A Virtue Epistemology of Scientific Explanation and Understanding

Abstract: In this paper, I aim to develop a virtue epistemological account of scientific explanation and understanding. In so doing, I build a link between intellectual virtue and scientific explanation through understanding. The central epistemological question I will focus on is *how human beings understand the world through scientific explanation*. The answer I will give is that our understanding of the world is achieved by *the alignment of intellectual virtue and explanation structure*.

1. Introduction.

There are various kinds of epistemology and different accounts of scientific explanation and understanding. The aim of this paper is to find a common ground on which philosophers' theory of knowledge agree with philosophers of science's theory of scientific explanation and understanding. This unification brings harmony to three lines of literature and settles their debates such as what the nature of understanding is.

2. Virtue Epistemology: Reliabilism vs Responsibilism.

Ernest Sosa (1980) proposes intellectual virtue as the key to solving the conflict between foundationalism and coherentism, which has given rise to a new trend in contemporary epistemology ─ virtue epistemology. Virtue epistemology marks a turning point of the primary focus of epistemic evaluation from *justification* and *truth* to *intellectual agents* and *intellectual virtues* (Turri, Alfano and Greco 2017).

First, what is an intellectual virtue? Broadly speaking, there are currently two main approaches to the concept of intellectual virtue in the literature on virtue epistemology ─ virtue reliabilism and virtue responsibilism (Code 1987/2020, Axtell 1997, Baehr 2004, Turri, Alfano and Greco 2017, Battaly 2019). They differ over the definition of virtue.

Virtue reliabilists (Sosa 1991, 2007, Greco 1999, 2002) identify virtues as *reliable cognitive abilities or faculties* such as reason, perception, introspection, and memory etc.

Besides hard-wired faculties, intellectual virtues can also be acquired skills, as long as they are *stable qualities that can reliably attain true beliefs*. In other words, they are *reliable, truth-conducive* qualities of an intellectual agent. Hence the term "virtue reliabilism".

Virtue responsibilists, on the other hand, characterize intellectual virtues as *personality or character traits*, as "the intellectual counterpart of moral virtues" (Baehr 2006, 193). For instance, open-mindedness, fair-mindedness, intellectual thoroughness, and intellectual courage are intellectual virtues (Zagzebski 1996). They are *excellent character traits of a good knower*, which makes the knower truth motivated (Montmarquet 2019) and guided by imperatives of epistemic responsibility (Code 1987/2020). Hence the term "virtue responsibilism".

Even though both camps mostly agree that intellectual virtue is conducive to knowledge (exc., Montmarquet 1993), they differ over which kind of virtue is *required or necessary and sufficient* for knowledge (Zagzebski 1996, Axtell 1997, Greco 2000, Montmarquet 2019). Besides, there are also attempts to reconcile the distinction and reduce the tension between two kinds of virtue, treating reliabilist faculty virtues as *fundamental/constitutive* and responsibilist character virtues as *auxiliary* in the process of knowledge formation (Sosa 2015, Fleisher 2017, reliabilism-centered). Although some have argued to the contrary, claiming that responsibilist virtues *also play a central role* in such a reconciling framework (Baehr 2017, responsibilism-centered).

In this paper I side with the (reliabilism-centered) reconciling strategy in treating reliabilist faculty virtues as *fundamental/constitutive* and responsibilist character virtues as *auxiliary.* First, I emphasize the *fundamental/constitutive* role played by reliabilist virtues. Following Sosa (2015), reliabilist virtues include both *faculties and skills* that are reliable and truth-conducive, call them "knowledge-constitutive virtues"[1]. I further argue that knowledge-constitutive virtues are fundamental in producing scientific knowledge, and they do so by mapping the knowledge-constitutive virtues onto *the explanation structures* identified in the literature on scientific explanation.

Explanation structures exhibit human reasoning abilities and skills, such as *inferential reasoning* in the structure of scientific deduction and induction, *causal reasoning* in the structure of causal explanation, *mathematical reasoning and skills* in the structure of mathematical explanation, etc. Hence, reliabilist knowledge-constitutive virtues are *grounds on which scientific explanations construct*. They are the bones of scientific explanation. They thereby prove to be fundamental/constitutive in forming scientific knowledge.

At the same time, responsibilist character virtues are treated as *auxiliary*, since they can only influence positively (or negatively) the functioning of reliabilist

1 The terms "reliabilist virtue", "knowledge-constitutive virtue", and "intellectual virtue" will be used interchangeably from now on.

knowledge-constitutive virtues when producing knowledge. Unlike reliabilist knowledge-constitutive virtues, *character virtues are not grounds for knowledge*. They might influence the production of scientific knowledge, such as being careful or careless in doing experiments, or being brave or fearful to challenge the dominant view in the filed. *But they don't shape the structure of scientific explanation.*

3. From Virtue Epistemology to Scientific Explanation and Understanding.

3.1. Literature Review: Scientific Explanation.

This sub-section is a literature review of scientific explanation, *from a virtue perspective*. Since the literature is massive and can be reviewed in different ways, a virtue perspective will illuminate the virtue path to explanation, and pave the way for developing a virtue account of explanation.

In traditional models of scientific explanation, we often see human *reasoning abilities* employed. Starting with Hempel (1965), I emphasize the role of *deduction and induction* in the initial model of scientific explanation. Hence the importance of inferential reasoning.

Causal theories of explanation (Salmon 1984, Woodward 2003) highlight the importance of *counterfactual and causal/mechanical reasoning* in scientific thinking. Besides reasoning abilities, other cognitive abilities are also employed, such as *generalization and combination* in Kitcher's (1989) unification structure, or *abstraction*

and simplification in mathematical structures (Batterman 2002, Morrison 2006, 2015).

Interestingly, some philosophers of science go beyond common reasoning patterns to invent new ones to accommodate the explanation structures they promote. For example, Batterman (2002) argues that *asymptotic reasoning* is essential for asymptotic explanations that rely on infinities that are not observed in the real world.

The above literature review shows an emerging, underlying trend in early models of scientific explanation that appeals to human cognitive abilities. Deduction and induction, causation, counterfactuals, asymptotics, etc. are all common structures of scientific explanation. These structures appeal to human reasoning abilities such as inferential, causal, counterfactual, asymptotic reasoning, etc.

3.2. Literature Review: From Explanation to Understanding.

Despite resistance from Hempel, discussions of *understanding* enter the field of scientific explanation after Friedman (1974) and Kitcher (1976, 1981). Despite their differences, both Friedman and Kitcher agree that, explanation that has the feature of unification yields understanding. However, as pointed out by Barnes (1992), both of them simply assume the connection between unification and understanding. No further explanation is provided to back up that assumption.

Similar criticism can be made to the newest development of Kitcher's framework

(Petkov, Wang, and Lei 2016), as well as other theories of scientific explanation, such as Salmon (1984, 1993, 1998) and Woodward (2003). They highlight *what it is about scientific explanation that provides understanding*—Kitcher's unification, Woodward's counterfactuals, and Salmon's causal mechanisms. However, they have little to say about *how such explanation can provide understanding* (Trout 2002).

Batterman (2002), on the other hand, builds the bridge between mathematical explanation and understanding through simplification. Similarly, Morrison (2006, 2015) argues that mathematical models, as mediators, produce understanding via abstract mathematical structures, through abstraction and idealisation.

More recently, de Regt and Dieks (2005) and de Regt (2017) present a new theory of explanatory understanding that requires *intelligible* scientific theories. For a theory to be intelligible, *qualitative consequences* should be recognized without any calculation being performed. Understanding of a phenomenon is therefore achieved if an explanation is based on an intelligible theory. In the meantime, *qualitative reasoning* is used several times in de Regt and Dieks' description of explanatory understanding.[2] Other than seeing qualitative consequences, visualization that employs *sense perception and visual reasoning*

2 In a discussion group hosted by the "East European Network for Philosophy of Science" on March 8, 2021, de Regt admitted that he might use the word "qualitative reasoning" in a very loose sense.

is also recognized as an important tool in constructing intelligible explanation.

This shows that the link between explanation and understanding should address *how explanations speak to humans via understanding*. Human cognition is the bridge between explanation and understanding. In other words, the way to address the question of *how explanations speak to humans via understanding* is through *human cognitive abilities*. When the structure of scientific explanation is built and tailored to fit human cognitive abilities, explanatory understanding is achieved.

3.3. The Justification of a Virtue Approach to Explanation and Understanding.

Other than cognitive abilities, the deployment of *skills* are also mentioned in the development of scientific theories, especially in model construction (Morgan and Morrison 1999, de Regt 2014, 2017). For example, de Regt (2014, 380) states that, in constructing models, "successful explanation requires an appropriate combination of a scientist's skills and theoretical qualities". *Following this trend*, *I attempt to flesh out the suggestion that explanation requires an appropriate combination of scientists' skills and theoretical qualities.*

My analysis, however, will not limit to *skills* only, but human *cognitive abilities and skills* in general; I will also diverge from theoretical qualities to *scientific explanation's structures*. Because, on the one hand, we have seen an underlying trend in traditional

models of scientific explanation emphasizing human reasoning abilities of various kinds.[3] They mostly agree *that* explanation provides understanding, but *how* understanding is provided remains underdeveloped. My account will make it clear that we understand the world through scientific explanation *because* our cognitive abilities and skills produce and thus correspond to explanation structures.

On the other hand, recent attempts to bridge explanation and understanding focus more on explanation structures that *respond and answer to human cognitive abilities* (simplification and abstraction for Batterman and Morrison, intelligibility for de Regt and Dieks), and that's how understanding is produced.

I shall follow this trend and offer a unifying epistemological account that captures those cognitive abilities and skills that are involved. I point out that philosophers of science mainly focus on the history of science and the development of scientific explanation. They only have so much to offer when it comes to the formulation of human cognitive abilities and skills. Virtue epistemology, or virtue reliabilism to be specific, demonstrates how knowledge is produced by reliable abilities and skills. It's therefore a suitable epistemological account of scientific explanation and explanatory understanding.

3 At one point, Kitcher (1981, 513-4) even cites the Newton's remarks on "the same kind of reasoning from mechanical principles". While Kitcher emphasizes on "one style of argument", I focus more on the reasoning evolved and its correspondence with the explanation structure provided.

3.4. How My Account Contributes to Scientific Explanation and Understanding.

As mentioned earlier, philosophers of science focus on the history of science and the development of scientific explanation. As a result, works on scientific explanation focus on the structure of scientific explanation, and works on scientific understanding on which explanation structure provides understanding. Human cognition is an under-addressed component of the big picture:

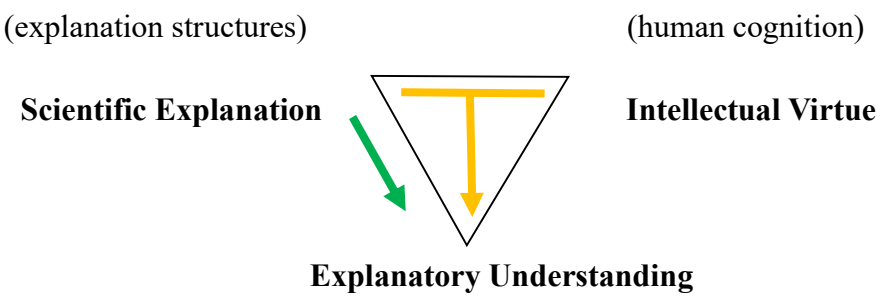

Figure 1. The picture of how humans understand the world through scientific explanation. The yellow line represents the inner workings provided by my virtue account: the alignment of explanation structure and intellectual virtue yields understanding (more in section 5). The green line represents what the current literature offers, which is less complete than my account.

My account introduces virtue epistemology to philosophy of science, and provides the concept of intellectual virtue to complete the picture of how humans understand the world through scientific explanation. As mentioned, even though virtue epistemology itself doesn't provide a detailed analysis of human's cognitive abilities and skills, it supplies a new way of thinking about how scientific explanation connects to understanding. I will develop such a detailed analysis in section 5.

4. Theories of Understanding: Knowledge vs Ability vs Cognitive Achievement.

4.1. Three Accounts of Understanding.

The knowledge-based account of understanding states that understanding is knowledge (Lipton 2004, Kelp 2015, 2016, in philosophy of science; Grimm 2006, 2014, Greco 2014, in epistemology). Nevertheless, they have different views on how understanding is connected to knowledge: understanding is knowledge of causes (Lipton 2004); understanding is systematic knowledge of dependence relations (Greco 2014); understanding is a species of knowledge (Grimm 2006); degrees of understanding are represented by its distance from "fully comprehensive and maximally well-connected knowledge" (Kelp 2015, 3812). All in all, the knowledge-based account of understanding is relatively more inclusive, addressing various kinds of knowledge.

The ability-based account of understanding claims that understanding is an ability

(Grimm 2006, 2010, 2011). By identifying understanding with the psychological act of "grasping", Grimm argues that understanding is a sort of modal ability "to anticipate or 'see' what things would have been like" (2011, 89). Other ability-based accounts of understanding include Hills (2016, abilities as "cognitive control"), and de Regt (2009, 2017, understanding of a phenomenon is achieved by means of pragmatic understanding -- the ability to use the theory). The ability-based account of understanding is mostly seen in philosophy of science.

Unlike the ability-based account, the cognitive achievement/success-based account of understanding has its origin in virtue epistemology (Zagzebski 1996, 2001 from virtue responsiblism, Kvanvig 2003 from virtue reliabilism). It states that *understanding is a cognitive achievement/success due to the exercise of virtues*, along with the proposal that knowledge is a kind of cognitive achievement. However, most epistemologists differentiate between knowledge and understanding, and argue that understanding is a different kind of cognitive achievement than knowledge (Kvanvig 2003, Pritchard 2009, 2014).

4.2. The Virtue Approach to Understanding.

Very recently, philosopher of science Khalifa (2017) adopts *the virtue approach to understanding*. Different from the "Classic Ability" account (such as Grimm and de Regt) that understanding is an ability, Khalifa's "Updated Ability" account of understanding

acknowledges degrees of understanding and *the exercise of cognitive abilities* in different degrees of understanding. Khalifa's account recognizes the difference between understanding as an ability and understanding as the result of *the exercise of abilities,* which is a big step towards a virtue epistemological approach.

However, Khalifa also drives away from virtue epistemology, in that he criticizes Pritchard that his "achievement-driven machinery is unnecessary" and unclear in many ways (Khalifa 2017, section 3.4). It could be argued that Pritchard doesn't make the "achievement-driven machinery" necessary and clear, but the achievement talk is still worth exploring. Thus, I shall argue that *understanding should be featured in terms of achievement, as the result of the exercise of abilities*. Therefore, understanding is more committed to the virtue approach than Khalifa suggests.

Moreover, Khalifa's EKS Model is only able to illustrate different *degrees* of understanding. I shall show that Khalifa's account that features different *degrees* of understanding is not able to address different *kinds* of understanding after all.

My virtue account will (1) furnish understanding in such an "achievement-driven machinery", namely defining understanding as a cognitive achievement due to the exercise of virtues, and (2) address both different *degrees* and *kinds* of understanding in a virtue account.

Furthermore, the target of my account is restricted to *explanatory understanding*

which is the understanding of phenomena that's *based on scientific explanation*.[4] Other forms of understanding, such as propositional, objectual, practical, procedural, linguistic etc. are not of my concern here.[5]

5. A Virtue Epistemology for Explanation and Understanding.

5.1. The Alignment of Intellectual Virtue and Explanation Structure.

As was argued in section 2, intellectual virtues or knowledge-constitutive virtues are reliable, truth-conducive qualities of intellectual agents. The virtues include both cognitive abilities and skills. In the context of scientific explanation, we often see deductive/inductive, causal/mechanical, counterfactual reasoning abilities, and mathematical, statistical skills, etc.

On the other hand, explanation structure is a form in which the explanandum phenomenon is explained by the explanans. The common structures are deduction and induction, causation, visualization, unification, idealization, mathematicalization, models, statistical structures, etc.[6] Explanation structures *correspond to and are shaped by*

4 My account of explanatory understanding, therefore, doesn't account for understanding without explanation, such as the cases brought up by Lipton (2009).

5 See Zagzebski (2019) for a structure-based analysis of other forms of understanding.

6 Note that qualities of explanations are not included in this table, such as simplicity,

intellectual virtues, which results in explanatory understanding. As such, I draw a correspondence between intellectual virtues and explanation structures:

Intellectual virtue		Explanation structure
Faculty or Ability	Deductive/Inductive reasoning	Deduction and induction
	Causal/mechanical reasoning	Causation/mechanism
	Counterfactual reasoning	Difference-making
	Generalization and categorization	Unification/consilience
	Approximation, abstraction and simplification	Idealization
Skill	Perception/Visual skills	Visualization
	Mathematical skills	Mathematical structures
	Model-building skills	Models
	Statistical skills	Statistical structures

Table 1. The alignment of intellectual virtue with explanation structure

Three points of clarification:

---

scope, fruitfulness, coherence, etc. They are features of explanations, rather than explanation structures—the ways in which the explanans explains the explanandum.

First, how it carries out in scientific practice: For example, a scientist who has the relevant mathematical skills can produce a mathematical explanation of a phenomenon, and her understanding of the phenomenon results from the alignment of her mathematical skills and the mathematical structure of the explanation. However, as an explanation producer, she needs not to be the only one who can understand the phenomenon through such an alignment. Other scientists who have the relevant mathematical skills can also achieve understanding through the alignment of their skills and the explanation structure.

Moreover, the one-to-one correspondence of intellectual virtue and explanation structure doesn't mean virtues cannot collaborate or overlap. For example, skills often require abilities, such as model-building skills make use of inferential or causal reasoning. Or statistical skills require a certain level of mathematical skills. In these cases, the key intellectual virtue that shapes the structure of explanation will stand out and correspond with the explanation structure, and that correspondence produces understanding.

Last, the proper employment/exercise of intellectual virtue means the alignment of intellectual virtue with explanation structure, and understanding comes as a result. An improper employment of intellectual virtue happens when intellectual virtue doesn't align with explanation structure, and understanding isn't achieved. More details will be provided in the next section on understanding.

5.2. How Explanatory Understanding Is and Isn't Achieved through the Alignment.

How understanding is achieved? This can be illustrated by showing how the alignment will serve as the measure for both *degrees* and *kinds* of understanding. It's measured by different levels and kinds of alignment between intellectual virtue and explanation structure, regulated in terms of *types and tokens*.

To be specific, different types/kinds of understanding are represented by different kinds of alignment. For example, causal understanding (or understanding of causes) results from the alignment of causal reasoning and causal explanation, such as smoking causes cancer death. Within a single type/kind of understanding, namely a single kind of alignment, more alignment tokens represent deeper understanding, such as smoking causes lung cancer and lung cancer causes cancer death.

What happens when intellectual virtues don't align with explanation structures? Understanding isn't achieved. How does it happen? It could happen due to (1) *a lack of intellectual virtue,* (2) *a lack of explanation structure, or* (3) *a mismatch between intellectual virtue and explanation structure*.

(1) A lack of *intellectual virtue* often appears in science when an intellectual agent isn't equipped with the necessary skills to comprehend explanation structures. For example, someone without the relevant mathematical skills cannot understand atoms through the quantum theory of atoms.

(2) A lack of *explanation structure* could happen when an agent is equipped with some intellectual virtue, but the corresponding explanation structure isn't provided. For instance, smokers in the 19th century had causal reasoning ability but weren't provided with the causal link between smoking and health problems. They therefore didn't understand what caused lung cancer.

(3) A *mismatch* between intellectual virtue and explanation structure can be demonstrated by the widely used example in mathematical explanation: a mother fails to distribute 23 strawberries evenly among her 3 children without cutting any, strawberries or children (e.g., Lange 2017). The explanation that 23 cannot be divided evenly by 3 is a simple mathematical division. But if subtraction is applied here by an agent, then explanatory understanding of the mother's failure won't be achieved; even though the agent can ultimately arrive at the conclusion, through subtraction, that the distribution of strawberries cannot be even (such as giving one strawberry to one child at a time, not all children have the same number of strawberries when the distributor runs out of strawberries).[7]

6. Case Study: Galileo's Pendulums.

7 More sophisticated examples of distinctively mathematical explanation that are non-causal can be found in Lange (2013, 2017). These examples further prove my point here that a mismatch can happen when intellectual virtues don't align with explanation structures, such as causal reasoning is deployed in non-causal explanations.

For an illustration in the history of scientific practice, consider Galileo's experiments with pendulums. Here is a sketch of how knowledge is produced by virtues: It starts with Galileo's observation that the period the of the pendulum is dependent on its length, which is produced by intellectual virtues ─ *perception and inferential reasoning*. Then he offers support for it by means of "the so-called first law of astronomy" (Ariotti 1968), the process of which is carried through more intellectual virtues ─ *mathematical reasoning and the ability to generalize and formalize*. This shows that Galileo's case falls in line with the tradition of virtue reliabilism that knowledge is produced by intellectual virtues (cognitive abilities or skills).

More importantly, Galileo's case is also a good illustration of my virtue account provided in the last chapter. With respect to explanation and understanding, we can draw three sets of conclusions regarding the virtue account:

(1) First, Galileo has the required mathematical reasoning abilities and skills, but Newton's laws are not available at the time; so, Galileo seeks theoretical support for his observation on pendulums from Kepler's laws. In this case, it *isn't* in nature a mismatch between intellectual virtue and explanation structure. Galileo's mathematical reasoning abilities and skills still *match onto* the mathematical structure of the pendulum. So, he can understand the isochrony of the pendulum, due to *the initial alignment* between intellectual virtue and explanation structure. *This is the first set of conclusions regarding explanation*

structures.

(2) However, Galileo's understanding of the isochrony of the pendulum is restricted to the mere correspondence of his mathematical reasoning ability with the mathematical structure of the pendulum, *provided by Kepler's law*. So, Galileo understands, *to some degree*, that the period is proportional to the square root of the length. Later, Newton formulates the laws of motion and universal gravitation, and he uses them to derive Kepler's laws. The pendulum law is thus formulated in terms of the gravitational constant. If Galileo were provided with Newton's work, his understanding would have been enhanced. That is to say, Galileo would have had a deeper understanding of the isochrony of the pendulum than his initial understanding based on Kepler's law.

Here, different degrees of the same type of understanding (mathematical understanding) are represented by more alignment tokens. Galileo's intellectual virtues aligning with Kepler's law results in a degree of mathematical understanding, namely one token of the mathematical type of understanding. But those virtues aligning with Newton's laws would result in a deeper understanding, another token understanding that is of the same kind ─ mathematical.

Moreover, a mismatch between intellectual virtue and explanation structure can also happen in Galileo's case. Since both Kepler's laws and Newton's laws are based on Euclidean geometry, Galileo would have been able to understand the pendulum through

Newton's work via Euclidean model of reasoning. If Galileo were provided with the Schrödinger equation for the pendulum (Baker and Blackburn 2005), he wouldn't have been able to understand the pendulum in a quantum-mechanical system, due to the lack of a proper training in quantum mechanics and the relevant mathematical skills. A mismatch thus happens, and understanding isn't achieved.

The above is the second set of conclusions regarding understanding.

(3) Besides mathematical, the pendulum example also exhibits an idealized understanding. Most of the time, idealization hardly counts as an *independent* structure, since it is often accompanied by a mathematical structure. However, when idealization aligns with the cognitive abilities of approximation, abstraction, and simplification, it yields an idealized understanding of the phenomenon, usually on top of mathematical understanding.

For example, Galileo hypothesizes that an ideal pendulum is isochronous if it's not subject to air resistance or material hindrances. Therefore, Galileo's understanding of the isochrony of the pendulum is in fact composed of mathematical *and* idealized understanding. In the later case, Galileo's abilities of approximation, abstraction, and simplification align with the explanation structure of idealization, and the alignment yields a new kind of understanding ─ idealized understanding.

This idealized understanding is usually hypothetical or *"false"*, in the sense that the

idealized phenomenon is usually approximately representing, sometimes misrepresenting, the real-world phenomena. However, this idealized nature doesn't prevent it from serving as a species of explanatory understanding, since idealization counts as an explanation structure ─ a way in which the explanandum is explained by the explanans.

Explanatory understanding, therefore, doesn't have to be factive or strictly true. Different from knowledge, explanatory understanding only has a loose truth component. Because in my account, explanatory understanding is based on scientific explanation, and scientific explanation is "riddled" with idealization (and abstraction)[8]. Explanatory understanding's loose truth component, therefore, comes from explanations "exemplifying features they share with the facts" in the real world (Elgin 2007, 39). In other words, even though idealizing explanations make idealized or "false" assumptions about the world, they provide true explanatory content for the explanandum phenomena (Strevens 2013).

Hence, idealized understanding itself is not to be described as true or false. It's a cognitive achievement which is valuable epistemically, since the idealizing explanation structures provide an epistemic access for the epistemic agent to understand the real-world phenomena. *This is the third set of conclusions regarding idealized understanding.*

---

8 Idealization and abstraction are taken as distinct sometimes in the literature (e.g., Levy 2018). Here I don't distinguish between idealization and abstraction. They all count as idealization for the sake of simplicity.

7. Conclusion.

In this paper I have provided a virtue epistemological approach to scientific explanation and understanding. It sheds light on the nature of virtue, explanation structure, and especially scientific understanding. This unification at a theorical level gives rise to a coherent philosophical picture which helps settle the debates in these three lines of literature.

References

Ariotti, Piero. 1968. "Galileo on the Isochrony of the Pendulum." *Isis* 59: 414-426.

Axtell, Guy. 1997. "Recent Work in Virtue Epistemology." *American Philosophical Quarterly* 34: 1-26.

Baehr, Jason. 2004. "Virtue Epistemology." *The Internet Encyclopedia of Philosophy* www.iep.utm.edu/virtueep. (Accessed on March 26, 2020).

Baehr, Jason. 2006. "Character, Reliability and Virtue Epistemology." *The Philosophical Quarterly* 56: 193-212.

Baehr, Jason. 2017. "Responsibilist Virtue and the 'Charmed Inner Circle' of Traditional Epistemology." *Philosophical Studies* 174: 2557-2569.

Baker, Gregory L., and James A. Blackburn. 2005. *The Pendulum: A Case Study in Physics*. New York: Oxford University Press.

Barnes, Eric. 1992. "Explanatory Unification and Scientific Understanding." In *PSA 1992*, David L. Hull, Micky Forbes, and Kathleen Okruhlik (eds.), vol. 1, 3-12. East Lansing, MI: Philosophy of Science Association.

Battaly, Heather. 2019. "Introduction." In *The Routledge Handbook of Virtue Epistemology*, Heather Battaly (ed.), 1-11. New York: Routledge.

Batterman, Robert. 2002. *The Devil in the Details: Asymptotic Reasoning in Explanation, Reduction, and Emergence*. Oxford: Oxford University Press.

Code, Lorraine. 1987/2020. *Epistemic Responsibility*. Hanover: University Press of New England. Reprinted by Albany: State University of New York Press.

De Regt, Henk W. 2009. "The Epistemic Value of Understanding." *Philosophy of Science* 76: 585-597.

De Regt, Henk W. 2014. "Visualization as a Tool for Understanding." *Perspectives on Science* 22: 377-396.

De Regt, Henk W. 2017. *Understanding Scientific Understanding*. New York: Oxford University Press.

De Regt, Henk W., and Dennis Dieks. 2005. "A Contextual Approach to Scientific Understanding." *Synthese* 144: 137-170.

Elgin, Catherine Z. 2007. "Understanding and the Facts." *Philosophical Studies* 132: 33-42.

Fleisher, Will. 2017. "Virtuous Distinctions: New Distinctions for Reliabilism and Responsibilism." *Synthese* 194: 2973-3003.

Friedman, Michael. 1974. "Explanation and Scientific Understanding." *The Journal of Philosophy* 71: 5-19.

Greco, John. 1999. "Agent Reliabilism." *Philosophical Perspectives* 13: 273-296.

Greco, John. 2000. "Review: Two Kinds of Intellectual Virtue." *Philosophy and Phenomenological Research* 60: 179-84.

Greco, John. 2002. "Virtues in Epistemology." In *Oxford Handbook of Epistemology*, Paul Moser (ed.), Chapter 9. New York: Oxford University Press.

Greco, John. 2014. "*Episteme*: Knowledge and Understanding." In *Virtues and Their Vices*, Kevin Timpe, Craig A. Boyd (eds.), Chapter 13. Oxford: Oxford University Press.

Grimm, Stephen R. 2006. "Is Understanding a Species of Knowledge?" *British Journal for the Philosophy of Science* 57: 515-535.

Grimm, Stephen R. 2010. "The Goal of Explanation." *Studies in the History and Philosophy of Science* 41: 337-344.

Grimm, Stephen R. 2011. "Understanding." In *The Routledge Companion to Epistemology*, Sven Bernecker, Duncan Pritchard (eds.), 84-94. New York: Routledge-Taylor & Francis.

Grimm, Stephen R. 2014. "Understanding as Knowledge of Causes." In *Virtue Epistemology Naturalized: Bridges Between Virtue Epistemology and Philosophy of Science*, Abrol Fairweather (ed.), 329-345. Springer, Cham: Synthese Library.

Hempel, Carl G. 1965. *Aspects of Scientific Explanation, and Other Essays in the Philosophy of Science.* New York: The Free Press.

Hills, Alison. 2016. "Understanding Why." *Noûs* 49: 661-688.

Kelp, Christoph. 2015. "Understanding Phenomena." *Synthese* 192: 3799-3816.

Kelp, Christoph. 2016. "Towards a Knowledge-Based Account of Understanding." In

Explaining Understanding: New Perspectives from Epistemology and Philosophy of Science, Stephen R. Grimm, Christoph Baumberger, and Sabine Ammon (eds.), 251-271. New York: Routledge.

Khalifa, Kareem. 2017. *Understanding, Explanation, and Scientific Knowledge*. Cambridge, New York: Cambridge University Press.

Kitcher, Philip. 1976. "Explanation, Conjunction, and Unification." *The Journal of Philosophy* 73: 207-212.

Kitcher, Philip. 1981. "Explanatory Unification." *Philosophy of Science* 48: 507-531.

Kitcher, Philip. 1989. "Explanatory Unification and the Causal Structure of the World." In *Scientific Explanation*, Philip Kitcher and Wesley C. Salmon (eds.), 410-505. Minneapolis: University of Minnesota Press.

Kvanvig, Jonathan. 2003. *The Value of Knowledge and the Pursuit of Understanding*. Cambridge, UK; New York, NY: Cambridge University Press.

Lange, Marc. 2013. "What Makes a Scientific Explanation Distinctively Mathematical?" *The British Journal for the Philosophy of Science* 64: 485-511.

Lange, Marc. 2017. *Because Without Cause: Non-Causal Explanations in Science and Mathematics.* New York: Oxford University Press.

Levy, Arnon. 2018. "Idealization and Abstraction: Refining the Distinction." *Synthese* 1-18.

Lipton, Peter. 2004. *Inference to the Best Explanation*. 2nd ed. New York: Routledge. Original edition, 1991.

Lipton, Peter. 2009. "Understanding Without Explanation." In *Scientific Understanding: Philosophical Perspectives*, Henk W. de Regt, Sabina Leonelli, and Kai Eigner (eds.), 43-63. Pittsburgh: University of Pittsburgh Press.

Montmarquet, James. 1993. *Epistemic Virtue and Doxastic Responsibility*. Lanham, MD: Rowman & Littlefield.

Montmarquet, James. 2019. "Do Epistemic Virtues Require a Motivation for Truth?" In *The Routledge Handbook of Virtue Epistemology*, Heather Battaly (ed.), 37-46. New York: Routledge.

Morgan, Mary S., and Margaret Morrison (eds.). 1999. *Models as Mediators: Perspectives on Natural and Social Science*. Cambridge: Cambridge University Press.

Morrison, Margaret. 2006. "Scientific Understanding and Mathematical Abstraction." *Philosophia* 34: 337-353.

Morrison, Margaret. 2015. *Reconstructing Reality: Models, Mathematics, and Simulations*. New York: Oxford University Press.

Petkov, Stefan, Wei Wang, and Yi Lei. 2016. "Explanatory Unification and Natural Selection Explanations." *Biology and Philosophy* 31: 705-725.

Pritchard, Duncan. 2009. “Knowledge, Understanding and Epistemic Value.” *Royal Institute of Philosophy Supplement* 64: 19-43.

Pritchard, Duncan. 2014. “Knowledge and Understanding.” In *Virtue Epistemology Naturalized: Bridges Between Virtue Epistemology and Philosophy of Science,* Abrol Fairweather (ed.), 315-327. Springer, Cham: Synthese Library.

Salmon, Wesley. 1984. *Scientific Explanation and the Causal Structure of the World*. Princeton: Princeton University Press.

Salmon, Wesley. 1993. “The Value of Scientific Understanding.” *Philosophica* 51: 9-19.

Salmon, Wesley. 1998. *Causality and Explanation*. New York: Oxford University Press.

Sosa, Ernest. 1980. “The Raft and the Pyramid: Coherence versus Foundations in the Theory of Knowledge.” *Midwest Studies in Philosophy* 5: 3-25. Reprinted in Sosa (1991).

Sosa, Ernest. 1991. *Knowledge in Perspective: Selected Essays in Epistemology*. Cambridge: Cambridge University Press.

Sosa, Ernest. 2007. *A Virtue Epistemology: Apt Belief and Reflective Knowledge, Volume I.* Oxford: Oxford University Press.

Sosa, Ernest. 2015. *Judgment and Agency*. New York: Oxford University Press.

Strevens, Michael. 2013. “No Understanding without Explanation.” *Studies in History and Philosophy of Science* 44: 510-515.

Trout, J.D. 2002. "Scientific Explanation and the Sense of Understanding." *Philosophy of Science* 69: 212-233.

Turri, John, Mark Alfano, and John Greco. 2017. "Virtue Epistemology." *Stanford Encyclopedia of Philosophy.* Available online: https://plato.stanford.edu/entries/epistemology-virtue/ (Accessed on: 29 Nov 2020)

Woodward, James. 2003. *Making Things Happen: A Theory of Causal Explanation*. New York: Oxford University Press.

Zagzebski, Linda. 1996. *Virtues of the Mind*. Cambridge: Cambridge University Press.

Zagzebski, Linda. 2001. "Recovering Understanding." In *Knowledge, Truth and Duty: Essays on Epistemic Justification, Responsibility and Virtue*, Matthias Steup (ed.), 235-251. Oxford: Oxford University Press.

Zagzebski, Linda. 2019. "Toward a Theory of Understanding." In *Varieties of Understanding: New Perspectives from Philosophy, Psychology, and Theology*, Grimm Stephen R. (ed.), 123-136. New York: Oxford University Press.