Genetic development of the concepts of Mechanics and application to teaching problems[1]

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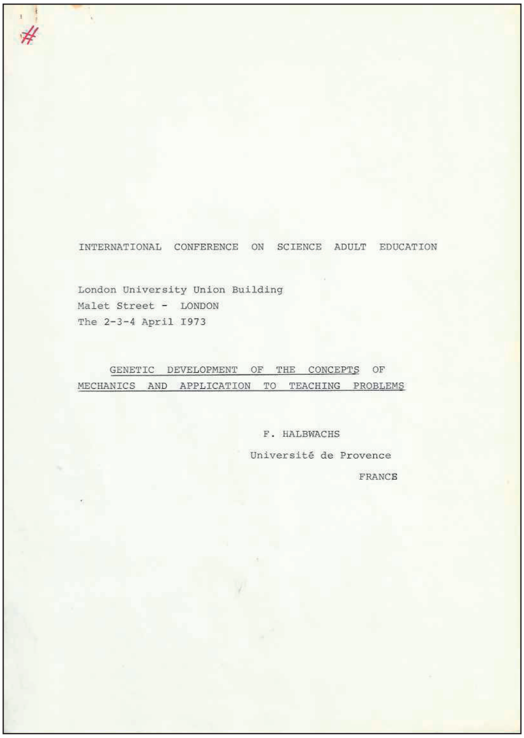

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GENETIC DEVELOPMENT OF THE CONCEPTS OF MECHANICS AND APPLICATION TO TEACHING PROBLEMS

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I feel puzzled as I am going today to speak about child teaching and not about adult education, because my point of view is rather philosophical. However, the first defect can cancel out the second defect. As a matter of fact, adult education, especially science adult education, is one of the most important tasks of our time. Like each global task met by modern mankind, this can only reach the required wide result if a systematic scientific method is constituted, founded in turn on one or more fundamental sciences.

Currently, as is well known, such a scientific method fails in a large measure to the teachers in the field of adult education; thus, they are restricted to empirical approaches, so they run the risk of being limited to partial and inefficient operations. It is the most imperative duty today to build up a science of educational methods and, it seems to me, after the most part of what was told there, it is just the task the present conference intends to begin with.

1 Draft of paper presented in the International Conference of Science Adult Education, London, 2-4 April 1973 (typed text, retrieved from Halbwachs archives, 2024).

Here, I want to present some observations and suggestions concerning an aspect - particularly, to tell the truth - of this program, dealing with the teaching of the basic notions of Mechanics; however, I shall do this regarding the general features of the science-teaching problem. Likewise, while I found my consideration of an experiment on children's teaching, I want to emphasize my insistence on the general characteristics of educational problems, which are also valid for adult education. In fact, until several years, I had to deal with young as well as with grown children, with adolescents, with students, end even with adults, as I took part in four years to teach in the most important French institution for adult education, the Conservatoire National des Arts et Metiers, which manages about hundred thousand students in the whole country, and where I had an interesting but difficult task to teach Quantum Mechanics to industrial workers. Now, to illustrate some general reflections, I chose the example I shall speak about because it is especially simple, and above all, because I had the opportunity to make capital out of the important and secure work of the main team of researchers in child psychology, that of Piaget in Geneva. However, I assert the general validity of most of the ideas I have put into evidence.

It is indeed this generality, which carries us into a methodological field we may consider scientific, and this is just why these considerations can be profitably applied to adult education problems.

To explore the conditions for science teaching to work conveniently at a deep level, we must specify - with the risk of looking pretentious - what is exactly the aim of scientific knowledge. We limit ourselves to Physics as an example, but it must be clear that at various levels, the distinctions introduced here can be found again in any field where there may be spoken of teaching.

A Physics lesson is generally composed of two elements. On the one hand, descriptive information that tell us what is to be *seen*, or which describes us phenomena as if they could be seen. For instance, planets turn around the sun, light propagates in a straight line, and crystals are composed of atoms disposed regularly. On the other hand, a statement of definite *relations* generally appears in mathematical form. For instance, the time derivative of the velocity of a material point equals the force acting on it divided by its mass. These relations are established between various notions that have the same name as concrete objects or physical qualities but represent *concepts* that are objects of thought and differ essentially from the objects of experience. Therefore, in the example quoted, force and velocity denote no other things than vectors with different transformation laws with respect to moving frames, and mass is an additive scalar. Many different opinions can be proposed regarding the relative importance of these two types of statements and their relative ability to properly constitute physical science. However, two points are out of the discussion:

First, from a didactical point of view, the building and management of concepts endowed with relations forms by far the most difficult part of Physics teaching. This part constitutes the most efficient aspect of Physics, by which Physics provides the man with peerless power and allows him to master and utilize the physical world. Therefore, this part is the most useful and important part to be taught.

The Physics teacher, if he has chosen this way - which is not at all obligatory, as can be seen from the opposite trends aimed at the description that are manifested among American teachers (for instance, PSSC) - he faces the following situation: any field of physical science, considered at a given level, appears as a system of organized *concepts*. These concepts are abstract; that is, they do not refer to a particular physical object or property, but to general classes: the force, no matter what its nature or the conditions of appearance, the material body, no matter what kind of substance it is constituted with, and the energy whatever its form is. These abstract concepts are bound together by logico-mathematical *relations*, which is precisely why the related concepts must be abstract concepts. Finally, the relationships are arranged to build global and consistent systems called *models*. The Physics teacher's aim is merely to build convenient models in the pupils' minds. More precisely, he must instigate and help the pupil build up such models in his own thoughts.

It is necessary to precisely define some features of the physical models. First, the most fundamental outcome of the logico-mathematical form of the relationships that constitute the model is the possibility of *transforming these relationships into other relationships* according to definite and precise rules. Any model is a dynamical mental edifice, the structure of which intelligence can transform to develop it and draw out more and more new consequences.

As the concepts which constitute the model are built up in parallel to the objects and properties of the physical world, the logico-mathematical transformations the thought performs on the model are likewise parallel to the transformations which happen in physical reality, so that the use of models gives rise to what some philosophers call "a theoretical practice" which allows the thought *to simulate the processes that take place in nature*. This is the deepest ground of what is properly called to *understand* these processes, which leads to foreseeing, handling, and mastering them. In this way, Newton's contemporaries were deeply impressed by his mathematical system that allowed the scientist to do the same thing as nature, and to build up by abstract computation, the same trajectories and motions that the actual planets are really travelling through in heavens.

On the other hand, if we want to draw the consequences of these ideas from a teaching point of view, we must insist on the nature and generation process of this basic model-building and model-managing activity of thought. In this field, as was shown by Piaget, the key notion is that of *operation,* which describes the elementary transformation peculiar to models built by intelligence. An operation is an action transposed in thought and endowed with the reversibility and composability properties that insert it into a global operation system. Piaget opened the way to a scientific understanding of the genetic development of the operative activity, which, from the concrete coordination of the actions and then from their systematization and completion, at a given stage ends with the complete building up of a model. This is a clue that may be used to guide scientific didactics and the way for education and training of model building and model managing activity.

Now, this conception tells us what the role of the *experimental activity* can be in Physics teaching - at least for the 13-14 years old children we are interested in; it is not to yield to the pupils the form of the mathematical relations ruling the model by the mere reading of experimental data. It is before all to allow them, by active manipulation, to keep contact with a concrete situation and to perceive certain qualitative covariations that can lead their actions and help them become aware of the coordination of these actions and build up the operative relations that constitute the model.

After we have specified what constitutes, in our opinion, the nucleus of scientific knowledge, as well as the system of thought and aptitudes, the teacher intends to build up in the pupil's mind, we may ask what the foundations of a general method can lead and promote such an operative model-building and model-managing activity. The assumption that our experiment is based on is that the most important instructions are brought out by a *genetic study* in the concerned field, that is, a study of the ways followed by the development of the concepts by the child (here, the concepts of Mechanics), as well as by the scientists considered through the history of science. Through such studies, we can directly observe the process of spontaneous building of operative models, and the analysis of this spontaneous process in terms of cognitive psychology yields precise suggestions that can lead to the construction of a science teaching curriculum scientifically suited to the operative level of the pupils under consideration.

Here, we want to present our experiment as an example of what is possible to do to build a detailed teaching program based on appropriate genetic studies. We deal with the assimilation of the concepts of Dynamics by 13-14 aged pupils in French secondary school. First, we would like to point out that in the usual French curriculum, Dynamics are taught only to 17-18 years old pupils because it is the most difficult part of Mechanics, while pupils learn Statics when they are about 15-16 years old.

However, many observations and experiments performed at Piaget's Psychology Institute in Geneva have shown that the static aspect of the force concept is very difficult for children, while the laws of Dynamics, as building an operative model, enter very early into an active development process, which ends in a correct apprehension of the acceleration concept and its variation factors, which is about 12 years in the period of transition from concrete to formal operation ability. Thus, it seems possible to propose an initiation program for 13-14 aged pupils, which starts directly from the child's intuition of Dynamics and finally builds a convenient model of the force, including its statistical measure. Therefore, we have put forward the plan of a teaching experiment for 12 classes in several secondary schools of Marseille, which was approved by the school authorities as a test that could lead to an improvement in the general Physics curriculum. We composed a sequence of lectures based on a detailed study of the building process of the principles of Dynamics by young children as well as by pre-Galilean philosophers and scientists. These preliminary studies, followed by the willing teachers taking part in the experiment, have provided us with many useful ideas on the logical model-building processes to be exploited didactically.

For instance, Piaget and Inhelder have shown that an 8-9 years old child, put in front of a ball rolling on a horizontal table implicitly looks for the cause of the ball rolling. At the age of 10-11 he reverses his question and seek the causes that ultimately stop the motion of the ball. And, after the age of 12, he can imagine a virtual situation in which all friction factors are removed, the ball goes on indefinitely, that is, to discover the fundamental inertia principle, through mere reflection and abstract operations, without any experimental evidence. Likewise, it is well known that Galileo's reasoning on the influence of air on falling bodies, as well as on the horizontal motion of a ball, is founded on qualitative observations of friction and symmetry considerations, and not at all on the actual removal of friction factors, nor on the effective observation of motions in vacuum (which was not feasible at the time). This was introduced in our lessons, where the pupils were asked to foresee what would happen if a train was freely thrown on the railway, and all the friction factors were made smaller.

In the concrete operation period, children build an original conception of mechanical causality. This conception reposes on the notion the child generally calls "impulse" (in French: élan); a notion which seems to be very close to the "impetus" of the Renaissance mechanics. The impulse of a ball is considered to increase with the velocity and weight or mass of the ball. It remains constant during free (horizontal) motion, as long as friction is removed and is transmitted with conserved magnitude in collisions with other balls. Further, if (what we call) an external force is acting continuously on the ball, its "action" along a certain range of space or time plays the role of a *global* operator transforming the initial state into a changed final state, more precisely increasing or diminishing the amount of impulse.

This global conception of the cause, considered an action, is analogous to the ideas of pre-Galilean philosophers. For Buridan or Benedetti, for instance, the "mover" communicates to the moving body a definite amount of impetus, and the longer the mover is acting, the higher will be the impetus. Once the moving body is disconnected from the mover, this impetus remains constant in the moving body and allows it to move freely, as it plays the role of a conserved "power of motion".

Now, if we consider this conception, along with the intuition of the inertia principle, as yielding the starting point for the development of the notions of Dynamics, from to 13-14 years of age, we can rationally formulate a teaching program for this development. Namely, the operative system of impulse and action corresponds to a loose intuition of both the linear momentum (the action is here the product of force by time) and kinetic energy (the action is there the product of force by distance, that is, the work); the final step of the program must be the model of a clearly defined force acting continuously and cumulatively, giving rise to a continuous acceleration.

As the intelligence of the child (as well as that of any untrained adult) works more easily in concrete situations, flowing directly from perception and imagination, we start with definite types of force and motion, namely, a heavy train pulled horizontally by a locomotive, then a system of two equal weights hung at a pulley and moved by a small overload, and finally a small parachute acted by the difference of its load and the resistance of air. In this way, the intelligence of the child progressively builds an abstract structure made up of the common features of all these concrete situations and forms an abstract concept of the force characterized by its dynamical role.

In the case of the starting train, the child finds immediately and spontaneously in his experience and imagination the schemas of a regularly increasing velocity of the pulling locomotive as the cause of this acceleration and of the dependence law of the acceleration on the locomotive traction, and on the train load. The Atwood machine introduces the gravity force and shows the dynamical difference between the weight, which is a vector that can be subtracted, and the mass, which is scalar and can only be added. Finally, the analysis of the parachute situation shows the possibility of a vectorial composition of two forces of different nature and ends in a higher status of abstraction of the force concept.

Furthermore, the composition of forces with different directions is very difficult to conceive for children in the case of equilibrium. For instance, in the situation of three concurrent strings acted on by springs or weights, 10 aged children asked by Piaget's collaborators say that 'if it moves, they draw'; 'if it does not move, they strain'; that is, in equilibrium, there are no forces. However, if the forces are in action, let us say to move a projectile, then the children understand the role of each force quite well. For instance, they properly describe the mechanism of a bow throwing an arrow and the role of the angle between the two parts of the string. Therefore, in our lessons, we introduce the composition of forces through a throw gadget made up of two concurrent rubber bands of various thicknesses and tensions and ask for the anticipated direction of the cast (Prof. Vinh Bang experiment). This appears to be a convenient method to understand the difficult problem of vector addition.

Therefore, a rigorous training approach has created a self-consistent operative model of the concepts of Dynamics in children's intelligence, as can be tested with control exercises, while the curriculum can be extended to include measurement of forces and further analysis of their static aspect.

As the experiment proceeds, I shall not say anything on assimilation testing, except regarding our computer-assisted checking plan. Together with a team of intelligence psychologists, we conducted a program corresponding to one of our lessons. It must be submitted to the trained pupils individually through a dialogue with a computer, not as a teaching program, but after the same lesson has been conducted directly, and as a test of the efficacy of this direct teaching. The computer is the 0.P.E. (IBC 360.60) of University Paris VII and the software was developed by my friend Prof. Jacoud. The computer is bound by a teletype set up in one of our schools in Marseille.

The program was schematized as a graph with many dispatching points and closed loops, as several answers were foreseen for each question. Thus, each pupil will follow a particular path in the graph, and by studying the result, we obtain a precise and detailed table for the frequency of each loop, which is a measure of each intellectual difficulty.

The most interesting feature of this procedure (which was strongly emphasized by Jacoud this morning) is that we are led to formalize the structure of the lesson very strictly, and to foresee the answers according to an explicit model of a child's intelligence. Therefore, the computer-assisted program represents in its formal structure the connection between the two models, the abstract physical model (with its seat in the scientist's mind), and the operative model of the child (hidden in the child's thought).

To summarize, through such a technique, which has a very wide validity, programming leads to an exact formalization of the model-building activity, as well as of the teaching activity that aims to induce such a model building. Therefore, it deserves to take its place among the methodological tools in the field of science education.