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UNIFYING PHYSICAL CONCEPTS OF REALITY*

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1. INTRODUCTION

Physics may be characterized as the science of matter and energy. It anchors the two ends of the frontiers of science: the frontier of the very small and the frontier of the very large. All of the phenomena that we observe and study at the frontiers of science--all external experiences--are manifestations of matter and energy.** One may, therefore, use physics to exemplify both the diversity and unity of science.

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**One must give serious consideration to the claim that there are spiritual phenomena transcending material phenomena in the sense that they occur by means that do not involve matter and energy. The dependence of spiritual phenomena on matter and energy in the restricted sense that observed manifestations of these phenomena always involve matter and energy is self-evident--the means by which we detect spiritual phenomena are inescapably material. One cannot deduce from this fact that all experience, including those patterns of experience that are commonly regarded as spiritual, are solely manifestations of different forms of matter and energy. However, many scientists believe that this is true, and there is, to my knowledge, no verifiable evidence that provides compelling reasons for believing otherwise. Spiritual phenomena are a topic of study in science (e.g., in the scientific study of religion), but they are customarily studied as phenomena that are manifestations of different forms of matter and energy. It should be noted, however, that the methods used by sociologists do not require resolution of the issue of whether or not spiritual phenomena are transcendent in the sense noted above.

This theme will be developed in two separate examples: first by sketching, very briefly, the historical origins of frontiers of the very small and very large and the converging unity of these two frontiers; and then by describing certain unifying concepts that play a central role in physics and provide a framework for relating developments in different sciences.

2. UNITY AND DIVERSITY IN THE EVOLUTION OF TWO FRONTIERS OF PHYSICS

Different sciences arose from different human needs and concerns--various combinations of practical necessity, curiosity, and religious belief. The concerns were often expressed in the form of guiding questions of a very fundamental kind. These questions are an important part of the scientific method and of the paradigms of science, and do not always receive the emphasis they deserve. One of the lessons that a scientist learns early in his research career is that asking the right question is the key to a successful research program.

The frontier of the very small has been guided by the question, "What are the ultimate building blocks of matter?" This question was, initially, posed in a somewhat different but equivalent form as a question of ascertaining the nature of the matter of which the entire universe is composed. Such questions were, to my knowledge, first raised by the "Ionian Physicists", starting with Thales of Miletus in the 6th century B.C. The pioneering studies of the Ionian Physicists could also be classified as belonging to cosmology, the science that deals with the nature of the universe (cosmos) and is linked to the frontier of the very large. There was, therefore, an initial unity in the physics of matter and the physics of the cosmos, the early frontiers of the very small and very large, respectively.

The unfolding diversity from this initial unity led to questions of ultimate reality, being, and change. The first school to formulate the question of the nature of matter in terms of ultimate building blocks was the school of Atomism in Abdera, founded by Leucippus in the 5th century B.C., of whom Democritus was the most distinguished representative. The work of these philosophers was almost entirely speculative and relied on logical coherence, with little attempt to establish correspondence with patterns of experience.

The rate of progress in providing convincing answers to the question of the nature of matter was limited for several millenia, in large part because of lack of emphasis on the importance of correspondence. The accumulation of knowledge in other areas of science and the evolution of methods of scholarship that place greater emphasis on correspondence (i.e., systematic observation and experimentation) have led to rapid progress in the past two centuries. This has led to a validation of the philosophical speculations of Democritus (with a consequent invalidation of competing ideas) and transformed them into a coherent theory that corresponds accurately to many patterns of experience. John Dalton, at the end of the 18th century, was the first to establish correspondence of an atomic theory with quantitative observations of physical phenomena. Subsequent research by others established correspondence with a wide variety of observations of many phenomena.

As a consequence of developments that started with the seminal work of Isaac Newton in the 17th century, the question of the nature of the ultimate building blocks of matter was extended to include the question, "What are the forces that hold the building blocks together?" Pursuit of these questions led Ernest Rutherford to a detailed elucidation of the structure of the atom in the early 20th century as a very small atomic nucleus surrounded by a cloud of electrons.* Further work led to an explanation of the structure of the nucleus in terms of more elementary particles, neutrons and protons, bound together by forces associated with still another kind of elementary particle, the pi meson. The latest development, which has occurred within the past two decades, has been the realization that the properties of neutrons, protons, and mesons can be explained by elementary particles called "quarks" bound together by forces associated with particles called "gluons". This also applies to a number of other "elementary" particles discovered by bombarding atomic nuclei with protons and other particles accelerated to high energy.

There are some who believe that we have finally found the ultimate elementary building blocks of matter in quarks and leptons** and the transient particles associated with the forces that bind these elementary particles together. But past surprises from new and unexpected discoveries justify skepticism for such claims; hence, the quest continues. The quest is now the almost exclusive domain of the field of physics known as "elementary particle" or "high energy" physics.

The discoveries made along the way during the journey from the speculations of Democritus to the theories of quarks and leptons have had an enormous impact on other fields of science, including the life sciences which are driven by the question "What is the origin and nature of life?". But one of the most striking demonstrations of the unity of science comes from the rejoining of the frontier of the very small with the frontier of the very large.

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*If the nucleus were scaled up to a diameter of 1 centimeter, the electron cloud would extend out past one kilometer for even the smallest atoms.

**Leptons are a class of particles that include electrons; also positrons (the electron antiparticle), neutrinos, and mu mesons.

The frontier of the very large is, currently, the domain of the field of astrophysics, including the related subfields of astronomy and cosmology. The historical roots of astrophysics may be attributed to human curiosity regarding the nature of the stars that we see in the night sky. (Human curiosity regarding features of our surroundings has always been an important motivating and guiding factor in science.) But the fundamental question, "What is the origin and fate of the universe?", has also played a crucial role. This question traces back in recorded history even further than the guiding questions posed by Greek philosophers for the frontier of the very small. It probably extends back to times well before the first written records.

An explanation of how the universe came into being and evolved is an integral part of most religions. For many millenia, until the past century, the best maps dealing with this question that we were able to construct were the myths of creation. These maps, of which the first chapter in the book of Genesis is an example, represented imaginative application of the coherence principle in the absence of relevant experience that would enable tests of correspondence. They were coherent (although less so than modern scientific maps), but lacking in correspondence. Relations between astronomical observations and human concerns were taken into account (e.g., in astrology), but they were based almost entirely on speculation, with points of correspondence chosen selectively to justify the speculation.* The slow progress for many millenia was, in part, due to an attitude of mind that favored past tradition and faith over change and skepticism, but a major factor was the sparsity of astronomical data that could be used to test the correspondence of the maps.

Modern astronomical instruments have changed the situation--one may reasonably argue that they were the major influence that impelled the change. We now have enough experience (data) to construct coherent maps (theories) that can be tested for correspondence and that permit inferences regarding the origin and fate of the universe to be based on observations rather than entirely on imaginative speculation.** These modern instruments include sensitive electronic devices that are capable of measuring the black-body radiation (the kind of radiation given off by a heated object, such as a hot coal) that permeates all space and is detected as an irreducible level of noise on radio

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*It may be noted that the tendency to test the correspondence of a map (i.e., the validity of a theory) by selecting only those patterns of experience that fit a preconceived map and discarding others is still practiced, even in the sciences. There are times during the initial development of a new theory that this approach may be temporarily justified, but the essence of modern science is a critical and skeptical attitude that demands testing by all relevant experience without subjective bias. Sophisticated techniques for ensuring objectivity in this process have been developed. A theory is not accepted as established by the scientific community as a whole until it has been tested for correspondence with many patterns of experience by many individuals. A large part of this correspondence testing is by coherence with other theories that have previously been tested by correspondence. A very accurate correspondence to a key pattern is often the decisive factor in acceptance. The scientific controversies that accompany this testing, some motivated by genuine skepticism and some motivated by an emotional attachment to a particular theory, are an essential part of modern science. These controversies are part of the process by which the tendency to fit experience to maps rather than conversely is kept in check.

**It must, however, be acknowledged that the extrapolation from data collected over a period of a few years to explaining events that happened billions of years in the past or to predicting events that are billions of years in the future still involves a great deal of imaginative speculation.

receivers connected to antenna aimed at the sky.* The discovery of this noise by Arno Penzias and Robert Wilson in 1965 was the crucial clue that led to a correspondence test which distinguished the "big bang" theory from competing theories as a more accurate map of reality. Large telescopes and sensitive spectrometers (instruments for analyzing light into its component colors) allow us to detect and study the structure of stellar objects. These and other instruments, which extend experience beyond the range of our unaided senses, provide data that enable us to develop coherent maps from which we may infer the origin and fate of the universe. These maps are still speculative--imaginative speculation is still needed because of the sparsity of data--but they are much more soundly based than the speculations embodied in the myths and legends of religion. They represent mileposts along a journey into the unknown during which the early frontier of our knowledge of the very large, represented by the story in the first chapter of the book of Genesis (and similar maps proposed by other religions), has advanced to the current map provided by the "big bang" theory of creation.

The current provisional answer to the question of the origin of the universe is that it started at an instant some 10 to 20 billion years ago. During a short time following the instant of creation, the universe was extremely small and extremely hot. Time starts with the instant of creation--it is meaningless to talk about prior times--and we will never (if the big bang theory is true and does not require major modification as it is tested by correspondence with new data) be able to test any speculation concerning times

*It is worth noting that the construction of electronic devices that enabled major advances at the frontier of astrophysics was possible only after the discovery of the electron and elucidation of its properties as a consequence of advances at the frontier of elementary-particle physics.

prior to the instant of creation. The big bang theory does not provide to an answer to the question of the fate of the universe, but it sharpens the question. If we can determine, by some means, the average density of matter in the universe, then we may infer from current cosmological theories* whether the universe will continue to expand forever or will collapse back to an infinitesimally small volume of exceedingly hot matter, such as existed a very short time after the instant of creation.

Developments in astrophysics have had less impact on the other sciences than developments in elementary-particle, atomic, and molecular physics because the direction of impact usually proceeds from small scale and high resolution to larger scale and lower resolution--from the building blocks to the structures formed from these building blocks. During the past few decades, developments in nuclear and elementary-particle physics have had a major impact on astrophysics, an example of the unity of different fields of science. This has enabled us to understand and develop coherent maps that explain the fate of dying stars--which can become white dwarfs, neutron stars, or black holes, depending on the initial size of the star. These different end objects of stellar evolution correspond to different states of matter that are not realizable on earth, but may be inferred from theories developed from a study of terrestrial matter.

Within the past decade or so, there has been an impact and flow of knowledge in the reverse direction, from astrophysics to elementary-particle

*Current cosmological theories are very coherent maps of the manner in which the universe evolves and have been tested by correspondence with a variety of astronomical data.

physics. The study of phenomena at the increasingly high resolution needed for progress in research in elementary-particle physics requires particle accelerators of increasingly high energy--and cost. We have reached the point where it is not feasible to construct machines to study phenomena at some energies of interest. We can reach energies of about 10^{12} electron volts in current machines, and may be able to go a few factors of 10 higher in the future before the cost becomes prohibitive.* But phenomena that would occur at much higher energies are of interest for investigating the consequences of current theories of the structure of elementary particles--in particular, "grand unification theories" (GUTS), which attempt to achieve a coherence that relates all of the known elementary particles and all of the forces between them except the force of gravity. (That unification is the ultimate goal of elementary-particle physics.)

The energies of interest in elementary-particle physics exceed those that can be attained on earth, and are even beyond the energies observed in the most energetic cosmic rays. They were attained only during a very short time following the instant of creation. Hence, the tests must be made by using elementary-particle theories to infer the state of matter in the universe during this time and, from these inferences, the manner in which the universe evolved. We can, from astrophysical observations, determine how the universe actually did evolve. The correspondence of these observations with inferences based on use of elementary-particle theories provides an indirect correspondence test of the validity of the elementary-particle theories. Astrophysical data

*An electron volt is the energy an electron gains when it moves from one point in space to another to another between which the electric potential difference is one volt. As a measure of comparison, the potential difference between the wires in a standard electrical outlet in Canada or the United States is about 10^2 volts, and the potential difference between the ground and long-distance transmission lines may be as high as 10^6 volts.

gathered by instruments placed in satellites above the atmosphere of the earth are an important part of these correspondence tests.

Another area where developments in physics exhibit a converging unity are in spectroscopic studies that reveal the existence of a variety of small molecules in the clouds of gas and dust particles that occur in interstellar and intergalactic space.* The existence of these molecular clouds provides clues that are useful for work at the frontier of science driven by the question, "How did life in the universe originate?"

The preceding examples indicate the manner in which knowledge gained in one field of science contributes to another field, thereby contributing to the converging unity of science. It is a unity of shared knowledge and cross-fertilization of ideas. However, it does not reveal some of the fundamental unifying concepts that tie all of the sciences together. Two such concepts, which evolved in different disciplines and fields of science** with different specific meanings and applications but a common underlying generic meaning, are the concept of a "system" and the concept of a "state". The generic meanings of these concepts, as used in the sciences, are developed below.

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*It should be noted that the density of matter in interstellar and intergalactic gas clouds is extremely low--less than the density in the best vacuum (lowest pressure) that can be achieved on earth. The amounts of matter are, however, exceedingly large because of the exceedingly large volumes involved. Detection of the molecules is possible because they emit characteristic patterns of radiation that can be used for identification, primarily in the microwave and infrared regions of the electromagnetic spectrum.

**A "scientific discipline" refers to scientific activities that are usually grouped together in a single department in a university--e.g., physics, chemistry, biology, psychology, sociology, geology. The different activities within a department--e.g., elementary-particle physics, nuclear physics, atomic and molecular physics, and astrophysics (which is sometimes in a separate department of astronomy)--are referred to as "fields" of science.

3. THE CONCEPT OF "SYSTEM"

One of the unifying concepts used in all disciplines and fields of science is that of a "system". In general terms, a "system" is a logical construct defined for the purpose of mapping some part of reality. It is used for the purpose of constructing a map of some part or aspect of reality that is to be studied separately from the rest of reality, i.e., for constructing a map that is in correspondence with some selected set of patterns of experience. It is closely related to the concept of a "model" which, in the current context, may be considered to be a synonym for the concept of a "map". The expression "model of a system" is commonly used. There is some confusion between the concept of a "model" and the concept of a "system" because we can identify parts of reality only by using maps of reality to point to these parts; hence, a part or aspect of reality cannot be defined without use of a map of reality. The concept of "model" refers to a map of some part of reality; the concept of "system" refers to a part of reality to which the map points, but is also sometimes used to refer to the map used for pointing.

The importance of the concept of "system" stems from the fact that reality as a whole is too complex to be comprehended in its entirety. Our comprehension develops from a comprehension of selected parts or "systems". After we have gained some comprehension of these parts, we must fit the maps (models) of these systems together to form a coherent whole. Examples of "systems" in the scientific sense that are parts of reality studied separately from the rest of reality include: an atom or molecule, a cell, an organ, a plant or animal, a human, a society, a planet, a galaxy, or the universe. The systems of interest in physics are usually fairly simple, either because they are small and elementary and, therefore, have a simple structure (as in the case of elementary particles) or because it is possible to suppress all of the detail and consider only a few distinguishing features (as in the case of galaxies and the universe as a whole). The systems studied in other sciences can be quite complicated. One such example is an ecosystem--the plants, animals, air, water, and soil in a particular locale, which may range from a small pond to a river basin to a continent or the entire planet. Another such example is a social system--a group of individuals with a common culture and/or system of government. In all of these examples, the system is defined by identifying certain patterns of experience and constructing a map (model) of these patterns, excluding explicit consideration of other patterns. The matter of the coherence of the model of the system of interest with models of other systems that take into account the excluded patterns of experience becomes a separate task.

There is a tendency for the scientific landscape to become cluttered with many different models, each capable of representing (in the sense of correspondence) a limited number of patterns of experience. One of the most important tasks of science is to unify these disparate models into a single, coherent map that exhibits the same accuracy of correspondence with patterns of experience as the individual maps (models). This task usually requires an interdisciplinary effort, and does not always receive the support it deserves because the support for science tends to be organized along disciplinary lines.

The largest system that can be conceived is the universe itself. In considering the universe as a system, only a few patterns on the largest possible scale, such as the distribution of matter averaged over intergalactic distances or the entire universe, are taken into consideration. Smaller details, such as the distribution of mass and velocity in individual galaxies and the characteristics of individual stars or clouds of interstellar gas and dust from which stars are formed, are ignored; they are taken into account separately in the study of the heirarchy of subsystems that constitute the universe. At several levels down in this hierarchy, one encounters the systems that correspond to human societies and individuals. These constitute the domains of study for sociology, psychology, and biology.

At each level, certain aspects of reality are explicitly considered and others are ignored. For example, in the first two levels down from the universe as a whole, galaxies and stars, the distribution of mass and temperature and the proportions of different chemical elements may be taken into consideration, but details on a finer scale are ignored. The sequence of systems used for mapping at successive levels of decreasing scale and higher resolution, starting from the immense scale and low resolution of the universe as a whole, exemplifies the unfolding diversity of science from an initial unity.

4. THE CONCEPT OF "STATE"

Another unifying concept of science is the concept of "state". A state may be defined as a property of a system, expressed in terms of values of a set of "observables" obtained by making appropriate measurements on the system that can be used to predict other properties: in particular, the future state of the system from a knowledge of the state of the system at present and past times. The state is usually considered to be a property of a system at a given instant of time, or a property that remains the same over an extended period of time. In order to explicate this concept, we must digress to examine certain features of the different stages in the development of a field or discipline of science that can be classified as the "descriptive", "relational", and "predictive" stages.

The descriptive stage refers to a period of time when the main emphasis is on identifying the phenomena of interest.* These phenomena constitute a set of patterns of experience that appear to be related and are believed to exhibit an underlying coherence that might be studied and understood with only minimal consideration of other patterns of experience. The primary emphasis during this period is on: (a) developing categories associated with identifying features of the phenomena and anticipated or presumed relationships and (b) classifying the phenomena according to these categories. Time and the concept of change do not usually play an important role during this stage.

For example, in the early history of physics, a major concern was the categories of the elementary "stuff" of which the universe was imagined to be composed: air, earth, fire, and water, or atoms. Early work in chemistry was primarily concerned with systematic classification of different chemicals and a determination of which were compounds that could be decomposed into elementary constituents and which were irreducible elementary constituents.

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*The word "phenomena" can be loosely interpreted as "patterns of experience". It carries the added implication that, in any particular situation, the phenomena constitute a coherent set of such patterns, usually associated with some "object" or "cause" that one would like to understand by constructing a coherent map of the phenomena.

The science of taxonomy--studies in which different observed forms of plant and animal life are classified according to their presumed natural characteristics into categories called phylum, class, order, family, genus, and species--was one of the first major activities in biology. These studies continue to be of major importance, reflecting the great diversity of biology that still requires a considerable effort for systematic classification.

Work during the descriptive stage lays the foundation for the relational stage, which can begin after a sufficient basis has been established by a systematic classification of observed phenomena. During this subsequent stage in the development of a science, the emphasis changes from description and classification to understanding and relating the features of different categories. A key task is that of determining the information that is needed for a unique characterization of the systems of interest in terms of a minimum set of irreducible characteristics or features to which all properties of the system are related in a manner that allows them to be deduced from a few principles or "rules of mapping" if the irreducible characteristics are known. These irreducible characteristics define the "state" of the system. Elucidation of the states of the systems is an important step for achieving coherence in the construction of maps of the systems.

In describing subsequent developments and the concept of state, it is useful to introduce the concept of an "observable". An observable refers to a pattern of experience that results from an observation of some feature of the system by means of a carefully specified procedure (the measurement procedure). Examples of observables for a simple physical system, such as an atom, are the position (expressed as distances from a reference point along a chosen set of coordinate axes), the velocity, the mass, and the charge. The shape, color, and other identifying features of more complicated systems are observables. More subtle observables include verbal responses to carefully formulated questions or patterns of electrical currents in the brain. A "state" of a system is specified in terms of the values of a selected set of observables that can, in principle, be determined from measurements made on the system.

An area of science (discipline or field) that has not progressed beyond the relational stage can make statements about what is or even what might occur--the forms that the systems or objects of study can take--and the relationships of the parts of a system. However, at the relational stage, it is unable to formulate systematic principles or laws that characterize the evolution of systems with time and permit predictions of future characteristics to be made from a knowledge of present or past characteristics. For example, in physics, a knowledge of the properties of the building blocks of matter or of the location and identifying features of planets and stars does not permit predictions of the motion of matter or future positions of the planets and stars. Knowledge gained during the descriptive and relational stages in chemistry may permit identification of thermodynamically stable chemical compounds, or even the new compounds that will form when two or more compounds are combined and react, but it does not help in determining the rates of reactions. The descriptive and relational stages in biology may enable identification of viable organisms, but not the manner in which they evolve; and similarly for the societies that are the objects of study in sociology.

The lack of capability for predicting what will happen in the future--how a system will evolve with time--from knowledge of the present and past is a serious deficiency and provides a strong motivation for further work. Much of the interest and public support of science stems from a strong universal desire to be able to foresee the future in order to be able to take actions that will avert future suffering and increase future happiness.

The predictive stage of a science is attained when it is possible to formulate principles (relational rules) that enable construction of coherent maps that link features (patterns of experience) at different times as well as at different points of space, and enable predictions to be made regarding the values of observables at some later time from measured values at present and past times. The principles used to make predictions are expressed quite differently in different sciences. In physics, the principles may be summarized in a concise and precise manner by mathematical equations that determine the paths of elementary particles (or aggregates of these particles) or the change in time of continuous distributions of matter and energy called "fields". In chemistry, the principles may be given as a set of equations that describe the time-sequence of concentrations of the constituents in a chemical reaction or, at a microscopic level, the equations governing the motions of colliding atoms and molecules. In biology, the principles are embodied in the theory of evolution by natural selection, as first developed by Charles Darwin. The diversity of science is apparent in these different dynamical principles; the unity is not. An underlying unity is uncovered if these different methods for mapping the evolution of a system with time--the dynamical aspects--are described in terms of the concept of a "state".

A "state" may be defined in the most general terms as everything that one can know about a system that will affect its observable form. It may not be necessary to know everything about a system in order to define a state because there may be some aspects that are uniquely determined by others; for example, the energy of a system of particles (in a classical model) is uniquely determined by the positions and velocities and is not, therefore, needed to specify the state. The amount known must, however, include the irreducible amount of information needed to determine all of the observable features that are included in the definition of the system. More specifically, a state is defined by everything that one must know about a system at a given time in order to be able to predict the observable form of the system at a future time.

A fundamental assumption should be introduced at this point: that is, the knowledge of a system at the present and past times determines the observable form of the system in the future. Using the aforementioned definition of a state, this is equivalent to the assumption that the state of a system in the past and present determines the state in the future. This assumption must, of course, be tested by correspondence with experience. It has been thoroughly validated for the simple systems of physics. It has not yet been validated (or refuted) for the more complex systems of biology, psychology, and sociology; that is a much more difficult task. It is, however, a plausible and widely accepted assumption that may be justified on the grounds that, because it holds for the elementary constituents of complex systems, it must hold for the complex systems as well.

At the level of smallest scale and highest resolution, such as for a system consisting of a few elementary particles, a state may be defined as everything that can be known about a system. For more complex systems--such as a cell, an organism, or a society--the definition of a state does not usually include fine details that can be observed only at a level of resolution that is higher than that used for defining the system and studying the phenomena of interest.

The concept of state in physics may be demonstrated by using a hypothetical system consisting of a collection of small round spheres in a box. We may imagine that the spheres are in a vacuum, so that there is no air friction; that the surfaces of the sphere are frictionless, so that the spheres do not rotate as they collide; and that the box is in outer space, so that there is no gravity acting on the spheres. This hypothetical system serves as a useful model for mapping a system consisting of atoms of a gas--such as helium, neon, or argon--in a closed container. When a two-dimensional box is used (so that the spheres are constrained to move in a plane), it also serves as a useful and rather accurate model of a system consisting of small round disks floating on an "air bed", i.e., a flat table perforated with small holes through which air is forced, so that the disks move around in an almost frictionless manner on a layer of air. (The reason for mentioning the more complicated air-bed system is that, unlike the hypothetical system of spheres in a box, air-bed systems are relatively easy to construct and can be used in practice as well as in principle to test the correspondence between an actual system and a model of the system.*)

*One must, however, take the rotation of the disks into account because the surfaces of the disks are not frictionless and the effects of rotation induced by the collisions cannot be neglected. The error introduced by air friction is small if the disks are not too light, but this limits the accuracy with which the correspondence tests can be carried out.

Experiments on the hypothetical spheres-in-a-box system would show that if the spheres were not too light (so that quantum effects, discussed below, could be neglected) and the velocities were small compared to the velocity of light (so that relativistic effects could be neglected), then if the positions and velocities of the particles at one instant of time were known, the positions and velocities at any future (or past) instant of time could be accurately predicted. Thus, the state of this simple system is completely determined by the positions and velocities of the spheres.

This remarkable result is a logical consequence of Newton's laws of motion. These physical laws (which may be described as "mapping principles") were formulated by Isaac Newton by inference from data on the motions of planets and terrestrial objects. These laws constitute the essence of classical physics. The maps constructed by use of Newton's laws of motion have a wide, but not universal, application. A model consisting of particles that move and interact in a manner determined by Newton's laws of motion is called a "classical model". Classical models have a high degree of coherence--they permit the reduction of an enormous range of phenomena to a logical consequence of three laws of motion that can be stated in very simple terms. However, they do not provide a universal description that is applicable to all observable phenomena. If a moving object is very light (of atomic size or less), or if the velocity of the object is not small compared to the velocity of light, then the correspondence of classical models with reality breaks down. The models that must be used in place of the classical models (which embody the quantum principles formulated by Planck, Bohr, Heisenberg, Schroedinger, and others, and the principles of relativity formulated by Einstein) lead to radically different procedures for defining a state in terms of observables but do not alter the defining features of a state, viz., that a state is the information about a system at one instant of time expressed as values of observables needed to determine the values of observables at future times.* For physical systems characterized by their elementary structure, it is sufficient to know the state at one instant of time. For more complex systems (in which the positions and velocities of the elementary particles are averaged out, leaving only a limited number of macroscopic features), a knowledge of the state at both past and future times may be needed to predict the state at future times.

The concept of state in other scientific disciplines involves quite different kinds of information and ways of expressing this information in words or other logical symbols, but the fundamental definition and use of the concept are essentially the same. In both chemistry and physics at a macroscopic level, the concept of the "thermodynamic state" of a system is used. This concept is consistent with the definition given earlier in that it provides a complete characterization of a system for all changes in a system under equilibrium conditions (i.e., for changes induced by very slow external forces acting on the system). It can be extended to nonequilibrium processes under certain conditions using the principles of mechanics (i.e., the classical or quantum equations of motion, usually the latter).

*The state of a system constructed according to quantum principles can also be defined in terms of values of observables; however, the observables must be selected from a restricted set (a complete commuting set), and the state determined by initial observations will depend on the choice of this restricted set. The general concept of a state discussed above is not affected by these paradoxical aspects of quantum states.

Other examples of using the concept of state are "state of mind" in psychology, "state of health" in medicine, and "state of the economy" in economics. In common usage, the meaning of these terms is often ill-defined and ambiguous, but the meaning is still consistent with the more precise definition of a state as a property of a system, expressed in terms of the values of a set of "observables" obtained by making appropriate measurements on a system, which may be used to predict other properties. In particular, the future state of the system may be predicted from a knowledge of the state at present and past times.

5. DYNAMICAL PRINCIPLES

The development of dynamical principles that enable predictions of future states of a system from a knowledge of the present and past states is the ultimate goal of every discipline and field of science. These principles extend the spatial coherence embodied in the concept of state to a space-time coherence. This provides a basis for the ultimate test of correspondence: the agreement between predicted and observed states at future times.

Some sciences have not reached the dynamical stage. Sciences that deal with the most complex phenomena, such as sociology and most fields of psychology, are the last to reach this stage. Physics, which deals with the simplest systems, was the first to reach the dynamical stage. Astronomy, a branch of physics, reached this stage many millenia ago. Although there have been radical changes in the paradigms of physics since the times of the Greek philosophers, even the Ptolemaic system was able to predict the motion of planets and the occurrence of eclipses with reasonable accuracy. But this was only an initial tentative step into the predictive stage. The entry into a predictive stage that radically affected all of physics and provided the "classical" paradigms that are still in use today for some systems and phenomena occurred in the 17th century. This was the century in which Isaac Newton formulated the laws of motion that bear his name. Newton's laws of motion enabled the formulation of equations that described the time evolution of physical states with sufficient completeness and generality to construct maps that corresponded accurately to a very broad class of phenomena. The equations of motion were later formulated in a more coherent way by Euler, Hamilton, and Lagrange (in the sense that they revealed, more directly and clearly, the relation between the time evolution of a system and concepts of energy and complementary variables, developments that were important in the later development of quantum principles). But these reformulations did not affect the validity of Newton's equations or constitute new paradigms in the sense of Kuhn.

Chemistry is well into the dynamical stage. Although chemistry and physics have separate roots--the roots of chemistry are in alchemy, which was quite distinct from physics in medieval and ancient times--they have converged in recent times until the methods and systems studied in many fields are the same. For example, the differences in methods and systems studied between the field of physical chemistry and the field of chemical physics are scarcely discernible. This convergence has occurred largely since the 1920s when the principles of quantum mechanics were formulated in the form that is still the basis for studies of atomic and molecular systems. The differences between chemistry and physics are primarily matters of emphasis: the emphasis in chemistry is on chemical reactions--the "heart of chemistry" in the view of many chemists. Equations governing the rates of chemical reactions have been known for about a century. The dynamical principles that provide a coherent basis for these equations, and which enable a determination of the time evolution of states of chemical systems, are a direct consequence of the quantum principles formulated by Heisenberg, Schroedinger, and others during the 1920s.

The steps by which biology entered the predictive stage include the enunciation of the laws of genetics by Gregor Mendel in the middle of the 19th century, the formulation of the theory of evolution by Charles Darwin shortly thereafter, and the discovery of DNA and its role in controlling the evolution of species by Watson and Crick in 1953. The dynamical principles of biology have not reached the level of completeness and generality of the dynamical principles of chemistry and physics because the systems are much more complex and a complete and general characterization of the states of organisms and populations of organisms has not yet been achieved. But progress has been accelerating during the past three decades. The understanding needed to make accurate predictions and perhaps determine, or at least influence, the future evolution of species is anticipated--with equanimity by some and apprehension by others.

Psychology is perhaps on the verge of entering the predictive stage. A universal dynamical principle for predicting the time evolution of a person's state of mind is still beyond us, but some limited predictions of future behavior from past experience are possible. The work on rhythms and regulating cycles by Dr. Arnold is a sample of some of the research that may eventually lead to attaining the goal in psychology of predicting the time evolution of states.

The predictive stage for sociology appears to be a long way off. We may anticipate interesting new developments in the future as a consequence of developments in sociobiology, which Dr. Wind will discuss in his presentation. But sociology and related fields, such as anthropology, deal with exceedingly complex systems for which it is difficult to identify the relevant observables needed to define a state, as one may infer from the presentation by Dr. Crocker. Economics, which is a branch of science closely related to sociology (the two are sometimes combined under the heading socioeconomics), has taken tentative steps into a predictive stage during the past few decades, but a general dynamical principle is still lacking, and economic forecasts are still rather unreliable.

6. QUANTUM PRINCIPLES

Returning to physics, Newton's laws of motion were, for a period prior to the 20th century, regarded by some as the ultimate and final description (mapping tool) of reality. But subsequent experience, aided by the development of instruments that extended experience beyond our unaided senses, revealed that the correspondence between predictions based on Newton's equations and experience failed at higher resolution. Predictions for phenomena involving elementary particles--such as photons, electrons, and nuclei--were found to be in serious disagreement with observations.

This lack of correspondence, which could not be restored by any coherent extension of classical physics (i.e., maps of physical phenomena based on Newton's principles), led to the development of quantum principles.

The extension of classical mechanics to quantum mechanics was one of the great milestones in the history of science.* It was a major scientific revolution. It should be noted, however, that the advent of quantum mechanics, even though it involved a major "paradigm shift" in the sense of Kuhn (i.e., a major change in the methods used for mapping experience and in the interpretation of patterns of experience, at least insofar as physical phenomena are involved), did not lead to an abandonment of classical mechanics. Classical mechanics is still used, in much the same manner as in the prequantum era (but with more sophisticated mathematical techniques), to describe phenomena involving macroscopic objects moving at velocities that are small compared to the velocity of light. What has changed is an understanding of the limitations of maps of reality that are constructed by using the tools of classical physics.

Quantum mechanics led to a major change in the concept of the "state" of a system. In classical mechanics, the state of a system was defined directly in terms of the values of observables, so that all observables had unique and well-defined values that could, in principle, be determined with unlimited accuracy. The fundamental observables commonly used in defining the classical state are the positions and velocities of the elementary particles of which the system is composed.** A state is defined by assigning a value to the

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*The word "mechanics" is commonly used to label the body of knowledge that is primarily concerned with the dynamical behavior of physical systems. For the purpose of this discussion, the labels "quantum theory", "quantum principles", and "quantum mechanics" can be used interchangeably; similarly for "classical theory", "classical principles", and "classical mechanics". In the sense in which these terms are used in this discussion, they all refer to methods used for mapping those patterns of experience that may be called "physical phenomena"

**In practice, the momenta rather than the velocities are used. The momentum of a particle is the product of the mass and the velocity of the particle (apart from corrections that are needed only when the velocity approaches the speed of light and are unimportant for this discussion).

position and velocity of each particle. These values are the values that would be observed if measurements of the observables were made on a system in a state specified by the values. Measurements will always disturb a system, but, in principle, there is no limit to the accuracy with which the positions and velocities of a classical model could be determined by measurement techniques designed to minimize this disturbance. The measured values of the observables would correspond to the values that specified the state of the system at that instant of time.

In quantum mechanics, the state must be expressed as a function of the values of the observables rather than values themselves. Furthermore, the observables for which the values appear as arguments must be restricted to a set referred to as a "complete commuting set". The positions of all of the elementary particles in the system constitute such a set; hence the state of the system may be expressed as a function of the particle positions alone.* Alternatively, the state may be expressed as a function of the particle momenta alone, which also constitute a complete commuting set; it cannot be expressed as a function of both the positions and momenta (in the same direction for the same particle). These functions are called "wave functions". There is a unique one-one correspondence between a wave function expressed as a function of particle positions and a wave function expressed as a function of particle momenta; either one can be used to define a unique "quantum state" of the system. The quantum description of a state of a physical system differs from the classical description in that the actual values of the observables for a

*Additional more exotic variables known as "spin" are also needed, but are unimportant for this discussion.

system in a particular state are indeterminate. Measurements of most observables on a system in a well-defined quantum state will not yield precise values, regardless of the care taken to minimize the disturbance introduced by the measurement. Instead, there will be a range of values with a certain probability distribution that can be calculated from the wave function for any observable. Certain states can yield precise values for some observables, but when this situation occurs, the values of other observables (called "complementary observables") are completely indeterminate. The position of a particle along a line and its component of momentum in the direction of this line are complementary variables; hence, it is impossible to specify a quantum state in which the positions and velocities of the particles are both accurately determined.

These esoteric aspects of maps of reality constructed according to the principles of quantum mechanics have been tested by the accurate correspondence of these maps with observations of a wide range of phenomena. There is still a lack of coherence at certain points; an example is the need to treat an observer and the measuring system as a classical system and the object of the measurement as a quantum system in the quantum theory of measurement. One would like to be able to develop a theory of measurement in which the observer, measuring device, and object of measurement are all treated from a strictly quantum viewpoint. There are also troubling aspects related to the manner in which a measurement at one point can affect the state of a system at a distant point. This paradoxical result was pointed out most clearly by Einstein and is one of the reasons that he was never able to accept quantum mechanics as more than a provisional mapping tool (Einstein et al. 1935). But tests of the correspondence of quantum maps of reality with experience have not yet revealed a basis for modifying the principles of quantum mechanics.

The important point in the present context is that the concept of state, in the general sense in which it has been defined herein, was retained in the revolutionary transition from classical to quantum mechanics. A quantum state still contains all the information about a system that is possible to know, and the quantum state of a system at a given time still completely determines the future quantum states of the system. This last point merits emphasis because it is often misunderstood.

Quantum theory predicts an indeterminacy in the value of an observable when a measurement is made. This indeterminacy is known as the "Heisenberg Uncertainty Principle" in honor of the man who first enunciated it clearly. The uncertainty principle is sometimes used, incorrectly, to imply that there is an uncertainty in the time evolution of a system. As long as a system is undisturbed by interaction with another system, such as a measuring device and observer, it evolves in a completely deterministic manner: the state at some future time is completely and exactly determined by the state at any past instant of time. If two initially isolated systems, each in a precisely known state, are allowed to interact and then separated again until isolated from each other (as occurs when one elementary particle is scattered by another), then the state of either one of the two systems becomes indeterminate as a consequence of the interaction. But the state of the total system is completely determined by the initial state, unless and until it interacts with another system, such as an observer.

The unifying aspect of the concept of state in science is not apparent because of the different ways in which the concept must be implemented in order to be useful in different disciplines and fields of science. However, all of the concepts may, in principle but not in practice, be related to the concept of state in physics by imagining that the observables appearing in the quantum (or classical) physical state of any system are transformed to define a new set of observables that include those few observables that are of particular interest for a selected system at a particular level of scale and resolution, and then averaging out all of the transformed observables (which must be equal in number to the original set) except the few of interest. This procedure can be carried out rigorously in the simple example of reducing the 10^{22} observables (the positions of the gas particles) used to describe the exact microscopic state of the atoms of gas in a container. It reduces the 10^{22} microscopic observables to two observables--pressure and temperature--which, together with the volume (a macroscopic variable used in both the microscopic and macroscopic definitions of the system) define the thermodynamic state of an ideal gas in equilibrium.

A microscopic physical state, expressed in terms of the positions of all of the constituent elementary particles, can in principle be defined for an organism or a society. The macroscopic state of that organism or society at the level of scale and resolution that is useful for biological or sociological studies could, in principle, be defined by an averaging procedure similar to that used to reduce 10^{22} microscopic observables to two macroscopic observables for an ideal gas--if one knew the appropriate macroscopic variables needed for biological or sociological studies of the system. This is not a very fruitful approach for scientific studies from a biological or sociological viewpoint, but is has interesting implications from the viewpoint of URAM.

The principles of quantum mechanics have been validated rather thoroughly on a microscopic scale by correspondence and have been shown to be coherent, except possibly for the inconsistency in the quantum theory of measurement noted above and the paradoxes pointed out by Einstein and others.* These bothersome aspects have not yet led to any inconsistencies that impede application of quantum principles to known areas of experience; hence, it is not unreasonable to extrapolate quantum principles and the concept of a quantum state to the largest possible scale and assume that it is meaningful to define a wave function for the entire universe.** The entire universe includes all possible observers, so that there is no observer who can disturb the state by a measurement (unless we introduce the untestable hypothesis that there is an observer separate from the universe whom we might identify with the concept of God). This extrapolation is purely speculative, but has the advantage of being a coherent extrapolation from well-established knowledge, and is worth exploring for possible new insights into the problems of URAM.

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*There are inconsistencies in theories of elementary particles. However, these incoherent aspects of our maps of the structure of the universe, which appear primarily in the form of divergent (infinite) expressions that must be treated in an ad hoc manner, do not necessarily indicate a need for a revision of the manner in which states are defined in quantum mechanics. Nevertheless, resolution of the lack of coherence between general relativity (which incorporates the principles used to map gravitational phenomena) and quantum mechanics (which incorporates the principles used to map all other physical forces) or work on "hidden variables" in quantum mechanics could lead to quite different views regarding the "state" of the entire universe and the manner in which it might evolve.

**A formulation that takes into account relativistic principles must be used, so that "a state defined at an instant of time" must be interpreted as "a state defined on a space-like surface in space-time". Relativistic considerations do not affect the implications of this discussion and can therefore be ignored.

Further exploration of the implications of such speculations are beyond the scope of this presentation. They will, almost certainly, be a topic of extended discussions in future URAM studies, for they are central to some of the fundamental questions of Ultimate Reality and Meaning, even though they are rather far from the concerns of everyday life.

It is perhaps not inappropriate to end this presentation after raising a provocative and unresolved (and possibly unresolvable) issue. But I would also like to add a caveat. The implications of the existence of a state of the universe that evolves in a deterministic manner does not resolve the theological problem of determinism vs. free will, for the concept of free will is much more subtle than one might infer from common usage of the term. Furthermore, the implications of an extrapolation of principles that have been validated on a very small scale to the largest possible scale must be viewed with skepticism. This is a valid application of the coherence criterion of truth, but we have seen from examples drawn from history that coherence, by itself, is an unreliable means for validating a map of reality. Application of quantum principles to the universe as a whole cannot yet be tested by application of the correspondence criterion (and may never be testable). Finally, as we test the concept of a quantum state at higher and higher resolution, we may find that radical revisions in the concept are needed. For example, we may find that space and time are discrete on a sufficiently fine scale so that the currently used mathematical tools, which assume that space and time are continuous variables on an arbitrarily fine scale, may require revision.

Nevertheless the implications for an extrapolation of quantum principles to define a wave function for the universe cannot be lightly dismissed if we are to take seriously the coherence criterion of truth and the fact that quantum principles have been thoroughly tested and found to be valid for elementary particles which constitute the building blocks for all matter in the universe. It is probably not valid, but it can suggest new approaches to the fundamental problems of URAM that we will have to face.

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