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Critical Examination of the Conceptual Foundations of Classical Mechanics in the Light of Quantum Physics

Abstract
It is well known that classical mechanics consists of several basic features like determinism, reductionism, completeness of knowledge and mechanism. In this article the basic assumptions which underlie those features are discussed. It is shown that these basic assumptions - though universally assumed up to the beginning of the 20th century - are far from obvious. Finally it is shown that - to a certain extent - there is nothing wrong in assuming these basic postulates. Rather, the error lies in the epistemological absolutization of the theory, which was considered as a mirroring of Nature.
Keywords: Perfect determination, determinism, mechanism, completeness, mirroring, causality.

Introduction

Classical mechanics (CM) is one of the greatest achievements of human knowledge. It is a compact building whose conceptual and mathematical aspects have been known and studied in all details and consequences, though the formation of the theory itself was a difficult process which took three centuries (the 17th to the 19th) to be completely achieved.
However, to the best of my knowledge, some basic postulates of CM have not been subjected to a critical examination - a state of affairs that can be partly explained by the fact that some of them have only been implicitly assumed. The consequence of this situation is that the basic postulates of the theory have not yet been considered in their connection as a system - as is the case for the formalism of the theory, which is presented in a systematic form from the beginning of 19th century. In fact, to the best of my knowledge, there is still no handbook which introduces these postulates in systematic order at the beginning of the exposition[1].
The aim of this paper is to expose these assumptions in a systematic form and study their relationships rather than to analyse them in detail. In the next section, I shall examine CM's determinism and the postulates from which it stems. In the second section a similar analysis is devoted to reductionism, while section 3 shows that mechanism is equivalent to determinism plus reductionism. Section 4 examines the postulate of the completeness of knowledge (and not that of the completeness of the theory itself, a problem which cannot be posed in this form today). Sections 5-7 are devoted to the general consequences of these assumptions while in section 8 some concluding remarks will follow.

[1] See Landau/Lifshitz 1976, Goldstein 1950, Hestenes 1986, Knudsen/Hjort 1995, for instance.

1. Determinism

Everybody admits that CM is deterministic. But determinism is a complex assumption that supposes other, more basic postulates or principles.

1.1 *Omnimoda determinatio*

The most basic assumption of CM is the postulate of perfect determination which may be expressed as follows: All properties of a physical system are perfectly determined, where a *physical system* can roughly understood to be an object or a collection of objects (somehow interrelated) which can be (directly or indirectly) experienced, and a *property* can be roughly considered to be the value which can be assigned to a physical variable or observable. *Perfectly determined* means that each variable of the system has a definite value at all times.
This principle was always implicitly assumed. For all `classical' physicists it was so self-evident that it was not even worth mentioning. In fact, modern physicists - like Galilei, Newton, and many others - inherited it from ancient and middle-age philosophy: Democritus, Plato, Aristotle, Aquinas, Roger Bacon, Descartes, Leibniz, Galilei, Kant, among others, assumed that all properties of being are determined (the problem was obviously to determine what the main or true being is). In fact, Kant says: All that exists is completely determined [KANT 1763: 76; B: 599-602], which means that, between any possible predicate of an object and its negation, one of the pairs must be actualised. Since every physical property can be reduced to a binary form, i.e. using what in quantum mechanics are called projectors - for example `being located in a certain space interval' or `being not located in a certain space interval' -, then the philosophical definition is a generalization of the physical one and, so far as physical objects are considered, they can be taken to be equivalent. For the following examination Kant is an especially interesting example because it has often been said that his philosophy is strictly related to Newtonian mechanics. The Latin traditional expression for the complete determination is *omnimoda determinatio* and can be found, for example, in Baumgarten's *Metaphysica* [1739: § 148].[2]
Now it turns out that quantum mechanics may violate the *omnimoda determinatio* at least through the superposition principle[3]: In fact, if a quantum system can be in a superposition state, say of a wave localized in an arbitrary location 1 and of another wave in an arbitrary but different location 2, then it is certainly impossible to say `either it is in location 1 or it is not' or `either it is in the location 2 or it is not', or, more simply, `either it is in location 1 or it is in location 2'. In this case, quantum mechanics would not acknowledge a generalized exclusion disjunction[4]. There are no means to reduce such an indetermination to subjective ignorance. In fact, superposition allows us to acquire objective information in the so-called interaction-free measurements[5]: An object located in one arm of a Mach—Zender interferometer can be detected even if no photon interacts with it, because its sole presence will change the measurement outcomes by destroying the interference generated by the superposition. Therefore, the indetermination due to the superposition principle should be taken as an ontologically basic feature of the theory.

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[2] On the problem see also Leibniz's letter to de Volder of april 1702 [PS: II, 239] and Wolff [1731: §§ 105—118].
[3] For argumentation on this point see chapters 24, 30 and 46 of Auletta 2000.
[4] On this specific point see Hardegree1979.
[5] See Elitzur/Vaidman 1993.

1.2 Continuity

The *omnimoda determinatio* may be easily confused with determinism. But they are not equivalent: In fact one can conceive a `classical' world where every `state of the world' (roughly: the complex of all states of all systems at a given instant) is in itself perfectly determined though without relationship with past and future states, in the sense that the world could jump from a state to another randomly. If this were the case, nobody could speak of a deterministic evolution (for a more formal definition of determinism see the next subsection).
For this reason, in order to dynamically bound two successive states of the world or of a physical system for the purpose of obtaining determinism, classical physicists also postulated continuity. This assumption is known as the principle of continuity and it states that the variables characterizing a physical system are supposed to be continuous, which in physics means that, given two arbitrary possible values of a physical variable, all intermediate possible real values are also allowed. For instance, if a body in motion is found at time t in location 1 and at time t' in location 2, then in the time interval $t' - t$ it must have occupied all the points that can be found in the trajectory that goes from 1 to 2. If we know that a body, starting its motion from location 1, can reach location 2, then it must occupy at any instant of time a point in the trajectory defined by all the pertinent variables (momentum of the body, forces acting on it, etc.).
The principle of continuity, though often not explicitly stated as such in handbooks, is widely adopted and was already used from the early days of CM: One may remember here, for example, the use of the principle made by Galilei in the law of fall[6]. Leibniz, in his *Animadversiones in partem generalem Principiorum Cartesianorum* (1692) [PS IV, 375-76], applied this principle (or, in his words, the *Lex continuitatis*) to the problem of the passage of a body from a state of motion to a state of rest.
It is true that a deterministic mechanics is conceivable which assumes the principle of perfect determination but not the continuity. In this case, one should formulate some rules that take the place of continuity and guarantee the necessary connection between present and future (past) physical states by allowing predictions and retrodictions. However, it is an historical fact that CM is founded on the continuity principle.
Obviously, the point of major conflict between CM and quantum mechanics was continuity. This is rejected by the quantum postulate, which states that the values of quantum observables can be discontinuous[7].

1.3 Determinism

Sufficient conditions of determinism are the postulate of the perfect determination and the principle of continuity. In fact, given the perfect determination of the state of a system at an arbitrary initial time, if its dynamic variables (for example the energy) are continuous, then every future state of the system will also be perfectly determined and unique, i.e. there are no alternative possibilities or branching[8]. In fact, a possible deviation from the evolution line of the world or of an isolated system would only be possible if there are new or different properties relative to the initial state so that the system will go through an alternative evolution. But the question is: Where do this modifications come from? Surely not from the initial state itself (it would have incompatible properties, e.g. a position x and a position x')

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[6] See Mach 1883: 130-131, 181 and 1905: 223.
[7] The quantum postulate was assumed by Planck [1900a-b] and generalized by Bohr [1913].
[8] One may think at Laplace's dictum that nothing is uncertain: See Cassirer 1957: 134-35 and Earman 1986: 7. The latter book represent a good analysis of classical determinism.

and not from a successive state too which can evolve from the initial state through a continuous evolution (the new properties are here a dynamical consequence of the old properties). On the other hand, we can exclude statistical fluctuations (statistics is only due to subjective ignorance in classical mechanics). The only possibility is that these modifications have been introduced abruptly by some violation of the continuity principle.

It is well known that a mathematical formulation of the assumption of determinism is given by Hamilton's canonical equations. The Hamiltonian, the energy function of the system, which is expressed as a function of the position and the momentum, fully describes the system at every moment of its future (and past) evolution. Note, however, that determinism does not coincide with predictability: In fact, it is well known that, for a large class of problems, almost identical initial conditions can have very different solutions for later times [see also subsection 2.2].

Determinism is an ancient philosophical concept too. It was probably introduced by ancient atomism and further developed by ancient stoicism.

In quantum mechanics the Schrödinger equation is also deterministic, but here what evolves deterministically are amplitudes (probabilities are square moduli of amplitudes in quantum mechanics), i.e. it - paradoxically - represents a determinism that is intrinsically probabilistic. In fact, in the general case, we cannot foresee what values the observables will have; we can only write their probability distributions (ruled by the statistical algorithm).

As we have already said, the break of continuity is a major feature of quantum mechanics. For this reason Bohr [1928; 1929] spoke of a break of determinism and of causality as such[9]. On a strict physical plane and leaving aside the ontological features of the problem, which are too complex to be analysed here[10], causality may be here understood in a narrow and in a wide sense, following the distinction between determinism and predictability. In fact, in a narrow sense it may be taken as equivalent to determinism. In a wide sense it may be understood in terms of predictability, and then it should rather be taken as equivalent to mechanism [see section 3], to the extent in which linearity and separability are also necessary in order to have a predictable future.

One could think that, besides perfect determination and continuity, determinism also supposes conservation laws. We may understand the problem of conservation in two forms:

1. Nothing that is real can disappear;
2. in an isolated system certain physical quantities such as angular momentum are conserved.

We shall return on the second point later on [see subsection 4.1].

Point 1. is a general metaphysical statement and can perhaps be reformulated in physical terms as a statement about the conservation of energy (which is obviously a conserved quantity in the second sense too): Mass is in fact equivalent to energy according to the Einstein's well known law $E = mc^2$. In statement 1. it is the universe as a whole which is considered as a closed system. It is then evident that this statement is a more basic one - but also a weaker one - than statement 2. In fact, we could think of a world where there can be no strict conservation of energy in the sense of statement 2. and notwithstanding would be deterministic. For instance, there could be a universal but unknown and unknowable `ether' so that all observable physical systems lose part of their energy. Then the energy would be conserved in the sense of statement 1. because a form of energy is transformed into another form of it by an interaction with the ether, but would not be conserved in the sense of statement 2. because, for instance, we could have a physical law of this form:

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[9] On this point see Tarozzi 1993.

[10] See Swimburne 1983 and van Fraassen 1989.

$$\frac{\mathrm{dp}}{\mathrm{dt}} = F \,\square\square p, \qquad (1)$$

where F is the force and $\square$ some parameter. Obviously, the `path' or the `trajectory' of every physical system should always be calculable, i.e. the loss of energy should follow strict laws and not be random. Otherwise, the world could not be said to be deterministic. On the other hand, as we have said, even if the `physics' in this universe was expressed in terms of equations like the (1), the ether is not nothing, so that, in a certain objective (or meta-physical) sense (God's point of view?), proposition 1. is also satisfied. But the difficulty of this position is to admit the existence of something real that in principle cannot be experienced.

2. Reductionism

Reductionism, as we shall see in what follows, is another basic piece of CM and, as determinism, it presupposes other assumptions, which need to be preliminarily examined.

2.1 Materialism

One may wonder if the assumption of materialism is basic for CM since one may think that it is a metaphysical assumption without consequence or relevance upon a physical science, which CM is. But this is not the case: CM is a mechanical theory, i.e. a theory of the motion of bodies and of the forces that act upon them. And a body is necessarily a material entity.

The existence and the basic properties of matter were assumed and defined already by Galilei[11] and Newton. In the third *regula philosophandi* of book III of the *Principia* [1687: 552-55], Newton wrote a list of properties of matter (bodies): Extension (a Cartesian property), hardness, impenetrability, capacity to move, inertia[12]. Regarding hardness, Newton [1704: 388-92] explained that the parts of all homogeneous hard bodies which fully touch one another stick together very strongly. From their cohesion Newton inferred that particles attract one another by some force, which in immediate contact is exceedingly strong. On the other hand all bodies seem to be composed of hard particles; otherwise fluids such as water would not freeze, or fluids such as «spirit of nitre and mercury» would not become hard «by dissolving the mercury and evaporating the flegma». Therefore hardness can be considered to be the property of all uncompound matter. It is then evident that all fluids can be reduced to hard bodies by freezing or evaporating: In the latter case, in my opinion, the particles cohere fully, which in turn means that some bodies are not hard only because they are rarefied to a certain extent, i.e. there is some vacuum between the particles[13]. In other words, following Newton, all matter can be reduced to some ground `state' in which it is fully homogeneous (without empty space within) and hence inelastic. In fact elasticity is possible only if there is some internal structure of the matter or some forces within, and both possibilities are excluded by the homogeneity postulated here[14].
One may discuss - and Newton himself had no final position on this point[15] - if matter is a continuous medium divisible *in infinitum* or if it is composed by elementary corpuscles that

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[11] See Cassirer 1906: II, 387-89. See also Mach 1883: 248-49 and Hall 1954: 106-107.
[12] See chapter 7 of Koyré 1957 for commentary.
[13] An important difference in respect to Descartes [see Koyré 1968: 33-34, 105-110].
[14] In Kant 1756 [486-87] elasticity depends on the interplay between attractive and repulsive forces acting in matter. As we shall see, Newton excludes the existence of forces in matter.
[15] See the mentioned *regula* III.

are strongly bound and fixed together by adhering to each other. In fact, both positions present difficulties: If matter is actually divided *in infinitum*, then it seems to lose its consistency [see Kant 1756: 479]; but if matter is constituted of hard elementary particles, then it is difficult to obtain a full homogeneity because there would be, almost certainly, empty space. In fact, there are few shapes of elements which allow a composition of macroscopic bodies without some emptiness: For example, it is well known that, for a plane, a solution is represented by hexagonal symmetry (honeycomb) - but no system of hexagones can enclose space. For three-dimensional space a solution is represented by the tetrakaidekahedron, a fourteen-sided figure introduced by Lord Kelvin, or by a combination of irregular polyhedra (14-hedron, 13-hedron, and 15-hedron) [THOMPSON 1942: 88-131, 157-59]. However, if I understand Newton well, even in the case where we have a minimum of empty space, such a structure would be rigid. Now, if we assume full homogeneity, in the case of a collision between two bodies of equal mass moving at the same speed from opposite directions, they will coalesce at the point of collision (because they are fully inelastic)[16]. One may say that the kinetic energy has been transformed into some activity of the particles composing the body, but this is impossible because there is no internal structure and no possibility for the particles to translate, to rotate or vibrate relative to one another[17]. Obviously, one could say that full homogeneity can only be ascribed to elementary particles constituting macroscopic bodies. But, in this case, elementary particles and macroscopic bodies would act differently in the case of collision, which would be a major difficulty and in conflict with the reductionistic methodology of CM. Note that Newton himself drew [1704: 398] the above conclusion about collision: «…by reason of the tenacity of the fluids, and attrition of their parts, and the weakness of elasticity in solids, motion is much more apt to be lost than got, and is always upon the decay. For bodies which are either absolutely hard, or so oft as to be void of elasticity, will not rebound from one other. Impenetrability makes them only stop. If two equal bodies meet directly *in vacuo*, they will by the laws of motion stop where they meet, and lose all their motion, and remain in rest, unless they be elastic, and receive new motion from their spring».

In a general way, note that Newton had not included force as an intrinsic property of matter as such - i.e. forces can only act ‘from outside’ upon the matter. In fact, Newton only attributes an *inertia*[18] to the matter and says [1704: 397-98] that it «is a passive principle by which bodies persist in their motion or rest, receive motion in proportion to the force impressing it, and resist as much as they are resisted. By this principle alone there never could have been any motion in the world. Some other principle was necessary for putting bodies into motion; and now they are in motion, some other principle is necessary for conserving the motion. For from the various composition of two motions, 'tis very certain that there is not always the same quantity of motion in the world. […] it appears that motion may be got or lost». Therefore, Newton concludes [1704: 401-403] by saying that it seems to him that «these particles [of matter] have not only a *vis inertiæ* … but also that they are moved by certain active principles, such as is that of gravity, and that which causes fermentation, and the cohesion of bodies». Newton then considers these principles as «general Laws of Nature» and says that «by the help of these principles, all material things seem to have been composed of the hard and solid particles above-mention'd, variously associated to the first Creation by the Counsel of an intelligent Agent. For it became him who created them to set them in order. […] blind fate could never make all the planets move one and the same way in orbs

[16] For examination see the chapter 9 of Koyré 1957.

[17] For all the problem of bodies' collision see Mach 1883 [310-31].

[18] Newton speaks of *vis inertiæ* but, as it is clear from that what follows, he means what we call *inertia* today.

concentrick … Such a wonderful uniformity in the planetary system must be allowed the effect of choice». These and the uniformities of living beings «can be the effect of nothing else than the Wisdom and Skill of a powerful ever-living Agent, who being in all Places, is more able by his will to move the bodies within his boundless uniform Sensorium, and thereby to form and reform the parts of the universe, than we are by our will to move the parts of our own bodies».

As it is clear, these principles are due to the direct action of God[19]. As regards the force which guarantees the cohesion of the bodies, Newton speaks [1687: 764--65] «de spiritu quodam subtilissimo corpora crassa pervadente, et in iisdem latente; cuius vi et actionibus particul\ae corporum ad minimas distantias se mutuo attrahunt, et contiguæ factæ cohærent». Therefore, one can understand that Leibniz, who introduced the concepts of force and kinetic energy against the Cartesian mechanism[20], in his letter to the Princess of Wales [PS: VII, 352] felt the necessity to defend the conservation law of «force and energy» against Newton. It is interesting that, in his first answer, Clark writes [Leibniz PS: VII, 354] that God «not only composes or puts things together, but is himself the Author and continual Preserver of their original forces and moving powers».

Therefore, we clearly see that materialism, i.e. the supposition of a fully homogeneous and inert matter, assumed since the early days of CM is far from obvious, and in fact this idea was very soon abandoned[21], but without a deeply critical examination. I think this is due to the divorce between physics and philosophy which was already a reality a generation after Newton and Leibniz (Kant himself was rather an exception). In quantum mechanics there can be no question of perfectly hard and localized corpuscles: Quantum entities intrinsically present a wave-like behavior or some fuzziness. Therefore it is better to speak of extended particles[22]. On the other hand, a property like impenetrability seems inadequate to quantum entities, which are able to tunnel.

2.2 Linearity

Linearity is an important property of classical systems as they were understood before the end of XIX century, in particular before Poincaré's contribution. In itself it is essentially a mathematical property, because it consists in the requirement that the basic equations of CM must be linear, i.e. reducible to a form like

$$a^0(x)y^n + a^1(x)y^{n-1} + \ldots a^n(x)y = f(x), \tag{2}$$

where $a^0(x), a^1(x), \ldots a^n(x)$ are coefficients, $f(x)$ is some function and y^n the n-th derivative of y. But linearity has a conceptual relevance to the extent in which it excludes feed-back, i.e. self-increasing processes.

Linearity allows an important aspect of the 'reductionistic methodology' of CM: The factorisation between component 'elements' of a system, for example the decomposition of motion in components by Galilei, the decomposition of forces by Newton or the decomposition of harmonic components[23]. In other words if the cause (the force) C_1 produces

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[19] On this point see chapters 7-8 of Koyré 1957.

[20] See the "Brevis Demonstratio Erroris Mirabilis Cartesii et aliorum" (1686) [MS VI, 117-23] and the "Systeme nouveau de la nature et de la communication des substances" (1695) [PS IV, 477-87.

[21] As we have seen, for instance, by Kant.

[22] On this point see chapters 30 and 33 of Auletta 2000.

[23] For these examples see Mach 1883 [144-45, 191-92].

the effect (the acceleration) E_1 and the cause (the force) C_2 the effect (the acceleration) E_2, then $C_1 + C_2$ produces $E_1 + E_2$. This principle is often called the principle of (classical) superposition.

One could think that in CM a small perturbation on a given system or the weak interaction of this with another system only causes a small deviation in the trajectory of the system in the phase space, so that the system will normally 'absorb' it and return to the ancient deterministic path. But a perfect classical system - as it is currently known - can show such a dependence on the initial conditions that its evolution can be chaotic (in fact in a chaotic regime this dependence is expressed by a strong divergence of initially very close and indistinguishable trajectories in phase space). Note that, in the chaos theory, chaos itself is intrinsic and deterministic and not stochastic and extrinsic - in other words, it is not due to random fluctuations of the environment or to noise[24]. In fact there can be also chaos with Hamiltonian systems. Chaos and complexity are possible when the requirement of linearity is abandoned. In this case we have feed-back. Roughly: An output of the system becomes an input. But even though CM had already abandoned linearity at the beginning of the 20th century, it further defended reductionism - as we shall discuss in subsection 2.4.

Linearity is not violated by quantum mechanics. In fact the Schrödinger equation is linear, and any attempt to introduce non-linear terms in this equation has failed up to now[25]. In general, it could be said that the principle of superposition of states guarantees linearity in quantum mechanics in a stronger form than in CM.

2.3 Separability

Separability is another key feature of CM. But it is again an implicit assumption, and was stated explicitly, by Einstein and his co-workers [Einstein *et al.* 1935], not before 1935, as CM was confronted with quantum mechanics. The principle of separability may be expressed in the following way: Given two non-interacting physical systems, all their physical properties are separately determined, or, in other terms, the result of a measurement on one system cannot depend on a measurement performed on the other system. The meaning of the principle is the following: Two systems can be interdependent only through a physical interaction (for example some form of potential energy).

Again quantum mechanics seems to violate the separability principle due to a consequence of the superposition principle for multiparticle systems: Entanglement. In fact, for entangled subsystems it is not possible to factorise the probabilities of the outcomes of experiments performed on each subsystem locally. In other words, probabilities calculated on one of two 'distant' subsystems, even if they do not physically interact, are not independent[26].

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[24] On this point see Schuster 1988 and Ruelle 1989.

[25] A non-linear equation for quantum mechanics was proposed in Bialynicki-Birula/Mycielski, 1976. Shimony proposed [1979] an experiment aiming to verify if there are non-linear terms and if they have the magnitude proposed by Bialynicki-Birula and Mycielski. A later experiment performed on these outlines seems to exclude [see Shull *et al.* 1980] such terms. Obviously this does not mean that the methods of quantum mechanics and chaos theory cannot be combined. They can be, and are in fact unified in what is now known as 'quantum chaos'.

[26] There exists a lot of literature on this subject. For a summary see chapters 31 and 34-35 of Auletta 2000.

2.4 Reductionism

We may now summarize the results of this section by saying that materialism plus linearity plus separability are sufficient and necessary conditions for reductionism. In fact, there can only be reduction of inert matter, this reduction is possible only if the elements are linearly combined and the equations ruling the behaviour of the system are themselves linear, and if there is a possibility of factorisation, i.e. if there is no entanglement such that the system is correlated with other systems. Roughly speaking, by reductionism[27] it is usually meant that a system is given as the 'sum' of its constituent components or, equivalently, that any system can be divided into "elementary" parts. In other words, the reductionistic methodology of CM can be defined as the idea that elementary bodies can be linearly added to form compound systems, and both the elements and the resulting systems are separable. Thus, the aim of reductionism is to find the ultimate elements of matter that cannot be further reduced. To our knowledge there is no certainty (and there are even doubts) that such a task will ever be accomplished. One speaks today, for example, of quarks and leptons as `divisible' particles. However, quantum mechanics violates this type of reductionism because it violates the separability principle and does not, as we have seen, violate linearity (leaving aside the problem of materialism). In fact, it is evident that, if separability is violated, no reduction of a whole to 'parts' is possible because the parts could be not treated as independent systems (and therefore disentangled).

The theory of complexity also violates a reductionistic methodology: In this case. as we have seen, by rejecting linearity. Feedback assures that in this case the connection between several parts can be more than their sum. Furthermore, after having divided a complex system, there is no guarantee that we can reconstruct it by simply adding or bounding the parts.

On the other hand, reductionism can also be understood to be the reduction of more complex theories and sciences such as chemistry and biology to physics and especially to quantum mechanics (this may be called *epistemological* or *methodological* reductionism relative to the first type, which may be called *ontological* reductionism). It is true that quantum mechanics also shows its effects (entanglement, for example) at mesoscopic level. But this does not mean that the mesoscopic or the macroscopic world are only 'illusions' - apparent realities. In fact, the process of decoherence and of localization, in particular, which goes together with decoherence, especially when the number and the complexity of systems exponentially grows, is objective throughout[28]. On the other hand, no necessity arises to conceive methodological reductionism as being a one-way operation: If one speaks of reduction to more elementary objects, one should speak - with more reason - of a methodological reduction of microscopic equations for the constituents of a system (via coarse graining) to differential equations for macroscopic variables, and from these (via numerical calculations of Poincaré sections) to low dimensional Poincaré maps[29].

Reductionism was almost universally applied in modern science[30] until the 1960s and was also used by many modern philosophers. An extreme form of reductionism can be found in Spinoza, since he wrote [1677: 99-100] that the unity of a body only consists of a coordinate motion of the parts: When elements go in different directions the body is destroyed.

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[27] See Primas 1993.

[28] See chapters 17 and 24-25 of Auletta 2000. This is exactly the problem faced by quantum computation.

[29] See Schuster 1988 [14-16] and Bergé et al. 1984 [63-78].

[30] For instance, to human behavior [see Skinner 1974].

3. Mechanism

Sufficient and necessary conditions for mechanism are determinism and reductionism. Classical mechanics is essentially built on these two requirements and supposes, therefore, mechanism. It is even difficult to conceive a form of `classical' mechanics that could violate one or the other assumption. In fact, a form of mechanics is supposed to consist in the theory that, given an input (some force), we have a fully automatic and proportional output (some acceleration), which surely would be impossible if the whole system were more than the sum of the `parts' (i.e. if the requirement of reductionism were violated), or if it showed a random reaction to a given action (i.e. if the requirement of determinism were violated). On the other hand, a system satisfying the features of determinism and reductionism would be necessarily mechanical. For instance, we distinguish the behaviour of organic life from pure mechanical behaviour precisely through the violation of one or the other requirement or of both[31].

4. Completeness

The possibility of a complete knowledge in the frame of CM is dependent on two assumptions, namely determinism and isolability. Firstly, let us examine the assumption of isolability.

4.1 Isolability

CM assumes that isolated systems are possible; i.e. that we can always theoretically treat and experimentally (at least in principle) generate a system without physical interdependence with other systems or with the environment. It is the isolability which guarantees conservation laws of pertinent quantities. In fact angular momentum, energy or motion can be conserved only if the system is considered as isolated from others, i.e. there is no interaction so as to cause dispersion or no action of an external force so as to change its motion. Quantum mechanics does not apparently violate this assumption. However, since in quantum mechanics measurement is the only means, for example, to acquire information about the position of a system, it can be questioned if one can speak reasonably of a quantum isolated system [see Bohr 1928: 586]. Finally, it may also be asked if fully isolated quantum-mechanical or macroscopic systems exist.

4.2 Completeness

In CM it is supposed that one can perfectly know (at least in principle) all the properties of a given system. In other words, the properties of the object system can be perfectly measured. Therefore, it is postulated that the measurement errors can be - at least in principle - always reduced below an arbitrarily small quantity. Hence this assumption may be called the postulate of reduction to zero of the measurement error.

Note that this postulate is not a direct consequence of the principle of perfect determination alone, because it can happen that a system is objectively, but not subjectively, perfectly determined. It presupposes continuity too: In fact, if the pertinent variables were discontinuous, then we could not approximate the measurement outcome to a point-like value in a given interval. Hence it presupposes determinism (which, as we know, presupposes perfect determination plus continuity). But isolability too: In fact, if the system could not be really isolated, we could never know its properties perfectly, not even in a very large time

[31] See Langton 1989a-b.

interval, because, during the flow of time, it may be that small interactions with external systems cause small uncertainties in the measurement results so that - even if these uncertainties do not cumulate or amplificate - one cannot go beyond a certain threshold.

If we speak of the perfect knowledge of all properties of a given system at the same time, then this assumption is obviously violated in quantum mechanics through the uncertainty principle. In fact, this principle states that, by increasing the knowledge or the determination of an observable of a conjugate pair, the complementary observable must proportionally increase its uncertainty. It can also be asked if there are ultimate limits to our knowledge of the microworld, in the sense that, by increasing the precision of our analysis, we will get to a point where the noise produced by our apparata is sufficient to cover useful information.
Furthermore, it was recently shown [Landsberg 1988] that, to a certain extent, one could also speak of uncertainties in CM. In fact, in classical mechanics position and velocity are treated on the same footing, so that both can have determined values at the same time. However, it is dubious that one can measure the velocity of a particle at a given point with infinite precision. It can only be said that it has a determined velocity *in a small space interval*, but it is surely conceptually erroneous to assign both a perfectly determined velocity and a perfectly determined position to it. Landsberg showed that it is possible to deduce some uncertainty relations, also in the classical case, by means of a concrete example.

5. *Classical Mechanics*

We can now draw the first general conclusion from the above analysis: CM consists of both mechanism and completeness (of knowledge). There is no doubt that there can be no CM without mechanism. But one may think that completeness is not a necessary condition of CM. It is a fact that CM is so built that a perfect transparency of the object system to the knowledge corresponds to the perfect ontological determination of it. But, in a certain sense, it could also not be otherwise: For a physicist the primary questions are objective and not subjective: In order to admit to having an incomplete knowledge together with the assumption of mechanism - and hence of a perfect ontological determination - one should know some basic limitations of the human mind, which, in principle, exclude the possibility for human beings to perfectly know systems that are objectively perfectly determined.

6. *Classical Epistemology*

Classical mechanics has been developed together with what may be called *classical epistemology* - i. e. the epistemology which is common to Galilei, Spinoza, Newton, Kant (in the *Critics of Pure Reason*), Einstein and many others – we do not take here into consideration the important differences that exist among these authors. Modern classical epistemology certainly presupposes the completeness of knowledge, i.e. that the properties of being can be perfectly known, but it also supposes what may be called a `mirroring' theory[32] (representationalism). Explicitly: Classical epistemology considers the act of knowledge as a mirroring of the properties of the object. In other words, knowledge is understood to be a reproduction of objective and given data and not a form of interaction between subject and object. This understanding of knowledge is very ancient and can also be seen in the works of Plato. Several philosophical schools have shared this point of view. Obviously, there is no agreement between the several schools about what the being to be reproduced is (ideas like

[32] See Rorty 1980 and Tarozzi 1996.

platonic substances, atoms, forms, material objects, and so on). When knowledge is so understood, then one assigns a mere reproductive and representative role to the subject.

However, this view is not so evident and presents several difficulties [see Auletta 2002a-b]. For this reason pragmatism[33] proposes a different theory of knowledge. It is seen as a problems-solving enterprise, which, by starting with a problem, assumes a hypothesis (out of many other possible ones) because it can solve the conflicts or the contradictions arisen from the problem itself in a satisfactory manner. This is not the place for examining this subject in detail, but I think that this explanation of how theories work and are generated is far more satisfactory for describing scientific knowledge than the traditional, classical approach. I only wish to stress the following aspects of this explanation:

1. Subject and object are not understood as static beings and knowledge not as a form of translation of data into a mind (and how would it be possible?).
2. Experience is dynamic and comprehends `subject' and `object'[34].
3. Knowledge is open and never represents a final answer.
4. Knowledge is a form of praxis and the theory is not completely separated from other human activities.

Also in Artificial Intelligence (in the last years) and in Artificial Life the operative feature of intelligence has been stressed against the traditionally representational view [see Brooks 1990, 1991; Clark 1997].

7. Modern Classical Philosophy

It is possible, in analogy with the previous definitions, to call the main stream in the 17th to 18th centuries *modern classical philosophy* (i.e. a compound of CM plus classical epistemology). The fact that philosophers and physicists of that age have acknowledged all or almost all the above principles can be seen from the following examples.
Let us first take Kant's criticism of the ontological proof of the existence of God [B: 627]. Kant says that when I affirm that *God exists*, I add no new predicate to the concept of God; rather I pose only the subject (God) in itself with all its predicates, i.e. the object in relationship to my concept. Both, the object and the concept, must have the same content. In other words, in the terminology that Kant uses here, what is real does not contain something more than what is only possible (the concept). If the object could contain more than the concept, then the latter would not express the whole object and would therefore not be adequate to this object (it is an evident requirement of the completeness of concepts). So far Kant. In this argumentation, the *ominimoda determinatio* is always taken for granted and three additional principles are (implicitly) assumed: (1) The concept is isomorphic with the object (the predicates contained in the concept correspond to properties that the object has: It is the mirroring theory); (2) therefore an adequate knowledge must be complete (all properties of the object must be considered in the concept); and (3) finally one can consider the object `in itself', i.e. in complete isolation from other objects (it is the assumption of isolation). Since this is a general argument that goes beyond the specific problem of the existence of God, one can consider any object without a relationship with the other objects of the universe. It is true that elsewhere [B: 599-602] one speaks of the *omnimoda determinatio* as an ideal, but in the above example it is taken as an ontological fact.
To my knowledge, Kant never rejected continuity and perhaps he had nothing against linearity. He surely assumed a form of materialism: Since our knowledge can only happen in

[33] On this point see Peirce 1878a-b.
[34] On this point see Dewey 1929.

an experience which is intrinsic spatial-temporal [B, 33-73], then the objects of knowledge can only be bodies; and in fact, as it is well known, Kant excludes that the subject of knowledge can also be the object of knowledge [B: 152-165]. In his first writings he also used a form of the principle of separability [1756: 477]: Composed objects should be separable in elements that can exist separately. Then he essentially acknowledged all the above principles.

Now let us also briefly discuss the assumptions (but not the details of the argumentation) of the article by Einstein *et al.* [1935]. There is no doubt that it acknowledges the *omnimoda determinatio*. In fact, the aim of the article is to show that there can be elements of reality which cannot be represented in quantum mechanics due to its uncertainty principle - in fact, it is well known that Einstein thought quantum mechanics could only represent a statistical (and therefore incomplete) theory of microentities. Specifically, the aim of the article is to show that quantum mechanics violates a sufficient condition of reality, which may be expressed as follows: If, without in any way disturbing a system, we can predict the value of a physical quantity with probability equal to unity, then there exists an element of physical reality corresponding to this physical quantity. It is evident that two things are supposed here: First, reality is perfectly determined in itself; second, that one can also know it perfectly (my completeness condition). Continuity is evidently acknowledged in the formal development of the argument itself. So there is no doubt that the article also acknowledged determinism (= *omnimoda determinatio* + continuity). Though no word is said about materialism and linearity, the core of the article is represented by a strong defence of the principle of separability (here for the first time formulated), so that one can suppose that reductionism was also a valid assumption for Einstein and his co-workers.
But their article goes even further. In fact, two definitions are formulated with great emphasis at the beginning: Those of correctness and completeness. It is said that a theory is totally correct if every element of the theory has a counterpart in reality: In other words, a totally correct theory is one without superfluous theoretical terms. It is evident that the necessary condition for assuming this definition is the mirroring theory: If theories could not mirror reality, they could also not mirror reality correctly. As regards completeness it is said that a theory is complete if every element of reality has a counterpart in it - it is evident that correctness together with completeness establish an equivalence relationship between physical theory and reality. This definition of the completeness of a theory is much stronger than the one previously formulated. In conclusion CM and classical epistemology, and therefore classical philosophy as such, are defended in Einstein's article.

It is very interesting that Kant and Einstein - both scientists and philosophers - essentially defend the body of modern classical philosophy, and that the latter does it in open conflict with quantum mechanics.

8. Conclusions

For three centuries CM has been the model of what Science is and should be. Therefore, it is a little surprising that its basic assumptions were assumed without critical examination. But two points are very important here:

1. Without quantum mechanics and its consequences nobody would have perceived the problems hidden in assumptions that ultimately stem from common sense or from a refinement of our ordinary experience regarding macroscopic objects. This does not mean that this experience is in itself wrong at all. We live and act in a macroscopic world where the struggle for life is the most important thing and for this practical

purpose it makes no sense - and it is perhaps even dangerous - to assume, for instance, that objects are not perfectly determined or fuzzy[35].

2. But neither are CM's assumptions wrong as such. CM has been and is in fact a powerful tool in order to explore nature and establish some basic features of the physical world. Stated in other terms, taking into account all that was known at that time, CM worked - and still works - very well. The only thing that is wrong is the supposition that CM's assumptions and laws are objective in the sense that they mirror what Nature is in itself. In other words, what was and is wrong about CM is a `mirroring' epistemology and an epistemology which has produced an absolutization of this physical theory. Therefore, here we have a confirmation *e contrario* of the rightness of the point of view of pragmatism.

As a conclusion are we forced to assume an idealistic or subjectivistic point of view? Not necessarily. In quantum mechanics it is impossible to conceive the properties as being intrinsic. But they can be understood to be relational very well, in particular as being relative to the interactions a given system has or may have with other systems (not necessarily apparata). It is therefore a non-classical form of realism[36].

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[35] And, with a high probability, macroscopic objects are also partly fuzzy; in fact one has shown theoretically and finally experimentally that, at mesoscopic level, `Schrödinger cats' are possible [see Brune *et al.* 1996 and Monroe *et al.* 1996].
[36] On the problem of realism see van der Merwe *et al.* 1988 and Auletta 2000, 795-800].

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Titolo: Esame critico dei fondamenti della meccanica classica alla luce della fisica quantistica.

Abstract: Com'è noto, la meccanica classica è caratterizzata per il fatto di essere una teoria determinista, riduzionistica e meccanicista. Tutte e tre le assunzioni discendono a loro volta da principi o postulati più fondamentali. In particolare il determinismo è una conseguenza del principio di perfetta determinazione dei sistemi fisici e del principio di continuità, mentre il riduzionismo è basato su un assunto materialistico congiuntamente ai principi di linearità e separabilità. Infine il meccanicismo è prodotto dalla congiunzione del determinismo e del riduzionismo. La meccanica classica, intesa qui come l’edificio storicamente prodotto tra gli inizi del XVII secolo e la fine del XIX, oltre al meccanicismo, assume un principio di perfetta conoscibilità dei sistemi fisici.

Nell’articolo si intende mostrare che, sebbene tali assunzioni siano state universalmente accettate fino all'inizio del XX secolo, non sono affatto così ovvie. In particolare, il fatto che questi principi e assunzioni, in un modo o nell’altro, non trovino applicazione in meccanica quantistica o addirittura siano violati da questa disciplina, mostra la loro limitatezza ‘regionale’. Pertanto si tratta, in genere, di assunzioni che derivano da una generalizzazione del nostro senso comune o almeno della nostra esperienza ordinaria con corpi macroscopici. Tuttavia l'errore non risiede tanto nelle assunzioni come tali, che erano e restano operativamente efficaci, quanto piuttosto nell'assolutizzazione epistemologica della teoria che ne ha fatto, da un mezzo di indagine sul mondo fisico, un riflesso della Natura come tale.