Open Questions on Spacetime and Gravitation

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Abstract. In this paper, open questions about the nature of gravitation and spacetime are discussed, including the emergence of spacetime, and the quest for a theory of quantum gravity. The contribution highlights the contingent nature of the question of spacetime emergence and concludes with some remarks on the possibility of reading different programs in quantum gravity in terms of scientific theory change.

1 Introducing Open Questions on Spacetime and Gravitation

The aim of this contribution is to foster reflection upon open questions on spacetime and gravitation, by introducing a clear separation between what I call the "unification problem" and the "transition problem".

I define the unification problem as amounting to incorporate gravity described by general relativity (GR) with the standard model that describes the quantum mechanical nature of the other three fundamental interactions. The transition problem, in turn, amounts to the description of the transition from/to quantum physics or the emergence of spacetime.

The two problems gave rise to different research programs aiming at answering fundamental questions which, however, must be distinguished in order to eventually attain clarity and cogency in future research. The literature on the transition problem is replete of references to what philosophers call "paradigm change" *à la* Kuhn. For instance, one tends to read the emergence of the four-dimensional continuum of spacetime as a result of an underlying dynamics, as it is the case in loop quantum gravity approaches. However, a paradigm change, at least with respect to inter-theoretic aspects[1] should bring with it new measured quantities, new mathematics, new predictions, new explanations for puzzling facts and anomalies, and new experimental evidence.

At present, these requirements are not satisfied and it is clearly premature to identify a theory that represents a paradigm change in theoretical physics with respect to GR and quantum mechanics. Furthermore, any paradigm change in the sciences brings with it a paradigm change in philosophy, amounting to the elaboration of a new worldview and research lines. More specifically, a new ontology is proposed during periods of revolutionary science. Thus, when a paradigm change occurs, the philosophical question "What is real?" leads to a new definition of reality that includes the most striking aspects of the new theory with respect to the old ones. For instance, in the advent of a new theory of gravity, we could expect that non-locality and its implications are considered within the new framework, not only from the physical, but also and foremost from the philosophical standpoint.[2]

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[1] I will leave aside the considerations that a Kuhnian approach could imply regarding the creation of a new language of the scientific community, or the creation of specialized journals to foster the debates in the new fields, as well as the psychological crisis that scientific communities experience in the revolutionary phases. The reader might want to deepen these issues independently in [21].

[2] With respect to the unification problem, we have examples in [8], [9], [4] , but there is no rich philosophical debate related to these works. On the contrary, in the case of the transition problem, philosophical discussion of locality as an emergent property in loop quantum gravity, causal set theory or group field theory is lively, as works by both philosophers and physicists testify, see [7], [27], [1], [23], [22], [17], [16].

As a matter of fact, we can only say that both with respect to the unification problem and the transition problem, there is a quest for a new theoretical framework, be it pointing to the quantum nature of gravity or its emergence, but none of the proposals is really imposing itself upon the others in a substantial way and the conceptual implications of current approaches only converge to one point: spacetime structure (along with its properties, e. g. locality) is expected to be emergent.

Thus, one could read the present state of theoretical physics as a period that Kuhn called "revolutionary science" with respect to GR, but, I argue, we are not witnessing a paradigm change in the strict Kuhnian sense. The quest for a new theory follows from the attempts to solve the unification and/or the transition problem, and these attempts include string theory, superstring theory, M-theory, as well as a variety of quantum gravity approaches, such as loop quantum gravity, group field theory and so forth.

After more than 100 years from Einstein's idea of a unified field theory, the scientific community is still struggling with the unification problem. The problem is particularly hard to solve given the success of GR at cosmological scales and the development of quantum theory, following the experimental success of the standard model of particle physics. Things do not go better with respect to the transition problem given the difficulty for quantum gravity approaches to recover the four-dimensional continuum that we call "spacetime". Furthermore, approaches aiming at studying the quantum deformations of spacetime lack the revolutionary character that would be needed to talk about a paradigm change and only partially address the unification problem.

In the following Sections, I will show how deep is the crisis that the scientific community of physicists and philosophers is experiencing, both in historical and philosophical terms. However, this picture is not meant to withdraw or undermine current attempts. In contrast, my aim is to stimulate awareness of the limits of current approaches to find a way out of the current impasse.

2 Hot Topics for Old Questions: On the Limits of Philosophy and Physics

This Section is meant to show that our current philosophical debates are revolving around core questions that are rooted in old insights and perhaps one should deeply change the philosophical questions in order to address the challenges of current physics. In particular, among the hot topics in philosophy of physics, we find today:

- Philosophy of spacetime with A) the debates on substantivalism, relationalism and functionalism that approach relativity and with B) the question of spacetime emergence from a functionalist or metaphysical perspective mainly approaching quantum gravity.
- Symmetries in physics and invariance (problem of objectivity)
- Interpretation of quantum mechanics
- Philosophy of cosmology

These hot topics revolve around the same bulk of questions that Einstein, for instance, approached in his career. In what follows, I introduce the historical perspective in order to show why the unification and the transition problems are still alive today and are responsible for shaping current debates in both physics and philosophy of physics. The comparison with the past, in turn, is helpful if we want to go beyond the state of the art and eventually assess whether we are witnessing a paradigm change when treating spacetime as emergent.

2.1 Einstein on the Incompleteness of General Relativity

In 1955 Einstein wrote a fundamental piece a few days before his death (see [2]). One could take this short writing as a legacy that he left to the scientific community. In 1950 the celebrations for the 50 years of the theory of relativity started being organized around the world. Many societies and universities aimed at inviting Einstein and other theoretical physicists from the IAS in the US, Europe, Japan, India and even in the Soviet Union. The Italian Physical Society elected Milan as the place for the 1955 meeting and through the publisher editor of the volume, Mario Pantaleo, invited Einstein himself, who happily accepted to write the Introduction to the volume of the proceedings.

Unfortunately, Einstein died on 18 April 1955, but he was able to send the manuscript of the Introduction through a letter dated 4 April 1955. The Introduction is very short, it amounts to a few pages and appears in German. It was translated into Italian for the special edition and to my knowledge there is no English version of this writing. I present here my translation to English of the relevant passages that help us in characterizing the unification problem and the transition problem also from a philosophical perspective. In his Introduction Einstein wrote:

"It is tempting to subsequently declare the general principle of relativity (general covariance) as a priori. However, I consider such a standpoint to be unjustified. There is no apparent a priori reason why the laws of nature could not be such that they take on a particularly simple form for certain coordinate systems. In this case, the requirement of general covariance of the laws would be completely fruitless. The requirement only appears to be justified on the basis of the equality of the inertial and gravitational mass. As far as we can see at present, the field concept is indispensable in order to formulate the equivalence principle mathematically (Γ-field). However, if one introduces the field concept as an elementary concept, i. e., as an element of the physical description that cannot be further reduced, it seems to me impossible to also introduce the particle as an elementary concept. Because the latter would have to be treated as a singularity of the field, which amounts to setting logically arbitrary boundary conditions for the field. It therefore seems necessary to me to demand that the field be free of singularities, so that the field laws alone come into consideration as elementary laws. The old contrast between continuity and discontinuity appears particularly harsh from a general relativistic point of view, because here space does not appear as something independent, but only as a continuous field of four dimensions. A discontinuous theory of matter therefore also means giving up space. Most contemporary physicists will be inclined to look for a way out in a 'quantized' field theory. However, I believe that such a solution does not get to the heart of the matter, because it dispenses with a complete real description of the individual case; I must limit myself to this brief hint, because a justification of this claim would be too extensive at this point. On the other hand, it must be admitted that the attempt to understand the indubitable atomistic and quantum structure of reality on the basis of a consistent field theory encounters great difficulties, which I am by no means convinced can be overcome. [...] It seems, however, that there are no relativistic systems of equations that are in any way natural (i. e. logically simple) from a formal point of view and that are not 'homogeneous' in this sense. But then it would be highly improbable that physics could be grounded on differential equations. We would have to look for a theory of a purely algebraic nature without a space-time continuum. The last, fleeting remarks are only intended to show how far we are, in my opinion, from having any kind of reliable conceptual basis for physics".[3] ([2], pp. XVI-XVII, translation is mine).

Einstein's reflections on the foundations of GR are thus the following:

1) If the field is considered as irreducible fundamental concept for physical description, it is impossible to avoid the clash with the concept of particle. This is due to a conceptual problem or contradiction that concerns the theory of matter underlying GR, a continuous theory, and quantum physics, which deals with particles. It is as if some natural philosopher of the 18th century might wanted to unify Newton's theory of matter and light with the theory of the aether. The four-dimensional continuum field is a concept at odds with the concept of particle, as well as with the concept of singularity, and this is an immanent conceptual difficulty of GR.[4]

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[3] The original reads: "Es liegt die Versuchung nahe, das allgemeine Relativitäts-Prinzip (allgemeine Kovarianz) nachträglich als a priori zu erklären. Einen solchen Standpunkt halte ich aber für unberechtigt. Es ist nämlich a priori kein Grund dafür ersichtlich, dass die Naturgesetze nicht so beschaffen sein könnten, dass sie für gewisse Koordinatensysteme eine besonders einfache Form annehmen. In diesem Falle wäre die Forderung der allgemeinen Kovarianz der Gesetze durchaus unfruchtbar. Die Forderung erscheint nur auf Grund der Gleichheit der trägen und schweren Masse gerechtfertigt. Soweit wir gegenwärtig sehen, ist der Feldbegriff unentbehrlich, um das Äquivalenz-Prinzip mathematisch zu formulieren (Γ-Feld). Wenn man aber den Feldbegriff überhaupt als Elementar-begriff, d.h. als nicht weiter reduzierbar Element der physikalischen Beschreibung einführt, so scheint es mir unmöglich daneben auch das Teilchen als elementaren Begriff einzuführen. Denn dies letztere müsste als Singularität des Feldes behandelt werden, was auf die Setzung logisch willkürlicher Grenzbedingungen für das Feld hinausläuft. Es scheint mir deshalb notwendig, Singularitätsfreiheit des Feldes zu fordern, sodass die Feldgesetze allein als Elementargesetze in Betracht kommen. Der alte Gegensatz Kontinuität versus Diskontinuität erscheint vom allgemeinen-relativistischen Standpunkt besonders hart, weil ja hier der Raum nicht als etwas selbstständiges, sondern nur als kontinuierliches Feld von 4 Dimensionen auftritt. Eine diskontinuierliche Theorie der Materie bedeutet dann also zugleich Verzicht auf den Raum. Die meisten gegenwärtigen Physiker werden zwar geneigt sein, in einen 'quantisierten' Feldtheorie den Ausweg zu suchen. Ich glaube aber, dass eine solche Lösung nicht das Wesentliche trifft, weil sie auf eine vollständige Real-Beschreibung des individuellen Falles verzichtet; auf diese kurze Andeutung muss ich mich ja beschränken, weil eine Begründung dieser Behauptung an dieser Stelle zu weitläufig wäre. Andererseits muss man zugeben, dass der Versuch, die unbezweifelbare atomistische und Quanten-Stuktur der Realität auf dem Boden einer konsequenten Feld-Theorie zu begreifen, auf große Schwierigkeiten stößt, von deren Überwindbarkeit ich keineswegs überzeugt bin. [...] Es scheint aber, dass es überhaupt keine vom formalen Standpunkte irgendwie natürliche (d.h. logisch einfache) relativistische Gleichungssysteme gibt, welche in diesem Sinne nicht 'homogen' sind. Dann aber wäre es höchst unwahrscheinlich, dass die Physik auf Differenzialgleichungen gegründet werden könnte. Es wäre eine Theorie rein algebraischer Natur ohne raum-zeitliches Kontinuum zu suchen. Die letzteren, flüchtigen Bemerkungen sollen nur dartun wie weit wir nach meiner Meinung davon entfernt sind, eine irgendwie verlässliche begriffliche Basis für die Physik zu besitzen".

[4] Nevertheless, it must be noticed that in recent work, singularity-free spacetime in BH solutions avoids the singularity, by introducing the dynamical mechanism of what I have called "atemporality", see [10].

2) According to Einstein, to quantize the gravitational field is wrong. A straightforward quantization of the gravitational field is going to fail no matter how hard we try. And it was the case, indeed, for all first attempts.

3) More interestingly, Einstein suggested that perhaps a pure algebraic theory without spatio-temporal continuum can solve the problem by shifting the unification problem to the transition problem.

4) However, in Einstein's view, our knowledge of GR is incomplete and we are therefore far from possessing a solid conceptual basis deriving from physics, which could provide a satisfactory and reliable ontology of spacetime.

Not only Einstein, but also Kurt Gödel was extremely critical with respect to the state of physics of his time. For instance, in his notes on Einstein's theory of relativity we read:

> "In the present imperfect state of physics, however, it cannot be maintained with any reasonable degree of certainty that the space-time scheme of relativity theory really describes the objective structure of the material world. Perhaps it is to be considered as only one step beyond the appearances and towards the things (i. e., as one 'level of objectivation', to be followed by others). Quantum physics in particular seems to indicate that physical reality is something still more different from the appearances than even the four-dimensional Einstein- Minkowski world. T. Kaluza's fifth dimension points in the same direction". ([19], p. 240)

Both Einstein and Gödel developed the same idea around 1950, namely they believed that the four-dimensional continuum cannot be taken as something embodying the complete structure of the world. It is a surrogate of a deeper reality still unknown to us. A deeper level of the objective structure of reality must still be identified, just like Einstein, Kaluza, Eddington and Weyl's first attempts to a unified field theory suggested. Therefore, also on the ground of Einstein's insight, we can clearly identify with the problem of unification the source of troubles that we are still witnessing today when we want to unify a continuous with a discrete theory of matter and this conflict seems to be a structural aspect of a (big) anomaly that does not disappear from theoretical physics, at least for the moment.

2.2 Space-time Emergence

We can now briefly look at what history can teach us about the problem of space-time emergence or the transition problem. Does it stem for a structural anomaly like the unification problem? Let us consider different linguistic meanings of emergence:

1. Appearance
2. Surfacing
3. Coming into being

In Western culture, the third meaning of emergence was preponderant thanks to the philosophical tradition based on Plato's *Timaeus*. The problem of the coming into being of the sensible world is indeed scrutinized in the dialogue (and in other works, such as the dialogue *Parmenides*), which offers the first-known written example of a geometrical account of matter and emergence of the world. In Plato's view, geometry gives form to matter and allows the coming into being (*to gignesthai*) of the world, even if geometrical forms are dictated by the World Soul and the Demiurge forges the latter according to universal a priori rules of mathematical construction.

We would say today that the laws of nature are embodied by rules that dictate the form of the interactions and shape the geometric patterns that we can find in matter. Thus, in line with this powerful and pervasive tradition, the scope of physics is to reveal the geometric structure of the physical world.

However, this view has been challenged by the great revolution of the 20th century. By introducing the notion of spacetime things got more complicated than in previous worldviews. Hermann Minkowski understood the great paradigm change imposed by relativity theory, as he underscored:

> "Henceforth, space for itself, and time for itself shall completely reduce to a mere shadow, and only some sort of union of the two shall preserve independence". ([24], originally presented on 21 September 1908)

Today we witness an inverse take with respect to GR, and we see a growing community that wants to bring back the distinction between space and time, by claiming the non-fundamentality of spacetime and eventually restore a sort of Platonic take on the explanation of spacetime emergence, by showing the ‘coming into being’ of its structure and properties. Does this move stem for a paradigm change?

In physics, spacetime is any mathematical model that merges the three dimensions of space and the one dimension of time into a single four-dimensional continuum (chronotope). Within some research programs in quantum gravity, this model is rejected as fundamental and a discrete geometry is proposed to describe the emergent nature of the four-dimensional continuum. So far, quantum gravity is a research program including a variety of approaches, and the idea of a unique theory describing the transition from a discrete to a continuous geometry of the world is plagued by problems that are not just of technical nature, but rooted in conceptual difficulties that invest the foundations of mathematics, the concept of field and the foundations of quantum physics.

Nevertheless, the literature is replete of expressions such as “spacetime is *expected* to be emergent”. This expectation, however, should be grounded on the capacity of synthesis of two radically different claims. According to GR, space, time and geometry are identified with the gravitational field, and are dynamical, physical entities, whereas quantum mechanics claims that all physical systems possess quantum properties, including irreducible uncertainty, probabilistic nature of physical observations, entanglement and so forth.

When it comes to quantum gravity one expects that spacetime should possess a similar quantum nature and this research program should fill the gap in present physics by giving a framework to describe physical situations featuring both strong gravitational fields and quantum fields, such as the early universe and black holes (BH interior and microscopic structure, how they process information).

Furthermore, the notion of “quantum-gravity research” can have a different meaning for different researchers. The quantum-gravity problem has a different look to particle physicists and to physicists working on relativity. For instance, Amelino-Camelia in [3] claims:

> “In particular, this affects the perception of the implications of the ‘double role’ of gravitational fields: unlike all other fields studied in fundamental physics the gravitational field is not just used to describe ‘gravitational interactions’ but it also characterizes the structure of spacetime itself.”

Thus, we witness the existence of at least two groups in the scientific community that perceive and attack the problem in a radically different way (they do not talk to each other in Kuhnian terms). Particle physicists focus on contexts: assume some given Riemannian-manifold spacetime background and gravitons as mediators of perturbative gravitational interactions. Other physicists, on the contrary, are primarily interested in speculations about how to replace Riemannian manifolds in the description of the structure of spacetime.

This fact clearly amounts to understanding the emergence of spacetime in very different terms and prevents the two groups from a fruitful interaction. However, let us stick to the fact that spacetime is expected to be emergent by both groups, but their understanding of emergence is different. The first one does not really break with the paradigm imposed by GR, and embrace the meaning of emergence as appearance, whereas the second one has potential to produce conceptual innovation, by replacing Riemannian manifolds and by explaining the coming into being of spacetime structure, but it does not necessarily lead to a paradigm change, since the final outcome is *to conserve* the structure of spacetime, by finding an analogue reproducing some of its fundamental properties. Therefore, these two research streams work on different problems really, and the second approach can produce conceptual innovation within the current paradigm, but not necessarily a paradigm change. Nevertheless, it must be noticed that to produce analogues of spacetime properties can heuristically lead to the creation of new mathematical structures that can be used in future scientific theories leading to a paradigm change.

3 When Physics and Philosophy Meet

At this point, one might ask whether philosophers of physics could provide a unitary picture of emergence such that the work of physicists could be unified under the same framework with shared research questions. Philosophy of physics provided positive definitions of emergence in the last twenty years. In particular, the standard definition appears in [5], [6]. According to him, emergence means properties or behavior of a system which are novel and robust relative to some appropriate comparison class. This broad definition aims at providing a useful and general framework when addressing the transition problem in quantum gravity and in physics in general. With respect to the further development in the debates on spacetime emergence, another positive definition is provided by Crowther ([11], [12], [13], [14]). For instance, she claims:

> “When you think of emergence, [. . .] what you think of is most probably some behavior, process, property, or object that occurs, or exists, in space and time. But what about the case of spacetime

itself—can this be considered emergent from some collective behavior of non-spatiotemporal objects? Or, could a spatiotemporal universe emerge from some 'prior' non-spatiotemporal state 'before' the beginning of the universe? Many philosophers and physicists believe that, indeed, both these scenarios are real physical possibilities in our own universe — these suggestions comes from research in quantum gravity and quantum cosmology, respectively." ([14])

In her view, emergent phenomena are dependent on, constituted by, or generated by underlying processes. Thus, merging these positive definitions when addressing the transition problem in quantum gravity, we obtain the following:

Emergence is when spatiotemporal phenomena display novel and robust behavior relative to some comparison class of underlying non-spatiotemporal processes on which they depend.

In order to assess to what extent quantum gravity programs offer a novel and robust perspective or even paradigm change with respect to 100 years ago, this definition of emergence can now be compared with Minkowski's statement reported in Subsection 2.2. As one can see, spacetime is expected to be emergent if and only if spacetime phenomenologically shows "anomalous" or unexpected behavior with respect to the prediction of GR. However, spacetime is still the "tested object" of the experimental or observational settings. In other words, this definition of emergence and research programs endorsing it, are still constraining "new physics" by using "old physics".

This can be done, of course, but it does not amount to a paradigm change of the same nature that we witnessed with the advent of quantum physics and relativity. It looks more similar to what Kuhn described in *The Structure of Scientific Revolutions* (1962; 1970) as conceptual innovation, rather than revolution, because the unification of space and time is not overcome, rather one seeks *to justify* it by explaining its "coming into being" from discrete structures, or its unexpected behavior from quantum symmetry groups deformations and so forth. Whereas a revolutionary move would be to show how the field and its 'laws' are generated from discrete entities.

For the sake of clarity, it should be added that there exists in the philosophy of physics literature a negative or more prudent definition of emergence that amounts to non-fundamentality. Rather than focusing on the positive definition of spacetime emergence, these approaches focus on the fundamentality of non-spatiotemporal structures (see [22], [15], [28]). However, according to these views an analysis of the laws of nature cannot depend on spacetime because it is not fundamental, but so far the laws of nature as we know and understand them appear to presuppose the (necessary) existence of spacetime. For instance, if we want to embody conservation laws by means of Noether theorem, we must calculate geodesics and spacetime curvature to see whether our invariants of energy and motion are conserved. This is clearly in tension with the idea that spacetime is not fundamental, even if the latter definition is *prima facie* revolutionary with respect to Minkowski's words.

The emergence in negative terms, i. e., the non-fundamentality, of spacetime would have serious implications for our conceptions of what it is to be a law of nature. How would one account of laws of nature if spacetime is at best emergent, rather than fundamental? Are there laws of nature at all? All these questions are not only relevant for philosophers of physics, but for theoretical physicists they become vital in order to build up a new framework.

In either ways, i. e., if one endorses a positive or negative definition of emergence, it is worth underlying that both physics and philosophy are currently forced to think of the status of scientific theories and their relationship to reality in at least two senses.

First, if they want to address the unification problem they have to find new objects constituting reality for a new scientific theory, and these new objects are not spatiotemporal if one wants to obtain a paradigm change.

Second, if they want to address the transition problem they could rethink of the notion of reality, thereby assuming that there are different levels of reality (e. g., a geometric or a non-geometric one) and that there is a more fundamental level with respect to the spatiotemporal reality described by GR, but they do not deny the effective nature of the theory and use spacetime structure as touchstone to progress in the search for a new theory. Think for instance of the geometrogenesis scenario admitted by Asymptotic Safety and GFT approaches to QG.[5] In that case, the transition from a non-geometric to a geometric phase should be an a-chronic or atemporal transition, but the way in which the RG flow is built

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[5] In this scenario a transition from an 'earlier' quantum state, which in general lacks any correspondence to a classical emergent state, to a 'later' classical cosmology well described by relativistic spacetime is admitted. For considerations on geometrogenesis and levels of reality, see [25]; for an account of the a-chronic transition, see [16].

and search for the relevant symmetry groups and degrees of freedom realizing the transition are going the other way around, i. e., from the geometric to the non-geometric phase. In other words, spacetime is assumed to be as a real physico-geometrical phase.[6]

Let me add an interesting remark here. Whereas this could in principle be in line with Minkowski's ideas, it is rather at odds with Einstein's own take on spacetime. In 1955, in the same Introduction to the volume reported in Section 2, Einstein warned the scientific community from attributing ontological meaning to spacetime. One should avoid any strong ontological commitment to spacetime and the object predicted by GR because, in Einstein's view, GR is incomplete in the deepest sense.

Not only we have *incomplete knowledge* of the solutions of the gravitational field equation, but this also results in incomplete knowledge of *predictions* and lack of observations of unknown predictions. This means that our knowledge of the universe is incomplete, our knowledge of the laws of nature is incomplete and it is so in a structural sense, because our knowledge of the theory is incomplete. However, quantum gravity programs must rely on GR and spacetime to progress at least towards conceptual innovation in physics. Indeed, this structural incompleteness of GR is not unique. All physical theories are incomplete, either because they concern specific scales or because they represent matter as continuous, rather than discrete, or vice versa. On the other hand, a unified field theory seems to be an impossible goal to attain.

We can certainly widen our knowledge of reality, explain new phenomena, add new predictions, identify invariants producing an approximately complete picture, discover anomalous or unexpected behaviors of particles at different energy scales, but a unique complete field theory is not attainable.

Now, "incomplete" is not synonym of "wrong", it means an opportunity to progress in physics and other fields: the search for a unified framework is necessary for innovation, but for paradigm change more is needed: a new physics that overcomes the old distinction between continuous and discrete theories of matter.

Many proposed theories of quantum gravity suggest that their fundamental quantities and structures do not include all the familiar ones of theories involving classical spacetime(s), yet it seems that only a novel geometry and conceptual framework disentangling space and time can produce a novel conception of "what is real" and produce a paradigm change.

4 Physics and Mathematics

In the history of scientific theory change, a pivotal role has been played by changing the relevant objects of the theories and the measured quantities by means of new mathematical objects. This happened with calculus or fluxions (depending on whether you sided with Leibniz or Newton) in classical mechanics, with tensors in GR and symmetry groups in quantum mechanics. In order to enrich the scenarios, new mathematical objects can always be found or created and signify something within a theory that appears to be ‘ìncommensurable" to present theories or "unquantifiable" in a previous framework. Progress in physics is necessarily attached to progress in mathematics. Hermann Weyl understood this fundamental step in terms of symbolic construction ([29]).

According to Weyl, human beings are structurally characterized by the capacity of generating new mathematical objects and of applying them for different purposes. Thus, new mathematics can generate new physical theories that are very (very) different from GR and its objects with regard to the notions of time and spatial distance, perhaps it won't even have the latter as notion, just like Einstein and Gödel seem to suggest in the passages quoted in Section 2. Attempts in this direction have been pursued, for instance, by string theory in the last decades. However, in a less radical way, we find approaches describing emergence of spacetime from correlations, starting from the observation that quantum field fluctuations are the more strongly correlated the shorter their spacetime distance. On the ground of this simple consideration, the notion of space-time distance, which is fundamental in relativity, can be dropped and replaced by the notion of correlation strength, thereby producing a new picture that is called "information-theoretic approach": the abstract 2-point and multi-point correlations are the primary structure, what counts as real in the theory. Thus, in low-energy regimes we find secondary notions of spacetime and matter that emerge as approximate representations of the abstract correlators, i. e., in the form of Feynman rules on curved spacetime ([20]).

Another option could be pursued by following approaches describing the emergence of spacetime from fluctuations ([26]). Nevertheless, the revolutionary character of quantum gravity, if any, will be manifest if in addressing the unification and the transition problems, it turns out that these problems become meaningless. This was already foreseen in the scientific community, as follows:

"We do expect that there is a regime of physics where quantum gravity does not simply amount

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[6] For a detailed discussion, see [16].

to small corrections to our currently adopted theories, but rather our current theories should be there completely inapplicable". ([3])

Future perspectives on the conceptual debates surrounding the unification problem could be enriched by an interesting case study, such as the ERC project UNIVERSE+. The proposal of the project is to employ novel geometric shapes called "positive geometries" that were discovered in the data describing the scattering of elementary particles and the correlated positions of cosmological structures on the sky. These positive geometries seem to provide the first concrete example of the way in which the principles of spacetime and quantum mechanics can arise from more basic mathematical principles that pertain to a more fundamental theory (for more details, see [18].

The project aims at associating a positive geometry to scattering processes and cosmological correlations. This geometry is constructed purely from the energies and momenta of the external particles, and makes no reference to the evolution in spacetime. What stems for a paradigm change, thus, is *dropping* the notion of spatiotemporal evolution. Future work will establish whether this approach is fruitful and successful, but can represent a potential paradigm change with respect to the objects of interest in both GR and quantum mechanics.

5 Closing Remarks

The scope of the present paper was to stimulate the reflection and the discussion on some pressing open questions on spacetime and gravitation with respect to the capacity of producing a paradigm change from current research. I have shown that both the transition problem and the unification problem can be considered as the bulk of the potential anomalies producing a paradigm change, but they have been considered as such for a long time (at least from 1955).

These old questions are now re-framed in the current debates on the emergent nature of spacetime and in unifying attempts pursued by string theory and quantum gravity programs. As I tried to show, at least for the case of quantum gravity, however, there seem to be some conceptual difficulties that prevent the realization of a proper paradigm change and one should rather recognize that most of these approaches lead to conceptual innovation, rather than revolution in a proper sense.

At the same time, I also highlighted the limits of the current philosophical debates on spacetime emergence and the big problems they open with respect to the character of the laws of nature. I have also provided some examples that leave us hope in the quest for new physics and scientific theories, i. e., for scientific progress, by assuming the structural incompleteness of physical theories and their dependence on symbolic construction in mathematics. I suggested that the future theory should at least provide:

- New algebra/geometry
- New quantities to be measured
- New ontology

So far, we know that we cannot quantize the gravitational field in a straightforward manner and that debates on the emergence of spacetime, understood in terms of the appearance of new features approximating the spacetime structure, are not providing the expected results of a paradigm change because they do not drop the notion of spacetime itself.

Also, a caveat is in order here, considering that there is more unknown information to be unpacked from GR and that we do not master the whole theory: GR is incomplete in a deeper sense, and spacetime emergence is an expected result very difficult to experimentally verify. Quantum gravity approaches generated multiple research streams and discussion–which is always good–, but if emergent spacetime is to be considered as an expected result, then it is understood as the anticipated outcome or behavior that is defined in the test case, but what is the test case? Are we really entitled to say that spacetime is expected to be emergent in a scientific sense?

Only phenomena or correlations that open fundamental questions that cannot be answered within GR and quantum mechanics can effectively represent a way out towards a paradigm change and time will tell whether current pivotal research programs can obtain such long-sought remarkable result according to which we will have new physics beyond any concept of spacetime.

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