TIME, THERMODYNAMICS, AND THEOLOGY

by George L. Murphy

Abstract. A theological approach to understanding time and change in a modern way must consider the relationships between thermal physics and time as elucidated during the past century and a half. The fact of temporal change, including death and decay, has been a religious problem since antiquity, so that some traditions have simply attempted to transcend the world of change. However, a major current of the Christian tradition has seen change as a fundamental aspect of God's creation, and one with which God becomes identified in the Incarnation. This implies approval of history, as having an ultimate value, rather than transcendence of it.

We examine thermodynamics, and especially its Second Law, in order to understand more precisely the issues of temporal change. The Second Law states a universal tendency toward increasing disorder, and several implications of this law are discussed. Of particular significance, however, is the work of Prigogine and others on nonequilibrium thermodynamics, drawing attention to such phenomena as the enhancement of chemical reaction rates and the formation of ''dissipative structures'' in nonequilibrium situations. Such possibilities may be of considerable importance for understanding chemical and biological evolution.

These ideas can be included in an evolutionary picture in which, following Teilhard de Chardin, the Body of Christ is seen as the future of evolution—an ''ultimate dissipative structure'' in which the world of time and change is united with God. Suffering, death, and decay receive their meaning from the future. Within this framework it is therefore possible to believe that the material world of history may be part of the eschatological future and that science provides hints, though not predictions, of how that may happen.

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Time has always been a topic worthy of theological consideration,

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but two centuries ago it would have seemed odd to devote theological attention to the subject of heat—to what we call today thermodynamics. Now we have come to recognize that important, subtle, and still imperfectly understood connections between time and thermodynamics are suggested by the Second Law of Thermodynamics. The apparent *irreversibility* of temporal change and the possibility that in some objective sense the physical universe is "running down" have to be considered by Christian theologians who take the doctrine of creation and, hence, the material world seriously. Thus I want to consider, in a relatively nontechnical fashion, the ways in which theology and modern science may interact in dealing with basic questions of change.

The Classical Tension between Being and Becoming

The title of a valuable book by Prigogine, *From Being to Becoming* (1980), calls attention to one of humanity's perennial concerns: the character of our world as one of change—in fact, of irreversible change. Flowers wither and cannot be *un*withered; things come apart and decay—they are *corruptible*. Indeed, becoming can almost be a synonym for *decay*. What comes to be is born to die.

It is, of course, the *material* world that suffers decay. If material things are "compound", it seems only natural that they are liable to come apart. A world of simple (i.e., noncompound) souls or intelligences might be quite different in this regard.

Thus people long ago recognized some of the consequences of the Second Law of Thermodynamics, which would not be formulated precisely until the nineteenth century. This law can be stated briefly as "the impossibility of a perpetual motion machine (of the second kind)," or "the law of increasing disorder" (Sears 1953, chap. 7 and 8; Gamour 1947, chap. 8). Energy is always becoming less available for the performance of useful work.

We may imagine, in contrast to the changeable world of becoming, a changeless world of *being*. This was characteristic of Greek thought, and was given classic expression by Plato and his followers. For them, this realm of being is in a technical sense the real world of ideas or forms. The realm of becoming is merely a shadow, an imperfect representation, of it. In general, one authority says, "The main concern of older Gk. philosophy is to know this abiding element in the changing, rising, and perishing forms of nature" (Theological Dictionary 1965, A. N. φθείρωχτλ).

In such a view, the realm of being is the real home of our immortal souls, which can neither come into being nor pass away (Plato 1963). Our goal should be to return to this world of pure being. In the meantime, there is little point in studying the realm of becoming, the material world, for its own sake. At best, it can only be a pointer to the true realm of being.

The tension between being and becoming appears in philosophy and in religion. In classical Gnosticism, an example of its religious expression, the realm of becoming is a huge mistake, and salvation means being freed from it. One means of escape from "the terror of history" (Eliade 1959, 139–62), is to regard becoming as just an interlude between states of "real" being. This is the *Urzeit-Endzeit*, primordial time–endtime motif, and the hope is that the *Endzeit* will be a recovery of the *Urzeit*. After all the happenings of history, the initial paradisiacal state will be restored. Ultimately, history does not matter, for the real realms of beginning and end are outside history.

INSIGHTS OF THE JUDAEO-CHRISTIAN TRADITION

Judaeo-Christian thought is well aware of the transitory character of our present existence. "The grass withers, the flower fades; but the word of our God shall stand forever" (Isd. 40:8), the prophet reminds us.[1] And in Romans 8:18–25, Paul speaks of creation longing to be freed from its "bondage to decay." The theologians of the early church were very much concerned with the problem of "corruption" (φθόρα).[2] Indeed, Origen used an *Urzeit-Endzeit* scheme to deal with it, while Irenaeus and Athanasius saw history as involving a progress, intended and directed by God, toward "incorruption" (ἀφθαρσία). And today, many Christians are familiar with the hymn which says,

Change and decay in all around I see;
O thou who changest not, abide with me.
(Lryte 1978, no. 272)

Christianity offers hope for an eschaton in which corruption will be overcome, but the idea of the resurrection of the body means that this eschatological future will have some continuity with the present, material world. Thus our scientific understanding of the world, and especially the Second Law of Thermodynamics, poses a serious question. Since the Second Law follows from very basic properties of matter, how can our resurrection portend a material character and still be free from decay? We will return to this question in our final section.

While it shares the human concern about being and becoming, the

Judeo-Christian tradition also introduces concepts radically at variance with the mythological worldviews of humanity. We should note in particular the significance of the ideas of creation, Incarnation, and eschatology.

The doctrine of creation means that the changeable realm of becoming is a *good* work of God (Gen. 1:31). It is not a mistake, nor a secondary production, nor a result of sin. In particular, *time* is part of God's creation, an idea to which Augustine gave classic expression: "*Non est mundus factus in tempore, sed cum tempore*" ("The universe was created not in time but along with time.") (Augustine 1968, 446–49). Thus in God's work of creation, change is *intended.* Such a belief is very important for a proper understanding of the relationship between theology and science, for theology must approve the scientific study of the world of becoming in its own right. Theology must also take seriously the understanding of time and change developed by science. Time—like all aspects of the created world—is knowable *etsi deus non daretur* (Murphy 1987, 221).

One might picture a timeless, changeless God creating a temporal world with no "back reaction" upon God. That is just what the traditional idea of divine *apatheia* expresses: God can create a world without its making any *difference* to God.

The doctrine of the Incarnation, however, makes such a concept problematic. It says that "the high and lofty One who inhabits eternity" (Isa. 57:15) becomes an inhabitant of our realm of becoming. God is born, lives, and dies—voluntarily subject to the Second Law of Thermodynamics—and is revealed to us within the framework of space-time relationships. This is the heart of the Christian message, in spite of the difficulty of formulating it in adequate philosophical categories. And in the Resurrection and Ascension of Christ we are assured of God's commitment to our world of becoming. Whatever God's intention for the world, God will not abandon it.

Christian eschatology is intimately connected with the Incarnation. Indeed, the universe finds its fulfillment in Jesus Christ. Modern cosmology has paid considerable attention to various "anthropic principles" which maintain that, in one degree or another, the development of intelligent life is an important and perhaps essential feature of the universe (Barrow and Tipler 1986). The doctrine of the Incarnation and the consequent eschatology may therefore be called a "*the*anthropic principle" (Murphy 1988, 10). It is the human race, indwelt by the eternal Word of God, which is the goal and fulfillment of history.

The mythological *Urzeit-Endzeit* language can be used here only with reservations. This primordial time–endtime motif is found in the

Bible, but like all myth is incorporated there in the form of "broken myth" (Childs 1960, 30–71). If we are to use these mythological terms, we must say that, in the Christian conception, the endtime is *richer* than the primordial time. A comparison of Revelation with Genesis shows some "paradisial" features in the former, but in Rev. 21:24–26 we are told that "the glory and honor of the nations" shall be brought into the New Jerusalem. History matters! All the good which is done in the processes of becoming is preserved for the Resurrection.

Thus the biblical tradition has very positive attitudes toward our world of change. To explore the significance of all this, it is necessary to examine what science has to say about change in the physical universe.

MODERN THERMAL PHYSICS AND TIME

The development of modern science in the sixteenth and seventeenth centuries meant that some types of change could be described and quantitatively predicted by Newton's laws of mechanics. For example, the motions of the planets in the solar system can be accurately predicted with these laws. However, a relatively simple system of that sort does not show the *irreversible* character which more complex systems have. Newton's laws make no fundamental distinction between past and future. If one were to imagine reversing the direction of time, Earth would simply orbit the sun in a clockwise sense rather than counterclockwise, as it does now. There would be no fundamental change. A film of Earth going around the sun could be run backward as well as forward and still look normal. However, the situation is radically different, for example, with a film of an egg being scrambled: we simply do not experience eggs being *un*scrambled in the real world.

Irreversibility entered physics in the nineteenth century with the development of the science of thermodynamics (Sears 1953; Gamow 1947, chap. 8; Mason 1962, chap. 39). The First Law of Thermodynamics says that the total energy of an isolated system, including mechanical energy dissipated in the form of heat, is conserved. This is simply a generalization of a well-known fact of mechanics—but the Second Law of Thermodynamics is different, and it can be expressed in various ways, each of which gives insight into its profound significance. Perhaps its simplest and most commonsense formulation is that heat flows by itself from a hot to a colder body, but not the other way. That is, some unaided processes can occur in only one direction. Also, it can be shown that this is equivalent to the statement that, while the total energy of an isolated system is conserved, that energy is always becoming *less* available for useful work. Heat can be converted into mechanical work, but never with 100 percent efficiency (there can be no "perpetual motion machine of the second kind"). William Thomson (later Lord Kelvin), who first expressed the Second Law in this form, recognized its cosmic character when he titled his basic paper "On the Universal Tendency in Nature to the Dissipation of Mechanical Energy" (Thomson 1852). Every isolated system—and finally the whole universe—is running down.

The Second Law is expressed mathematically in terms of a system's *entropy,* which in turn is defined in terms of heat and temperature. The entropy of an isolated system can never decrease in the course of time, but in all realistic systems it will only increase. Thus there is a fundamental difference between past and future. Natural processes can go in only one direction (that of increasing entropy), but not the opposite way.

We see this law in yet another light when we consider the atomic structure of matter. Boltzmann related entropy to the probability of a system's atoms to be in a given state. Increasing entropy then corresponds to more probable, and thus less orderly, states. The Second Law means that the total *disorder* in the universe always increases.

The Second Law in these forms applies only to an entire isolated system. The entropy of part of a system can decrease, but that is made up for by an increase in other parts. Heat will not flow from cold to hot, but it can be "pushed" (as in a refrigerator).

The widest application of the Second Law leads to the concept of the "heat death" of the universe, the "running down" of the cosmos. This would occur when the flow of heat has made the temperature uniform throughout the universe; no heat engine can operate, and life has become impossible. The universe would still exist, with the same total energy as always, but nothing of significance from the human standpoint could happen. Thus the heat-death idea seems to point toward a final meaninglessness of the universe.

Boltzmann's probabilistic interpretation of the Second Law has been used to argue that a continual increase of entropy toward heat death is not certain but only highly probable. Thus a statistical fluctuation could return the universe from its heat death to a state of low entropy. However, the required time, even on a much smaller scale (e.g., all the air molecules in a room spontaneously collecting in one half of the room), is vastly greater than the age of the universe. It is therefore questionable whether the laws of science can legitimately be extrapolated so far beyond the limits of observed phenomena (Gamow 1947, 213–19; Bridgman 1936, 97–100).

Clearly, there is some correlation between the direction in which time normally "flows" and the increase of entropy. It is an observed fact that the "arrow of time" points in the direction in which entropy increases. But can we see a connection, and not a mere correlation, between time and entropy? One may argue that the increase of entropy is fundamental, as merely representing a tendency toward greater probability (Prigogine 1980, 9–11). The question then is why our internal time sense correlates precisely with this tendency. Eddington argued that our brains must somehow be equipped with "entropy-clocks" to measure the sense of time (of which he gave a simple macroscopic example using thermoelectric currents) (1929, 100–101).

Since Hubble's 1929 discovery of cosmic expansion, it has seemed to some that the Second Law may be rooted in this expansion. Theoretical and observational discoveries in cosmology in the twentieth century have led to important new insights into the time-entropy connection and the heat-death idea. But the significance of these insights is still debated.[3]

Of more immediate significance is the fact that classic discussions of the Second Law, though part of a science called *thermodynamics,* really belong in large part to the more restricted discipline of *thermostatics*. The latter deals with processes which occur so slowly that physical systems can remain in thermal equilibrium (i.e., at a uniform temperature). Such idealized processes are called *reversible,* and many of the quantitative results of traditional thermodynamics are only valid for such processes. But even so simple a process as the flow of heat from the hot to the cold end of a metal bar requires consideration of irreversible, or nonequilibrium, processes (Sears 1953, 3–4, 110–24; King 1962, chap. 20). That is especially the case, moreover, if we want to deal with the complex processes that occur in living organisms.

One might think that processes far from equilibrium would always be more chaotic than those near equilibrium, but this is not the case. Prigogine and others have shown that a full treatment of nonequilibrium thermodynamics may produce results as radical and surprising as the ideas of relativity or quantum theory.[4] Prigogine has argued that it is necessary to give up the simple idea of time as a mere number and to treat it as an operator-valued entity. It has also been shown that the process of catalysis in chemical reactions can increase concentration of a reaction product far above its equilibrium value. That result, clearly, is very important for our understanding of the ways in which the first living molecules might have arisen at the beginning of the evolutionary process.

Perhaps the most important thing to note from this significant recent work is the possibility of nonequilibrium "dissipative structures" in systems through which a flow of energy occurs. The convection cells that can form in a fluid provide one example of such dissipative structures. Thus the irreversible dissipation of energy can give rise to a "higher-order order." Again, the possible significance of this for theories of the evolution of living systems is clear. This important work on nonequilibrium processes in physics, chemistry, and biology has begun to show how there can be order and structure in the realm of becoming. Such order need not be sought in an ideal realm of being.

THEOLOGY-SCIENCE INTERACTIONS AND ANALOGIES

As with all conversations at the science-theology interface, we must deal with two basic questions if we want to have a science-theology dialogue and not two isolated monologues. First, in what theological directions are we urged by scientific developments? Second, how can theology help us to understand the meaning of scientific discoveries? The asymmetry of these questions reflects a difference in the realms of competence of natural science and theology. Science attempts to describe, understand, and predict events in the physical world in ways that are as independent as possible of the different religious beliefs that people may hold. Theology attempts to speak as profoundly as possible about the meaning of what happens in the world and therefore may use revelation, which is not directly testable by scientific means. Science and theology do not have identical concerns, but even the fact that we ask our two questions indicates a belief that there is some overlap between the competence of science and that of theology, because both take the material world seriously.

In some cases, science may place real constraints on the ways we can use theological language consistently—for example, with questions pertaining to the age of the universe. An extensive body of observation and theory from different branches of science strongly indicates that the ages of the Earth and the universe must be measured in billions of years. If this indication is taken seriously, theological models in which the initial creation of the world was only a few thousand years ago are ruled out.

It is significant that the above example uses observations, theories, and a considerable amount of data relating to the past, such as light signals and fossil "time capsules." Although we must be careful about our assumptions with regard to causality, it is obvious that we do not have the same kind of scientific data about the future. The extrapolation of such data into the distant future is not as compelling as scientific discussions of the early universe, though the implications of well-tested theories for the future certainly should be taken into account by theologians. We will return to this point toward the end of this essay.

In some situations we may be able to see helpful analogies between science and theology, or theology may be able to suggest a wider significance for some scientific concepts—such as dissipative structures. We will therefore consider the possibility that, in the evolutionary context, the hyperpersonal Body of Christ can be thought of as a dissipative structure. Of course, to suggest such a possibility is not to argue that nonequilibrium thermodynamics validates theology, or that theology demonstrates the truth of nonequilibrium thermodynamics. Nevertheless, more is involved here than a scientific illustration of a theological concept. The community of human beings in the Body of Christ involves physical bodies to which the science of thermodynamics applies, though the theological concept is concerned with more than just physical interactions. Thus a genuine extension of the concept of dissipative structures is suggested, and whether or not this extension is useful must be determined by working out its implications.

The Christian doctrine of creation implies that God creates both *ex nihilo* and mediately. Creation is entirely the work of God but is done through instrumentalities which are open to scientific understanding (Murphy 1987, 221). Thus the theory of biological evolution is seen as part of our understanding of creation.

Opponents of such an understanding have sometimes argued that the Second Law refutes evolution because it would require greater and greater organization (e.g., Klotz 1955, 546). This is incorrect, however, for the statement that order cannot increase applies only to isolated systems. (If an increase in order for all systems were forbidden or impossible, one couldn't sort a deck of cards.) It is true, nevertheless, that the development of life goes counter to the trend of processes in the universe. But as Sir James Jeans said somewhere, the evolution of life is "like a sailor who runs up the flag on a sinking ship."

Scientific explanations of the first stages of *chemical* evolution, of the origin of life, face difficult problems (Crick 1981; Thaxton et al. 1984). It seems impossible to explain the origin of the first living molecules in terms of equilibrium, or even near-equilibrium, processes. The recent work in nonequilibrium thermodynamics, discussed in the previous section, does not solve these problems, but it *does* provide hope for eventual solutions. The enhancement of reaction-product concentrations through autocatalysis and the existence of dissipative structures are two features of nonequilibrium thermodynamics that are relevant to the problem of biogenesis. A great deal of work needs to be done before we can say that such approaches explain the origin of life, but the possibility should not be dismissed.

Teilhard de Chardin emphasized the development of different levels of structure and organization—nucleotides and proteins, cells, multicelled organisms, and conscious structures—in evolution. In fact, he offered a rough thermodynamic analogy for the development of consciousness. Just as a *gradual* increase in temperature can at some points produce a *sudden* phase change, so, he argued, the gradual process of evolution could "boil over" into consciousness (1959 bk. 3, chap. 1). But perhaps Teilhard's most helpful contribution has to do with the *future* of evolution. He argued that just as at one stage of evolution there was a transition from one-cell to multi cellular organisms, the next stage in human evolution will be development of a suprapersonal organism, which he identified with the Body of Christ as spoken of by St. Paul (Teilhard 1971, 16, 66–72). Individual human beings are in the process of being brought together into one body. That is to say, the church as the Body of Christ, whose head is Christ, is the structure of reality that God is developing for the cosmos. This is a social body, in which there is spiritual and intellectual communion, and also a mystical body, because its organic character and the source of its life are discernible only by faith, as well as a physical body (because it is made up of human beings). Thus the Body of Christ is partly, though not wholly, visible.

As Ephesians and Colossians say, the church is the instrument through which God is working to bring the whole of creation to fulfillment. In the largest sense, the Body of Christ is the ladder between being and becoming (Jn. 1:51), the ultimate dissipative structure. Out of the suffering and turmoil of earthly life God creates a structure of eternal life, a structure which is already, in its head, "in the heavenly places" (Eph. 1:20–23). Here is the possibility of becoming "partakers of the divine nature" (2 Pet. 1:4).

To speak of an eschatological future may seem to be relegating any radical newness of creation to some religious Greek kalends. For this reason, it is essential to realize that the Incarnation—the total sequence of the conception through the ascension of Jesus—implies a certain amount of realized eschatology. The Pharisaic expectation in the time of Jesus was for a resurrection of the just, but at the end of history. From such a perspective we have to say, with Pannenberg, "If Jesus has been raised, then the end of the world has begun" (1977, 67). As the *Urzeit* for Israel involved the historical events of the exodus and wilderness wandering (Childs 1960, 72–83), the *Endzeit* has broken into the world in the historical events associated with Jesus of Nazareth, *circa* A.D.30.

Thus our everyday work and human relationships—our scientific investigations, suffering, and success—are constantly transformed by the presence of the risen Christ. Indeed, Ross has spoken of a "creation of time" in connection with the Eucharistic presence of Christ (1986, 10). God creates a "sacral time" in the midst of and out of our nine-to-five lives.

Our ideas about time tend to be limited by "commonsense" ideas of causality. It is well to remember, however, that this is not a requirement in physics, where such concepts as advanced potentials, particles that travel backward in time, and "wormholes" in space-time are possible. This is even truer in theology, where we have to deal with the *meanings* of events. The events of the Old Testament have different meanings for Christians, who see them in the light of Jesus Christ, than they did for the people who lived through them. History receives its meaning from the future, and ultimately from God's eschatological future. We should try to keep this in mind in our thinking about time (Murphy 1986, 19; Hawking and Ellis 1973; Pannenberg 1977; Cullman 1950).

As we look toward the future, we should also keep in mind the Pauline and deutero-Pauline passages which point toward cosmic salvation. Romans 8:18–25 speaks of a final victory over decay. (It does not seem proper to limit "the creation" [mentioned in Romans] to humanity, which would make the passage almost tautological; *αὐτὴ ἡ κτίσις* in verse 21 corresponds to *τὰ πάντα* in Col. 1:20.) The hope of liberation from corruption has been expressed in some branches of the Christian tradition by the belief that the incorruptibility of a body after death is a sign of special sanctity (Cruz 1977). (See, e.g., Dostoyevski's use of this theme in *The Brothers Karamazov*.) This idea has its origin in Acts 2:31, and although much of the resultant veneration of corpses seems excessive, we should remember that there is a sound theological kernel here: the doctrine of the Resurrection, as expressed in Philippians 3:21.

God's victory over death and decay does not involve simply forgetting suffering and death. Indeed, the gospel witness (Luke 24:40 and John 20:27) is that the risen Christ bore in his body the marks of the crucifixion. (And Pascal says, "I think Jesus Christ only allowed his wounds to be touched after the resurrection" [1961, 734]). This suggested to the later Christian tradition that even after death and decay have been transcended, the saints will bear the marks of their suffering as "trophies." Thus even God's new creation bears the sign of the cross as an emblem of victory.

The material creation is not to be destroyed but is to be freed from decay. How that can be so in light of the Second Law of Thermodynamics is a sign of the ongoing tension between the "now" and the "not yet." The suggestion from nonequilibrium thermodynamics, that the Second Law does not abolish *dynamic* order, and the existence of orderly structures in our universe are perhaps signs (σημετα) that point to God's eschatological order, much as the butterfly or the Phoenix could be analogies or signs from nature for the Fathers, pointing toward the Resurrection.

Analogies are interesting and suggestive, but of course not compelling. In speaking of God's hope for the future we must consider what we know of the present creation, for the promise is that it will be redeemed. But we also have to recognize the eschatological transcendence of the constraints of physical law: "The things that are seen are transient, but the things that are unseen are eternal" (2 Cor. 4:18). If one attempts to make eschatology entirely a branch of physics, then one may conclude that Teilhard's convergence of the cosmogenetic process upon Omega/Christ is either foiled by the Second Law or must be recast in a way which removes much of its religious or divine content (see, e.g., Barrow and Tipler 1986, chap. 10). It is significant that Teilhard himself recognized that his vision required an ultimate transcendence of the space-time framework (Teilhard 1970, 321–37, and esp. n. 16). We treat with great honor the material universe and its rational order, as both the Judeo-Christian tradition and natural science demand, and we hope that the creation will be renewed and fulfilled in Christ. At the same time, we recognize that scientific investigation of the world can find only pointers to the plan of God, for whom nothing is impossible (Luke 1:37), who justifies the ungodly, who raises the dead, who brings into being the things that do not yet exist, and in whom we may hope against hope (Rom. 4).

The doctrine of creation implies that God's creation is so good that it is knowable "from the inside," without explicit reference to God as Creator (Murphy 1987, 221). Thus human beings can understand the origins of the universe and life scientifically, in terms of known processes and laws, because we live in the world which is governed by these laws. We are "downstream" from the original creative acts so that our relationship with those acts is quite different from our relationship with the eschatological future.

Though we have genuine hints and prolepses, especially in the

Resurrection of Jesus, the eschatological future *is* future. Inasmuch as we do not know its patterns with the completeness with which we know the patterns embodied in our present laws of physics, it should come as no surprise that we cannot know with fullness how death and corruption can be forever done away with in a new heaven and a new earth. Science and theology can provide hints of the future, but, as St. Paul reminds us, "Now we see through a glass, darkly" (1 Cor. 13:12).[5]

NOTES

1. Unless otherwise noted, biblical quotations are from the Revised Standard Version.
2. See, for example, the "Prolegomena" by Archibald Robertson to the works of Athanasius in vol. 4 of *The Nicene and Post-Nicene Fathers* (reprint, Grand Rapids, Mich.: Eerdmans, 1980), pp. lxix-lxxiii and note 3.
3. For new ideas in thermodynamics introduced by relativity, see Richard C. Tolman, *Relativity, Thermodynamics, and Cosmology* (Oxford, England: Oxford Univ. Press. 1934), chaps. 9 and 10, and G. Neugebauer and W. Meier, "Friedman-Kosmen mit Irreversiblem Expansionverhalten," *Annelan der Physik* 33 (1976): 161. Connections between cosmic expansion and the "arrow of time" are considered in T. Gold, *Proceedings of the International Solvay Congress,* 1958 (Brussels: Stoops, 1959), and George L. Murphy, "On the 'Nonclassical Many-Valuedness' of the Universe," *Foundations of Physics* 4(1984): 351. The discovery of microwave background radiation from the early universe shows that the universe is already most of the way toward its heat death, a point discussed in Heinz R. Pagels, *Perfect Symmetry* (New York: Bantam Books, 1986), pp. 234-43.
4. See especially the two books by I. Prigogine: *From Being to Becoming* (San Francisco: Freeman, 1980) and *Thermodynamics of Irreversible Processes,* 3d ed. (New York: Interscience, 1967). See also S. R. De Groot and P. Mazur, *Non-Equilibrium Thermodynamics* (Amersterdam: North Holland, 1961), and Richard T. Cox, *Statistical Mechanics of Irreversible Change* (Baltimore, Md.: Johns Hopkins Univ. Press, 1955).
5. King James Version.

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