VIII. The Strong Cosmological Principle, Indeterminacy, and the Direction of Time

D. LAYZER

Summary

The strong cosmological principle asserts that a *complete* description of the universe does not distinguish between different positions or directions in space at a given instant of cosmic time. It therefore implies that a complete description of the universe has a statistical character, a conclusion that seems at first sight to be inconsistent with the apparently unlimited possibilities for acquiring detailed information about the universe through observation. A careful examination of this question discloses, however, that, in a certain well-defined sense, microscopic information is actually not present in a universe satisfying the strong cosmological principle. A complete set of ideal observations would just suffice to fix all the parameters that figure in a complete statistical description. If the universe is spatially infinite, any two realizations of the same statistical description are observationally and mathematically indistinguishable. If it is spatially finite, distinguishable realizations exist. But if one regards the time axis as a closed loop of finite extent, the multiplicity of distinguishable representations has no physical significance; the various realizations are not ordered in time, but coexist as members of a Gibbs ensemble.

The kind of indeterminacy considered here is basically different from, though of course compatible with, that introduced by quantum mechanics. It does not affect the accuracy with which any physical quantity can be measured. Instead it introduces an asymmetry between the two directions of time. The strong cosmological principle, together with an assumption concerning the uniqueness of the universe, implies that a mathematical description of the universe can unfold in a single time direction only, the direction that corresponds to an initial cosmic expansion. The future is then uniquely characterized by its predictability, the past by the fact that its traces are contained in the present state of the universe. The irreversibility of such macroscopic processes as heat conduction in nearly isolated systems derives ultimately from the absence of microscopic information about the initial state, and hence all subsequent states, of the universe, which implies that, except in specially contrived situations, microscopic information about the initial state of a nearly isolated system is nonexistent. The macroscopic transport equations, which are time-asymmetrical, then follow from the time-symmetrical microscopic equations.

It is generally agreed that irreversibility in macroscopic systems has its origin in the asymmetry of the initial or boundary conditions that are normally imposed on them. This asymmetry has a statistical character. The irreversibility of transport phenomena, for example, depends on the irrelevance of microscopic information about initial states. Thus, in heat conduction a knowledge of the initial temperature distribution suffices for a prediction of the temperature distribution at all later times. But if microscopic information is unnecessary for the prediction of future macrostates, it must be necessary for the prediction of past macrostates. In this way the postulate of microscopic irrelevance singles out a direction in time.

The modern notion of entropy as a measure of uncertainty enables one to formulate the assumption of microscopic irrelevance in precise mathematical terms. The difficulty lies in understanding where the uncertainty about initial states comes from. That a detailed microscopic description of a physical system comes closer to reality than a statistical description seems almost self-evident. But it is hard to reconcile this intuition with the postulate of microscopic irrelevance. One might, perhaps, be tempted to regard irreversibility as being contingent on the macroscopic viewpoint. But the problem of accounting for the asymmetric character of macroscopic initial and boundary conditions would still remain.

I wish to suggest that a natural solution to the problem emerges from considerations of the space-time structure of the universe as a whole.

Such an approach may at first sight seem unnecessarily speculative. But the problem of understanding why certain kinds of boundary and initial conditions are appropriate in macroscopic physics is essentially one of understanding how macroscopic systems are related to the rest of the universe. Cosmology seems to offer a more adequate framework for a discussion of this question than macroscopic physics.

In the present context cosmology must be understood in a broader sense than the usual one, for it is essential to consider not only the large-scale structure of the universe but the local irregularities as well. The behavior of a universe without irregularities is completely reversible. Relativistic models that expand indefinitely from a state of maximum density may equally well be thought of as contracting from a state of infinite dispersion; oscillating models, of course, are invariant under time reversal. As for the steady-state universe, time reversal converts it into a contracting universe with continuous annihilation of matter—a process that would seem to be as acceptable as continuous creation. If, then, irreversibility is a property of the universe as a whole, it must be intimately related to the existence of local irregularities. What considerations can we rely on for guidance in constructing a realistic nonuniform model of the universe?

i.e. not ACCEPTABLE

It is often said that the universe is unique. As applied to the actual universe, this statement is a truism; but as applied to the class of conceivable model universes, it has considerable heuristic value. Used in this way, it is not a new principle peculiar to cosmology but merely an application of the usual criterion of economy or simplicity; it directs us toward the simplest cosmological postulates whose consequences are in accord with observation.

Cosmology in the restricted sense is based on the postulate of spatial uniformity and isotropy—the so-called cosmological principle. As applied to a universe with local irregularities, the cosmological principle states that neither the mean density field nor the mean velocity field at a given instant of cosmic time serves to define a preferred position or direction in space. The obvious generalization of this postulate is a statement that I shall call the strong cosmological principle: Every spatial section of the universe is statistically homogeneous and isotropic. By this I mean that any complete mathematical description of the universe is invariant under spatial translation and rotation, so that at any given instant of cosmic time there are no preferred positions or directions in space.

First!

how different to this?

The mathematical properties of statistically homogeneous and isotropic distributions are familiar from the theory of turbulence. However, the strong cosmological principle has a basically different meaning from the assumption of statistical homogeneity and isotropy in turbulence theory.

floating preferred flow (co-moving)

When we describe the state of a bounded system in statistical terms, we ignore a large quantity of detailed information about the system, because it is inaccessible or uninteresting or both. Nevertheless, we regard the detailed information as meaningful and potentially relevant. We could, for example, make detailed predictions about a particular realization of a turbulent flow if we knew enough about the initial and boundary conditions. The situation is fundamentally different in an unbounded distribution characterized by statistical homogeneity and isotropy.

Let us first consider the case of an infinite universe satisfying the strong cosmological principle. It can be shown that a statistical description specifies the microscopic state of such a universe as closely as it can be specified. Conversely, the average properties of such a universe—"average" being used here to mean a spatial average—completely determine all the statistical quantities—joint probability distributions, moments, and so on—that figure in the statistical description. In short, an infinite, statistically homogeneous and isotropic universe *contains no microscopic information.*

over the top

As the simplest example of such a universe, consider a Poisson distribution of mass points in Euclidean space. This distribution is characterized by a single number, the mathematical expectation of the number density of points in a cell of arbitrary volume. Because the distribution is ergodic, this expectation can be approximated arbitrarily closely by a spatial average extended over a sufficiently large region of space. Now suppose that we try to compare two realizations of the same Poisson distribution. Let us focus attention on a particular finite volume in the first realization. Dividing this volume into cells, we may characterize the distribution of mass points within it by a set of occupation numbers. No matter how large the volume or how small the cells, the probability associated with this set of occupation numbers is, of course, finite. Hence it must be possible to find in the second realization a volume—in fact infinitely many volumes—in which the distribution of mass points reproduces the distribution in the first region to any given degree of precision. It follows that the two realizations are indistinguishable.

Essentially the same argument applies to any statistically homogeneous and isotropic distribution of infinite extent.

The argument applies also to finite, oscillating, model universes, provided that we regard the time axis as a closed loop. The statistical description specifies a complete ensemble of finite realizations, all of which are on exactly the same footing.

If the preceding considerations are correct, the strong cosmological principle can account in a general way for the irrelevance of microscopic information in certain macroscopic contexts. But of course microscopic information is not *always* irrelevant. We are therefore preface to Cosmogony — ApJ.

obliged to consider how situations in which it *is* irrelevant actually arise. This leads directly to the problem of the formation of astronomical systems. Fortunately, we are here concerned only with a few broad aspects of this problem, which may be amenable to more or less rigorous investigation. Although such an investigation has been begun, it is still in a preliminary stage [Layzer, 1963]. Nevertheless, a brief account of the lines along which it is proceeding may illuminate the present discussion.

Near the beginning of the expansion, when, as I shall assume, the density of matter was extremely high, the distribution of matter must have been much simpler than it is now. If we go sufficiently far back in time, we may even find that only a small number of free parameters—or perhaps none at all—is needed to specify the state of the universe completely. It is conceivable, for example, that the state of maximum compression is unique, being determined entirely by physical laws. Suppose that we take some sufficiently simple early state of the universe as our starting point. Can we then infer from the laws of physics how local irregularities will subsequently form and develop, and thereby predict the highly complex distribution of matter and motion we observe today? I have tried to show that the gradual development of local irregularities, leading ultimately to the formation of a hierarchy of self-gravitating systems, results from gravitational interactions in an expanding medium, after electromagnetic processes in an early stage of the expansion have caused the energy per unit mass associated with the local structure to assume its present (negative) value. For the purpose of the present discussion, then, let us assume that one can arrive at a statistical description of the present-day universe by tracing its development from an earlier state characterized by a small number of parameters. We have already concluded that the description, in spite of its statistical character, is complete. What implications does this picture of the universe and its evolution have for the nature of time?

Although our only assumption concerns the spatial structure of the universe, our picture does exhibit a clear asymmetry between the two directions of time, because the spatial structure automatically causes the postulate of microscopic irrelevance to be satisfied. Since the universe is at the same time a single realization and a complete ensemble of realizations, its microscopic properties are entirely determined by statistical laws. It follows that a mathematical description of the universe can "unfold" in one direction only; by definition, this is the direction of the future. Thus the future is uniquely characterized by its predictability. On the other hand, the present state contains traces of the past only, not of the future. Thus memory pertains uniquely to the past.

These features of the temporal structure of the universe have obvious correlates in our subjective experience of time. We remember the past but not the future; we can predict the future but not the past; without records, the historian's task would be impossible. Finally, the awareness of succession—the feeling of time gradually unfolding (though not always at the same rate)—corresponds to the way in which the mathematical description unfolds; in the description, as in the reality, one must traverse the past in order to reach the future. In these matters, as with other aspects of perception and awareness, the structure of subjective experience seems to correspond in a more or less simple way to the structure of our mathematical description of what is being experienced.

WHEELER

For the sake of clarity, I should say that the concept of a single quantum state of the universe is really rather different from the idea that there is a unique state of maximum condensation for an oscillating universe. The concept I was speaking about was one of an ergodic universe which undergoes a different kind of bounce each time. It bounces, so to speak, in accordance with a kind of probability factor governing the chances about how a cycle is related to the one preceding it. No other essential information is given. This is a very loose way of talking about something that should be treated as a quantum-mechanical system. I do not know how to improve on this treatment. I would not think of a unique state of maximum condensation, nor even of a unique macrostate.

MORRISON

Would you then in some sense envision that there is a predictability, in the sense of an expectation value of any operator, but not that the realization of any given development in a system should come from a single measurement?

WHEELER

I do not even know how to talk sensibly about this question because I do not know how to describe the measurement of this system. It has to be measured from the inside. One cannot form a wave pattern if he is talking about a system that is built out of one quantum state. This is a question for the "relative state formulation" type of description. There is a significant difference in interpretation.

HARWIT

The problem Layzer described looks very much like what Lifshitz did. He started out with a homogeneous, isotropic universe which is quite arbitrary, except that he set the cosmological constant equal to zero. Then, for all linear types of interaction, he traced the evolution of general, growing tensorial perturbations. Unless some nonlinearity is introduced which will complicate the theory, I do not see how this description would differ from the one you suggest in which the initial state is a superposition of different harmonics, which then evolve at calculable rates. What are the differences between your treatment and Lifshitz'?

LAYZER

Lifshitz studied the rate of growth of linear disturbances and showed that in fact some grew and others decayed, but that if one relied on statistical fluctuations to provide the initial irregularities, they would not grow large enough in the available time to account for the existence of galaxies. My approach proceeds from a consideration of the energy associated with local irregularities and of the spectral distribution of this energy. At present the local irregularities—chiefly galaxies and galaxy clusters—have a mean binding energy per unit mass of about 10^{14} erg/gm. It can be shown that as we look backward in time this number will remain approximately constant as long as gravitational forces dominate the motions of particles. On the other hand, the amplitude of the density fluctuations will diminish as we look farther and farther back in time. Specifically, the binding energy per unit mass is proportional to the product $\alpha^2 G\bar{\rho}\lambda^2$, where α is the r.m.s. fractional density fluctuation, G is Newton's constant, $\bar{\rho}$ is the mean density, and λ is the density-autocorrelation distance. This formula, by the way, is not restricted to small values of α. As the universe expands, $\bar{\rho}$ varies as S^{-3} and λ increases no faster than S, where S is the cosmic scale factor. Hence α^2 increases at least as fast as S. The upshot of this argument is that enough binding energy to account for the existence of galaxies and other astronomical systems can be stored in very inconspicuous density fluctuations at a sufficiently early stage of the cosmic expansion.

Layzer theory

But these initial density fluctuations, while inconspicuous, are nevertheless very much greater than the random fluctuations considered by Lifshitz. How do they arise? Again we may profitably consider the energetic aspects of the problem. I mentioned that the binding energy per unit mass was approximately conserved as long as gravitational forces dominated the motions of particles. At a sufficiently early stage in the cosmic expansion, when the mean density is comparable to atomic density, matter will be fully ionized and, if large-scale density fluctuations have not yet come into being, Coulomb forces will greatly overshadow the gravitational forces. You will recall that the electrostatic interaction between a proton and an electron is 10^{39} times as great as the gravitational interaction. In these circumstances it can be shown that the mean energy per unit mass associated with local irregularities is not conserved but decreases. Rough estimates indicate that Coulomb interactions at this stage of the expansion *could* produce a negative mean energy of the required magnitude, but more detailed calculations are needed to decide whether this will actually happen. Such calculations are now in progress. The temperature is assumed to be zero initially, and the effects of nuclear reactions, Coulomb interactions, and radiation are all taken into account.

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COLD UNIVERSE

To sum up, Lifshitz' treatment and mine are mutually compatible, but they focus on different aspects of the problem. The apparent contradiction between Lifshitz' result and mine vanishes when one recognizes that the initial conditions contemplated in the two treatments are very different and that in my treatment nongravitational forces play an essential part in shaping the energy spectrum associated with local irregularities at an early stage of the cosmic expansion.

GOLD

Your question about information is the famous geneticist's problem. Either the information content required to construct a human is entirely in the genes, or else the information content of the genes is much less than the required amount. The question is essentially about how the information should be defined. It is not clear to me whether we should define the quantity of information in such a way that it appears to grow spontaneously, or whether we should define it so that the content of information is conserved.

MORRISON

That is exactly what I would have said. This question is the same as that of whether the number π contains infinite or a relatively small amount of information. I think that Layzer's view must be that it contains an infinite amount, and of course there is a certain plausibility to that. But this view also implies that the initial stage or quantum state of energy should be calculable without error. Any error would be enormously magnified. This question about information is the central issue.

BONDI

It seems to me that in any scientific work we must agree to disregard certain things. We must disregard certain features of experiments in order to undertake a formal treatment. If we had to give full details of any phenomenon in the classical picture, certainly we could never predict anything at all.

We can apply this principle of relevance to the significant subsystems of universe only if there is an infinity of them, either because the universe is infinite in space or because it is infinite in time either through being in a steady state or being an oscillating universe. With a single circle of growth, we would be very much limited in applying this principle. I think this is the way to get around the problem of uniqueness. What I am saying probably is essentially equivalent to Layzer's point of view, but unless we make some such assumption about this, then we are caught in the uniqueness complex, which means essentially that things are unpredictable.

LAYZER

The behavior of the universe can be both unique and predictable if we admit the kind of indeterminacy discussed in my paper—that is, if we regard a certain kind of microscopic information about the universe as unspecified beforehand. As far as I can see, this point of view does not bring us into conflict with experiment. We can, of course, acquire microscopic information of the kind I say is not specified beforehand, but we need to expend negative entropy to do it. That is, we must in a sense supply the required information ourselves. If we do not actually do this, then, I suggest, no significance can be attached to the statement that, say, a particular atom is at a particular place in space and time and not at some other place.

MORRISON

What do you mean by saying that no significance is ever attached to such a statement? Do you mean simply that some things cannot be predictable on this basis, and that these things are therefore irrelevant? If you give any independent criteria of significance, things might satisfy it, but it is only internal information that you set in advance.

LAYZER

By significant information I mean information that ought to figure in a complete description of the universe. Conversely, I would regard as insignificant any information whose existence had no observable consequences.

universe as a whole?

meaning (ROD)
purposeful info (Johnson)
non redundant info
teleonomic info (MONOD)