quantum Mechanics and Wave Function Realism

Classical mechanics dominated physics until the 20th century, when quantum mechanics and relativity were proposed as more successful alternatives. To get a clear metaphysical picture of the world out of quantum mechanics is notoriously difficult and controversial. The problem is that if, as quantum mechanics states, the complete description of any material object is provided by the so-called wave function, and the wave function evolves in time according to the equation developed by Schrödinger, then objects may have contradictory properties, like 'being here' and 'being not here' at the same time, which is extremely problematic. Nonetheless, in the last century few better quantum theories have been developed, most famously Bohmian mechanics [Bohm 1952], Everettian mechanics [Everett 1957], and the GRW theory [GRW 1986]. Bohmian mechanics avoids the inconsistencies of 'orthodox' quantum mechanics denying that the wave function provides the complete description, Everettian mechanics that it's problematic for objects to have contradictory properties as long as they are instantiated in different words, and the GRW theory denies that the wave function evolves according to the Schrödinger equation.

3.2. An Argument for Wave Function Realism

Nevertheless, it is controversial what matter is made of. One possibility is 'wave function realism:' the wave function represents matter in all the three theories above, even if they differ by either adding something to the wave function (like Bohmian or Everettian mechanics, which add particles and worlds), or modifying its dynamics. This view is motivated by focusing on the dynamics [North 2013]: since in Newtonian mechanics the fundamental equation described the temporal evolution of three-dimensional points, then matter is made of point-particles in three-dimensional space. Similarly, since the fundamental equation of quantum theory, Schrödinger's equation, describes the evolution of the wave function, whatever object the wave function mathematically represents it is the fundamental constituent of matter, and space is whatever space the wave function lives in [Albert 1996], [Lewis 2004], [Ney 2012]. This space, introduced in the classical framework, is called 'configuration space:' the space of the configurations of all the particles in the world (given that matter is made of wave function, there are fundamentally particles, so the name 'configuration' should not be taken literally). Thus, if there are N particles in the universe (estimated to be 10^{80}), the dimension of configuration space is 3N. If so, contrarily to what our everyday experiences suggest, space is a very high dimensional space.

3.3. Arguments against Wave Function Realism

One problem for this view is that it cannot account for our experience of three-dimensional objects [Monton 2002], [Maudlin 2007], [Allori 2013a]. One could argue that they exist 'functionally' rather than fundamentally [Albert 1996]. The preliminary problem here is that there are infinitely many functions from configuration space to three-dimensional space, and to select a privileged one amounts to add an ontology, which the wave function realist denies. Other proposals use symmetries [Ney forthcoming], or grounding [North 2013]. These approaches are all work-in-progress, and the debate over which is more promising is still open.

In addition, wave function realism may not be viable in the framework of quantum field theories [Wallace-Timpson 2010], [Myrvold 2015]. A first problem is that the definition of configuration space requires that the number of particles does not change in time, contrarily to what happens in quantum field theories, in which particles are created and annihilated. See most notably [Ney 2013] for a strategy to address this problem.

Furthermore, some question the motivation for the approach: wave function realism prescribes that the world is very different from what we perceive it to be. Before accepting such a revisionary metaphysic, one should rule out the existence of viable, less counterintuitive alternatives. Since they exist (see Section 6), it is difficult to see the appeal of wave function realism [Monton 2002], [Allori 2013b]. This is connected with the so-called problem of empirical incoherence [Maudlin 2007]. Loosely speaking, a theory is supported by observations when it predicts that objects have certain features, and these features are actually observed. Since our observations are all observations of three-dimensional objects (pointer pointing in certain directions in three-dimensional space), a theory should make predictions about them. Wave function realism predicts instead that there are no three-dimensional object, so it cannot be supported by observations. Wave function realists (see e.g. [Ney 2015]) respond that they do not deny three-dimensional object exists, rather they deny that they are fundamental, and accordingly they attempt to provide an account of how they emerge from a deeper reality.

3.4. String Theory and Extra Dimensions

Quantum field theory, the first proposed extension of quantum mechanics in a relativistic framework, is mathematically ill-defined. In order to overcome such difficulties, string theory, among other theories, has been proposed. In this theory, matter is described by one-dimensional objects called strings. On distances larger than the string scale, a string looks just like an ordinary particle, with properties determined by the vibrational state of the string. Since one of them corresponds to the graviton, a particle connected to gravity, string theory promises to be a unified description of all the fundamental forces. There are several versions of string theory, but for their mathematical consistency, they all require extra dimensions of space-time: for instance, in 'superstring' theory space-time is ten-dimensional. These extra dimensions are assumed to close up on themselves to form little circles, so that they are not macroscopically observable, similarly to what happens when we observe a garden hose from a distance and it appears to have only one dimension instead of two (this is the so-called 'compactification'). So, just like in the quantum framework the dimensionality of space is not as it seems, but contrarily to the quantum case in which the mappings from the high dimensional fundamental space to the perceived three-dimensional are arbitrary, here the compactification mechanism is part of the definition of the theory.

4. Is Space-Time Fundamental?

Many additionally have suggested that recent developments in quantum gravity, namely the theories that attempt to unify general relativity and quantum mechanics, imply that space-time is not fundamental but rather emergent.

4.1. Arguments for Emergence

As we saw, string theory was originally developed assuming a space-time background (as inert container) but the so-called 'dualities,' suggested to some otherwise. As symmetries relate possible physical description a given theory to one another, dualities connect different types of strung theories. Two theories are said to be dual, roughly, whenever they provide the same physics. There are various dualities. T-duality is a kind of scale invariance. As we saw, the extra dimensions are compactified but different theories have different compactification mechanisms. Suppose in a theory T_1 a dimension is wrapped around a circle of radius R. It turns out that, schematically, a theory T_2 in which the dimension is wrapped around a circle of radius 1/R is dual to T_1. That is, the transformation R →l/R leaves the physics invariant. There is no difference between the physics generated by T_1, in which the space is 'large,' and by T_2, in which the space is 'small.' Mirror symmetry is the generalization of T-duality: the extra dimensions can be compactified so that they form a particular manifold (the Calabi-Yau manifold), which turns out to be dual to a manifold with a different topology. Then we have S-duality, which connects theories with different coupling constants (that is, the strength of the interaction is different): a theory T_1 with coupling constant g is dual to a theory T_2 with coupling constant 1/g. Another duality is the AdS/CFT (Anti-deSitter/Conformal Field Theory) duality, which connects a string theory, which includes gravity and is defined in ten dimensions on an Anti-deSitter space, with a quantum field theory, which does not include gravity, and is defined in three dimensions on the boundary of the AdS space. Some have argued that the metaphysical lesson we should draw from dualities is that space-time is emergent. The idea is very similar to the symmetry arguments we discussed previously, now applied at dualities: if T_1 and T_2 are dual, they are empirically indistinguishable, and we cannot choose between them. Only invariant properties describe something real: in the case of T-duality, for instance, there is no fact of the matter about whether the space is 'small' or 'large:' space is not fundamental [Dawid 2013], [Huggett-Wuthrich 2013], [Rickles 2013].

The 'rival' of string theory is quantum gravity, in which general relativity is quantized. A particular type of quantization leads to canonical quantum gravity, newer approaches include loop quantum gravity, in which, arguably, space can be viewed as an extremely fine fabric or network of finite loops, called spin networks. The evolution of a spin network over time is called a spin foam. The spin network can either persist, fuse or split into several nodes, and "the resulting structure is taken to be the quantum analogue of a four-dimensional space-time and is called 'spin foam'"[Huggett Wuthrich 2013]. The theory has not been completely developed but the idea is that the spin foam represents what is fundamental, rather than space-time, and that the perceived three-dimensionality thus have to suitably emerge from such structure.

4.2. Arguments against Emergence of Space-Time

The view according to which space-time suitably emerges from a deeper physics faces very similar problems as wave function realism: first of all, how to account for the appearance of three-dimensional objects evolving in time? Why should we believe the theory? [Huggett-Wuthrich 2012] take on the challenges and sketch possible solutions. The problem that seems to remain is about the motivation: given that there are alternatives, why would one commit to such a radical metaphysical picture?

5. What about Time?

So far, we have focused our attention on space, leaving aside many issues regarding the nature of time. I wish to outline just two connected questions, leaving aside many other interesting debates, namely whether time passes and whether it has a direction.

5.1. Arguments against the Passage of Time

The ongoing debate in metaphysics about the nature of time is between those who believe that the passage of time is objective, and those who believe that this is just an illusion. Some have argued that in the framework of relativity, in which we go from space and time to space-time, we should think of time just as another dimension of a bigger fundamental space, and that the passage of time is just an illusion (see, e.g. [Goedel 1949]). Others instead argue that it is perfectly coherent to believe that time passes in a relativistic framework [Maudlin 2002a], [Zimmerman 2007].

In addition, there is a tension between microscopic laws and macroscopic behavior [Albert 2000], [North 2012]. In fact, on the one hand all macroscopic behavior has a natural temporal order: eggs break and do not un-break. On the other hand, the microscopic laws that govern the macroscopic behavior (whether classical, relativistic or quantum) are time-symmetric. That is, if a process is possible, then so is the process run backwards. So, why is it possible for the molecules that constitute an egg to follow both the trajectories corresponding to 'the egg breaks' and to 'the egg un-breaks,' while on the macroscopic level we only see eggs that break? The problem is to explain where the law that describes these macroscopic processes, the second law of thermodynamics according to which entropy never decreases, is coming from. Arguably, the puzzle has been solved in the framework of statistical mechanics by Boltzmann, in which it is overwhelmingly likely for a process to develop towards maximal entropy, but it is possible that entropy decreases. As such, eggs can un-break, it is just overwhelmingly unlikely to happen. In order for the derivation to go through, many, including Boltzmann, believe that it is necessary to assume the so-called 'past hypothesis,' the assumption that the universe started out with an extremely low entropy. Critics of this strategy complain that this condition calls for an explanation [Price 2004], since the probability of the universe starting in the requisite state is astronomically small (see [Callender 2004] for a defense).

5.2. An arguments for the Unreality of Time

Similarly to the argument for the emergence of space-time, some have argued that canonical quantum gravity, one of the contenders to unify general relativity and quantum mechanics, suggests time does not exist. Canonical quantum gravity gives rise to the Wheeler-de Witt equation for a universal wave function, the interpretation of which seems to describe a static universe. How can this theory describe a world like ours in which there is change? This is the so-called 'problem of time' (for a review, see [HVW 2012]). The possible reactions to this problem can be either endorse timelessness or to attempt to quantize gravity in a different way. For the latter approach, see [Kuchar 1999]. The former path has been taken most notably by [Wheeler 1994], [Barbour 2001], [Earman 2002], [Rovelli, 2011]. In particular, Rovelli's basic idea is that we can describe change without time relating physical systems directly to one another.

5.3. Arguments against the Unreality of Time

Objections to this suggestion are of two sorts: some suggests that the lack of change in the Wheeler-de Witt equation should not be taken metaphysically seriously, since it is an artifact of framing the theory in terms of canonical variables [Maudlin 2002b] [Goldstein-Teufel 2011]. Others have stressed that it is difficult to see how one can come to believe in a theory in which time does not exist [Healey 2002]. As one can see, this is a variety of the problem of empirical incoherence mentioned above.

6. A New Look into the Debates: Primitive Ontology

If the reader has remained with me up to this point, if we set aside the issues connected with the direction of time, I hope she will be able to see a trend: on the one hand we have the relationists, the wave function realists, the space-time emergentists, the antirealist about time, which essentially resort to the intuition that if something is unobservable then we have no reason to believe it is real; on the other hand we have the substantivalists, the fundamentalists about space-time (i.e. the critics of wave function realism and of space-time emergentism), and the realist about time that instead seem to appeal to the idea that if something has an explanatory role then we have reason to believe that it exists, even if it is not detectable. In fact, many prominent arguments for the former positions are based on symmetries and invariant features: in classical mechanics, position and velocities are not invariant, and therefore theory are not real; general relativity is covariant, therefore space-time points are not real; since there are dualities connecting different string theories, we have no reason to believe one theory over the other. These, fundamentally, are all varieties of underdetermination arguments, and the opponents of these views essentially reply that observability is not the only virtue a theory may possess: explanatory power, in particular, should be taken into account.

The other arguments are slightly different: in quantum mechanics one needs nothing more than the wave function in order to account for the experimental results; general relativity suggests that space and time are part of the same continuum, so space and time are not fundamentally different and time does not pass; in canonical quantum gravity we have an equation that suggests that noting evolves in time, so time does not exist. Nonetheless, I think there is still something in common with the previous arguments: the wave function realist and the antirealist about time start off the bare formalism of the theory (respectively quantum mechanics, general relativity and canonical quantum gravity) in order to interpret it. In contrast, their opponents emphasize that the 'interpretation' comes first, and the theory should follow: we make a hypothesis about what the world is made of, and then we construct a mathematical theory to describe it. In particular, the problems of the macro-object and of empirical incoherence stem from this reflection: one theory should be able to account for what we experience, they should be able to explain empirical data, and three-dimensional space (or four-dimensional space-time) seems to be essential for that.

In this last section, I wish to briefly describe a unifying account of fundamental physical theory that essentially captures the ideas just outlined: the primitive ontology approach (for an updated version, see [Allori 2015]). The main idea is that fundamental physical theories are about three-dimensional entities which evolve in time (the primitive ontology). The prototype of a theory with primitive ontology is classical mechanics, according to which macroscopic objects are composed of microscopic three-dimensional point-particles, and the temporal evolution of such objects is determined by Newton's equation. The proponents of this view point out the macro object problem and the problem of empirical coherence in quantum mechanics and quantum gravity as a motivation for their view: that is, theories with a primitive ontology are explanatory successful and empirically coherent, in contrast with their rival views. Because of these reasons, they propose that not only Bohmian mechanics, but also GRW and Everettian mechanics are actually theories about three-dimensional entities, may that be particles, or continuous three-dimensional fields, or space-time events ('flashes') [AGTZ 2008, 2011]. The idea is that the wave function does not describe matter, in contrast to what the wave function realist believe, but rather should be seen more like a nomological entity, needed to implement the law of evolution for the primitive ontology. Similarly, in the context of quantum gravity [Goldstein-Teufel 2011] dissolve the problem of time by arguing that the metric is the primitive ontology of the theory, whose evolution is governed by the wave function, which obeys to the Wheeler-de Witt equation. When confronted by dualities in string theory, the primitive ontologist will similarly argue that empirical adequacy and observability are not the only virtues a theory should have, and that space-time and objects in it are essential to explain theory experiences. Finally, in the context of the substantivalism-relationism debate, what does this approach have to say? At least one thing: in classical mechanics position is fundamental, being the primitive ontology, and symmetry arguments are completely ineffective in this context.

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