manuscript No.
(will be inserted by the editor)

Simplicity in Astrophysics and Cosmology

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Received: date / Accepted: date

Abstract The significance of simplicity in theoretical frameworks has been a longstanding subject of discussion within the realm of the philosophy of science. This ongoing debate has generally revolved around two contrasting viewpoints. The initial perspective regards simplicity as an epistemic virtue that provides justification for believing in the truth of a theory. In contrast, the second perspective views simplicity merely as a practical virtue, contributing to prediction, computation, or bestowing aesthetic value upon a theory. I propose that there is an overlooked role that simplicity plays in physics. Simplicity can serve as an indirect epistemic virtue oriented towards understanding. In this context, simplicity does not directly bolster our confidence in the truth of a theory but aids in comprehending relevant physical phenomena, thereby facilitating further progress in theoretical development. I will elucidate this perspective, demonstrating its applicability to physics by drawing on historical instances from J.C. Maxwell's early work on electricity and mechanical models of gases. Subsequently, I will illustrate that this interpretation of simplicity finds manifestation in contemporary astrophysics and cosmology, with examples drawn from orbital modeling and the study of cosmological perturbations.

Keywords Simplicity · Astrophysics · Modeling · Cosmology

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1 Introduction

Simplification holds widespread utility in scientific practice, with accounts of its nature generally falling into two broad categories. The first perspective sees simplicity as epistemic, suggesting that it guides us toward truth or provides compelling reasons to believe in a theory. Consequently, proponents of this viewpoint, such as Newton (2016), Whewell (2004), Einstein (1934), Reichenbach (1938), as well as more contemporary scholars like Kelly (2011) and Lipton (2004), argue for a preference for simpler theories on epistemic grounds. On the other hand, the opposing stance posits that simplicity is purely pragmatic. In this view, simplifying assumptions are introduced not to indicate truth but for practical reasons. Advocates of this standpoint, including Duhem (1991), van Fraasen (1980), and Norton (2020), emphasize the utilitarian nature of simplification in scientific practice.[1]

Unfortunately, the goal of establishing comprehensive global accounts of simplicity is unlikely to succeed. The term "simplicity" itself is inherently vague, lacking a distinct threshold at which a theory can be deemed simple. Instead, theories exist on a spectrum, being simpler than some and more complex than others (Gauch 2003). Compounding the challenge is the absence of an absolute standard for simplicity; it is a relative concept, varying from one scientist's perspective to another (Kuhn, 1977). Simplicity, moreover, proves to be ambiguous, manifesting in various forms. A theory may exhibit ontological simplicity, like string theory, yet possess mathematical intricacies. Conversely, a theory could be mathematically elegant while being ontologically complex, as exemplified by the standard model of particle physics, which encompasses an array of fundamental particles.

The multifaceted nature of simplicity often leads to conflicting interpretations, rendering a theory not unequivocally simple (Kuhn, 1977). Given these inherent challenges, global accounts of simplicity encounter difficulties. Such accounts hinge on well-defined notions of simplicity that can be uniformly applied across diverse scientific disciplines and contexts. However, the inherent vagueness, relativity, and ambiguity of the term "simple" cast doubt on the existence of a universal and unequivocal notion of simplicity. Consequently, what emerges as imperative is the pursuit of a "local" account of simplicity (Achinstein 2019). This approach entails scrutinizing individual theories or scientific disciplines to discern the specific roles played by simplifying assumptions, acknowledging the nuanced and context-dependent nature of simplicity in scientific inquiry.

The primary objective of this paper is to provide a localized account of simplicity within the realms of astrophysics and cosmology. Anderl (2018) has previously presented an insightful analysis of simplifying assumptions in the modeling of interstellar shocks. However, there exists another dimension to the role of simplicity in the modeling of astrophysical and cosmological

[1] A related, but distinct view is that simplicity is an aesthetic value. Simpler theories are more beautiful, though not necessarily closer to the truth, but should be preferred on aesthetic grounds. See von Neumann (1961) for an example of this position.

phenomena. This role can be best characterized as occupying a middle ground between the epistemic and pragmatic positions. The simplifying assumptions, while pragmatic in nature and not inherently reflective of physical realism, serve a purpose beyond direct truth indication. Instead, they facilitate an understanding of intricate phenomena, thereby fostering the development of more realistic models. I will refer to this perspective, as detailed in section 2, as the "indirect understanding-oriented epistemic value" view of simplicity.

The concept I will defend aligns with Maxwell's approach, as evident in both his 1855 paper "On Faraday's Lines of Force" (2011) and his 1860 paper "Illustrations on the Dynamical Theory of Gases" (2011), as will be elaborated upon later. It's crucial to note that I do not assert this as the exclusive manner in which simplicity contributes to astrophysical modeling. Instead, my contention is that this represents a significant avenue through which it does so. This assertion will be substantiated through examples drawn from orbital modeling in astrophysics and the modeling of cosmological fluctuations, which give rise to anisotropies in the Cosmic Microwave Background radiation and the evolution of large-scale structure.

In section 2 I will provide a more detailed analysis of the notion of simplicity. I will set out the notion I argue is relevant in the case of astrophysics and cosmology. In section 3 I will present historical examples from Maxwell that illustrate the proposed view of simplicity. In section 4 I will turn to astrophysics and show that the view espoused here can be found in modeling of orbital dynamics in galaxies. In section 5 I turn to cosmology and show that the view can be found in cosmological modeling of cosmological fluctuations as well. I will conclude in section 6 with some further thoughts.

2 Simplicity

2.1 Epistemic and Pragmatic Simplicity

The debate concerning the nature of simplicity is often regarded as a debate between two positions.The first stance posits simplicity as an epistemic virtue.

Definition 1 Simplicity is an epistemic virtue iff, all things being equal, the fact that a theory is simple is a good reason to believe the theory is (approximately) true.

This definition is really just a schema, since what is meant by “simple” is not defined and in fact will vary from context to context. But, the definition captures what many writers mean when they imply that simplicity is an epistemic virtue. The contrasting position is that simplicity is not a good reason to believe the theory. Rather, simplicity is a practical value that is useful for certain purposes.

Definition 2 Simplicity is a pragmatic virtue iff the fact that a theory is simple assists in the making of accurate predictions or calculations, the development of technology or provides some aesthetic value.

These definitions are not inconsistent. A simple theory can be both epistemically and pragmatically virtuous in the senses mentioned here. In fact, it is reasonable to assume that if simplicity is an epistemic virtue then it will contribute to making accurate predictions. What opponents of the epistemic view claim is that simplicity is *merely* a pragmatic virtue. Simple theories are not more likely to be true, they are just easier to work with and so provide more utility.

2.2 Direct and Indirect Epistemic Virtues

These accounts, however, do not fully encompass the role that simplicity plays in scientific theorizing. Even if taken locally, the definitions do not exhaust the virtues of simplicity. A further distinction can be drawn between direct and indirect epistemic virtues.

Definition 3 A virtue V is a direct epistemic virtue iff the fact that a theory has V is, all things being equal, a good reason for believing that it is (approximately) true.

This is just a broader statement of Definition 1. However, there is another way in which something can be an epistemic virtue.

Definition 4 A V is an indirect epistemic virtue iff theories that have V are more likely to be the basis of a (approximately) true research programs.

The idea is that the theories themselves are not true and the fact that they are simple doesn't give you reason to think that they are. But, the theories constitute the foundation of a continuing research program that will eventually lead to an approximately true theory. One might think that string theory exhibits this sort of virtue. The simplicity of string theory does not give you reason to think that the theory is true, but it may give you reason to think that the theory is part of a truth-directed research program. Of course, whether or not simpler theories exhibit indirect epistemic virtue is an empirical question, not to be addressed here. Rather, the point is that the typical narrative surrounding the virtue of simplicity is too restricted and there are indirect ways in which a virtue can be epistemic.

2.3 Truth-Oriented and Understanding-Oriented

This leads to the important distinction to be drawn for the present cases in astrophysics and cosmology. There are (at least) two epistemic ends that can be met by appealing to epistemic virtues. The first is a truth-oriented virtue.

Definition 5 V is a truth-oriented epistemic virtue iff V leads to the truth, whether directly or indirectly.

Again, this is what most writers have in mind when they discuss an epistemic theoretical virtue. But, there is another epistemic end that is related to, but not identical with, truth. This is the end of understanding.[2]. Often observed phenomena are too complicated to make an approximately true model at the outset. Instead, what is required are simpler models that can be used to understand certain aspects of the relevant physics in order to eventually synthesize a model that is approximately true. Importantly, while understanding is an epistemic end, it often falls short of the whole truth. One can have understanding of a particular process in nature without a full picture. This leads to the notion of an understanding-directed virtue.

Definition 6 V is an understanding-oriented epistemic virtue iff theories that have V provide us with understanding of the phenomena being explained.

While truth-directed and understanding-directed virtues are related, they diverge in some cases, as we will see with Maxwell's examples below. The argument being made below is that in astrophysics and cosmology some uses of simplifying assumptions should be regarded as indirect understanding-oriented virtues. The assumptions don't lead directly to the truth, but rather provide understanding of a particular aspect of the phenomena that allow for further development of a realistic model. Before turning to astrophysics, I'll provide a historical example of an indirect understanding-oriented use of simplicity.

3 Maxwell's Method

It is instructive to look at a case from the history of science to illustrate the proposed view of simplicity. Maxwell exemplifies the position in two examples. The first is in his 1855 paper "On Faraday's Lines of Force". The context is that theorizing about electricity was not progressing. So, Maxwell wonders what can be done in the absence of a theory. His suggestion is that

> "The first process therefore in the effectual study of [electrical] science must be one of simplification and reduction of the results of previous investigations to a form in which the mind can grasp them. The results of this simplification may take the form of a purely mathematical formula or of a physical hypothesis. In the first case we entirely lose sight of the phenomena to be explained; and though we may trace out the consequences of given laws, we can never obtain more extended views of the connexions of the subject. If on the other hand, we adopt a physical hypothesis, we can see the phenomena only through a medium, and are liable to that blindness to facts and rashness in assumption which a partial explanation encourages. We must therefore discover some method of investigation which allows the mind at every step to

[2] There is a good bit of literature on the epistemology of understanding. The goal here is not to invoke a particular account of understanding, but just to appeal to the intuitive notion. For a fuller account of understanding see Pritchard, Turri & Carter (2018)

> lay hold of a clear physical conception, without being committed to any theory founded on the physical science from which that conception is borrowed, so that it is neither drawn aside from the subject in pursuit of analytical subtleties, nor carried beyond the truth by a favourite hypothesis." (Maxwell 2011, p. 155).

There are two relevant ideas that can be gleaned from this passage. The first is that in the case where no theory is available, we should begin with a simplification that allows the mind to grasp the experimental results. The second is that this simplification should be physical, otherwise the simplification will not provide any physical understanding. The way he accomplishes this in the 1855 paper is to model the flow of electricity as an imaginary incompressible fluid. In doing so, various electrical phenomena such as the electrical potential and the fact that the electrical force varies as an inverse square force can be modeled using the flow of the fluid (Achinstein 2013, p. 133). Importantly, the incompressible fluid does not exist. Rather the fluid is used as a simplified analogy that allows Maxwell to gain some sort of understanding as to the nature of electricity and allows him to deduce various mathematical results on the basis of the simplification.[3] The reason behind using a fluid is that the laws of hydrodynamics were much better understood in Maxwell's day (Achinstein 2019, p. 59). As such, Maxwell is appealing to something well understood to give him understanding of a phenomena less well understood, though the analogy cannot be taken as physically realistic.[4]

The simplification used by Maxwell is explicitly aimed at providing an understanding of electrical phenomena. So, the simplification exhibits an understanding-oriented epistemic virtue in line with Definition 6. The simplification is also indirect. The use of the incompressible imaginary fluid to model electricity does not give one reason to believe that electricity is a fluid. Rather, it allows for the further development of a realistic theory of electricity using the understanding and results deduced from the simplification. Since it is the simplicity that allows for the production of the results, the simplification is an indirect epistemic virtue. Putting these results together we find that Maxwell's examples are examples of simplicity as an indirect understanding-oriented epistemic value. This is exactly the sort of situation that I will argue is found in (some) astrophysical and cosmological modeling.[5]

[3] As Achinstein (2013, p. 134) notes, Maxwell spends the majority of the paper deducing mathematical consequences of the analogy.

[4] It is important to note that an analogy can be physical without being physically realistic. Fluids exist, and so the analogy is physical in the sense that electricity is compared to something physical. However, the simplification of the fluid is not physically realistic since it does not describe an actual fluid.

[5] One worry that might be mentioned is that Maxwell's method did allow him to produce a theory that united electricity and magnetism, but the theory is strictly speaking not true. To get the full theory we need quantum electrodynamics (QED). This is true, but the development of Maxwell's equations are necessary to formulate QED and so even if the development of Maxwell's theory was not the final word, it was still an indirect step towards developing a more realistic theory.

To drive the point home, there is another example from Maxwell that supports the indirect understanding-oriented view of simplicity. In 1860 Maxwell published "Illustrations on the Dynamical Theory of Gases" in which he attempts to develop a mechanical model of gases. At the time it was unknown whether a mechanical account of gases was even possible. Maxwell's aim is not to produce a physically realistic model of gases, but to produce a model that provides some sort of physical understanding and from which important results may be deduced. He does this by introducing a number of simplifying assumptions. He assumes that the molecules are perfectly elastic spheres that only act on one another via contact forces and that move in a uniform velocity along straight lines (Achinstein 2013, pp.144-145). These simplifying assumptions, though physically unrealistic, allow for Maxwell to deduce various important equations (such as the ideal gas law) concerning gases. The result of Maxwell's simplification here is that he assists in the development of the molecular theory of gases. Again we see that the introduction of simplifying assumptions is understanding-oriented. Furthermore, like the 1855 exercise, the introduction of the simplifying assumptions does not provide direct epistemic support, but does allow for the deduction of important results that contribute to the production of an approximately true theory. Since it is the simplicity that allows for this we can say that the simplicity in this example is an indirect epistemic virtue. Therefore, just as in the previous example from Maxwell, the role of simplicity in this case is as an indirect understanding-oriented epistemic value.

4 Simplicity in Astrophysics

4.1 Orbital Modeling

The modeling of orbits in galaxies is a tremendously complicated task. Unlike the relatively clean orbits the planets of our solar system exhibit, stars do not orbit on ellipses, but rather exhibit exotic patterns such as tori, rosettes, and even more complicated patterns. There are a variety of different gravitational potentials that can be found in galaxies. Some of them are simple enough to permit analytic solutions and provide a realistic description of the orbits (e.g. the isochrone potential (Binney & Tremain 2008, p.149). Others are far more complicated and cannot be solved analytically, such as orbits in an axisymmetric potential that leave the equatorial plane of the galaxy (Binney & Tremain 2008, p.159).

To get a sense of an important problem, a few terms need to be introduced. A constant of motion is a function of phase space coordinates $x(t)$ and $v(t)$ such that for any time t_1 and any later time t_2

$$C[x(t_1), v(t_1), t_1] = C[x(t_2), v(t_2), t_2] \tag{1}$$

(Binney & Tremain 2008, p.156). A special case of a constant of motion is called an integral of motion $I(x(t), v(t))$ such that

$$I[x(t_1), v(t_1)] = I[x(t_2), v(t_2)] \tag{2}$$

(Binney & Tremain 2008, p.156). What makes an integral of motion a special case of a constant of motion is that an integral of motion is not time-dependent, but depends only on the phase-space coordinates. Constants of motion may be time-dependent. For any orbit in any sort of potential, there are six constants of motion while there are between zero and five integrals of motion (Binney & Tremain 2008, p.156). The constants of motion can be easily determined. The integrals of motion, however, are not always easily determined. In fact, only in a few special cases can all the integrals be written down (Binney & Tremaine 2008, p.156). In general, for realistic orbits the first two integrals of motion can be written down, while the third integral cannot. The third integral is called the "non-classical integral" (Binney & Tremain 2008, p.162). An important task of orbital modeling is to determine the non-classical integrals. These integrals play a crucial role in describing the physics of rotations of galaxies and orbits of stars in galaxies (Davies et.al. 1983).

Returning to Maxwell, there is a clear similarity between the situation Maxwell finds himself in in 1855 and the current state of orbital modeling. Maxwell did not have a theory of electrical phenomena and so he used a simplification to gain some understanding of the physical phenomena, as well as to deduce mathematical results that could be used to further develop the theory. The situation in orbital modeling is perhaps a bit less severe, but nevertheless, there is something missing from realistic models and astrophysicists use simplifications to learn something about the physics of the unknown integral in spite of the fact that the integral cannot be written down. The hope is that these simplifications will lead to some understanding of the physical phenomena, as well as allow for analytic calculations, that will result in the development of a realistic model of stellar orbits.

4.2 Stäckel Potentials

The simplifications used by astrophysicists to learn something about non-classical integrals of motion vary in terms of sophistication. A special example is when the gravitational potential is spherical. Such a potential is generally unrealistic for most orbits (except for globular clusters) and is primarily used to provide results that can be generalized to more realistic orbits (Binney & Tremaine 2008, p.143). When the potential is spherical, the third integral is approximated by the total angular momentum **L** (Binney & Tremain 2008, p.163).

A more sophisticated example of the use of simplifying assumptions is the case of Stäckel potentials, named after German mathematician Paul Stäckel (1891). Stäckel potentials are separable potentials that take the following form

$$\varPhi = -\frac{F(\lambda)}{(\lambda-\mu)(\lambda-\nu} - \frac{F(\mu)}{(\mu-\lambda)(\mu-\nu)} - \frac{F(\nu)}{(\nu-\lambda)(\nu-\mu)} \tag{3}$$

where (λ, μ, ν) are ellipsoidal coordinates and $F(x)$ is a function of those coordinates (de Zeeuw 1983, p.279)[6]. This equation looks rather complicated, but the potential is in fact a useful simplification. In particular, the separability of the potential allows for analytic calculations, which cannot be done in more complicated (but realistic) potentials. The Stäckel potential is an appropriate potential for the use of an analogy of the orbits with a harmonic oscillator. This results in the classical integrals of motion taking a particularly simple form (Binney & Tremaine 2008, p.226)[7]

$$H_x = \frac{1}{2}(p_x^2 + \omega_x^2 x^2) \tag{4}$$

$$H_y = \frac{1}{2}(p_y^2 + \omega_y^2 y^2) \tag{5}$$

This analogy is a useful simplification that allows for the derivation of an expression for the momenta in terms of the unknown non-classical integral I_3 (Binney & Tremaine 2008, p.228). Likewise we can use the non-classical integral I_3 to express the actions (Binney & Tremaine 2008, p.228). Thus, through the use of the simplified Stäckel potential and the analogy to a simple harmonic operator, relations of the non-classical integral can be obtained. Importantly, the non-classical integral I_3 is still unable to be fully written down, but an understanding of the relation of the integral of motion to various physical quantities can be obtained.

Returning to Maxwell, the case of Stäckel potentials incorporates elements of both of Maxwell's examples. Like the case of a mechanistic model of gases, the Stäckel potentials themselves involve simplifications that are not physically realistic, but allow for the derivation of results that give insight into the underlying physics. In this case the insight is into the nature of the unknown integral of motion. Like Maxwell's use of the imaginary fluid, the use of the analogy between orbits and harmonic oscillators results in derivations of some relations that characterize the unknown integral. Orbits are not harmonic oscillators, but can be modeled as such under simplified assumptions, such as in Stäckel potentials. Again this simplification aids in the understanding of the physics of the non-classical integral. In light of this, we can say that the simplification introduced by the Stäckel potentials is an understanding-oriented epistemic virtue.

In addition to providing understanding, the use of Stäckel potentials since the 1980s has proven to be useful in the further development of models of stellar orbits. While there still is no full description of the non-classical integral for generic cases, the models used now are much better approximations of the actual orbits. This indicates that the simplification of Stäckel potentials

[6] A potential is separable when the potential can be decomposed into separate potentials for the coordinates, e.g. $\Phi(R, z) = \Phi(R) + \Phi(z)$ for a spherical coordinate system (R, ϕ, z) (Binney and Tremaine 2008, p. 164).

[7] This is just the Hamiltonian of a two-dimensional harmonic oscillator that has been separated out into its components.

functions is an indirect epistemic virtue. The simplicity of the potentials does not give us reason to believe the model. We know that realistic potentials are not Staäckel potentials. What the simplicity does contribute to is the further development of more realistic models, and hence serves as a basis for a fruitful research program.

In sum, in the case of modeling of orbits and galactic rotations, simplicity assumptions have proven to function as an indirect understanding-oriented theoretical virtues. While this is not the only way that simplicity assumptions factor into astrophysical modeling, it is an important way in which understanding of complex phenomena can be produced, which further aids the process of developing realistic models.

5 Simplicity in Cosmology

The standard model in cosmology, the ΛCDM model, is generally very well confirmed. However, there are a few aspects of the cosmological story that are not well understood. One such aspect is the cosmological fluctuations that are thought to give rise to large-scale structure, such as galaxy clusters and dark matter distributions, as well as produce the anisotropies in the CMB. The evolution of large-scale structure is one of the most important open problems in cosmology. The most commonly used method of modeling the cosmological fluctuations is through the use of scalar or density perturbations[8]. It turns out that the equations for scalar perturbations, in order to be physically realistic, have to be coupled to the Boltzmann equation, which can be written in a deceptively simple abstract form

$$\frac{df}{dt} = C[f] \tag{6}$$

where the left side of the equation represents gravitational effects on photon distribution and the $C[f]$ term represents a series of collision terms (Wu, 1995).[9] The collision terms are the ones that cause computational difficulty, especially when considered in the context of cosmology. In fact, the solutions of the Boltzmann equation for scalar perturbations are so complicated that they cannot be done analytically (Weinberg, 2008). Instead, numerical techniques need to be utilized in order to solve these equations. This is done with programs such as CMBfast and CAMB (Ma & Bertshinger 1995). The use of numerical calculations is common in cosmology, but Weinberg notes a problem with their use here. He says "Unfortunately such computer programs do not lend themselves to an exposition aimed at an understanding of the physical

[8] The equations for scalar perturbations are too involved to write out here. See Weinberg (2008) equations 6.1.1 and 6.1.2 for the most general scalar perturbation equations.

[9] There is a collisionless Boltzmann equation that is much simpler to deal with an that is useful for the modeling of stars (Binney & Tremaine 2008, Chapter 4). However, in the context of scalar perturbations the collisionless equation is not applicable.

phenomena involved." (2008, p.257-258). Therefore, in order to acquire physical understanding, and hence develop physically realistic models, a series of simplifications are necessary.

The simplification used first involves decoupling the perturbed Einstein Field Equations (EFE) into the respective scalar, vector and tensor modes (Weinberg 2008)[10]. This is helpful in that it allows for three sets of equations that are individually easier to solve than the perturbed EFEs. However, this is not enough. The scalar equations of the decomposition are still too complicated to solve. So, a further simplification is introduced in the choosing of a gauge. In effect, the choice of a gauge is choosing a set of conditions that eliminate some degrees of freedom (Weinberg 2008). In the case we are interested in, this amounts to specifying certain conditions the scalar fields must satisfy. There are two preferred gauges that factor into the analysis of scalar perturbations. The first is the Newtonian gauge. Here two of the perturbations of the metric, denoted B and F are set to zero.[11] This produces a formulation of the scalar mode equations in a simpler form that allows them to be solved and provides some sort of physical understanding. For instance, in using the Newtonian gauge we learn that two of the scalar fields are physically dependent on one another (Weinberg 2008, p.242). Another choice of gauge is the synchronous gauge, which sets perturbations E and F to zero. Again, this gauge simplifies the equations for scalar modes and allows for analytic solutions that contribute to physical understanding.

It is important to see that the choice of gauge is not dictated by the physics, but rather is a practical choice. The choice of gauge is nevertheless a physical simplification, though not a physically realistic simplification. Setting some of the perturbations to zero is physical, but the setting does not correspond to the actual perturbations. It is a simplification that allows the cosmologist to compute some relevant physical quantities and to gain some physical insight into the perturbations. There are known problems with the gauges and each has its own benefits and detriments (Weinberg 2008, p.243). The relevance for our purposes is that the synchronous gauge is chosen in order to simplify the equations of scalar perturbations and allow them to be put into a simple hydrodynamical form that is amenable to analytic calculations. The ability to do the calculations analytically provides insight into the nature of the physical processes that the complex equations do not.

So, the example of scalar perturbations and the simplification of choosing a particular gauge is an example of simplicity as an indirect understanding-oriented epistemic virtue. The simplification of the synchronous gauge is used in order to simplify the equations so that they are amenable to understanding. This understanding is then used to develop physically realistic equations (Weinberg 2008, p.258). Therefore, the simplicity in this case is an indirect

[10] In the perturbed EFEs the metric $g_{\mu\nu}$ is replaced with a perturbed metric $g_{\mu\nu} + h_{\mu\nu}$ where $h_{\mu\nu}$ is a small perturbation.

[11] There is a set of perturbations of the metric, ranging from A to F. Their definitions are too involved to write out here, so the reader is referred to Weinberg (2008, p.224 fn.2) for the definitions.

epistemic virtue. Recall that for Maxwell the goal is to develop a physical understanding of the phenomena, not an abstract mathematical understanding. That is precisely what is being done here, as the complex equations provide a mathematical characterization of the phenomena, rather than a physically comprehensible one.

6 Conclusion

In conclusion, we've observed that the concept of simplicity as an indirect understanding-oriented epistemic virtue has historical roots and defines key aspects of simplification in modern astrophysical and cosmological modeling. This underscores that simplicity transcends its role as solely a pragmatic or direct epistemic virtue. Focusing exclusively on these two perspectives overlooks a crucial aspect of simplicity. Its application in physics extends beyond these limitations and plays a vital role in enhancing our comprehension of physical processes.

Conflict of interest

The authors declare that they have no conflict of interest.

References

1. Achinstein, P. (2013). *Evidence and method: Scientific strategies of Isaac Newton and James Clerk Maxwell*. Oxford: Oxford University Press.
2. Achinstein, P. (2019). *Speculation: Within and about science*. Oxford: Oxford University Press.
3. Anderl, S. (2018). Simplicity and simplification in astrophysical modeling. *Philosophy of Science* 85, 819-831.
4. Baker, A. (2016). Simplicity. *Stanford Encyclopedia of Philosophy*. E. Zalta (Ed.). https://plato.stanford.edu/archives/win2016/ entries/simplicity. Accessed 24 September 2020.
5. Binney, J. & S. Tremaine. (2008) *Galactic Dynamics, 2nd. Ed.* Princeton: Princeton University Press.
6. Davies, R.L., G. Efstathiou, S.M. Fall, G. Illingworth & P. Schechter. (1983). The kinematic properties of faint elliptical galaxies. *The Astrophysical Journal*, 266, 41-57.
7. de Zeeuw, T. (1985). Elliptical galaxies with separable potentials. *Monthly Notices of the Royal Astronomical Society*, 216, 273-334.
8. Duhem, P. (1991). *The aim and structure of physical theory*. Princeton: Princeton University Press.
9. Einstein, A. (1934). On the method of theoretical physics. *Philosophy of Science*, 1, 163-169.
10. Gauch, H. (2003) *Scientific Method in Practice*. Cambridge: Cambridge University Press.
11. Hu, W. (1995). *Wandering in the background:A cosmic microwave background explorer*. Ph.D Thesis, University of California Berkeley.
12. Kelly, K. (2011). Simplicity, truth and probability. In S. Bandyopadhyay & M. Forster (Eds.) *Philosophy of Statistics* (pp. 983-1027). Amsterdamn: Elsvier.

13. Kuhn, T. (1977). *The essential tension: Selected studies in scientific tradition and change*. Chicago: University of Chicago Press.
14. Lipton, P. (2004). *Inference to the best explanation*. London: Routledge.
15. Ma, C.P. & E. Bertschinger. (1995). Cosmological perturbation theory in the synchronous and conformal Newtonian gauges. *Astrophysical Journal*, 455, 7-25.
16. Maxwell, J.C. (2011). *The scientific papers of James Clerk Maxwell Vol.1*. W.D. Nivin (Ed.) Cambridge: Cambridge University Press.
17. Pritchard, D., J. Turri & J.A. Carter. (2018). The value of knowledge. *Stanford Encyclopedia of Philosophy*. E. Zalta (Ed.). https://plato.stanford.edu/archives/spr2018/entries/knowledge-value/. Accessed 25 September 2020.
18. Newton, I. (2016). *The Principia: The authoritative translation and guide: Mathematical principles of natural philosophy*. I.B. Cohen, A. Whitman, & J. Budnez (Eds). Berkeley: University of California Press.
19. Norton, J. (2020). *The material theory of induction*. https://www.pitt.edu/∼ jdnorton/papers/material
_theory/Material_Induction_Apr_24_2020.pdf
20. Reichenbach, H. (1938). *Experience and prediction*. Chicago: University of Chicago Press.
21. Smolin, L. (2007). *The trouble with physics*. Boston: Mariner Books.
22. Stäckel, P. (1891). Über die Integration der Hamilton-Jacobischen-Differentialgleichung mittels der Separation der Variabeln. *Habilitationsschrift*. Halle.
23. van Fraasen, B. (1980). *The Scientific Image*. Oxford: Oxford University Press.
24. von Neumann, J. (1961). Method in the physical sciences. In A.W. Taub (Ed.) *The collected works of John von Neumann*. Oxford: Pergamon Press.
25. Weinberg, S. (2008). *Cosmology*. Oxford: Oxford University Press.
26. Whewell, W. (2004). *Philosophy of the inductive sciences*. Reprinted in P. Achinstein (Ed.) *Science Rules: A historical introduction to scientific methods* (pp. 150-168). Baltimore: Johns Hopkins University Press.