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MARIAN SMOLUCHOWSKI'S CONTRIBUTIONS TO THE PHILOSOPHY OF CAUSATION*

Abstract. Marian Smoluchowski was a prominent Polish physicist whose greatest achievement was the development – independently of Albert Einstein – of the mathematical theory of Brownian motion. In his theoretical view of the problem of Brownian motion Smoluchowski employed the concept of causal relevance, which was never analysed in numerous publications devoted to his scientific achievement. In this article I am attempting to demonstrate that the concept of causal relevance which Smoluchowski employed in his works devoted to the issue of Brownian motion may be interpreted as analogous to the concept of causal relevance articulated by Max Kistler. I present a number of arguments which demonstrate that just such a concept of causal relevance was established by Smoluchowski. Since the explanation of the phenomenon of Brownian motion presented by Smoluchowski has been universally accepted, so in the same way the physicalistic concept of causal relevance has been widely propagated. In this I detect Smoluchowski's contribution to the philosophy of causality.

Keywords: Marian Smoluchowski, causality principle, Brownian motion, causal relevance, transference theory.

1. Introduction

In his scientific publications Marian Smoluchowski (1872–1917) didn't

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take on the issues of causality directly, but attempting to explain the phenomenon of Brownian motion causally, he assumed a specified concept of causal relevance. This concept also appears in his articles devoted to the statistical laws of the kinetic theory of gases, but only in a few works devoted to the philosophical aspects of Smoluchowski's scientific heritage was there any attempt to mention his contributions to the philosophy of causation[1].

2017 was designated by the Polish Physical Society as Smoluchowski Year. During the first half of this year many events took place under the auspices of this initiative, *inter alia* the magazine *Philosophical Problems in Science* published an edition specially devoted to Marian Smoluchowski's philosophy of physics. This edition contained a number of Smoluchowski's works which up to now could be found only in manuscript. However, the concept of causal relevance, which nevertheless was not reconstructed and analysed in discussions from the scope of the philosophy of causality, was implicitly established in earlier published works by Smoluchowski. The issue of Marian Smoluchowski's contribution to the concept of causal relevance was not tackled in the same way.

The aim of this article is to interpret the concept of causal relevance established by Marian Smoluchowski in his scientific works devoted to the issue of Brownian motion. The realisation of this aim will be preceded by the introduction of one of the foremost contemporary, physicalistic, concepts of causal relevance. This concept was articulated by Max Kistler, but it has its sources not only in numerous works by contemporary philosophers (among others P. Dowe, J. Aronson, and D. Fair), but also in the works of 19th century philosophers (among others A. Bain, A. Lalande, and W. Wundt)[2]. My claim is that the physicalistic concept of causal relevance in his physics–related works, especially in fact in his works on the subject of Brownian motion, were established by Marian Smoluchowski. The aim of the attempt to interpret the concept of causal relevance contained in Smoluchowski's works with the help of the achievements of contemporary philosophers is to capture Smoluchowski's achievements in relation to contemporary research into the issues of causality[3].

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[1] See P. Forman, *Weimar Culture, Causality ...* , p. 67 & J. D. Struik, *On the Foundations of the Theory of Probabilities*, pp. 69–70. About Smoluchowski's achievements we may find very interesting comments on the origins of modern probability in J. von Plato, *Creating Modern Probability ...* , p. 104, pp. 130–132, pp. 140–141, and esp. pp. 171–173. In this context it is worthwhile to cite the words of S. Ulam, *Marian Smoluchowski and the Theory of Probabilities in Physics*, p. 242: *It is interesting, even today, to reread some of Smoluchowski's general speculations on the idea of chance and the origin of principles of the theory of probability in physics and then follow the subsequent development of ideas in this direction.*

[2] Max Kistler's physicalistic concept of causal relevance is a certain version of the materialistic concept of causal relevance, which has many more precursors, among them H. Helmholtz, M. Planck, A. Mittasch, M. Hartmann, F. Martius, K. Lorentz. See W. Krajewski, *Energetic, Informational, and Triggering Causes*, p. 194. See also I. Drouet, *Causal reasoning ...* , p. 761: [...] *the epistemology of causation may depend on its metaphysics and, further, that pluralistic positions concerning the metaphysics of causation may lead to incoherent epistemologies*.

[3] See Ph. Illari & F. Russo, *Causality ...* , p. 3: *Most recently, there has been an explosion of literature on causality, developed on connection with the fascinating problems of causality that arise developed constantly with the practice of the sciences*. My task is also empirical analysis in the sense established by Phil Dowe. According to P. Dowe, *Physical causation*, p. 3 & p. 11: [...] *empirical analysis seeks to establish what causation in fact* is *in*

The article will consist of two parts. The first part will present Max Kistler's view on causal relevance based on the idea that causation can be reduced to transmission of an amount of some conserved quantity between events as well as the sources of this concept. The second part will talk about the concept of causal relevance established by Marian Smoluchowski in his works devoted to the issue of Brownian motion.

2. Max Kistler's concept of causal relevance and its sources

The idea according to which the essence of causal relevance is the influence of one material body on another appeared together with the modern concept of causality. Such a concept of causal relevance was explicitly developed by Thomas Hobbes, but he employed a very general category of motion, not yet having at his disposal such physical ideas, developed later, as energy and momentum[1]. Together with the explanation of the idea of energy by Robert Mayer, later actually called the Law of the Conservation of Energy or the First Principle of Thermodynamics, the possibility of grasping the essence of causal relevance presented itself with the help of strictly physical categories. As early as the second half of the 19th century such philosophers as Alexander Bain (1818–1903) attempted to define the concept of causal relevance with the help of the principle of energy (force) conservation[2]. Talking about the Law of Causation, Bain notes that [t]*he Law of Uniform Causation appears in a form still more pregnant with consequences, namely, the Law of Persistence, Conservation, Correlation, or Equivalence of Force*[3]. As antecedents of this view he names Galileo and Newton, as well as Lavoisier, who introduced the law of conservation of mass.

By the way updating his view, he attaches to the law of force conservation other influences (forces) such as chemical and electrical, which in his opinion also fall under the law of conservation, since they can be neither created nor destroyed. Apart from specific scientific laws Bain highlights a more general law which he calls the Law of Causality, which in his opinion can be formulated as follows: *In every change, there is a uniformity of connection between antecedents and the consequents*[4]. In the fourth chapter of the second tome of his monograph on the logic devoted to the Law of Causality, he ties in this category with the idea of conserving certain physical proportions. According to him [c]*ausation, viewed as Conservation is thus the transferring or re–embodying of a definite amount of Force*[5]. He illustrates his concept of causal relevance

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the actual world. [...] *any empirical analysis will still be a kind of conceptual analysis, for example, of the concept implicit in scientific theories.*

[1] See C. Leijenhorst, *Hobbes's theory of causality* ... , p. 426: *Hobbes* [...] *develops a notion of causality that leaves out the power–act distinction. Then, he reinterprets this distinction in mechanistic terms.*

[2] See W. Krajewski, *Four conceptions of causation*, pp. 223–224.

[3] A. Bain, *Logic*, vol. 2, p. 21. A close connection between causality and energy conservation was developed in Mach's philosophy. See L. Guzzardi, *Energy, Metaphysics, and Space* ... , pp. 1269–1291.

[4] A. Bain, *Logic*, vol. 2, p. 15.

[5] A. Bain, *Logic*, vol. 2, p. 30.

with the example of a ship which runs on a steam engine or sails and a human who derives his energy from food. In both cases the cause of movement is energy delivered by the sun. The transfer of energy between bodies is in his opinion the only explanation of any changes: [a]*ny fact of causation not carried up into this supreme law, may be correctly stated, but it is unaccounted for*[1].

The existence of causal relevance was similarly perceived by Wilhelm Wundt, and André Lalande, in his widely disseminated and updated works on the methodology of the empirical sciences (*Lectures sur la philosophie des sciences*, Librairie Hachette, Paris 1926) reinforced this point of view. Unfortunately in contemporary philosophy during attempts to build a physicalistic concept of causal relevance there was no sight of the 19th century precursors of this concept. Neither Jerrold Aronson[2] nor David Fair[3] sees the connection between their concepts and the works of Bain or Wundt. David Fair, however, goes further, claiming that there are no currently living philosophers formulating a similar concept of causal relevance[4]. Neither does Max Kistler dig so deep[5]. As precursors of his concept he names above all Aronson and Fair, but he also discerns *inter alia* the critical meaning of the remarks of W. Krajewski and D. Dieks[6].

However, neither Kistler nor Aronson and Fair see the possibility of their concept of causal relevance depending on the works of physicists. At the same time it is those works which form the realm of physics, especially those devoted to the issue of Brownian motion, which to a large degree contribute to the development by contemporary philosophers of a naturalistic concept of causal relevance. Max Kistler in his monograph devoted to the problem of causality, after critical analysis of polemical remarks[7], articulated his concept of causal relevance as follows:

> *Causation can be reduced to a physical relation that depends on the transference of an amount of a conserved quantity. According to our analysis, condition (S) is necessary and sufficient for the existence of causal relevances between the events c and e.*
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> *(S) Two events c and e are related as cause and effect if and only if there is at least one physical quantity P, subject to a conservation law, exemplified*

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[1] A. Bain, *Logic*, vol. 2, p. 30.

[2] See J. L. Aronson, *On the Grammar of 'Cause'*.

[3] See D. Fair, *Causation and the Flow of Energy*.

[4] See D. Fair, *Causation and the Flow of Energy*, p. 239: *Jerrold Aronson is the only contemporary philosopher to my knowledge to explicitly defend in print anything like the view here espoused*.

[5] E.g. M. Kistler, *Causation as transference and responsibility*, pp. 115–116. According to P. Dowe, *Physical causation*, p. 90: [...] *Brian Skyrms, in his 1980 book Causal Necessity (1980: 111), was the first to suggest a conserved quantity theory, the first detailed conserved quantity theory did not appear until 1992* [...].

[6] See D. Dieks, *A Note on Causation and the Flow of Energy*.

[7] See M. Kistler, *Reducing Causality to Transmission*, pp. 8–13.

> *in c and e, and a determinate amount of which is transferred between c and e.*
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> *(S) is supposed to provide an* a posteriori *reduction of the causal relation. This relation is not conceptually identical to the relation of transference. Rather, if our analysis is correct, causal relations form a natural kind whose members share the property of being transmissions of amounts of conserved quantities.*[1]

This conception assumes that causality is not a primordial concept. Moreover the idea of causality can be reconstructed on the basis of physical concepts such as energy and momentum. The transfer of these physical properties creates the essence of causal relation. In particular this concept of causal relation rejects the oft–accepted thesis in modern philosophy according to which causality is a sort of epistemic relationship, in which causes are determined as a request for information[2].

The ontological status of the branches of causal relation is overstated. According to Kistler they are only events. To be precise, in Kistler's opinion events [...] *are what occupies a spatio–temporal zone or region. This makes events particularisms in the same sense as ordinary objects; objects are what occupy a spatial region*[3]. Using such an interpretation, liquid molecules, in which microscopic atoms are suspended, as well as the atoms themselves, can be regarded as events. The concept of causal relation as described by Kistler is equally relevant to Brownian motion. In Kistler's monograph there is, however, no mention of Brownian motion. However, this is understandable, as its aim was the composition of the general concept of causal relevance which would form scientific practice. However, although it's good to show that this concept not only adapts itself to contemporary research practice but also describes the research activities at the beginning of the last century. On the other hand, it should be noted that the publication of the causal explanations of Brownian motion was a crucial factor which had an influence on the naturalistic composition of causal relevance[4]. Smoluchowski's works devoted to the issue of Brownian motion, but also the works of physicists which inspired Smoluchowski's research into this phenomenon – in my judgement – paved the way for the physicalistic concept of causal relevance.

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[1] M. Kistler, *Causation and Laws of Nature*, pp. 71–72. The new concept of causal relevance was initially presented in M. Kistler, *Reducing Causality to Transmission*, which appeared only a year earlier than his monograph written originally in French (*Causalité et lois de la nature*, J. Vrin, Paris 1999). See also M. J. García–Encinas, *Transference, or identity theories of causation?*, pp. 31–48. This paper examines the transference theory of causation.

[2] E.g. E. Sosa, *Scriven on causation*, p. 357: *According to Scriven, causation is a relation between explanatory factors of a particular kind and what they explain*. M. Kistler, *Causation and Laws of Nature*, p. 145, is unequivocal: *Our conclusion that it is impossible to reduce causation directly to a form of explanation* [...].

[3] M. Kistler, *Causation and Laws of Nature*, p. 215.

[4] The physicalistic concept of causal relevance has recently been depicted by M. Frisch, *Causal Reasoning in Physics*, p. 13: [...] *three dimensions of the notion of cause indeed play a particularly important role in physical theorizing: first, that causes determine their effects; second, that causes act locally; and third, that the causal relation is asymmetric and that this asymmetry is closely related to the temporal asymmetry*.

3. Marian Smoluchowski's concept of causal relevance

In his research into Brownian motion Marian Smoluchowski did not restrict himself to the physical aspect of this issue[1]. Historical matters also occupied him. In support of the historical works available in his era he presented further historical research into this phenomenon. As predecessors of Brown in research into this phenomenon he names two 18th–century biologists, John Needham (1713–1781) and Wilhelm von Gleichen–Rußwurm (1717–1783), who observed this phenomenon respectively in 1750 and 1764. He demonstrated that not only he was an excellent physicist but that he also knew the history of his discipline[2].

In his works devoted to the issue of Brownian motion Smoluchowski did not accept the phenomenalistic concept of causal relevance[3], in fact he criticised anti–atomistic phenomenalism and positivism for not appreciating speculation and clipping the wings of reason. Smoluchowski was convinced of the molecular–kinetic properties of Brownian motion from 1900. The search for evidence on the subject of the kinetic–molecular theory in his case coincided with his search for the causes of Brownian motion[4]. In line with Mario Bunge's formulation of the principles of causality the effect is accompanied in a

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[1] Nobel Prize laureate Subrahmanyan Chandrasekhar (1910–1995) wrote about the significance for physics of Smoluchowski's achievement in S. Chandrasekhar, *Stochastic Problems ...* , pp. 88–89: *The theory of density fluctuations as developed by Smoluchowski represents one of the most outstanding achievements in molecular physics. Not only does it quantitatively account for and clarify a wide range of physical and physico–chemical phenomena, it also introduces such fundamental notions as the "probability after–effect" which are of very great significance in other connections.* [...] *It is somewhat disappointing that the more recent discussions of the laws of thermodynamics contain no relevant references to the investigations of Boltzmann and Smoluchowski* [...]. *The absence of references, particularly to Smoluchowski, is to be deplored since no one has contributed so much as Smoluchowski to a real clarification of the fundamental issues involved.* See also S. Chandrasekhar, *Marian Smoluchowski as the Founder of the Physics of Stochastic Phenomena*, p. 21.

[2] Contemporary works of science historians indicate that there were also other researchers to whom the discovery of Brownian motion can be attributed. It is claimed that one such researcher was Jan Ingen–Housz (1730–1799), who in 1784 described the phenomenon of the chaotic movement of particles of coal dust on the surface of alcohol. On the other hand, this claim is questioned as too enthusiastic a supposition and it is even considered that there is decisive evidence that Ingen–Housz wasn't observing Brownian motion. See F. M. Shlesinger, *Physics in the noise*, p. 641, P. Smit, *Jan Ingen–Housz ...*, p. 125, P. W. van der Pas, *The Discovery of the Brownian Motion*, p. 132, N. Beale & E. Beale, *Echoes of Ingen Housz*, p. 344–345, P. Pearle & al., *What Brown saw ...* & M. Kerker, *Brownian movement ...* .

[3] The phenomenalist concept (Regularity Theory of Causation or Regularity View of causation) reduced causality to a constant succession of two observed events but according to S. Psillos, *Regularity Theories*, p. 155, [t]*he Regularity View of Causation is not currently very popular among philosophers, so it is hard to find recent papers and/or books that have mounted serious defences of it.* According to phenomenalist conception of causality our knowledge of the causal relation can only be drawn from sensual perception. See J. Mingers & C. Standing, *Why things happen ...* , p. 173: [...] *basic notion of causality that underpins positivism, and all the statistical analysis that goes with it, is one of simple event regularities*.

[4] The roots of determinism lie in Causality Principle but since quantum mechanics began to be formulated determinism has become separable from these roots. Some physicists (e.g. W. Heisenberg, *Kausalgesetz und Quantenmechanik*, p. 172) claims that quantum theory is indeterministic but other physicists holds that quantum theory is deterministic. See B. Falkenburg & F. Weinert, *Indeterminism and Determinism in Quantum Mechanics*, p. 307: *What is tacitly assumed in such views is a chain of reasoning, which leads from determinism to causality. One form of determinism – predictive determinism – is the view that a sufficient knowledge of the laws of nature and appropriate boundary conditions will enable a superior intelligence to predict the future states of the physical world and to retrodict its past states with infinite precision.* [...] *Laplacean demon* [...] *identifies determinism and causality.* [...] *But the experimental results from quantum mechanics* [...] *seemed to threaten the Laplacean identification of determinism and causality*.

permanent and necessary way by cause because it is generated by the cause[1]. However the generation of the effect occurs by way of the transfer of energy. It's thanks to the kinetic energy of liquid molecules – in line with the explanation of Brownian motion presented by Smoluchowski – that atoms suspended in liquid perform a motion observed under a microscope. The description of the phenomenon of Brownian motion coincides with the mechanical model. According to Smoluchowski there exists such a thing as the mechanism of Brownian motion[2]. Such a formulation demonstrates that Smoluchowski was searching for a (mechanical, exterior) cause, which would generate Brownian motion, and in no way does he limit himself to stating the truths to which this phenomenon belongs[3].

The main inspiration for Smoluchowski were the works of the French physicist Louis Gouy (1854–1926), who in turn followed the hypothesis of Joseph Delsaulx (1828–1891)[4] in his experimental research. This hypothesis states that the cause of Brownian motion is the thermal movement of liquid molecules in which were suspended Brownian particules[5]. Gouy wasn't the first physicist to point to the chaotic motion of molecules as the cause of Brownian motion. Christian Wiener (1826–1896)[6], who observed Brownian motion in what we now call a colloidal silica sol, made in 1863 a first attempt to relate it to inherent fluctuations of the suspending fluid. It was, however, the Belgian

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[1] See M. Bunge, *Causality*, p. 48: *Therefore I propose to employ the statement: If C happens then (and only then) E is always produced by it as an adequate formulation of the causal principle* [...]. Bunge's view of the principle of causality rejects the philosophical identification of determinism with causalism. The solution proposed by Bunge was criticised among others by Richard Schlegel, *Mario Bunge on Causality*, pp. 72–74, who was not a professional philosopher but a physicist employed at the Department of Physics at Michigan State University.

[2] See M. Smoluchowski, *Zur kinetischen Theorie ...* , p. 773.

[3] In this context it is worth drawing attention to the claim that the search for a mechanical explanation has an ontological aspect. See C. Craver, *Explaining the Brain ...* , p. 27: [...] *explanations* [mechanisms] *are objective features of the world*.

[4] In 1877 Delsaulx wrote: *In my way of thinking the phenomenon is a result of thermal molecular motion in the liquid environment (of the particles)*. (Quoted after: W. Ebeling & I. Sokolov, *Statistical Thermodynamics ...* , p. 13).

[5] See J. Delsaulx, *Thermo–dynamic Origin of the Brownian Motions*, p. 2: *My intention in this note is 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's hypothesis was based on the analysis of the activity of Crookes' radiometer and claimed that the cause of observed movement of microscopic atoms is movement that doesn't allow the observation of liquid molecules. The activity of Crookes' radiometer was similarly (erroneously) explained. The observed movements of a windmill were supposed to be caused by the pressure of light. See D. Dusenbery, *Living at Micro Scale*, p. 78: *The influence of the motion of translation of the liquid molecules acting on the surface of the particles permits us to explain easily all displacement hitherto observed*.

[6] Ludwig Christian Wiener (1826–1896) was a German mathematician who specialised in descriptive geometry, but he was a skilled experimenter too (from 1848 he became a teacher of physics, mechanics, and hydraulics at the Technische Hochschule in Darmstadt). See H. B. Casimir, *Haphazard Reality...*, p. 41: [as early as in 1863 Christian Wiener] *showed convincingly that this motion is not due to external influences; it must be caused by inner motion in the liquid*. He was interested in moral philosophy especially in such topics as free will. It's worth just adding a note regarding the character of this mathematician and physicist, of whom H. B. Casimir, *Haphazard Reality ...* , p. 41 expressed a surprise that [...] *seventy years later another mathematician of the same name Norbert Wiener (1894–1964), also made an important contribution to the study of Brownian motion*.

Jesuit Delsaulx[1] who stated in 1877 for the first time explicitly that Brownian motion results from the interior dynamic state that the mechanical theory of heat attributes to liquids. He also noted that the Brownian motion is a remarkable confirmation of this mechanical theory[2]. But it was thanks to Gouy's works Delsaulx's hypothesis gained in importance. Smoluchowski knew these works and quoted them in his articles[3] devoted to Brownian motion[4].

Another argument for the thesis on searching for a (mechanical) cause which generates Brownian motion is that Smoluchowski criticises rival hypotheses on the causal explanation of that phenomenon. Such hypotheses were propounded on the assumption that the cause that was being sought had the character of an internal energy source. In this context there have been pointers to the existence of repellent forces among molecules, capillary forces and electrical forces. His criticism was aimed at specific solutions and not the methodological demand of seeking that type of explanation or still less in the ontological interpretation of the principle of causality. Neither did Smoluchowski treat these solutions as mathematical prognostic models, for which nothing in reality is suitable.

The solution presented by Smoluchowski to the problem of Brownian motion makes use of the physicalistic concept of causal relevance. Although Smoluchowski doesn't write about this directly, nevertheless the attainment of velocity by microscopic bodies is connected with the transfer of momentum, which is in line with the concept of cause as energy delivering reactions. He writes about the mechanism of the phenomenon and its causes as well as the physical properties such as the growth of viscosity or the drop in temperature, which have an impact on the process[5].

In his works devoted to the issue of Brownian motion he wrote directly that he is attempting to explain the internal mechanism of diffusion, and to connect

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[1] The qualitative explanation of the Brownian motion as a kinetic phenomenon was put forward by several authors. Apart from Delsaulx, B. Fernandez & G. Ripka, *Unravelling the Mystery of the Atomic Nucleus ...* , p. 494, name also Italian physicist Giovanni Cantoni (1818–1897) and Belgian Jesuit Ignatius Carbonelle.

[2] A. P. Philipse, *Notes on Brownian motion*, p. 7.

[3] See among others M. Smoluchowski, *Zur kinetischen Theorie ...* , pp. 761–762: *Wir gehen also zu den kinetischen Theorien über, welche die innere Wärmeenergie als das eigentliche Agens ansehen. Wenn man die Brownsche Bewegung unter dem Mikroskop beobachtet, erhält man unmittelbar den Eindruck, daß so die Bewegugen der Flüssigkeitsmoleküle aussehen müssen. Es ist das keine schwingende Bewegung und auch keine fortschreitende, sondern ein Zittern oder wie Gouy sagt: ein Wimmeln (fourmillonnement); die Teilchen beschreiben unregelmäßige Zickzackbewegungen, als ob sie infolge der zufälligen Zusammenstöße mit den Flüssigkeitsmolekülen angetrieben würden, und trotz ihrer fieberhaften Bewegung rücken sie nur langsam von der Stelle. Dies Phänomen wurde auch tatsächlich von zahlreichen Forschern (Wiener, Cantoni, Renard, Boussinesq, Gouy) von diesem Standpunkt aus erklärt.*

[4] Smoluchowski wasn't the only one familiar with Gouy's works, but also Einstein, who developed the theory of Brownian motion before Smoluchowski and independently of him. Probably Einstein's as well as Smoluchowski's source of information on this subject were the works of Poincaré. D. Cahan, *The Zeiss Werke ...* , p. 102, writes directly [...] *he* [i.e. Einstein] *learned about George–Louis Gouy's work on Brownian motion from Henry Poincaré's* Science et hypothèse [...].

[5] See M. Smoluchowski, *Drei Vorträge ...* , p. 541: *Wenn wir uns den Mechanismus dieser Erscheinung vor Augen halten,* so *ist klar*, *daß die eigentliche Ursache der Veränderlichkeit der Konzentrationsschwankungen auf der Brown'schen Bewegung beruht, und daß alle Umstände, welche dieselbe verlangsamen, wie Zähigkeitszunahme, Temperaturabnahme, auch jene Schwankungsgeschwindigkeit herabsetzen müssen, wie dies tatsächlich von Svedberg bemerkt wurde*.

it with the phenomena of molecular movements. What is crucial is that Smoluchowski is searching for the cause of the macroscopic phenomenon which allows itself to be directly observed at the microscopic level which doesn't allow itself to be directly observed. In line with this research strategy, Brownian motion is generated by the thermal fluctuations of molecules[1]. That's why also in contemporary scientific philosophy it is accepted that the thesis according to which Smoluchowski's (and Einstein's) theoretical explanation of Brownian motion is a causal explanation and it's considered *inter alia* that it is relevant to the realistic interpretation of scientific theory[2].

We may also find Smoluchowski's contribution to the philosophy of causality in his posthumous paper entitled *On the concept of chance and the origin of probabilistic laws in physics*[3]. In this article, Smoluchowski argues against the view that determinism implies a subjective interpretation of the concept of probability. He insists that probabilistic statements can be objective. In this study, Smoluchowski treated chance (in the theory of probability) as a special kind of causal connection[4]. The conceptual distinction between two

[1] See J. Piasecki, *Centenary of Marian Smoluchowski's theory of Brownian motion*, p. 1629: *Coming back to the decisive role of Smoluchowski's work in the acceptance of the atomic hypothesis it seems appropriate to recall his way of understanding the status of physical theories. He was close in this respect to the attitude of Boltzmann*. Relations between Smoluchowski's predecessors in this task and James C. Maxwell (1831–1879) and especially Ludwig Boltzmann (1844–1906) was excellently characterized by Marek Kac (1914–1984) an American mathematician. See M. Kac, *Marian Smoluchowski ...* , p. 16–17: *Like Maxwell, Smoluchowski was a pragmatist and he was less concerned with* why *probability is introduced into kinetic theory than with* how *it can be* used *to explain known phenomena and to predict new ones. Unlike Boltzmann to whom probabilistic and statistical arguments were a line of defense against logical assaults on his theory, Smoluchowski, in the spirit of Maxwell, turned them into everyday working tools of physics.*

[2] See Ch. Hitchcock, *Causal explanation and scientific realism*, pp. 161–162: *It was known from the theoretical work of Smoluchowski and Einstein, and from the experimental work of Perrin, that the atomic theory presented a potential explanation of the peculiar motions of small particles suspended in a liquid* [...] *the particles were being bombarded by molecules, and thus were constantly gaining linear momentum in random directions*. It's worth to mention that Einstein's theoretical explanation of Brownian motion was completely different from that of Smoluchowski. See J. Piasecki, *Centenary of Marian Smoluchowski's theory of Brownian motion*, p. 1623: *Both scientists explained the phenomenon as a result of collisions between the suspended particles and the molecules of the surrounding fluid and arrived at almost the same quantitative predictions. However, their approaches were so different that they can be looked upon as two complementary studies reflecting the original ideas of each of the two authors*. Those differences were splendidly explained by M. Kac, *Marian Smoluchowski ...* , p. 17: *Einstein's treatment of Brownian motion avoids any analysis of molecular collisions which give rise to it and relies instead on general statistico–mechanical arguments. Smoluchowski on the other hand has a clear kinetic picture in mind and he therefore is led to treating Brownian motion as random walk*.

[3] This paper oryginally was published under the title *Über den Begriff des Zufalls und den Ursprung der Wahrscheinlichkeitsgesetze*. Smoluchowski was fully aware that his works had a philosophical significance. See e.g. p. 109: *Es scheint uns aber ein auch für den Philosophen äußerst wichtiges Ergebnis zu sein, wenn sich auch nur auf einem beschränkten Gebiet – dem der mathematischen Physik – zeigen läßt, daß der Begriff der Wahrscheinlichkeit, in der üblichen Bedeutung eines gesetzmäßigen Häfigkeitswertes zufälliger Ereignisse, eine streng objektive Bedeutung besitzt, daß man den Begriff und die Genese des Zufalls genau präzisieren kann, auch wenn man am Determinismus festhält* [...].

[4] See J. von Plato, *Creating Modern Probability ...* , p. 171: *First, chance is defined as instability, the typical element in many games of chance. Second, it is required that a physical and objective notion of probability be determined, not from our degree of ignorance concerning an event, but from the conditions that have an effect on its occurrence*. [...] *Von Smoluchowski defines chance as a* causal relation *of the following kind: The effect* y *is assumed to be a function* f *of the 'variable cause'* x, or y = f(x), *such that the effect* y *depends on 'very small' variations in the cause* x.

kinds of chance (in a broader and narrower sense), as it was formulated by Smoluchowski, is also important for the philosophy of causality[1].

However, his concept of causal relevance is best demonstrated in experimental projects which were meant to demonstrate the influence of the thermal fluctuations of gases on macroscopic objects. Smoluchowski presented this as a type of intellectual experiment, which nonetheless soon became reality[2]. This experiment was supposed to demonstrate the reactions of gas molecules on a small mirror suspended on a very thin (a few tenths of a micron) quartz thread. A ray of light falling on that mirror was supposed to indicate its vibrations, which – in Smoluchowski's opinion – were generated by the chaotic motion of gas molecules. The motion of the pendulum was conditional on the transfer of momentum from gas molecules. Of course these impulses were partially balanced, but after evening out there remained an increased momentum which was transferred to the mirror and caused observable macroscopic motion[3]. This experiment visualised Brownian motion and demonstrated how the kinetic energy of gas molecules becomes a cause of observable motion. In this experiment the concept of causal relevance was established, as communicated by Max Kistler, as kinetic energy belongs to those physical volumes (magnitudes) which are preserved in isolated systems.

4. Conclusions

In his research into Brownian motion Smoluchowski did not respect the positivist provenance of phenomenalism which brought with it causal prequalification as to the regularity of phenomena, but detected the generative power of cause (causality). Attempting to measure up to the standards of scientific methods designated on the cusp of the 19th and 20th centuries by empiriocriticism, he couldn't declare openly that he was seeking the causal structure of the world. He knew that philosophers often questioned the possibility of a

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[1] See M. Smoluchowski, *Über den Begriff*, p. 93: *Der einer Wahrscheinlichkeitsberechnung entsprechende – vielleicht darf man sagen: der „geregelte" Zufall zeichnet sich also vor dem Zufall in weiterem Sinne durch ein wesentliches Charakteristikum aus:* eine gewisse Regelmäßigkeit der Wirkung *bei oftmaliger Wiederholung des Vorganges,* unabhängig von der speziellen Art der Ursache.

[2] The first time Smoluchowski presented the project of such an experiment was at a Naturalists' Congress in Munster in 1912, in other words six years after presenting his explanation of Brownian motion. After that he returned many times to this concept in his later publications. See e.g. M. Smoluchowski, *Über Brownsche Molekularbewegung...*, p. 1106: *Was die experimentelle Verwirklichung dieses Falles anbelangt, wurde schon damals darauf hingewiesen, daß die Winkelverschiebungen eines an einem Torsionsfaden befestigten Spiegelchens von demselben Wahrscheinlichkeitsgesetze beherrscht werden, und daß die Möglichkeit diesbezüglicher Messungen nicht ausgeschlossen erscheint.*

[3] The construction using light reflected from a mirror suspended from a torsion scale was already applied in Cavendish's famous experiment, but there it was a question of a moment of a stronger force. Later such a solution was applied in the construction of galvanometers. On account of the very high sensitivity of these instruments they demonstrated Brownian motion, but these indications were interpreted at that time as the result of seismic micro–tremors. The immobility of thermal noise led to the natural sensitivity boundary of these instruments. G. Ising, *A natural limit ...* , was the first to notice that the cause of these phenomena is Brownian motion, at the same time pointing to Marian Smoluchowski who (in 1912) theoretically foresaw (predicted) such a phenomenon. See M. Niss, *Brownian Motion as a Limit*, p. 34: *Ising might have been introduced to Smoluchowski's work through his compatriots Svedberg and Arne Westgren, who both had studied Brownian motion. The former even received the Nobel Prize for his work on the Brownian motion of colloid particles and collaborated with Smoluchowski.* See also B. Średniawa, *The Collaboration of Marian Smoluchowski and Theodor Svedberg ...* , p. 325.

causal explanation of phenomena. At the turn of the last century when positivism – which saw the task of science mainly in the description of phenomena – was very strong, only an epistemological interpretation of the principle of causality seemed correct. However, scientific practice, especially the successes of atomism in explaining the natural facts, allowed a break from that interpretation. In researching Brownian motion Smoluchowski attempted to discover the cause of this motion, remaining firm in his opposition to the phenomenalistic interpretation of causal relevance. His view of the principle of causality really concurred with Mario Bunge's formulation of it. Thanks to the works of academics like Smoluchowski a breakthrough in philosophy was possible, which relied on moving away from the positivist vision of science, but also to crossing the barrier which positivist philosophy placed in the way of getting to know and control nature.

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