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The Crisis about the Origin of Irreversibility and Time Anisotropy

New interrelationships advocated by the astrophysical school of thermodynamics.

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All the rivers run into the sea, yet the sea is not full.—King Solomon, in Ecclesiastes 1:7

An old crisis in science is receiving renewed attention in response to recent discussions of the thermodynamic foundations of the natural sciences. The crisis manifests itself most clearly when attempts are made to provide answers to such fundamental questions as: Is the origin of irreversibility in nature local or cosmological? Is it in the laws or in the boundary conditions? What might be the physical interrelationships underlying the expansion of the universe, information theory, and the thermodynamic, electromagnetic, biological, and statistical arrows of time? What is the basic nature of the somewhat mysterious time coordinate system in which the very physical laws are embedded? Is there a close connection between the principle of wave retardation, causality, and the temporal application of Bayes's probability principle?

Such questions, and many related ones, are so fundamental that every thoughtful scientist has given them consideration. However, it is an embarrassment for many that, after they have gained what they believe to be a basic understanding of the subject, their views are found to be in serious divergence from those of their colleagues. Therefore, a growing number of scientists believe today that such basic questions, which are related to the foundations of many of our theories, should be reexamined periodically in publications and in international meetings until a more unified approach is established. This was the motivation in recent years for at least three major international conferences. The first, and probably the most important one, was organized by T. Gold and took place in 1963 at Cornell University, with the participation of some leading scientists. The informal discussions were edited later by Gold (*1*) and contain, among other things, the new and revolutionary view, expressed by Gold and a few other participants, that the origin of irreversibility in all local processes, as well as all time asymmetries observed in nature, can be traced back to the boundary conditions that gave rise to the present expansion of the universe as a whole. The origin of irreversibility is thus not in the symmetrical laws of dynamics but in the boundary (or initial) conditions. Cosmology, according to this view, generates thermodynamics (that is, the origin of the second law of thermodynamics can be traced back to the present expansion of the universe). We will return to this question later in our discussion.

The aim of the other two conferences was to provide fresh critical reviews of the foundations of classical, statistical, and relativistic thermodynamics. The second conference was held at the University of Pittsburgh in 1969, and its proceedings were edited by Stuart, Gal-Or, and Brainard (*2*); the third, organized by P. T. Landsberg, took place at Cardiff, England, in 1970 (*3, 4*). In these conferences some of the leading thermodynamicists provided reviews and criticisms of the foundations of present-day thermodynamic theories. It is a remarkable fact, however, that no agreement was reached about the origin of irreversibility and time asymmetries in nature. While the answers may not be known with certainty for some time to come, the discrepancy of opinions among the participants is indicative of the crisis at the foundations. Some of the roots of these problems may be found in established traditional thinking and teaching, which in turn carry their momentum from the impact of past authorities in thermodynamics, statistical mechanics, relativity theory, and so on. In conflict with these is the spirit of revolution, which was described by Schrödinger (*2*):

> Our age is possessed by a strong urge toward the criticism of traditional customs and opinions. A new spirit is arising which is unwilling to accept anything on authority, which does not so much permit as demand independent rational thought on every subject, and which refrains from handling any attack based upon such thought even though it be directed against things which formerly were considered to be as sacrosanct as you please. In my opinion this spirit is the common cause underlying the crisis of every science today. Its results can only be advantageous: no scientific structure falls entirely into ruin; what is worth preserving preserves itself and requires no protection.

The fact that the existing crisis has not yet been given due consideration in the literature is partly a result of

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the attitude often expressed by practical thermodynamicists that any new answers to the fundamental questions have no practical implications for thermodynamics and related subjects and are, therefore, only of philosophical interest. The logical havoc produced for science by such misconceptions may not be commonly recognized. Indeed, such answers may actually change our conceptions of entropy, temperature, and other related thermodynamic functions (*4a, 4b*).

The Four Main Schools of Thought

Over the last decades there have been remarkable developments in irreversible thermodynamics and statistical mechanics, yet many of the basic problems in thermodynamics have remained largely unsolved. In the spectrum of opinions expressed by authors who have attempted to solve these problems (*5–25*), one can roughly distinguish four main schools of thought:

1) Traditional axiomatic thermodynamics with some new and refined modifications.

2) The more established statistical school, which generates time asymmetries from a combination of initial conditions, probability theory, and the local behavior of the universe (see below).

3) The astrophysical revolutionary school, which deduces the origin of irreversibility and electromagnetic and thermodynamic time asymmetries from the large-scale nonequilibrium dynamics of the expanding universe. The latter, in turn, are intimately related to the initial conditions imposed on the time-symmetrical field equations. This school also includes some new cosmological modifications to information theory.

4) The "dual" quantum-geometrodynamical school, which takes the quantum principle and relativity as the two overarching principles of nature and, by employing also the revolutionary concept of "superspace," ties together the world of the very large (gravitational collapse and expansion-contraction evolutions of the universe) with the world of the very small (elementary particles).

Because the basic ideas of the first two schools are by far better known and more accepted, and because of the limited length of this article, it is concerned mainly with the last two schools of thought. However, a few topics raised recently in the statistical school in regard to initial conditions are first evaluated, as they are also important to the fundamental concepts of the astrophysical school.

On Initial Conditions in the Statistical School

Many questions have been raised about the origin of the statistical arrow of time. For instance, the theories of statistical mechanics and thermodynamics are believed by many scientists to contain "paradoxes," notably the well-known Loschmidt (*11, 26*) and Zermelo (*22, 27*) "paradoxes." However, the latter should be related to a much older "paradox" inherent in the probability theory since the early days of Pascal, Fermat, and Bayes, when it was termed the "principle of probability of causes" (*7*). This has since been related to the empirical fact that blind statistical prediction is "physical," while blind statistical retrodiction is not (that is, one can calculate the probability that something physical will happen but not the probability that something did happen). The statistical arrow of time is, therefore, recognized today as an initial condition imposed by the physicist upon probability theory and macroscopic evolution equations.

For instance, according to Costa de Beauregard (*7, 28*) this "boundary" condition (which is an initial and not a final condition) reads "blind retrodiction forbidden," very much as the boundary condition in macroscopic wave theories reads "advanced waves forbidden"—two wordings for the same statement. Thus, according to Costa de Beauregard there is a close connection between the principle of wave retardation, the temporal application of Bayes's principle, and the causality concept. The Einstein-Ritz controversy (in which Einstein maintained that the law of wave retardation should follow from the principle of probability increase, while Ritz insisted on deducing the law of entropy increase from the principle of wave retardation) is thus resolved. In connection with the question of initial conditions in the electromagnetic theory of radiation it is significant to note that Hoyle and Narlikar (*29*) and Narlikar (*20*) have demonstrated how the expanding space generates the electromagnetic arrow of time out of the time-symmetrical electrodynamics given by the Wheeler-Feynmann theory (see also Fig. 2).

In closing this section I stress only three points.

1) According to some authors [for example, see (*5, 13*)] the mathematical expressions of irreversibility possess a "factlike" rather than a "lawlike" character.

2) The introduction of statistics does not by itself produce irreversibility (*8*). One must add a specific assumption of asymmetry to the statistics (*11*).

3) Essentially, the statistical and astrophysical schools agree (*1, 24, 28*) that macroscopic irreversibility is extracted from time-symmetrical laws through an initial condition (very much as one-way traffic is secured by the imposition of a one-way signpost (*7*). Disagreement, as we shall see, is inherently about the status and origin of "proper" initial conditions (*4a*).

While many authors (*1, 7, 8, 11–13, 15, 19–21, 24, 29, 30*) tend to agree today that irreversibility is essentially cosmological in origin, little agreement has been reached about the precise nature of the connection between the "large" and the "small" systems. In the following I review the foundations of the main current theories, their inherent difficulties, and the main criticisms they encounter.

Thermodynamic and Cosmological Arrows of Time

There are, as is well known, several arrows of time. Why is there any arrow at all? Why are all the known arrows consistent in pointing to the positive time direction? Here, I first consider the thermodynamic arrow and later show how, according to the astrophysical school (*11, 12, 15, 20*), it can be deduced from the cosmological arrow, which in turn can be explained in terms of relativistic cosmology. Since the foundations of the more established thermodynamic theories are entirely different from those of relativity theory, it may seem surprising to find basic interrelationships between the two. Yet when one attempts to apply statistical (or classical) thermodynamics to the entire universe, regarded as a single closed system, a glaring contradiction between theory and experiment arises. According to statistical thermodynamics, the universe, or any finite region of it, however large, should have a finite relaxation time and should be in equilibrium. However, throughout the vast region of the universe accessible to our observation the properties of nature bear no resemblance to those of an equilibrium system (examples are the red shift, Hubble's law, and the nonequilibrium expansion of photons into the nonreflecting space that surrounds the galactic material). The escape from this contradiction, according to Landau and Lifshitz (*17*), is to be sought in general relativistic cosmology. They maintain that when statistical properties of bodies are considered the metric properties of space-time may be regarded as nonsteady external conditions since the metric tensor is in general a function not only of the space coordinates but also of time. Thus, the universe as a whole or any finite region of it must be considered as a nonequilibrium system in a variable gravitational field (*17*). Accordingly, the classical formulations of the law of increase of entropy cannot hold for larger and larger portions of the universe. This conclusion is intimately coupled with the well-known Olbers' paradox, according to which the night sky should be intensely brilliant in a static universe. The escape from this paradox can be found in the red shift, which operates to diminish the contribution of distant matter to the radiation field. Thus, the sky is dark because in most directions the material on a line of sight is receding very rapidly (the expanding universe) (*12*). This is the most striking aspect of the cosmological arrow of time. It is based on the facility of an expanding space to soak up any amount of radiation (*8, 11, 12*). Since the red-shift effect shows that thermodynamic equilibrium does not prevail throughout the vast regions of the expanding universe, the latter becomes a huge "thermodynamic sink" for all the radiation flowing out into empty space (*11*). This conclusion is not only supported by cosmological observations, but it agrees with the theoretical prediction of general relativistic cosmology. Perhaps no test of Einstein's theory of relativity is more dramatic than the expansion of the universe itself (*31*). If Einstein had held fast to his original theory (without introducing the so-called cosmological constant to avoid Friedmann's prediction of an expanding universe), Hubble's discovery years later could hardly have been considered as anything but the fourth test of relativity (*32*). In establishing this central point, Gold (*12*) suggests that the expanding space is the most basic cosmological arrow of time. It gives rise to other cosmological arrows, such as those encountered by the radiation diminishing into the universal "thermodynamic sink" (*11*). Significantly, the basic cosmological arrow of time can be generated from time-symmetrical field equations of relativity plus initial conditions (*1, 8, 12, 24*). If this arrow can be shown to be the origin of irreversibility in nature, then according to Gold (*12*) irreversibility should not be in the laws themselves but in our fundamental distinction between the time-symmetrical laws of nature and the boundary (or initial) conditions. This distinction, or rather this combination, generates irreversibility in the large-scale phenomena of the universe by defining the sense in which the pattern of the world line diverges. Yet, as we know, a differential equation with boundary conditions is equivalent to an integral equation. Perhaps irreversibility is introduced by the integration process itself over macroscopic regions of the universe, while on microscopic scales the laws of nature are reversible (*11*) (see Fig. 1). Is this not, for instance, the reason why Lorentz invariance and reversibility are applicable in small but not in large systems (*8*)? As we have already seen, the distinction between laws invariant under time reversal and boundary conditions is basic and is not confined only to cosmology. It appears, for instance, in defining the statistical arrow of time.

Does the Cosmological Time Asymmetry Generate Others?

At this point, one may wonder how the basic cosmological arrow can dictate, according to the astrophysical school (*1, 11, 15, 20*), processes far away along the world lines. What possible meaning is there in talking about the expansion of the universe and its

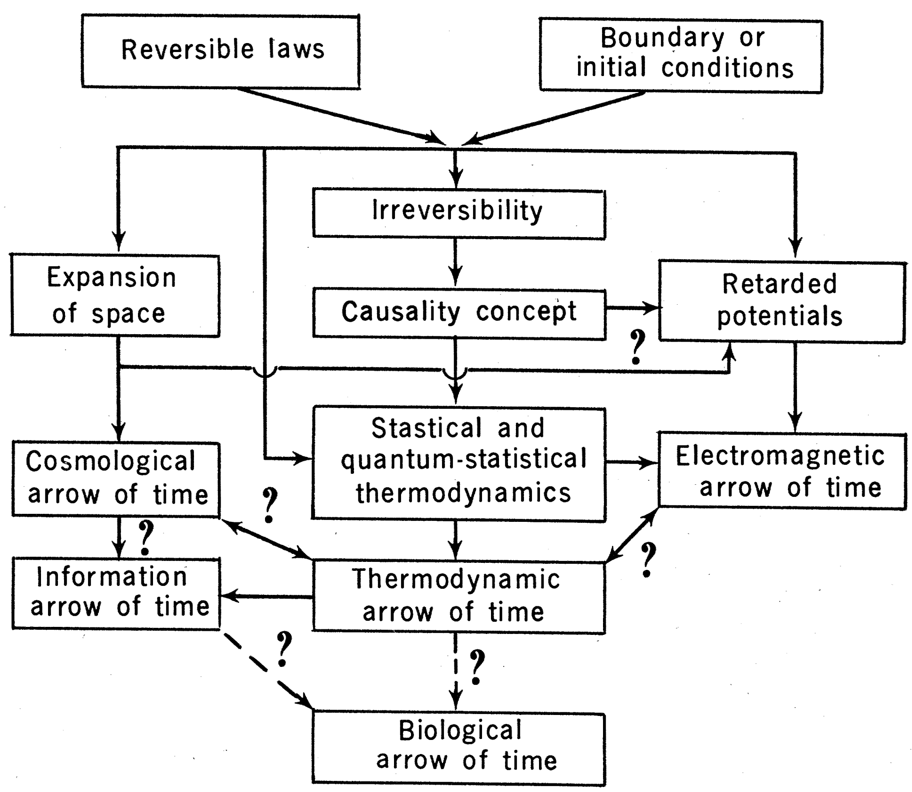

Fig. 1. Some of the possible interrelationships among the arrows of time. According to the astrophysical school (*1, 11, 15, 20*) (see also Fig. 2), the cosmological arrow of time is generated from the time-symmetrical field equations of relativity plus initial conditions. The concepts that blind statistical prediction is physical and blind statistical retrodiction is not are generally accepted as being generated by a boundary condition (which is an initial and not a final condition) imposed upon macroscopic evolution equations. This boundary condition introduces irreversibility very much as the boundary condition in macroscopic wave theories reads "advanced waves forbidden." There are, therefore, close connections between the principle of wave retardation, the temporal application of Bayes's principle, and the causality concept (*7, 33, 39*).

effects on local macroscopic processes, say, on Earth?

Before trying to answer these questions, one must note first that the actual expansion is not homogeneous throughout space. The radius of Earth's orbit, for example, does not change during the expansion, nor does the size of our galaxy increase. The separation from one supergalaxy to another increases. Yet, these facts are consistent with other observations that demonstrate that the visible part of the expanding universe is, as far as we can tell, roughly homogeneous and isotropic. The radiation expansion going on around most galactic material is the most basic asymmetry (*8, 11, 12, 15, 29*), and it appears to give rise to all the other known time asymmetries and irreversibilities (see Fig. 2).

To demonstrate this point, Gold (*12*) points out that all time's arrows will eventually be lost if any galactic system on which they appear can be completely isolated in an imaginary box, which would prevent the expansion of the photons into space. This conclusion agrees with Narlikar's (*20*) derivations, which deduce the electromagnetic time asymmetry from the expanding universe. Hoyle and Narlikar (*29*) maintain that the thermody-

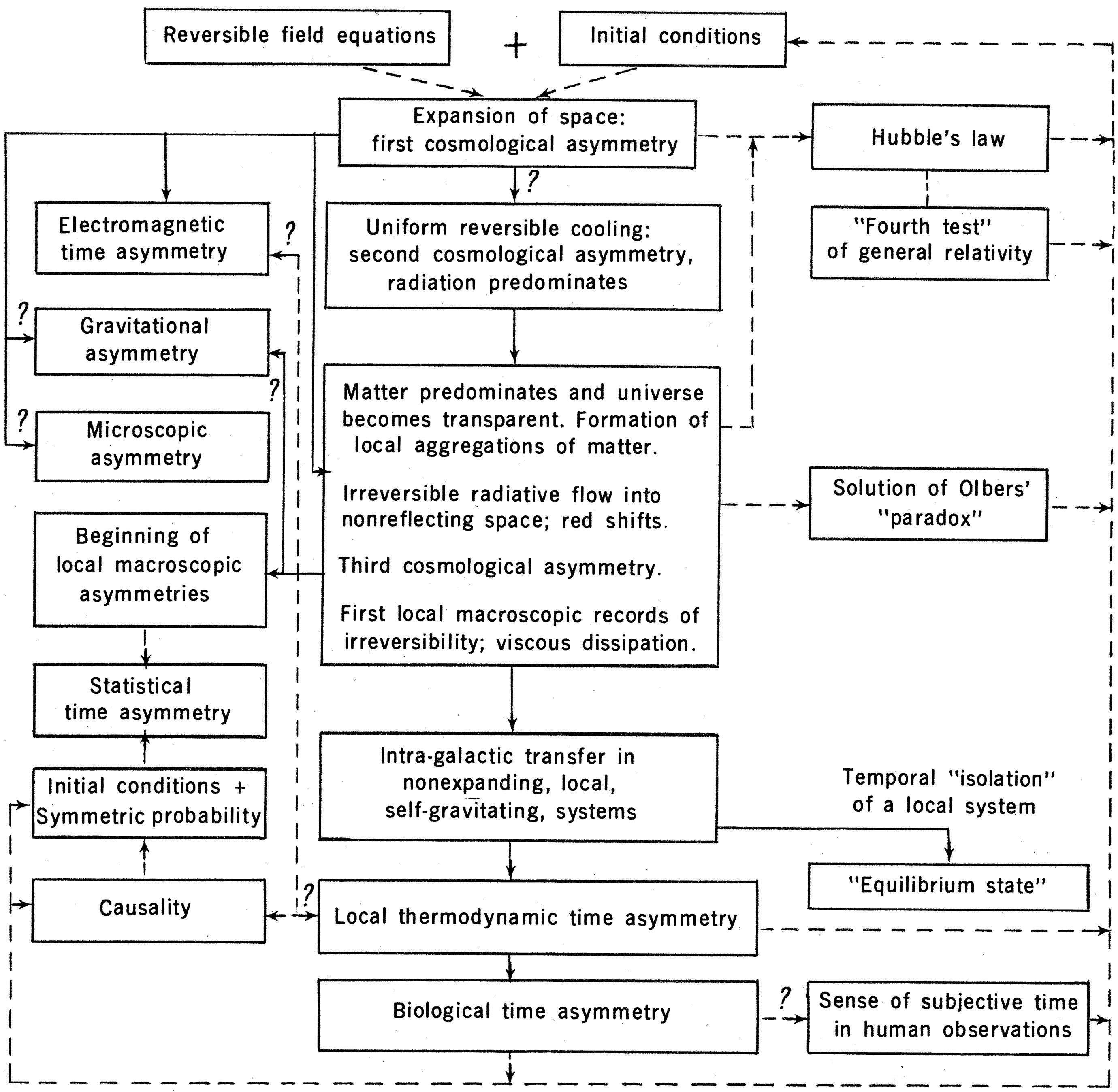

Fig. 2. The main sequence of interrelationships, according to the astrophysical school of thought concerning the origin of irreversibility in nature (*1, 11, 15, 20*). The one-sided dynamics of the universe originates all the arrows and causes them to be consistent with each other (*33, 42*). Yet this school leaves the question of the choice of boundary or initial conditions largely open. Is this choice the result of our position as macroscopic observers? The usual answer of the astrophysical school is that we cannot cause macroscopic processes (or the whole universe) to run backward by our personal choice (*33, 38*). Accordingly, the initial conditions may have the character of laws on the same epistemological basis as any of the other reversible laws (*39*). The solid lines represent assumed physical links (*4a*).

namic arrow follows from the cosmological arrow and the electromagnetic arrow (expansion of space → electromagnetic arrow → thermodynamic arrow). The concepts of the astrophysical school also agree with the concepts supported by Costa de Beauregard (*7, 33*). The main difficulty in explaining this view is in showing how the thermodynamic and electromagnetic time asymmetries are linked to the cosmological one in a nonuniformly expanding universe. What might be the mechanism in nonexpanding galactic systems?

I maintain that the mechanism of transfer of energy in a nonuniform expanding universe must be thought of as being subdivided into two different mechanisms (*4a, 11*). The first transfer of energy is carried out, as previously described, by the expansion of radiation from the surfaces of hot galactic bodies into the nonreflecting, expanding, intergalactic space, which thus becomes a huge thermodynamic sink. The second transfer mechanism occurs inside nonexpanding galactic bodies and involves a very large number of intermediate stages. As we know from earthbound observations, this mechanism is much more complicated since, in addition to radiation, energy is released and transferred by such local processes as conduction, convection, and chemical and nuclear reactions. However, since the net result in the part of the universe accessible to our observation is that the nonexpanding galactic systems continuously release energy from their surfaces, then any energy released inside them should, eventually, find its way out into the expanding space, which never reaches the equilibrium state. The time constant for this intragalactic transfer depends, therefore, on the scale and details of the nonexpanding galactic system. For each local system the time constant for the intragalactic transfer can be estimated in the laboratory by a temporal isolation, during which the arrow of time persists for a while, not definable with complete certainty, but with a probability that decreases from a high value initially to zero eventually. When this state is reached, the system is said to be in a state of equilibrium. This local equilibrium state may, at the laboratory scale, be extended in time by the imposition of time-invariant boundary conditions through interaction with other local systems, which supply the required energy (and are therefore not in an equilibrium state, since they form part of the rest of the universe, which is never in an equilibrium state). This mechanism thus explains the occurrence of local equilibrium states in overall nonequilibrium surroundings. The scale and details of such a local system in an equilibrium state as well as its exact position inside a bigger nonexpanding galactic system determine in this way the duration of all possible impositions of time-invariant boundary conditions (*4a, 4b*).

If the expansion of space is thus taken as the most fundamental time asymmetry, then the formulation of a unified (and entropy-free) thermodynamic theory can be started directly from the proper field equations that govern the expansion of the universe as a whole [most likely those of general relativity (*24*)]. In such a context one can take the observed expansion as the point of departure in laying new foundations for thermodynamics (*4a, 11*). The main difficulty that challenges this school in the near future is to formulate the proper links between the world of the very large and the world of small, local, macroscopic systems, within the framework of a single, entropy-free, unified theory of thermodynamics (*4a, 4b*).

Cosmology, Information, and the Second Law

Another approach to cosmology, information, and the second law of thermodynamics has been described by Layzer (*19*). He discusses two paradoxical aspects with interesting implications. Assuming that the initial state of the universe was very simple (and hence required a very small quantity of information for its specification) and noting that the present state of the universe is exceedingly complex (hence requires a large quantity of information for its specification), he points out the contraction with the second law of thermodynamics, which requires, among other things, that the information contained in a macroscopic description of an isolated physical system never increase.

Relatedly, Layzer discusses the evolution in time of a universe whose mean spatial curvature is positive. Here the assumption that the initial state is one of thermodynamic equilibrium at zero temperature makes sense only if the universe returns to this state at the end of each cycle of expansion and contraction. But the identity of the initial and final states seems to contradict the fact that in the course of the expansion an irreversible generation of entropy (loss of information) must occur.

According to Layzer (*19*), information can always flow from the macroscopic to the microscopic degrees of freedom. Broadly speaking, this necessary condition for the law of increasing entropy to be valid is that the entropy associated with the microscopic degrees of freedom of a system should initially have its maximum possible value (that is, initial microscopic information should be absent). This is considered as an objective property of the universe. Thus, the arrow of time is transferred from the universe as a whole to the astronomical systems that separate out in the course of the expansion. Every newly formed system, no matter how complex its structure may be, is devoid of microscopic information. The justification for applying the second law of thermodynamics to the universe as a whole, according to Layzer, is the additivity of entropy (that is, if the law applies locally, it must also apply globally). The question is, then, whether entropy remains an additive quantity over large volumes of space. Up to a point, the amount of information required to describe the content of a given volume of space undoubtedly increases in direct proportion to the volume. In principle, however, the content of a volume whose dimensions greatly exceed the scale of local irregularities is largely predictable. Thus, the accuracy of predictions generally increases with volume. Since only a finite quantity of information is required to specify the entire universe, the entropy per unit volume approaches zero as the volume increases indefinitely. Consequently, the very concept of additive entropy fails. As to the origin of the electromagnetic arrow, Layzer (*19*) believes, contrary to Narlikar (*20*), that it is determined by the thermodynamic arrow of time.

Isolated Systems and Mach's Principle

If one accepts Mach's principle, which states that the inertial mass of a body (and the metrical field) is due to its interactions with all the other masses in the universe according to their distribution in space and time, another contradiction immediately arises in regard to "isolated" macroscopic systems. Here the concept (and assumption of existence) of an isolated thermodynamic system should be viewed as a postulate that must always be questioned and reexamined. Touching on this point while defending Mach's principle (*34–36*), Dicke (*37*) writes

> From the very beginning the physicist has kept his sanity and made the most progress with his science by isolating his problem, eliminating unwanted disturbances, and ignoring the complexities of the rest of the universe. It would indeed be disquieting if now it were to be found that the laboratory could not be isolated, even in principle.

Is it possible, therefore, to assume that the origin of irreversibility is due to the impossibility of completely isolating a system from the rest of the universe (*9, 11*)? We do not know yet.

Criticism of the Astrophysical School

Other authors look for the origin of irreversibility in the nature of the Hamiltonian and the interaction terms that occur in it (*16*), in the coarse graining of phase space that is required to take account of the fact that all measurements are macroscopic (*4, 18*), in the passage to the limit of an infinite number of degrees of freedom (*6*), or in the interpretations of the Liouville equation (*22, 23, 25*). No general agreement on these matters has been reached (*14*).

The main criticism of the astrophysical school comes from the classical and statistical schools. For instance, according to Rosenfeld (*23*), irreversibility originates in the macroscopic instrument (or observer), which records information and retains a record of it (but which did not have the record in the past). Accordingly, the asymmetry in time may be imposed by the observer and not created by the system of which the observer is part (*38*). In short, the choice of initial conditions is not a law of nature but only a result of our position as macroscopic observers. The defenders of the astrophysical school usually respond to this criticism by noting that we cannot cause macroscopic systems (much less the whole universe) to run backward by our personal choice (*4a, 38*). Furthermore, observers cannot be isolated from the rest of the universe and are therefore not entirely independent. Accordingly, initial conditions may have the character of laws or "auxiliary conditions" (*19*) on the same epistemological basis as any of the other reversible laws of nature, which are intimately coupled to observations. Yet observations are limited to what our epistemological (*39*) position allows [for example, we cannot distinguish between two possible symmetric universes—of matter and antimatter—since we happen to live in only one of them (*12*)]. We calculate only the probability that something will happen but not the probability that something did happen, since we live in a one-sided expanding universe that originated by an initial and not a final condition. In this way, the one-sidedness of the dynamics of the universe dictates a priori the irreversible nature of the observations that generate thermodynamics (*40*). The problems of man in the small, and the universe in the large, are thus not entirely disconnected. For life to exist, with its own biological arrow of time, there must exist temperature gradients, which would not be maintained for a long time without the sun, which originated in the expanding universe. Therefore, there may be some links between initial conditions, the expansion of outer space, thermodynamics, and the origin of life (see Fig. 2). In other words, it is reasonable to assume, along this pattern of thought, that life (as well as all other time asymmetries) could not have developed in a static universe. While this may never be known with certainty, it is more reasonable to think that our subjective understanding is inadequate and is perhaps holding us back from a better description of an objective time concept. No compulsive or conclusive answer should be imposed now on these fundamental questions. They should be kept open until, with the passage of time, some new physical theory may be devised that would define entirely new concepts of time and time asymmetries (*41*).

However, this is not the end of the road in thermodynamics. Another school of thought has arisen in which the addition of the quantum principle to relativity may connect the world of the very small (elementary particles) and the world of the very large (cosmology) (*42, 43*).

The "Dual" Quantum-Geometrodynamical School

If the quantum principle and relativity are taken as the two overarching principles of nature, their union in "quantized general relativity" generates a new viewpoint about the nature of time. According to Wheeler (*24*), during the initial phases of the universal expansion as well as in the final phases of the gravitational collapse of stars (and the possible eventual collapse of the universe itself), the phenomenon of indeterminism dominates; thus, one evolutionary history is inescapably coupled with other histories, which causes the concepts "before," "after," and "next" to lose their meaning. At these stages, the relevant physical dimensions reduce to values comparable to the Planck length (10^{-33} cm), and the very concept of time fails (*44*). According to Wheeler, the phenomenon of gravitational collapse ties together cosmology and elementary particles (*42*). Yet, even this approach leaves open the question of the origin of irreversibility, since it does not allow specification of initial conditions for one dynamical history of the universe (that is, how the initial positions and velocities of the objects that follow the equations of motion were first set). Thus, the problem of the origin of irreversibility in nature, which is intimately coupled to the very concept of time and initial conditions, incorporates in it issues that are as far beyond our reach now as they were in the early days of thermodynamics.

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31. The other three tests are the precession of the perihelion of Mercury around the sun, the bending of light by the sun, and the red shift of spectral lines by the gravitational field of the sun.
32. A. Friedmann [*Z. Phys.* **10**, 377 (1922)] pointed out that the correct treatment of Einstein's field equations leads to a class of expanding and contracting universes. Since Einstein believed (as most did at that time) that the universe ought to be static, he reluctantly changed his original theory by adding to it the so-called cosmological constant. A number of years later, Hubble found that the universe is, indeed, expanding, and Einstein thereafter renounced the cosmological constant, which he called the "worst blunder of his life." Thus, the original theory admits no static solutions.
33. In supporting the astrophysical revolutionary school and disagreeing with the philosophy of those who dissociate the phenomena of world expansion and entropy increase, Costa de Beauregard (*28*) suggested that the emission and absorption of gravitational waves should be a significant cosmological phenomenon and that one more important manifestation of time asymmetry should be the preponderance of emission over absorption (in terms, of course, of the usual time arrow); thus, the world's expansion should go hand in hand with a general decay of gravitating subsystems and a general emission of gravitons on the corresponding retarded waves. As another demonstration that the arrow of time is not to be found in the mathematics (but rather in a deliberate choice by the mathematician), as claimed by the astrophysical school, Costa de Beauregard mentions the Robertson-Walker metrics, which describe a very wide class of models of worlds that expand or contract, or both, and which are invariant by time reflection. Furthermore, in agreement with the astrophysical school, he maintains that if a reflecting box is not expanding, all the enclosed quantal systems will keep fluctuating around an equilibrium energy state and exchanging quanta on stationary waves. Yet, if the reflecting box is expanding, all the enclosed quantal systems will be decaying and emitting quanta on electromagnetic, electronic, and neutronic waves, and so on.
34. As to the historical role of Mach's principle, it might be instructive to note here that Einstein (*35, 36*) was influenced by Mach's principle in constructing the basis for the conceptual framework of the general theory of relativity and in attempting to describe the universe as a whole. He pointed out that, if this principle is valid, space-time cannot be flat at infinity (since this would imply the existence of absolute space-time and would single out inertial frames of reference). This led him to the closed universe, which can be described in a manner not involving any boundary conditions at infinity.
35. A. Einstein, *The Meaning of Relativity* (Princeton Univ. Press, Princeton, N.J., ed. 3, 1950), pp. 56, 99.
36. ———, in *Albert Einstein, Philosopher-Scientist*, P. A. Schilpp, Ed. (Harper, New York, 1959), vol. 2, p. 687.
37. R. H. Dicke, *Phys. Today* **20**, 55 (1967).
38. The statistical and astrophysical schools may become compatible with each other even when the origin of macroscopic irreversibility is traced back to the earliest possibility of recording macroscopic information. According to this lemma (*4a*), the origin of Rosenfeld's irreversibility is the astrophysical mechanism that had first generated the local condensation of macroscopic (self-gravitating) irregularities of matter (which thus may record information in an expanding world). Yet, the first cosmological asymmetry (that is, the world expansion), which according to the astrophysical school dictates all other asymmetries, is usually assumed to precede the formation of macroscopic aggregations of matter.
39. One must always distinguish between physical time and psychological time. For a discussion of the philosophical problems of irreversibility and the anisotropy of time, see (*7, 10, 13*) and the numerous works that they review.
40. According to another criticism of the astrophysical school (*22*), there is yet no evidence for the relevance of the world's expansion on, say, the nature of the viscosity of a gas However, it was recently demonstrated (*4a, 4b*) that the world's expansion dictates a positive viscous dissipation of energy and that, therefore, the viscosity coeficient must be positive.
41. I find it logical as well as useful to define time by $t = V^{1/3}$, where V is the volume of space at a given epoch. This definition of an absolute (anisotropic) time also possesses the attractive property (*4a*) that the rate of the world expansion or contraction dV/dt is never negative and is independent of any cosmological model (that is, whether or not it accelerates or decelerates, expands or contracts). Furthermore, it is in agreement with some other philosophical views on an absolute time (*44*).
42. We do not consider here the quantitatively small departures from microscopic time reversibility suggested by experiments on the decay of the K° meson. It may be possible that the violations of parity and charge conservation observed in elementary particle physics imply time-reversal violations that should be superimposed as a slight perturbation on the preceding scheme (*7*). Even in this case, a link with world expansion has been recently suggested (*43*).
43. A. Aharony and Y. Ne'eman, *Int. J. Theor. Phys.* **3**, 437 (1970).
44. Note: Spinoza's "There was no time or duration before creation" [*Principles of Cartesian Philosophy* (Philosophical Library, New York, 1961), p. 175].