More Reflection on Physics

IS THERE A BASIS FOR TELEOLOGY IN PHYSICS?

by Carl S. Helrich

Abstract. The basic laws of physics for particles and fields can be formulated in terms of variational principles. The initial development of a variational principle had distinct teleological implications. The formulation of physical laws in terms of variational principles is outlined with specific reference to classical and quantum mechanics and field theory. Because of time irreversibility no variational principle exists for thermodynamics. In order to obtain time irreversibility molecular trajectories must be abandoned in the lowest-level description of complex multicomponent systems. A more open set of possibilities results. I suggest that this may be more consistent with a modern teleology.

Keywords: classical; distributions; quantum; teleology; thermodynamics; variational principles

---

Physics is an experimental science. The laboratory of our experiments is the universe, and we tease our data from sources as diverse as radio telescopes and atomic force microscopes. On these data we have built our present understanding of the universe adhering to a philosophical position that comes from Isaac Barrow and Isaac Newton and has been restated more recently by Paul A. M. Dirac (Helrich 2006). Out of this we have constructed our present understanding of the basis of the universe. This understanding is in the form of a set of laws in mathematical form and is always tentative. The final arbiter remains the laboratory. But theory and laboratory experiment are so tied together that physicists cannot easily claim a complete distinction. Albert Einstein pointed out that theory tells us what our experiments mean.

Carl S. Helrich is Professor of Physics at Goshen College, 1700 South Main Street, Goshen, IN 46526; e-mail carlsh@goshen.edu.

[*Zygon*, vol. 42, no. 1 (March 2007).]

Mathematics plays a prominent role in physics. On the surface we can claim that because physics deals with measured quantities the role of mathematics is self-evident. Such an explanation is insufficient, however. There has not always been unanimity on the role of mathematics in physics. At this time in our history there is no question that mathematics is the language of physics, and language is very important in any intellectual pursuit. But the role of mathematics in physics differs from that of language in discourse.

Mathematics is separate from physics, and the development of mathematics is a creative activity that exists independently of theoretical physics. Almost any development in mathematics finds an application in theoretical physics. Examples are the use of matrices and group theory in the quantum mechanics, of tensor analysis relativity, and of fractal geometry in nonlinear dynamics. But the mathematical developments were not undertaken to solve any difficulties in the physics.

Mathematicians are also divided on the philosophical question of whether mathematics is simply a creative product of the human mind or something that already exists and is being discovered. Regardless of where we find ourselves on this question, we must recognize that our mathematical representation of the laws of physics, and the relationships among those laws deduced from the mathematics, reveals a striking relationship between the mathematics and the organization, structure, and function of the universe. This, declared Eugene Wigner (1960), is a miracle and a gift we neither understand nor deserve. As a result we can claim with confidence that the mathematical consequences we may deduce from the laws of physics are as rigorously correct as the original laws.

This is one of the roles of theoretical physics. At any stage in the development of science we may ask questions about the broader implications of the laws as we understand them at that time. In a certain sense this working with the laws of physics and investigating the implications of those laws is doing what Thomas Kuhn called normal science. We are not attempting to investigate anomalies that may lead to new understanding of the structure of the universe. Our results may suggest further experiments and areas for investigation and may lead to new applications, or we may be simply asking questions about general implications of the laws, which may even lead at times to metaphysical speculation.

Physicists are notoriously reticent to make any fundamental metaphysical statements publicly. This reticence has any number of sources. It is possibly related to a collective memory of attempts to generalize physics, such as those in the late nineteenth century by the energetists (Cercignani 1998). In some cases the reticence may be a result of a strain of agnosticism or even atheism that runs through the physics community. So, even as we obtain what may appear to be generalizations we are very hesitant to consider these as indications of teleology. Nevertheless, there is a distinct thread that runs through theoretical physics that can be interpreted as evidence of teleology. It is this thread that I discuss here.

In the discussion I am as clear as I can be about the physics without using any actual mathematics. I feel obliged to present the situation without any personal interpretations. I leave those to the reader. And the reader will see that an interpretation is ambiguous. Physics will continue to refuse a commitment to a specific metaphysics other than that already inherent in science.[1]

I consider first the general formulation of physical laws and then the representation of these laws in terms of variational principles. The history of the development of variational principles in optics and mechanics I outline in some detail for the understanding that it brings of the underlying teleological ideas originally present. Essentially all of physics, with the exception of thermodynamics, can be formulated in terms of variational principles, as is shown here. The requirement for the formulation is a time reversibility in the basic laws. Thermodynamics is time irreversible, and a formulation in terms of a variational principle fails. I explore the consequences of this and suggest that the more open system required by thermodynamics is more in keeping with a modern perspective on teleology.

Formulation

Physicists adhere very closely to the prescripts of an experimental and mathematical philosophy. But this is not done blindly. Interpretation and human judgment are always parts of the formulation of physical laws. During certain periods in the history of science we can point to the logical connection between classic laboratory experiments and mathematical law. We can even present a basic chronology of the development, which meets our classroom objectives. An example is the path that led to the final formulation by James Clerk Maxwell of the laws governing electromagnetic fields. However, while we present this to our students as a beautiful mathematical structure emerging neatly from a set of classic experiments, we realize that the hunches and genius of people like Hans Ørsted and Michael Faraday are not described neatly in the mathematical picture we are developing.

Perhaps we understand more fully the role of human thought and the presence of the unknown when we look at the story of the development of quantum theory and the eventual emergence of quantum mechanics in the last century, because this took place over a brief span of time. The quantum theory, however, has also compelled physicists to confront deep questions. If we believe that the quantum theory presents us with fundamental truths about the universe, we must ask these deep questions—and we find ourselves in the territory of philosophers and theologians.

In general the laws of physics are represented by sets of differential equations. Differential equations describe the small change in one quantity that results from small changes in other quantities. Because the experiments from which the laws are formulated are conducted with finite bodies undergoing finite changes, the laws often are first formulated in what is termed an integral rather than a differential form.[2] However, a formulation in terms of differential equations is normally more powerful in application than the integral formulation, so we reformulate the integral laws in differential form.

Sometimes the original integral formulation lends itself neatly to this reformulation, as in the case of Maxwell's field theory. In other cases, such as that encountered in the development of thermodynamics, the differential equations must be coaxed from the experimental laws. The path leading to the differential statement of the second law is particularly circuitous and is a tribute to the genius of Sadi Carnot, Rudolf Clausius, and Constantin Carathéodory (Cropper 2001; Wilson 1960).

In general the laws of physics, represented by sets of differential equations, are referred to jointly as the differential equations of (mathematical) physics. From these differential equations we can, in principle, compute the properties of a physical system. The practical mathematical difficulties encountered in many systems may be formidable. Generally our interest is in the time dependence of these system properties as the system responds to its surroundings.

Variational Principles

Perhaps remarkably, the form of many of the differential equations of mathematical physics can be obtained from what is called a variational principle. That is, the value of a particular quantity, S, is either a maximum or a minimum for the actual motion of a real dynamical physical system. We designate the value of S for the actual motion of the system by S_{actual}. Paths for the system motion that are close to but deviate slightly from the path followed by the physical system in the actual motion are called virtual. If we know the actual path we can construct virtual paths by simply allowing positions or momenta to vary slightly from the values they have on the actual path. If the value of S_{actual} is a limiting value of the results obtained for S_{virtual}, a variational principle holds.

We do not know whether S is a maximum or a minimum for the actual motion. We know only that it is an extremum. Therefore we cannot point to the variational principle as an indication that the laws of nature demand that the general path of a system be such that a certain quantity is a minimum. The fact that there is an extremum, however, provides ground for speculation about the structure of the laws.

The quantity S is a number. Its value depends on the path taken by the system. That is, the numerical value of S depends on the form of the laws of motion. Such a quantity is called a *functional* of the path. The variational principle is then that the functional S has an extremum for the actual motion undertaken by the physical system.

Conditions for the extrema of a functional may be found in a mathematically straightforward manner. These conditions produce a set of differential equations for the system, which are completely equivalent to Newton's Laws. These are called the Euler-Lagrange equations if written in terms of coordinates alone or the canonical equations of Hamilton if written in terms of coordinates and momenta.

To decide whether these extrema of S are maxima or minima is extremely difficult. No general result exists that will allow us to say that variational principles in physics produce foundationally either maxima or minima. We must content ourselves with conditions of weak extrema. That is, we can establish that an extremum exists for the actual motion but cannot decide if that extremum is a maximum or a minimum.

Origins in Optics and Mechanics. The first proposal that a minimum was important in physical science was made by Pierre de Fermat in 1662. Fermat proposed that the actual path between two points taken by a beam of light is the one that is traversed in the least time. He also supposed that light traveled more slowly in denser media, such as glass, which was in contradiction to the position of René Descartes and of Newton. Fermat's Principle of Least Time was based on a metaphysical assertion that nature operates in a most efficient fashion. Although Fermat's principle could be used to establish Willebrord Snell's law of refraction (1621) (Lemons 1997), there are many examples showing that the transit time for light is not a minimum but a maximum (Encyclopedia Britannica 1969, 13:1105c).

The origin of the calculus of variations is found in the problem, posed by Johann Bernoulli in 1696, of finding the curve along which a body can slide without friction from one point to another such that the time required is a minimum. Apparently he posed the problem intending to embarrass his brother Jacob, whom Johann claimed was not competent to solve it. Solutions were returned by Johann and Jacob Bernoulli, Gottfried Wilhelm Leibniz, Newton, and Guillaume de l'Hôpital (Lemons 1997).

The first step toward a variational principle for Newtonian mechanics came with a proposal by Pierre-Louis Moreau de Maupertuis in 1744 (Yourgrau and Mandelstam 1968). This was the celebrated principle of least action. Maupertuis's idea was metaphysical. In 1746 he wrote that his least quantity of action is "a principle so wise and so worthy of the Supreme Being, and to which nature appears to be so constantly subject that she observes it not only in her changes but she tends to observe it in her permanence." Maupertuis's action was the product of the mass, momentum, and distance, and his principle was similar to Fermat's.

Maupertuis was interested in establishing a theological foundation for mechanics. In 1744 mechanics and optics formed essentially the only branches of physics with a rational basis in the experimental and mathematical philosophy. In scientific terms, Maupertuis was inspired by Fermat's ideas. He was also apparently influenced by Leibniz. Maupertuis's least action principle is not the principle later established by Leonhard Euler, Joseph Louis Lagrange, Carl Gustav Jacob Jacobi, and Sir William Rowan Hamilton. There also was some energetic discussion of whether or not Leibniz originally had the idea of such a principle. It seems, however, that the idea was original with Maupertuis (Yourgrau and Mandelstam 1968); it was simply not the final word.

Maupertuis was ridiculed by the French writer and philosopher François-Marie Arouet, better known by his pen name, Voltaire. Both Maupertuis and Voltaire were at one time part of the court of Frederick II of Prussia. The two Frenchmen apparently were of rather different and difficult personalities. A dispute between them resulted in Voltaire's writing a lampoon on Maupertuis, *Histoire du docteur Akakia et du natif de Saint-Malo*, in 1752. Because this was widely read, considerable damage was done to Maupertuis's ideas (Park 1988). His idea, however, was fruitful in further scientific development.

Euler first published the principle of least action as an exact mechanical theorem in 1744. The variation of the sum (integral) over distance (s) of the product of mass (m) and velocity (v) $mvds$ vanishes. In this Euler considered that the energy of the system was a constant (Yourgrau and Mandelstam 1968). The systems Euler considered were conservative.

If we are concerned about giving credit for the original idea, that still belongs to Maupertuis, who had mentioned maximum and minimum principles in 1740. These were contained in a paper on the law of bodies at rest (*Loi du repos des corps*) presented to the Paris Academy of Sciences in 1741. He had corresponded about this with Euler. In a letter to Maupertuis (1745) Euler praised the 1741 paper and claimed that Maupertuis's thoughts were greater than his own mathematical results. Apparently, at least, the somewhat vague ideas of Maupertuis provided the inspiration for the foundational work of Euler (Yourgrau and Mandelstam 1968).

The correct mathematical formulation of the principles of the calculus of variations was, however, carried out by Lagrange. In 1758 Lagrange and his students established a society that later became the Turin Academy. The academy published a transactions in five volumes. Most of Lagrange's early writings are found in these transactions, which are reprinted in the *Oeuvres de Lagrange* (1867). These include works on the propagation of sound, the calculus of variations, and works on mechanics. Of particular interest to us here is the second volume, in which Lagrange deduces the principle of least action as a variational problem and solves certain problems in dynamics.

In 1766 Euler left the court of Frederick II of Prussia, who then invited Lagrange to come to Potsdam. Lagrange accepted and spent the next twenty years in Prussia. During that time, between 1772 and 1788, Lagrange produced the masterful work *Mecanique Analytique*, which became the basis for later work in mechanics. These are reprinted as volumes 11 and 12 of the *Oeuvres de Lagrange.* Lagrange wrote of this work, “The reader will find no figures in this work. The methods which I set forth do not require either constructions or geometrical or mechanical reasonings; but only algebraic operations, subject to a regularity and uniform rule of procedure” (Lagrange 1867, Bibliography). With this book we have the beginning of Lagrangian Mechanics.

Hamilton removed the constant energy limitation on the variational principle of Lagrange by requiring that the virtual paths considered in the variation begin and end at the same initial and final configurations of the physical system in the actual motion. In this form the variational principle for mechanical systems is known as Hamilton’s principle and S becomes known as Hamilton’s principle function.

Hamilton also considered a total variation of S, including the end point times and configurations. In this case S becomes a function of the end points. This allowed Hamilton to consider S to be the principle function of mechanics, rather than a functional used to derive the equations, and to obtain a pair of differential equations for S. Jacobi recognized that only a single equation was necessary, which is now termed the Hamilton-Jacobi equation. The most elegant formulation of Newtonian mechanics is in terms of the Hamilton-Jacobi equation (Yourgrau and Mandelstam 1968).

Relativity. Einstein’s theories of relativity do not replace Newtonian mechanics. The two principal papers on relativity are those of 1905 and 1916 (Einstein [1905] 1952; [1916] 1952). The 1916 paper provides a new theory of gravitation to replace Newton’s. But the basic principles of mechanics as we have discussed them here remain unscathed by the theory of relativity. Indeed, the first postulate of Einstein’s 1905 paper, which he called the Principle of Relativity, was “The same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good.”

The Lagrangian function, which appears in Hamilton’s principle function, takes on a modified form, however, owing to the dependence of mass on velocity for velocities near the speed of light.

Fields. Fields, such as electric and magnetic fields, are quantities that depend on spatial positions as well as on the time. The spatial coordinates and the time are independent variables. This situation is fundamentally different from that encountered in the motion of a physical system. In the case of the physical system the coordinates (and momenta) of the constituents are dependent variables which are functions of a single independent variable, which is the time. A variational principle for field quantities must then involve an integral over spatial coordinates as well as the time.

The inclusion of the spatial coordinates as independent variables causes no real problem, and a variational principle still holds for electromagnetic fields. Einstein's 1916 gravitational theory is also a field theory. David Hilbert was able to obtain a variational principle for this field theory as well (Yourgrau and Mandelstam 1968).

Quantum Theory. With the wisdom of hindsight, we can track the emergence of the quantum theory almost logically. But each step in the development of new ideas is more an experience of chaos with the hope of an eventual emergence of order. Some semblance or order in quantum theory came with the work of Erwin Schrödinger in the 1920s. In mathematical terms nonrelativistic quantum theory is based on the Schrödinger equation (Schrödinger 1926; Moore 1989). One of the more radical ideas in the path to a quantum theory was that of Louis de Broglie, which appeared in his November 1924 doctoral thesis (de Broglie 1924, cited in Moore 1989). This idea was a union of waves and particles. As de Broglie put it, "the particle being a little localized object incorporated in the structure of a propagating wave" (Moore 1989, 186). In his thesis he was rather concrete about the idea, placing it in the context of Fermat's and Hamilton's principles. This was the inspiration for Schrödinger's development of the so-called quantum wave equation in 1925–26.

Schrödinger provided a "derivation" of his equation in the paper received by *Annalen der Physik* in January 1926. Of course one cannot derive this equation from anything more fundamental. The mechanics available to Schrödinger was that of Newton, and the equation he sought was more fundamental than Newton's laws. But with the idea of de Broglie and the relationship between energy and frequency obtained by Max Planck and Einstein, Schrödinger knew the form of what he was after. He left many records of personal thoughts but no illumination of the path that led to this immortal equation, so we can only surmise that what he wanted was to produce a legitimizing approach (Moore 1989).

Schrödinger turned to the Hamilton-Jacobi equation, which, as we have seen, is the fundamental equation of classical mechanics. In place of Hamilton's principle function he introduced Ψ, which is related to S by $S = K \ln \Psi$, where K is a constant. The form taken by the Hamilton-Jacobi equation Schrödinger then chose as the integrand in a functional the extremum of which produced what is now known as the Schrödinger equation (Schrödinger 1926; Moore 1989).

Of interest to us here is that the fundamental equation of nonrelativistic quantum theory comes from a variational problem. Note also that Schrödinger made no mention of matter waves in this development. His published route to the equation was via a variational principle that stood independently of any of the radical ideas of the emerging quantum theory.

Richard Feynman took a different approach to formalizing the quantum theory. His approach considered possible trajectories from an initial state to a final state, and he expressed the transition amplitude between two quantum states as a summation over all possible paths connecting the states. The only significant contributions to this are those for which Hamilton's principle function is an extremum. Feynman's theory is not itself based on a variational principle; it is, however, an integral formulation that generates a variational principle in the classical limit (Feynman 1948; 2005).

Julian Schwinger produced a true variational principle, which can also be obtained from the Feynman formulation. Schwinger's formulation is specifically for the treatment of quantum fields. This does not sweep the difficulties of quantum filed theory under any cosmic rug. We may claim, however, that we have a variational principle for the present form of the quantum theory (Schwinger 1951).

Thermodynamics. At this time we have no formulation of a variational principle for thermodynamics. This is in spite of the original intuitive hope of people of the stature of Hermann von Helmholtz and Planck. In 1886 von Helmholtz attempted a derivation of a variational principle for thermodynamics. The result is, however, a somewhat contrived formal relationship of thermodynamics to mechanics, which is valid only for reversible changes in the system (Yourgrau and Mandelstam 1968).

We know considerably more now about the relationship between thermodynamics and mechanics and about the difficulties presented by irreversibility than was known in 1886. But this knowledge only reveals the depth of the problem with no indication of the possibility of formulating a variational principle for thermodynamics.

Physicists believe that the basis of matter is particulate. And we feel (almost) confident that our mechanical picture of particles and their interactions must yield macroscopic thermodynamics. The work of Josiah Willard Gibbs ([1902] 1960) has provided this for systems in equilibrium. But when we consider the irreversibility present in real systems, particularly biological systems, we encounter a paradox. Our mechanics, whether classical or quantum, is time reversible; but in real systems the direction of time is provided by the increase in entropy in irreversible processes. Unless this paradox is resolved there can be no rational transition from mechanics to thermodynamics.

One of the most authoritative treatments of modern statistical mechanics is Linda Reichl's *A Modern Course in Statistical Physics, Second Edition* (1998), in which she discusses the paradox of irreversibility indicating that a new field of statistical physics is resolving the paradox. She cites specifically Ilya Prigogine (1997) and Hiroshi H. Hasegawa and Dean J. Driebe (1994). The work of Hasegawa and Driebe has shown that in order to obtain a mathematical description of the irreversible time-evolution of a multi-body dynamical (thermodynamic) system a description of the system based on particle trajectories must be given up. For unstable systems the concept of trajectory loses operational meaning. I alluded to this in a previous contribution to *Zygon* (Helrich 1999).

This is in part a measurement problem, which is present whether we consider the system to be classical or quantum. This possible resolution to the paradox points, as well, toward the complexity of multi-body systems. It is extremely difficult for us to relinquish what we have constructed in our mind's eye, so we ask what the molecules are doing and expect answers in terms of our mental pictures. Our only honest recourse in this is, however, to the microscopic picture that agrees with thermodynamics.

What is emerging is a microscopic picture that requires us to give up our hope of understanding physical reality based on the dynamics of individual molecules if we wish to include the irreversibility of time. We must accept the fact that the trajectory of a molecule cannot be measured and has, therefore, no meaning in our concept of reality. This is similar to Werner Heisenberg's statement about the electron orbit in the atom (Heisenberg 1930). The limitations here, however, are not quantum. This is the measurement problem.

The emerging resolution of the irreversibility paradox does not point to a failure of the fundamental reversible equations of classical or quantum mechanics. Rather the instability of the time reversible dynamics has been shown to result in an irreversible kinetic description. A kinetic description is based on distribution functions, which are not reducible to the trajectories of individual particles. Distribution functions are properties of an ensemble of systems that are identical at the level of our measurements.

The particular system, composed of a vast number of molecules, that we have before us on the laboratory bench is a single system. Any measurement we may make on this system requires an amount of time, and the probe we use occupies a volume. Both of these may be very small, but neither is zero. Therefore our most detailed measurement of any property of the single system is an average over time and the probe volume. The equality of this time (and volume) average and the ensemble average over phase space is the content of the ergodic hypothesis, which cannot be proven for general systems but seems to be essentially universally valid (Toda, Kubo, and Saitô 1983). Therefore, in basing our understanding of time irreversibility on ensemble-level distribution functions we are not venturing any farther away from the real system than our measurements. The resolution of the irreversibility paradox that seems to be emerging from statistical physics is then not an approximation but a true resolution.

I am very hesitant to say that this resolution is simply statistical, because that brings to mind simple images and a reduction to combinations of chance and necessity. I think that the issue here is far more subtle. Time irreversibility is a real and fundamental part of physics. If the physics of time irreversibility is found to be based on distributions, which are irreducible to distinct particle trajectories, we may have to relinquish the concept of a single molecule in a complex system. The quantum theory has required us to give up our concept of single electrons in complex atoms and molecules, which we now accept. Nevertheless I consider the relinquishing of the concept of a single molecule in a complex system to be a nontrivial step.

The irreversibility of time for these systems is then related to what can result from processes occurring in these systems. For these systems questions of teleology are then no longer rooted in the variational principles discussed above. They are rooted in the entropy production arising from instabilities in those complex systems. The relationship may be intimate rather than statistical.

Prigogine (1997) points out that matter far from equilibrium acquires new properties. He is able to discuss this in terms of the dynamics of classical as well as quantum systems. The continuous interaction of the particles of matter with one another is the root of the time irreversibility that results.

Discussion

My intention in this essay has been to discuss the details of what come very close to guiding principles in physics: variational principles. From its initial discovery, even in a most rudimentary form, the variational principle in mechanics was thought of as a teleological principle. This was particularly the case when it seemed apparent that this variational principle definitely asserted that some fundamental quantity was a minimum. Even when the result was not a minimum, however, we could still claim that nature is revealing a fundamental direction by requiring that a certain integral function or functional has an extremum for processes matching reality.

Classical and quantum physics and field theory can all be cast in terms of variational principles. In a certain sense we may then claim that we have established the foundational formulation of the theoretical or mathematical physics of particles and fields based on variational principles. If we accept that particles and fields embrace all that is present in the universe, we are free to address the metaphysical question of whether or not this implies a teleology in physics. Physics will already have supplied as much insight as possible by formulating the variational principles.

In the last chapter of their book, Wolfgang Yourgrau and Stanley Mandelstam (1968) present an insightful and historically based discussion of the significance of variational principles in natural philosophy. They claim that although certain scientists may choose to speculate on the metaphysics, this is scientifically unintelligible. They close their discussion with the words of Max Born, who does not himself condemn metaphysics but does point out that metaphysical speculation is an act of faith and says that we must accept that if we are to be honest.

I believe, however, that we can say more even before we leave the physics for any metaphysical speculation we may choose. Time is the fundamental concept with which we must deal if we are to consider any question related to teleology. In the instances for which we have a variational principle time is reversible. The instance for which a variational principle fails is that for which time is irreversible. This is a mathematical consequence of the formulation of variational principles.

Both classical mechanics and quantum mechanics are time reversible. Thermodynamics is not. For this reason there is no variational principle for thermodynamics. This does not necessarily deny the existence of a teleology for thermodynamic systems. The lack of a variational principle for thermodynamics may, however, be sufficient reason to claim that teleology cannot be inferred from a variational principle. Thermodynamics is too central to physics to be ignored in this discussion. Any real consideration of the physics of the universe must recognize that the universe is irreversible in time.

Thermodynamic irreversibility is a consequence of entropy production. Entropy is one of the most subtle of all concepts in physics. Unlike energy, entropy cannot be defined for single molecules. It is a system property.

As I have indicated, Gibbs was able to obtain a statistical mechanical formulation for entropy at equilibrium. And Ludwig Boltzmann (1871; 1872; 1877) was able to obtain a kinetic theory entropy for low-density gases near equilibrium. Boltzmann's entropy has the same form as uncertainty in Claude Shannon's information theory, which yields an understanding of entropy in information theory terms for low-density systems near equilibrium (Jaynes 1957a, b; 1963; Shannon 1948).

But these near-equilibrium approaches fail if we want to encounter situations of interest in biology or those encountered in chemical reactions in nongaseous systems far from equilibrium. Our scientific understanding of such systems of necessity is built on expansions around the thermodynamics of equilibrium. Prigogine has shown that stationary states are characterized by minimum entropy production (Prigogine 1967). But there is no such general principle in the far-from-equilibrium nonlinear regime (Kondepudi and Prigogine 1998).

Thermodynamics requires that entropy production in a system cannot be negative. Far from equilibrium there may be a number of possible states to which a system may evolve. Some of these states may possess great geometric spatial symmetry or an oscillatory ordering in the time. Transitions between states are induced by fluctuations, which are always present in complex interconnected systems. Prigogine and his coworkers have referred to this as order through fluctuations (Nicolis and Prigogine 1989; Prigogine and Stengers 1984; Prigogine 1980). In this case the general time direction is determined, since the system must, according to the laws of physics, evolve in a direction of increasing entropy. But this evolution may be toward one of a number of structured states.

In teleological terms, the direction of the time evolution of a system has a general sense, but the exact system path is unspecific. We can speak of such a path as open and undetermined in a detailed sense. This conclusion is more in keeping with a modern understanding of teleology. The future is not completely determined scientifically, and the reason may be a result not of the Heisenberg Indeterminacy Principle but of thermodynamics and the indeterminacy of fluctuations.

Any discussions of teleology based on variational principles must, it seems to me, deal with the understanding we may gain from these principles regarding the structure of the basic laws governing the motion of isolated systems. Here we may gain insight into the elegance and beauty of the basic structure of the physical universe. This may be of fundamental importance in our attempt to understand what Einstein termed the thoughts of God.

If we are to comprehend the dynamical evolution of the universe in scientific terms we must encounter the reality of interconnected complex systems. Here we must give up our hope of understanding even small parts of the universe in terms of a picture, regardless of how elegant, based on single particles. Our comprehension of these complex systems and of teleology must be based on the properties of ensembles of systems, which to us are indistinguishable from one another. We cannot follow in detail even the passage from a point of instability to the next stable level.

It seems then that there is finally no proof that an unambiguous teleology is evidenced in physics. But I do not think that speculation here must necessarily be simply a question of faith in a specific metaphysics. If we speculate without a grounding in the physics, Born may be correct that we are carrying out an act of faith (alone); but it seems to me that physics reveals a direction and an openness in nature that invites exploration.

NOTES

1. Robert John Russell (2006) has provided a very coherent argument that science itself is based on Christian concepts and ideas.
2. Present experiments on single quantum particles are not conducted for the formulation of laws, but for the testing of laws.

REFERENCES

Boltzmann, Ludwig. 1871. Einige allgemeine Sätze über Wärmegleichgewicht, Wien. Ber., 63, 679.

———. 1872. Weitere Studien über Wärmegleichgewicht unter Gasmolekülen (H-Theorem), Wien. Ber., 66, 275.

———. 1877. Beziehung zwischen dem zweiten Hauptsatz der Wärmetheorie und der Wahrscheinlichkeitsrechnung resp. den Sätzen über das Wärmegleichgewicht (Complexionen-Theorie), Wien. Ber., 76, 373.

Cercignani, Carlo. 1998. *Ludwig Boltzmann, the Man Who Trusted Atoms*. Oxford: Oxford Univ. Press.

Cropper, William H. 2001. *Great Physicists*. New York: Oxford Univ. Press.

De Broglie, Louis V. 1924. *Recherche sur la Theorie des Quanta* (Research on the Quantum Theory). Doctoral thesis, Univ. of Paris. Paris: Masson & Cie.
Einstein, Albert. [1905] 1952. “Zur Elektrodynamik bewegter Körper” (On the Electrodynamics of Moving Bodies), *Annalen der Physik* 17, reprinted in English translation in the *Principle of Relativity*. New York: Dover.
———. [1916] 1952. “Die Grundlage der allgemeinen Relativitätstheorie” (The Foundation of the General Theory of Relativity), *Annalen der Physik* 49, reprinted in English translation in the *Principle of Relativity*. New York: Dover.
Feynman, Richard P. 1948. “Space-Time Approach to Non-Relativistic Quantum Mechanics.” *Revs. Mod. Phys*. 20:367–87.
——— 2005. *Feynman's Thesis, A New Approach to Quantum Theory*. Ed. Laurie M. Brown. Singapore: World Scientific Publishing.
Gibbs, Josiah Willard. [1902] 1960. *Elementary Principles in Statistical Mechanics*. New York: Dover.
Hasegawa, Hiroshi H., and Dean J. Driebe. 1994. “Intrinsic Irreversibility and the Validity of the Kinetic Description of Chaotic Systems.” *Physical Review E* 50:1781–1809.
Heisenberg, Werner. 1930. *The Physical Principles of the Quantum Theory*. Chicago: Univ. of Chicago Press.
Helrich, Carl S. 1999. “Thermodynamics: What One Needs to Know.” *Zygon: Journal of Religion and Science* 34:501–14.
———. 2006. “On the Limitations and Promise of Quantum Theory for Comprehension of Human Knowledge and Consciousness.” *Zygon: Journal of Religion and Science* 41: 543–66.
Jaynes, E. T. 1957a. “Information Theory and Statistical Mechanics.” *Phys. Rev*. 106:620–30.
———. 1957b. “Information Theory and Statistical Mechanics II.” *Phys. Rev.* 108:171–90.
———. 1963. “Information Theory and Statistical Mechanics.” In *Statistical Physics, The 1962 Brandeis Lectures*, 181–219. New York: W. A. Benjamin.
Kondepudi, Dilip, and Ilya Prigogine. 1998. *Modern Thermodynamics*. New York: John Wiley.
Lagrange, Joseph Louis. 1867. *Oeuvres de Lagrange*. Ed. Joseph Alfred Serret. Paris: Gauthier-Villars. Available at *gdz.sub.uni-goettingen.de/en/news-e/index.shtml.*
Lemons, D. S. 1997. *Perfect Form*. Princeton, N.J.: Princeton Univ. Press.
Moore, Walter. 1989. *Schrödinger: Life and Thought*. Cambridge: Cambridge Univ. Press.
Nicolis, Grégoire, and Ilya Prigogine. 1989. *Exploring Complexity*. New York: W. H. Freeman.
Park, David. 1988. *The How and the Why: An Essay on the Origins and Development of Physical Theory*. Princeton, N.J.: Princeton Univ. Press.
Prigogine, Ilya. 1967. *Thermodynamics of Irreversible Processes*. New York: Interscience.
———. 1980. *From Being to Becoming*. San Francisco: W. H. Freeman.
———. 1997. *The End of Certainty*. New York: The Free Press.
Prigogine, Ilya, and Isabelle Stengers. 1984. *Order out of Chaos*. New York: Bantam.
Reichl, Linda. 1998. *A Modern Course in Statistical Physics, Second Edition*. New York: Interscience.
Russell, Robert John. 2006. *Cosmology, Evolution and Resurrection Hope*. Proceedings of the Fifth Goshen Conference on Religion and Science. Ontario, Canada: Pandora.
Shannon, Claude E. [1948] 1949. “A Mathematical Theory of Communication.” Bell System Technical Journal 27:379–623. Reprinted in C. E. Shannon and W. Weaver, *The Mathematical Theory of Communication*. Champaign: Univ. of Illinois Press.
Schrödinger, Erwin. 1926. “Quantisierung als Eigenwert Problem.” *Annalen der Physik* 79: 361–76.
Schwinger, Julian. 1951. “The Theory of Quantized Fields I.” *Phys. Rev*. 82:914–27.
Toda, Morikazu, Ryogo Kubo, and Nobuhiko Saitô. 1983. *Statistical Physics I, Equilibrium Statistical Mechanics*. New York: Springer-Verlag.
Wigner, Eugene. 1960. “The Unreasonable Effectiveness of Mathematics in the Natural Sciences.” *Communications in Pure and Applied Mathematics* 13, no. 1.
Wilson, A. H. 1960. *Thermodynamics and Statistical Mechanics*. London: Cambridge Univ. Press.
Yourgrau, Wolfgang, and Stanley Mandelstam. 1968. *Variational Principles in Dynamics and Quantum Theory*. New York: Dover.