# Newton's laws of motion revisited: some epistemological and didactic problems

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**Abstract**

Newton's laws of motion constitute a coherent system. From a didactic and practical point of view, «Newton's School» is relatively the most appropriate one, but the conceptual problems it raises are real, particularly those having to do with the inertia and force concepts. It is not only a problem of how to deal with learners' misconceptions through the use of various didactic methods and increasingly clever teaching tools. The problem is much deeper. Certain basic concepts deserve to be re-examined. In this paper, we propose a reflection on Newton's laws of motion and suggest some ways of dealing with the conceptual problems they raise, especially at college level where some deep questions that seemed to have been fully answered in high-school regain a new life.

**Keywords:** Newton's laws of motion, Epistemology, Didactics, Classical Mechanics teaching.

**Resumen**

Las Leyes de Newton del movimiento constituyen un sistema coherente. Desde un punto de vista didáctico y práctico, «la Escuela de Newton» es relativamente uno de los más apropiados, pero los problemas conceptuales que plantea son reales, en particular los que tienen que ver con los conceptos de fuerza e inercia. No es sólo un problema de cómo hacer frente a concepciones erróneas de los alumnos mediante el uso de diversos métodos didácticos y herramientas de enseñanza cada vez más inteligentes. El problema es mucho más profundo. Algunos conceptos básicos valen la pena volver a examinar. En este trabajo, proponemos una reflexión sobre las leyes de Newton del movimiento y sugerir algunas formas de lidiar con los problemas conceptuales que plantean, especialmente a nivel universitario, donde algunas de las preguntas profundas que parecían haber sido plenamente contestadas en la escuela secundaria recuperan una vida nueva.

**Palabras clave:** Leyes de Newton del movimiento, Epistemología, Didácticas, Enseñanza de la Mecánica Clásica.

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## I. INTRODUCTION

More than three centuries after the publication of the Principia, Newton' laws of motion are still stirring up lively debates. Indeed, despite their evident and formidable power in the description of motion, they nevertheless leave us with a feeling of uneasiness with regard to the key concepts of inertia and force which are at the base of the theory. Is this only due to learners' misconceptions which are very difficult to eliminate, as often suggested in the abundant literature on the subject (see, for example [1, 2, 3, 4, 5, 6]), or is there a truly much deeper problem which is not wise to occult?

In what follows, we propose some reflections on these laws, formally taken one after the other, in their original order, but without forgetting to emphasize the bonds that link them together and make of them a coherent system.

## II. THE INERTIA PRINCIPLE

It is very often called "the first law of motion" as if the words principle and law were synonymous. We will return to this point later on, but let us state this "principle" first:

"An object will remain at rest or in uniform motion in a straight line unless acted upon by an external force", or "An isolated body, i.e., a body which is subjected to no force, stays at rest or keeps the same speed in a straight line".

It is well known that this "principle" does not have any direct experimental proof. It is only a generalization (an "idealized" extrapolation). One justifies it, in general, by the repetition of the experiment of a block with smoothed faces (a block of dry ice, for example) on a smooth surface (a large glass plate, for example). By using increasingly smooth blocks, one finds that the distance covered by the body, once set in motion, becomes increasingly longer. One concludes that if it were ideally possible to eliminate frictions completely, the body would continue, forever, its course in uniform rectilinear motion, in the absence of external forces.

There are of course more clever modern versions of this experiment but the basic one remains essentially the same.

It should be noted, first of all, that this "principle" will remain, as stated, a source of confusion, for several reasons:

The first one is that the key word, i.e. inertia, is defined by Newton as the resistance that a body opposes to its acceleration relative to absolute space. His force of inertia, which opposes acceleration, would violate the "principle of action and reaction", for absolute space cannot sustain the required reaction force [7]. We will return to the force of inertia in the following section where we evoke the solution, based on Mach's principle, proposed by Assis *et al*. to the problem raised above.

As for the concept of inertia itself, It is certainly preferable to say, with E. Kant, that "The inertia of matter is, and means, nothing else than its lifelessness, as matter itself" [8]. The inertia of (inert) matter implies at once that an (inert) body does not start moving from rest, and once moving at a constant speed, does not stop to do so, unless an external cause ("force") is applied. In order to avoid any pseudo metaphysical drift, one must admit that, in the realm of physical reality, i.e. for real bodies, there must necessarily be a beginning to the motion, i.e. an initial impulse. Hence the state of rest and the state of rectilinear uniform motion are admittedly equivalent but not strictly so. This is particularly of major importance from a didactic point of view.

The second reason is that this "principle" talks about an isolated body, which is thus supposed to be subjected to no external force, even though we cannot affirm that at all. The total isolation of a body is impossible. Despite the claim that this is only an idealization, what do we benefit from it, one could argue, if it cuts us off totally from reality? It is certainly not our aim to minimize the importance of idealization in formulating the laws of physics. We only advise its introduction to learners with a lot of caution.

As M. Hulin puts it so well: "Physics, being only an approximate science, should recognize its limits. The relationship with reality, which is at the heart of the scientific approach, generates, by essence, multiple cognitive conflicts that perturb learning" [9].

On this point, H. Poincaré, even if he only evokes the force of gravity, comments, not without a bit of irony: "… Is then the principle of inertia, which is not an a priori truth, an experimental fact? Have there ever been experiments on bodies acted on by no force, and if so, how did we know that no forces were acting? The usual instance is that of a ball rolling for a very long time on a marble table; but why do we say it is under the action of no force? Is it because it is too remote from all other bodies to experience any sensible action? It is not further from the earth than if it were thrown freely in the air; and we all know that in that case it would be subjected to the attraction of the earth" [10].

Poincaré's point of view keeps all its relevance, in particular the remark on the need to include forces which might not be a priori obvious, and the implications, from the point of view which one adopts on the structure of space-time, on the concept of reference frame. We will return to this problem with more details.

The third reason, related to the first, and which causes a lot of confusion in the minds of learners (especially at college level), is that it is conceptually hard to conceive of a body pursuing its uniform rectilinear motion indefinitely because of the following points:

The ambiguity of the notion of vacuum. The question about the very «content» of the latter is far from being resolved. A lot has been said on the subject throughout the history of science, but the problem has not faded away and the end does not seem to be in sight. In fact, it has regained a new life since the advent of quantum mechanics. We can say, with B. Green, that:" Debates…will no doubt continue as we grope to understand what space, time, and space-time actually are. With the development of quantum mechanics, the plot only thickens…Moreover,…, the most basic role that space plays in a classical universe- as the medium that separates one object from another, as the intervening stuff that allows us to declare definitively that an object is distinct and independent from another-is thoroughly challenged by startling connections." [11].

The existence of an indefinitely linear motion, which presupposes a certain conception of space-time, i.e., a flat space-time indefinitely extended to all universe, whereas its curvature necessarily implies a variable distribution of mass and energy which does not allow the extension of the concept of inertial frame to all of space. This being said, the approximation remains valid in small areas of space.

The existence of a perfectly homogeneous and eternally stable body which would never undergo any kind of corruption. We consider that this remark deserves attention and constitute, by no means, a return to "pre-scientific groping", even though it is obvious that, in practice, we can do without. Grasping the ontological aspect of concepts is, in our opinion, a necessity.

It also good to recall that the "inertia principle" is only valid in galilean referentials. On this point, we will note the following:

It is necessary to make a distinction between mathematical referentials which are the fruit of speculative thinking (so-called thought experiments), and physical referentials, which are linked, by definition, to material objects. The abstraction (or the occultation) of the physical, concrete and material aspect of reference frames, leads to confusion. When one speaks of the motion of reference frames, it must be clear that one refers to physical frames, i.e. concrete reference frames. As A. Koyré puts it so well: "In geometrical space, one can only place geometrical bodies. One cannot place real bodies. So, Aristotle will tell us that we should not confuse geometry and physics. A physicist deals with reality. A geometrician only deals with abstractions" [12].

As galilean referential frames are idealized, and do not thus have an existence in reality, the aforementioned principle is conceptually limited. It is necessary to insist on the fact that what matters in a theoretical model, is not only its accord with experiments but what it represents from a conceptual point of view. On this point, we can quote F. Balibar: "… It is not a priori obvious that there exist such reference frames. Nothing proves that uniform rectilinear motion corresponds to physical reality … The power of Newton's laws in giving an account of the real world rests on the supposed reality of uniform rectilinear motion. To this limitation of the theory, related to the question of knowing whether it actually describes reality … is added another limitation, internal to the theory: if one supposes that rectilinear motion does exist (and common experience leads us, after all, to believe that), Newton's dynamic description is only valid in referentials where, precisely, a body, free from the action of other bodies, moves in a straight line, at a constant speed. In other words: Newton's laws are only valid in inertial frames. However, reference frames are not all inertial, as common experience shows once more" [13].

In fact, the aforementioned "principle" is only a hypothesis; the latter being defined as a proposition resulting from an observation and that one subjects to the control of experiment, or that one verifies by deduction. It is not an axiom, as some authors suggest [14], if an axiom is defined as an indemonstrable truth which imposes itself with force. It is not a law either; the latter being defined as a general proposition stating necessary and constant relationships between physical phenomena or between the constituents of an ensemble. This term should be reserved to fundamental interactions such as, for example, the universal gravitational interaction. In all cases, it is far from constituting a universal principle because there is no experience to prove or refute it.

It is certain that the concept of inertia is far from being theoretically achieved as many published books and articles suggest.

One should add that this "principle" does not tell us what a force actually is. It gives us at best an operational definition. All that has been said, on this point, to justify this deficiency, although satisfying from a purely practical point of view, leaves us nonetheless with a feeling of unfulfillment (acknowledged or not) on the conceptual level. We will return to this point in the following section.

It is also perhaps interesting, for the sake of completeness, to conclude this section by recalling that the "principle of inertia", such as originally stated, does not make a distinction between a body on which no force is applied (isolated body) and a body that is subjected to forces whose resultant is zero. Later statements came, in point, to fill up this gap. One finally notes that the "principle of inertia" needs the "third principle" to be justified.

## III. THE FUNDAMENTAL PRINCIPLE OF DYNAMICS

We should first remark that this is the way this law is dubbed in some textbooks on classical mechanics (the same remark applies to the third law).

Enunciation of the principle: "The change of motion is proportional to the impressed force, and is in the direction of the right line in which that force is impressed". We express it mathematically as follows

$$\vec{F} = \frac{d\vec{p}}{dt}$$

or

$$\vec{F} = m\vec{a} \text{ (constant mass).}$$

One should recall that the "principle of inertia" is included in this "second principle" as a special case, i.e.

$$\vec{F} = \vec{0} \implies \vec{a} = \vec{0} \;\; \vec{v} = const.$$

The problem is, as has often been remarked, that Newton considered the "principle of inertia" as a primary truth, whereas it is clear that it not the case, which deprives it from the status he conferred to it, because it was supposed to define a force, even though some would argue that the "first principle" is necessary because it makes it possible to define an inertial frame. The explicit definition of an inertial frame should precede the "first principle" [14].

We also should note that this "principle" does not inform us about the definitions of force and mass, as H. Poincaré underlines it so rightly [10].

The notion of force, as such, being perceived as an abstract concept very far from any direct experiment, it would have been surprising if difficulties of comprehension were not raised about it. *"It has the appearance of a kind of faculty or occult quality that physicists sought, for a long time, to replace. One tried to define it materially as that which balances a weight via a mechanical system, like a stretched string, a spring, etc., but this point of view, although acceptable in a practical sense, was conceptually unsatisfactory. That is why J. R. Mayer, Helmholtz and mostly Hertz tried to build a mechanics where the concept of force is not considered among the basic concepts and has no definition other than $F = ma$ "* [15].

It is in the same perspective that the formalization of mechanics has taken on many forms, particularly those developed by Hamilton et Lagrange, in the framework of analytical mechanics, which do not use this concept, but which unfortunately have the disadvantage of introducing some other concepts which can be contemplated, for learners, only at an advanced stage in their studies, i.e. after acquiring appropriate knowledge in mathematics. The advantage, on the other hand, is that one gets rid of bizarre notions like that of "fictitious forces" which we will discuss later on. In addition, as H. Poincaré notes: *"The difficulties raised by classical mechanics have led certain minds to prefer a new system which they called Energetics". He adds a little later on "…, but it raises, in turn, fresh difficulties: the definitions of the two kinds of energy (potential and kinetic) would raise difficulties almost as great as those raised by force and mass in the first system (Newton's system)"* [10].

That is why Leibniz's mechanics, essentially based on the *vis viva* or *kinetic energy*, opposed, for some time, a resistance to Newton's mechanics. It seems appropriate to us to note, before saying more on the force concept, that, with regard to the difficulties evoked by H. Poincaré, concerning the two kinds of energy , that the latter are, from an epistemological point of view, the same *thing* manifesting itself according to *two degrees (or types) of existence*.

In most textbooks, force is considered as a well assimilated concept which does not require any explicit definition. *Mass* is then simply defined as a proportionality constant between the applied force and the measured acceleration. It is clear that this manner of proceeding confuses learners' minds and so gives of physics a far from brilliant image. As M. Hulin puts it: "Physics is extremely difficult to teach because it accumulates difficulties... Its analyses are neither very convincing nor natural at the outset, and are, at the same time, vague, compared to mathematics which will more easily allure gifted beginners" [9]. Is this judgment too severe? In all cases, difficulties encountered by learners are corroborated by an abundant literature and tend rather to reinforce it.

Other textbooks, on the other hand, give of mass a dynamical operational definition, according to Mach's reaction car experiment, or Mach sequence as A. B. Arons calls it [16], which has the advantage of not being circular [17, 18].

We think, as some authors do [19], that the purely relational Machian approach (or sequence), regarding the definition of mass, should be introduced, rather early, in all classical mechanics textbooks, in order to save us, not only from the various tautologies on this subject, but also from arbitrary definitions. We will recall it in the following section when we discuss the third law.

We should also note that the "second principle" is not a universal principle because it is intimately related to the other two.

A second critical point is related to its application in inertial and non inertial reference frames. In the first case, it is necessary to define with precision the reference frames in question. The definitions one finds are either approximate or idealized. In the second case, we are obliged to call upon pseudo forces or fictitious forces; but what do these fictitious forces really represent? The problem, as has been often observed, is that we feel them "really"! This constitutes, in our opinion, a serious conceptual problem. Physics teachers will not generally fail to feel uneasy when they are obliged to introduce the aforementioned fictitious forces in order to justify the application of the "second principle" in non inertial frames. The latter constitute a true conceptual minefield as the abundant research on the subject attests. Learners are confronted with enormous difficulties in their attempts to apprehend the concepts in question. Confusion in the use of centripetal and centrifugal forces is a good illustration in this respect. Interactions and their effects can only be objective. That is why we believe that the introduction of Mach's principle, and what it entails regarding the reality of the so-called inertial forces, should be incorporated, even in a simplified way, in classical mechanics textbooks, because the fact of considering that these forces come from the gravitational attraction between a given body and the remaining of the universe has a strong convincing force. What was lacking was a positive theory. It is not anymore the case. The works of Assis and al in particular, on this subject, are very elaborate and should reinforce the Machian point of view [7, 20, 21]. Here, we will content ourselves with the summary of the essential idea: the strict proportionality between inertial mass and gravitational mass intrigued Mach all his life. It led him to suggest that distant matter in the universe could regulate local interactions inertially. According to the Mach-Weber model, all the forces known as inertial (centrifugal, Coriolis, etc.) are due to the gravitational interaction of a given body with the remainder of the universe. This can explain the aforementioned proportionality. Using an invariant equation and what they call "the principle of dynamic equilibrium", Assis and al were able, benefitting from the work of other physicists, to explain the origin of inertia and the reality of inertial forces whose actual existence was considered very far-fetched.

There is also a very important point on the subject of fictitious forces on which we would like to comment. These are defined as follows: "It is the quantity which must be added to the real force in order to apply the second principle in non inertial reference frames". This expression is far from being clear, and even constitutes a source of confusion, because it raises the following question: up to what point do the laws of motion depend on the chosen referential, and how can we practically determine such a referential? For more clarity, we will note that when one calculates the force starting from the "second principle", we know that it depends on acceleration; but the latter depends on the referential with respect to which it is measured. Consequently, we could find values of the force which could differ according to the selected reference frame.

On this confusion, H. Hertz comments thus: "… I would mention the experience that it is exceedingly difficult to expound to thoughtful hearers the very introduction to mechanics without being occasionally embarrassed, without feeling tempted now and again to apologize, without wishing to get as quickly as possible over the rudiments and on to examples which speak for themselves" [22].

## IV. THE PRINCIPLE OF ACTION AND REACTION

Enunciation of the principle: "For every action, there is an equal and opposite reaction", or "If two particles interact, the force $\vec{F}_{12}$ exerted by the first particle on the second particle (called the action force) is equal in magnitude and opposite in direction to the force exerted by the second particle on the first particle (called the reaction force)", i.e. $\vec{F}_{21} = -\vec{F}_{12}$.

The existence of an isolated single force is thus impossible. It should be recalled that Newton's force of inertia does not satisfy that. We should note furthermore, following the example of R. Guénon, that: «The principle de action and reaction is not at all a principle because it is immediately deduced from the general law of balance of natural forces: each time this balance is broken, it tends at once to be restored, whence a reaction whose intensity is equal to that of the action which caused it» [23].

In fact, E. Kant went as far as to criticize Newton for having called upon experiment to formulate his third law instead of showing it a priori [8].

The "third principle" allows for a purely relational definition of mass, which we owe to Mach, and which can be summarized as follows: In a collision between two bodies, each one of them is submitted to the same force, but in opposite directions, i.e. $\vec{F}_{21} = -\vec{F}_{12}$. Since forces, and therefore accelerations, apply along the same straight line, we can consider their absolute values. Using the "second principle", we can write

$$\frac{a_2}{a_1} = \frac{m_1}{m_2}.$$

By measuring the ratio of accelerations, we will know the ratio of masses, and specifying a unit mass, the mass of the other body will be known, and we will thus be able to determine the applied force by using the "second principle".

We should also emphasize the fact that this "principle" is a prerequisite to the "second principle". It should therefore logically precede it.

It seems to us, before concluding, that is imperative to mention that, to the famous "laws of motion", should be added a fourth one, namely the "law of superposition of forces" which establishes the independence of the effects of several forces acting together at the same point. It should not simply appear as a corollary to the other "laws", as it is unfortunately the case in most textbooks of classical mechanics.

## V. CONCLUSION

Newton's "three laws of motion" are imbricate and constitute thus a coherent system where none of them could be detached from the others, but they do not give us however a clear vision of the concepts of inertia and force which are supposed to be at the base of the model. The conceptual problems are real. The problem of "fictitious forces", for example, is a good illustration in this respect. Mach's principle, and what it entails, should be introduced, even in a simplified way, in mechanics textbooks, because to persuade learners that the best way to learn Newtonian mechanics is to get rid of common sense is far from being a sinecure. The description or the prediction of the motion is not sufficient by itself, because what counts in a model is not only its accord with experiment but also its ontological scope. The concept of inertia is not theoretically achieved because ambiguities about its interpretation persist.

The concept of force, as proposed by Newton, rests on his three "laws". It is thus only a conventional definition. It is desirable to see these "laws" lie on logical and precise foundations which would make the key concept of force emerge in its ontological aspect instead of being content with operational definitions which can only be descriptive and limited. It seems to us, in this respect, that it imperative that learners be introduced, even in rather a concise way at the beginning, to the various "Schools of Mechanics", other than that of Newton, which constitute alternatives to the latter and which do not use the ambiguous concept of force.. Moreover, the three "laws" of Newton should not be called "principles". For example, the so-called principle of inertia is not a principle. It should be regarded as a hypothesis. Within the framework of this hypothesis, force is defined in the way proposed by Newton in his second law which, in turn, cannot be applied without using the third law which itself comes out of the universal law of balance of natural forces. Logically thus, the third law should precede the second one. The epistemological status of the laws of motion, their order with respect to each other, and their relationships with true principles should be explicitly clarified.

The merit of Newtonian mechanics lies particularly in its simplicity and its applicability to concrete problems. From a didactic point of view, it is thus the most appropriate one, whence its great success, because it constitutes a system with a solid internal coherence. Problems emerge at the conceptual level, and there, unless "*science has lapsed into the trivial hope of describing exhaustively reality while forbidding itself from understanding it"* [24] (a rather severe statement?), a "*serious cleanup is necessary*" [9]. Otherwise, the difficulties to which learners are confronted will not decrease whatever the didactic approaches and the teaching tools that will be used.

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