LETTER TO A LOGICIAN

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This article is adapted from a 10-page letter written to one of my students about a year ago. He was a senior highly accomplished in formal logic who was taking my Science, Technology, and Society (STS) course, an overview of the relationships between ourselves and nature, our machines, and other lives as these are affected by science and technology.

The previous semester he took our Philosophy of Science course, team-taught with a philosophy professor. This student's weekly STS essays continued class discussion themes from the Philosophy of Science course. The student's privacy has been respected; Diodorus Cronus, to whom my letter is here addressed, was a Greek philosopher distinguished for logical innovations. The story goes that, while at dinner with the king and another philosopher, he was given a logical puzzle which he could not solve. He returned home, wrote a treatise on the problem, and died from despair (c. 284 BCE).

Dear Diodorus,

You are well on your way to being a superb master of logic. When I see you and your philosophy professor walking together across campus, I am reminded of *The School of Athens,* a fresco by Raphael that shows Plato and Aristotle, teacher and pupil, discoursing as equals.

I appreciate your genuine engagement with our readings and class discussions. Philosophy students have earned my respect. You care about your discipline and are serious about critical thinking. Your insights have helped me think more deeply about what my colleagues and I are doing in physics. Like you, we care about our discipline.

You have developed considerable skill in formal logic, which I admire. Examples of careful logical thinking in physics are abundant. Here is one that uses logical principles you will find familiar.

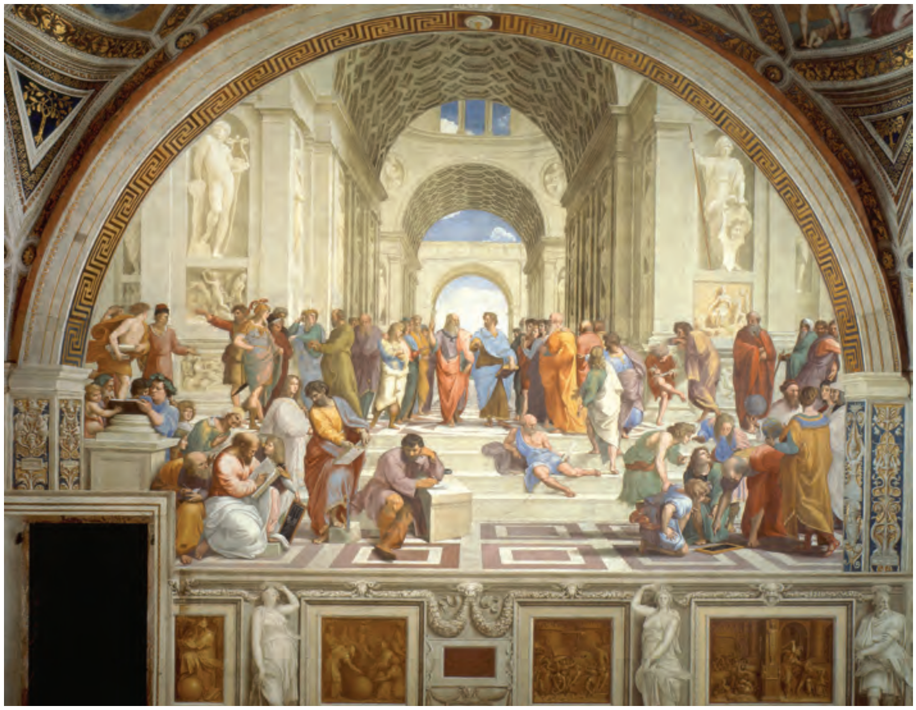
In the nineteenth century two statements of what we now call the second law of thermodynamics were articulated. Both statements were inductive generalizations from empirical observations. One maintained that no engine converts 100 percent of its heat input per cycle into work output. The other postulated that heat never flows spontaneously from a cold body to a hot one. These statements elevated to the status of axioms the notion that these unobserved processes do not occur because they *cannot* occur. To see if these postulates offer insight into reality, we work out their inferences and see to what extent they correlate to the real world.

The two statements are readily demonstrated to be logically equivalent by showing that if either one is false, then so is the other. Then another question arises: If no engine can achieve 100 percent efficiency, how efficient *can* an engine be, limited only by the matters of principle articulated in the second law? In 1824 Sadi Carnot offered a path to an answer by inventing a conceptual engine that operates between two temperatures while maintaining thermal equilibrium with its surroundings. Carnot's idealized engine led to a result, now called Carnot's theorem, which shows that the efficiency of any engine operating between a "cold" absolute temperature T_C and a "hot" temperature T_H cannot exceed 1—T_C/T_H. Engines operating between more than two temperatures can be conceptualized as a sequence of Carnot engines. By such reasoning one deductively climbs to the summit of this subject, the Clausius inequality. In its simplest version for the two-temperature engine, it says that if the engine has efficiency e less than the Carnot efficiency e_o, so that $e = e_o - \delta$ where $\delta > 0$, then in each cycle during which the engine accepts heat Q_H from the hot side, performs work, and dumps the remaining energy as heat on the cold side, the sum of all the heat exchanged per temperature equals $-\delta Q_H/T_C$. In other words, more heat per temperature is dumped into the environment than is required by the second law if the efficiency is less than ideal. This result readily generalizes to arbitrary cycles, for which the Clausius inequality says $\oint \frac{dQ}{T} \leq 0$.

From this follows the slide down to deductive consequences, including the existence of a new state variable called "entropy," a corollary that the entropy of an isolated system never decreases, and thermodynamic criteria for the occurrence of spontaneous processes. To make this logical exercise into a science, one tests, with measurements, these inferences against real systems. The second 1aw of thermodynamics echoes the real world so well that its inferences revealed some important limitations of classical mechanics and led to the development of quantum mechanics.[1]

As you appreciate, both logical rigor and empirical observations are essential in science. As we discussed in the Philosophy of Science class, the logical positivists tried to describe all of science in terms of classifying the logic of statements. A scientific assertion would have meaning only insofar as it could be correlated, with the precision of formal logical statements, to our sensory experiences.[2] But they quickly learned what scientists have found: that science sometimes has to color outside of logic's rigid lines. This predicament is not from lack of respect for logic. The devotion of physics to logic is illustrated by the persistence shown in reconciling quantum mechanics with electrodynamics—which took from 1900 to 1948.[3] It took that long for a community of exceptionally bright, hard-working people to work through the difficulties of showing how quantum mechanics and electrodynamics could be made mutually consistent.

Formal logic offers a powerful lens for scrutinizing science. However, like all lenses, it may contain aberrations. Over the years I have observed curious patterns of behavior among students who see rigorous logic as trumping all else. These include a tendency toward literalism in analyzing sentences while ignoring the larger perspective, and an irresistible urge to classify everything into taxonomic categories with maximal worry about the ambiguity of language. I am not writing to argue but to relate empirical observations I have seen over the years. I speak only for myself.



ABOVE
"The School of Athens," by Raphel. Public domain image, courtesy of wikipaintings.org.

Literalism and Perspective

Once a sentence is written or uttered it becomes a potential object of logical scrutiny. A literal reading is certainly essential for analyzing the legal possibilities open to a defendant's lawyer, for instance. But we must remember that context is crucial for most statements. Where is the other person coming from? What does he or she care about? What motivates him or her? What competing values is one trying to reconcile?

For example, during our discussion of environmental sustainability in the Science, Technology, and Society course, someone asked the follow-up discussion question, "Why should we care?" We suggested several reasons, such as our dependence on healthy ecosystems, our concern about our own quality of life and that of our descendants, and so on. One reason was recast as the following question about ethics: "What gives us the right to wantonly destroy the lives of other creatures who value their own lives?" To focus what we were trying to say, we turned to Albert Schweitzer's "Reverence for Life" writings. Starting from his observation, "I am life which wills to live in the midst of life which wills to live," he taught that all life, not only human life, should be treated with reverence.[4] He advocated an ethic based on the foundational principle that we kill no living thing unless doing so is unavoidably necessary. One illustration of "necessity" that arose in class discussion came from the prereservation Lakota, who depended on the buffalo for their survival. As part of the buffalo hunt, they held ceremonies to thank the slain buffalo and apologize to them.[5] Another illustration came from Schweitzer's own experience, when a pelican took up residence at his clinic in Lambaréné.[6] Pelicans survive on fish, so Schweitzer regretfully fed fish to the pelican.

Your response to Schweitzer's ethics was a virtuoso performance on the meanings of "necessity." You reminded us that every dictator or general who orders a genocide rationalizes such colossal crime as "necessary." While your demonstration scored a point for logic by exploiting the unavoidable ambiguity of the word, it left me concerned that your focus on a pedantic analysis of Schweitzer's words led you to overlook his message. Any "ethnic cleansing" or genocide is a machine for destroying lives on a large scale. By comparison and contrast, the meatpacking industry also ends lives on an industrial scale. Leaving aside the question of whether we should eat other sentient creatures at all, we can still notice one important distinction between scenarios: One treats its victims with deliberate cruelty and contempt, but the other can be done in a way that shows respect to the creatures raised for slaughter, doing everything possible to eliminate their terror and suffering.[7] Do we need to have "necessity" spelled out in single-valued rigor for us to recognize the difference? If so, then perhaps we need wider perspective more than we need narrower precision. Schweitzer's point was to urge a robust principle for ethics: If I treat all life with reverence (to the point of carrying a beetle outside instead of squashing it),[8] then I will not be susceptible to the propaganda of those who would have me buy into the "necessity" of genocide or any other expression of contempt for any life.

When Schweitzer turned 30, he kept a promise he had made to himself to spend the rest of his career in service to others. Even though he already had a PhD with a dissertation on Kant and was a Bach organist of international reputation, he returned to university to earn a medical degree. Preparing to spend the next several decades as a jungle doctor in equatorial Africa, Schweitzer had a powerful reaction to the science he learned, as he recalls in his autobiography:

> *But the study of the natural sciences brought me even more than the increase of knowledge I had longed for. It was to me a spiritual experience. I had all along felt it to be psychically a danger that in the so-called humanities with which I had been concerned hitherto . . . a mere opinion can, by the way in which it deals with the subject matter, obtain recognition as true. . . . The argument from facts is never able to obtain a definite victory over the skillfully produced opinion. How often does what is reckoned as progress consist in a skillfully argued opinion putting real insight out of action for a long time!*
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> *. . . Now I was suddenly in another country. I was concerned with truths which embodied realities, and found myself among men who took it as a matter of course that they had to justify with facts every statement they made. It was an experience which I felt to be needed for my own intellectual development.*[9]

Classification and Ambiguity

Philosophers have brought attention to the problem of classification, and have long pointed out that something can be categorized more than one way, depending on the experiences of the person doing the classifying. Thus I have found puzzling the rigidity that so many students, highly trained as logicians, bring to the task of classifying things and concepts and people.

A revealing incident occurred one day in our first Philosophy of Science section. We were discussing whether the quantum-mechanical wave function ψ is part of the real world. Physicists do not observe it *directly*; we observe its *consequences*. The wave function (times its complex conjugate ψ^*) is interpreted as a probability density for locating a particle. I told the class that the Schrödinger equation that one solves for the wave function ψ, can, if one wishes, be seen as a "black box" into which one inputs the particle's mass and potential energy. The black box produces as output the distribution function $\psi^*\psi$. At this point a senior student declared to me, "Oh, you are an instrumentalist." Had this student said, "Your scenario represents an instance of instrumentalist thinking," he would have been correct. Although I may use instrumentalist reasoning on today's problem, on some other topic I might apply, say, utilitarian thinking. There is a profound distinction between pronouncing *what I am* rather than noting a *tool* I use to address a specific problem.

Classification schemes are useful boxes that help us get organized. Thus I was fascinated by your letter that defined three categories and insisted that numbers must fit exclusively into one and only one of them:

> *Numbers can be one of three things. (1) Numbers can be ontologically existing entities. (2) Numbers can be mental conceptions. (3) Numbers can be symbols that are shifted around in a type of game. However, if option 2 is true, then numbers should not be able to predict the exterior world. Hence, if numbers can predict the exterior world, then there is evidence that options 2 and 3 are false. . . . If numbers are ontologically real, then objects exist without mass and without energy.*[10]

Very tidy categories—but why should numbers fit in only one of these three? Why can't numbers be all of these entities? Whatever a proton may be, each atomic nucleus contains an integer number of them; a pair of human hands contains ten digits. These are about as close to ontologically existing entities as nature will offer. The notion that *nothing* can be represented as a *number* is rather astonishing; "zero" as a number was invented twice in human history. That numbers are symbols which can be shifted around in a "type of game" is evident to anyone who has ever done a physics problem, worked out an amortization schedule, or estimated the cost of a construction project. Sometimes the games seem to be only for intellectual play, as non-Euclidean geometries and hypercomplex numbers initially were. Then they were found to fall readily to hand respectively in general relativity and in the Dirac equation that describes the quantum state of a relativistic electron. We use such mental conceptions as symbols to manipulate our thoughts and conclude something about nature that can be tested against the real world. One could imagine other categories too: shall we say that numbers either *mean* things, or that they *do* things? In digital computers numbers have *both* roles. [11] Granted that the philosophical status of numbers is a difficult and controversial problem, nevertheless the versatility of their uses and interpretations would, it seems to me, caution against demanding that they fit into only one category.

Whatever numbers *are*, perhaps the more interesting puzzle is why numbers—and other mathematical concepts that spring to mind, such as derivatives and Lie algebras and Legendre polynomials—correlate so well with nature. In a 1960 paper, Eugene Wigner, whose work in using symmetry groups to classify nuclei and elementary particles was recognized with the 1963 Nobel Prize in Physics, discussed the "unusual effectiveness of mathematics in the physical sciences." He wrote,

> *[I]t is important to point out that the mathematical formulation of the physicist's often crude experience leads in an uncanny number of cases to an amazingly accurate description of a large class of phenomena. This shows that the mathematical language has more to commend it than being the only language which we can speak; it shows that it is, in a very real sense, the correct language.[12]*

One might think that at least the term "science" would be unambiguously classified or defined. Another revealing incident occurred in the Philosophy of Science course when we read one of Jacob Bronowski's books. As a mathematician, biologist, historian, and poet, he was well acquainted with the flexibility of language in both science and the humanities. Here is a partial list of Bronowski's descriptions of science, from *Science and Human Values*:[13]

> *"I define science as the organization of our knowledge in such a way that it commands more of the hidden potential in nature." (p. 7)*
>
> *"Science is nothing else than the search to discover unity in the wild variety of nature—or more exactly, in the variety of our experience. Poetry, painting, and the arts are the same search." (p. 16)*
>
> *" . . . All this is plain once it is seen that science also is a system of concepts . . ." (p. 41)*
>
> *"Science is the creation of concepts and their exploration in the facts." (p. 60)*

The logic specialists in the class took these statements as a set of axioms and gleefully proceeded to show how dreadfully inconsistent they appear to be: "Science" is a noun ("a system") in some places and a verb ("the search") elsewhere; it is sometimes the organization of what we know and sometimes the discovery of what we don't know. By viewing him through the soda straw of sentence deconstruction and picking his sentences apart as if each one was meant to stand alone, these students, it appeared to me, were oblivious to Bronowski's message. The statements in question are not axioms or definitions intended to be unique. They are photographs taken from different angles; they are explorations of the many facets of science offered by one who has lived it.

What, then, are numbers? What are "laws of nature?" What is "science?" These questions are easy to ask and hard to answer. Here is one description of the latter. Science is a conversation we carry on between two worlds: the *conceptual* world, and the *real* world.[13,14] The real world contains rocks, trees, stars, sunlight, magnets, water, horses, engines, bugs, and brains. The conceptual world contains geometries, coordinate systems, entropy, atomic orbitals, angular momentum, electric charge, Lagrangians, isospin, mass, and evolution. Concepts are symbols we manipulate in the imagination, working out the consequences they imply in various situations.

For example, gravity—whatever it is—has held the Earth together throughout its history. I can assert, empirically, that gravity is real. I know from experience that when you fall off a roof there's only one way to go—down—and that you fall at a definite rate. Those are facts about gravity. But any "law of gravity" is a creation of the versatile human mind.

How we conceptualize gravity requires the informed use of imagination and intuition. Newton's "law of universal gravitation," which describes gravity as force acting across space, offers one conceptualization. Einstein's general theory of relativity, which describes gravity as the curvature of spacetime, offers another. As a logical structure, the former is contained as a limiting case within the latter. Whatever gravity *really is* ontologically we do not know, and perhaps we cannot know. But we do know that, from concepts such as force or spacetime curvature, specific predictions in the conceptual world can be made and tested against the real world, by stepping off a roof or tracking a light ray skimming by the Sun. Creativity for the concepts, logic for the inferences, data for the comparison, then iterating—these are elements essential for doing science.

Science is a hybrid of poetry and logic, intuition and mathematics. Our definitions, principles, and laws are statements of observed patterns that we have compressed into words and equations. Equations are precise, but they apply to conceptual representations, or models, of real things. If words must always adhere rigidly to precise definitions, it would be difficult to discover in mass, for instance, a form of energy. Definitions expand with experience.

Words carry multiple shades of meaning, giving the soil of poetry—and of physics—their fertility. Poetry uses ambiguity to say more than the words themselves. The poet may write, for instance, that love is a river, a razor, a hunger, a flower.[15] The question for poetry is not, "Which metaphor is *correct*?" Each one is *correct within its context*, but the poet does not spell out those contexts. That is left to our personal experience and imagination. We accept this as the method of poetry. However, if love were a science (and it is not![16]), then as scientists we would start from this ambiguity and try to spell things out: Under what circumstances is love a razor, a river, a hunger, a flower?

Physics as the Poetry of Nature

The Society of Physics Students used to distribute a lapel button that declared PHYSICS IS THE POETRY OF NATURE. Poets exploit the flexibility of language to create impressions that go beyond words. Physicists sometimes find themselves confronting similar situations. The challenge for physics is to prevent the flexibility of words from carrying us into a state of confusion. Wave-particle duality offers a dramatic example of a fruitful response to ambiguity.

We can engineer with electrons to make electric lights and semiconductors for the computer industry, but we still don't know what an electron really is. The only languages that come close to describing electrons are the mental pictures of waves and particles. Waves spread out and particles are localized, so these mental pictures are contradictory. Unfortunately for those who insist on mutually exclusive choices, real electrons sometimes behave indistinguishably from waves, and in other circumstances they behave as particles.

In experiments or applications in which electrons behave like particles (e.g., television picture tubes), the wave model is irrelevant. In situations where electrons act like waves (e.g., electron microscopes), the particle model is irrelevant. So far no one has been clever enough to invent a single model in terms of which all the doings of electrons can be understood. But although we do not know what electrons "really" are, we do know what they are like, and under which circumstances they are like that. Particles and waves are mental pictures gleaned from our macroscopic experiences with billiard balls and ocean surf. When we carry these concepts into the microscopic world of the atom—where we have no direct experience—we should not be astonished to find that neither model, by itself, adequately describes everything that electrons do.

In 1949 Niels Bohr described two kinds of truth, a "simple truth" for which the opposite statement is false, and a "deep truth" for which the opposite statement is also true.[17] This remarkable insight came from his confrontations with wave-particle duality. In physics or any other science, as in life, not every premise is either true or false. Furthermore, premises in physics are almost always, if not always, expressed through metaphors and analogies. Logicians do not like the use of metaphors or analogies in arguments, but we can only explain unfamiliar things in terms of things we already understand.

The logical and empirical positivists said that "facts" are "applied to singular, particular occurrences" and from a pattern of facts come "laws."[18] But one has to exercise value judgments and actively search for the relevant facts; patterns are not there for the mere looking; promising hypotheses come from intuition and informed imagination. To paraphrase Robert Pirsig, your search for what's *true* is guided by your sense of what's *best*.[19] In a 1918 speech Albert Einstein made this point explicitly:

> *The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction. There is no logical path to those laws; only intuition, resting on sympathetic understanding of experience, can reach them.*[20]

The practice of science rests on aesthetic values such as elegance and simplicity. Questions worth asking must be recognized as valuable, which means that others are passed over. More hypotheses can be proposed than tested, so some must be discarded in advance. Physicists have found that starting with ideas that are beautiful and economical, and working outward from there, has consistently been a fruitful strategy.

The School of Athens is Still In Session

In Raphael's fresco *The School of Athens*, Plato and Aristotle are surrounded by a host of luminaries engaged in investigation, including Pythagoras, Epicurus, Zeno, Averroes, Euclid, and a constellation of others. Some figures are engaged in discussion. Some meditate in solitude. All exist within a community of critics and supporters, ready to sharpen one another's ideas. If there were no disagreements, and if meaning could not take on multiple shades, the world would be far less interesting. Each of us has a partial view to add to the discussion. But we are all like the blind men in the parable of the elephant.

I am glad to have you as my colleague and friend. I always learn more from my students than they learn from me. Thank you for taking my courses, for sharing your thoughts, and for listening.

Best wishes,
Prof N

Acknowledgments

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References

[1] Max Planck's quantum hypothesis of 1900, that an oscillator has quantized energy, came from the thermodynamics of light in thermal equilibrium with matter, an instance of the breakdown of the classical equipartition of energy that had also been noted in predictions of the specific heats of gases. Albert Einstein's 1905 postulate of light "corpuscles," later called "photons," came from comparing the entropy of light to that of an ideal gas. For a short review of the second law, the Clausius inequality, and entropy, see "Elegant Connection in Physics: The Second Laws of Thermodynamics and Non-Conservation of Entropy," *SPS Newsletter* (June 1998), pp. 9-13.

[2] Peter Godfrey-Smith, *Theory and Reality* (University of Chicago Press, Chicago, 2003), Ch. 2.

[3] 1900 to 1948 began with the Planck hypothesis, and ended with Freeman Dyson's showing the equivalence of the quantum electrodynamics methods of Richard Feynman, Julian Schwinger, and Sin-itiro Tomonaga; see Silvan S. Schweber, *QED and the Men Who Made It* (Princeton University Press, Princeton, NJ, 1994).

[4] Albert Schweitzer, *Out of My Life and Thought* (Henry Holt & Co., New York, 1933, 1949), tr. by C.P. Campion. See also *Reverence for Life: The Ethics of Albert Schweitzer for the Twenty-First Century* (Meyer & Bergel, eds., Syracuse University Press, Syracuse, NY, 2002).

[5] Luther Standing Bear, *Land of the Spotted Eagle* (originally published 1933; University of Nebraska Press, Lincoln, NE, 2006), p. 165; Joseph Marshall III, The Lakota Way (Penguin Compass, New York, 2001), p. 49.

[6] Ann Cottrell Free, *Animals, Nature, and Albert Schweitzer* (Flying Fox Press, Washington, DC, 1988), pp. 47-48.

[7] The work of Temple Grandin is noteworthy in this regard. The People for the Ethical Treatment of Animals recognized her with the 2004 PETA Award. The citation read "Dr. Grandin's improvements to animal-handling systems found in slaughterhouses have decreased the amount of fear and pain that animals experience in their final hours, and she is widely considered the world's leading expert on the welfare of cattle and pigs." For a sample of her thoughts see T. Grandin, *Animals Make Us Human* (Mariner Books, Boston, 2009).

[8] See J. Marshall III, Ref. 5, p. 51, for his account of "Bailey the beetle."

[9] Schweitzer autobiography, Ref. 4, pp. 104-105.

[10] Student letter, STS class week 7, Spring 2013.

[11] George Dyson, *Turing's Cathedral* (Vintage Books, New York, 2012), p. ix: "The stored-program computer, as conceived by Alan Turing and delivered by John von Neumann, broke the distinction between numbers that mean things and numbers that do things. Our universe would never be the same."

[12] Eugene Wigner, "The Unreasonable Effectiveness of Mathematics in the Natural Sciences," *Commun. Pure and Appl. Math. 13* (1960), 1-14, doi:10.1002/cpa.3160130102.

[13] Jacob Bronowski, *Science and Human Values* (Harper & Row, New York, 1965).

[14] David Hestenes, "Modeling Games in the Newtonian World," Am. J. Phys. 60 (8), 732-748 (1992).

[15] This example from "The Rose," written by Amanda McBroom, Fox Fanfare Music, Inc., BMI; sung by Bette Midler in the 1979 movie *The Rose* and in *Bette Midler Greatest Hits* (Atlantic Recording Corp., 1993).

[16] Richard Feynman wrote, "We must, incidentally, make it clear from the beginning that if a thing is not a science, it is not necessarily bad. For example, love is not a science." R.P. Feynman, *The Feynman Lectures on Physics* (Addison-Wesley, Reading, MA, 1963), Vol. 1, pp. 3-1.

[17] Niels Bohr, "Discussions with Einstein," in *Albert Einstein, Philosopher-Scientist*, Paul A. Schlipp, Ed. (MJF Books, New York, 1949), pp. 239-240.

[18] Rudolf Carnap, *Philosophical Foundations of Physics* (Basic Books, New York, 1966), p. 5.

[19] Robert Pirsig, *Zen and the Art of Motorcycle Maintenance: An Inquiry into Values* (William Morrow & Co., New York, 1974, 1999), pp. 293-297.

[20] Albert Einstein, "Principles of Research," *Ideas and Opinions* (Three Rivers Press, New York, 1954, 1982), pp. 226-227.