4 Realism and Explanatory Perspectives

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1 Introduction

A realist portrayal of science should accommodate the fact that science describes the world from numerous "perspectives." The nature of these perspectives and their interrelationships have for long been the bread and butter of history and philosophy of science. Realists continue grappling with challenges arising from the contingencies of grand theoretical perspectives (or "paradigms") and the ever-increasing plurality of models used for predicting and explaining various phenomena. These challenges turn on the inconsistencies that science seems to harbor, threatening the realist credo that science successfully works by virtue of "getting things right about the world." A natural realist hope is that these inconsistencies can be accommodated through an apt notion of "perspective," which is compatible with the basic realist credo.

What notion of "scientific perspective" should realism incorporate then? Answering this question helps with understanding scientific realism, and it is further instigated by recently developed perspectivist foils to more traditional realism by Ronald Giere, Paul Teller, and Michela Massimi.[1] These self-proclaimed "perspectival realists" have developed and defended views about the *perspectival nature of scientific knowledge* that put emphasis on it "being situated" in historical and modeling contexts (Massimi 2018b, 164). Thus perspectivists characterize scientific knowledge as "the inevitable product of the historical period to which those scientific representations, modeling practices, data gathering, and scientific theories belong," and as being embedded in "a prevailing cultural tradition in which those scientific representations, modeling practices, data gathering, and scientific theories were formulated" (Massimi 2018b, 164).

I am doubtful that the realist's optimism and commitment toward scientific progress and theorizing (especially in the fundamental sciences) are best captured in terms of scientific knowledge. Articulating an alternative vision for realism is a book-length project. The limited aim of this chapter is to present a different, realist-friendly notion of scientific perspective that does not concern knowledge. In particular, I wish to focus on what I call "explanatory perspectives" in relation to a (minimally) realist commitment to accumulating scientific *understanding*. Shifting the focus from knowledge to understanding yields a different kind of perspectivism, since understanding (as presently explicated) is not knowledge but rather an ability. The factivity of knowledge (namely that knowledge entails truth) is an almost universally accepted platitude about knowledge. By contrast, I will argue that explanatory perspectives in science and their indispensability spring specifically from the *non-factive* aspects of theoretical representations that maximize our scientific understanding.

In particular, I will argue that insofar as scientists' understanding can be enhanced by idealizations and/or false metaphysical presuppositions—whether mistakenly believed or merely entertained as useful fiction—such non-factive aspects of theorizing naturally give rise to mutually incompatible perspectives on natural phenomena. Briefly put, explanatory perspectives are ways of thinking about and representing a subject matter (say, light) in an explanatory context, which function to augment our understanding of the natural phenomena we are theorizing about (say, the rainbow). We will see, furthermore, that understanding-enhancing non-factive aspects can be involved in theories that best support genuine explanatory understanding in a given historical or modeling context, without scientists necessarily knowing all the respects in which these theories are idealized or false. All in all, I will conclude that increasing scientific understanding does not just amount to accumulating knowledge, since understanding is not factive in the way knowledge is, and non-factive aspects of theoretical representations can increase our understanding without us knowing their non-factive status. Rather, what matters for explanatory progress is that understanding-providing theories and models de facto latch on to reality in appropriate ways so as to satisfy explanations' basic factivity requirement (to be explicated below).[2]

The present focus on explanatory understanding is limited, of course, but not unprincipled. Taking a stance on scientific explanations, and the kind of understanding they provide of natural phenomena, is critical for demarcating realist commitments, since realists typically take scientific explanations seriously in a way that antirealists do not. For realists, "explanation" is a success term: the mind-independent reality determines whether scientists have actually succeeded in explaining and providing genuine understanding. To this end, realists defend a suitably *factive* conception of scientific explanation: genuine explanations must "latch on to" explanatory features of the unobservable reality.

The realist conception of explanations' factivity must be immediately qualified. On the one hand, the assumption that (genuine) explanations are in some sense factive is an integral part of the realist stance toward scientific reasoning and its progress. On the other hand, clearly, scientific explanations do not require "truth and nothing but the truth," for otherwise none of our current theories or models (which invariably incorporate falsehoods, approximations, and idealizations) would count as explanatory. The burgeoning literature on scientific explanation contains various suggestions for how to understand explanations' (qualified) factivity. I will begin by sketching one idea below, based on the counterfactual-dependence account of explanation (section 2). Regarding the issue of perspectivism more specifically, I will then argue that the ensuing account of explanatory understanding allows the realist to identify, accommodate, and motivate various perspectival aspects of science. The argument is based on a study of different theoretical perspectives from which optical phenomena have been explained and understood. Focusing on various explanations of the rainbow, I will show how a realist commitment to steady progress in scientific understanding is compatible with the fact that it has involved numerous mutually incompatible metaphysical perspectives on light (sections 3 and 4). In conclusion, I will reflect on the "realist" content of the ensuing perspectivism about explanatory understanding (section 5).

2 Explanatory Understanding and Perspectives

A realist portrayal of explanatory understanding is best painted with a clear conception of scientific explanation in mind. It is hard to make sense of how explanations "latch on to" reality unless we begin with a sufficiently clear account of what explanations *are* and how they *work* (Saatsi 2018b). To this end, I will now sketch one account discussed in detail elsewhere.[3] The key idea of this *counterfactual-dependence account* is that explaining is a matter of providing information about systematic patterns of counterfactual dependence. Explanatory counterfactuals are appropriately directed and change-relating, capturing objective, mind-independent modal connections in the world that show how the explanandum depends on the explanans. The explanandum and the explanans, conceptualized as variables that can take different values, stand for suitably individuated worldly features. Explanatory counterfactuals provide what if things had been different information, indicating how the explanandum would have been different had the explanans been different. Paradigmatic explanation-supporting relations are causal, but the counterfactual-dependence account also applies to various kinds of non-causal explanations, which appeal to geometrical, mathematical, or non-causal nomological dependencies based on, for example, symmetries.[4]

If explaining is a matter of providing information that correctly answers *what-if* questions, it is natural to regard as more powerful those explanations that enable us to answer *more* such questions (with respect to a given explanandum). This simple idea has rich implications regarding the notion of explanatory power (or "depth"), since there are many ways in which explanations can be compared regarding their potential to enable us to answer more or less such questions. Detailed analyses of explanatory power along these lines have been provided by, for example, Hitchcock and Woodward (2003) and Ylikoski and Kuorikoski (2010). The latter distinguish four aspects of explanatory power:[5]

> "**Non-sensitivity**" stands for an explanatory generality, having to do with the range of values that the explanans variables can take without breaking the explanatory relationship.
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> "**Precision**" stands for the degree of precision in which the explanandum is individuated relative to some contrast class.
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> "**Degree of integration**" stands for the connectedness of an explanation to other theoretical frameworks as a means of extending the range of *what-if* questions that an agent can (more easily) answer with respect to particular explananda, for example, by virtue of equipping the agent with new inferential resources.
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> "**Cognitive salience**" stands for "the ease with which the reasoning behind the explanation can be followed, how easily the implications of the explanation can be seen and how easy it is to evaluate the scope of the explanation and identify possible defeaters or caveats."
>
> (Ylikoski and Kuorikoski 2010, 215)

Explaining is a distinctive human activity, the goal of which is the provision of *explanatory understanding*, which we can think, along with Ylikoski and Kuorikoski (2010), as an ability to answer correctly a range of *what-if* questions in relation to a given explanandum. The more such answers an agent is able to provide (by an appropriate measure), the better understanding she has. In the light of this conception of understanding, there are both epistemic and pragmatic dimensions to explanatory achievements and progress of science. While the counterfactual-dependence account is a broadly speaking realist one (assuming an appropriate reading of the modalities it involves), the way in which explanations provide understanding requires that human beings stand in an appropriate cognitive relationship to them. It is a realist account by virtue of incorporating the *basic factivity requirement* that explanatoriness primarily derives from explanation latching on to worldly things that bear an objective, explanatorily relevant dependence relation to the explanandum. But explanatory theories and models also typically involve non-factive aspects that have to do with the pragmatic, human-related dimension of understanding. This is due to the way in which explanatory power can in various ways be increased by allowing a degree of misrepresentation in an explanatory theory or model.

Two of these ways are particularly pertinent to us. First, information about explanatory dependence can often be conveyed more effectively by using a representation that idealizes either the target phenomenon or the explanatory dependence at stake. The simplifying falsehoods that idealizations incorporate can thus contribute to an explanation's cognitive salience, and/or its degree of integration, and/or its non-sensitivity (Ylikoski and Kuorikoski 2010). Second, information about explanatory dependence can be most effectively grasped through a non-veridical metaphysical image of the system at stake. For instance, in many theoretical contexts human beings find it easier to cognitively operate in terms that are more familiar and concrete. Even if these cognitive benefits are brought about through partially misrepresenting the target or conceptualizing it in a wrong way—for example, in the way that *fluid* models of energy and electricity do (de Regt and Gijsbers 2017, 70–71)—they can help to provide genuine understanding, to the extent they enable theorists to correctly answer *what-if* questions that are underwritten by relevant explanatory dependencies in the world. (For example, one can use a fluid model to efficiently grasp dependences between electric current, resistance, and voltage.)

For a quick illustration, consider a simple explanatory model of tides as a sine function mapped on to the relative positions of the moon and the sun. Although the real explanatory dependence is not exactly sinusoidal, considerable mathematical convenience and cognitive salience (for anyone familiar with sine functions) is gained by modeling it as sinusoidal. Similarly, representing the gravitational effect of the sun and the moon in terms of Newtonian gravitational force ("pulling" the water) can enhance this explanation's cognitive salience (in a typical explanatory context), despite misrepresenting gravity as a force (acting at a distance). Modeling tidal phenomena in these terms can provide a powerful explanation, tracking the dependence of tides on the explanans variables (namely relative positions of the moon and the sun) accurately enough, in a way that enables an agent (with suitable training) to answer numerous *what-if* questions regarding the explanans.

This simple example illustrates the interplay between explanations' factive and non-factive aspects in providing explanatory understanding. On the one hand, tides really do counterfactually depend on the relative positions of the sun and the moon; the explanation is factive and explanatory to the extent it captures this dependence. On the other hand, an idealized representation, with non-veridical metaphysical posits to boot, can provide better understanding than a more faithful representation by virtue of enabling us to better answer more *what-if* questions, by making the dependence of tides on the explanans variables cognitively more salient to us. In this way the "user-friendliness" of an explanatory theory or model can trump fidelity as an explanatory virtue, since what matters is the understanding that it provides limited cognitive beings like us with particular inferential skills and training. Recognizing the importance of cognitive salience also helps to appreciate how the factivity requirement leaves room for the possibility that maximal explanatory understanding is effectively gained from several mutually incompatible theoretical contexts. For instance, while some *what-if* questions regarding tides can only be correctly answered in the context of general theory of relativity (with curved space-time and no gravitational force), the various *what-if* questions that arise in, for example, oceanography are best answered in the context of Newtonian gravity in a way that involves gravitational force.[6]

I will argue below that this kind of interplay between factive and non-factive aspects of explanations accounts for how different "explanatory perspectives" naturally arise in science. To anticipate the discussion of the rainbow below, consider 19th-century wave theorists of light, who advanced scientific understanding from the perspective of various ether theories. Going further back, the likes of Descartes and Newton presumably also advanced scientific understanding of light from their respective theoretical perspectives. More synchronically, in the contemporary context we can regard geometric ray and electromagnetic wave models of light, along with the models of modern quantum optics, as offering complementary perspectives on the whys and hows of light phenomena. These different theories and models have steadily advanced the scientific understanding of light, I will argue, by virtue of providing accumulating information about the dependence of light phenomena on various features of the world. These explanatory features are captured by explanans variables upon which the explanandum phenomenon depends in a way that is quantitatively encapsulated in these theories and models. This accumulation of factive explanatory content is compatible with radical differences in these theories' and models' ontologies and metaphysical presuppositions, which need not be factive. These (often) non-factive presuppositions can nevertheless form a cognitively indispensable part of the theoretical context in which the explanations are situated, as we will see below in relation to various explanations of the rainbow.

As a scientific realist, I wish to maintain that advances in scientific understanding are achievements that relate to the way the world is beyond the observable phenomena. Here is an obvious challenge: how to explicate the sense in which Descartes, Newton, Fresnel, and others advanced *genuine* explanatory understanding of light given that their explanations presupposed mistaken explanatory posits (e.g., elastic ether). Is it not the case that their explanatory successes were merely *apparent*, undermined by the subsequent ontological shifts away from their mistaken explanatory posits? In response, some philosophers forgo the factivity assumption (and realism), construing "explanatory understanding" so as to allow them to maintain that past scientists achieved genuine understanding despite their radically mistaken theories (de Regt and Gijsbers 2017; de Regt 2017). In the realist spirit, I am inclined to insist that genuine understanding requires factivity with respect to the relevant explanatory dependencies; hence I will respond to the question above by explicating this factivity in a way that is compatible with past theorists' understanding of light being irretrievably entwined with their particular theoretical and metaphysical perspectives. Luckily, the counterfactual-dependence framework provides a way to do this by virtue of allowing factive explanations to naturally incorporate also non-factive aspects that are broadly pragmatic and contextual.

From this point of view, theories and models that are false in various ways and degrees can provide genuine explanatory understanding by underwriting theorists' ability to make correct what-if-things-had-been-different inferences. To the extent these inferences are furthermore made true by (causal or non-causal) dependence relations in the world, a theory or model latches on to reality in a way that fulfills its explanatory function regardless of its non-veridical aspects. Moreover, these explanatory counterfactuals can invoke explanans and explanandum variables that relate to unobservable features of reality, giving sufficient substance to realist commitment regarding explanatory understanding.[7] So while the non-factive, pragmatic dimension of explanations, involving idealizations and metaphysical presuppositions, can give rise to different explanatory perspectives, one's realist commitment need only concern explanations' factive dimension and the progress that science de facto makes with respect to it (regardless of whether or not scientists *know* which aspects of their explanations are factive).

3 Reflections and Refractions on Explanatory Perspectives

Different explanations of the rainbow illustrate well realist commitment toward accumulating scientific understanding. From the dawn of science, the rainbow has challenged scientists, primarily as an object of explanation (as opposed to experimentation or intervention).[8] Various explanations of (different aspects of) the rainbow have been provided by generations of physicists, including many of the most illustrious minds in the history of science. These explanations have been provided from varied theoretical and metaphysical perspectives, spanning different scientific paradigms and modeling practices. Nevertheless, we will be able discern a steadily accumulating factive backbone of scientific understanding that transcends the radical shifts in the changing perspectives, from Descartes, through Newton and ether theorists like Fresnel, to the modern day. From the viewpoint of the counterfactual-dependence account, we can view the radical shifts in the metaphysics of light, which have motivated antirealist arguments from the history of science (Laudan 1981), as being part of the non-factive aspects of these explanations. This account thus enables the realist to explicate the sense in which there has been genuine accumulation of scientific understanding of the rainbow from Descartes onward.[9]

What does it take to "explain the rainbow"? Like any typical physical phenomena, there are various *aspects* of the phenomenon that can be singled out as the explanandum, as reflected by the following questions.

1. Why does a rainbow have the shape it does?
2. Why does the (primary) rainbow form an angle of approximately 42° from the antisolar point?[10]
3. Why do we see a secondary rainbow at approximately 51° from the antisolar point?
4. Why is there a darker (Alexander's) band of sky between the primary and the secondary rainbow?
5. Why does the primary rainbow have the color pattern it does (red on the outside rim, violet on the inside)?
6. Why does the secondary rainbow have the color pattern it does (red on the inside, violet on the outside)?
7. Why are there smaller "supernumerary arcs" occasionally visible inside the primary rainbow, with a specific spacing between them?

René Descartes conducted a detailed study of the rainbow, and published explanations of (1) through (4) in *Discours sur la méthode* (1637). According to Descartes, these aspects of the rainbow can be explained in terms of the spherical shape of the raindrops in combination with a refraction of light (into a raindrop), internal reflection, and a further refraction (out of a raindrop). By using a combination of graphical analysis and numerical calculations to trace the geometry of light rays, Descartes discovered that these assumptions about light and rain give rise to a higher concentration of light at the scattering angle of 138° for a single internal reflection and 129° for two internal reflections (corresponding to 42° and 51° angles of the primary and secondary bows from the antisolar point, respectively). Furthermore, the fact that no ray involving one internal reflection can be deflected less than 138°, and no ray involving two reflections can be deflected more than 129°, can be related to the relative darkness of Alexander's band.

Descartes's explanations were provided from within his "modificationist" theory of light, according to which our perception of colors is due to the way in which light's transmission rotates otherwise stationary ether particles, the variable spin of which causes our sensation of different colors. Needless to say, this metaphysics is radically at odds with our physics. For example, since Descartes assumed light's transmission to be *instantaneous*, it was not possible for him to think of this transmission as unfolding *over time*, involving refraction, a subsequent internal reflection, followed by a further refraction. Another metaphysical presupposition of Descartes's theory was that the law of refraction was due to light traveling *faster* in a denser medium (e.g., water) than it does in air (Dales 1973). (Many have puzzled over the consistency of this presupposition with Descartes's assumption that the speed of light is not finite!) Such vastly mistaken metaphysical notions and non-referential terms involved in Descartes's theorizing might seem to render his explanation of the rainbow wholly surpassed by later theories, and unsuitable as an object of realist commitment of any sort.

This would be hasty, however. The realist can side with the standard historical narrative, according to which Descartes was the first to gain understanding of several important features of the rainbow. In essence, this is because the features of light relevant for Descartes's geometrical analysis are entirely continuous with high-school-level geometrical ray optics, namely, the law of reflection and Snell's law of refraction. We can further explicate Descartes's understanding and its factivity from the viewpoint of the counterfactual-dependence account. Descartes managed to explain (1) and (2) by virtue of grasping the way in which the rainbow's apparent location (relative to the location of the light source and the observer) depends on the shape of the raindrops and the density of water (responsible for the specific angle of refraction).[11] By virtue of getting these dependencies right, Descartes gained the ability to correctly answer various *what-if* questions. For example, he would have been able to work out how things would be different if the reflecting drops were made of glass instead of water.[12] To the extent he gained this ability, Descartes had genuine understanding of the rainbow. The historical fact that he wasn't able to theorize and express the relevant dependencies independently of his overarching mechanistic worldview and metaphysics of light rays does not nullify this understanding.

Notably, Descartes was altogether unable to account for the colors of the rainbow. Newton's advance is standardly taken to consist in realizing that the index of refraction (e.g., for water) is different for different colors, and that white light from the sun is in some sense a "combination" of many colors. These critical ideas of the color-variability of refraction allowed Newton to answer questions (5) and (6). These ideas are, of course, again embedded in Newton's broader corpuscular theory of light, according to which light is composed of non-spherical particles, with red corresponding to the larger and more massive particles than those corresponding to blue, for instance. Mechanical laws involving corpuscles' motion through luminiferous ether would account for the law of refraction in terms of differences of velocity in different media. (In Newton's "emissionist" theory denser media, such as water, "pulled" these corpuscles differently depending on their size and mass, resulting in a higher velocity component perpendicular to the interface.) Again, the broader perspective within which Newton's explanation was embedded is well off the mark on the whole, but a realist can nevertheless maintain the standard story according to which Newton genuinely advanced scientific understanding of the rainbow. From the viewpoint of the counterfactual-dependence account this advance can be explicated in terms of the *further explanatory dependences* that Newton got right, involving a new explanatory variable corresponding to the color of light and a dependence of the angle of refraction upon that variable.[13] The key to Newton's explanatory advance is an approximately correct *quantitative* representation of this dependence.[14] This enabled Newton to calculate the widths of the primary and secondary rainbow, for example, and it enabled him to answer new *what-if* questions about rainbows. For example, unlike Descartes, Newton was in a position to consider how these widths would be different if the drops were made of more or less dispersive medium. Similarly, Newton and his followers explicitly worked out how tertiary (and higher-order) rainbows would appear, were the light intense enough to give rise to them (Boyer 1959, 247).

The Newtonian account still leaves some directly observable features of the rainbow unexplained. In particular, it says nothing about the *supernumerary arcs* that can occasionally be seen inside the primary rainbow (and sometimes also on the outside of the secondary bow). An explanation of these supernumeraries requires the introduction of new explanatory variables that go beyond geometrical ray optics that Newtonian corpuscular theory exemplified. These variables can be found in the wave theory of light, which encompasses optical interference phenomena responsible for the supernumeraries. Thomas Young first realized that the spherical shape of raindrops makes it possible for there to be two ray paths with different angles of incidence (into the drop), internally reflected at the same point at the drop's rear surface, such that their final angle of refraction is the same. For light of an appropriate wavelength this gives rise to destructive and constructive interference, resulting in the supernumerary arcs. This theoretical treatment renders the drop size (relative to the wavelength of light) a new explanatory variable upon which the spacing of the supernumeraries depends. Furthermore, Young's interference theory of the rainbow explained also a number of other puzzling qualitative features that had been observed. For example, it explained why the bow is brighter near the earth and why the supernumerary arcs usually only appear near the highest part of the bow: these features depend on the relative size of raindrops, which tend to increase in size as they fall.

Again, these advances in scientific understanding were embedded within a particular broader perspective on the nature of light: Young (at the time in question) not only adhered to an optical fluid ether theory but also regarded light waves as longitudinal, akin to sound. This early wave theory was radically mistaken in many ways and unable to account for, for example, the polarization of light, but it nevertheless encompassed the right explanatory dependencies between the relevant explanatory variables, which are carried over to the later theoretical perspectives of the elastic solid ether theory, as well as the electromagnetic theory and beyond.

The subsequent idea that light waves were transverse was developed in a mathematically sophisticated way by Fresnel to explain various polarization phenomena. This now provided understanding of features of the rainbow that aren't visible by the naked eye, such as the fact (first noted by Biot in 1811) that the rainbow light is strongly polarized in the tangential direction.[15] Again, this explanatory advance was embedded within Fresnel's broader elastic ether theory of light. Since such ether does not exist, prominent antirealists have hailed Fresnel's theory an exemplar of a highly successful theory that is not even approximately true, undermining (certain kinds of) "convergent" realism (Laudan 1981).[16] Be the status of Fresnel's theory as "approximately true" as it may, the realist can stand by the standard story that takes Fresnel's contribution to explanatory understanding of the rainbow to be both genuine and lasting: the new explanatory variables introduced by Fresnel's explanations (e.g., light's wavelength relative to the drop size and the direction of light's polarization) capture further explanatory dependencies in the world. The historical fact that Fresnel (and his contemporaries) were unable to express and theorize about the relevant explanatory dependencies independently of the metaphysics of elastic ether does not nullify this contribution.

A realist would, of course, expect the theoretical perspectives on light subsequent to Fresnel to also recognize and build upon the explanatory dependencies that his theory captures. As far as I can see, this expectation is fully borne out in the rich history of accumulating understanding of the rainbow that continues still today. For example, over the last couple of decades there have been advances in understanding further aspects of meteorological rainbows in terms of their dependence on the distribution of *non-spherical* (oblate) raindrops (see Haußmann 2016 for a review).[17] The shape of raindrops has thus become an explanans variable in a deeper, more concrete way than it was before.[18] Furthermore, typical rain showers feature a broad variety of different drop sizes. It is an outstanding (although already partly met) challenge to work out how different observable features of the rainbow (e.g., colorization or the exact shape or brightness distribution) depend on new explanans variables that quantify a rain shower's physical features, such as its drop-size distribution and the drops' deviation from perfectly spherical shape.

These challenges largely belong to the domain of applied mathematics, a solid basis to which is provided by an exact description, in terms of Maxwell's electromagnetic theory, of the scattering of plane wave from a transparent dielectric homogeneous sphere, provided by Lorentz (in 1890) and Mie (in 1908). In the next section I will briefly discuss some developments in this area of applied mathematics, but I have already said enough to outline a realist stance toward the progressive trend that started with Descartes and has continued ever since. In the realist spirit we can view science as providing genuine understanding of natural phenomena, such as the rainbow, in terms of features of reality "behind the appearances." This presupposes a conception of explanation and understanding that is *factive* (albeit in an immediately qualified sense), supported by the counterfactual-dependence account of explanation. This account allows us to explicate the accumulating understanding in terms of scientists' increasing ability to answer counterfactual *what-if* questions regarding various explanatory variables. Our theories and models capture better and better how different explanandum variables depend on different explanans variables. These variables capture the dependence of different aspects of the rainbow on physical features of the world that are not observable, such as the raindrops' shape and their size relative to light's wavelength, and the direction of light's propagation and polarization. The accumulation of this factive content is fully compatible with the fact that different explanatory theories and models also have non-factive elements that give rise to mutually incompatible perspectives on light, due to, for example, the different ontological and metaphysical presuppositions that were an inextricable part of Descartes's, Newton's, and Fresnel's theorizing about light.

4 Which Explanation Is the "Best"?

So far, I have looked at the accumulation of understanding over the history of changing "paradigms" in optics. Let's now consider the (minimal) realist outlook in relation to mutually incompatible models employed in the current state of the art. The classic Lorentz-Mie theory of scattering can be regarded as the "complete and fundamental" theory of rainbow scattering. It is taken to deductively entail all the optical properties of an "ideal" rainbow.[19] Since this model of Maxwell's theory contains all the answers to different *what-if* questions about the (ideal) rainbow, one might think that we have reached the explanatory bedrock (regarding "ideal" rainbows)—the ultimate explanatory framework. Yet understanding of the rainbow has progressed much further since the inception of the Lorentz-Mie theory. Since scientists regard the subsequent development of, for example, idealized "semi-classical" explanatory models to provide deeper understanding, a realist must acknowledge the indispensability of further explanatory perspectives beyond the "complete and fundamental" theory. Hence, in some sense the fundamental theory only provides a limited explanatory perspective, which needs to be complemented by other vantage points to yield more comprehensive understanding. How should a realist interpret this plurality of explanatory models?

Different explanatory perspectives at stake here can again be understood from the viewpoint of the counterfactual-dependence account. In order to explicate the explanatory value of the idealized "semi-classical" models, I first need to say a few words about these further advances on the Lorentz-Mie theory.[20] These advances primarily turn on approximation schemes, such as the Complex-Angular-Momentum (CAM) method, which aim to extract the key features of the dynamics of the electromagnetic wave in a way that makes them transparent to us. As Nussenzveig puts it:

> A vast amount of information on the diffraction effects that we want to study lies buried within the Mie solution. In order to understand and to obtain physical insight into these effects . . . it is necessary to extract this information in a "sufficiently simple form."
>
> (Nussenzveig 1992, 45)

This simplicity, which is "to some extent . . . in the eye of the beholder" (Nussenzveig 1992, 210), can be achieved by suitable "semi-classical" approximations, occupying the rich theoretical borderland between geometrical ray theory and the wave theory. By working with idealized ray-theoretic concepts, while simultaneously making sufficient room for interference and diffraction effects, these approximations yield theoretical representations that render the relevant explanatory dependencies cognitively more transparent.

Although the Lorentz-Mie theory provides an exact solution of plane wave scattering by ideal spherical drops, it has the pragmatic downside of leading to a mathematical series that converges very slowly for particles of the size of raindrops. Thus, this theory is *oracular*: a powerful enough computer can crunch through a sufficient number of terms (typically several thousands) to yield however precise values of scattering amplitudes one desires, against which approximate solutions can be compared. However, due to the high number of terms and the series' lack of further physically interpretable structure, it provides no insight into aspects of the scattering process upon which the spacing of supernumerary bows depends. (A Laplacean demon might disagree, of course!) The first step beyond the Lorentz-Mie theory is to shift to the Debye series, which mathematically decomposes the wave front into "partial" waves, some of which are externally reflected, some transmitted directly through the drop, and some transmitted after *n* internal reflections. This series, which also provides an exact solution (equivalent to the Mie series), captures at the level of the wave theory the idea that the overall scattering dynamics can be represented as a sum of different processes, involving, for example, light that undergoes one internal reflection before transmission (responsible for the primary bow), light that undergoes two internal reflections (responsible for the secondary bow), and so on, with some of the light being "trapped" inside the drop for a number of revolutions before transmitting. However, the Debye series by itself does not allow us to identify which aspects of the scattering dynamics thus represented critically contribute to the features of the supernumerary bow.

Enter the CAM method. This approach allows the slowly converging partial wave series to be transformed into an approximate, rapidly converging expression in terms of "poles" and "saddle-points" in a complex-valued angular momentum space, representing the main contributions to the scattering amplitude at the primary rainbow angle. An interpretation of these poles and saddle-points in terms of both wave theoretic concepts (e.g., "tunneling" and "evanescent waves" near the drop's surface), *as well as* ray-theoretic concepts, provides the best means to bring out those aspects of the overall scattering process upon which the explanandum depends. By doing so it improves our explanatory understanding of the supernumeraries. Thus our best understanding of the rainbow involves representing light both as a wave and as a ray. How should a realist understand this plurality of incompatible perspectives? On the face of it, the explanatory indispensability of ray concepts could be taken to suggest that the ray-theoretic perspective is revealing features of light scattering that the wave theoretic perspective somehow misses.

I think the counterfactual-dependence account nicely captures the explanatory power of the semi-classical CAM perspective, even if we take Maxwell's theory to provide the "fundamental" story.[21] This is due to the importance of explanations' cognitive salience (cf. section 3). To illustrate this, consider a specific explanandum: why is the spacing *S* of the supernumeraries of a given rainbow 1.65°? From the counterfactual-dependence viewpoint, an agent understands the spacing if she is in a position to answer *what-if* questions of the sort "how would *S* be different if . . ." with respect to explanans variables, that is, wavelength and drop size, over some range of possibilities. Using the Lorentz-Mie theory the agent is capable of answering these questions, but only if assisted by a sufficiently powerful computer. The way in which the explanandum depends on the explanans is cognitively opaque to her.[22] The CAM approach provides deeper understanding by virtue of enhancing the agent's ability to answer such questions by revealing a much simpler explanatory dependence of the scattering amplitude on the explanans variables, without compromising the level of accuracy required for answering the explanandum at stake. This simplicity is not just an increase in computational efficiency but also a matter of representationally breaking down, in an idealized way, the overall Mie scattering into distinct processes, only some of which effectively contribute to the rainbow by largely determining *S* as a function of the explanans variables. This explanatory dependence is cognitively more transparent to us, and hence a theory that captures it provides (in a sense) a better explanation. In this way the counterfactual-dependence framework explicates the progress in the understanding of the rainbow achieved by moving from the *exact* Lorentz-Mie theory to the CAM *approximation*, the less fundamental explanatory notions of which (such as light rays and evanescent "surface" waves) can thus feature in our "best" explanation of the rainbow. This improvement is not a matter of introducing new explanatory variables that ontologically transcend the Lorentz-Mie theory (Pincock 2011), nor is it a matter of providing more fine-grained information about the explanatory dependence. Rather, the improvement has to do with the way in which the CAM approach identifies critical explanans variables upon which the explanandum depends *in a simple way*. These variables and the explanatory dependencies are fully grounded in the wavelike nature of light and its dynamics; they are not indicative of properties that somehow transcend Maxwell's theory.

What counts as the "best" explanation partly depends on the context that determines how the different dimensions of explanatory depth are weighed. The CAM approach can be taken to provide the most powerful explanation in the context of "pen and paper" mathematical physics, while in the context of a computer-assisted study of actual (non-ideal) meteorological rainbows, with variable-sized hamburger-bun-shaped drops, the generalized Lorentz-Mie theory backs the most powerful explanatory understanding.[23] There is no objective answer as to which explanation is the "best" independently of such contextual factors. By the same token, even though the earlier explanatory accounts from Descartes onward are all strictly speaking false (even if we ignore their supererogatory metaphysical content), these accounts can still be valuable sources of understanding, and they can indeed be viewed as providing the "best" explanation of certain aspects of the rainbow in suitable explanatory contexts. For example, in the context of high school physics the gist of Descartes's account (sans Cartesian metaphysics) provides the best explanation, simply because it provides the cognitively most transparent way to capture the dependence of the approximate angles of primary and secondary bows upon the spherical geometry of raindrops given the laws of reflection and refraction. Overall, the indispensable plurality of (strictly speaking) incompatible explanatory perspectives can thus be accommodated in terms of the pragmatic dimension of understanding, in a way that is compatible with the basic factivity requirement of (minimal) realism.

5 Implications for Scientific Realism

The case of the rainbow typifies the way in which scientific understanding is situated in and colored by radically different ways of thinking about what there is in the world and what laws of nature describe. Our current science provides one set of perspectives, and we should be open to yet different, further theoretical perspectives that may be conceived in the fullness of time. In so far as scientific realism involves a commitment to genuine scientific understanding and progress thereof, it must embrace and make sense of such explanatory perspectives.

Notwithstanding the plurality of explanatory perspectives, there is a standard story of the accumulating understanding of the rainbow due to Descartes, Newton, Young, Fresnel, and many others. I have argued that a well-motivated philosophical account of explanatory understanding vindicates and further explicates this story. The realist dimension of this account is due to the assumption that genuine explanations are underwritten by explanatory dependencies in the world. This is the basic factivity requirement of the counterfactual-dependence account. Explanatory understanding, in turn, can be construed as an agent's ability to make correct counterfactual *what-if* inferences. Thus construed, understanding has several distinctly pragmatic aspects, which can be associated with the non-factive elements of explanatory theories and models, such as idealizations and mistaken metaphysical presuppositions, that are involved in different explanatory perspectives. From the viewpoint of this account, a realist can make sense of the steady accumulation of genuine understanding of various optical phenomena, including the paradigmatic rainbow, regardless of the fact that all explanations are situated in one or another theoretical perspective.

Clearly, this realist account is rather minimal in its commitments to what the unobservable world is like. In particular, it does not incorporate the ("standard" realist) notion that our current best theories are "approximately true," or that they approach some kind of "ultimate" (God's-eye) perspective. And it neither supports nor presupposes inference to (the approximate truth of) the best explanation. (Indeed, as we have seen, what counts as "best" partly depends on the context in which explanations are given and assessed.) At the same time, the kind of understanding that we can attribute to scientists satisfies (suitably minimal) realist ambitions given the factivity assumption, and it certainly goes beyond antirealism according to which theories of light are merely effective instruments for making predictions of observable phenomena and guiding practical applications and interventions.[24] The factivity assumption requires that genuine understanding is underwritten by objective worldly facts about how the explanandum really depends on the explanans. Understanding accumulates when our explanatory theories and models give us the ability to make more *what-if* inferences, the correctness of which corresponds to worldly dependence facts. This accumulation can be partly a matter of new explanations containing explanatory information in a cognitively more salient form, given our cognitive makeup, inferential abilities, and training. And, more importantly for the realist, the accumulation of understanding is often a matter of introducing new explanatory variables that represent further explanatory dependencies, typically in the form of functional equations linking the explanans and the explanandum. These variables capture physical features of the world that need not be observable. In a given theoretical perspective, these variables can be given a rich metaphysical interpretation, which the realist should not be committed to. Or, these variables can be presented in an idealized way, which the realist should not be committed to either. Rather, she should only be committed to the most minimal interpretation of the explanatory variables that allows her to speak of the explanatory dependencies.

In the case of the rainbow, this commits the realist to explanatory variables that capture properties of light and rain, such as the shape of the raindrops, their size relative to light's wavelength, and the direction of light's propagation and polarization. The fact that there are various perspectives in which such explanatory variables have been embedded is an essential part of the way *human beings* understand the world, involving also non-factive aspects of our explanatory theories and models. Exactly which aspects are non-factive? We do not know. Some aspects of explanations are justifiably regarded as non-factive idealizations, given their discord with our theoretical beliefs and (typically) the prospects of de-idealization. But on the whole we are not reliably able to sharply demarcate between our current explanations' factive and non-factive aspects, especially when it comes to the interpretation of the variables that feature in functional relationships that support explanations in the counterfactual-dependence mode. This is a lesson we have to learn from the history of science, as some of the more minimally inclined (for example, structural) realists have acknowledged (Saatsi 2019). At the same time, nothing in the history of science speaks against the broader realist notion that steady and genuine explanatory progress is being made with understanding-providing theories and models that de facto latch on to reality better and better (in the sense of the basic factivity requirement). This progress in scientific understanding of the world does not amount to accumulating knowledge, however, since understanding is not factive in the way knowledge is, and non-factive aspects of theoretical representations can increase our understanding without us knowing their non-factive status. Thus while I agree with the self-proclaimed "perspectival realists" that a notion of "perspective" helps in articulating scientific realism, I do not think we should necessarily associate this notion with knowledge the way they do.

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Notes

1. See, e.g., Giere (2006), Massimi (2018a), and Teller (2018). Massimi (2018b) offers a review.
2. This account of progressive scientific understanding dovetails with my view that theoretical progress in science in general does not reduce to accumulation of knowledge. See Saatsi (2019).
3. See, e.g., Hitchcock and Woodward (2003), Woodward (2003b), Woodward and Hitchcock (2003), Ylikoski and Kuorikoski (2010), and Jansson and Saatsi (2017).

4. See, e.g., Saatsi and Pexton (2013), Reutlinger (2016), Saatsi (2018a), Jansson and Saatsi (2017), and French and Saatsi (2018).
5. Ylikoski and Kuorikoski (2010) also present "factual accuracy" as an aspect of explanatory power. In my presentation this is built into the characterization of explaining being a matter of *correctly* answering *what-if questions*.
6. See Bokulich (2016) for related, more general discussion of the usability of the Newtonian gravitational theory in oceanographical explanations, in the context of which "the classical Newtonian force picture does [the best] job of making transparent the relevant patterns of counterfactual dependence" (Bokulich 2016, 273).
7. Woodward (2003a) has called a position along these lines "instrumental realism."
8. Experiments with prisms and such have of course been central to the scientific study of the rainbow from the Middle Ages onwards.
9. Such accumulation is recognized in the standard history of this area of science, as told by both historians of science and scientists themselves. See, for example, Boyer (1959); Haußmann (2016).
10. The antisolar point is the point on the celestial sphere that is directly opposite the sun from an observer's perspective.
11. Clearly Descartes was not in a position to answer correctly any appreciable range of *what-if* questions regarding these variables; for example, what if raindrops were oblate thus and so, as opposed to being spherical? Thus, his explanation should be considered quite shallow. But for a realist it marks a genuine explanatory advance nevertheless.
12. This is indeed something that Christiaan Huygens explicitly calculated in 1652. The answer is that the bow angle would be approximately 25° instead of 41° (Boyer 1959).
13. In due course this variable comes to be associated with light's wavelength.
14. As Newton put it: "the Science of Colors becomes a speculation as truly mathematical as any other part of *Opticks*" (Boyer 1959, 241).
15. For the primary rainbow, the single internal reflection angle near the caustic is very close to Brewster's angle, at which no p-polarized light (corresponding to the radial direction as seen from the observer) is reflected.
16. See Saatsi (2015) for further discussion of Laudan's reasoning and its limitations as an argument against realism.
17. A natural raindrop typically resembles an asymmetrically squashed sphere due to air resistance (the bottom part being flatter than the dome-like top, like a hamburger bun), so the optical scattering properties for real-life rain showers differ from those of a collection of perfect spheres.
18. See note 10.
19. The generalized Lorentz-Mie theory goes beyond plane waves and spherical drops (Gouesbet and Gréhan 2011).
20. The details that I must brush over here are well summarized in Pincock (2011) and reviewed in more detail in, for example, Adam (2002) and Nussenzveig (1992). I broadly agree with Pincock's assessment of the explanatory virtues of these models, which he however expresses independently of any particular way of understanding explanation or explanatory understanding. A further important part of the scientific understanding of the rainbow, which I do not even touch here, concerns the universality of rainbow phenomena over variation in, for example, drop shapes. See Batterman (2001, 2005) and Belot (2005).
21. Of course, Maxwell's theory does not provide a truly fundamental theory of light, since it is not a quantum theory.

22. In this tune, an epigraph in Nussenzveig's classic exposition of the CAM approach reads: "it is nice to know that the computer understands the problem, but I would like to understand it too" (Nussenzveig 1992, 37).
23. The Debye approximation, upon which the CAM approach builds, is not valid for non-spherical drops.
24. Here I differ from de Regt (2017), whose account of understanding also emphasizes the contextual nature of understanding, but articulates it in a way that is empty of any realist commitment. See also de Regt and Gijsbers (2017). Unfortunately, I don't have space to engage here with de Regt's account, which I regard as insufficient for making sense of the intertheoretic relations between different theories and models of light. See also Khalifa (2017) and Woodward (2003a).

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