The historical burden on scientific knowledge

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Abstract

The development of scientific knowledge is compared with the evolution of biological systems. Just as every biological system inevitably contains fossils our physics syllabus contains obsolete concepts and methods. It is argued that the potential for simplifying the teaching of science by eliminating these historical burden is high. Several examples for obsolete concepts in physics are given.

Zusammenfassung

Die Entwicklung der Inhalte des wissenschaftlichen Lehrgebäudes wird mit der Evolution biologischer Systeme verglichen. Genauso, wie jedes biologische System zwangsläufig Fossilien enthält, so enthält auch der Physikkanon veraltete Begriffe und Methoden. Wir sind der Meinung, daß die Eliminierung solcher historischer Altlasten ein sehr großes Potential für die Vereinfachung der Lehre der Naturwissenschaft darstellt. Es werden einige Besipiele für veraltete Konzepte vorgestellt.

1. Introduction

The amount of scientific knowledge increases rapidly, whereas the time we dispose of to teach science remains essentially constant. Thus, in order to give a new generation of students an overview of what is considered the essence of contemporary science, knowledge has to be processed in some way. This problem is mostly solved by specialization: The students learn the nucleus of a science, physics for instance, in a more general and, inevitably, more superficial way and deepen their understanding only in a special subbranch of physics. Apart from specialization there is another way of coping with the increasing amount of knowledge. In this article we will argue that our scientific knowledge bears a great potential of simplification.

In section 2, we will compare the growth process of the physical knowledge with the evolution of biological systems. A consequence of this evolution is that the system appears to be very conservative and has frozen-in detours. It has preserved features which can be compared with biological fossils. In section 3, several examples of such historical burdens will be discussed. Section 4 contains conclusions and a proposition.

When presenting the ideas which are the subject of this paper to collegues or to students we often find a wide spectrum of opinions: from enthusiastic approval to vehement repudiation. We therefore should like to stress that we consider this paper as open to debate.

2. The evolution of scientific knowledge

In a certain sense, the growth of scientific knowledge is similar to the evolution of biological systems. Every person who is teaching science acquired his scientific knowledge before. Thus, facts are first received and later transmitted. This transmission, however, doesn't proceed without changes, because research brings new results and the teaching person will try to take these results into account. Such changes can be compared with mutations in genetics.

Generally, the changes and improvements a teacher makes concern only his specialty, whereas the general structure of science will be transmitted without alterations. Thus, the basic knowledge is not subject to the same selective pressure as more recent developments. Accordingly, the new knowledge is essentially attached to the old one without questioning the old nucleus. In the theory of evolution this phenomenon is known as *prolongation*. A greater restructuring will be more and more difficult, whereas the driving force for such changes becomes weaker and weaker. In other words: The more complex a system is the more conservative it will be. For this reason, the scientific knowledge reflects quite accurately its historical development. This statement reminds us of a rule which every student of biology has to learn: E. Haeckel's biogenetic law according to which “ontogeny recapitulates phylogeny”.

As a result, detours in the development of scientific knowledge may be preserved. Constructions which, in a larger context, reveal to be superfluous or inappropriate may be maintained. An old transient state may survive as a *living fossil* as geneticists like to call such a phenomenon. Even apparent errors may survive. Considering the actual physics syllabus very much can be learned about the history of physics. Indeed, one can even pursue a kind of archaeology in this manner. As a consequence, every student has to reproduce the historical developments. The individual student's process of learning proceeds, often up to the details, according to the same pattern as the development of science as a whole.

By citing the analogy between the evolution of science and that of biological systems, we want to show that the development of science toward more and more inflexibility is an inevitable and normal process and it is not a daring accusation to say that science is unnecessarily complicated and cumbersome. When we claim that science, as a whole, is in a bad state we don't mean that scientists have been incompetent. Those who worked for the advancement of science usually did the right thing in their time. Just like a biological fossil in a remote time accomplished an important function, many components of science, which nowadays may be considered to be superfluous or inappropriate, have played an indispensable part in the past.

The following objections regarding the elimination of historical detours might be put forward. The actual teaching of physics essentially follows the path history has taken. But isn't the historical way the most natural and the most efficient way to learn science? From the point of view of cognitive psychology isn't the path which the scientific community followed in the first place when making discoveries the easiest method to learn for an individual? Our answer is clearly no. The examples in section 3 tell us that very simple facts were often discovered only after going through complicated intermediate states. Only at the end one noticed that there was a shorter and easier way. Another possible objection might be the following: But isn't the history of science an important subject in itself? Yes, of course it is. But what we are commonly doing is not teaching the history of science. Teaching history means to analyse history and to reason about it, but not simply to retrace the historical path.

For several years, we have been searching systematically for subjects in the physics syllabus which might be considered historical burdens, i. e. superfluous or inappropriately presented subjects. We now have a list of such concepts which is long and continuously increasing (Herrmann and Job 1994).

We noticed that it is possible to classify scientific fossils. Some subjects have become obsolete because the basic concepts of science have been changed. One example is, that we still begin the teaching of mechanics with the Newtonian action-at-a-distance ideas. Some of the outdated concepts we have spotted refer only to a single word. The word “power” for the quantity P is an example. It stems from a time when energy and its currents could not be yet localized. The words energy flow or energy current say much more about the meaning of the quantity and are in agreement with the use of similarly structured quantities like electric current or mass flow. There are themes which have become obsolete because of the progress in experimental technique. So, we still introduce ferromagnetic materials as we did 50 years ago when the best hard-magnetic materials available changed their magnetization by the slightest magnetic field. Another type of historical burden is, that in different fields of physics which developed independently very different descriptions have come into being. Although the same quantities could have been used, the same models applied, the same intuitive ideas employed, all these concepts are different and the student has to learn two or three conceptual structures instead of one. An example is nuclear physics and chemistry. What in nuclear physics is the half-life the chemist will describe with the reaction velocity. What a chain reaction is for the nuclear physicist is called an autocatalytic reaction in chemistry.

In order to find fossils a certain attitude is necessary which might be considered a lack of respect. Indeed, it is a kind of disrespect in view of convictions which have developed by mere habit and indolence. It is no disrespect, however, for the achievements of the scientists who developed a new concept in the first place.

3. Examples

We have made the experience that often when we point to a subject which we judged to be an example of a scientific fossil we provoked a reaction of defense. In fact, questioning something to which one is accustomed and which one believes has proved to be correct is unpleasant. We can be convincing only by discussing a subject in all its details. This, of course, is not possible in the frame-work of one single article. In the following, we will therefore choose from our list of obsolete concepts only those about which we had published already in recent years in the European Journal of Physics or in the American Journal of Physics. The following is, thus, nothing more than a review and résumé of other articles, where the respective subjects are discussed in more detail.

The following presentations of seven examples will all be structured in the same manner. First, we will introduce *the subject*. Then we will describe what we believe is the inappropriateness or obsoleteness in the subject: *the flaw*. Finally, we will briefly explain how the subject came into being, i. e., what was the positive role it had played in the past: *the origin*.

a) Actions at a distance

The subject: The teaching of mechanics begins with Newtonian mechanics and thus, with the Newtonian view of the world. One essential feature of this view is the existence of actions at a distance. A manifestation of actions at a distance in our teaching is for instance to say that a body A exerts a force on body B without mentioning the role which is played by the system which is mediating the interaction.

The flaw: Since the great success of the first field theory, i. e. Maxwell's theory, we are convinced that actions at a distance are not an appropriate model of mechanical interactions (Herrmann and Schmid 1985a).

The origin: Although Newton disliked the idea of an action at a distance the time was not yet ripe for constructing a local field theory.

b) Newton's laws

The subject: Newton's three laws.

The flaw: All of the three laws are, from the viewpoint of modern physics, no more than the expression of the conservation of momentum. The first and the third are statements of momentum conservation for two special situations. This becomes particularly clear when expressed in the momentum current picture. Indeed, when considering that a force is no more than another word for a momentum current Newton's laws read as follows:

1. The momentum of a body remains constant as long as no momentum current is flowing to or from it.

2. The rate of change $d\boldsymbol{p}/dt$ of the momentum of a body is equal to the momentum current $\boldsymbol{F}$ flowing into the body:

$$d\boldsymbol{p}/dt = \boldsymbol{F}$$

3. Whenever a momentum current is flowing between two bodies A and B, the current F_A entering body A is equal to the current F_B leaving body B.

Expressing momentum conservation in such a complicated way is more obscuring than elucidating. Nobody would have the idea of stating the conservation of the electric charge in a similar manner (Herrmann 1979, di Sessa 1980, Herrmann and Schmid 1984, Herrmann and Schmid 1985b, Heiduck et al 1987).

The origin: For Newton his three laws appeared independent because they were part of a complicated network of definitions and observations. Of course, Newton did not put the conservation of momentum at the beginning of his arguments.

c) Energy forms

The subject: Energy appears in various forms: Kinetic and potential energy, electrical and chemical energy, heat, work and many others.

The flaw: Although we currently speak about energy forms we often enter into trouble when we have to define them. Often we are not consequent in distinguishing the classification methods for stored energy and for flowing energy. Many physicists are unable to explain why it is physically incorrect to claim that energy is stored in the form of heat. What part of the energy of a spring or an oxygen molecule is mechanical, thermal, chemical, electrical, magnetic, kinetic, potential, ordered or disordered? Classifying energy in forms is simply unnecessary and in those cases where it really has a clear meaning more appropriate ways to distinguish the systems or processes under consideration are available (Falk et al 1983).

The origin: When the concept of energy was introduced into physics in the middle of the 19th century speaking of energy forms was unavoidable. The new quantity had the strange property of having no property at all: Indeed, no property was known which would allow for a recognition of the energy content independent of the particular system. No general method was known to measure the energy content of a system. The construction of the new quantity energy was thus a great achievement and it was natural to speak about the energy as a quantity which appears in different forms. Certain devices or machines were consequently called energy transformers or converters. However, this situation lasted only half a century. In 1905, with the publication of the special theory of relativity, it became clear that energy is not so mysterious as it seemed to be. Since energy and mass are no more than two different names for the same quantity, energy has the same properties as mass: weight and inertia. It can thus always be recognized and measured, at least in principle, in the same manner.

d) Different structures in different fields of physics

The subject: Mechanics, electricity, thermodynamics and chemistry are four parts of science which have to be learnt separately. Each of these fields has its own structure and its own mathematical methods. Each uses its own models and paradigms.

The flaw: The four fields could be presented in such a way that a great similarity between them becomes apparent. When in each of them a characteristic extensive quantity and a conjugated intensive quantity are put in the center a similarity of the mathematical structures becomes obvious. The extensive quantities are momentum for mechanics, electric charge for electrodynamics, entropy for thermodynamics and amount of sustance for chemistry. The conjugated intensive quantities are velocity, electric potential, absolute temperature and chemical potential, respectively. One manifestation of the analogy is that in each of the four fields of science a particular energy transport exists, and for each of these energy currents a similar expression holds: The energy flow P is proportional to the flow of the characteristic extensive variable. Thus we have

$$P = v \cdot F$$

for an energy transport through a mechanical drive belt for instance (here v is the velocity and F the force or momentum flow). The energy flow by means of an electric cable can be calculated by

$$P = U \cdot I$$

(with the electric potential difference U and the electric current I), an energy current by a thermal conductor is related to the entropy current I_S through the conductor and the absolute temperature T by

$$P = T \cdot I_S$$

and the energy current carried by a substance current (entering a combustion cell for instance) is related to the molar current I_n and the chemical potential difference $\Delta\mu$ of the reaction in the cell according to

$$P = \Delta\mu \cdot I_n.$$

Another example of how the analogy works is the description of dissipative processes. In a mechanical dissipative process, i. e. a process with mechanical friction, momentum is always transferred from the body of the higher to the body of the lower velocity. Electric charge flows in a resistor from high to low electric potential. Entropy flows spontaneously from high to low temperature and a chemical reaction runs from high to low chemical potential.

These are only two of many other examples which show that teaching and learning can be simplified by taking advantage of this analogy (Schmid 1984, Herrmann 1995).

The origin: Different parts of physics have been developed independently. The structural similarities became apparent only at the end of the last century.

e) Fields as "regions of space with properties"

The subject: Fields are introduced as regions of space with particular properties. Sometimes, fields are considered as mathematical constructions which allow for the calculation of forces on a body, where that field strength has to be used which was valid before the body was there.

The flaw: In the traditional way of teaching the concept of field appears as a difficult concept. The student learns that space which is free of matter is empty, a kind of container without anything in it, or full of "nothing". Then fields are introduced as regions of space with certain properties. The cognitive conflict is unavoidable: How can "nothing" have any properties?

According to the point of view of modern field theory, the space filled by a field is not fundamentally different from space filled by matter. Just as a material system is characterized by the standard variables of physics (energy, momentum, electric charge, entropy, velocity, pressure, electric potential, temperature etc) and the relationship between them, in a field all these standard variables have certain values and are related in a certain way (Herrmann 1989). Thus, it is justified to introduce the field as a concept which is as concrete as a material system. It is not incorrect to say about a field that it "…attaches to every point in a system a *local property…*" (Purcell 1965). But we would promote a clearer view of a field by speaking about it as we are used to do when referring to a gas for instance: A kind of "stuff" with certain properties. It would neither be incorrect to introduce a gas by saying it attaches to every point in a system a local property, but nobody would do so.

The origin: For Faraday, the inventor of the field concept, the whole space was filled with a medium, called ether in this time. A field was no more than a particular state of the ether (a state of mechanical stress). This was a very simple idea. With the theory of relativity the ether was eliminated from the majority of the physics text books (but not from all). The field remained as a very strange concept: a state of empty space, i. e. of something which does not exist. Shortly after its expulsion from the textbooks the ether was admitted again, however, under the new name of vacuum. Now, the field concept could have taken back its original simplicity. It fossilized, however, into the awkward state of being a property of an object which doesn't exist.

f) Magnetic materials

The subject: Introducing the magnetism of materials one generally begins with the small para- and diamagnetic effects and then discusses ferromagnetism via the hysteresis curve.

The flaw: Not only students, but also teachers are more ignorant about magnetostatics than about electrostatics, although the magnetic forces we experience in our everyday life are much stronger than electrostatic forces. One of the reasons seems to be that we introduce ferromagnetism via the hysteresis effect. The student gets the impression that the behaviour of magnets is essentially determined by the hysteresis. For many modern *hard-magnetic* materials, and in particular those which are used to manufacture the majority of magnets around us, hysteresis plays only a minor role. For these magnets we have a constant magnetization $\boldsymbol{M}$ = const, which is imparted to the magnet in the process of fabrication. Modern *soft-magnetic* materials on the contrary can be described by the condition $\boldsymbol{H} = 0$. Of course, one can place a hard-magnetic material in an external field which is so strong that the "engraved" magnetization will change and one can place a soft-magnetic material in an external field which is so strong that saturation begins to manifest. But in a first introduction to ferromagnetism one should disregard these effects in the same way as we disregard deviations of a resistor from Ohm's law or deviations of an elastic spring from Hooke's law (Herrmann 1991).

The origin: Only 50 years ago ferromagnetism could not be reasonably discussed without referring to the hysteresis. The materials one was able to produce were yet far from what one might call an ideal hard-magnetic and an ideal soft-magnetic material. It was easy to change the magnetization of a permanent magnet by means of an external field. An unsuitable geometry of a magnet even caused a demagnetization of the magnet by its own field. The complicated behaviour of these imperfect materials could be understood only by considering the hysteresis curve.

g) The state variable entropy

The subject: When introducing entropy in the context of the so-called phenomenological thermodynamics one starts with the differential form δQ, called heat, and defines a new variable S by forming the integral

$$S = \int_{\text{rev}} \frac{dQ}{T}$$

It is generally insisted that S is a state variable.

The flaw: The properties of the physical quantity entropy coincide so perfectly with what in everyday language is called heat that entropy could be one of those quantities to which an intuitive access is most easy. Indeed, the correspondence between entropy and the everyday heat is better than the correspondence between what in physics is called heat and the everyday heat in one fundamental point: It is not allowed to say that a hot body *contains* heat when using the word heat in the sense of the quantity Q whereas it is correct to say it when using the word heat in the sense of entropy. Unfortunately, the students learn entropy in such an esoteric wrapping and with so many metaphysical connotations that he or she gets the idea that entropy is one of the most difficult quantities of the whole of physics. If entropy would be introduced in the same manner as any of the more familiar extensive quantities, electric charge for instance, it would be clear right from the beginning, that entropy is an extensive quantity, that it is reasonable to make a statement about its conservation or non-conservation (in fact, entropy can be produced but not destroyed), that an entropy density and an entropy flow can be defined and, of course, that it is a state variable. By the way, almost all physical quantities are state variables and we almost never find it worth mentioning. Never do we learn that electric charge or momentum are state variables, simply because these magnitudes are introduced in such a way that the fact is clear from the beginning (Callendar 1911, Job 1972, Falk 1985, Fuchs 1986, Fuchs 1987, Herrmann 1992).

The origin: From the time in which an extensive quantity with the name “heat” was introduced into physics by Joseph Black it was clear that heat was a state variable. Carnot used it in the same sense (the French wording was chaleur and calorique). Unfortunately, the word heat was taken away from this state variable in the middle of the last century when energy came into being. When the missing thermodynamic extensive state variable was introduced again some years later by Clausius the word heat couldn't be used anymore as a name: the name was already appointed to the process variable Q.

4. Conclusion

We have tried to show that a great part of what we consider to be the essential and indispensable contents of the physics syllabus have come to be part of it only by historical coincidence.

We are aware of the fact that some readers will argue that one or the other of what we gave as examples of obsolete concepts do not merit this judgement. However, the main purpose of our paper is not to convince the reader that every example given above is a fossil. Rather we wanted to show that antiquated concepts exist and that they are among those subjects which we are used to consider as fundamental. We also should like to encourage the readers to look for such concepts on their own and to stimulate a discussion in order to get a new consensus. Such a discussion is very gratifying. It leads to the insight about how much of our teaching is based not so much on the structure of our discipline, but simply on convention.

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