2 THE UNIVERSAL LAWS OF PHYSICS

Inflated Ontologies?

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Faith in Law

Science provides humanity with a special kind of knowledge—a truism in which one may place considerable confidence. The philosophy of science, after all, prescribes a rigorous protocol for the testing of its propositions that no other field of inquiry can match. Popper, for example, prescribed that each scientific law or proposition should be subjected to vigorous efforts to *disprove* its validity.[3] Although Popper's falsificationism is rarely practiced by those who actually formulate a particular constraint, the impetus for testing nonetheless remains in widespread practice.

While rules and laws abound in science, a few propositions stand above the rest by virtue of their universality. These include the force laws of physics and the two phenomenological laws of thermodynamics (the conservation of energy and the increase of entropy). Some physicists would limit the universals to the four laws of force (nuclear strong and weak, electromagnetic, and gravitational), believing that the thermodynamics of energy and matter is derivative of the forces among elementary particles.

Because violations of the force laws are perceived as virtually nonexistent, these universal laws take on in the minds of some leading physicists the status of metaphysical absolutes. Witness Nobel

Laureates Murray Gell-Mann, Stephen Weinberg, and David Gross, who, when asked whether causality might exist outside the aegis of the four laws, declared that all causality points downward and that there is nothing else "down there" but the laws of physics.[4] This attitude of *nothing else* leads many, both in and out of physics, to attach to the universal laws the deepest ontology possible. Steven Hawking and Carl Sagan, for example, made the theological statement in their assertion that there simply is "nothing left for a Creator to do,"[5] and rare indeed is anyone who has not encountered friends or colleagues who eschew any and all religious belief in favor of ultimate faith in rationality and the laws of science.

The purpose of this chapter is to take seriously Popper's spirit of falsification and to examine whether universal laws truly deserve the status of deepest ontologies. The reader should rest assured, however, that no one is calling into question the inviolability of the universal laws under the framework within which they were formulated, nor seeking to gainsay the formidable benefits those laws have imparted to society. Rather, at issue here is whether the laws are so absolute and universal that all other forms of causality and modes of explanation are ultimately derivable from them.

Inquiry will begin with an examination of the received perceptions about the origins of the laws. Scrutiny will then shift to the completeness of the laws in describing natural phenomena. In particular, it will be asked whether the laws are sufficient to *determine* all natural phenomena. Should causal closure be incomplete? What are the ramifications of an open universe upon the status of parallel, nonscientific beliefs? That is, how can the status of the universal laws best be amended to reassess the stature of science vis-à-vis other modes of knowledge?

Obscure History

Historically seen, laws that use the notion of *force* begin with Isaac Newton's *Principia* of 1687. But ask almost anyone familiar with at least freshman physics to state Newton's second law of motion and the reply probably will be something like, "The force exerted on a body is equal to the product of its mass times its acceleration," or algebraically, $F = ma$, where F is the force, m the mass of the body, and a its acceleration. The problem with this rendition, it may surprise many to learn, is that Newton never formulated his second law in an algebraic fashion.[6] Rather, he found that impressed force is proportional to the change in momentum, or F is proportional to delta p, where *p* is the momentum of the body ($p = mv$, v being the body's velocity). It was not by chance that Newton applied his formula using *geometric proportions* rather than algebra: *Proportional* does not mean *equal* or *equivalent*. The law, therefore, in its most general form reads F/p = c = constant, showing force and momentum as heterogeneous entities. (The importance of this distinction will reappear in section "The Natures of Contingencies" when the *heterogeneity* of natural entities will be discussed.)

The familiar algebraic formula was rather the work of Leonhard Euler, based on Leibnizian principles such as the presupposed equivalence of cause and effect.[7] To the contemporary inquirer, the chief difference between Newton's and Euler's principles is that the latter's formula is continuous and symmetrical with respect to time (i.e., it is *reversible*). The algebraic logic of the Euler formula and the three successor force laws is strictly Parmenidean. The Parmenidean (Leibnizian–Eulerian) world is closed to any other form of causality. Everything that possibly can happen in such a system is imbedded within the description of its state at the current instant. By contrast, the original Newtonian quantification remains open and *irreversible,* owing to Newton's formulation of the second law as a geometric proportionality (force over change of motion = constant), wherein the variables represent heterogeneous entities.

The irreversibility inherent in Newton's description turns out to be noteworthy and most intriguing. About a century after the misnamed *Newtonian* way became the common approach to all physical problems, Pierre-Simon Laplace apotheosized the closed and conservative nature of Euler's mathematics by way of analogy to a *divining angel* who knew the positions and momenta of every atom in the universe, and therefore, could forecast the entire future and hindcast every past event in the universe. It was only some fifteen years after Laplace that Sadi Carnot made the empirical observation that the macroscopic world was decidedly *irreversible.*[8] Carnot's results posed a major challenge to the Parmenidean version of natural events: If all motion at microscopic scales was governed by reversible laws, how could it be possible for the macroscopic ensemble of such motions to exhibit any irreversibility whatsoever?

Carnot's challenge went unanswered for about a half century, as theoreticians scrambled to redeem the Parmenidean worldview. Finally, Ludwig von Boltzmann[9] and Josiah Willard Gibbs[10] independently described a simplistic system behaving under several very restrictive and not-so-realistic set of assumptions, wherein reversibility at the microscale gave rise to irreversibility at macro-dimensions. Thus was born the discipline of statistical mechanics. Elated by their conviction that a bridge had been forged to resolve the conundrum posed by thermodynamic empiricism, physicists rejoiced that Parmenides had been rescued, so that further discussion of the enigma was abruptly terminated and did not reappear for well over a hundred years. (In fairness to the physicists of that era, it should be noted that Karl Popper had not yet articulated his doctrine of falsification.)

While the search to redeem the notion of a closed world was going on, some major empirical strides were interpreted under the same Parmenidean framework in fields such as electricity, magnetism, and particle physics to round out the full complement of universal physical laws. No one should deny that this was a heady and ebullient time, as science moved boldly forward in its equilibrium guise. Nor should anyone question that these advances worked admirably and precisely wherever they were applicable and contributed to substantial material benefits for humankind.

There were some bumps along the way, however. Beyond Carnot's irreversibility lay the discovery that the laws of classical mechanics did not seem to hold whenever relative motions of systems were exceedingly great.[11] The universality of classical mechanics was amended in the light of what appears to be a relativistic universe. Furthermore, the validity of the continuum assumption became questionable in the light of what appeared to be discrete behaviors of matter and energy at very small scales and infinitesimal times—the discovery of which gave rise to the discipline of quantum physics.[12]

It is possible to view the disciplines of thermodynamics, relativity, and quantum physics as *exceptional* sciences in the sense that they arose because of the inadequacy of classical descriptions. Dellian cites the irreversible nature of the original Newtonian formulation as reason to believe that, had Newton's description not been abandoned in favor of the Eulerian–Leibnizian formulation, the exceptional sciences might not have become necessary. Dellian[13] sketches avenues via which relativity and quantum phenomena might have been incorporated as natural aspects of a unified theory based on Newton's geometrical quantitative tool of "first and last ratios."

History then suggests limits to the Parmenidean vision. But where the laws do work, they do so unerringly and with uncanny accuracy. Such efficacy is sufficient for some, as with Gell-Mann, Weinberg, and Gross, to hold fast to the belief that the universal laws of force are sufficient to determine all that transpires in the world. Such conviction, however, is usually held in abstraction of how these laws are actually used in practice.

Universal Laws and Real Problems

Because the universal laws were formulated to be as general as possible, they can *never* be applied without having to identify at least some specifics of the problem at hand.[14] Articulating those particular conditions constitutes what is known as the *boundary value problem.* A universal law must be stated in terms of some very general quantitative variable, such as position, momentum, mass, or temperature, which it then regulates over a specified domain of space and duration in time. The adjective *boundary* here means that the values of those variables (or some function thereof) must be specified by the investigator for the start of the interval and/or at the edges of the spatial domain. For example, one might wish to calculate the trajectory of a cannonball. The appropriate law would be Newton's second law of motion in the presence of gravity. The specific trajectory and impact point cannot be calculated, however, until one stipulates at least the location of the cannon, the muzzle velocity, and the angle of the cannon with respect to the earth. These particular specifications comprise the necessary boundary constraints.

It is usually understood that the investigator has a free rein in formulating the boundary conditions. It is usually not emphasized, however, that the forms of those boundary conditions are, in general, completely arbitrary. The necessity for absolute freedom follows as a logical consequence of the universality of the law: If it were possible to state boundary conditions to which the law cannot conform, then the law would no longer be universal.[15] Usually, the boundary statement is clear and determinate, like with the example of the cannonball trajectory. Nothing, however, prohibits less regular boundary contingencies that can be characterized, for example, as *blind chance.*[16]

In general, one is free to choose boundary statements that are wholly contingent, and those contingencies are what *drive* the eventual solution.

Those who see the universal laws as ordering a determinate world implicitly make the assumption that boundary conditions can always be predicated in a regular and determinate fashion.[17] The investigator, however, is free to choose any form he/she desires for a boundary statement.[18]

Juxtaposition of the arbitrariness of the boundary statement against the uniformity and regularity of the operant laws naturally poses the question whether anything can be truly indeterminate in a world where laws are inviolate. But is this issue as dichotomous as it first appears? Resolution of this tension requires one to consider the full range of events that may transpire in terms of their varying degrees of arbitrariness.

The Natures of Contingencies

It has already been mentioned how blind chance is a legitimate form of boundary condition. Now most realize that blind chance can be treated in the aggregate as regular phenomena using statistics and probability theory. What usually goes unmentioned in such treatment is that the events must be simple, directionless, indistinguishable, and repeatable. Whenever matters do not conform to all of these assumptions, conventional mathematical tools begin to break down. In particular, most events in the biological world are complex and distinguishable, which is to say the world of biology is decidedly *heterogeneous.*

The ramifications of dealing with a heterogeneous world are profound. Bateson[19] and Elsasser,[20] for example, both note how the laws of physics are all formulated in terms of homogeneous variables; that is, they apply only to indistinguishable tokens like charge, mass, or energy. Elsasser further cites results by Whitehead and Russell[21] to the effect that the logic behind the symmetrical force laws is equivalent to operations upon homogeneous sets (collections of indistinguishable tokens). Once the collection of tokens becomes heterogeneous, the logic that undergirds the universal laws no longer pertains.

The requisite homogeneity of the variables in the fundamental laws implies that they are Platonic essentials. That is, all the particulars of any real situation must be abstracted from consideration in order for the laws to prevail. In using Newton's laws to calculate the orbit of a manned satellite, for example, all of the innumerable complex features of an astronaut must be ignored, save for his/her body mass. All real situations fall short of the homogeneous ideal covered by the law. It was in this sense that Nancy Cartwright[22] characterized the fundamental laws as "lies" about reality, because no real situation can fully satisfy the *ceteris paribus* assumption inherent in those laws.

Determinate lawfulness becomes even more precarious when it is noted that Elsasser earlier had demonstrated that the preponderance of events in a sufficiently heterogeneous world will be perfectly unique (unrepeatable).[23] This surprising statement owes to the combinatoric nature of heterogeneity. If, for example, there exists in proximity to each other n different types of events, the possible number of compound (combined) events increases roughly as n-factorial ($n!$), where

$$n! = n \times (n-2) \times (n-2) \times (n-3) \times \ldots \times 3 \times 2 \times 1.$$

Furthermore, n! grows rapidly as n increases, so that it becomes easy to demonstrate that whenever eighty or more distinguishable events are at play (a small number in comparison to the distinguishable organisms extant in even simple ecosystems), the number of possible compound events exceeds the maximum number of simple events that could possibly have occurred over the entire known universe since its inception in the big bang. Unless some agency is available to foster repetition of such an event, it will not arbitrarily reoccur over an interval that exceeds a thousand times the age of the universe! It is appropriate to call such unique compound events *radical chance,* and they defy conventional statistical analysis by virtue of their uniqueness.

But of course, the world is not a hopeless confusion of unique events. Even in the manifoldly heterogeneous world, some combinations persist with almost unfailing regularity, while others reoccur most of the time. Perplexed by reservations similar to those expressed by Cartwright, Karl Popper asserted that determinate laws pertain only "in a vacuum." In all real situations the laws are always subject to contingent "interferences."[24] For example, the fall of an apple from a tree is governed not only by gravity, but also by the wind, the biochemical status of the stem, and so on. Popper suggested that the concept of determinant law be replaced by the notion of "propensity"—that most of the time, when condition A occurs, B will be the outcome; but, on occasion, C or D might result. For example, during the early twentieth century over nine out of ten young immigrants to the United States married someone from their own ethnic group, although a few would venture to take native-born spouses. One notes in passing is that the actors in propensities are usually tokens that exhibit intrinsic *directions.*

Looser still are situations where physical constraints impart preference to certain outcomes above what would occur under blind chance. These partialities, such as might occur with loaded dice, are termed *conditional probabilities,* and their accompanying directionalities are correspondingly weaker than those of propensities.

One thus comes to see that the world is not a simple bifurcation into Monod's "chance and necessity," but rather contingencies come in all degrees. They span a spectrum that ranges from radical chance to conventional blind chance to conditional chance to propensities and finally grades into determinism. Not even intentionality, human or divine, can be excluded from the mix.[25] But what, if not the known universal laws, accounts for the appearance of ordered phenomena and for the directionalities that one commonly observes in a heterogeneous nature?

Order Withal

To begin, it should be made clear that no one is denying a necessary role for universal laws in the creation of order and regularity. But active *creation* of order is not an ability of the known reversible laws. Therefore, to understand what activity is at the leading edge of evolving ordered systems, it is necessary to consider configurations of processes known as *mutualisms.*[26]

Simple mutualisms appeared first in chemistry under the rubric of *autocatalysis.*[27] One may regard autocatalysis as a cycle of processes in which each member accelerates its downstream neighbor. If, then, in any triad of processes, A generates or facilitates another process, B, and B catalyzes C, which in its turn augments A, then the activity of A indirectly promotes itself. The same goes, of course, for B and C. In general, A, B, and C can be objects, processes, or events, and the linkages can be deterministic (mechanical) or any form of contingency.[28]

In chemistry, where the actors are usually few and simple, autocatalysis can be depicted in a mechanistic fashion. In the larger living realm, however, life is replete with heterogeneity and contingency, and the character of autocatalysis can take on a decidedly nonmechanical nature.[29] Most importantly, autocatalysis exerts selection pressure upon all of its participating elements. For example, if some contingent change should occur in the behavior of compartment B that either advances the catalysis of B on C or makes B more sensitive to catalysis by A, then in either case that contingency will culminate in greater reward for B. The same consideration applies to contingencies in C and A, so that an arbitrary contingency that facilitates any component process will be rewarded. By similar reasoning, contingencies that interfere with facilitation anywhere will be decremented.

One notes that autocatalysis always acts in a preferred sense, and that *direction* is always toward greater autocatalytic activity. A secondary but equally important observation is that autocatalytic dynamics are self-preserving and self-stabilizing. Even before the advent of specialized materials to store memories (such as RNA/DNA), autocatalytic ensembles possessed an inherent tendency to persist.

Autocatalytic selection, when acting upon sources of material, information, or energy required for any component process, contributes to another necessary attribute of living systems. In particular, any contingency in a compartment that augments its ability to acquire resources and perform better will be rewarded. Once again, that scenario applies to all members of the autocatalytic cycle, making the aggregate behavior resemble that of *centripetality,* or the tendency of autocatalysis to aggregate ever more resources into its own orbit. Centripetality is evident, for example, in coral reef communities, which sequester concentrations of nutrient resources well in excess of those present in the surrounding oceanic desert.

This ratcheting up of activity via centripetality is commonly referred to as *growth,* and growth played a major role in Darwin's original description of evolution. Unfortunately, the growth side of the evolutionary dialectic has since almost disappeared from the conventional neo-Darwinian paradigm. Mutualism is rarely mentioned in contemporary discussions of evolution, which focus instead upon competition and physical impacts as the key players in what is now deemed *natural selection.* This subordination of mutuality represents a major inversion of reality, because it is autocatalytic centripetality that makes competition possible. Whenever multiple autocatalytic centers arise within the same limited pool of resources, *competition* among them is inevitable. That is, competition is strictly derivative of centripetality, which owes its existence to mutualities at the next level down. For example, a fox could not compete with a coyote, were there not exquisite mutualities at work within the bodies of each.

An Open World

The universe thus described differs markedly from the reductionistic picture painted by Gell-Mann et al. To physicalists, all causation is described with relations among homogeneous entities (A = B = A); it issues from the fundamental universal laws and propagates only *up* the hierarchy of scales. By contrast, in a heterogeneous world, the universal laws continue to constrain possibilities, but by virtue of their necessary generality and their reversibility, they remain insufficient to generate and *determine* the actual course of events. The focus shifts instead to mutualities among contingent events that arise arbitrarily, and once engaged they tend to accrue select new contingencies that favor the persistence and performance of the incipient ensemble. In this manner autocatalytic configurations act as *proximate laws* that *determine* their own constituents. The natures of the emerging proximate laws were never specified by the foundational universal laws, but rather by historical contingencies. This world is ever open to new possibilities and new regularities.

Whereas the essentially unchanging world of the Enlightenment à la Leibniz resembled a universal clockwork,[30] the emerging process scenario behaves more like a dialectic. The new dynamic actually resembles earlier conceptions of nature. Heraclitus (500 BC), for example, perceived the world as the outcome of opposing tendencies that build up and tear down. In the East, the Tao (sixth century BCE) portrayed reality as a conversation between the contrasting natures of Yin and Yang. Active agency is initiated by Yang and those influences are received by the more passive and supporting Yin. In the unfolding alternative scenario, actual agency for change (Yang) is embodied in and regulated by configurations of processes (proximate laws) that have accrued from historical contingencies. The actions of this emergent organization are both constrained and supported by (but not determined or driven by) the laws of physics (Yin).

The conclusion one draws from the burgeoning new perspective on reality seems, at first sight, quite radical: *There exist very few enduring physical forms and no biological configurations that do not owe their inception to antecedent contingencies.* Actually, this truth was always implicit in the conventional approach to problem solving, but remained obscured by a preemptive emphasis on the constraining universal laws in abstraction from necessary boundary contingencies.

Thermodynamic Laws

While discussion has thus far centered on evaluating the force laws of physics, attention needs also be paid to the phenomenological laws of thermodynamics. The first law states that energy cannot be created or destroyed, only changed to another form. Of all the universal laws, this is perhaps the most unusual in that it holds without any recorded exception. Such an unblemished legacy raises suspicion as to its ontological stature.[31] The law is explicitly Parmenidean, and one wonders whether it was prompted by actual phenomenology or whether matters weren't intentionally (or subconsciously) *constructed* so as to preserve the appearance of strict conservation. Leibniz and Euler had depicted the world as a closed system, and during the century that elapsed after their formulation, significant advances in the understanding of natural phenomena had accumulated using the Leibnizian template. Julius Mayer and James Joule had performed careful experiments that yielded accurate conversion factors between several manifestations of energy. Why not simply declare energy to be conserved for purposes of bookkeeping? Besides, some twenty to thirty years earlier Carnot had muddied the waters with his discovery of irreversibility. What better way to reaffirm the primacy of the static worldview than to declare the law of conservation of energy, formulated well after Carnot's results, to be the *first* law and accord the bothersome irreversibility a decidedly secondary status?

One may argue, with justification, that the first law has served science well. To be fair, it must also be added that there is at least some phenomenological content in the first law: It remains true that energy cannot be destroyed without leaving any discernible residual. This fact, however, does not suffice to justify strict quantitative conservation. Moreover, there remains the embarrassing fact that only about fifty years ago it was empirically discovered that the performance of power-generating machines could be substantially improved by abandoning the calculation of first-law efficiencies and reckoning performance instead on second-law calculations.[32] One also notes current cosmological attempts to balance energies in the known cosmos lead to enigmas such as *dark energy*. There seems to be growing reasons to question the ontological depth of the first law.

As for the second law, it appears in manifold equivalent versions. One typical statement might say that it is impossible to convert energy entirely into work without losses in the form of heat. As already mentioned, this discovery posed a major threat to the conservative worldview and purportedly was reconciled with classical physics through the invention of statistical mechanics. Subsequently, most physicists have come to conflate thermodynamics with statistical mechanics—a position that is strongly at odds with the engineering dogma that thermodynamics is preeminently an empirical endeavor.

Some have attempted to draw eschatological conclusions from the second law: It is widely accepted that the second law condemns the universe to *heat death,* by which is meant that the final state of the universe will be one solely of widely dispersed low-energy photons. John Haught cites this as a prime example of the "cosmic pessimism" that has characterized academic attitudes over the past few centuries.[33] Such pessimism, however, is predicated upon models that were homogeneous, rarefied, and consisted of tokens that at best interacted only weakly with one another. Under such conditions the *only possible final state* becomes heat death. Enter heterogeneity and realistic interactions between elements of a system and an alternative final state appears that resembles a collection of perpetual harmonies.[34] Under this dual-endpoint scenario it becomes possible for a dissipative structure,[35] when subjected to declining resources, to separate into two final states. One state consists of perpetual harmonies and the other is rank chaos (heat death). One sees remnants of such a separation occurring about 380,000 years after the big bang, when neutral matter emerged out of a maelstrom of radical particles while contributing a complementary residual to the ubiquitous 3K background radiation. Although no one can currently envision how humanity might pass into a perpetual harmony, neither can one rationally foreclose such possibility as grounds for hope in a Chardinian Omega Point.[36]

Rational Ontologies

There are numerous scientists who insist that religion has absolutely nothing to say to science. Conversely, many faithful would rather shun any consideration of science out of fear that new discoveries there might extirpate closely held beliefs. Neither attitude contributes either to good science or to a healthy faith, and is certainly not helpful to the dialogue between the two realms.

Recognizing that many with a scientific bent are inclined to regard science as a rational alternative to belief, the argument here focuses on whether the ontologies of the universal laws are deep enough to serve in the stead of religious belief. In the course of such inquiry, no one is disputing that the formulations of the universal laws of physics are among the crowning achievements of the human intellect. Every reader is aware of the significant benefits to humanity wrought by their application. Furthermore, the laws appear inviolate so long as they are applied to the circumstances under which they were formulated.

Problems arise, however, in that the circumstances under which the laws can be usefully applied do not appear to be universal. Difficulties are encountered especially in their application to heterogeneous systems. It's not that the laws are violated, but rather that their generality renders them insufficient to determine outcomes when enormous numbers of possibilities are all capable of satisfying the same lawful constraints.[37] Furthermore, history has shown that the continuum assumption, enormously useful as it may be, does not seem to apply to all situations, and particularly to many events at the extremes of spatial and temporal scales.

Those who attempt to use the universal laws to exclude any possibility of divine existence or intervention appear to be inflating the ontological depth of these laws. Conventional wisdom holds that if there are gaps in human understanding of certain phenomena, then theory will eventually be developed to cover over such lacunae. This belief constitutes the argument against the *God of the Gaps*. To be sure, one hopes that new theories will continue to emerge to cover gaps in the current knowledge about nature, but recent insights into the realities of complex systems have indicated that residual gaps are a necessary and natural feature of the fabric of reality,[38] and that no conceivable theory based on relations among homogeneous entities will ever cover them—even if one were to posit that God does not exist.

The reversible universal laws of physics may indeed be special, but they are not absolutes. They are, in essence, models—extremely good models to be sure, but models nevertheless—and all models are finite and limited.[39] While a more realistic assessment of the ontological depth of universal laws might seem to detract from the special, privileged position of science, such reevaluation is strictly in keeping with scientific orthodoxy. Challenges are, after all, demanded by Popper's call that all scientific theories to be subjected to continued attempts at falsification. Attitudes about those theories are hardly immune from the same test.

Challenging the absoluteness of the fundamental laws serves to mitigate the current lopsided dialogue between science and religion. Furthermore, recovering the authentic meaning of Newton's second law as a proportional relation among heterogeneities (cause and effect) might provide a mathematical tool for the description of processes of generation and corruption. In any event, such reassessment benefits all participants in the growing conversation, because each of the communities stands much to gain in being informed by the other.

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Notes

1. Department of Biology, University of Florida

2. Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science

3. Karl Popper, *Conjectures and Refutations* (Seoul: Minumsa, 1954).

4. Stuart Kauffman, *Reinventing the Sacred: A New View of Science, Reason, and Religion* (New York: Basic Books, 2008).

5. Stephen Hawking, *A Brief History of Time: From the Big Bang to Black Holes* (New York: Bantam, 1988).

6. Ed Dellian, "Die Newtonische Konstante," *Philosophiae Naturalis* 22, no. 3 (1985):400–5; Ed Dellian, "Inertia, the Innate Force of Matter: A Legacy from Newton to Modern Physics," in *Newton's Scientific and Philosophical Legacy*, eds. P. B. Scheurer and G. Debrock (Dordrecht: Kluwer Academic Publishers, 1988), 227–37; Ed Dellian, "Newton on Mass and Force: A Comment on Max Jammer's Concept of Mass," *Physics Essays* 16, no. 2 (2000):1–13; Max Jammer, *Concepts of Mass in Contemporary Physics and Philosophy* (Princeton: Princeton University Press, 2000).

7. Ed Dellian, *Galileo Galilei, Discorsi* (Berlin: Ed Dellian, 2014). The reader is left to decide whether this equivalence of cause and effect is a micro-version of the merology that Juarrero (this volume) posits as a necessary dynamic of self-organizing dynamics.

8. Nicolas Léonard Sadi Carnot, *Reflections on the Motive Power of Heat,* translated 1943 (New York: ASME, 1824), 107.

9. Ludwig Boltzmann, "Weitere Studien über das Wärmegleichgewicht unter Gasmolekülen," *Wiener Berichte* 66 (1872):275–370.

10. Josiah Willard Gibbs, *Elementary Principles in Statistical Mechanics* (Woodbridge: Ox Bow, 1902).

11. A. Einstein, "Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?" *Annalen der Physik* 323, no. 13 (1905):639–41.

12. Commonly referred to as *quantum mechanics,* despite the fact that almost no behavior in this realm bears any resemblance to the mechanical.

13. Ed Dellian, "Die Newtonische Konstante"; Ed Dellian, "On Cause and Effect in Quantum Physics," *Speculations in Science and Technology* 12, no. 1 (1989):45–48.

14. Robert E. Ulanowicz, "A World of Contingencies," *Zygon* 48 (2013):77–92.

15. It is implicit, of course, that the boundary statement must be relevant to the variable that characterizes the law.

16. Boltzmann, for example, introduced stochasticity into his simplistic gaseous system in the form of a random variation of the positions and momenta of the gas atoms.

17. Such tractable boundary conditions are called *holonomic.*

18. If one assumes that human volition is indeterminate (Juarrero 1999), then intentionality may not be proscribed from being a legitimate agency in the natural world. Alicia Jarrero, *Dynamics in Action Intentional Behavior as a Complex System* (Cambridge: MIT Press, 1995).

19. Gregory Bateson, *Steps to an Ecology of Mind* (New York: Ballantine Books, 1972).

20. Walter M. Elsasser, "A Form of Logic Suited for Biology?" in *Progress in Theoretical Biology*, Vol. 6, ed. Robert Rosen (New York: Academic Press, 1981), 23–62.

21. Alfred North Whitehead and Bertrand Russell, *Principia Mathematica* (Cambridge: Cambridge University Press, 1927).

22. Nancy Cartwright, *How the Laws of Physics Lie* (Oxford: Oxford University Press, 1983).

23. Walter M. Elsasser, "A Causal Phenomena in Physics and Biology: A Case for Reconstruction," *American Scientist* 57 (1969):502–16.

24. Karl Popper, *A World of Propensities* (Bristol: Thoemmes, 1990), 51.

25. For example, the gunner's decision to fire the cannon.

26. Robert Ulanowicz, *Ecology, the Ascendent Perspective* (New York: Columbia University Press, 1997).

27. *Auto* meaning *self,* and *catalysis,* the act of quickening—a process that, through its interactions with others, tends to speed up itself.

28. For example, a quaternate proportion of heterogeneous entities A/B = C/D, which can perhaps be identified as the geometric structure of the double helix (Dellian 2014).

29. Ulanowicz, *Ecology, the Ascendent Perspective.*

30. This metaphor was used by Leibniz, not by Newton.

31. Ulanowicz, *Ecology, the Ascendent Perspective.*

32. K. W. Ford, G. I. Rochlin, and R. H. Socolow, *Efficient Use of Energy* (New York: American Institute of Physics, 1975), 304; Richard A. Gaggiolo, *Thermodynamics: Law Analysis* (Washington: American Chemical Society, 1980); H. Hevert and S. Hevert, "Second Law Analysis: An Alternative Indicator of System Efficiency," *Energy-The International Journal* 5 (1980):865–73.

33. J. F. Haught, *God after Darwin: A Theology of Evolution* (Boulder: Westview Press, 2000).

34. Robert Ulanowicz, "Increasing Entropy: Heat Death or Perpetual Harmonies?" *Design and Nature & Ecodynamics* 4, no. 2 (2009):1–14.

35. A dissipative structure is an organized pattern of matter and transformations that is sustained by an input of material and energetic resources. When the inputs disappear, the structure breaks down.

36. Pierre Teilhard de Chardin, *The Future of Man* (New York: Random House, 2004).

37. Robert Ulanowicz, *A Third Window: Natural Life beyond Newton and Darwin* (West Conshohocken: Templeton Foundation Press, 2009), 196.

38. Robert E. Ulanowicz, "Process and Ontological Priorities in Evolution," in *Biological Evolution: Facts and Theories*, eds. Gennaro Auletta, Marc Leclerc, and Rafael A. Martínez (Vatican City: Gregorian & Biblical Press, 2011), 321–36.

39. Robert Rosen, "Organisms as Causal Systems Which Are Not Mechanisms: An Essay into the Nature of Complexity," in *Theoretical Biology and Complexity: Three Essays on the Natural Philosophy of Complex Systems*, ed. Robert Rosen (Orlando: Academic Press, 1985), 165–203.