Einstein's Relativity/Thermodynamics Analogy: Some Evidence from His Later Years

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Einstein began using the relativity theory/thermodynamics comparison not merely as a *post hoc* justification but as a description of the path he had followed in developing special relativity. In particular, Einstein emphasized that he was motivated by his skepticism toward Maxwell's equations. The Lorentz transformations are not simply a by-product of Maxwell's equations or any specific dynamical law. Like the principles of thermodynamics, they were derived from well-established empirical facts. For this reason, they could be elevated to a constraint that *all* laws of nature must satisfy. Additional results are obtained by modifying the existing laws of nature, valid in the limiting case, so that they satisfy this constraint.

In September 1933, Einstein left Europe and permanently settled in the United States in October, taking on the position of professor at the Institute for Advanced Study in Princeton. At the end of December of 1934, in one of his first public appearances in his newly adopted country, Einstein delivered the Gibbs lectures in Pittsburgh. They were published the following year (Einstein 1935). The paper attempted to provide a new proof of mass-energy equivalence that relied solely on mechanics, avoiding any reference to electrodynamics. Special relativity, Einstein pointed out in the opening paragraph, emerged from the Maxwell electrodynamics. Consequently, even in the derivation of mechanical concepts, electrodynamic considerations played an essential role. However, upon closer inspection, this is a misunderstanding: "The Lorentz transformation, the real basis of the special relativity theory in itself, has *nothing to do* with the Maxwell theory" (Einstein 1935, 223). As we shall see, this viewpoint would be repeated in various forms in many writings from Einstein's American years. Lorentz and Poincaré uncovered the Lorentz transformations as a formal property that the Maxwell's equations equations happen to satisfy. Einstein, however, doubted that "the energy concepts of the Maxwell theory [could] be maintained in the face of the data of molecular physics" (Einstein 1935, 223). Thus, he derived the Lorentz transformation from well-confirmed empirical facts and elevated it to a fundamental requirement that *any* fundamental law of nature must satisfy. In this sense, the content of special relativity could be "summarized in one sentence", with the characteristic form of an imperative: “all natural laws *must* be so conditioned that they are covariant with respect to Lorentz transformations” (Einstein 1940, 490; my emphasis). “At first”, as Einstein explained in private correspondence a few years later to Swann, “nothing is stated about the structural laws of nature other than the fact that they should be Lorentz-invariant” (Einstein to Swann, Jan. 24, 1942; EA, 20-624). Relativity theory establishes only a formal dependency on how coordinates must enter into structural laws, imposing a strong constraint on their formulation.

“At first,” as Einstein explained in private correspondence a few years later, in special relativity Swann , “nothing is stated about the structural laws of nature other than the fact that they should be Lorentz-invariant” (Einstein to Swann, Jan. 24, 1942; EA, 20-624). Relativity theory only establishes a formal dependence on how the coordinates must enter into the structural laws, imposing a strong constraint on their formulation. The introduction of this particular set of rules for coordinate conversion is, in principle, arbitrary. However, once coordinate numbers are interpreted as readings on rods and clocks, the Lorentz transformation makes predictions that can be experimentally validated or disproved. Then, only one choice is possible. The privileged role played by rods and clocks as “(idealized, but in principle conceived as realizable) as independent physical objects, which, [are] linked to the coordinates of the theory”, is undoubtedly questionable from a logical point of view (Einstein to Swann, Jan. 24, 1942; EA, 20-624). Indeed, rods and clocks are ultimately physical systems like any other, governed by some ‘structural’ law of nature, which in turn requires coordinates for its formulation. Nevertheless, Einstein insisted that the strategy to assign physical meaning to spatial and temporal coordinates before introducing any dynamical law was a conscious one. Indeed, “from the standpoint of our experience,” “the (in principle) existence of those objects that can serve as measures for coordinates” could be considered “*better justified than any particular structural laws, e.g., Maxwell’s equations* (Einstein to Swann, Jan. 24, 1942; EA, 20-624)”. The claim that relativistic kinematics was ‘better justified’ than any particular law of nature is key to understanding Einstein’s comparison between thermodynamics and relativity theory. This hypothesis is confirmed by sparse but consistent textual evidence that can be gathered from several writings of this period.

In Spring 1946, Einstein accepted (Einstein to Schilpp, May 29, 1946; EA, 42-513) to write what he jokingly called his “autobiographical obituary” for the Schilpp volume (Schilpp 1949) in his honor. The manuscript (Einstein 1946) was completed a few months later (Schilpp to Einstein, Feb. 8, 1947; EA, 42-515). As with other issues, the text constitutes a fundamental document for understanding Einstein’s relativity/thermodynamics analogy. Indeed, for the first time, Einstein claims that, in setting up special relativity, he had consciously chosen to follow the model of thermodynamics. While Einstein’s later recollections might be unreliable, what is noteworthy is the very fact that Einstein’s use of the relativity theory/thermodynamics analogy shifted from the ‘context of justification’ to the ‘context of discovery.’

Einstein recalled that, already at the turn of the century, he had realized that Planck’s radiation law “contradicts the mechanical and electrodynamic basis, upon which the derivation otherwise depends” Einstein 1946, 17; tr. 1949a, 45. In other words, the thermodynamic equilibrium between matter and radiation could never be achieved if Newton and Maxwell equations held exactly. The energy of a mechanical system capable of oscillations (Planck’s electromagnetic resonators representing the atomistic constituents of matter) probably did not vary continuously, as it did in classical mechanics. Furthermore, Einstein began to speculate that the expression for the density of radiation energy implicitly presupposed by Maxwell's equations might also need to be challenged. Einstein claimed that he already knew in 1905 that Maxwell's theory led to incorrect fluctuations of radiation pressure on a freely moving mirror immersed in heat radiation, as described by Planck's law (Einstein 1946, 17; tr. 1949a, 45; cf.above **??**). The 'electromechanical worldview' resting on Newtonian point mechanics and Maxwell's field equations began to waver. As Einstein recollected, "[i]t was as if the ground had been pulled out from under one, with no firm foundation to be seen anywhere, upon which one could have built" (Einstein 1946, 17; tr. 1949a, 45; cf. (Klein 1980; Rynasiewicz and Renn 2006)). It was apparently in this context that Einstein decided to construct special relativity following the example represented by thermodynamics:

> Reflections of this type made it clear to as long ago as 1900, shortly after Planck's trailblazing work, that neither mechanics nor electrodynamics[1] could (except in limiting cases) claim exact validity. By and by I despaired of the possibility of discovering the true laws by means of constructive efforts [*konstruktive Bem hüngen*] based on known facts. The longer and the more despairingly I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to the assured results. The example I saw before me was thermodynamics. The general principle was there given in the theorem: *the laws of nature are such that it is impossible to construct a perpetuum mobile (of the first and second kind).* How, then, could such a universal principle be found?. Einstein 1946, 19; tr. 1949a, 52

This famous passage represents Einstein's direct attempt to explain the relativity/ thermodynamics analogy. Here, Einstein points more explicitly to what he had only alluded to forty years earlier in the letter to Sommerfeld of January 1908 that we have quoted above (**??**): it was the failure of the *electromechanical worldview* that led him to adopt an unconventional approach to the electrodynamics of moving bodies (**??**). Einstein could have attempted to find a solution to this problem by directly modifying classical mechanics and electrodynamics. Indeed, he famously attempted to formulate an emission theory of light (Shankland 1963). When all direct 'constructive efforts' failed, Einstein raised a different kind of question: "which is the law-making or constraining principle on which your constructive efforts should be based?" (Einstein to Waldinger, Mar. 12, 1946; EA, 27-358). This question represents the core of the principle strategy. Such 'constraining principles' can be found once we follow the "logical equivalent" of the strategy used in thermodynamics. "In both theories, it's about deriving deductively the consequences from a general formal principle (in thermodynamics the postulate of the impossibility of a *perpetuum mobile*) where the formal principle is based on empirical grounds)" (Einstein to Amiet, Dec. 17, 1947; EA, 25-335).

As Einstein explained in a letter to Robert Amiet written at the end of 1947, in setting up special relativity he could rely on "a plenty of experience, with the addition of Newton's mechanics, of the equivalence of all inertial frames," (Einstein to Amiet, Dec. 17, 1947; EA, 25-335), an equivalence that could never be violated despite all attempts. "A plenty of experiential knowledge" (Einstein to Amiet, Dec. 17, 1947; EA, 25-335), together with Lorentz-Maxwell theory, suggested "considering the constancy of the vacuum speed of light as secure", thereby excluding emission theories of light. "The apparent incompatibility of these two principles [*Grundsaetze*]," Einstein further

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[1] The word 'thermodynamics' which appears in the manuscript and in the first English edition is a typo (cf. Abiko 2003).

explained to Amiet, “forced a critical consideration of the physical meaning of spatial and temporal coordinates in physics” (Einstein to Amiet, Dec. 17, 1947; EA, 25-335). By dropping absolute simultaneity, Einstein could obtain the Lorentz transformations as the sought-for formal dependence between coordinates, ensuring that the speed of light remains invariant. This set of transformations is not arbitrary; once coordinates are interpreted as readings on rods and clocks, they can be verified as true or false. There is nothing special “per se” in the variables x, y, z, t, except for the fact that, in fundamental laws of nature, dynamics are usually expressed as a single-valued function of the coordinates. Thus, the formal dependence between coordinates encoded in the Lorentz transformations enters into the formulation of *all* fundamental laws of nature, imposing a strong constraint on the forms they can assume: “This is a restricting principle for natural laws, comparable to the restricting principle of the non-existence of the *perpetuum mobile*, which underlies thermodynamics” Einstein 1946, 21; tr. 1949a, 57.

The motivation for the relativity/thermodynamics analogy then becomes understandable. Just as the two principles of thermodynamics can be derived independently of mechanics, Einstein aimed to derive the Lorentz transformation independently of Maxwell electrodynamics, which “does not do justice to the energetic properties of radiation” 63[Einstein1949]. Einstein started from two empirically confirmed principles and asked how the laws of nature should look if the two postulates must hold. This “reversal of the trend” (Wigner 1949) was the key point: “Maxwell’s equations imply the ‘Lorentz group,’ but the Lorentz group does not imply Maxwell equations” 14[Einstein1950]. Instead of being derived from Maxwell’s equations, in Einstein’s approach, the Lorentz transformations are *defined independently* of Maxwell equations, as the coordinate transformations, “which leave a particular value of the velocity—the velocity of light—invariant”[14][Einstein1950]. Precisely because they are defined independently from Maxwell’s equations, such transformation equations become a “*heuristic principle* valid far *beyond the range of the applicability or even validity of the equations themselves*” 14[Einstein1950]. The advantage of the theory consists in the fact that Lorentz covariance “limits the possible natural laws in a definite manner” 14[Einstein1950], without having been derived from any of them. The drawback of this approach is that it tells “us what is possible but does not tell us what reality is” (Einstein in conversation with R.S. Shankland on February 4, 1950; in Shankland 1963, 49). Once relativistic kinematics has been established, theories describing the dynamical behavior of matter and fields must be set up. This is, however, an entirely different ‘constructive’ approach. A special-relativistic particle dynamics, electromagnetism, elasticity, etc., must be developed starting from their non-relativistic counterparts. One should require that solutions to the appropriate dynamical equations exist that serve as a ‘model’ for the behavior of existing physical systems.

Einstein explained more explicitly the rationale behind this indirect strategy in an often-quoted letter to Laue at the beginning of 1952. Laue, in the newly published 5th edition of his relativity textbook (Laue 1952), had indicated Maxwell electrodynamics among the empirical confirmations of special relativity. Einstein objected that this was misleading. Around 1905 (based on his thought experiment of a Brownian motion of a mirror in a field of radiation), he was already convinced that the Maxwell equations had to be modified in light of quantum phenomena. For this reason, special relativity “is based essentially only on the constant c, and *not on the presupposition of the reality of the Maxwell field*” (Einstein to Laue, Jan. 17, 1952; EA, 16-168; my emphasis). Thus, in addition to the relativity postulate, Einstein—incapable of accounting for the structure of radiation—elevated only one isolated aspect of Maxwell's theory to the status of a second, more restrictive postulate. The new kinematic requirement is not dependent on the complete truth of Maxwell electrodynamics, but only on a small part of it, which seemed robust to Einstein and was expressed by the light postulate. In the last fifty years, Einstein pointed out, nothing new had been discovered to explain the granular structure of radiation. Einstein hoped that this point of view could make his quixotic search for a unified field theory clearer. "One cannot trust Maxwell's equations," he wrote, "and, because of the general relativity principle, one has to rely on field and differential equations" (Einstein to Laue, Jan. 17, 1952; EA, 16-168). If one relies on the principle of general covariance, the field concept becomes inevitable, and Einstein did not see any possible way other than a pure field theory, despite the challenge of deriving the atomistic and quantum structure of reality from it. Nevertheless, trusting the general principle of relativity was, according to Einstein, the only way when "one has come to despair of arriving at a deeper basis [*Tieferlegung*] of the theory by intuitive [*anschaulich*] constructive means" (Einstein to Laue, Jan. 17, 1952; EA, 16-168).

In spite of the usual rhetoric of the 'physics of desperation,' this was one of Einstein's most important and original methodological insights. In the same year, his first biographer Carl Seelig asked Einstein for some comments about his 1919 London time article. In his reply, Einstein described to Seelig his work in relativity theory as guided by the search for restrictive principles, "formal conditions which constrain [*einschränken*] the number of possible theories" (Einstein to Seelig, Jan. 1, 1952; EA, 39-025). Einstein considered this an essential feature of his work. Einstein's major successes as a theorist were indeed obtained by searching for progressively more restrictive 'requirements' to impose on the laws of nature. special relativity ultimately introduced nothing but the restriction on the form that possible laws of nature can assume. By providing a field-theoretical account of gravitation, general relativity, through its incorporation of the principle of general covariance, imposed a stronger restriction on any future physical theory that includes gravitation. If the principle of general covariance has to hold, reality should be represented by a continuous field, and the particle-like character should be deduced by the integration of a non-linear system of equations (Einstein to Mauritius Renninger, May 3, 1953; EA, 20-027). However, without the heuristic guide of a further restrictive principle, one does not have any clue as to what may be the mathematical structure of the 'total field.' One faces again the "dangerous obstacle in arbitrary choice (*embarras de richesse*)" (Einstein 1949b, 680). In pursuit of a unified field theory, Einstein was forced to proceed "in a constructive way" (Einstein to Mauritius Renninger, May 3, 1953; EA, 20-027), trying out new mathematical approaches and then discarding them when they did not produce the expected results. However, this procedure is usually less reliable: "I came to this opinion not only through the futility of many years of efforts but also through the experience of gravitational theory" (Einstein to De Broglie, Feb. 8, 1954; EA, 8-311). The letter would be impossible to find, without a formal principle, the principle of general covariance, that restricts the range of possible generalizations of the Poisson equations to essentially one single choice.

Conclusion

The first and prototypical example of this indirect strategy remains the case of special relativity, as Einstein pointed out again in correspondence with Seelig just before his death. In 1953, Edmund Whittaker, a mathematician at the University of Edinburgh, finished the second volume of the new edition of his history of the aether theories (Whittaker 1910). The volume (Whittaker 1953) included a chapter entitled 'The Relativity Theory of Poincaré and Lorentz '. In the chapter, as one might guess from the title, Einstein's role in the relativity revolution was downplayed. Born, who was at that time working in Edinburgh and was a good friend of Whittaker, wrote to Einstein to warn him (Born to Einstein, Sep. 26, 1953; Born and Einstein 1969, Doc. 102). Einstein did not show much interest (Einstein to Born, Oct. 2, 1953; Born and Einstein 1969, Doc. 103). However, later, he offered a brief comment to his biographer Carl Seelig (1954), who had asked his opinion on the same matter (Seelig to Einstein, Feb. 17, 1955; EA, 39-070). The letter has become famous, and it offers a good summary of Einstein's stance towards the difference between his 'principle' approach and Lorentz's and Poincaré's 'constructive' one.

Einstein conceded that, around 1905, special relativity was, so to speak, in the air. "Lorentz had already recognized that the transformations named after him are *essential for the analysis of Maxwell equations*, and Poincaré deepened this insight still further" (Seelig to Einstein, Feb. 17, 1955; EA, 39-068; my emphasis). Einstein recalled that he was accustomed only to the older literature. However, most of all, he emphasized what he thought were the two peculiarities of his approach: (1) "The new feature of it was the realization that the Lorentz transformation *transcends its connection with Maxwell's equations* and has to do with the nature of space and time in general", that is, with a reflection about the physical meaning of spacetime coordinates (Seelig to Einstein, Feb. 17, 1955; EA, 39-068). Once one interprets coordinates as measured with rods and clocks, this new set of transformation laws becomes empirically testable independently from any particular dynamical law, including Maxwell's equations. This latter aspect was "of particular importance," since, as we have seen, according to Einstein, "Maxwell's theory did not account for the microstructure of radiation and could, therefore, have no general validity" (Einstein to Seelig, Feb. 19, 1955; EA, 39-070). But, of course, setting up new kinematics does not bring about any further physical results. The next step is to recognize that "'Lorentz invariance' is a general condition *for any physical theory*" (Einstein to Seelig, Feb. 19, 1955; EA, 39-068; my emphasis). Existing laws valid for low velocities that do not satisfy this condition have to be modified; through this adaptation, one obtains *new* relativistic laws. Some of the effects predicted by these modified theories could be tested empirically. As we have seen, this was precisely the strategy that led to Einstein's successful derivation of the speed-dependent mass of the 'electron.' Both stages are essential: (1) The new kinematics based on the Lorentz coordinate transformations are not a byproduct of Maxwell's equations and could be obtained without any reference to them (or to any other existing law of nature) from the two postulates, given a physical meaning and compared to experience in terms of the behavior of rods and clocks; (2) Precisely for this reason, it could assume the role of a constraint imposed on all possible laws of nature, insofar as coordinates enter into their formulation.

Einstein died in April 1955, a few months after this letter was drafted. On July 16, 1955, Born delivered a keynote lecture on relativity at the Bern conference on general relativity (Kervaire and Mercier 1956), celebrating the 50 years of general relativity. On that occasion, Born mentioned the Seelig-Einstein correspondence in public for the first time. Born's remarks, it seems to me, grasp the essential point. According to Born, the letter shows that, in Einstein's view, "the principle of relativity was more general and should be founded on considerations *which would be still valid when Maxwell's equations had to be discarded*", that is, replaced by a theory that would account for the discrete structure of radiation, such as "our present quantum electrodynamics" (Born 1956, 249). The difference between Einstein's approach and the Lorentz-Poincaré approach lies precisely here, as Wolfgang Pauli pointed out just before his death in 1958 by commenting on the very same letter. According to Pauli, Lorentz or, better, Poincaré —who was the first to recognize the group property of the Lorentz transformations—"*starts from the familiar equations of Maxwell* and shows that they admit certain transformations" (Pauli 1959, 241; 1994, 118; my emphasis). By contrast, Einstein sensed that Maxwell electrodynamics could not be generally correct. "He, therefore, formulated the invariance of the laws of nature with respect to Lorentz transformations as *a general postulate which is more reliable than Maxwell equations*"(Pauli 1959, 241; my emphasis; 1994, 119). For this reason, "[h]e established the postulate *independently of these equations*" (Pauli 1959, 241; 1994, 119; my emphasis), from kinematic considerations "on the compatibility of the principle of relativity in translational motion with the principle of constancy of the velocity of light, assuming the relativity of simultaneity" (Pauli 1959, 241; my emphasis; 1994, 119).

These few remarks reveal the rationale behind Einstein's characterization of special relativity as a principle theory, by forgoing any reference to mechanics or electrodynamics. As Cornelius Lanczos—Einstein's former assistant and lifelong correspondent—made a similar point in a celebratory article written after Einstein's death. The Lorentz transformation, he wrote, "occurred in consequence of certain mathematical properties of Maxwell's equations and were investigated by Lorentz and Poincaré " (Lanczos 1955, 1202). However, "it was Einstein, who discovered the proper interpretation of the Lorentz transformations as relations between coordinates" in general. As a consequence, "all equations of physics had to be revised in order to bring them in harmony with the relativity principle" (Lanczos 1955, 1202). In this way, as Lanczos wrote some years later, Einstein transformed physics into a two-floor building. Previously, physics remained on the first floor, attempting "to find some mathematical law which will fit the experiments", but Einstein erected "a new *second floor*", "in which the mathematical law is no longer accepted as a more or less accidental description of natural events", but as a consequence "of some sweeping philosophical principles" (Lanczos 1959, 51). The success of Einstein's work derived from the fact that he "never dealt with *specific equations* but with all-comprehensive *principles* from which profound consequences could be deduced" (Lanczos 1965).

The characterization of a second-order theory seems indeed to reflect how relativity was pursued by early relativists. As Valentine Bargmann, Einstein's former assistant, noted, in the early years, the goal was "to extend relativity to various parts of physics by *adjusting already existing theories to the relativistic postulates*" (Bargmann 1960, 190; my emphasis). For small velocities, the theories could be taken for granted, and "although their relativistic generalization required ingenuity and penetrating analysis", "no radical change" was needed. With the progress of atomic physics and especially of quantum theory, the role of special relativity revealed a stronger heuristic power (Bargmann 1960, 191). "The problem was no longer to 'translate' a previously established theory into a relativistic form" (Bargmann 1960, 191), but increasingly "the theories were relativistic from the start, and relativistic considerations were crucial for the choice of their basic postulates" (Bargmann 1960, 191). Dirac's theory of the electron, e.g., "was not obtained from an established non-relativistic theory, but derived from basic quantum theoretical and relativistic postulates" (Bargmann 1960, 191). The relativistic energy-momentum relation uniquely determined the form of the Dirac Hamiltonian, leading to the four components of the wave function (together with their curious transformation properties) and to the electronic spin (Bargmann 1960, 191).

As is well known, the current debate about the foundations of -theories has taken the form of the opposition between a geometrical and a dynamical approach. In both cases, relativity theory is treated as a constructive theory: a constructive theory of the material structure of rods and clocks (Brown) or a constructive theory of the geometrical structure of Janssen). As has been rightly pointed out, these are ultimately only two sides of the same coin. In this sense, the geometrical/dynamical opposition does not capture the critical difference between the Einstein/Minkowski and Lorentz/Poincaré approaches. In my view, the real issue at stake can be better framed by resorting to Marc Lange's opposition between 'byproducts' and 'constraints.' For Lorentz and Poincaré, the Lorentz transformations were a byproduct of *certain* laws governing field and matter, as a feature that they *happen to* possess. Einstein transformed such a coincidence into a constraint. He derived the new kinematics from generalizable facts summarized in the two postulates that *all* laws of nature *must* be Lorentz invariant. The insertion of the word 'all' turned the Lorentz transformation, from a 'analytic' principle satisfied by the existing laws, into a 'synthetic' principle from which one can extract new laws starting from the existing ones.

Precisely in this sense, relativity theory, like thermodynamics, is best characterized as a 'theory of principles.' As we have tried to show, the characterization of special relativity as a 'theory of principles' has two meanings that are often hard to disentangle. It indicates (a) a *class of existing theories*: principle theories, unlike the usual physical laws, do not directly say anything about the properties of any specific physical system; rather, they put constraints on them (b) a *strategy for finding new theories*: instead of searching directly for the laws of nature, first search for constraints that limit the number of possible candidates . In this sense, Einstein was indeed a *Prinzipienfuchser*, a physicist who was extremely successful in formulating 'principle theories' and in using the 'principle strategy' for obtaining his main results. Indeed, Einstein seemed to have realized that his major achievements as a theoretical physicist were ultimately the application of a sort of algorithm for generating new knowledge: (1) search for empirical facts that can be translated into mathematically formulated principles; (2) check if the existing laws of nature are compatible with those principles; (3) if not, modify them so that they do; (4) compare the modified laws with experience .