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From Watt's Steam Engine to the Unified Quantum Theory of Mechanics and Thermodynamics

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Abstract

Thermodynamics is the science that deals with all the phenomena that involve the transfer of energy, i.e. heat and work. Its development started in 1824 with the efforts of Sadi Carnot to improve the closed-cycle steam engine discovered by James Watt in 1764. In 1850, R. Clausius laid the foundations of the laws of thermodynamics. Soon thereafter a conflict between the second law of Thermodynamics and the laws of mechanics was pointed out by Maxwell in 1871 and was illustrated clearly by what has come to be known as Maxwell's demon. This conflict was addressed by Brillouin (1949) based on the work of Szilard (1929) and of many others. They all claimed that although the objective state of a system is fully describable by mechanics, classical or quantum, and evolves according to the laws of mechanics, some states of the system as perceived by an observer are subjective and reflect the lack of information the observer has about the actual mechanical state of the system. This point of view is, in effect, the information-theory interpretation of thermodynamics which, currently, is widely accepted. The central point of this paper is to describe the reasons why the information-theory interpretation of thermodynamics is contrary to physical reality. It shows that a logically viable hypothesis which reconciles mechanics with thermodynamics is the existence in nature of physical states that have objective uncertainties broader than those implied in quantum theory as it is traditionally formulated. The consequences of this hypothesis are presented in *the Unified Quantum Theory of Mechanics and Thermodynamics*, by Hatsopoulos and Gyftopoulos.

Keywords: Thermodynamics, Unified Quantum Theory of Mechanics and Thermodynamics, information-theory interpretation of thermodynamics, physical states with broader objective uncertainties, quantum theory

1. Thermodynamics

Thermodynamics is a physical science dealing with the transfer and the transformation of energy. Its development started in 1824 by Sadi Carnot, an engineer; more than a century after Isaac Newton established the foundations of classical mechanics. Ever since that time there has been, on and off, concerns expressed relating to conflicts between these two sciences.

The motivation behind Carnot's scientific effort was to find the basis of improving Watt's steam engine, invented 60 years earlier. Unlike steam engines in the past, Watt's engine was the first steam engine that did not consume water, it only received heat and produced work. Thus, it was the first true "*Heat Engine*". At that time the scientific community thought that heat was a fluid called *caloric* and that Watt's engine was nothing but a turbine that takes that fluid from a high level (a boiler at high temperature), produces useful work, and ejects it at a lower level (a condenser at lower temperature).

Carnot devised a reversible engine operating in a different cycle than Watt's engine. In Carnot cycle the working substance of the engine undergoes four successive changes: It

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receives heat (from the heat source) while expanding at high temperature, delivers work during a reversible adiabatic (no heat) expansion, rejects heat (to the heat sink) during a compression at low temperature, and finally receives work during a reversible adiabatic compression. The ratio of the net work output to the heat input, called the efficiency of a cyclical engine, is proportional to the difference between the temperatures of the heat source and the heat sink. Carnot asserted that it is the largest such ratio of any engine operating between the two temperatures. This assertion is known as Carnot's principle. It follows that an engine that produces work by exchanging heat with a single reservoir is impossible. Such an engine is called a *perpetual motion machine of the second kind* (PMM2). This definition is analogous to that of *a perpetual motion machine of the first kind* (PMM1) which produces work from nothing.

During the period from 1840 to 1848 James Prescott Joule showed experimentally that heat and work can produce the same effect on bodies when used in a fixed proportion. Thus, in a cyclic process, such as that of a cyclic engine, the net work produced must be proportional to the net heat received. He concluded that either heat or work results in a change of something stored in the bodies which is conserved. We now call that something energy.

In 1849 Lord Kelvin, a Scottish engineer, pointed out the conflict between the caloric basis of Carnot's argument in which heat (caloric) is conserved and the conclusion reached by Joule in which the sum of work and heat is conserved. Moreover, Joule's theory poses no limits on how much of the heat can be transformed into work, whereas Carnot's theory does. One year later, in 1850, Clausius reconciled Carnot's principle with the work of Joule by introducing the concept that bodies possess a property he called *entropy* having the following characteristics: In the absence of heat interactions with other bodies, it either remains constant if the body undergoes a reversible process, or increases. During heat interactions, on the other hand, the entropy of a body changes in proportion to the heat transferred to the body. It is this later characteristic that limits the efficiency of any work-producing cyclical engine, as required by Carnot's principle.

During the 50 years that followed Clausius, Maxwell, Planck and Poincaré completed the structure of thermodynamics and coined the terms *Second Law* for Carnot's principle and *First Law* for Joule's principle. The *First Law* asserts that the energy of an isolated body always remains the same. The *Second Law*, on the other hand, asserts that the entropy of an isolated body either stays fixed or increases but never decreases.

Soon thereafter J. Willard Gibbs produced his famous paper on *The Equilibrium of Heterogeneous Substances* and brought the science of generalized thermodynamics to the same degree of perfection and comprehensive generality that Lagrange and Hamilton had in an earlier era brought to the science of generalized dynamics (*The Scientific Papers of J. Willard Gibbs*, 1906*)*.

2. Statistical Mechanics

Concurrent with the development of thermodynamics as an axiomatic science was the development of the mechanical theory of heat which relates heat to changes in the motion of elementary particles of matter such as molecules. The history of that theory can be traced back to Democritus (c. 400 B.C.) and Epicurus (c.300 B.C.). The mechanical theory of heat, however, was not firmly established until Joule demonstrated experimentally that a quantitative relation exists between heat and work when they produce identical effects. In effect, Joule's finding directly relates the First Law of thermodynamics to Newton's laws of motion.

On the other hand, relating the Second Law to Newtonian mechanics proved more difficult. In particular a search to find what entropy meant within the framework of mechanics proved fruitless. As a result the scientific community at the time of Clausius believed that the Second Law applies only to macroscopic systems and, therefore, a way to find the meaning of entropy was by way of a new science called *statistical mechanics.* The essence of statistical mechanics is that most macroscopic bodies we study are too complicated for us to know their exact mechanical state at any given time and observations we make on these bodies represent averages either over time or space. The most we can know, therefore, at a particular time of the microscopic state of a physical body (system) is the probability of finding the system in that microscopic state.

The development of statistical mechanics can be traced through Helmholtz, Clausius, Maxwell, and Boltzmann. It culminated in the work of J. W. Gibbs who in 1901 presented an exposition of statistical mechanics that excels in completeness, rigor, and generality. Although Gibbs stated his exposition in terms of Newtonian mechanics, it is even better adapted to quantum mechanics, which in some ways it anticipates.

Perhaps because Gibbs' contribution was not fully understood, the less general and less rigorous approach of Maxwell and Boltzmann prevailed in the literature, with a few exceptions, until after World War II. A major contribution to the recent reawakening to Gibbs' methods is a book published by Erwin Schrödinger, in 1946, in which he explains the difference between the two approaches as follows: *"The older and more naïve application is to N actually existing physical systems in actual physical interaction with each other, e.g., gas molecules or electrons or Planck oscillators or degrees of freedom … The N of them together represent the actual physical system under consideration. This original point of view is associated with the names of Maxwell, Boltzmann, and others.*

"But it suffices only for dealing with a very restricted class of physical systems – virtually only with gases. It is not applicable to a system which does not consist of a great number of identical constituents with 'private' energies. In a solid the interaction between neighboring atoms is so strong that you cannot mentally divide up its total energy into the private energies of its atoms. And even a 'hohlraum' (an 'ether block' considered as the seat of electromagnetic-field events) can only be resolved into oscillators of many – infinitely many – different types, so that it would be necessary at least to deal with an assembly of an infinite number of different assemblies, composed of different constituents.

"Hence a second point of view (or, rather, a different application of the same mathematical results), which we owe to Willard Gibbs, has been developed. It has a particular beauty of its own, is applicable quite generally to every physical system, and has some advantages to be mentioned forthwith. Here the N identical systems are mental copies of the one system under consideration – of the one macroscopic device that is actually erected on our laboratory table."

The essence of Gibbs' statistical mechanics can be summarized as follows: The state of a macroscopic system can be represented by an ensemble of N mental copies of the one system under consideration each at specified microscopic mechanical state s_i such that the percent frequency p_i of the members of the ensemble at a particular mechanical state is the probability that the macroscopic system is in that microscopic state. He then shows that the entropy S of the macroscopic system is

$$S = -k\sum_i (p_i \ln p_i) \quad \text{where} \quad \sum_i p_i = 1$$

In this way he relates the Clausius entropy to mechanics. In the limit, of course, when one of the p_i equals 1 all others are zero. It means there is 100% probability that the macro system is in a specific micro-state. Then the entropy of the system is zero.

The era of quantum mechanics began in 1901 with the publication by Max Planck of his work on the distribution law for black-body radiation. That same year Gibbs published his famous paper on statistical mechanics. It should be pointed out that although the mechanical states Gibbs refers to are Newtonian his analysis applies, without change, to quantum mechanical states as well.

3. Maxwell's Demon

Although statistical mechanics relates the thermodynamic entropy to mechanics two major conflicts between the two sciences remain. The first was pointed out by Maxwell in 1871 and is illustrated very clearly by what has come to known as Maxwell's demon.

Concerning this conflict, Maxwell comments as follows: *"One of the best established facts in thermodynamics is that it is impossible for a system enclosed in an envelope which permits neither change of volume nor passage of heat, and in which both the temperature and the pressure are everywhere the same, to produce any inequality of temperature or of pressure without the expenditure of work. This is the second saw of thermodynamics, and it is undoubtedly true so long as we can deal with bodies only in mass and have no power of perceiving or handling the separate molecules of which they are made up. But if we conceive a being whose faculties are so sharpened that he can follow every molecule in its course, such a being, whose attributes are still as essentially finite as a our own, would be able to do that which is at present impossible to us. For we have seen that the molecules in a vessel full of air at uniform temperature are moving with velocities by no means uniform though the mean velocity of any great number of them, arbitrarily selected, is almost exactly uniform. Now let us suppose that such a vessel is divided into two portions A and B, by a division in which there is a small hole, and that a being who can see the individual molecules opens and closed this hole, so as to allow only the swifter molecules to pass from A to B, and only the slower ones to pass from B to A. He will thus, without expenditure of work, raise the temperature of B and lower that of A, in contradiction to the Second Law of thermodynamics."*

This conflict results from the fact that although mechanics allows under all circumstances the extraction of any fraction of the energy of any physical system confined within a given volume in the form of work, the Second Law limits the amount of work that can be extracted from such a system, depending on the value of a property called entropy, possessed by all systems in any specified condition. Only if the entropy of a system has the lowest value possible at the given energy, can all of its energy be extracted in the form of work. Under that condition, the laws of mechanics and thermodynamics become identical

The second conflict is stated by Gilbert N. Lewis in the following words: *"Willard Gibbs, in his early paper, first showed the incompatibility between molecular theory and the statement of classical thermodynamics that every system proceeds steadily toward a unique final state. We now have abundant experimental evidence that a system left to itself for an indefinite time assumes no single equilibrium state, but passed back and forth through a great number of different states which, however, are not easily distinguishable."*

This second conflict arises from the fact that thermodynamics allows the possibility of irreversible processes such as those that make an isolated system in a non-equilibrium state spontaneously proceed to equilibrium in the long run. On the other hand, the equations of motion in both Newtonian and quantum mechanics are reversible.

The advent of the wave theory of matter (quantum mechanics) and, specifically, the introduction in 1927 of Heisenberg's principle of indeterminacy raised great hopes that the paradox posed by Maxwell's demon might be resolved and, moreover, that a complete proof of the Second Law of thermodynamics could be obtained based only on quantum-mechanical principles. Slater attempted the former and Watanabe the latter. Both attempts failed. Watanabe proved that it is impossible to deduce the Second Law from the principles of quantum mechanics without using a further postulate which in effect is equivalent to the Second Law.

4. Szilard's Resolution

Many scientists believe that the conflicts between thermodynamics and mechanics were resolved by Szilard in his famous paper of 1929, and Brillouin who in 1956 combined Szilard's concept with the information theory developed by Shannon in 1948.

Szilard's premise may be summarized as follows: We shall accept the proposition that it is possible to construct mechanical devices that make use of any one fluctuation of a system in stable equilibrium so as to produce work. Moreover, we shall accept the Second Law in the form that no net positive work may be obtained on the average from a system in stable equilibrium without producing any other effects on the environment. From these assumptions, we conclude that any instrument used to identify any given fluctuation of a system in stable equilibrium will absorb a quantity of work which is at least as much as the work that may be obtained from the fluctuation.

Szilard gives the following example. A cylindrical enclosure of volume V contains one molecule and is maintained in equilibrium with a heat reservoir at temperature T. The cylinder is separated into two equal volumes by means of a sliding partition, and an instrument operating in a cycle and exchanging heat with the reservoir at T is used to identify which part contains the molecule. The partition is then operated as a piston and the part containing the molecule is expanded slowly against the evacuated part. From simple kinetics theory, we find that the average pressure, p, on the piston will be given by the perfect gas relation:

$$PV = C \qquad \text{where } C \text{ is a constant.}$$

It follows that the work W done by the piston on the environment during the expansion from volume V/2 to volume V will be given by:

$$W = C \ln 2.$$

He concludes that by virtue of the Second Law the work received by the instrument in order to determine on which side of the partition the molecule is to be found must equal $C \ln 2$.

The information theory interpretation of the Second Law in effect implies that what we call the thermodynamic state of a physical body (system) is not an objective condition of the body but rather the information an observer possesses about the actual micro-state of the body. Such characterization not only attempts to resolve the first conflict mentioned (the impossibility of a PMM2) above but also the second. The evolution of a system from a non-equilibrium state towards equilibrium designates loss of information on the part of an observer.

5. My Involvement in Thermodynamics

While attending Athens Polytechnic the only subject I didn't like was Thermodynamics which, I was told consisted of two axioms, the First and Second Laws. The First Law, which in effect says that the change of energy of a system equals the heat received by it less the work done by it, appeared to me trivial. The Second Law, which in effect says that all of the heat extracted from a single body can not be transformed into work, appeared to me contrary to the laws of mechanics. Contributing to my dislike of thermodynamics was the fact that my aging professor was unable to answer my questions.

A year later, after arriving at MIT to study electronics, I decided to try again and take a course in thermodynamics to see if the thermodynamics professor there, Professor Joseph H. Keenan, made more sense than my professor in Greece. Professor Keenan was well known in engineering schools around the world for his clarity of thought and his emphasis on precise definitions of terms. His text book *Thermodynamics*, Wiley, New York, 1941 was adopted by most prominent engineering schools in both the United States and abroad. His other publications, *Mollier Diagram* (1930), *Thermodynamic Properties of Steam* (1938) and *Gas Tables* (1945), still occupy prominent places on the bookshelves of engineers in the power-plant and chemical process industries.

After taking Professor Keenan's courses I was greatly impressed. Nevertheless, I only got hooked on to thermodynamics in 1950, after I pointed out my objections to his articulation of the Second Law.

In his classical book *Thermodynamics (Keenan, 1941)*, professor Keenan adopted the statement of the Second Law proposed by M Planck in his *Treatise on Thermodynamics (Planck, 1927),"It is impossible to construct an engine which will work in a complete cycle, and produce no effect except the rising of a weight and cooling of a reservoir."* This statement constitutes the most widely used statement of the Second Law.

I argued, as follows, that this statement is a tautology: The term reservoir in Planck's statement may mean a system in either stable equilibrium or not. If not, Planck's statement is incorrect, because one can always get work from a system in a non-equilibrium state or in a meta-stable state. If on the other hand it means a system in stable equilibrium, Planck's statement is true by the definition of a stable state. This is so because if one could cool the reservoir and get work, he could use that work to heat some part of the reservoir by friction, and thus have the reservoir change state while leaving no effect in the environment – a violation of what is meant by stable equilibrium.

After a long discussion, he agreed and then asked me to propose my own presentation. It took me ten years to complete Keenan's assignment. After many tries, I concluded that the Second Law is nothing different than a generalized statement that stable states exist. It may be expressed as follows: *A system having specified allowed states and an upper bound in volume can reach from any given state one and only one stable state and leave no net effects on its environment.*

I then showed that from this statement, one can derive not only all the corollaries of the Second Law but the First Law as well.

In 1959 Professor Keenan and I developed a new interpretation of thermodynamics that is applicable to a much wider range of systems and physical phenomena than any other interpretation presented in the past. This new interpretation applies to systems in non-equilibrium as well to equilibrium states, to systems having a few degrees of freedom, such as a single molecule, as well as systems with many degrees of freedom, such as a gas, quantum systems as well as classical systems, and systems undergoing nuclear as well as chemical reactions. It is presented in a book we coauthored, *Principles of General Thermodynamics,* published in 1965 (Hatsopoulos and Keenan, 1965) and adopted by the graduate engineering schools of several major universities, both in the United States and abroad.

6. Physical Reality

About the time when the book "*Principles of General Thermodynamics*" was being completed, we began to have doubts about the information theory interpretation of thermodynamics and concluded that it is contrary to physical reality. In other words, it is wrong.

To illustrate the point consider the following situation: There is a room held at a constant temperature T_0. We are told that in the room there are several identically constructed batteries, all at the same temperature--nothing else. Some of these batteries are charged and some are dead. The charged batteries can produce power, namely work, and the dead ones can not. From a thermodynamic point of view, the ones that are charged have lower entropy than the dead ones. I ask the question: can an observer having no further information determine which of these batteries are charged? Not only I believe the answer is a definitive yes, but also I believe we can experimentally determine how much charge its battery has and, therefore, calculate the difference in entropy between each of the charged batteries and the dead ones. Any logically thinking person, therefore, must conclude that entropy is an objectively determined property of these batteries.

Furthermore, other sciences such as physical chemistry and biology describe phenomena in terms of Gibbs chemical potential, a property which strongly depends on the partial entropy of a species in a mixture. Could we possibly imagine that the chemical potential of sodium ions in a living cell depends on the knowledge of an observer?

These concerns led us to the following conclusion: ***There are states of physical systems, such as stable equilibrium states, that are not describable by a single quantum mechanical wave function.***

7. A New Theory

In 1967, I teamed up with Elias Gyftopoulos, professor of nuclear engineering at MIT, to develop an axiomatic theory that includes all states of systems encountered in nature, and is entirely consistent with both quantum theory and the Second Law of thermodynamics.

The new theory is described in a four-part paper entitled "*A Unified Theory of Mechanics and Thermodynamics*" published in 1976 (Hatsopoulos and Gyftopoulos, 1976). It is derived from four postulates: Three are taken from quantum mechanics, and the forth is the following paraphrase of the generalized statement of the Second Law: *Any independent and separable system subject to fixed parameters has for each set of (expectation) values of energy and of numbers of particles of constituent species a unique stable equilibrium state.*

Thus, the Second Law of Thermodynamics is presented as a fundamental proposition which is inviolable and not as one which arises from human inability or ignorance. Unlike information theory, it treats all probabilities related to the state of a system as objective characteristics of the system, and independent of the knowledge of an observer.

In this theory the state of any system at any time is described by a *Density Matrix (Density Operator)* representing a Gibbs-type of ensemble of pure quantum states, each associated with a wave function, appearing in specific frequencies. These frequencies, in turn, represent probabilities that a state is describable by means of a single wave function associated with any one particular pure quantum state.

Newtonian mechanics stipulates that any physical body at any given time is in a particular mechanical state having specific positions and specific momenta for its constituent elementary particles. In contrast, quantum mechanics stipulates that the state of physical body at a given time can, at best, be described by a cloud of probabilities to find its particles in specific mechanical states. In other words, quantum theory postulates that the state of any physical system incorporates irreducible quantal dispersions that are inherent to it and can be described by means of a wave function.

The new theory goes one step beyond quantum mechanics. It stipulates that although a physical body can sometimes be found in conditions fully describable by means of wave function, as in pure quantum states, it can also be found, at other times, in conditions that incorporate broader quantal dispersions can at best be described by a cloud of probabilities to find it in any one particular quantum state. The uncertainties associated with such states, therefore, are much larger than those associated with pure quantum states. An example of these latter conditions is the state of stable equilibrium.

8. Reactions of the Scientific Community to the New Theory

With few exceptions, the reaction of the scientific community to the new theory was mostly non-committal and occasionally negative. The exceptions include Professor Henry Margenau (The Eugene-Higgins Professor of Physics and Natural Philosophy at Yale University) of Yale University, Professor J. H. Keenan of MIT, and Professor James Park of Washington State University. Their views are described below:

- In a letter of March 19, 1974 to Professor Louis De Broglie of the French Academy of Sciences, Professor Henry Margenau wrote: *"The [Hatsopoulos-Gyftopoulos] paper presents the Second Law of thermodynamics as a fundamental axiom deeply embedded in quantum theory and connects the two disciplines in a way previously unknown to me. And it sheds new light on the Second Law presenting it as a proposition which is inviolable, not as one which arises from human inability or ignorance.*

"It treats the probabilities of quantum mechanics as objective, independent of the knowledge of an observer. In view of the current trend, induced by the successes of information theory, which reduced thermodynamics to matters of what an observer knows, the seemingly flawless arguments of this article are to me encouraging.

"It rejects von Neumann's projection postulate; indeed it shows that if this axiom is used the attempted unification does not occur. At this point I speak with a personal bias, for I have tried to expose this postulate as invalid and useless for some 40 years. An early discussion with Einstein convinced me and him that I was on the right track. But while the literature does show diminishing reliance on this strange phenomenon of "collapse of a wave packet", most textbooks still feature it as a necessary ingredient of wave mechanics. It makes sense only in connection with a subjective interpretation of quantum mechanics, an interpretation which reduces physics to psychology.

"The paper leads to the astonishing but fascinating conclusion that the customary quantum mechanical equation of motion is not universal, suggesting that the prevalent formulation of quantum mechanics may not be complete or indeed correct…"

- In a letter of March 12, 1974 to Professor Eugene P. Wigner of Princeton University, Professor Joseph H. Keenan wrote:

"Entropy in classical thermodynamics is related to "the available work of the body and medium" (Gibbs, Collected Works, Vol. 1, p. 53) as well as to the impossibility of a perpetual motion machine of the second kind. No such concept as available work arises from mechanics.

"When Hatsopoulos and I wrote our 'Principles of General Thermodynamics' in 1965 we attempted to resolve the difficulty by means of Szilard's ideas about information and negentropy. We have since become convinced that this explanation is defective in that it does not show how work can be obtained from a system that is far from equilibrium with the environment, such as fossil fuel, by a person who approaches the system with no previous information about it. The theory of Hatsopoulos and Gyftopoulos claims that this work is determined by irreducible quantal dispersions of results of measurement that are inherent in the nature of a system.

"Instead of being a measure of our ignorance, in this theory a nonzero value of entropy becomes a measure of irreducible quantal dispersions of results of measurement associated with mixed states. The mixed states in question are operationally defined, objective, and irreducible to mixtures of other states.

"Any subjective imperfection of knowledge about the state results in the need to consider additional dispersions which must be superimposed on those that are inherent to quantum physics. It is this subjective ignorance with which the anthropomorphic interpretation of thermodynamics is principally concerned but which is related to the basic unavailability of energy which is the essence of the Second Law. The unavailability is related only to irreducible quantal dispersions associated with results of measurements and in no sense involves the knowledge of an individual observer. Beyond the irreducible dispersions considered by von Neumann in connection with pure states, the authors prove the existence of irreducible dispersions associated with mixed states and these dispersions express the basic implications of the Second Law of classical thermodynamics."

- In a letter of June 18, 1974 to The Physical Review Professor James Park wrote:

"Beyond question this [Hatsopoulos-Gyftopoulos] paper contains profound new content. The unified theory constructed in the paper contradicts nothing in experience. Yet it does point the way toward the resolution of contradictions which at present do exist (despite extravagant claims of information theorists) between orthodox quantum mechanics and thermodynamics. Especially noteworthy is an original analysis of state preparation which establishes the necessity and probes the hereto forth uninvestigated possibility that a mixed density operator may describe an ensemble physically irreducible to pure constituents. That such a quantal discovery should occur in the context of thermodynamical argument is fascinating, for it is somewhat reminiscent of the role of thermodynamics in the early history of quantum mechanics."

9. Concluding Remarks

The discussion given above leads to the following conclusions: (1) The Second Law is probably as universally valid as is the First Law, namely the conservation of energy, and (2) Entropy is not a subjective property of a system related to what an observer knows about it but an objective and measurable property of any system in any state.

The Second Law restrictions have enormous practical importance. The human needs for energy relate almost exclusively to work: Work is needed to power our vehicles, to produce electricity, to cool an environment to below ambient temperature, to heat an environment to above ambient temperature, and to perform a multitude of physical or chemical transformations in the processing of materials. The only human needs that don't require work are to heat or cool something to ambient temperature. Every other need requires work. The ultimate solution to the energy need of our society, therefore, is to invent a machine that draws upon the enormous energy existing in our environment and produces work. Such a machine is called the *perpetual motion machine of the second kind* (PMM2), which, unlike the *perpetual motion machine of the first kind* (PMM1), does not violate the law of conservation of energy.

Still, a literature review reveals that most physicists from 1850 to the mid 20th century believed that the prohibition of Second Law is not absolute, but merely reflects limitations of the prevailing state of micro-technology. After that period most physicists still believe the prohibition does not relate to the objective condition of a system but rather reflects lack of knowledge of the observer.

In contrast to physicists, virtually all engineers reject both these explanations and believe that the impossibility of a PMM2 is an irrefutable law of nature. In other words they believe that entropy is an objective property of any physical system that can never decline unless the entropy of another system increases by at least the same amount. This view prevailed to such an extent that, although enormous effort is constantly made to find new sources of energy, no organized activity to develop a PMM2 has ever been undertaken. In fact the US Patent Office has ruled that any invention violating the Second Law be rejected. In this connection, one may mention, somewhat facetiously, that a US Congressman once objected to this ruling on the grounds that the U.S. Congress had never, to his knowledge, passed any law called The Second Law of Thermodynamics.

9.1 An unanswered question

The Hatsopoulos-Gyftopoulos theory resolves the conflict pointed out by Maxwell but not the one pointed out by Gilbert N. Lewis. The latter results from the fact that thermodynamics permits, but does not mandate, irreversible processes that increase the sum of the entropies of all systems involved. Yet the equation of motion, we know, is reversible. Margenau comments in his letter to DeBroglie: "*The paper [by Hatsopoulos-Gyftopoulos] leads to the astonishing but fascinating conclusion that the customary quantum mechanical equation of motion is not universal,…*"

The question arises whether we need to devise a more general equation of motion that permits irreversible processes. It is very difficult to answer this question because we don't know what makes a process irreversible. All we actually know for a fact is that in the absence of heat and work interactions, a condition we call isolation, a system sometimes proceeds towards equilibrium at constant energy and, therefore, its entropy increases. On that basis we conclude that irreversible processes exist.

9.2 Developments after 1976

In 1979 a doctoral student of Elias Gyftopoulos, Gian Paolo Beretta, joined our team and after two years came up with an equation of motion that satisfies the long list of necessary properties for it to be compatible with the unified theory, including the feature that it reduces exactly to the Schrödinger equation for states that can be described by a single wave function. The Beretta equation implies a spontaneous and irreversible tendency of the cloud of probabilities that describe the state of an isolated system to rearrange themselves so as to increase the entropy at constant energy until eventually an equilibrium distribution is reached, which turns out to be dynamically stable. Thus, by postulating this equation of motion in the unified theory, our generalized statement of the second law becomes a theorem. Gyftopoulos, Beretta and coworkers have proved (Beretta et al., 1984) several other mathematical and physical features, including proofs of Onsager reciprocity and steepest-entropy-ascent theorems. The theory, now completed with a dynamical principle that entails the second law, prompted the encouraging reactions outlined above.

Since then, with few exceptions, the theory has been almost ignored, until in 2001 it was literally 'rediscovered' by Georghiu-Svirschevski who published a paper in the Physical Review A (Gheorghiu-Svirschevski, 2001a) entitled "*Nonlinear quantum evolution with maximal entropy production*" in which he proposes "that a physically meaningful nonlinear extension emerges when the fundamental postulates of quantum mechanics are supplemented by the first and second principles of thermodynamics, at the sole expense of ignoring the constraint of a linear, unitary evolution in time" and derives the Beretta equation from a maximal entropy production variational principle entirely equivalent to the original steepest entropy ascent hypothesis. Although this paper makes no reference to any of our original papers, an Addendum published soon after in *Physical Review A* by the same author (Gheorghiu-Svirschevski, 2001b) acknowledges his oversight of our pioneering contributions.

What is important is that recent advances in technology and laboratory techniques towards micro-devices and experimental setups have moved the interest of the physical community towards the microscopic world, where the implications of thermodynamics still hold. Therefore, slowly, there appears to have been a drift towards reformulations of the statistical mechanics and the information theory approaches that tend to gradually incorporate the fundamental hypothesis presented in this paper.

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