The views of Francis Halbwachs on the nature of *explanation* in Physics and how they affect research in Didactics of Science

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Abstract

In this paper we argue that the epistemological views of Francis Halbwachs, a close collaborator of Jean Piaget, and in particular his views on the various kinds of explanation in the field of Physics are of considerable relevance to research conducted in the context of Didactics of Science. This paper describes these views and comments, in their point of view, the research related to the explanatory schemes that students use to describe and explain physical phenomena and, in particular, mechanical phenomena. Also, the implications of Halbwachs' views on the analysis and (re)design of conceptual content of Physics curricula are discussed.

Keywords

Francis Halbwachs, explanation, Didactics of Science, conceptual content of Physics curricula

Résumé

Dans cet article, nous soutenons que les idées épistémologiques de Francis Halbwachs, un proche collaborateur de Jean Piaget, et en particulier ses idées sur les différents types d'explication dans le domaine de la Physique, sont particulièrement pertinentes pour la recherche menée dans le contexte de la Didactique des Sciences. Cet article décrit ces idées et commente, à leur lumière, la recherche relative aux schémas explicatifs utilisés par les élèves et les étudiants pour décrire et expliquer les phénomènes physiques et, en particulier, les phénomènes mécaniques. Les implications des idées *de Halbwachs sur l'analyse et l'élaboration du contenu conceptuel des programmes d'enseignement de la Physique sont également discutées.*

Mots-clés
Francis Halbwachs, explication, Didactique des Sciences, contenu conceptuel des programmes d'enseignement de la Physique

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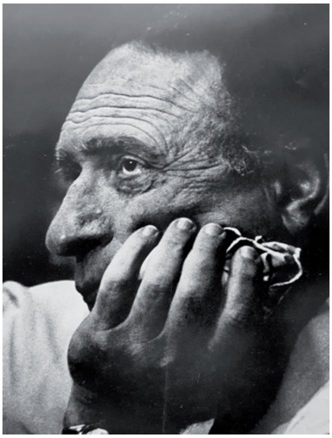
Introduction



The work of Francis Halbwachs (22/4/1914-27/7/1986) was varied and interesting. As a theoretical physicist and a student of Louis De Broglie, he joined the group at the Institut Henri Poincaré in Paris with relativistic quantum mechanics as his main field of study (Halbwachs, 1960). At the same time, because of the rivalry that developed between the views of the Paris group and those of the Copenhagen school, he was driven to work on issues of the History and Philosophy of Physics, taking firmly anti-positivist positions on the nature and characteristics of scientific knowledge. His Marxist background helps in this (Halbwachs, 1949). Much later, he contacts the Centre for Genetic Science in Geneva and becomes one of Jean Piaget's closest collaborators. Piaget himself, in introducing his important work *La pensée physique chez l'enfant et le savant*, considers him a valuable collaborator in the research carried out there (see Piaget's text in the same issue).

Halbwachs is considered one of the pioneering researchers to whom the first steps in the construction of a francophone theoretical framework for the study of the school version of scientific knowledge are attributed. His article in which he introduces the distinction between the 'physics of the child', the 'physics of the teacher' and the 'physics of the physicist' is one of the milestones of this research framework which emerged in the 1970s (Halbwachs, 1975; see also text of J. J. Dupin in this issue). Of particular interest are Halbwachs' epistemological conceptions of the notion of *explanation* in Physics, which were formulated even as early as the 1960s in the context of his collaboration with the Geneva *Centre International d'Épistémologie Génétique* and are described in depth and with great rigour in his seminal texts *Causalité linéaire et causalité circulaire en physique* (Halbwachs, 1971), *L' histoire de l'explication en physique* (Halbwachs, 1973) and *La pensée physique chez l'enfant et le savant* (Halbwachs, 1974). It is precisely this aspect of Halbwachs' mature work that we are interested in developing in this paper. More specifically, we are interested in outlining the main points of his views on the nature and characteristics of explanation in Physics as it is understood both at the level of science and at the level of the child's thinking, while at the same time trying to highlight the value of these views for commenting contemporary research in Didactics of Science[1], as well as for the analysis and design of Physics curricula, especially in primary and secondary education.

Halbwachs' views on the nature of explanation in physics

The forms of explanation in the History of Physics

Halbwachs' anti-positivist positions lead him to relate the concept of *explanation* in the natural sciences to the attribution of *meaning* to scientific knowledge. He uses for this a structuralist, genetic approach which focuses on the historical analysis of the concept of explanation in the field of natural sciences and especially in the field of physics. This analysis leads to a categorization of the forms of explanation used in different historical periods. This categorisation demonstrates that the form and structure of the concept of explanation varies from one historical period to another and therefore the type of explanation in one historical period appears in the next period either as a simple tautology or as an incomprehensible type of explanation. Halbwachs distinguishes three broad categories of explanation: (a) *homogeneous [homogène]* explanation, (b) *heterogeneous [hétérogène]*or *causal* explanation, and (c) *bathigeneous [bathygène]* explanation. Here is an extended excerpt from Halbwachs' seminal text *L'histoire de l'explication en physique* (Halbwachs, 1973) in which the characteristics of these categories are attributed in the form of illustrative examples:

> "Let's start with an example that refers to gas pressure. Let us consider, first of all, Torricelli's experiment on the elevation of mercury in the 'barometric tube' and the

1 The terms *Science Education* and *Didactics of Science*, although sometimes used indistinguishably when it comes to denoting the research conducted in this field, do not have the same content since the first term refers to research activities carried out mainly in the Anglo-Saxon area, while the second refers to the continental European area and Latin America (Aduriz-Bravo et al., 2003; Aduriz-Bravo & Izquierdo-Aumerich, 2005). In this article we have adopted the second term since we have been working within this field for many years, but Halbwachs' work also belongs to it.

explanation proposed first by Torricelli himself and then by Pascal. The appearance of a vacuum in the tube led Torricelli to go beyond the Aristotelian paradigm of 'the abhorrence of the vacuum by nature'. Thus, if we accept that there is *nothing* inside the barometric tube, then the higher surface of the mercury cannot possibly be subjected to any action. Instead, the other level is in contact with 'free air' and so we must attribute the elevation of the mercury to the *action of the air.* The nature of this action was concretized by Pascal through a device where the inner vessel is closed, trapping a certain volume of air. We can therefore compress or dilute this 'trapped' air and show that it is indeed the air which, through 'elastic' pressure, determines the height of the mercury in the tube. The explanation of the elevation of mercury by the action of air is formulated in such a way that the effect associated with one body (passive agent [patient]) is attributed to a cause associated with another body (active agent [agent]). We will call this type of explanation *heterogeneous* explanation. Let us now consider the explanation given by Pascal through the pressure itself of 'free air' exerted on the inner surface of mercury. Repeating and generalizing the proof given by Stevin in the 16th° century for the pressure in liquids, he proves that at two different altitudes we ought to observe two different values of pressure and that this difference is due to the *gravity of the air* (which was confirmed by the so-called Puy-de-Dome experiment). The demonstration uses an imaginary vertical cylinder made of a material of the same specific weight as air, which is in equilibrium under the influence of its own weight on the one hand and the pressure forces exerted by the air on the other. He establishes a relationship between the vertical variation in pressure and the specific weight of the air, i.e. a relationship between two properties of the same medium at one point. We can no longer distinguish here between an active and a passive agent, a cause and an effect, [...]. We will the term *homogeneous* explanation. Finally, in order to take into account all aspects, and in particular the quantitative aspect of the phenomenon, we must show that reciprocally the pressure of the air determines its specific weight through the law of compressibility (Boyle-Mariotte). This law, when formulated, was not explanatory in nature since it was the result of experience. However, modern molecular theory (Boltzmann) makes it possible to explain the law: molecules moving in all directions exert on the walls of a container, on a piston, etc., a pressure resulting from the *sum of their interactions*. The more crowded the molecules are, the more collisions there are, the greater the pressure, and this is the 'raison d'être' of the Boyle-Mariotte law. The explanation here refers to the molecular structure which is attributed to the system when we proceed to its in-depth analysis. We shall therefore use the term *bathigeneous* explanation (from the Greek word βαθύς, deep)" (Halbwachs, 1973, pp. 75-77).

Generalizing the characteristics of each type of explanation, Halbwachs links the concept of explanation to the concept of *representation* of natural systems through theoretical *models*. The representation of natural systems (sets of well-defined objects or entities that we isolate by thought and distinguish from the rest of the natural world) is not a mere description of them, nor is it simply derived from experience, but is constructed during transformations that both the natural systems (through experimentation) and the theoretical models that represent them (through logical-mathematical reasoning) undergo, at various levels that partially approach reality, but never constitute a faithful reproduction of it. In this context, explanation according to Halbwachs becomes *meaningful* when there is a change in the level of construction of a theoretical model at which a new relationship is established between the structure of a theoretical model and the structure of the natural system it represents, as revealed at the empirical level (Halbwachs, 1973, 1974).

Based on the foregoing, the *causal (heterogeneous)* explanation consists in introducing the action of the external world into the natural system we have defined. In this case it is possible to specify a passive agent, which is the natural system under study, and an active agent, which is the external world. The changes occurring in the active agent are interpreted as the cause of the changes occurring in the passive agent (effect). The most elementary form of cause-effect relationship is the so-called *simple causal explanation* where a change in one characteristic of the external world causes a change in a corresponding characteristic of the physical system. The simple causal explanation is usually accompanied by a definition of the *conditions* which are likely to allow the cause to act. For example, in the causal explanation of the composition of water, the system of the mixture of oxygen and hydrogen is the cause of the production of water. This cause is a necessary but not sufficient factor to produce an effect and therefore we take into account the possible conditions of its production which may be local heating or some other catalyst. In the case where the effect of one cause is able to produce in turn another effect, we are talking of *linear causality* in which a *causal chain of* simple causal explanations is established. The motion of a ferromagnetic material near an electromagnet which is magnetized when an electrical circuit is activated can be described by a series of simple causality relations. The simple causal explanation is usually incomplete because it is often possible that the same change-cause can cause different changes-effects or even that the same effect can be the result of different causes. In these cases, we either look for more causes, or we need to go beyond simple causality by approaching other forms of explanation.

A more sophisticated type of causal explanation is the *circular causality*. This arises, for example, when phenomena are observed which correspond to the inverse causal relation of a simple causal relation. The inverse causal relation may occur simultaneously or succeed in time the preceding causal relation. From the very interesting examples of circular causality given by Halbwachs in his text *Causalité linéaire et causalité circulaire* *en physique* (Halbwachs, 1971), we choose the one concerning the explanation of the motion of a simple pendulum. In this case it appears that the force exerted on the pendulum ball can modify its motion (du/dt = F/m) but, *reciprocally*, it is possible to claim that the motion of the ball can modify the constitutive force (F = -kx). The logical difficulties that characterize circular causality (in this example, e.g., the possibility of determining the change in distance by means of a force that ought to be determined by distance) are removed when there is a change in the level of the theoretical model and, hence, of the type of explanation. In this particular case, the logical contradiction is removed within the more abstract model of Analytic Dynamics (through the solution of the differential equation $d^2x/d^2t = - kx/m$). The circular causal explanation, which historically defines large areas of classical Physics such as Newtonian Mechanics and the classical theory of Electromagnetism, is according to Halbwachs a necessary intermediate stage to lead from the simple causal explanation, which is a heterogeneous explanation, to the homogeneous or formal explanation (Halbwachs, 1971).

In the *homogeneous* (formal) explanation, changes in the physical system are explained without reference to external causes. The concept of explanation in this case characterizes the evolution of the state of the system under study and is limited to highlighting a relationship between the various variables of the system itself. These relationships take on an explanatory meaning because they highlight certain characteristics of the system such as the simplicity of its description, the *symmetry* of its structure or the existence of an *invariant characteristic* during the various transformations that the system undergoes. Typical cases of homogeneous explanation are the mathematical relations describing the motion of a body in free fall or, more generally, any relation in kinematics, as well as the Lagrange and Hamilton equations of motion in Analytical Dynamics. The fundamental law of Mechanics, when expressed in the form of the Lagrange or Hamilton equations, loses its causal form and appears as an expression of a "homogeneous" law (Halbwachs, 1971). In the category of homogeneous explanation, we can also place the description of how an electrical circuit works by means of the laws of conservation of electric charge and electric energy.

Finally, the third category of explanation, the *bathigeneous* (microscopic) explanation, consists in referring to a deeper level of analysis where the description of the changes in the system becomes more sophisticated and is done using new, qualitatively different, variables. The explanatory value of the relations described by these new variables is that the relations described at this level take account of what happens at the immediately preceding level of representation of reality, while at the same time this representation makes it possible to incorporate new phenomena into the same theoretical framework, as, for example, in the case of the molecular theory of matter, which makes it possible to explain not only the laws of gases but also the laws of Brownian motion, the diffusion of light in homogeneous fluids, etc. (Halbwachs, 1971).

The relationship between forms of explanation and children's thinking

As already mentioned earlier, Halbwachs worked closely with the *Centre International d'Épistémologie Génétique* in Geneva and with Piaget himself. In the context of this collaboration, he proceeded to correlate the various types of explanation in the natural sciences with the various explanatory schemes that children develop during the four stages of childhood intellectual development, particularly with causal explanations and, more generally, with the psychological dimension of knowledge (Piaget & Garcia, 1971; Halbwachs, 1974, 1981a). Halbwachs links the concept of explanation at the epistemological level with the concept of *understanding* at the psychological level and argues that children's understanding of the natural world, through subjects' actions on objects and the transformation of these actions into logical-mathematical schemas, occurs *mainly* through causal (heterogeneous) explanation. Causal explanation is the *privileged* way with which children represent physical reality (Halbwachs, 1971). Based on research conducted at the *Centre*, it is claimed that circular causal explanation, which can play the role of an intermediate knowledge between a causal explanatory schema and a homogeneous scheme of greater explanatory value, does not appear by the age of 13 (Halbwachs, 1971). He also admits that in far *fewer cases* one can also find homogeneous explanatory schemas such as all those related to the acquisition of the concept of conservation (e.g, the construction of the conservation of the shape of a piece of plasticine that occurs not through direct observation, but through an a priori idea that is suddenly born) or even certain bathigeneous explanatory schemes (e.g., the construction of the notion that sugar dissolved in a quantity of water splits into smaller and smaller pieces that end up becoming invisible). He also points out that some of the children's ideas that seem to fit the homogeneous explanatory scheme, such as their use of the concept of force (or "momentum") when attempting to describe the changes in motion of two balls colliding, rather belong to the causal explanatory scheme. In this particular example, children perceive "force-momentum" not as a state of the system, but as the cause of the motion of one of the bodies (Halbwachs, 1974). At the epistemological level, the concept of this undifferentiated concept of force can be associated with the concepts of momentum and kinetic energy which belong to the category of homogeneous explanation of the phenomenon. The explanatory function of the relevant theoretical model results from highlighting the feature of the conservation of these entities during the transformations that the system undergoes. However, by younger children this phenomenon is usually understood in the context of a causal explanation.

Halbwachs accepting the parallelism between explaining at the epistemological level, and understanding at the psychological level, i.e., attributing significations and *rational causes* (*raisons d'être*) to the changes that natural systems undergo, not only tries to interpret the child explanatory schemes, but also reaches particularly interesting conclusions about the meanings that can be attributed to the concepts with which the various theoretical models of Physics are constructed at the level of their historical development. Thus, for the fundamental law of Mechanics he claims that:

> "[this relation] is not only a mathematical relation between two vectors, but it contains above all a *causal* meaning according to which force is the cause and acceleration (i.e. motion) is the effect. [...] it is clear that although the mathematical expression alone allows the solution of the theoretical problem of motion, on the contrary, at the psychological level, the causal meaning becomes necessary for its understanding" (Halbwachs, 1981a, p. 210).

Although it is also possible to determine force through motion (as was the case with Newton's determination of the force exerted by the sun on the planets starting from Kepler's equations of motion of the planets), the reverse determination always reveals a different cognitive status. "We will easily say that the law of force [$F = ma$] is the *logical cause of* the law of motion [$a = F/m$] and not the opposite" (Halbwachs, 1981a, p. 212).

Finally, the example related to the description of the operation of an electrical circuit is even more informative:

> "Let us observe the non-causal character of this system of propositions [refers to the relations describing the principle of conservation of electric charge and electric energy in the circuit]. But if we were to reveal a causality (and thus give the theory a causal meaning) we should have to start with the generators and the power they supply to the circuit. This power, which would play the role of a 'causal influx', would then be distributed in a defined way to the various parts of the circuit. But, except in certain very simple cases, we will not be able to solve the problem in this way and consequently it is not the *cause* (generators supply) that is able to provide us with the *logical cause* (*raison*) of the specific operation of the system and in particular of the distribution of the current intensity in the various parts of the circuit" (Halbwachs, 1981a, p. 215).

In what follows we are going to argue that Halbwachs' views on explanation in Physics, both at the epistemological and psychological level, can be analytical and synthetic methodological tools in the context of the field of Didactics of Physics which deals with the constructivist approach to learning and teaching. More specifically, we will argue that Halbwachs' views are able on the one hand to *explain* certain aspects of contemporary research on students' cognitive representations of natural phenomena and Physics concepts and on the other hand to contribute to the *evaluation of* Physics teaching programmes and/or to *the design of* programmes that go beyond the traditional conception of Physics curriculum construction (Koliopoulos, 2006).

The impact of Halbwachs' views on the analysis of students' mental representations

In the context of the constructivist approach to learning and teaching in science, a research current has been developed for at least four decades that has focused on the investigation of the mental representations that students have when they attempt to describe objects, events and situations encountered in the natural world (Boilevin et al., 2022; Driver et al., 1985; Koliopoulos, 2006; Viennot, 2001). Students' cognitive representations and their evolution are cognitive classification systems of the views expressed by students that have been produced through specific research strategies and techniques. This research now goes beyond the level of mere accumulation of empirical data and is considered mature enough to attempt valid generalizations with a view to their effective use in the development of appropriate teaching strategies at different educational levels. Halbwachs' views may help us, on the one hand, in *reading* the findings of relevant research, i.e., in trying to make *sense of* the results of such research, and, on the other hand, in formulating *hypotheses* related to the investigation of students' mental representations in various areas that have already been studied or are of interest to be studied in the future. In this paper we will comment, in the light of these views, on the results of investigations coming from different fields of Physics, especially from the fields of Mechanics and (macroscopic) Thermodynamics which, for historical, scientific and social reasons, are fundamental subjects in modern Physics curricula (Koliopoulos & Meli, 2022).

The first studies on the nature and characteristics of students' mental representations were conducted in the field of Mechanics. These investigations revealed a number of alternative mental representations that students use frequently, repeatedly and over time when asked to describe mechanical phenomena such as the motion of bodies under different conditions and to solve related problems that require the use of the conceptual framework of Newtonian Dynamics. Some of the most important mental representations are the presence of a force, when there is motion, in the direction of that motion (Viennot, 1979) and the absence of force when there is no motion (Minstrel, 1982). In both cases, a causal force-motion relation occurs (in modern terms Viennot represents it in the vector relations $\overline{\mathrm{F}} = a\overline{\mathrm{v}}$ and F = 0 if v = 0), but where the meaning of the force concept is completely different from that of the Newtonian force. This force presents more the features of the "Aristotelian force" and appears as the cause of motion, especially when the motion is an initial condition. It is closely related to the *overall motion of* the object, i.e. it does not appear as a function of a point (Viennot, 1979).

On the other hand, there seem to be appropriate physical situations, such as the collision of two spheres (Grimellini-Tomasini et al., 1993), where the students' conception of the force that one sphere "has" can be related to the concept of *work* that causes a change in the motion of the other sphere or the medieval concept of *impetus* that is transferred to another body. In both cases, it is not the Halbwachs homogeneous explanation which refers to the conservation of the quantities of energy or momentum (which the students do not seem to handle well), since the explanatory scheme involves an external cause in the physical system under study. The preceding as well as other cases of related research (Bliss & Ogborn, 1994; Gutierrez & Ogborn, 1992; Halloun & Hestenes, 1985; McCloskey & Kargon, 1988; McDermott, 1984) show that in the field of Mechanics, students' mental representations associated with mechanical phenomena and especially with the phenomenon of motion on the one hand show a qualitative difference from the explanatory models of Physics and its traditional school version and on the other hand highlight the fact that "the most pregnant relations [which children use] are those expressing causality" (Halbwachs, 1979, p. 170). Also, another science education researcher, Besson (2004, 2010) compared causal explanatory schemes of high school students with the corresponding types of explanations in solid and fluid Mechanics situations and found that students' explanatory schemes are indeed fundamentally causal but either confuse the actual cause with the conditions that allow the cause to act, or they identify as the cause another entity with similar characteristics to those of the real cause (for example, they confuse the entity 'force' with the entity 'pressure').

Causal explanations given by students of different educational levels have been identified for other fields than Mechanics. Anderson (1986), in a well-known study, presents empirical data according to which students, in order to explain natural situations related to different fields of Physics (Heat, Electricity, Optics, Mechanics, etc.), use a reasoning whose common core is its causal character ("experiential gestalt of causation"). In this explanatory model, an active agent (cause) is identified which, indirectly or directly, affects an object and creates perceived changes (effect) in it. In fact, the *greater* the action of the active agent on the object, the greater the perceived changes may be. For example, students consider that the greater the amount of heat added to a quantity of water, the greater the temperature of the water will increase. Using this reasoning can give both correct and incorrect predictions (many students, usually of younger age groups, predict that the temperature of water will continue to increase beyond 100^0 C). Students also assume that connecting more batteries to a simple electrical circuit will result in an increase in the brightness of the bulb, but this is only true in the case of connecting the batteries in parallel.

Tiberghien (2004) in an interesting review of work related to the study of students' mental representations in the light of causality, confirms the specificity of students' causal thinking which takes the form of linear causal reasoning but seems to depend on the type of *physical situation* to which it is applied. He states, for example, that the type of causality used by younger pupils differs in situations in which a body is heated and in situations of insulation. In the former, students usually refer to the term "heat" as a mediator between the active agent (the body which heats or cool) and the object of heating/cooling. But in the case of an insulating situation (e.g., keeping a beverage hot in a container), the active agent is the material of which a container is made (or its ability to retain "heat" or "cold") which affects the object to be insulated ("cotton keeps hot bodies warm", "aluminium keeps cold bodies cold"). This type of causality, unlike the type of causality used in the heating condition, does not allow the use of a mediator and so no term "heat" appears.

The concept of causal explanation, according to Halbwachs, requires a special discussion of the importance of time as a criterion for the constitution of a causal relation. According to him, in causal explanation, depending on whether or not the various physical systems are separated in space, two events in the causal chain under study may be considered to take place simultaneously or to precede one another (Halbwachs, 1973). Viennot (1993) has been particularly concerned with the way in which pupils and, especially, university students conceptualize the relationships of various physical quantities in terms of time. The data presented by this researcher show that simple causal explanation is most often accompanied by the notion of *temporal succession*. Thus, in the case of pupils or students who claim that a ball continues to rise after it has been thrown because it "has" a force pushing it upwards, the cause of the phenomenon lies in an earlier moment in time (the force exerted by the person throwing the ball and subsequently "acquired" by the ball). From the foregoing it can be seen, therefore, that the notion of temporal succession that accompanies a simple linear explanatory scheme is a characteristic obstacle to the development of (independent of time) explanatory schemes that are approached through either circular causal or homogeneous explanation. At the same time, Viennot and colleagues argue that the use of temporal succession can negatively affect the responses of students when trying to solve problems related to transformations of natural systems with many variables. Typical examples are related to the field of (macroscopic) Thermodynamics. It has been observed that students give explanations of the form $\Phi_1 \rightarrow \Phi_2 \rightarrow \Phi_3 \rightarrow \ldots \Phi_n$ where each phenomenon Φ is characterized by a single variable. Thus, first-year students trying to explain the isobaric heating of a perfect gas use the linear causal explanation: Q (heat) → T (temperature) ↗ → p (pressure) ↗ → V (volume) ↗ where the increase in pressure contradicts the isobaric process. For students, however, this contradiction does not exist because they perceive the process in a time sequence which is often explicitly expressed. A typical example of the formulation of this perception is the following: "In a first time (Q → T ↗ → p ↗), the piston is blocked, while in a second time the piston is released, the gas volume increases and the pressure returns to its initial value, equal to the external pressure" (Rosier & Viennot, 1991; Viennot, 1993). This reasoning, which ignores the simultaneous change undergone by the various variables that characterize a thermodynamic system, certainly constitutes a serious obstacle to the study of this system by changes of thermodynamic equilibrium states as is the case with the commonly accepted scientific knowledge taught in secondary and tertiary education.

More recent research confirms these findings. A number of studies investigating the mental representations of students at different educational levels regarding the concept of energy show that they are able to formulate a spontaneous physical causal explanation that allows them to describe the operation of different objects as chains of objects in terms of their *function* and/or in terms of the transfer of an *action* from one object to another (e.g., the operation of a simple electrical circuit or the movement of an object by means of a spring) (Koliopoulos et al., 2009; Lemeignan & Weil-Barais, 1994). It seems, however, that while these pre-energy mental representations provide a suitable background for the construction of energy explanations by children of these ages, for students of higher educational levels they constitute a conceptual obstacle as we have already mentioned. Recent investigations related to the nature and characteristics of the mental representations of high school or introductory level university students regarding concepts of macroscopic Thermodynamics have confirmed the generalized use of linear causal reasoning. This led students to formulate alternative explanations by adopting a temporal sequence of phenomenological states (e.g., changes in a gas), omitting physical quantities when solving related problems and/or focusing on an exclusive relationship between two physical quantities, which is only valid if the other quantities remain constant during a thermodynamic change (Kautz, et al., 2005; Leinonen et al., 2012; Meli, et al., 2016).

From what has been said above it becomes, in our opinion, clear that Halbwachs's positions on the different types of explanation in Physics can largely determine the extent of the qualitative difference between the thinking of pupils and students and the proposed scientific knowledge at different levels of education. That is, the distinction between homogeneous, heterogeneous (causal) and bathygeneous explanation is able to give a more general *meaning* to the difficulties encountered by pupils and students in their attempt to describe and interpret the natural world, as identified in the various investigations. At the same time, this distinction may provide reference knowledge and a source of inspiration for the design of *new research* related on the one hand to the identification or confirmation of mental representations in new cognitive domains or new age groups, and on the other hand to the design of teaching interventions aimed at overcoming conceptual and methodological obstacles in the effort to limit and bridge (where epistemologically possible and didactically feasible) the differences between students' thinking and the proposed scientific knowledge.

The impact of Halbwachs' views on the analysis and design of the conceptual content of physics curricula

Halbwachs' positions seem to be able to explain not only the findings of various studies on students' mental representations in mechanics, macroscopic thermodynamics and other branches of physics, but also to contribute to the formulation of general hypotheses related to the design of the *conceptual content* of the Physics curriculum and the corresponding teaching interventions[2].

Various researchers (Dumas-Carré, 1987; Hestenes, 1992; Küçüközer, 2006; Lemeignan & Weil-Barais, 1994; PROPHY, 1990; Tiberghien et al., 2009) propose the introduction of intermediate, *qualitative models of interactions* between different objects, which can then lead to the formalistic description of natural systems by means of the vector entity of the force. This option leads students to build a representation of reality at the experimental, cognitive and symbolic levels through hypotheses about the *reciprocity* of the effects that different objects have on others. This model seems to be related to the explanatory scheme of circular causality which Halbwachs considers appropriate for the *transition* from linear causality to more sophisticated forms of explanation which are required in the field of Mechanics. As he says, however, in order to build this sophisticated explanatory scheme, the mind first needs a long exercise at the level of simple causality (Halbwachs, 1971). At the same time, he points out the historical difficulties in moving from one type of explanation to another type of explanation, and identifies the nature of epistemological discontinuities between different explanatory schemes already in existence (e.g., the change from the causal explanatory scheme of the collision of two spheres to a homogeneous explanatory scheme of a change in their movement), which may have the effect that the change in an explanatory scheme cannot be achieved in an evolutive, linear way.

Other researchers suggest the introduction of the concept of *momentum* as an alternative perspective in the teaching of Mechanics at the introductory level of higher education. DiSessa (1980) introduces the concept of force as the rate at which momentum changes (flows) from one object to another by accompanying the corresponding theoretical model with a graph where the different interacting systems are clearly defined. This researcher claims that this model is closer to the experiential mental representations of students and that they are able to conceptualize certain physical states

2 The literature on teaching and learning concepts and methods in Mechanics is very rich. In this paper we are not so much interested in a systematic review of this literature, but in highlighting those epistemological and teaching choices that are consistent with the context of the nature of Halbwachs' explanation. Halbwachs himself, of course, has published relevant texts (see the paper *by* D. Koliopoulos in this issue), and his paper *Genetic development of the concepts of mechanics and application to teaching problems* which is also published in this issue refers to just such an alternative proposal for teaching Mechanics addressed to students aged 13-14).

situations better than using the formalism of the second law of Newtonian mechanics. Hermann & Bruno Schmid (1984) also use the same concept to explain states of mechanical equilibrium. Using Halbwachs' views as a tool to analyze the two previous, heretical one might say, approaches, we realize that the replacement of the formalism of the second law of Newton by the formalism of the change (flow) of momentum is consistent with the need to exploit the scheme of simple causal explanation in case this scheme can *assist* the spontaneous mental representations of pupils/students (a "force" transferred from one object to another) to develop into explanatory schemes compatible with modern scientific knowledge (Newton's 2nd law in the form of the change of momentum, conservation of momentum).

Mechanics is one of the fields where there has been a long and thorough investigation of the students' mental representations. The main long-standing conclusion of these investigations is that the structure and characteristics of the explanatory schemes used, even after teaching, do not correspond to the structure and characteristics of the explanations given through traditional teaching programmes. An entirely typical example of the findings of these studies is the work of Clement (1979, 1982). In one of his papers, the researcher reports that the conceptions of the students who participated in that research (first-year students of a department of Physics) were modeled as a network of *causal expectations,* and pointed out that causal conceptions of this type represent an important level of student knowledge that can provide an intuitive foundation for understanding many quantitative laws of Newtonian Mechanics and that they are also natural starting points for building such a foundation (Clement, 1982). Curiously, there seem to be few papers in the field of Didactics of Science that explore the possibilities of designing contents and teaching activities in Mechanics that, on the one hand, take into account this basic conclusion and, on the other hand, offer contents and teaching activities that lead students to improve, transform and/or overcome their simplistic mental representations. In our opinion, therefore, Halbwachs' views on the different types of explanation, on the nature and characteristics of each of them, on the intermediate steps leading to a more sophisticated type of explanation, and on the correlation of these different types of explanation with the possible explanatory schemes used by students/students (precisely because they were produced through an anti-empiricist, historical and genetic analysis), contain the potential not only of an *epistemological reading of* the findings of research on the evolution of students' mental representations (cf. previous section), but also of a *teaching strategy* for integrating these findings into the process of designing and implementing the conceptual content of Physics curricula.

Based on the foregoing, it is possible to propose frameworks for possible reconstructions of the conceptual component of the school science knowledge[3] of the cur-

3 Halbwachs' views may lead to didactic hypotheses related to the *conceptual component of*

ricula that result from the connection between Halbwachs' views and the findings of relevant research on students' cognitive representations. We distinguish two directions of reconstruction frameworks:

(a) It is possible to implement *local modifications* to the conceptual content and teaching activities of existing curricula of Mechanics through the introduction of *qualitative theoretical models* that will act as intermediate conceptual steps from the initial mental representations of students towards the desired version of school scientific knowledge. These modifications concern the introduction of natural situations which require, in principle, the activation of the predominantly experience-based explanatory schema of linear causality and the step-by-step modification of this schema towards more sophisticated forms of explanation.

The activation of the simple causal explanatory scheme in mechanical phenomena can lead to the construction of mental models even in early childhood, as in the case of the construction by preschool children of a *precursor model* for the concept of *friction* (Ravanis et al., 2004, 2008). It is also possible to replace part of the subject matter of Mechanics, in which the dominant explanation is Newtonian Dynamics, with appropriate content in which the type of explanation is closer to the causal mental representations of the students. A typical example of such a proposal is the replacement, at the lower secondary level, of the study of the simple pendulum through the dynamic analysis of its motion with an approach that favours the use of simpler causal schemes, such as the study of the factors affecting its period (Dossis & Koliopoulos, 2005; Koliopoulos & Constantinou, 2005). The introduction, also in both primary and secondary education, of qualitative intermediate models, at the basis of which lies the qualitative concept of *interaction* (Lemeignan & Weil-Barais, 1994; Sensevy et al., 2008) which can lead, first of all, to the evolution/transition of the simple causal explanatory scheme and the construction of a more abstract form of causality such as, for example, circular causality.

In Greece, unfortunately, there are no coherent views on the introduction of mechanical phenomena through the field of Mechanics in the curriculum with the proposed modifications. This is not only due to the traditional curriculum's adherence to the field of Mechanics as the predominant field for the conceptualization of natural

scientific knowledge (Baltas, 1990; Koliopoulos, 2006; Nersessian, 2008) which, although necessary, are not sufficient for an overall picture of a proposed alternative form of content and teaching activities. At the same time, hypotheses related to the *methodological component of* scientific knowledge (e.g., empirico-inductive vs. hypothetico-deductive images of science, laboratory work, nature of science approach [Astolfi et al., 1991; Hodson, 1988; Koponen & Mäntylä, 2008; Paraskevopoulou & Koliopoulos, 2011]) and/or the *cultural component* of this knowledge (e.g., scientific knowledge as a cultural object, History of science in the teaching of Physics) [Galili, 2017; Gauld, 2014; Koliopoulos et al., 2022]) should be formulated.

phenomena, but also to the insufficient relevant research that takes into account the constructivist approach of teaching and learning, which would highlight the need for the *gradual construction* of various types of explanations according to Halbwachs. However, the second framework for reconstruction of the curriculum that we propose is considered to help overcome the above difficulties.

(b) The idea of downgrading the important role that Mechanics plays both internationally and in the Greek curriculum can be supplemented by the idea of a corresponding upgrading of the role of (macroscopic) *Thermodynamics* on the basis of the principle of conservation of energy and especially of the first law of Thermodynamics. This is currently a minority idea, but nevertheless possesses interesting historical roots and, in our opinion, a solid epistemological background. At the epistemological level, the physicist and philosopher Ernst Mach, who lived in the second half of the 19th century and the early 20th century, is known, among other things, for his position that the field of Mechanics, although it has a historical lead in the development of scientific knowledge of Physics, does not constitute the foundation for the constitution of this knowledge. On the contrary, in his work *The Science of Mechanics, a critical and historical account of its development* he identifies as fundamental knowledge the principle of conservation of energy as the expression of an invariant, quantitative correlation between mechanical and other types of phenomena (Mach, 1919)[4] . In fact, at the level of teaching, Drago (1994), adopting Mach's positions, proposes a teaching program that emphasizes and gives a leading role to Thermodynamics not only for epistemological but also for social reasons ("The concepts of work and energy can be considered 'social' concepts as opposed to the anthropomorphic and isolated concept of force", p. 195). At the same time, he proposes that Mechanics be taught in a mathematically equivalent way to Thermodynamics by replacing the abstract second law of Newtonian Mechanics with a generalized form of the principle of virtual work. Halbwachs himself, although he does not explicitly express the idea of upgrading the role of Thermodynamics and the concept of energy in general in the Physics curriculum, systematically deals both with the historical and epistemological aspects of various energy concepts such as work, heat and the conservation principles (Halbwachs, 1980, 1981b, 1983), as well as with the psychogenetic specificity of children's thinking about this field of knowledge (Halbwachs, 1978; Vergnaud, et al., 1978; Halbwachs's text in this issue). Moreover, in his attempt to translate some of

4 Our acceptance of Mach's views does not mean that we adopt, in this text, his instrumentalist view and his empirico-positivist orientation. Nevertheless, much of his views on the teaching of science, such as the introduction of historical and philosophical elements in science teaching or the anti-dogmatic introduction of scientific knowledge, which seem to have influenced contemporary views in science teaching and learning (Matthews, 1990), are fully compatible with the ideas developed in this paper.

his ideas into didactic proposals (such as the idea of introducing into the teaching of Physics at lower educational levels the concept of heat as a flowing substance precisely because it possesses data according to which children easily formulate an a priori idea of the conservation of heat), he contradicts the traditional educational system of his time (see Dupin's text in this issue).

In Greece, similar ideas have been expressed to upgrade the teaching of energy. Appropriate didactic interventions have been proposed so that secondary school students are able to approach *mechanical phenomena* not through the abstract and mathematized field of Mechanics, which requires mainly homogeneous Halbwachs explanations, but through the didactic transposition of elements of macroscopic Thermodynamics by exploiting, initially, the familiar to students explanatory scheme of linear causality (Koliopoulos & Ravanis, 2000a; Koliopoulos & Ravanis, 2001). It has also been observed that even preschool and primary school children are able to evolve the spontaneous natural causal explanation that allows them to describe the operation of different objects as chains of objects in terms of their function and/or in terms of the transfer of an action from one object to another. This development takes the form of *pre-energy models* of thought based on linear causality, while at the same time it broadens their *phenomenological field* of application (Delegkos & Koliopoulos, 2020; Koliopoulos & Argyropoulou, 2011; Sissamperi & Koliopoulos, 2021).

In the above relevant research, it seems that "teaching cannot ignore the simple causality with which students operate and that this is not necessarily a barrier, but can be a *learning factor*" (Tiberghien, 2004, p. 69). At the same time, as other research with students at higher educational levels shows, it is possible to design appropriate teaching activities that will lead these students, through overcoming the conceptual obstacles of linear causality, which we have already mentioned in the previous section, to the construction of quantitative energy relations in the context of the *first thermodynamic law*. Therefore, taking into account both Halbwachs' ideas and the conclusions of the above studies, we could claim that the upgrading of the role of macroscopic *Thermodynamics* in the Physics curriculum could be the *organizing principle* of the whole curriculum, at least at the level of compulsory education, in such a way that mechanical phenomena could be part of a balanced phenomenological field of application and not the par excellence field of initiation of students into the ideas of Physics (Koliopoulos & Ravanis, 2000a, 2000b; Koliopoulos & Meli, 2022).

Epilogue

It often happens that data concerning the research on students' mental representations are produced without having formulated specific epistemological or/and didactic hypotheses, so that a group of researchers come to the conclusion, wrong in our opinion, that the current of research on students' mental representations has exhausted its potential. On the contrary, we believe that it is imperative to continue the relevant research, as long as it is accompanied by clear and comprehensive hypotheses about content and teaching activities that lead to clear cognitive progress for the intended audience. Halbwachs's views may still act as a catalyst in this direction.

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