2 Imagination, Fiction and the Reality of Minkowski's Discovery of Spacetime

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Abstract One of the greatest achievements of modern physics is the discovery of spacetime by Hermann Minkowski. Still, talking about the "discovery" of spacetime cannot be done without further questioning its ontological status. Did Minkowski discover a real physical substrate? What is the creative role of his scientific imagination in the process of discovery? To what extent the explanatory power of spacetime supports the conclusion that it is a true description of the physical world? I consider those questions in that paper, and I claim that for Minkowski's discovery of spacetime, imagination and explanation work together in a fictionalist strategy. I explain why there is no reason to doubt the veracity of the discovery of spacetime and its physical reality.

Keywords: Minkowski spacetime, Scientific discovery, Scientific imagination, Fictions, Explanation, Realism

1 Introduction

One of the greatest achievements of modern physics is the discovery of spacetime by Hermann Minkowski. If we take for granted that spacetime offers a compelling explanation of relativity and its physical effects, then it is no surprise that its discovery should count as one of the most significant success of modern history of science (Petkov 2009). Nevertheless, I would like to suggest that talking about the "discovery" of spacetime cannot be done without further questioning its status as a scientific object. Claiming that spacetime was discovered, I suggest, implies the following two philosophical questions. Firstly, what kind

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of thing is it: Is it an entity, a physical substrate (i.e. an underlying physical layer on which material entities are said to be coincident), or a mathematical model? Secondly, was spacetime discovered as a real object, or was it invented as an alternative description of the classical space-time structure of the world.

The challenge with the concept of discovery is that it involves two contradicting interpretations of the status of what was discovered. While "soft" discovery can be seen as an act or process by which a scientific construct is thought and devised, without there being any concrete evidence of the reality of the construct itself (fantasies like complex numbers, supersymmetries, twistor space), "strong" discovery can be taken as finding the existence of a physical thing (the electron, white dwarf stars, black holes) (Achinstein 2011; Penrose 2016). Accordingly, one can dispute the claim that spacetime was discovered, if discovery is understood in the strong sense. Indeed, the disagreement concerns the ontological status of spacetime (Sklar 1974). The substantival view asserts that spacetime is a physical substance that does have an independent existence of its own. In contrast, the relationist view claims that spacetime is not a real existing physical structure; only spatiotemporal entities, events and the relations between them, exist out there. The complication also stems from the fact that spacetime was not found through direct observation and experimental work, but imagined and invented by Minkowski (Corry 1997; Galison 1979; Holton 1996; Minkowski 2020b).

My plan in this contribution is to present, in section 2, the general conundrum created by the idea that scientific imagination can be taken as a source of strong discoveries about the physical world. In section 3, I outline the philosophical debate on the ontological status of spacetime, and I point out that substantivalism appears to be the appropriate position to justify the claim that Minkowski discovered spacetime. In section 4, I explain what role scientific imagination played in Minkowski's discovery of spacetime, and I show to what extent scientific imagination enables to find hidden structure in the physical world. Section 5 should provide an overview of the extent to which the spacetime structure imagined by Minkowski furnishes crucial elements of explanation of the relativistic effects we observe in the world. Finally, by showing how imagination and explanation work together in a fictionalist strategy, I intend to show in section 6 that there is no reason to doubt the veracity of the discovery of spacetime and its physical reality.

2 Imagination, reality, and scientific discovery. An overview of the problem

Spacetime can be taken as a scientific model which represents the motion of bodies and fuses the three dimensions of space with a fourth dimension of time in a single four dimensional differentiable manifold. Thus, being a model, i.e a mathematical construct used for the investigation of physical motion, it appears that spacetime was imagined and invented. After all, Minkowski himself claimed that mathematical imagination, a mixture of logical reasoning and “pure fantasies”, had lead him to his “radical” views on the nature of space and time (Minkowski 2020b, p. 57). Accordingly, one could think that spacetime was not discovered, in the sense used to convey that we discover things that exist but were unknown before, but was merely devised as a scientific construct, i.e. a kind of mathematical abstraction. If the latter claim is true, then philosophers have to make sense of the fact that scientists can think up hypothetical objects, properties and structures, - so-called “fictions”, - that turn out to be categorized and conceived as discoveries about the real world. The philosopher has to make sense of the gap between scientific fictions and the reality of scientific discoveries.

Nevertheless, the fact that spacetime is conceived as a model does not imply that it cannot be real and have counterparts in the physical world. On the contrary, empirical evidence, the absence of conclusive refutation and the predictive successes of that model all contribute to validate the claim that spacetime is indeed the true dimension of the physical world. Accordingly, one can claim that spacetime was indeed discovered: Because spacetime is a true description of the structure of the physical world, it is the discovery of a physical thing that does exist. Yet, if we assume the latter claim to be true, it then seems odd to say that spacetime is an abstract object that has been imagined and constructed. If spacetime was discovered as being the real structure of the physical world, then it must be known to exist as a physical thing, and it cannot only be the product of Minkowski’s imagination. The philosopher should make sense of the gap between the reality of scientific discoveries and the role and function of scientific imagination.

While it might seem paradoxical to assert that a scientific object was discovered by a scientist, but that the discovery came in the first place out of the scientist’s imagination, I contend that the contradiction between imagination and the reality of scientific objects can be resolved if we correctly construe the role of imagination and its proper function in scientific research. Additionally, I maintain that while we can consider scientific objects (which encompass models, theories, and hypothetical entities posited through the history of science) to be the products of scientific imagination, we can conceive these objects as scientific discoveries if we justify the use of a particular scheme of inference that enables us to conclude that a hypothetical scientific object *must be true*, and thus that it can be taken as having real counterparts in the world. The scheme of inference I refer to is abduction. Abduction proposes the following scheme of reasoning: If a scientific hypothesis (defining a theory, a model, or an entity) does explain the anomalies implied by a given physical phenomenon (e.g. the abnormal result of the Fizeau experiment, the null result of the Michelson-Morley experiment), then given a genuine scientific evaluation (logical and empirical tests) of that hypothesis, we are warranted in believing that the hypothesis is true. Then, by further taking the assumption of scientific ontological realism (*true scientific propositions describe objective properties of the natural world, and we should commit to a belief in the existence of the ontology posited by scientific theories*) to be correct, we can infer that the hypothesis, by being true, also is a description of the natural world as it really is. The upshot is that because a scientific hypothetical statement is shown to be a satisfactory explanation of some physical phenomenon, we are justified in believing that the ontological content of the hypothesis consists of a discovery of something true and real about the world.

Because relativistic effects (time dilation, length contraction, doppler-effect, scattering of elementary particles) have been experimentally observed, and that none of these kinematic effects would be possible in a world which is not four-dimensional, spacetime undeniably appears to be a correct explanation of those effects. Minkowski thought that relativity and the geometric structure of spacetime accounting for it was not solely a consequence of observations, but a truly new kind of axiom or physical law, i.e a demand imposed on our mathematical equations governing physical phenomena. Thus, spacetime was indeed postulated as a first principle explaining observables (Corry 1997, p. 278). That considered, I define a scientific explanation as a definition of a correct reason for the occurrence of an observable phenomenon. Einstein wrote that we have a scientific explanation if we cease to be astonished by the occurrence of a phenomenon when we identify what will cause, or at least may possibly cause, the phenomenon. In other words of Einstein, a scientific explanation is the definition of a set of circumstances, “a real something”, to which we can attribute what we observe (Einstein 2018, p. 55). That being said, if we can show that spacetime is a correct explanation of relativistic effects, then we should consider those effects as the physical manifestation of the four-dimensionality of the world[1]. Thus, the belief that spacetime is a real physical substrate along which the history in time of material particles unfolds is warranted.

I understand the word "real" to denote that a scientific object is not just a concept or an abstraction, but that it has a counterpart in the physical world which is manifested and observed through physical effects. Consequently, I don't claim that we have to commit to the ontological assumption that all scientific objects must be real, and that all scientific objects are real physical entities existing in the world. Nonetheless, if we take for granted that a hypothesis does explain physical effects that are experimentally observed by stating the scientific reasons why those effects happen, then I share the philosophical attitude according to which "the essential elements of physical theories should correspond to real objects or properties of the world" (Petkov 2012, p. 4). For the opposite attitude would be unreasonable: How could a scientific hypothesis, which is supported by empirical evidence and which explain relativistic phenomena, be false and define a structure which is unreal? Thus, because it can hardly be disputed that Minkowski spacetime does indeed provide reliable knowledge and true understanding of relativistic effects, then it is justifiable to claim that Minkowski spacetime did not just introduced a conventional description of reality; in contrast, we should indeed claim that "Minkowski consciously announced a major discovery about the world, not a discovery of a mathematical abstraction" (Petkov 2020, p. 47).

With the present work, I would like to defend the following claim: Imagination was crucial in Minkowski's formulation of spacetime, and spacetime was discovered by Minkowski as a fundamental explanation of relativistic effects. I will show why we should take the fact that spacetime does indeed explain those effects as a basis from which we can infer that spacetime must be true, and therefore real. The thesis I argue for is the following: Minkowski's discovery can be construed as an imaginative fictionalist model-based strategy. The core of my argument lies in the idea that we can reconstruct Minkowski's discovery through an abductive scheme: because spacetime explains some phenomena, we can take it as being true. If it is true about counterparts in the physical world, we can take spacetime to be real.

[1]For a fully-fledged argument on that point, see Petkov 2009, chapters 4 and 5.

3 The philosophical debate on the reality of spacetime

As I mentioned above, the problem is that as long as we talk about scientific discovery, - in our case the discovery of spacetime, - then we should be able to support the claim that discovery is about something that really exists and that has physical characteristics and implications. Discovery should not be about the invention of an abstract, imaginary, scientific construct. That point is made clearly by Peter Achinstein, when he writes that what discovery is about "is discovering some physical thing or type of thing (such as the electron, the Pacific Ocean), rather than discovering some abstract object (such as a proof)" (Achinstein 2001, p. 268). Hence, talking about scientific discoveries should imply that we have strong evidence of the reality of the object discovered. I will adopt Achinstein's position: "Discovering something requires the existence of what is discovered. You cannot discover what doesn't exist (...)" (Achinstein 2001, p. 268).

That being said, the philosophical debate on the reality of spacetime revolves around substantivalism, relationism, and conventionalism. The substantival view is as clear as crystal about its ontological commitment to the existence of spacetime as a real physical entity. Indeed, that view proposes to take spacetime as a physical substance with an independent reality (Sklar 1974, p. 161). The word "substance" suggests that spacetime carries and support space and time relations between objects. Thus, spacetime can be taken as a structure that exists and that has specified features independently of the existence of any ordinary material objects (Sklar 1974, p. 161). Our universe, even without matter, would be a universe with a four-dimensional structure, where time flows, and locations are ordered in space. The crucial point is that spacetime not only has an independent existence from matter, but also that that structure is responsible for the relativistic effects we observe in the motion of matter. What I would like to show is that the substantival view is coherent with Minkowski's own ontological conception of spacetime.

Sklar writes that the substantivalist position is a natural position to hold since it can be read off from the scientific discourse on relativity. Sklar explains that once the spacetime structure of the world is defined, it is correct to assume that objects move, and that time flows, "in" spacetime (Sklar 1974, p. 164). It is the fact that events are given "in spacetime", and not with respect to an absolute space and an absolute time, that allows to trace the motion of physical object as building blocks entirely given in an independent four-dimensional structure, and to realize the absence of absolute uniform motion. Thus, the observation of relative motions can be seen as being dependent on the existence of a fundamental spacetime structure of the world. Yet, a counterposition to the substantival view, called relationism, asserts that the existence of spacetime is merely an illusion. According to that view, what there is are material entities, and material events, and what is fundamental are the spatiotemporal relations between objects. The idea of a spacetime structure existing independently is a confusion, since spatiotemporal relations exist only insofar as there are concrete events that happen in the world. Events do not happen in spacetime, but rather spatiotemporal relations are possible only because material points can be taken as happening in relation to each other.

I contend that if we take the relationist view of spacetime, then it is difficult to support the idea that spacetime was discovered as a real structure carrying events in the world. Indeed, the relationist view seems to suggest that spacetime is merely a convention used to describe spatiotemporal events, and that other alternative frameworks would be equally good to furnish the conceptual means for the description of spatiotemporal relations between objects. In fact, the conventionalist view asserts that when there is a competition between equally good theories and that we cannot discriminate among those theories on the basis of their observational consequences, we are free to decide, by convention or decision, which theory we want to use in order to save the phenomenon (Sklar 1974, p. 121). Usually, we choose the theory that is the most convenient in terms of simplicity and utility, and we accept that theory as true by convention. It should be noted that the conventionalist position was endorsed by Poincaré with regard to spacetime. Indeed, Poincaré showed that the standard geometric operations needed for relativity theory could be performed in an alternative four-dimensional framework. Poincaré showed that the Lorentz transformations could be carried out like a rotation as if ordinary space and time were combined in a four-dimensional formalism. Poincaré knew that "it would be possible to translate our physics into the language of geometry of four dimensions" (Poincaré 2017, p. 427). Nevertheless, Poincaré thought that the four-dimensional structure was just a matter of mathematical convention, and not a matter of a real physical substrate. He also believed that it was an inconvenient convention. Indeed, he writes: " To attempt that translation (to translate our physics into the language of geometry of four dimensions) would be to take great pains for little profit. (...) It seems that the translation would always be less simple than the text, and that it would always have the air of a translation, that the language of three dimensions seems the better fitted to our description of the world" (Poincaré 2017, p. 427). We can see that Poincaré did not endorse a substantivalist position on spacetime. As Petkov emphasizes, Poincaré failed to comprehend the profound physical meaning of the four-dimensional framework, and by neglecting the thought that spacetime can be seen as real physical dimension of the world, certainly was prevented in being attributed the discovery of spacetime (Petkov 2020, p. 22).

4 The role of explanation for Minkowski's discovery

All that being considered, the question that remains to be answered is the following: What explanatory power does Minkowski's spacetime have that supports the belief that spacetime is a true description? If it turns out that the explanatory power of spacetime is so obvious that it makes it unreasonable to deny its truth, then the argument suggests that spacetime is not just an imagined fiction, but a true description of reality. Consequently, the explanation provided by spacetime shall be taken as a real discovery about the physical world.

As remarked above, Minkowski imagined a model in which events are represented in space and in time through a particular value of a coordinate quadruple x, y, z, t. An event is thus represented by a point of space at a particular time, which is called a world-point. Minkowski further suggested that we could imagine all world-points of a singular object as tracing the trajectory of an object in spacetime through a world-line. For Minkowski, the set of all possible systems of values of these world-points constitutes the world, and world-lines are trajectories in that world. Accordingly, the world is made of as many infinite spaces as there are world-points, where time is individually given as a fourth dimension for every-world-point, defining the different moments of the existence of an object. We can see that spacetime provides a natural explanation of the requirement imposed by relativity that all laws of nature be the same in every reference frame. Indeed, since a world-point can be associated with an inertial observer in her or his reference frame, what the observer perceive is singular to that world-point, i.e can be described in terms of her or his own space and time in which she or he is at rest. In other words, every inertial observer describes what she or he perceives according to the same exact physical laws, in terms of the space and time in her or his reference frame. For the same reason, Minkowski spacetime explains why an observer at rest in an inertial reference frame cannot detect absolute motion. The fact that the observer is at rest at a singular world-point in spacetime makes it impossible for her or him to determine his motion *in* space, because there is not one privileged space with respect to which the observer can compare her or his motion, but an infinite set of possible values for other coordinate quadruples.

Moreover, it appears that while the observer should confirm that the time it takes for light to travel is always the same in her or his spacetime reference frame, it will be noted that since two observers have different times corresponding to their respective frames, then two observers can disagree on the time it takes for light to travel as observed in the other's reference frame. If we consider the world-lines of objects in spacetime, the fact that time is not absolute also finds a natural explanation: it is a consequence of the structure of spacetime. Indeed, since all moments of the time of every particle is entirely given in spacetime through the trajectory of its world-line, the world-lines of two different particle are distinct, in such a way that observers at rest can choose their time axes along a given world-line. Consequently, we see that the time of an observer at rest with respect to another world-line is relative to the other world-line. The comparison of the observers' time cannot be made with respect to an absolute time, but to the time given in their respective frames of reference. In spacetime, the shape of world-lines, i.e. their inclination of curvature, thus indicates the extent to which the motion of inertial frames with respect to another influences the perception of the events that are happening in every reference frame. The inclination of a world-line with respect to another involves a distance accounts for the dilation of time; also, the curvature of a world-line with respect to another makes it clear that the distance between the reference frames changes with time because of acceleration.

These two explanations show that we can attribute the physical meaning of the relativity principle and some of its effects to the structure of spacetime. Accordingly, it appears that spacetime is not just a description of relativistic effects, but the element that tells why these relativistic effects appear and are observable. Thus, spacetime enables to understand the observable effects of relativity. As the two examples above show, spacetime explains the two postulates of relativity, i.e. that natural phenomena run their course according to the same general laws in all reference frames, because the real times in all these frames can be treated equally, and that the velocity of light is constant. Yet, while spacetime tells that the proper times of the observers will not differ if they cover the same distance in inertial motion, it explains why the observers can disagree about the time in another frame, as measured from the other. Because spacetime tells that time is dependent on space, we see that the fact that the other world-line is inclined because it is in another frame which is not parallel to the other observer, we conclude that the distance between the spatial components of the frames as projected in the other frame implies that time will be observed as dilated. That is attributed to spacetime since it tells us that there is not just one absolute time, but that there are many times.

5 The role of imagination in the discovery of spacetime

I gave an overview of the debate about the reality of spacetime, and I suggest that a reconstruction of Minkowski's discovery of spacetime is coherent with a substantivalist view. Yet, as I explained in the first section of the paper, the question concerning the role of imagination in the formulation of spacetime, and the fact that one could argue that spacetime was invented as a mathematical construct, needs to be addressed. The problem to repeat, is the following: If spacetime was discovered as being the real structure of the physical world, then it must be known to exist as a physical thing, and it cannot be the product of Minkowski's imagination. We need to bridge the gap between the reality of scientific discoveries and the role and function of scientific imagination.

In any case, Minkowski himself claimed that mathematical imagination was the ability that had lead him to arrive at his conception of spacetime. He describes mathematical imagination as the habit of mathematicians to see a given problem through different points of view. In other words, mathematicians have the capacity of analyzing if different theoretical structures are equivalent, or if they differ in their mathematical and physical consequences. Minkowski saw how different groups of geometrical transformations could be approximated mathematically while they had disparate physical implications. Indeed, Minkowski showed that the Galilean group of geometric transformations appropriate to Newtonian mechanics, where the x axis is left fixed and the t axis is completely free such that all frames agree on simultaneity, was just a limiting case contained in the more general group of Lorentz-transformations. Minkowski considered the latter group by introducing an additional parameter c of the finite speed of light in the graphical representation of the rotations of space and time around the origins of coordinates. Minkowski demonstrated that the latter group of transformations was more intelligible and theoretically more satisfying considering the new developments in theoretical physics. Yet, he did so by stressing that privileging that group of transformations implied a belief that spatio-temporal phenomena manifest themselves in terms of a four-dimensional world. Minkowski called the latter implication the "world-postulate". He stressed that the world-postulate was not only more convenient for a symmetrical treatment of space and time coordinates, but also to show in a novel fashion how the true form of the laws of physics appear. Accordingly, Minkowski could claim that the whole world presents itself through that structure (Minkowski 2020b, p. 112).

The strength of Minkowski's imagination lies in the fact that the physical consequences of the Lorentz-transformations could be understood through visualization. Minkowski found how the algebraic relations of the Lorentz-transformations could be visualized through a geometric representation. The geometric visualization of the physical consequences of the algebraic features of the Lorentz-transformations, illustrated by the hyperboloid diagram on the basis of which Minkowski could further introduced the concepts of world-lines and light-cone, facilitated the intuition and understanding of the concept of spacetime and its implications. Still today, the visualization of specific geometrical relations between lines in four-dimensional spacetime diagrams are crucial in understanding why relativistic effects like time dilation, length contraction and the relativity of simultaneity are consequences of the geometric structure of spacetime. Consequently, imagination is not only a creative ability; its visual component has an explanatory power. Because what is imagined can also be communicated through visualization, the imagination of a scientist can be understood while being shown to others, and the others can see and become aware of special relations that could not be seen before. Hence, Minkowski's imagination can be seen as an essential factor in the reception of the discovery of spacetime.

Minkowski claims that mathematicians have the capacity to open new territories of investigation "within their pure fantasies" (Minkowski 2020a, p. 39). Mathematical imagination is a realm within which new facets of the physical world can be discovered. If it shown that mathematics interprets and corresponds to physical phenomena, we witness the power of the application of mathematical imagination to the physical world. In other words, "the visualization of nature's laws through geometry enters as the primary motivation for the creation of a new physical and metaphysical outlook" (Galison 1979, p. 117). For Minkowski, that the world in space and time is a four dimensional, non-euclidean manifold, should be seen as "almost the greatest triumph that the application of mathematics has brought about as of today" (note relativity principle). Furthermore, mathematical imagination is not just a description of the physical world; the mathematician's fantasies "contain the most complete real existence" (Minkowski 2020a, p. 39).

That being considered, the "thematic" aspect of Minkowski's imagination should be stressed. Thematic imagination refers to the core presuppositions and beliefs a scientist holds (Holton 1996, p. 201). Those presuppositions and beliefs are linked to a scientist's imagination because they circumscribe her or his thoughts on what exists, and what is fundamental. Hence, they are individual attitudes towards a specific scientific content and they shape individual beliefs concerning the status of specific objects. They should consequently be distinguished from paradigms, or research programmes, that are not linked to the faculty of imagining, but to theoretical and methodological guidelines of a whole community. Thematic imagination includes a scientist's core conceptual and ontological choices, and these are found in the way a scientist ranks entities, properties and relations according to their status in a theory. Accordingly, "themata" in science are the individual preferences and commitments that scientists adopt that constrain and motivate research (Holton 1975). For example, in the context of the philosophy of spacetime, "presentism", the view that holds that what the world is is the present as defined as everything that exists simultaneously at the present moment, as opposed to four-dimensionalism, which in contrast holds that the world is timelessly existing, time being already given, where the past and the future are already mapped out, constitute opposite themata. They are opposite, because if we consider the same thought experiments, but through the two different themata, we are lead to imagine scenarios that are totally different. Another example of the function of thematic imagination in providing fundamental thinking categories can be seen in the opposition between "relationism" and "substantivalism" in the philosophy of spacetime. Relationism asserts that while matter is what exists in the world, spacetime is an abstraction realized by metrical relations between material bodies. Substantivalism, in contrast, claims that spacetime is a "substance", and that that substance does exist independently of matter. The commitment to either of these themata indicates how profoundly they can influence how one can imagine the structure of spacetime and how they determine the description of properties of matter.

Concerning Minkowski's thematic imagination of spacetime, the crucial point is that he believed that spacetime is the true dimension of the world, and that physical events do happen in a four-dimensional world. For Minkowski, what we perceive are not objects in a unique three-dimensional space, but past images of objects that existed before at various distances in different three-dimensional spaces belonging to different moments of time. The objects we perceive are not evolving in a unique absolute space, but in multiple sections of three-dimensional spaces that are fragmented by time. Thus, the existence of spatially extended objects in the world must be imagined as a set of events containing different three-dimensional entities at all given moments in time of their histories. Consequently, we can visualize an object only by imagining its existence as being resolved through all its space points at different moments of time in spacetime. In other words, the identity of an object can be recognized by the identity of a substance in all time elements through the changes of its worldpoints in space. For Minkowski, we obtain "an image, so to say, of the eternal course of life of the substantial point, a curve in the world, a worldline" (Minkowski 2020, p. 112). Accordingly, the laws of physics, and the natural world itself, can be seen as resolved through these worldlines in spacetime.

6 How Minkowski's discovery can be taken as the outcome of a fictionalist strategy

As it was explained in the first section, it is difficult to assume that imagination alone can lead a scientist to a scientific discovery. Indeed, we have to admit that for a scientific construct (theory, model, hypothetical entity) to be counted as a scientific discovery, it should provide a true description of some aspects of the world, such that its confirmation should reveal that it has physical counterparts that are real features of the natural world. From the considerations of Minkowski's imagination presented above, we can claim that Minkowski believed that spacetime was indeed a true description of the real dimension of the world, and that Minkowski's imagination makes us believe that it is the case. Nonetheless that does not suffice to claim that Minkowski made a discovery about the physical world. It could be the case that Minkowski found an innovatory way to describe the abstract dimension of space and time in accordance to physical knowledge, but that spacetime is only a conventional way to frame physical claims in terms of a four-dimensional geometry.

What I would like to show in the following section is that imagination plays a crucial role in inventing and presenting scientific models, and that imagination has a function for scientific discovery if we conceive it as providing models that explain what we observe of physical reality. I would like to claim that if an imagined model does explain some aspect of the natural world, then it should be taken as a true model. By being true, it is rational to believe that what the model describes has real counterparts in the physical world, as long as evidence supports that belief. To think the contrary would be irrational, and contradicting evidence when there is some. I will develop that claim by presenting how scientific imagination fits into a fictionalist model-based strategy.

The problem with scientific imagination considered in itself is that it does not provide any clue as to the truth of the imagined object. When we imagine and think about an entity, a model or a theory, nothing in the act of imagining it provides us with reasons to believe that it is true of the world. In other words, even if a scientist has a priority over a certain object by being the first to have imagined it, that is not enough to classify that object as a scientific discovery, and to claim that the scientist is the discoverer. In fact, when leading scientists engage with imagination in order to visualize a scientific object and think about its implications, what is in play is a type of attitude toward a specific theoretical scenario. In other words, imagining the existence of physical bodies involved in relativistic effects in a three-dimensional space, or in a four-dimensional spacetime, is thinking about these objects *as if* the world could have different geometrical dimensions. Yet, even if one scenario happens to be theoretically more satisfying than another, nothing prompts us to believe that what is imagined is true. Therefore, we can imagine as many scenarios as we want without having to believe that one scenario constitutes a discovery about the world (Levy and Godfrey-Smith 2020, p. 5). Whoever is engaged in imagining that scenario is not logically required to believe that the scenario is true about the world, nor that the entities involved in the scenario are real and have counterparts in the natural world. Consequently, imagining the scenario in question with all its consequences cannot be seen as providing reasons for thinking that what was imagined constitutes a scientific discovery. As long as we take a realist standpoint on scientific discoveries, then we cannot take the products of imagination, things that are fictional, as true descriptions of the real world without further reasons to make us believe that what they describe is indeed the case.

As Salis and Frigg point out (Salis and Frigg 2020), while scientific imagination can be distinguished according to its content, which can be "propositional" or "objectual", what characterizes imagination is the epistemological attitude we have towards the content imagined. It must be noted that we can imagine a proposition, for example "an event happens in spacetime", and we can imagine an object, for example "a curved line in a light cone", but both varieties of imagination can be taken as being propositional because imagining an object can be seen as entertaining, or thinking about, the concept of the object, without forming a mental image of the object. According to the authors, there is a minimal core of propositional imagination (Salis and Frigg 2020, p. 30). It contains three features: Freedom, mirroring, and quarantining. Freedom is the feature that accounts for the fact that we are free to imagine whatever we want. As far as rationality is concerned, we are not free to believe whatever we want. To believe a proposition about a scientific object is to believe that proposition to be true, and the state of affairs that makes that proposition true does not depend on us. Yet, we are free to imagine that proposition, whether or not that proposition is true. We can think about it without commitment to its truth. Nonetheless, mirroring implies that if we imagine a given scenario and its consequences, then we should be committed to the inference that brings us to these consequences. Put differently, the inferences brought by an imagined scenario cannot be ignored whether or not the scenario is real. Finally, quarantining suggests that imagining a proposition does not entail believing that proposition. If we imagine a certain scenario, then that scenario is valid as long as it is quarantined by a certain context. In other words, because the scenarios are imagined, they are set apart in a fictional context, and consequently they do not engage to believe the scenario to be the case. Thus, for Salis and Frigg, the minimal core determining the necessary and sufficient conditions for something to be an instance of scientific imagination suggests that imagination does not imply the commitment to the truth or the existence of the content imagined. The upshot of the analysis of the minimal core is that scientific imagination does not imply commitment and belief of the truth of a given scientific object. Thus, claiming that scientific discovery can be the outcome of imagination is one step removed from the what the imagination itself is.

That being said, if imagination, alone by itself, is not a ground for taking something to be true, and to believe that it is a true description of the world, then we need to define its function in facilitating scientific discovery. If the imagination alone cannot provide us with the proofs of a scientific discovery, then its role in pointing to possibilities for new discoveries should be defined. In fact, if we are looking for the confirmation that an imagined scientific object should be considered as a scientific discovery, then we should consider to what degree that object tells us anything true about the actual world. Indeed, it might be that imagining scientific objects is one way to consider what scenarios provide a better understanding of the world. If imagining a scenario helps to explain a given phenomena, then we shall assume that the imagined object leads to the discovery of what is involved in the explanation.

The preceding discussion brings to the fore the idea that scientific objects that are thought and presented through the imagination can be taken as fictions. We can see them as fictions, because when a scientist develop a model or a mathematical structure from imagination, that model or mathematical structure can be taken as purely hypothetical. As we just saw, the minimal core of propositional imagination puts the commitment to the truth of imagined objects outside of the scope of imagination. However, independently of the way the scientific object is described, be it through a specific formalism, concepts or diagrams, it should be taken for granted that the object is indeed the description of an actual real-world system, yet not necessarily a true description.

The model-based science strategy has been put forward by Peter Godfrey-Smith and Roman Frigg (Godfrey-Smith 2005; 2009; Frigg 2009) to make sense of the fact that many scientists, to tackle scientific problems, come up with models that are "imagined physical systems" (Frigg 2009, p. 253). The scientific object is seen as an "imagined concrete thing" (Godfrey-Smith 2005, p. 734). In other words, before it is demonstrated that the model has explanatory power, and that the model has some empirical support, then the model remains imaginary or hypothetical, but it would "be concrete if it was real" (Godfrey-Smith 2005, p. 735). Hence, that strategy tries to account for the fact that before coming to genuine and actual scientific discoveries about the physical world, scientists usually present an hypothetical system as object of study and then demonstrate how that system explains some particular part of the world. The upshot is that when scientists talk about clocks, measuring-rods and rotating discs, these entities are fictional because they are imagined objects in a hypothetical situation. Nevertheless, the entities involved in the competing models can be taken as real physical things. Also, what a model explains about the world can be believed to occur in reality. If the model starts as a "fiction, a creature of the imagination", once it is shown that it does explain the target phenomena it is supposed to describe, then the model, if it existed, could be seen as a "concrete, physical thing" (Godfrey-Smith 2009, p. 101). As such, it can be concluded that the model provides understanding of the natural world. With respect to scientific discovery, what confirms that an imagined model can be considered as a scientific discovery is the fact that the model provides an explanation of a problematic aspect of the world. In other words, as long as a model provides understanding of a specific aspect of the natural world, what has been discovered is not fictional, but a novel explanation of a given phenomena through an innovatory model. The function of imagination is thus the medium with which explanations of a given phenomenon are created and represented.

If a model does explain a certain phenomenon, then the model can be taken as true. A scientific explanation is satisfying if it is grounded on empirical evidence, if it defines the factors that define why a phenomenon is observed, and it should have a certain predictive power. Those criteria suffice to rule out the objection that there are always multiple things that could explain a given scientific problem. The theoretical and empirical context together with the fact that revolutionary ideas and paradigms are not easily accepted in scientific communities always reduces the set of possible explanations to a very few competing ones. Consequently, it must be stressed that it would be unreasonable to admit that a given model is an explanation of a phenomenon, but to deny that the entities and relations the model posits do not have counterparts in the physical world. To be sure, empirical evidence has always the last word in confirming if a model is indeed a correct representation of the natural world. But if there is no empirical evidence *against* a given model that satisfyingly explain a given phenomena, then it is unreasonable to admit that the model is successful and resolve open questions, but to doubt that the model reflects real properties of the world. In contrast, it seems that the correct attitude to have toward that model is to conclude that the model is true, and by being true, we should conclude that what it describes has analogs in the natural world. For the opposite attitude is unsound. If one admits that a model is a correct explanation of a certain phenomenon, then one is bounded to acknowledge the truth of the model. Without any empirical evidence to the contrary, it would be unreasonable to claim that the model do not reflect real properties and object of the physical world. Hence, if one doubts that a model does explain a given phenomenon, but claims that the model is not adequate, then one should be able to point out what theoretical entities are not essential to the model, or do not in fact exist, and why another competing model can discard the latter model because it describes and explains the phenomenon more adequately. As such, the burden of proof is on the one who is in need of refuting a given theory, who needs to find evidence refuting the given model, a not on the one who provides a satisfactory explanation of a scientific problem.

7 Conclusion

The larger problem studied in that paper is to justify the claim that Minkowski discovered spacetime. The challenge stems from the realist position, and lies in finding an argument that support the view that Minkowski discovered a real physical substrate that exists out there in nature. As I emphasized, the difficulty is also rooted in the fact that scientific imagination was crucial for the definition and development of the fiction of spacetime. Thus, my objective was to bridge the gap between a realist and a fictionalist approach to scientific discovery. I attempted to answer two questions: Firstly, what kind of thing is spacetime: Is it an entity, a physical substrate (i.e. an underlying physical layer on which material objects are said to be coincident), or a mathematical model? Secondly, what grounds the claim that spacetime was discovered and is a real object, and not, in contrast, that it was invented, or suggested as an alternative fictional description of the classical space-time structure of the world. I suggested that the answer to the first question requires the substantivalist view of spacetime. According to it, spacetime is a physical substance with an independent reality, such that it carries and support space and time relations between objects. I showed how that view is coherent with a realist conception of scientific discoveries. Concerning the second question, my proposal is that the explanatory power of spacetime to explain why relativist effects are observable in the world supports the inference that spacetime must be a true description of reality. Since it is assumed by Minkowski, and by the substantivalist view, that spacetime is a real substrate, and not only an abstract mathematical model, I claimed that by being true, spacetime must be real. I focused on the fictionalist strategy to underscore the fact that while imagination is the realm of creation of abstract scientific models, the explanatory power of those models together with the empirical evidence of its truth allows one to infer that the fictional constructs implied in the model description can be taken as real natural objects of nature.

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