Of Water Drops and Atomic Nuclei:

Analogies and Pursuit Worthiness in Science

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Abstract

This article highlights a use of analogies in science that so far has received relatively little systematic discussion: providing reasons for pursuing a model or theory. Using the development of the liquid drop model as a test case, I critically assess two extant pursuit worthiness accounts: (i) that analogies justify pursuit by supporting plausibility arguments and (ii) that analogies can serve as a guide to potential theoretical unification. Neither of these fit the liquid drop model case. Instead, I develop an alternative account, based on the idea that analogies facilitate the transfer of a well-understood modelling strategy to a new domain.

1 Introduction

For much of the twentieth century the main focus in debates about analogies in philosophy of science was whether they play any philosophically interesting role in scientific reasoning. In defending the relevance of analogies, Norman Campbell ([1920], Chapter 6) and Mary Hesse ([1953], [1966]) were responding to Pierre Duhem ([1954], Chapter 4) and his intellectual heirs among the logical empiricists, such as Hans Reichenbach. Although these critics of analogy usually admitted (grudgingly) that analogies sometimes guided the development of a scientific theory, they regarded this as a mere psychological curiosity, not something that plays any interesting, normative role in scientific reasoning (Reichenbach [1944], pp. 66–72). Arguing that analogies can serve important purposes that philosophers of science ought to account for, Campbell and Hesse opposed these at-the-time widely accepted views.

Today, the centre of gravity in the debate has shifted. Philosophers interested in analogies now generally agree with Hesse that analogies play a number of important and philosophically interesting roles in science. While different uses of analogy are often mentioned (Bartha [2013], Section 1), most philosophers have tended to focus on two types of questions: (i) whether analogies can function as evidence or an inference to provide epistemic support for a hypothesis and (ii) whether analogies enable the formulation and development of new theoretical ideas. Call accounts that focus on these two questions 'justificatory accounts'[1] and 'generative accounts'[2], respectively.

[1] For recent discussions of general justificatory accounts of analogy, see (Bartha [2010], [2013]; Norton [unpublished]; Pietsch [unpublished]). Justificatory accounts of analogy have also been developed in more specific contexts, for example, concerning extrapolation in biomedical and social sciences (Steel [2010]), convergence arguments in evolutionary biology (Currie [2013]), and analogue simulations of black holes in physics (Dardashti *et al*. [2017]).

[2] Examples of generative accounts include (Morgan [1997], [1999]; Gentner *et al.* [1997]; Nersessian [1988], [2002], [2008], Chapter 5). Hesse also emphasized the generative use of analogies in science ([1953], pp. 212–14, [1966]).

In this article, I highlight a third use of analogies that has so far received relatively little attention: providing reasons for pursuing a model or theory, that is, reasons for testing and developing it further. As Larry Laudan ([1977], pp. 108–14, [1980], pp. 173–5) pointed out, evaluating whether a hypothesis is worth pursuing is a question distinct from both (i) how epistemically justified the theory is and (ii) how it was generated. However, while philosophers have noted that analogies often provide reasons for giving a model or theory further consideration, few systematic discussions exist of what I will call 'pursuit worthiness accounts'.[3] My aims in this article are (1) to critically assess extant pursuit worthiness accounts of analogies in science and (2) to propose a new pursuit worthiness account.

Concretely, my discussion will be guided by a case study, outlined in Section 2, concerning the development of the liquid drop model of the atomic nucleus. My discussion of pursuit worthiness accounts in the remainder of the article will focus on how well they fit this case. In Section 3, I consider accounts, defended most recently by Paul Bartha ([2010]), according to which analogies primarily provide reasons for pursuit by virtue of supporting plausibility arguments, thus subsuming pursuit worthiness uses of analogies within a justificatory account. In Section 4, I consider an account, suggested by Campbell ([1920]), where analogy-based hypotheses are taken to be pursuit worthy, not by being more plausible, but because they provide opportunities for theoretical unification. While these accounts are plausible for some cases, I argue that they do not fit the liquid drop model case.

[3] The notion of pursuit worthiness has since has been developed in more detail in (Whitt [1990], Achinstein [1993], Šešelja and Straßer [2013]; Nyrup [2015]), among others. I borrow the terms 'generative', 'justificatory', and 'pursuit worthiness' from (McKaughan [2008]), who uses these labels to distinguish different interpretations of Peircean abduction. Notice also that I avoid the term 'context of discovery' as it tends to unhelpfully conflate a number of distinct issues (see Nickles [1980]; Hoyningen-Huene [1987]) that are better captured by the terminology employed here.

My alternative to these accounts is based on the idea that analogies can facilitate the transfer of an already well-understood modelling strategy to a new domain. As argued in recent discussions of scientific understanding (de Regt [2009]; Strevens [2013]), to understand a phenomenon using some explanatory model or theory, scientists need to have understanding-with, that is, they must also understand the theoretical representation itself. Using these ideas, I argue that analogy-based modelling strategies are often worth pursuing because they provide an efficient means of developing models with a high degree of understanding-with. I provide some of the set-up for this account in Section 5, where I discuss the relation between generative accounts and pursuit worthiness accounts and consider the suggestion that analogies only played a generative role in the liquid drop model case. Section 6 then develops my positive account in more detail and explains how it helps us make sense of the liquid drop model case.

Before I begin, a note on terminology: In this article, I will distinguish models, in the sense of specific theoretical representations of a target phenomenon, from analogies, in the sense of apparent or conjectured similarities between two domains of phenomena. So, in my use, 'the liquid drop model' actually refers to a family of theoretical models that were developed on the basis of the same analogy, namely, that atomic nuclei might be similar (in certain respects) to a water drop. I will refer to this as 'the drop analogy'. When important, it will be clear from the context if a specific of these models is being referred to.

2 Case Study: The Development of the Liquid Drop Model

The liquid drop model was developed from the late 1920s onwards, during a time when physicists were trying to extend their understanding of atoms to encompass the structure of the nucleus itself.[4]

[4] This section primarily draws on Roger Stuewer's ([1994]) detailed historical account. Norton ([unpublished]) also analyses the liquid drop model as an example of analogies in science, but focuses on what I call justificatory uses of the analogy. Little ([2008]) analyses Gamow's use of analogy from a rhetorical point of view.

The liquid drop model was first formulated in 1928–29 by George Gamow, then a Russian doctoral student visiting Western Europe. In the discussion note where he first introduced the model, Gamow stated that the nucleus 'may be treated somewhat as a small drop of water in which the particles are held together by surface tension' (Rutherford *et al.* [1929], p. 386). In line with common assumptions at the time, he modelled the nucleus as consisting of a collection of α-particles held together by some mutually attracting force and calculated the resulting surface tension force on the outer layer of particles. This inward-directed force would be counteracted by the internal pressure due to the kinetic energy of the particles and the Coulomb repulsion between the positively charged α-particles. Assuming these forces to be in equilibrium, Gamow was able to derive an expression for the mass defects (the nuclear binding energy) of the different nuclei (Gamow [1930], pp. 632–7).

Niels Bohr and Ernest Rutherford were enthusiastic about the model and secured additional support for Gamow to continue working in Western Europe between 1929 and 1931. However, while Gamow made some progress with his model, he soon ran into problems. Although his theoretically predicted mass defects traced a curve of the same general shape as the experimentally determined ones, it only gave reasonably accurate quantitative predictions for the lighter elements. He tried to remedy this by including free nuclear electrons in the model, which some physicists had theorized to exist, in addition to α-particles. However, this move was soon blocked by a major theoretical problem, the so-called Klein paradox, which precluded the existence of electrons inside the nucleus. Gamow was unable to overcome this problem and, by the summer of 1930, he turned his attention elsewhere (Stuewer [1994], pp. 78–85).

Despite these problems, many physicists regarded the model as promising (Steuwer [1994], pp. 86–7). For instance, Rutherford (Rutherford *et al*. [1930], p. 534) wrote that Gamow's model 'while admittedly imperfect and speculative in character is of much interest as the first attempt to give an interpretation of the mass-defect curve of the elements'. The model was further developed during the 1930s, along two broad trajectories. First, following the discovery of the neutron in 1932, Werner Heisenberg and subsequently Carl von Weizsäcker tried to rework the model on the assumption that the nucleus contains a combination of protons and neutrons. Their aim was the same as Gamow, namely, to explain the mass defects. Their efforts resulted around 1935-6 in what is today known as the semi-empirical mass formula (Stuewer [1994], pp. 87–97).[5] Second, from circa 1936 onwards, Bohr and several of his collaborators in Copenhagen (including Fritz Kalckar and Otto Frisch) tried to adapt the model to account for artificially induced radioactivity, that is, radioactive elements produced by bombarding stable elements with neutrons. Briefly, their idea was that the excitation caused by impinging neutrons could be seen as vibrations in the surface tension layer of the nucleus, resulting in the 'evaporation' of particles from the drop of 'nuclear fluid' (Stuewer [1994], pp. 97–107). Finally, in December 1938, Lise Meitner and Frisch realized that the liquid drop model could potentially explain nuclear fission, a newly discovered and at the time highly puzzling and unexpected phenomenon (Stuewer [1994], pp. 107–16)[6]: if the vibrations induced by an impinging neutron were large enough for the nucleus to assume an elongated dumbbell shape with most particles concentrated at the two ends, this would allow the Coulomb repulsion to drive the two ends apart, splitting the nucleus in two.

From this brief outline, it is clear that the drop analogy not only inspired Gamow's original model, but played an important role in guiding subsequent revisions and extensions of the model. There are two questions we might ask about this. The first concerns why this analogy suggested certain revisions and extensions, that is, why the analogy enabled those working on the model to

[5] This formula is so called because it is not derived from purely theoretical principles. Rather, it was constructed by calibrating certain parameters in a formula based on the revised liquid drop model to best fit the empirical data.

[6] See also (Andersen [1997]) on the experimental and theoretical developments that lead to the discovery of fission.

think of these extensions rather than others. These are the types of questions that generative accounts aim to answer. I will say more about this in Section 5.

The second, which I will focus on for now, is why it was reasonable for physicists at the time to work on models based on the drop analogy, including the revisions and extensions this analogy subsequently suggested. That is, rather than asking why the model inspired or enabled physicists to come up with the relevant ideas, the question here concerns why it was reasonable for physicists to invest further time and efforts into pursuing these ideas. We can distinguish several such decisions. First, after Gamow noticed the analogy, he chose to spend some of his limited time in Western Europe developing it into a formal theoretical model. Second, Bohr and Rutherford were sufficiently impressed with Gamow's initial model to secure financial support, allowing him to continue working on it. Third, after 1930, Rutherford and others praised the model as 'of much interest', despite its empirical and theoretical problems. Fourth, Heisenberg and von Weizsäcker tried to revise the model after the discovery of the neutron. Finally, Bohr and later Meitner and Frisch tried to extend the model, along the lines suggested by the drop analogy, to account for other nuclear phenomena.

Accounting for all factors involved in each of these decisions would need a more fine-grained analysis than I aim to undertake here. In this article, my focus will be on just one question, namely, whether the drop analogy itself contributed to the pursuit worthiness of the model. While some might suspect that the drop analogy played a merely generative role in this case, I will argue, in Sections 5 and 6, that there were in fact positive reasons to pursue an analogy-based modelling strategy. First, I examine two extant pursuit worthiness accounts and explain why they do not work for the liquid drop model case.

3 Plausibility Accounts

It might be thought that an appropriate justificatory account of analogies will also provide a straightforward answer to why scientists should pursue analogy-based models. For, although analogies rarely provide conclusive reasons for accepting a model, they can still provide some epistemic support for it. By granting the model this initial degree of plausibility, the analogy makes it reasonable to pursue the model further, or at least contributes to its pursuit worthiness.

Several philosophers have construed reasons for pursuit, roughly along these lines, in terms of plausibility judgements (Hanson [1958]; Salmon [1967]; Kordig [1978]; McLaughlin [1982]). For instance, N. R. Hanson noticed that before scientists have sufficient reasons for accepting a hypothesis, they need to have some 'reasons for suggesting H in the first place' ([1958], p. 1074), that is, reasons for giving H further consideration. He identified these with 'reasons which make H a *plausible conjecture*' ([1958], p. 1074), arguing that, amongst other things, analogies can provide this kind of reasons ([1958], pp. 1077–9). In an influential discussion of Hanson's argument, Wesley Salmon ([1967], pp. 113) agrees that plausibility judgements are important to scientific reasoning including, in particular when deciding 'whether the hypothesis deserves to be seriously entertained and tested or whether it should be cast aside without further ceremony'. Salmon then argues that on a Bayesian account of scientific reasoning, plausibility judgements can be identified with estimates of prior probabilities.[7] Like Hanson, Salmon mentions analogies as one source of such plausibility judgements (p. 125–6; see also Salmon [1990], pp. 186–7). However, Salmon does not analyse analogy-based plausibility arguments in any detail.

Recently, Paul Bartha ([2010], [2013]) has developed a more sophisticated and detailed plausibility account that I will focus on in the following. I start by outlining some details of his account of analogical inference and the relation between plausibility and pursuit worthiness.

[7] Salmon uses this analysis to argue that reasons for suggesting a hypothesis and reasons for accepting it can be captured within the same framework, and are thus not 'logically' distinct, as Hanson had claimed.

3.1 Bartha on plausibility and analogical inference

Following Hesse ([1966], p. 59), Bartha endorses a 'two-dimensional' account of analogical arguments. Rather than merely looking at the horizontal relations—the similarities and differences between the source domain (water drops) and target system (the atomic nucleus)—two-dimensional accounts also emphasize the vertical relations, consisting of dependency relations (such as causal, modal, or explanatory relations) within the two domains.

Specifically, Bartha ([2010], Chapter 4) defends an inference schema that can be summarized as follows:

> BAR1: There is a structure of dependency relations *R*(a, b, c, …) between features a, b, c, … of the source system S1.
>
> BAR2: The target system, S2, has at least one of the features a', b', c', … analogous to a, b, c, …
>
> BAR3: S2 does not have any features that would preclude *R*' (analogous to *R*) from obtaining.

Therefore:

> BAR4: It is *prima facie* plausible that *R*' (a', b', c', …) obtains for S2 and, *a fortiori*, that S2 has the rest of a', b', c', ….

The first premise states that there is a 'prior association', that is, a structure of dependency relations, between some of S1's features. Which kinds of dependency relations to look for varies between contexts, but a good example is how the parts of a mechanism interact and constrain each other to produce certain effects. Second, we notice that the target system has some features analogous to those involved in the prior association in S1. Finally, we consider whether there are any 'critical differences' between the two systems, that is, whether S2 has any features that would preclude a relation analogous to the prior association from obtaining. Given these premises, according to Bartha, it is *prima facie* plausible that the prior association obtains in S2 as well.

According to Bartha, analogical arguments of this type are often used to support hypotheses before they have been tested ([2010], p. 6) and to provide reasons for investigating them further ([2010], p. 16). Unlike Salmon, however, Bartha does not equate all plausibility judgements with estimates of prior probability. Rather, he distinguishes a probabilistic conception of plausibility from a modal conception. The former is used in phrases like '*p* is highly plausible', '*p* is more plausible than *q*' and 'the evidence makes *p* more plausible'; here, the term 'plausible' can simply be replaced by 'probable' ([2010], p. 16). The modal conception applies to phrases like 'it is plausible that *p*', which Bartha takes to mean 'roughly speaking [there] are sufficient grounds for taking *p* seriously' ([2010], p. 16). Bartha believes this captures an epistemic notion 'somewhat stronger than ordinary epistemic possibility' (Bartha [2013], Section 2.3), which he sometimes glosses as *p* having 'an appreciable likelihood of being true' ([2010], p. 18). But asserting a plausibility judgement of this form usually also has the 'pragmatic connotation' that 'we have good reason to investigate it (subject to the feasibility and value of investigation)' ([2010], p. 15).[8] In a footnote, he further clarifies that this pragmatic implication depends on the epistemic dimension 'in a decision-theoretic sense' given 'contextual information about costs and benefits' ([2010], p. 18, Footnote 19).

[8] At times, Bartha seems to equate plausibility with 'worthy of investigation' (for example, [2010], p. 256; see also Footnote 13 below), rather than taking the latter to be a pragmatic connotation of plausibility. This would collapse the distinction between plausibility and pursuit worthiness; I set this interpretation of plausibility aside here.

Bartha thus allows that the pursuit worthiness of a hypothesis depends on factors apart from its epistemic support, namely, the costs and benefits of pursuing it. It should therefore be possible to argue for the pursuit of a hypothesis by showing it is more valuable or feasible to investigate than previously thought, rather than by increasing its epistemic support. However, in practice Bartha ([2010], p. 18) tends to focus on the epistemic dimension, claiming, for instance, that 'Any argument that a hypothesis is prima facie plausible […] should provide reasons to think the hypothesis might be true'. As I read Bartha, analogies primarily provide reasons for pursuing hypotheses by providing epistemic support for it. Since it is typically only worth pursuing theories that have a serious chance of being true (or at least of being broadly on the right track),[9] if an analogy shows that a hypothesis or model that would otherwise have been dismissed is in fact plausible, this would provide some reason for pursuing it. Once this is established, whether we are then justified in pursuing a hypothesis, all things considered, depends on further 'contextual information', that is, information in addition to that provided by the analogy, about the feasibility (costs) and interest (benefits) of pursuit. I shall return to the relevance of the latter factors. First, I argue that it was not by adding to the liquid drop model's epistemic support that the drop analogy contributed to its pursuit worthiness.

3.2 Plausibility and the drop analogy

To be sure, the relevant actors in 1928–30 regarded Gamow's model as at least to some degree plausible: they regarded the model (or something close to it) as a serious possibility that could not be rejected out of hand. For instance, while Rutherford called it 'speculative', he clearly thought

[9] In some cases, it can be worth pursuing models that are known to be false in order to learn about counter-factual situations. For example, as Weisberg ([2007], pp. 653–4) mentions, biologists might study three-sex models of reproduction even though they are not true of anything in the actual world, since this might help us better understand why evolution has only produced two-sex systems of reproduction. At other times, scientists might continue pursuing a model after it has been conclusively rejected in order to explain its empirical successes. However, neither seem to be what is going on in the liquid drop model case, so I ignore these qualifications here.

there was some chance that this model, or some suitably modified version of it, could provide a correct explanation of the mass defect curve. The case also fits Bartha's schema. First, atomic nuclei and water drops share some features: they are both relatively stable collections of smaller, interacting constituent particles (BAR2). Second, in water drops this stability is due to the equilibrium between the surface tension, which results from the mutual attraction of its constituent particles, and internal pressure due to the particles' kinetic energy (BAR1). Since there is no known reason why an analogous account could not apply to the atomic nucleus (BAR3), it is *prima facie* plausible (on Bartha's account) that atomic nuclei are held together by an equilibrium between its surface tension force and internal pressure.

However, it is not clear that drop analogy was needed to establish the plausibility of the model. Notice that a general worry about Bartha's account is whether our knowledge of similarities between the source and target domains (BAR2) plays any essential role in the inference schema. After all, if we already have the premise that a given causal structure is consistent with our knowledge of the target system (the 'no critical difference'-step), is this not sufficient to show the hypothesis plausible? In other words, what epistemic force does the analogy with the source system add to this? Bartha ([2010], p. 264) himself raises this problem, calling it the 'disappearing analogy problem'. His solution ([2010], pp. 302–4) to the general problem is inspired by Whewell's and Herschel's concept of *vera causa*.[10] Briefly, the idea is that for a causal structure to count as genuinely plausible, it should not be a mere logical or epistemic possibility, in the sense of merely being consistent with our background knowledge; we should also have some kind of positive reason to think it could exist. Analogies provide such a reason, by showing that a similar causal arrangement already exists somewhere in nature. It is thus this kind of additional, positive reason that the analogy, according to Bartha, contributes to his inference schema.

[10] Bartha ([2010], Chapter 8) also explicates this idea within a Bayesian framework, but the following informal account is sufficient for my purposes here.

Now, one might doubt whether this kind of positive reason is always required to make a hypothesis pursuit worthy.[11] However, at least in some cases, such as when scientists need to postulate novel types of forces or causes, Bartha may be right that analogies can be used to reinforce the plausibility of a hypothesis. The problem is that in formulating the liquid drop model, Gamow did not need to postulate any new causes. As Gamow ([1930], p. 632) notices, an attractive nuclear force had already been postulated to explain the stability of nuclei and its existence had been empirically supported by scattering experiments. What Gamow tried to show was rather (a) that it was possible to construct a model of the nucleus based on the idea of an equilibrium between surface tension and internal pressure using principles of quantum mechanics and commonly accepted assumptions about the nucleus; and (b) that this model could potentially explain certain empirical phenomena, namely, the mass defects. To the extent that Gamow provided a plausibility argument for his model, it was by showing it consistent with existing knowledge and perhaps because of its modest empirical success. The fact that this model was based the drop analogy does not seem crucial to whether it should be regarded as a serious possibility. Similarly, when Heisenberg, and subsequently von Weiszäcker, decided to take up the model again, this was because the discovery of the neutron—not any analogy—made the model plausible once more. The partial success of this project may also have contributed to the plausibility of the model later on, in 1936–37, when Bohr was thinking about possible explanations of artificial radioactivity. But again, here it was the empirical and theoretical successes of the model, rather than the drop analogy, which showed the model plausible.

[11] The following case is arguably a counter example: In 1956, T. D. Lee and C. N. Yang proposed that the so-called principle of parity conservation in particle physics might be violated in weak interactions. Most particle physicists regarded this hypothesis as highly implausible. However, since it could explain an otherwise puzzling set of decay patterns, they nonetheless carried out the experiments that Lee and Yang had proposed to test their proposal. As it turned out, the experiments confirmed the parity violation hypothesis, to the great surprise of most physicists involved, who had expected the experiments to merely be a first, negative step towards explaining the anomalies (Franklin [1986], pp. 7–38).

To be clear, these considerations are not intended to show that analogies cannot form the basis of plausibility arguments, along the lines proposed by Bartha, in some or even many cases. My point is simply that it does not work for the liquid drop model and cases like it.

A proponent of plausibility accounts might object that, insofar as the drop analogy provided any reasons for pursuing the hypothesis, that is, if it did not just play a generative role, it must have been because it increased the plausibility of the model. How else could analogies justify pursuit? However, this objection assumes that plausibility is the only relevant factor in deciding what to pursue. As noted above, Bartha clearly recognizes that pursuit worthiness also depends on a number of factors apart from epistemic support.[12] But if this is the case, why assume that the analogy increased the plausibility of the model, rather than one of these other factors?

In the remainder of this article, I will look at pursuit worthiness accounts of analogies that focus on factors apart from plausibility or epistemic support.

4 Analogies as a Guide to Unification

One such possibility would be to focus on the value of the hypothesis: perhaps scientists have reason to pursue analogy-based hypotheses because it would be more valuable to learn that they are correct, even if they are not more likely to be true. In this section, I consider an account along these lines, specifically, the idea that analogies are a guide towards hypotheses with a high potential for theoretical unification.

An account along these lines was suggested by Campbell ([1920]) in his defence of analogies in physics. Campbell argued that only analogy-based physical theories are worth considering.

[12] In fact, on a plausible decision-theoretic construal of pursuit worthiness, increasing the probability of a hypothesis can sometimes lower the overall expected utility of pursuing it, ceteris paribus. Thus, even if the drop analogy did increase the plausibility of the liquid drop model, this does not guarantee that it increased its pursuit worthiness. By contrast, increasing the value of correctly accepting a hypothesis does raise its pursuit worthiness, ceteris paribus. See (Nyrup [2015]) for a formal model and the details of this argument.

Otherwise, if the only aim of physical theories were to correctly entail known laws, this could be achieved by some more or less arbitrary symbolic calculus plus a bit of mathematical ingenuity ([1920], pp. 123–9). But, for Campbell ([1920], p. 152), such a 'theory' would be 'absurd and unworthy of a single moment's consideration […] it is just because an analogy was not used in its development that it is so completely valueless'. He regarded different kinds of analogies as valuable for different reasons. For theories based on mechanical analogies, however, Campbell took their value to be based on the fact that they offer the chance to unify quantities from previously distinct domains, for instance, heat and momentum in case of the billiard ball model of gases.

Now, one question is what Campbell means by 'value' here. Bartha sometimes interprets Campbell's view as a forerunner to his plausibility account. For instance, he claims: 'Campbell, following the lead of 19th century philosopher-scientists such as Herschel and Whewell, thinks that analogies can establish this sort of *prima facie* plausibility' ([2013], Section 2.3). Specifically, Bartha ([2010], pp. 16–18) suggests that Campbell was drawing on Herschel and Whewell's *vera causa* notion of plausibility discussed in Section 3.2, above. As a historical point, this interpretation of Campbell is almost certainly false. First, Campbell argued that since theories based on mechanical analogies are logically stronger than ones that merely extrapolate general laws from observed regularities, they are in fact more likely to be false. So insofar as we find unification valuable, 'we must balance that value against the chance of error ([1920], p. 152). It obviously only makes sense to balance this increased 'value' against a reduced probability if the two can come apart. Second, Campbell ([1920], p. 132) explicitly stated that analogy-based theories are valuable 'simply because the ideas which they bring to mind are intrinsically valuable'. It is because we ascribe this kind of intrinsic value to theoretical unification that we should prefer theories based on mechanical analogies ([1920], pp. 151–2). While Campbell did not elaborate much on why unification is valuable, it is clear that he did not identify it with plausibility. Rather, the value seems to do with what characteristics we would like a theory to possess apart from being true or empirically adequate.

This account also fits one line of justification that Bartha ([2010], Chapter 7) offers for his schema, namely, that analogies tend to promote the traditional theoretical virtues, in particular unification. The first premise, BAR1, identifies the existence of a particular explanatory pattern, *R* (the prior association) in S1, while BAR2 points out that there are a number of features in S2 that could potentially be explained by the same pattern. Since BAR3, there is no known reason to rule out this possibility, there is a potential for unifying the relevant features of S1 and S2 in single explanatory schema. So, if we were to discover that *R* holds for S2, we would have increased the unification of our knowledge of the world. Again, if we value unification, this is enough to provide some reason for pursuing a hypothesis, regardless of whether unifying theories are also more likely to be true.[13] Notice, also, that this justification avoids the disappearing analogy problem: it is the existence of similarities between the two domains that suggests the potential for theoretical unification, so BAR2 here plays an essential role in the argument.

In my view, this unificationist idea provides a plausible account of why analogy-based hypotheses are worth pursuing in some cases, but not in all. For example, the billiard ball analogy for gases did seem to promise to unify thermodynamical phenomena with the theoretical framework of classical mechanics, at least from the perspective of nineteenth-century physicists. If a model of gases based on this analogy could be confirmed, the thermodynamics of gases would be explainable in terms of the same kinds of quantities (mass, force, momentum, and so on) and governed by the same laws as collisions between billiard balls.

However, this story does not work for cases like the liquid drop model. While Gamow, Rutherford and others took the drop analogy to suggest a very promising line of research, it was

[13] Bartha ([2010], p. 256) argues that as long as we consider it valuable to achieve unification, this is sufficient to show a hypothesis 'plausible' in the pragmatic sense of 'worthy of investigation', regardless of whether unification or other theoretical virtues are also truth-tracking. But he also points out that his argument can be combined with the common view that the theoretical virtues are 'indicators of empirical adequacy (or truth)'.

clear that explanations of nuclear phenomena would rely on a different theoretical framework than water drops. In water drops, the attractive force between its constituent particles is electrostatic attraction, due to the polarity of H_2O molecules. This effect is governed by the laws of chemical bonding and electrostatics. In the liquid drop model, Gamow posited an attractive force between nucleons that would be governed by quantum mechanical laws. Even if physicists might have hoped to eventually be able to unify chemical bonding, electrostatics and quantum mechanics within a single framework, this was not what the liquid drop model promised to achieve when it was developed in the 1920s and 1930s. Although the model employed modelling techniques analogous to those applied to water drops, it did not promise to unify the physics of water drops and atomic nuclei in the same straightforward way that models based on the billiard ball analogy promised to unify mechanical and thermodynamical phenomena.

5 Generative Accounts

I mentioned in Section 2 that the drop analogy clearly played a generative role in the development of the liquid drop model. Since the pursuit worthiness accounts considered so far have failed to account for this case, one might wonder whether the drop analogy played anything more than a generative role.

In particular, consider the following account[14]: As argued in Section 3.2, once Gamow had used the drop analogy to generate the basic idea for the model, there were reasons (based on relevant background knowledge) for regarding the different versions of the liquid drop model as at least somewhat plausible. Since there were few other plausible candidate explanations of the relevant nuclear phenomena, and since Gamow, Bohr, Meitner, and the other physicists regarded it as important to be able to explain these phenomena, this gave them sufficient reason to pursue the

[14] I am grateful to an anonymous reviewer for suggesting this version of the objection.

model. Unless there are many competing explanations available (which there was not at the time), no further criterion is needed to motivate pursuit.

Before addressing this objection, in Section 5.2 I will need to discuss two issues that have been supressed from my discussion thus far, concerning the relation, first, between scientific models and hypotheses and, second, between generative and pursuit worthiness accounts.

5.1 Analogy-based modelling strategies

I have talked as if a model of the kind Gamow developed is more or less equivalent to a hypothesis, that is, as if the pertinent question is whether the analogy shows the model plausible or whether it would be valuable to learn that the model is true. However, this way of thinking is slightly misleading. Gamow knew, or at least had good reasons to suspect, that his original model was incorrect. For one thing, he had not included free nuclear electrons in the model although he suspected these would make a difference to the result. More generally, he had little reason to expect these first attempts to theorize about a previously unexplored domain to result in a true model.

Now, many philosophers of science (such as Giere [2004]) have argued that since models are often constructed using deliberate distortions and idealisations, it is usually more accurate to say that scientists test hypotheses about the fit between the model and the world, rather than the truth of the model itself. Furthermore, as Wendy Parker ([2009]) has pointed out, this makes it misleading to talk as if a given piece of evidence confirms or disconfirms the model. Depending on exactly what kind of hypothesis is being tested, the same evidence may or may not be relevant to whether the model should be deemed 'adequate'. Similarly, I want to suggest that when discussing the pursuit worthiness of a model, we need to pay attention to the specific kind of hypothesis being pursued.

In the liquid drop model case, what Gamow and others were interested in was not, in the first place, a hypothesis about the similarity between water drops and nuclei. Rather, developments seem to have progressed by trying to model the atomic nucleus as if it were a water drop in order to construct a potential explanation of some otherwise puzzling phenomenon—the mass defect curve for Gamow, Heisenberg, and von Weizsäcker, artificial radioactivity for Bohr and his colleagues, and nuclear fission for Meitner and Frisch. Of course, ultimately, they were still hoping to construct a model that provided an accurate (or at least empirically adequate) description of the nucleus. However, their efforts were not directed towards confirming or disconfirming any specific hypothesis about the structure of the atomic nucleus; rather, they were adapting a modelling strategy to the atomic nucleus, guided by their explanatory interests. So if we want to say that they pursued a hypothesis, it was not one of the form 'the atomic nucleus has features a, b, c, … analogous to a water drop', but rather something like 'modelling the atomic nucleus analogously to a water drop will allow us to formulate (potential) explanations of phenomena x, y, z, …'. Or, we can say that they were pursuing an analogy-based modelling strategy to formulate potential explanations of the relevant nuclear phenomena.

One implication of this point is that pursuit worthiness accounts and generative accounts cannot be completely disentangled. If what is being pursued is an analogy-based modelling strategy, rather than a specific analogical model, pursuit worthiness judgements will depend on the kinds of models we expect to generate on the basis of a given analogy. This does not mean that the distinction between the two kinds of accounts completely collapses. Generative accounts tend to focus on spelling out how analogies can inspire or guide the development of new scientific concepts, for instance, by looking at what 'imaginative leaps' the analogy allowed scientists to make or how working through the analogy led to the formulation of novel theoretical concepts.[15] Here, the focus is on how the analogy helped scientists formulate novel theoretical ideas that go beyond the

[15] See, for instance, Nersessian ([2002]) on Maxwell's development of the concept of the electro-magnetic field and Morgan ([1997], [1999]) on Irving Fisher's use of the mechanical balance analogy to clarify and reinterpret the quantity theory of money.

conceptual resources of their existing frameworks. By contrast, pursuit worthiness accounts aim to explain why it can reasonable to adopt an analogy-based modelling strategy in the first place.

5.2 Did analogies play a merely generative role?

The notion of an analogy-based modelling strategy allows us to address the objection raised above. The objection correctly highlights that pursuit worthiness judgements are comparative: what is relevant at a given stage of inquiry is which of the lines of research available to scientists would provide the best use of their resources (time, energy, money). If there is only one practically sensible option available for obtaining a desired goal, this is option is usually worth pursuing.

As should be clear by now, however, the available options do not just include pursuing already generated models or ideas for models. In principle, there is always the further option of trying to generate additional candidates. Decisions about whether and how to generate new ideas are also subject to pursuit worthiness considerations. Now, it might be argued that since it is often difficult to generate even one plausible explanation, once Gamow had found a seemingly plausible model, this provided sufficient reason to postpone the generation of further candidates and focus on pursuing this model. But even if we accept this, we can still ask what reasons Gamow had for employing an analogy-based modelling strategy to generate this first plausible candidate rather than, say, focusing on more abstract mathematical modelling approaches or trying to derive an explanation from existing quantum mechanical theory. Similarly, we can ask what reasons there were for Bohr, and later Meitner and Frisch, to continue using the drop analogy to suggest extensions of the model to account for other nuclear phenomena.[16] Even if they knew that an existing plausible

[16] The 'Campbellian' in the opening dialogue of (Hesse [1963], pp. 26–33) also highlights that analogies are often used to suggest extensions to models to account for new phenomena.

model of the nucleus was based on the drop analogy, this does not necessarily mean that revisions or extensions of the model based on the same analogy would also be plausible.

Since I have granted that analogies can help generate novel theoretical ideas, it is tempting to think this explains why one would use analogies to suggest new models or extensions of existing ones. However, novelty is rarely worth pursuing for its own sake. Campbell ([1920], p. 130), for one, argued that the value of analogies consists rather in the restrictions they impose on theory generation:

> Analogy, so far from being a help to the establishment of theories, is the greatest hindrance. It is never difficult to find a theory which will explain the laws logically; what is difficult is to find one which will explain them logically and at the same time display the requisite analogy […] To regard analogy as an aid to the invention of theories is as absurd as to regard melody as an aid to the composition of sonatas.

Now, *pace* Campbell, it might be harder to come up with genuinely novel ideas, ones that go beyond merely tinkering with one's existing conceptual resources, than he seems to suppose. It may be that imposing some kind of systematic structure or constraint on one's thinking, such as an analogy, can help going beyond one's current conceptual frameworks. (On the other hand, analogies might act as a force of inertia, biasing one towards more familiar types of explanations). However, Campbell's deeper point—suggested by his comparison with the role of melodies in composing sonatas—is this: the relevant question is not how to most effectively come up with novel ideas, but rather how to come up with ideas that are worth developing or pursuing further. If we worry that our thinking is likely to be problematically biased or constrained, trying to produce genuinely novel ideas may (under some circumstances) be a good strategy for transcending these constraints. But in other cases—for example, if we are concerned about being overwhelmed by too many hypotheses—we may instead prefer to restrict ourselves to only generate hypotheses we think are likely to be useful.

6 A New Pursuit Worthiness Account of Analogies

This brings us back to the question of whether there is any reason to think that analogies are likely to generate pursuit worthy ideas. One could of course deny that there is anything special about analogies and that Gamow, Bohr, and Meitner simply used whatever generative strategy came to mind. Now, exactly what went on in their minds is a difficult historical question that I will not attempt to answer here. However, in this section I want to propose an account according to which there is something special about analogies, which makes them a good option for generating new models. I will first outline the general account and then explain how it applies to the liquid drop model case.

6.1 Transferring understanding-with through analogies

In brief, the proposal that I want to develop here is based on the idea that analogies facilitate the transfer of an already well-understood modelling strategy to a new domain.[17] Let me first clarify what I do not mean. First, I do not want to argue that analogy-based modelling strategies are more likely to produce correct explanations; that would simply take us back to a plausibility account. Nor is my point that the models constructed through this approach could potentially explain some of the phenomena scientists are interested in. This would not give any distinctive role for analogies, but simply make it about potential explanations, constructed by whatever means. Finally, unlike Campbell, I do not want to simply claim that explanations based on analogies are somehow intrinsically more interesting or that analogies have some special explanatory value.[18]

[17] Bartha sometimes describes analogical inferences as 'transferring' the prior association from one domain to another. Morgan ([1999], pp. 386–7) also discusses how to 'transfer' lessons learned within an analogical model to a real-world target system. My account differs by focusing on the transfer of a general modelling strategy, rather than specific results or hypotheses, to a new domain.

[18] Hesse ([1966], pp. 157–77) seems to propose an idea along these lines, arguing that the covering law account of explanation can be salvaged by requiring that all explanations rely on a metaphor (see also Rentetzi [2005]). But I will not try to defend such an account here.

A better account, in my view, is that transferring a modelling strategy through an analogy can often reduce the costs of pursuit, since trying to adapt an already existing modelling strategy to a new domain is typically easier and less time consuming than developing a new one from scratch. Thus, it can be reasonable to use analogies to generate explanations in a new domain, not just because of the novelty of the explanations thus generated, but because analogies provide a cost-effective means of generating new potential explanations.

In my view, this simple cost-effectiveness account does go some way towards explaining why there are often good reasons to pursue analogy-based modelling strategies. But I think we can also say something more directly connected to the cognitive or epistemic value of analogy-based explanations. My idea is, as already mentioned, that modelling strategies that are transferred to a new domain through analogies are themselves already well understood. To flesh out this idea, I will employ a distinction between 'understanding-why' and 'understanding-with', drawn by Michael Strevens ([2013], p. 513) based on the recent literature on scientific understanding. Understanding-why is the understanding of a phenomenon or state of affairs in the world; the sense in which we can say that someone understands combustion, heat conductivity, or nuclear fission. In science, this is typically achieved by grasping an explanation based on some theory or model that represents the phenomenon of interest with sufficient accuracy. Understanding-with, by contrast, is the kind of understanding one can have of a model or theory; the sense of 'understanding' employed when we say, for instance, that a historian of science understands the phlogiston theory of combustion. One has understanding-with to the extent that one is able to construct and grasp potential explanations based on the model or theory in question. To grasp an explanation here means to understand how the explanation works and why it would explain a given phenomenon if the theory or model accurately represented that phenomenon. As argued by Strevens and others (de Regt [2009]), understanding-with is a precondition for understanding-why, at least of the more interesting kind. For a scientist to understand a phenomenon through some explanation, it is not enough that the model or theory used provides an explanation of the phenomenon and that this explanation is factually correct. The scientist must also grasp how the explanation works in order to fully 'cash in' the potential understanding afforded by the model or theory, and this requires understanding-with.

This allows us to say more about why using an analogy-based modelling strategy is a cost-effective way of constructing new explanations. It is not just that it will be quicker or easier to construct these new explanations (though that matters too), but furthermore that if this strategy can be adapted to the new domain without too much modification, this will allow scientists to transfer most of their understanding-with to the new models constructed through this strategy.[19] Thus, insofar as the scientists succeed in constructing potential explanations of the phenomena of interest, little extra work is required to realize their explanatory potential.

Of course, pursuing an analogy-based modelling strategy is not the only way to obtain models with a high degree of understanding-with. For instance, there may be a pre-existing modelling approach available for the target phenomenon with sufficient degrees of understanding-with. While this is even more cost-effective than analogy-based modelling, a pre-existing framework is unlikely to be available when trying to explain novel phenomena. Another salient option is to pursue an abstract mathematical modelling approach to construct a novel, purpose-built framework. However, while scientists might eventually achieve sufficient levels of understanding-with of this framework (although this is not necessarily guaranteed), it would typically require extra effort to achieve. Thus, what distinguishes analogy-based strategies is that they are often able to strike a favourable balance between (1) retaining a high degree of understanding-with and (2) having the potential to cost-effectively generate explanations of novel phenomena.

[19] Plausibly, we may also say that to the extent the strategy can be transferred without modification, this will allow scientists to transfer their understanding-with to the new domain. However, this stronger claim is not strictly necessary for my argument here.

6.2 Understanding-with and the liquid drop model

Having developed my general account, let me return to the liquid drop model and explain how my account applies to this case.

First, the understanding-with account provides a rationale for why Gamow initially chose to pursue a modelling strategy based on the drop analogy: if this modelling strategy were to result in a workable model, physicists would likely already have a high degree of understanding-with of this model, thus allowing it to provide readily grasped explanations of nuclear phenomena (in the first instance the mass defects). Even if the drop analogy in itself provided no positive reason to think this strategy would work in the nuclear domain, it was still reasonable for him to prioritize analogy-based approaches before trying to construct something more unfamiliar.

Second, Gamow's work, though not empirically very successful, provided evidence that this modelling strategy was indeed feasible. While it did not yet make it especially likely that the strategy could provide a correct or accurate representation of the nucleus, the fact that Gamow was able to construct a quantum mechanical model of the nucleus based on the drop analogy suggested that this modelling strategy was compatible with quantum mechanics. Of course, the Klein paradox and the lack of alternatives to the nuclear electron hypothesis was initially an obstacle to further research. However, Gamow's results provided some evidence that pursuing this modelling strategy did not require physicists to sacrifice their existing understanding-with of the quantum mechanical framework. This strengthened the pursuit worthiness of the liquid drop model, providing a further rationale for other physicists, such as Heisenberg and later Bohr, to pursue it during the 1930s, after the discovery of the neutron.

Third, this gambit—to use the drop analogy as a cost-effective strategy for developing models with a high degree of understanding-with—was spectacularly vindicated in Frisch and Meitner's explanation of fission. As Stuewer ([1994], pp. 112–16) argues, it was because Meitner had worked in the Heisenberg–von Weiszäcker tradition in Berlin, and Frisch with Bohr in Copenhagen, that they were able to combine elements of both traditions in the construction of their explanation. In the terms used here, we can say that Frisch and Meitner were able to 'pool' their understanding-with of the liquid drop model, developed separately in Berlin and Copenhagen, to construct a potential explanation of fission.[20] Furthermore, once formulated, other physicists such as Bohr were immediately able to recognize the explanatory potential of the model. According to Frisch's ([1967], p. 47) later recollection, as soon as he started telling Bohr about their explanation of fission, Bohr exclaimed, 'Oh, what fools we have been! We ought to have seen that before!'. Bohr immediately took up the idea, and the liquid drop model formed the basis for his and John Wheeler's 1937 studies of the fission process (Stuewer [1994], p. 117).

Although Gamow, Heisenberg, nor Bohr could have predicted this particular success when they originally chose to pursue the liquid drop model, they had good reasons to think that pursuing a modelling strategy guided by the drop analogy would be an effective means of generating models with a high level of understanding-with. Indeed, this proved to be the case, thus enabling physicists such as Frisch and Meitner not only to quickly formulate potential explanations in response to surprising empirical discoveries, but to formulate an explanation that was easily grasped by their colleagues.

7 Conclusion

In this article, I have used the liquid drop model case to investigate whether analogies can provide reasons for pursuing theories or models. I have argued that neither plausibility accounts, nor unificationist accounts, nor purely generative accounts of analogies work for cases like the liquid drop model. Instead, I have argued that rather than providing reasons for pursuing a specific model,

[20] It is unclear whether Frisch and Meitner deliberately chose to pursue the liquid drop model in order to produce their explanation. It seems rather that they simply had the requisite ideas ready to mind and spontaneously brought them to bear in response to each other's suggestions (Stuewer [1994], pp. 114–15).

analogies provide a cost-effective modelling strategy for generating explanations of novel phenomena that retain a high degree of understand-with.

It is worth highlighting that the pursuit worthiness account developed here is not necessarily in competition with other accounts of analogies in science. First, nothing I have said is meant to rule out that analogies can sometimes form the basis of a plausibility argument or supply other kinds of epistemic support. My main objection has been to the assumption—made, for instance, by Hanson and Salmon—that this is sufficient to also account for all pursuit worthiness uses of analogy. In particular, I have argued that this is not how analogies were used in the liquid drop model case. Second, as indicated in Section 5.1, my account is to some extend complimentary to generative accounts of how analogies can suggest new models or novel extensions to existing ones.

More generally, analogies are a heterogeneous phenomenon and are likely to play many different roles in science. There is no reason to suppose that any single account will provide a comprehensive picture of this. In this article, I have focused on developing an account that works for the liquid drop model case. Exploring whether it can be applied to other cases or whether further accounts beyond those discussed in this article need to be developed will be crucial to securing a richer philosophical understanding of how analogies are used in science.

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References

Achinstein, P. [1993]: ‘How to Defend a Theory without Testing It: Niels Bohr and the “Logic of Pursuit”’, *Midwest Studies in Philosophy,* **18**, pp. 90–120.

Andersen, H. [1997]: ‘Categorization, Anomalies, and the Discovery of Nuclear Fission’, *Studies in the History and Philosophy of Modern Physics*, **27**, pp. 463–92.

Bartha, P. [2010]: *By Parallel Reasoning: The Construction and Evaluation of Analogical Arguments*, New York: Oxford University Press.

Bartha, P. [2013]: ‘Analogy and Analogical Reasoning’, in E. N. Zalta (*ed.*), *The Stanford Encyclopedia of Philosophy*, available at <plato.stanford.edu/archives/fall2013/entries/reasoning-analogy/>.

Campbell, N. R. [1920]: *Physics: The Elements*, Cambridge: Cambridge University Press.

Currie, A. [2013]: ‘Convergence as Evidence’, *British Journal for the Philosophy of Science*, **64**, pp. 763–86.

Dardashti, R., Thébault, K. and Winsberg, E. [2017]: ‘Confirmation via Analogue Simulation: What Dumb Holes Could Tell Us about Gravity’, *British Journal for the Philosophy of Science*, **68**, pp. 55–89.

de Regt, H. [2009]: ‘The Epistemic Value of Understanding’, *Philosophy of Science*, **76**, pp. 585–97.

Duhem, P. [1954]: *The Aim and Structure of Physical Theory*, Princeton, NJ: Princeton University Press.

Franklin, A. [1986]: *The Neglect of Experiment*, Cambridge: Cambridge University Press.

Frisch, O. [1967]: ‘How It All Began’, *Physics Today*, **20**, pp. 43–8.

Gamow, G. [1930]: ‘Mass Defects and Nuclear Constitution’, *Proceedings of the Royal Society of*

London A, **126**, pp. 632–44.

Gentner, D., Brem, S., Fergusson, R., Wolff, P., Markman, A. and Forbus, K. [1997]: 'Analogy and Creativity in the Works of Johannes Kepler', in T. B. Ward, S. M. Smith and J. Vaid (*eds*), *Creative Thought: An Investigation of Conceptual Structures and Processes*, Washington, DC: American Psychological Association, pp. 403–59.

Giere, R. [2004]: 'How Models Are Used to Represent Reality', *Philosophy of Science*, **71**, pp. 742–52.

Hanson, N. R. [1958]: 'The Logic of Discovery', *Journal of Philosophy*, **55**, pp. 1073–89.

Hesse, M. [1953]: 'Models in Physics', *British Journal for the Philosophy of Science*, **4**, pp. 198–214.

Hesse, M. [1966]: *Models and Analogies in Science*, Notre Dame, IN: University of Notre Dame Press.

Hoyningen-Huene, P. [1987]: 'Context of Discovery and Context of Justification', *Studies in History and Philosophy of Science*, **18**, pp. 501–15.

Kordig, C. [1978]: 'Discovery and Justification', *Philosophy of Science*, **45**, pp. 110–17.

Laudan, L. [1977]: *Progress and Its Problems*, Berkeley, CA: University of California Press.

Laudan, L. [1980]: 'Why Was the Logic of Discovery Abandoned?', in T. Nickles (*ed.*), *Scientific Discovery, Logic, and Rationality*, Dordrecht: Reidel, pp. 173–83.

Little, J. [2008]: 'The Role of Analogy in George Gamow's Derivation of Drop Energy', *Technical Communications Quarterly*, **17**, pp. 220–38.

Morgan, M. [1997]: 'The Technology of Analogical Models: Irving Fisher's Monetary Worlds', *Philosophy of Science*, **64**, pp. S304–14.

Morgan, M. [1999]: 'Learning from Models', in M. Morgan and M. Morrison (*eds*), *Models as Mediators*, Cambridge: Cambridge University Press, pp. 347–88.

McKaughan, D. [2008]: 'From Ugly Duckling to Swan: C. S. Peirce, Abduction, and the Pursuit of Scientific Theories', *Transactions of the Charles S. Peirce Society*, **44**, pp. 446–68.

McLaughlin, M. [1982]: 'Invention and Appraisal', in R. McLaughlin (*ed.*), *What? Where? When? When?* Dordrecht: Reidel, pp. 69–100.

Nersessian, N. J. [1988]: 'Reasoning from Imagery and Analogy in Scientific Concept Formation', *Proceedings of the Biennial Meeting of the Philosophy of Science Association*, **1988**, pp. 41-7.

Nersessian, N. J. [2002]: 'Maxwell and "the Method of Physical Analogy": Model-Based Reasoning, Generic Abstraction and Conceptual Change', in D. Malament (*ed.*), *Reading*

Natural Philosophy: Essays in the History and Philosophy of Science and Mathematics, Chicago, IL: Open Court, pp. 129–66.

Nersessian, N. J. [2008]: *Creating Scientific Concepts*, Cambridge, MA: MIT Press.

Nickles, N. [1980]: ‘Scientific Discovery and the Future of Philosophy of Science’, in T. Nickles (*ed.*), *Scientific Discovery, Logic, and Rationality*, Dordrecht: Reidel, pp. 1–60.

Norton, J. [unpublished]: ‘4. Analogy’, available at <www.pitt.edu/~jdnorton/papers/material_theory/4.%20Analogy.pdf>.

Nyrup, N. [2015]: ‘How Explanatory Reasoning Justifies Pursuit: A Peircean View of IBE’, *Philosophy of Science*, **82**, pp. 749–60.

Parker, W. [2009]: ‘Confirmation and Adequacy-for-Purpose in Climate Modelling’, *Proceedings of the Aristotelian Society*, **83**, pp. S233–49.

Pietsch, W. [unpublished]: ‘A Causal Approach to Analogy’, available at < philsci-archive.pitt.edu/12998/>.

Reichenbach, H. [1944]: *Philosophic Foundations of Quantum Mechanics*, Berkeley, CA: University of California Press.

Rentetzi, M. [2005]: ‘The Metaphorical Conception of Scientific Explanation: Rereading Hesse’, *Journal for General Philosophy of Science*, **36**, pp. 377–91.

Rutherford, E., Aston, F., Chadwick, J., Ellis, C., Gamow, G., Fowler, R., Richardson, O. and Hartree, D. [1929]: ‘Discussion on the Structure of Atomic Nuclei’, *Proceedings of the Royal Society A*, **123**, pp. 262–7.

Rutherford, E., Chadwick, J. and Ellis, C. [1930]: *Radiations from Radioactive Substances*, Cambridge: Cambridge University Press.

Salmon, W. [1967]: *The Foundations of Scientific Inference*, Pittsburgh, PA: University of Pittsburgh Press.

Salmon, W. [1990]: ‘Rationality and Objectivity in Science, or: Tom Kuhn Meets Tom Bayes’, in C. W. Savage (*ed.*), *Scientific Theories*, Minneapolis, MN: University of Minnesota Press, pp. 175–204.

Šešelja, D. and Straßer, D. [2013]: ‘Kuhn and the Question of Pursuit Worthiness’, *Topoi*, **32**, pp. 9–19.

Steel, D. [2010]: ‘A New Approach to Argument by Analogy: Extrapolation and Chain Graphs’, *Philosophy of Science*, **77**, pp. 1058–69.

Strevens, M. [2013]: ‘No Understanding without Explanation’, *Studies in History and Philosophy* *of Science*, **44**, pp. 510–15.

Stuewer, R. [1994]: 'The Origin of the Liquid-Drop Model and the Interpretation of Nuclear Fission', *Perspectives on Science*, **2**, pp. 76–129.

Weisberg, M. [2007]: 'Three Kinds of Idealization', *Journal of Philosophy*, **104**, pp. 639–59.

Whitt, L. A. [1990]: 'Theory Pursuit: Between Discovery and Acceptance', *Proceedings of the Biennial Meeting of the Philosophy of Science Association*, **1990**, pp. 467–83.