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Experimental criteria for accessing reality: Perrin's experimental demonstration of atoms and molecules

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Abstract

This paper develops an approach to the scientific realism debate that has three main features. First, our approach admits multiple criteria of reality, i.e., criteria that, if satisfied, warrant belief in the reality of hypothetical entities. Second, our approach is experiment-based in the sense that it focuses on criteria that are satisfied by experiments as opposed to theories. Third, our approach is local in the sense that it focuses on the reality of particular kinds of entities. We apply this approach to a case that many philosophers have debated, namely, Jean Perrin's work on atoms and molecules. We provide a novel account by arguing that Perrin's work warranted a minimal belief in the reality of atoms and molecules as unobservable, discrete particles by satisfying a criterion of reality that we call *experimental determination of number per unit*. By doing so, he confirmed Avogadro's hypothesis, but he did not confirm other key constituents of the atomic theories involved. We argue that our account of Perrin's work is preferable to several other accounts, and we use this as a reason in support of our approach to the realism debate more generally.

Keywords: scientific realism, criteria of reality, Jean Perrin, experimentation, Avogadro's number

1. Introduction

The scientific realism debate invites us to consider questions regarding which parts of science we are justified in believing. Philosophers engaged in the debate take a number of approaches to answering such questions. We consider such approaches along the following three dimensions.

First, there is the contrast between globalists and localists. Globalists attempt to answer the central questions of the debate by arguing for conclusions regarding our best theories in general, the claims they make, and the entities they posit (Worrall, 1989; Psillos, 1999, 2005; Ladyman and Ross, 2007; Harker, 2013; Peters, 2014). In contrast, localists attempt to answer such questions on a case-by-case basis by examining the first-order evidence for particular theories, claims, and entities (Achinstein, 2002; Magnus and Callender, 2004; Saatsi, 2010, 2017; Fitzpatrick, 2013; Park, 2016; Asay, 2019; Chen and Hricko, 2021).

Second, there is the contrast between theory-centric and experiment-based approaches. For those who take a theory-centric approach, the central questions of the debate concern such issues as whether the explanatory and predictive successes of our best theories warrant belief in those theories, or at least belief in certain parts of those theories. The globalists cited above all take a theory-centric approach. In contrast, for those who take an experiment-based approach, the central questions of the debate concern such issues as whether particular experimental results warrant belief in various theories, theoretical claims, and/or entities (Cartwright, 1983; Hacking, 1983; Eronen, 2019; Chen and Hricko, 2021).

Third, there are some issues concerning criteria of reality, i.e., criteria that, when satisfied, warrant belief in theories, claims, and/or entities. One way in which philosophers attempt to answer the central questions of the debate, however they understand them, is to consider the viability of such criteria. There is currently debate regarding whether various criteria are vulnerable to counterexamples (Gelfert, 2003; Lyons 2006), whether they ought to be theoretical or experimental (Psillos, 1999, pp. 256-257; Chakravartty, 2007, p. 31), and whether there ought to be just one criterion or multiple criteria (Psillos, 2005, pp. 398-399; Eronen, 2019, p. 2345; Chen and Hricko, 2021, p. 2314).

Given these three dimensions, philosophers face a number of choices when it comes to developing and defending an approach to the realism debate. Should we opt for a global approach or a local one? Should we opt for a theory-centric approach or an experiment-based one? And what sorts of criteria of reality should we rely on? Moreover, once we answer these questions, we must also be careful that those answers are not in tension with one another but rather fit together within a coherent whole. Our main goal in what follows is to motivate an approach to the realism debate that is local, experiment-based, and admits the possibility of multiple criteria of reality. We aim to show that this approach is preferable to other approaches based on other ways of answering these questions. In section 2, we provide more detail about each of these three dimensions of our approach as well as some reasons why our approach is preferable to other sorts of approaches.

Since our approach is a local one, it will be necessary to apply it to a concrete historical case in order to argue that it is preferable to other approaches. We therefore examine in detail a case that has proved popular for those who take a local, experiment-based approach, namely, Perrin's work on atoms and molecules (Achinstein, 2002; Saatsi, 2010; Fitzpatrick, 2013; Henderson, 2018). According to our approach, Perrin's main achievement was the experimental determination of Avogadro's number. Avogadro's number is the number of atoms/molecules in one mole of a chemical substance. Perrin experimentally determined that the value of Avogadro's number is a constant, which is equal to about 6×10^{23}. This number allows us to count the total number of constituent particles contained in a specified amount of a chemical substance. One thus has a reason to claim that those particles, which the atomic theory of matter describes as atoms/molecules, are real. The reason is that we can determine how many particles there are in a specified amount of a chemical substance.

We argue that, by determining the value of Avogadro's number, Perrin experimentally demonstrated the existence of atoms and molecules in the minimal sense of unobservable, discrete particles. He did so by satisfying an experimental criterion of reality that we call *experimental determination of number per unit* (the *number-per-unit criterion* for short). By satisfying this criterion, Perrin confirmed Avogadro's hypothesis, and also the proposition that chemical substances are ultimately composed of atoms and molecules. That said, his experiments did not confirm other key constituents of the chemical atomic theory and the kinetic theory. Hence, we offer an interpretation of Perrin's achievement in which the reality of atoms and molecules is not demonstrated by means of the truth of the relevant theories.

Our discussion of Perrin's work is organized in the following way. In section 3, we examine Achinstein's (2002), Psillos's (2011a, 2011b, 2014), Chalmers's (2009, 2011), and Hudson's (2014, 2020) interpretations of Perrin's work. In section 4, we show in detail how Perrin determined the value of Avogadro's number. In section 5, we argue that he thereby satisfied the number-per-unit criterion. Moreover, we argue that it is the satisfaction of this criterion that offers strong warrant for a belief in atoms and molecules in the minimal sense of unobservable, discrete particles. In section 6, we argue that Perrin's work did not thereby confirm the atomic/molecular theory of matter, the kinetic theory of gases, or Einstein's theory of Brownian movement. The kinetic theory and Einstein's theory are used as theoretical means to experimentally determine Avogadro's number and so cannot be confirmed by the determination of Avogadro's number. However, there are some constituents of the atomic/molecular theory that are confirmed, and this lends support to our claim that Perrin's work warrants belief in atoms and molecules in a minimal sense.

Our final goal, in section 7, is to use the Perrin case to argue that our approach to the realism debate is better than some competing approaches. We argue that our account of the Perrin case is preferable to Psillos's and Chalmers's accounts of that case. And we use this as a reason to conclude that our local, experiment-based approach is preferable to the sort of global, theory-centric approach that Chalmers and especially Psillos apply to the Perrin case.

2. Our approach to the scientific realism debate

In this section, we discuss the three dimensions we introduced in section 1 in order to motivate our own approach to the realism debate.

In the first dimension of the debate, localists argue that we should determine whether some particular kinds of entities exist or whether some particular theoretical claims are true on a case-by-case basis. Achinstein's (2002) use of Perrin's work to defend a realist conclusion about the existence of atoms is often held up as an exemplar of taking a local approach (Saatsi, 2010; Fitzpatrick, 2013). Importantly, one cannot use an argument about this or that case to build an argument for realism in general. In contrast, globalists argue for conclusions regarding our best theories in general, the entities they posit, and the claims they make.

The second dimension of the debate concerns the opposition between experiment-based and theory-centric approaches. Hacking (1983) has famously developed an experiment-based approach which combines realism about entities with instrumentalism about theories. For Hacking, we can be realists about entities to the extent that we can manipulate those entities in experimental settings. Hacking argues that we needn't be realists about theories in order to be realists about entities, though he admits that theories can be useful instruments when it comes to designing and performing experiments. To take another example, Cartwright (1983) developed an experiment-based approach that emphasizes the importance of causal explanations that can be tested via controlled experiments over theoretical explanations that can only be justified by an inference to the best explanation. Achinstein (2002) employs an experiment-based approach insofar as he sees Perrin's work as the basis for a valid experimental argument for scientific realism. Theory-centric realists reject such an approach on the grounds that we need to use theories in order to justify realism about entities and their properties (Psillos, 1999, pp. 256-257; Chakravartty, 2007, p. 31). For theory-centric realists like Psillos (1999), realism amounts to belief in the approximate truth of (parts of) our best theories, which is justified by certain features of those theories, e.g., the fact that they exhibit certain kinds of explanatory and/or predictive success.

The third dimension of the debate concerns criteria of reality, i.e., criteria for determining whether belief in the (approximate) truth of theoretical claims or belief in the existence of hypothetical entities is warranted. A number of criteria of reality have been proposed in the literature on the realism debate. For example, Psillos (1999, p. 110) proposes a criterion of predictive success: we are justified in believing a theoretical constituent to be approximately true if that constituent makes an indispensable contribution to the generation of a successful novel prediction. To take another example, Hacking (1983, pp. 22-23) proposes a criterion of manipulation, which is encapsulated in his famous slogan: "If you can spray them, then they are real." As these examples make clear, criteria of reality can be theoretical or experimental.[1] Insofar as predictive success concerns the success of theories and their constituent claims, it is a theoretical criterion. In contrast, manipulation is an experimental criterion insofar as it concerns what scientists can do with entities in experimental settings. For some philosophers, the goal is to articulate a single criterion that reliably picks out what we are justified in believing in every case. Psillos (2005, pp. 398-399), for example, claims that "the only workable criterion of reality" is "the explanatory criterion: something is real if its positing plays an indispensable role in the explanation of well-founded phenomena." Other philosophers propose criteria while admitting that there may be multiple workable criteria of reality (Eronen, 2019, p. 2345; Chen and Hricko, 2021, p. 2314). For such philosophers, different criteria are appropriate for different cases, and the satisfaction of any appropriate criterion of reality justifies belief in the existence of a hypothesized entity.

In this paper, we adopt a local, experiment-based approach to the realism debate that allows for multiple criteria of reality. Our approach does not endorse global realism about all of the entities posited in our best theories, and it does not resist local anti-realism about some of those entities. It is a methodologically local approach in the sense that belief in the reality of an entity is warranted by the satisfaction of some appropriate criterion of reality, where different criteria are appropriate for different cases. Our approach makes use of experimental criteria of reality as opposed to theoretical ones. We use such experimental criteria in order to further develop the idea of an experimental argument for realism. We also find it useful to conceive of

[1] By saying this, we don't claim that all criteria of reality are either experimental or theoretical because there may be criteria (for example, observation) that are neither theoretical nor experimental.

theories, in line with Hacking's theory instrumentalism, as instruments for designing and performing experiments. Our approach is therefore also an experiment-based approach.

This approach provides some resources for addressing a number of criticisms that philosophers have raised against similar views. To begin with, some criteria of reality may be susceptible to counterexamples. For example, Lyons (2006) argues that there are counterexamples to Psillos's (1999) theoretical criterion of predictive success, and Gelfert (2003) does the same for Hacking's (1983) experimental criterion of manipulation. Since we admit multiple criteria, there is a sense in which we are less susceptible to counterexamples than those who maintain that a single criterion is applicable to all cases. On our approach, some examples may not be genuine counterexamples because the criterion in question is not an appropriate criterion for the case at hand. That said, our approach is not immune to counterexamples. When it comes to dismissing purported counterexamples, we must have an independent reason (i.e., independent of the fact that it is a purported counterexample) for concluding that the criterion involved is inappropriate for the case at hand.

Another issue concerns whether criteria of reality should be theoretical or experimental. Theoretical criteria of reality frequently appeal to various kinds of explanatory and predictive success of theories to justify claims about the approximate truth of parts of those theories and the existence of the entities they posit. It's fair to say that such theoretical criteria have been the primary focus of the realism debate in recent years. One upshot of the recent debate seems to be that increasingly sophisticated theoretical criteria are still susceptible to counterexamples. For example, Vickers (2013) has updated Psillos's (1999) *divide et impera strategy*. Tulodziecki (2017) draws on the history of medicine to raise a counterexample to Vickers's updated strategy. Hricko (2021) raises another counterexample, which comes from the history of chemistry. Our focus on experimental criteria is motivated both by this dissatisfaction with theoretical criteria and by the idea that it is primarily experiments that provide us with access to unobservable reality. We aim to provide some new experimental criteria in the hopes that such criteria are less susceptible to counterexamples, though there can be no guarantee that they are.

This issue regarding whether criteria of reality should be theoretical or experimental is also related to an objection that we discussed above, namely, that a Hacking-style, experiment-based approach must rely on the truth of theories. If this objection is correct, then purely experimental criteria of reality may be unworkable. Our response depends on some of the details of the Perrin case, and so we delay our response until section 5.

Yet another sort of criticism concerns the objections that globalists have raised against localism. For example, Psillos (2011a, p. 189) argues that Perrin's work, on its own, is not an argument for realism in general. This is because Perrin's arguments occur within the context of a global realist framework, i.e., a framework that explains observable phenomena by positing unobservable entities and infers the existence of such entities via inference to the best explanation (IBE). In that case, Perrin's argument is a first-order instance of IBE and the global realist framework provides the best explanation for the reliability of such first-order instances of IBE. Hence, some sort of global realism is still required, contrary to what localists maintain.

We agree that a local argument based on Perrin's work cannot be an argument for realism in general; but we deny that a local argument for the existence of a particular kind of unobservable entity must occur within the context of a global realist framework. Since our approach employs experimental criteria, it needn't take place within a global realist framework like Psillos's since we needn't, in general, endorse explanation by posit or IBE. Our approach merely requires that, in certain sorts of experimental contexts, the satisfaction of criteria of reality that are appropriate for those contexts provides a good reason to believe in certain sorts of entities.

Moreover, a number of philosophers have objected to localism on the grounds that localists face some sort of dilemma. Dicken (2013), for example, raises the following dilemma. On the one hand, if localists focus exclusively on our first-order scientific practices, then we have no second-order assessment of those practices, and such an assessment of those practices is presumably one of the main goals of the realism debate. On the other hand, offering such a second-order assessment seems to be incompatible with localism insofar as it requires global arguments. To take another example, Henderson (2018, pp. 160-161) presents the following dilemma. On the one hand, if there is nothing general to say about the reasoning used in a particular case, localists may have nothing to say about what makes a particular instance of scientific reasoning legitimate. On the other hand, if localists do offer a more general account of what makes such reasoning legitimate, the danger is that localism collapses into a form of globalism.

When it comes to Dicken's and Henderson's dilemmas, localists can appeal to something more general to offer a second-order assessment of our first-order scientific practices and to show that a particular instance of scientific reasoning is legitimate, namely, criteria of reality. A local approach that admits multiple criteria does not automatically collapse into globalism since the appropriateness of applying a particular criterion and the satisfaction of a particular criterion are issues to be addressed locally.

Our main goal in the remainder of the paper is to show that our approach to the realism debate is preferable to other approaches. We apply our approach to the Perrin case because doing so allows us to engage with other philosophers who have written about this case, both with their accounts of Perrin in particular and with their approaches to the realism debate more generally. We aim to show that the application of our approach to the Perrin case yields an account of that case that is preferable to other accounts of Perrin's work that result from the application of other approaches to the debate. Doing so provides a reason to prefer our approach to the realism debate to those other approaches.

3. Philosophers on Perrin's work

Many philosophers have used Perrin's work as a relevant case for the scientific realism debate (Cartwright, 1983; Salmon, 1984; Achinstein, 2002; Roush, 2005; Maddy, 2007; Stanford, 2009; van Fraassen, 2009; Chalmers, 2009, 2011; Psillos, 2011a, 2011b, 2014; Egg, 2016; Henderson, 2018; Hudson, 2014, 2020). Our goal in this section is to review four of the existing accounts of Perrin's work (namely, the accounts developed by Achinstein, Psillos, Chalmers, and Hudson), and to use this literature review to raise some questions at the end of this section regarding the Perrin case. But first, it will be helpful to provide some background information regarding the situation in which Perrin found himself in the early 20th century.

In the 19th century, the kinetic molecular theory of gases was proposed to explain the Boyle-Charles law, i.e., the ideal gas law, $PV = nRT$, where P, V, and T represent the pressure, volume, and temperature of a gas, respectively, n is the number of moles of the gas, and R is the ideal gas constant. The pressure, volume, and temperature of a gas in a container are proportional to one another. According to the kinetic molecular theory, all gases are made up of unobservable particles. This theory was linked to the atomic/molecular theory in general; and according to the general theory, matter consists of atoms and molecules, and all molecules consist of atoms. This kinetic molecular theory classifies the unobservable particles that make up a gas as atoms/molecules, and attributes many other properties (such as flexibility, rebounding in collision, random motion, etc.) to them. It also states that the average kinetic energy is the same for all gases at a given temperature, regardless of what kind of gas it is. Furthermore, the total kinetic energy of a gas is proportional to the absolute temperature of the gas.

In 1827, the botanist Robert Brown first observed that pollen from a particular kind of plant, when suspended in water, constantly moves in a random and irregular way. Scientists went on to recognize that the same goes for all kinds of pollen suspended in water, and also for dust in the air. They called this phenomenon Brownian movement (Perrin 1910, p. 1-2; Maiocchi, 1990). What causes pollen and dust to move in such a way? In 1905, Albert Einstein suggested that the pollen granules in water, and particles suspended in liquids more generally, are moved by the individual molecules that make up the liquid. He further hypothesized that the nature of Brownian movement is the same as that of the motion of molecules in a gas. Therefore, the kinetic molecular theory of gases (the kinetic molecular theory of heat in Einstein's terminology) can be used to model Brownian movement. Einstein (1989 [1905]) established such a model and provided equations to determine Avogadro's number, i.e., the number of atoms/molecules in one mole of a chemical substance.

Both the kinetic molecular theory of gases and Einstein's model of Brownian movement hypothesize the existence of micro-particles that constitute gases, water, and other kinds of matter. This hypothesis is also connected with the atomic theory of the elements in chemistry. However, the hypothesized entities, atoms and molecules, are unobservable with the unaided eye and even with optical microscopes. If matter is composed of unobservable particles, then it has a discontinuous structure. Is the hypothesis of the discontinuity of matter true? Are the kinetic theory and Einstein's theory of Brownian movement true? Answers to these questions depend on the existence of unobservable particles. Do they exist? Are their properties really as they are described by the relevant theories?

This is the situation in which Perrin found himself. Because "direct perception of the molecules in agitation is not possible" (Perrin, 1916, p. 83), Perrin sees Brownian movement as a way to uncover and understand the motion of invisible molecules. Perrin provides the following analogy: "But if a ship comes in sight, he [an observer] will be able to see that it is rocking, which will enable him to infer the existence of a possibly unsuspected motion of the sea's surface" (1916, p. 83).

As Psillos (2014, p. 151) has made clear, Perrin's views changed quite a bit over the course of ten years. In 1901, Perrin published a paper in *Revue Scientifique* titled "The molecular hypotheses," which concerns the atomic conception of matter. In that paper, he saw the debate over whether matter is continuous or discontinuous as having a "uniquely philosophical character" and as being a matter of "taste" (quoted in Psillos, 2014, p. 151). At that point, Perrin thought that the molecular hypothesis is still useful even though scientists could not confirm its truth. In 1911, Perrin published another paper in the same journal titled "The reality of molecules." In that paper, he concluded that the objective reality of molecules had been demonstrated based on his performance of several experiments, the results of which he took to warrant this conclusion. How did Perrin demonstrate the reality of molecules and atoms?

Realist philosophers of science have provided a number of different ways of answering this question. Cartwright (1983, pp. 83-85) first argued that Perrin provided strong evidence for the existence of atoms in terms of the inference to the most probable cause. Salmon (1984, pp. 214-221) also argued in detail that Perrin provided a valid experimental argument for scientific realism and that this argument convinced at least some anti-realist scientists of the reality of molecules. Achinstein (2002) develops the idea of an experimental argument and defends the validity of Perrin's experimental argument against various anti-realist objections. He reconstructs Perrin's argument for the reality of atoms and molecules into a general mode of reasoning involving the following two components (2002, p. 492):

> (a) causal-eliminative reasoning to the existence of the postulated entity, and to certain claims about its properties, from other experimental results;
> (b) an argument to the conclusion that the particular experimental results obtained are very probable given the existence of the postulated entity and properties.

Causal-eliminative reasoning, in this case, involved considering and eliminating other possible causes of Brownian movement besides molecules, e.g., vibrations from traffic and convection currents (2002, p. 474). While the mode of reasoning that involves these two components is general, Achinstein (2002, pp. 492-493) is clear that it does not secure realism about unobservable entities in general:

> No general empirical argument can be given for all unobservables postulated. Nor can the issue of the existence of unobservables be settled a priori.

Thus, Achinstein's approach is local and experiment-based.

In contrast to Achinstein's experiment-based approach, Psillos (2011a, 2011b, 2014) takes a theory-centric approach to Perrin's work. He analyzes Perrin's technical work, *Brownian movement and molecular reality* (Perrin, 1910), and reconstructs Perrin's argument as a Bayesian inference that shows that the probability of the truth of Perrin's atomic hypothesis is very high given that the number of molecules in a mole of a substance is equal to Avogadro's number (Psillos, 2011a, pp. 179-185; Psillos, 2014, pp. 151-156). Psillos (2011a, p. 183) claims that Perrin's argument can be put in the following way, where f is the Bayes factor, which, in this case, is equal to prob(n = N/–AH)/prob(n = N/AH); n represents Avogadro's number; N is 6×10^{23}; and AH is the atomic hypothesis:

1. *f* is very small.
2. N = n is the case.
3. prob(AH) is not very low.
Therefore, prob(AH/n = N) is high.

Psillos (2011a, pp. 183-184) goes on to argue that Perrin's work establishes the three premises and that this argument is therefore compelling. Premise 2 is established by the different experiments that Perrin reports regarding the different methods of determining the value of Avogadro's number. This experimental demonstration also establishes premise 1 since it shows that obtaining this particular value for Avogadro's number would be very improbable if the atomic hypothesis were not true. And Perrin establishes premise 3 by ruling out alternative explanations of Brownian movement and thereby providing some initial plausibility for the atomic hypothesis. Psillos concludes that, if one doesn't think that accepting the existence of an entity requires observing that entity with the naked eye, then one should find his Bayesian reconstruction of Perrin's argument convincing.

Psillos (2011a, pp. 188-189) makes it clear that his account differs from Achinstein's insofar as Psillos emphasizes explanatory considerations rather than experimental ones. Psillos maintains that labelling the argument for realism as an experimental one, as Achinstein does, is not quite accurate. The argument depends primarily on the prior probability assigned to the atomic hypothesis, and explanatory considerations rather than experimental ones play the crucial role in assigning the prior probability. Another reason why Psillos thinks these explanatory considerations are crucial is because, in his view, Perrin is working within a global realist framework that involves IBE and explanations of observable phenomena in terms of unobservable entities.

Chalmers (2009, 2011) also offers a detailed and comprehensive analysis of Perrin's work from the view of testing theories. In his analysis, Perrin's experimental demonstration of the reality of atoms and molecules depends on the kinetic theory of Brownian movement. However, Chalmers (2011, p. 714) thinks that we should partition the claims of a theory and test them individually in order to determine which parts of the theory are really supported by the evidence. After analyzing Perrin's experimental testing of the kinetic theory, Chalmers (2011, pp. 729-730) concludes that, at the time, Perrin's case for the existence of atoms and molecules was stronger than anything that came before. While Chalmers believes that Perrin demonstrated the existence of atoms and molecules, when it comes to the kinetic theory itself, Chalmers proposes a view that is quite subtle. He points out that, even in the aftermath of Perrin's work, the atomic theory was "inadequate and incomplete" (2011, p. 730). Moreover, he maintains that the kinetic theory, and theories in general, get some things wrong because they are "speculative and general" (2009, p. 242), and as such, it is inappropriate to evaluate them in terms of whether they are true or confirmed. That said, Chalmers still emphasizes that the kinetic theory was "strictly false" (2009, p. 245). However, he argues that many of the claims of the kinetic theory were nonetheless "at least roughly correct" (2009, p. 245). He does so by appealing to an argument from coincidence, according to which it would be quite improbable for such a variety of evidence to correspond to the predictions of the kinetic theory if that theory were not roughly true (2009, pp. 243-244).

According to Hudson (2020), Achinstein, Chalmers, and Psillos all use the strategy of robustness reasoning to argue that Perrin offered a sufficiently strong argument for the reality of unobservable atoms and molecules. However, Hudson (2020, p. 45) argues that robustness reasoning is at best uninformative when it comes to the existence of the entity in question; at worst, it is misleading because it may seem to confirm an experimenter's theoretical presuppositions even in cases in which such presuppositions are problematic. He instead suggests an alternative form of reasoning, which he calls "calibration," for understanding Perrin's experiments. In an analogous sense to that of calibration in measurement, the form of calibration reasoning is to 'calibrate' theoretical assumptions by referring to an established theoretical assumption. Perrin's calibration reasoning involved examining whether the values of Avogadro's number obtained from the experiments based on Einstein's theoretical models are in agreement with the value from the experiments based on the vertical distribution in an emulsion, which is the value Perrin preferred (Hudson, 2020, pp. 47-48). When it comes to the realism debate more generally, Hudson (2020, p. 56) proposes that we should focus on the theoretical developments that scientists make to their picture of an unobservable entity, and on whether they develop that picture in a way that confirms those theoretical developments. Hudson (2020, p. 57) goes on to argue that Perrin uses calibration reasoning in such a way that confirms his theoretical developments, while the theory that matter is continuous had no empirically confirmed theoretical developments. Therefore, he concludes, one should take a realist attitude toward Perrin's atoms and molecules.

By carefully examining Psillos's, Chalmers's, and Hudson's analyses, we are left with the following questions: What is the atomic theory? Does the atomic theory include the molecular kinetic theory? Has the approximate or likely truth of the atomic theory been demonstrated by Perrin's experimental determination of Avogadro's number, even if the kinetic theory is, strictly speaking, false? Is the truth of (parts of) the atomic theory confirmed by Perrin's experiments? In the following sections, we will offer an account of Perrin's work which is quite different from each of these philosophers' accounts.

4. Perrin's experimental determination of Avogadro's number

No matter how philosophers reconstruct Perrin's work, Perrin's experimental determination of Avogadro's number always plays a crucial role in their reconstructions of his argument for the reality of atoms and molecules. At this point, we turn from our examination of what philosophers have said about Perrin's work to Perrin's work itself, as well as what some other physicists at the time said about it.

When Professor C. W. Oseen, a member of the Nobel Committee for Physics of the Royal Swedish Academy of Sciences, awarded the Nobel Prize to Perrin, he stated that Perrin's achievement was to "put a definite end to the long struggle regarding the real existence of molecules" (Oseen, 1926, p. 135). Oseen's speech provided a brief introduction to Perrin's work and focused on Perrin's three experimental methods for determining Avogadro's number. Oseen's speech represents the view of the Nobel Committee for Physics, according to which the experimental confirmation of

Einstein's mathematical theory of Brownian movement was first given by the German physicist Max Seddig rather than Perrin. According to Oseen (1926, p. 137), Perrin's experimental achievements were that his "measurements on the Brownian movement showed that Einstein's theory was in perfect agreement with reality" and "[t]hrough these measurements a new determination of Avogadro's number was obtained."

Oseen's speech can be read as an abstract of Perrin's 1926 Nobel Lecture, "Discontinuous structure of matter," which in turn can be read as a summary of his two monographs, *Brownian movement and molecular reality* (1910) and *Atoms* (1916),[2] which provide a complete account of Perrin's theoretical and experimental work on these topics. In what follows, we reconstruct Perrin's experiments according to his 1926 lecture. We do so not only because it is a summary of Perrin's two monographs but also because it focuses on his three experimental methods for determining Avogadro's number. Moreover, the Nobel Lecture represents the view through which Perrin himself, as well as contemporary scientists at the time, saw his achievement. Perrin's two monographs include many theoretical characterizations of the atomic/molecular theory of matter, the kinetic molecular theory of gases, and Einstein's theory of Brownian movement. We discuss these characterizations in section 6.

Perrin developed his first experimental method according to the model of the vertical distribution of gas rarefaction, which can be applied to an emulsion in a liquid. The model underlying the method is constructed out of the laws of ideal gases including Avogadro's law, the Boyle-Charles law, the law of rarefaction, Raoult's law, and the law of Van't Hoff that provides a way to extend Avogadro's law to solutions (Perrin, 1926, pp. 145-149). This experimental method is used to calculate Avogadro's number *N* through the following equation derived from the model (Perrin, 1916, pp. 89-93):[3]

$$\frac{n}{n\prime} = 1 - \frac{Nmg(1-\frac{d}{D})h}{RT} \qquad (1)$$

In this equation, *N* is Avogadro's number, *n* and *n'* are the number of molecules per unit volume at the upper and lower levels of an emulsion in a cylindrical container, *mg* is the weight of a molecule, *d* is the density of the liquid, *D* is the density of the emulsion, *h* is the height of a cylindrical container, *T* is the temperature of the liquid, and *R* is the gas constant.

In order to use this equation to determine the value of *N*, Perrin conducted a series of experiments by using a kind of dilute emulsion in which very small granules of gamboge were suspended. Those granules appear to exhibit perpetual Brownian movement when examined under a microscope. These experiments allowed Perrin to extrapolate from the observable granules in the emulsion to the unobservable molecules of gases.[4] For Perrin, all particles, whether granules in an emulsion or smaller gas molecules, obey the same laws. When it comes to the reality of molecules,

[2] The French originals were published in 1909 and 1913, respectively.
[3] See also Achinstein (2002, pp. 471-473) and Hudson (2020, pp. 37-38).
[4] Hudson (2020, p. 38) sees this as an analogical inference from observable granules to unobservable molecules of gases.

the key law is Avogadro's law since, as Perrin (1926, p. 141) says, "if molecules and atoms exist, their relative weights are known to us, and their absolute weights would be known at the same time as Avogadro's number." Therefore, if one can determine a value for Avogadro's number *N* and prove that *N* is indeed a constant, then one can experimentally demonstrate the reality of molecules. On the basis of various emulsion experiments involving different values for the observable quantities *Nmg*, *h*, and *T*, Perrin (1926, p. 156) used the equation to obtain the number whose approximate values are 68×10^{22}, 62×10^{22}, and 60×10^{22} in three states of emulsions.

Perrin developed his second and third experimental methods according to Einstein's mathematical theory of Brownian movement. The goal of these experiments was to check "Einstein's formulae by seeing whether they led always to the same value for Avogadro's number and whether it was appreciably equal to the value already found" (Perrin, 1926, pp. 153-154). According to Einstein's theoretical analysis of Brownian movement,

> the steady state in a vertical column of emulsion is produced and maintained by the interplay of two opposing actions, gravity and the Brownian movement; this can be expressed by writing that at each level the flow through diffusion towards the poor regions is equal to that which gravity produces towards the rich regions. (Perrin, 1926, p. 153)

Assuming all granules are equivalent to each other in regard to the osmotic pressures, Einstein introduced an equation of diffusion (Perrin, 1926, p. 153; 1916, p. 113):

$$\frac{X^2}{2t} = \frac{1}{6\pi a z}\frac{RT}{N} \tag{2}$$

In the equation, $X^2/2t$ is the diffusion coefficient, *N* Avogadro's number, *T* the temperature, *R* the gas constant, *a* the radius of granules as spherules, and *z* the viscosity. This equation was the basis of Perrin's second experimental method. However, this equation describes only the translational Brownian movement. A granule rotates at the same time as it is displaced. Einstein thus introduced another equation to describe the rotation of Brownian particles (Perrin, 1926, p. 153; 1916, p. 114):

$$\frac{A^2}{t} = \frac{1}{4\pi a^3 z}\frac{RT}{N} \tag{3}$$

In this equation, A^2/t is the agitation coefficient of rotation and A^2 denotes the mean square of the component of the angle of rotation around an axis in a time *t*. This equation was the basis of Perrin's third experimental method.

Perrin believed that these two formulas can be tested experimentally if one knows how to prepare spherules of a measurable radius. By preparing large spherules of mastic and experimenting with different sizes of granules (in the ratio of 1 to 70,000), different liquids (water, solutions of sugar or urea, glycerol), and different viscosity (in the ratio of 1 to 125), Perrin (1926, p. 154) obtained values of Avogadro's number between 55×10^{22} and 72×10^{22}.

According to the experimental determination of Avogadro' number, Perrin concludes that "[t]he *objective reality of molecules and atoms* which was doubted twenty years ago, can today be accepted as a *principle* the consequences of which can always be proved" (Perrin, 1926, p. 156; emphasis in original).

5. Experimental determination of number per unit as a criterion of reality

Perrin and other scientists have seen the determination of Avogadro's number as the key to demonstrating the reality of, and warranting belief in the reality of, atoms and molecules. Why? The answer to the question is not obvious. As Hudson (2020, p. 36) notes, "it is claimed that arriving at a univocal value for Avogadro's number is connected to a belief in the reality of molecules, but the connection here is unclear."

Here we suggest that the determination of Avogadro's number satisfies a criterion of reality that we call *experimental determination of number per unit* (the *number-per-unit criterion* for short). Scientists generally define Avogadro's number as the number of atoms or molecules per mole of a substance, where a mole is an amount of a substance whose mass in grams is equal to the atomic or molecular mass of the substance in question. For example, since the atomic mass of carbon-12 is 12, one mole of carbon-12 has a mass of 12 grams. Determining the value of Avogadro's number, and determining that it is a constant, gave scientists a way to count the number of atoms and molecules per mole without being able to observe them. If scientists are able to experimentally use various measurable quantities to count the number of individual unobservable entities per unit (e.g., per mole), they satisfy the number-per-unit criterion. Their work may be only an indirect means to estimate the number of those unobservable entities, but it suffices to conclude that those entities exist. In light of this criterion, we argue that it is primarily Perrin's experimental determination of the value of Avogadro's number that supports a realist conclusion regarding atoms and molecules as discrete particles.

A further question is why the number-per-unit criterion is a criterion of reality. In short, it is a criterion of reality for discrete entities because to be discrete is to be countable. In general, if x is real and discrete, then x is countable; and if one knows x is countable in practice, then one has a good reason to infer that x is discrete and real. In such an inference, counting the number of something serves as a criterion regarding the reality of those things as discrete bodies. Therefore, if one can obtain a definite number of a kind of unobservable entity in a particular quantity (e.g., volume or weight) by some method, then one can justify that the kind of entity is real.

If one demonstrates that something is countable in practice, then one has good evidence for the existence of those things, and the evidence constitutes a strong reason for believing that those things are real. However, the number-per-unit criterion does not always succeed for every case because it is neither a sufficient condition nor a necessary condition for granting the reality of an unobservable entity. After all, neither 'All real entities are countable' nor 'All countable entities are real' is true. Obviously, some things that are named by non-count nouns (e.g., chemical substances like water) are real but not countable, so the criterion is not a necessary condition.[5]

[5] That said, liters and molecules of water are, of course, countable. The point is that the substance itself is not countable—we cannot count 'waters' as we can liters and molecules.

And fictional entities (e.g., characters in a novel) may be countable but not real, in which case the criterion is not a sufficient condition either.

In response to the point about fictional entities, it's worth emphasizing that the number-per-unit criterion is an experimental criterion, which is to say that it is applicable to experimental contexts as opposed to, say, contexts in which we are counting characters in a novel. Relying on experiments to count the number of discrete entities per unit is different from the methods one would use to count, say, entities in a work of fiction. To be sure, there are many non-trivial issues regarding the metaphysics of fictional entities. That said, the important point for our purposes is just that, when we count, say, the characters in a novel, we don't have even a *prima facie* reason to infer that those characters are real in the same sense that the entities with which we interact in experimental contexts are real. So that sort of example is irrelevant to evaluating an experimental criterion, and the issue is whether the number-per-unit criterion provides a strong reason to believe in the entities that we can count in experimental contexts. The most relevant sorts of examples of fictional entities would be entities like phlogiston and caloric which featured in scientists' interpretations of their experimental results. But it's fair to say that scientists never experimentally determined the number of phlogiston or caloric particles per unit of volume or mass, and so these examples are insufficient to show that our proposed criterion is inadequate for Perrin's case. Another relevant sort of example concerns scientists' hypothetical assumptions, which frequently involve various idealizing conditions to the extent that the entities that the scientists reference do not actually exist. This is the case with regard to the sorts of populations referenced in, for example, the hawk-dove game and the Lotka-Volterra model.[6] But when we know that these sorts of idealizing conditions are at work, we ought to consider the number-per-unit criterion inapplicable since we already have good reason to think that we cannot make any experimental contact with fictional, idealized entities.

Perrin's own argument for the key role of Avogadro's number provides some textual evidence for our claim that the number-per-unit criterion is a criterion of reality. He examines the outcomes achieved in contemporary chemistry and concludes that these successes, though brilliant, could not demonstrate the reality of atoms:

> If they all became at the same time a thousand times smaller, a milliard times smaller, infinitesimal in the mathematical sense of the word, with matter becoming again continuous at each reduction, our chemical laws and our formulae would be unchanged, and the idea of the atom, then driven back infinitely far beyond all experimental reach, would lose its interest and its reality. (1926, p. 141)

In other words, these chemical laws tell us only proportions or ratios, and these ratios would hold even if matter were continuous. Perrin goes on to claim that we need to go beyond these ratios and determine the weights of atoms if we wish to demonstrate their reality (1926, p. 141). By determining the value of Avogadro's number, we can count atoms per mole and thereby compute their weights and demonstrate their reality.

[6] See, e.g., Tan's (2022) recent discussion of these two cases, and of hypothetical modeling more generally.

More generally, the number-per-unit criterion involves demonstrating that there are a definite number of individual bodies in a definite quantity. By doing so, one can demonstrate that the objects are discrete, individual bodies. Consequently, counting the number of a kind of entity in a definite quantity provides evidence for the reality of the entity. The evidential power is shown both by the fact that real discrete entities must be countable, and by the fact that experiments must make contact with some objects that have some measurable quantities such as weight, volume, and so on. As a result, satisfying the number-per-unit criterion by determining Avogadro's number offers a good reason for believing in the existence of atoms and molecules in the case of Perrin's experimental work.

However, one might object that Perrin's experimental work at most offers a good reason for believing in unobservable, discrete particles. Are these unobservable, discrete particles atoms and molecules? Do they have the properties described by the atomic theory of matter and the kinetic molecular theory? These two questions are related to the objection to Hacking's experiment-based approach, which we briefly discussed in section 2. According to that objection, experiments alone cannot demonstrate the existence of entities and the attribution of properties to those entities. Theories are necessary for doing so. When it comes to Perrin in particular, theory-centric realists will say that an experiment-based approach cannot warrant the claim that Perrin experimentally demonstrated the reality of atoms/molecules because such an approach suspends judgment regarding the truth of the atomic/molecular theory.

Our response is that Perrin demonstrated the reality of atoms and molecules only in the minimal sense of unobservable, discrete particles. His experimental work alone is not sufficient to attribute other properties to these particles. As we argue in section 6, Perrin's experimental work did not confirm most of the key constituents of the atomic and kinetic theories, and confirming these constituents is necessary to attribute additional properties to atoms and molecules. Furthermore, Perrin's experimental demonstration does not depend on the truth of the kinetic theory but rather on the satisfaction of the number-per-unit criterion of reality, which merely required the instrumental use of the kinetic theory. That said, Perrin's experimental work did confirm the claim that the number of component particles in one mole of a chemical substance is the same (i.e., Avogadro's number) regardless of the kind of chemical substance. This claim is a generalization from Avogadro's hypothesis ("*equal volumes of different gases, under the same conditions of temperature and pressure, contain equal numbers of molecules*" (Perrin, 1916, p. 18; emphasis in original)) and the gas law (one molar mass of every kind of chemical substance in the gaseous state has the same volume).[7] This claim, in turn, presupposes the idea that chemical substances are ultimately composed of unobservable, discrete particles. But these particles are just the atoms and molecules of the chemical atomic theory stripped of all of their other properties besides unobservability, discreteness, and weight. This is the minimal sense in which Perrin demonstrated the reality of atoms and molecules.

[7] According to Perrin (1916, p. 20), "[t]hese consequences of Avogadro's hypothesis have been fully confirmed by chemical analysis and the measurement of densities in the gaseous state, for thousands of substances, no single exception having been discovered." In addition, the gas law is also stated as follows: "at a fixed temperature the density of a gas (mass contained in unit volume) is proportional to the pressure" (Perrin, 1916, p. 17). According to Perrin (1916, p. 17), the gas law stated in this form has been known since the 17th century.

6. Were the atomic and kinetic theories confirmed by Perrin's experimental work?

At the end of section 3, we raised the following two questions which were prompted by our examination of the recent philosophical literature on Perrin's work: Has the approximate or likely truth of the atomic theory been demonstrated by Perrin's experimental determination of Avogadro's number, even if the kinetic theory is, strictly speaking, false? Is the truth of (parts of) the atomic theory confirmed by Perrin's experiments? We will now provide some answers to those questions.

In addition to his experimental work, Perrin made a theoretical contribution by integrating the atomic theory in chemistry with the kinetic theory of gases in physics. Our goal in this section is to argue that, apart from a few exceptions, Perrin's experimental work doesn't confirm the key constituents of these theories. In order to make a comparison between our approach and theory-centric approaches to the realism debate, we partition Perrin's theories into separate constituents, examine them one by one, and determine which can be confirmed by the experiments Perrin performed. We won't consider whether these constituents have been confirmed by other scientists' experiments because the focus is Perrin's series of experiments.

In his 1913 monograph *Les Atomes*,[8] Perrin develops at least three related theories or subtheories about atoms and molecules: (T1) the atomic/molecular theory of matter, which focuses on the laws of definite proportions and multiple proportions and the periodic table of chemical elements; (T2) the kinetic molecular theory of gases, which focuses on explaining the Boyle-Charles law of gases and other phenomena such as diffusion, effusion, viscosity, and osmosis; and (T3) Einstein's kinetic molecular theory of heat, which focuses on explaining Brownian movement in fluids.

Perrin develops (T1) in chapter 1, which is titled "Chemistry and the atomic theory," and connects (T1) to (T2) by means of Avogadro's hypothesis. We extract six basic and general theoretical constituents from his writing:

> (C1) "[*W*]*e suppose that any substance whatever, that appears to be homogenous to observations on our scale of dimensions, would be resolved at a sufficient magnification into well-defined molecules*" (1916, p. 4).

Determining the value of Avogadro's number, and determining that it is a constant, does confirm (C1) because a mole of any substance has the same number of molecules as a mole of any other substance, and that number is just Avogadro's number. The fact that (C1) is confirmed lends support for our claim that the unobservable, discrete particles that Perrin counted should be considered atoms and molecules in some minimal sense.

> (C2) "*Any material system whatsoever can be decomposed into masses each composed of one of these simple substances; these masses are absolutely*

[8] In what follows, we rely on the 1916 English translation *Atoms*. All italics in the quotations of Perrin (1916) are in the English translation.

> *independent, in quantity and in their nature, of the operations that the given system has been made to undergo*" (1916, p. 8).

This proposition is followed by the laws of definite proportions and multiple proportions.

> (L1) The law of definite proportions: "*The proportions in which two elements combine cannot vary continuously*" (1916, p. 9).

> (L2) The law of multiple proportions: "*If two definite compounds are taken at random from among the multitude of those containing the simple substances A and B, and if the masses of the element B that are found to be combined with the same mass of the element A are compared, it is found that those masses are usually in a very simple ratio to each other*" (1916, p. 10).

Chemists in the 19th century knew these laws and could derive them from versions of the chemical atomic theory at that time. While a particular value of Avogadro's number is not needed to derive these laws, knowledge of that value does contribute to the theoretical explanation of why the laws hold. This lends further support for our claim that the unobservable, discrete particles that Perrin counted should be considered atoms and molecules in some minimal sense.

> (C3) "[E]ach of the *elementary substances* of which all the various kinds of materials are composed is made up of a *fixed species* of particles, all absolutely identical; …, being indivisible…, they can be called atoms, in the etymological sense" (1916, p. 10).

Perrin's experimental work was not designed to test (C3), so it does not confirm the claim that every elementary substance is made up of a fixed species of particles because confirming this claim involves experiments in chemistry. Perrin's experiments also did not confirm the other claim of (C3) that each particle of a species is identical and indivisible; and, of course, it is currently known to be false that each particle is identical (because of the existence of isotopes) and indivisible.

> (C4) Avogadro's hypothesis: "*equal volumes of different gases, under the same conditions of temperature and pressure, contain equal numbers of molecules*" (1916, p. 18).

In his theoretical and experimental work, Perrin extended Avogadro's hypothesis from gases to fluids, and his experiments confirm Avogadro's hypothesis of fluids including gases. This lends further support for our claim that the unobservable, discrete particles that Perrin counted should be considered atoms and molecules in some minimal sense.

Perrin goes on to develop (T2) (the kinetic molecular theory of gases) in chapter 2, which is titled "Molecular Agitation." This theory contains a set of propositions and mathematical relations that concern temperature, pressure, volume, molecular velocities, and energy. These propositions and relations explain the translation, rotation, and vibration of molecules. In chapter 1, Perrin first supposes that molecules exist and thus infers from the phenomenon of diffusion that the molecules of all fluids move constantly. He also supposes that the gaseous pressure is produced by the impacts of the molecules upon the containing walls, and thus the molecular motion must become stronger with higher temperature. Accordingly, he derives the following theoretical constituents as principal assumptions of the kinetic theory:

> (K1) “[T]he molecules of any fluid whatever are in constant motion” (1916, p. 6).
>
> (K2) “Molecular agitation must therefore increase with rise in temperature” (1916, p. 7).

Perrin introduces (K1) and (K2) in chapter 1. The other basic propositions of the kinetic theory from chapter 2 are extracted as follows:

> (K3) “*For any given mass of gas, the product of the volume by the pressure is equal to two-thirds of the energy of translation associated with the molecules in the mass*” (1916, p. 57).

This proposition is a statement of the mathematical equation $3pv = MU^2$, where p is the pressure, U^2 is the mean square of the molecular velocity, and M is the mass of gas occupying the volume v.

> (K4) “*The sum of energies of translation of the molecules contained in a gramme-molecule is the same for all gases at the same temperature*” (1916, p. 58).
>
> (K5) “Absolute temperature [is] proportional to the molecular energy” (1916, p. 58).

These propositions are highly abstract generalizations and presuppose the existence of molecules and a concept of energy, which, at that time, were hypothetical. Many mathematical equations (such as $3pv = MU^2$) used to relate various quantities that Perrin measured are derived from these basic assumptions and other established laws. In this process of derivation, Perrin (1916, pp. 53-61) made many other hypotheses (such as “molecules are perfectly elastic,” molecules “rebound from the wall without gain or loss of energy” (1916, p. 56), etc.) to help establish the mathematical equations of the kinetic theory. Perrin concludes:

> The Kinetic Theory justly excites our admiration. It fails to carry complete conviction, because of the many hypotheses it involves. If by entirely independent routes we are led to the same values for the molecular magnitudes, we shall certainly find our faith in the theory considerably strengthened. (1916, p. 82)

One of these independent routes is an account of Brownian movement of granules suspended in an emulsion and a series of experiments on this phenomenon, which is presented in chapter 3. We suspend judgment about whether multiple independent routes would strengthen our faith in the kinetic theory. Perrin’s point here is just that, given the hypothetical nature of the kinetic theory, one route alone is insufficient to overcome its hypothetical status. Moreover, if, as Chalmers (2009, p. 245) claims, the kinetic theory is strictly false, then perhaps it's not entirely appropriate to consider whether Perrin's experimental work confirms it, as Chalmers (2009, p. 242) suggests. Perrin used the kinetic theory as a theoretical instrument to determine Avogadro's number, as he himself said that the kinetic theory involves many hypotheses. And insofar as Perrin uses the mathematical equations of the kinetic theory as instruments, the determination of Avogadro's number doesn't confirm that theory.

Perrin's second and third experimental methods use the equations that Einstein established to model Brownian movement. Einstein (1989[1905]) assumes that Avogadro's number N is equal to 6×10^{23} and uses the following equations to calculate the value of the mean displacements of the particles, where x is the mean displacement in the x-axis and D is the diffusion coefficient (see also section 4):

$$x = \sqrt{2Dt} \tag{4}$$

$$D = \frac{RT}{N}\frac{1}{6\pi kP} \tag{5}$$

From these equations, he suggests that the mathematical equation:

$$N = tRT/x^2 3\pi kP \tag{6}$$

can be used for the determination of N (1989[1905], pp. 133-134). However, Einstein uses his equations to model the translational movement which is only horizontal displacement in the x-axis. This model neglects the true but unmeasurable velocity of grains and disregards the intricate path of a grain in a given time (Perrin, 1916, p. 110). This implies that Einstein's theory is a typically ideal model which should be regarded as a theoretical instrument rather than a true description of Brownian movement. In this sense, Perrin's experimental work did not confirm Einstein's kinetic model of Brownian movement (T3) either.

In summary, Perrin's experimental determination of Avogadro's number did not confirm the kinetic theory or Einstein's kinetic model of Brownian movement. For the most part, it did not confirm the key constituents of the chemical atomic theory either, though it did confirm Avogadro's hypothesis as well as the proposition that chemical substances are ultimately composed of atoms and molecules. The fact that it confirmed these propositions lends further support to our claim that Perrin demonstrated the reality of atoms and molecules in the minimal sense of unobservable, discrete particles.

7. A comparison with other approaches

At this point, we've introduced our approach to the realism debate (section 2) and illustrated it in terms of the Perrin case (sections 4, 5, and 6). With this illustration in hand, we can flesh out our approach in more detail. After that, we compare our approach to the philosophical accounts of Perrin's work discussed in section 3 and the more general approaches to the realism debate that those accounts exemplify.

As we discussed in section 2, our approach has three main features. First, it admits multiple criteria of reality. Applying this approach to a particular historical case may require making use of a criterion that has already been developed elsewhere, introducing a new criterion, or extracting a criterion from some body of scientific work in which it is implicitly applied. Extracting an implicit criterion is one way to introduce a new criterion, and that is a good way to describe what we did in sections 4 and 5 with the number-per-unit criterion. Moreover, when introducing a new criterion of reality, one must motivate the claim that it is, in fact, a criterion of reality by providing both scientific and philosophical arguments, as we did in section 5. Because we admit multiple criteria of reality, we don't claim that a single criterion is applicable and appropriate for every case, and we don't deny that criteria proposed by others are applicable and appropriate for some cases. For example, we can admit the possibility that Hacking's (1983) manipulation criterion is appropriate for some cases while denying that it is appropriate for the Perrin case since Perrin did not manipulate atoms and molecules.

Second, our approach is experiment-based. On our approach, it would be a mistake to always require that the case for the existence of a particular kind of entity be made by confirming a part of a theory about that entity. As we argued in section 6, this sort of strategy does not work for the Perrin case. Instead, we focus on criteria of reality, and the particular criterion that we focused on is the number-per-unit criterion, which is, as we made clear in section 5, an experimental criterion. It differs from theoretical criteria of reality, which frequently appeal to various kinds of explanatory and predictive success of theories to justify claims about the approximate truth of parts of those theories and the existence of the entities they posit (Psillos, 1999, 2005). Based on our reconstruction of Perrin's argument, Perrin does not ground the reality of atoms and molecules in their indispensability for explaining and predicting observable phenomena. These sorts of theoretical criteria are therefore inappropriate for the case at hand. More generally, as we discussed in section 2, theoretical criteria have been susceptible to counterexamples, and our hope is that experimental criteria may succeed where theoretical criteria have failed. But there can, or course, be no guarantee in advance that they will.

Third, our approach is local in a number of senses. It does not attempt to provide an answer to the global question regarding what our attitude should be towards the entities posited in our best theories. Rather, it focuses on local questions regarding what sort of commitment is appropriate for particular kinds of entities, e.g., Perrin's atoms. Moreover, showing that a particular criterion is applicable and appropriate for a particular historical case, as well as extracting criteria that are implicit in scientific practice, are both issues that we address locally. These local aspects of our approach also provide us with a potential way of dealing with purported counterexamples to our criteria of reality insofar as examples in which the criteria are applied inappropriately may not be genuine counterexamples. For example, it would be technologically impossible to demonstrate the reality of dark matter by way of satisfying the number-per-unit criterion if the posited entity (dark matter) does not consist of discrete particles. Therefore, this is not a genuine counterexample even if scientists cannot determine the number per unit of dark matter. If dark matter exists and does not consist of discrete particles, then we must find another criterion according to which scientists can demonstrate the existence of such a kind of entity.[9]

[9] Hudson (2014, pp. 141-149) discusses the case of dark matter and whether the method he calls "targeted testing" can demonstrate the existence of dark matter.

Now we can compare our approach to the approaches discussed in section 3. Psillos's (2011a, 2011b, 2014) account of Perrin's work involves taking a global, theory-centric approach. He reconstructs Perrin's argument as a Bayesian inference to the conclusion that the probability of the atomic hypothesis is high, and emphasizes the role played by explanatory considerations in establishing that the probability of the atomic hypothesis is not low. Applying this global, theory-centric approach to the Perrin case is not completely satisfactory. To begin with, an evaluation of Psillos's account of Perrin's work depends on what, exactly, the atomic hypothesis is. Psillos (2011b, p. 340) claims that its "key assumption" is "that matter is discontinuous." According to our account, this key assumption is confirmed by Perrin's experimental work. But we doubt that this key assumption alone has the explanatory power necessary to show that the probability of the atomic hypothesis is not low. After all, this was the key assumption of atomic theory throughout history, and that key assumption was largely unsuccessful until it was incorporated into the chemical atomic theories of the 19th century. If the atomic hypothesis involves more than this key assumption (for example, key constituents from the chemical atomic and kinetic theories), then, as we have argued, Perrin's experimental work does not confirm the atomic hypothesis so understood. For these reasons, we take our account of Perrin to be preferable to Psillos's account. And the fact that it is preferable provides a reason for preferring our local, experiment-based approach to the realism debate to Psillos's global, theory-centric approach.

Chalmers (2009, 2011) takes another sort of theory-centric approach to the Perrin case. He focuses primarily on Perrin's experimental testing of the kinetic theory and claims that it was this testing of the theory by which Perrin made the case for the existence of atoms and molecules. The challenge for Chalmers is to make this claim consistent with the fact that Perrin did not demonstrate the truth of the kinetic theory. Chalmers claims that "appraising the case for the kinetic theory from the point of truth or falsity … is inadequately nuanced" (2009, p. 242), that "the kinetic theory was nevertheless strictly false" (2009, p. 245), and that "most of its claims were at least roughly correct" (2009, p. 245). At the very least, these claims seem to be in tension with one another. The key to reconciling them is presumably Chalmers's idea that the kinetic theory should be partitioned before testing it. The theory as a whole may be "strictly false." And it may be "inadequately nuanced" to merely consider whether the theory, as a whole, is false without partitioning it. But once we partition it, we may find that it contains many claims that are "roughly correct" even if "strictly false."

Our experiment-based approach differs from Chalmers's theory-centric approach. On Chalmers's approach, the case for the existence of atoms and molecules must be made through the testing of the kinetic theory. Hence, Chalmers must walk a fine line when maintaining that, though strictly false, the theory has parts that are true enough to make the case for atoms and molecules. But as we argued in section 6, Perrin did not confirm the kinetic theory, and the case for atoms and molecules did not proceed through the testing of the kinetic theory. In accordance with our experiment-based approach, we take it to be a mistake to require that the case for the existence of a particular kind of entity must always proceed through the testing of a theory about that entity. Hence, we take our approach to the realism debate to be preferable to Chalmers's theory-centric approach.

We take our approach to be compatible with Achinstein's (2002) and Hudson's (2020) approaches. Like us, both Achinstein and Hudson apply a kind of experiment-based approach to the Perrin case; and Achinstein's approach is, like ours, explicitly local. We do not deny that Achinstein's causal-eliminative reasoning and Hudson's calibration reasoning played a role in Perrin's work. However, we maintain that Perrin's case for the existence of atoms and molecules relies primarily on the satisfaction of the number-per-unit criterion. Our account explains why the determination of Avogadro's number is the key to demonstrating the reality of atoms and molecules. It does so by extracting the number-per-unit criterion from Perrin's work, in which it is merely implicit, and by showing why counting the number of a particular kind of entity per unit is a criterion of reality. As a result, our argument is more conformable to Perrin's and other contemporary scientists' intuitions as discussed in section 4.

8. Conclusion

We have argued that Perrin's experiments demonstrate the reality of atoms and molecules in the minimal sense of unobservable, discrete particles, and that they do so by satisfying the number-per-unit criterion. His experimental work confirmed Avogadro's hypothesis as well as the central claim of the chemical atomic theory, namely, that all chemical substances are ultimately composed of atoms and molecules. However, his experimental work did not confirm the truth of the atomic theory of matter more generally or the kinetic theory of molecular agitation. Importantly, the crucial warrant for the reality of atoms and molecules comes from the satisfaction of the number-per-unit criterion rather than some theory-centric argument.

We have also argued that our account of Perrin's work is preferable to other accounts of his work that we discussed in section 3, especially Psillos's and Chalmers's accounts. Psillos's and Chalmers's accounts of Perrin's work result from applying a theory-centric approach to the realism debate, while our account of Perrin's work results from applying our local, experiment-based approach to the debate. We use the fact that our account of Perrin's work is preferable to Chalmers's and Psillos's accounts as a reason to prefer our local, experiment-based approach to the realism debate to global, theory-centric approaches to the debate.

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