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Resource Letter MD-1: Maxwell's Demon

Harvey S. Leff
Physics Department, California State Polytechnic University, 3801 W. Temple, Pomona, California 91768

Andrew F. Rex
University of Puget Sound, rex@pugetsound.edu

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RESOURCE LETTER

Roger H. Stuewer, Editor
School of Physics and Astronomy, 116 Church Street
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This is one of a series of Resource Letters on different topics intended to guide college physicists, astronomers, and other scientists to some of the literature and other teaching aids that may help improve course content in specified fields. No Resource Letter is meant to be exhaustive and complete; in time there may be more than one letter on some of the main subjects of interest. Comments on these materials as well as suggestions for future topics will be welcomed. Please send such communications to Professor Roger H. Stuewer, Editor, AAPT Resource Letters, School of Physics and Astronomy, 116 Church Street SE, University of Minnesota, Minneapolis, MN 55455.

Resource Letter MD-1: Maxwell's demon

Harvey S. Loff
Physics Department, California State Polytechnic University, 3801 W. Temple, Pomona, California 91768

Andrew F. Rex
Physics Department, University of Puget Sound, 1500 N. Warner, Tacoma, Washington 98416

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This Resource Letter provides a comprehensive guide to the voluminous literature that has developed around Maxwell's demon, and offers a perspective on issues for which the hypothetical character Maxwell introduced over 120 years ago has inspired continuing research and debate. The code (E) indicates elementary level or general interest material useful to persons just learning the field; (I) indicates intermediate level or somewhat specialized material; and (A) indicates advanced or highly specialized material. No accompanying AAPT reprint book will be available, because an extensive reprint collection (Ref. 29) edited by the authors will be published separately.

I. INTRODUCTION

James Clerk Maxwell first revealed what has come to be called Maxwell's demon in an 1867 letter to Peter Guthrie Tait. He envisioned an intelligent being who could literally direct molecular flows molecule by molecule. Maxwell thought of this hypothetical controller as a selective valve that could allow passage of certain molecules through a partition separating two halves of a gas, generating a temperature difference across the partition. In his 1871 Theory of Heat, Maxwell published his idea, cleverly using it to illustrate the statistical nature of the second law of thermodynamics. In 1874 William Thomson (later Lord Kelvin) coined the term "demon," a name that has stuck with Maxwell's imaginary character for the last 115 years.

Why has Maxwell's temperature demon survived for such a long time? Primarily because it has been a key element in the development and understanding of thermal physics, particularly with respect to the concepts of entropy and irreversibility. Its historical importance and its current interest value make it a natural teaching and learning tool. This can be seen by several examples. First, the tiny demon works on a microscopic scale, in a sea of molecular fluctuations. While its success or failure depends upon how well it can harness this "noise," the demon (and its apparatus) is also subject to thermal noise, which could destroy its effectiveness.

Second, the demon's observations of individual molecules involve quantum measurement phenomena (even though the quantum revolution occurred well after Maxwell's death!). Third, the demon must gather information to reduce the entropy of the gas, and its operation is amenable to an information-theoretic analysis. Leo Szilard realized this in 1929, and Leon Brillouin and Dennis Gabor independently extended Szilard's ideas about 20 years later. Not only were the connections between information and thermodynamic entropy unknown to Maxwell, they are still not entirely agreed upon today. Fourth, the demon sorts molecules on a microscopic level but can affect macroscopic behavior. Maxwell's demon lives at the interface between microscopic and macroscopic physics, and between reversibility and irreversibility. These are rare characteristics.

Fifth, operation of the demon raises the question of how molecular information can be obtained. Until recently, most researchers assumed the use of light signals. This assumption was a key element in the "exorcism" of Maxwell's demon in 1951 by Brillouin and Gabor. But light is not the only way to carry information, and a complete solution of the Maxwell's demon puzzle ought not depend upon its use.

Sixth, the trait of "intelligence" originally ascribed to the demon by Maxwell is somewhat murky, but of interest in the realm of physics. It was addressed by Leo Szilard in his famous 1929 paper, using a pressure demon to operate a one-molecule heat engine. Although Szilard did not specify
how the demon acquires information, his treatment suggests that an essential aspect of the demon's intelligence is memory. In 1957, Rothstein pointed out the importance of memory to the informational view of entropy. A statistical mechanical treatment of a demon's memory is evidently given first by Oliver Penrose in 1970. He observed that periodically resetting a demon's memory is essential to its operation, and that such resetting generates entropy in the environment.

In 1982, Charles Bennett, drawing upon Rolf Landauer's landmark 1961 paper on dissipation in computing, independently discovered the importance of memory for a demon, and argued further that information acquisition need not be dissipative. He concluded that information destruction (i.e., memory erasure, which requires use of a work source) is the fundamental act that saves the second law from a Maxwell's demon. This was a surprising, remarkable event in the history of Maxwell's demon, and stimulated new research and debate.

Other examples of the demon's importance can be cited. The original temperature demon was intended to generate a temperature difference in the gas that could then be used to run a heat engine. Kinetic theory, developed by Maxwell but not used by him in this context, enables an estimate of how long it takes to generate a specified temperature difference. Thus the demon can illustrate the utility of kinetic theory. Additionally, Szilard's one-molecule system with a "pressure demon" is amenable to a quantum mechanical analysis, and is a valuable conceptual tool for understanding quantum measurement theory, entropy, and information. For these and other reasons, Maxwell's demon continues to play an important role in our understanding of thermophysics, quantum theory, information theory, analyses of the limits of computing, and the philosophy and history of science.

The considerable span of time since Maxwell's idea emerged and the substantial scope of disciplines it touches give rise to a rich literature that is usefully categorized by the section headings below. The bibliography that follows includes all known primary literature and a significant fraction of the secondary literature on Maxwell's demon.

II. BACKGROUND SOURCES

A. Early contributions

These references cover the period 1867-1914, and constitute fundamental contributions prior to the advent of quantum theory and information theory.


3. Theory of Heat, J. C. Maxwell (Longmans, Green, London, 1871). Maxwell's public presentation of the demon in his classic book on thermodynamics. His description (Chap. 12) of "a being...who can follow every molecule in its course" is one of the most directly quoted passages in physics. (E)


5. "Ueber den Zustand des Wärmegleichgewichtes eines System von Körpern mit Rücksicht auf die Schwerkraft," J. Loschmidt, Sitzungsber. Akad. Wiss. Wien 73, 128-142 (1876). The second law cannot be a mechanical principle because Newtonian mechanics allows the same sequence of motions backward as forward. (A)

6. "Diffusion," J. C. Maxwell, in Encyclopedia Britannica, 9th Edition (New York, 1878), pp. 214-221. Maxwell writes..."the idea of dissipation of energy depends on the extent of our knowledge...It is only to a being...who can lay hold of some forms of energy while others elude his grasp, that energy appears to be passing inevitably from the available to the dissipated state." (1, A)


10. "Mechanism and Experience," H. Poincaré, Rev. Metaphys. Morale 1, 534-537 (1893), reprinted in Kinetic Theory, Vol. II. Irreversible Processes, edited by S. G. Brush (Pergamon, Oxford, 1966), pp. 203-207. Poincaré writes..."to set heat pass from a cold body to a warm one, it will not be necessary to have the acute vision, the intelligence, and the dexterity of Maxwell's demon; it will suffice to have a little patience." (1)

References 11 and 12 focus on the validity of the second-law in view of Brownian motion of the trap door. See also Ref. 74.


B. Historical works

These references underscore the important historical role played by Maxwell's demon.


18. The Kind of Motion We Call Heat, S. G. Brush (North-Holland, New York, 1976). (1)


C. Reviews

The references in this section provide a good overview of Maxwell’s demon and its connections with thermodynamics, information theory, quantum mechanics, and computation.


D. General background books

The following semipopular and technical books serve as good introductions to Maxwell’s demon and related topics.


32. Life and Energy, I. Asnin (Bantam, New York, 1965). Elementary discussion (pp. 65–76) showing Maxwell’s demon as a tool to dramatize the statistical nature of molecular motion. (E)


37. God and the New Physics, P. C. W. Davies (Simon & Schuster, New York, 1983), pp. 211–213. Davies asks: If a supreme being existed, constrained to act within the laws of physics, could it prevent the end of the universe? He concludes the answer is negative. (E)

38. Order Out of Chaos, I. Prigogine and I. Stengers (Bantam, New York, 1984). Maxwell’s demon is used in discussions of biological systems. (E)


III. SIZILARD’S ONE-MOLECULE ENGINE

These papers focus on the one-molecule heat engine introduced by Leo Szilard in 1929, quantum mechanical extensions thereof, and related matters. Szilard’s simple and elegant model, which entails a Maxwellian “pressure demon,” leads to a remarkable range of ideas and results.


50. Foundations of Statistical Mechanics, O. Penrose (Pergamon, Oxford, 1970), pp. 221–238. Apparently the earliest account of irreversible memory erasure for a Maxwell’s demon. Penrose shows that resetting (i.e., erasing) a demon’s memory is essential, increasing entropy by an amount at least as great as the entropy decrease made possible by the newly available memory capacity. (A)

mation with the negative physical entropy is found to be unjustified, in
contrast with a large body of literature. (A)
52. “Information Theory and Thermodynamics,” O. Costa de Beauregard
Jauho–Barron (Ref. 51) attack of Szilard’s one-molecule model. (A)
53. The Philosophy of Karl Popper, K. Popper (Open Court, LaSalle, IL,
1974), pp. 129–133. Also published under the title, Unended Quest: An
Intellectual Autobiography (Open Court, LaSalle, IL, 1976). Criticism of
Szilard’s suggestion that knowledge and entropy are related. See Ref.
220. (A)
54. “La Logique des Experiences de Pennee et l’Experience de Szilard,”
and Feyerabend’s criticisms of Szilard’s one-molecule heat engine. (I, A)
55. Reference 55 and 56 are quantum mechanical analyses of
Szilard’s one-molecule heat engine that support the view
that resetting the demon’s memory saves the second law.
56. “Maxwell’s Demon, Szilard’s Engine and Quantum Measurements,”
W. H. Zurek, in Frontiers of Nonequilibrium Statistical Physics, edited by
G. T. Moore and M. O. Scully (Plenum, New York, 1984), pp. 151–
161. (A)
57. “Keeping the Entropy of Measurement: Szilard Revisited,” E. Lubkin,

IV. MAXWELL’S TEMPERATURE DEMON

In contrast with Szilard’s one-molecule heat engine,
Maxwell’s original temperature demon operates in a gas
containing many molecules. The following references pro-
vide analyses of such systems, focusing on the implications
of quantum theory and information theory.
In Refs. 57 and 58, Demers argues that the operation of
Maxwell’s demon within the limits of the second law of
thermodynamics demands blackbody radiation and
quantum theory.
57. “Les Demons de Maxwell et le Second Principe de la Thermodynamique,”
Res. 23, 47–55 (1945). (A)
Maxwell’s demon and the (then) new science of information theory,
and introducing the term “negentropy.” (I, A)
60. “The Role of Information Theory in the Inactivation of Maxwell’s
of Brillouin’s arguments, exorcising Maxwell’s demon using prob-
ability arguments. Further details are in Ref. 135. (I)
61. “Les Relations d’Incertitude d’Heisenberg Empeche-t-elle le Demon
de Maxwell d’Opérer,” N. L. Balazs, C. R. 236, 998–1000 (1953). Maxwell’s
demon is not restricted by the uncertainty principle
if the gas is nondegenerate. See also Refs. 57 and 58. (A)
62. “L’Effet des Statistiques sur le Demon de Maxwell,” N. L. Balazs,
C. R. 236, 2385–2386 (1953). Restrictions on Maxwell’s demon by the
uncertainty principle are discussed for Bose–Einstein and Fermi–Dirac
gases. (A)
63. “Some Comments on Entropy and Information,” P. Rodd, Am. J.
Phys. 32, 333–335 (1964). Helpful clarification of Brillouin’s exorcism
of Maxwell’s demon. (I)
64. “A Relation Between the Second Law of Thermodynamics and Quan-
demon’s failure to beat the second law is attributed to energy quantiza-
tion. (I)
results to the case in which the two chamber temperatures are initially
unequal. (I)
66. “Available Work from a Finite Source and Sink: How Effective is
demon delivering maximum work, using a finite heat source and sink
with initial temperatures Tl and Th, has thermal efficiency
\[\eta = \frac{1 - (1 / T_l / T_h)^2)}{(1)}\]
58, 135 (1990). A demon is found to generate power < 1 nW and to take
an average > 4 million years to get a 2-K temperature difference in a large
roomful of air. (I)

V. RELATED DEMONS

In this section, references are concerned with variants of
Maxwell’s original temperature demon and Szilard’s one-
molecule heat engine.
Compton, Phys. Rev. 30, 349–353 (1927). Experimental measurement of
Maxwell’s speed distribution inspired by Maxwell’s demon. (I, A)
69. Thermodynamics for Chemical Engineers, H. C. Weber (New
to Boltzmann, alleged to avoid the need for intelligence in the demon’s
operation. (I)
70. “Can the Rectifier Become a Thermodynamical Demon?,” L. Brill-
ouin, Phys. Rev. 78, 627–628 (1950). Illustration that thermal noise in
a resistor cannot be rectified to transform heat to electric work. (I)
19, 109–112 (1951). Examination of a variant of Maxwell’s demon
that takes advantage of density fluctuations in a gas. (I)
The demon concept is generalized to show that any law can be formu-
lated in terms of the nonexistence of some type of demon. (I, A)
mond’s well-informed heat engine is reexamined to get estimates of
efficiency and power output. (I)
74. The Feynman Lectures on Physics - Vol. 1, R. P. Feynman, R. B.
Leighton, and M. Sands (Addison-Wesley, Reading, MA, 1962). Highly
recommended discussion (pp. 46.1–46.9) of the ratchet and pawl,
discussed a half century earlier by Smoluchowski in connection with
Maxwell’s demon. It cannot operate as a heat engine that violates
the second law. (E, I)
75. “Seeing Entropy—The Incomplete Thermodynamics of the Maxwell
(1974). A demonstration device that illustrates mixing and unmixing,
simulating the action of a Maxwell’s demon, and helping to understand
entropy. (E)
76. “Maxwell’s Demon and Computation,” R. Laing, Philos. Sci. 41,
171–178 (1974). Maxwell’s demon is viewed as a computing automaton. (E, I)
77. “Brownian Movement and Microscopic Irreversibility,” L. G. M.
appears to violate the second law of thermodynamics is proposed. (A)
78. “The Vortex Tube: A Violation of the Second Law,” M. P. Silver-
a Maxwell’s demon. (I)
Discussion (Part I, Sec. 8) of the statistical nature of the second law. (E)
80. “Maxwell’s Demon and Detailed Balancing,” L. G. M. Gordon,
membrane, each pore of which is controlled by an independent molecu-
lar trap door that can exist in either of two states. (A)
References 81–83 deal with the possibility of using
Doppler-shifted radiation to allow Maxwell’s demon to
operate. Denur suggests and supports the idea; Motz and
Chardin give arguments against it.
(1983). (I)
83. “No Free Lunch for the Doppler Demon,” G. Chardin, Am. J.
84. The Second Law, F. W. Atkins (Scientific American Books, New
York, 1984). Discussion (pp. 67–79) of the second law using the idea of
a “Boltzmann’s demon.” (E)
VI. INFORMATION AND THERMODYNAMICS

Maxwell's demon has been the most important case that illustrates connections between thermodynamics and information. The following references concentrate on these linkages.

A. General

86. "Certain Factors Affecting Telegraph Speed," H. Nyquist, Bell Syst. Tech. J. 3, 324–346 (1924). The rate per character at which "intelligence" can be transmitted is taken to be $K \log m$, where $m$ is the number of possible distinct characters and $K$ is a constant. (1, A)


90. "Physical Entropy and Information, II," L. Brillouin, J. Appl. Phys. 22, 338–343 (1951). Discussion of how information can be linked to a decrease in a system's entropy. (A)


In Refs. 95–97, statistical mechanics is developed using the maximum entropy principle of information theory. References 95 and 97 focus mainly on equilibrium statistical mechanics, and the anthropomorphic nature of entropy. Reference 96 covers time-dependent phenomena and irreversibility.


101. "Measurements and Information for Thermodynamic Quantities," G. Lindblad, J. Stat. Phys. 11, 231–255 (1974). Entropy decrease induced by an observer in a system described by a fluctuating thermodynamic parameter is found to be less than the information obtained by the observer. (A)

102. "Loschmidt's and Zermelo's Paradoxes Do Not Exist," J. Rothstein, Found. Phys. 4, 83–89 (1974). These paradoxes are argued to result from self-contradictory language. Resolution entails an operational, informational analysis. See also Ref. 98. (A)


B. Subjectivity of entropy

Entropy in thermodynamics is defined such that entropy differences can be determined experimentally. In statistical mechanics and information theory, probability assignments are required to calculate entropy and to associate it with missing information. Does this imply that entropy is...
subjective? This is addressed in the following references. See also Refs. 98 and 102.


116. "Is the Coarse-Grained Entropy of Classical Statistical Mechanics an Anthropomorphism?," A. Grunbaum, in Modern Developments in Thermodynamics, edited by B. Gal-or (Wiley, New York, 1974), pp. 413–428. Although entropy depends on human choice of cell size in phase space, it is argued that the answer to the title question is negative. (A)


120. Entropy in Relation to Incomplete Knowledge, K. G. Denbigh and J. S. Denbigh (Cambridge U. P., London, 1985), pp. 1–5; 108–112. Critical, detailed analysis of the notion that entropy is subjective, and rejection of commonly used links between information theory and thermodynamics. It is argued that Brillouin’s exorcism of Maxwell’s demon can be accomplished without appeals to information theory or negentropy. (A)

C. Contrasts with Brillouin’s work

Brillouin’s analysis of Maxwell’s demon has met with critical responses from some authors. The following references contain criticisms of, or contrasts with, Brillouin’s ideas. These are distinct from objections (see Sec. VI B) to subjective interpretations of entropy associated with information theoretic approaches.


123. Entropy: The Devil on the Pillion, J. Zernike (Kluwer–Deventer, Deventer, The Netherlands, 1972), Chap. 4. It is argued that the demon and its apparatus must be at the same temperature as the gas, which excludes use of a torch. (1)


D. Biological systems

These references address uses of information concepts in biology. See also Refs. 21, 220, and 221.

126. Thermodynamics and The Free Energy of Chemical Substances, G. N. Lewis and M. Randall (McGraw-Hill, New York, 1923), pp. 120–121. Brief account that predates Szilard’s work and focuses attention on the demon’s entropy. (1)


128. "Communication, Entropy, and Life," R. C. Raymond, Am. Sci. 38, 273–278 (1950). A living system’s entropy is viewed as the sum of positive thermodynamic entropy the system’s constituents would have at thermodynamic equilibrium, and a negative term proportional to the information necessary to build the actual system from its equilibrium state. (1)

129. The Physical Foundation of Biology, W. M. Elsasser (Pergamon, New York, 1958), pp. 203–214. Maxwell’s demon is viewed as a special case of an idealized “Laplacian spirit” observer. Limitations to the concept of an ideal observer are identified as a central point in the question of compatibility between biological and physical law. (A)


E. Information theory, cybernetics, and related books

The following books each develop the theory of information and/or cybernetics, and most include Maxwell’s demon as an example.


135. Science and Information Theory, L. Brillouin (Academic, New York, 1956), Chap. 13. Thorough discussion of Brillouin’s contributions to Maxwell’s demon. Information is categorized as either free or bound, an idea not present in Brillouin’s original exorcism of Maxwell’s demon, Ref. 59. (1)


137. Cybernetics, N. Wiener (MIT, Cambridge, MA, 1961). A significant volume in the development of information theory. (1, A)


139. Intelligent Machines: An Introduction to Cybernetics, D. A. Bell (Blaisdell, New York, 1962), pp. 7–10. Maxwell’s demon is described along the lines of Brillouin and Raymond (Refs. 59 and 71). (1)

140. Great Ideas in Information Theory, Language, and Cybernetics, J. Singh (Dover, New York, 1966), Chap. VII. (1)


142. Cybernetics A to Z, V. Pekelis (Mir, Moscow, 1974), pp. 104–110. Maxwell’s demon is used to impart an understanding of entropy. (E)


144. Optics and Information Theory, F. T. S. Yu (Wiley, New York, 1976), Chaps. 4–6. Detailed treatment of Maxwell’s demon, referring heavily to the work of Gabor and Brillouin (Refs. 47, 59, and 135). (1)
F. Kinetic theory, thermodynamics, and statistical mechanics books

The following thermal physics books deal with aspects of Maxwell's demon. References 145 and 146 contain Jeans' idea that a demon could "effect in a very short time what would probably take a very long time to come about if left to the play of chance." For a contrasting view based on kinetic theory, see Refs. 66 and 67.


146. An Introduction to the Kinetic Theory of Gases, J. H. Jeans (Macmillan, New York, 1940). (1)

147. Introduction to Chemical Physics, J. C. Slater (McGraw-Hill, New York, 1939). Irreversibility is linked to the Heisenberg uncertainty principle, which prevents demons from operating on arbitrarily small scales. See Refs. 61 and 62. (1)

148. Introduction to Chemical Thermodynamics, L. E. Steiner (McGraw-Hill, New York, 1941). p. 166. Maxwell's demon is considered in connection with a fluctuation whereby a gas spontaneously collapses to a volume smaller than the container, and a retaining wall is put in place. (1)

149. Chemical Engineering Thermodynamics, B. F. Dodge (McGraw-Hill, New York, 1944), pp. 48–49. The author argues that a demon could violate the second law. (1)


151. The Nature of Thermodynamics, P. W. Bridgman (Harper, New York, 1961), pp. 155–159. Important issues that threaten a demon's ability to operate are addressed. (1)


153. Statistical Mechanics, R. Kubo (North-Holland, Amsterdam, 1965), p. 13. A Maxwell's demon cannot operate continuously because it will heat up, get sick, and lose control. A similar view is in Ref. 74. (1)


155. Entropy and Low Temperature Physics, J. S. Dugdale (Hutchinson University Library, London, 1966), pp. 151–153. It is emphasized that fluctuations cannot be used systematically to violate the second law. (1)


158. An Introduction to Thermodynamics, R. S. Silver (Cambridge U. P., London, 1971), pp. 42 and 125. The demon's operation is contrasted with macroscopic engineering processes. (1)


160. Two Essays on Entropy, R. Carnap (University of California Press, Berkeley, 1977), pp. 72–73. Mathematical treatment in which, among other things, a distinction between logical and physical entropy is made. (A)


VII. LIMITS OF COMPUTATION

A fundamental issue in the theory of computation is whether computing processes, in principle, are necessarily dissipative. There's still debate among researchers on this issue. The dominant view is that reading and writing operations can be done with arbitrarily little dissipation—but information erasure must be accompanied by heat transfer to the environment (though not necessarily by irreversibility in the thermodynamic sense; see Ref. 191). References in this section illustrate the progress and spirited debate on dissipation in computing, and address the relevance of this issue to Maxwell's demon.


References 170–175 illustrate the spirited debate on dissipation in computation.


A. Quantum theory and thermodynamics

References 194 and 195 helped establish the connections between quantum theory and thermodynamics.


199. The Philosophy of Quantum Mechanics, M. J. J. Schmidt (New York, 1974). Smoluchowski's and Szafran's influences on von Neumann's measurement theory (Ref. 198) are discussed. (A)


203. The Ghost in the Atom, P. C. W. Davies (Cambridge U. P., Cambridge, 1986). Discussion of an electron in a partitioned box has relevance to Szafran's heat engine model and a related thought experiment of Einstein. See also Ref. 201. (E)


B. Time in thermodynamics

Much of classical thermodynamics is "timeless" in the sense that it deals with time-independent equilibrium states and reversible thermodynamic paths. On the other hand, time is central to the issue of irreversibility. The following references address aspects of time in thermodynamics and information gathering. See also Refs. 66 and 67.


207. The Enigma of Time, P. T. Landsberg (Adam Hilger, Bristol, 1982). The demon is discussed in relation to energy requirements and the statistical character of the second law. (A)


C. Entropy articles

This section contains articles that provide perspectives on the entropy concept and the relationship between entropy and information. See also Ref. 98.


210. "Order, Organization, and Entropy," M. J. Klein, Br. J. Philos. Sci. 4, 158–160 (1953). A system's organization and entropy can increase (or decrease) simultaneously. The former relates to the wavefunction; the latter is linked to the number of relevant energy states. (A)
Feynman’s proof of the Maxwell equations

Freeman J. Dyson
Institute for Advanced Study, Princeton, New Jersey 08540

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Feynman’s proof of the Maxwell equations, discovered in 1948 but never published, is here put on record, together with some editorial comments to put the proof into its historical context.

I. THE PROOF

As I mentioned in my talk at the Feynman Memorial Session of the AAAS meeting in San Francisco,1 Feynman showed me in October 1948 a proof of the Maxwell equations, assuming only Newton’s law of motion and the commutation relation between position and velocity for a single nonrelativistic particle. In response to many enquiries, I here publish the proof in a form as close as I can come to Feynman’s 1948 exposition. Unfortunately, I did not have Feynman’s manuscript nor my original notes. What follows is a version reconstructed at some unknown time from notes which I discarded.

Assume a particle exists with position \( \mathbf{x}_j \) \((j = 1, 2, 3)\) and velocity \( \mathbf{v}_j \) satisfying Newton’s equation

\[
m \mathbf{v}_j = F_j (\mathbf{x}_j, \mathbf{v}_j, t),
\]

with commutation relations

\[
[m_j, m_k] = i \hbar \delta_{jk}.
\]

Then there exist fields \( E(x, t) \) and \( H(x, t) \) satisfying the Lorentz force equation

\[
F_j = E_j + \epsilon_{jkl} \mathbf{v}_k H_l,
\]

and the Maxwell equations

\[
\begin{align*}
\text{div } H &= 0, \\
\frac{\partial H}{\partial t} + \text{curl } E &= 0.
\end{align*}
\]

Remark: The other two Maxwell equations,

\[
\begin{align*}
\text{div } E &= 4\pi \mathbf{\rho}, \\
\frac{\partial E}{\partial t} - \text{curl } H &= 4\pi \mathbf{j},
\end{align*}
\]

merely define the external charge and current densities \( \mathbf{\rho} \) and \( \mathbf{j} \).

Proof: Equations (1) and (3) imply

\[
[x_j, F_k] + m [\mathbf{v}_j, \mathbf{v}_k] = 0.
\]

The Jacobi identity

\[
[x_j, [x_k, x_l]] + [x_j, [x_l, x_k]] + [x_l, [x_k, x_j]] = 0
\]

with (3) and (9) implies

\[
[x_j, x_l] = 0.
\]

Equation (9) also implies

\[
[x_j, F_k] = - [x_k, F_j].
\]