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INFERENCE TO THE BEST EXPLANATION: THE CASE OF POTENTIAL ENERGY

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ABSTRACT

It has been claimed that kinetic energy is an objective physical quantity whilst at the same time maintaining that potential energy is not. However, by making use of the method of 'inference to the best explanation', it may be readily concluded that potential energy is indeed an objective physical quantity. This is done for an example drawn from the foundations of modern chemistry. In order to do so, the criteria of what counts as 'most probable' and 'most reasonable' are defined and then employed for choosing the best explanation.

Keywords: *Potential energy; inference to the best explanation; objectivity of energy; instrumental hypothesis*

1. Introduction

Any physics textbook will apprise its readers that potential energy is the energy stored in physical systems and is central to the law of the conservation of energy (see e.g. Serway and Jewett 2008, chap. 7-8; Halliday et al. 2013, chap. 8; Young and Freedman 2016, chap. 7; Shankar 2019, chap. 5-6). Physics, engineering and chemistry textbooks are full of examples showing the operation of potential energy in all sorts of physical situations. Potential energy as a principal feature of physical phenomena has been accepted wholeheartedly for more than a century by the vast majority of physicists, chemists, and engineers worldwide.

It is somewhat surprising then, that the respected American physicist Eugene Hecht made the claim in 2016 that potential energy does *not* physically exist. He wrote:

> Although PE [potential energy] describes a significant aspect of the state of a system and is therefore indispensable theoretically, it is *no longer required to be a physical actuality* […]. (Hecht 2016, 2, italics added)

It seems here that Hecht is declaring potential energy to be "indispensable theoretically" so that his conclusion about potential energy not having "physical actuality" would not be immediately dismissed as ridiculous by most scientists and by many philosophers of science. It was not that Hecht was claiming energy *per se* does not exist as he explicitly maintained the "physical actuality" of kinetic energy (i.e. he affirms that kinetic energy exists in the physical world). Hecht, in effect, claimed that potential energy is only an instrumental hypothesis (albeit an indispensable one), i.e. only a theoretical 'device' or 'instrument', used for tracking changes in physical systems and for making predictions. Such theoretical 'instruments' are also referred to by some philosophers of science as 'conceptual fictions' (see Stace 1934; Quine 1951; Smart 1968, 152; Giere 1988, 26).

Hecht is pursuing his own realist agenda claiming that kinetic energy exists in the physical world and denying this for potential energy. We'll briefly summarise, in the next section, Hecht's justification for this position and why it fails. However, we need to acknowledge upfront that because scientific realism conjures up all sorts of issues, problems and images (see e.g. Giere 1988, chap. 4-5; Okasha 2002, chap. 4; Psillos 2009; McCain 2016, 219–223), we cannot do justice to it in the space of this article. Instead, we shall take the (minimal) realist ontological perspective of energy which holds that energy is a quantity (as it can be given a numerical value) having a physical existence and which is an essential attribute of physical systems. Such a realist ontology is rejected by instrumentalists who view energy as only a theoretical 'device' for making predictions and a kind of hypothetical 'ledger' to describe changes in physical systems. The expressions 'physically objective quantity' and 'physical objectivity' will be used as a shorthand for the minimal realist ontology in which energy has an essential physical existence (rather than using Hecht's terms 'physical actuality' and 'objective reality'). The relevant issues may then be discussed without having to venture into the wider morass of philosophical realism.

The aim of this article is to present a case for potential energy being a physically objective quantity. The rest of the article will proceed as follows. Section 2 discusses the failure of Hecht's physical argument and highlights the philosophical implications to be examined. Section 3 discusses the importance of potential energy and its explanatory role in contemporary physics. Section 4 outlines the method of 'inference to the best explanation' and presents a concrete example of how to find the best explanation. Section 5 applies this method to the case of potential energy. Section 6 delivers a verdict on the ontological status of potential energy. Section 7 answers the question about potential energy's theoretical indispensability and summarises the article's conclusions.

2. Failure of Hecht's Physical Argument and its Philosophical Implications

Hecht's physical argument against potential energy is based on his claims about what is and what is not directly measurable. He assumed that if a quantity could be directly measured then it has physical objectivity (Hecht 2016, 8). Hecht concluded that potential energy is not a physically objective quantity chiefly because he maintained that it cannot be directly measured. On the other hand, he claimed that kinetic energy is directly measurable and hence is a physically objective quantity. Hecht's approach has some features in common with the view of prominent instrumentalist Bas van Fraassen (1980), except for Hecht's acceptance of the physical objectivity of kinetic energy. Nonetheless, Hecht is excessively instrumental as his view:

- must accept that the quantitative formalism of potential energy has enormous utility, i.e. the widespread usefulness and accuracy of the (mathematical) formalism for description and prediction of phenomena in physics, engineering and chemistry, but does so without explaining why potential energy has this immense utility; and
- concedes that the potential energy hypothesis cannot be done away with (i.e. is "indispensable theoretically"), again without explaining why this is so.

In addition to these shortcomings, it has become evident that Hecht's view ultimately 'derails' for, most critically, kinetic energy is no more directly measurable than is potential energy. The lack of direct measurability of kinetic energy may be seen as follows.

In order to 'measure' the kinetic energy of an object, a number of steps are required and this usually includes the empirical determination of the object's speed. Speed may be determined by performing measurements of successive positions of an object over specified time intervals. The object's speed is then calculated using these values of position and time and this result is substituted into an equation for kinetic energy to obtain a numerical value (Riggs 2019, 3). Furthermore, it turns out that detailed analyses of alternative empirical methods for 'measuring' an object's kinetic energy reveal that the operations involve direct measurements only of position and/or time (Riggs 2019, 4). In other words, there simply cannot be any direct measurement of kinetic energy. Therefore, if Hecht's assumption regarding how to establish physical objectivity is accepted, then neither kinetic energy nor potential energy could be accepted as objective quantities! Hecht's argument thereby fails to achieve his goal of establishing that potential energy is not physically objective whilst still affirming the objectivity of kinetic energy.

There are obviously some pertinent philosophical issues arising in this context. Consider the following broad questions:

— What is implied if potential energy does *not* have physical objectivity? and
— What follows if potential energy *is* an objective physical quantity?

In particular, what issues immediately stand out from these questions? In respect to the first question, if potential energy is not an objective physical quantity then we have the seemingly inexplicable situation where, despite not having physical objectivity, potential energy nevertheless quantitatively describes a significant aspect of the state of *any physical system*, irrespective of the constitution of the system (e.g. being composed of 'dark' matter) and of any and all extreme conditions in its vicinity. Such conditions could include being subject to the pressure in the core of a planet, or the temperature inside a star, or the gravitational 'tidal forces' exerted near a stellar-mass black hole. In respect to the second question, if potential energy is an objective physical quantity then it should be possible to validly infer its objective status. The method of 'inference to the best explanation' will be applied below as part of a case which concludes that potential energy is a physically objective quantity. This conclusion will also resolve the above described seemingly inexplicable situation.

3. Potential Energy in Contemporary Physics and its Explanatory Significance

There is no *general* expression for energy, as articulated by the French physicist and philosopher of science, Henri Poincaré:

> […] In every particular case we clearly see what energy is, and we can give it at least a provisory definition: but it is impossible to find a general definition of it (Poincaré 1905, 132).

Our observations of the natural world have led to the stipulation that there are only two *fundamental* types of energy. Needless to say, these are kinetic energy (energy of motion) and potential energy (stored energy). We typically illustrate these two types of energy with reference to individual physical situations. There are, of course, countless numbers of very common examples including: falling objects, ferrous metal fragments pulled towards magnets, pieces of paper attracted to plastic rubbed on wool, etc. Such instances also show the working of the law of energy conservation, i.e. energy may be transformed from potential to kinetic (and vice versa) thereby conserving total energy.

Potential energy in contemporary physics is understood as an aspect of physical systems, as stated in a leading physics textbook:

> […] [i]f the energy change of the system is not in the form of kinetic energy […] we call the energy storage mechanism […] potential energy […] [and] find that the potential energy of a system can only be associated with specific types of forces acting between members of a system. (Serway and Jewett 2008, 178)

The quantification of a system's potential energy is expressed in terms of the relative configuration of the parts of the system, e.g. positions of particles making up the system. It is also well established that each force is mediated by a physical field which ensures causal connection and conservation of energy. Consequently, potential energy may be characterised as the energy stored in physical fields. An electrically charged particle such as an electron, for example, placed inside an external electric field will gain kinetic energy and accelerate by drawing on some of the potential energy in the electric field enclosing it.

The enormous utility of the potential energy hypothesis allows for both qualitative and quantitative descriptions of dynamical phenomena (i.e. of the changes that occur in physical systems). In this context, it should be pointed out that phenomena explained by the hypothesis of potential energy are *exceedingly familiar* in our homes, workplaces, and in research laboratories and industrial facilities. The most commonplace of such phenomena include:

- conversions of practical energy modes as observed every day, e.g. electrical to light, chemical to mechanical, solar to heat; and
- the self-restoration of deformed elastic materials with accompanying motion, e.g. compressed or extended springs.

In its quantified expressions, the hypothesis of potential energy is a *crucial part* of descriptions of the changes in physical systems in accordance with known laws of nature in specific areas of science, e.g. with the laws of electromagnetism, nuclear reactions, gravitation, materials science, and chemical reactivity. The quantitative expressions of potential energy, not surprisingly, are different for each of the fundamental forces of nature. The expression for the electrostatic potential energy in a given spatial region, for example, depends on the number, polarity, and distribution of electric charges in that region. This is totally different from say, the expression for the potential energy of an atomic nucleus due to the Strong Nuclear force (i.e. the force which holds the nucleus together). The various expressions for potential energy reflect the different natures of the fundamental forces.

Subject to the law of energy conservation, quantitative changes in potential energy appear as kinetic energy in its various forms, e.g. heat (as increased kinetic energy of surrounding particles). Indeed, the (factual) outcomes of a staggering number of physics, chemical, and biological experiments and also engineering processes (see Jaffe and Taylor 2018, esp. chap. 9) which are predicted and explained by the hypothesis of potential energy testifies to it being crucial to describing changes in physical systems. Although these empirical outcomes highlight the utility of potential energy, enquiring into their basis inevitably leads back to the questions of whether potential energy is an objective physical quantity and why it is that potential energy (in Hecht's words) "describes a significant aspect of the state of a system […]" (Hecht 2016, 2). We shall provide suitable answers to these questions.

4. Finding the Best Explanation

Arguments for and against the method of 'inference to the best explanation' are easily found in the philosophical literature (e.g. Harman 1965; Vogel 1998; Okasha 2002; Lipton 2004; Psillos 2009; Mackonis 2013; McCain and Poston 2017). It is beyond the scope of this article to review these arguments. Instead, we shall accept (as many philosophers do) that this method yields explanations which are true (or at least very likely to be true), when based on accurate premises and properly conducted (see Psillos 2009, chap. 10; Brössel 2013, 53) as the method "exploits the truth-conducive virtues of explanation" (Kosso 1992, 98). In order to assist in a determination of the ontological status of potential energy (i.e. to conclude that it is a physically objective quantity), we shall perform an inference to the best explanation.

The schema for making an inference to the best explanation has the general form (McCain 2016, 158):

(1) There is a set F of related facts (e.g. observation statements, measurements, etc.) requiring an explanation.
(2) A particular explanation E accounts for all the facts in F.
(3) E accounts for F better than any other known explanation.

Yet, the schema (1) – (3) is just the 'bare bones' and we need to 'flesh out' an inference to the best explanation by initially adding the following to this schema (cf. Schick and Vaughn 1995, chap. 5):

(4) Any acceptable explanation must not be logically inconsistent.
(5) Any acceptable explanation must be compatible with relevant, established theories or confirmed data (i.e. with background knowledge).
(6) Any acceptable explanation must not postulate entities or activities of dubious kinds, e.g. violations of known natural laws, speculative (and unverified) physical effects, animated cadavers, magical spells, etc.

A domestic example will serve to demonstrate the operation of the schema (1) – (6) and how we ought to decide which explanation counts as best, before this schema is applied to the case of potential energy. Suppose that I arrive at my (locked) house one night to find that the pieces on my chessboard have been orderly rearranged from where they were earlier that same day. I observe that no one is in the house, there are no indications of forced entry, no items appear to be missing, and nothing seems to have been disturbed except for the chess pieces. How then might this orderly rearrangement of the chess pieces be explained? I begin my deliberations with bringing to mind aspects which are relevant to this situation by:

- attempting to recall all of my actions before leaving my house this morning;
- noting that no visitors nor deliveries were expected or scheduled today;
- noting that house burglaries are quite common in my city;
- noting who has a key to my house;
- noting that several people have previously told me that the chess pieces should be rearranged on aesthetic grounds; and

- discounting any dubious entities and processes which might be postulated as causes of the movement of the chess pieces (e.g. psychic levitation).

I thereby incorporate conditions (4) – (6) into the process of formulating suitable explanations from which the best one may be inferred.

Using both my observations and thoughts on the situation, I am led to the formulation of four possible explanations:

a) It was myself who repositioned the chess pieces before leaving the house in the morning but, as I had several pressing issues on my mind needing immediate attention, I simply forgot that I had moved them and have not been able to recall this.
b) There has been a ground shaking event at my house’s location during the day which caused the chess pieces to shift position.
c) An unknown individual broke into my house in a way yet to be discovered, moved the chess pieces on motives unknown and then departed without taking anything.
d) A particular friend who has the only other key, let herself into my house, rearranged the chess pieces, removed nothing, and locked the house upon leaving.

Since I am not prone to having memory lapses and there are no apparent signs of a break-in, or of robbery, nor any obvious indications of a ground shaking event, I would tend to accept explanation (d). However, just because I have not found any evidence of a break-in, or of ground shaking, or of definite forgetfulness does not, by themselves, eliminate explanations (a), (b) and (c), i.e. all four explanations still account for the movement of the chess pieces and satisfy conditions (4) – (6) above. In the absence of evidence to the contrary, the four explanations remain in contention and I need something more to decide which of the four explanations is the best explanation and why it is best.

Additional factors have to be taken into account to make and justify this decision. There is (as a minimum) one relevant factor which applies to each of the explanations (a) – (d). First, on the basis of my medical history and current medical state, my personal physician assures me that any loss of memory of recent experienced events is extremely unlikely. Second, the local geology is so stable that a ground shaking event would be highly improbable. Third, given what usually occurs in house burglaries in my city, it would also be improbable that a stranger should go to the trouble of breaking into my house and then take nothing when there are valuable items inside. Fourth, knowing the character of my friend with the house key, it is quite likely that she would let herself into my house when I am not there so that she can 'play a joke' on me.

My analysis of the situation and its additional factors leads me to arrive at the following deductions. The possibility of any continuing inability to recall recent events on my part may safely be dismissed. A ground shaking event strong enough to shift the chess pieces would not leave them as found, i.e. all upright and orderly. A burglar would not be bothered to orderly shift the chess pieces (or anything else). My friend with the house key would move the chess pieces if she was alone in my house.

The criteria for choosing which particular explanation is best out of a competing set of explanations has been argued over in the philosophical literature (at least) since the publication of Gilbert Harman's seminal papers on the topic (Harman 1965, 1968) and remains the subject of debate (cf. Glass 2012, 412; McCain 2016, 159-160). This debate is obfuscated by the situation that the meanings of some of the terms used in discussions of the criteria vary. Most prominent amongst criteria deemed suitable is the criterion of coherence which is considered central to determining the best explanation (Kosso 1992, 100). Adolfas Mackonis, for example, draws attention to the term 'coherence' sometimes being used to mean 'consistency with background knowledge' and on other occasions to mean 'plausibility with respect to background knowledge' (Mackonis 2013, 980). We shall avoid adding to the confusion over 'coherence' by not utilising the term at all. How then shall we decide which explanation is *best*?

Although explanations (a), (b) and (c) are not logically excluded, in light of the facts, the additional factors and my deductions, I infer that explanation (d) is the *best* explanation. Why? There are two clear reasons for reaching this conclusion. Given how the argument developed following the schema (1) – (6), these reasons are that explanation (d) is:

❖ the most probable of the four explanations as it has likely circumstances in its favour and the other three explanations do not; and
❖ the most reasonable of the four explanations as it stands up better to rational analysis than the other three explanations do.

These are sufficient for deciding which of the explanations (a) – (d) is *best*. Therefore, the criteria for choosing the best explanation may be limited to 'most probable' and 'most reasonable' (as defined). This outcome vindicates our use of the same criteria in the case of potential energy and we need look no further for suitable criteria.

5. Applying 'Inference to the Best Explanation' to the Potential Energy Case

It was stated in Section 2 that potential energy (and also kinetic energy) are not directly measurable. The method of 'inference to the best explanation' is the appropriate form of inference when dealing with quantities that are not directly measured, as pointed out by Adolfas Mackonis:

> *Any* argument for the truth or reality of a theoretical term, concept, entity or theory in general is an instance of IBE [Inference to the Best Explanation]. IBE is a fundamental component of theoretical reasoning in general and of scientific practice in particular. (Mackonis 2013, 975–976, italics in original)

We shall now apply the schema for finding the best explanation to the potential energy case. Returning to the schema (1) – (6), suppose explanation E has both kinetic energy and potential energy as components. Let the set F in condition (1) be the huge number and assortment of both commonplace and scientific facts as mentioned in Section 3. Let condition (2) hold for E being the potential energy explanation, i.e. all the facts comprising this set F are explained by E. On the basis of both empirical and theoretical findings made over more than a century, conditions (4) – (6) also all hold for E. The question which then emerges is whether condition (3) holds. If so, then this might be considered enough justification for taking E to be correct.

Just as in the domestic example, we need to stipulate the relevant alternatives to E to answer this question. These alternatives may be denoted, for current purposes, as explanations which accept kinetic energy as a component but *not* potential energy. Assume that conditions (4) – (6) apply to the alternatives to E and that these alternatives can explain (by various means not including potential energy) the facts in set F. Given the depiction of E and its alternatives, we have a situation paralleling the domestic example as, in order to decide whether condition (3) holds, other factors are required. Fortunately, a decision regarding condition (3) is readily ascertainable by contemplating an example drawn from the foundations of modern chemistry. In doing so, we will proceed in a similar manner to the domestic example and employ the same criteria of 'most probable' and 'most reasonable' for choosing which explanation is *best*.

Much of chemistry and biochemistry is based on an understanding of the bonds between atoms/molecules, i.e. on chemical bonds and their reactivity (Luo 2007, 1; Kolasinski 2017, 570; Sagan and Mitoraj 2019, 4616). There can be little doubt that chemical bonds (of some kind) do have physical objectivity or else macroscopic matter (including biological organisms) would not exist. Moreover, the objectivity of chemical bonds is now well established by the empirical data collected from a variety of experiments (see Shin et al. 2002; Friedrich 2018; Wilson et al. 2019; Hu et al. 2019; Cao et al. 2020), as frankly expressed by Valerio Magnasco: "Experimental evidence shows that molecules [...] have a structure made of bonds [...]" (Magnasco 2010, xi).

There are three main classifications of chemical bonds: covalent, ionic, and metallic. These bonds are constituted, to some extent, by the forces between parts of atoms/molecules (i.e. between parts of microscopic physical systems). It was already noted in Section 3 that it is generally accepted that the potential energy of any physical system is associated with specific types of forces between parts of the system. This association of potential energy does, of course, apply to the forces acting on atoms/molecules (Housecroft and Constable 2006, 113–114) and accordingly, applies to chemical bonds. The physical fields which mediate each force not only ensure causal connection and conservation of energy but also (in chemical reactions) ensure the contiguity of bonding.

How are chemical bonds made? Let's consider a standard account of their formation. The most common bond in molecules is the covalent bond where the electrons from individual atoms are shared in a molecule. The simplest illustration is the single covalent bond between two hydrogen (H) atoms in the hydrogen molecule (H_2). When two hydrogen atoms initially separated by a large distance (in comparison to their size) approach each other, the electrons and protons in each atom have kinetic energy and each atom has potential energy. When the atoms become sufficiently close, each will contribute an electron which are then shared between the two atoms forming a covalent bond (Kolasinski 2017, 570–571). Why should these electrons get into a shared arrangement? The answer is straight-forward in terms of potential energy and because natural processes always tend (other things being equal) towards the lowest available energy state (Zumdahl 2009, 595). The standard account for the creation of chemical bonds is that when the atoms closely approach each other, there is a *lowering* of the total potential energy in the course of forming the molecule (Levine 2009, 457; Silberberg 2012, 329). The amount by which the potential energy is reduced appears as (i.e. is converted into) heat which disperses into the surrounding environment (Zumdahl 2009, 411). In general, the lower energy state that arises when atoms bond together creates stability and permits the growth of elaborate physical structures to proceed. We shall see that examining two factors concerning energy and chemical bonds brings out the issues which are important for making an inference to the best explanation in this example.

The first factor is about the decreases in the energy of the bonding atoms. These decreases actually happen when chemical bonding occurs, e.g. heat is released during the formation of chemical compounds. Such decreases are confirmed by measurements of temperature changes in numerous chemical reactions of relevant kinds showing, independent of specific theoretical models, that decreases in energy do occur when atoms bond. The potential energy explanation offers a mechanism which quantitatively accounts for the energy released when bonds form as the amount of heat measured correlates with the calculated decreases in potential energy (cf. Luo 2007; Zumdahl 2009, 361; Silberberg 2012, 345; Gupta 2016, 391-392). Conversely, reactions in which chemical compounds are dissociated, i.e. reactions that break bonds, require precise energy inputs (e.g. by applying heat or an electric current) for the reactions to proceed (see Luo 2007). Note that chemical reactions will not proceed and no structures will grow unless energetically possible (Gupta 2016, 387).

These energy correlations *tie* potential energy to chemical bonding and therefore strongly support the potential energy explanation. Alternative explanations, i.e. ones without potential energy and for which conditions (4) – (6) apply, are not generally supported by these energy considerations since they must postulate (rather than calculate) some other means to account for the heat released/absorbed in chemical reactions. These alternative explanations lack the very specific *correlations* between the heat released/absorbed and the quantitative changes that are calculable from the formalism of potential energy. This indicates a higher probability for the potential energy explanation than for its alternatives, i.e. the potential energy explanation is the most probable explanation for the formation of chemical bonds.

The second factor concerns potential energy and bond characteristics. Chemical bonds have characteristics such as bond length, bond angle and bond strength, which are quantifiable. Bond length in the hydrogen molecule, for example, is the distance between the nuclei of the two H atoms when the energy of the molecule as a whole is a minimum (Zumdahl 2009, 595). The bond angle is the angle formed by the bonds in a molecule consisting of three or more atoms (Housecroft and Constable 2006, 200). Bond strength is defined in terms of the energy needed to break a particular bond (Silberberg 2012, 339). Potential energy is intimately linked to the characteristics of chemical bonds. Consider the changes in the energy of a molecule which occur when its structure is altered, e.g. when there are changes in bond length. Such changes are quantified by chemists using an extremely powerful analytical tool called the 'potential energy surface' (PES) which gives a molecule's energy as a function of the positions of its atoms (Gupta 2016, 216). The PES allows molecular shapes (e.g. bond lengths and angles) and reaction rates to be determined, as succinctly stated by chemist V. P. Gupta:

> During a reaction process, the molecules undergo structural changes that change their energies. The way the energy of a molecule changes with small changes in its structure is specified by its potential energy surface. (Gupta 2016, 390)

The PES displays potential energy linkages to chemical bonds in the context of their characteristics and demonstrates that potential energy is integral to molecular structure and the conduct of chemical reactions (Wales 2003, 1; Gupta 2016, 218).

These potential energy linkages are vital to the *consistency* of accounts of the stability of chemical compounds, their reactivity, and their resulting structures in conjunction with the forces acting within and between atoms/molecules. This is *not just a matter of its utility* for the following reason. The extent to which the potential energy linkages are essential to the characteristics of (empirically verified) chemical bonds and the chemical structures which arise from them is such that chemical reactions and structure building *does not make sense* without the potential energy linkages. Accordingly, the potential energy explanation stands up to rational analysis in a way that its alternatives do not. Therefore, the potential energy explanation is also the most reasonable explanation for the formation of chemical bonds.

Since the potential energy explanation not only accounts for the relevant facts about chemical bonds but is more probable and more reasonable than its alternatives, the set criteria are met for choosing the best explanation. Therefore, the potential energy explanation is the *best explanation* for the formation of chemical bonds.

6. The Ontological Status of Potential Energy

Does potential energy have the ontological status of being a physically objective quantity? Since it has been shown that the potential energy explanation is both the most probable and the most reasonable explanation for the formation of chemical bonds and that the criteria of 'most probable' and 'most reasonable' are sufficient for making an inference to the best explanation, it has also been inferred that the potential energy explanation is the *best* explanation for the formation of chemical bonds and, by extension, the chemical structures which subsequently stem from them.

Is this enough to justify concluding that potential energy is an objective physical quantity? Those who think that best explanations are true would answer affirmatively. Although the best explanation argument presented here does offer very compelling grounds for accepting the physical objectivity conclusion, it remains contestable for even best explanations cannot *guarantee* the truth of a conclusion. Therefore, we are arguably still a step removed from conferring physical objectivity on potential energy. What is needed to bridge the gap in this case is one or more instances where the denial of potential energy's physical objectivity would have outcomes contrary to established results. Instances of this kind would allow the argument to advance past the terminal point achieved by 'inference to the best explanation'.

There is at least one such instance relevant to chemical bonds. If potential energy were not an objective physical quantity, then what would follow in light of the energy linkages outlined in the previous section? Let's consider this issue. We have seen that potential energy is intimately linked to chemical bonds in a manner that goes beyond the utility of the potential energy formalism. It was especially emphasised that the potential energy linkages are so essential to chemical bonds that the characteristics and structure of bonds would not make sense without these linkages. Yet, if potential energy was not an objective physical quantity then the potential energy linkages *could not be physically objective either*. In the absence of these linkages, there would be an absurd situation where molecules would not have the physical conditions needed for their existence. Consequently, it would follow from potential energy *not* being physically objective that chemical bonds would also *not* have an objective physical existence, contrary to the experimental evidence. We conclude then, that this finding in conjunction with the potential energy explanation being the best explanation, does indeed warrant the status of physical objectivity for potential energy. More poetically, we might say that *potential energy is no fiction*!

7. Final Remarks

The conclusion reached with the aid of the method of 'inference to the best explanation' is that potential energy is a physically objective quantity and not just a theoretical 'instrument'. Acceptance of potential energy as physically objective provides an explanation which extends further than mere theoretical utility can. This conclusion also provides an answer to the question of why potential energy "describes a significant aspect of the state of a system". It is precisely because potential energy is an objective physical quantity which is essential to the workings of any physical system that the potential energy formalism provides precise descriptions of aspects of a system's state. This is why potential energy proves to be theoretically indispensable.

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REFERENCES

Brössel, P. 2013. Correlation and Truth. In *EPSA11: Perspectives and Foundational Problems in Philosophy of Science*, eds. V. Karakostas and D. Dieks. Cham, Switzerland: Springer International.

Cao, K. et al. 2020. Imaging an Unsupported Metal–Metal Bond in Dirhenium Molecules at the Atomic Scale. *Science Advances* 6 (3): eaay5849.

Friedrich, J. 2018. *Metal–Polymer Systems: Interface Design and Chemical Bonding*. Weinheim, Germany: Wiley-VCH.

Giere, R. N. 1988. *Explaining Science: A Cognitive Approach*. Chicago: University of Chicago Press.

Glass, D. H. 2012. Inference to the best explanation: Does it track truth? *Synthèse* 185: 411–427.

Gupta, V. P. 2016. *Principles and Applications of Quantum Chemistry*. Amsterdam: Academic Press.

Halliday, D., R. Resnick and J. Walker. 2013, 10th edn. *Fundamentals of Physics*. Hoboken, N. J.: Wiley.

Harman, G. H. 1965. The inference to the best explanation. *Philosophical Review* 74: 88–95.

Harman, G. H. 1968. Enumerative induction as inference to the best explanation. *Journal of Philosophy* 65: 529–533.

Hecht, E. 2016. Relativity, potential energy, and mass. *European Journal of Physics* 37: 065804-1–065804-21.

Housecroft, C. E., and E. C. Constable. 2006, 3rd edn. *Chemistry: An Introduction to Organic, Inorganic and Physical Chemistry*. Upper Saddle River, N.J.: Pearson Prentice Hall.

Hu, F., L. Shi, and W. Min. 2019. Biological Imaging of Chemical Bonds by Stimulated Raman Scattering Microscopy. *Nature Methods* 16: 830–842.

Jaffe, R. L., and W. Taylor. 2018. *The Physics of Energy*. Cambridge: Cambridge University Press.

Kolasinski, K. W. 2017. *Physical Chemistry: How Chemistry Works*. Chichester, West Sussex: Wiley.

Kosso, P. 1992. *Reading the Book of Nature: An Introduction to the Philosophy of Science*. Cambridge: Cambridge University Press.

Levine, I. N. 2009, 6th edition. *Quantum Chemistry*. Upper Saddle River, N.J.: Pearson Prentice Hall.

Lipton, P. 2004, 2nd edition. *Inference to the Best Explanation.* London: Routledge.

Luo, Y. -R. 2007. *Comprehensive Handbook of Chemical Bond Energies*. Boca Raton, FL.: CRC Press.

McCain, K. 2016. *The Nature of Scientific Knowledge: An Explanatory Approach*. Cham, Switzerland: Springer.

McCain, K., and T. Poston, eds. 2017. *Best Explanations: New Essays on Inference to the Best Explanation*. Oxford: Oxford University Press.

Mackonis, A. 2013. Inference to the Best Explanation, Coherence and Other Explanatory Virtues. *Synthèse* 190: 975–995.

Magnasco, V. 2010. *Models for Bonding in Chemistry*. Hoboken, N.J.: Wiley.

Okasha, S. 2002. *Philosophy of Science: A Very Short Introduction*. Oxford: Oxford University Press.

Poincaré, H. (trans. G. B. Halsted). 1905. *Science and Hypothesis*. New York: Science Press.

Psillos, S. 2009. *Knowing the Structure of Nature: Essays in Realism and Explanation.* Basingstoke, Hampshire: Palgrave Macmillan.

Quine, W. V. O. 1951. Two Dogmas of Empiricism. *Philosophical Review* 60: 20–43.

Riggs, P. J. 2019. Comment on 'Relativity, potential energy, and mass'. *European Journal of Physics* 40: 028001-1–028001-5.

Sagan, F., and M. P. Mitoraj. 2019. Kinetic and potential energy contributions to a chemical bond from the charge and energy decomposition scheme of extended transition state natural orbitals for chemical valence. *The Journal of Physical Chemistry A* 123: 4616–4622.

Schick, T. and L. Vaughn. 1995. *How to Think About Weird Things: Critical Thinking for a New Age*. Mountain View, Calif.: Mayfield Publishing.

Serway, R. A., and J. W. Jewett Jr. 2008, 7th edition. *Physics for Scientists and Engineers with Modern Physics*. Belmont, Calif.: Brooks Cole.

Shankar, R. 2019. *Fundamentals of Physics I: Mechanics, Relativity, and Thermodynamics*, expanded edition. Yale: Yale University Press.

Shin, S. -H., T. Luchian, S. Cheley, O. Braha, and H. Bayley. 2002. Kinetics of a reversible covalent-bond-forming reaction observed at the single-molecule level. *Angewandte Chemie International Edition* 41: 3707–3709.

Silberberg, M. S. 2012, 6th edition. *Chemistry: The Molecular Nature of Matter and Change*. New York: McGraw-Hill.

Smart, J. J. C. 1968. *Between Science and Philosophy: An Introduction to Philosophy of Science*. New York: Random House.

Stace, W. T. 1934. The Present Dilemma in Philosophy. *Journal of Philosophy* 31: 365–372.

van Fraassen, B. C. 1980. *The Scientific Image.* Oxford: Clarendon Press.

Vogel, J. 1998. Inference to the Best Explanation. In *Routledge Encyclopedia of Philosophy*, ed. E. Craig [online]. London: Routledge. <www.rep.routledge.com/articles/thematic/inference-to-thebest-explanation/v-1>. Accessed: 6 March 2020.

Wales, D. J. 2003. *Energy Landscapes*. Cambridge: Cambridge University Press.

Wilson, T. R. et al. 2019. Observing the 3D chemical bond and its energy distribution in a projected space. *ChemPhysChem* 20: 3289–3305.

Young, H. D., and R. A. Freedman. 2016, 14th edn. *Sears and Zemansky's University Physics with Modern Physics.* London: Pearson Education.

Zumdahl, S. S. 2009. *Chemical Principles*. Boston: Houghton Mifflin.