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Emmy Noether's Wonderful Theorem (rev ed.). FREE

Emmy Noether's Wonderful Theorem (rev ed.).. Dwight E. Neuenschwander 337 pp. Johns Hopkins U.P., Baltimore, MD, 2017. Price: $30 (paper). ISBN 978-1-4214-2267-1.

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BOOK REVIEWS

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Foundations of Quantum Mechanics: An Exploration of the Physical Meaning of Quantum Theory. Travis Norsen. 310 pp. Springer, 2017. Price: $59.99 (softcover) ISBN 978-3-319-65866-7; $44.99 (e-book) ISBN 978-3-319-65867-4. (Tim Maudlin, Reviewer.)

Travis Norsen's *Foundations of Quantum Mechanics* could be the spark that ignites a revolution. There is nothing new in it.

If those two sentences sound contradictory, they should. How could a book without a novel thesis change everything?

Welcome to the world of foundations of quantum mechanics. Everyone knows, in some vague way, that there exists such a field as foundations of physics in general, and of quantum theory in particular. But it may be unclear exactly who does this work and what they do. One stereotype is that foundations of physics is what some physicists do on the weekends or after they have run out of real physics to do. Also some philosophers do it full time. This last fact is a huge red flashing warning sign that there is something disreputable about the whole business.

In the case of quantum theory, a terminological marker has been created. Quantum theory is the most predictively accurate theory in history. There is no doubt that it is in some sense correct. But even though we have every reason to trust its predictions, there is still another question: how to *interpret* it.

According to this elucidation, quantum theory has everything one could want from a theory save an "interpretation." And whatever it is to interpret a theory, it can't be of any importance to physicists in their everyday life. Quantum theory has gone from triumph to triumph without having an "interpretation." An "interpretation" must be some inessential luxury add-on, like heated seats in a car: it makes you feel warmer and more comfortable, but plays no role in getting you from here to there.

On this understanding, worrying about interpreting quantum theory is inessential to pursuing the basic aims of science.

This is where Norsen comes in. Think of *Foundations of Quantum Mechanics* first and foremost as what it is: a textbook for students. As such, it should not and does not contain any novelty in its content. Textbooks are judged by the logic of their organization, the clarity of their presentation and the lucidity of their style. This one covers many of the topics of a standard introduction to quantum physics, but focuses its attention on the foundational questions: What is there? How does it behave when no one is looking? How does it behave when someone is looking? (Separating these questions indicates that we are doing quantum theory.) Which parts of the mathematical apparatus represent real physical properties and which are merely gauge degrees of freedom? What sort of thing does the wavefunction of a system represent?

Standard textbooks gloss over these questions. Norsen dwells on them. The first chapter covers familiar ground: the structure of pre-quantum theories including Newtonian Mechanics and Maxwellian Electrodynamics. Even here, the presentation foregrounds issues that are commonly ignored. In these seemingly unproblematic theories, how do we determine the physical ontology (i.e., the basic physical entities) postulated by the theory? A familiar example is the scalar and vector potentials of classical electro-magnetism. In certain gauges (e.g., Coulomb gauge) the potentials react instantaneously to distant states of affairs. But the sting of this appearance of action-at-a-distance is drawn if one denies physical reality to the potentials, regarding them instead as mere calculational devices. Already we find ourselves contemplating questions about what is real, and about whether anything physically real goes faster than light.

The second chapter presents basic quantum phenomena involving interference and entanglement. This will be familiar to any student who has had an introduction to quantum mechanics, but playing around with particular examples encourages developing a "feel" for the theory.

Deviation from the standard textbook begins in the next three chapters. Each of these presents a "problem" confronting attempts to understand quantum mechanics as a physical theory. Chapter 3 discusses the Measurement Problem, Chapter 4 the Locality Problem, and Chapter 5 the Ontology Problem.

The Measurement Problem is the best known of the three. Succinctly: is there any fundamental physical difference between interactions that count as "measurements" and those that don't? A "fundamental" difference shows up when articulating the basic laws of the theory.

John von Neumann's axiomatization of quantum mechanics treats measurement as fundamental. The wavefunction evolves by smooth deterministic laws when the system is not being measured and by sudden indeterministic collapses when measured. This approach contradicts the conviction that measurements are physical interactions like any others, governed by the same laws. What's a measurement depends on the physical dynamics rather than the other way around.

The Measurement Problem poses a difficulty if measurement is a trigger for wavefunction collapse. But the collapse itself, no matter how triggered, raises a different puzzle: the Locality Problem. This is what bothered Einstein about quantum theory from the beginning. Collapses, as physical events, are wildly non-local. Thus the famous "spooky-action-at-a-distance" that Einstein could not abide.

Finally, the Ontology Problem concerns the physical significance of the wavefunction. One way to pull the non-local sting from wavefunction collapse is to regard the wavefunction as a mathematical object that does not represent any physical property of an *individual system*. Does it rather represent only statistical features of an *ensemble of systems*? Does it represent any *objective, mind-independent fact*? Or rather reflect just the *information an agent has about the system*?

All of these options have been defended, and it is easy to see their attraction. The wavefunction of an electron spreads out in space. Does that mean the electron itself spread out? Or that a huge collection of electrons spreads out? Or that my information about where the electron is dilutes? But if it is not the single electron physically spreading, how can one explain two-slit interference?

Further, the mathematical wavefunction is not defined over three-dimensional physical space but over the 3N-dimensional configuration space of N particles. Fields in 3N-dimensional space don't have any evident relation to the three-dimensional world we find ourselves in, the world that physics is meant to explain. Norsen recounts how Schrödinger tried to solve this problem by defining a three-dimensional "charge density" for each electron, and then superimposing all of these in a common three-dimensional space. However, the "smeariness" of the charge density could not be quarantined to the microscopic, but amplified up to macroscopic scale. That is the problem of his eponymous cat.

How might one solve the Measurement, Locality and Ontology Problems? These are questions that a typical physics textbook either ignores altogether or tries to finesse. They are also problems that many physics students are intensely interested in. It is here that you least want to hear the command: "Shut up and calculate!".

If calculation will not address these problems, what will? Each problem reflects an unclarity about the physical significance of the mathematical formalism. And making precise statements about the physical ontology and dynamical laws is just what it is to *precisely specify a physical theory*. Standard quantum textbooks do not exposit a physical theory that lacks an interpretation: they present a predictive formalism without any accompanying physical theory! "Interpreting quantum theory" is actually constructing alternative physical theories that can account for the accuracy of the predictive formalism.

Chapter Six discusses the most famous "interpretation" of all: the Copenhagen Interpretation. It is not a precisely formulated physical theory. It does not say what physically exists and how it behaves. The contemporary Copenhagen Interpretation is just an attitude: the refusal to ask, much less attempt to answer, foundational questions about quantum theory.

That is not how Bohr saw things. He thought that deep morals about the nature of the world had been revealed by quantum theory. Einstein found Bohr's exposition largely incomprehensible. One lovely thing in these chapters, and indeed throughout the whole book, is the judicious but extensive use of quotations from Einstein, Schrödinger, Heisenberg, Born, Bell, Bohr, etc. Their discussions are sharp and clear, and students will delight at reading the masters debating what they have done. Nothing could be more gratifying to an undergraduate physics student than reading Einstein complain about his difficulties with quantum mechanics.

Chapter 6 ends without any clearly articulated physical theory in hand. Here *Foundations of Quantum Mechanics* departs most dramatically from standard textbook presentations: it presents three clear, mathematically formulated physical theories that aspire to make the same—or nearly the same—predictions as the quantum predictive formalism. Each of these three theories exemplifies a response to Schrödinger's cat problem.

Here's Schrödinger's puzzle. Initially, we assign a wavefunction to the system containing the cat and apparatus. Suppose that wavefunction always evolves in accord with the linear Schrödinger equation. It becomes a superposition of macroscopically different states, some with a live cat and others with it dead. If the wavefunction is *complete* (i.e., if it represents every physical characteristic of the cat) we have a problem. The cat ends up neither simply dead nor simply alive. As John Bell put it: "Either the wavefunction, as given by the Schrödinger equation, is not everything or it is not right."

Regarding the wavefunction as incomplete—as not everything—yields a *hidden variables* theory. The term is a terrible misnomer. If the extra variables are to determine the health of the cat then they had better not be hidden, else we would not be able to tell if the cat ends up alive or dead. Regarding the wavefunction as complete but not right (as given by Schrödinger's equation) yields a *collapse* theory. The Copenhagen Interpretation is often taken to be a collapse theory that ties the collapses to measurements, an option that highlights the measurement problem.

Chapter 7 presents the most famous "hidden variables" theory: the pilot wave theory or Bohmian mechanics. In this theory "particles" are particles—point objects that have definite positions and follow continuous trajectories through space-time. The wavefunction always evolves by Schrödinger's equation and the point particles also evolve deterministically, in accord with the *guidance equation*. The evolving microscopic particles congregate into macroscopic objects, which are shaped and behave just like ones we see in the real world. At the end of Schrödinger's experiment, for example, there will either be a cat-shaped collection of particles moving like a live cat or a cat-shaped collection inert like a dead cat. No problem.

If Bohmian mechanics solves Schrödinger's problem so cleanly, why has it not been universally adopted? Because the dynamics of the Bohmian particles is wildly non-local: which way a particle *here* goes can depend on the disposition of a piece of matter way over *there*. Bohmian mechanics incorporates the spooky action-at-a-distance that Einstein hated.

Chapter 8 exposits Bell's theorem: John Bell's proof that non-locality is unavoidable given the predictions of standard quantum mechanics. That removes the main objection to Bohmian mechanics, although, as Bell says, in the way Einstein would have liked least.

Chapter 9 presents the most highly developed collapse theory, due to GianCarlo Ghirardi, Alberto Rimini and Tulio Weber, universally known as GRW. GRW avoids the difficulty of tying the collapses to measurements by tying them instead to……nothing. The collapses just happen randomly with fixed probability per unit time.

Finally, Chapter 10 investigates escaping Bell's dilemma by maintaining that the wavefunction evolving by Schrödinger's equation is both everything and is right. This yields the *Many Worlds* or *Everett* Interpretation. It is a famously weird physical theory, not least due to the multiplying worlds. It is, for example, problematic what the *probabilistic predictions* of the quantum predictive apparatus even mean in this setting.

GRW, Many Worlds and Bohmian mechanics are not presented in any standard quantum mechanics textbook. How adequate is Norsen's exposition?

The writing is not just so clear and straightforward that a non-expert can understand it; it is so clear and straightforward that an expert cannot manage to misunderstand it.

What shortcomings does *Foundations of Quantum Mechanics* have? Norsen, like many others, attributes the electromagnetic gauge of Ludvig Lorenz instead to Hendrik Lorentz. And there are many topics that have been omitted: the PBR theorem, the Bohm-Aharonov effect, field theory, the challenge of Relativity, particle creation and annihilation, etc.

But this last complaint is really a call for a successor volume: *Advanced Foundations of Quantum Mechanics*. May this book ignite a revolution in the pedagogy of quantum mechanics. *Vive la Révolution!*

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Emmy Noether's Wonderful Theorem (rev ed.).

Dwight E. Neuenschwander. 337 pp. Johns Hopkins U.P., Baltimore, MD, 2017. Price: $30 (paper). ISBN 978-1-4214-2267-1. (Peter Olver, Reviewer.)

In 1918, the mathematician Emmy Noether published two wonderful theorems that had a tremendous impact in physics, mathematics, and beyond. While Noether's primary interest and lasting contribution to mathematics was laying the foundations of modern abstract algebra, the term "Noether's Theorem" belongs to the lexicon of physicists and applied mathematicians.

Nevertheless, many of them remain unaware of the true scope and formulation of her fundamental theorems. In part, this is due to the inadequate and misinformed treatments of her results that continue to proliferate in the literature. Unfortunately, despite the best of intentions, the book under review is of this very nature.

Noether's First Theorem—the one in the book's title—establishes a one-to-one correspondence between the continuous (Lie) symmetry groups of a variational principle and the conservation laws of the associated Euler-Lagrange equations, whose solutions are the (smooth) extrema (more correctly, stationary points). While Neuenschwander states that symmetries produce conservation laws, he does not mention the reverse, which is an integral part of her statement of the Theorem (see below). Noether's Second Theorem states that if the variational principle admits an infinite-dimensional symmetry group depending on one or more arbitrary functions of the physical coordinates, then the associated conservation laws are trivial, but there are nontrivial differential identities among the field equations, which thus form an underdetermined system of differential equations. For proofs of both results see Ref. 1.

Neuenschwander's book does a commendable job detailing Noether's personal and professional history, illustrated by numerous quotes, and how she came to these theorems. In brief, in 1915, Noether, as a leading young expert (albeit unpaid due to her sex) in invariant theory and Lie groups, was invited by David Hilbert and Felix Klein to visit the University of Göttingen. The reason for Hilbert's invitation was that so she could help him in his intense ongoing competition with Einstein to establish the foundations of general relativity and, in particular, to resolve an apparent paradox: the triviality of the energy conservation law derived from time-translational symmetry of the Hilbert variational principle. (At that time, many special cases of Noether's Theorem, including the connections between translational and rotational symmetries and conservation of linear and angular momentum, and time translations with conservation of energy, were already known.[1,2]) Noether's Second Theorem resolved Hilbert's dilemma; as she showed, the triviality of the energy conservation law was because the time translational symmetry group belongs to such an infinite-dimensional variational symmetry group, that, consequently, produces the Bianchi identities among the field equations.

Despite the fundamental importance of her theorems in classical and quantum field theories as well as in mathematical analysis, for the most part there have been major misunderstandings about what she actually accomplished in her seminal paper. In Ref. 1, I state and prove the full versions and further argue that her paper contains another fundamental but largely unrecognized contribution—the introduction and application of generalized symmetries, meaning those whose infinitesimal generators are allowed to depend upon the derivatives of the field variables—which did not appear in the earlier literature. A half century later, such higher order symmetries and their consequential higher order conservation laws played an essential role in the discovery of integrable (soliton) partial differential equations, such as the nonlinear Schrödinger and Korteweg-deVries equations. Their importance for Noether was that they allowed her to obtain the aforementioned one-to-one correspondence between symmetries and conservation laws. While writing Ref. 1, I started investigating the history of her Theorems in the literature, which contains a strange mixture of papers claiming special cases to be the "Noether Theorem," followed by a rash of subsequent papers purporting to generalize it, when they were merely restating special cases of her marvelous and very general result. My initial historical forays were taken up in earnest by Yvette Kosmann-Schwarzbach in her masterly history of Noether's Theorem and its reception and development over the last century.[2]

Unfortunately, Neuenschwander's book is representative of the aforementioned genre, stating a special case of her first result as if it were the general Noether Theorem. If he read Noether's original paper, he did not fully understand it. Nor did he consult the detailed discussion of the two Theorems in the first edition of Ref. 1. Even worse, in his revision Neuenschwander cites Kosmann-Schwarzbach's book, so there is no excuse for remaining ignorant of what is written in it. Indeed, a major concern is that his book will foster yet another generation of physicists who do not understand the full scope and power of Noether's First Theorem.

Neuenschwander also appears to be confused by Noether's Second Theorem. On Page 8 he says it includes the first as a special case, and repeats this claim on page 203, where he makes the bizarre claim that the Second Theorem is the Noether Identity. Now, while the Second Theorem does rely on this fundamental identity that underlies the First Theorem, this is not the point. The Second Theorem, as stated by Noether, only applies to certain kinds of infinite-dimensional symmetry groups, e.g., gauge symmetries, that depend upon arbitrary functions of the independent variables, whereas the First Theorem and its key identity apply to *all* continuous symmetry groups (both finite-dimensional Lie groups and infinite-dimensional Lie pseudo-groups), the only issue being triviality of the resulting conservation laws. The latter question was finally dealt with in Ref. 1, where it was shown that a "normal system" (meaning one without integrability conditions) has a one-to-one correspondence between nontrivial symmetry groups and nontrivial conservation laws. Underdetermined systems of Euler-Lagrange equations, such as those arising in general relativity, fall under the ambit of Noether's Second Theorem, and admit nontrivial differential relations among the field equations, such as the relativistic Bianchi identities. These points are properly explained in the relativistic framework on pages 225–234, but the initial characterization of the Second Theorem on pages 8 and 203 remains deeply flawed.

Neuenschwander also exhibits a rather shaky knowledge of the calculus of variations. His derivation of the Euler-Lagrange equations is unnecessarily complicated. In particular on pages 37–38, the variation ς is assumed to be continuously differentiable but the lemma used to complete the proof only assumes its continuity, and hence is not immediately applicable. It is also worth pointing out that only sufficiently smooth extrema satisfy the Euler-Lagrange equations. On page 33, he makes the strange claim that maxima and minima "lie outside the mathematics of the calculus of variations," and later on page 94 states that "when a functional (sic) is said to be a minimum and not a maximum, or vice versa, it is for physical reasons, not mathematical ones." This effectively ignores the entire history of the calculus of variations, particularly the theory of the second variation, the importance of conjugate points, the variety of necessary and sufficient extremal conditions due to Legendre, Weierstrass, Erdmann, Jacobi, Hilbert, Caratheodory, etc., none of which are mentioned in the text. And this does not even include powerful direct methods based on modern functional analysis. He also misstates a number of basic results in analysis. For example, page 36 claims that Leibniz's rule allows one to bring derivatives under the integral sign. But this rule is merely the formula for the derivative of the product of two functions and thus justifies integration by parts, which underlies all calculations in the classical calculus of variations, including Noether's Identities and Theorems.

The descriptions of symmetry and group theory are particularly poor. He gives a reasonable explanation of an infinitesimal transformation, but then, in Exercise 4.7 describes the infinitesimal generators in terms of matrices, which only works for linear actions and is false as stated (and the definition of "Killing vector" is not correct). He fails to develop the connection between the infinitesimal generator, which should be thought of as a vector field on the underlying space, and the induced one-parameter group, which can be identified with the flow of the vector field in the sense of dynamical systems. This is basic physics of, say, fluid mechanics, where the velocity vector field generates a steady state fluid flow, with time playing the role of the group parameter. Furthermore, I could not find a clear statement that the symmetries of the variational problem are symmetries of the Euler-Lagrange equations, but not conversely, the most common counterexamples being scaling groups. Page 79 says "functionals can be extremals but not invariant, and they can be invariant but not extremal" which makes no sense at least to me, in the same fashion as the above quoted sentence on page 94. How can a functional (as opposed to a solution) be extremal?

Sophus Lie, whose remarkable theory of symmetry groups of differential equations underlies Noether's results, makes only a cameo appearance on page 75. In section 5.4, the author states two "problems": "(1) given a transformation, seek a Lagrangian whose functional is invariant; or (2) given a Lagrangian seek transformations that lead to invariance." For some reason, he calls one or both of them an "inverse problem" which is not the standard terminology used in the calculus of variations, where it refers to the problem of determining whether a given system of differential equations is the Euler-Lagrange equation of a variational principle.[1] For continuous transformation groups, the solution to both problems was already found by Lie well before Noether appeared on the scene; she was well aware of Lie's contributions. For the second problem, one merely applies a general infinitesimal generator to the Lagrangian to find the infinitesimal determining equations, which can then be solved for the most general symmetry generator. Alternatively one can compute the symmetry group of the associated Euler-Lagrange equations using the standard infinitesimal Lie algorithm, and then determine which ones satisfy the additional variational condition. All of these are straightforward computations, now encoded in computer algebra systems such as Mathematica and Maple. As for the first problem, which is not dealt with here, as Lie proved, the most general invariant Lagrangian is a function of the differential invariants of the group multiplied by an invariant volume element, quantities that Lie (and Noether) were very familiar with, and knew how to find. Indeed, the theory of differential invariants, which is fundamental to the study of invariant variational problems and invariant differential equations,[1] has never been properly appreciated among the physics community, and the author squandered an opportunity to present it here.

Despite my negative review, there are some aspects of the book I like. As noted previously, the history is quite good, and bringing the career of Emmy Noether to the attention of a broader audience is commendable. The physical exercises and examples are commendable, particularly the material on quantum mechanics. I also like the inclusion of exercises as well as the sections on questions for reflection and discussion—except when they perpetuate some of the author's confusion and inadequate explanations.

But, despite the best of intentions, which I applaud, the bottom line is that Neuenschwander's book does a disservice to both Emmy Noether the mathematician, and her indeed marvelous theorem(s). I am surprised he did not seriously try to address the shortcomings of the first edition, as pointed out for instance in a review by Kosmann-Schwarzbach.[3] In the preface, he compares Noether's Theorems to a "magnificent summit in an impressive range of ideas," but unfortunately he has mistaken a lesser peak for the truly majestic mountain towering beyond. She and the physics community deserve much, much better.

[1] P. J. Olver, *Applications of Lie Groups to Differential Equations*, 2nd ed. (Springer-Verlag, New York, 1993).

[2] Y. Kosmann-Schwarzbach, *The Noether Theorems. Invariance and Conservation Laws in the Twentieth Century* (Springer, New York, 2011).

[3] Y. Kosmann-Schwarzbach, "Review of first edition of Emmy Noether's wonderful theorem," Phys. Today **64**(9), 62 (2011).

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What is Real? The Unfinished Quest for the Meaning of Quantum Physics.

Adam Becker. 379 pp. Basic Books, New York, 2018. Price: $32.00 (hardcover). ISBN 978-0-465-09606-0. (Christopher A. Fuchs, Reviewer.)

"If you strike at a king, you must kill him," Ralph Waldo Emerson once advised a famous law student. In this vividly written first book by Adam Becker, the overt intention is to strike at a king, Niels Bohr, key architect of the so-called Copenhagen interpretation of quantum mechanics. Becker does not kill him. This is not because of the invincibility of Bohr, but a weakness of the author: So taken with his intent for destruction, Becker neglected to do much homework on the subject. Advance praise on the back cover declares "In this immensely well-researched book…," but anyone who has seriously studied Bohr, Heisenberg, Pauli, von Weizsäcker, Rosenfeld, and other contributors to what Heisenberg more aptly named "the Copenhagen spirit" (for there are many Copenhagen interpretations) will quickly detect that this is simply not true. The bibliography appears rich with sources (206 items), but on closer examination one finds just five collections of writings from any of the Copenhageners, and even these were not particularly used in the text—the only substantial quotes of Bohr come from two essays and an interview. But what about material from the 36 other essays in Bohr's collected philosophical papers, or the extensive writings of Léon Rosenfeld and C. F. von Weizsäcker, or any of the analyses of Henry Folse, Arkady Plotnitsky, and John Honner explaining the ways in which Bohr was a realist about quantum objects? For an author who cries out "What the hell is going on here?" over what the Copenhagen interpretation actually says about reality, one might wonder whether he ever really wanted to know.

What is served instead of a scholarly "know thine enemy" is an extended takedown of a single quote, "There is no quantum world. There is only an abstract quantum physical description," presented as if it were from Bohr himself. Only if one were to look into the book's endnotes and follow its trail to the actual sources, would one learn that Becker knows better: The quote is not from Bohr himself, but from Aage Petersen after Bohr's death, recollecting how he remembered Bohr speaking. This rhetorical technique is part of a larger pattern of bait in the text and switch in the notes. Some instances are insubstantial for a reader who seeks entertainment only. An example: After telling a riveting tale of a speaker's bad treatment upon reporting David Bohm's hidden variable theory, one finds in the endnotes, "This story must, at best, be taken with a sizable grain of salt." On the other hand, the example of the Petersen quote is more insidious, as much of the theme of the book is built on it.

"There is no quantum world"—what might Bohr or Petersen have meant by this? Without much context for how the words were meant to be used, one is essentially free to fantasize. And that the author certainly does. The Bohr and other Copenhageners Becker constructs tip close to believing in no reality at all. They are solipsists… or positivists… or idealists… or operationalists… or, well it doesn't really matter, as Becker doesn't much bother to recognize distinctions between these positions anyway. (He even calls the noted pragmatist philosopher Charles Morris a positivist.) More often than not though, his explicit target is a supposed connection between the Copenhagen interpretation and positivism, viz., "the overthrow of logical positivism and the rise of scientific realism radically changed philosophy of science—and ultimately struck a major blow at the root of the Copenhagen interpretation itself." But if so, why would Heisenberg write in *Physics and Philosophy*, "It should be noticed… that the Copenhagen interpretation of quantum theory is in no way positivistic." Or again, this time paraphrasing Pauli in *Physics and Beyond*, “The positivists have gathered that quantum mechanics describes atomic phenomena correctly, and so they have no cause for complaint. What else we have had to add—complementarity, interference of probabilities, uncertainty relations, separation of subject and object, etc.—strikes them as just so many embellishments, mere relapses into prescientific thought…”

To be fair, Becker does recognize a weakness in his identification of the Copenhagen interpretation with positivism. But as per the larger pattern, one will only see his confident exposition wane if one troubles to plumb the endnotes. In a remarkable passage, Becker writes, “Whether Bohr himself was a positivist was and is a subject of much debate. …But the particulars of Bohr’s views are far less significant, historically, than the fact that his views were obscure [and] that positivist reasoning was ubiquitously deployed in defense of the Copenhagen interpretation, and such defenses were often presented as the views of Bohr himself.” If everyone else does it, I can do it too?

Would Bohr accept the ways Becker tries to speak for him: “There is no problem with reality in quantum physics because there is no need to think about reality in the first place.” “The theory needs no interpretation, because the things that the theory describes aren’t truly real.” “Quantum physics tells us nothing whatsoever about the world.” Surely not! As Bohr related to Thomas Kuhn in his final interview, “I felt … that philosophers were very odd people who really were lost, because they have not the instinct that it is important to learn something and that we must be prepared really to learn something of very great importance. …[I] think it would be reasonable to say that no man who is called a philosopher really understands what one means by the complementary description.” Bohr certainly thought we learned something deep and profound about nature with the discovery of quantum theory. In one of the endnotes Becker marvels that Kuhn in his historical work and the philosopher Norwood Russell Hanson—two thinkers he clearly respects—could be philosophically anti-positivistic, yet fairly keen on the Copenhagen interpretation. Reflection on the idea that maybe they knew what he didn’t, i.e., that the issues might be more subtle than he imagined, does not appear to be in his list of options.

Perhaps Pauli of all the Copenhageners described best the distinction between what they aimed for (no matter what their errors) and the way Becker portrays them: “[I] invariably profited very greatly even when I could not agree with Einstein’s views. ‘Physics is after all the description of reality,’ he said to me, continuing, with a sarcastic glance in my direction, ‘or should I perhaps say physics is the description of what one merely imagines?’ This question clearly shows Einstein’s concern that the objective character of physics might be lost through a theory of the type of quantum mechanics, in that as a consequence of its *wider conception of objectivity of an explanation of nature* the difference between physical reality and dream or hallucination become blurred. …Einstein however advocated a *narrower form of the reality concept*.” [Emphasis added.] The Copenhageners saw in quantum theory not a *less robust reality* than in classical physics, but one that was *more* than can be captured in classical-style terms. It is this idea that most modern philosophers of physics and apparently Becker himself have a hard time getting their heads around. And thus perhaps their reaction is no wonder: When something cannot be expressed in the limited vocabulary native to their ears, what else could follow but frustration?

But, this is no excuse to flub the very basics of the debate. There are a number of historical errors in the book, most of them minor. For instance, Wigner did not introduce the term “the problem of measurement” in 1963; it goes back at least to a 1949 paper of Jordan. The Nobel prize of 1938 was not valued at $1 000 000, even in 2017 dollars. And Kramers, Gamow, von Weizsäcker, Peierls, and Wheeler were not Bohr’s students, but his postdoctoral employees. However, one error is absolutely unforgivable given the subject of the book: Becker actually gets the Einstein, Podolsky, Rosen (EPR) argument wrong! In his scenario, starting with two entangled particles and the assumption of locality, he tries to establish that each particle simultaneously has a position and a momentum by supposing the one measurement on one and the other measurement on the other. But that is not what EPR consider: Their hypothetical measurements are made only on one particle, from which they draw inferences about what would happen if they were to perform the *same* measurement on the other. This change makes all the conceptual difference in the world. When an author does not understand the argument himself, should he have the right to declare. “It’s unclear how [Bohr’s response] relates to the EPR argument,” and dismiss it as “muddled writing?”

But I did say the book is vividly written, and indeed it is. It shines when it reports on those attempts to interpret quantum theory along the lines of what Pauli called a “narrower form of the reality concept”—technically speaking, those interpretations where nonlocality is a genuine feature of nature and/or quantum states are understood to represent actual attributes of quantum systems, not just information, knowledge, or beliefs. Becker’s sketches of David Bohm, Hugh Everett III, John Bell, and others involved in those developments are compelling and humane. Many of these great names are his heroes, and it comes through in the care with which he tells their stories. In this review, however, I opted to focus on the side of the book critical to Copenhagen because I know there will be many reviews positive on it through and through, such is the mood in the philosophy of physics community.

It is only that there is a need for damage control with a book so disingenuous. I will be the first to admit that Bohr, Pauli, Heisenberg, and all the others were no oracles, no ultimate authorities. Their views did often contain inconsistencies. But, what this book leaves out is the spur to thought the Copenhagen interpretation has been for so many in the quantum information and computing communities. E. T. Jaynes put the challenge of how to right the wrongs of Copenhagen this way: “[O]ur present [quantum mechanical] formalism is… a peculiar mixture describing in part realities of Nature, in part incomplete human information about Nature—all scrambled up together by Heisenberg and Bohr into an omelette that nobody has seen how to unscramble. Yet we think the unscrambling is a prerequisite for any further advance in basic physical theory." From this point of view, the tools and concepts of quantum information are what were needed to make sense of the deeper elements of the Copenhagen interpretation all along. Yet, this is an interpretative route hardly mentioned in Becker's book, though it now commands a significant portion of quantum foundations research worldwide. To quote from an essay of D. M. Appleby, one of the researchers in that community, "If I am asked to accept Bohr as the authoritative voice of final truth, then I cannot assent. But if his writings are approached in a more flexible spirit, as a source of insights which are not the less seminal for being obscure, they suggest some interesting questions. I do not know if this line of thought will be fruitful. But I feel it is worth pursuing." The worry to my mind is what if a young student encounters Adam Becker's book, with its tale of the Copenhagen interpretation being a "mishmash of solipsism and poor reasoning" before she has a chance to read any of the Copenhageners herself? She may never follow the pursuit Appleby suggested, and physics could be impoverished for it.

Christopher A. Fuchs is a Professor of Physics at the University of Massachusetts Boston and a Fellow of the Stellenbosch Institute for Advanced Study in South Africa. Notwithstanding the irony of it, he once compiled a list of every sentence in Bohr's philosophical writings that started with the word "notwithstanding." He found 39.

Signatures of the Artist: The Vital Imperfections That Make Our Universe Habitable. Steven E. Vigdor. 359 pp. Oxford U.P., New York, 2018. Price: $32.95 (hardcover). ISBN 978-0-19-881-482-5. (Don Lincoln, Reviewer.)

Professor Steven E. Vigdor's book "Signatures of the Artist" is an interesting and unique contribution to the crowded field of popular scientific literature, with an ambitious, although somewhat ill-defined, intent. The author's stated goal is to introduce the reader to many of the experiments that underlie our modern understanding of the universe. It covers important and cutting-edge topics in particle physics, surveys the origin of life and its subsequent evolution, and then even dabbles a bit with quantum mechanics. With such a broad set of subject matter, such a book demands a unifying theme that ties it all together and while Professor Vigdor seems to have attempted to employ more than one theme to do so, I am not sure that he succeeded with any of them.

First, I would like to describe the strengths of the book. Vigdor is a well-educated and informed scientist, with an impressive and encyclopedic grasp of the subject matter. The topics he chose to include are well selected, and he omits no fundamental physics mysteries of consequence. While he is a physicist and consequently his descriptions of particle physics, cosmology, and quantum mechanics are the strongest parts of the book, his descriptions of chemical evolution and recent scholarship in the field of abiogenesis are done well and are a helpful introduction to people who are not expert in those fields. His discussion of biological evolution is more cursory and is included as a necessary part of the question of why the universe seems to be so well tuned to result in humans.

In his preface, Professor Vigdor describes his target audience as being college level physics students or even freshman level honor students, and I think that he has gauged his intended audience pretty well. The book has an extensive list of citations and references, sprinkled liberally throughout the text, making it easy for an inspired reader to easily dig more deeply into any particular topic that catches his or her eye. I think that even particle physics or cosmology graduate students or postdocs (who often focus on a specific research topic) will find the book valuable, as it provides a broad overview of the subject matter. An especially strong feature of the book is that it does not only describe research at such scientific powerhouses as the well-known Large Hadron Collider, which attempt to concentrate as much energy into as small a volume as possible to try to discover new laws of nature. He also describes many precision experiments which have the potential to teach us even more.

Within the subject matter of particle physics and cosmology, he spends a great deal of time on the concept of symmetry, including the symmetries of charge conjugation and parity (CP). He describes the Higgs field and the breaking of its symmetry in the early universe. I found his discussion of symmetry breaking in both the electroweak and strong forces to be particularly dense, requiring consultation of other sources to make sense of his explanations.

This denseness does not appear everywhere throughout the book. His discussion of dark matter and dark energy is interesting and given at a level appropriate for his target audience, as are his chemical, biological, and quantum mechanical descriptions. His writing style is also a little dry and academic, especially in the earlier parts of the book.

My main concern about this book is not the descriptions of individual topics. The challenging passages covering symmetry breaking aside, each topic is described quite well, by and large. My main critique is that the book doesn't seem to be…well…a book. I found myself trying to determine what the author intended as a core narrative arc to tie the entire work together.

There seemed to be a couple of possibilities. For instance, the book's title appears to have been inspired by a particular piece of art by M. C. Escher, called "Plane-filling motif with reptiles." A yin/yang symbol, first flipped around a vertical axis, then a horizontal axis, and finally with white and black swapped, will look exactly like it did before those operations. Escher's artistic piece is composed of intertwined black and white lizards and has the same property, except that the author signed it in one corner. When the flipping and color changing operations are applied to the artwork, the lizards look as they did before the changes, but the author's signature has moved. Thus, the author's signature has broken the symmetry.

Vigdor extends this metaphor to physics theories. Many physics theories have a fundamental symmetry, allowing an important property or properties to be swapped. The use of the Escher metaphor maps naturally onto CP symmetry, which interchanges directions (e.g., left/right, up/down, and forward/back) and matter and antimatter. CP is nearly a perfect symmetry in nature, but it is broken to a tiny degree. This small broken symmetry might explain a very large mystery of the universe, which is why the cosmos is made exclusively of matter, when matter and antimatter should exist in equal quantities. The title of the book highlights how these small imperfections in much larger symmetries are likely clues as to the solution of a number of different unexplained questions about the universe—essentially signatures of the creator, although he does not imply a literal one. This metaphor arises more than once, but somehow is never employed as powerfully as it might have been.

I also had the impression that Vigdor really wanted to take on those members of society who believe in the principle of intelligent design (ID) as a proof of the existence of an intelligent creator of the universe. Throughout the book, he mentioned many examples of instances where small changes in the laws of the universe would have led to a cosmos in which life would be impossible; indeed, it is for this reason that he included in what might have been a book about particle physics and cosmology the chapter on abiogenesis and evolution. This book could have been one about the debate between ID and modern science, but he never quite stood his ground and drew a line in the intellectual sand.

As I read the closing words of the book, I found myself unsatisfied. I was looking for a conclusion; a literary punctuation mark that told me, the reader, just why I had read this book. I found that piece missing. I remain uncertain just what story Vigdor was trying to tell.

Yet, the book contained many fascinating tidbits of information not seen in most popular science books, heavily cited and referenced, with a very broad and expert eye. Despite the weakness of the book's narrative arc, if the reader knows that weakness in advance and simply wants to understand a lot of very fascinating science, then I recommend this book.

Don Lincoln is a senior scientist at Fermilab interested in the question of quark and lepton generations. Currently, he is using data collected by the Compact Muon Solenoid collaboration and using the Large Hadron Collider to explore that topic. In addition, he is a science popularizer, having written several books for the public on particle physics, cosmology, and xenobiology. He is a frequent contributor to CNN and other media outlets. He is a fellow of both APS and AAAS, and he was awarded the 2017 Gemant award from AIP for his science outreach efforts.

BOOKS RECEIVED

It Keeps Me Seeking: An Invitation from Science, Philosophy, and Religion. Andrew W. Briggs, Hans Halvorson, and Andrew Steane. 360 pp. Oxford U.P., New York, 2018. Price: $25.95 (hardcover) ISBN 978-0-19-880828-2.

A Student's Guide to Analytical Mechanics. John L. Bohn. 216 pp. Cambridge U.P., New York, 2018. Price: $24.99 (paper) ISBN 978-1-316-50907-4.

Analytical Mechanics. Nivaldo A. Lemos. 472 pp. Cambridge U.P., New York, 2018. Price: $79.99 (hardcover ISBN 978-1-108-41658-0.

The Scientific Method: Reflections from a Practioner. Massimiliano Di Ventra. 125 pp. Oxford U.P., New York, 2018. Price: $19.95 (paper) ISBN 978-0-19-882562-3.

Solid State Insurrection: How the Science of Substance Made American Physics Matter. Joseph D. Martin. 296 pp. University of Pittsburgh Press, Pittsburg, PA, 2018. Price: $45 (hardcover) ISBN 978-0-8220-4583-3.

Anxiety and the Equation: Understanding Boltzmann's Entropy. Eric Johnson. 180 pp. MIT Press, Cambridge, MA, 2018. Price: $22.95 (hardcover) ISBN 978-0-262-03861-4.

Ludvig Lorenz: A Nineteenth-Century Theoretical Physicist. Helge Kragh. 282 pp. The Royal Danish Academy of Sciences and Letters, Copenhagen, 2018. Price: 240 DKK (≈$37) (paper) ISBN 978-87-7304-417-9.

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