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Entropy, information and Maxwell's demon after quantum mechanics

RAJENDRA BHANDARI
Raman Research Institute, Bangalore 560006

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Abstract. The problem of the subjective nature of entropy and its relation to information and irreversibility is examined in the light of the quantum measurement problem. The main thesis of the paper is that state collapse during a measurement and hence entropy increase in the observed universe is seen by observers who are only able to observe a restricted manifold of states determined by their concepts, language, etc., in short by their level of perception. The thesis leads to the assertion that any universe with a structure must evolve.

Keywords. Entropy; information; quantum measurement; observer.

1. Introduction

The concept of entropy has been with us for well over a century. During this time it has enjoyed the unique status of being a physical quantity that has been used in practical day to day calculations with enormous success, while controversy and debate over its real meaning has occupied the minds of physicists ever since it was introduced by Clausius in 1864. It would not be an exaggeration to say that no satisfactory and well-accepted definition of entropy exists. The main reason for the special interest in entropy is its unidirectional behaviour in all spontaneous processes and its close association with the second law of thermodynamics, the latter being a statement of the unidirectional nature of macroscopic physical phenomena. Unlike most other physical quantities, entropy does not obey conservation laws. It can be created out of nowhere but can never be destroyed.

An important aspect of the controversy over the meaning of entropy and that of the second law is whether these are independent of the abilities of an observer. The question is an important one, since it has a bearing on the philosophical foundation on which all physical sciences rest, namely, that scientific laws are independent of the existence of an observer.

The controversy started in 1871 when James Clerk Maxwell introduced his now famous demon. Maxwell's demon was endowed with the ability to see and follow the motions of individual molecules of a gas. By operating a trap door between two chambers at appropriate times the demon was able to separate fast and slow molecules at will, creating a temperature difference without producing any effect elsewhere. The demon was thus able to violate the second law of thermodynamics by virtue of his sharpened faculties. Maxwell's demon has been discussed ever since, most discussions seeking to re-establish the validity of the second law irrespective of the faculties of an observer. A good review of the main developments in the problem is contained in an article by Ehrenberg (1967). An important by-product of the efforts to 'exorcise' Maxwell's demon was the appreciation of the intimate relation between entropy and information discovered by Szilard and further developed by Brillouin (1960 *a*, 1960 *b*). The latter showed with the help of a series of thought experiments that if the demon is restricted to using known physical means of perception, he would require a source of negentropy to observe the molecules and the amount of negentropy spent in an observation would always out-balance the amount of negentropy that can be created with the help of the information obtained in the observation, thus preventing the demon from being able to violate the second law on a global basis. Brillouin draws the conclusion from this that information is equivalent to negentropy and *vice-versa.** The idea has been developed further by Jaynes (1957 *a, b*) who has proposed a 'subjective statistical mechanics' based on information theory and the 'principle of least biased inference' It is not uncommon to find in recent literature the terms information and negentropy being used synonymously.

The identification of entropy with an inherently subjective quantity like information is, however, not without difficulties. We intend to show in this paper that if this identification be made the basis of a fundamental definition of entropy, far reaching implications, both physical as well as philosophical must result. This is particularly true in view of developments in physics like quantum mechanics and high energy physics.

The second main point we wish to deal with in this paper concerns the Maxwell's demon problem. Most treatments, including those of Brillouin have regarded the demon as a measuring instrument obeying the laws of physics, and hence subject to the inevitable fluctuations in the environment. We feel, however, that a new dimension is added to the problem when we take into account the new facts revealed by quantum mechanics, particularly by the quantum measurement problem. There has been ample discussion of the measurement problem in quantum mechanics to show that one has to go beyond this simple-minded concept of an observer to deal with observed phenomena. We intend to do this in this paper and discuss the problems of entropy, irreversibility, quantum measurement and their inter-relationships from a point of view that regards the observer as an indispensible element in a complete description of physical reality (whatever the term might mean). Some preliminary thoughts along this line were reported elsewhere (Bhandari 1974).

2. Subjectivity of entropy

We shall discuss in this section from very general considerations the elements of subjectivity present in the statistical as well as in the phenomenological definitions of entropy, without going into the implications of quantum mechanics.

In statistical thermodynamics the entropy S of an isolated system is defined as

$$S = k \ln W \tag{1}$$

where k is Boltzmann's constant and W is the number of microstates or 'complexions' accessible to the system. The definition of what constitutes an accessible

* Brillouin was preceded in this identification by Shannon who had, in 1948 given the name entropy to his newly formulated uncertainty function in communications.

microstate requires some care. In principle there is no reason why any conceivable microstate of the system should be considered inaccessible. One has to go further, therefore, and say that all microstates that are compatible with available 'knowledge' about the system should be considered accessible and those that are not should be considered inaccessible. In fact, according to the principle of least biased inference, one must assign equal a-priori probabilities to all states unless one has additional knowledge that requires one to favour some microstates over others. In the latter case, the entropy is given by a more general expression:

$$S = -k \sum_{i} p_i \ln p_i \qquad (2)$$

where p_i is the a-priori probability for the i-th microstate. The entropy defined this way is manifestly a subjective quantity and would be of little use in physics. For example, if one wanted to calculate the entropy of a glassful of water and one did not know anything about the system except that it is 100 grams of water, one must count all the states with energies corresponding to the entire temperature range between 0° and 100° C as accessible states. We, therefore, have to restrict the definition even further before it can represent the objective, physical entropy of physics. We have to decide on a definite set of parameters of a system which can be considered to be given irrespective of whether one measures them or not and knowledge of these quantities must be used as constraints on the possible microstates of the system. The entropy would then have a definite common value for all observers who agree on this set of parameters beforehand. The most commonly used parameters are the macroscopic parameters like energy, temperature, pressure, volume, magnetization, electric polorization, applied stresses and so on. The entropy calculated with known values of these parameters is then the physical entropy of the system. An important property of these macroscopic parameters is that the entropy thus calculated is insensitive to the precise accuracy with which these parameters are known. One must count all the states compatible with any values of the parameters lying within the range of errors of measurement, but the parameters chosen are such that the change in the total number of states when the experimental accuracy changes make an insignificant change in the entropy. This is the additional factor that accounts for the seemingly objective nature of the physical entropy. The fact remains, however, that the value of the entropy depends upon the choice of macroscopic parameters as being special by the observer and is, in this sense, subjective. This choice is in turn determined by the fact that the observer is unable to deal with individual molecules.

It could be argued that after all there does exist a well-defined procedure for measuring the entropy experimentally, using the phenomenological definition according to which the entropy change $\triangle S$ between two thermodynamic states 1 and 2 is given by,

$$S = \int_{\substack{1 \\ \mathrm{rev}}}^{2} \frac{dQ}{T} \qquad (3)$$

where dQ is the heat given to the system at T, the system being taken from state 1 to state 2 along a reversible path. A discrepancy between the measured and calculated values would then presumably be revealed if the observer lacked some knowledge about the system. This is, however, not true. The reason lies in the requirement that the process used for calculating the entropy change be *reversible*. In order to ensure that the transformation from state 1 to state 2 be reversible, the experimenter has to put appropriate constraints on the system to prevent the process from proceeding irreversibility. *The ability of an observer to put enough constraints on the system to make the process reversible would depend upon the observer's knowledge about the system, thus bringing in the same element of subjectivity in the measured entropy as in the calculated entropy.* For example, if we have two different gases which are allowed to mix, an observer who knows that the gases are different can use a semi-permeable membrane and obtain a certain maximum amount of work during the mixing by making the mixing infinitesimally slow. He can then supply the required amount of heat quasi-statically to bring the mixture to its original temperature, thus measuring an entropy increase. On the other hand, for the observer who does not know that the gases are different, nothing happens during the mixing and he measures no entropy increase.

Thus if all observers were unaware of certain degrees of freedom of the system, they would make the same mistake in the measured as well as in calculated values of entropy and would still agree. We can therefore make the following addition to Jaynes' assertion (Jaynes 1957 *b*, p. 172): " Even if the class of experimentally reproducible phenomena do not differ from the class of phenomena predicted by maximum entropy inference, new laws of physics, or new kinds of physical states could be involved. "

3. Quantum measurement problem

In quantum mechanics the problem of measurement has a status which is quite different and much more fundamental than the corresponding problem in classical mechanics. A measurement performed on an arbitrary state of a quantum system results in an unpredictable and indeterminate collapse of the original state onto one of the eigenstates of the observable being measured. The state of the system after the measurement is in general different from the state before the measurement. From the results of a quantum measurement, therefore, one cannot reconstruct the state before the measurement; one can only make statistical predictions about the outcome of future measurements. Putting it very simply, the basic characteristics of a classical measurement namely—when you look you see what is already there—is not shared by a quantum measurement.

It can be said that the problem of measurement in quantum mechanics contains the essence of all that is mysterious in quantum mechanics. The problems of w ve-particle duality, the uncertainty principle, non-locality, non-separability, etc. are in one way or the other, related to the fundamental enigma presented by quantum mechanics, namely why should the state function collapse during a measurement ? The technical aspects of the measurement problem and the various solutions proposed have been widely discussed in the literature (d'Espagnat 1971 *a*, *b*) we shall therefore not repeat them here.

Our own standpoint is that the essence of the problem lies in that nature admits of a much larger manifold of states—the manifold of quantum states—rather than the restricted manifold of classical states that we, as classial observers, are able to observe. By classical states we mean states that describe objects, each having a well-defined position in a three-dimensional space at every instant and fields having a well-defined value at every point in this three-dimensional space at each instant. By classical observers we mean observers who are able to perceive directly only those states that satisfy these requirements. Every phenomenon of our direct experience therefore satisfies these requirements. Our indirect experience of quantum phenomena tells us, however, that these requirements are not satisfied by phenomena at the quantum level. As long as we are classical observers, therefore, we can never observe phenomena at the quantum level directly. We can observe quantum phenomena only *via* the effects they produce on phenomena at the classical level. It is this necessity of indirect observation through the intermediary of classical states that causes quantum states to collapse during an act of measurement. For a hypothetical observer who is not restricted to observing only the manifold of classical states, but is sensitive to all quantum states, wave collapse should not occur. We shall call such an observer a non-classical observer.

The belief stated above that the classical nature of all human observers is an important element in understanding the mystery of quantum mechanics is not new. Niels Bohr emphasized the point quite strongly in his discussions of the epistemological situation in quantum mechanics (Bohr 1958). In these discussions, however, the classical nature of a human observer has been taken more or less as a fundamental and immutable fact of human existence. Consequently, the implications of the existence of a non-classical observer have received little attention. We believe, however, that there is no logical basis for excluding the possibility of such an observer and that it should be considered as the modern analog of Maxwell's demon.

Before attempting to speculate on what features this non-classical observer must have in order to 'see' quantum phenomena without a collapse we must ask the question: What makes us classical observers? To answer this question, we suggest the hypothesis that 'it is our commitment to a minimal set of concepts as being the *a-priori* pre-condition of experience which makes us classical observers, these concepts being a three-dimensional space, an absolute time, isolated objects which include massive objects as well as massless fields, the principle of casuality, etc.' The reasons for our being classical observers according to this hypothesis are purely psychological, hence not absolute. The seemingly inevitable nature of these concepts only reflects their deep-rootedness. The minimum requirement the non-classical observer must satisfy, therefore, is freedom to observe phenomena more general than objects moving in a three-dimensional space.

4. Macroscopic and classical levels—are they the same?

In classical statistical thermodynamics, we work in terms of two levels, the macroscopic and the microscopic levels. The microscopic level is assumed to describe things as they 'really are' and as they 'really happen'. The macroscopic level describes things as they appear to us. Moreover as we have seen already, the macroscopic level provides the parameters which may be taken to be given whether or not one measures them, while the parameters at the microscopic level, for example atomic positions and velocities, cannot be considered as being known unless one measures them.

When faced with the question as to why the two levels are different, in other words, why do we not see things as they really are, one has to resort to arguments which are ad-hoc and are not part of the main scheme of quantitative physical laws. For example, one says our senses are too crude to follow the rapid motions of atoms, our eyes are too crude an instrument to resolve extremely small distances or one says our brains have a limited capacity to process information and so on. The necessity of such arguments, in our view, implies the existence of an extra-physical and indeterministic element in the total process of cognition. If the entire process of cognition were subject to deterministic physical laws, there would be no room for any randomness. The aim of physics, however, is to explain observed phenomena. As such there is no principle or clear-cut postulate in classical statistical thermodynamics that determines why the separation in orders of magnitude of the two levels should be what it is. The explanations of observed phenomena in terms of statistical mechanics are, in this sense, incomplete.

When we come to quantum mechanics, once again we find two levels—the quantum level and the classical level. The distinction here is more subtle and is not as simple as between big and small or between what appears and what really is. The classical level consists of phenomena that can be described in simple everyday concepts of objects, space, time, motion, casuality and so on. The quantum level consists of phenomena that, by implication, do take place but cannot be described in terms of the above concepts. Usually it is the phenomena at extremely short distances and at short time scales that show quantum behaviour. There are phenomena, however, that show quantum behaviour over 'macroscopic' distances.

Unlike the distinction between 'microscopic' and 'macroscopic' in classical statistical mechanics, we have in this case, however, a fundamental physical constant h that determines the separation between the quantum and the classical levels. The question as to why are there two levels, though not answered, is faced much more directly in this case. We have dealt with this already while discussing the quantum measurement problem.

The important suggestion we wish to make in this section is that the above two distinctions—that between microscopic and macroscopic and that between quantum and classical which have, *a-priori*, nothing to do with each other, are really the same. In other words, *the macroscopic regime of classical statistical mechanics and the classical regime of quantum mechanics are the same.*

This provides an important link between statistical thermodynamics and quantum mechanics. With this, link, we have taken at least one step further towards explaining the special status assigned to macroscopic parameters in statistical thermodynamics, for we can say that macroscopic parameters are the ones that behave classically and are, therefore, special for us as classical observers.

5. Irreversibility in quantum measurement

The most fundamental and widely discussed enigma in statistical mechanics is the irreversibility of macroscopic phenomena, which cannot be explained entirely in terms of microscopic phenomena. It provides the strongest challenge to the view that phenomena on the macroscopic scale can be 'explained' in terms of microscopic phenomena. The quantitative description of irreversibility is given in terms of an increase in entropy, which accompanies every macroscopic process. In order to derive the increase in entropy of a system containing a large number of degrees of freedom, one has to introduce new features in the description of the time evolution of the system in addition to the dynamical laws of time evolution (ter Haar 1954). These features are, statistical averaging over macroscopic distances and time scales, also called coarse-graining. The justification usually given for these additional steps is the macroscopic nature of our measurements. It is implied in the argument that entropy increase occurs only for observers who are unable to make microscopic measurements.

We propose in this section that:

(1) The entropy increase belongs only to phenomena as they are observed and not to unobserved phenomena and

(ii) the state-collapse involved in any observation of a microscopic phenomenon by a classical observer is the cause of irreversibility and that of entropy increase in the observed phenomenon.

The complete quantum measurement can be looked upon as a two-stage process for this purpose, *i.e.*, the state collapse proceeds in two steps:

(i) In the first step, the wave-function of the combined system consisting of the object of measurement and the measuring instrument goes from a pure wave-function to a density matrix which is diagonal in the basis of the eigenstates of the observable being measured. This step involves an entropy increase related to the *loss of information* on the relative phases of the basis states in the original state. This is the 'unread measurement'.

(ii) In the second step, the apparatus is read by an observer and the density matrix collapses to a pure state corresponding to a definite value of the observable being measured. This step involves an entropy decrease corresponding to the *gain of information* about the actual state of the system.

The first step involving an entropy increase is a purely quantum mechanical feature and has no analog in a classical measurement. The second step is the entropy decrease associated with every classical measurement as discussed by Brillouin and others. The relation between entropy and information established by Szilard and Brillouin by pointing out the minimum negentropy required for obtaining information applies to the second step and saves the second law for classical observations. After taking this negentropy into account we are assured that the entropy of the observed universe goes on increasing.

The main problem, however, is to explain this universal entropy increase. It is the first step, we believe, that accounts for just this. Any observer for whom the state must collapse during an observation sees irreversible behaviour and entropy increase.

6. Entropy associated with concepts

In the previous section we asserted that irreversible behaviour is seen by any observer for whom the state must collapse during an observation. We have also argued that the state must collapse during an observation for any observer whose conceptual framework does not admit all states allowed in nature. For such an observer, the entropy of the observed universe goes on increasing. In this section, we shall analyse the relation between statistical entropy, information and 'knowledge', keeping in view the possibility of a variety of observers each with a different conceptual framework and shall draw some conclusions regarding the nature of an observer who never sees an entropy increase and for whom the universe is, therefore, always in thermodynamic equilibrium.

A quantitative measure of information involves three things (Tribus and Irvine 1971); (i) a well-defined question Q, (ii) a set of all possible answers to the question Q and (iii) a measure of our knowledge X about the question Q. The knowledge X determines the *a-priori* probabilities p_i that we should assign to the various possible answers i. In a state of total ignorance or no knowledge about Q we assign the same value to p_i for every answer i, simply because there is no reason to prefer any one answer to any other. If we know the correct answer with certainty, we assign $p_i = 1$ to the correct answeer and $p_i = 0$ to all other answers. The most appropriate quantitative measure of our ignorance (or knowledge) about the qeusiion Q is found to be the function $S(Q/X)$, first defined by Shannon as,

$$S(Q/X) = -K \sum_i p_i \ln p_i \tag{4}$$

where K is a constant that depends upon the choice of units and p_i is the probability that the answer i is the correct answer. These must satisfy the relation:

$$\sum_i p_i = 1 \tag{5}$$

The function $S(Q/X)$ has all the properties desired of a measure of ignorance. For example, it has the property of additivity for ignorance about two completely independent questions. It has a maximum value when all p_i's are equal, which is intuitively the state of maximum ignorance about the question Q and so on.

The function $S(Q/X)$ acquires all the properties of entropy in statistical mechanics if we (i) identify Q with the question : 'What is the exact microstate of the system ?' (ii) identify p_i with the probability that the system is in the ith microstate and (iii) replace the constant K by Boltzmann's constant k. A state of maximum entropy then corresponds to maximum ignorance about the actual microstate of the system, when all p_i's corresponding to the possible answers are equal.

The important point we wish to bring out in this section is that even in the state of supposed total ignorance about the question Q, when all p_i's corresponding to the possible answers are equal and $S(Q/X)$ has its maximum value, we do have some 'knowledge' about the system. This is the knowledge that goes into constructing the possible answers to the question Q, i.e., for constructing the possible microstates of the system. Before we can construct the possible microstates of a system, we have to start with a minimal set of concepts and assumptions to which the states of the system must conform under all circumstances of interest. We propose that this knowledge should also be considered as contributing to the negentropy of the system, because after all, the use of a given set of concepts can be looked upon as putting $p_i = 0$ for all states that contradict these concepts. For example, in constructing the possible microstates of an ideal classical gas, we have to assume that the gas consists of a fixed number of immutable particles, that each particle is completely described by assigning three position coordinates and three velocities in a classical three-dimensional space.

We know, however, that each of these concepts and assumptions has its limits and ceases to be relevant for the same mass of gas under different conditions. For example, if the gas were heated to a temperature high compared to the binding energies of electrons within the atoms, we would have to consider a new set of assumptions regarding the number of particles, etc. If the system were heated to still higher temperatures, at temperatures large compared to the rest energies of electrons and protons, one would need a further new set of assumptions and even concepts before one can construct possible states of the system. In each successive step, we have an enlargement of the total set of states accessible to the system associated with relaxation of certain constraints which are appropriate at one level, but not at the next.

We therefore propose, as a very qualitative hypothesis, that 'every set of concepts and assumptions used to construct the possible states of the universe has associated with it a certain amount of negentropy; the more restrictive the concepts, the larger is the negentropy'. It follows that the state of absolute maximum entropy occurs for an observer *who has no concepts whatsoever.* For such an observer, there is no room for any entropy increase in the universe, because this observer already considers *all* states as being equally probable and does not put $p_i = 0$ for any state, even unconsciously. This is the only state, in our view, which can be called a state of true thermodynamic equilibrium for the observed universe. Such a universe, quite properly speaking, has no structure, no particles, no laws and no time-evolution.

7. Non-separability and entropy associated with the concept of isolated objects

To illustrate the idea developed in the previous section, we shall consider as an example the concept of isolated objects and show that there is a negentropy associated with this concept. It has been well known that the concept of isolated objects is difficult to maintain for quantum systems. The problem is related to the famous 'Einstein-Podolsky-Rosen paradox' (*see* d'Espagnat 1971 *a*, Ch. 7,9).

We call something an isolated object if at each instant we can assign to it a definite state such that this state is independent of the state of every other object. In other words, the results of measurements made on an isolated object are independent of the results of measurements made on any other object. This requires that the object have or have had no interaction (hence correlation) with any other object. No two objects in the universe can therefore be considered as completely isolated. In classical mechanics, however, objects separated from each other by a large distance come arbitrarily close to being isolated objects, for the simple reason that all interactions fall off with distance. In case of quantum systems, the situation is different. Correlations between quantum systems do not necessarily fall off with distance. If we have a pair of quantum systems which have interacted at some instant in the past, none of the two systems can, in general, be assigned a state in which the result of measurements made on one system is independent of the result of measurements made on the other system, no matter how far apart the two systems are at a later instant.

The essence of the problem is in the principle of superposition that applies to the states of quantum mechanical systems. The state of a quantum mechanical system is completely described by a wave-function. Let us consider two quantum mechanical objects 1 and 2. Let us label the possible states of object 1 by ϕ_i and those of object 2 by ψ_i. A general quantum state ϕ of object 1 is then given by

$$\phi = \sum_i a_i \phi_i$$

while that of object 2, ψ is given by,

$$\psi = \sum_j b_j \psi_j$$

where a_i and b_j are complex numbers satisfying $\sum_i |a_i|^2 = \sum_j |b_j|^2 = 1$. A general quantum state Ψ of the combined system consisting of objects 1 and 2 is then given by

$$\Psi = \sum_{i,j} C_{ij} \phi_i \psi_j.$$

According to the criterion mentioned earlier, the combined system can be considered as consisting of two separate objects only if the state Ψ could in general be written as a simple product of a suitably chosen state ϕ of object 1 and a suitably chosen state ψ of object 2. This is, however, not true. The set of all states Ψ is larger than the set of all states $\tilde{\Psi}$ which are of the form

$$\tilde{\Psi} = \phi\psi.$$

In treating the system as consisting of two separate objects, therefore, we restrict the possible states of the system to the set $\tilde{\Psi}$, which is smaller than the set Ψ. This restriction should be considered as constituting 'knowledge' about the system, hence as contributing to the negentropy of the system.

In the case of quantum systems we do not make this restriction because states of coupled quantum systems which are of the more general type Ψ are easily observed. Quantum objects cannot, therefore, be considered as separate, independent objects. The entropies of two quantum objects will, for the same reason, not be additive. This can be seen very easily.

Let us consider the system of two coupled quantum mechanical objects discussed earlier. Let the combined system be in a pure state Ψ given by

$$\Psi = \frac{1}{\sqrt{2}} [\phi_1\psi_1 + \phi_2\psi_2].$$

The entropy S of the combined system, being in a pure state, is zero. The entropy of each of the individual systems is given by

$$S_1 = S_2 = -kTr\, \rho \ln \rho$$

where ρ is the density matrix of each of the individual systems in the basis of the states of that system alone, *i.e.*, in the basis of ϕ_i or ψ_i. This is given by,

$$\rho = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix}$$

Clearly, $S_1 = S_2 > 0$. Hence $S_1 + S_2 > 0$ and therefore

$$S \neq (S_1 + S_2).$$

The important fact that emerges from this analysis, however, is that in the realm of classical objects where we do make the approximation of separate objects whose entropies are additive, the total system consisting of all 'objects' has a negentropy associated with the fact that the system has been broken up into separate objects.

8. Discussion

We have tried to present in this paper an unconventional view on the problems of entropy, quantum measurement and irreversibility. This view attributes a role to the observer in determining the nature of observed phenomena, which is far more prominent than hitherto considered necessary or desirable in physics. It abandons the common interpretation of our experience in terms of an external world with a given structure, evolving according to fixed laws of time-evolution and an observer who can observe, think and discover these fixed laws and the given structure. 'Phenomena' and the observer are inextricably mixed in this view. It introduces 'levels of perception' as a new element in the description of physical reality. Each of these levels of perception is characterised by a set of concepts and assumptions which determine the totality of states that can be 'seen' by an observer at this level. With a change in the level of perception, he sees a qualitatively different universe (for any reasonable meaning of the word 'universe').

We have argued that a totally concept-free observer cannot see any phenomena for such an observer sees a universe without any structure. The implication is that the structure an observer sees on the universe is by virtue of his conceptual frame-work. We have shown that such an observer necessarily sees an evolving universe if the second law of thermodynamics is true. The conclusion is that 'structure implies evolution.' This is a statement that has physical implications. It says, for example, that a universe consisting of a finite number of elementary particles can never cease to evolve, hence can never reach a state of thermal equilibrium, the latter being a state with no structure.

Several epistemological and metaphysical questions arise if one accepts the viewpoint of this paper. The meaning of the word 'observer' which clearly does not mean here a physico-chemical system obeying fixed laws of physics and chemistry needs to be elaborated further. The relevance of 'observers with various levels of perception' to the situation of human beings also needs to be discussed. The author's own views on these questions will be discussed elsewhere.

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