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GUSTAVO ROMERO

Newton famously claimed that space and time are some kind of entities. Leibniz equally famously denied that, and held that there is nothing but relations among things. How this debate has changed with the introduction of the concept of spacetime and the theory of general relativity?

The introduction of spacetime by Minkowski in 1908 as the most economical and most elegant way to encode the inertial and chronometric background of special-relativistic physics and the formulation of the general theory of relativity in 1915 havedefinitely reinvigorated the classic debate. The original debate can be seen as having been won by Newton: although Leibniz had a number of good objections to Newton's substantivalism (and some not so great ones), his relationalism struggled to accommodate the dynamical shifts proposed in Newton's bucket thought experiment, where detectable inertial effects such as the concavity of the surface of the water in the bucket arose from accelerations that could not be explained, it seemed, merely by relative motion. In the late 19th century, Mach reignited the debate by arguing that these effects could be explained by relative motion after all, viz. the motion relative to the distant star masses. At this point, it then appeared as if relationalism could offer the more attractive metaphysics in principle, although in practice our best physics remained formulated in ostensibly substantivalist terms.

The introduction of spacetime enriches the debate, in at least two ways. On the one hand, Einstein's special relativity was formulated precisely in order to accommodate seemingly contradictory aspects of classical physics: it turned out that the empirically well-confirmed principles of Galilean relativity and the constancy of the velocity of light jointly required that we give up intuitive assumptions about the frame-independence of spatial distances and temporal durations, and of simultaneity, as well as natural presuppositions about how to add velocities of different bodies. In short, the spacetime structure encapsulated by Minkowski spacetime can be seen as arising from a careful consideration of the physics of material objects, such as rigid bodies and electromagnetic fields. This is clearly grist to the relationalist mill. On the other hand, special relativity contained models with non-trivial spatiotemporal structure yet completely or almost devoid of material objects —Minkowski spacetime could, after all, be empty. But according to relationalism, there cannot be such as a thing as an empty spacetime —spacetime without material bodies.

The advent of general relativity further complicated the picture. First, the relationalist problem of empty spacetimes becomes more acute, as more, and spatiotemporally clearly distinct, vacuum spacetimes are discovered (such as de Sitter and anti-de Sitter spacetimes, along Minkowski spacetime); but how could space and time not only exist, but exist in different ways, on a relationalist view if the universe contained absolutely no material content? Einstein had hoped that his general relativity would vindicate what he dubbed 'Mach's principle', the idea that the distribution of the material content of the universe would uniquely determine the geometry of spacetime. Clearly, this principle is inconsistent with the finding that Einstein's equation permits distinct geometries if there is no material content to be distributed at all. Second, there is the infamous ‘hole argument’, rediscovered from Einstein’s own writings and reformulated by John Stachel, John Earman, and John Norton in the 1980s. Without going into the details here, the hole argument seems to preclude certain ways of identifying the spacetime ‘substance’ in the mathematical formulation of general relativity. But surely, a substantivalist ought to be able to say what in that formulation corresponds to that spacetime ‘substance’ we should be substantivalists about.

What is the role of time in quantum mechanics and quantum field theory?

In non-relativistic quantum mechanics, time has essentially the same role as in pre-relativistic classical physics: it is simply the dynamical parameter which enters the equations of motion and with respect to which the dynamics of the physical system studied then ensue. The significant changes to the concept of time really only occur once special and particularly general relativity are combined with quantum physics. In quantum field theory, quantum physics is brought together with special relativity, and consequently becomes a theory of fields, rather than particles, at least on the orthodox interpretation. These quantum fields, which are the fundamental constituents of the material content of our world, ‘live on’ Minkowski spacetime. In this sense, according to quantum field theory, time is absorbed into a spacetime where it no longer enjoys an independent existence. The background assumptions of rigorous approaches to quantum field theory, such as microcausality, refer to this background spacetime structure as a whole.

Thus, time in quantum field theory suffers precisely the same fate as it did in special relativity: temporal durations and simultaneity are no longer absolute, but only relative to an inertial frame of reference. Thus, time in itself is not fundamental in quantum field theory. Although the revisions to our concept of time that were foisted on us by special relativity appeared radical at the time, seen from the perspective of general relativity and beyond, they seem rather mild in comparison to the revolutions that await time there.

What is the origin, in your opinion, of the irreversibility observed in the world and the so-called “arrow of time”?

The world as we experience it is steeped in irreversible processes: our coffees, if left to themselves, become colder, not hotter, eggs crack and never spontaneously reassemble from their pieces, and our very existence unfolds inexorably and irreversibly from the cradle to the grave. If there is anything absolutely obvious and undeniable about the manifold changes in the world as we experience it, it is that many of them are temporally directed. This becomes deeply puzzling in the context of fundamental physics, which is almost entirely time-symmetric. Except for the decay of kaons, everything in established fundamental physics can just as well unfold in the opposite direction of time from the one in which it actually occurs. In other words, any dynamical behaviour of any physical system licenced by fundamental physics can be time-reversed in the sense that if we flip the direction of time (and hence the ordered sequence of its dynamical states ‘at a time’), we end up with another dynamical behaviour which is equally permitted by the theory. Thus, our fundamental theories are ‘time-reversal invariant’.

But thermodynamics, which is not a fundamental theory, is not time-reversal invariant: what occurs in one direction of time may not occur in the reverse direction. This is because the Second Law of thermodynamics, which states that the entropy of a thermodynamic system cannot decrease over time, prohibits, or at least declares as extremely unlikely, ‘anti-thermodynamic’ behaviour such as the spontaneous heating of our coffees. This suggests the interesting and plausible view according to which the observed irreversibility only arises in the physics of sufficiently complex systems, i.e., systems with many degrees of freedom, from the way in which these fundamental degrees of freedom collectively interact and so aggregate as to produce irreversible behaviour. Since we humans are of course complex thermodynamic systems with a rich physics, it should not come as a surprise to us that at our scales, we find rampant irreversibility.

There is, however, one element missing in this explanation. It turns out that thermodynamic and anti-thermodynamic behaviour are equally likely from generic initial conditions. Only the additional assumption that the past state of the universe, and of almost all macroscopic systems in it, must have been one of low entropy then results in the asymmetry between past to future in the direction we observe it. What is the status of this additional assumption? Perhaps it is itself a law of nature, or perhaps it can be explained by some more fundamental asymmetry that we haven’t found yet.

Does time exist at the Planck length?

It seems that it does not. In order to understand the physics at the Planck scale, most physicists and many philosophers agree that we need to find a ‘quantum theory of gravity’, a theory that correctly describes physical systems where both general-relativistic and quantum effects become important. To many, the best bet to find such a theory is to stay as close as possible to physical principles that proved to be central in understanding either gravity and general relativity, or the physics of material systems and their interactions in the standard model of particles physics. Thus, one approaches the problem either by starting from general relativity, which is a classical field theory, and tries to convert it to a quantum theory; or, alternatively, one start out from the standard model and tries to incorporate gravity. The latter leads, for example, to string theory, while the former results, for instance, in loop quantum gravity and causal set theory.

If one studies the details of these and many other approaches, one realizes that in one way or another, most of them propose a view of a fundamental reality that seems non-spatiotemporal in important ways. Just in what way, and to what extent, this reality is non-spatiotemporal differs from approach to approach, of course; but in most of them, spacetime as we know and love it has vanished from the ontology of the world. So rather than being fundamental—being the first thing which exists, as it were—space and time seem to emerge from the fundamental structures, in a similar way as tables and chairs emerge from collective action of more fundamental degrees of freedom. Just as elementary particles may fail to combine to tables and chairs, therefore, the fundamental quantum-gravitational structures may fail to combine in such a way that space and time emerge. We seem to be living in a world, or part of a world, which is clearly spatiotemporal; but if these theories are correct, then we are lucky to do so, as the world might well have been non-spatiotemporal. Nick Huggett and I explore the vanishing and the re-emergence of spacetime in various approaches to quantum gravity in a forthcoming book entitled 'Out of Nowhere: The Emergence of Spacetime in Quantum Theories of Gravity'.

One might worry that space and time, or spacetime, are necessary conditions to have any physics or any empirical confirmation thereof. All observational and measurement outcomes are, after all, ultimately some detection or readings of particular events, such as of the flashing of a green light or of a coincidence of a pointer needle with a mark on a scale, occurring somewhere in space at some moment of time. Any theory denying the (fundamental) existence of space and time, therefore, seems to be empirically incoherent in that they deny the conditions necessary for any empirical confirmation we could ever have for them. This is not inconsistent: we might be scientifically so unfortunate to live in a world in which the conditions for the empirical confirmation of any theory about this world are just not given; if we believed we could do empirical science in such a world, we would simply be deluded. Now as Huggett and I have argued, this worry can be put to rest if one can show that in worlds like ours, the fundamental structures generically give rise to something like spacetime. In those cases, scientists operating at human scales thus enjoy all the benefits of a spatiotemporal environment, such as the possibility of empirically confirming their theories, even though fundamentally, there is no spacetime.

Although all theories of quantum gravity remain to be completed and confirmed, these considerations suggest that unifying general relativity and quantum physics will challenge our notions of space and time in a way that goes much beyond what we have seen so far in general relativity.

Is backwards causation possible?

Just like the direction of time, and perhaps space and time altogether, causation may be an emergent concept that really only applies once the systems become sufficiently complex and their physics sufficiently rich. In other words, it may be useful, and perhaps even unavoidable, that our best understanding of our macroscopic world requires that we conceive of it in at least partially causal terms; simultaneously, however, it may well be that this is not necessary, or even possible, for the fundamental physics which best describes what grounds this macroscopic world. If that is so, we would definitely expect there to be some explanation of why causation seems to be temporally asymmetric, at least most of the time, and at least in those aspects of the world closest to our immediate experience. So although causation might be implemented at the fundamental level, as some programmes in quantum gravity suggest, it seems at least very plausible to assume that it might be emergent at the same levels and applicable to similar systems as the time asymmetry. If that's the case, then we shouldn't be surprised to find causation similarly asymmetric.

Having said that, this picture is of course consistent with the possibility that occasionally (but rarely), effects might occur before their causes. In this case, backward causation is possible though rare, just as anti-thermodynamic behaviour.

Another possibility, suggested by general relativity, is that although causation is strictly temporally 'forward' locally, the larger causal structure may contain 'causal loops', such that sequences of causal connections between causes and effects close back on themselves: A is a cause of B, which is a cause of C, which, in turn, is a cause of A. General relativity permits spacetimes with such causal structures. This may occur, for instance, inside black holes. Such pathological causal structures may not be locally detectable in the sense that we might do whatever experiments we want in our terrestrial laboratories or even in our solar system, and still not notice anything out of the ordinary. So it is even possible that we are caught on a gigantic causal loop without noticing it. Given our best local physics, this seems unlikely as all seemingly irreversible processes would have to be reversed in at least the sense that our forward evolution has to smoothly lead into our past at some—perhaps very destructive—point.

Can you sum up what you understand by "time"?

Let me try to summarize the view that emerges from considering our best, but partly speculative, physics. Space and time turn out to be rather different from what we would intuitively expect them to be. At the very least we have to reconcile the insights from relativistic physics with our manifest image of how the natural world appears to us; specifically, we have to accept that space and time are both frame-relative aspects of a more fundamental unity of a spacetime. Thus, time, including the temporal irreversibility and the direction of physical processes in time, arise in complex ways from more fundamental physics, which lacks both the particular directionality and the purely temporal features of our manifest world. In fact, it may well turn out that most aspects of spacetime and much of the time-reversal invariant, but still temporal, dynamics of the presently most fundamental parts of physics will ultimately have to be replaced by a yet more fundamental physics which foregoes many or most of these temporal aspects in favour of a picture of physics which is essentially timeless. This view offered by quantum gravity constitutes an interesting and challenging philosophical possibility, which deserves further philosophical and scientific scrutiny. It is an exciting prospect for me to take up this challenge and consider the implications of this possibility.

Finally, what are you researching right now?

I continue to work on the philosophy of quantum gravity generally, with a particular interest in the questions arising from a potentially fundamentally spacetime-less world and run several funded research projects connecting to this problem in different ways. To give you a concrete example, Huggett and I are currently working on a paper, which explores approaches to quantum cosmology coming out of string theory and loop quantum gravity. Cosmology offersa particularly perplexing challenge, as any viable cosmological model must surely be such that at sufficiently ‘late’ times after the big bang, we must obtain, to a very close approximation, a fully spatiotemporal universe as it is predicted by our best cosmological models based on general relativity. On the other hand, the cosmological models based on quantum gravity suggest that in the very ‘early’ universe, quantum effects become non-negligible such that this ‘early phase’ is non-spatiotemporal. However, how can a (spatio)temporal phase be temporally later than, and yet in a non-temporal sense emerge from, a non-(spatio)temporal phase? We are studying these physical models and attempt to answer this question. These cosmological models and their interpretation is just one—particularly stark—example of the novel and exciting philosophical questions that come out of frontier physics. For philosophers of space and time, these are very exciting times!

ABOUT THE INTERVIEWEE

Christian Wüthrich
Has degrees in Theoretical Physics from the University of Bern, in History and Philosophy of Science from the University of Cambridge, and in Philosophy from the University of Pittsburgh. He got a PhD in History and Philosophy of Science at the University of Pittsburgh. He has been Associate Professor of Philosophy and Science Studies at the University of California, San Diego, and currently is Associate Professor of Philosophy at the University of Geneva. Prof. Wüthrich is Principal Investigator (along with Nick Huggett) of the John Templeton Foundation Project "Space and Time After Quantum Gravity". He has published extensively on the philosophical problems of time, in particular in connection with the different approaches to quantum gravity. He is the author, with N. Huggett, of the forthcoming book Out of Nowhere: The Emergence of Spacetime in Quantum Theories of Gravity (Oxford: Oxford University Press).

ABOUT THE INTERVIEWER

Gustavo E. Romero
Full Professor of Relativistic Astrophysics at the University of La Plata and Superior Researcher of the National Research Council of Argentina. As former President of the Argentine Astronomical Society, he has published more than 350 papers on astrophysics, gravitation and the foundations of physics. Dr. Romero has authored or edited 10 books (including Introduction to Black Hole Astrophysics, with G.S. Vila, Springer, 2014). His main current interests are on high-energy astrophysics, black hole physics, and ontological problems of spacetime theories.
Email: romero@iar.conicet.gov.ar