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On Methodological Problems in Cosmology and Quantum Gravity

The author demonstrates that researchers in quantum physics and inflationary cosmology have in practice loosened the rigorous traditional principles of scientific methodology (in particular, observability and experimental reproducibility). He formulates some principles of the new methodology.

The methodology (and the philosophy) of physics and of contiguous scientific disciplines arose and developed predominantly on the basis of the experience of laboratory research and the experience of observations of regularly recurring celestial (astronomical and meteorological) phenomena. As a result, the methodology is well adapted precisely to this context and implicitly assumes that no other context exists. In particular, such methodological principles as the observability principle and the principle of experimental reproducibility have proven very useful and effective in this context.

According to the observability principle, the results of physical theories must be formulated in terms that can be defined operationally—that is, in terms that can be connected directly with some measurement procedure. In other words, any theory must be formulated in terms of measurable values, while the measurable values themselves acquire meaning within the framework of specific theoretical models. To avoid misunderstandings, it should be noted that some elements of a theory that arise at intermediate stages in its mathematical apparatus may not correspond directly to any observable

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values. Such, for instance, is the arbitrary phase multiplier preceding the wave function in quantum mechanics or the precise value of the potentials of an electromagnetic field in electrodynamics. Such values are often associated with various types of gauge invariance or gauge freedom, but they can also arise for other reasons. The observability principle has shown its exceptional effectiveness—for example, in discussion of the meaning of the concepts of time and simultaneity in the creation of relativity theory, and in discussion of the uncertainty principle (Heisenberg's microscope) and complementarity during the emergence of quantum theory.

In my opinion, the above-cited formulation of the observability principle not only corresponds quite precisely to how this principle was used in creating the special relativity and quantum mechanics; the principle is also used in practically the same way in quantum field theory and in the general relativity for so long as cosmological models are not introduced. Establishment of the observability principle in physics is associated, in the main, with the names of Heisenberg and Einstein, and the corresponding formulations are cited, in particular, in the article[1] where Heisenberg, among other things, describes his discussion of the observability principle with Einstein. One aspect of the observability principle—namely, that theories must be formulated in terms of observable values—is formulated by Heisenberg in the aforementioned article on page 303 as "the idea of describing phenomena only with the aid of observed values."* The second aspect of the observability principle—that measurable values themselves acquire meaning only within the framework of specific theoretical models—was formulated by Einstein in words that Heisenberg quotes in the same article: "Whether a given phenomenon can be observed depends on your theory. It is precisely a theory that must establish what can be observed and what cannot." However, Einstein's attitude toward the observability principle was complex. In particular, he remarked that "any reasonable theory must allow us to measure not only directly observed values but also values observed indirectly"[2] and, according to Heisenberg, spoke with disapproval of the observability principle in general. Einstein did not define precisely what should be understood by indirect measurement in the general case, so it is not completely clear what he had in mind. The question of indirect observation is not a simple one, and it has great significance for the discussion that follows.

According to the principle of experimental reproducibility, scientific information can be yielded only by an experiment (or observation) that (at least in principle) can be reproduced any number of times and generate recurring (self-reproducing) results. However, the reproducibility principle has to do

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*All excerpts in this article are translated from the Russian.—Ed.

not only with the interpretation of experimental results. Closely connected theoretically with the reproducibility principle is the concept of an ensemble of systems, which is the core of many theoretical schemas. Experimental reproducibility implies the possibility of having an unlimited number of copies of the system under study in a given state, on which a given measurement can be made. Such a potentially infinite set of copies of a system in a given state is called an ensemble. It is important to note that in physics reproducibility does not necessarily mean that the results of measurements can be repeated exactly (within the bounds of expected error) on a system in the same initial state; it may mean merely that the average values or probability distributions of magnitudes are statistically stable. In this case, different series of measurements will generate identical statistical results within the bounds of expected statistical variation. It is precisely this type of measurement on an ensemble and the very existence of ensembles that are of fundamental importance for the formulation of quantum theory, because only within the framework of an ensemble of systems is it possible to make clear and unambiguous the concept of average values and probabilities that is used to formulate the connection between quantum theory and experiment. It should be added that the principle of experimental reproducibility and the existence of ensembles determine the possibility, in principle, of measurements with any preset degree of precision, because statistical errors can be made as small as required by means of unlimited expansion of the ensemble. Thus, the interpretation of the observability principle as measurability, in principle, with any preset degree of precision depends on the reproducibility principle.

Below I shall consider the relationship between the observability and reproducibility principles and current research trends in fundamental physics. In doing so, I shall have to discuss certain new concepts for which there is no established terminology. Instead of introducing new terms for them, I shall give certain existing concepts a new meaning and use them in the present article in a not wholly traditional manner. Such usage must be understood in a purely formal fashion, just as in mathematics, for example, the term " germ" is understood to mean a set of functions with identical local behavior at a given point and not a germ in the biological sense. The concepts introduced below—the traditional methodology, objective measurement and predictability, and model realness—will be formal terms of this kind.

In this article, I shall call the methodology based on the principles of observability and experimental reproducibility *the traditional methodology*. Besides these two principles, a third very important methodological principle is the principle of falsifiability, which means that a theory must yield empirical predictions that can in principle be categorically refuted by experiment. The principles of falsifiability, observability, and reproducibility together constitute what could be called the criterion of the scientific character of knowledge as currently understood. It must, however, be noted that in the application of this criterion there have always been many fine points, on which I cannot dwell here. Thus, for instance, series of meteorological observations represent fully scientific knowledge even though they do not satisfy the criterion of reproducibility, because by definition they pertain to unique events. However, in applying the traditional methodology there have also arisen problems that can hardly be called fine points.

In physics, the principles of observability and reproducibility were extraordinarily useful and constructive and did not lead to serious difficulties for so long as it was possible for scientists to confine themselves to the study of relatively simple and compact objects. However, the extension of this same methodology to more complex cases leads to very serious problems. Here are a couple of characteristic examples.

One example concerns the concepts of quantum probability and quantum state as applied to complex macroscopic objects. If we consider some relatively simple quantum system (for instance, the spin of an electron) in a given state, then in principle it is possible to consider an ensemble consisting of an unlimited number of copies of that system. This means that such an ensemble can in principle be prepared for experimental study. By carrying out on this ensemble a sufficiently large number of mutually complementary (in the quantum sense) measurements, we can determine with any preset degree of precision the probability distributions and expected values of the corresponding observed variables, and with their aid fully reconstruct the initial state of the system (this is sometimes called the state's quantum tomograph). For example, for the ensemble representing a certain spin state of an electron it suffices to measure the average values of the spin along three different axes.[3] An analogous procedure can also be applied in more complex cases. In this sense, quantum probabilities and the quantum state, fully satisfy the observability principle, are normal physical characteristics of the system, and are observable elements of physical reality.

If we consider a pair of electrons or, for example, a hydrogen atom consisting of a proton and an electron, then we shall have complex quantum systems consisting of simpler quantum systems. These more complex systems can also be characterized by quantum probabilities and quantum states that can be defined operationally in the language of ensembles, in the same way as shown above. No fundamental problem arises. A complex system consisting of two or several simpler quantum subsystems is itself a quantum system and possesses a quantum state, as we might have expected.

However, if we consider, for instance, a certain specific person as a complex system consisting of atoms and molecules as quantum subsystems, then it turns out to be impossible in principle to construct an ensemble of such systems in a given state. It is not just that each person is absolutely unique; one and the same person does not occupy the same state even twice throughout his life (due, among other things, to his ineradicable quantum interaction with his surroundings), not to mention an unlimited number of repetitions of the same state. Let me emphasize that the state of a large and complex macroscopic object is, generally speaking, in principle nonreproducible in our universe, because it is subject to continuous and uncontrollable influence from all the rest of the universe (for example, in the form of thermal radiation and cosmic microwave background radiation).[4] In fact, each state of the macroscopic object is almost as unique as the state of the whole universe due to the continuous, ineradicable, and uncontrollable quantum entanglement of the state of this macroscopic object with the state of the remaining part of the universe. Hence, strictly speaking, the quantum probabilities and quantum states of complex macroscopic objects are, like those of a person, in principle undefinable operationally. Does this mean that the quantum state of a person simply does not exist and that a person cannot be regarded as a quantum system at all? This seems absurd: after all, we know full well that a person's body consists of parts—that is, atoms—each of which is a quantum system. Moreover, a very fruitful role is played in quantum theory by various kinds of thought experiments that consider systems of which an observer, treated as a quantum system, is a component part. Strictly speaking, from the point of view of the principles of observability and repeatability it is methodologically unacceptable to take such thought experiments into account.

Another example is connected with quantum cosmology. Here the situation is even worse, because the object studied by quantum cosmology can only be the quantum behavior of the universe as a whole. In quantum cosmology, the universe acquires the status of a physical object that is all-encompassing and therefore in principle the sole one of its kind;[5] at the same time, it has an essentially quantum character and undergoes a unique quantum evolution.[6] In this case, a multitude of problems arise. One of them is that the quantum probabilities and quantum state of such an all-encompassing clearly lack a simple operational meaning, because from the experimental point of view it is impossible to have anything like an ensemble of universes in the same initial state. However, it is necessary to regard the universe as a quantum object in order to understand certain phenomena that are really observed. Most important among them are the anisotropy of the background radiation and the highly heterogeneous distribution of matter in the universe, which are consequences of quantum fluctuations at a very early stage in the evolution of the universe, when there were important large-scale quantum effects. What is more, quantum-cosmological ideas have already been applied with exceptional success to predict the angular spectrum of the anisotropy of the background radiation (including very subtle details of the phenomenon) and the degree of heterogeneity of the observed distribution of matter in the universe. How is this result to be understood? From the point of view of the traditional methodology, it is unacceptable because within the framework of the principles of observability and repeatability the conception of the universe as a quantum object is meaningless. However, the success of this "methodologically unacceptable" approach is all too obvious.

Let me make one important remark concerning quantum cosmology. There is a very close connection between quantum cosmology and quantum theories of gravity. The connection is this. Not every cosmological model or theory in which quantum effects are important is at the same time a model of quantum gravity. For example, the quantum fluctuations that lead to the anisotropy of the background radiation have nothing to do with quantum-gravity effects (at least in part) and can be considered outside models of quantum gravity. I refer here to the quantum fluctuations of the inflaton field—the scalar field that leads to inflation; these are ordinary quantum-field fluctuations that bear no direct relation to quantum gravity or to space–time quantization. But almost every theory of quantum gravity describes the whole of space–time as a single quantum system—in other words, is in fact at the same time a model of quantum cosmology. As such, quantum gravity shares all the methodological problems that were mentioned above in relation to quantum cosmology. All that is said below concerning problems in quantum cosmology will apply equally to analogous problems in quantum gravity.

It is as yet not fully clear how these paradoxes (that is, why and how methodologically unacceptable theories lead to practically useful results) can be resolved. One possible explanation is that these paradoxes are a consequence of an attempt mechanically to extend the traditional methodology beyond the bounds within which that methodology was previously established and tested. Probably we should honestly admit that the methodology of science is not something absolutely fixed: a specific methodology may be applicable only within certain boundaries, just as each physical law has its boundaries of applicability. It is important that we should be aware of the possibility that such boundaries may exist and of the necessity of revising the most important methodological principles when we are forced to go beyond these boundaries. But where are these boundaries situated and what may the new methodological principles be?

It seems to me that cosmology (and especially quantum cosmology), quantum gravity, and certain other subfields of physics like the quantum theory of consciousness clearly lie beyond these boundaries, as the aforementioned paradoxes suggest. Here, evidently, we cannot get away merely by somehow fine-tuning existing methodological principles: the changes in methodology must be explicit and quite radical. As a matter of fact, however, researchers in these subfields of science have for a long time already been going beyond the bounds of the standard scientific methodology (as this concept is defined above), but they have been doing so implicitly and often, it appears, not fully consciously.

In my opinion, there is a need to replace the principles of observability and experimental reproducibility by some more general propositions. I shall try to formulate them as follows. First, theories must *yield predictions that are at least indirectly verifiable by means of experimental observations*, but it is not obligatory that all the significant data produced by a theory should be strictly definable in operational terms. I shall call this proposition the *principle of predictive power*; it replaces the observability principle. Second, the experimental observations themselves must possess the property of objectivity, but not necessarily that of reproducibility. I shall call this proposition the *observational objectivity principle*; it replaces the experimental reproducibility principle. These new methodological propositions require clarification (in particular, they rely on the undefined concept of indirect measurement). Of course, I would like to give exact, rigorous, and exhaustive definitions of the concepts that I have introduced, but this seems to me too complex a task and I shall not try to accomplish it here. Instead, I shall simply explain what the new concepts mean in commonsense terms, using a few examples.

By "objective experimental observations" (the objectivity principle) I mean observations that possess the following two properties. First, the results of such observations must be directly accessible to an unlimited number of expert observers. This excludes, for instance, the experimenter's observations of the state of his own individual consciousness and other similar observations of a subjective character. This is a nontrivial requirement, because some approaches to the interpretation of quantum theory—relating, in particular, to the quantum structure of the universe—may include such self-observations (Menskii 2007). The admission of subjective methods of this kind would entail further expansion of the methodological base, which in the given case is not required. Second, observations must have been made with the aid of equipment that generates reproducible results in the ordinary sense in *test experiments and calibration measurements*. Reproducibility is not in general required of the actual results of measurements, because they may be in some sense unique or not be reproducible in a controllable fashion. Examples of objective but nonreproducible observations are observations of certain unique astrophysical events—for instance, the neutrino burst from the explosion of Supernova 1987A in the Magellanic Cloud (Imshennik and Nadiozhin 1988; Morrison 1988). The nonreproducibility of some objective observations not infrequently creates problems. Thus, for example, while there are no special doubts regarding the authenticity of the recording of the neutrino signal of Supernova 1987A (because it was recorded by several neutrino telescopes with different degrees of reliability), the same cannot be said of the recording of a gravitational impulse accompanying the supernova explosion by a single installation in the Rome experiment for the discovery of gravity waves (Imshennik and Nadiozhin 1988; Morrison 1988).

The principle of observational objectivity is weaker than the principle of reproducibility, because the reproducibility of an experiment always implies the objectivity of the corresponding observation but the converse is not in general true. It may be noted that for quite a long time already the principle of observational objectivity has very often been used implicitly instead of the principle of experimental reproducibility as the criterion of the scientific character of experimental results.

Let us now examine in greater detail the principle of the predictive power of theories. This principle requires that theories should have consequences that are *in principle* verifiable (not necessarily verifiable at the already attained level of technology!), that are connected in *some* way (albeit indirectly) with experiment, but it does not require that every essential element of a theoretical model should have a rigorous operational meaning. I find it difficult to define in general form what should be understood by the indirect connection of a theory with experiment, which is essentially the core of the concept of a predictive theory. Instead, I shall examine the meaning of the concept of predictive power using the important and very nontrivial real example of predicting the anisotropy of the background radiation in inflationary cosmology, leaving the matter of an exact definition for future research.

Quantum theory, when applied to the early (inflationary) stages of the evolution of the universe, predicts a certain distribution for the quantum fluctuations of the inflaton field, which eventually become the source of the heterogeneity of the distribution of matter in the hot universe and then of the anisotropy of the background radiation. The transition from the phase of inflation to the phase of warming of the universe (Dolgov, Zel′dovich, and Novikov 1988; Linde 2007) is equivalent to some measurement (in the sense in which measurement is understood in quantum theory) of the amplitude of these quantum fluctuations. In the classical result of such "measurement," virtual quantum fluctuations are recorded in the form of fluctuations in the density of matter. Strictly speaking, quantum theory predicts only the distribution of probabilities for obtaining various pictures of the spatial distribution of these fluctuations and, correspondingly, for obtaining various distributions of the angular anisotropy of the temperature of the background radiation across the sky.[7] Two things are of extraordinary importance. First, the corresponding quantum probabilities, which are the basic result of the theoretical model, are undefinable in operational terms (because an ensemble of universes is impossible). That is, we are dealing with a theory that clearly does not satisfy the classical principle of observability. Second, what we see is a result of just one "measurement" of the picture of the distribution of fluctuations out of the multitude of measurements described by the probability distribution. So precisely what we see is, from the point of view of quantum theory, unpredictable in principle, because quantum theory does not predict the results of single measurements—it predicts only probability distributions. But we are dealing with a single result of measurement, which according to theory could be simply anything. What in this case is it possible to compare (and really is compared) with the theory?

In fact, the theory predicts that the *most probable* distributions of density fluctuations at the moment of warming of the universe are those which lead to a quite definite spectrum of density heterogeneities (namely, to an almost flat spectrum) and then to definite correlations in the distribution of the temperature of the background radiation across the sky (to a definite type of anisotropy). If we assume that it is precisely this most probable picture that has been realized, then we can compare what we see with what the theory predicts as the most probable result. But we have no a priori guarantee that it is precisely the most probable result that has been realized. So if we discover in our observations a substantial deviation from this most probable result, then there is no way of deciding what this means—whether the theory is incorrect or whether we are dealing with a large quantum statistical fluctuation.

Interestingly enough, this is indeed the situation. There is a substantial shortfall in anisotropy with large angles (the lowest or two lowest angular harmonics in anisotropy), and it is impossible to tell whether we are dealing with a statistical fluctuation or there is something wrong with the theory. There is an essential difference between the situation that we face and the normal situation in the quantum theory of measurement. Normally we are able to measure all probability distributions or average values with any preset degree of precision, simply by using a sufficiently large ensemble of systems. In the cosmology of background radiation anisotropy, by contrast, we are dealing with a single result of quantum measurement, or with an ensemble consisting of just one copy of the system and one measurement on it, and there is nothing we can do to reduce statistical error. And in principle we have no guarantee (except for commonsense and statistical estimates) that the correspondence or discrepancy between theory and observation that we have discovered is not simply the result of statistical fluctuation. Thus, although a connection between theory and experiment exists (and from a purely external perspective looks like a very good confirmation of the theory by observations), in reality this connection is very indirect (this can be regarded as an example of indirect measurement) and the theory does not fulfill the observability principle. The theory yields predictions that are connected with observation only in a quite complex manner, and this is an example of fulfillment of the principle of predictive power but not of the observability principle in an exact sense. In the given case, this merely indirect connection of the theory with measurements means that the theory cannot in principle be verified to any required degree of precision. This fundamental uncertainty is well known; it is called cosmic variance (Mukhanov, 2004). For the multipole with number l in anisotropy of the background radiation, the relative amplitude of this ineradicable variance is a magnitude of the order of $(l + 1/2)^{-1/2}$; for the lowest multipole $l = 2$, which corresponds to an angle of 90°, this gives a magnitude of the order of 50 percent. It is precisely here that we find the maximum divergence between theory and experiment, which constitutes a magnitude of about 90 percent of the expected value (that is, we observe one tenth of the expected anisotropy). Although in the context of an expected ineradicable variance of 50 percent such a divergence cannot be considered statistically significant, we still feel an uneasy uncertainty regarding the nature of this divergence. It is important to realize that this uncertainty cannot be removed by any kind of improvement in experimental methods. Notably, neither the article cited (Mukhanov 2004) nor other sources that discuss cosmic variance show a clear understanding of the fact that this uncertainty is an expression of a fundamental weakening of the empirical methodological base of quantum cosmology by comparison with the traditional methodology.

It may be noted that in ordinary quantum measurements (or, indeed, in any other measurements) the result is also always obtained only with a finite degree of precision. In principle, however, this degree of precision can always be increased without limit by using ensembles of increasingly large size, while in the case of observation of the anisotropy of the background radiation no increase in the degree of precision is possible because we are confined to an ensemble consisting of a single quantum measurement. This bounded precision is for us just as fundamental a property of our universe as the uncertainty principle; it is an expression of the narrower empirical base of a predictive theory by comparison with a theory that satisfies the observability principle.

In relation to predictive theories, there arises the following important question. Let us suppose that some theory has been verified by experiment and has yielded important predictions of new phenomena whose existence has also been confirmed by observations. At the same time, the theory contains *essential*[8] elements that are not directly connected with feasible observations and have no direct operational meaning. Such elements may be certain objects or certain properties of any objects. What is more, the theory may explicitly rule out the possibility of direct observation of these elements. In justifiably considering the theory "correct" because it yields correct and useful predictions, must we regard such nonobservable elements as real together with the "realness" of the theory?

I think that the problem here is a result of incorrectly posing the question in terms of "either–or." When we ask whether some object is real or not, we are implicitly appealing to the traditional methodology based on the observability principle. Within the framework of the traditional methodology, the concept of realness is well defined: what is observable is real. But we are working within the framework of a new methodology, and within this framework objects of this kind acquire a status that does not exactly correspond either to "realness" or to "nonrealness" within the framework of the old methodology. It is logical to give such an object the status of being *model-real*, and this status does not exactly correspond to any of the old concepts. It is also important to note that an object that at a certain stage in the development of a theory has the status of being model-real may later, in principle, change its status to being simply real—that is, accessible to direct observation. In order to clarify the concept of the model realness of theoretical objects (elements of a theory), it is useful to consider a few examples.

I have in fact already mentioned a couple of examples of model-real objects—namely, the quantum state of the universe in models of quantum cosmology and quantum gravity and the quantum states of complex macroscopic objects. Other objects of this type—some of the most interesting, perhaps—are the inflationary multiverse and the "other universes" that fill it.

As is well known, inflationary cosmology (for the most recent survey, see Linde 2007) has succeeded in solving many of the riddles of Friedman cosmology and yielded a very important prediction of the anisotropy of the background radiation that has been brilliantly confirmed by the latest observations. However, the majority of inflation scenarios—including the simplest and most natural scenarios, which so far best correspond to observations—describe the inflationary birth not of a single universe (our own) but simultaneously of an enormous number of universes (we may suppose, actually an infinite number). These additional universes are a practically unavoidable (or at least very natural) component of a theory that corresponds very closely with observations. The set of these universes is called the multiverse, or the inflationary multiverse. The geometry of the multiverse is such that in the simplest case (in the case of the absence of topological defects of space: see below) all the other universes are beyond our event horizon and therefore not directly accessible to observation. For this reason, the multiverse—according to the theory of inflation, which generated this concept—does not satisfy the observability principle. Thus, if we adhere to the traditional methodology, we must consider the multiverse nonexistent and the structure of the theory of inflation unsatisfactory because it predicts essential objects that are not observable.

Let us note that the multiverse, after all, is not some sort of secondary element of the theory that appears only at intermediate stages of the calculations, like the phase multiplier preceding the wave function in quantum mechanics. The multiverse is an "essential" object in particular because our own universe has exactly the same status in inflationary cosmology as all the other local universes of the multiverse. They are all observable to hypothetical local observers situated in these local universes; it is just that they are not observable from our own local point of view. In other words, here the reason for counting an object in a theory as essential is the existence of hypothetical observers to whom the object is real. This reason differs from the reason for the essential character of operationally undefinable probabilities in quantum cosmology and in the quantum theory of macroscopic objects (see above).

Thus, because inflationary cosmology is a very successful theory confirmed by observations but at the same time implies the existence of a nonobservable multiverse, the multiverse in this theory has the status of a model-real object.

Let me explain how the multiverse may in principle change its status from a model-real to simply a real object. Universes in the multiverse may have topological defects in the form of the space–time tunnels known as wormholes; if so, we cannot exclude the possibility that wormholes may connect different universes. (There are corresponding models, which are solutions to the equations of the general theory of relativity; see Shatskii, Novikov, and Kardashev 2008.) In that case, universes may in principle exchange information or even matter through such a tunnel. Wormholes in our universe may manifest themselves as astrophysical objects of a special kind (Novikov, Kardashev, and Shatskii 2007). If such objects are ever discovered and it is shown that they really do connect different universes, then the existence of the multiverse will be proven by direct observations; thereafter the multiverse will have the status of a real object.

The multiverse is a rather exotic object, so its status as a model-real object is not all that surprising. However, it is possible to show that the much more ordinary conception of the global homogeneity of the universe also has the status of a model-real element of a theory. Actually, when we make astronomical observations of very remote regions of the metagalaxy, we are simultaneously peering into the distant past. Because the universe is expanding, the density of matter in it was much higher in the distant past than it is now. So when we directly observe remote regions of space, we discover a higher average density of matter than in our immediate environs. The assertion that the universe is globally homogeneous pertains to the density of matter measured at one and the same moment in cosmological time at all points in space. But cosmically remote regions of space that are contemporaneous with us in terms of cosmological time are situated beyond our event horizon and are in principle inaccessible to direct observations. In other words, if by direct observations we mean observations of objects that have a causal connection with us,[9] then the homogeneity of the universe is not a directly observable property of the universe. It is possible to establish the global homogeneity of the universe only by comparing the predictions of the homogeneous cosmological model of Friedman, Robertson, and Walker with the results of observations or by recalculating the directly observed picture of the density distribution for different times (depending on distance) so that it applies to one and the same moment in cosmological time throughout space in accordance with the Friedman–Robertson–Walker model. The global homogeneity of the universe acquires realness only thanks to the interpretation of experimental data with the aid of homogeneous and isotropic cosmological models; it is inaccessible to direct observation because it has the status of a model-real object, like the multiverse. In this sense, the picture of the anisotropy of the background radiation that is predicted by models of inflation can (and even must) also be interpreted as an indirect manifestation of the existence of the multiverse. Moreover, the multiverse and the homogeneity of the universe have not fully real but merely model-real status for one and the same reason: in both cases, it is a matter of the realness of objects situated beyond our event horizon.[10]

The example of the global homogeneity of the universe shows that the difference between real and model-real status for theoretical objects is quite subtle. Often people are unaware of the difference and naively accept model-real objects simply as real objects.

Let us return to the principle of the falsifiability of theories. Using the traditional methodology, if some theory has verifiable consequences then these consequences can in principle be verified to any required degree of precision by virtue of the principle of experimental reproducibility. Therefore, provided that the consequences of the theory are not too trivial, the theory is automatically falsifiable—falsifiable, moreover, to any required degree of certainty (when it leads to consequences that contradict the results of observations). With the new methodology the situation is more complex, as we saw from the example of measuring the anisotropy of the background radiation. Because the experiment may not possess the property of reproducibility in relation to the theory under consideration (we have only one copy of the picture of the anisotropy of the background radiation across the sky, while we would need an infinite sample of such pictures), the theory likewise may not be falsifiable to any preset degree of certainty. The divergence of observations from the theory can always be attributed to uncontrollable fluctuation. The new methodology permits the falsification of theories only with a limited degree of precision. Thus, change in the principles of observability and reproducibility unavoidably entails change in our understanding of the principle of falsifiability.

Without a doubt, adopting the new methodology means lowering the level of scientific rigor, and this cannot but arouse anxiety. It would be altogether unjustified to apply the new methodology in traditional fields of science. However, the alternatives, insofar as we understand them, are as follows—either we must regard a substantial part of contemporary cosmology and quantum theory as lying outside of science (if we adhere strictly to the traditional methodology) or we can adopt a new methodology (the one presented in this article or some modification thereof) and progress further in inflationary and quantum cosmology, quantum gravity, the quantum theory of consciousness, and some other disciplines that urgently require a broadening of the methodological base.

It cannot be proven that the new methodology is in any sense more or less correct than the traditional methodology. Whether to adopt it is a matter of agreement or personal choice. In the final reckoning, the degree to which a choice is justified can be determined only by its productivity, subjectively understood.[11] In practice, some version of the new methodology is used by the majority of researchers working in the aforementioned fields. However, there is very little self-awareness of this choice; it remains implicit. This gives rise to quite a few misunderstandings—even, for instance, to cosmologists being declared charlatans, the multiverse a "scientific myth," and so on.

A very interesting publication that reflects a clear *understanding* of the limitations of standard scientific methodology in relation to cosmology and quantum gravity but nonetheless insists that it is necessary to remain within the bounds of the traditional methodology is an article titled "The Unique Universe" that appeared recently in the electronic journal physicsworld.com; the author is the well-known specialist in the fields of cosmology, quantum gravity, and string theory Lee Smolin (2009).

Smolin argues his position at many levels; his article is not very easy to understand. I shall not present his argument here in all its diversity. Rather, I shall try to convey my own understanding of those aspects of it which pertain to the questions discussed above.

The leitmotif of the article is the idea that the conceptions of the multiverse and of the quantum state of our own universe are meaningless in physical terms. The first conception is meaningless because the multiverse is not observable, the second because the concept of quantum probability cannot be defined in operational terms when applied to the single copy of the once-evolving universe that alone is accessible to our observation. As we have seen, these assertions are absolutely correct within the framework of the traditional methodology of physics, based on the principles of observability and reproducibility. Indeed, I started my analysis with these propositions, so what objection could I have to them? Lee Smolin goes further and, consciously and firmly adhering to the standard methodology, takes the analysis to its logical conclusion.

He proposes the following assertion as one of the basic principles of cosmology: "There is only one universe. There are no others, nor is there anything isomorphic to it." This very firm assertion is a quite logical and even beautiful consequence of the observability principle for the simple reason that neither other universes nor objects isomorphic to other universes or to the multiverse can have the attribute of existence *within the framework of an exact observability principle*. Everything that is observable is, by definition, part of our universe; what is nonobservable simply does not exist.

I would like to note that the consequences of such a rigid declaration are highly significant (Lee Smolin himself writes nothing in this regard). Inasmuch as inflationary cosmology definitely contains objects that are isomorphic to other universes, namely, the whole conception of the multiverse, it has no right to exist—that is, it cannot be considered a viable theory. In abandoning it, we also abandon its proposed solutions to the riddles of Friedman cosmology (the flatness problem, the problem of the horizon, etc.), its prediction of the anisotropy of the microwave background radiation and of the perturbations of the matter from which protogalaxies formed, and the entire wealth of ideas of the science to which the conception of inflation has given birth. This, I emphasize, is all quite logical: if we accept an exact observability principle, then we can make no objection to it. The only problem with such an approach is that it can hardly be called productive.

It is my deep conviction that the basic purpose of science is the understanding of nature—at least, it is precisely this motive that guides the researcher. Science, of course, also has significance in terms of its application; from a purely logical point of view, it may be regarded as a means of predicting the behavior of systems on the basis of initial data. But this is not the most important thing—the most important thing is understanding. It is hard to deny that inflationary cosmology has given us a colossal breadth and depth of new understanding of nature—and now all this understanding has to be declared unacceptable. From the logical point of view this situation is quite normal within the bounds of the traditional methodology, but psychologically it is difficult to accept. The point here, evidently, is that we just have to acknowledge that inflationary cosmology has gone beyond the bounds of the traditional methodology. It is the methodology that must be changed, and not inflationary cosmology.

Lee Smolin goes even further. He rightly notes the following two circumstances. First, the initial conditions of the universe that led to the Big Bang are in principle not fully accessible to our observation (in particular, due to the event horizon), and in addition it is not possible for us to investigate various initial conditions because we have only one evolution of the universe. Second, because only one example of the evolution of the universe is accessible to us, the concept of the configurational space of the universe—that is, the set of all its possible states—has no operational meaning. From this Smolin draws the conclusion that the usual schema of a physical theory (which he calls the Newtonian schema), in which the initial state of a system is given and the trajectory of the system in configurational space is calculated, has no meaning for cosmology (inasmuch as none of its ingredients has meaning). In other words, it is meaningless to imagine the dynamic of the universe as the dynamic of a system that potentially can start with various initial states and evolve along different trajectories in configurational space. The fundamental laws of physics together with the initial state of the universe must constitute a single whole—or, to put it another way, the initial state has the same status as the fundamental laws: it is equally fundamental. To divide scientific description of the universe into an initial state and an evolution in configurational space is incorrect. The initial state and the evolution must be represented as a single theoretical object. This produces a new situation in which not only must the *answers* of inflationary cosmology to the question of why there arose a very special initial state of our universe (flatness, density perturbations, etc.) be considered inadequate due to the inadequacy of inflationary cosmology itself, but even the very *question* of why we have such an initial state is meaningless. We are simply forbidden to ask why the initial state is what it is, because this is a fundamental and irreducible fact. And again it is necessary to note that in the context of the traditional methodology of observability and reproducibility these conclusions are quite logical.

However, we already have many convincing answers to the various *why*'s of the structure of the initial state of the universe. From a purely logical point of view, it must be admitted that according to the traditional methodology of physics all these answers are meaningless because the question itself is meaningless (not to mention the method of answering it by using inflationary cosmology). This, it seems to me, is not an especially productive stance, and the way out is to make a deliberate departure from the traditional methodology. Lee Smolin himself, it should be noted, does not indicate in concrete terms how cosmology is to be constructed within the rigid bounds of classical methodology as he defines it. There are no references to concrete models.

Smolin connects the question of the singularity of the universe and its lack of a quantum state with the question of the fundamental character of the concept of time. The connections that he examines are quite numerous and I shall not analyze them in detail, but the essence of his argument comes down to the following.

In contemporary physics there are at least two sources from which the idea emerges that time is not a fundamental concept but arises merely as some sort of effectual image in our macroscopic perception of the world. One source of this idea was the earliest models of quantum cosmology and gravity (see, for example, DeWitt 1967). Contemporary models retain this property. Quantum-cosmological models define a wave function for the universe that does not contain time—it is atemporal. The corresponding equation (the Wheeler–DeWitt equation) also does not contain time: it defines a certain kind of static object—an atemporal universe. The general reason is simple: the evolution of the universe cannot be parametrized in terms of any kind of measure of time that is external to the universe, because time is measured by clocks and outside the universe there is nowhere to place a clock. Everything that exists is by definition situated inside the universe and cannot be situated outside it. The evolution that is actually observed inside such a universe is an effectual concept for observers situated inside the universe, and is represented in terms of the correlation among certain observed values. If one of these values is called hours, then there arises an effectual evolution of subsystems of the universe in which time can be regarded as a parameter.

The second source of the idea of the emergent character of time is the concept of the multiverse in inflationary cosmology. Here there is no single time within which exists the whole of this object. Effectual time arises only inside local universes (and even there with many reservations). The multiverse as a whole must be described in terms of some atemporal physics that describes the probabilities (in some operationally undefinable sense!) of the appearance of different types of universes.

As we have seen, in Smolin's approach (more precisely, in the rigorous traditional methodology to which he strictly adheres) both the multiverse and quantum states of the universe, together with quantum cosmology, are meaningless. Thus, both sources of the idea that the concept of time is not fundamental are invalid. Therefore Smolin considers that it is necessary to construct a physics, including a theory of quantum gravity, using models in which time is restored to its fundamental role. He cites three examples of quantum-gravity models that possess this property: causal dynamical triangulation, quantum graphity, and unimodular gravity (see references in Smolin 2009).

It cannot be denied that Smolin's logic is quite clear. However, I would like to clarify what does and what does not follow from this logic. It does indeed follow that it makes sense to seek models of quantum gravity in which time plays a fundamental role. But it does not follow that more general models, in which time arises only effectually, are impermissible. Thus, in the given case Smolin's conclusions in no way restrict free choice of research orientation.

Several other interesting ideas are discussed in the article. In particular, Smolin proposes, in view of the fundamental role played by time, that serious examination be given to the possibility that fundamental laws manifestly depend upon fundamental time. This idea is open to objection. The problem is that even if the universe is strictly singular it contains no *single* fundamental time upon which fundamental laws might depend. The general theory of relativity, which controls the dynamic of the universe, admits the well-defined concept of each individual observer having *his own* time, and this time really may be in some sense fundamental, but no single universal time is defined for a system of general relativity. Indeed, to speak of our universe, time close to the surface of a neutron star, for instance, flows quite differently from time in intergalactic space, although they both exist in the same universe. It is possible to adduce other examples (see, for example, Rovelli 2009). Cosmological time can be introduced only to a certain approximation, due to the fact that the universe is approximately homogeneous and isotropic. It can be linked, for instance, to the scale factor or to the temperature of the background radiation, which in homogeneous and isotropic models is unambiguously connected with the scale factor. It is precisely use of the temperature of the background radiation as a cosmological clock that makes it easy to convince yourself that exact cosmological time does not exist. The problem lies in the anisotropy of the background radiation. At each point in space there is no one single temperature: it depends upon the direction in which you look. The relative value of this anisotropy is a few hundred-thousandths—and this is the degree of approximation in the concept of a single cosmological time. This approximation is quite rough, and deviations can easily be measured. Such a measure of time cannot be a parameter in fundamental laws because it itself is not fundamental, and apparently there is no other fundamental time in our universe.

Lee Smolin's article contains a very interesting and witty examination of the physical nature of mathematics. Smolin also links the nature of mathematics to the existence of fundamental time. This question, however, is not directly connected with the theme of the present article, and I refer the interested reader to the original (Smolin 2009).

To sum up the results of the discussion, let me note again that the methods used in contemporary cosmology and quantum gravity have already de facto gone beyond the bounds of the standard scientific methodology of physics, based on the principles of observability and experimental reproducibility. In this article I have tried merely to register this departure explicitly. The new methodology means a weakening (or erosion) of the empirical base of the new areas of physics by comparison with its traditional subfields, and this is a price that has to be paid for the possibility of a deeper understanding of nature. It must be emphasized, however, that a weakening of the empirical base does not mean its absence. Thus, for example, an important empirical criterion that in principle enables us to distinguish quantum theories of gravity from one another is the Lorentz invariance test (Smolin 2003). Under the new conditions, however, it is noticeable that such nonempirical criteria of truth as the self-consistency and beauty of a theory are playing a growing role.

Lee Smolin's article (Smolin 2009) is an extraordinarily striking example of the results of trying to adhere strictly to the traditional methodology in cosmology. In my opinion, this approach, though logically permissible, is unproductive. A more productive approach is explicitly to broaden the traditional methodology by registering the corresponding generalized methodological principles, as I have tried to do here. I again emphasize: for each researcher the choice of a methodological base is a matter of agreement, and the correctness of one or another choice cannot be proven by means of pure logic.

In conclusion, let me note that the conceptions contained in the present article require further refinement and development. In particular, I have been able to explain the meaning of a number of concepts that I have introduced only by giving concrete examples of their use, and more exact and general definitions still need to be formulated.

Notes

I wish to express my gratitude to participants in the roundtable "Philosophical Problems in Cosmology," held in 2008–9 at the Institute of Philosophy of the Russian Academy of Sciences, for fruitful discussion of the questions considered in the present article and to V.V. Kaziutinskii for suggesting that I write the article. I began to ponder these questions during the roundtable sessions; in preparing the article, I have tried to give completeness to the corresponding ideas.

1. V. Geizenberg [Heisenberg], "Teoriia, kritika i filosofiia," *Uspekhi fizicheskikh nauk*, 1970, vol. 102, no. 2, pp. 298–312.

2. Geizenberg, "Teoriia," p. 303.

3. In each separate measurement, we measure the projection of the spin onto only one axis. We cannot measure projections onto different axes simultaneously. But having an ensemble of systems in the same initial state, we can measure projections of the spin onto different axes for different subensembles and find the corresponding average values or probabilities for the initial ensemble. These average values will enable us to reconstruct the spin state that characterizes the initial ensemble.

4. There do exist macroscopic objects of a special kind for which the concept of quantum state is well defined operationally. These are macroscopic objects whose state is separated from states of lesser excitation by an energy gap that blocks the transmission of excitations from the surroundings to the object. Such objects are, for instance, superfluid liquids and currents in superconductors.

5. The status of the universe as an all-encompassing *physical* object within various

cosmological theories is examined in the article by V.V. Kaziutinskii, "Epistemologicheskie problemy universal'nogo evoliutsionizma," in *Universal'nyi evoliutsionizm i global'nye problemy* (Moscow: IFRAN, 2007). The article explains that in this sense the ontological content of the concept "universe" depends on the specific cosmological theory and essentially differs from the philosophical category "all that is real" [*vse sushchee*].

6. More precisely, it does not undergo any kind of evolution. In the majority of quantum cosmological models, the quantum universe as a whole is a stationary object and is described by the atemporal Wheeler–DeWitt equation. Evolution arises as an effective concept only for observers located within the universe.

7. Let us note that the exact quantum meaning of the analysis is usually somewhat masked by the semiphenological and semiclassical character of the calculations actually performed (see, for instance: Dolgov, Zel'dovich, and Novikov 1988, Ch. 11). Calculations, for example, may start by making correct quantum estimates of the value of virtual fluctuations in the inflaton field, but then these fluctuations are treated as ordinary classical field variations and a calculation is made of the time interval by which variations in the amplitude of the field shift the moment at which inflation ends (this is the cause of fluctuation in the density of matter). In reality, it is necessary to understand that in an exact quantum picture the entire evolution of quantum fluctuations, including the various moments at which inflation ends, takes place virtually. In other words, it must be presented as a quantum superposition of a set of various classical evolutions. The warming of the universe and the ending of inflation make one of these evolutionary trajectories real for us, for observers. The semiclassical approach ignores these subtleties; this does not change the general quantum meaning of the analysis.

8. The word "essential" in this context requires a definition. However, I am not as yet able to provide such a definition in a sufficiently closed and general form. Examples of essential elements of a theory are the probabilistic predictions of any quantum theory, because in general they are the sole means for connecting the theory with observations. At the same time, as we have seen, in theories of quantum cosmology and in the quantum theory of macroscopic objects these probabilities are undefinable in operational terms—that is, unobservable. Another type of "essential" element of a theory is the multiverse in inflationary cosmology (see below).

9. The idea of distinguishing between direct and indirect observations in accordance with the presence or absence of a causal connection between the object or phenomenon and the observer was suggested by E.A. Mamchur.

10. This analysis omits certain inessential subtleties. For example, if I now enter in my laboratory journal a record of the density of matter in the vicinity of our galaxy, then in 14 billion years direct information will become accessible regarding regions of space that are now situated close to my event horizon. At that time, by comparing directly measured data with the journal record entered 14 billion years before, I shall be able directly to convince myself of the homogeneity of the universe within the bounds of the horizon that existed 14 billion years before (but not at the moment of verification). It is not very clear whether it is possible to consider such measurements direct for us now. In any case, this does not change the situation very fundamentally, because if our universe is expanding at an accelerating rate then there may exist regions in it that will always remain beyond our event horizon. For such regions there is no way in which the homogeneity of space can be established directly.

11. I note that there is no objective criterion of productivity, because assessment

of productivity itself also depends on methodological principles. What some will call a valuable result of a theory others, who disagree a priori with the methodological principles adopted in this theory, will simply not consider a result at all. The circle closes.

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