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THE RISE OF SPECIAL RELATIVITY: HENRI POINCARÉ'S WORKS BEFORE EINSTEIN[0]

Abstract - Since at least 1953 - date of publication of Edmund Whittaker's book on the history of aether and electricity theories, containing a chapter entitled *The Relativity Theory of Poincaré and Lorentz* - a very alive, and sometimes polemic, debate has been opened on the history of special relativity and on the role of Lorentz and Poincaré before Einstein. Nevertheless, almost all among historians, often on the ground of an incomplete analysis of original papers, undervalue the contribute given by Lorentz and Poincaré. Also the deepest studies until today performed by Arthur I. Miller on this aspect of Poincaré's work, agree with the common undervalue of the specific works of the great french physicist. Here, I would like to show by a new historical analysis of Poincaré's and Einstein's papers, that there is no doubt Poincaré must be considered the actual creator of special relativity.

1. Introduction

Since at least 1953, when Edmund Whittaker published the second volume of *A History of the Theories of Æther and Electricity*, containing a chapter

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[0] Parts of the material presented in this paper were discussed for the first time in a conference, entitled *Jules-Henri Poincaré e la nascita della relatività speciale*, and delivered at the *LXXIX Congresso Nazionale Società Italiana di Fisica, Udine 27 Settembre - 2 Ottobre 1993* on 27 September 1993; then, in a conference entitled *Jules-Henri Poincaré and the Rise of Special Relativity*, delivered at the *Congrès International Henri Poincaré, Nancy 14-18 Mai 1994*, on 18 May 1994; in a conference entitled *Henri Poincaré and the Rise of Special Relativity*, delivered at the *International Seminar Devoted to the 140th Birthday of Henri Poincaré, High Energy Physics and Field Theory XVII Seminar, Protvino (Moscow) June 27 - July 1, 1994*, on 27 June 1994 (see a Russian interview-summary published on *Yckoriteav* **4** (**181**) (14 July 1994), p. 2; in a conference entitled *La fisica del '900: Henri Poincaré e la relatività*, delivered at the *Seminari di Storia delle Scienze, Almo Collegio Borromeo, Pavia 1995*, on 30 March 1995. Partial results of this historiographical inquiry were discussed in: *Henri Poincaré and the rise of special relativity* , in *Quanta Relativity Gravitation: Proceedings of the XVIII (1995) Workshop 'Problems on High Energy Physics and Field Theory*, Protvino (Mosca),1996, pp. 3-31; a review of the book *Relatività Speciale* by A. A. Tyapkin, in *Le Scienze* n. **307** (March 1994), p. 92; a review of the book *Scritti di Fisica-Matematica* by J.-H. Poincaré, edited by U. Sanzo, in *Le Scienze* n. **312** (August 1994), pp. 88-89; *Note Storico-Critiche sul Mutamento e il "Realismo": Henri Poincaré, la Relatività Speciale e le Teorie Fisiche*, in *Ancora sul Realismo. Aspetti di una Controversia della Fisica Contemporanea*, ed. by G. Giuliani, Goliardica Pavese, Pavia 1995, pp. 241-249; *Note sul tempo e sul moto attraverso la storia della fisica e le critiche filosofiche*, in *Atti del XIII Congresso Nazionale di Storia della Fisica*, ed. by A. Rossi, Conti, Lecce 1995, pp. 9-43.

entitled *The Relativity Theory of Poincaré and Lorentz*,[1] the indeed older controversy on the authorship of special relativity was opened again to a wide and long debate.[2]

From that date, many historians and physicists have again recognized the Poincaré's contribution and Lorentz' too (indeed, in 1953, for the first time also Einstein spoke explicitly about Poincaré's contribution); other authors have stated a sort of a *simultaneous* [3] "discovery or invention", but only some

[1] *The Relativity Theory of Poincaré and Lorentz* , in E. Whittaker, *A History of the theories of Aether and Electricity. The Modern Theories 1900-1926*, Nelson, London 1953, ch. II, pp. 27-77.

[2] Already Wolfgang Pauli, in his *Relativitätstheorie*, in *Encyclopädie der mathematischen Wissenschaften*, vol. V, 19, Teubner, Leipzig 1921, had stressed the contribution given by Poincaré: in particular, see the §§ 1, 4, 7, 50. See also: H. Thirring,*Elektrodynamik bewegter Körper und Spezielle Relativitätstheorie*, in *Handbuch der Physik*, Band XII, *Theorien der Elektrizität Elektrostatik*, Springer, Berlin 1927, pp. 245-348, in particular, pp. 264, 270, 275, 283; V. Volterra, *Enrico Poincaré*, in *Saggi scientifici*, Zanichelli, Bologna 1920, pp. 119-157, and in particular pp. 144-148: this was the text of a conference delivered at the Rice Institute in Houston, Texas, on 10 October 1912, published in *Revue du Mois*, 10 February 1913 and in the third volume of the *Book of the Opening of the Rice Institute*, and in the *Rice Institute Pamphlets*, vol. 1, no. 2, May 1915; M. von Laue, *Das Relativitätsprinzip*, Vieweg, Braunschweig 1911, 1955, in particular §§ 14, 15, 28, 29, 30, 38. An aknowledgement, among others, of Poincaré's work was present in: R. Marcolongo, *Relatività*, Principato, Messina 1921, 1923[2]. Indeed, Marcolongo was the second, after Poincaré and before Minkowski, to use a four-dimensional formulation, and then developed an original covariant formulation of special relativity: R. Marcolongo, *Sugli integrali dell'equazione dell'elettrodinamica*, Rendiconti della Regia Accademia dei Lincei, s. 5, v. 15 (I sem. 1906), pp. 344-349. The controversy on the authorship of special relativity was unfortunately related also with the nazist campaign against "Jewish physics" in Germany: see A. I. Miller, *A Précis of Edmund Whittaker's "Relativity Theory of Poincaré and Lorentz"*, in *Archives Internationales d'Histoire des Sciences* **37** (1987), pp. 93-103: in particular see note 6, pp. 95-96 and references therein. However, Miller himself emphasizes that there were other non-ideological "attempts to gain more 'credit' for Poincaré" as the one by Felix Klein. For the ideological question, see also: H. Goenner, *The Reaction to Relativity Theory. 1. The Anti-Einstein Campaign in Germany in 1920*, in *Science in Context* **6** (1993), pp. 107-133; P. Frank, *Albert Einstein, sein Leben und seine Zeit*, Vieweg, Braunschweig 1979.

[3] What a contradiction: an anti-relativistic concept! Historiographical time is still treated as pre-relativistic! For a discussion of the relationship between physical and historiographical time see: M. Heidegger, , *Der Zeitbegriff in der Geschichtwissenschaft*, in *Zeitschrift für Philosophie und philosophische Kritik*, CLXI (1916), pp. 173-188 and reprinted in *Frühe Schriften*, Klostermann, Frankfurt am Main 1972, pp. 355-376. A suggestion of a very strict correlation of physical and historiographical times was given by Ernst Bloch, who introduced, even if within a very rigid marxist schema, a "relativistic-time historiography" based on the relativity of simultaneity (non-simultaneity: *Ungleichzeitigkeit*) and

historians and physicists have recognized that Poincaré was the actual creator of special relativity and indeed in some cases from a reductionist point of view by which the different works have been identified *tout court* in respect only to the mathematical formalism.[4]

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on "curved" time: *Ungleichzeitigkeit und Plifcht zu ihrer Dialektik* (1932), in *Erbschaft dieser Zeit*, Gesamtausgabe Bd 4, Suhrkamp, Frankfurt am Main 1962-1977; *Differenzierungen im Begriff Fortschritt* (1955), in *Tübinger Einleitung in die Philosophie*, Gesamtausgabe Bd. 13, Suhrkamp, Frankfurt am Main 1970.

[4] This position is often made by mathematicians or physicists who are unaware of epistemological problems reducing physical theories to their mathematical structures or to experimental consequences. I will deal with this issue in the successive paragraph. Implicitly or explicitly against the thesis of Poincaré's authorship of special relativity there are, among others, the following papers: P. Langevin, *L'oeuvre d'Henri Poincaré. Le physicien*, in *Revue de Métaphysique et de morale*, Supplément au n. 5 (1913), pp. 675-718, in particular pp. 698-704; G. Holton, *Thematic Origins of Scientific Thought. Kepler to Einstein*, Harvard University Press, Cambridge (Mass.) 1973; M. Paty, *Einstein philosophe*, PUF, Paris 1993; F. Balibar, *Einstein 1905. De l'éther aux quanta, PUF*, Paris 1992; S. Petruccioli & C. Tarsitani, *L'approfondimento della conoscenza fisica dall'affermazione delle concezioni maxwelliane alla relatività speciale (1890-1905)*, in *Sulla genesi storica e sul significato teorico della relatività di Einstein*, *Quaderni di storia e critica della scienza*, n. s. **4**, Domus Galilaeana, Pisa 1973, pp. 11-245; M. Biezunski, *Einstein à Paris*, Press Universitaires de Vincennes, Saint-Denis 1991; I. Yu. Kobzarev, *Henri Poincaré's St. Louis lecture, and theoretical physics on the eve of the theory of relativity*, in *Usp. Fiz. Nauk* **113** (1974), pp. 679-694 (in russian) and in *Sov. Phys. Usp.* **17** (1975), pp. 584-592. See also V. A. Ugarov, *Special Theory of Relativity* (in russian), Nauka, Moscow 1977, engl. transl., Mir, Moscow 1982; H. A. Lorentz, *Deux Mémoires de Henri Poincaré sur la Physique mathématique*, in H. Poincaré, *Oeuvres de Henri Poincaré*, eleven volumes, Gauthier-Villars, Paris 1934-1956, **11**, pp. 247-261. For a historical but also theoretical interpretation of special relativity in the spirit of Poincaré, see: A. A. Tyapkin, *Expression of the General Properties of Physical Processes in the Space-Time Metric of the Special Theory of Relativity*, in *Soviet Physics Uspekhi*, v. **15** (1972), pp. 205-229; A. A. Tyakin, *Relatività Speciale*, engl. trans. by G. Pontecorvo, Jaca Book, Milano 1994; A. A. Logunov, *Lectures on Relativity and Gravitation. A Modern Look* (in russian), Moscow University Press, Moscow 1984, engl. transl., Mir, Moscow 1990; A. A. Logunov, *On the articles by Henry Poincaré - On the Dynamics of the Electron* (in russian), Moscow University Press, Moscow 1988, engl. trans. by G. Pontecorvo, JINR, Dubna 1995. See also: E. Zahar, *Einstein's Revolution. A Study in Heuristics*, Open Court, La Salle Ill. 1989; A. Pais, *'Subtle is the Lord...'. The Science and the Life of Albert Einstein*, Oxford University Press, Oxford 1982; T. Hirosige, *The Ether Problem, the Mechanistic Worldview, and the Origins of the Theory of Relativity, in Historical Studies in the Physical Sciences* **7** (1976), pp. 3-82; J. Renn, *Einstein as a Disciple of Galileo: A Comparative Study of Concept Development in Physics*, in *Science in Context* **6** (1993), pp. 311-341.

On the other hand, the historical "deepest" studies on Poincaré's work on this subject have been made by Arthur I. Miller, who has been stating that Poincaré does not create "special relativity" and has been trying to explain why: in my opinion, he has had to deal with "epistemological obstacles" just to avoid an epistemological reductionism and this has influenced his analysis.[5]

Here, I would like to analyse again this question and to give new arguments to recognize Poincaré's authorship without any reductionism. I based my inquiry almost on the same texts already discussed, but my hermeneutical reading of them is different from Miller's and other historians' ones and so my conclusions will be different.

First of all, I would like to show what is the importance to recognize the Poincaré's priority on Einstein, pointing out that it is *not only* a legitimate question of priority. Very briefly I can anticipate what will emerge in the text: this recognition is needed to understand the new rules of enunciate formation of special relativity as a new theoretical practice, and so the meaning of the new concepts, the historical reasons of its origin, and indeed its theoretical value and its epistemological implications which are not the same Einstein-Minkowski's realistic, objectivistic ones.

I have also to stress that one must distinguish the question of the creation of the new theoretical framework from the question of its institutionalization as a *discipline* separated from other branches of physics, which is a sociological question as long as its disciplinary constitution - that in our times has brought also to the institution of specific universitary chairs - involved the diffusion and acceptance by the international physicists' community.[6] This sociological aspect is indeed related to the Einstein-Minkowski's presentation of special relativity, to their axiomatic (not problematic) formulation, to their epistemological views which, beyond the

[5] See the previous note 4, and the following books and papers by A. I. Miller: *Albert Einstein's Special Theory of Relativity: Emergence (1905) and Early Interpretation (1905-1911)*, Addison-Wesley, Reading (MA), 1981; *Imagery in Scientific Thought: Creating 20th-Century Physics*, Birkhäuser, Boston 1984 & MIT Press, Cambridge (MA), 1986; *Frontiers of Physics: 1900-1911*, Birkhäuser, Boston 1986; *A Study of Henri Poincaré's 'Sur la dynamique de l'électron'*, in *Archives for History of Exact Sciences* **10** (1973), pp. 207-328 & reprinted in *Frontiers of Physics...*, op. cit., pp. 29-150; *Scientific Creativity: A Comparative Study of Henri Poincaré and Albert Einstein*, in *Creativity Research Journal* 5 (1992), pp. 385-418. See also: *Why Did Poincaré Not Create Special Relativity In 1905?* , preprint, Henri Poincaré Conference, Nancy, May 1994.

[6] I will not focus my inquiry on this sociological aspects. For this kind of sociologically oriented history of science see: M. Foucault, *L'archéologie du savoir*, Gallimard, Paris 1969; M. Foucault, *Les mots et le choses*, Gallimard, Paris 1966; M. Foucault, *Nietzsche, la généalogie, l'histoire*, in *Hommage à Jean Hyppolite*, ed. by S. Bachelard et al., P.U.F., Paris 1971, pp. 145-172; J. Rouse, *Knowledge and Power: Toward a Political Philosophy of Science*, Cornell University Press, Ithaca, New York 1988; T. Lenoir, *The Discipline of Nature and the Nature of Disciplines*, in *Knowledges: Historical and Critical Studies in Disciplinarity*, ed. by E. Messer-Davidov, D. R. Shumway & D. J. Sylvan, University Press of Virginia, Charlottesville 1993, pp. 70-102.

seeming conflict of "philosophical relativism" and objectivism, contributed to a specific historical *episteme* or *regime of truth* that has still its roots in that historical western form of life.[7] In my opinion, Poincaré's position (problematic formulation of the theory, "conventionalism", non-separability and historicity of physical systems, features of which I will give some account in the course of this text) was not viable to be embodied in this form of life and so some "revolutionary" aspects of the new physical framework (given by Poincaré) have been lost.

In facts, one of the most frequent objections to the recognition of Poincaré's authorship was a sort of "transcendental" argument: it was often said that it was Poincaré's "conventionalism" to not allow him to create special relativity. However, "conventionalism" has had a role only in the 'reception' of Poincaré's formulation by physicists' community.[8] Indeed, we will see that new inquiries on the possibility of formulating special relativity in different ways show us that Poincaré does not only create special relativity, but also that he was conscious about the different ways by which one can formulate the theory.

Another strong objection, as we know, is that Poincaré does not create special relativity just because he was interested in *something more than* special relativity, that is in a 'unified' theory of that time known interactions.[9] In my opinion, there is no doubt that Poincaré's purpose was also a deeper theory but this can be recognized only pointing out his formulation of special relativity, and

[7] See references given in note 6. For a sociological analysis of the rise of special relativity, even if with the strong pre-conception of Einstein's complete authorship, see: L. S. Feuer, *Einstein and the Generations of Science*, Transaction, New Brunswick 1982. For the concept of "form of life" (*Lebensform*) and its relation to linguistic games the reference is to the reflections of Ludwig Wittgenstein, to which, in my opinion, also Foucault analysis must be related to be completely understood: L. Wittgenstein, *Philosophische Untersuchungen. Philosophical Investigations*, Blackwell, Oxford 1953.

[8] On the question of conventionalism, see for example the papers and books written by J. Giedymin: *On the Origin and Significance of Poincaré's Conventionalism*, in *Studies in History and Philosophy of Science* **8** (1977), pp. 271-301; *Science and Convention. Essays on Henri Poincaré's Philosophy of Science and the Conventionalist Tradition*, Pergamon Press, Oxford 1982; *Geometrical and Physical Conventionalism of Henri Poincaré in Epistemological Formulation*, in *Studies in History and Philosophy of Science* **22** (1991), pp. 1-22; *Conventionalism, the Pluralist Conception of Theories and the Nature of Interpretation*, in *Studies in History and Philosophy of Science* **23** (1992), pp. 423-443. See also: D. A. Gillies, *Poincaré: Conservative Methodologist, but Revolutionary Scientist* , preprint, Henri Poincaré Conference, Nancy, May 1994; D. A. Gillies, *Philosophy of Science in the Twentieth Century. Four Central Themes,* Blackwell, Oxford 1993. In my opinion, the recognition by Poincaré of the experimental roots of physical concepts, principles and theories is not incompatible with the awareness of conventionalism related to different theoretical constructions in correspondence with the different possible operational (experimental) definitions: all this, in turn, is not incompatible with a form of 'realism' of motion and physical processes.

[9] This is another point, for example, of Miller's position: see note 5.

again this characteristic has had a role only in the 'reception' of it by the community.

In paragraph 2, I shall give a brief account of Poincaré's steps in the conceptual elaboration of special relativity, formulated in the paper on June 5, 1905 and July 23, 1905 (date of submission), limiting myself to the first one written before Einstein's paper (received on June 30, 1905).

2. A Very Brief Account of the Formation of Special Relativity by Poincaré

2.1 The First Step: Classical Mechanics is not Newtonian

Here, I would like only to recall some of the most relevant possible quotations from Poincaré's works which show us the historical conceptual steps towards the formation of special relativity.

In 1889, Poincaré already wrote about aether as a metaphysical concept, announcing that some day it will be thrown aside:

Peu nous importe que l'éther existe réellement, c'est l'affaire des métaphysiciens; l'essentiel pour nous c'est que tout se passe comme s'il existait et que cette hypothèse est commode pour l'explication des phénomènes. Après tout, avons-nous d'autre raison de croire à l'existence des objets matériels? Ce n'est là aussi qu'une hypothèse commode; seulement elle ne cessera jamais de l'être, tandis qu'un jour viendra sans doute où l'éther sera rejeté comme inutile.[10]

And already in a paper of 1895 (*A propos de la théorie de Larmor*), Poincaré stated the impossibility of absolute motion:

L'expérience a révélé une foule de faits qui peuvent se résumer dans la formule suivante: il est impossible de rendre manifeste le mouvement absolu de la matière, ou mieux le mouvement relatif de la matière pondérable par rapport à

[10] H. Poincaré, *Préface* to *Théorie mathématique de la lumière*, I, Naud, Paris 1889, reprinted in H. Poincaré, *La science et l'hypothèse*, Flammarion, Paris 1902, 1968, p. 215. This book was read by Einstein (before writing his paper *Zur Elektrodynamik bewegter Körper*, in *Annalen der Physik* **17** (1905), pp. 891-921, received on 30 June 1905; reprinted in *The Collected Papers of Albert Einstein*, vol. **2**, *The Swiss Years: Writings 1900-1909*, ed. by J. Stachel, Princeton University Press, Princeton 1989, pp. 276-310; engl. transl., *On the Electrodynamics of Moving Bodies*, in *The Collected Papers of Albert Einstein*, vol. **2**, *The Swiss Years: Writings 1900-1909, English Translation*, A. Beck, transl. and P. Havas, consul., Princeton University Press, Princeton 1989, pp. 140-171) and his friends Maurice Solovine and Conrad Habicht in the "Akademie Olympia". '(This) book profoundly impressed us and kept us breathless for weeks on end' wrote Solovine: A. Einstein, *Lettres à Maurice Solovine*, Gauthier-Villars, Paris 1956, p. VIII. This comment will receive an explanation by means of the following quotations from this book.

l'éther; tout ce qu'on peut mettre en évidence c'est le mouvement de la matière pondérable par rapport à la matière pondérable.[11]

In 1898, in *La mesure du temps*, there were the first critical inquiries about time and simultaneity, where he stated their "conventionality", the possibility of their definition by the velocity of light, which has to be conventionally assumed to be the same constant in all directions:

Nous n'avons pas l'intuition directe de l'égalité de deux intervalles de temps. Les personnes qui croient posséder cette intuition sont dupes d'une illusion... Le temps doit être défini de telle facon que les équations de la méquanique soient aussi simples que possible. En d'autres termes, il n'y a pas une manière de mesurer le temps qui soit plus *vrai* qu'une autre; celle qui est généralement adoptée est seulement plus *commode.* ...Il a commencé par admettre que la lumière a une vitesse constante, et en particulier que sa vitesse est la même dans toutes les directions. C'est là un postulat sans lequel aucune mesure de cette vitesse ne pourrait être tentée. Ce postulat ne pourra jamais être vérifié directment par l'expérience; il pourrait être contredit par elle, si les résultats des diverses mesures n'étaient pas concordants. Nous devons nous estimer hereux que cette contradiction n'ait pas lieu et que les petites discordances qui peuvent se produire puissent s'expliquer facilement. ...c'est que je veux retenir, c'est qu'il nous fournit une règle nouvelle pour la recherche de la simultanéité... Il est difficile de séparer le problème qualitatif de la simultanéité du problème quantitatif de la mesure du temps; soit qu'on se serve d'un chronomètre, soit qu'on ait à tenir compte d'une vitesse de transmission, comme celle de la lumière, car on ne saurait mesurer une pareille vitesse sans *mesurer* un temps. ...La simultanéité de deux événements, ou l'ordre de leur succession, l'égalité de deux durées, doivent être définies de telle sorte que l'énoncé des lois naturelles soit aussi simple que possible. En d'autres termes, toutes ces règles, toutes ces définitions ne sont que le fruit d'un opportunisme incoscient.[12]

[11] H. Poincaré, *A propos de la théorie de Larmor*, in *L'éclairage électrique* **5** (1895), pp. 5-14, reprinted in H. Poincaré, *Œuvres de Henri Poincaré,* eleven volumes, Gauthier-Villars, Paris 1934-1953, **9**, pp. 395-413. Quotation is from p. 412.

[12] H. Poincaré, *La mesure du temps*, in *Revue de métaphysique et de morale* **6** (1898), pp. 1-13. Quotations are from pp. 2, 11, 12, 13, reprinted partially in H. Poincaré, *La valeur de la science*, Flammarion, Paris 1905, engl. transl. by G. B. Halsted, *The Value of Science*, Dover, New York 1958. Also this book was read by Einstein (before writing his paper *Zur Elektrodynamik bewegter Körper*, op.cit.) and his friends Maurice Solovine and Conrad Habicht in the "Akademie Olympia": this is known by a letter of 14 April 1952 from Solovine to Carl Seelig. For this information, see: *Introduction to Volume 2*, in *The Collected Papers of Albert Einstein*, vol. **2**, op. cit., p. XXIV, note 42. One must also point out that, as written at p. XXV, note 55 of the *Introduction to Volume 2* to *The Collected Papers of Albert Einstein*, vol. **2**, op. cit., pp. XVI-XXIX, Einstein may have read the German edition of Poincaré's book *La science et l'hypothèse* : *Wissenschaft und Hypothese*, germ. transl. by Ferdinand and Lisbeth Lindemann, with annotations by F. Lindemann, Teubner, Leipzig 1904. As pointed out in note 9 to

In 1899, speaking about Michelson's experiment, he stated the dependence of optical phenomena only on relative motions of heavy bodies as a principle:

... les termes du second ordre auraient dû devenir sensibles, et cependant le résultat a encore été négatif, la théorie de Lorentz laissant prévoir un résultat positif. On a alors imaginé une hypothèse supplémentaire: tous les corps subiraient un raccourcissement dans le sens du mouvement de la Terre... cette étrange propriété semblerait un véritable coup de pouce donné par la nature pour éviter que le mouvement de la Terre puisse être révélé par des phénomènes optiques. Ceci ne saurait me satisfaire et je crois devoir dire ici mon sentiment: je considère comme très problables que les phénomènes optiques ne dépendent que des mouvements relatifs des corpes matériels en presence...et cela non pas aux quantités près de l'ordre du carré ou du cube de l'aberration, mais rigouresement. A mesure que les expériences deviendront plus exactes, ce principe sera vérifié avec plus de precision.[13]

In *La théorie de Lorentz et le principe de réaction* (1900), Poincaré used the relativity of motion by him for first assumed as a principle to deduce the action-reaction principle extended to the consideration of the electromagnetic field, and introduced analytically the method of synchronization of clocks by light signals (already discussed in *La mesure du temps*), which Einstein followed in 1905:

Le principe de réaction nous apparait donc comme une conséquence de celui de l'énergie et de celui du mouvement relatif...
...Je suppose que des observateurs placés en différents points, règlent leurs montres à l'aide de signaux lumineux; qu'ils cherchent à corriger ces signaux du temps de la transmission, mais qu'ignorant le mouvement de translation dont ils sont animés et croyant par conséquent que les signaux se transmettent également vite dans les deux sens, ils se bornent à croiser les observations, en envoyant un signal de *A* en *B*, puis un autre de *B* en *A*. Le temps local *t* est le temps marqué par les montres ainsi réglées...[14]

the reprinted Einstein's paper in *The Collected Papers...*, vol. **2**, op. cit., pp. 307-308, in the German translation of Poincaré's book, pp. 286-289, "the relevant passage of *Poincaré 1898* is translated in an editorial note to this paragraph, which includes a lenghty discussion of Poincaré's comments on simultaneity". In these notes to Einstein's papers, the editors of *The Collected Papers* (pp. 306-310) indeed have pointed out many Poincaré's references as actual sources for Einstein's work. For such a comparison, see also: J. Leveugle, *Henri Poincaré (1873) et la relativité*, in *La Jaune et la Rouge* **494** (1994), pp. 29-51.

[13] H. Poincaré, *Électricité et optique. La lumière et les théories électrodynamiques. Lecon professées à la Sorbonne en 1888, 1890 et 1899*, Paris, Carré et Naud 1901, p. 536.

[14] H. Poincaré, *La théorie de Lorentz et le principe de réaction*, in *Archives néerlandaises des Sciences exactes et naturelles*, s. 2, v. **5** (1900), pp. 252-278 and also in *Recueil de travaux offerts par les auteurs à H. A. Lorentz*, Nijhoff, The

Here, he gave also a momentum density for the electromagnetic density which implicitly involved a mass density which was equal to $1/c^2$ times the energy density, recovering a first relation between mass and energy of "relativistic" kind, but it was only after, when he recognized the mass as variable with velocity as long as a self-induction effect of electromagnetic origin, that he obtained a general relation like $E=mc^2$.[15]

Fundamental conclusions were traced by Poincaré in 1902, in the chapter on *La Mécanique classique* of *La Science et l'hypothèse*:

1° Il n'y a pas d'espace absolu et nous ne concevons que des mouvements relatifs...

2° Il n'y a pas de temps absolu; dire que deux durées sont égales, c'est une assertion qui n'a par elle-même aucun sense et qui n'en peut acquérir un que par convention...

3° Non seulement nous n'avons pas l'intuition directe de l'égalité de deux durées, mais nous n'avons même pas celle de la simultanéité de deux événements qui se produisent sur des théâtres différents; c'est ce que j'ai expliqué dans un article intitulé la *Mesure du temps* (1);

4° Enfin notre géometrie euclidienne n'est elle-même qu'un sorte de convention de langage; nous porrions énoncer les faits mécaniques en les rapportant à un espace non euclidien qui serait un repère moins commode, mais tout aussi légitime que notre espace ordinaire; l'énoncé deviendrait ainsi beaucoup plus compliqué; mais il resterait possible. Ainsi l'espace absolu, le temps absolu, la géométrie même ne sont pas des conditions qui s'imposent à la mécanique; toutes ces choses ne preéexistent pas plus à la mécanique que la langue francaise ne préexiste logiquement aux vérités que l'on exprime en francais.[16]

Hague 1900; reprinted in H. Poincaré, *Oeuvres* ..., op. cit., **9**, pp. 464-488. Quotation is from pp. 482-483.

[15] H. Poincaré, *La théorie de Lorentz...*, op. cit., pp. 468 and following ones. Also Einstein quoted this Poincaré's paper as implying the relativistic mass-energy relation: A. Einstein, *Das Prinzip von der Erhaltung der Schwerpunktbewegung und die Trägheit der Energie*, in *Annalen der Physik* **20** (1906), pp. 627-633, reprinted in *The Collected Papers...*, v. **2**, op. cit., pp. 360-366, and *The Principle of Conservation of Motion of the Center of Gravity and the Inertia of Energy*, in *The Collected Papers...English Translation*, v. **2**, op. cit., pp. 200-206. See the end of this paragraph for the Einstein's specific quotation. See also E. Whittaker, *A History...*, op. cit., p. 51; A. Miller, *Albert Einstein's Special...*, op. cit., pp. 40-45; A. Miller, *A precis...*, op. cit., pp. 96-98: here, Miller was right to say that the relativistic mass-energy relation is not completely involved in 1900 paper, but he did not point out that it was involved in 1902, 1904 and 1905 Poincaré's works; as it will be clear in the following, Miller's statements (pp. 100-103) that Poincare's works were not a relativistic theory of space and time implies a misunderstanding of them.

[16] H. Poincaré, *La science et l'hypothèse*, op. cit., ch. VI, pp. 111-112. Portions of ch. VI and VII were already published by Poincaré in these two papers: *Les*

It is evident how Poincaré gave here the conceptual basis for the construction of special relativity and partially also for general relativity. However, this is not all the truth: this is still a critical reconsideration of classical mechanics. The above Poincaré's statements are true for classical mechanics! That is, by analysing the language of classical mechanics, Poincaré pointed out the misunderstandings and the meta-physical hypostasis which have characterized its interpretation. Absolute space, absolute time and absolute motion, as empty parameters external to physical processes, are concepts which have no meaning already within *classical mechanics*, because there is no possible experimental operation correspondent to them and such to determine them. The formal-symbolic language of classical mechanics is only a convention in respect to them, but it acquires an actual physical meaning in relation to the actual experimental measurement operations which are different for different reference frames. That is, *classical mechanics is not Newtonian*.

Thus, Poincaré made, in respect to the physical language, an operation analogous to the one later made by Ludwig Wittgenstein in respect to natural language and philosophy.[17] That is, Poincaré de-constructed the referential and denotative semantics of the newtonian ontology and indicated a physical theory as a 'linguistic game' with performative character: a language whose enunciates acquire meaning only by the correspondently realized, experimental physical practices.[18] Indeed, Poincaré introduced a new theory of *physical meaning* in correspondence with a new conception of a physical theory.

In the successive chapter of the same book, entitled *Le mouvement relatif et le mouvement absolu*, Poincaré introduced a first version of his principle of relativity (one must remember that relativity was not a "principle" in the strict sense even for Galilei, and certainly not for Newton which presented it as a corollary; indeed it was a principle *only* for Leibniz):[19]

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idées de Hertz sur la mécanique, in *Revue générale des sciences* **8** (1897), pp. 734-743, reprinted also in *Oeuvres* **7**, op. cit., pp. 231-250; *Sur les principes de la mécanique,* in *Bibliothèque du Congres International de Philosophie tenu à Paris du 1 au 5 août 1900,* Colin, Paris 1901, pp. 457-494.

[17] See reference quoted in note 7.

[18] See also the analysis of physics given from a wittgensteinian perspective in: W. H. Watson, *On Understanding Physics*, Harper, New York 1959; W. H. Watson, *Understanding Physics Today,* Cambridge University Press, Cambridge 1967.

[19] Consider the formulation of the so-called "principle" of relativity by Galilei: he spoke about butterflies, fishes and other animals and natural elements; it is not an actual principle and it comes from an experience within lifeworld. There is yet no actual (complete) separation between the lifeworld and the world of science: see G. Galilei (1632), *Dialogo sopra i due massimi sistemi del mondo, tolemaico e copernicano,* ed. by L. Sosio, Einaudi, Torino 1970, pp. 227-229. Regarding Newton, see: I. Newton (1687), *Philosophiae Naturalis Principia Mathematica,* the third edition (1726) with variant readings, ed. by A. Koyré & I. B. Cohen, Harvard University Press, Cambridge, Mass. 1972. For Leibniz, see: G. W. Leibniz, *Leibnizens mathematische Schriften,* ed. by C. G. Gerhardt, Halle 1850-63; E. Cassirer, *Leibniz' System in seinen wissenschaftlichen Grundlagen*,

LE PRINCIPE DU MOUVEMENT RELATIF. - ...Le mouvement d'un système quelconque doit obéir aux mêmes lois, qu'on le rapporte à des axes fixes, ou à des axes mobiles entraînés dans un mouvement rectlingne et uniforme...les accélérations des différent corps qui font partie d'un systeme isolé ne dépendent que de leurs vitesses et de leurs positions relatives, et non de leurs vitesses et de leurs positions absolues, pourvu que les axes mobiles auxquels le mouvement relatif est rapporté soient entraînés dans un mouvement rectiligne et uniforme. Ou, si l'on aime mieux, leurs accélérations ne dépendent que des différences de leurs vitesses et des différences de leurs coordonnées, et non des valeurs absolues de ces vitesses et de ces coordonnées.

Si ce principle est vrai pour les accélérations relatives, ou mieux pour les différences d'accélération, en le combinant avec la loi de la réaction, on en déduira qu'il est vrai encore pour les accélérations absolues...pou parler le langage mathématique, que ces différences de coordonnées satisfont à des équations différentielles du second ordre...Ainsi énoncé, en effet, le principe du mouvement relatif ressemble singulièrement à ce que j'appelais plus haut le principe de l'inertie généralisé; ce n'est pas tout à fait la même chose, puisqu'il s'agit des différences de coordonnées et non des coordonnées elles-mêmes.[20]

This is the first time that relativity of motion assumed *the status of a principle* for inertial reference frames, situated at the foundation level of classical mechanics and related to the actual relativity of space and time. Poincaré showed the fundamental link between the inertia principle and the relativity principle, considering them as derived from experience and generalized in a way which is never *completely* verified and which implies an element of 'linguistic' convention. Notwithstanding the accepted conventionality of language, Poincaré, as I shall show in the following, reintroduced a Leibnizian point of view on motion: motion is considered to be 'real', not reducible to space and time relations, but also completely relative. Indeed, after the formulation of the principle of relativity for inertial reference frames, Poincaré considered the argument of Newton about the absoluteness of rotation and, against Newton, concluded for the relative nature of all motions, including rotations and accelerated ones:

L'ARGUMENT DE NEWTON. - ...Mais alors, pourqoi le principe n'est-il vrai que si le mouvement des axes mobiles est rectiligne et uniforme? Il semble qu'il devrait s'imposer à nous avec la même force, si ce mouvement est varié ou tout au moins s'il se réduit à une rotation uniforme...Je n'insisterai pas longtemps sur le cas où le mouvement des axes est rectiligne sans être uniforme; le paradoxe ne résiste pas à un istant d'examen. Si je suis en wagon, et si le train,

Elwert, Marburg 1902 & Wissenschaftliche Buchgesellschaft, Darmstadt 1962; E. Cassirer, *Erkenntnisproblem in der Philosophie und Wissenschaft der neuren Zeit*, Berlin 1911-1920; D. Bertoloni Meli, *Equivalence and Priority: Newton versus Leibniz. Including Leibniz's Unpublished Manuscripts on the Principia*, Clarendon Press, Oxford 1993. The correlation Leibniz-Poincaré will be analysed in paragraph 4.

[20] H. Poincaré, *La science et l'hypothèse*, op. cit., ch. VII, pp. 129-130; for the Poincaré's principle of generalized inertia, see pp. 112-117 of the same book.

heurtant un obstacle quelconque, s'arrête brusquement, je serai projeté sur la banquette opposée, bien que je n'aie été soumis directement à aucun force. Il n'y a rien de mistérieux; si je n'ai subi l'action d'aucun force extérieure, le train, lui, a éprouvé un choc extérieur. Que le mouvement relatif de deux corps se trouve troublé, dès que le mouvement de l'un ou de l'autre est modifié par une cause extérieure, il ne peut rien y avoir là de paradoxal...Cela n'empêche pas que l'espace absolu, c'est-à-dire le repère auquel il faudrait rapporter la terre pour savoir si réellement elle tourne, n'a aucune existence objective. Dès lors, cette affirmation: "la terre tourne", n'a aucun sens, puisqu'aucune expérience ne permettra de la vérifier; puisqu'une telle expérience, non seulement ne pourrait être ni réalisée, ni rêvée par le Jules Verne le plus hardi, mais ne peut être concue sans contradiction; ou ploutôt ces deux propositions: "la terre tourne", et: "il est plus commode de supposer que la terre tourne", ont un seul et même sens; il n'y a rien de plus dans l'une que dans l'autre...Pour nous en rendre compte, il vaut mieux prendre un exemple simple. Je suppose un système analogue à notre système solaire, mais d'où l'on ne puisse apercevoir des étoiles fixes étrangères à ce système, de telle façon que les astonomes ne puissent observer que les distances mutuelles des planètes et du soleil, et non le longitudes absolues des planètes. si nous déduisons directement de la loi de Newton les équations différentielles qui définissent la variation de ces distances, ces équations ne seront pas du second ordre. Je veux dire que si, outre la loi de Newton, on connaissait les valeurs initiales de ces distances et de leur dérivées par rapport au temps, cela ne suffirait pas pour déterminer les valeurs de ces mêmes distances à un instant ultérieur. Il manquerait encore une donnée, et cette donnée, ce pourrait être par exemple ce que les astronomes appellent la constante des aires...Notre univers est plus étendu que le leur, puisque nous avons des étoiles fixes, mais il est cependant limité, lui aussi, et alors nous porrions raisonner sur l'ensemble de notre univers, comme ces astronomes sur leur système solaire. On voit ainsi qu'en définitive on serait conduit à conclure que les équations qui définissent les distances sont d'ordre supérieur au second. Pourquoi en serions-nous choqués, pourquoi trouvons-nous tout naturel que la suite des phénomènes dépende des valeurs initiales des dérivées premières de ce distances, tandis que nous hésitons à admettre qu'elles puissent dépendre des valeurs initiales des dérivées secondes? Ce ne peut être qu'à cause des habitudes d'esprit crées en nous par l'étude constante du principe d'inertie généralisé et de ses conséquences.[21]

Here, Poincaré overcame the limitated context of inertial reference frames for the principle of relativity by also stating (with Leibniz,[22] contra

[21] H. Poincaré, *La science et l'hypothèse,* op. cit., ch. VII, pp. 130-137.

[22] See, for example, the letters of Leibniz to Huyghens, written on 22 June 1694 and 14 September 1694, in C. Huyghens, *Œuvres complètes de Christian Huyghens*, Der Haag 1905, vol. **X**, p. 609 and p. 681, or in G. W. Leibniz, *Leibnizens mathematische Schriften*, op. cit., vol. **II**, pp. 179-185 and pp. 193-199; the english version of these letters can be found in G. W. Leibniz, *Philosophical Papers and Letters*, ed. by L. E. Loemker, Reidel, Dordrecht 1956, 1976^2, pp. 416-418 and p. 419. See also: M. Jammer, *Concepts of Spaces. The History of Theories of Space in Physics*, Harvard University Press, Cambridge (Mass.) 1954, chap. IV.

Newton) the relative nature of all motions, including rotations and accelerated ones. Here, again, there is not only a way opened towards a 'general relativistic' theory of motion, but the statement that *the relativity of all motions is true already within classical mechanics*. Absoluteness of space and of accelerated motions is related only to a linguistic convention which has no real expererimentable counterpart. Again, one can say that *classical mechanics is not Newtonian*.

Indeed, when one has to consider the invariance properties of the physical laws of motion for rotating reference frames, one must properly consider (to discover the dynamical symmetries) the equations for a physical system different from the single one material point which cannot rotate, that is for a system composed of at least two material points which can have a motion of rotation. That is the equation for the two-bodies' system, or equivalently the second cardinal law of dynamics. Looking at these equations, one can immediately see that *uniform rotations and also precession motions are inertial motions* : the inertia principle for physical systems has a wider content than for the single material point.[23] From this, it follows that rotational dynamics

[23] See, for example: H. Goldstein, *Classical mechanics*, Addison-Wesley, Reading (Mass.) 1950, 1980^2, § 5.6, pp. 205-213; R. Marcolongo, *Meccanica Razionale*, voll. I & II, Hoepli, Milano 1905. Indeed, in some way, this was clear also to Newton, who, after writing the first axiom of motion (*Corpus omne perseverare in statu suo quiescendi vel movendi uniformiter in directum, nisi quatenus a viribus impressis cogitur statum illum mutare*), made the following comment: *Trochus, cujus partes cohærendo perpetuo retrahunt sese a motibus rectilineis, non cessat rotari nisi quatenus ab aere retardatur. Majora autem Planetarum & Cometarum corpora motus suos & progressivos & circulares in spatiis minus resistentibus factos conservant diutius.* (I. Newton, *Philosophiæ Naturalis Principia mathematica*, Londini 1687, impression anastaltique, Culture et Civilisation, Bruxelles 1965, p. 12). Indeed, one can say with C. Truesdell about the first Newtonian law of motion that "*In the generality mantained in modern mechanics, this axiom is not always valid, for a body may be subject to internal or external constraints not expressed in terms of a system of forces. For example, a rigid body subject to no applied force spins about some axis through its center of mass; its parts, which are also bodies, move in such a way that their center of mass describe circles about that axis.*" (C. Truesdell, *A First Course in Rational Continuum Mechanics*, vol. **I**, *General Concepts*, Academic Press, New York 1977, p. 57. Similarly, discussing the law of inertia, G. J. Whitrow noted the problem that, considering the motion of a body under the action of no forces, "*Not only may such abody rotate about an axis, but, in general, the axis about which it spins may itself be continually changing its position. In point of fact, then, the 'state of rest, or of uniform motion in a straight line' is not that which the physicist postulates to describe the motion of a body under no force. It may be argued that the law refers to the centre of mass of a body; this interpretation, however, would depend on Newton's third law of motion concerning action and reaction, and the status of the latter and the definition of centre of mass have become somewhat obscure as the result of recent relativistic theories.*[1] *In any case, it is clear that Newton's first law is not a descriptive law*

is not modified, is invariant for rotation or precession motions of reference frames, just as well as uniform translation motions of reference frames do not modify the translational dynamics of one single material point. Poincaré argumented that indeed rotational equations of motion are *third-order* differential equations for coordinate differences, and this mathematical feature corresponds to a sort of *'rotational inertia'* (this is the change of our mental habits, as implied by Poincaré's argument but not explicitly stated by him: a recovering of a medieval and indeed also galilean idea)[24] and implies a correspondent invariance for rotational dynamics.

For example, for the two-body problem, as J. Earman has shown by analysing Poincaré's argument, one could write:[25]

$$m_{12}\, d^2\mathbf{r}_{12}/dt^2 = \mathbf{F}_{21}$$

where

$$m_{12} = m_1\, m_2\, /\, (m_1 + m_2\, ;\ \mathbf{F}_{21} = f(r)\, \mathbf{r}_{12}/r;$$

$$\mathbf{r}_{12} = \mathbf{r}_1 - \mathbf{r}_2\, ;\ r = /\mathbf{r}_{12}/$$

In this case we have to rewrite the equation in terms of r :

$$m_{12}\, d^2r/d\,t^2 = f(r) + L^2\, /\, m_{12}\, r^3$$

From this, it yields:

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applying to the behaviour of actual bodies. It applies to particles, but these are conceptual, for Newtonian dynamics with its presuppositions concerning precise location in space and time is not appropriate to the study of the actual fundamental particles occurring in Nature. Classical dynamics applies to vast aggregates of these, but the Newtonian particle is an abstraction from the aggregate." (G. J. Whitrow, *On the Foundations of Dynamics*, in *British Journal for the Philosophy of Science*, **1** (1950-51), pp. 92-107: quotation from pp. 96-97).

[24] For the medieval *impetus* theory of John Buridan and Nicole Oresme, implying a "rotational or circular inertia" and the relation of Galileo to this kind of thinking, see for example: M. Clagett, *The Science of Mechanics in the Middle Ages*, The University of Wisconsin Press, Madison 1959, in particular chapters 8 & 11.

[25] J. Earman, *World enough and Space-Time. Absolute versus Relational Theories of Space and Time*, MIT Press, Cambridge (Mass.) 1989, pp. 84-89: however, in my opinion, the relevance of Poincaré's argument is undervalued. Poincaré's argument is also analysed in a paper by J. B. Barbour: *Relational Concepts of Space and Time*, in *British Journal for the Philosophy of Science* **33** (1982), pp. 251-274, in particular pp. 257-261. Here, Barbour has shown how Mach's and Poincaré's criticism of Newtonian thinking is related to Leibniz' "law of identity of indiscernibles": however, the emphasis on the relation of Poincaré's argument with the so-called "Mach's principle" has prevented him from recognizing the actual point of the rotational invariance of rotational dynamics.

$$m_{12}(3dr/dt\,d^2r/dt^2+r\,d^3r/dt^3)=$$
$$=dr/dt\{3f(r)+r\,df(r)/dt\}$$

The cases of inertial translational motions and inertial rotational motions of reference frames correspond in their respective correspondent dynamical contexts to dynamical separability of the observed system from the observing system. In the general case, dynamics of observed system depend, is not-separable from the dynamics of observing system: the general relativity of motion, thus, does not always imply an invariance or a dynamical symmetry, but *a general principle of non-separability of the dynamics* of the observed system from the dynamics of the observing system and by this from the dynamics of the remaining part of the universe. Only the dynamics of the whole universe can be considered invariant, but in this case the general relativity of motion is reduced to a sort of truism, referred only to the proper reference frame of the universe, that is solidal to the relative motion (if any) of the parts (one in respect to each other) of the universe as a whole, because there cannot be any measuring observer external to the universe as a whole.[26]

2.2 The Second Step: The Suggestion of a New Mechanics

The actual crisis of classical mechanics was outlined in all its respects by Poincaré in a lecture, given in 1904 at the St. Louis Conference, and entitled *The Principles of Mathematical Physics*.[27] Here, he looked in retrospect to the so-called "mathematical physics" (in a sense which does not make any distinction among proper mathematical physics, theoretical physics and experimental physics, that is in the sense of physics after the so-called "scientific revolution") by noting that it was born at the end of eighteenth century by separating itself

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[26] Here, my interpretation is related to the discussion of these problems given with greater extension in a successive paper by Poincaré: *L'espace et le temps*, conference delivered at the University of London on 4 May 1912, in *Scientia* **XII** (1912), pp. 159-171, reprinted as chapter 2 in H. Poincaré, *Dernières pensées*, Flammarion, Paris 1913.

[27] H. Poincaré, *The Principles of Mathematical Physics*, translated by G. Halsted, in *Philosophy and Mathematics, v.* ***I*** *of Congress of Arts and Science: Universal Exposition*, St. Louis 1904, ed. by H. Rogers, Houghton Mifflin, Boston 1905, pp. 604-622, reprinted in *Physics for a New Century, Papers Presented at the 1904 St. Louis Congress*, a compilation selected and a preface by K. R. Sopka, introduction by A. E. Moyer, Tomash Publishers, American Institute of Physics, The History of Modern Physics 1800-1950, v. **5**, 1986, pp. 281-299; reprinted also in *Relativity Theory: Its Origins and Impact on Modern Thought*, ed. by L. Pearce Williams, J. Wiley & Sons, New York 1968, pp. 39-49; ; and also: H. Poincaré, *The Principles of Mathematical Physics*, in *The Monist*, v. **15** (1905), p. 1. See also the french version of this paper: H. Poincaré, *L'état actuel et l'avenir de la Physique mathématique*, in *Bulletin des Sciences Mathematiques*, v. **28** (1904), pp. 302-324 and in *La revue des Idèes*, v. **1** (1904), pp. 801-814. For a first critical analysis on the status of physics at his time, see also the chapters IX & X of H. Poincaré, *La science et l'hypothèse*, op cit.

from the "mother", celestial mechanics, but resembling it very much in the ideal form of physical law given by Newton's law of gravitation. Poincaré wrote:

Neverthless, a day arrived when the conception of central forces no longer appear sufficient, and this is the first of those crisis of which I just now spoke. Then investigators gave up trying to penetrate into the detail of the structure of the universe, to isolate the pieces of this vast mechanism, to analyze one by one the forces which put them in motion, and were content to take as guides certain general principles which have precisely for their object the sparing us this minute study.[28]

Thus, there was a transition from the physics of central forces to the physics of principles and Poincaré gave a list of the most important principles which lie at the foundations of our physics. They are six: the Mayer's principle of the conservation of energy, the Carnot's principle of the degradation of energy, the Newton's principle of the equality of action and reaction, the principle of relativity, the Lavoisier's principle of the conservation of mass, and the principle of least action. It is worth noting that the only principle which Poincaré had to clarify in this list was the principle of relativity as far as relativity as a principle was introduced just by him:

...The principle of relativity, according to which the laws of physical phenomena should be the same, whether for an observer fixed, or for an observer carried along in a uniform movement of translation; so that we have not and could not have any means of discerning whether or not we are carried along in such a motion.[29]

Poincaré continued his historical analysis starting to outline the crisis of physics at that time as a crisis of its principles:

The most remarkable example of this new mathematical physics is, beyond contradiction, Maxwell's electro-magnetic theory of light...we know that this transmission should be made conformably to the general principles of mechanics, and that suffices us for the establishment of the equations of the electromagnetic field. These principles are results of experiments boldly generalized; but they seem to derive from their generality itself an eminent degree of certitude...Such is the second phase of the history of mathematical physics, and we have not yet emerged from it...the second phase could not have come into existence without the first? The hypothesis of central forces contained all the principles; it involved them as necessary consequences; it involved both the conservation of energy and that of masses, and the equality of action and reaction; and the law of least action, which would appear, it is true, not as experimental verities, but as theorems, and of which the enunciation would have at the same time a something more precise and less general than under the

[28] H. Poincaré, *The Principles of Mathematical Physics*, translated by G. Halsted, in *Philosophy and Mathematics*,..., op. cit., p. 606.

[29] H. Poincaré, *The Principles of Mathematical Physics*, translated by G. Halsted, in *Philosophy and Mathematics*,..., op. cit., p. 607.

actual form...One has to compare them to the data of experience, to find how it was necessary to modify their enunciation so as to adapt them to these data; and by these processes they have been enlarged and consolidated. So we have been led to regard them as experimental verities; the conception of central forces became then a useless support, or rather an embarassment, since it made the principles partake of its hypothetical character...Are we about to enter now upon the eve of a second crisis? Are these principles on which we have built all about to crumble away in their turn? ...In hearing me speak thus, you think without doubt of radium, that grand revolutionist of the present time, and in fact I will come back to it presently; but there is something else. It is not alone the conservation of energy which is in question; all the other principles are equally in danger, as we shall see in passing them successively in review.[30]

After Carnot's principle, Poincaré discussed the principle of relativity:

We come to the principle of relativity: this not only is confirmed by daily experience, not only is it a necessary consequence of the hypothesis of central forces, but it is imposed in a irresistible way upon our good sense, and yet it also is battered...all attempts to measure the velocity of the earth in relation to the ether have led to negative results. This time experimental physics has been more faithful to the principle than mathematical physics; the theorists, to put in accord their other general views, would not have spared it...The means have been varied in a thousand ways and finally Michelson has pushed precision to its last limits; nothing has come of it...Lorentz...The most ingenious idea has been that of local time. Imagine two observers who wish to adjust their watches by optical signals; they exchange signals, but as they know that the transmission of light is not instantaneous, they take care to cross them. When the station B perceives the signal from the station A, its clock should not mark the same hour as that of the station A at the moment of sending the signal, but htis hour augmented by a constant representing the duration of the transmission. Suppose, for example, that the station A sends its signal when its clock marks the hour 0, and that the station B perceives it when its clock marks the hour t. The clocks are adjusted if the slowness equal to t represents the duration of the transmission, and to verify it the station B sends in its turn a signal when its cloks marks 0; then the station A should perceive it when its clock marks t. The time-pieces are then adjusted. And in fact, they mark the same hour at the same physical instant, but on one condition, namely, that the two stations are fixed. In the contrary case the duration of the transmission will not be the same in the two senses, since the station A, for example, moves forward to meet the optical perturbation emanating from B, while the station B flies away before the perturbation emanating from A. The watches adjusted in that manner do not mark, therefore, the true time; they mark what one may call the *local time*, so that one of them goes slow on the other. It matters little, since we have no means of perceiving it. All the phenomena which happen at A, for example, will be late, but all will be equally so, and the observer who ascertains them will not perceive it, since its watch is slow; so, as the principle of relativity would have it, he will have no

[30] H. Poincaré, *The Principles of Mathematical Physics*, translated by G. Halsted, in *Philosophy and Mathematics*,..., op. cit., pp. 607-608.

means of knowing whether he is at rest or in absolute motion. unhappily, that does not suffice, and complementary hypotheses are necessary; it is necessary to admit that bodies in motion undergo a uniform contraction in the sense of the motion. One of the diameters of the earth, for example, is shrunk by 1/200.000.000 in consequence of the motion of our planet, while the other diameter retains its normal lenght. Thus, the last little differences find themselves compensated. And then there still is the hypothesis about forces. Forces, whatever be their origin, gravity as well as elasticity, would be reduced in a certain proportion in a world animated by a uniform translation; or, rather, this would happen for the components perpendicular to the translation; the components parallel would not change. resume, then, our example of two electrified bodies; these bodies repel each other, but at the same time if all is carried along in a uniform translation, they are equivalent to two parallel currents of the same sense which attract each other. This electro-dynamic attraction diminishes, therefore, the electro-static repulsion, and the total repulsion is more feeble than if the two bodies were at rest. But since to measure this repulsion we must balance it by another force, and all these other forces are reduced in the same proportion, we perceive nothing...Thus, the principle of relativity has been valiantly defended in these latter times, but the very energy of the defence proves how serious was the attack.[31]

At this stage of the discussion, Poincaré recognized that to save the principle of relativity one has to admit new "transformations" relating different observers in uniform relative translation for time (on the base of exchange of light signals), for space (involving Fitzgerald contraction) and forces, which are to be considered together with mass transformations discussed in this lecture in relation to Lavoisier's principle. The emphasis on compensation of effects and the conventional distinction between a true time and a local one, in my opinion, are to be understood pointing out Poincaré's implicit conception of motion which derived from Leibniz' one: motion is real even if completely relative, that is even if we can never perceive or experiment its actual subject.

Poincaré analysis continued on the principle of equality of action and reaction, understood in terms of its fundamental link with the relativity principle:

Let us speak now of the principle of Newton, on the equality of action and reaction. This is intimately bound up with the preceding, and it seems indeed that the fall of the one would involve that of the other. Thus we should not be astonished to find here the same difficulties...The electrons, therefore, act upon one another, but this action is not direct...Under these conditions can there be compensation between action and reaction, at least for an observer who should take account only of the movement of matter, that is to say, of the electrons, and who should be ignorant of those of the ether that he could not see? Evidently not. Even if the compensation should be exact, it could not be simultaneous. the perturbation is propagated with a finite velocity; it, therefore, reaches the second electron only when the first has long ago entered upon its rest. This second

[31] H. Poincaré, *The Principles of Mathematical Physics*, translated by G. Halsted, in *Philosophy and Mathematics*,..., op. cit., pp. 610-612.

electron, therefore, will undergo, after a delay, the action of the first, but certainly it will not react on this, since around this first electron nothing any longer budges. The analysis of the facts permit us to be still more precise. Imagine, for example, a Hertzian generator, like those employed in wireless telegraphy; it sends out energy in every direction; but we can provide it with a parabolic mirror...so as to send all the energy produced in a single direction...It is that the apparatus recoils as if it were a gun and as if the energy it has projected were a bullet; and that is contrary to the principle of Newton, since our projectile here has no mass, it is not matter, it is energy. It is still the same, moreover, with a beacon light provided with a reflector, since light is nothing but a perturbation of the electromagnetic field. this beacon light should recoil as if the light it sends out were a projectile.What is the force that this recoil should produce? It is what one has callled the Maxwell-Bartoli pressure...If all the energy issuing from our generator falls on a receiver, this will act as if it had received a mechanical shock, which will represent in a sense the compensation of the recoil of the generator; the reaction will be equal to the action, but it will not be simultaneous...If the energy propagates itself indefinitely without encountering a receiver, the compensation will never be made...If energy in its diffusion remained always attached to some material substratum, then matter in motion would carry along light with it, and Fizeau has demonstrated that it does nothing of the sort, at least for air. This is what Michelson and Morley have since confirmed. One may suppose also that the movements of matter, properly so called, are exactly compensated by those of the ether; but that would lead us to the same reflections as just now...But if it is able to explain everything, this is because it does not permit us to foresee anything; it does not enable us to decide between different possible hypotheses, since it explains everything beforehand. It therefore becomes useless. And then the suppositions that it would be necessary to make on the movements of the ether are not very satisfactory.[32]

Thus, here Poincaré showed how there is the breakdown of the principle of equality of action and reaction in relation to electromagnetism (it is worth noting the different position of Poincaré in respect to his paper on *La théorie de Lorentz et le principe de réaction* written in 1900 and already briefly discussed) and the ether is a useless mean to save the Newton's principle. Then, Poincaré discussed the Lavoisier's principle of the conservation of masses:

And now certain persons believe that it seems true to us only because we consider in mechanics merely moderate velocities, but that it would cease to be true for bodies animated by velocities comparable to that of light. These velocities, it is now believed, have been realized...The calculation of Abraham and the experiments of Kaufmann have then shown that the mechanical mass, properly so called, is null, and that the mass of the electrons, or, at least, of the negative electrons, is of exclusively electro-dynamic origin. This forces us to change the definition of mass; we cannot any longer distinguish mechanical mass and electro-dynamic mass, since then the first would vanish; there is no mass other than electro-dynamic inertia. but in this case the mass can no longer be

[32] H. Poincaré, *The Principles of Mathematical Physics*, translated by G. Halsted, in *Philosophy and Mathematics*,..., op. cit., pp. 612-614.

constant, it augments with the velocity, and it even depends on the direction, and a body animated by a notable velocity will not oppose the same inertia to the forces which tend to deflect it from its route, as to those which tend to accelerate or to retard its progress. There is still a resource...The negative electrons have no mass, this is understood; but the positive electrons, from the little we know of them, seem much greater...Alas, this resource also evade us. Recall what we have said of the principle of relativity and of the efforts made to save it. And it is not merely a principle which it is a question of saving, such are the indubitable results of the experiments of Michelson...Lorentz has been obliged to suppose that all the forces, whatever be their origin, were affected with a coefficient in a medium animated by a uniform translation; this is not sufficient; it is still necessary, says he, that the masses of all the particles be influenced by a translation to the same degree as the electro-magnetic masses of the electrons. So the mechanical masses will vary in accordance with the same laws as the electro-dynamic masses; they cannot, therefore, be constant. Need I point out that the fall of the principle of Lavoisier involves that of the principle of Newton? This latter signifies that the centre of gravity of an isolated system moves in a straight line; but if there is no longer a constant mass, there is no longer a centre of gravity, we no longer know even what this is. This is why I said above that the experiments on the cathode rays appeared to justify the doubts of Lorentz on the subject of the principle of Newton.

From all these results, if they are confirmed, would arise an entirely new mechanics, which would be, above all, characterized by this fact, that no velocity could surpass that of light, any more than any temperature could fall below the zero absolute, because bodies would oppose an increasing inertia to the causes, which would tend to accelerate their motion; and this inertia would become infinite when one approached the velocity of light.

Nor for an observer carried along himself in a translation he did not suspect could any apparent velocity surpass that of light; there would then be a contradiction, if we recall that this observer would not use the same clocks as a fixed observer, but, indeed, clocks marking "local time".[33]

Many points are to be noted about this quotation. First of all, it becomes clear that the principles discussed by Poincaré do not have the same status: after the doubts on Carnot's principle, Newton's principle and Lavoisier's principle are falsified and rejected in relation to electrodynamics and in relation to experiments which are the same ones which verify the principle of relativity, and indeed in order to save the principle of relativity: saving the principle of relativity is the only one consistent possibility.

Second, it is necessary to point out that, even if Poincaré seems to prefer the hypothesis of an electrodynamic world view within which matter properly

[33] H. Poincaré, *The Principles of Mathematical Physics*, translated by G. Halsted, in *Philosophy and Mathematics,...*, op. cit., pp. 614-616. It is very important to point out that this paper was also reprinted on the chapters 7, 8, and 9 of the book *La valeur de la Science*, quoted in note 12, and, as already discussed there, read by Albert Einstein with the friends Maurice Solovine and Conrad Habicht in the "Akademie Olympia" before writing his paper *Zur Elektrodynamik bewegter Körper*, op. cit.

does not exist and within which dynamics of material bodies is embedded, there is no doubt he separated this radical point of view from the consequences which do not depend on it. Even if proper mechanical masses exist, they have to depend on velocity by the same law for electromagnetic masses; and all the forces, whatever be their origin, are transformed by a uniform translation of the reference frame. Masses and forces are no more absolute quantities, but depend on velocity and so on the reference frame. The relation of forces and accelerations is no more given by a scalar mass, but in some sense by a "tensorial" mass, because it depends on the direction of forces.

Third and most important point, it becomes clear the aim of the whole historical and theoretical analysis of the principles of mathematical physics: Poincaré, by means of a great synthesis of the experimental results, expecially of Michelson-Morley's and Kaufmann's ones, and of the *ad hoc* hypotheses of Lorentz to save the old mechanics, outlined, without writing the explicit formulas but with precise indications and in its principles, an entirely new mechanics. This new mechanics is based first of all on the principle of relativity of motion for inertial reference frames. The second principle, characterizing the new mechanics and analogue to the third principle of thermodynamics, stated the impossibility to surpass the velocity of light: this is justified by the consideration that the inertia of material bodies would become infinite when one approached the velocity of light. After this, Poincaré added that consistency of the descriptions of different inertial reference frames implies that the limiting light velocity is invariant for inertial reference frames and that one has to consider time transformation to measured "local time". From all this, it is implicitly involved that the principle of relativity and the new mechanics cannot be simply realized by Galilean transformations for inertial reference frames.

The problems involved by gravitation in this new mechanical framework were immediately pointed out by Poincaré:

> If there is no longer any mass, what becomes of the law of Newton? Mass has two aspects, it is at the same time a coefficient of inertia and an attracting mass entering as factor into Newtonian attraction. If the coefficient of inertia is not constant, can the attracting mass be. That is the question.[34]

After the discussion and the doubts about the principle of energy conservation, Poincaré outlined the conclusions of his analysis:

> In the mist of so many ruins what remains standing? The principle of least action has hitherto remained intact, and Larmor appears to believe that it will long survive the others; in reality, it is still more vague and more general. In the presence of this general ruin of the principle, what attitude will mathematical physics take?...All these apparent contradictions to the principles are encountered only among infinitesimals; the microscope is necessary to see the Brownian movement; electrons are very light; radium is very rare, and no one has ever seen more than some milligrams of it at a time. And, then, it may be asked if, beside the infinitesimal seen, there be not another infinitesimal unseen

[34] H. Poincaré, *The Principles of Mathematical Physics*, translated by G. Halsted, in *Philosophy and Mathematics*,..., op. cit., p. 616.

counterpoise to the first. So, there is an interlocutory question, and, as it seems, only experiment can solve it...we have enough to employ our activity during this period of doubts. And as to these doubts, is it indeed true that we can do nothing to disembarrass science of them? It may be said, it is not alone experimental physics that has given birth to them; mathematical physics has well contributed...it is the theorists who have put in evidence all the difficulties...Well, then, if they have done their best to put us into this embarrassment, it is proper also that they help us to get out of it. They must subject to critical examination all these new views I have just outlined before you, and abandon the principles only after having made a loyal effort to save them. What can they do in this sense? That is what I will try to explain...Should we not also endeavor to obtain a more satisfactory theory of electro-dynamics of bodies in motion? It is there expecially, as I have sufficiently shown above, that difficulties accumulate. Evidently we must heap up hypotheses, we cannot satisfy all the principles at once; heretofore, one has succeded in safeguarding some only on condition of sacrificing the others; but all hope of obtaining better results is not yet lost. Let us take, therefore, the theory of Lorentz, turn it in all senses, modify it little by little, and perhaps everything will arrange itself. Thus in place of supposing that bodies in motion undergo a contraction in the sense of the motion, and that this contraction is the same whatever be the nature of these bodies and the forces to which they are otherwise submitted, could we not make an hypothesis more simple and more natural? We might imagine, for example, that it is the ether which is modified when it is in relative motion in reference to the material medium which it penetrates, that when it is thus modified, it no longer transmits perturbations with the same velocity in every direction. It might transmit more rapidly those which are propagated parallel to the medium, whether in the same sense or in the opposite sense, and less rapidly those which are propagated perpendicularly. The wave surfaces would no longer be spheres, but ellipsoids, and we could dispense with that extraordinary contraction of all bodies. I cite that only as an example, since the modifications one might essay would be evidently susceptible of infinite variation...Michelson has shown us, I have told you, that the physical procedures are powerless to put in evidence absolute motion; I am persuaded that the same will be true of the astronomic procedures, however far one pushes precision...While waiting, I believe the theorists, recalling the experience of Michelson, may anticipate a negative result, and that they would accomplish a useful work in constructing a theory of aberration which would explain this in advance. But let us come back to the earth. There also we may aid the experimenters. we can, for example, prepare the ground by studying profoundly the dynamics of electrons; not, be it understood, in starting from a single hypothesis, but in multiplying hypotheses as much as possible. It will be, then, for the physicists to utilize our work in seeking the crucial experiment to decide between these different hypotheses. This dynamics of electrons can be approached from many sides, but among the ways leading thither is one which has been somewhat neglected, and yet this is one which promise us most of surprises. It is the movements of the electrons which produce the line of the emission spectra; this is proved by the phenomenon of Zeeman; in an incandescent body, what vibrates is sensitive to the magnet, therefore electrified. This is a very important first point, but no one has gone farther; why are the lines of the spectrum distributed in accordance with a regular law?...And from the particular point of view which we to-day occupy, when we know why the vibrations of incandescent bodies differ from ordinary elastic vibrations, why the electrons do not behave themselves like the matter which is familiar to us, we shall better comprehend the dynamics of electrons and it will be perhaps more easy for us to reconcile it with the principles. Suppose, now, that all these efforts fail, and after all I do not believe they will, what must be done? Will it be necessary to seek to mend the broken principles in giving what we French call a *coup de pouce* ? That is evidently always possible, and I retract nothing I have formerly said. Have you not written, you might say if you wished to seek a quarrel with me, have you not written that the principles, though of experimental origin, are now unassailable by experiment because they have become conventions? And now you have just told us the most recent conquests of experiment put these principles in danger. Well, formerly I was right and to-day I am not wrong. Formerly I was right, and what is now happening is a new proof of it. Take, for example, the calorimeter experiment of Curie on radium. It is possible to reconcile that with the principle of the conservation of energy? It has been attempted in many ways; but there is among them one I should like you to notice. It has been conjectured that radium was only an intermediary, that it only stored radiations of unknown nature which flashed through space in every direction, traversing all bodies, save radium, without being altered by this passage and without exercing any action upon them. Radium alone took from them a little of their energy and afterward gave it out to us in divers forms. What an advantageous explanation, and how convenient! First, it is unverifiable and thus irrefutable. Then again it will serve to account for any derogation whatever to the principle of Mayer; it responds in advance not only to the objection of Curie, but to all the objections that future experimenters might accumulate. This new and unknown energy would serve for everything. This is just what I have said, and we are thereby shown that our principle is unassailable by experiment. And after all, what have we gained by this *coup de pouce* ? The principle is intact, but thenceforth of what use is it? It permitted us to foresee that in such or such circumstance we could count on such a total quantity of energy; it limited us; but now where there is put at our disposition this indefinite provision of new energy, we are limited by nothing; and as I have written elsewhere, if a principle ceases to be fecund, experiment, without contradicting it directly, will be likely to condemn it. This, therefore, is not what what would have to be done, it would be necessary to rebuild anew. If we were cornered down to this necessity, we should moreover console ourselves. It would not be necessary to conclude that science can weave only a Penelope's web, that it can build only ephemeral constructions, which it is soon forced to demolish from top to bottom with its own hands. As I have said, we have already passed through a like crisis. I have shown you that in the second mathematical physics, that of the principles, we find traces of the first, that of the central forces; it will be just the same if we must learn a third...We cannot foresee in what way we are about to expand; perhaps it is the kinetic theory of gases which is about to undergo development and serve as model to the others. Then, the facts which first appeared to us as simple, thereafter will be merely results of a very great number of elementary facts which only the laws of chance make cooperate for a common end. Physical law will then take an entirely new aspect; it will no longer be solely a differential equation, it will take the character of a statistical law.

Perhaps, likewise, we should construct a whole new mechanics, of which we only succeed in catching a glimpse, where inertia increasing with the velocity, the velocity of light would become an impassable limit. The ordinary mechanics, more simple, would remain a first approximation, since it would be true for velocities not too great, so that we should still find the old dynamics under the new...[35]

Here Poincaré, first of all, looked for an equilibrate and open position, saying what one should do to be sure that a new mechanics, with its breakdown of the old principles, is the only way for the physics of the future. From one side, one should wait for a confirmation of experiments, being aware that one could also conceive other new microphysical contexts where other changes in physics could be required; from the other (theoretical) side, saving the old view and a form of the relativity principle, one could choice other conventions on the velocity of light and indeed there were infinite possible conventions.[36]

[35] H. Poincaré, *The Principles of Mathematical Physics*, translated by G. Halsted, in *Philosophy and Mathematics,...*, op. cit., pp. 617-621.

[36] The possibility of other conventions will be pointed out by Poincaré also in other successive papers, to which we shall also refer in the following, even if it is already clear from the conclusions of this paper that the other conventions to save the old principles are not preferable because physically useless. See: H. Poincaré, *L'espace et le temps*, op. cit.; H. Poincaré, *La mécanique nouvelle*, conference delivered at the Congrès de Lille 1909 de l'Association française pour l'Avancement des Sciences, published in a reprint volume, containing also the 1905 papers written *Sur la dynamique de l'électron* on the *Comptes Rendus de l'Académie des Sciences* and on the *Rendiconti del Circolo matematico di Palermo*, entitled *La mécanique nouvelle*, Gauthier-Villars, Paris 1924, and reprinted in turn by Gabay, Sceaux 1989 with the 1924 introduction of Édouard Guillaume on these problems, pp. V-XVI; H. Poincaré, *La mécanique nouvelle*, sixth Wolfskehl lecture delivered at Göttingen (22-28 April, 1909), published in *Sechs Vorträge über ausgewählte Gegenstände aus der reinen Mathematik und mathematischen Physik*, Teubner, Leipzig 1910; a new version of this paper on *La mécanique nouvelle* was published as chapters X, XI and XII of his book *Science et Méthode*, Flammarion, Paris 1908; another different paper (in german language) on the same subject is *Die neue Mechanik* , conference delivered at the "Wissenschaftlichen Vereins zu Berlin" on 13 October 191O, Sonderabdruck aus dem XXIII Jahrgange der illustrierten naturwissenschaftlichen Monatsschrift *Himmel und Erde*, Leipzig, Teubner 1911. A modern discussion about the possibility of different conventions on the so-called one-way light velocity related to that one on simultaneity can be found in: A. A. Tyapkin, *Expression of the General...*, op. cit.; A. A. Tyapkin, *Relatività Speciale*, op. cit.; A. A. Logunov, *Lectures on Relativity...*, op. cit., all quoted in note 4. See also: A. O. Barut, *Geometry and Physics. Non-Newtonian Forms of Dynamics*, Bibliopolis, Napoli 1989, pp. 5-9; J. A. Winnie, *Special Relativity without One-Way Velocity Assumptions: Part I & Part II*, in *Philosophy of Science*, v. **37** (1970), pp. 81-99 & 223-238; C. Giannoni, *Relativistic Mechanics and Electrodynamics without One-Way Velocity Assumptions*, in *Philosophy of Science*, v. **45** (1978), pp. 17-46; P. Havas, *Simultaneity, conventionalism, general covariance, and the special theory of relativity*, in *General Relativity & Gravitation*, v. **19** (1987), pp.435-453; P.

After this disgression, he stated what one should do to extend the impossibility of revealing absolute motion in astronomical contexts: a new theoretical framework for the phenomenon of light aberration;[37] and, then, what one should do to give content and consinstency to the new mechanical framework: the dynamics of electron. This was indeed, as we shall see, the next step in Poincaré's work:[38] at variance with Miller's analysis,[39] here it is clear that the electrodynamical work of Poincaré is at all related to the construction of a new mechanics.

Then, Poincaré gave us the key to understand his position about principles and conventions in physics, at variance with the ideas of all the criticism of his conventionalism as an epistemological obstacle to the foundation of a new physics.[40] Poincaré indeed pointed out that there is no contradiction between his statements in *La Science et l'hypothèse* on the principles as "conventional generalizations of experiments"[41] and the statements in this paper on the need to abandon the old principles: there are contexts in which a so-called *coup de pouce* to preserve the old principles as conventions does not solve anything, just because in these contexts these principles as such become useless at all. That is, even if experiments do not directly contradict them for their partial conventional content, experiments condemn them because saving them is equivalent to give them only a mere formal content which cannot say us anything about the phenomena to be understood.

From this analysis, it is clear that the crisis of principles in physics has to be related to the use of new instruments (like the interpherometer of Michelson-Morley's experiments), and to correspondent new experiments (like

Havas, *Four-Dimensional Formulations of Newtonian Mechanics and their Relation to the Special and the General Theory of Relativity*, in *Reviews of Modern Physics*, v. **36** (1964), pp. 938-965; S. J. R. Anderson & G. E. Stedman, *Distance and the Conventionality of Simultaneity in Special Relativity*, in *Foundations of Physics Letters* , v. **5** (1992), pp. 199-220.

[37] The phenomenon of light aberration was discussed by Einstein in his famous paper *Zur Elektrodynamik...*, op. cit., quoted in note 10, within the presentation of the new mechanics. One could argue that this Poincaré's paper was of great inspiration for Einstein (also in relation to his paper on Brownian motion, written in 1905 too).

[38] H. Poincaré, *Sur la dynamique de l'électron*, in *Comptes Rendus de l'Académie des Sciences*, v. **140** (1905), pp. 1504-1508, reprinted in *Œuvres*, v. **IX**, op. cit., pp. 489-493 and in *La mécanique nouvelle*; op. cit.; H. Poincaré, *Sur la dynamique de l'électron*, in *Rendiconti del Circolo Matematico di Palermo*, v. **21** (1906), pp. 129-175, reprinted in *Œuvres*, v. **IX**, op. cit., pp. 494-550 and in *La mécanique nouvelle*; op. cit.; H. Poincaré, *La dynamique de l'électron*, in *Revue générale des Sciences pures et appliquées*, v. **19** (1908), pp. 386-402, reprinted in *Œuvres*, v. **IX**, op. cit., pp. 551-586; H. Poincaré, *La dynamique de l'électron*, lecture delivered at l'École Supérieure des Postes et des Télégraphes on July 1912, Danel, Lille 1912; H. Poincaré, *La dynamique de l'électron*, Dumas, Paris 1913.

[39] See note 5.

[40] See note 8.

[41] H. Poincaré, *La Science et l'hypothèse*, op. cit., pp. 111-128.

Michelson-Morley's and Kaufmann's ones) and new measurements (like the measurements of electron's velocities very near to light one), which introduced "new conditions (means and contexts) of possibility for experience" contradicting the previous conditions for experience.

From Poincaré's perspective, no criticism about the general possibilities of physics is needed: after the mathematical physics of the central forces and after the one of principles, there will be *a third new mathematical physics* .[42] In Poincaré's words, such a new mathematical physics will be probably characterized from the recognition of the statistical fundamental character of physical laws, may be no longer formulable in terms of differential equations[43] and from the new mechanics already sketched on the basis of the relativity principle and of the principle of the impossibility of overcoming the limiting light velocity. And thus Poincaré formulated a "*correspondence principle* " between the new mechanics and the old one: ordinary classical mechanics will remain a first approximation to the new one in the case of small velocities in respect to light velocity.

2.3 The Mathematical Formulation of the New Special Relativistic Mechanics before Einstein

As already noted, Poincaré followed the idea to give content and consistency to the new mechanics by analysing the dynamics of the electron, that is in the microphysical context where it has to replace the old one. Thus, he

[42] Poincaré indeed gave no name to this third mathematical physics. In the second mathematical physics of principles, principles played the role of a sort of epistemic, transcendental (kantian a priori principles of intellegibility of nature) foundation for physics. In the third mathematical physics, even if some principles remain, they have no more a preferred a priori status, but they are the a posteriori synthesis of mathematical (theoretical) physics and experimental physics, where physics is understood, as already noted in the discussion on *La Science et l'hypothèse*, as *a linguistic and an experimental practice*.

[43] This, as well known, will be the characterization of physics related to the so-called "quantum revolution", which Poincaré too dealt with, suggesting that it could imply the renounce to the differential equation identification of physical laws: see the *Discussion du rapport de M. Einstein*, in MM. P. Langevin et M. de Broglie (eds.), *La théorie du rayonnement et les quanta. Rapports et discussions de la Réunion tenue à Bruxelles, du 30 Octobre au 3 Novembre 1911 sous les auspices de M. E. Solvay*, Gauthier-Villars, Paris 1912, pp. 436-454, in particular p. 451 and *Abhandlungen der deutschen Bunsengesellschaft* **7** , pp. 330-364; H. Poincaré, *Sur la théorie des quanta*, in *Comptes Rendus de l'Académie des Sciences*, v. **153** (1912), pp. 1103-1108, reprinted in *Œuvres*, v. **IX**, op. cit., pp. 620-625; *Sur la théorie des quanta* , in *Journal de Physique théorique et appliquée*, v. **2** (1912), pp. 5-34, reprinted in *Œuvres*, v. **IX**, op. cit., pp. 626-653; *L'hypothèse des quanta*, in *Revue Scientifique*, v. **50** (1912), pp. 225-232, reprinted in *Œuvres*, v. **IX**, op. cit., pp. 654-668 and as chapter 6 in H. Poincaré, *Dernières pensées*, op. cit. See also: H. Poincaré, *L'évolution des lois*, conference delivered at the Congresso di Filosofia di Bologna on 8 April 1911, in *Scientia*, v. **IX** (1911), pp. 275-292, reprinted as chapter 1 in *Dernières pensées*, op. cit.

formulated the new mechanics in a paper entitled *Sur la dynamique de l'électron*, published on the *Comptes Rendus de l'Académie des Sciences*, on June 5, 1905:

Il semble au premier abord que l'aberration de la lumière et les phénomemènes optiques qui s'y rattachent vont nous fournir un moyen de déterminer le mouvement absolu de la Terre, ou plûtot son mouvement, non par rapport aux autres astres, mais par rapport à l'ether. Il n'en est rien; les expèriences où l'on ne tient compte que de la première puissance de l'aberration ont d'abord échoué et l'on en a aisément découvert l'explication; mais Michelson, ayant imaginé une expérience où l'on pouvait mettre en évidence les termes dépendant du carré de l'aberration, ne fu pas plus hereux. Il semble que cette impossibilité de démontrer le mouvement absolu soit une loi générale de la nature. Une explication a été proposée par Lorentz, qui a introduit l'hypothèse d'une contraction de tous les corps dans le sens du movement terrestre...Lorentz a cheché à completer et à modifier son hypothèse de façon à la mettre en concordance avec le postulat de l'impossibilité *complète* de la determination du movement absolu. C'est ce qu'il a réussi à faire dans son article intitulé *Electromagnetic phenomena in a system moving with any velocity smaller than that of light* (*Proceedings* de l'Académie d'Amsterdam, 27 mai 1904). L'importance de la question m'a déterminé à la reprendre; les résultats que j'ai obtenus sont d'accord sur tous les points importants avec ceux de Lorentz; j'ai été seulement conduit à les modifier et à les compléter dans quelques points de détail.

Le point essentiel, établi par Lorentz, c'est que les équations du champ électromagnétique ne sont pas altérées par une certaine transformation (que j'appellerai du nom de *Lorentz*) et qui est de la forme suivante

a) $x' = kl\,(x + \varepsilon\, t),\ y' = l\, y\,,\ z' = l\, z,\ t' =$
$= kl\,(t + \varepsilon\, \chi)$

x, y, z sont les coordonnées et t le temps avant la transformation, x', y', z' et t' après la transformation. D'ailleurs ε est une constante qui définit la transformation $k = (1 - \varepsilon^{2})^{-1/2}$

et l est une fonction quelconque de ε On voit que dans cette transformation l'axe des x joue un rôle particulier, mais on peut évidemment construire une transformation où ce rôle serait joué par une droite quelconque passant par l'origine. L'ensemble de toutes ces transformations, joint à l'ensemble de toutes les rotations de l'espace, doit former un groupe, mais, pour qu'il en soit ainsi, il faut que $l = 1$; on est donc conduit à supposer $l = 1$ et c'est là une conséquence que Lorentz avait obtenue par une autre voie.[44]

Here, Poincaré wrote for the first time in a complete and correct form the coordinate transformations, which he called "Lorentz transformations": we can recognize them as written in our present notation, pointing out that $\varepsilon=\beta$ and $k=\gamma$. In 1976, Miller discovered three letters from Poincaré to Lorentz, written between late 1904 and mid-1905, which contain, among other very important

[44] H. Poincaré, *Sur la dynamique de l'électron*, in *Comptes Rendus*...,op cit., pp. 1504-1505.

things, Poincaré's proof that the requirement that Lorentz transformations (including rotations of space) form a group implies $l = 1$.[45] The essential point here stressed by Poincaré is that Lorentz transformations realize the electrodynamical relativity symmetry group, that is they are the invariance transformations of electrodynamics which obey to the relativity principle.

Poincaré continued:

Soient ρ la densité électrique de l'électron, ξ, η, ζ sa vitesse avant la transformation; on aura pour les mêmes quantités ρ', ξ', η', ζ' après la transformation (2)

$$\rho' = k\rho\,(1 + \varepsilon\xi) / l^3,\quad \rho'\xi' = k\rho\,(\xi + \varepsilon) / l^3,\quad \rho'\eta' = \rho\eta / l^3,\quad \rho'\zeta' = \rho\zeta / l^3$$

Ces formules diffèrent un peu de celles qui avaient été trouvées par Lorentz. Soient maintenant X, Y, Z, et X', Y', Z' les trois composantes de la force avant et après la transformation, la force est rapportée à l'unité de volume; je trouve

$$(3)\quad X' = k\,(X + \varepsilon\,\Sigma X\xi)/l^5,\quad Y' = Y/l^5,\quad Z' = Z/l^5$$

Ces formules diffèrent également un peu de celles de Lorentz; le terme complémentaire en $\Sigma X\xi$ rappelle un résultat obtenu autrefois par M. Liénard. Si nous désignons maintenant par X_1, Y_1, Z_1, et X_1', Y_1', Z_1' les composantes de la force rapportée non plus à l'unité de volume, mais à l'unité de masse de l'électron, nous aurons

$$(4)\quad X_1' = k\rho\,(X_1 + \varepsilon\,\Sigma X_1\xi) / (\rho' l^5),$$

$$Y_1' = \rho Y_1 / (\rho' l^5),\quad Z_1' = \rho Z_1 / (\rho' l^5)$$

Here Poincaré gave for the first time the relativistic transformations for the charge and current density, implicitly for the velocity of an electron, and for the force density (as referred to unit volume or to unit mass):[46] the fundamental

[45] See A. I. Miller, *Albert Einstein's...*, op. cit.; A. I. Miller, *Frontiers of...*, op. cit.; A. I. Miller, *Why did Poincaré...*, op. cit., pp. 25-28. However, Miller's interpretation is misleading, because, among other points, noting that simultaneity, "the very core of relativity", is not explicitly mentioned here by Poincaré, Miller has concluded that what Poincaré had done has no relation with the construction of the new mechanics of special relativity. Indeed, we have already pointed out how, since 1904, the dynamics of electron in Poincaré's work is strictly related to the formulation of the new mechanics. Poincaré's criticism of simultaneity, as already seen, was already formulated in 1898. In respect to Lorentz transformations, we have to note that the general invariance transformations of electrodynamics were already discovered by Voigt in 1887. This Poincaré's paper and the other published on *Rendiconti*, have been presented for the first time in a complete english translation and with very important and enlightening comments by A. A. Logunov in: A. A. Logunov, *On the articles by Henri Poincaré - On the Dynamics of the Electron*, op. cit., quoted in note 4.

[46] For the differences between Poincaré's and Lorentz' works and positions, see H. A. Lorentz, *Deux Mémoires...*, op. cit. and A. A. Logunov, *On the articles by*

requirement that also forces are Lorentz-transformed implies that Lorentz group is assumed not only as the electrodynamics (Maxwell-Lorentz equations for the electromagnetic field) relativity symmetry group but also as the dynamics-of-the-electron (Lorentz force) relativity symmetry group, that is the dynamical equations of motion for the electron must be invariant under Lorentz transformations to obey to the relativity principle. This new dynamics of the electron is special-relativistic and it gives mathematical content to the new mechanics outlined by Poincaré at the 1904 St. Louis Conference.

Moreover, Poincaré wrote:

Lorentz est amené également à supposer que l'électron en mouvement prend la forme d'un ellipsoïde aplati; c'est également l'hypothèse faite par Langevin, seulement, tandis que Lorentz suppose que deux des axes de l'ellipsoïde demeurent constants, ce qui est en accord avec son hypothèse $l = 1$, Langevin suppose que c'est le volume qui reste constant. L'hypothèse de Langevin aurait l'avantage...Mais je montre, d'acord en cela avec Lorentz, qu'elle est incapable de s'accorder avec l'impossibilité d'une expérience montrant le mouvement absolu. Cela tient, ainsi que je l'ai dit, à ce que $l = 1$ est la seule hypothèse pour laquelle l'ensemble des transformations de Lorentz forme un groupe. Mais avec l'hypothèse de Lorentz, l'accord entre les formules ne se fait pas tout seul; on l'obtient, et en même temps une explication possible de la contraction de l'électron, en supposant que *l' électron , déformable et compressible, est soumis à une sorte de pression constante extérieure dont le travail est proportionnel aux variations du volume.* Je montre, par une application du principe de moindre action, que, dans ces conditions, la compensation est complète, si l'on suppose que l'inertie est un phenomène exclusivement électromagnétique, comme on l'admet généralement depuis l'expérience de Kaufmann, et qu'à part la pression constante dont je viens de parler et qui agit sur l'électron, toutes les forces sont d'origine électromagnétique. On a ainsi l'explication de l'impossibilité de montrer le mouvement absolu et de la contraction de tous les corps dans le sens du mouvement terrestre. Mais ce n'est pas tout: Lorentz, dans l'ouvrage cité, a jugé nécessaire de compléter son hypothèse en supposant que toutes les forces, quelle qu'en soit l'origine, soient affectées, par une translation, de la mème manière que les forces électromagnétiques, et que, par conséquent, l'effet produit sur leurs composantes par la transformation de Lorentz est encore défini par les équations (4). Il importait d'examiner cette hypothèse de plus près et en particulier de rechercher quelles modifications elle nous obligerait à apporter aux lois de la gravitation. C'est ce que j'ai cherché à determiner; j'ai été d'abord conduit à supposer que la propagation de la gravitation n'est pas instantanée, mais se fait avec la vitesse de la lumière. Cela semble en contradiction avec un résultat obtenu par Laplace qui

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Henri Poincaré - On the Dynamics of the Electron, op. cit., quoted in note 4, in which it is stressed the novelty of Poincaré in respect to Lorentz, as strictly related to the Poincaré's complete assumption of relativity as an irrenunciable physical postulate, that puts the inertial reference frame indicated by the coordinates x', y', z', t' as relativistically equivalent to the inertial reference frame indicated by the coordinates x, y, z, t . A complete understanding of the details of this Poincaré's note requires the reading of the *Rendiconti* 's paper.

annonce que cette propagation est, sinon instantanée, du moins beaucoup plus rapide que celle de la lumière. Mais, en réalité, la question que s'était posée Laplace diffère considérablement de celle dont nous nous occupons ici. Pour Laplace, l'introduction d'une vitesse finie de propagation était la *seule* modification qu'il apportait à la loi de Newton. Ici, au contraire, cette modification est accompagnée de plusieurs autres; il est donc possible, et il arrive en effet, qu'il se produise entre elles une compensation partielle. Quand nous parlerons donc de la position ou de la vitesse du corps attirant, il s'agira de cette position ou de cette vitesse à l'instant où l'*onde gravifique* est partie de ce corps; quand nous parlerons de la position ou de la vitesse du corps attiré, il s'agira de cette position ou de cette vitesse à l'instant où ce corps attiré a été atteint par l'onde gravifique émanée de l'autre corps; il est clair que le premier instant est antérieur au second. Si donc x, y, z sont les projections sur les trois axes du vecteur qui joint les deux positions, si la vitesse du corps attiré est ξ, η, ζ, et celle du corps attirant ξ_1, η_1, ζ_1, les trois composantes de l'attraction (que je pourrai encore appeler X_1, Y_1, Z_1) seront des fonctions de $x, y, z, \xi, \eta, \zeta, \xi_1, \eta_1, \zeta_1$. Je me suis demandé s'il était possible de déterminer ces fonctions de telle façon qu'elles soient affectées par la transformation de Lorentz conformément aux équations (4) et qu'on retrouve la loi ordinaire de la gravitation, toutes les fois que les vitesses ξ, η, ζ ξ_1, η_1, ζ_1 sont assez petites pour qu'on puisse en négliger les carrés devant le carré de la vitesse de la lumière. La réponse doit être affirmative. On trouve que l'attraction corrigée se compose de deux forces, l'une parallèle au vecteur x, y, z, l'autre à la vitesse ξ_1, η_1, ζ_1. La divergence avec la loi ordinaire de la gravitation est, comme je viens de le dire, de l'ordre de ξ^2; si l'on supposait seulement, comme l'a fait Laplace, que la vitesse de propagation est celle de la lumière, cette divergence serait de l'ordre de ξ, c'est-à-dire 10000 fois plus grande. Il n'est donc pas, à première vue, absurde de supposer que les observations astronomiques ne sont pas assez précises pour déceler une divergence aussi petite que celle que nous imaginons. Mais c'est ce qu'une discussion approfondie permettra seule de décider.[47]

Here, Poincaré dealt with the problem of the Lorentz-Fitz-Gerald contraction. The previous explanations of the contraction were related to the hypotheses that the molecular forces which are responsible for the dimensions of bodies were of electromagnetic origin and that electrons, the stuff constituting matter, underwent a contraction; Poincaré showed that the contraction of electrons must be obtained by a pression force of non-electromagnetic origin, which work is proportional to the electron variation of volume. This explanation of the Lorentz contraction is one of the most problematic point: here, it is explained as a dynamical effect, even if a non-electromagnetic one; on the contrary, as well known, Einstein's and the modern relativistic point of view explained the contraction only as a kinematical effect, related to our way of

[47] H. Poincaré, *Sur la dynamique de l'électron*, in *Comptes Rendus de l'Académie des Sciences*, v. 140 (1905), pp. 1506-1508.

measuring space and time.[48] Indeed, these two interpretations (the dynamical and the kinematical ones) of the contraction phenomenon are not mutually exclusive or contradictory. At variance with Lorentz' perspective, Poincaré had no privileged reference frame but a completely relativistic point of view, by which also dynamical effects are no more absolute ones, but relative to the reference frame: that is, dynamics is relative to the kinematics of the reference frames. Dynamical forces are no more concevaible as "real causes" (in classical mechanics, for Poincaré, force is only the Kirchhoff's definition of the product of mass *x* acceleration) non-affected by relativity appearances but depend also on the choiced *inertial* reference frame. That is, the physical content of dynamics is no more invariant for inertial reference frames (there is only a formal invariance of the equations of motion, or "covariance"), and so, given the same initial conditions, there is only a similitude, and no identity, of the physical phenomena as considered from different inertial reference frames. Neo-positivistic approach[49] has been influencing till today the epistemology of relativistic mechanics by considering the reduction of dynamics to kinematical appearances (as well as the reduction of the reality of motion only to kinematic appearances) "better" than the recognition of the "translation" of dynamical effects into kinematics. However, such a reduction has many epistemological flaws, as I shall show in the following.

Then, Poincaré reminded to us that to realize a relativistic dynamics it is necessary to take count of the mass dependence on velocity, and by this point he remembered also that this becomes possible when we look at the electrodynamical origin of mass of the electron. Indeed, it is clear that Poincaré at this step was stating something more than a mere special-relativistic dynamics, because this dynamics was related by him to an electrodynamical conception of inertia and indeed of nature itself. However, we have to note that here Poincaré was speaking only about electron inertial mass, and, as already noted on commenting his 1904 paper, he was aware that it was not certain that the inertial mass of the other particles could be completely explained by the hypothesis of its electrodynamical origin, and so that one must consider that anyway mechanical masses transform as electromagnetical masses. That is, Poincaré's special-relativistic dynamics is independent from his global suggestion of an electrodynamical view of nature: it is this very subtle point that has been generating confusion about the actual realization of a special-relativistic mechanics by Poincaré before Einstein. Here, we can recognize the main difference between Poincaré's special-relativistic mechanics, created within an electrodynamical conception of nature, and the posterior Einstein's special relativity (special relativity accepted by the physicists' community as a *separate* discipline) which is only a mechanistic theory.

Furthermore, we have still to point out that, by analysing the problem of the electron (as a finite-volume particle) stability, Poincaré discovered the need of a non-electromagnetic force, and so Poincaré was completely aware of the necessity of the independence of the special-relativistic dynamics from a global electrodynamical point of view. This is still more evident by Poincaré's extension

[48] See, for example, H. Reichenbach, *Raum-Zeit Lehre* . Here, however, the comparison between Lorentz' and Einstein's contractions is wrong.

[49] See, for example, H. Reichenbach, *Raum-Zeit Lehre*

of the special-relativistic dynamics of the electron subjected to electromagnetic forces to the special-relativistic dynamics of all the kind of forces, *whatever their origin may be* : they must be Lorentz-transformed to obey to the relativity principle. And, in particular, the other known "fundamental" force, gravitation.

Here, Poincaré was no more dealing with the special-relativistic dynamics of the electron, but he was giving its mathematical content to *an actual "complete" special-relativistic mechanics.* From this point of view, one must note that only Poincaré (twenty five days before Einstein's paper date of submission) constructed an actual "complete" special-relativistic mechanics which could replace classical mechanics, because Einstein's special relativity was not dealing with gravitation.

Dealing with gravitation, Poincaré overcame problems which Laplace had pointed out in his trials to modify Newton's law of gravitation.[50] This Poincaré's reference to Laplace's work can give us another suggestion about Poincaré's background to the creation of a new special-relativistic mechanics. Indeed, in the *Traité de méchanique céleste*,[51] Laplace had done the hypothesis of a more general mechanics, in which the force impulse and so the momentum (the "quantity of motion") would not be simply proportional to velocity, but a general function of the velocity and this would imply that force is no more parallel to acceleration. However, for Laplace there was no experimental evidence and he wrote his new mechanics only as a mathematical generalization. Indeed, for Poincaré, Kaufmann's experiment gave the evidence for a new relation between force and acceleration, and the mass dependence on velocity gave the determination to the general function of velocity written by Laplace.

Poincaré pointed out that all forces must propagate with the finite light velocity, that interaction implies a time delay and is mediated by field waves. Thus, Poincaré made for the first time the hypothesis of the existence of gravitational waves. One has to note an important point evident here, but neglected in the usual presentation of special relativity: the dependence of forces on positions and velocities at different (finitely-retarded) times implies irreversibility and hereditary effects in mechanics, and indeed the breakdown of the Poincaré's "generalized principle of inertia" (second order differential equations of motion).[52] If we translate the language of forces in the language of *local* fields, in general we have infinite order differential equations of motion, because

$$x(t+\tau) = \{\exp(\tau\, d/dt)\}\, x(t) \,.$$[53]

[50] Laplace, North, Gravitation Theories

[51] P. S. Laplace, *Traité de mécanique céleste*, 1796-1799. See also Dugas.

[52] H. Poincaré, *La Science et l'hypothèse*, op. cit., pp. Indeed, this is evident in the more recent trials to realize a relativistic mechanics without introducing fields in the so-called time-retarded direct-particle-inter-action-at-a-distance theories; see for example: Kerner, Lecture Notes in Physics, F. Hoyle & J. Narlikar.

[53] Indeed, otherwise (without introducing fields) we have integro-differential equations or finite difference equations. For this point, see also H. Poincaré, *La Science et l'hypothèse*, op. cit., pp. 180-181, and, for a first criticism of Newton's

Second order differential equations (Poincaré's generalized principle of inertia) imply the dependence of forces only on positions (central forces) and on velocities (infinitesimally-near positions at infinitesimally-near instants) at the same instant. In the language of local fields there are no more explicit time delays, and the hereditary effects are translated in "non-separability" effects embedded in the existence of a field at every space point and at every time instant, as noted by Federigo Enriques.[54]

law of gravitation, pp. 162-163; see also H. Poincaré, *Les limites de la loi de Newton*, in *Bulletin Astronomique* **42** (1953), pp. 121-269.

[54] F. Enriques, *Problemi della scienza*, Zanichelli, Bologna 1906, 1909^2, 1926, pp. 202-315, and in particular pp. 242-248 & 303-315: here, we can look at the reception and at one of the first recognition of Poincaré's work before the reception of Einstein's work. Enriques, within a proper own epistemological framework, gave a very enlightening analysis of the principles of classical mechanics, by pointing out the deepest physical meaning of many Poincaré's more mathematically formulated statements (like the generalized principle of inertia, and often without quoting explicitly Poincaré) and giving them very great strength within a historical perspective on Newton's dynamics. Then, analysing Poincaré's new relativistic dynamics, which he called "electrical dynamics" for its global electrodynamical perspective at variance with the classical mechanistic one, noted that one can write the new equations for the electron in almost-stationary motions (that is, motions for which the variations of velocity are so slow that the electrical and magnetic energies due to electron motion present only some little difference from the energies related to its uniform motion), formally analogous to Newtonian ones for a material point:

$$(m + m_{e.m.})\, \boldsymbol{a} = \boldsymbol{f} \,,$$

where m is the mechanical mass, $m_{e.m.}$ is the electromagnetic mass of the electron (due to self-induction force: $\boldsymbol{f}_{s.i} = - m_{e.m.}\boldsymbol{a}$) which is not a constant but depends on the geometric form of the electron and on its electric charge, on its velocity strenght and direction in respect to the force direction. Experimental results looked to give $m = 0$, and Poincaré's theory for electromagnetic mass gave a longitudinal mass (parallel to the direction of motion) $m_{,,} = m_0 k^3$ and a transversal mass (perpendicular to the direction of motion) $m_{\#} = m_0 k$ with $m_0 = e^2 / (8 \pi r)$ as rest mass (e being the electronic charge, and r the electron radius). From this, it follows that force is no more parallel to acceleration and mass is no more a scalar but like a "tensorial" quantity depending on velocity and on the direction of motion in respect to force direction. For low velocities in respect to the velocity of light, one recover Newtonian mechanics with a constant scalar mass. Thus, one cannot identify an electron with a material point, but within an electrodynamical theory of matter, one has to look at the Newtonian idealized material point as an aggregate of electrons, which satisfies the same new equations of motion: the mass is given by the sum of electromagnetic mass contributions related to the constituent (high-velocity) electrons within atoms or molecules, but, if the dimensions of the material body are very great in respect to the electron ones, it is given by a statistical computation which yields a constant quantity; the global motion of the material body with low velocity does not modify the electromagnetic mass. Thus, for low velocity of such a material point, he showed how "electrical dynamics" can be approximated by Newtonian dynamics. Moreover, he noted that the electromagnetic origin of mass implies to consider also inertial forces as forces of electromagnetic origin, by turning upside down the mechanistic view of electromagnetism of Maxwell himself who looked at the magnetic forces as particular inertial forces. From this point of view, it is clear that Poincaré's new relativistic dynamics cannot be seen as a continuation of Maxwell's perspective, but as a revolution in the foundations of physics by regarding electrodynamics at the foundation level of dynamics and not viceversa. Enriques embedded Poincaré's new relativistic dynamics in a general outlining of non-Newtonian dynamics, which do not satisfy the generalized principle of inertia. For Enriques, the generalized principle of inertia means that in every instant the motion of a material point happens as if this moves starting from rest, given that: 1) the mutual positions of the relevant external bodies are not modified by such an ideal stop; 2) for calculating the motion of the material point, one has to add to the momentum due to the statically measured force corresponding to the rest of the material point, the momentum corresponding to the actual velocity of the material point. This means that the generalized principle of inertia indeed implies the reduction of dynamics to a statics at the considered instant. It corresponds to the hypothesis of positional forces (central forces), beyond which one can consider also velocity(-at the same instant)-dependent forces to deal with the problem of the medium friction to represent the motion of a wider system of material points interacting only by positional forces into a phenomenological (medium) description of the motion of a partial, incomplete (not analysed in terms of material points and their interactions) system. Generalized inertia principle, with its reduction of dynamics to a statics at an instant, means that the present state of motion of a material point depends only on the present (at the same instant) velocity of the point and on the forces related to the position of the point at the same instant (the present state). That is, the present or future state of motion depends only on the present state (the initial conditions) and not on the previous past states of the material point: inertia generalized principle implies a *principle of non-hereditariness.* This involves that the motion of the material point does not affect the force field or at least that the modification of the force by the motion of the material point can be considered as an instaneous one, that is the presence of the material point in the force region of action at a previous instant does not modify the force acting on the point at the present position. It is clear that the finite time propagation of the electromagnetic interaction involves the breakdown of this principle, and that the new Poincaré's mechanics, which looks also at gravitation as a finite time propagation interaction, does not satisfy the principle of non-hereditariness and indeed the generalized inertia principle. The breakdown of the principle of non-hereditariness, moreover, induces the breakdown of the principle of determinism. Such principle of determinism is related to the theorem of existence and unicity of the solutions of a system of differential equations, and, as already noted, the finite time propagation of interactions implies the use of infinite order differential equations or integro-differential or finite difference equations which, in general do not satisfy this theorem. For classical mechanics, the principle of determinism can be formulated in these terms: the initial state of a mechanical system, that is the determined set of the positions and of the velocities of the material points of the system at a certain instant, determines *univocally* its whole motion. Thus, for example, for infinite order differential equations, positions and velocities are not enough to determine the motion, but one need the knowledge of all the higher derivatives at that instant. As Enriques pointed out, one can overcome the problem of hereditariness (but not the problem of "indeterminism") by conceiving the previous states of the material point as contiguously acting in space and in time in such a way to define a physically given *field* of forces which represents in its present state, locally in space and time, the modifications of forces induced by the motion and the previous states of the material point. Thus, the effect of the motion of the material point on dynamics (forces) is "translated" in the fact that (it is as if) the material point is everywhere and always given into and joint to an existent field of force (that is, it is not isolated in empty space but like in a medium, the field, which moves with it), defined at every space point and at every instant of time, with which the material point "interacts" only locally in space and in time. That is, we can replace the new "principle of hereditariness" by *a principle of solidarity or of relatedness or of non-separability* : one cannot speak of an isolated material point in interaction at distance and on finite times with other material points but of material points as connected all over the world in a non-separable way (no more as individuals interacting by individual forces, but as "singular" parts of a universal *field of motion* : for Poincaré, as for Kirckhhoff, force is nothing else than a name which indicates a particular function of motion). There are local variations of the field of motion for a material point, which depend on the motion of the point and propagate with a velocity c . Generalized inertia principle corresponds to $c = \infty$, and one can do such an assumption whenever the velocity of motion of the material point for a reference frame is small in respect to c . Indeed, the replacement of the principle of hereditariness with a principle of solidarity of the field of motion was already implicit at least for electromagnetism in Maxwell's theory as well as in its developments by Hertz and Lorentz. However, Maxwell-Hertz-Lorentz theory of electromagnetism was conceived as implying an absolute velocity in respect to the ether, and furthermore Maxwell, W. Thomson and others (inspiring also the reduction of all forces to "effects" of hidden masses in Hertz' mechanics Descartesian point of view) looked for a mechanistic explanation of electromagnetic forces as inertial forces: this indeed could explain why electromagnetism involves a breakdown of Galilei's relativity principle (as realized by the so-called Galilei transformations) as long as electromagnetic forces would be related to non-inertial reference frames; see Giorgi, S. Notarrigo, F. Dyson. Thus, also within such a perspective, the treatment of electromagnetism would imply a "universal" solidarity of motion (related to the dependence of dynamics on the non-inertial reference frame motion which is linked to the motion of the remaining part of the world) and an overcoming of Galilei's relativity. However, the mechanistic and materialistic reduction of light and electromagnetic phenomena and indeed of the reality of motion is completely *ad hoc*, non-univocal and useless. On the contrary, Wilhelm Weber's electrodynamics, generalizing Coulomb's and Ampere's Newtonian action-at-a-distance paradigm, involved forces which depend on relative velocities and accelerations of fundamental charges (accelerations are present because the subjects of electrodynamical or magnetic forces are the electrical currents whose motion variations imply acceleration of charges: Enriques' physical content of generalized principle of inertia is no more valid) and so was in agreement with Galilei's relativity: here, moreover, light velocity appeared in the treatment of electromagnetism as a sort of "limiting" velocity for charged particles (as a trace of finite-time propagation of interaction). Such a theory, more than falsified by experiments (Hertz' experiments were not crucial), was abandoned for the problems related to the energy conservation principle (here valid only globally, not locally) and to non-positional forces (electromagnetic inertia too). See also: S. D'Agostino, *Saggi di Storia della Fisica Moderna*, preprint, pp. 34-44; F. Bevilacqua, . Thus, anyway Poincaré's new relativistic dynamics was born for the impossibility to deal with electromagnetic phenomena within the classical mechanics framework (at least for inertial reference frames). For Enriques, Poincaré's "electrical dynamics" is a particular form of a general non-Newtonian dynamics for which the generalized inertia principle does not hold (the principle of the equality of action and reaction is a consequence of the principle of static equilibrium and of the generalized inertia principle): in the "electrical dynamics" the generalized inertia principle of classical mechanic is replaced by a principle of solidarity of the field of motion. Indeed, even if the physical content of the generalized principle of inertia as clarified by Enriques is no more valid for the new Poincaré's dynamics, its formal statement (second order differential equations), as Poincaré noted in other papers (see, for example, H. Poincaré, *Sur la dynamique de l'électron*, in *Rendiconti del Circolo Matematico di Palermo*, v. **21** (1906), pp. 129-175, as analysed in the following), is *saved*, in Enriques' terms, by the assumption of the principle of solidarity of the field of motion, when one consider almost-stationary motions (neglecting non-stationary motions). However, as I shall show, for Poincaré the treatment of the case of non-stationary motions, even if within the assumption of a principle of solidarity of the field of motion, cannot satisfy even the formal principle of generalized inertia (and obviously also the simple principle of inertia) and the principle of determinism because one cannot neglect higher derivative terms and one has to deal with infinite order differential equations which, even if do not formally imply the new principle of hereditariness, take count of the *whole irreversible history of motion* of the physical system (on the other side, the calculus of a field at a space point and at a time instant is based on the calculus of the so-called "retarded potential" in which *mechanical irreversibility* is embedded). Therefore, Enriques' analysis of Poincaré's new relativistic mechanics does not perfectly cover all its implications. For Enriques, furthermore, the breakdown of the physical generalized principle of inertia has to be understood also noting that it does not hold also for Newtonian dynamics in non-inertial reference frames, in which we have to take count of the "universal solidarity". This enlightening discussion of Poincaré's new relativistic dynamics by Enriques is so affected by a sort of anxiety to restore a mechanistic point of view over Poincaré's electrodynamical one. The relevant point from a dynamical point of view, thus, is *the impossibility of reducing dynamics to a statics at an instant*. Classical dynamics validity is limited to the analysis of the incipient motion from rest; in the new dynamics the reality of motion as a finite-time process (the reality of time) is irreducible, cannot be done

Finally, Poincaré gave also an actual mathematical meaning to the "correspondence principle" between the new special-relativistic mechanics and the old classical one, by the analysis of the modification of Newton's law of gravitation: the effects are of the order of β^2, and so go to zero for velocities small in respect to light velocity.

equivalent to rest (general motion is not equivalent to incipient motion from rest), and, even if one prefers a local-in-space-and-time formulation of dynamics, one cannot reduce dynamical problems to deal with a statical material point, but one has to consider a whole field of motion as a finite-time process of which the material point or particle is part. Poincaré's relativity principle as realized by Lorentz transformations reflects directly the finite-time process of communication between different inertial reference frames as well as of propagation of "interaction" or of motion. See also: F. Enriques, *Le principe 'inertie et les dynamiques non-Newtoniennes*, in *Scientia* , v. **II**, n. **III** (1907), pp. 21-34. Criticism on "electrical dynamics" from a mechanistic point of view was also expressed in: T. Levi-Civita, *Sulla massa elettromagnetica*, in *Nuovo Cimento*, ser. **V**, v. **XIV** (1907), pp. 1-36.