Chapter 8
Controlling the Unobservable: Experimental Strategies and Hypotheses in Discovering the Causal Origin of Brownian Movement

Klodian Coko

8.1 Introduction

Brownian movement is the seemingly irregular movement of microscopic particles—of a diameter less than approximately 10^{-3} mm—of solid matter when suspended in liquids.[1] Although experimentally investigated in the nineteenth century, it was only at the end of that century that the phenomenon's importance was recognized for the kinetic-molecular theory of matter, i.e., the theory that matter is composed of atoms and molecules in incessant motion. Historians of science have expressed both surprise and lament that Brownian movement played no role in the early development and justification of the kinetic theory of gases. Today, we know that the movement is an observable effect of the molecules' motions constituting the liquid state of matter. If molecular motion had been identified from the beginning as the cause of the phenomenon, some of the most important philosophical and scientific objections raised against the early kinetic theory could have been answered. For example, the molecular explanation of Brownian movement could have resolved the nineteenth-century philosophical debates over the empirical status of molecular hypotheses, which centered on the question of whether the existence of unobservable entities such as atoms and molecules could be resolved by observation and

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[1] *Brownian movement, mouvement Brownien, moto Browniano, Molecularbewegungen* were the terms used in the nineteenth century to refer to the movement of microscopic particles suspended in liquids. In this chapter, I use these same terms to describe the nineteenth-century investigations of this phenomenon. I avoid the term *Brownian motion,* which is more recent, and which already includes the randomness of the motions; it therefore has wider connotations. According to Encyclopedia Britannica, for example, "Brownian motion" concerns "various physical phenomena in which some quantity is constantly undergoing small, random fluctuations" (Britannica, March 21, 2023).

K. Coko (✉)
Philosophy Department, Ben-Gurion University of the Negev, Beersheba, Israel
e-mail: coko@post.bgu.ac.il

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experiment. In addition, Brownian movement could have provided independent empirical evidence for one of the theory's controversial claims: that at a molecular level, the Second Law of Thermodynamics had only statistical as opposed to absolute validity. Relatedly, it is often claimed that most nineteenth-century experiments on the nature and cause(s) of Brownian movement were less rigorous than later experiments, which successfully established molecular motion as the proper and unique cause (Brush 1968, 1; Nye 1972, 9; Maiocchi 1990).[2]

In this chapter, I focus on the experimental practices and the reasoning strategies used by nineteenth-century investigators of Brownian movement, in their quest to determine the phenomenon's causal origin. By focusing on these practices and strategies, we may better appreciate the century's investigative efforts in and of themselves, and not only insofar as they relate to later scientific and methodological developments. Nevertheless, this account presents some of the practical and conceptual complexities of the investigations on the cause of Brownian movement, which help to make sense of its delayed connection with the kinetic-molecular theory of matter. I argue that there was extensive and sophisticated experimental work done on the phenomenon of Brownian movement throughout the nineteenth century. Most investigators were aware of the methodological standards of their time and tried to align their work with them. The main methodological strategies they employed were two.

The first was the traditional strategy of varying the experimental parameters to discover causal relations. In the nineteenth century, this strategy was codified into explicit methodological rules by John Herschel (1830) and then, perhaps more famously, by John Stuart Mill ([1843] 1974). In nineteenth-century investigations of Brownian movement, we find that the reasoning underlying this strategy was already embedded in experimental practices prior to this codification, and independently of Herschel and Mill (see also the chapters by Schürch and Nickelsen, Chaps. 3 and 7 in this volume). More specifically, the basic rationale underlying these investigations was that: (a) all the circumstances and factors that could be introduced, varied, or entirely excluded without influencing Brownian movement, were not causes of the phenomenon; (b) all the circumstances and factors whose introduction, variation, or exclusion influenced the phenomenon were considered to play a causal role in its production. As mentioned in the introduction to this volume, employing this strategy required (implicitly or explicitly) at least three notions of control: (1) control over the introduction, variation, or exclusion of the circumstance or factor whose causal influence was to be examined; (2) control over the rest of the circumstances or factors, which ought to be kept as much as possible the same; and (3) control in the more familiar sense, of comparing the experimental situation after the intervention (i.e., the introduction, variation, or exclusion of the factor whose causal influence was being investigated) or with it, with the (control) situation before the intervention or without it (see also Boring 1954; Schickore 2019).

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[2] These sentiments echo those of the historical actors who played important roles in connecting Brownian movement with the molecular theory of matter. See, for example, Perrin (1910) and Poincaré (1905).

The strategy of varying the circumstances succeeded more in excluding various suspected causal factors than in establishing a positive causal explanation. Even when some causal influence was detected, not all investigators shared the conclusion. Disagreements over the influence of various causal factors led to the recognition of the importance of a different notion of "control": that of the independent confirmation of experimental results by other researchers. Despite the difficulties surrounding its implementation, the strategy of varying the circumstances, by showing the insufficiency of the various causal explanations of Brownian movement, enhanced the importance of the fact that the newly developed kinetic-molecular conception of matter seemed to provide a plausible explanation of the phenomenon.

The second strategy was similar to what at the time was called the *method of the hypothesis*. This method, at least according to some scholars, re-emerged in the nineteenth century as the proper strategy for validating explanatory hypotheses about unobservable entities, processes, and phenomena (Laudan 1981). Amid all the criteria for evaluating explanatory hypotheses, the ability of a hypothesis to explain, successfully predict, and/or be supported by a variety of facts—especially facts playing no role in the hypothesis' initial formulation—was considered to be the most important criterion for its validity. Proponents of this strategy appealed to the ability of the kinetic-molecular hypothesis to offer a natural explanation of Brownian movement. What was remarkable about this explanation, they argued, was the fact that the elements of the hypothesis invoked to explain the phenomenon were developed independently of it. The ability of the kinetic-molecular hypothesis to explain a variety of unrelated phenomena and experimental evidence was offered, by some investigators, as an important "control" for the validity of the kinetic-molecular explanation of Brownian movement.

Neither methodological strategy could, on its own, establish molecular motion as the cause of Brownian movement. Their combination and their accompanying notions and practices of control, at the end of the nineteenth century, to the recognition of molecular motion as the most probable cause. From then on, the goal of experimental practices and reasoning strategies shifted to that of probing and evaluating the kinetic-molecular explanation of Brownian movement.

8.2 First Observations of the Curious Phenomenon

The phenomenon of Brownian movement owes its name to the Scottish botanist Robert Brown (1773–1858), who experimentally investigated it beginning in the summer of 1827 (Brown 1828). An already eminent botanist, Brown was not the first to observe the phenomenon. All earlier investigators, however, seem to have connected it with the motion of infusory animalculæ, and had attributed it to some sort of vitality possessed by the moving particles (Brown 1829, 164; Brush 1968). Brown's main contribution, and his claim to priority, lies in establishing that the movement of microscopic particles when suspended in liquids was a general phenomenon exhibited by all microscopic particles, independently of their chemical nature. We start, therefore, by examining the methodological ideas and practices Brown used to establish this claim.

Brown offered an account of his initial investigations in a pamphlet he originally circulated privately among his friends, but which aroused enough interest to appear, in 1828, in the *Edinburgh New Philosophical Journal*. It appeared soon afterwards in numerous other journals (Mabberley 1985). The pamphlet provides an interesting step-by-step account of his investigations. Brown was investigating the mechanism of fertilization in the plant *Clarckia pulchella*, whose grains of pollen were filled with microscopic particles of different sizes that were easy to observe with a simple microscope. "While examining the form of these particles immersed in water, I observed many of them evidently in motion; …These motions were such as to satisfy me, after frequently repeated observations that *they arose neither from currents in the fluid, nor from its gradual evaporation, but belonged to the particle itself* (Brown 1828, 162–63, my emphasis).

Brown extended his observations to particles derived from the pollen of plants belonging to different families, and found similar spontaneous movements when they were suspended in water. Having found these movements in the particles of pollen of all the living plants he examined, Brown inquired whether they continued after the death of the plant and for how long they were retained (Brown 1828, 164). Unexpectedly, he found that specimens of dead plants, some of which were preserved in an herbarium for no less than one hundred years, produced similar moving particles. Soon he discovered that the moving particles—or *active molecules*, as he began to call the smallest particles of apparently spherical shape not exceeding 1/15000 of an inch—were not limited to the grains of pollen, for they could also be produced from other parts of the plant as well. Even more surprisingly, however, Brown found that these molecules were not limited to organic matter but could be equally acquired in inorganic matter. He found that fragments of window glass, various minerals,

> [r]ocks of all ages, including those in which organic remains have never been found, yielded the molecules in abundance. Their existence was ascertained in each of the constituent minerals of granite, a fragment of the Sphinx being one of the specimens examined…In a word, in every mineral which I could reduce to a powder, sufficiently fine to be temporarily suspended in water, I found these molecules more or less copiously. (Brown 1828, 167)

The next step for Brown was to investigate whether the movement of the molecules derived from organic substances was affected by the application of intense heat on the substance from which they were derived. A comparative experiment was conducted. Small portions of wood (both living and dead), linen, paper, cotton, wool, silk, and hair were heated, and immediately quenched in water. In all cases molecules could be derived, and they were found to be as evidently in motion as those obtained from the same substances before burning (Brown 1828, 168).

To sum up, during these initial investigations, Brown used the seeming invariance of the suspended particles' movements to the variation or change of the suspected causal factors—namely, currents and evaporation in the suspending liquid, the chemical nature of the suspended particles, the application of heat on the particles' originating material—to conclude the causal independence of these movements from the varied factors.[3] As already mentioned, this strategy of varying the circumstances to discover causal dependencies involves at least three notions of control: (1) control over the variation of the suspected causal factor, (2) control over the remaining circumstances that should remain the same as much as possible,[4] and (3) control in the sense of comparing the experimental situation with the variation or after it to the situation without the variation or before it. Brown did not use the term "control," and these three notions of control are only implied in the description of his observations and experiments. In the rest of this chapter, we shall see that these and other forms of control became more explicit when the validity of the initial observations was challenged.

The invariance of the movements to the variation of some of the suspected causal factors led Brown to exclude these factors as causes of the surprising phenomenon. But they could not help him identify a positive cause. His conclusions regarding the cause of the movements of the "active molecules" were cautious: "I shall not at present enter in any additional details, nor shall I hazard any conjecture whatever respecting these molecules, which appear to be of such general existence in organic as well as inorganic bodies" (Brown 1828, 169).

In the pamphlet presenting the results of his early research, Brown stated that he knew close to nothing about the phenomenon before beginning, and that he was only acquainted with the abstract of a memoir that the French botanist Adolphe Brongniart (1801–1876) had read before *l'Académie des Sciences* in Paris, in December 1826. The abstract was later published in the *Annales des Sciences Naturelles* (Brown 1828, 171–72; Brongniart 1827). Brongniart was also studying the process of fertilization in plants. Using an Amici microscope, which provided a magnification of up to 1050 times, Brongniart found that the microscopic granules contained in the pollen grains of numerous plants, or *granules spermatiques*, as he called them, performed clearly distinguishable spontaneous movements when suspended in water. The granules formed *la poussiere fecondant* (i.e., the most essential part of the pollen fertilizing the ovum). These movements seemed impossible to attribute to an external cause (Brongniart 1827, 45). These observations corroborated, according to Brongniart, his initial hypothesis that the spermatic granules found in the pollen of plants were analogous to the *spermatic animalculæ* found "swimming" in the sperm of animals (Brongniart 1827, 48).

As they were published in prestigious scientific journals, Brown's and Brongniart's observations drew great attention and elicited a strong reaction against the claim that the moving microscopic particles were self-animated.[5] The most influential critique came from the French physiologist François Raspail (1794–1878),

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[3] This early use of the varying-the-circumstances strategy seems to be a case of what Steinle (2002, 2016) has identified as *exploratory experimentation*.

[4] Brown explicitly stated that, to give greater consistency to his statements, and to bring the subject as much as possible to the reach of general observation, he continued to use the same microscope with one and the same lens throughout his initial investigations (Brown 1828, 161).

[5] Brush (1968) provides an extended bibliography of these reactions.

who claimed that his conclusions on the subject were the result of many repeated and varied experiments (Raspail 1829a, b). First, Raspail attacked Brongniart's claim that the granules discharged in the explosion of grains of pollen were analogous to the spermatic animalculæ. His numerous experiments, argued Raspail, showed that the granules derived from the explosion of the grains of pollen, even those of the same plant, varied in shape, diameter, size, and other characteristics (Raspail 1829a, 97). This result challenged the claim that these granules were of an organized nature and that they belonged to a distinguishable category of entities. Second, Raspail rejected the claim that the movements of the particles suspended in water belonged to the particles themselves. He argued that the movements were easily distinguishable from the spontaneous movements of the infusory animalculæ, and that they could be attributed to the influence of various mechanical causes (Raspail 1829a, b). Raspail listed several such causes that, based on "a great number of consecutive observations" (Raspail 1829a, 97), could communicate even to the most inactive particles the appearance of spontaneous motion. The list included the motion communicated to the granules from the explosion of pollen discharging them, capillarity, the evaporation of the suspending water, the evaporation of the volatile substances with which the granules issuing from pollen may be impregnated, the ordinary motions of great towns, the motions caused by the air's agitation, the motions caused by the observer's hands, the inclination of the object plate, and the electricity communicated to particles of metallic origin by friction (Raspail 1829a, 97; b, 106–7).

Raspail's list proved to be influential. For the greater part of the nineteenth century it constituted the essential list of causes that, singly or in combination, were invoked to explain the movements of microscopic solid particles suspended in liquids. The list is also important because it reveals the difficulties surrounding the ascertainment of the concrete cause(s) of the observed movements by means of the experimental strategy of varying the circumstances. Such an experimental effort would require rigorous control over the many suspected causes and possible confounding factors.[6] Regarding his own methodological efforts, and faced with claims about the existence of spontaneous motion, Raspail maintained that, although his numerous earlier experiments on the subject had made him aware of the various contributing causal factors, he felt it incumbent on himself "to repeat all my experiments, and to vary them in every way, as if I had doubted the accuracy of my former ones" (Raspail 1829a, 99).

Replying to this criticism, Brongniart defended his original observations on both methodological and experimental grounds. Besides claiming that his conclusions were the result of repeated experiments performed on pollen from different kinds of plants, Brongniart appealed to another kind of experimental control: that of

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[6] Schickore (2022) and Schürch (Chap. 3, this volume) provide detailed accounts of the difficulties surrounding the concrete applications of the varying-the-circumstances strategy in establishing causal claims.

independent confirmation by other researchers.[7] Independent confirmation, Brongniart asserted, was essential for the verification of claims concerning phenomena that were not readily observable and that contradicted in certain respects widely established theories.[8] Brongniart emphasized especially the fact that some of this confirmation came from research done without prior knowledge of his conclusions (Brongniart 1828, 392–93).[9] This specific kind of independent confirmation was important because it precluded the possibility that the other researchers had simply adjusted their conclusions to achieve consensus.[10] Among the claims that Brongniart maintained had been independently confirmed by other researchers were that the granules contained in the pollen of the same plant were of a well-determined form, that they had exactly measurable dimensions, and that each one performed extremely small motions which, because of their irregularities, seemed to be independent of any external cause (Brongniart 1828, 382). To these independently confirmed observations Brongniart added new ones conducted on twenty-four species of plants from different families. He also discussed new experiments that, he claimed, established without any doubt that the "spermatic granules" were different from the irregularly shaped particles of non-organized matter also found in the pollen of plants (Brongniart 1828, 386–88).

Regarding the movement of the "spermatic granules," Brongniart cited the irregular way they changed their positions relative to one another in order to argue that the movement was not caused by any external influences. It was instead dependent, he said, on a cause existing in the granules themselves (Brongniart 1828, 389). He too used the strategy of varying the circumstances to show that the movement continued without the smallest difference, even when some of the mechanical causes in Raspail's list—like the agitation of the liquid caused from evaporation, the trembling of ground or air, or the influence of sunlight—were either excluded or varied. More specifically, Brongniart burst the grains of pollen in very small glass capsules filled with a drop of water. He then covered the capsules with a thin film of mica to stop evaporation and the agitation of the water's surface. He conducted microscopy

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[7] This kind of experimental control is discussed in detail in the chapters by Schürch, and Christopoulou and Arabatzis, Chaps. 3 and 9 in this volume.

[8] "Les phénomènes de la nature, qui s'éloignent de ceux qui frappent habituellement nos yeux, qui contredisent à quelques égards les systèmes fondés sur des observations anciennes et généralement reconnues; qui, par cette raison, sont d'ordinaire plus difficiles à saisir, exigent, pour être admis au nombre des vérités non contestées, des recherches souvent répétées, présentées avec ces détails qui éloignent toute espèce de doute, et vérifiées par de observateurs différens; car le concours des opinions d'hommes indépendans les uns des autres, est la seule preuve de la vérité pour ceux qui ne peuvent pas la rechercher eux-mêmes" (Brongniart 1828, 381–82).

[9] "Cette observation est d'autant plus curieuse qu'elle a été faite par une botaniste qui ne pouvait avoir à cette époque aucune connaissance des résultats auxquels l'examen du pollen des plants phanérogames m'avait amené; qui n'y était conduit par aucune théorie, et qui même, par ces raisons n'a pas pu sentir la liaison de ces phénomènes avec d'autres analogues" (Brongniart 1828, 393).

[10] For a discussion of this notion of (genetically) independent confirmation and its differences from other notions of independent confirmation see Soler (2012) and Coko (2020b).

observations of this preparation under the lamp light but also during cloudy days. Despite the measures taken to control (i.e., to exclude or lessen the influence of the suspected mechanical causes), the movements of the suspended granules continued without any difference. In contrast, when he replaced water with alcohol in the same experimental setting, the movements ceased completely instead of becoming livelier, as one would expect if they were caused by the liquid's evaporation (Brongniart 1828, 389–90).

Of special interest is the *note additionelle* to the paper which Brongniart wrote after learning about Brown's observations of the irregular movement of suspended particles derived from inorganic matter (Brongniart 1828, 393–98). Brongniart stated that Brown's observations prompted him to conduct new ones on suspended inorganic particles. These observations generally agreed with Brown's.[11] Because Brongniart initially claimed that the "spermatic granules" in pollen were analogues of the spermatic animalcules in the sperm of animals, and that they were clearly distinguishable in both their form and movement from the (irregularly shaped) microscopic agglomerations of matter also found in pollen, asserting agreement with Brown's observations was an exaggeration. In fact, even in the *note*, Brongniart continued to distinguish between the movement of the "spermatic granules" in pollen from that of inorganic particles. The movements of the inorganic particles seemed to him less constant and more dependent on the nature of the inorganic substance from which they were derived. In general, the movements were more evident in inorganic particles derived from substances that were better conductors of electricity. Despite the differences between his observations and Brown's, and in line with his previous assertion about the importance of independent confirmation, Brongniart was eager to emphasize the points of agreement. The most important one was the claim that the movements of both the spermatic granules and inorganic particles seemed to be caused by a force inherent in the particles and not by any external factors.[12] The crucial point, he continued, was to determine whether they were attributable to the same cause(s). In particular he wished to determine whether they were caused by the particles' vitality or by some hitherto unaccounted for internal factor or external influence (Brongniart 1828, 394–96).

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[11] "Quant aux molécules des corps inorganiques, on observe en effet assez souvent, dans plusieurs substances broyées dans l'eau de très-petits corpuscules arrondis semblables aux plus petites molécules du pollen, et doués de mouvemens analogues en apparence à ceux des granules du pollen" (Brongniart 1828, 394).

[12] "La seule chose sur laquelle je ne puis conserver aucun doute, et sur laquelle j'ai le bonheur de voir mon opinion entièrement confirmée par celle des commissaires de l'Académie et de M. Brown, c'est l'indépendance complète de ce mouvement de toutes les causes extérieures influant sur le liquide ambiant. Il me paraît bien certain que la cause du mouvement, quelle quelle soit, réside dans une force physique ou organique inhérente aux corpuscules mêmes qui se meuvent. C'était la seule chose que j'avais avancée dans mes premières observations sur ce sujet, puisqu'en disant que ce mouvement était spontané, j'avais observé que j'entendais seulement exprimer par ce mot que ce mouvement était inhérent aux granules eux-mêmes" (Brongniart 1828, 396).

Brown rejected too the charge that his original memoir had implied that the moving suspended particles were animated (Brown 1829, 161–62). He also claimed to have conducted additional research on the subject, this time using different microscopes and different kinds of particles suspended in various liquids (Brown 1829, 162). The additional research, Brown asserted, confirmed the main results he had advanced in his 1828 pamphlet:

> that extremely minute particles of matter, whether obtained from organic or inorganic substances, when suspended in pure water, or in some other aqueous fluids, exhibit motions for which I am unable to account, and which from their irregularity and seeming independence resemble in a remarkable degree the less rapid motions of some of the simplest animalcules of infusions…I have formerly stated my belief that these motions of the particles neither arose from currents in the fluid containing them, nor depended on that intestine motion which may be supposed to accompany its evaporation. (Brown 1829, 162)

Brown cited the complete irregularity of the movements—i.e., the seemingly total independence in the movements of every two particles—to reject the various mechanical explanations of the phenomenon. In addition, he described two experiments demonstrating that the particles continued to move with their usual degree of activity even when the principal mechanical causes suspected of their motion were either reduced or completely excluded.

In the first experiment, Brown was able to isolate minute drops of water, some of them containing few or only one microscopic particle, in almond oil. In this manner, the drops, which if exposed to air would dissipate in less than a minute, were retained for more than an hour. But in all the drops, the motion of the suspended particles continued with undiminished activity. This was true even though the mechanical causes suspected for their motion, namely evaporation and the particles' mutual attractions and repulsions, were either reduced or entirely excluded.

In the second experiment, Brown was able to show that the motion of the particles was not produced by causes acting on the surface of the water-drop—e.g., currents in the surrounding liquid. Inverting his first experiment, he mixed a very small proportion of almond oil with the water drops containing the particles and was able to produce almond oil drops of extreme minuteness, some of them not exceeding the size of the particles themselves, attached to the surface of the water drops. The oil drops remained nearly or altogether at rest while the material particles isolated in the water drops continued to move with their usual degree of activity (Brown 1829, 163–64).

Brown and Brongniart's observations and experiments seemed to have aroused much interest over the cause of this curious phenomenon. Because many researchers at the time considered vitalist explanations questionable, the idea of the particles' vitality was rejected and, despite Brown and Brongniart's experimental efforts, various mechanical causes, singly or in combination, were proposed as explanations. In 1829 Georg Wilhelm Muncke from Heidelberg cited experimental research on the phenomenon to conclude that: "The movement certainly bears some resemblance to the one observed in Infusoria, yet the latter shows more voluntary action. Vitality, like many possibly have believed, is out of the consideration [as an explanation]. I rather consider the motion to be purely mechanical and caused by the uneven temperatures in strongly illuminated water, evaporation, air and heat currents, etc."[13]

These mechanical explanations of the phenomenon persisted, despite Brown's and Brongniart's experiments showing the phenomenon's invariance even when explicit measures were taken to control and/or exclude the influence of the relevant mechanical causes. It seems that one important factor was the impression that rejecting those causes would leave the particles' vitality as the only plausible explanation. For example, the renowned Scottish physicist David Brewster, then-editor of the *Edinburgh Journal of Science*, referred to the sufficiency of Raspail's mechanical causes to explain the motions of the suspended particles. He remarked that "even if they did not afford a sufficient explanation of the motions in question;—nay, if these motions resisted every method of explanation, it is the last supposition in philosophy that they are owing to animal life" (Brewster 1829, 219). For Brewster, an explanation showing that the motions of the suspended particles obeyed physical laws like the ones governing the motions of larger bodies would always take precedence over any hypothesis claiming the particles to be in some way animated (Brewster 1829, 219–20).

8.3 Experimental Investigations of Brownian Movement: 1830–1860

Despite the disagreement regarding the causal origin of the curious phenomenon, Brownian movement was not neglected during the period 1830–1860, as is sometimes claimed. In fact, what was neglected was rather the study of some of the investigators of the phenomenon by subsequent historiography of science. One of these neglected figures was Giuseppe Domenico Botto (1791–1865), professor of experimental physics at the University of Torino, who conducted experimental investigations into Brownian movement in the late 1830s (Guareschi 1913). Knowing the disagreements about the characteristics and causes of the phenomenon, Botto called for a cautious, purely experimental approach, and for a multiplication of experiments.[14]

In his own investigations, Botto found that the movement of suspended particles derived from organic matter had different characteristics from that of inorganic particles. Using an Amici horizontal microscope, Botto conducted extensive

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[13] "Die Bewegung hat allerdings einige Aehnlichkeit mit der bei Infusorien wahrgenommenen, jedoch zeigt letztere mehr Willkühr. An Vitalität, wie vielleicht Einige geglaubt haben, ist dabei gar nicht zu denken, vielmehr halte ich die Bewegung für rein mechanisch, und zwar durch ungleiche Temperatur des stark erleuchteten Wassers, durch Verdampfung desselben, durch Luftzug und Wärmeströmung u. s. w. Erzeugt" (Muncke 1829, 161).

[14] "Au milieu de ces contradictions, et dans un sujet aussi important et complexe, ce qu'il y a de mieux à faire, est de multiplier les expériences, sans franchir trop à la légère les limites de l'observation" (Botto 1840, 459).

microscopic observations on suspended microscopic globules derived from different plants, vegetable products, and inorganic substances. In all his observations of suspended microscopic globules derived from vegetable matter, Botto found the phenomenon exhibited in the manner described by Brown: "one sees them changing their relative positions every moment, approaching one another, receding from one another, spinning, as if these movements originated on their own."[15] The lively oscillatory movement was invariantly found on suspended globules derived from all the parts of the individual plant: the grains of pollen, the ovary before and after fertilization, the pistil, the stamen, the anther, the buds, the tubers, the seeds, and so on (Botto 1840, 465). However, Botto argued, the globules derived from pollen had a vivacity of motion not encountered in globules derived from other parts of the plant. Such lively motion, he claimed, qualified as the effect of a spontaneity peculiar to animal nature. Botto proceeded to investigate the influence of various chemical substances and physical agents on the movement of organic globules suspended in water. He found that a small quantity of ammonia ceased almost all movement. Sulfuric, nitric, and hydrochloric acids, as well as opium, produced similar deadening effects. The application of strong heat and electricity on the suspending liquid also immobilized the moving globules (Botto 1840, 462).

Contrary to Brown, Botto claimed that the movement of suspended inorganic particles had different features from that of organic globules: "Neither powdered glass, neither quartz, nor the granite of our Alps, nor the pebbles of our rivers, nor rocks of any kind, offered particles endowed with movements analogous to those of organic globules. I could not either certify their presence anymore in the organic substances after carbonization or incineration."[16] The explanation for the movement of the inorganic particles by familiar mechanical causes seemed to him to be "neither impossible nor difficult" (Botto 1840, 467). On the other hand, the movement of the organic globules could not be explained by known physical causes. It must, therefore, be considered a proper quality of the globules themselves, and of their organic and vital nature (Botto 1840, 468). Botto's research shows that vitalist claims, although distrusted by most researchers, remained a viable option, at least for the movement of organic particles. Although these observations did not seem to have much influence on subsequent Brownian movement research, they are important from a historiographical point of view. Once again, they reveal the difficulties in applying the varying-the-circumstances strategy for reaching consensus on the causal influence various factors had on the phenomenon.

One of the most widely accepted explanations of Brownian movement during this period was offered by Felix Dujardin (1801–1861). Although he used similar methodological reasoning, Dujardin reached entirely different conclusions

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[15] "On les voit changer à chaque instant de position relative, s'approcher, s'éloigner, tournoyer, comme ci ces mouvements venaient de leur propre fait" (Botto 1840, 459).

[16] "Ni le verre pilé, ni le quartz, ni le granit de nos Alpes, ni les cailloux de nos rivières, ni les roches de toute espèce ne m'ont offert de globules doués de mouvements analogues à ceux des globules végétaux. Je n'ai pas pu en constater non plus la présence dans les substances végétales après la carbonisation ou l'incinération" (Botto 1840, 466–467).

from Botto regarding the generality of the phenomenon, the influence of physical agents such as heat and electricity, and the cause. Dujardin gave his view in his influential treatise on microscopy, in a chapter titled "Du Mouvement Brownien ou Mouvement Moléculaire" (Dujardin 1843, 58–60). This chapter followed one that expounded some of the main causes of illusions and errors in microscopy observations. It seems that disagreements regarding the basic features and causes of the phenomenon invited reflection about possible sources of error. Dujardin cited the phenomenon's invariance amid the influence of various physical and chemical agents—light, electricity, magnetism, chemical reagents—to argue that the movement was a purely physical phenomenon, belonging to all particles of solid matter sufficiently small to be suspended in liquids. In fact, he wished to warn the uninitiated observer who might perceive in it the manifestation of life and other kinds of organic activity (Dujardin 1843, 59–60). Studying oil globules suspended in milk, Dujardin found that the vivacity of the movements depended on the particles' size. The smallest particles, of a radius of less than 1/600 mm, moved the most vigorously, those of radii of between 1/400 and 1/300 mm showed movement noticeable only if one observed carefully, whereas those of larger size remained motionless. He also found the movement to be livelier as the density of the material from which the suspended particles were derived was less than that of water (Dujardin 1843, 59). Dujardin claimed heat as the only physical agent affecting the phenomenon: it caused the movements to become more rapid. Reflecting on these results, he concluded that the movements of the suspended particles could be attributed to the various impulses that each particle receives from the radiant heat emitted by the particles adjacent to it.[17]

Dujardin's views on the cause of Brownian movement were shared by Griffith and Henfrey in Britain and were included in their *Micrographic Dictionary* (Griffith and Henfrey 1856). Like Dujardin's treatise, the *Dictionary* too began with a methodological introduction concerning the proper use of microscopes and the main sources of errors in their employment. The remarks on Brownian motion were included in the entry *Molecular Motion*—where the term "molecule" refers to extremely minute particles of any substance. Although the entry suggests it was based on original experimental work, it was in fact a summary of Dujardin's text, with the part referring to the probable causes of motion being simply the English translation of Dujardin's words.[18]

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[17] "si l'on chauffe le liquide, le mouvement devient notablement plus vif, et comme tout autre agent physique ou chimique, la lumière, l'électricité, le magnétisme, le contact des réactifs chimiques ou des divers solides est sans influence sur le mouvement Brownien, on est conduit à penser que c'est le résultat des impulsions variées que chaque particule reçoit de la part du calorique rayonnant émis par tous les corps voisins" (Dujardin 1843, 59–60).

[18] "Heat is the only agent which affects it [molecular motion]; this causes the motion to become more rapid. Hence it may be attributed to the various impulses which each particle receives from the radiant heat emitted by those adjacent" (Griffith and Henfrey 1856, 429).

In 1858, Jules Regnauld (1822–1895), physics professor at the École de Pharmacie in Paris, cited extensive experimental work on the phenomenon to conclude that Brownian movement was caused by the solar heat absorbed in suspended particles. When transferred to the surrounding liquid, this heat created very small currents responsible for the observed motions.[19]

Those investigating the phenomenon during these earlier phases of experimental research failed to agree on its essential characteristics and the influence of the various suspected causal factors. To clarify the disagreements, it would be useful to distinguish between *causal claims* and *causal explanations* made regarding the causal origin of Brownian movement.[20] A causal claim asserted the identification of a "difference-maker," i.e., the causal influence of a suspected factor—evaporation, heat, electricity, and so on—on the movement of the suspended particles. By changing or varying the suspected causal factors, the experimental strategy of varying circumstances tried to identify a difference-maker and thus make a causal claim. A causal explanation of Brownian movement, on the other hand, aimed at providing a more or less detailed account of a concrete mechanism linking a causal factor with the effect, i.e., the observed Brownian movements. A causal explanation was more speculative than a causal claim because its details could not be established by varying the circumstances. Causal claims, however, could identify the difference-maker, which could then be used to offer a probable causal explanation of the observed movements.

Early experimental investigations of Brownian movement failed to reach consensus in identifying a difference-maker. This was to be expected, given the difficulties with the varying-the-circumstances strategy in such a complex phenomenon. Even when reaching agreement on the influence of some (macroscopic) agent, like heat, on the movement of the suspended particles, researchers still disagreed about the exact mechanism by which this agent, at the microscopic level, produced the observed movements. In the rest of this chapter, we see various permutations of the relationship between causal claims and causal explanations in the nineteenth-century investigations of Brownian movement.

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[19] "M. J. Regnauld est porté à conclure que les oscillations des corps très-divisés nageant au sein d'un liquide diathermane sont dues à leur échauffement par la portion de la radiation solaire que, absorbée par eux, les rend visibles. Cette faible quantité de chaleur se transmettant par voie de de conductibilité au liquide en contact avec les particules semblé la cause de petits courants rendus manifestes par les changements de position relative des substances tenues en suspension" (Chatin 1858, 141).

[20] In making this distinction, we are following Russo and Williamson (2007), who claim that a causal connection can be established only if it can be shown (a) that there is a difference-making relationship between the cause and the effect, and (b) that there is a mechanism linking the cause and the effect responsible for the difference-making relationship.

8.4 Non-molecular Causal Claims and Explanations of Brownian Movement: 1860–1880

The explanation of Brownian movement by the absorption and radiation of heat turned out to be quite popular. In Britain, a prominent defender of the view was John Benjamin Dancer (1812–1877), a microscopist from Manchester. Dancer claimed to base his conclusions on experiments performed over 30 years with various substances and solutions (Dancer 1868, 162). He asserted that the intensity of the movements depended on the size and shape of the particles as well as on the nature of the solutions. The particles approaching a spherical shape usually exhibited a more marked movement. To further support his claim, Dancer excluded chemical and electrical influences as causes. This he did by demonstrating that the particles showed no marked alterations in their movements when exposed to electric and chemical influences (Dancer 1868, 164; Jevons 1870, 83).

Dancer's claim went against another popular view in Britain regarding the causal origin of the movement, which presented it mainly as an electric phenomenon. The most prominent defender of this claim was William Stanley Jevons (1835–1882), the British philosopher and polymath. Jevons coined the name *pedesis* from the Greek *πήδησις* (meaning "leaping" or "bounding"), and the adjective *pedetic* from *πηδητικός*, as more appropriate for describing the dancing movement of the suspended particles. The term *molecular movement* used by Brown was inadequate because the moving particles were not molecules in the new chemical sense, whereas the term *Brownian movement* was an inconvenient two-word expression which, in addition, concealed the fact that Brown was not the first to observe the phenomenon (Jevons 1878, 171). Jevons too claimed that his conclusion was the result of extended experimental investigations (Jevons 1870).

In looking for its cause, Jevons conducted observations and experiments to test the validity of the various available causal claims (i.e., claims in the sense of identifying a difference-maker). First to be tested and disproved was the claim, by Dancer and others, that the movement was caused or excited by light or heat falling on the liquid. Working with particles derived from substances such as kaolin (or China clay, as it was known at the time), road dust, and red oxide of iron suspended in distilled water, Jevons found that their vibratory movements were the same both in relative darkness and in intense sunlight. The movements showed no apparent change even when differently colored glass screens were interposed between the liquid and the sunlight (Jevons 1878, 172). He reached the same conclusion by means of a comparative experiment. Two suspensions of China clay in water were taken, with one placed in a dark environment and the other exposed to the sun's direct rays for 3 hours. He saw no difference in the rapidity of subsidence of the particles (Jevons 1878, 172). Regarding the influence of heat in particular, Jevons' conclusions were surprisingly opposite to those of previous researchers. He thought that the increase of temperature decreased the motion. Jevons perceived no difference in the movements of the suspended particles when he warmed the microscope plate. He then tried a comparative experiment. A mixture of charcoal-powder and boiled water was surrounded with ice, while a similar mixture in boiling water was maintained at 100 °C. At the end of the hour the heated mixture had deposited nearly all the charcoal, whereas the ice-cold water had as much in suspension after 8 hours. A similar experiment with suspensions of China clay gave similar results. Trying to explain these surprising results, Jevons surmised that they were produced by the increase of electrical conductivity of liquids caused by the rising temperature (Jevons 1878, 173).

Jevons called these comparative experiments "indirect," but not because he sensed a difference in their epistemic import compared with traditional experimental intervention, where the comparison is between the situation before and the situation after an intervention or variation of circumstance. He called them indirect because, rather than investigating the effect of light and heat on the vibratory movements, the comparative experiments looked at how these agents affected the particles' rate of subsidence. In other words, Jevons ascertained the association of pedesis with the suspension of particles in water and then performed comparative experiments investigating the influence of various factors on the particles' suspension, rather than on their movement.

The comparative experiments, however, differed from traditional experimental interventions (or variations) with respect to their epistemic role.[21] Jevons used the comparative experiments to investigate the longer-term effects of the change or variation of the suspected cause, as opposed to its instantaneous or immediate effects. This difference in epistemic role manifests in another (indirect) comparative experiment, which convinced Jevons that no causes external to the suspending liquid were involved in the production of pedesis. Trying to test the effect of light and heat, Jevons took a suspension of China clay in water and frequently heated it in fire for 2 days, allowing it to cool at various intervals. A similar suspension was sunk in sawdust that had been undisturbed for several years in a wine-cellar. After remaining for 52 hours in complete darkness at a constant temperature of 9 °C, the second preparation was found to contain more clay in suspension than the first, which had been moved and heated many times. Even after 7 days the buried preparation "showed a slight cloudiness" (Jevons 1878, 173).

Another time-sensitive question was whether pedetic motion exhausted itself rapidly or was retained for a long time. Jevons found that ink many months or even years old exhibited the motions clearly. A slow, distinct motion of suspended particles was observed in a drop of lees from a wine bottle that had been undisturbed in a wine-cellar for several years. The drop was placed under the thin glass cover of the microscope with the least exposure to air. The motion did not increase when some of the dregs were shaken in a bottle with air. The most surprising and conclusive fact of this investigation, however, came from a comparative experiment. Old mixtures of China clay and water were compared with fresh ones. Two glass tubes containing China clay and distilled water were laid in a drawer for a long period of time.

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[21] In her contribution to this volume, Schürch also discusses how eighteenth-century researchers investigating the influence of electricity on plant growth perceived the difference between comparative and intervention-based experimentation (see also Bernard 1856, 80–82).

The drawer was usually opened several times in a day, so the tubes would be shaken every now and then. Frequently the two tubes were shaken by hand. At long intervals the old tubes were opened and drops of the milky liquid were examined. Comparing the motion of the suspended China clay particles in the old mixtures with the motion of newly mixed particles found that "*no diminution of motion was apparent*; on the contrary, *the motion seemed to be even more remarkable than in a fresh mixture*" (Jevons 1878, 174; emphasis in original). This comparative trial lasted for 9 years and led Jevons to declare pedetic motion "the best approach yet discovered to perpetual motion" (Jevons 1878, 174).[22]

To investigate the relation of the movement with the shape of the particles, Jevons compared under a microscope "the fine needle-shaped particles of asbestos dust with the spherical globules of milk, the minute spheres of gamboge, the flat particles of talc, the small cubes of galena, and the wholly irregular fragments of glass." Given that all the differently shaped particles exhibited pedesis, he concluded that no particular shape was essential to its production. Contrary to Dancer, however, Jevons found that, *ceteris paribus*, sharp-pointed and irregularly shaped particles oscillated more quickly than spherically shaped particles (Jevons 1878, 173–74).

Jevons considered inconclusive all experiments rejecting the relevance of electricity for pedetic motion because external electrical currents applied to the liquid had no effect on the movements of the suspended particles. His conclusion that pedesis was caused by electricity was based on experiments that placed more weight on the variations of suspending liquid's chemical nature. He did not learn much by varying the nature of the suspended particles, finding that particles from substances of the most different chemical character exhibited similar pedetic motion (Jevons 1870, 78; 1878, 176). In varying the chemical nature of the liquid by dissolving various substances therein, however, he discovered that only the purest distilled water showed the movements in their highest perfection. With a few exceptions, all acids, alkalis, or salts tended to diminish the movement, but in a manner that was wholly independent of their peculiar chemical qualities and dependent only on their electric properties (Jevons 1870, 79; 1878, 179). More specifically, what convinced Jevons that pedesis was caused by electric action was the close analogy between his

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[22] In *Against Method* ([1975] 1993), Paul Feyerabend used the example of "Brownian motion" to support the claim that empirical facts are not simply "given" but that the description of every single fact depends on *some* theory; in addition, some empirical facts cannot be unearthed except with the help of alternative theories to the one being tested. More specifically, Feyerabend claimed that *without the introduction of the kinetic theory*: (a) it is not clear whether the relevance of Brownian motion for the phenomenological second law of thermodynamics could have been discovered, and (b) it is certain that it could not have been demonstrated that Brownian motion actually *refutes* the phenomenological second law (Feyerabend ([1975] 1993, 27). Jevons' longer-term comparative experiments show that the relevance of Brownian movement for the phenomenological second law could be perceived without considering the kinetic theory. In addition, as we show in this chapter, the nineteenth-century investigations of Brownian movement, which ended up demonstrating the persistence of the phenomenon despite the variation of the factors external to the suspending liquid, make it less certain that an experimental investigation of Brownian movement could not, by itself, pose a challenge to the phenomenological second law.

findings when varying the chemical nature of the liquid, and the circumstances in which electricity was produced by the hydro-electric machine. Only pure water produced the greatest amount of electricity in the hydro-electric machine, and almost any salt, acid, or alkali prevented production by rendering the water a conductor (Jevons 1870, 79–80).[23] Pure caustic ammonia, a substance that, remarkably, did not render water a good conductor and did not prevent the hydro-electric machine from giving electricity, was used in a crucial experiment. Jevons dissolved ammonia in water in different amounts and found that it had no effect on the movement of the microscopic suspended particles (1870, 79–80). He emphasized that his conclusions were based on a great number of experiments done with suspended particles from different substances, and they involved a great number of substances dissolved in the suspending water in various amounts. All the variations in the chemical nature of the suspending liquid, with only few "doubtful exceptions," showed that dissolved substances turning the water into a conductor also inhibited pedetic motion. Jevons distinguished his causal claims regarding the relevance of electricity for the phenomenon—which he regarded as more or less certain, because they were based on a large number of observations and experiments[24]—from his more speculative explanations regarding the mechanism of electric action on the suspended particles. More specifically, regarding the exact *modus operandi* of the electric action, Jevons speculated that it was probably connected with the phenomenon of electric osmose (Jevons 1878, 183).

In later experiments, Jevons used a solution of common soap to decide between the causal claim of electric action and the newly proposed claim that asserted that pedesis was caused by surface tension in water (Jevons 1878, 175; 1879). Soap could serve as a crucial substance for deciding between the two alternative claims because it reduces the surface tension of water in which it is dissolved without affecting its electric conductibility. If pedesis was caused by surface tension, reasoned Jevons, then the motion of the suspended particles would be destroyed or diminished when soap was dissolved in the suspending water. He tried the experiment with particles derived from China clay, red oxide of iron, chalk, barium carbonate, etc., and it gave the opposite result: the pedetic motion of the suspended particles appeared to increase. For Jevons the experiment constituted further proof that pedesis was a phenomenon of electric origin, appearing only in liquids of high electric resistance (Jevons 1879, 435).

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[23] "The analogy of these circumstances to those of pedesis is so remarkable that little doubt can be entertained that the same explanation applies. *It is perfectly pure water which produces electricity and pedesis.* Almost all soluble substances prevent both one and the other; but ammonia is one of a few exceptions—it allows both electric excitation and pedesis. Boracic acid is another exception, and gum a third one" (Jevons 1878, 182; emphasis in original).

[24] "My recorded observations amount to nearly eight hundred, and the solutions named were tried not only in different strengths, varying according to circumstances, from one part in ten to one part in a million, but they were tried with various suspended powders, such as charcoal, red oxide of iron, amorphous phosphorous, precipitated carbonate of lime, red oxide of lead, black oxide of manganese, and occasionally with other substances. I don't think, then, that I can be much mistaken in my chief conclusions" (Jevons 1878, 180).

Jevons' conclusions regarding the cause of pedesis were challenged, in turn, by William Ord. Ord preferred retaining the term "Brownian movement," because "everyone knows at once knows what is meant when Brownian movements are spoken of, and, what is of no little importance, the term is extensively used in the continent" (Ord 1879, 656). Although not aware of Jevons' experimental work before its publication, Ord claimed to have independently repeated and confirmed some of his experimental findings, such as the hindering action of acids on the movement of the suspended particles (Ord 1879, 658–60). While he admitted that heat, electricity, capillary action, water's surface tension, and chemical and other forces may each or all play a part in producing Brownian movements, Ord claimed its main cause to be "vibrations or intestinal disturbances in the colloid suspending fluid, such as attend its decomposition, or its metamorphosis or its resolution into a crystalloid" (Ord 1879, 658).[25]

This conclusion was based on reasoning similar to Jevons'. Ord found that the Brownian movements were more active and persistent under conditions that favored the activity of chemical changes in the suspending fluid; conversely, the movements were diminished or altogether stopped by introducing conditions that hindered such chemical reactions. Ord explicitly stated that he used, what Mill had recently named as, *the method of concomitant variations* and *the method of difference* to support his induction. Regarding the first, he found that "the concomitant variations set forth" showed "that the movement of particles is more or less active according to the presence in the surrounding fluid of conditions favouring or hindering chemical changes in the colloid" (Ord 1879, 660). Ord claimed he used the method of difference in studying mixtures of India-ink with distilled water.[26] When the solid ink was rubbed gently with water, a mixture of suitable thickness was obtained, consisting of particles of solid black matter suspended in water that was now dissolving the colloid matter binding the ink particles. On the other hand, when a large quantity of ink was rubbed with water, and the mixture left in a tall vessel to allow the subsidence of particles, the colloid matter was gradually washed away, leaving a mixture of particles with nearly pure water. When compared with particles of the same size and number in the first mixture, particles in the second showed less active and persistent movement (Ord 1879, 660).

Finally, Ord reinterpreted Jevons's experiments with solutions of soap in a way that supported his own conclusion. Whereas for Jevons introducing soap into the suspending fluid increased the movements of the suspended particles because soap retained or did not conduct electricity, for Ord it was a colloid that kept up the movements by revolutionary perturbations (Ord 1879, 660–61).

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[25] "To sum up…I claim the intestine vibration of colloids as in many cases an agent in the process, and more especially in the fluid and semi-fluid parts of animal and vegetable organisms" (Ord 1879, 662).

[26] "I may cite an experiment in which the method of difference gives results in the same direction" (Ord 1879, 660).

8.5 Brownian Movement and Atomic-Molecular Theories of Matter: Early Investigations

According to historian of science Mary Jo Nye, a major reason for the delayed connection of Brownian movement with a molecular conception of matter was that, until the second half of the nineteenth century, there was no atomic theory of matter capable of offering a suitable mechanism to causally connect the atomic-molecular structure of liquids with a phenomenon having the characteristics of Brownian movement. Atomic theories prior to the middle of the century offered a static conception of atoms that interacted with one another primarily through acting-at-a-distance attractive and repulsive forces (Nye 1972, 46; Gouy 1895, 5).

Nye is right to observe that the explanation of Brownian movement in terms of the molecular motions constituting the liquid state of matter required a molecular theory capable of offering a suitable mechanism explaining how the cause (molecular motions) produced the effect (observed Brownian movements). We should acknowledge, however, the complexity of the nineteenth-century relationship between the ability to make a causal claim regarding Brownian movement, and the ability to provide a causal explanation of it, as noted at the end of Sect. 3. So far, we have seen that most nineteenth-century investigators of Brownian movement began with the experimental strategy of varying the circumstances aiming to identify a difference-maker (i.e., a causal circumstance influencing the phenomenon). In a second step, some of them speculated about a (more or less) concrete mechanism that, by linking the difference-making circumstance with the observed Brownian movements, was responsible for the experimentally detected difference-making relationship. In the rest of the chapter, I examine some of the permutations of the relationship between causal claims and causal explanations emerging in the efforts to connect the observed Brownian movements with an atomic-molecular theory of matter during the second half of the nineteenth century.

The first to explicitly connect Brownian movement with an atomic theory of matter was Christian Wiener (1826–1896), professor of descriptive geometry and geodesy at the University of Karlsruhe. In fact, Wiener used the phenomenon of Brownian movement (*Molecularbewegungen*) to provide support for his atomic theory of matter (Wiener 1863). Wiener's atomic theory was a hybrid between the older static conception of atoms and the newer kinetic conceptions, which were beginning to emerge at the time. According to Wiener, matter is composed of matter atoms, which attract one another, and aether atoms, which repel one another. The aether atoms are found in the empty spaces between the mutually attracting matter atoms, with aether and matter atoms repelling each other (Wiener 1863, 79). The network of forces exerted between matter and aether atoms meant that matter was in a state of permanent vibration. *Molecularbewegungen*—the trembling motion of microscopic particles suspended in liquids—was then the result of the constant vibrational atomic motions constituting the liquid state of matter (Wiener 1863, 85). Wiener supported his causal explanation of Brownian movement not by providing independent (empirical) evidence for it, but by rejecting other alternative claims about the causal origin of *Molecularbewegungen*.

Lacking positive evidence for his atomic explanation, Wiener used the strategy of varying the circumstances to experimentally disprove, one by one, (all) other alternative causal claims (Wiener 1863, 86). First, Wiener argued, the motion could not be that of infusoria or caused by the vitality of the particles, because he could observe it in finely divided suspended particles derived from inorganic matter. To reject the possibility that the moving particles derived from inorganic substances were actually organic particles trapped in inorganic matter, Wiener annealed quartz particles and found that this had no effect on their movements when suspended in liquids. This same possibility was also excluded by the fact that all the suspended particles exhibited the movements, as opposed to just a few (Wiener 1863, 86). Second, the movement was not caused by mechanical or any other external influences communicated to the suspending liquid. The movements of the suspended particles were more like vibrations, and no one had ever observed such irregular, tremulous movements being caused by external influences. In addition, if the movements were caused by external influences, they ought to change or decrease with time. But Wiener's microscopy observations, made over many days, revealed an incessant movement showing no signs of decrease (Wiener 1863, 86). Third, the movement could not be caused by attractive or repulsive forces, electric or otherwise, between the suspended particles. This was because it was independent both of the number of particles present in the liquid and of the distances between them. Suspended particles in a dilute emulsion and in relatively large distances from one another exhibited the same trembling motion as that of many particles close together (Wiener 1863, 87). Fourth, the movement could not be caused from temperature differences between the different parts of the liquid. These temperatures differences would offset or decrease with time, whereas the main characteristic of the particles' trembling motion was its invariance through time. In addition, the temperature differences would produce currents from the surface to the interior of the liquid and could not explain the trembling motion of the particles, which constantly changed direction even in very small volumes. If the temperature differences were the cause of the trembling motion, the motion would have to increase its liveliness when the environment temperature was changed abruptly. But no changes in the movement were observed despite sudden temperature changes in the surrounding environment (Wiener 1863, 87–89). Fifth, the movement was not caused by evaporation, because evaporation usually takes place near the surface of the liquid, whereas Wiener's microscopy observations revealed that the movement of the suspended particles occurred at all levels of the liquid, and it continued in the same manner even when measures to preclude any evaporation were taken (Wiener 1863, 89–90).

In short, Wiener excluded all the plausible causal claims that could provide the empirical basis for an alternative causal explanation of Brownian movement. He did this by showing that the phenomenon remained invariant when each of the suspected causal factors was either varied or entirely excluded from influencing the phenomenon. He concluded that the exclusion of all these suspected difference-makers left no other explanation besides the one attributing Brownian movement to the vibration of the atoms constituting the liquid state of matter: "It remains nothing left but for us to seek the cause [of the phenomenon] in the liquid, and *to ascribe it to the movements constituting the liquid state*."[27]

Another investigator who connected Brownian movement with a mechanical theory of heat was Giovanni Cantoni, professor of experimental physics at the University of Pavia (Cantoni 1867). Cantoni's investigations on the phenomenon, like those of Botto, were ignored by his contemporaries and rediscovered only by the efforts of the historian Icilio Guareschi in the beginning of the twentieth century (Guareschi 1913).[28] Cantoni saw in the phenomenon of Brownian movement (*moto Browniano*) the confirmation of a mechanical theory of heat.

For Cantoni, the heat of a body consists in the vibratory movements of its constituent molecules. Every chemical substance, at a given temperature, has a characteristic vibratory motion of its constituent molecules. This was macroscopically indicated by the fact that different amounts of heat are required to increase by the same degree of temperature the same weight of different substances (i.e., by the existence of the different substances' specific heats).

According to Cantoni's proposed explanation, Brownian movement was caused by the different molecular velocities that must exist at the same temperature between the molecules constituting the solid suspended particles, on the one hand, and the molecules of the suspending liquid hitting the suspended particles from every direction, on the other.[29] Cantoni argued that this explanation could be experimentally tested and positively confirmed: *ceteris paribus*, Brownian movements ought to be livelier the greater was the difference between the velocities of the molecules constituting the solid particles from the velocities of the molecules constituting the suspending liquid. At the macroscopic level, the difference between the molecular velocities of different substances was simply the difference between their specific heats (Cantoni 1867, 163). If the difference between molecular velocities was the real cause of Brownian movements, then varying the difference between the specific heat of the suspended particles and the specific heat of the suspending liquid ought to bring a corresponding variation in the intensity of Brownian movements. Cantoni claimed that his numerous experiments, performed with various suspended particles and suspending liquids, showed that this was indeed the case. For example, particles derived from the same substance moved far more intensely in water than in alcohol. Because alcohol has a lower specific heat than water, there was a smaller difference between the specific heat of the suspending liquid and that of the suspended

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[27] "[E]s bleibt uns daher Nichts übrig, als die Ursache in der Flüssigkeit an und für sich zu suchen, und sie *inneren dem Flüssigkeitzsustande eigenthümlichen Bewegungen zuzuschreiben"* (Wiener 1863, 90, emphasis in original).

[28] According to Guareschi (1913, 50), Cantoni was the first to clearly discover the true cause of the phenomenon.

[29] "Ebenne, io penso che il moto di danza delle particelle solide estremamente minute entro un liquido, possa attribuirsi alle differenti velocità che esser devono ad una medesima temperatura, sia in codeste particelle solide, sia nelle molecole del liquido che le urtano d'ogni banda" (Cantoni 1867, 163).

particles. Following similar reasoning, one could explain why the Brownian movement of identical particles was even less marked in gasoline and ether than in water (Cantoni 1867, 163–67). All this evidence, according to Cantoni, led to the conclusion that the cause of the phenomenon resided in the different velocities the molecules of different substances have at the same temperature. From here Cantoni inferred that the existence of Brownian movement provided one of the most beautiful and direct experimental demonstrations of the fundamental principles of the mechanical theory of heat, manifesting the assiduous vibratory state that must exist both in liquids and solids, even when their temperature does not change.[30]

Wiener's atomic explanation of Brownian movement was based on the rejection of all other alternative causal claims. For Wiener, the rejection of all possible macroscopic difference-makers left no other explanation than the one attributing the movement of suspended particles to the vibratory movements of aether and matter atoms. These movements, according to Wiener's atomic theory, constituted the liquid state of matter. Embedded as it was in an idiosyncratic theory of matter that had no independent empirical evidence in its favor, Wiener's explanation was deemed inadequate. Cantoni, on the other hand, explained Brownian movement in terms of the different molecular velocities that, according to his molecular theory of heat, must exist at the same temperature between the molecules of the suspended particles and the molecules of the suspending liquid. In contrast with Wiener's, Cantoni's explanation manifested itself in a macroscopic difference-making relationship that could be experimentally manipulated to provide empirical support. Cantoni's work, however, did not receive any attention and thus had no influence on subsequent research (Guareschi 1913). To my knowledge, even the difference-making relationship detected by Cantoni was not replicated by anyone else. One possible reason for the neglect of Cantoni's explanation may have been his peculiar mechanical theory of heat, which contradicted some of the basic tenets of the newly developed and more successful kinetic-molecular theory (see next section). The main obstacle facing all (kinetic-) molecular explanation of Brownian movement during this period, however, was the emergence of arguments challenging the adequacy of the hypothesized molecular motions to cause a phenomenon with the observable characteristics of Brownian movement (Nye 1972, 23; Nägeli 1879; Ramsay 1882).

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[30] "Ora tutti gli esposti particolari concorrano alla deduzione, che la condizione fisica del moto browniano stia nella diversa velocità che hanno le molecole dei corpi differenti sotto una stessa temperatura. E di tal modo il moto browniano, così dichiarato, ci fornisce una delle più belle e dirette dimostrazioni sperimentali dei fondamentali principii della teoria meccanica del calore, manifestando quell' assiduo stato vibratorio che esser deve e nei liquidi e nei solidi ancor quando non si muta in essi la temperatura" (Cantoni 1867, 167).

8.6 Brownian Movement and the Kinetic-Molecular Theory of Matter

In this section, I examine the reasoning of the researchers who first explicitly connected the phenomenon of Brownian movement to the thermo-dynamic motion of molecules, as proposed in the recently developed kinetic theory of gases. These were a group of Jesuit scholars associated with the journal *Revue des questions scientifiques*, published by the Scientific Society of Brussels (Nye 1976). These proponents of the kinetic-molecular explanation did not start by varying the circumstances to exclude alternative causal claims and/or identify difference-makers. They tried to show that that the tenets of the kinetic-molecular conception of matter, which were developed independently to explain a different range of observable phenomena—namely the macroscopic behavior of gases and liquids—could give a causal explanation for the altogether different phenomenon of Brownian movement. The ability of the kinetic-molecular theory to account for a range of unrelated phenomena and experimental evidence was used to "control" its validity as well as the validity of the offered explanations.[31]

The first explicit connection of Brownian movement with the kinetic theory of gases was made by Father Joseph Delsaulx, a Brussels-born Jesuit, in a paper whose aim was to show "that all the Brownian motions of small masses of gas and of vapour in suspension in liquids, as well as the motions with which viscous granulations and solid particles are animated in the same circumstances, proceed necessarily from the molecular heat motions, universally admitted, in gases and liquids by the best authorized promoters of the mechanical theory of heat" (Delsaulx 1877, 2).

Delsaulx gave a detailed account of how the invisible molecular motions, postulated by the kinetic theory of heat to explain the macroscopic behavior of gases, would cause the dancing movement of microscopic particles suspended in liquids. More specifically, it followed from the principles of the mechanical theory of heat that a favorable concourse of the movements of oscillation, rotation, and translation of the molecules of the suspending liquid would, by necessity, produce a pressure of an exceptional intensity at isolated points on the surface of a suspended particle. These pressures were averaged out in particles of larger dimensions, but not in the microscopic dimensions of Brownian particles. They were thus the real cause of the particles' continuous oscillatory motions (Delsaulx 1877, 3–6). "All these [Brownian] movements," Delsaulx concluded, "result from the interior dynamic state that the mechanical theory of heat attributes to liquids, and are a remarkable confirmation of it" (Delsaulx 1877, 5).

The kinetic-molecular explanation of Brownian movement could make sense of the phenomenon's observed features: Brownian movement is more active in heated liquids than in those of a low temperature; supposing equal diameters, the oscillatory displacement is more rapid and more extended in fatty granulations than in

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[31] This way of reasoning is similar to that which we encounter in William Whewell's (1847, 1858) notion of the *consilience of inductions*. See also Coko (Forthcoming).

metallic granulations, whose density is very great; and the duration of the phenomenon may be said to be without limit, because it has been observed in gas-bubbles imprisoned in microscopic (liquid-filled) cavities of quartz for supposedly millions of years (Delsaulx 1877, 2).

In a lengthy 1880 paper, another Belgian Jesuit, Julien Thirion, similarly argued that Brownian movement could be easily explained by the mechanical theory of heat. According to that theory, explained Thirion, all bodies are composed of molecules in a perpetual state of motion. Although these molecular motions cannot be directly observed, various phenomena and surprising experimental facts could be easily explained by appeal to their existence (Thirion 1880, 6). For instance, the new and surprising experimental facts established in William Crookes' experiments on cathode rays could be readily explained by the tenets of the kinetic-molecular conception of gases, as proposed in the mechanical theory of heat. What made this explanation even more remarkable, Thirion claimed, was the fact that the kinetic-molecular conception of gases was originally developed to explain a totally different range of phenomena—the macroscopic behavior of gases. The simplicity with which the kinetic-molecular conception accounted for these unexpected facts, the fruitfulness of the insights it suggested, and the variety of evidence it predicted and explained gave the conviction that one was not mistaken in taking it as a guide.[32]

Thirion used Brownian movement as another example of a surprising phenomenon that could be explained by the tenets of the mechanical theory of heat. Thirion explained that the theory predicted that sufficiently small particles suspended in water would be in a state of permanent oscillation. According to the mechanical theory of heat, the surface of a solid body suspended in a liquid is continually and unequally bombarded by the movement of the unobservable molecules constituting the liquid state of matter. In large particles with sufficiently large surfaces, the inequalities of molecular collisions would compensate for one another. In these particles, therefore, despite their high irregularity, the molecular collisions would produce no visible effects. In very small particles, however, surfaces would be sufficiently small that irregularities could not be compensated for. The result would be that the total pressure exerted at any moment from the molecular collisions would no longer be zero, but would vary continuously in intensity and direction. The particle's center of gravity would be continuously displaced and so the particle would oscillate continuously. The inequalities in pressure and the resulting oscillations would be more and more apparent the smaller the suspended particles were (Thirion 1880, 43–45). For Thirion, the phenomenon of Brownian movement was a remarkable empirical verification of this prediction by the kinetic-molecular conception of liquids. What made the prediction even more remarkable was the fact that the

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[32] "Si cette science maîtresse avait encore besoin de preuves, il nous semble qu'elle les trouverait ici solides et nombreuses. La simplicité avec laquelle elle rend compte de ce grand nombre de faits inattendus, la fécondité des aperçus qu'elle suggère, la variété des détails qu'elle prévoit et qu'elle explique, donnent à l'esprit la conviction qu'il ne s'est point fourvoyé en la prenant pour guide" (Thirion 1880, 39).

molecular conception of liquids was not developed to accommodate this kind of phenomenon. It was a happy coincidence that such a phenomenon could be detected experimentally.[33]

8.7 Brownian Movement and the Kinetic-Molecular Theory of Matter: Controlling the Evidence and the Kinetic-Molecular Hypothesis

The French physicist Louis Georges Gouy (1854–1926) is credited as the first to firmly connect Brownian movement with the molecular motions postulated by the kinetic-molecular theory of matter.[34] In this section, I show that Gouy's success stems from the fruitful combination of the experimental strategy of varying the circumstances with the theoretical and hypothetical reasoning on the causal origin of the phenomenon. More specifically, Gouy (a) used the invariance of Brownian movements to the variation of various suspected factors to reject claims identifying the cause with influences external to the suspending liquid, and (b) showed how hypotheses regarding the internal constitution of liquids—which were developed independently in the context of the kinetic theory of matter, and which were already employed successfully to explain various phenomena—were sufficient to explain the experimental facts of Brownian movement.

Gouy performed many experiments on the phenomenon during the late 1880s and was able to conclusively establish its essential features. He presented his results in a short note published in the *Journal de Physique* (Gouy 1888). He claimed that Brownian movement was characteristic of all microscopic solid particles suspended in liquids. Initially he worked with suspensions of gamboge and China ink in water. The water-drop containing the particles was covered with a slip, and the preparation was enclosed with paraffin to avoid evaporation and external influences. Using an immersion lens, Gouy observed a striking trembling motion of the suspended particles. Every particle seemed to move independently of its neighbors, and experienced a series of displacements difficult to describe because they were

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[33] "[C]e ne sont pas des phénomènes qui se présentent à nous et qu'il faut expliquer, *ce sont des conséquences d'une théorie édifiée pour expliquer d'autres phénomènes.* Si l'expérience venait à montrer que ces conséquences ne se vérifient pas, il en faudrait conclure que la théorie est au moins inexacte, peut-être tout à fait erronée. *Heureusement* l'expérience fait tout le contraire" (Thirion 1880, 41–42, my emphasis). In addition, "Tous ces faits, observés par R. Brown, peuvent vraiment être considérés comme une vérification anticipée d'un théorème trouvé un demi-siècle plus tard" (Thirion 1880, 50).

[34] "On the contrary, it was established by the work of M. Gouy (1888), not only that the hypothesis of molecular agitation gave an admissible explanation of the Brownian movement, but that no other cause of the movement could be imagined, which especially increased the significance of the hypothesis. This work immediately evoked a considerable response, and it is only from this time that the Brownian movement took a place among the important problems of general physics" (Perrin 1910, 4–5). See also Poincaré (1905, 199).

essentially irregular. In particles with elongated form or some mark in their surface, Gouy detected an irregular rotational movement. The movements were more vivid the smaller the size of the particles, they increased with temperature, and they were more active in less viscous liquids (Gouy 1888, 561–62).

The careful observation of the phenomenon left no doubt, according to Gouy, that the movements were not the result of vital forces, external vibrations, temperature differences, or other accidental currents in the liquid. Rather, they were a normal phenomenon, occurring at a constant temperature, and attributable to the internal constitution of liquids. The independence of the movements from the nature of the particles; their irregular nature; their persistence in time even when precautions to exclude all external influences were taken—all of these results showed the cause to be the internal agitation of the liquid. Brownian movement provided a "direct and visible" proof of the molecular-kinetic hypotheses regarding the nature of heat: "Brownian movement, therefore, shows us, of course not the movement of molecules, but something very close to it, and it provides us a direct and visible proof of the correctness of current hypotheses on the nature of heat. If one adopts these views, the phenomenon, whose study is long from over, surely takes a higher order of importance for molecular physics."[35]

Gouy's (1889, 1895) next two papers on the topic present his experimental strategy and theoretical reasoning in more detail. He experimentally identified the phenomenon's essential characteristics and inquired into its causal origins. Brownian movement, he remarked, was essentially irregular and seemed to be governed only by chance. It consisted in a series of little impulses that were oriented indistinguishably in all directions and that were not subject to any law. The movement was a sort of oscillation in place, although in the long run it could produce noticeable displacements in a suspended particle's position. The rapidness and amplitude of the movement depended above all on the size of the particles, becoming greater as the particles got smaller. The movement was not influenced by the form, the state, or the chemical and physical nature of the suspended particles. It was more intense in suspending liquids with greater degrees of fluidity. Although the movement was irregular, with each particle moving independently of its neighbors, the phenomenon as a whole had an obvious regularity, in that it was always found exhibiting the same essential characteristics (Gouy 1895, 2–3). Gouy claimed that he had observed the movements under the most varied conditions using liquids and particles with different chemical and physical properties, but did not notice any difference in its essential features.[36] Regarding the question of the causal origin of Brownian

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[35] "Le mouvement brownien nous montre donc, non pas assurément les mouvements des molécules, mais quelque chose qui y tient de fort près, et nous fournit une preuve directe et visible de l'exactitude des hypothèses actuelles sur la nature de la chaleur. Si l'on adopte ces vues, le phénomène, dont l'étude est loin d'être terminée, prend assurément une importance de premier ordre pour la physique moléculaire" (Gouy 1888, 563).

[36] "Les observations ont été faites avec des particules minérales ou organiques, solides ou liquides, en suspension dans des liquides variés, eau, solutions aqueuses, acides, alcools, éthers, carbures d'hydrogène, essences, etc. D'autres observations ont été faites sur les bulles gazeuses que renfer-

movement, Gouy was explicit that it "can only be answered by a detailed study of the phenomenon, under the most varied circumstances possible, by striving to reduce or increase at the outmost limits the external causes of agitation and examining the resulting effects."[37] That is, the question could be answered only using the varying-the-circumstances strategy.

First, Gouy claimed that it was easy to show that Brownian movement was not of a vital nature, because it had been observed in liquids where no living entity could exist: toxic substances, acids, and the strongest alkalis never stopped the movements. Indeed, temperatures high enough to destroy life increased the movements instead of stopping them (Gouy 1895, 2). Second, the phenomenon's generality, and the fact that it seemed to last indefinitely—it appeared in air bubbles suspended in liquids in cavities of quartz crystals for thousands of years—was sufficient to show that it was not attributable to any external and accidental causes. For those must act with a varying intensity depending on the circumstances (Gouy 1889, 103). To establish this last point decisively, however, Gouy conducted several rigorous experiments. To test claims about the causal origin of Brownian movement, Gouy examined how its essential characteristics changed while varying or excluding the different suspected causes. His detailed descriptions show the effort toward controlling the influence of disturbances external to the suspending liquid. The first claim to be tested was whether the Brownian movements were caused by external vibrations communicated to the suspending liquid, or undetected tremors coming from the ground. To avoid external disturbances, he installed the microscopy apparatus in a basement away from any source of agitation. To control for ground tremors or any external vibrations, he placed a basin of mercury next to the apparatus. The mercury's surface acted as a perfect mirror of extreme sensibility for detecting the slightest disturbances. While the mercury remained undisturbed, the Brownian movement continued showing its usual characteristics and intensity; the movement did not increase significantly when external disturbances were noticeable. Based on similar, often repeated, experiments Gouy concluded that external vibrations or ground tremors were not causes of the phenomenon (Gouy 1889, 103–4; 1895, 4).

The second claim to be tested was whether the Brownian movements were caused by currents in the liquid as a result of temperature differences. Gouy reduced these currents by immersing the preparation in a water trough, which ensured the attainment of a uniform temperature. He used an immersed lens for observation and saw no variations in the Brownian movement of the suspended particles during the

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mement les inclusions liquides fréquentes dans certains quartz, et qui sont animées d'un mouvement tout à fait comparable à celui des particules solides ou liquides…. Le point le plus important est la régularité du phénomène des milliers de particules ont été examinées, et, *dans aucun cas*, on n'a vu une particule en suspension qui n'offrît pas le mouvement habituel, avec son intensité ordinaire, eu égard à la grosseur de la particule" (Gouy 1889, 103, my emphasis). See also (Gouy 1895, 2–3).

[37] "A la question ainsi posée, on ne peut répondre que par l'étude détaillée du phénomène, dans des conditions aussi variées que possible, en s'efforçant de réduire ou d'augmenter dans les limites le plus étendues les causes extérieures d'agitation, et examinant les effets produits" (Gouy 1895, 4).

entire procedure. In addition, currents in the liquid produced coordinated movements of adjacent Brownian particles, but they looked nothing like the individual vibrations constituting Brownian movement (Gouy 1889, 104; 1895, 4).

A third claim was whether the light required for the microscopy observations, affected the particles as it passed through the liquid—by heating them unequally, for example. The individual vibrations of the particles would then be the result of such temperature differences. To test this claim Gouy varied the nature and the intensity of light used to illuminate the preparation, and observed no difference in the particles' movements. Light, he concluded, played no perceptible role on Brownian movement (Gouy 1889, 104; 1895, 4–5).

Fourth, Gouy contended that other hypothetical causes, such as terrestrial magnetism and electric currents, had no influence on Brownian movements. For he observed no variation when placing the preparation in an electromagnetic field or when applying electric currents. The only agent to influence the movement was heat. At temperatures of 60° to 70 °C, the movement was a little more noticeable than at temperatures (Gouy 1889, 4; 1895, 5).

Gouy explicitly used the term "control" to indicate that his observations and experimental results could be easily verified independently and were, therefore, independent of any theoretical idea and interpretation:

> These observations which are easy to control, seem to establish as experimental facts and apart from any theoretical idea: *1st that Brownian movement occurs with any kind of particles, with an intensity that is the lesser the more the liquid is viscous and the more the particles are larger; 2nd that this phenomenon is perfectly regular, it occurs at a constant temperature and in absence of any external cause of movement*. (Gouy 1889, 104–5)[38]

Leaving the solid ground of observation and experiment, Gouy entered the second part of his argument, which relied on hypothetical and theoretical reasoning for the causal origin of Brownian movement. Theories and hypotheses, contended Gouy, have been abused and slandered, but their importance for scientific inquiry is indisputable. They may shed unexpected light on many questions. In addition, the history of the physical sciences showed that theoretical speculations have been the source of the finest discoveries and the greatest progress. The use of hypotheses was thus legitimate as long as they were used cautiously and *controlled* by empirical evidence: "Let's give them their due, the consideration deserved by eminent services, and that limited confidence that never sleeps and does not neglect any means of control."[39]

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[38] "Ces observations qu'il est facile de contrôler, paraissent établir comme faits d'experiénces et en dehors de toute idée théorique: *1° que le mouvement brownien se produit avec des particules quelconques, avec une intensité d'autant moindre que le liquide est plus visqueux et les particules plus grosses; 2° que ce phénomène est parfaitement régulier, se produit à température constante et en absence de toute cause du mouvement extérieur*" (Gouy 1889, 104–5, emphasis in original).

[39] "Accordons leur ce qui leur est dû, la considération que méritent des services éminents, et cette confiance limitée qui ne s'endort jamais et ne néglige aucun moyen de contrôle" (Gouy 1895, 5).

Gouy argued that the cause of Brownian movement, which lasted indefinitely without an apparent cause, should not be sought in the nature of the particles or in any external factors. Rather it was to be found in the constitution of the suspending liquid itself. In fact, the hypotheses made in the context of the modern kinetic theory of matter were directly related to the phenomenon's explanation. More specifically, "the kinetic theory could make us predict this phenomenon, and it *explains* it to us in its essential features" (my emphasis).[40]

After showing how the kinetic-molecular hypotheses could explain the experimentally determined features of Brownian movement, Gouy conceded that the kinetic-molecular explanation faced a problem of underdetermination. It assumed that there were no unknown causes of which the Brownian movement could be an effect. He maintained, however, that supposing such causes was unnecessary if the kinetic-molecular hypotheses were sufficient to explain it. In addition, the hypotheses were not entirely beyond all means of control. They had already led to considerable insights about a variety of physical and chemical phenomena.[41] Among the successes of the kinetic theory Gouy listed the molecular explanations for heat and radiation. Furthermore, agreement on the numerical values for molecular dimensions, obtained by diverse theoretical methods, gave the kinetic theory's claims an aura of plausibility.[42]

To sum up, Gouy used the experimental strategy of varying the circumstances (a) to identify the essential characteristics of Brownian movement, (b) to identify macroscopic difference-makers that influenced its intensity—heat and the size of the Brownian particles—and (c) to exclude other factors as possible causes. The strategy left kinetic-molecular motions as the only plausible explanation. Although he admitted the problem of underdetermination, Gouy appealed (a) to the ability (or necessity, as Gouy saw it) of the kinetic-molecular motions to produce a phenomenon with the observable characteristics of Brownian movement and (b) to the plausibility of the kinetic-molecular conception of matter, given its ability to explain a variety of other phenomena. These arguments made unnecessary the appeal to other (unknown) causal factors and thus eased the underdetermination problem.

This summary of Gouy's reasoning helps us to make sense of his contention that "Brownian movement provides us with what the kinetic theory of matter was lacking: a direct experimental proof. No doubt, we cannot observe, and we will never be

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[40] "La théorie cinétique pouvait nous faire prévoir ce phénomène, et elle nous l'explique dans ses traits essentiels" Gouy 1895, 7).

[41] "La théorie cinétique de la matière a conduit à des aperçus fort intéressants sur un certain nombre de phénomènes physiques et chimiques, et la part qu'elle a prise dans l'œuvre scientifique de notre époque est déjà considérable" (Gouy 1895, 6).

[42] "C'est aussi la conclusion à laquelle sont arrivés par d'autres voies les physiciens qui ont essayé de se faire une idée des dimensions moléculaires. Par des méthodes diverses, assez concordantes pour qu'on leur accorde crédit, ils sont arrivés à évaluer l'intervalle des molécules dans les liquides à la millième partie environ des dimensions des plus petits corps visibles au microscope. Il faudrait donc environ un milliard de molécules pour former le poids d'une de plus petites particules sur lesquelles nous observons le mouvement brownien" (Gouy 1895, 7).

able to observe the molecular movements; but at least we can observe something which results directly from them and necessarily indicates an internal agitation of bodies."[43]

This synthesis of experimental and theoretical modes of reasoning was perfected in Jean Perrin's (1870–1942) experimental work, which established molecular motions as the *proper and unique* cause of Brownian movement. Perrin determined by means of multiple, independent experiments that the internal motions of the liquid causing the experimentally established characteristics of Brownian movement were identical with the molecular motions postulated in the kinetic theory of matter (Coko 2020a). The multiple determination of molecular magnitudes proved to be the ultimate criterion for "controlling" the veracity of the kinetic-molecular explanation of Brownian movement.

8.8 Summary and Conclusions

In this chapter, I have argued that there was important and sophisticated experimental work done throughout the nineteenth century to investigate the characteristics and causal origin of Brownian movement. Investigators followed as rigorously as possible the methodological standards of their time to make causal claims and formulate causal explanations. They used two distinct methodological strategies.

The first was the experimental strategy of varying the circumstances. Suspected causal factors were varied to study the resulting effect on Brownian movements. The main goal of this strategy was to identify difference-making factors (i.e., factors having a causal influence on the phenomenon). All factors that could be varied without influencing the suspended particles' movement were excluded from playing a causal role in its production. On the other hand, all factors whose variation influenced the phenomenon were considered to have a causal role. The identification of a difference-making factor was sometimes followed by theoretical speculation about the concrete mechanism linking the difference-making factor with the observed movements.

This strategy was already implemented in the earliest identifications and investigations of the phenomenon—at first implicitly, and later, when the initial observations were challenged or led to conflicting results, more explicitly. The varying-the-circumstances strategy involved three notions of control: (1) control over the factor to be varied, (2) control over the rest of the factors which had to remain constant, and (3) control in the sense of comparing the situation with the varied factor to the experimental situation without it. We can distinguish two types of experimentation employing this strategy. First, there was "classic" (or direct)

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[43] "[L]e mouvement brownien nous fournit ce qui maquait à la théorie cinétique de la matière: une preuve expérimentale directe. Sans doute, nous ne voyons pas et nous ne verrons jamais les mouvements des molécules; mais nous voyons du moins quelque chose qui en résulte directement et suppose d'une manière nécessaire une agitation interne des corps" (Gouy 1895, 7).

experimental intervention, where the comparison was between the situation before and the situation after the intervention (or variation of the investigated factor). Second, there was comparative experimentation, where the comparison was between two distinct experiments that were made to vary only with respect to the investigated factor. Although no distinctions between these two types of experimentation were made with respect to their underlying rationale and epistemic import, the second kind was used to investigate effects of longer duration, as opposed to instantaneous and immediate effects. It was also used in cases where direct intervention was not possible.

Using the varying-the-circumstances strategy did not lead to consensus regarding the essential characteristics and causal origin of Brownian movement. Disagreements revealed the importance of another notion of "control": that of the verification of experimental findings by other researchers, preferably independently from one another. Because most claims regarding the causal origin could not be verified independently, the strategy succeeded more in excluding various suspected factors as causes than in establishing a positive causal claim. Brownian movement proved to be what we would call today a *robust phenomenon*, remaining invariant to the variation of most experimental factors that the experimenters could directly vary and control. Today, with hindsight, we know why. Even when the causal influence of some factor, such as heat or particle size, made a difference for the observed movements, and received independent confirmation, investigators disagreed on the causal explanation offered. That is, they disagreed over how to describe the concrete mechanism responsible for the difference-making relationship.

The second strategy was the hypothetico-deductive strategy or *method of hypothesis*, recognized during the nineteenth century as the proper approach for validating explanatory hypotheses regarding unobservables. Rather than starting or relying exclusively on experimental work to identify difference-making factors or exclude alternative causal claims, its proponents tried to show that the tenets of the recently developed kinetic-molecular conception of matter provided a natural explanation for the essential characteristics of Brownian movement. What was remarkable about this explanation, researchers claimed, was the fact that the elements of the theory explaining Brownian movement were developed independently to explain an entirely different range of observable phenomena—the macroscopic behavior of gases and liquids. Seen in this vein, the existence of Brownian movement provided unexpected empirical evidence for the kinetic-molecular conception of matter. The ability of the kinetic-molecular theory to account for a range of unrelated phenomena and experimental evidence was therefore used to "control" its validity as well as the validity of the offered explanation.

Neither methodological strategy could, on its own, establish molecular motion as the cause of Brownian movement. It was only the combination of the two and their accompanying notions and practices of control that led, at the end of the nineteenth century, to the recognition of molecular motion as the most probable cause of the phenomenon. From then on, the main goal of experimental investigation on Brownian movement became that of evaluating and probing the validity of the kinetic-molecular explanation. This shift in goals wrought changes in the experimental strategies for establishing the validity of claims about unobservable entities and processes such as molecules and molecular motion. These changes also changed the understanding of what is meant by "rigorous" experimental research.

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Klodian Coko is a postdoctoral fellow in the Philosophy Department at the Ben-Gurion University of the Negev. His research focuses on the historical emergence and development of scientific methods and experimental practices.