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The Lazy Universe: An Introduction to the Principle of Least Action

The Lazy Universe: An Introduction to the Principle of Least Action.. Jennifer Coopersmith 279 pp. Oxford U.P., New York, 2017. Price: $39.95 (hardcover). ISBN 978-0-19-874304-0.

C. G. Gray

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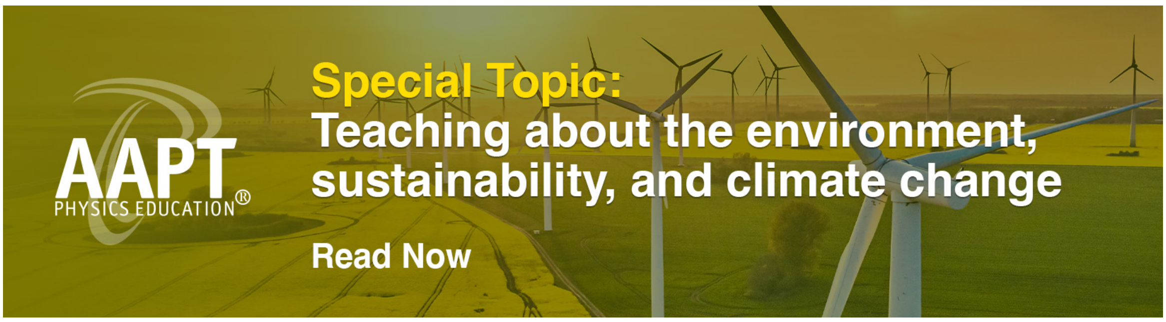

BOOK REVIEWS

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The Lazy Universe: An Introduction to the Principle of Least Action. Jennifer Coopersmith. 279 pp. Oxford U.P., New York, 2017. Price: $39.95 (hardcover). ISBN 978-0-19-874304-0. (C. G. Gray, Reviewer.)

In his first-year undergraduate lecture on the Principle of Least Action [*Feynman Lectures on Physics* (1964), Vol. II, Chap.19], Richard Feynman says that after his high school teacher told him about this principle, he found it "…absolutely fascinating, and have, since then, always found fascinating. Every time the subject comes up, I work on it. In fact when I began to prepare this lecture I found myself making more analyses on the thing.…" Feynman wrote his Ph.D. thesis on the subject [*The Principle of Least Action in Quantum Mechanics*, republished as a book in 2005, with L. M. Brown as editor], and the last conference he attended, shortly before his death, was on action/variational principles [Difficulties in Applying the Variational Principle to Quantum Field Theories, in *Variational Calculations in Quantum Field Theory*, edited by L. P. Polley and D. Pottinger, 1988, p. 28]. Many others have been so captivated, including Coopersmith and me. In fact, in preparing this review, I found myself "making more analyses on the thing." Jennifer Coopersmith has written a most welcome book, the first historically and philosophically motivated full study since two classics written nearly a half-century ago (both still available in inexpensive Dover editions): C. Lanczos, *The Variational Principles of Mechanics*, 4th ed. (1970), and W. Yourgrau and S. Mandelstam, *Variational Principles in Dynamics and Quantum Theory*, 3rd ed. (1968). This follows her earlier acclaimed book *Energy, the Subtle Concept*, revised edition, 2015, and is written in the same style, a pleasing combination of qualitative and quantitative arguments.

Action principles are usually taught at the senior undergraduate and graduate levels, but some scholars are making the case for their introduction earlier in the curriculum [see, e.g., Edwin Taylor, A Call to Action, AJP guest editorial **71**(4), 2003]. The attractions of action principles include the following: (1) they are brief and elegant in expressing the laws of motion, (2) they are covariant (valid for any choice of coordinates), (3) they readily yield conservation laws from the symmetries of the system (Nöther's theorem), (4) they automatically generate covariant equations of motion (Euler-Lagrange equations), and (5) they can also generate true trajectories directly, bypassing equations of motion, via the direct or Rayleigh–Ritz method of the calculus of variations. Action principles transcend classical particle and rigid body dynamics and extend naturally to other branches of physics such as relativistic mechanics, continuum mechanics (e.g., fluid mechanics and elasticity theory), quantum mechanics, and field theory (classical and quantum) and thus play a unifying role. They have occasionally assisted in developing new laws of physics, with general relativity being perhaps the best example. Each of these points can and has been greatly elaborated. Briefly, regarding point (1), for example, the role of the importance and usefulness of elegance in physics and in mathematics, engineering and other sciences, in both theory and experiment, has a huge literature; a recent discussion in this journal is given by Stanley Deser [Truth, Beauty and Supergravity, AJP guest editorial **85**(11), 2017]. Many scientists endorse elegance, but there are some distinguished dissenters, e.g., Boltzmann and the applied mathematician, historian of science, and iconoclast, Clifford Truesdell. But even Truesdell reserves his negative opinion on the elegance of variational principles to the application of such principles to continuum mechanics and states explicitly that the variational principles in particle mechanics are beautiful and elegant [C. Truesdell and R. Toupin, *The Classical Field Theories*, 1960, p. 595]. Regarding point (5), the direct method has been widely applied as an approximation technique, in competition with and complementary to perturbation theory, in classical continuum mechanics and field theory, and in quantum particle mechanics, but not in classical particle mechanics and quantum field theory.

Here is a brief summary of the action principles. There are two major versions of the action, due to Maupertuis (1744) and Hamilton (1834), and two corresponding action principles. The Hamilton principle is nowadays more used. The Hamilton action S for any conceivable (real or imagined) trajectory $A \rightarrow B$, connecting two given points q_A and q_B in a given time T, is defined by the integral $S = \int_0^T L(q, \dot{q}, t)\,dt$ along the space-time trajectory $q(t)$ connecting the specified space-time events, initial event $A = (q_A,\ t_A = 0)$ and final event $B = (q_B,\ t_B = T)$, where the Lagrangian L depends on coordinate q, its rate of change $\dot{q}$, and in general the time t. For a system with f degrees of freedom, q will stand for the complete set of generalized coordinates $q_1, q_2, \ldots, q_f$. In the simplest cases, $L(q, \dot{q})$ has no explicit time-dependence, it is equal to the difference in the kinetic and potential energies $K - V$, the kinetic energy K depends quadratically on $\dot{q}$, and the potential energy V depends only on q (conservative system). Hamilton's principle states that among all conceivable trajectories $q(t)$ connecting q_A to q_B in time T, a true one is one for which S is stationary, i.e., S is unchanged to first order when the trajectory is varied a small amount $\delta q(t)$ from the true one, with the true one and the varied one each satisfying the prescribed constraints ($q(t) = q_A$ at $t = 0$ and $q(t) = q_B$ at $t = T$). There may be more than one true trajectory, or no true trajectory, satisfying these constraints (boundary conditions). A briefer statement is that the extremals of the functional $S[q(t)]$, defined by the first order variation condition $\delta S = 0$, are the true trajectories. The terminology "least" action is historical. S is *stationary* for true trajectories; whether it is actually a minimum for true trajectories, or a saddle point, depends on the sign of the second-order variation, usually not discussed in the textbooks [see Am. J. Phys. **75**, 434 (2007)]. The second major version of the action is Maupertuis' action W which can be defined for a conceivable trajectory by the spatial integral $W = \int_{q_A}^{q_B} p\, dq$, with p being the canonical momentum (which equal to the ordinary momentum is the simplest cases). For f degrees of freedom, $p\ dq$ stands for $p_1\ dq_1 + p_2\ dq_2 + \cdots + p_f\ dq_f$. For normal systems (systems with K quadratic in $\dot{q}$), an equivalent time-integral definition is $W = \int_0^T 2K\, dt$. Maupertuis' principle states that with prescribed end points q_A and q_B and prescribed trajectory energy E, W is stationary ($\delta W = 0$) for true trajectories. Unlike the Hamilton principle, the Maupertuis principle is restricted to conservative systems but has been generalized to apply to nonconservative systems in recent years. It is very important to note the different constraints which apply to the two principles. With Hamilton, two points and the time are fixed; with Maupertuis, two points and the energy are fixed. Thus, with Hamilton, T is fixed and E is not, with the reverse holding for Maupertuis. For conservative systems, the two principles can be shown to be related by a Legendre transformation (see the last paragraph); for nonconservative systems, the generalized Maupertuis principle is again related to the Hamilton principle by a Legendre transformation. The solution of the Hamilton variational problem $\delta S = 0$ yields true space-time trajectories. The solution of the Maupertuis variational problem $\delta W = 0$ yields true space-time trajectories if one uses the time-dependent form for W and yields true orbits (spatial paths) if one uses the time-independent form for W.

The usual procedure is to use the action principles to derive Euler-Lagrange equations of motion for the true trajectories and then to solve these equations for the true trajectories. But as noted in point (5) in the second paragraph, we can obtain the true trajectories directly from the action principles without the equations of motion. There has always been speculation about whether something deeper underlies the action principles, with questions like "why does nature act in such an economical way?" Some (including the author of *The Lazy Universe*, p. 194) see the justification of Hamilton's principle in the Feynman path integral of quantum mechanics, which implies Hamilton's principle in the classical limit. Others feel any justification of classical action principles should be done within the framework of classical mechanics [T. Toffoli, "What is the Lagrangian Counting?" Int. J. Theor. Phys. **42**, 363 (2003)]. Many others do not think that the question is relevant and no underlying *a priori* physical principle exists: the action is not always a minimum, and besides, it is just mathematics since any equation can be reformulated as a variational statement [E. Gerjuoy, A. Rau, and L. Spruch, "A unified formulation of the construction of variational principles," Rev. Mod. Phys. **55**, 725 (1983)].

Jennifer Coopersmith has attempted and succeeded admirably I believe in her aim to write a modern book on the history and philosophy of the action principles, as well as to give the technical details. She accomplishes this difficult task by focusing the main text (nine chapters) on the history, philosophy, and intuitive notions involved, while relegating many of the mathematical details to short appendices (twelve in all). Her intended audience is the general reader. She states explicitly that her book is not a textbook (there are no problem sets), as it is meant to be a more qualitative and discursive treatment, trying to bring the equations to life with a lot of motivating discussion of their meanings. Still I think that students can profit by reading this book in parallel with a textbook, as the technical matters they need are indeed covered, many clearly and succinctly, in the appendices. Getting a qualitative feel for a subject is greatly assisted by seeing different viewpoints. She aims for a "shorter and simplified" version of Lanczos' classic book, mentioned in the first paragraph. An aside: Lanczos was an outstanding scientist. Some of his early work was in general relativity; he spent a year in Berlin as Einstein's assistant, he published a paper on an equation for quantum energy eigenfunctions just before Schrödinger, based on Heisenberg's recently published paper on matrix mechanics, but it had the form of an integral equation with the kernel not determined and so he did not quite discover wave mechanics, and he later published some very useful books on applied mathematics and some interesting popular books, as well as his pedagogical masterpiece on action principles. There is a very nice short biography by Barbara Gellai [*The Intrinsic Nature of Things: the Life and Science of Cornelius Lanczos* (AMS, 2010)].

In the early chapters, *The Lazy Universe* discusses the precursors (e.g., Fermat's principle in optics) and early history well, including anecdotes about Maupertuis, his multiple talents, idiosyncrasies (e.g., teleological views), and the priority dispute over the origin of the Maupertuis principle. The work of the greats Euler, Lagrange, Hamilton, and Jacobi is well covered. Jacobi devised a third form for the Maupertuis action; in multiple dimensions, Jacobi's form involves an integral along the arc length in q-space so that the action principle then resembles a geodesic problem of finding the shortest path between two points. The calculus of variations background needed to carry out variations of the action integrals is nicely summarized. Hamilton's principle is developed from the dynamical version (D'Alembert) of the principle of virtual work, and the exposition of the latter principle is thorough and meticulous. Maupertuis' principle is not derived. Lagrangian and Hamiltonian mechanics each get a chapter. The Nöther theorem relating conservation laws to symmetries of the action is discussed well for the special case of energy conservation arising from time translational invariance (pp. 129, 222). She gives Jacobi's simple intuitive argument (p. 127) why the action, although always stationary for true trajectories, can never be a maximum. The argument is that if someone claims to have a trajectory with maximum action, I will modify that trajectory by adding wiggles to it at some place along the trajectory, of high frequency but small amplitude, so that K increases a lot while V is not much changed. Thus, $L = K - V$ increases in the region of the wiggles and so does its integral S. (We also need to ensure that the overall travel time T does not change.) Hence, the original trajectory cannot be one of maximum S. Now, that is an elegant argument! And so is this book as a whole.

My criticisms are few and mostly minor.

- Misprint (p. 24). Maupertuis made his discovery in 1744, not 1644.
- Notation. She uses the modern notations used above for the actions, S (Hamilton) and W (Maupertuis), on. p. 250, but mostly (e.g., pp. 223, 241) she uses Lanczos's notation A for the Hamilton action and S for the Maupertuis action. This may cause confusion for modern readers.
- Why kinetic energy K is quadratic in the velocity (pp. 119, 217). I think that she missed the essential point of the Landau-Lifshitz argument, that the assumption of Galilean invariance yields this result.
- Frictional forces and nonholonomic constraints. These are not handled easily by the standard action principles. But, she overlooks (p. 184) modern work which can include friction directly in the Lagrangian for some systems, including all one-dimensional ones, and thereby can avoid the awkward Rayleigh dissipation function method [see, e.g., V. Chandrasekhar *et al.*, "On the Lagrangian and Hamiltonian description of the damped linear harmonic oscillator," J. Math. Phys. **48**, 032701 (2007)]. She briefly mentions that systems with nonholonomic constraints (which depend on velocity, not position, e.g., a disc rolling without slipping on a horizontal plane) do not obey the standard action principles, but it would have been instructive to mention that many researchers, even some distinguished ones, have stumbled over this point.
- Confusing statements. On p. 126, she states that "L has exactly the form $K - V$ and no other," but on the very next page, she agrees that L need not have the form $K - V$. On pages 187 and 192, she states that the initial and final events A and B used to define the action principles "must be close together," but on p. 193, she states (correctly) that they can be "a finite 'distance' apart." On p. 185, she gives a relativistic Lagrangian for a free particle. But she forgets her own admonition (p. 127) that one can multiply L by any constant C with no change in the physics. If she chooses $C = -1$ in this case (as does Lanczos on. p. 324 of his book), her equating the relativistic principle of maximal aging with the principle of least action breaks down; the principle of maximal aging will now be equivalent to a principle of greatest action. Both equivalences are correct, as are both action principle statements; the action allows a great deal of arbitrariness in its definition.
- Stationary or minimum action. On p. 112 (also see p. 4), she states that in section 6.6, we will see that the action for true trajectories is a minimum, not just stationary. But in Sec. 6.6 (p. 126), she (correctly) states the opposite that the action need not be a minimum: it can be a minimum or a saddle point. (She does not delve into when one gets one or the other but refers readers to the relevant literature.)
- Einstein's 1917 paper. She has a lovely appendix (p. 256) on Einstein's somewhat under-appreciated paper. Einstein considers the most general quasi-periodic systems with f degrees of freedom, systems which are not "separable" like the hydrogen atom, which has separable radial and angular actions. Using action-angle variables, one can define the f "good actions" $J_1,\ldots,J_f$, the ones for which the Hamiltonian H depends only on the actions and not the angles so that (from Hamilton's equations of motion) they are constants of the motion. J_i are special values of the Maupertius W action. In modern language, the actions define "invariant tori" surfaces in phase space (q, p), which confine the motion of the representative point to these subspaces of the constant energy surface in phase space. If one then quantizes these actions by setting $J_1 = n_1h$, $J_2 = n_2h$, etc., where n's are integers and h is Planck's constant, one gets an energy quantization using the relation $E = E(J_1,\ldots,J_f)$. The n's become the "good quantum numbers." This is the basis of what is nowadays called the Einstein–Brillouin–Keller or EBK semiclassical quantization scheme for quasiperiodic systems (not pointed out in the book), which generalizes the Bohr-Sommerfeld-Wilson or BSW scheme for separable systems. But there is a second gem in Einstein's paper, not mentioned by Coopersmith. Einstein realized that this scheme would fail for chaotic or ergodic systems where f good actions do not exist, and for an ergodic system energy E is the only constant of the motion and so the representative point in phase space wanders pseudo-randomly over the whole energy surface defined by $H(q,p) = E$; he raised the question of how one would quantize such systems. The problem was forgotten with the advent of matrix and wave mechanics in 1925–1926 but was resurrected in the 1970s by Martin Gutzwiller and others. Gutzwiller showed that for such systems, one can relate the complete set of quantum energy levels to the complete set of classical periodic orbits. The main result, Gutzwiller's semiclassical trace formula, is derived using path integrals [M. Gutzwiller, *Chaos in Classical and Quantum Mechanics*, 1990]. I think that it would be interesting to readers of *The Lazy Universe* to learn about this solution to the problem raised by Einstein.

The Lazy Universe is a fine book, and in my opinion, its author has succeeded in achieving her stated goals. My hope is that in future editions (Lanczos needed four to perfect his story), she will bring her considerable pedagogical skills to bear in discussing additional topics such as (1) The Legendre transform relation between S and W. She states (p. 250) the relation $S = W - ET$, which holds for the actions along true trajectories but does not give the general relation $S = W - \bar{E}T$ valid for arbitrary (conceivable) trajectories, where $\bar{E}$ is the mean energy along the trajectory between the endpoints. From this general relation, one can derive the Maupertuis principle from the Hamilton principle and vice-versa. (2) The action principles that have been developed in recent years, including the extension of the Maupertuis principle to nonconservative systems, reciprocal Hamilton and reciprocal Maupertuis principles, and principles which allow end-point variations and relaxation of other constraints. (3) The relations between the classical action principles and the quantum variational principles. One can in fact derive the reciprocal Maupertius principle from the quantum variational principle in the classical limit, and the reciprocal Maupertuis principle provides the basis of a simple semiclassical quantization scheme. (4) The direct variational method. One can employ the Maupertuis and Hamilton principles, and the newer action principles mentioned in point (2), to obtain trajectories directly from an action principle without using equations of motion. This method can be used to get exact analytical expressions for trajectories only for simple systems (just as with the equations of motion) but provides approximate analytical expressions when used as an approximation method (similar to the Rayleigh-Ritz method widely used in quantum mechanics), and if used as a numerical method, it can produce essentially exact trajectories. (5) Continuum mechanics and field theory. Inclusion of these topics might extend the book too much, but a sketch, an example, and some good references could be appropriate. A bit more on the relativistic principles might also be worth considering.

As one expects from OUP, the book is beautifully produced and is reasonably priced.

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Classical Field Theory. Joel Franklin 216 pp. Cambridge U.P., New York, 2017. Price: $69.99 (hardcover). ISBN 978-1-107-18961-4. (David Boozer, Reviewer.)

Classical field theory plays a key role in fundamental physics. Of the four fundamental forces, three of them, the strong nuclear, weak nuclear, and electromagnetic forces, are described by quantum field theories that are formulated by quantizing a corresponding classical field theory. The remaining fundamental force, gravity, does not have a quantum description yet and is currently best described by the classical field theory of general relativity. Franklin's book provides an introduction to classical field theory, which will be accessible to advanced undergraduates and beginning graduate students. The book consists of four chapters, covering special relativity, the electrodynamics of point particles, Lagrangian methods in field theory, and gravity. There are also three appendices that discuss analytical mathematical methods, numerical methods, and the derivation of classical electrodynamics from an action.

The focus of the first three chapters is largely on classical electrodynamics. Any textbook covering this material will invite comparison with the two standards: Griffiths at the undergraduate level and Jackson at the graduate level. In terms of difficulty, Franklin's book is intermediate between the two: it is more advanced than Griffiths but is written in a similar informal, conversational style. It differs from both books, however, in that the intent here is not to systematically develop the theory of classical electrodynamics, but rather to use classical electrodynamics as a stepping stone towards graduate-level study in quantum field theory and general relativity. To this end, three topics are particularly emphasized: the use of tensor notation, Green's functions, and field Lagrangians. Tensor notation is widely used in both quantum field theory and general relativity. Green's functions serve as the foundation of Feynman diagram methods and the perturbative formulation of quantum field theories. Field Lagrangians provide a compact way of describing classical and quantum field theories and, via Noether's theorem, of understanding the important role that symmetries and conservation laws play in these theories. Franklin introduces each of these topics by showing how it applies to the familiar example of classical electrodynamics, but the ultimate goal here is to develop the student's facility with these techniques so they can be applied to general field theories.

The fourth chapter, on gravity, is the most novel. Here, the author considers how Newtonian gravity might be modified to incorporate some of the features of special relativity. Such modifications are shown to qualitatively account for several classic predictions of general relativity, such as the deflection of starlight by gravity and the perihelion precession of Mercury, and the discussion offers some physical insight into the origin of these effects. This approach puts the reader in the position of Einstein faced with the challenge of formulating a relativistic theory of gravity: it is shown how a new theory might be developed, based on physical reasoning and extrapolation from the known theories of classical electrodynamics and Newtonian gravity. The full theory of general relativity is not discussed, but by the end of the book the student will be well prepared to take up its study. Indeed, the author has already paved the way by outlining many of the problems encountered in developing a relativistic theory of gravity and sketching some of the features that one might expect of such a theory. For example, the author uses the field theory techniques developed in previous chapters to show that scalar and vector field theories yield unphysical predictions, but that a theory involving a symmetric rank-two tensor field might be viable.

One feature of the book that I particularly liked is that often before solving a problem, the author first uses physical reasoning to deduce as much about the qualitative behavior of the solution as possible. Only then does he proceed to a detailed calculation. This approach offers greater physical insight than would be achieved by a direct calculation and provides a good model of how a working physicist would actually approach a real problem.

Another nice feature is that the author often incorporates numerical results into the discussion. Computers are powerful tools for developing physical insight and intuition, but their full potential has not yet been realized in physics education. There are two reasons why students would benefit from a greater emphasis on computers: first, computer simulation provides an excellent way to interact and tinker with physical systems that would be impractical to study in the lab, and second, numerical methods are an increasingly important part of the toolkit of most physicists. One appendix of Franklin's book is entirely devoted to numerical methods that are relevant to classical field theory, and at several places in the main text he indicates how such methods could be applied to the topic at hand. For example, in the chapter on special relativity, the equations of motion for a relativistic harmonic oscillator are numerically integrated, and in the chapter on point particles, there are diagrams of radiation fields that are produced numerically. Also, many radiation problems of the sort described in Chapter 3 involve retarded time calculations that cannot be performed analytically, so, numerical methods significantly expand the repertoire of radiation problems that can be treated.

Although on the whole the book is carefully written, I did notice several mistakes. In particular, in two places (sections B.2.3 and C.3.1) the author discusses a particle moving in the electromagnetic field generated by a charged wire sliding parallel to itself at constant velocity. In both instances, the described particle trajectory is incorrect: the particle is shown as "bouncing" along the wire, periodically moving away and then cycling back to a location further along the wire, whereas in fact this behavior does not occur, as can be seen by working in the rest frame of the wire. In the first instance, the incorrect trajectory is obtained by integrating a Newtonian equation of motion in a regime where the Newtonian approximation breaks down; in the second instance, it appears that the full relativistic equation of motion has been incorrectly integrated. There is also a minor pet peeve: the book uses SI units throughout, whereas Gaussian units with $c = 1$ would be more appropriate. For an introductory textbook, SI is preferable because students are already familiar with units like Amps and Ohms, but here, where the focus is on relativistic invariance, the profusion of c's, ϵ_0's, and μ_0's only serves to obscure the symmetry and physical meaning of the equations.

Despite these slight flaws, Franklin's book is a worthwhile introduction to classical field theory. There are three settings in which I think the book would be particularly useful:

(1) The book could be used to supplement the treatment of special relativity or radiation in an undergraduate course on classical electrodynamics. Although much of this material is standard, there are still features here that are new. I particularly liked the discussion of the relativistic harmonic oscillator in Chapter 1 and the derivation of the fields of a charged particle moving at the speed of light in Chapter 2. There is also a good selection of problems, some of which involve numerical computation.

(2) The book could be used as a preliminary to graduate-level quantum field theory and general relativity. The topics of tensor methods, Green's functions, and field Lagrangians covered here are of fundamental importance in these subjects, and students will greatly benefit from having a solid grounding in these techniques.

(3) The book could be easily mined for undergraduate thesis projects, especially those involving the numerical exploration of classical field theories. The appendices in particular provide just what one would want for this purpose: a succinct discussion of the relevant topic, an illustrative example, and references to a more extensive discussion.

Addendum: The author has contacted the reviewer to inform him that conceptual errors, including those noted in the review, have been deliberately introduced into the text without warning in order to test readers.

David Boozer has a Ph.D. in physics from the California Institute of Technology; his interests include classical and quantum field theory, atomic physics, and statistical mechanics.

BOOKS RECEIVED

A Practical Guide to Experimental Geometrical Optics. Yuriy A. Garbovskiy and Anatoliy V. Gluschenko. 239 pp. Cambridge U.P., New York, 2018. Price: $44.99 (hardcover) ISBN 978-1-107-17094-6.

An Introduction to the Atomic and Radiation Physics of Plasmas. G. J. Tallents. 312 pp. Cambridge U.P., New York, 2018. Price: $69.99 (hardcover) ISBN 978-1-108-41954-3.

Conquering the Physics GRE (3rd ed.). Yoni Kahn and Adam Anderson. 295 pp. Cambridge U.P., New York, 2018. Price: $39.99 (paper) ISBN 978-1-108-40956-8.

Extreme-Temperature and Harsh-Environment Electronics: Physics, Technology, and Applications. Vinood Kumar Khanna. 483 pp. IOP Publishing, Bristol UK, 2018. Price: $150 (hardcover) ISBN 978-0-7503-1156-4.

Geophysical Waves and Flows: Theory and Applications in the Atmosphere, Hydrosphere, and Geosphere. David E. Loper. 516 pp. Cambridge U.P., New York, 2018. Price: $84.99 (hardcover) ISBN 978-1-107-18619-4.

Precise Dimensions: A History of Units from 1791–2018. Malcolm Cooper and Jim Grozier (eds.). 179 pp. IOP Publishing, Bristol UK, 2018. Price: $150 (hardcover) ISBN 978-0-7503-1485-5.

Solitons in Crystalline Processes: Statistical Thermodynamics of Structural Phase Transitions and Mesoscopic Disorder. Minoru Fujimoto. 339 pp. IOP Publishing, Bristol UK, 2018. Price: $150 (hardcover) ISBN 978-0-7503-1512-8.

The Heroic Age: The Creation of Quantum Mechanics 1925–1940. Robert D. Purrington. 418 pp. Oxford U.P., New York, 2018. Price: $69.95 (hardcover) ISBN 9780190655174.

The History of Physics: A Very Short Introduction. J. L. Heilbron. 191 pp. Oxford U.P., New York, 2018. Price: $11.95 (paper) ISBN 978-0-19-968412-0.

What is Real? The Unfinished Quest for the Meaning of Quantum Physics. Adam Becker. 379 pp. Basic Books, New York, 2018. Price: $32 (hardcover) ISBN 978-0-465-09606-0.