teorema
Vol. XL/3, 2021, pp. 49-64
ISNN 0210-1602
[BIBLID 0210-1602 (2021) 40:3; pp. 49-64

Sympathy for the Demon
Rethinking Maxwell's Thought Experiment in a Maxwellian Vein

Javier Anta

RESUMEN

En este articulo defenderé una aproximación al problema conocido como 'demonio de Maxwell' en base a una concepción maxwelliana de la mecánica estadística. En lugar de suponerr que las descripciones termodinámicas dependen reductivamente de la dinámica de los componentes moleculares, adoptaremos una concepción de la termofísica como una 'teoría de recursos' en la línea maxwelliana [Myrvold (2011)] recientemente defendida por Myrvold (2011) y Wallace (2017). Desde esta estancia interpretativa, el demonio de Maxwell no dirigiría directamente a la plausibilidad de contradecir la segunda ley de la termodinámica, sino a mostrar la imposibilidad pragmática de conocer deterministamente la microscópica exacta de los sistemas térmicos.

PALABRAS CLAVE: *demonio de Maxwell; termodinámica; filosofía de la física; James Maxwell; inaccesibilidad epistémica; imposibilidad pragmática*.

ABSTRACT

In this paper I will defend an approach to the thought experiment known as 'Maxwell's Demon' based on a Maxwellian conception of statistical mechanics. Instead of assuming that thermodynamic descriptions depend reductively on the dynamics of molecular components, I will adopt a conception of thermophysics as a 'resource theory' in the Maxwellian line recently defended by Myrvold (2011) and Wallace (2017). From this interpretative stance, Maxwell's demon would not lead directly to the plausibility of violating the second law of thermodynamics, but to show the pragmatic impossibility of knowing deterministically the exact microscopic of thermal systems.
KEY WORDS: *Maxwell's Demon; Thermodynamics; Philosophy of Physics; James Maxwell; Epistemic Inaccessibility; Pragmatic Impossibility.*

The fact that the most avant-garde physicists talk about Demons, is at least surprising. As recently defended by the historian of science Jimena Canales (2020) in her "*Bedevilled. A Shadow History of Demons in Science"* a remarkable number of physicists from Laplace to the present day have used certain demon-like beings to mentally explore physical possibilities that otherwise (i.e., experimentally or in mathematical modeling) could not be proven. One of the main ones is the so-called 'Maxwell's demon'. It is often stated in the literature that this creature was originally developed by James Clerk Maxwell in 1867 to point out how the kinetics of gases contradicted one of the principles on which contemporary physics is based: the second law of thermodynamics [see Leff and Rex (1999]. In this paper I will reject this line of interpretation, defending instead to revisit Maxwell's demon problem from a properly Maxwellian conception of thermal physics as the one recently defended by Myrvold (2011) or Wallace (2017): namely, understanding thermodynamics not as a theory subordinated to microphysics, but as a discipline that studies how the controlled manipulation of certain macroscopic properties (e.g. pressure or temperature) of matter leads to the obtaining of other properties (energy or work). From this view, the problem of the demon would not constitute a threat to the foundations of thermophysics but an opportunity to mentally explore the limits of physical reality that real scientists cannot observe or manipulate.

I. Maxwell's Demon

Before assessing the problem of Maxwell's demon, it must be established its theoretical and historical context. It was during the 1850s that the foundations of what we know today as 'thermodynamics' were laid, a discipline dedicated to analyze the behavior of macroscopic properties of matter such as temperature, pressure or volume, independently of their constituent elements. Its theoretical foundations were, on the one hand, the principle of energy conservation (first law), and on the other hand, the principle (implicitly developed by Sadi Carnot in 1824, [*cf.* Uffink (2007) pp. 934-937] of the limit of efficiency in the conversion of heat into useful work. The latter is the so-called second law of thermodynamics, formulated explicitly first by William Thomson (Lord Kelvin) in 1851 and later by Rudolph Clausius in 1854 by the fact that it is not possible for a cold body to transmit heat to a body at a higher temperature.

It was precisely Clausius who in 1857 postulated to link the thermodynamic behavior of macroscopic substances with the dynamics of the molecular components (then a mere hypothesis within the scientific community) of these substances, connecting macroscopic values of temperature with the kinetic energy of microscopic molecules. Influenced by this proposal, the Scottish James Clerk Maxwell developed in 1860 the first well-defined statistical model of a physical system by formulating the probability distribution that determines the frequency of certain ranges of position and velocity values in the molecules (prima facie observationally inaccessible) of the target system when it is in its macroscopic state of thermal equilibrium; namely, that state in which the macroscopic values of the system do not change during thermodynamically reversible processes. Five years later, Clausius (1865) named 'entropy' the state function or measure of the degree of energy dispersion during thermodynamically irreversible processes, associating it with the degree of molecular disgregration. This allowed to define in simple terms the second law as the impossibility of the entropy of a closed system to be reduced.

The theoretical potential of this thermodynamic concept and the progressive advance of the atomist program driven from the gas kinetics of the 1860s encouraged two divergent attitudes within thermal physics. On the one hand, German-speaking people sought to reduce phenomenological thermodynamics to the principles of Newtonian or Hamiltonian analytical mechanics, as Maxwell himself noted: "in is rare sport to see those learned Germans contending for the priority in the discovery that the second law of thermodynamics is the Hamiltonsche Princip. [Knott (1911), p.115-116]. On the other hand, scientists like Maxwell or later Loschmidt [*cf.* Uffink (2007), pp. 970-71] proposed that the deterministic and time-symmetrical dynamics of the molecular components of matter could be problematic to the empirical and asymmetric predictions of thermodynamics. In a letter to his friend and physicist Peter Tait in 1867, Maxwell proposed one of the most important thought experiments in modern physics:

> Now conceive a finite being who knows the paths and velocities of all the molecules by simple inspection but who can do no work except open and close a whole in the diaphragm by means of a slide without mas. Let him first observe the molecules in A and when he sees one coming the square of whose velocity is less than the sq. vel. of the molecules in B let him open the hole and let it go into B. [and vice versa] (…) the hot system has got hotter and the cold system colder and yet no work has been done, only the intelligence of a very observant and neat-fingered being has employed [Maxwell 1867, quoted on Knott 1911, p.214].

Therefore, the 'finite being' would manage to violate the second law of thermodynamics in its Clausius formulation by increasing the temperature gradient between A and B without doing any work or spending energy, only redistributing the molecules that make up the gas depending on its kinetic energy. That is, this creature would end up reducing the entropy of the closed gas-box system against the empirical predictions of thermodynamics. Maxwell literally referred to this being as a 'very observant and neat-fingered being' (Ibid), recovering this approach in his famous '*Theory of Heat*' of 1872 [Maxwell (1952)]. In 1874, Thomson gave it the name of 'demon' [Knott (1911), p.214], with which it would pass to the posterity of the history of science.

II. THE DEMON AS AN ENEMY: AFTER ALL THOSE EXORCISMS

There is no doubt that Maxwell's demon is one of the main problems about the fundamentals of contemporary thermal physics, as Uffink (2007), p. 931, certainly points out. After more than a century and a half of existence, the debate about the demon, both within the community of philosophers of physics and for physicists themselves, is still very much alive today. However, have we learned anything during all this time? To answer this question, it must be delimited what this debate has been about.

As the historiography of Maxwell's demon has shown us [*cf.* Leff and Rex (1990)], the problem of the demon has been considered fundamentally during its more than 150 years of life as the problem about the microphysical possibility of violating the second law of thermodynamics through the dynamics of the molecules that constitute matter: in fact, the phenomenon of random molecular fluctuations discovered at the beginning of the 20th century could be considered as 'demonic actions', [*cf.* Earman & Norton (1998)]. The dimension of the problem can be appreciated through the popularization of the second law as a fundamental axiom of physics: "The law that entropy increases-the second law of thermodynamics-holds, I think, the supreme position among the laws of Nature." [Eddington (1928)]. In the line of Eddington, the mere possibility of Maxwell's demon would undermine one of the central principles that articulate our physical reality; therefore, one of the most expected intellectual attitudes within the scientific community would be to seek to refute this experiment. This is what has been popularized in the literature as 'demon exorcisms' [*cf.* Earman & Norton (1998), (1999)].

One of the most historically influential proposals of exorcism strategies is found in this suggestive statement by Marian Smoluchowski, one of the discoverers of molecular fluctuations "it is not to be excluded that the activity of intelligence (...) is connected with the expenditure of work and the dissipation of energy and that perhaps after all a compensation still takes place" [Smoluchowski (1912), quoted on Earman & Norton (1998), p.451]. Taking up his baton, Leo Szilard will defend in a famous

1929 paper that Maxwell's demon will not be able to violate the second law, precisely because the demon acquisition of knowledge about gas through measurement would necessarily entail a minimum of dissipated energy (i.e. *k* log 2 per measured binary data) which would compensate for the plausible decrease in entropy. To this end, Szilard 'naturalistically' conceived of the demon as a machine composed of a single molecule, a vessel with a partition dividing it into two compartments of equal volume, and a piston inserted into each side of the partition. Twenty years later, it was Léon Brillouin [1951] who reinterpreted Szilard's exorcism by the thesis that all demonic obtaining of 'information' (or equivalently 'negative entropy') on the gas-molecule would necessarily imply an increase in entropy precisely because both quantities are the same.

During the second decade of the 20th century, the exorcist strategy changed substantially. This was thanks to the IBM scientist Charles Bennett, who on the one hand defended (against Szilard-Brillouin) in his 1982 paper that the acquisition of information about a physical system does not have any entropy cost, and therefore would be thermodynamically reversible. On the contrary, he used Landauer's principle (i.e., the elimination of a bit necessarily entails an increase of *k* log 2 entropy) to defend that the fact of eliminating part of the demon's memory would imply an entropic cost that would compensate the demonic action and therefore save the second law. Interestingly, the main criticism of the exorcisms of Szilad-Brillouin and Landauer-Bennett was not made within the scientific community but by the philosophers of physics John Earman and John Norton (1998), (1999) in their double paper '*The Wrath of Maxwell's Demon*'. In this work, the authors argued that all these 'theoretical-informational' exorcisms (due to the interpretation of the knowledge of the demon in terms of Shannon's information theory) fell without exception into a dilemma: either they presupposed the validity of the second law they intended to save (sound horn), or they unjustifiably presupposed a connection between the thermodynamic entropy of the gas-system and the information about it of the demon (profound horn).

In a recent paper, Norton (2018) defended that the Szilardian intellectual trend (defined by exorcising the demon by searching for quantities of generated entropy hidden in the demon's actions) had distracted us from the fact that random and spontaneous (i.e., without the need for an agent to promote them) fluctuations of the molecules already generate microscopic violations of the second law of thermodynamics. For the sake of my argument, I will defend in Norton's line that the historical tendency to consider Maxwell's demon as an attack on the foundations of physical reality has distracted us from the profound value that Maxwell's thought experiment has in understanding the foundations of contemporary thermal physics. For this reason, it would be useful to introduce some interpretative coordinates in this field that could help in developing my proposal regarding this central problem.

III. MAXWELLIAN STANCE ON THERMAL PHYSICS

The philosopher of physics David Wallace (2017) has defended in the last decade the distinction between two conceptions or interpretative stances on particular physical theories, specifically those belonging to the domain of statistical physics such as statistical mechanics or quantum mechanics, namely dynamicism vs. inferentialism.

On the one hand, what Wallace calls 'dynamicism' consists in conceiving that statistical mechanics (the discipline that concerns us here) must provide us with the most accurate descriptions possible of the dynamic behavior of the molecular components of the target system, regardless of our knowledge of it. From this interpretative attitude, the content of statistical mechanics would be exhausted in the deterministic specification of the dynamic evolution of each gas molecule by means of Hamilton's equation of motion[1] (the 'Hamiltonsche Princip' referred to by Maxwell in the quotation seen above), where each possible solution would be time-symmetric: the same dynamic values that allow the system-molecule to evolve into the future, this evolving equally into the past.

One of the historical examples of this dynamicist attitude was Boltzmann's intellectual work up to 1872, who sought to mechanically model the deterministic evolution of molecular systems by means of a single equation that today it is called 'Boltzmann's kinetic equation', trying to derive the second law and Clausius' thermodynamic entropy from exclusively mechanical principles [Uffink (2007)]. However, this radically dynamic program of Boltzmann was greatly criticized in the following years. The critical argument was developed by Loschmidt in 1875, who argued that if we reversed the velocity of gas molecules (something compatible with the laws of Hamiltonian analytical mechanics, as I have pointed out above) the entropy of the system would not only increase in favor of the second law, but also decrease against the second law. This led to Boltzmann introducing in 1877 key statistical considerations in his mechanical descriptions of kinetic systems [Uffink (2007)].

On the other hand, what Wallace calls 'inferentialism' consists essentially in interpreting statistical mechanics as a set of theoretical tools that allow the agent to statistically infer the behavior of the dynamic values of the system from its macroscopic knowledge of it. An illustrative example of this position is found in Tolman, who stated that "the principles of SM are to be regarded as permitting us to make reasonable predictions as to the future condition of a system, which may be expected to hold on average, starting from an incomplete knowledge of its initial state" [Tolman (1938), p.1]. Interestingly, this position would also apply to the field of phenomenological thermodynamics, understanding it as an autonomous domain (without the need to base it on a microphysical framework) centered on the controlled and agent-dependent manipulation of certain macroscopic resources of matter, which is why it is also called 'resource-theoretical' view within the literature. Note that, contrary to the dynamicist view, the knowledge of the agent is key for the understanding of the theory.

Interestingly, Wallace argues that "the inferential-vs.-dynamical dispute naturally captures much of the basic disagreement within statistical mechanics" [Wallace (2017), p.179] as opposed to other interpretive coordinates in the literature, notably those of 'reductionism-autonomy' or 'determinism-antideterminism'. This author illustrates the clarifying virtues of this distinction in key debates in this discipline. The compatibility between macroscopic irreversibility and microscopic reversibility is unsuccessfully raised from the 'reductionism-autonomy' debate (ibid.) by the plausibility of reducing the former into the latter. While this approach has proved unsuccessful for decades [see Callender (2021)], the inferential-dynamical perspective allows us to grasp the two main ways of assimilating the problem: from the derivation of irreversible descriptions from the reversible microdynamics of the system (dynamicism) or as the ability of an agent to obtain macroscopic-irreversible knowledge from reversible data (inferentialism). Therefore, this distinction would allow us to clarify the irreversibility-reversibility compatibility from a set of interpretative coordinates sufficiently shared to generate progress on this issue.

Another philosopher who defends this inferential stance (or resource-meteorological) conceptions about thermal physics is Wayne Myrvold (2011), who argued that Maxwell was precisely the main exponent of this vision in the face of the dynamism-mechanism prevailing in part of the German-speaking scientific community of the 1870s (e.g. Clausius, Boltzmann or Helmholtz). For Maxwell, the mechanical statistical models of the material systems would not fulfill the objective of offering a microphysical framework to the thermodynamic properties and behaviors à la Boltzmann, but properly to increase the capacity that the agent possesses to predict with greater accuracy (than the phenomenological thermodynamics) these behaviors on the basis of its observational knowledge. This position is clearly shown in his conception of the statistical mechanical meaning of energy dissipation or Clausius entropy, exposed in his 1878 article in the Encyclopedia Britannica on 'diffusion': "the idea of dissipation of energy depends on the extent of our knowledge (...) the notion of dissipated energy would not occur to a being who could not turn any of the energies of nature to his own account, or to one who could trace the motion of every molecule and seize it at the right moment" [Maxwell (1952), p. 646].

Although the Maxwellian assertion that the statistical mechanical meaning of entropy is dependent on the knowledge of the agent may at first sight appear to be an attack on the objectivity of this discipline, being the object of appellations such as 'subjective' or 'anthropomorphic', the truth is that this is a well-established fact within contemporary statistical mechanics. Let us consider the case of the concept of entropy formulated within the Boltzmannian framework. In it, all possible values of position and velocity of the molecular components of a system would be encoded in a 6n-dimensional 'phase space', where n is the number of molecules that make up the system. Note that for realistic systems such as noble gases, this n will be (based on Avogadro's constant) approximately $n = 10^{24}$ for a 1 mole of this gas. In this context, a 'microstate' of the system at time t_1 would represent the specification of the position and velocity determined for each molecular component at that precise moment t_1, encoded in individual points of its phase space.

In 1877, Boltzmann introduced the notion of 'macrostate', defined as sets of different microstates to which were associated the same set of macroscopic observable values (e.g., temperature or pressure) of the system. Therefore, statistical considerations in the Boltzmannian framework [Uffink (2007), p. 974-976)] are introduced by partitioning the mechanical phase space into different non-overlapping macrostates, where the different microstates contained in each macrostate M would be observationally indistinguishable for the agent and equally likely to be the actual microstate x considering the set of macrovariables associated to M. It is further assumed in this framework that the vast majority of the system's phase space would be occupied by the macrostate M_{eq} associated to the thermal equilibrium state. Based on these elements, the Boltzmann entropy of a physical system would correspond to the logarithm of the number (or volume, since classical phase space is continuous) of microstates contained in the actual macrostate of the system at the moment

t_1, multiplied by Boltzmann's constant k_B. Then, the entropy of the system would increase if its actual microstate x moves dynamically from lower volume macrostate M_0 to a higher volume macrostate M_1, until eventually reaching the thermal equilibrium macrostate.

Because the Boltzmannian partition of the system's phase space in macrostates would usually be justified by the microscopic resolution capacity of the agent [Penrose (2005)], the volume of each macrostate depends on the observational knowledge of the scientists. Thus, according to the Maxwellian view of thermal physics, Boltzmann entropy depends on the capabilities of the agents. In Penrose's words: "There is undoubtedly something 'arbitrary' in the particular division into boxes that one might happen to select. The definition seems to depend upon how closely one chooses to examine a system" [Penrose (2005)]. Having briefly exposed the Maxwellian control-theoretical conception of thermal physics advocated by Wallace (2017) and Myrvold (2011), we must now face the task of reinterpreting Maxwell's demon problem from this same perspective.

IV. Demonic Lessons in Thermal Physics

At this point in my argument, I defend that Maxwell's thought experiment should not be understood (as it has been predominant during the last century and a half) directly as an attack on the second law of macroscopic thermodynamics, but as a plausible scenario that shows the pragmatic limits that underlie the obtaining of microscopic knowledge about systems with a high number of components. Therefore, here I align dialectically with Norton [2018] in criticizing the constant attempts to exorcise the demon by searching for hidden entropic costs, proposing instead to show their incompatibility with the principles of statistical mechanics. However, the value of this proposal consists mainly in defending from a Maxwellian perspective [Myrvold (2011), Wallace (2017)] that the demon should not be 'exorcised' or refuted, but that we should learn from it by understanding it as a sort of argument ad absurdum.

IV.1. *A Very Observant Being*

First of all, Maxwell points out a fundamental point in his 1867 letter to Tait that has been largely disregarded in the literature because of its 'apparent' obviousness: namely, that it is not possible for a scientist to specify the positions and velocities of all molecules (i.e., individual microstate) that constitute a macroscopic substance of the order of $n = 10^{24}$

components. Of course, this is a well-known fact in the literature: "The definition [of microstate] requires one to know the initial position and velocities of all n particles and to follow these motions for all time. Since n is typically of the order of 10^{24}, this is of course impossible" [Ellis (2006), p. 65 quoted on McCoy (2020)]. However, the character of this impossibility of a scientist to obtain knowledge about the microstate of gas imagined by Maxwell has been largely ignored within the literature on philosophy of physics. But what kind of impossibility is this?

Assuming the epistemic inaccessibility of individual microstates, it is often stated that the impossibility of determining or accessing the microstate of a gas is a practical impossibility: "it is (at least) practically impossible to adequately determine their classical microstate" [McCoy (2020)]. However, to simply say that this is a 'practical impossibility' does not clarify the reasons for this impossibility. The fact is that it is pragmatically impossible to determine the microstate precisely because scientific agents do not possess the microscopic capabilities to directly observe the position and velocity of the molecules that constitute matter. However, as Maxwell suggested in his 1867 thought experiment, the inability of microscopic resolution is a socio-historically contingent fact: it would be prima facie compatible with the principles of analytical mechanics governing the behavior of individual molecules (nomically possible) and even conceivable (conceptually possible) to be able to imagine the existence of an epistemic agent with sufficient microscopic resolution capacity to allow it to directly observe the exact microstate of the system under analysis. This nomic-conceptually plausible agent is none other than the 'very observant being' to which Maxwell referred in his letter to Tait:

> *Demonic Lesson 1*: Although it would be pragmatically impossible to determine a particular micro-state of macroscopic physical systems, it would not be nomic-conceptually impossible to achieve this task by 'a very observant being'.

Of course, this 'very observant being' should not be misinterpreted as a tiny monster with horns and a tail, as it has been done during its more than century and a half of life not only in its popularization but also within the scientific community [*cf.* Leff and Rex (1990)]. This 'very observant being' could correspond to an experimental scientist of the year 2027 who has the microscopic instruments with enough resolution to observe positions and velocities of all the molecules that constitute a kinetic system. As the French-American physicist Brillouin accurately pointed out, "The physicist in his laboratory is no better off than the demon" [Brillouin (1951)].

From Boltzmannian statistical mechanical context, this 'Demonic Lesson 1' would imply that it would be conceptually possible to conceive an epistemic agent whose increase in its observational capacity would make it divide the phase space of the agent into macrostates with progressively less phase volume, representing the capacity of this agent to distinguish between more and more distinct microstates of the system (Section 3). According to this path settled by the Maxwellian thought experiment, it would be possible to find an epistemic agent for which it would not be necessary to divide the phase space into macrostates (thus avoiding the use of probabilistic descriptions), due to its plausible epistemic access to individual microstates of the system. As the reader may note, this would imply that, for those extremely observant beings like those mentioned by Maxwell to Tait, the Boltzmann statistical mechanical entropy (well-defined by the Ehrenfests in 1911, forty-four years after the letter, see Uffink 2007) of a system at any time would be reduced to zero[2], which is highly problematic with respect to its empirical meaning.

However, these demonic lessons have a restricted domain of application: classical thermal physics. In the quantum domain, (i) Planck's length 'ℓ_P' objectively limits the ability of the agent to distinguish microstate in phase volumes smaller than 'ℓ_P^2', as well as (ii) Heisenberg's uncertainty principle limits the ability to simultaneously obtain accurate measurements of molecular positions and velocities within a system. Therefore, what in classical physics was shown by Maxwell as a mere pragmatic impossibility (although conceptually-nomically possible), in quantum physics would fundamentally be a nomic impossibility (because of the two previous principles).

IV-2. *A Very Neat-Fingered Being*

On the other hand, and central to the conception of Maxwellian thermophysics [Myrvold (2011)], even assuming the conceptual-nomic possibility (our 'Demonic Lesson 1') of epistemically accessing microsystems states, it would be pragmatically impossible for the scientific community of the late 1860s to directly manipulate or control the positional and deterministic velocity values of all molecules that make up macroscopic systems. This practical impossibility could be reformulated precisely as the instrumental impossibility of carrying out this task. Even one hundred and fifty years later and after substantial advances in the field of nanotechnology, it is still practically-instrumentally impossible to carry out the manipulation of each of the approximately 6 x 10^{24} positional and velocity values underlying macroscopic material substances. The only difference is that today (unlike in 1867) it would be possible to manipulate the position and velocity of individual molecules when the number of molecules involved is relatively low.

Note that by 'manipulation of molecular values' I do not literally mean the demon's ability to directly manipulate individual molecules, as this is unnecessary for Maxwell's experiment. On the other hand, I refer properly to its ability to alter molecular values by manipulating any mechanism depending on its knowledge of the current microstate, such as opening or closing the mass-less slide that allows molecules to pass back and forth, thus allowing the indirect manipulation of values required by its thought experiment. But as derived from Maxwell's thought experiment, despite this practical-instrumental impossibility of manipulating individual molecular values, it would not be incompatible with the principles of Hamiltonian analytical mechanics (nomically possible) or inconceivable (conceptually possible) that an agent could have the technical precision to manipulate accurately individual molecular position and velocity values that it has previously been able to observe (see previous section). Similarly, this nomically-conceptually plausible agent is the 'near-fingered being' referred to by Maxwell in his letter to Tait:

> *Demonic Lesson 2*: although it would be pragmatically impossible to manipulate particular molecular positions and velocities in macroscopic systems, it would be nomically-conceptually possible to achieve by 'a neat-fingered being'.

As noted above, Maxwell conceived thermodynamics not from the microdynamic of its molecular components (as if Clausius did) but from the possibility of extracting observable properties of material substances from the controlled manipulation of other properties of these, i.e., increasing the pressure of a gas in a vessel by increasing its temperature, but not varying its volume (Gay-Lussac's law). Therefore, for Maxwell the possibility of considering molecular statistical thermophysics at the same level of empirical significance as phenomenological thermodynamics did not depend ultimately on effectively reducing macroscopic thermodynamic quantities to molecular mechanical properties (as Boltzmann claimed until 1872, [*cf.* Uffink (2007)], but on the possibility of observing and manipulating-controlled these latter properties.

In this interpretative line, the 'neat-fingered' agent should not be imagined as a demon that catches molecules like these were basketballs, but as a scientist capable of altering thermodynamic properties of matter through controlled manipulation of molecular positions and velocities "If the very concepts of thermodynamics are means-relative, and we cannot even state the second law of thermodynamics without invoking a means-relative between heat transfer and doing work, then anthropomorphizing the demon no longer seems like a mistake." [Myrvold (2011), p. 243]. Therefore, the concern that Maxwell sought to express in his letter to Tait was not so much about the microphysical possibility of contradicting the second law of thermodynamics (as has been assumed throughout virtually all of the literature on this thought experiment), but about the possibility that the microstatistical properties of molecular position and velocity could possess an observational and controlled manipulability status similar to the properties of thermodynamics.

Maxwell's thought experiment helps us to understand (Demonic Lessons 1-2) that it is nomically possible with respect to Hamiltonian mechanics and conceptually possible with respect to what we can suppose that the scientific community is capable of (i) observationally accessing the actual microstate of the target system and (ii) manipulating those microstatistical values to alter the macroscopic properties of the systems. In this way, this 'very observant and neat-fingered' epistemic agent could conceptually access observationally and subsequently manipulate in a controlled manner the actual microstate of the gas homogeneously distributed in thermal equilibrium between the two volumes of the vessel, until finally obtaining a microstate of the gas that is far from thermal equilibrium.

Therefore, even without assuming any molecular thesis à la Clausius-Boltzmann, Maxwell raises to Tait the conceptual possibility (although impossible in practical terms) that observing and manipulating controlled molecular positions and velocities to alter thermodynamic quantities such as temperature or Clausius entropy. In this, Maxwell did not intend to alarm his fellow countryman that the second law could be violated at the molecular level, precisely because the Scottish physicist was fully aware that the micro-physical meaning of the second law could only be statistical: that is, although molecularly the entropy of a closed system could be punctually decreased, the entropy of closed systems will never decrease if we consider the average values [Maxwell (1952)]. Maxwell, unlike Clausius or Boltzmann[3], was fully aware of the finiteness of scientists' knowledge regarding the analysis of systems as highly complex as material substances, where statistical modeling was not an embarrassing failure of the mechanical-deterministic dream, but a sample of the wealth of epistemic resources available to the scientific community [Uffink (2007)]. Precisely the demon constitutes a way of, assuming this practically-conditioned epistemic finitude, cognitively assisting the observational and manipulative capacity of real scientists through a theoretically robust imaginative exercise.

> This is only one of the instances in which conclusions which we have drawn from our experience of bodies consisting of an immense number of molecules may be found not to be applicable to the more delicate observations and experiments which we may suppose made by one who can perceive and handle the individual molecules which we deal with only in large masses. In dealing with masses of matter, while we do not perceive the individual molecules, we are compelled to adopt what I have described as the statistical method of calculation, and to abandon the strict dynamical method, in which we follow every motion by the calculus [Maxwell (1871), pp. 308-309; Niven (1965)].

V. CONCLUSION

Maxwell's demon problem has been mainly considered throughout the history of thermal physics as an attack on the theoretical validity of the second law of thermodynamics, so the scientific community devoted a vast intellectual effort for more than a century to refute or 'exorcise' it at any cost, without much success [Norton (2018)]. In this article I have defended that under a properly Maxwellian conception or theoretical resource of thermal physics, recently claimed by philosophers such as Myrvold (2011) or Wallace (2017), Maxwell's thought experiment in 1867 did not directly intend to show how molecular physics undermines the second law, but to provide us with rich heuristic resources to explore the balance between practical impossibility and conceptual-nomic possibility that underlay the molecular thermophysics of the time, still in force for contemporary statistical mechanics.

> The data of the statistical method as applied to molecular science are the sums of large numbers of molecular quantities. In studying the relations between quantities of this kind, we meet with a new kind of regularity, the regularity of averages, which we can depend upon quite sufficiently for all practical purposes, but which can make no claim to that character of abso-

lute precision which belongs to the laws of abstract dynamics [Maxwell (1873), p. 440; Niven (1965) p. 374].

Universitat de Barcelona,
Carrer de Montalegre 6-8
4º Floor, office 4013
08001, Barcelona
E-mail: antajav@gmail.com

NOTES

[1] What Wallace calls 'dynamicism' about thermal physics is a deeply reductionist attitude, assuming that the theoretical legitimacy of phenomenological thermodynamics is reduced to its microphysical description.

[2] The reason why the Boltzmann entropy is reduced to zero is because the number of microstates contained in each macrostate (due to its enormous precision) is one. Thus, the logarithm of one is zero, which multiplied by the Boltzmann constant is still zero. By definition the Boltzmann entropy of a system at any time for an 'observer' à la Maxwell would be zero

[3] A clear example of Maxwell's criticism of Clausius and Boltzmann's [Wallace's (2016)] interpretation of thermal physics "The Hamiltonsche Princip. The while, soars along in a region unvexed by statistical considerations while the German Icari flap their waxes wings in nephelococcygia, amid those cloudy forms which the ignorance and finitude of human science have invested with the incommunicable attributes of the invisible Queen of Heaven" [Maxwell quoted on Knott (1911), pp.115-116]

REFERENCES

BRILLOUIN, L. (1951), "Maxwell's Demon Cannot Operate: Information and Entropy I; *Journal of Applied Physics* 22, pp. 334-337.

CALLENDER, C. (2021), "Thermodynamic Asymmetry in Time; *The Stanford Encyclopedia of Philosophy*, Edward N. Zalta (ed.), URL = <*https://plato.stanford.edu/archives/spr2021/entries/time-thermo/*>.

CANALES, J. (2020), *Bedevilled. A Shadow History of Demons in Science*. Princeton University Press.

CLAUSIUS, R. (1865), *The Mechanical Theory of Heat – with its Applications to the Steam Engine and to Physical Properties of Bodies*; London: John van Voorst, 1 Paternoster Row. MDCCCLXVII.

EARMAN, J. and NORTON, J. (1998), "Exorcist XIV: The Wrath of Maxwell's Demon. Part I. From Maxwell to Szilard"; *Studies in History and Philosophy of Modern Physics* 30(1), (1999) pp. 436-468.

— (1999), “Exorcist XIV: The Wrath of Maxwell’s Demon. Part II. From Szilard to Landauer and beyond”; *Studies in History and Philosophy of Modern Physics* 30(1), (1999) pp. 1.40.

EDDINGTON, A. (1928), *The Nature of the Physical World*; New York, MacMillan.

KNOTT, C. G. (1911), *Life and Scientific Work of Peter Guthrie Tait*; Cambridge UNIVERSITY PRESS.

LEFF, H. S. and REX, A. F. (1990), *Maxwell’s Demon: Entropy, Information, Computing*; Princeton University Press.

MCCOY, C. (2020) “An Alternative Interpretation of Statistical Mechanics”; *Erkenntnis* 85 (1), pp. 1-21.

MAXWELL, J.C. (1952), *Scientific Papers of James Clark Maxwell*, edited by W. D. Niven; New York Dover.

MYRVOLD, W. (2011), “Statistical Mechanics and Thermodynamics: A Maxwellian View; *Studies in History and Philosophy of Science Part A* 42 (4), pp. 237-243.

NORTON, J. (2018), “The Worst Thought Experiment”; In Michael T. Stuart, Yiftach J. H. Fehige and James Robert Brown (eds.), *The Routledge Companion to Thought Experiments*, Routledge, pp.454-468.

PENROSE, R. (2005), *The Road to Reality*; London: Vintage Books.

UFFINK, J. (2007), Compendium of the Foundations of Classical Statistical Physics”; in J. Butterfield and J. Earman, (Eds.), *Handbook for philosophy of physics*. Elsevier, Amsterdam. Available online at ⟨*http://philsci-archive. pitt.edu*⟩.

WALLACE, D. (2017), “Inferential vs. Dynamical Conceptions of Physics”; in O. Lombardi, S. Fortin, F. Holik, C. López (eds.), *What Is Quantum Information?* Cambridge University Press, pp. 179-204.