
Gary Patterson

Theology and Thermodynamics: In Praise of Entropy

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Thermodynamics is an exact macroscopic theory with no known exceptions. It has a long history of development that includes many famous Christian scientists. Recent developments in theology have occasionally invoked thermodynamic quantities or concepts in ways that are not consistent with either good science or theology. The present article presents a brief introduction to both classical and statistical thermodynamics, with an emphasis on the role of the entropy in the description of our physical world.

Several attempts to imprecate entropy are examined and refuted. Thermodynamics is then discussed as a way of thinking that provides a sound basis for appreciating the importance of the God-given entropy for our life and thoughts.

We live in a rich and complicated universe. The physical universe is well described by an exact macroscopic physical theory known as thermodynamics.[1] The study of God and his relationship to the entire universe, including the physical, biological, personal, social, and spiritual worlds is the subject of theology.[2]

This article will describe the nature of thermodynamics at a level that allows reflection on its significance for theology. While an attempt will be made to minimize the use of abstract mathematics, it should be understood that the "language of science" is mathematics. Just as considerable effort needs to be expended to learn and comprehend the abstract language of theology, there is no easy street to thermodynamics. Failure to acknowledge this fact has often led to severe misunderstandings of the highly technical aspects of thermodynamics and unfortunate conflations of precise scientific concepts with vague colloquial notions. This type of error has especially appeared in connection with the thermodynamic quantity known as *entropy*.

The basic stance of this article is that theologians should understand thermodynamics well enough to avoid obvious errors, and perhaps even well enough to benefit from many useful paradigms developed during the history of the subject. Since many of the "Fathers of Thermodynamics" were devout Christians,[3] it is fitting for their followers to continue to bring the benefits of thermodynamic thinking to the process of rational religious reflection on the purpose and meaning of humanity.

Gary Patterson *was educated at Harvey Mudd College (BS, 1968) and Stanford University (PhD, 1972). He was a member of the Chemical Physics Department at AT&T Bell Laboratories from 1972–1984. He has been Professor of Chemical Physics at Carnegie Mellon University since 1984.*

In addition to teaching thermodynamics and other subjects in chemical physics, he teaches an academic course in Christianity and Science: A Multidisciplinary Approach. He has published more than one hundred articles in peer-reviewed journals, more than twenty chapters in technical books, and two books: Physical Chemistry of Macromolecules *and* A Prehistory of Polymer Science. *He is currently a historian of chemistry and physics.*

Outstanding treatments of thermodynamic issues and their relationships to religion have previously appeared. Two good examples are "The Uses and Abuses of Thermodynamics in Religion" by Erwin N. Hiebert[4] and "Pierre Duhem, Entropy, and Christian Faith" by Helge Kragh.[5] In the nineteenth century, many theologians worried about the consequences of the proposed "heat death" of the universe. The French physicist and historian, Duhem, was an expert in thermodynamics who practiced in the late nineteenth and early twentieth century. He was a contrarian in many of his thoughts, but he was a deep scientific thinker as well as a Roman Catholic believer. This article focuses on some current theological issues, especially the misuse of the concept of entropy, and the current understanding of classical, statistical, and nonequilibrium thermodynamics.

Energy

One of the landmarks of modern science was the development of the concept of energy.[6] The universe is conceptualized in terms of a set of objects known as particles. Typical particles include entities such as electrons, light (photons), and protons, but there are a very large number of different kinds of particles currently included in the conceptual world of physics.[7] Although the understanding of physical matter and electromagnetic energy is greatly helped by adopting a microscopic perspective, the science of thermodynamics is concerned with large quantities of matter and energy as it is normally observed with macroscopic instruments.[8] The restriction to systems of many particles is actually essential for understanding some of the most important principles of thermodynamics. Eventually a very formal version of thermodynamics was developed that emphasized its independence from the microscopic details of the physical system. This positivistic system was exemplified by the work of Mach, Ostwald, and Duhem.

A precise picture of the state of a physical system requires the introduction of an important physical concept: temperature. The thermodynamic temperature, T, is a measure of how the energy of the system is distributed among its microscopic states. Thermodynamic analysis consists of a set of relationships between measurable macroscopic properties.[9] The thermodynamic energy, U, is the *average* value of the system energy. If the temperature is fixed by contact with a heat bath at temperature T, the instantaneous energy fluctuates in a stationary way around the value of U. The existence of fluctuations is the key to understanding the actual properties of equilibrium physical systems.[10]

The thermodynamic energy of a single component system can be expressed as a mathematical function of T; volume, V; and the mass of the system, m. Changes in U can then be expressed in terms of changes in T, V, and m. If the system is isolated (no exchanges of energy or mass with the outside world) and fixed in volume, the energy of the system must remain constant, since no energy may enter or leave the system. One way to change the energy of the system is to change the temperature by placing the system in thermal contact with a heat bath at a different temperature. The amount of heat, Q, which flows into or out of the system, is then equal to the change in thermodynamic energy, ΔU.

Another way to change the thermodynamic energy is to change the volume of the system under conditions where no heat can flow into or out of the system. The energy change under these conditions is called work, W. In a more general circumstance, the total energy change can be expressed as: $\Delta U = Q + W$. This expression is often called the *First Law of Thermodynamics*.[11] However, the full expression of the First Law includes every way that the thermodynamic energy can change, and it concludes that if no matter can enter or leave the system, no heat or light can enter or leave the system, and no work is done on or by the system, then the value of U must remain the same. Isolated physical systems are characterized by conservation of energy. The absolute principle of energy conservation is associated with James Prescott Joule.[12]

Thermodynamics is inherently relational. This way of thinking has also been introduced into discussions of theology.[13] Rather than focusing mostly on the properties of isolated concepts, this new form of Christian theology emphasizes the relationships between God, humans, and their physical and spiritual worlds. Keeping track of the relationships between entities in the human and spiritual world helps to clarify the changes that are seen. While some scientists insist that changes in the spiritual world can have no influence in the physical world, it is not thermodynamics that drives them to this conclusion. Thermodynamics warns us to be constantly on the lookout for correlated changes and the mechanisms that are associated with these changes. Careful observation is just as valuable in theology as it is in thermodynamics.

Entropy

If the temperature were at absolute zero, T=0 K, where K is the absolute unit of temperature named after Lord Kelvin, then an equilibrium system would adopt a state in which the microscopic particles were in the lowest possible energy level. The notion that in this lowest energy state, the kinetic energy is still above zero, is one of the great insights of modern statistical thermodynamics.[14] When the temperature is positive, the system can sample the available microscopic energy states, and an equilibrium state includes a distribution of microscopic states. The system is constantly fluctuating in instantaneous energy, either by interaction with an external heat bath or by local fluctuations in temperature within the system.

The dynamic nature of equilibrium requires an additional concept in order to describe the thermodynamic state of the system. It is found that the meaning of temperature is best expressed in terms of the partial derivative of the energy with respect to a variable called entropy, S, at constant volume: $T = (\partial U / \partial S)_v$. At very low temperatures, the energy of the system changes very slowly, even though the entropy changes enormously. What is this new variable that is so important to an understanding of thermodynamic equilibrium and temperature?

The *Third Law of Thermodynamics* states that for a perfect monatomic crystal, the entropy, S, approaches 0 as T approaches 0.[15] This state of zero S corresponds to a system in its unique ground state energy level. In order for the temperature to rise, there must be slightly higher energy states of the system that can be populated by some mechanism, such as the absorption of heat, light, or magnetic energy. For the same change in U, the temperature of the new state of the system will be determined by how many microscopic states of the system are accessible under the conditions of increased internal energy, U. A system with very many microscopic states is much more "stable" physically than one with only a few states. The system at absolute zero is often described as fully ordered. A system at a higher value of U will have a value of S that is determined by the extent to which the distribution of microscopic energy states achieves a maximal breadth, consistent with the total energy and equilibrium. This state is often described as "disordered," but from a thermodynamic perspective states of high S are more stable.

The ordinary English usage of the word "disorder" has negative moral connotations, but the thermodynamic usage has none of these negative tones. When theologians use "scientific" terms, but imply their colloquial meanings, great mischief results. An example of this kind of confusion is found in the book *The Jesus I Never Knew* by Philip Yancey: "Death, decay, entropy, and destruction are the true suspensions of God's laws."[16] There is nothing spiritually positive about absolute zero, even though this may imply a perfectly ordered state. The world God actually created is characterized by temperatures higher than zero, even in the deep regions of space!

Changes in the entropy can also be related to changes in other thermodynamic variables. If the system is closed to mass flow, and the volume is fixed, the entropy change for a heat flow Q at temperature T is $\Delta S = Q/T$. One of the insights that flow from this relationship is that under high temperature conditions, the entropy changes only slightly for the same heat flow. The entropy will also increase as the volume increases. If the internal energy U is held constant, a system will only change spontaneously if the entropy increases. This is an insight known as the *Second Law of Thermodynamics*.[17] Like the First Law, there are no known violations. A system of maximal entropy is already at equilibrium. The equilibrium state is the most probable state for a system and hence has the highest entropy, consistent with the temperature, volume, and mass. While fluctuations do occur, they are part of a stationary pattern of changes and no change in the thermodynamic entropy occurs. The thermodynamic entropy is determined by the *long time average* of the system, not an instantaneous state of the system.

When the value of S does change, the details of the distribution of fluctuations also change. This is the key insight that leads to the physical phenomenon of *"irreversibility."* The two states of the system involve different fluctuations around a different average, not just a change in S. Recognition of this fact eliminates many supposed "paradoxes" with regard to the entropy.

The importance of the Second Law was elegantly expressed by Sir Arthur Eddington in *The Nature of the Physical World:*

> The law that entropy always increases holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations—then so much the worse for Maxwell's equations. If it is found to be contradicted by observation—well, these experiments do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.[18]

What does all this discussion have to do with theology? Entropy is one of the most important concepts in the understanding of the normal behavior of our universe. Left to themselves, physical systems at constant energy change in such a way as to achieve the most probable dynamic state of the system, and hence the maximum entropy. Suggestions by theologians that entropy is "evil" only serve to marginalize them in the public square.

The most prominent proponent of the view that entropy is evil was Henry M. Morris of the Institute for Creation Research. A typical expression of his views is contained in the chapter entitled "Thermodynamics and Biblical Theology" in the Creation Research Society publication *Thermodynamics and the Development of Order*.[19] Morris attempts to paint a picture of the earth "in the beginning" that does not have entropy. This is a serious misunderstanding of the physical world. If the system is not at absolute zero (and is not a monatomic, single crystal), it must have a positive entropy. The textual assertion in Genesis 1 that the earth was "good" is not equivalent to a claim that the entropy is zero. Morris is also concerned with the consequences of the Fall. He proposed that after the Fall, entropy increased and sin proliferated. I have been in the room at the Institute for Creation Research devoted to imprecating entropy. It demonstrates a profound misunderstanding of thermodynamics. While the detailed interpretation of Genesis 3 and the physical consequences of the Fall are beyond the scope of this article, there is no physical evidence that chemistry and physics have changed in the last 13.7 billion years.

Theological Misconstrual of Entropy

One of the least attractive assertions of some evangelical theologians is that the universe must be described by "fallen physics" and that "in the beginning" matter behaved in a qualitatively different way. One of the most explicit statements of this perspective is given by Greg Boyd in *Satan and the Problem of Evil:*

> Creation does not have to operate exactly the way it does. Chemicals do not *have* to interact with each other the way they do. Animals, weather patterns, geological plates, genetic codes, viruses and body cells do not *have* to behave the way they do. There is no known reason for why things *have* to die. Indeed, from a strictly scientific perspective there is no reason why there *has* to be a second law of thermodynamics. It is conceivable that the physical cosmos could have tended towards increasing complexity and design rather than degenerating towards randomness. Thus it is reasonable to ask why it does not. If it is all God's handiwork, should it not operate differently? Science has nothing to say about this question.[20]

This notion has no physical basis (there are no observations of "spiritual physics") and no compelling theological basis, but it does have a visible community of discourse. The cognitive dissonance between the proclamations of the pulpit and the observations of physical reality creates a crisis for thinking Christians. Are theologians and Bible scholars free to assert such claims about the physical world in the absence of either observable evidence or specific scripture?

Is there a theological lesson to be learned from this thermodynamic analysis? Perhaps the lesson is that the Creator of the universe is more subtle than we ever imagined. The notion of a "blind watchmaker" is grotesquely crude when compared to the Creator of our universe. We have only begun to appreciate the complexity and beauty underlying our physical universe. John Polkinghorne has discussed the suppleness of our world, and its suitableness for a life of soul making.[21]

There have been persistent suggestions that the chemistry that is observed today is substantially different from the "ideal" chemistry that existed before the Fall. A proponent of the change in the principles of chemistry associated with the Fall of humans is Gilbert L. Wedekind in his book *Spiritual Entropy*.[22] However, it is not clear what this spiritual chemistry would be like. Would chemical reactions be forbidden, since the chemistry of decay seems to exercise the souls of many of these theologians? Would equilibrium be forbidden, since the entropy increases as the most probable state is achieved? The whole notion of a "different" chemistry is without observational foundation and proceeds from a largely ignorant stance toward the present state of chemistry. The geology of the earth has been largely explained in terms of processes that are observed in the present or reasonably extrapolated from current phenomena. To suggest on theological grounds that any science would be different, without any physical evidence to support such a conjecture, is not likely to convince anyone and will certainly marginalize the author of such thoughts. Unless there is either clearly demonstrable physical evidence or compelling theoretical arguments, no scientist should welcome unwarranted theological conjecture about science.

Thermodynamics and Life

The area of science that seems to create the largest rebellion against the principles of thermodynamics is the study of life. Living systems are definitely not at equilibrium. Living organisms are slowly changing, highly nonequilibrium systems. The science of nonequilibrium thermodynamics is also a highly developed paradigm with a substantial empirical base and coherent key concepts.[23] The notion of fluctuations plays a central role. Biological systems are explicitly open and require a constant source of energy to remain viable. The chemical reactions of life are highly coupled and many feedback mechanisms are active.

There is apparently a theological notion that life ought to be "easy." In an "ideal" (pre-Fall) world, all creatures great and small would live in ease and harmony, and no perturbations would disturb their persistent life. The thermodynamic perspective is that all life is fragile, and that the miracle is not that death occurs, but that life ever occurred. It is so complicated and so far from equilibrium that only the most unlikely events or the direct intervention of outside agents could produce it. The notion that left to themselves (in isolation) nonequilibrium systems tend toward equilibrium sounds like a truism, but for some theologians, it is the smoking gun of the Fall, just as the microwave background radiation is the smoking gun of the Big Bang.[24]

The current paradigm for the Big Bang proposes an ancient history that is even more out of equilibrium than we are today. The standard model of Earth science suggests an initial system unfriendly to the existence of life. When the earth changed enough, in response to both external and internal changes, water condensed and life appeared. There is no "evidence" of an idyllic period in the truly ancient past. The magnetic field of the earth reverses on a predictable and observable timescale. Is this the result of the "Fall" when it has been going on for millions of years in response to thermodynamic forces in the earth? Some theologians then resort to a separate Fall for the earth, perhaps brought on by the Fall of Satan.[25] But there is neither physical nor scriptural evidence for this. Suggesting that thermodynamics is "fallen" in our times just seems incoherent. What better system is being proposed when current thermodynamics has no known exceptions? Is there some revelation of a new chemistry that other Christians have missed?

One of the most important facts about living systems is that they are entropy generators. The processing of food is an irreversible process that produces entropy. The transport of chemicals into and out of cells is an irreversible process that produces entropy. Any process that involves viscosity, diffusion, or resistance leads to the production of entropy. Life is an inherently nonequilibrium, irreversible process!

In order for life to persist at all, the organism must have both conservative and evolutionary processes available. When the environment is relatively stable, the organism needs to count on the faithfulness of biological chemistry to continue its existence. When conditions change, either the individual organism must have a mechanism to adapt, or the group of organisms must have enough biological diversity to manifest a successful pattern in some specific members of the group. Otherwise, the species will become extinct. It is not at all clear how changing the principles of thermodynamics will solve the problem of finite plasticity in every actual biological organism. It is sometimes asserted that in the distant past, animals did not die. There is no evidence for this assertion; it is just an unsupported theological deduction. It is more important to recognize that we are made of "dust." God did not create a "magical" world in which physics and chemistry were "different," but he did create one that could support life, even under difficult circumstances. Perhaps it is time to accept the fragility of human, or any biological, existence. God has chosen our actual world as the place of our sojourn. He will never leave us nor forsake us.

Strangely, some theologians invoke the second law of thermodynamics as an argument against the observed history of life on earth. They claim that the observed increase in "order" violates thermodynamics. Thermodynamics applies to equilibrium systems. Living systems are far from equilibrium and are explicitly open with regard to mass and energy transfer. The trajectory of a physical system through the nonequilibrium world can be truly bizarre, and many counterintuitive results are observed.

But good science starts with good observations. Denying the observations or trying to explain them away is not the way forward. A simple example is the crystallization of a liquid far below the equilibrium melting temperature. It is relatively easy to prepare a liquid in the metastable state well below the melting temperature. When the right fluctuation occurs, the system will start to crystallize (the waiting time can be from seconds to years). As the crystals grow, they release the heat of crystallization and the system warms up. If the liquid is completely isolated during this process, the energy stays the same. The spatial "order" of the crystalline state is higher than the liquid state, but the process proceeds until either the whole sample is crystalline or the temperature reaches the equilibrium melting temperature, at which point the sample could be a mixture of liquid and crystalline regions. The Second Law assures us that since the isolated process did occur, the entropy change must be greater than or equal to 0. But the sample is now a crystal! It all makes good thermodynamic sense. Thermodynamics never contradicts actual observations.

Thermodynamics as Analogy

Since thermodynamics is such a successful paradigm, perhaps it can provide a guide to theology and point to a richer world of discourse. Classical thermodynamics focused on those aspects of macroscopic physical reality that could be observed and measured. An actual body of data that can be appealed to by any member of the community aids public discussion. I do believe that there is a body of observations that provide one of the aspects of theological reflection. The human stories of Jesus and the earliest Christians provide a potentially useful body of narrative episodes. The lives of Christians living under different political and economic conditions help us to discern those universal aspects of spiritual life that call for theological reflection. This knowledge can be subject to all the rigorous methods of the historical sciences, but without grist, the mill produces no flour.

The constructive task is to induce relationships that emerge from these narratives. Are there effective ways of living that have characterized Christian communities throughout the last two millennia? This body of theological reflection could perhaps produce what might be called a phenomenological theory of Christianity. Unless the more speculative or systematic theology can explain the actual history of Christianity, it is just as useless as a scientific theory that contradicts the known facts.

Classical thermodynamics is still a very useful subject, but eventually scientists became ever more eager to "explain" some of the more startling observations. Early speculations tried to use known paradigms and extend them to the new observations. Ultimately, this approach failed. An explicitly microscopic approach was required. The behavior of the microscopic world was then studied, and it was discovered that on short length scales and for light particles, the macroscopic laws were a poor predictor of what actually happens on a microscopic level.

Some have attempted to explain the phenomenological observations of Christianity in terms of a richer ontology than that of physical science. Is there any evidence that entities such as angels and demons actually exist? Narrative episodes in the Gospels suggest that they do. Does their existence provide an effective explanation for certain known phenomena? The writings of Paul and James suggest that it does. Statistical thermodynamics suggests that a consilience can be obtained if continued effort is expended in full view of both the macroscopic and microscopic worlds. The fictive chemical atoms of John Dalton (1766–1844) became the standard reality of Lord Rutherford (1871–1937). Is there a Lord Rutherford for Christianity? It is certainly worth the search. Christianity is much more than a set of propositions in a book; it is a Way of life that is visible to other humans. Many Christian phenomena can only be explained in terms of the "spiritual" dimension of human life. Just as the microscopic perspective enriched our understanding of matter, so the spiritual worldview is essential for our understanding of humanity.

Too many theologians are obsessed with "perfection." One of the biblical insights about our "physical world" is that it is not a sphere of perfection (Rom. 8:22). It is a place of good (Job 5:10); rain is good. In a physical system, too little rain causes a drought; too much rain produces a flood. God used both of these calamities to deal with humans during history. Isaiah described God as one who created both blessings and "ra," calamity (Isa. 44:7). The clockwork perfection preferred by some theologians was not "chosen" by God as the mode of our existence. Our actual existence is "messy." But then, love is messy. And God is love (1 John 4:8). Thermodynamics can deal with macroscopic physical reality quite well, even though the microscopic reality is truly bizarre. It is incumbent on theology to deal as well with the actual reality of human existence and its relationship to God.

The essence of entropy is the multitude of possibilities that God has given us in this world. In a world of no entropy, there are no possibilities, except for one. In the conceptual world of neo-Platonism, the One was unique and fully separated from humanity. In the conceptual world of the Bible, God is intimately related to humanity, through prayer and through Jesus. There are many possibilities in this universe of interaction. Changes in one aspect of spiritual reality lead to changes in other aspects. This sounds much more like thermodynamics than like entropy-less sterility at T=0. The God of the Bible is full of warmth and seeks to interact with living thermodynamic systems known as humans. Fluctuations constantly occur, and can shock or thrill us, but the promise of God is that the macroscopic end is predictable, even though the steps along the way may be on a more chaotic path. Theological discussions will be more accurate and insightful if they understand and take into account the God-given entropy of this world. ✶

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Notes

[1]Thermodynamics is an essential part of the educational experience of all scientists and engineers. I teach the subject to physicists, chemists, biologists, chemical engineers, civil engineers, mechanical engineers, and materials scientists.

[2]Two good examples of this broad paradigm for theology are *The Science of God* by Alister E. McGrath (Grand Rapids, MI: Eerdmans, 2004) and *Science and the Study of God* by Alan G. Padgett (Grand Rapids, MI: Eerdmans, 2003).

[3]Two prime examples are James Clerk Maxwell (1831–1879) and Lord Kelvin (1824–1907).

[4]Erwin N. Hiebert, "The Uses and Abuses of Thermodynamics in Religion," *Daedalus* 95 (1966): 1046–80.

[5]Helge Kragh, "Pierre Duhem, Entropy, and Christian Faith," *Physics in Perspective* 10 (2008): 379–95.

[6]The history of the development of the concept of energy is well told in *The Science of Energy: A Cultural History of Energy Physics in Victorian Britain* by Crosbie Smith (Chicago, IL: University of Chicago Press, 1999).

[7]A readable treatise on elementary particles by John Polkinghorne is *The Particle Play* (New York: W. H. Freeman, 1979).

[8]Macroscopic is often demarcated by the limit of visible resolution, 0.5 microns. Macroscopic also implies a very large number of particles, of the order of Avogadro's number: 6.02×10^{23}.

[9]A classic modern standard text for the most general development of thermodynamics is *Thermodynamics: An Introduction to the Physical Theories of Equilibrium Thermostatics and*

Irreversible Thermodynamics by Herbert Callen (New York: John Wiley & Sons, 1960).

[10] Albert Einstein was one of the major scientific figures who developed the paradigm of fluctuations and their relationship to macroscopic measureable properties.

[11] William Thomson (Lord Kelvin) is generally credited with formulating the First Law of Thermodynamics in its present form.

[12] James Prescott Joule (1818–1889) was another highly devout English natural philosopher.

[13] A good collection of essays on this subject is *The Trinity and an Entangled World: Relationality in Physical Science and Theology,* edited by John Polkinghorne (Grand Rapids, MI: Eerdmans, 2010).

[14] Nineteenth century discussions of absolute zero often defined it as the temperature where all motion ceased. The advent of quantum mechanics led to the realization that even at T=0, the zero point kinetic energy does not vanish.

[15] The formulation of the Third Law of Thermodynamics is usually attributed to Walther Nernst (1864–1941) and is often called the Nernst Heat Theorem. The statement given above is due to Gilbert N. Lewis and Merle Randall in their classic book, *Thermodynamics and the Free Energy of Chemical Substances* (New York: McGraw-Hill Book Co., 1923).

[16] Philip Yancey, *The Jesus I Never Knew* (Grand Rapids, MI: Zondervan, 1995), 182.

[17] The formulation of the Second Law of Thermodynamics is generally attributed to Rudolf Clausius (1822–1888).

[18] Sir Arthur Eddington, *The Nature of the Physical World* (Ann Arbor, MI: University of Michigan Press, 1928), 73.

[19] Emmet L. Williams, *Thermodynamics and the Development of Order* (San Diego, CA: Creation Research Society Books, 1981).

[20] Gregory Boyd, *Satan and the Problem of Evil: Constructing a Trinitarian Warfare* (Downers Grove, IL: InterVarsity Press, 2001).

[21] A recent book by John Polkinghorne, *Science and Religion in Quest of Truth* (New Haven, CT: Yale University Press, 2011), stresses the beauty and subtlety of the physical world.

[22] Gilbert L. Wedekind, *Spiritual Entropy* (Fairfax, VA: Xulon Press, 2003).

[23] Ilya Prigogine (1917–2003) received the Nobel Prize in chemistry for his development of nonequilibrium thermodynamics and its application to living systems.

[24] Sean Carroll presents the evidence for the Big Bang theory in a pleasing and transparent way in his book *From Eternity to Here* (New York: Dutton, 2010).

[25] Greg Boyd is especially clear in his advocacy of this position.

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There are close parallels between the mathematical expressions for the thermodynamic entropy, usually denoted by S, of a physical system in the statistical thermodynamics established by Ludwig Boltzmann and J. Willard Gibbs in the 1870s, and the information-theoretic entropy, usually expressed as H, of Claude Shannon and Ralph Hartley developed in the 1940s. Shannon commented on the similarity upon publicizing information theory in A Mathematical Theory of Communication.