A Pursuit Worthiness Account of Analogies in Science

Abstract: Analogies often provide reasons for pursuing hypotheses or models. This is illustrated with a case study on the liquid drop model of the atomic nucleus. I criticise accounts in which analogies provide reasons for pursuit through epistemic support, proposing instead that analogies increase the value of learning the truth. I consider two accounts of this type: first, that analogies indicate potentials for theoretical unification; second, that analogies facilitate the transfer of already well-understood modelling frameworks to new domains. While the first is plausible for some cases, only the second can account for the liquid drop case study.

1. Introduction

For much of the 20th century it was hotly contended whether analogies play any normatively interesting role in scientific reasoning. Defending analogies, Norman Campbell (1920, ch. 6) and Mary Hesse (1966) responded to Pierre Duhem (1914/1954) and his intellectual heirs among the logical empiricists, such as Hans Reichenbach. Although the latter critics admitted (grudgingly) that analogies sometimes guide the development of scientific theories, they regarded this as a mere psychological curiosity, not something that plays any interesting normative role in scientific reasoning (e.g. Reichenbach 1944, 66-72). Arguing that analogies serve important purposes that philosophers of science ought to account for, Campbell and Hesse opposed these at the time widely accepted views.

Today, most philosophers interested in the issue agree that analogies play an important role in scientific reasoning. A number of different roles for analogies have been discussed (Bartha 2013, §1). Some challenge the presumption that generative reasoning is beyond the scope of normative theorising. For instance, Nersessian (1988), drawing on cognitive psychology and computational modelling, has argued that analogies can function as heuristics for developing or articulating scientific theories in ways that are both "systematic and subject to evaluation" (1988, 42). Call these *generative accounts* of analogical reasoning. Others take analogies to provide epistemic support for hypotheses and consequently propose accounts of how or when analogical arguments can provide this kind of support. Call these *justificatory accounts*.

My focus in this paper is on what can be called *pursuit worthiness accounts*, i.e. accounts according to which analogies provide reasons for testing or developing a hypothesis further.[1] While compatible with the other two, pursuit worthiness accounts are necessary for explaining some aspects of scientific reasoning that cannot be captured by purely justificatory or generative accounts. To illustrate this point, I outline a case study in Section 2, involving the early development of the liquid drop model of the atomic nucleus. I argue that in this case the liquid drop analogy motivated physicists to pursue the model despite it initially facing empirical and theoretical problems. In the remainder of the paper I consider different accounts of how analogies justify pursuit.

I start, in Section 3, by criticising accounts defended by Wesley Salmon (1967) and Paul Bartha (2010), according to which analogies provide reasons for pursuing a hypothesis in virtue of providing reasons for their truth. I argue that even if analogies sometimes provide epistemic support, this is not always a reason in favour of pursuit. Instead, I propose that analogies are better seen as justifying pursuit by increasing the value of learning whether the hypothesis is true. In Section 4 I consider an account where hypotheses based on analogies have a high potential for unification. I argue that while this account is plausible for some cases, it does not fit the case of the liquid drop model. Finally, in Section 5, I propose an alternative account of this case according to which analogies facilitate the transfer of an already well-understood modelling framework to a new domain of phenomena.

2. Case Study: The Development of the Liquid Drop Model

The liquid drop model of the atomic nucleus was developed from the late 1920s onwards, during a time where physicists were trying to extend their understanding of the structure of atoms to the atomic nucleus itself.[2] The model was first proposed in 1928-29 by George Gamow, at the time a Russian doctoral student visiting Western Europe, who suggested

[1] I borrow the terminology of 'generative', 'justificatory' and 'pusuitworthiness' accounts from McKaughan (2008).

[2] The following is based on Stuewer's (1994) account.

that the nucleus "may be treated somewhat as a small drop of water in which the particles are held together by surface tension" (cited from Stuewer 1994, 80). In line with common assumptions at the time, he modelled the nucleus as consisting of a collection of α-particles, and assumed that the nucleus was in equilibrium between the kinetic energy of the particles and the surface tension. On this basis Gamow then tried to derive an expression for the mass defects (i.e. the nuclear binding energy) of the different nuclei.

Niels Bohr and Ernest Rutherford were enthusiastic about the model, providing support for Gamow to develop it from 1929 to 1931. However, while Gamow made some progress, he quickly 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 suspected this could be remedied by taking into account the nuclear electrons that were thought to exist at the time. However, when he tried to incorporate these into his model he ran into a major theoretical problem (the so-called Klein paradox) that he was unable to overcome. Consequently, by the summer of 1930 Gamow began to turn his attention elsewhere (Stuewer 1994, 78-85).

Despite these problems, the model quickly became popular among physicists, not because they were confident it accurately represented the nucleus, but as a speculative attempt to solve certain problems. For instance, in 1930 Rutherford wrote that the 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" (cited from Steuwer 1994, 86-7). During the 1930s the model was further developed, following two broad trajectories. First, following the discovery of neutrons in 1932, Werner Heisenberg and Carl von Weizsäcker tried to revise the assumptions of the model to yield an empirically more accurate mass defect curve (*ibid*., 87-97). Second, Bohr and several others modified the model in order to account for artificially induced radioactivity (i.e. radioactive elements produced by bombarding stable elements with neutrons) as an excitation and subsequent 'evaporation' of particles from the drop of 'nuclear fluid' (97-

107).[3] Finally, in 1938-39 Lise Meitner and Otto Frisch, combining insights from both research programmes, realised that the liquid drop model could be adapted to explain nuclear fission, a newly discovered and at the time highly puzzling phenomenon (107-116).[4]

As is clear from the latter part of this story, the analogy played an important role in guiding the revisions and extensions of Gamow's original model. This use of analogy is what generative accounts aim to analyse. I return to this use of the liquid drop analogy in Section 5. For now, I want to highlight that already when Gamow proposed the liquid drop model in 1928-30, it was received positively and was taken up by a number of physicists, despite its initial problems. The analogy also seems to have motivated pursuing the model in the first place, before there was any particular reason to think it even approximately true. The question that I will focus on in the rest of this paper is *why* it was more reasonable to spend time and resources pursuing this particular model, rather than some alternative mathematical model not grounded in analogies.

3. Pursuit Worthiness, Plausibility and Probability

It might be thought that there is a straightforward answer to this question. Although there might not have been grounds for *accepting* Gamow's model in 1930, the analogy could still have shown it *plausible* and, the idea goes, the fact that the model was plausible made it reasonable to pursue it. But since reasons for regarding a model or hypothesis as plausible are merely a weaker form of epistemic support, these are not fundamentally different from reasons for its truth.[5]

A version of this account was suggested by Wesley Salmon (1967). Salmon was responding to N.R. Hanson's (1958, 1074) claim that there is a fundamental difference between reasons for accepting a hypothesis H and "reasons for suggesting H in the first

---

[3] A number of alternative (but sometimes related) analogies also influenced this line of physical theorising about atomic nuclei (Stuewer, *ibid.*).

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

[5] See Kordig (1978) for an account along these lines, not specifically concerned with analogies.

place” since the latter are “reasons which make H a *plausible conjecture*” (*ibid.*). Hanson (1077-79) argued that reasons for suggesting hypotheses (what I here call reasons for pursuit) can be based on analogies, among other things. Against this, Salmon (1967, 113-18) argues that plausibility judgements should be understood as estimates of the prior probability of a hypothesis. Since in a Bayesian framework it is necessary to make some judgement of prior probabilities to evaluate the posterior probability of a hypothesis, this furnishes an important role for plausibility judgements without these being fundamentally different from reasons for acceptance. According to Salmon, analogical arguments are plausibility arguments in this sense (127).

Whereas Salmon thus equates reasons for pursuit with estimates of prior probability, Paul Bartha’s (2010) recent work on analogical reasoning gives a more nuanced account of their relation. I here outline some details of Bartha’s account of analogical reasoning, since I draw on some of them later on. Following Hesse (1966, 59), Bartha endorses a *two-dimensional analysis* of analogical arguments. While many accounts only focus on *horizontal relations*, i.e. the similarities and differences between the source and target system, two-dimensional accounts also emphasise the *vertical relations*, consisting of dependency relations (e.g. causal, modal or explanatory relations) within the two domains. Building on this idea, Bartha (2010, ch. 4) defends an inference schema that may be summarised as follows:

(B1) There is some structure of dependency relations *R*(a, b, c, …) between features a, b, c, … of the source system, S1. [*Prior association*].

(B2) The target system, S2, has one or more features a’, b’, c’, … analogous to a, b, c, … [*Potential for generalisation*].

(B3) S2 does not have any features which would preclude *R*’ (analogous to R) from obtaining. [*No critical difference*].

Therefore:

(B4) It is prima facie plausible that *R*’(a’, b’, c’, …) obtains for S2, and *a fortiori* that S2 has features a’, b’, c’, …

The first premise states that there is a "prior association" in S1, in the form of some structure of dependency relations between its features. Which kinds of dependency relations to look for varies between contexts, but a good example of a structure of dependency relations is how the parts of a mechanism interact and constrain each other to produce certain effects. Second, we look at whether there is a "potential for generalisation", meaning 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, i.e. whether S2 has any features precluding a relation analogous to the prior association from obtaining. Given these premises, according to Bartha, it is prima facie plausible to "transfer" the prior association to the target system, and thus infer that the relevant further features involved in the prior association obtain in S2 as well.

Bartha highlights that arguments of this type are often used to support hypotheses before they have been tested (2010, 6) and that they provide reasons for investigating hypotheses further (16). Like Salmon, he thinks this is because analogies support plausibility judgements, but Bartha does not equate plausibility judgements with estimates of prior probability. That a hypothesis *p* is 'prima facie plausible', he takes instead to mean "roughly speaking, … There are sufficient grounds for taking *p* seriously" (2010, 16). This is partly an epistemic notion. A plausible hypothesis, according to Bartha, "has epistemic support: we have some reason to believe it, even prior to testing" (15) and it has "an appreciable likelihood of being true" (18). But he also takes plausibility judgements to have pragmatic connotations: "To say that a hypothesis is plausible typically implies that we have good reason to investigate it (subject to the feasibility and value of investigation)" (15). In a suggestive footnote (p. 18, note 19) Bartha furthermore mentions that reasons for pursuit depend on epistemic support "in a decision-theoretic sense" given "contextual information about costs and benefits." However, he adds that absent this information "the two points are at least partially independent" (*ibid.*). So although epistemic support is important to what Bartha means by plausibility, considerations about 'feasibility' and 'value' are relevant as well.

Given this elucidation of what he means by 'prima facie plausibility', it is consistent with Bartha's account that analogical inferences can provide reasons for investigating a hypothesis without necessarily providing reasons for its truth. However, in practice he tends to focus on epistemic support. For instance, he claims, "Any argument that a hypothesis is prima facie plausible … should provide reasons to think the hypothesis might be true" (18). Furthermore, he still follows Salmon in identifying a hypothesis' *degree* of plausibility with its prior probability (e.g. pp. 15-6, 291-302). As I read Bartha, analogies primarily provide reasons for pursuing hypotheses by providing epistemic support for them. Once this is established, whether we are then justified in pursuing a hypothesis all things considered depends on 'contextual information', i.e. information in addition to that provided by the analogy, about the costs and benefits of pursuing it.

Although Salmon and Bartha might be right that analogies sometimes give reasons for ascribing higher prior probability to a hypothesis, I do not think this gives a satisfactory account of how analogies justify pursuit in cases like the liquid drop model. First, it is not clear that physicists in 1930 regarded the liquid drop model as significantly more probable than so many other possible models. Second, while I agree with Bartha that having reasons for pursuing a hypothesis can be elucidated in decision-theoretic terms, he fails to take the implications of doing so fully into account. Since being justified in pursuing a hypothesis depends on a number of factors apart from its epistemic support, why assume that the analogy increased its epistemic support rather than some of the other factors? One cannot simply assume that when analogies motivate pursuing a hypothesis, the analogy must therefore have provided reasons for its truth. Third, it is not always the case that increasing the probability of a hypothesis is a reason in *favour* of pursuing it, let alone a sufficient reason.

When considering whether to pursue a hypothesis *H*, we need to take into account the different possible outcomes of doing so. We might learn that *H* is true, but we might equally learn that it is false. Furthermore, we should also take into account the possibility of getting no useful evidence or – even worse – getting misleading evidence, i.e. evidence that leads us to mistakenly accept or reject *H*. Following Nyrup (2015, 755-6), this can be represented in a simple decision-theoretic model. Suppose we only distinguish between two possible states of the world, that *H* is true and that it is false, and that we are interested in a range of epistemic attitudes $EA_1, EA_2, \ldots, EA_n$ we might end up having towards *H*, (e.g. accepting *H*, rejecting *H* and staying agnostic).[6] Then the expected utility of pursuing *H* is given by:

$$(1) \quad EU(p(H)) = Pr(H) \times \sum [U(EA_i(H), H) \times Pr(EA_i(H) \mid p(H), H)] + Pr(\neg H) \times \sum [U(EA_i(H), \neg H) \times Pr(EA_i(H) \mid p(H), \neg H)] - C(p(H))$$

The unconditional probabilities in this model represent the probability of *H* being true (or false, respectively) at the given state of inquiry, before further testing. They can both be initial probabilities prior to *all* testing or posterior probabilities given previous testing in situations where we are considering whether to pursue *H* further. It is this quantity that Salmon and Bartha take analogical arguments to manipulate. The conditional probabilities represent how likely we are, given that *H* is true (or false), to obtain evidence sufficient to adopt the attitude EA_i towards *H*. For instance, if EA_1 is acceptance then $Pr(EA_1(H) \mid p(H), H)$ represents how likely we are to get *reliable* evidence in favour of *H*, while $Pr(EA_1(H) \mid p(H), \neg H)$ is how likely we are to get *misleading* evidence in favour of *H*. $U(EA_1(H), H)$ represents the value of, e.g., correctly accepting *H*, while $U(EA_1(H), \neg H)$ measures how problematic it would be to mistakenly accept *H*, and mutatis mutandis for other epistemic attitudes. Finally, $C(p(H))$ is the cost (time, resources, etc.) of pursuing *H*.[7]

This analysis highlights that there are a number of different factors relevant to whether it is worth pursuing a hypothesis. In order for an argument to provide additional reasons for pursuing *H*, it must be the case that it increases our estimate of $EU(p(H))$. But there is no reason to suppose that it must increase the probability of *H* being true rather than, e.g., showing that it would be more interesting to know whether *H* is true, showing that *H* is less costly to pursue or showing that pursuing *H* is more likely to produce reliable

[6] It is possible to include further states of the world, e.g. various degrees to which *H* is partially true, or a broader range of epistemic attitudes without changing the conclusions I draw from this model.

[7] I assume for simplicity that these costs are commensurable with the utility of knowing whether *H* is true and that the costs of pursuing *H* are independent of its truth.

evidence. In fact, unlike these other factors, it is *not* generally the case that increasing Pr(*H*) raises EU(p(*H*)). For instance, if it would be easy to falsify *H* but difficult to get reliable evidence to confirm it, or if knowing that *H* is false would be more interesting than knowing that it is true, *reducing* Pr(*H*) could raise EU(p(*H*)) (cf. Nyrup 2015, 759).

4. Analogies as Guides to Unification

I have so far criticised the assumption that analogies provide reasons for pursuit by providing epistemic support. I propose that analogies instead justify pursuing *H* by increasing the value of knowing whether *H* is true. I develop this proposal in the remainder of this paper. More specifically, I consider two accounts of this type. I start with the idea that analogies indicate hypotheses that would provide increased theoretical unification, if shown true. While plausible for some cases, I will propose an alternative account in the next section which better accounts for the liquid drop case.

Campbell's defence of analogies in physics was arguably based on the unificationist idea. While he thought that theories based on mechanical analogies are more likely to be false than ones which merely posit generalised laws extrapolated from observed regularities (152), he argues that analogically based theories are valuable "simply because the ideas which they bring to mind are intrinsically valuable" (1920, 132). The reason is that they offer the chance of laws capable of unifying quantities from previously distinct domains, e.g., heat and momentum, in the case of the billiard ball model of gases. Insofar as we consider it an intrinsically valuable project to achieve this kind of unification, we "must balance that value against the chance of error" (152). Although Campbell does not elaborate much further on these remarks, it is clear that the value he ascribes to analogies is not that they provide increased epistemic support for theories.

The idea that the value of obtaining unifying theories has to be balanced against the risk of error fits the decision-theoretic model outlined above. If we agree with Campbell that it is intrinsically valuable to discover that a unifying theory is true, this would increase the first term of equation (1). If this value is sufficiently high, it could outweigh a decreased prior probability, which would otherwise shift the weight towards the second term of the equation (but notice, again, that reducing prior probability does not necessarily decrease overall the expected utility of pursuit).

This account also fits one line of justification Bartha (2010, ch. 7) offers for his account, viz. that it tends to promote the traditional theoretical virtues, in particular unification.[8] If we construe unification as the ability to explain a wide range of phenomena using the same basic explanatory pattern (Kitcher 1989), we can see how this fits Bartha's inference schema. Premise (B1) identifies the existence of the explanatory pattern *R* (the prior association) in S1, while (B2) points out that there are a number of features in S2 that could potentially be explained by the same pattern. Since (B3) 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.

In my view, this account of analogies provides a plausible account of how analogical reasoning justifies pursuit in some cases but not all. In cases such as the billiard ball analogy for gases or the 'waves in a mechanical medium' analogy for light (discussed e.g. by Hesse 1966, Nersessian 1988), the analogies do seem to promise to unify thermodynamical and optical phenomena, respectively, with the theoretical framework of classical mechanics. From the perspective of nineteenth-century physicists, these analogies pointed to potential increases in theoretical unification. However, this story does not work for cases like the liquid drop model. Although Bohr, Rutherford and other physicists regarded Gamow's analogy as suggesting a very promising line of research, this does not seem to be because it promised to unify the physics of water drops and atomic nuclei. The liquid drop model employs modelling techniques analogous to those applied to water drops, but it was clear that the explanations for the two kinds of phenomena would be very different. Even if one might hope that an increased understanding of the atomic nucleus could eventually lead to a unified account of the two types of systems, the liquid drop

---

[8] Bartha argues that analogies are also conducive to coherence, simplicity and fruitfulness, but regards unification as the most central. Bartha (2010, 256) here recognises that as long as we consider these virtues valuable to achieve, this is sufficient to show a hypothesis 'plausible' in his sense of 'worthy of investigation'. However, he also suggests that his argument can be combined with the argument that the theoretical virtues are "indicators of empirical adequacy (or truth)" (*ibid*.).

model does not in itself promise to achieve this kind of unification in the way that the billiard ball model and mechanical ether models did.

5. Transferring Modelling Frameworks Through Analogies

In order to account for how analogies justify pursuit in cases like the liquid drop model, we need to switch to a more dynamic account of the relation between analogies and scientific models. I have so far focused on whether analogies can justify pursuing a specific hypothesis. However, in the liquid drop case, Gamow and those who subsequently worked on the liquid drop model did not exactly pursue any specific hypothesis about the structure of the atomic nucleus. Rather, they tried to model the atomic nucleus as if it were a water drop in order to construct a potential explanation of some otherwise puzzling phenomenon – i.e. the mass defect curve for Gamow, Heisenberg and Weizsäcker, artificial radioactivity for Bohr and his colleagues, and nuclear fission for Meitner and Frisch. They were of course still interested in achieving a correct (or at least empirically accurate) description of the nucleus, but their first priority was to formulate a potential explanation of the target phenomenon. Rather than pursuing a specific *hypothesis*, the water drop analogy motivated the pursuit of the *research project* of adapting a modelling framework to the atomic nucleus for certain explanatory purposes. Or, 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 can provide a (correct) explanation of phenomena x, y, z, …."

That analogies guide the development hypotheses is also emphasised by proponents of generative accounts, such as Nersessian (1988). But it is important to notice that adopting a dynamic view of the relation between models and analogies does not in itself answer the question of why it was reasonable to pursue an analogical modelling framework, rather than so many others. This is how pursuit worthiness accounts differ from generative accounts. The latter primarily describe the cognitive role analogies play in shaping and guiding the development of novel scientific theories. Pursuit worthiness accounts, by contrast, justify why one should choose to develop a theory using analogies in the first place.

That analogies should be a *help* in developing theories is not obvious. Campbell (1920, 130), for instance, disagreed: "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 that imposing constraints actually makes it easier to come up with genuinely novel ideas. However, the core point here is that 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 pursuing*. Sometimes, e.g. if we lack any possible explanations, coming up with genuinely novel ideas might be intrinsically desirable. But in other cases, e.g. if we are overwhelmed by too many hypotheses, we may instead prefer to *restrict* ourselves to generating hypotheses of high quality.

So why are modelling frameworks based on analogies more pursuit worthy in cases like the liquid drop model? I want to end by proposing that these frameworks are more pursuit worthy because they facilitate the transfer of a modelling framework to construct explanations in a new domain.[9] One simple reason for trying to adapt an already existing modelling framework to a new case is that this is typically easier and less time consuming than developing a new one from scratch. Thus, transferring a modelling framework by analogy can often reduce the costs of pursuit.

However, constructing new explanations using analogically transferred modelling frameworks arguably also increases the potential understanding one can achieve through those explanations. This is because achieving scientific understanding of some phenomenon depends upon having a well-understood modelling framework. Understanding *why* a phenomenon occurs requires that one understands the model one

---

[9] This account is inspired by Hesse's and Bartha's idea that analogical inferences "transfer" explanations from one domain to another. However, as emphasised above, I focus on adapting a framework to produce new explanations rather than one-off inferences. In this respect, it is closer to Hesse's (1966: 157-177) suggestion that analogies provide a form of explanation by "metaphorically redescribing" the target domain in terms of the source analogy.

understands the phenomenon *with* (Strevens 2013: 513; cf. de Regt 2009). Thus, if an already well-understood modelling framework can be adapted to produce a correct explanation, little work is needed to realise its explanatory potential. One might eventually achieve a similar understanding of a new, purpose-built modelling framework. But, first, it would typically require a lot more effort to achieve this level of understanding. And, second, the analogically based framework offers an already proven explanatory power, as opposed to a merely potentially achievable one. In this way, even though in physicists in 1930 did not know that Gamow's model could be adapted to explain the respective phenomena they sought to explain, they still had good reasons to pursue the modelling approach indicated by the liquid drop analogy.

References

Andersen, Hanne. 1997. "Categorization, Anomalies and the Discovery of Nuclear Fission", *Studies in the History and Philosophy of Modern Physics* 27:463-492.

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

———. 2013. "Analogy and Analogical Reasoning". In *The Stanford Encyclopedia of Philosophy* (Fall 2013 Edition), ed. Edward Zalta, http://plato.stanford.edu/archives/fall2013/entries/reasoning-analogy/.

Campbell, Norman. 1920. *Physics: The Elements*, Cambridge: Cambridge University Press.

de Regt, Henk. 2009. "The Epistemic Value of Understanding", *Philosophy of Science* 76:585-97.

Duhem, Pierre. 1914/1954. *The Aim and Structure of Physical Theory*. Repr. Princeton, NJ: Princeton University Press.

Hanson, Norwood Russell. 1958. "The Logic of Discovery", *Journal of Philosophy* 55:1073-1089.

Hesse, Mary. 1966. *Models and Analogies in Science*, Notre Dame: University of Notre Dame Press.

Kitcher, Philip. 1989. "Explanatory Unification and the Causal Structure of the World." In

Scientific Explanation, Minnesota Studies in the Philosophy of Science, vol. 13, eds. Philip Kitcher and Wesley Salmon, 410–505, Minneapolis: University of Minnesota Press.

Kordig, Carl. 1978. "Discovery and Justification", *Philosophy of Science* 45:110-117.

McKaughan, Daniel. 2008. "From Ugly Duckling to Swan: C. S. Peirce, Abduction, and the Pursuit of Scientific Theories", *Transactions of the Charles S. Peirce Society* 44:446-468.

Nersessian, Nancy. 1988. "Reasoning from Imagery and Analogy in Scientific Concept Formation". In *PSA 1988, Volume One: Contributed Papers,* eds. Arthur Fine and Jarrett Leplin, 41-47, East Lansing: Philosophy of Science Assocation.

Nyrup, Rune. 2015. "How Explanatory Reasoning Justifies Pursuit: A Peircean View of IBE", *Philosophy of Science* 82:749-760.

Reichenbach, Hans. 1944. *Philosophic Foundations of Quantum Mechanics*, Berkeley and Los Angeles: University of California Press.

Salmon, Wesley. 1967. *The Foundations of Scientific Inference,* Pittsburgh: University of Pittsburgh Press.

Strevens, Michael. 2013. "No understanding without explanation", *Studies in History and Philosophy of Science* 44:510-515.

Stuewer, Roger. 1994. "The Origin of the Liquid-Drop Model and the Interpretation of Nuclear Fission", *Perspectives on Science* 2:76-129.