Excess Baggage*

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Many advances in physics have in common that some idea which was previously accepted as fundamental, general, and inescapable was subsequently seen to be consequent, special, and dispensable. The idea was not truly a general feature of the world, but only *perceived* to be general because of our special place in the universe and the limited range of our experience. It was *excess baggage* which had to be jettisoned to reach a more a more general perspective. This article discusses excess baggage from the perspective of quantum cosmology which aims at a theory of the universe's quantum initial state. We seek to answer the question 'Which features of our current theoretical framework are fundamental and which reflect our special position in the universe or its special initial condition?' Past instances of cosmological excess baggage are reviewed such as the idea that the Earth was at the center of the universe or that the second law of thermodynamics was fundamental. Examples of excess baggage in our current understanding are the notion that measurement is central to formulating quantum mechanics, a fundamental quantum mechanical arrow of time, and the idea that a preferred time is needed to formulate quantum theory. We speculate on candidates for future excess baggage.

I. QUANTUM COSMOLOGY

It is an honor, of course, but also a pleasure for me to join in this celebration of Murray Gell-Mann's sixtieth birthday and to address such a distinguished audience. Murray was my teacher and more recently we have worked together in the search for a quantum framework within which to erect a fundamental description of the universe which would encompass all scales – from the microscopic scales of the elementary particle interactions to the most distant reaches of the realm of the galaxies – from the moment of the big bang to the most distant future that one can contemplate. Such a framework is needed if we accept, as we have every reason to, that at a basic level the laws of physics are quantum mechanical. Further, as I shall argue below, there are important features of our observations which require such a framework for their explanation. This application of quantum physics to the universe as a whole has come to be called the subject of quantum cosmology.

The assignment of the organizers was to speak on the topic "Where are our efforts leading?" I took this as an invitation to speculate, for I think that it is characteristic of the frontier areas of science that, while we may know what direction we are headed, we seldom know where we will wind up. Nevertheless, I shall not shrink from this task and endeavor, in the brief time available, to make a few remarks on the future of quantum cosmology. The point of view that I shall describe owes a great deal to my conversations with Murray.

One cannot contemplate the history of physics without becoming aware that many of its intellectual advances have in common that some idea which was previously accepted as fundamental, general, and inescapable was subsequently seen to be consequent, special, and dispensable. Further, this was often for the following reason: The idea was not truly a general feature of the world, but only *perceived* to be general because of our special place in the universe and the limited range of our experience. In fact, it arose from a true physical fact but one which is a special situation in a yet more general theory. To quote Murray himself from a talk of several years ago: "In my field an important new idea ..... almost always includes a negative statement, that some previously accepted principle is unnecessary and can be dispensed with. Some earlier correct idea .... was accompanied by unnecessary intellectual baggage and it is now necessary to jettison that baggage."[1]

In cosmology it is not difficult to cite previous examples of such transitions [2]. The transition from Ptolemaic to Copernican astronomy is certainly one. The centrality of the earth was a basic assumption of Ptolemaic cosmology. After Copernicus, the earth was seen not to be fundamentally central but rather one planet among others in the solar system. The earth was in fact distinguished, not by a law of nature, but rather by our own position as observers of the heavens. The idea of the central earth was excess baggage.

The laws of geometry of physical space in accessible regions obey the Euclidean laws typified by the Pythagorean theorem on right triangles. Laws of physics prior to 1915, for example those governing the propagation of light, incorporated Euclidean geometry as a fundamental assumption. After Einstein's 1915 general theory of relativity, we see Euclidean geometry not as fundamental, but rather as one possibility among many others. In Einstein's theory, the geometry in the neighborhood

of any body with mass is non-Euclidean and this curvature gives a profound geometrical explanation for the phenomena we call gravity. On the very largest scales of cosmology, geometry is significantly curved and it is the dynamics of this geometry which describes the evolution of the universe. Euclidean geometry is the norm for us, not because it is fundamental, but only because our observations are mostly local and because we happen to be living far from objects like black holes or epochs like the big bang. The idea of a fixed geometry was excess baggage.

In each of these examples there was a feature of the current theoretical framework which was perceived as fundamental but which in truth was a consequence of our particular position and our particular time in the universe in a more general theoretical framework. Our description was too special. There was excess baggage which had to be discarded to reach a more general and successful viewpoint. Thus, in our effort to predict the future of quantum cosmology, the question naturally arises: Which features of our *current* theoretical framework reflect our special position in the universe[1] and which are fundamental? Which are excess baggage?

We live at a special position in the universe, not so much in place, as in time. We are late, living some ten billion years after the big bang, a time when many interesting possibilities for physics could be realized which are not easily accessible now. Moreover, we live in a special universe. Ours is a universe which is fairly smooth and simple on the largest scales, and the evidence of the observations is that if we look earlier in time it is smoother and simpler yet. There are simple initial conditions which are only one very special possibility out of many we could imagine.

The question I posed above can therefore be generalized: Which features of our current theoretical framework are fundamental and which reflect our special position in the universe *or* our special initial conditions.[2] Are there natural candidates for elements of the framework which might be generalized? Is there excess baggage? This is the question that I would like to address today for quantum cosmology.

II. QUANTUM MECHANICS

First, let us review the current quantum mechanical framework today as it was developed in the twenties, thirties and forties, and as it appears in most textbooks today.

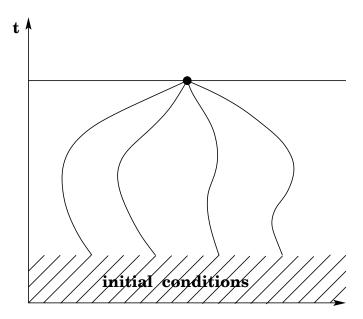It is familiar enough that there is no certainty in this

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[1] In a currently (2005) popular terminology the regularities associated with these features would be called *emergent*.

[2] The current (2005) usage is *initial condition* (singular) since there is only one wave function of the universe.

FIG. 1: In quantum mechanics the probability for a particle to be observed at position x at time t is the absolute square of the amplitude to arrive there. In Feynman's sum over histories formulation, that amplitude is the sum over all paths which are consistent with the initial conditions and arrive at x at t of the amplitude for each path $\exp[iS(\text{path})/\hbar]$. In the Hamiltonian formulation of quantum mechanics, this sum is called the wave function.

world and that therefore we must deal in probabilities. When probabilities are sufficiently good we act. It wasn't certain that my plane to Los Angeles wouldn't be blown up, but I came because I thought that the probability was sufficiently low. Experimentalists can't be certain that the results of their measurements are not in error, but they publish because they estimate the probability of this as low. And so on. It was the vision of classical physics that fundamentally the world *was* certain and that the use of probability was due to lack of precision. If one looked carefully enough to start, one could with certainty predict the future. Since the discovery of quantum mechanics some sixty years ago, we have known that this vision is only an approximation and that probabilities are inevitable and fundamental.

Indeed, the transition from classical to quantum physics contains a good example of excess baggage. In this case it was classical determinism. Classical evolution was but one possibility out of many although by far the most probable evolution in the great majority of situations we were used to.

Quantum mechanics constructs probabilities according to characteristic rules. As a simple example let us consider the the quantum mechanics of a slowly moving particle such as an electron in a solid. Its path in spacetime is called its history.

In classical mechanics the time history of the electron is a definite path determined by the electron's initial conditions and its equation of motion. Thus, given sufficiently

precise initial conditions, a later observation of position can yield only a single, certain, predictable result. In quantum mechanics, given the most precise possible initial conditions, all paths are possible and all possible results of the observation may occur. There is only a probability for any one of them. The probability of an observation of position at time t yielding the value x, for example, is constructed as follows:

A complex number, called the amplitude, is assigned to each path. This number has the form $\exp[iS(\text{path})/\hbar]$ where the action S the inertial properties of the electron together with its interactions and $\hbar$ is Planck's constant. The amplitude to arrive at x at t is the sum of the path amplitudes over all paths which are consistent with the initial conditions and which end at x at t (Figure 1).

$$\begin{pmatrix} \text{amplitude to} \\ \text{arrive at position } x \\ \text{at time } t \end{pmatrix} = \sum_{\text{paths}} \exp[iS(\text{path})/\hbar].$$

(2.1)

The sum here is over all paths consistent with the initial conditions and ending at position x at time t. For example, if the position of the particle were actually measured at a previous time but not in between, one would sum over all paths which connect that position with x. The probability to arrive at x at t is the absolute square of this amplitude. In essence, this is Feynman's sum over histories formulation of the rules of quantum mechanics.

There is another, older, way of stating these rules called the Hamiltonian formulation of quantum mechanics. Here, the amplitude for observing the electron at x at time t is called the wave function $\psi(x,t)$. If, as above, we can construct the amplitude $\psi(x,t)$ at one time, we can also employ this construction at all other times. The time history of the wave function gives a kind of running summary of the probability to find the electron at x. The wave function is thus the closest analog to the classical notion of "state of a system at a moment of time". The wave function obeys a differential equation called the Schrödinger equation

$$i\hbar \frac{\partial \psi}{\partial t} = H\psi \qquad (2.2)$$

where H is an operator, called the Hamiltonian, whose form can be derived from the action. It summarizes the dynamics in an equivalent way. Thus, although the electron's position does not evolve according to a deterministic rule, its wave function does.

Feynman's sum over histories formulation of quantum mechanics is fully equivalent to the older Hamiltonian formulation for this case of slowly moving particles. One can calculate the wave function from (2.1) for two nearby times and demonstrate that it satisfies the Schrödinger equation (2.2). One can use either formulation of quantum mechanics in this and many other situations as well.

More generally than the probability of one observation of position at one time, the probabilities of time *sequences* of observations are of interest. Just such a sequence in needed, for example, to check whether or not
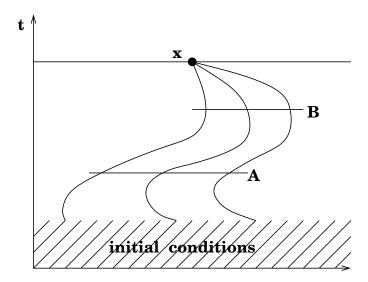

FIG. 2: Checks may be carried out as to whether the particle passed through position intervals A, B, $\cdots$ at times in between the initial conditions and t. The amplitude to arrive at position x at time t with a sequence of positive answers to these checks is the sum over all paths which meet the initial conditions and arrive at x and t having threaded the intervals A, B, $\cdots$ The probability to arrive at x at t will depend on whether these checks are carried out *even if nothing is known of the results*

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the electron is moving along a classical path between the initial conditions and time t. The amplitude for positive answers to checks of whether the electron is located inside a sequence of position intervals is the sum of the amplitude for a path over all paths which thread these intervals (Figure 2). The joint probability for the sequence of positive answers is the square of this amplitude.

This means that the probability of finding the particle at x at t depends not only on the initial conditions, but also on what measurements were carried out between the initial conditions and t. Even if one doesn't know the results of these measurements, the probabilities at t will still depend on whether or not they were carried out. Thus, there are in quantum mechanics different rules for evolution depending on whether measurements occurred or did not. In the Hamiltonian formulation this means that the wave function evolves by the Schrödinger equation only in between measurements. At a measurement it evolves by a different rule – the notorious "reduction of the wave packet".

In some circumstances it makes no difference to the probabilities whether prior measurements were carried out or not. For example, the classical limit of quantum mechanics occurs when the initial conditions are such that only a single path to x — the classical one — contributes to the sum over histories. Then, as long as sufficiently crude measurements are considered, it makes no difference to the probability of x at t whether they are made or not. The electron follows the classical evolution.

In such cases the classical history is said to "decohere ".

III. FROM BOHR, TO EVERETT, TO POST-EVERETT

The framework of quantum mechanics described in the previous section was the starting point for the "Copenhagen" interpretations of this subject. An idea characteristic of the Copenhagen interpretations was that there was something external to the framework of wave function and Schrödinger equation which was necessary to interpret the theory. Various expositors put this in different ways: Bohr [3] spoke of alternative descriptions in terms of classical language. Landau and Lifshitz [4] emphasized preferred classical observables. Heisenberg and others [5] stressed the importance of an external observer for whom the wave function was the most complete summary possible of information about an observed system. All singled out the measurement process for a special role in the theory. In various ways, these authors were taking as fundamental the manifest existence of the classical world that we see all about us. That is, they were taking as fundamental the existence of objects which have histories whose probabilities obey the rules of classical probability theory and, except for the occasional intervention of the quantum world as in a measurement, obey deterministic classical equations of motion. This existence of a classical world, however it was phrased, was an important part of the Copenhagen interpretations for it was the contact with the classical world which mandated the "reduction of the wave packet".

The Copenhagen pictures do not permit the application of quantum mechanics to the universe as a whole. In the Copenhagen interpretations the universe is always divided into two parts: To one part quantum mechanical rules apply. To the other part classical rules apply [6].

It was Everett who in 1957 first suggested how to generalize the Copenhagen framework so as to apply to cosmology [7]. His idea (independently worked out by Murray in 1963) was to take quantum mechanics seriously and apply it to the universe as a whole. He started with the idea that there is one wave function for the universe always evolving by the Schrödinger equation and never reduced. Any observer would be part of the system described by quantum mechanics, not separate from it. Everett showed that, if the universe contains an observer, then its activities — measuring, recording, calculating probabilities, etc. — could be described in this generalized framework. Further, he showed how the Copenhagen structure followed from this generalization when the observer had a memory which behaved classically and the system under observation behaved quantum mechanically.

Yet, Everett's analysis was not complete. It did not explain the manifest existence of the classical world much less the existence of something as sophisticated as an observer with a classically behaving memory. Classical behavior, after all, is not generally exhibited by quantum systems. The subsequent, post-Everett, analysis of this question involves a synthesis of the ideas of many people. Out of many, I might mention in particular the work of Joos and Zeh [8], Zurek [9], Griffiths [10], and latterly Murray, Val Telegdi, and myself. It would take us too far to attempt to review the mechanisms by which the classical world arises but we can identify the theoretical feature to which its origin can, for the most part, be traced.

A classical world cannot be a general feature of the quantum mechanics of the universe, for the number of states which imply classical behavior in any sense is but a poor fraction of the total states available to the universe. Classical behavior, of course, can be an approximate property of a *particular* state as for a particle in a wave packet whose center moves according to the classical equations of motion. But, the universe *is* in a particular state (or a particular statistical mixture of states). More exactly, particular quantum initial conditions must be posed to make any prediction in quantum cosmology. It is to the particular features of the initial conditions of the universe, therefore, that we trace the origin of today's classical world and the possibility of such information gathering and utilizing systems as ourselves.

In retrospect, the Copenhagen idea that a classical world or an observer together with the act of measurement occupy a fundamentally distinguished place in quantum theory can be seen to be excess baggage. These ideas arose naturally, in part from our position in the late universe where there *are* classically behaving objects and even observers. In part, they arose from the necessary focus on laboratory experiments as the most direct probe of quantum phenomena where there *is* a clear distinction between observer and observed. However, these features of the world, while true physical facts in these situations, are not fundamental. Quantum mechanically, the classical world and observers are but some possible systems out of many and measurements are but one possible interaction of such systems out of many. Both are unlikely to exist at all in the very early universe. They are, in a more general post-Everett framework, *approximate* features of the late universe arising from its particular quantum state. The classical reality to which we have become so attached by evolution is but an approximation in an entirely quantum mechanical world made possible by specific initial conditions.

The originators of the Copenhagen interpretation were correct; something beyond the wave function and the Schrödinger equation *is* needed to interpret quantum mechanics. But, that addition is not an external restriction of the domain to which the theory applies. It is the initial conditions of the universe specified within the quantum theory itself.

IV. ARROWS OF TIME

Heat flows from hot to cold bodies, never from cold to hot. This is the essence of the second law of thermodynamics that entropy always increases. In the nineteenth century this law was thought to be strict and fundamental [11]. A direction of time was distinguished by this law of nature. After the success of the molecular theory of matter, with its *time symmetric* laws of dynamics, the increase in entropy was seen to be *approximate* — one possibility out of many others although the overwhelmingly most probable possibility in most situations. A direction of time was distinguished, not fundamentally, but rather by our position in time relative to initial conditions of simplicity and our inability to follow molecular motion in all accuracy. The idea of a fundamental thermodynamic arrow of time was excess baggage.

Exchanging the thermodynamic arrow of time for simple initial conditions might seem to be exchanging one asymmetry for another. "Why", one could ask, "was the universe simple in the past and not in the future?" In fact, this is not a question. There is no way of specifying that direction in time which is the past except by calling it the direction in which the universe is simple. Its not an arrow of time which is fundamental, but rather the fact that the universe is simple at one end and not at the other [27].

The Hamiltonian formulation of quantum mechanics also possesses a similar distinction between past and future. From the knowledge of the state of a system at one time *alone*, one can predict the future but one cannot, in general, retrodict the past [13]. This is an expression of causality in quantum theory. Indeed, quantum mechanics in general prohibits the construction of history. The two slit experiment is a famous example (Figure 3). Unless there was a measurement, it is not just that one can't say for certain which slit the electron went through; it is meaningless even to assign a probability. In this asymmetry between past and future the notion of "state" in quantum mechanics is different from that of classical physics from which both future and past can be extrapolated. In Hamiltonian quantum mechanics, the past is the direction which is comprehensible by theory; the future is the direction which is generally predictable.

As long as the distinction between future and past in cosmology is fundamental, it is perhaps reasonable to formulate a quantum cosmology using a quantum mechanics which maintains this same distinction as fundamental. However, it would seem more natural if causality were an empirical conclusion about the universe rather than a prerequisite for formulating a theory of it. That is, it would seem more natural if causality were but one of many options available in quantum mechanics, but the one appropriate for this particular universe. For example, one might imagine a universe where both initial *and* final conditions are set. The generalization of Hamiltonian quantum mechanics necessary to accommodate such situations is not difficult to find [14]. In fact, it is ready
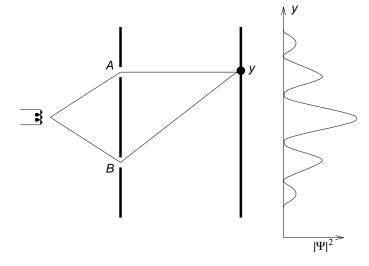

FIG. 3: The two slit experiment. An electron gun at left emits an electron traveling toward a screen with two slits, its progress in space recapitulating its evolution in time. From a knowledge of the wave function at the detecting screen alone, it is not possible to assign a probability to whether the electron went through the upper slit or the lower slit.

to hand in the sum over histories formulation described briefly in Section II. The rules are the same, but both initial and final conditions are imposed on a contributing history. In the context of such a generalization, the arrow of time in quantum mechanics, and the associated notion of state [15] would not be fundamental. Rather they would be features of the theory arising from the fact that those conditions which fix our particular universe are comprehensible at one of its ends but not at the other.

V. QUANTUM SPACETIME

Gravity governs the structure and evolution of the universe on the largest scales, both in space and time. To pose a quantum theory of cosmology, therefore, we need a quantum theory of gravity. The essence of the classical theory of gravity – Einstein's general relativity – is that gravity is curved spacetime. We thus need a quantum theory of space and time themselves in which the geometry of spacetime will exhibit quantum fluctuations.

Finding a consistent, manageable quantum theory of gravity has been one of the goals of theoretical research for the last thirty years. The chief problem has been seen as finding a theory which puts out more predictions then there are input parameters. But, in cosmology there is also a conflict with the existing framework of quantum mechanics. These difficulties are called "the problem of time" [16]

Time plays a special and peculiar role in the familiar Hamiltonian formulation of quantum mechanics. All observations are assumed to be unambiguously character-

ized by a single moment of time and we calculate probabilities for "observations at one moment of time". Time is the only observable for which there are no interfering alternatives (as a measurement of momentum is an interfering alternative for a measurement of position). Time is the sole observable not represented in the theory as an operator but rather enters the Schrödinger equation as a parameter describing evolution.

If the geometry of spacetime is fixed, external and classical, it provides the preferred time of quantum mechanics. (More exactly, a fixed background spacetime provides a family of timelike directions equivalent in their quantum mechanics because of relativistic causality.) If the geometry of spacetime is quantum mechanical – fluctuating and without definite value – then it cannot supply a notion of time for quantum mechanics. There is thus a conflict between the familiar Hamiltonian quantum mechanics with a preferred time and a quantum theory of spacetime. This is the "problem of time".

The usual response to this difficulty has been to keep Hamiltonian quantum mechanics but to give up on spacetime. There are several candidates for a replacement theory. Perhaps space and time are separate quantum mechanically with the beautiful synthesis of Minkowski and Einstein emerging only in the classical limit [18]. Perhaps spacetime needs to be augmented by other, now hidden, variables which play the role of a preferred time in quantum mechanics [19]. Perhaps spacetime is simply a totally inappropriate notion fundamentally and emerges only in the classical limit of some yet more subtle theory.

Each of these ideas could be right. I would like to suggest, however, that there is another alternative. This is that the notion of a preferred time in quantum mechanics is another case of excess baggage. That the Hamiltonian formulation of quantum mechanics is simply not general enough to encompass a quantum theory of spacetime. That the present formulation of quantum mechanics is but an approximation to a more general framework appropriate because of our special position in the universe.

It is not difficult to identify that property of the late universe which would have led to the perception that there is a preferred time in quantum mechanics. Here, now, on all accessible scales, from the smallest ones of the most energetic accelerators to the largest ones of the furthest seeing telescopes, spacetime *is* classical. The preferred time of quantum mechanics reflects this true physical fact. However, it can only be an approximate fact if spacetime is quantum mechanical. Indeed, like all other aspects of the classical world, it must be a property of the particular quantum initial conditions of the universe. The present formulation of quantum mechanics thus may be only an approximation to a more general framework appropriate because of particular initial conditions which mandate classical spacetime in the late universe.

What is this more general quantum mechanics? Feynman's sum over histories supplies a natural candidate [20, 21, 22] I shall now sketch why. We saw earlier that Feynman's approach was equivalent to the Hamiltonian one for particle quantum mechanics. It is also for field theory. A little thought about our example shows, however, that this equivalence arises from a special property of the histories – that they do not double back on themselves in time. Thus, the preferred time enters the sum over histories formulation as a restriction on the allowed histories.

In a quantum theory of spacetime the histories are four dimensional spacetimes geometries $\mathcal{G}$ with matter fields $\phi(x)$ living upon them. The sums over histories defining quantum amplitudes therefore have the form:

$$\sum_{\mathcal{G}} \sum_{\phi(x)} \exp\left(i\, S[\mathcal{G}, \phi(x)]/\hbar\right) \qquad (5.1)$$

where S is the action for gravity coupled to matter. The sums are restricted by the theory of initial conditions and by the observations whose probabilities one aims to compute.

The interior sum in (5.1)

$$\sum_{\phi(x)} \exp\left(i\, S[\mathcal{G}, \phi(x)]/\hbar\right) \qquad (5.2)$$

defines a usual quantum field theory in a temporarily fixed background spacetime $\mathcal{G}$. The requirement that the fields be single valued on spacetime is the analog of the requirement for particles that the paths do not double back in time. This quantum field theory thus possesses an equivalent Hamiltonian quantum mechanics with the preferred time directions being those of the background $\mathcal{G}$.

When the remaining sum over $\mathcal{G}$ is carried out the equivalence with any Hamiltonian formulation disappears. There is no longer any fixed geometry, any external time, to define the preferred time of a Hamiltonian formulation. All that is summed over. There would be an *approximate* equivalence with a Hamiltonian formulation were the initial conditions to imply that for large scale questions in the late universe, only a single geometry $\hat{\mathcal{G}}$ (or an incoherent sum of geometries) contributes to the sum over geometries. For then,

$$\sum_{\mathcal{G}} \sum_{\phi(x)} \exp\left(i\, S[\mathcal{G}, \phi(x)]/\hbar\right) \approx \sum_{\phi(x)} \exp\left(i\, S[\hat{\mathcal{G}}, \phi(x)]/\hbar\right)$$

$$(5.3)$$

and the preferred time can be that of the geometry $\hat{\mathcal{G}}$. It would be in this way that the familiar formulation of quantum mechanics emerges as an approximation to a more general sum over histories framework appropriate to specific initial conditions and our special position in the universe so far from the big bang and the centers of black holes. The preferred time of familiar quantum mechanics would then be another example of excess baggage.

In declaring the preferred time of familiar quantum mechanics excess baggage, one is also giving up as fundamental a number of treasured notions with which it is closely associated. These include the notion of causality,

any notion of state at a moment of time, and any notion of unitary evolution of such states. Each of these ideas requires a background spacetime for its definition and in a quantum theory *of* spacetime there is none to be had. Such ideas, however, would have an approximate validity in the late universe on those scales where spacetime is classical. Many will regard discarding these notions as too radical a step but I think it no less radical than discarding spacetime – one of the most powerful organizing features of our experience.

VI.   FOR THE FUTURE

In this discussion of the excess baggage which has been discarded to arrive at a quantum mechanical framework general enough to apply to the universe as a whole, we have progressed from historical examples, through reasonable generalizations, to topics of current research and debate. Even in the last case, I was able to indicate to you candidates for the necessary generalizations. I would now like to turn to features of the theoretical framework where this is not the case; where there may be excess baggage but for which I have no clear candidates for the generalizations.

A.   "Initial" Conditions

A candidate for excess baggage is the idea that there is anything "initial" about the conditions which are needed in addition to the laws of dynamics to make predictions in the universe. Our idea that conditions are initial comes from big bang cosmology in which the universe has a history with a simple beginning ten and some billion years ago. The global picture of spacetime is that there is a more or less uniform expansion everywhere from this moment. Perhaps the very large scale structure of spacetime is very different. Perhaps, as A. Linde has suggested [23] there are many beginnings. Our local expanding universe might be just one inflationary bubble out of many others. Perhaps, therefore, the idea that conditions should reflect a simple state at one end of the universe is excess baggage arising from our confinement to one of these bubbles. Conditions in addition to dynamics would still be needed for prediction but they might be of a very different character [24].

B.   Conditions and Dynamics

In the framework we have discussed so far there are three kinds of information necessary for prediction in quantum cosmology: First, there are the laws of dynamics summarized by the action. Second, there is the specification of initial (or other) conditions. Third, there are our specific observations. Is it fundamental that the process of prediction be structured in this way?

Our focus on laboratory science, I believe, is the origin of the idea that there is a clean separation between dynamics and conditions. Dynamics are governed by the laws of nature; that which we are seeking, not that which we control. By contrast, the conditions represented in the experimental arrangement are up to us and therefore not part of the laws of nature. This ideal of control is not truly realized in practice in the laboratory, but in cosmology it is never realized. The initial conditions of the universe are most definitely not up to us but must be specified in the theoretical framework in the same law-like way as the dynamics. A law of initial conditions has, therefore, become one of the central objectives of quantum cosmology [26]. However, is it not possible that the distinction between conditions and dynamics is excess baggage arising from the focus on laboratory science to which our limited resources have restricted us? Is it not possible that there are some more general principles in a more general framework which determine both the conditions and dynamics? Is it not possible, as it were, that there is a principle which fixes both the state and the Hamiltonian?

Recent work by Hawking [27], Coleman [28], Giddings and Strominger [29] among others gives some encouragement to this point of view. They show that in a quantum theory of spacetime which includes wormholes — small handles on spacetime connecting perhaps widely separated spacetime regions – that there is a closer connection between initial conditions and dynamics than had been previously thought. Specifically, the initial conditions determine the form of the Hamiltonian that we see at energies below those on which spacetime has quantum fluctuations. Indeed, they may determine a range of possibilities for the Hamiltonian only one of which is realized in our large scale universe. Dynamics and initial conditions are thereby entwined at a fundamental level.

C.   The Laws of Physics

The last candidate for excess baggage that I want to discuss is the idea that the laws of physics, and in particular laws of initial conditions, are unique, apart from the universe, apart from the process of their construction, and apart from us [30, 31] Scientists, like mathematicians, proceed as though the truths of their subjects had an independent existence. We speak, for example, of "discovering" the laws of nature as though there were a single set of rules by which the universe is run with an actuality apart from this world they govern.

Most honestly, the laws of physics are properties of the collective data that we have about the universe. In the language of complexity theory, this data is compressible. There are computational algorithms by which the data can be stored in a shorter message. Take, for example, an observed history of motion of a system of classical particles. This history could be described to a given accuracy by giving the position and momentum of each particle

at a suitably refined series of times. However, this message can be compressed to a statement of the positions and momenta at *one* time plus the equations of motion. Some of these initial values might be specified by observation but most, for a large system, will be specified by theory and statistically at that. For large systems the result is a much shorter message. Further, we find for many different systems that the data can be compressed to the form of initial conditions plus the *same* equations of motion. It is the universal character of this extra information beyond the initial conditions which gives the equations of motion their law-like character. Similarly in quantum mechanics. Thus we have:

$$
\text{All Observations} \rightarrow
\begin{cases}
\text{Some Observations} \\
+ \\
\text{Laws of Dynamics} \\
+ \\
\text{Laws of Initial Conditions}
\end{cases}
\tag{6.1}
$$

The laws of physics, therefore, do not exist independently of the data. They are properties of our data much like "random" or "computable" is a property of a number although probably (as we shall see below) in a less precise sense [32].

This characterization of compression is incomplete. Any non-physicist knows that one can't just take a list of numbers and compress them in this way. One has to take a few courses in physics and mathematics to know what the symbols mean and how to compute with them. That is, to the list on the right should be appended the algorithms for numerical computation for practical implementation of the theory, that part of mathematics which needed to interpret the results, the rules of the language, etc. etc. Yet more properly we should write:

$$
\text{All Observations} \rightarrow
\begin{cases}
\text{Some Observations} \\
+ \\
\text{Laws of Dynamics} \\
+ \\
\text{Laws of Initial Conditions} \\
+ \\
\text{Algorithms for Calculation} \\
+ \\
\text{Mathematics} \\
+ \\
\text{Language} \\
+ \\
\text{Culture} \\
+ \\
\text{Specific Evolutionary History} \\
+ \cdots
\end{cases}
\tag{6.2}
$$

What confidence do we have that our data can always be compressed in this way? I have discussed the possibility that a clear division between initial conditions and equations of motion may be excess baggage. Bob Geroch and I have discussed similar questions for the division between algorithms and the rest of physical theory [33].

However it is subdivided, what guarantee do we have that the resulting theory will be unique, independent of its process of construction, independent of the specific data we have acquired? Very little it seems. As we move down the list on the right we encounter more and more items which seem particular to our specific history as a collectivity of observers and to our specific data. It is an elementary observation that there are always many theories which will fit a given set of data just as there are many curves which will interpolate between a finite set of points. Further, when the data is probabilistic as it is in quantum theory, there is always the possibility of arriving at different theories whatever criteria are used to distinguish them.

Beyond this, however, what confidence do we have that different groups of observers, with different histories, with growing but different sets of specific data, will, in the fullness of time, arrive at the same fundamental theory? I do not mean to suggest that the theories might vary because they are *consequences* of specific history, for that is not science. Rather the question is whether there observationally indistinguishable theories which are different because of the processes of their discovery.

There may be specifically cosmological reasons to expect non-uniqueness in theories of initial conditions. A theory of initial conditions, for example, must be simple enough that it can be stored within the universe. If the initial conditions amounted to some particular complex specification of the state of all matter this would not be possible. The act of constructing theories may limit our ability to find them. The gravitational effect of moving a gram of matter on Sirius by one centimeter in an unknown direction is enough to ruin our ability to extrapolate classically the motions of a mole of gas particles beyond a few seconds into the past [34]. In view of this there must be many theories of initial conditions rendered indistinguishable simply by our act of constructing them.

It would be interesting, I think, to have a framework which dispensed with the excess baggage that the laws of physics were separate from our observations of the universe, a framework in which the inductive process of constructing laws about the universe was described in it, and in which our theories were seen as but one possibility among many.

VII. CONCLUSION

The assignment of the organizers was not just to speak on the subject "Where are our efforts leading?". They also wanted to know "In fifty or one hundred years time how do you think today's efforts will appear?". I have been bold enough to try their first question, I shall not be foolish enough to essay the second. I shall, however, offer a hope, and that is this: That in the future this might be seen a the time when scientists began to take seriously the idea that it was important to consider the

universe as a whole and science as a unity, the time when they began to take seriously the search for a law of how the universe started, began to work out its implications for science generally, and began to discard the remainder of our excess baggage.

[1] M. Gell-Mann, Talk given at the Symposium in memory of Arthur M. Sackler to celebrate the opening of the Arthur M. Sackler Gallery at the Smithsonian Institution, September 11, 1987.

[2] A number of developments in physics are considered from this point of view by the philosopher C.A. Hooker in *Bell's Theorem, Quantum Theory, and Conceptions of the Universe*, ed. by M. Kafatos (Kluwer, Boston, 1989).

[3] See especially the essays "The Unity of Knowledge" and "Atoms and Human Knowledge" reprinted in N. Bohr, *Atomic Physics and Human Knowledge*, John Wiley, New York (1958).

[4] L. Landau and E. Lifshitz, *Quantum Mechanics*, Pergamon, London (1958).

[5] For clear statements of this point of view see F. London and E. Bauer, *La théorie de l'observation en mécanique quantique*, Hermann, Paris (1939); R.B. Peierls, in *Symposium on the Foundations of Modern Physics*, ed. by P. Lahti and P. Mittelstaedt, World Scientific, Singapore (1985).

[6] Some have seen this division as motivation for restricting the domain of application of quantum mechanics and introducing new non-linear laws which apply in a broader domain. Examples are Wigner's discussion of consciousness [E.P. Wigner in *The Scientist Speculates*, ed. by I.J. Good, Basic Books, New York (1962)] and Penrose's discussion of gravitation [R. Penrose, in *Quantum Concepts of Space and Time*, ed. by C. Isham & R. Penrose, Oxford University Press, Oxford (1986)].

[7] The original paper is H. Everett, *Rev. Mod. Phys.* **29**, 454 (1957). There is a useful collection of papers developing the Everett approach in B. DeWitt and N. Graham, *The Many Worlds Interpretation of Quantum Mechanics*, Princeton University Press, Princeton (1973). A lucid exposition is in R. Geroch, *Noûs* **18** 617 (1984). Even a casual inspection of these references reveals that there is considerable diversity among the various Everett points of view.

[8] H. Zeh, *Found. of Phys.* **1**, 69 (1971) and especially E. Joos and H.D. Zeh, *Zeit. Phys. B* **59**, 223 (1985).

[9] W. Zurek, *Phys. Rev. D* **24**, 1516 (1981); *Phys. Rev. D* **26**, 1862 (1982).

[10] R. Griffiths, *J. Stat. Phys.* **36**, 219 (1984).

[11] See, *e.g.* the discussion in A. Pais, *Subtle is The Lord*, Oxford University Press, Oxford (1982).

[27] Arrows of time in quantum cosmology are discussed in S.W. Hawking, *Phys. Rev. D* **32**, 2989 (1985); D. Page, *Phys. Rev. D* **32**, 2496 (1985); S.W. Hawking, *New Scientist* July 9, p. 46 (1987).

[13] The arrow of time in quantum mechanics is discussed in many places. See, for example, Y. Aharonov, P. Bergmann and J.L. Lebovitz Phys. Rev. B **134**, 1410, 1964 and R. Penrose in *General Relativity: An Einstein Centenary Survey*, ed. by S.W. Hawking and W. Israel (Cambridge University Press, Cambridge, 1979).

[14] M. Gell-Mann and J.B. Hartle, in *The Physical Origins of Time Asymmetry*, ed. by J. Halliwell, J. Pérez-Mercader, and W. Zurek, Cambridge University Press, Cambridge (1994). gr-qc/9309012.

[15] This was stressed by W. Unruh in *New Techniques and Ideas in Quantum Measurement Theory*, *Ann. N.Y. Acad. Sci.* **480**, ed. by D.M. Greenberger, New York Academy of Sciences, New York (1986).

[16] For reviews see J.A. Wheeler, in *Problemi dei fondamenti della fisica*, Scuola internazionale di fisica "Enrico Fermi", Corso 52, ed. by G. Toraldo di Francia, North Holland, Amsterdam (1979); K. Kuchař, in *Quantum Gravity 2*, ed. by C. Isham, R. Penrose, and D. Sciama, Clarendon Press, Oxford, p. 329 ff (1981). For recent views see the articles and discussion in [17].

[17] *Proceedings of the Osgood Hill Conference on the Conceptual Problems of Quantum Gravity*, ed. by A. Ashtekar and J. Stachel, Birkhauser, Boston (1989).

[18] See, especially articles by K. Kuchař and A. Ashtekar in [17].

[19] See, *e.g.* W. Unruh and R. Wald, *Phys. Rev. D* **40**, 2598-2614 (1989).

[20] C. Teitelboim, *Phys. Rev. D* **25**, 3159 (1983); *Phys. Rev. D* **28**, 297 (1983); *Phys. Rev. D* **28**, 310 (1983).

[21] R. Sorkin, in *History of Modern Gauge Theories*, ed. by M. Dresden & A. Rosenblum, Plenum Press, New York (1989).

[22] J.B. Hartle, in *Gravitation in Astrophysics*, ed. by J.B. Hartle and B. Carter Plenum Press, New York (1987); *Phys. Rev. D* **37**, 2818 (1988); *Phys. Rev. D* **38**, 2985 (1988); and in [17].

[23] See, *e.g.* A. Linde, *Mod. Phys. Lett.* **A**, 1, 81 (1986); *Physica Scripta* **T15**, 169 (1987).

[24] Few of the proposals currently under investigation as candidates for the conditions of the universe genuinely have the character of "initial" conditions in the sense of posing conditions at a definite moment of time. Indeed, characteristically, as described in Section V, the notion of a sin-

gle time breaks down in the early universe. Rather these proposals fix something like the quantum state of the universe for all times. But also typically these proposals imply simplicity in the early universe and a global spatial structure which consists of a single inflationary bubble. The "no boundary" proposal [25] is a case in point. The point of the remarks in section VI.A is that there may be other possibilities.

[25] S.W. Hawking, in *Astrophysical Cosmology*, ed. by H.A. Brück, G.V. Coyne, and M.S. Longair, Pontifica Academia Scientarum, Vatican City (1982); S.W. Hawking, *Nucl. Phys. B* **264**, 185 (1984).

[26] For reviews of these efforts from the author's perspective see J.B. Hartle in *Proceedings of the International Conference on General Relativity and Cosmology*, Goa India, 1987, (Cambridge University Press, Cambridge,1989); and in *Proceedings of the 12th International Conference on General Gravitation*, Boulder, Colorado, 1989 (Cambridge University Press, Cambridge, 1989). For a bibliography of papers on this subject as of 1991 see J.J. Halliwell at the end of his lectures in *Quantum Cosmology and Baby Universes: Proceedings of the 1989 Jerusalem Winter School for Theoretical Physics*, eds. S. Coleman, J.B. Hartle, T. Piran, and S. Weinberg, World Scientific, Singapore (1991) pp. 159-243.

[27] S.W. Hawking, *Phys. Lett. B* **195**, 337 (1985).

[28] S. Coleman, *Nucl. Phys. B* **310**, 643 (1988).

[29] S. Giddings and A. Strominger, *Nucl. Phys. B* **307**, 854 (1988).

[30] J.A. Wheeler has for many years stressed the "mutability" of the laws of physics from a viewpoint which would entail much more fundamental revisions in physics than those suggested here but yet which has something in common with them. See, *e.g.* J.A. Wheeler in *Foundational Problems in the Special Sciences*, ed. by R.E. Butts and K.J. Hintikka, D. Reidel, Dordrecht (1977) and J.A. Wheeler, *IBM J. Res. Dev.* **32**, 4 (1988).

[31] For a general discussion of the status of the laws of physics and references to other points of view see, P.C.W. Davies "What are the Laws of Nature" in *The Reality Club No. 2*, ed. by J. Brockman, Lynx Communications, New York (1989).

[32] For an effort at making such ideas more precise see R. Sorkin, *Int. J. Theor. Phys.* **22**, 1091 (1983).

[33] R. Geroch and J.B. Hartle, *Found. of Phys.* **16**, 533 (1986).

[34] As discussed by H. Zeh in *Die Physik der Zeitrichtung*, *Springer Lecture Notes in Physics* **200**, Springer, Heidelberg (1984) [Translated and updated as *The Physical Basis of the Direction of Time*, 2nd ed., Springer-Verlag, Berlin, 1992]. He attributes the remark to E. Borel, *Le Hasard*, Alcan, Paris, (1924).